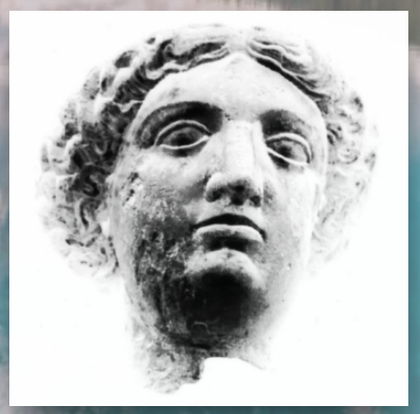
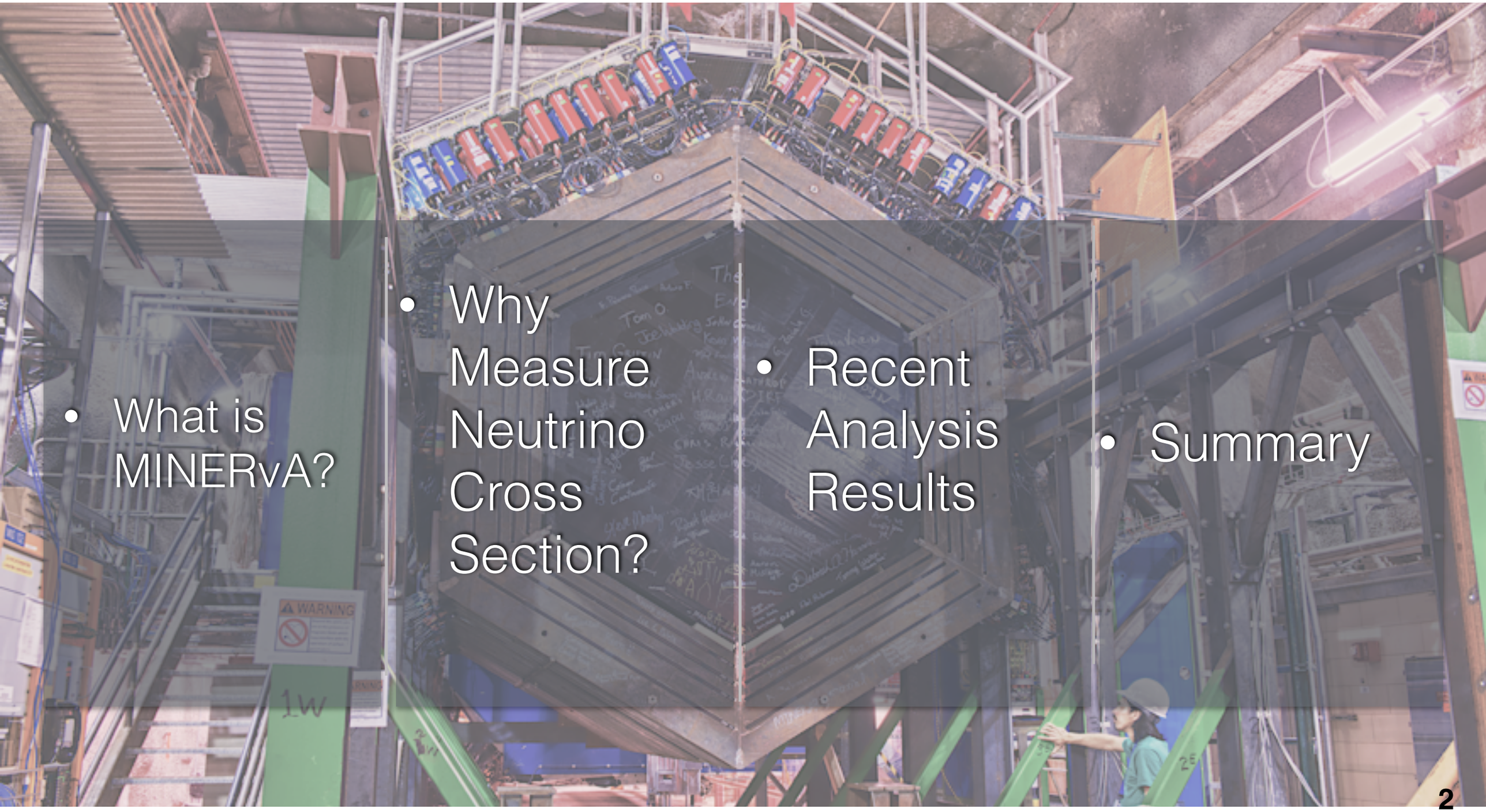
MINERvA Recent Results

Lake Louise Winter Institute
Chateau Lake Louise
2017 February 24

Marianette Wospakrik
University of Florida
(Representing the MINERvA collaboration)



Outline

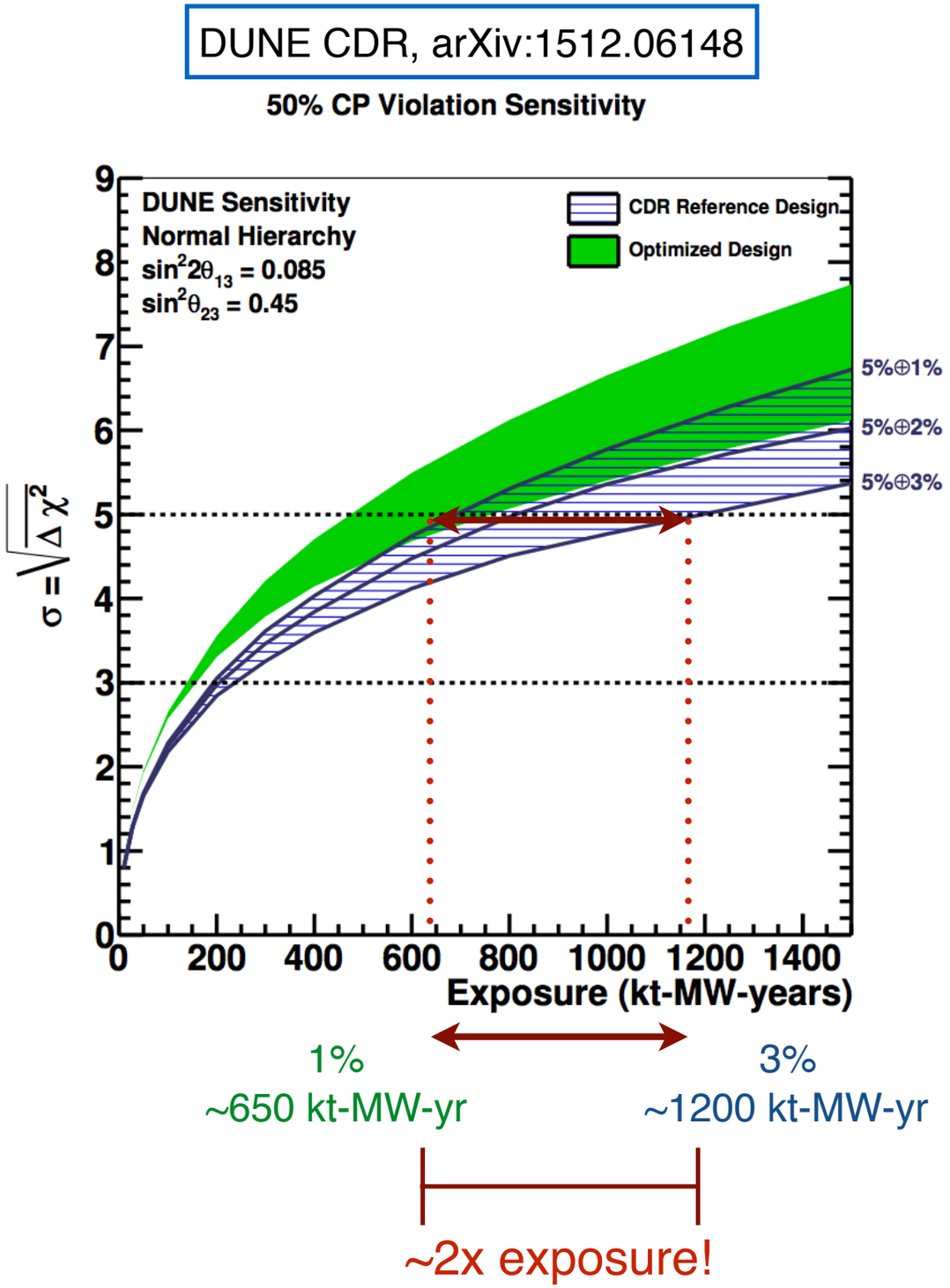

What is MINERvA?
Why Measure Neutrino Cross Section?
Recent Analysis Results
Summary

What is MINERvA?

- **MINERvA**: a dedicated on-axis neutrino-nucleus scattering experiment running at Fermilab in the NuMI (Neutrinos at the Main Injector) beamline.
- Our goal:
  - Make **high precision measurement** of **neutrino interaction cross sections** in the energy region of interests (1-20 GeV).
  - Study **nuclear effects**

Why care about cross section?

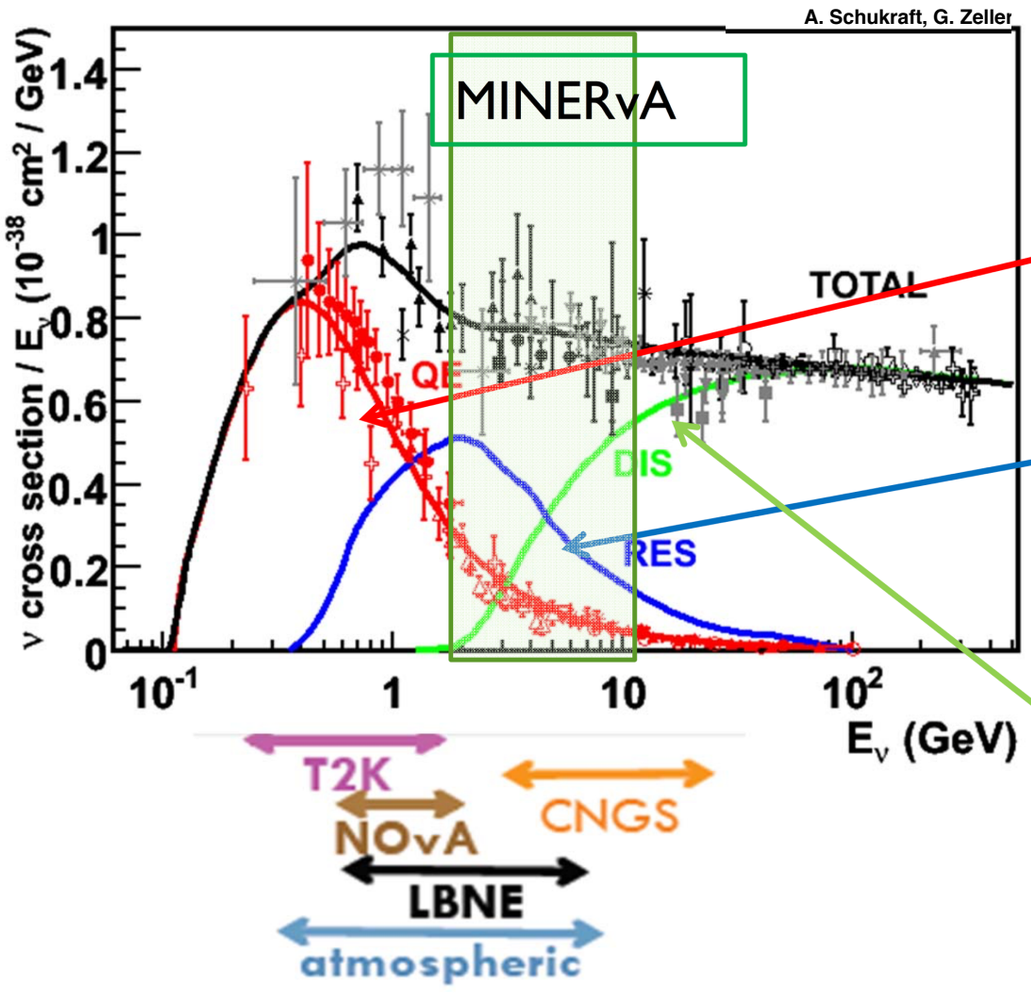
DUNE CDR, arXiv:1512.06148

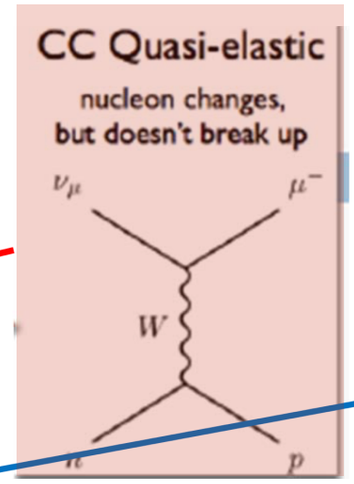


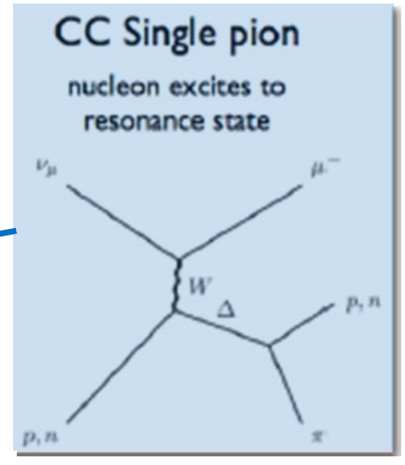
- In a period of precision neutrino oscillation measurements
  - Reducing systematics uncertainties is critical
- Reaching low systematics goals requires control of all systematics, including neutrino interaction cross sections.
- Oscillation experiments rely on neutrino-nucleus interaction models in neutrino event generators.
  - Need better model and high precision data -> goals of MINERvA

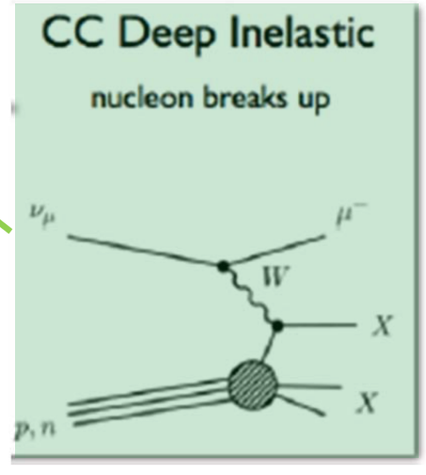
Charged Current Interaction

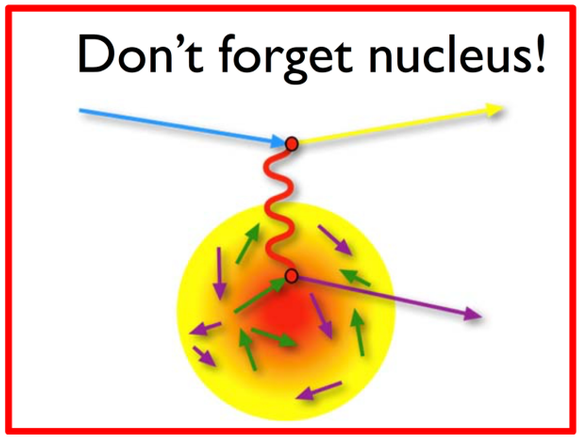
- Oscillation experiments (DUNE, NOvA, T2K, etc.) measure neutrino energy Ev in the 1-20 GeV region, where many interactions channels are active.
  - These interactions channels are signal and the majority of backgrounds in the oscillation experiment



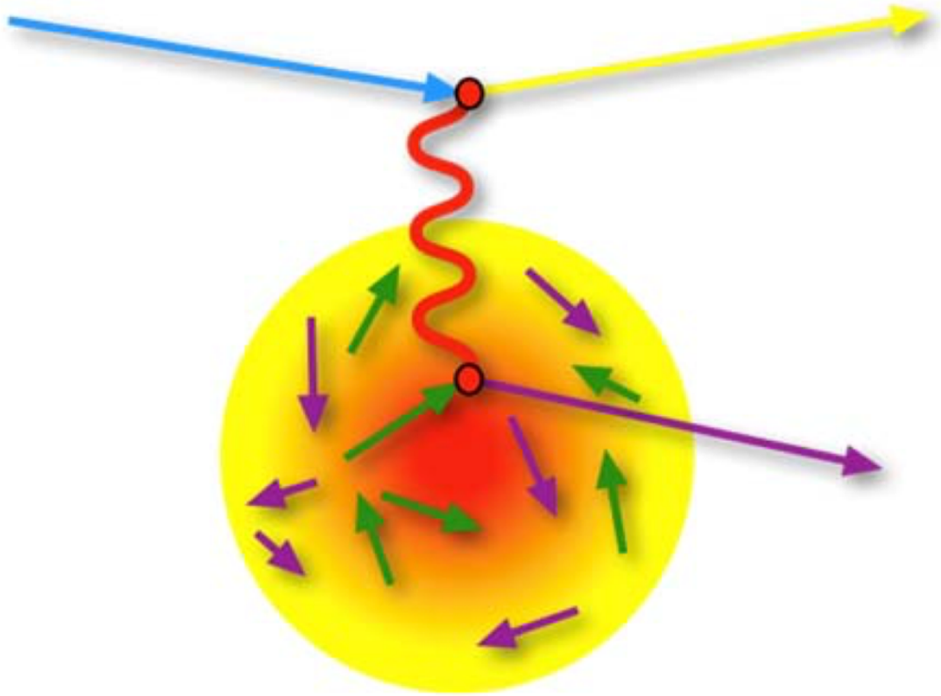




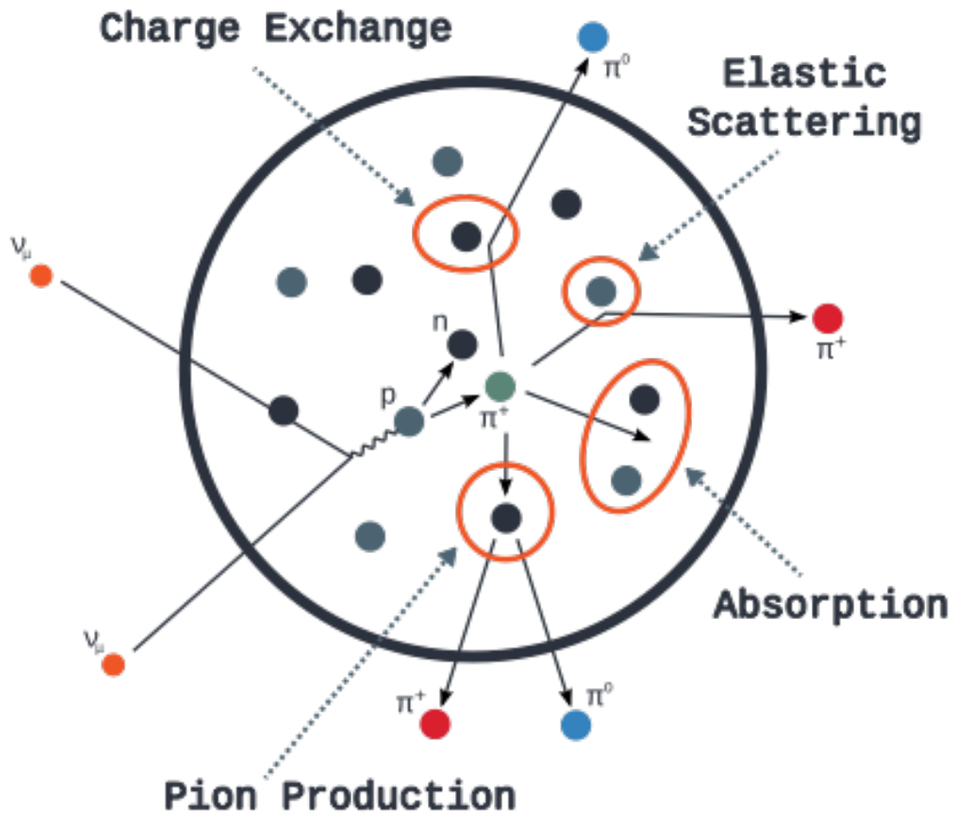




Study of Nuclear Effects



- short range correlation and medium range correlation.
  - scattered off a pair of correlated nucleons - “2p2h” effect
- long range correlation - “RPA” effect



Particles created have to work their way out of the nucleus - final state interactions (FSI)

MINERvA provides information big source of uncertainties in the neutrino interaction!

Neutrino Generators

- GENIE

  Widely used by neutrino oscillation and cross section experiments. Comprehensive physics model and tools to support neutrino interaction simulation.

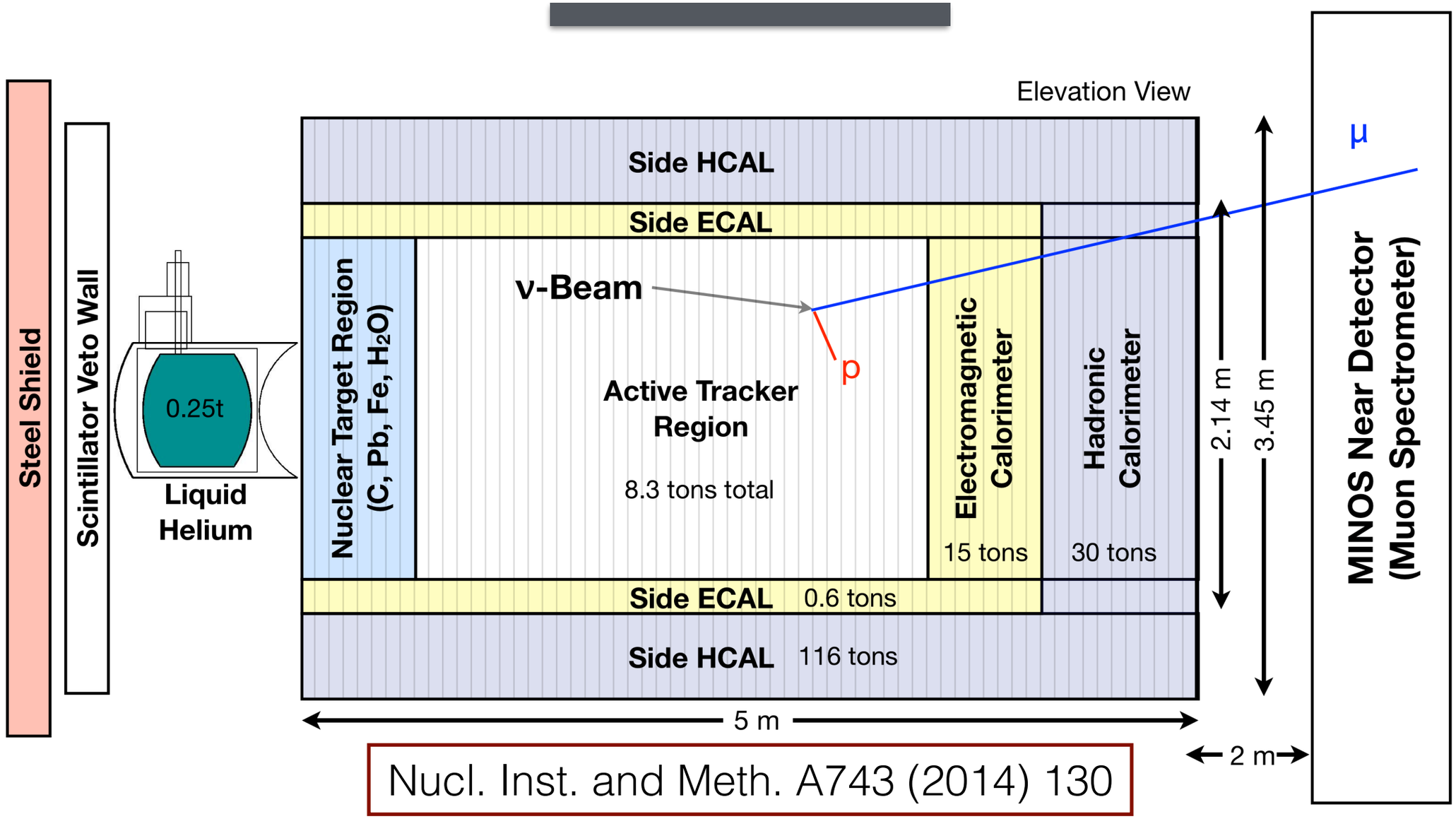
- NuWRO

  Gives predictions for neutrino-nucleus interactions at neutrino energies between **0.1** and **100 GeV.**

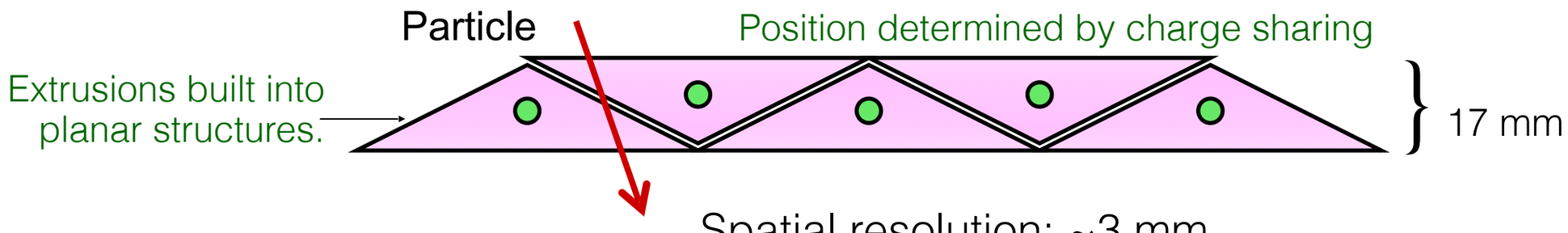
- NEUT

  Developed for Kamiokande, updated continuously for Super-K. Gives background prediction to proton decay in Super-K

MINERvA Detector

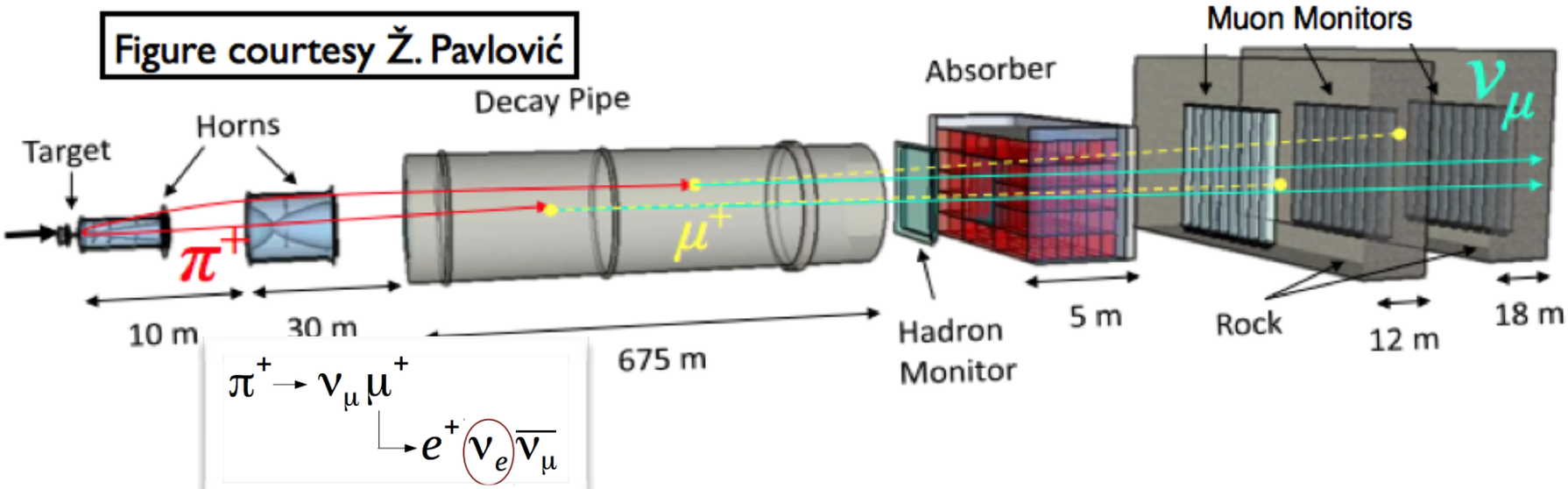


Nucl. Inst. and Meth. A743 (2014) 130

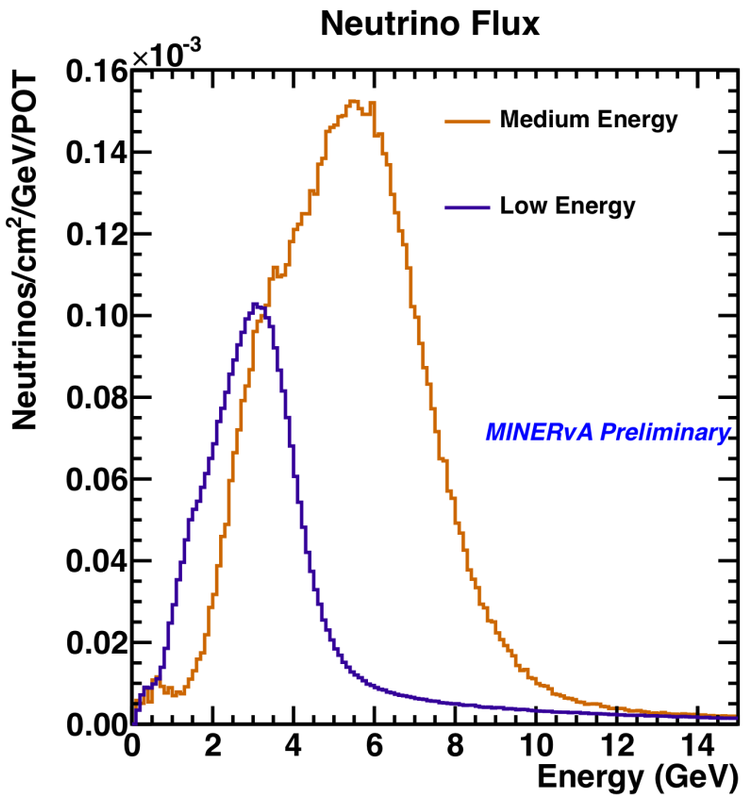


Spatial resolution: ~3 mm
Timing resolution: ~3 ns

Neutrino Beam and Flux



MINERvA



- MINERvA sits on-axis in the NuMI Beam at Fermilab
- Completed low-energy run which peaks at 3.5 GeV.
- Currently accumulating data in medium-energy run which peaks at 6 GeV.
- Recently produced the most precise estimate available of NuMI neutrino fluxes.
  - Combining external and in-situ flux constraint gives us 7% uncertainties in focusing peak.

Recent Results from MINERvA

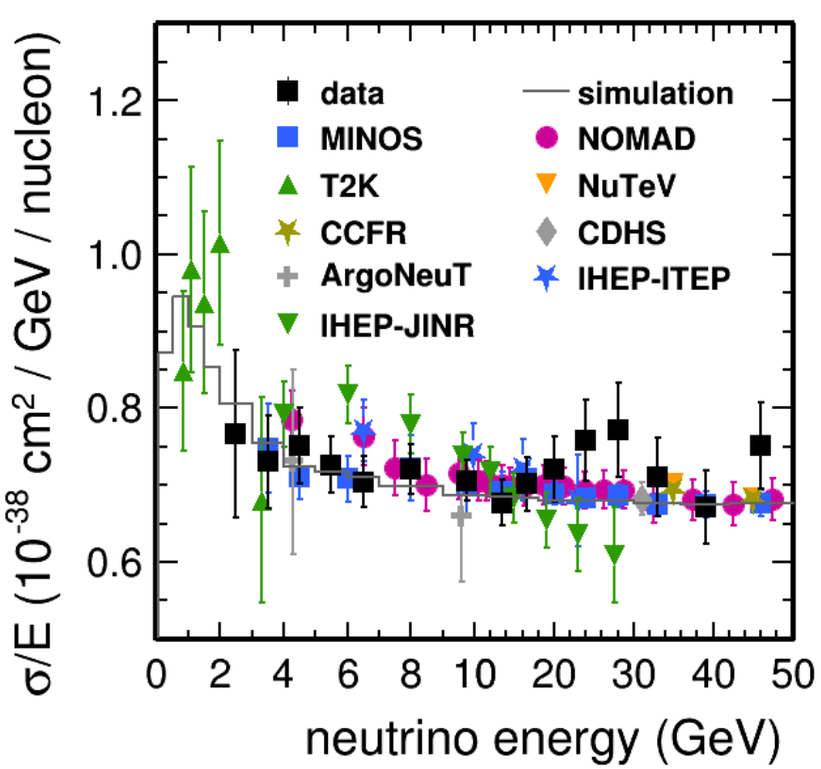
1. In situ Flux-constraint:
   - Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low ν-Flux Method.
2. Nuclear Effect Study:
   - Nuclear Dependence of Quasi-Elastic Scattering at MINERvA
   - Measurement of K+ production in charged-current ν_μ interactions.
3. Background for oscillation experiment/proton search decay:
   - Measurement of neutral-current K+ production by neutrinos using MINERvA.
   - Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon.

- **BONUS:** First evidence of coherent K+ meson production in neutrino-nucleus scattering.

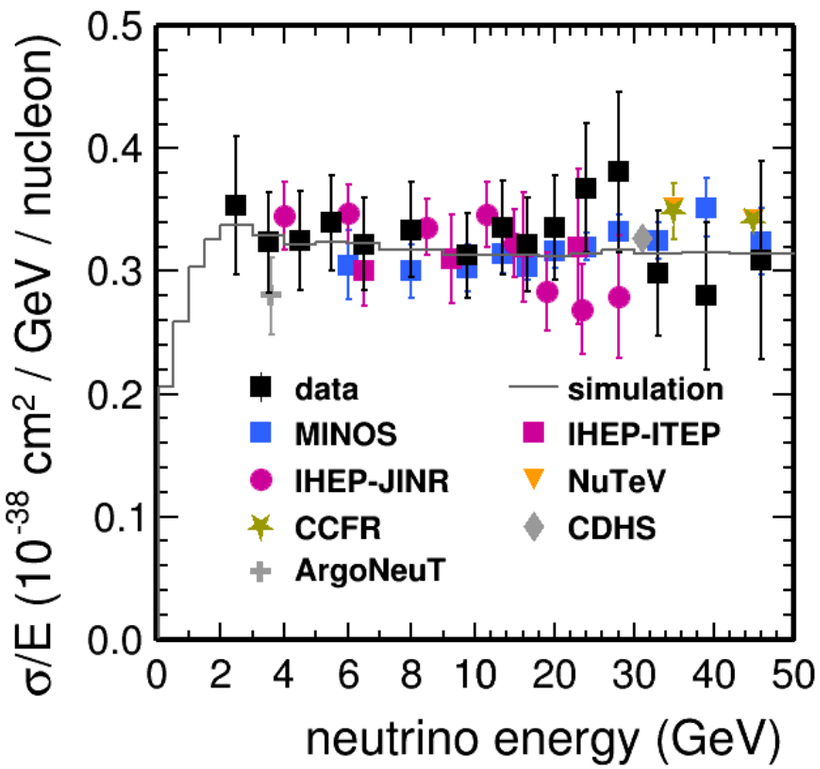
Total Neutrino and Antineutrino Cross Section using low-Nu Method

- Takes advantage of the fact that the cross section for events with low hadronic energy (ν) is approximately flat with neutrino energy.
- **Data** agree with the NOMAD and MINOS results, but extend to lower energies.
- **First low-ν-based** technique application in **NuMI antineutrino-enhanced beam**.
- Shows that the technique is applicable to future neutrino experiments operating at multi-GeV energies.

ν_μ in FHC



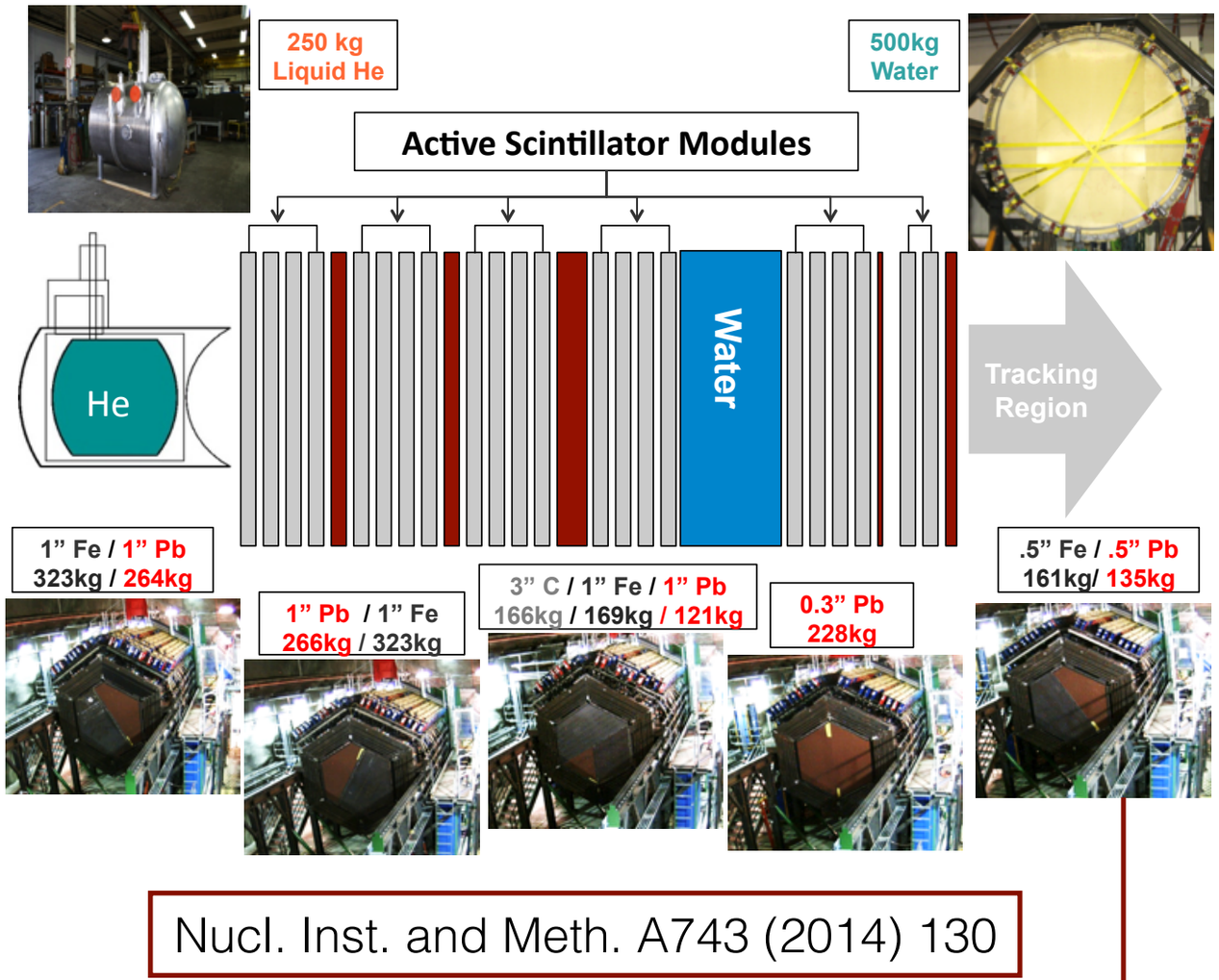
$\bar{\nu}_\mu$ in RHC



Phys. Rev. D 94, 112007 (2016)

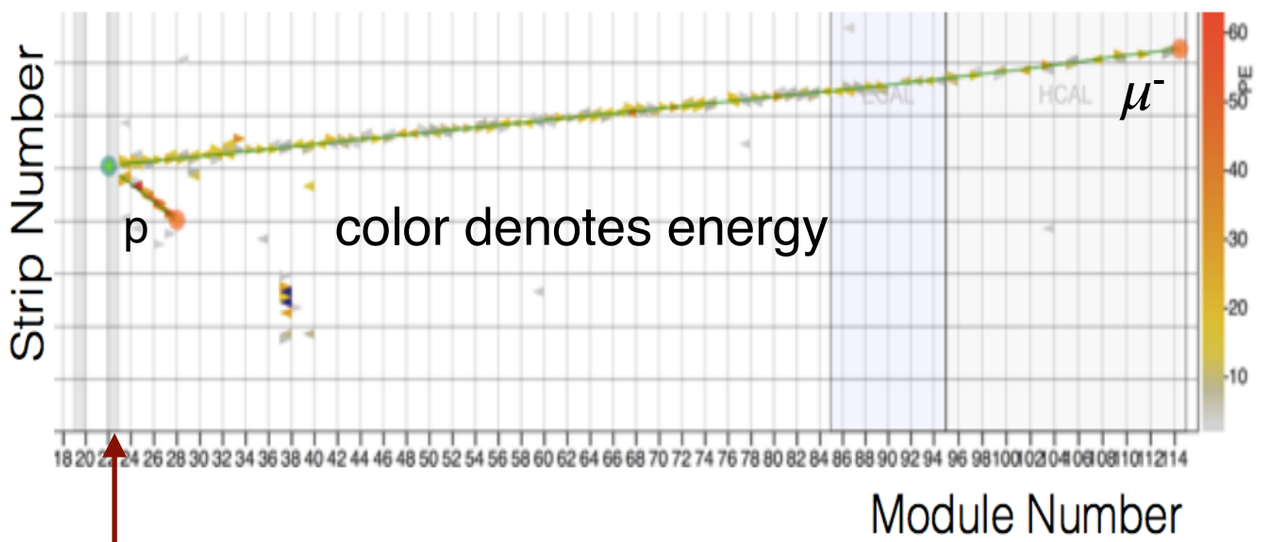
Most precise measurements to date below 5 GeV!

CCQE Cross Section Ratios: A-dependence



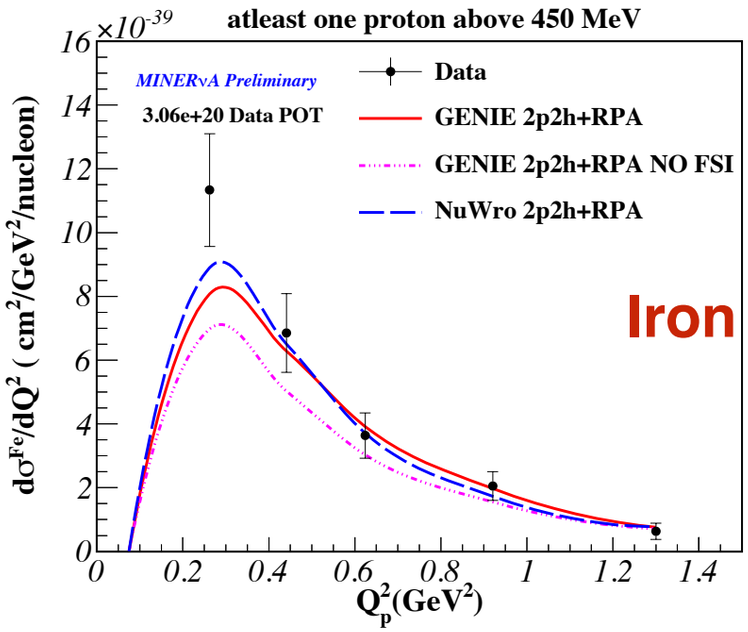
Nucl. Inst. and Meth. A743 (2014) 130

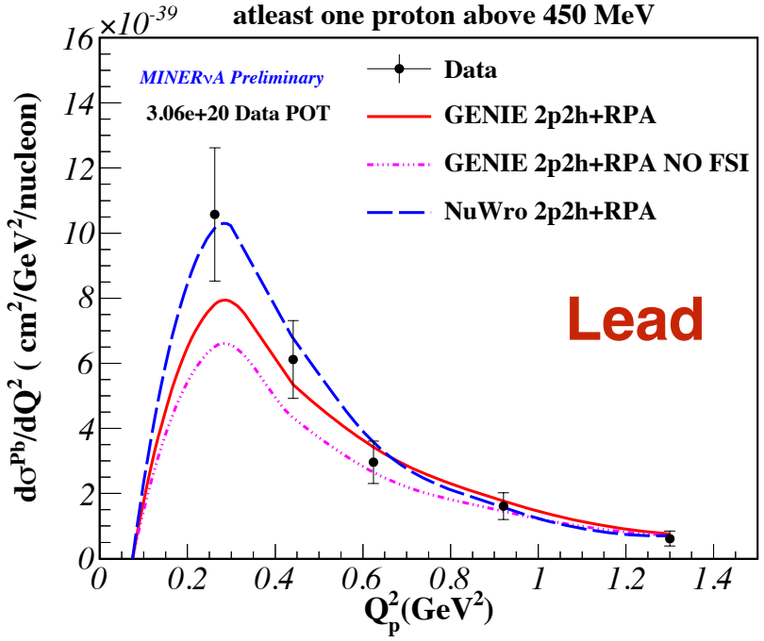
First measurements of quasielastic-like events on multiple nuclei for A-dependence study!

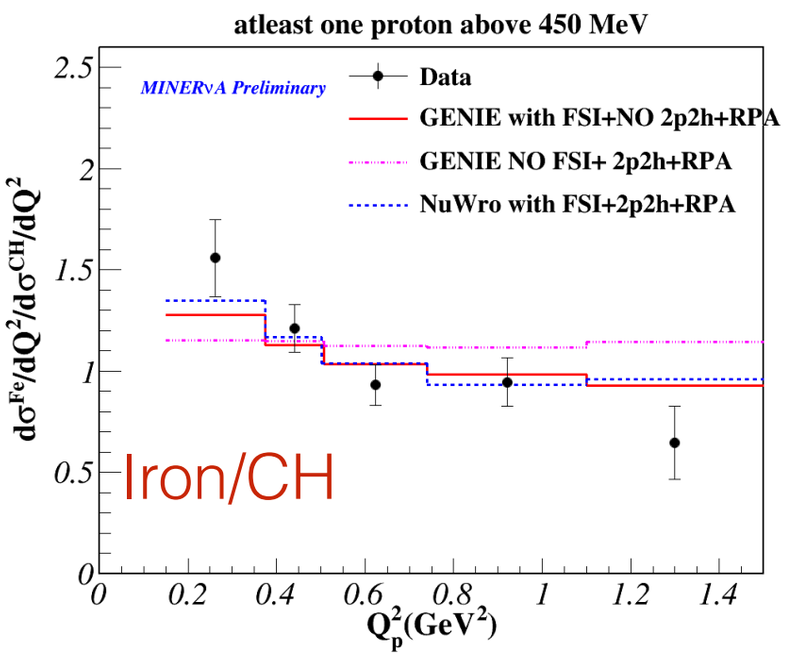


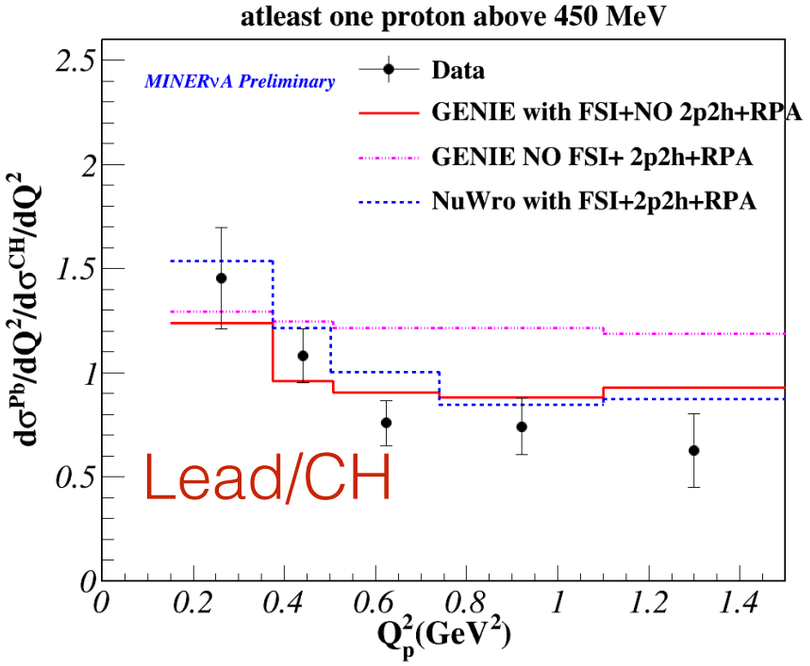
Side by Side Comparisons for Different Nuclei!

- Data prefers the simulation with final state interactions
- The A dependence in NuWro seems to be more favored by the data







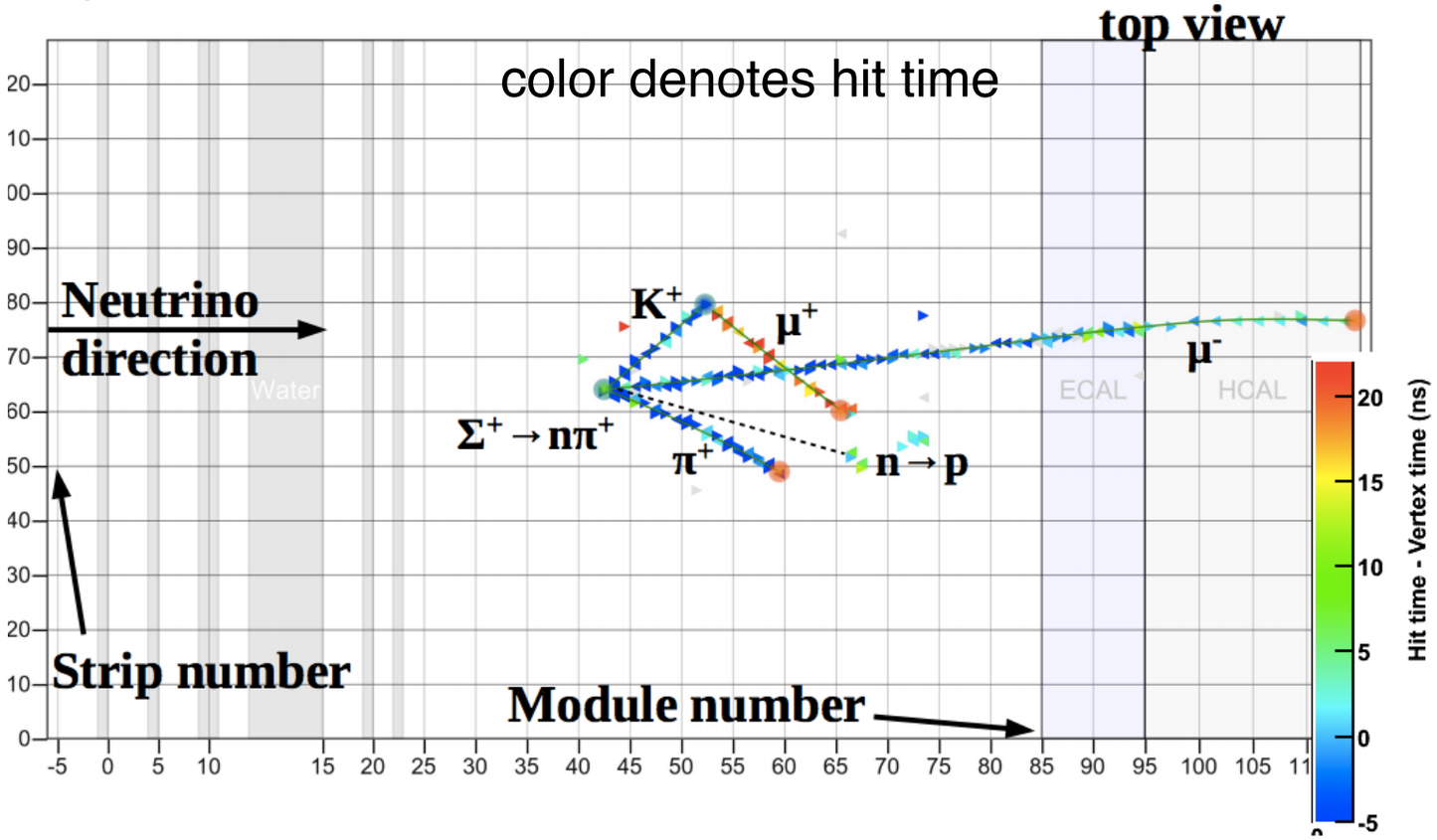


M. Betancourt
FNAL JETP Seminar
5 Oct 2016

Data ratios show more nuclear effects due to FSI, at low values of four momentum transfer $Q^2 < 0.6\ GeV^2$

Kaon Production

- K^+ production by atmospheric neutrinos (especially neutral current interactions) are backgrounds for SUSY-preferred proton decay p → K+ ν
  - NC K+ event with no particles above Cherenkov threshold will fake the signal process.
  - Mismodeled rates for Kaon + nothing would also be a problem in liquid Argon detectors
- Both charged and neutral current K^+ production is sensitive to FSI which is important to model

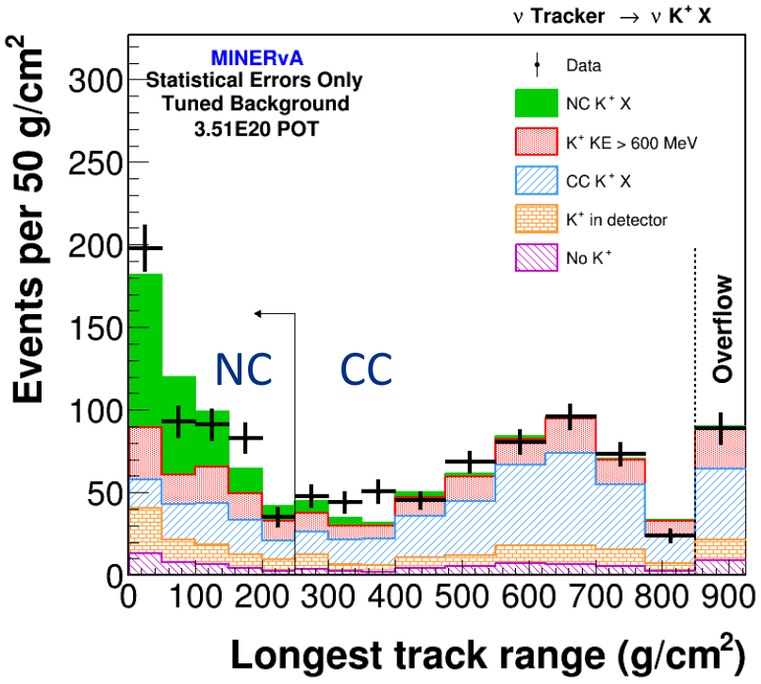


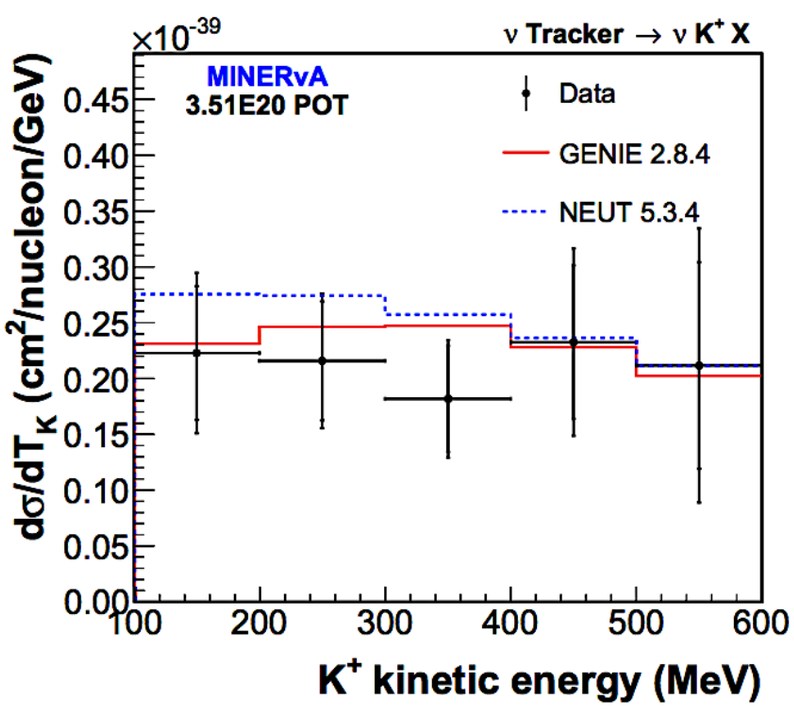
MINERvA's **timing resolution** enables identification of kaon production via observation of the time delay between a kaon track and its decay products.

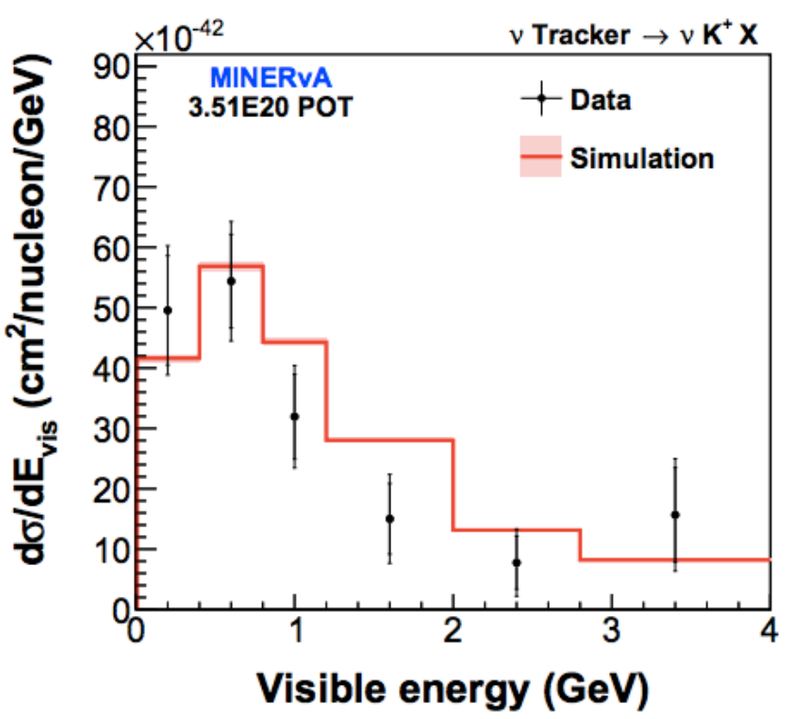
C.Marshall
FNAL JETP Seminar,
5 Feb 2016

Neutral Current Kaon Production

- **Important background in proton decay search!**
- Neutral current K+ production cross section are in good agreement with simulation.
- We need improvements in the interaction and FSI models, but this result supports the idea that background estimates in proton decay searches are reasonable.

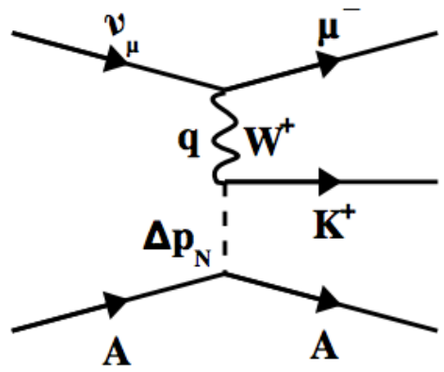




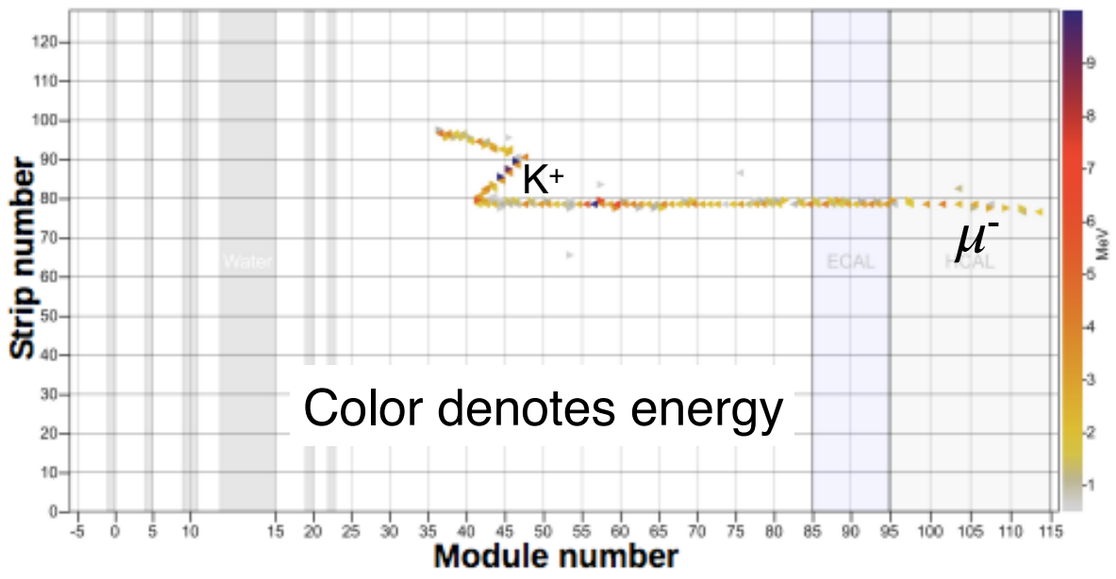


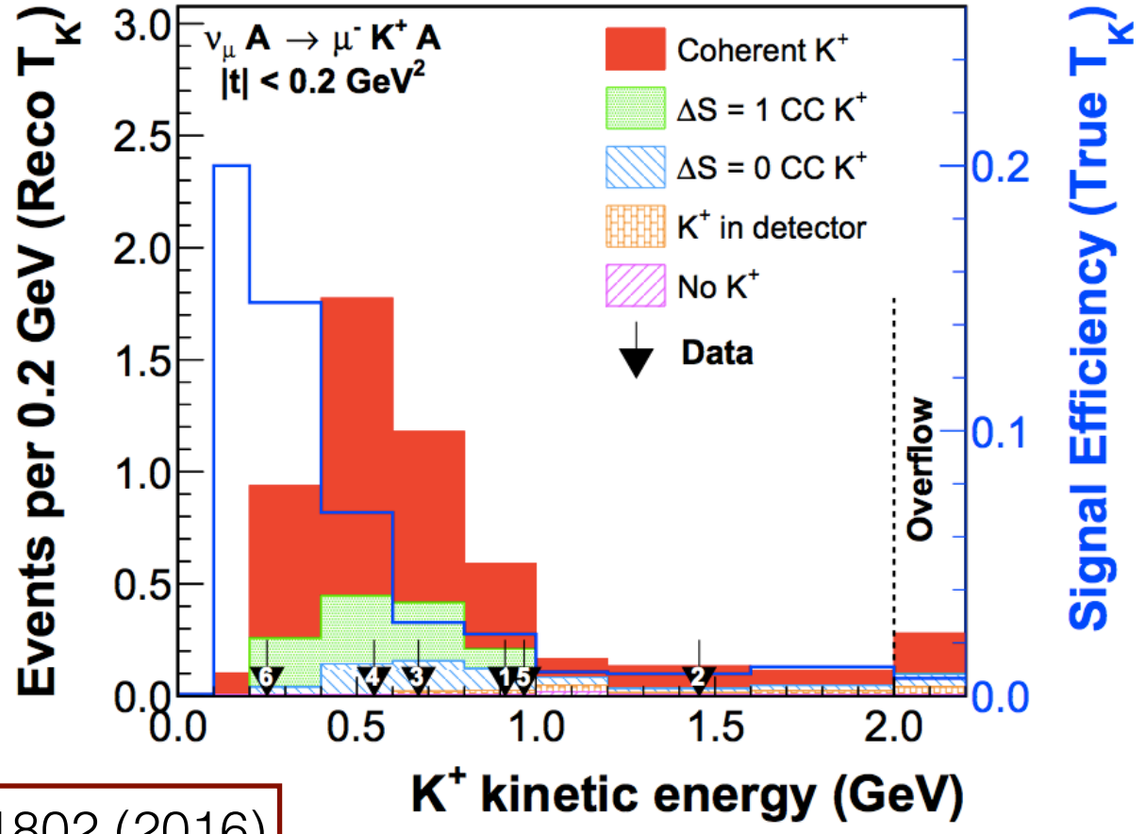
arXiv:1611.02224 (2016)

Coherent K+ Production



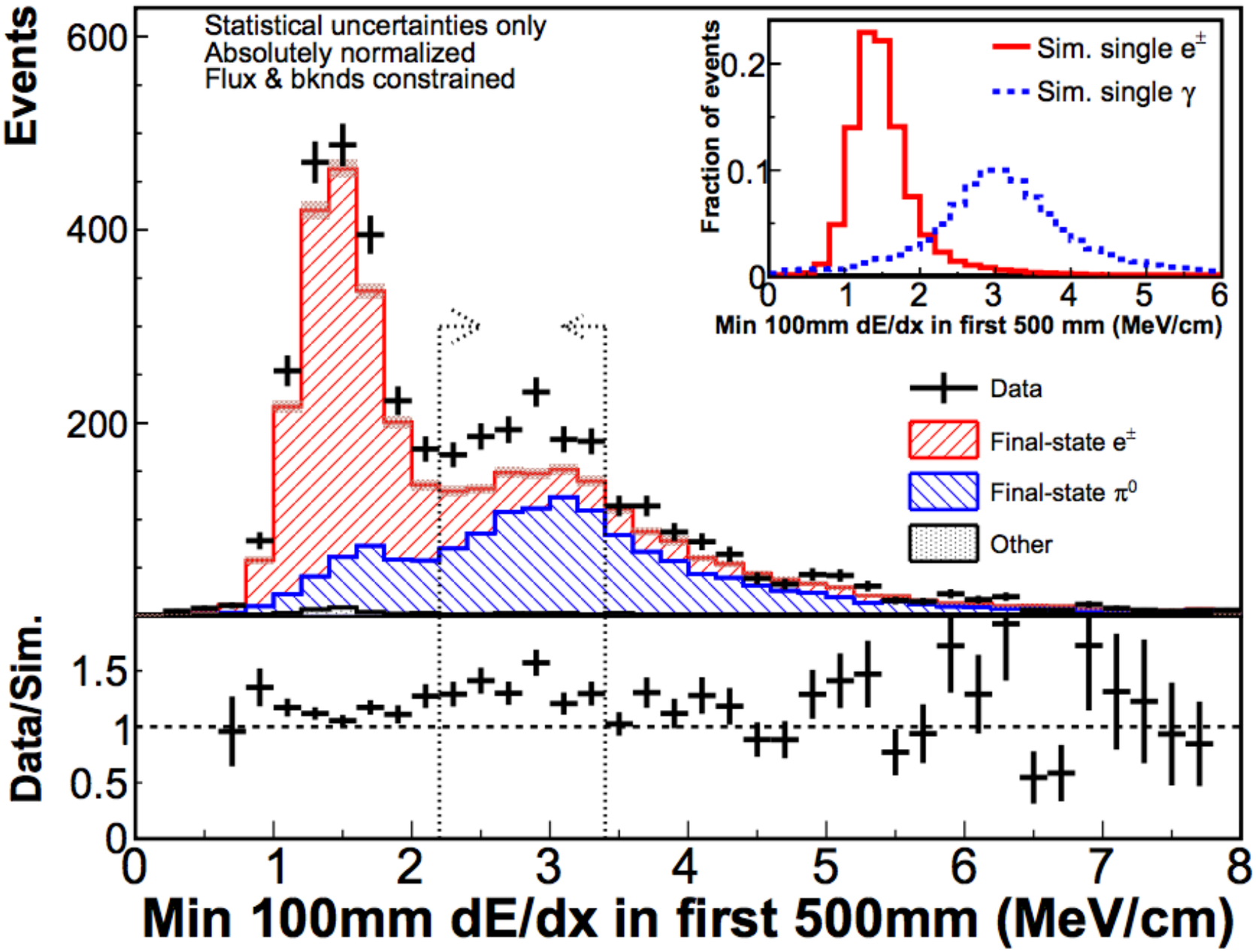
- Very rare process due to small cross sections.
- Isolate events with a $\mu^- K^+$ final state, low momentum transfer to the nucleus, and no evidence of nuclear breakup.
- We find 6 events in signal region. Fit estimates $3.77^{+2.64}_{-1.93}$ signal events. This is the first experimental evidence for the process at 3σ significance.





Phys. Rev. Lett. 117, 061802 (2016)

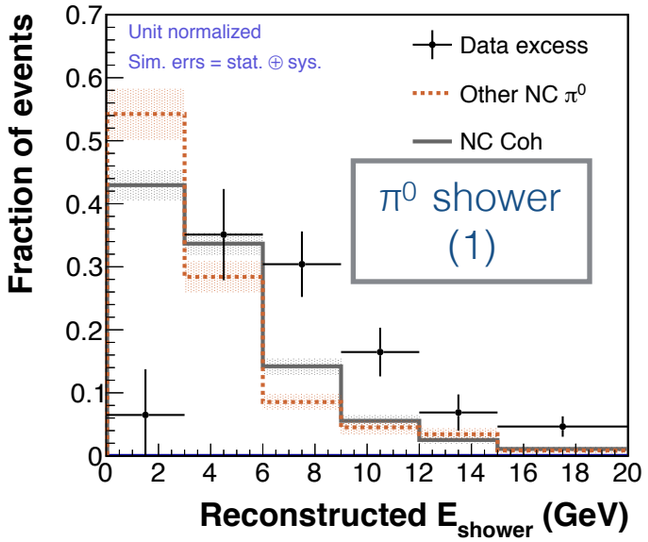
Excess EM Shower Events

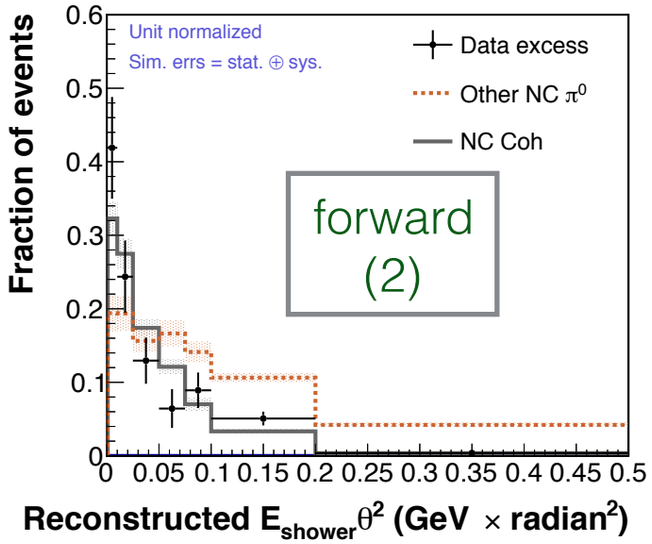


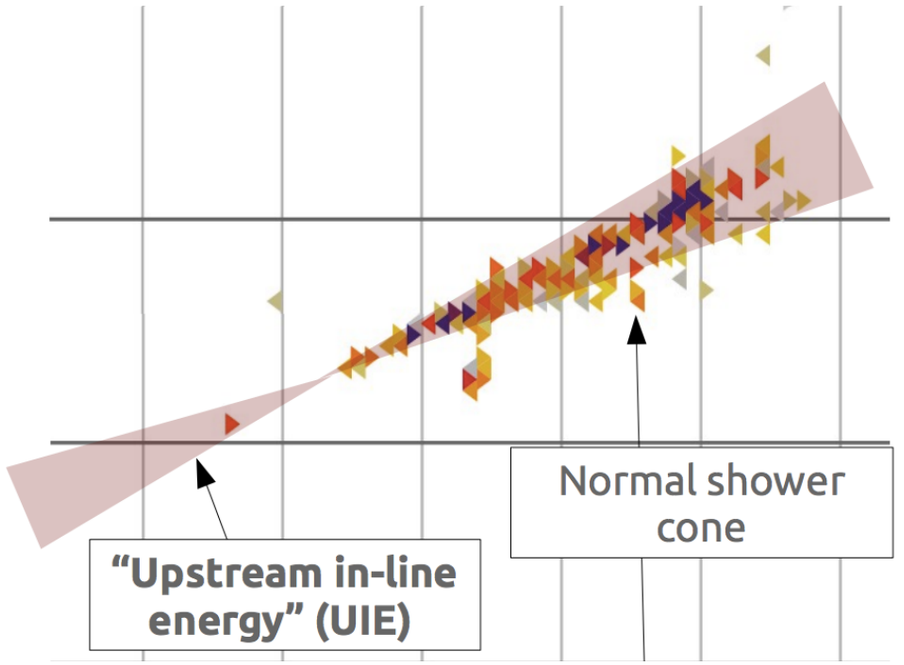
Observed as excess EM shower events in photon region of front dE/dx

Phys. Rev. Lett. **117**, 111801 (2016)

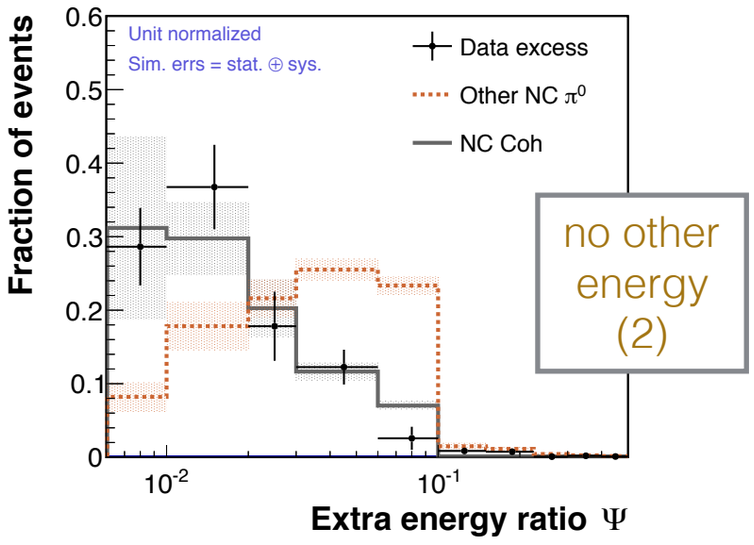
Neutral Current Diffractive Pion Production from Hydrogen

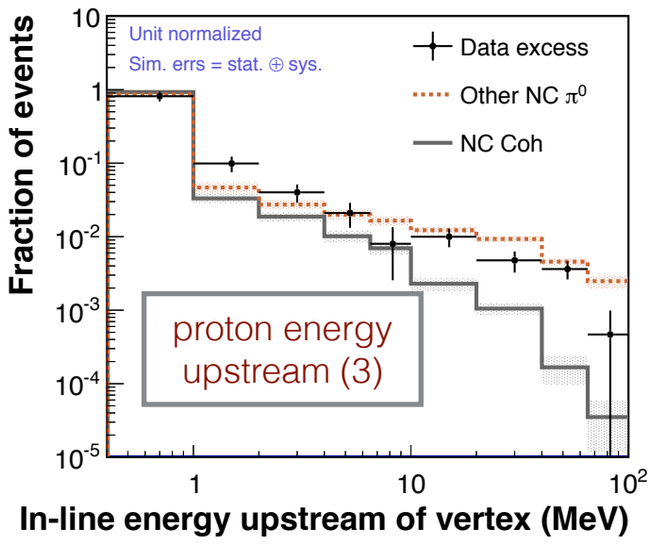






Phys. Rev. Lett. **117**, 111801 (2016)



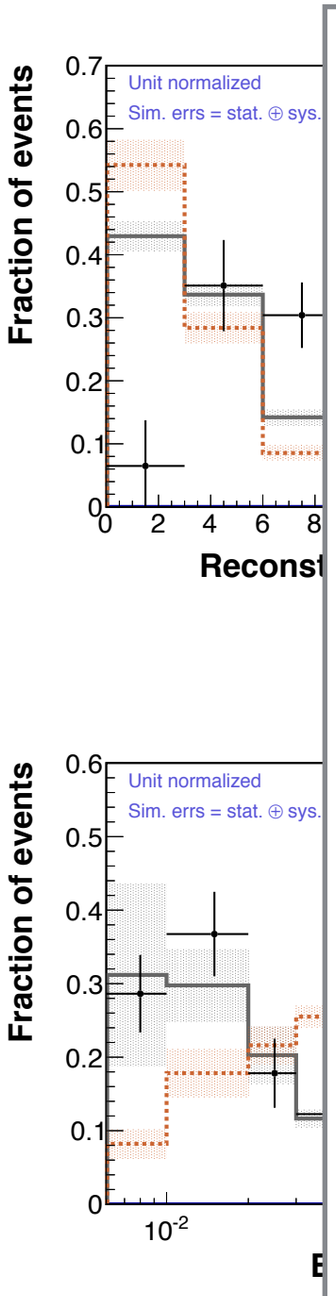


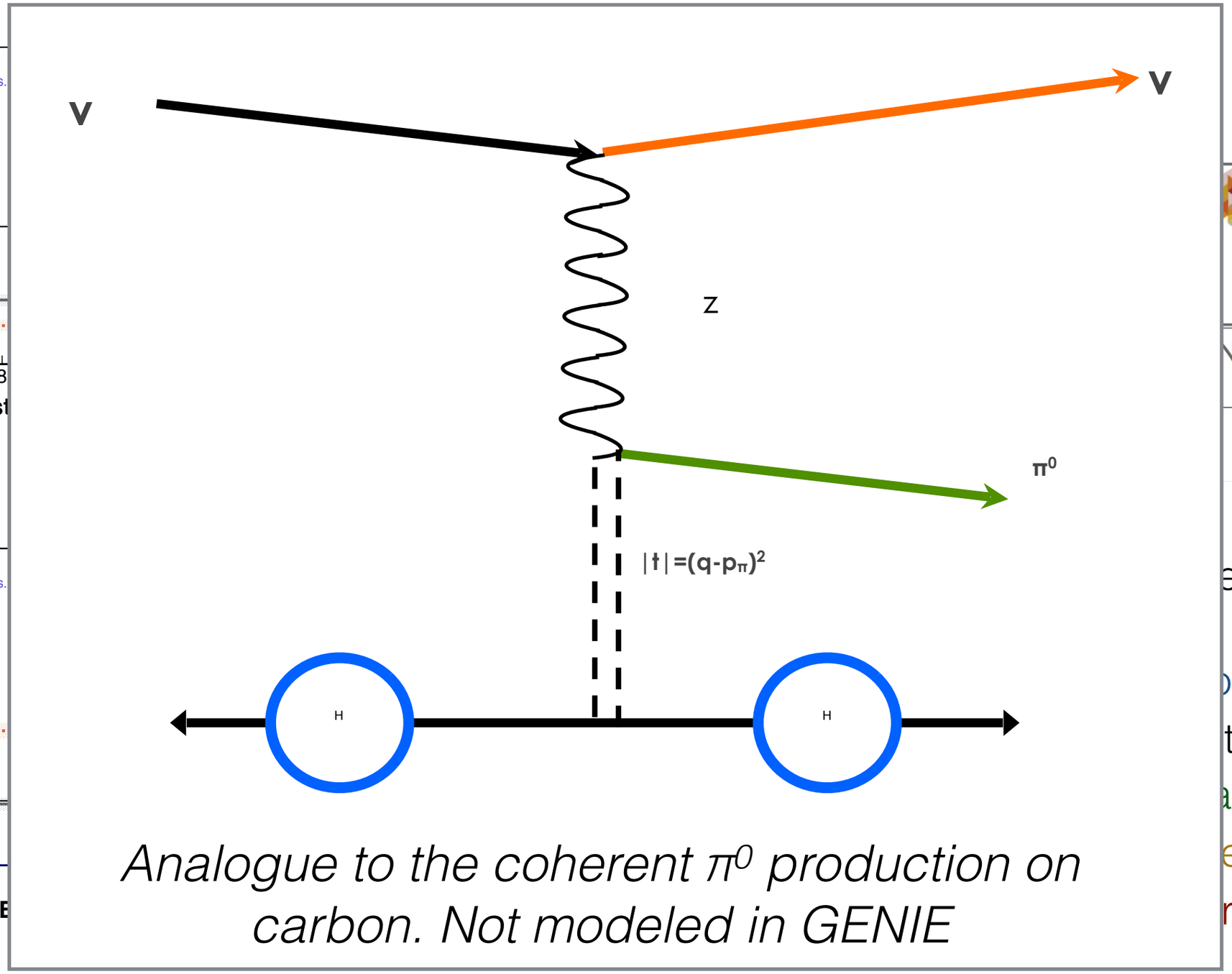
Characteristic of the excess match diffractive process:

1. Two-photon π^0 shower
2. Coherent-like scattering:
   - Forward kinematics
   - Very little other energy
3. Visible proton energy

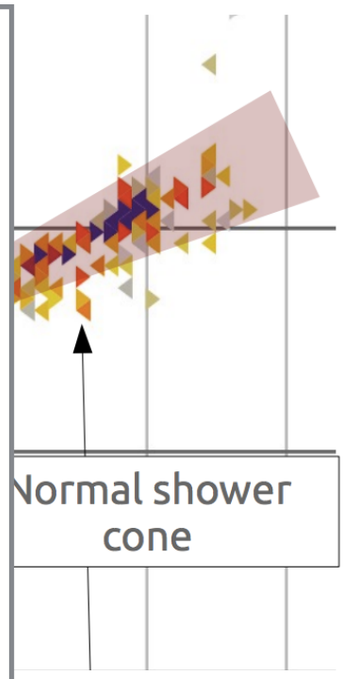
First direct experimental observation and characterization of this process!

Neutral Current Diffractive Pion Production from Hydrogen





Analogue to the coherent π^0 production on carbon. Not modeled in GENIE



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First direct experimental observation and characterization of this process!

Summary

- **MINERvA provides measurement for signal and background rates** in **oscillation experiments**: quasi elastic scattering, kaon production, etc., **improving model descriptions** used by both theory and oscillation experiments.
- **MINERvA has performed many first time measurements**: direct data constraint of backgrounds from atmospheric neutrinos to proton decay: p → Kν, coherent kaon production, and nuclear dependence in neutrino cross-sections.
- **MINERvA is building a rich set of results** that nicely span the **first oscillation peak at DUNE.**
- Currently taking data in the medium energy range:
  - Higher statistics yields improve comparisons across nuclei
  - Access to expanded kinematics and nuclear structure functions

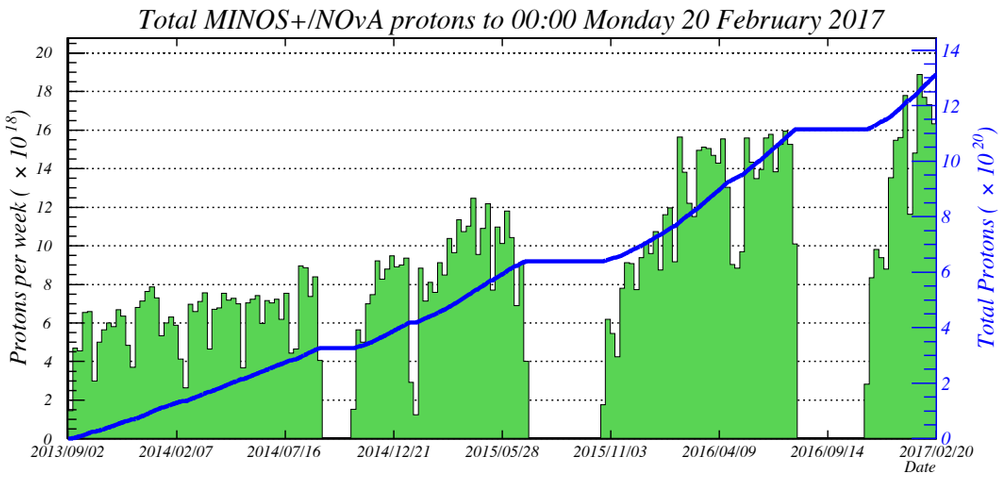
From MINERvA Collaboration:

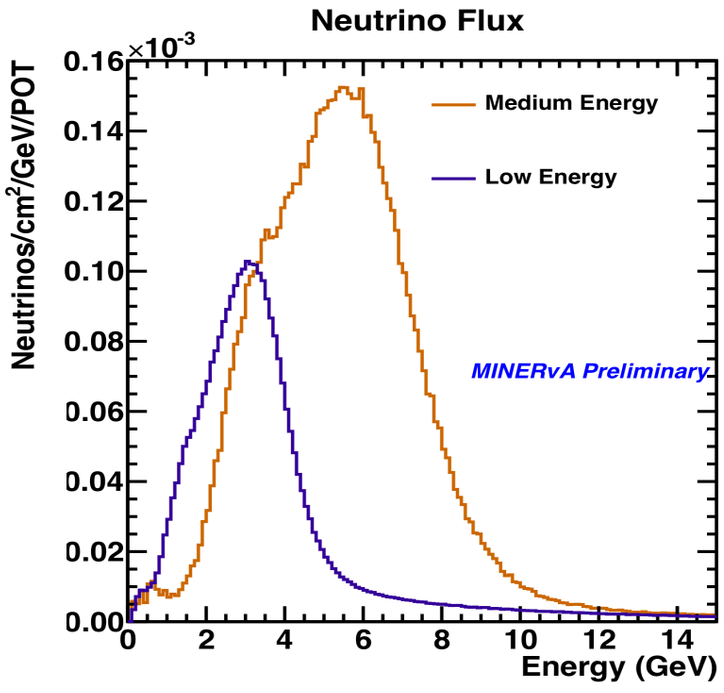
Thank You!!

BACKUP SLIDES

What Next?

- High-statistics dataset in hand, and almost fully calibrated.





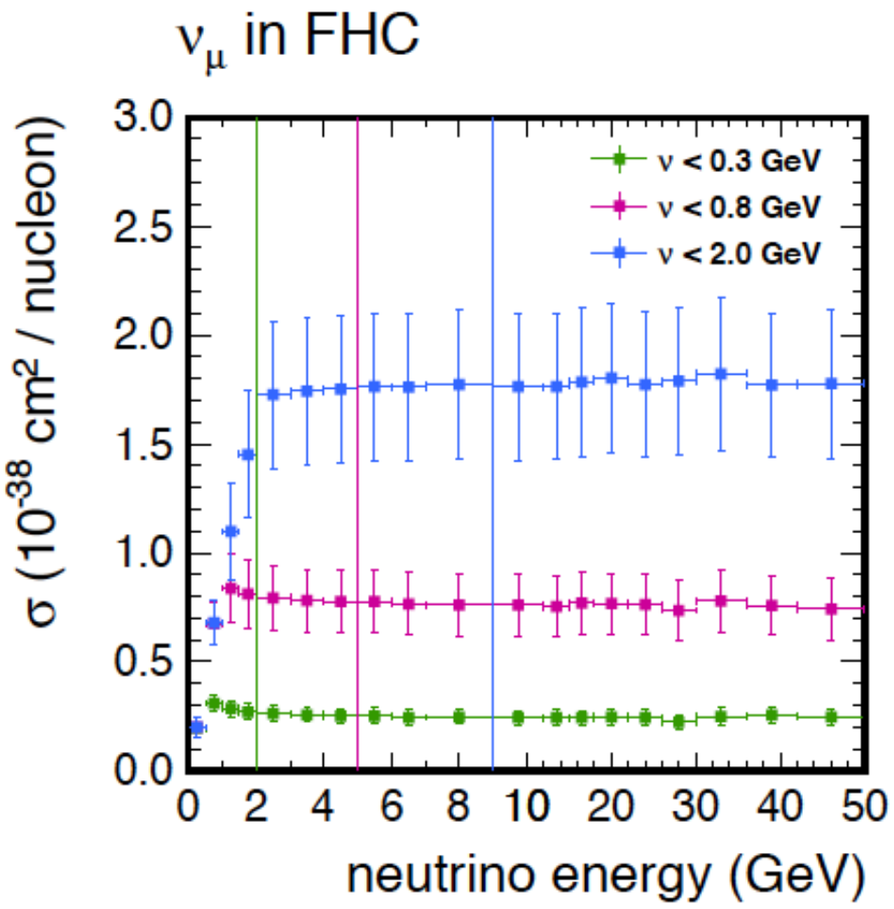
In-situ Flux Constraints: Low Nu Method

Phys. Rev. D 94, 112007 (2016)

- Charged-current scattering with low hadronic recoil energy (ν) is flat as a function of E_ν

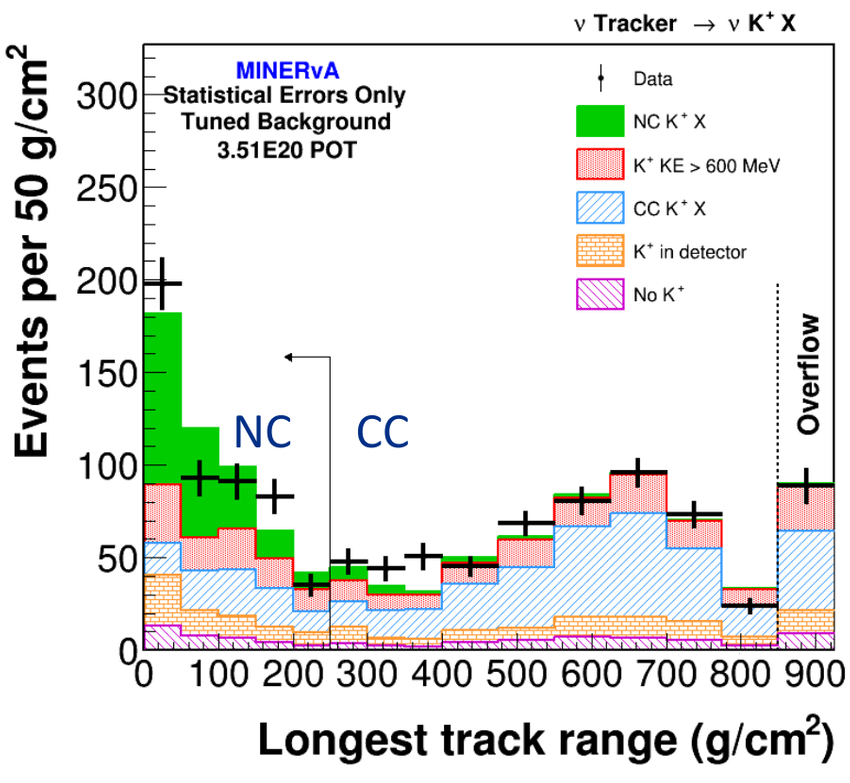
$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

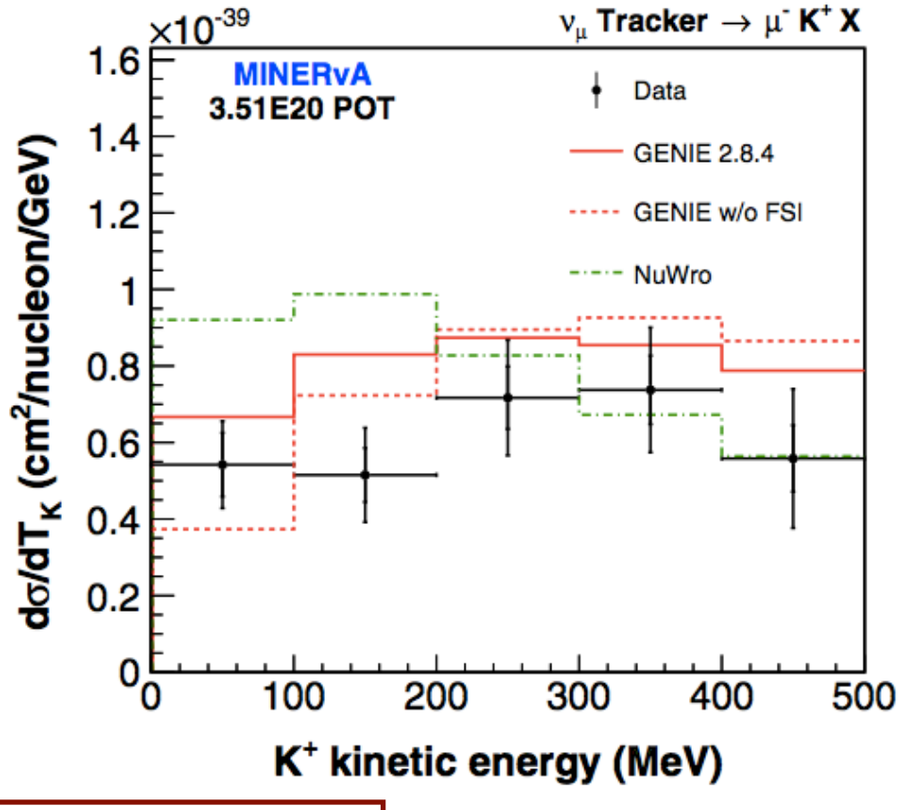
- Gives a measurement of the flux's shape.
- Total flux is extracted using external inclusive cross section data (NOMAD).



Charged-Current Kaon Production

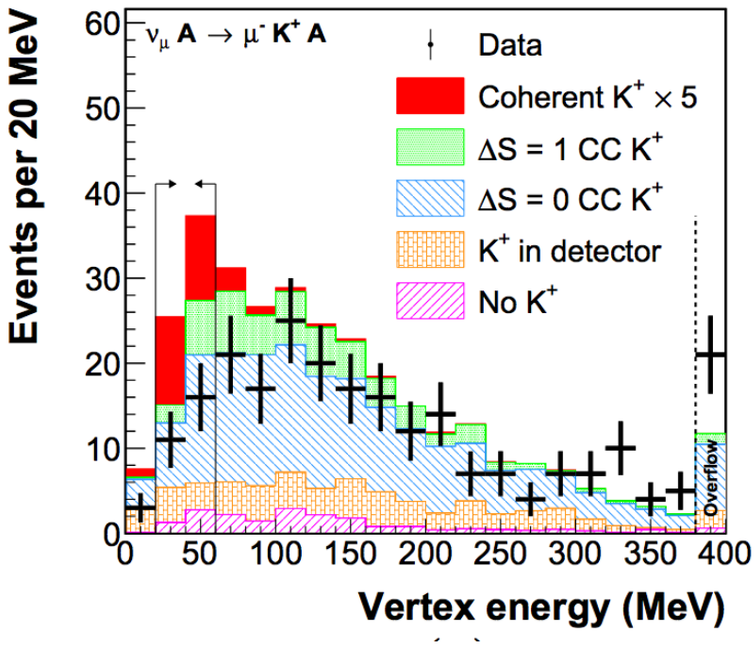
- Charged current K^+ production cross section shows reasonably good agreement with simulation (GENIE and NuWRO).
- First high-statistics measurement of the K^+ production in ν_μ charged-current interactions.
  - ~50 times more events than have been observed in previous experiments

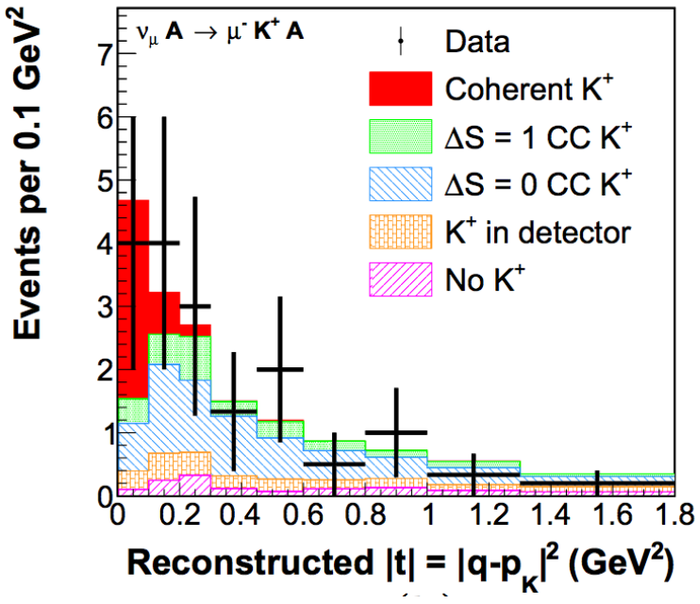


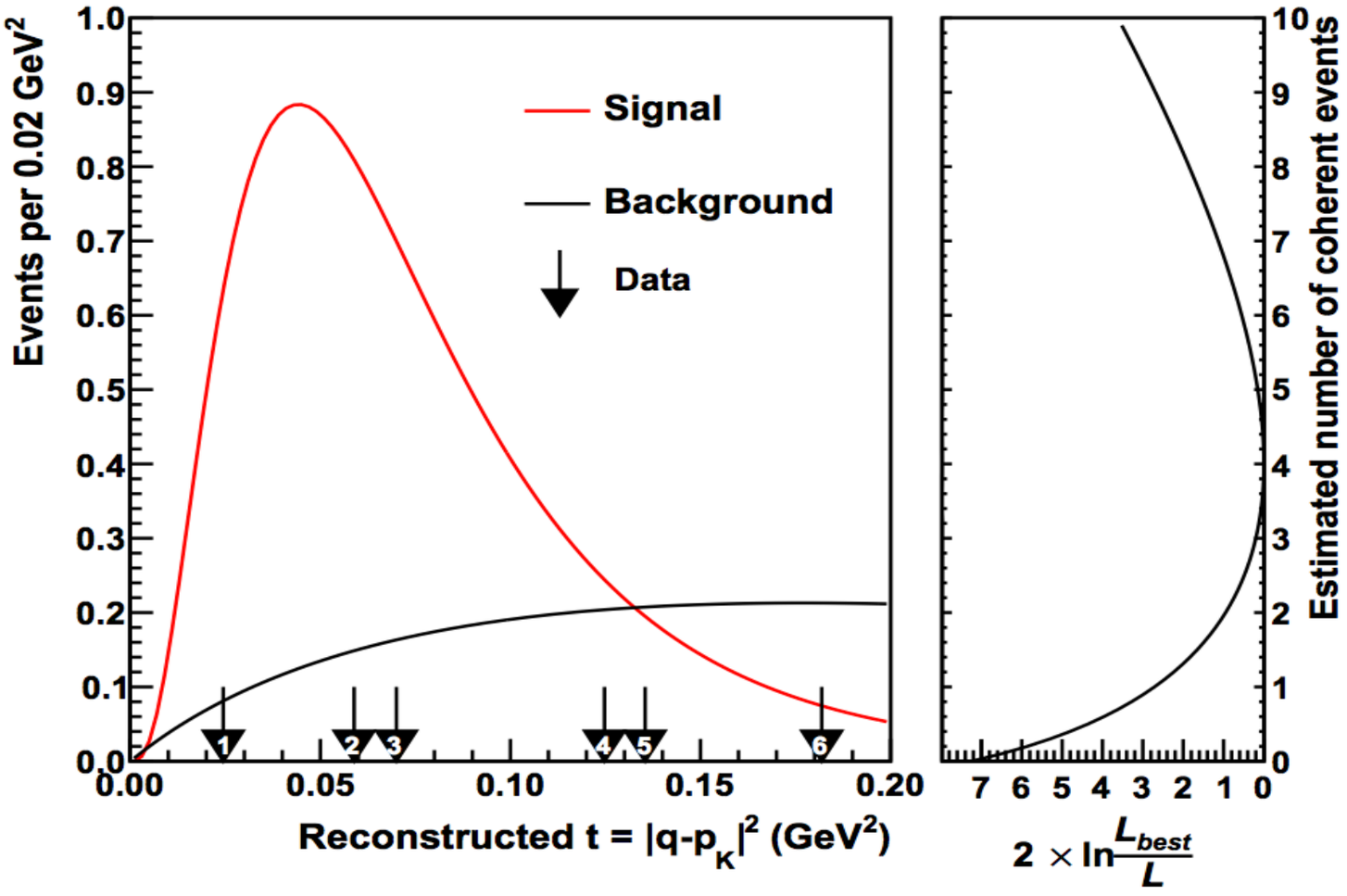


Phys. Rev. D. **94**, 012002

Coherent Kaon Production

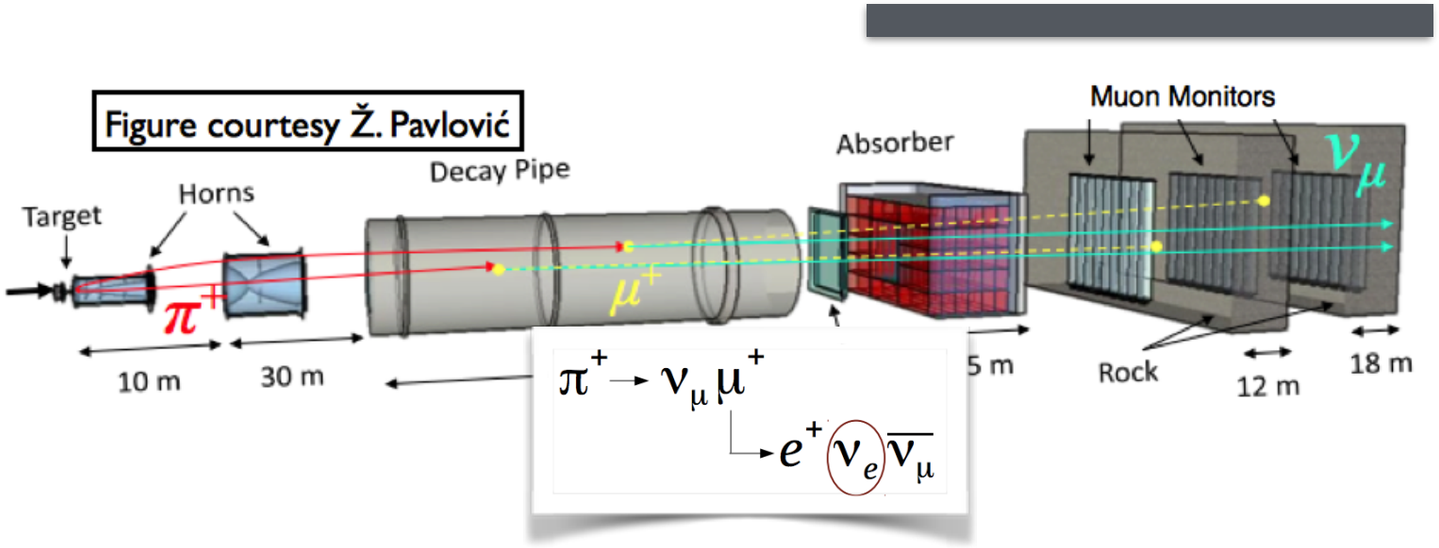


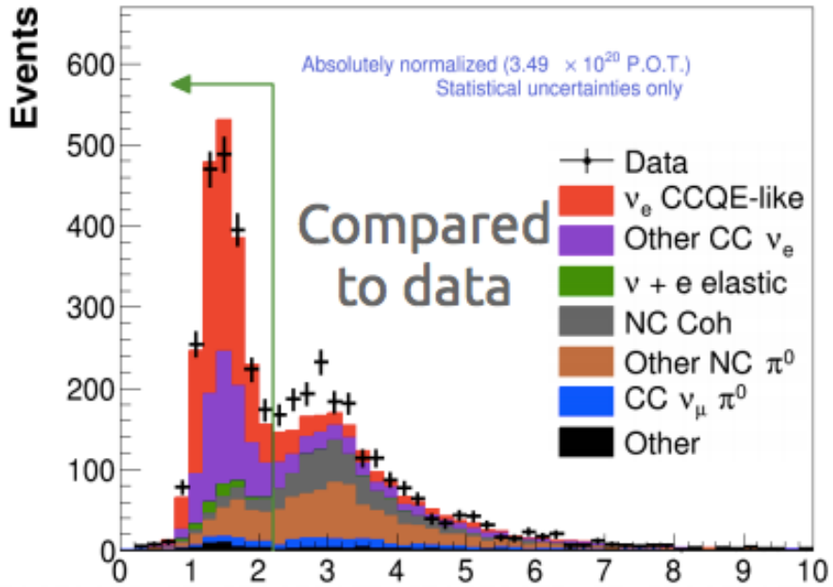


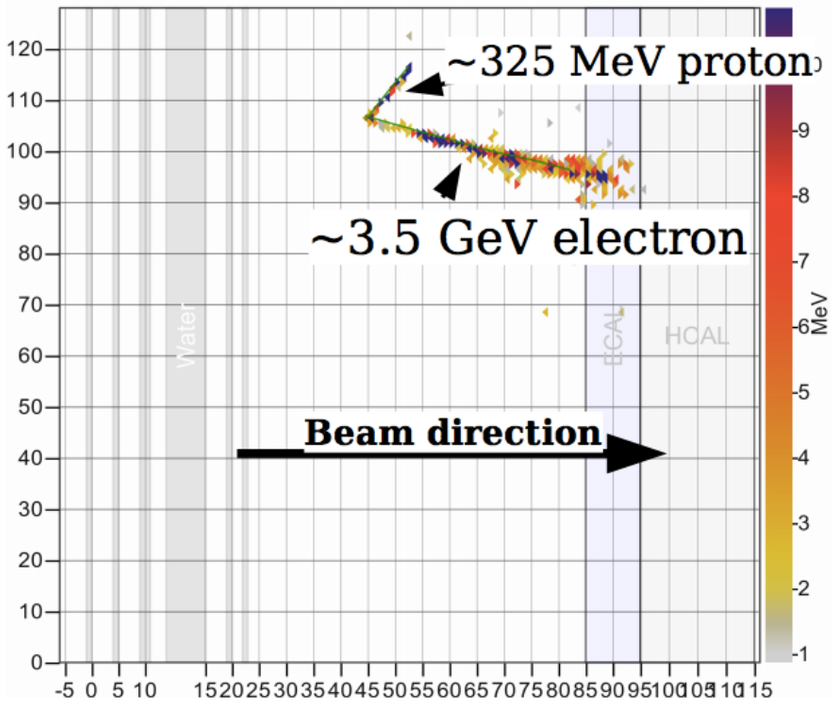


We compare the ratio of likelihoods of the null hypothesis of zero signal events to the best fit of 3.77, and find a p-value of 0.28% including systematic uncertainties, equivalent to a 3.0 standard deviation exclusion of the null hypothesis of no coherent kaon production

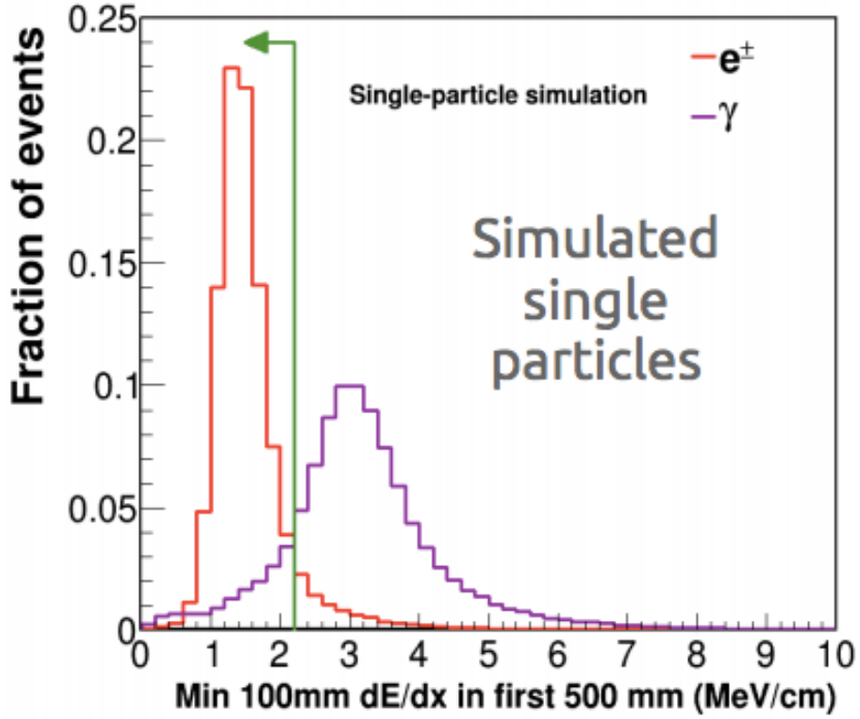
Electron Neutrinos







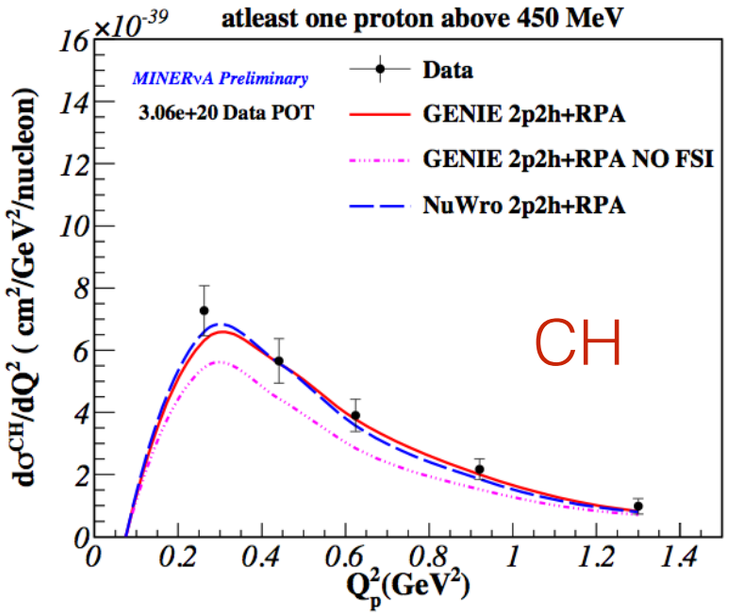
- "QE-like" (0 pion final state) electron neutrinos using 1% ν_e component of NuMI.
- ν_e uncertainty relative to ν_μ is critical to oscillation measurements.
  - ve appearance (T2K, NOvA, etc.)

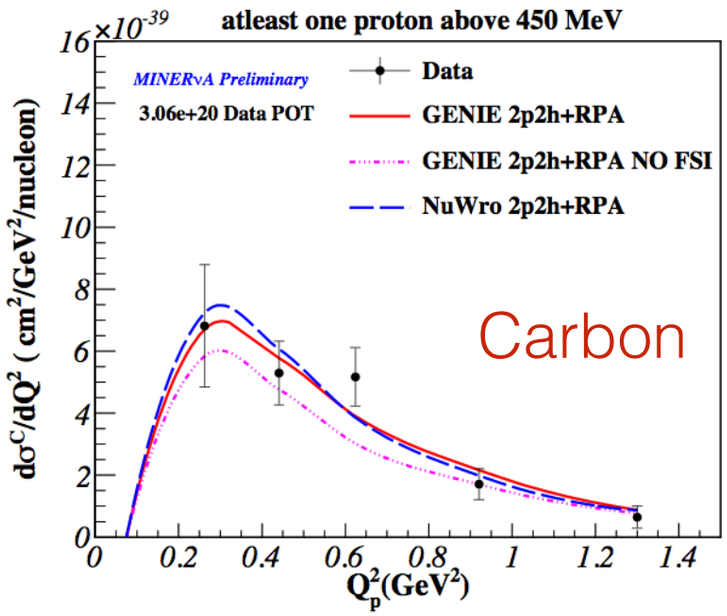


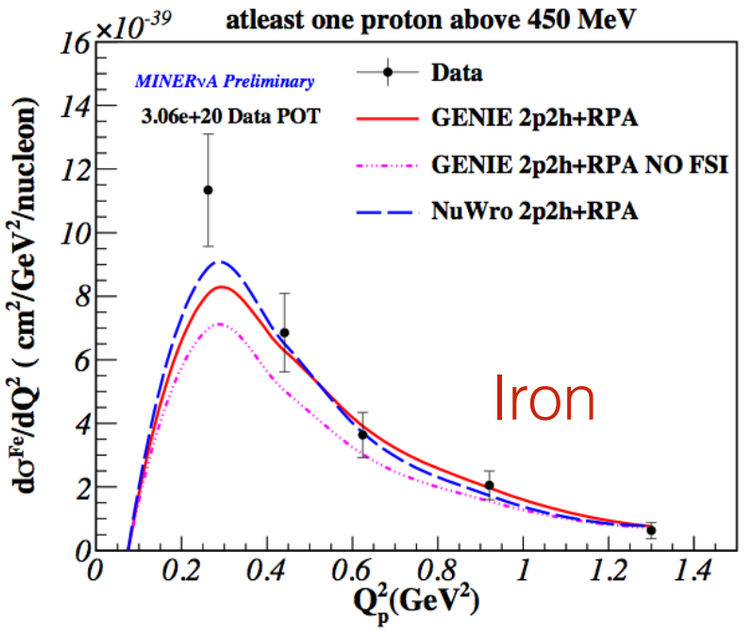
J. Wolcott
FNAL JTEP Seminar, 18 Sept. 2015

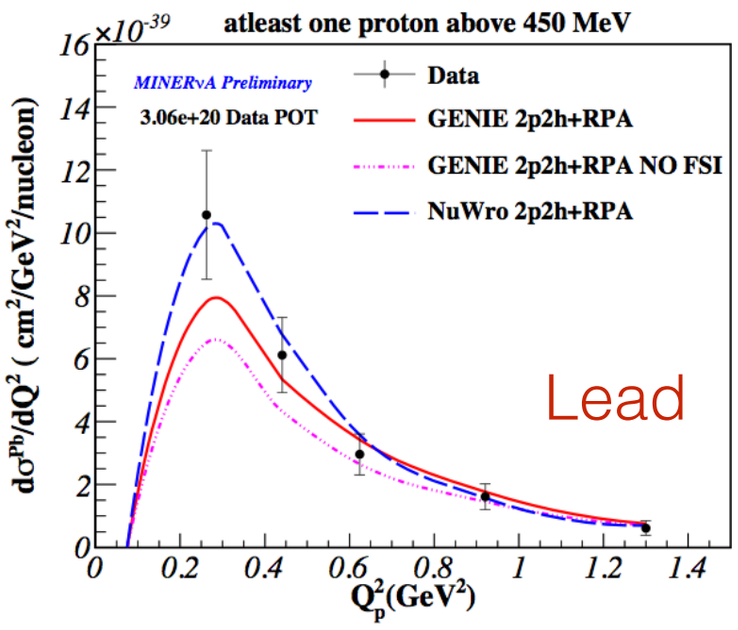
Comparisons with the generator

- Data prefers the simulation with final state interactions









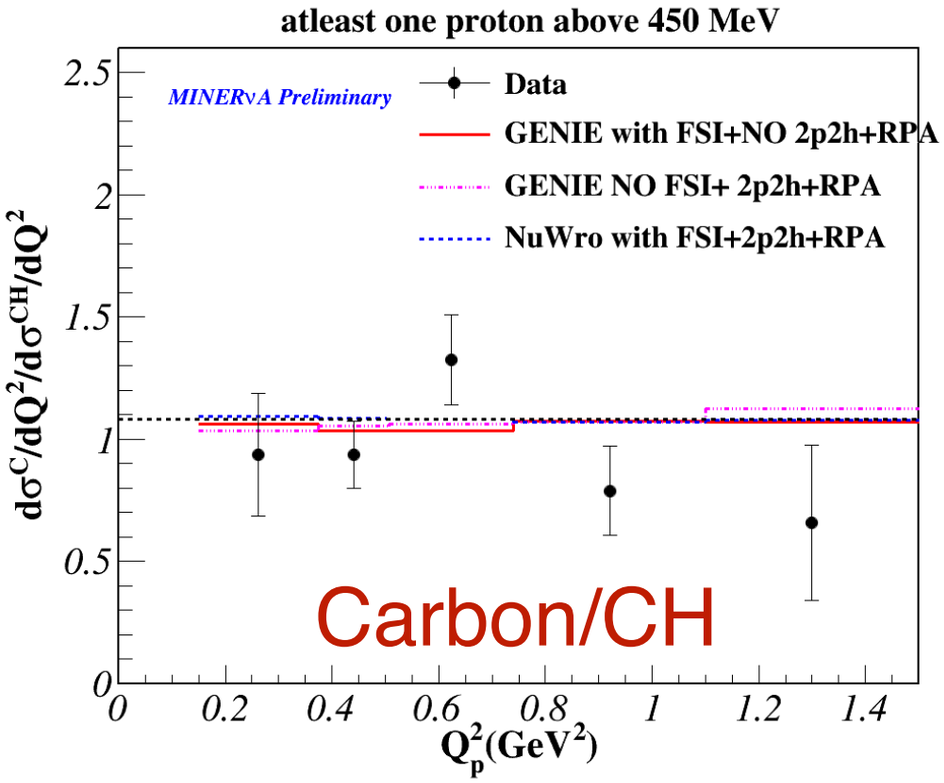
X^2/d.o.f

	carbon	iron	lead
GENIE	5.9/5	19.9/5	17.5/5
NuWro	6/5	14.6/5	11.1/5

M. Betancourt
FNAL JETP Seminar
5 Oct 2016

- The A dependence in NuWro seems to be more favored by the data

CCQE Cross Section Ratios



The data ratios show more nuclear effects for lead and iron compared with carbon, at low values of four momentum transfer $Q^2 < 0.6\ GeV^2$