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MINERvA

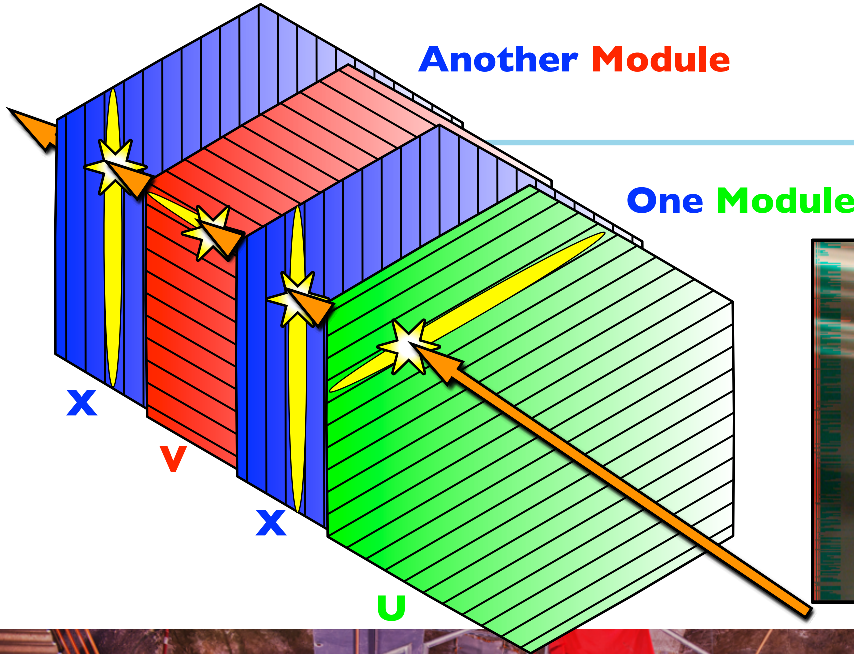
Gabriel N. Perdue

49th Annual Fermilab User's Meeting

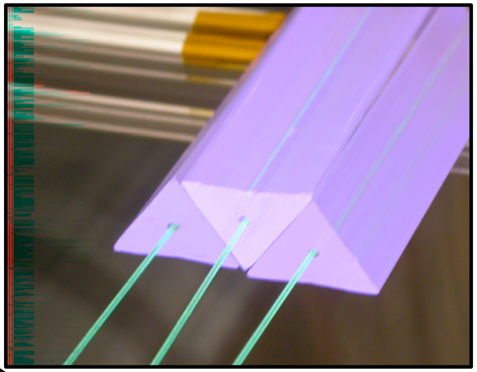
16 June 2016

Overview

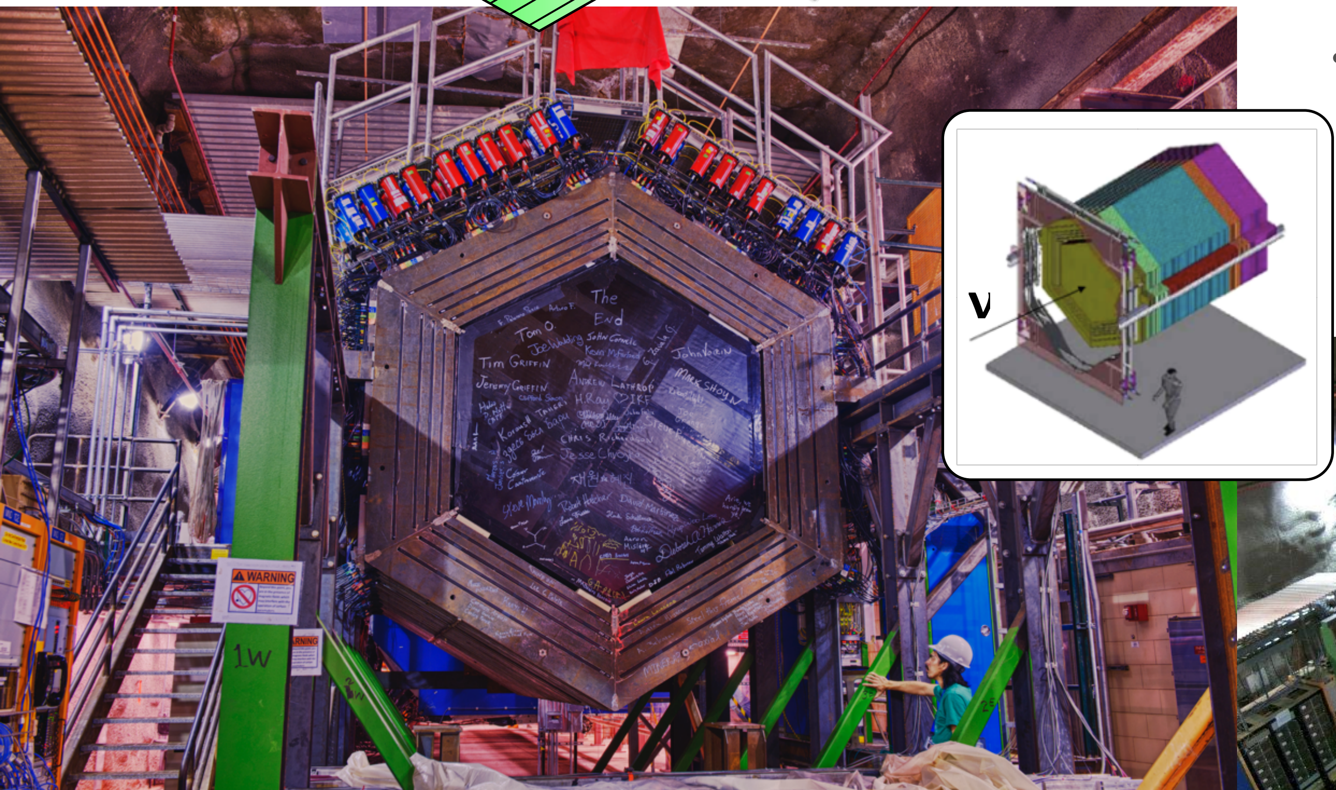
- Introduction to the experiment
  - Some motivation and a jargon-decoder
- Year in review
- Operations status
- Physics results
  - Strange physics
  - Multi-nucleon effects
  - Electron-neutrinos
    - Wish I had time for more!
- Ramping up on the "Medium Energy" beam
- Conclusions



MINERvA



- Fine-grained, high-resolution scintillator tracker for detailed kinematic reconstruction of neutrino-nucleus interactions.
- Cross-section program well-suited to next-generation oscillation experiments.
- Nuclear effects with a variety of target materials ranging from Helium to Lead.

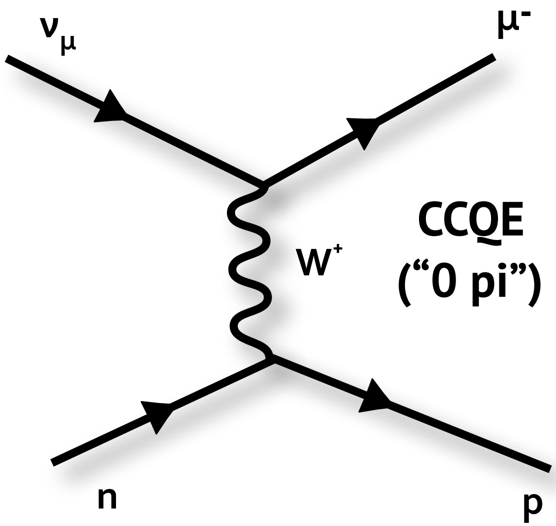


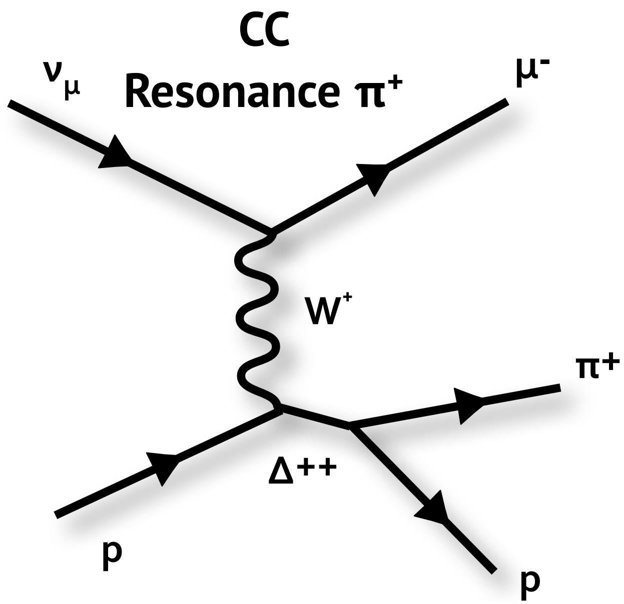
Motivation

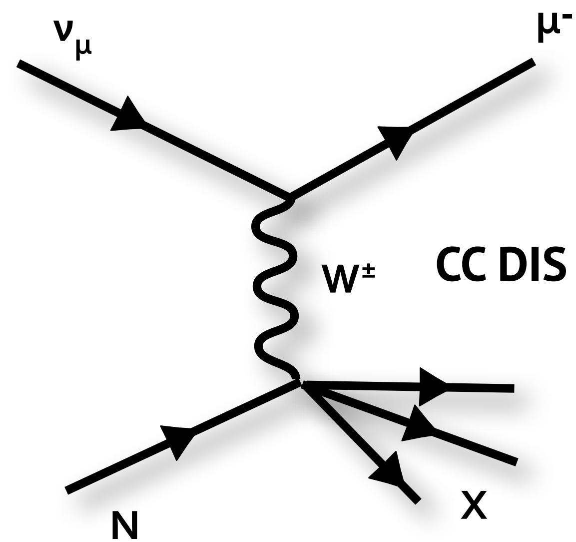
- Why measure cross sections?
  - *Because they're there.* Also…
  - Important and useful ingredients for oscillation experiments:
    - We measure the rates for important backgrounds.
    - We improve models for measuring neutrino energy.
    - We help experiments to understand their signal efficiency.
  - We're going to report on results today that illustrate all three of these points.
  - To properly measure a cross section, you must also understand your neutrino flux - we contribute a lot to techniques for doing this that are very useful to the whole community. We're down to ~7% uncertainty in our flux.
- New information about the structure of the nucleus that is only available with a Weak probe is a natural (and awesome) by-product.

Reaction channel menagerie

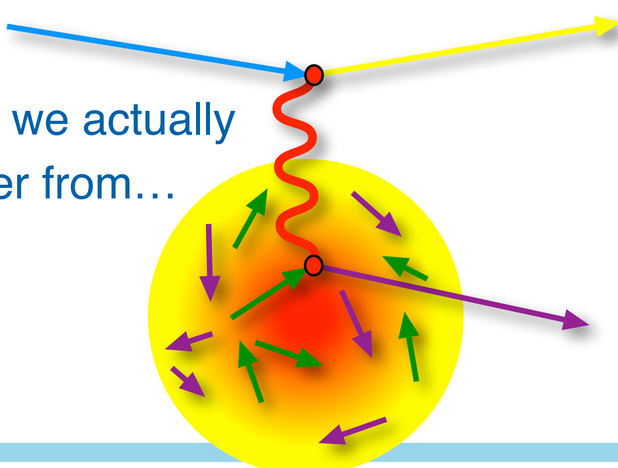
What we pretend we scatter from…

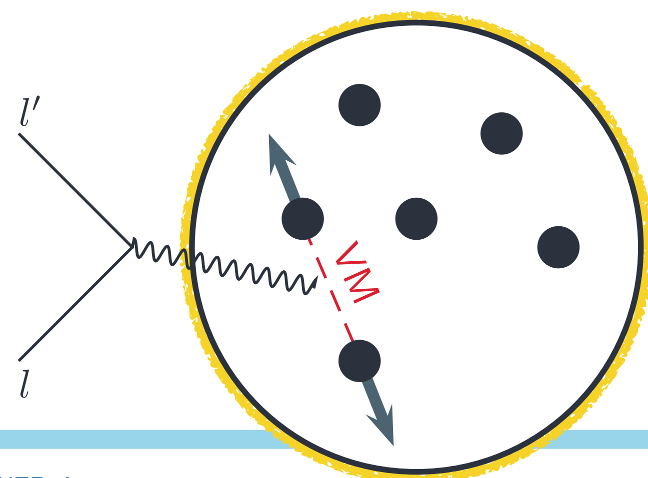






What we actually scatter from…





We can even scatter from correlated pairs of nucleons - "2p2h" events…

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Year in Review (from last User's Meeting)

- **7 Wine and Cheese Seminars at FNAL (including a *back-to-back-to-back run*).**
  - **And another Wine and Cheese *tomorrow!* Double-differential cross sections for CCQE-like antineutrinos!**
- **6 PhDs awarded**
- Papers!
  - Measurement of Electron Neutrino Quasielastic and Quasielasticlike Scattering on Hydrocarbon at $\langle E_\nu \rangle$=3.6 GeV, PRL 116, 081802
  - Identification of Nuclear Effects in Neutrino-Carbon Interactions at Low Three-Momentum Transfer, PRL 116, 071802
  - Measurement of partonic nuclear effects in deep-inelastic neutrino scattering using MINERvA, PRD 93, 071101(R)
  - Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering, PRD 93, 112007
  - Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon, arXiv 1604.01728, submitted to PRL
  - Measurement of K^+ production in charged-current ν_μ interactions, arXiv 1604.03920, submitted to PRD
  - And more coming soon:
    - Observation of Coherent Production of K+ in Neutrino Interactions on Carbon Nuclei - *Very soon!*
    - Differential cross sections for Nu-mu-CC-pi-plus and Nu-mu-bar-CC-pi-zero interactions on hydrocarbon in the few GeV region in MINERvA - *Very soon!*
    - Neutrino Flux Predictions for the NuMI Beam - *Very soon!*
    - plus several others coming later this year!

Year in Review

PRL **116**, 081802 (2016) PHYSICAL REVIEW LETTERS week ending 26 FEBRUARY 2016

Measurement of Electron Neutrino Quasielastic and Quasielasticlike Scattering on Hydrocarbon at $\langle E_\nu \rangle = 3.6$ GeV

J. Wolcott,[1,2] L. Aliaga,[3] O. Altinok,[2] L. Bellantoni,[4] A. Bercellie,[1] M. Betancourt,[4] A. Bodek,[1] A. Bravar,[5] H. Budd,[1] T. Cai,[1] M. F. Carneiro,[6] J. Chvojka,[1] H. da Motta,[6] J. Devan,[3] S. A. Dytman,[7] G. A. Díaz,[1,8] B. Eberly,[7,†] J. Felix,[9] L. Fields,[4,10] R. Fine,[1] A. M. Gago,[8] R. Galindo,[11] H. Gallagher,[2] A. Ghosh,[6,1] T. Golan,[1,4] R. Gran,[12] D. A. Harris,[4]

Evidence for neutral-current diffractive π^0 production from hydrogen in neutrino interactions on hydrocarbon

PRL **116**, 071802 (2016) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2016

Identification of Nuclear Effects in Neutrino-Carbon Interactions at Low Three-Momentum Transfer

P. A. Rodrigues,[1,†] J. Demgen,[2] E. Miltenberger,[2] L. Aliaga,[3] O. Altinok,[4] L. Bellantoni,[5] A. Bercellie,[1] M. Betancourt,[5] A. Bodek,[1] A. Bravar,[6] H. Budd,[1] T. Cai,[1] M. F. Carneiro,[7] J. Chvojka,[1] J. Devan,[3] S. A. Dytman,[8] G. A. Díaz,[1,9] B. Eberly,[8,‡] M. Elkins,[2] J. Felix,[10] L. Fields,[5,10] R. Fine,[1] A. M. Gago,[9] R. Galindo,[12] H. Gallagher,[4] A. Ghosh,[7,1]

PHYSICAL REVIEW D **93**, 071101(R) (2016)

Measurement of partonic nuclear effects in deep-inelastic neutrino scattering using MINERvA

J. Mousseau,[1,*] M. Wospakrik,[1] L. Aliaga,[2] O. Altinok,[3] L. Bellantoni,[4] A. Bercellie,[5] M. Betancourt,[4] A. Bodek,[5] A. Bravar,[6] H. Budd,[5] T. Cai,[5] M. F. Carneiro,[7] M. E. Christy,[8] J. Chvojka,[5] H. da Motta,[7] J. Devan,[2] S. A. Dytman,[9] G. A. Díaz,[5,10] B. Eberly,[9,†] J. Felix,[11] L. Fields,[4,12] R. Fine,[5] A. M. Gago,[10] R. Galindo,[13] H. Gallagher,[3]

Measurement of K^+ production in charged-current ν_μ interactions

C.M. Marshall,[1] L. Aliaga,[2,3] O. Altinok,[4] L. Bellantoni,[5] A. Bercellie,[1] M. Betancourt,[5] A. Bodek,[1] A. Bravar,[6] H. Budd,[1] T. Cai,[1] M.F. Carneiro,[7] J. Chvojka,[1] H. da Motta,[7] J. Devan,[2] S.A. Dytman,[8] G.A. Díaz,[1,3]

PHYSICAL REVIEW D **93**, 112007 (2016)

Measurement of neutrino flux from neutrino-electron elastic scattering

J. Park,[1] L. Aliaga,[2,3] O. Altinok,[4] L. Bellantoni,[5] A. Bercellie,[1] M. Betancourt,[5] A. Bodek,[1] A. Bravar,[6] H. Budd,[1] T. Cai,[1] M. F. Carneiro,[7] M. E. Christy,[8] J. Chvojka,[1] H. da Motta,[7] S. A. Dytman,[9] G. A. Díaz,[1,3] B. Eberly,[9,*] J. Felix,[10] L. Fields,[5,11] R. Fine,[1] A. M. Gago,[3] R. Galindo,[12] A. Ghosh,[7] T. Golan,[1,5] R. Gran,[13] D. A. Harris,[5] A. Higuera,[1,10,†]

"Modern" 😁 neutrino scattering scoreboard

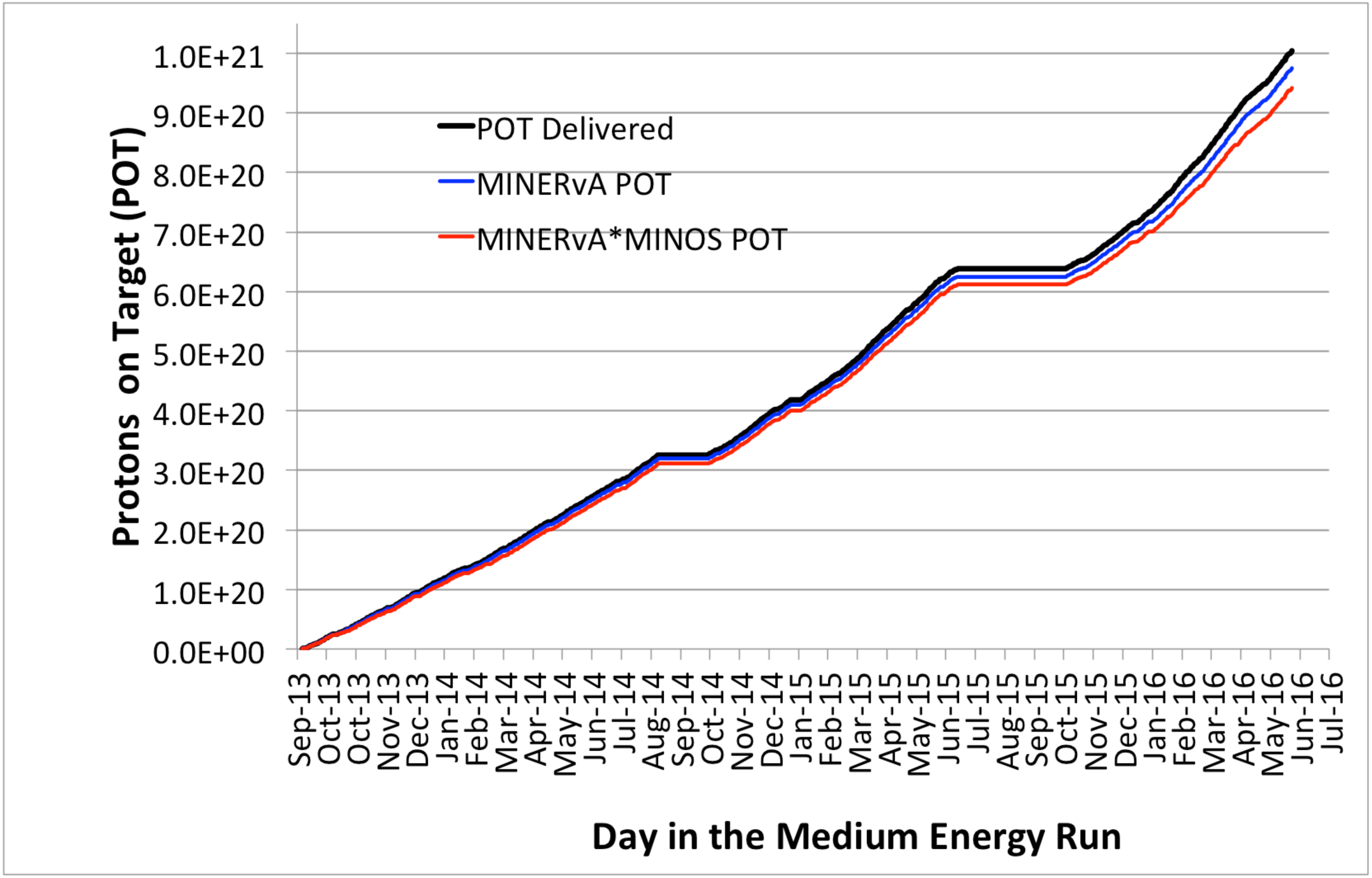
Published σ papers	PRL	PRD	PLB	Total
MINERvA	6	4	1	11
MiniBooNE	1	7		8
T2K	1	6		7
ArgoNEUT	2	2		4
SciBooNE		4		4
MINOS		2		2

(Of course, we have 0 oscillation papers. 😁)

Can't wait to see MicroBooNE, SBND, and NOvA on this list!

Beam! Lots and lots of beam!

Our warmest thanks to the accelerator division for the great beam!



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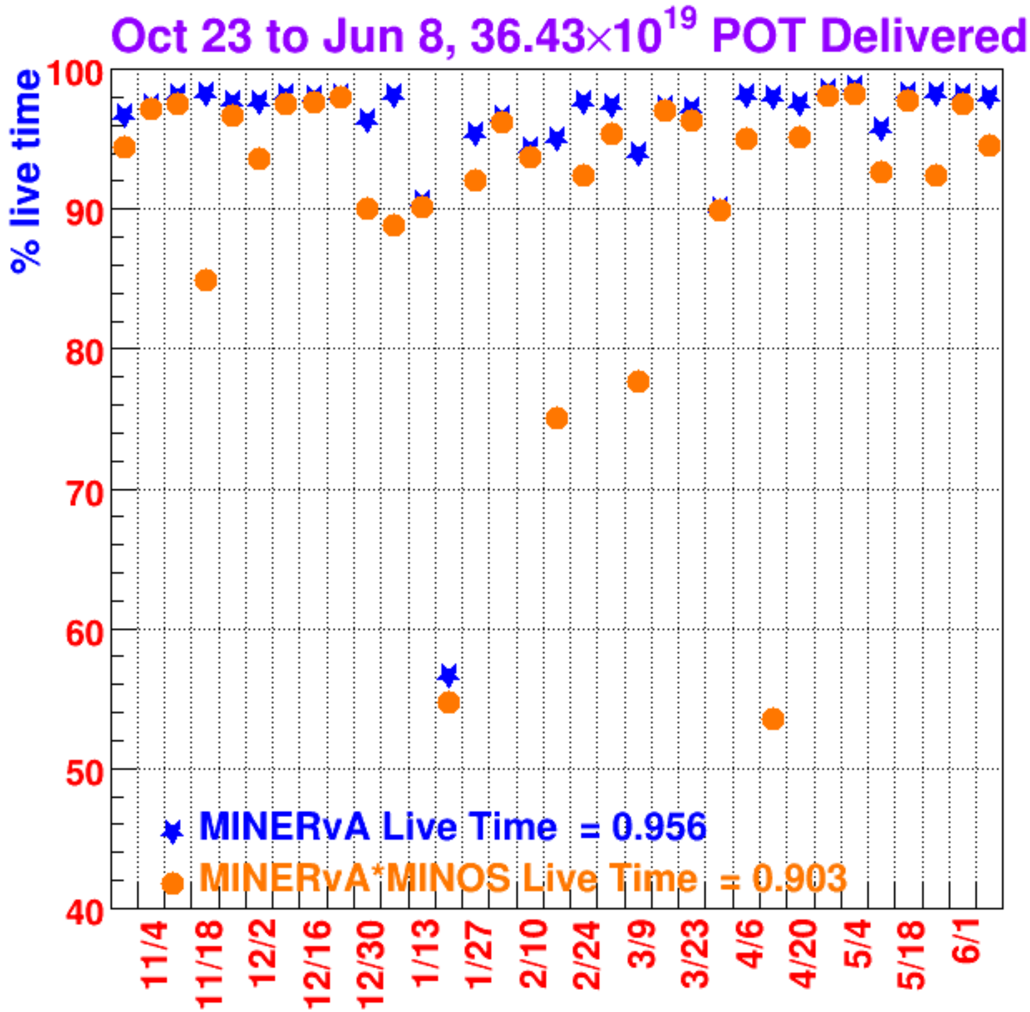
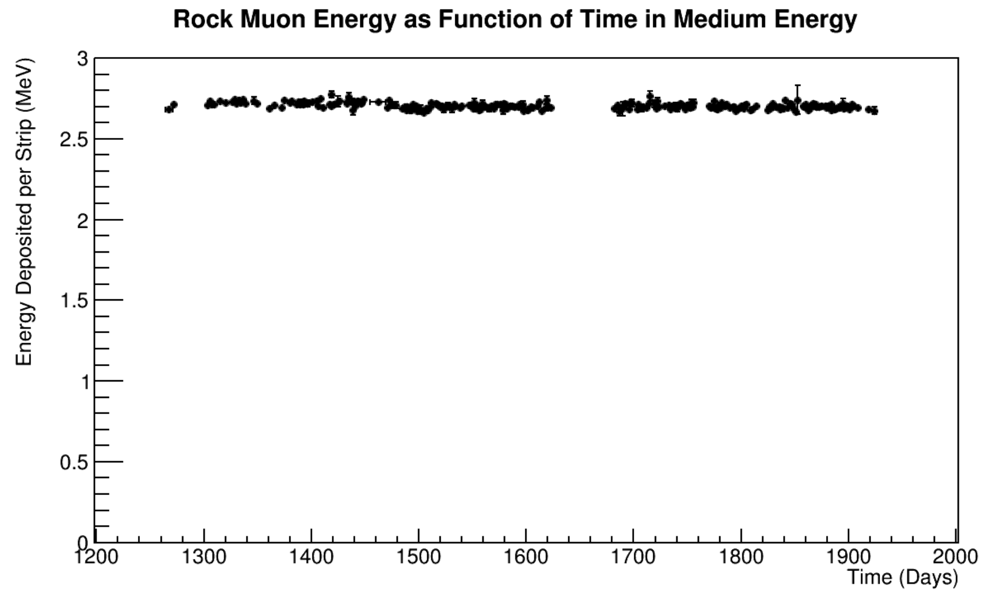
Keeping it all working

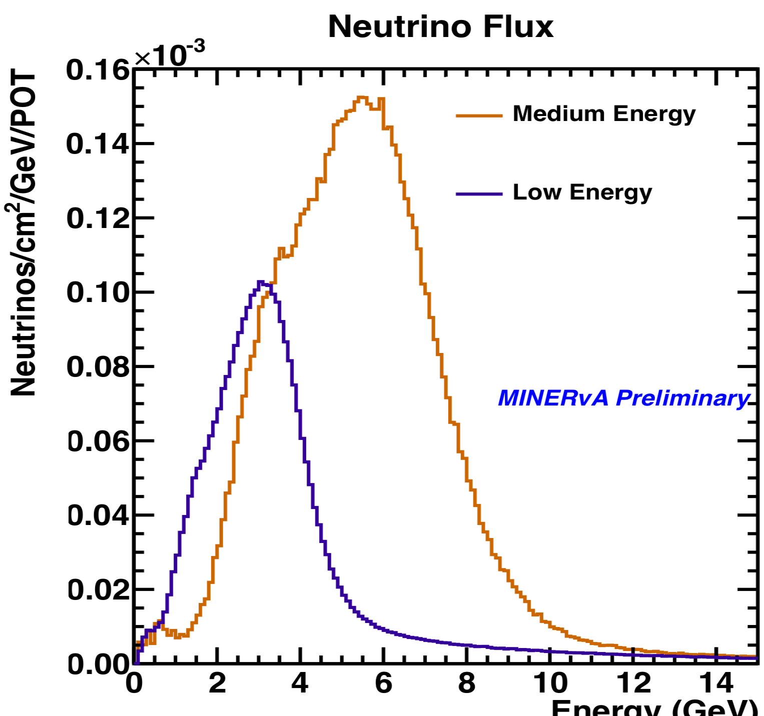
- We rely on the MINOS near detector for muon sign identification.
- Many thanks to the MINOS+ collaboration for sharing this data with us and for a productive and successful partnership maintaining the Near Detector over the past few years.
- Thanks also to the Fermilab operations team that has helped keep both detectors operating smoothly!

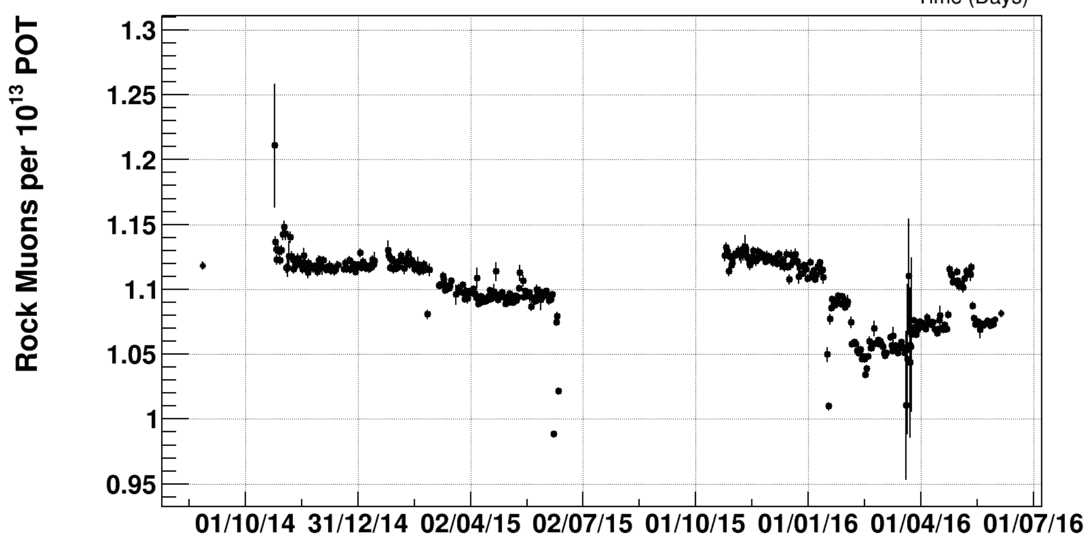


Data quality in the "Medium Energy"

- NuMI has been running in the "Medium Energy" mode since NOvA began taking data.
  - Low Energy prior to NOvA turn on.
- This is a natural "second epoch" for MINERvA.
- The detector is performing well and understandably according to all of our various data quality metrics in this period.







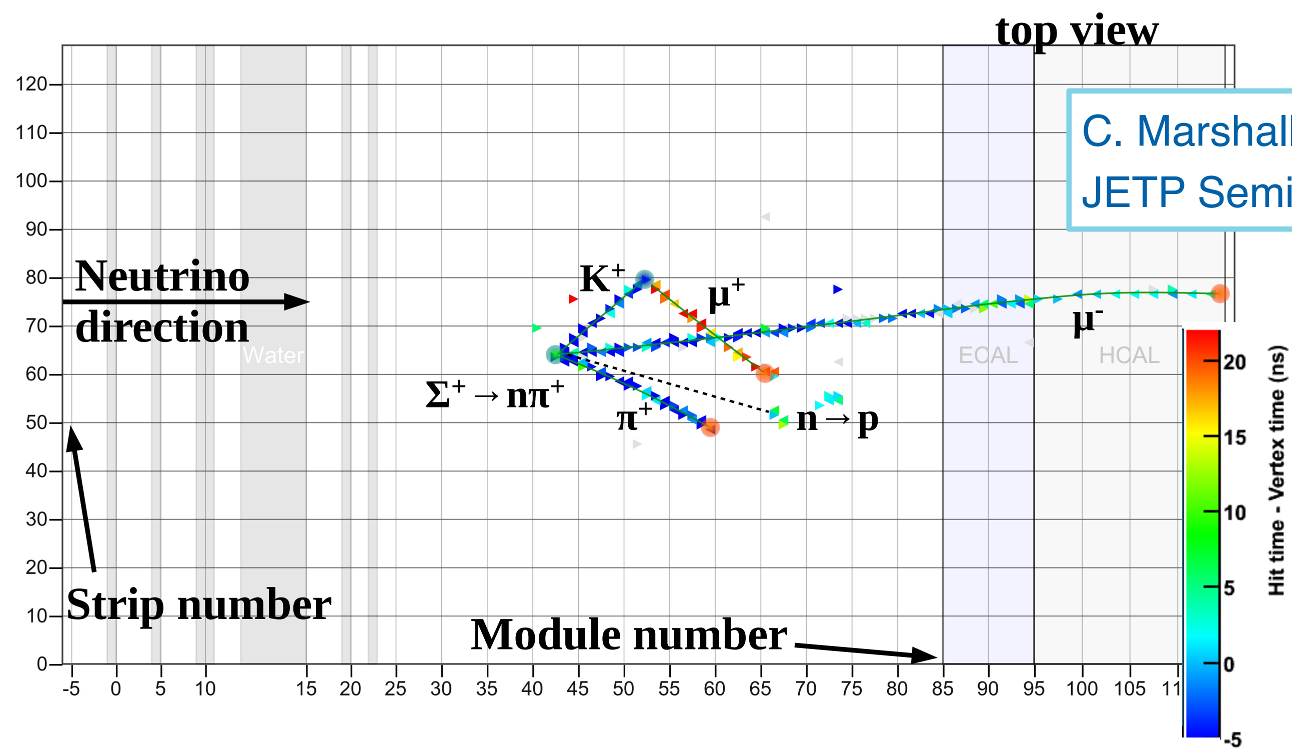
Recent physics highlights...

- Strange production
- Nuclear effects at low three-momentum transfer
- Electron neutrinos
- Medium energy CCQE (early work-in-progress)

Strange physics

- K+ production by atmospheric neutrinos (especially NC) is an important background for proton decay searches, p → Kν
  - DUNE background prediction is 1 event per Mton-year*. Are we even close?
- K+ production complements π+ production as a probe of hadronic FSI.

My guess: $\nu_\mu p \rightarrow \mu^- K^+ \Sigma^+$



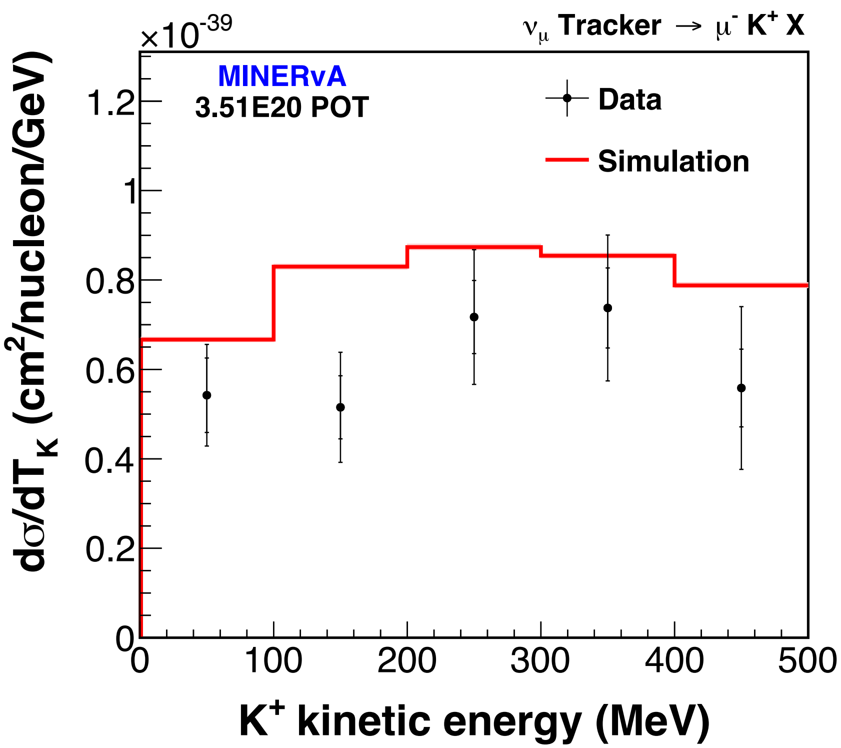
C. Marshall,
JETP Seminar, 5 Feb 2016

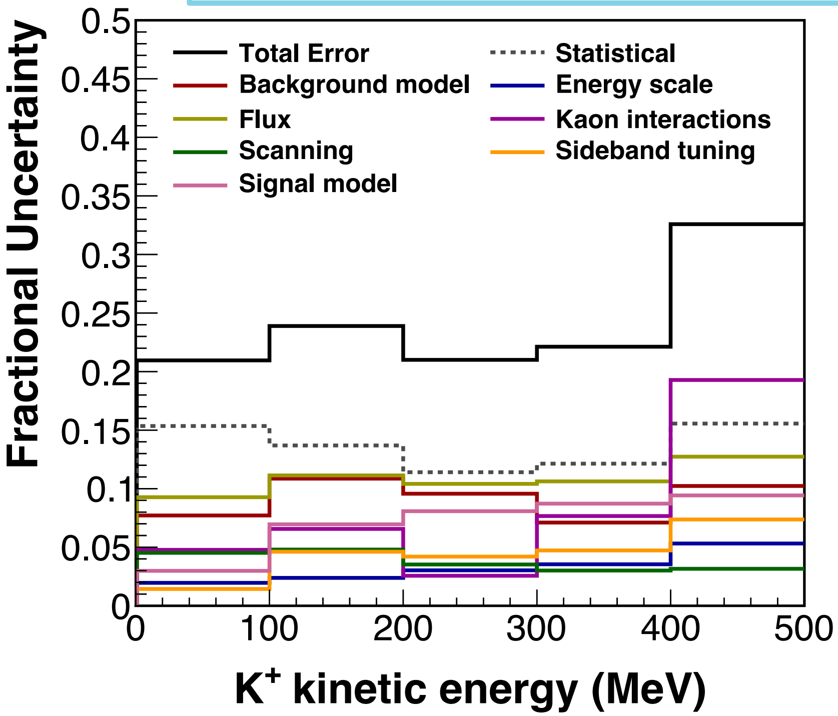
*JHEP **0704** 041 (2007)

Strange physics

- Charged current K+ production cross section shows reasonably good agreement with simulation.
- This measurement increased the world's sample of K+ production events from neutrinos from dozens to thousands!

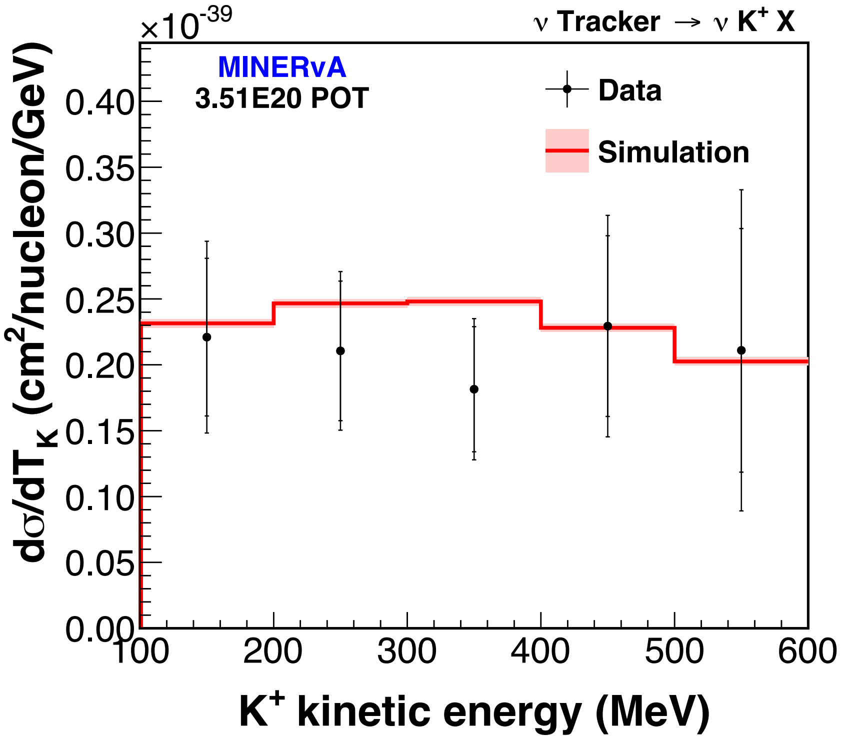
https://arxiv.org/abs/1604.03920

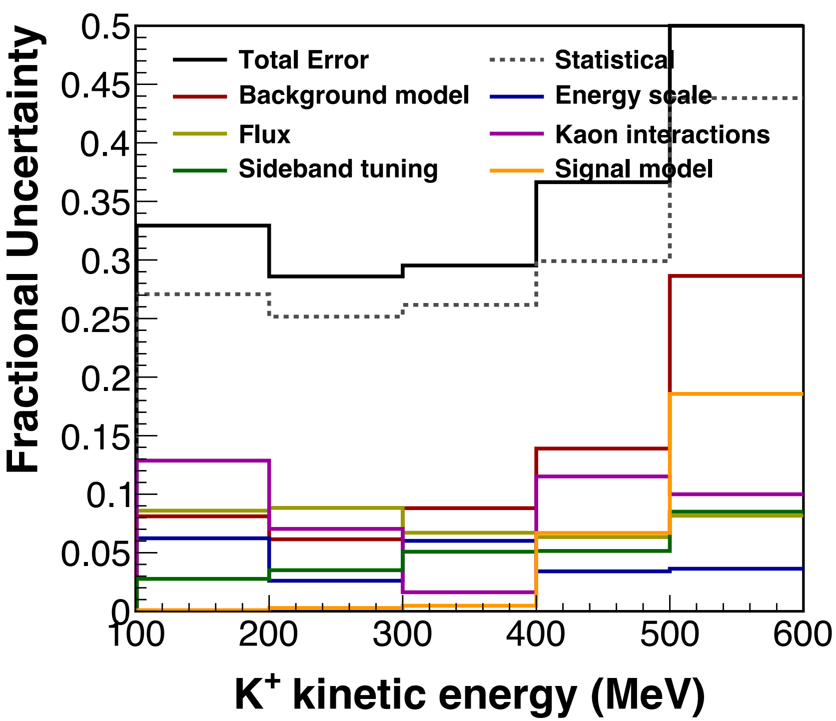




Strange physics

- Neutral current K+ production cross section shows reasonably 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.

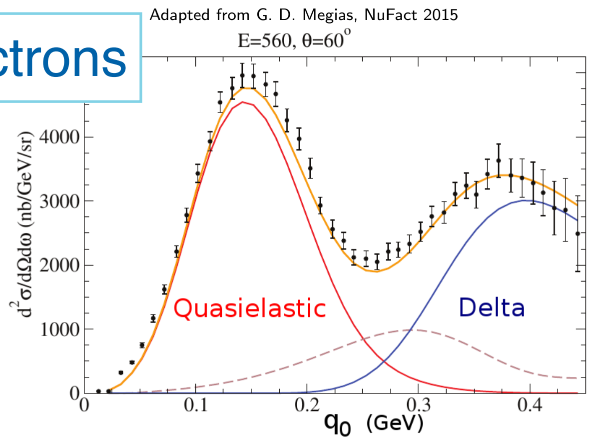




C. Marshall,
JETP Seminar, 5 Feb 2016

Nuclear effects at low three momentum transfer

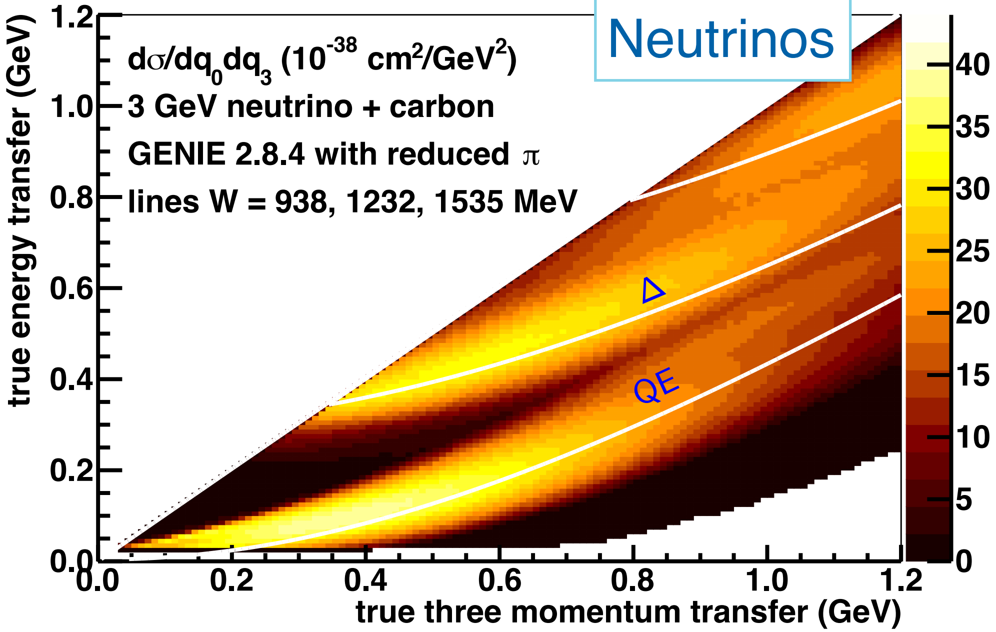
Electrons

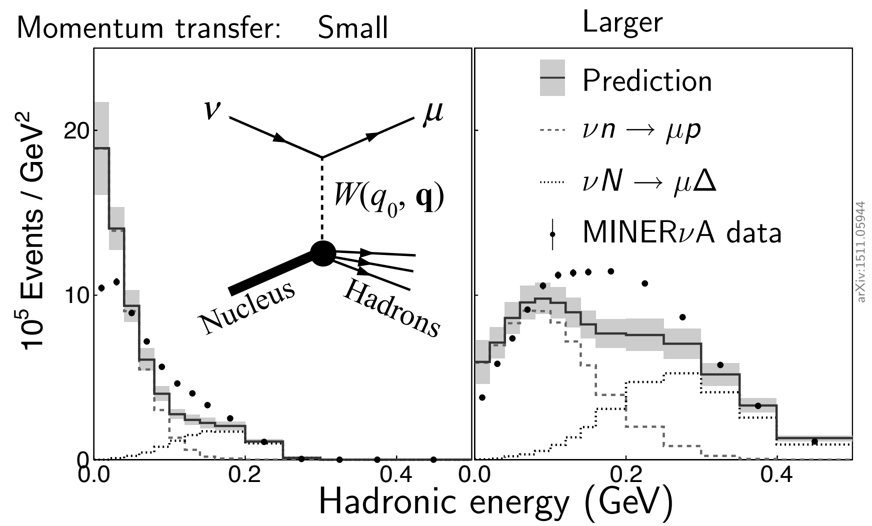


$q_0 = E_e - E_{e'}$

- Inclusive charged current events.
- Isolating energy and momentum transfer allows us to isolate channels in a fashion (somewhat) analogous to electron scattering.
- Default nuclear model struggles to explain data

Neutrinos





P. Rodrigues,
JETP Seminar, 11 Dec 2015

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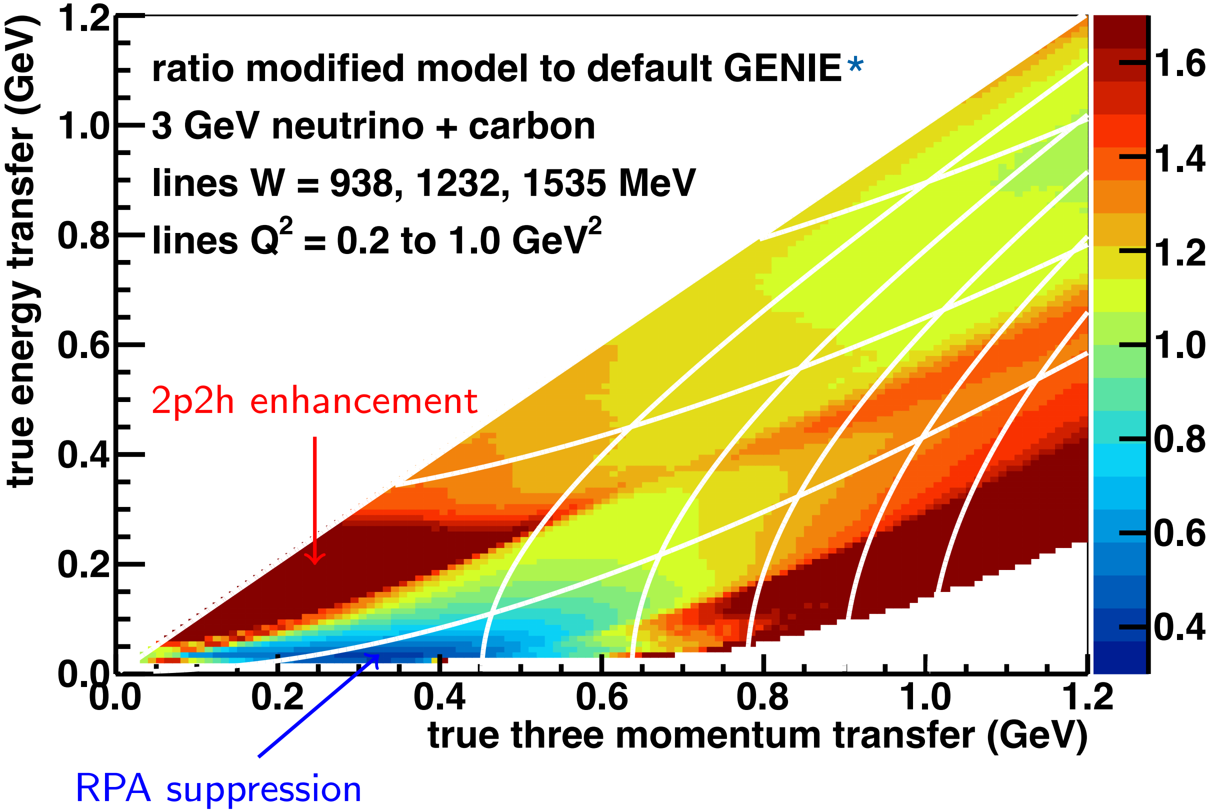
Nuclear effects at low three momentum transfer



- *Build a more sophisticated nuclear model* - include RPA (Weak charge screening) and 2p2h effects (Nieves, et al. PRC 70, 055503 & PRC 83, 045501) in private modification of GENIE (now a permanent contribution to the generator code).

* Also with pion production re-tuned.

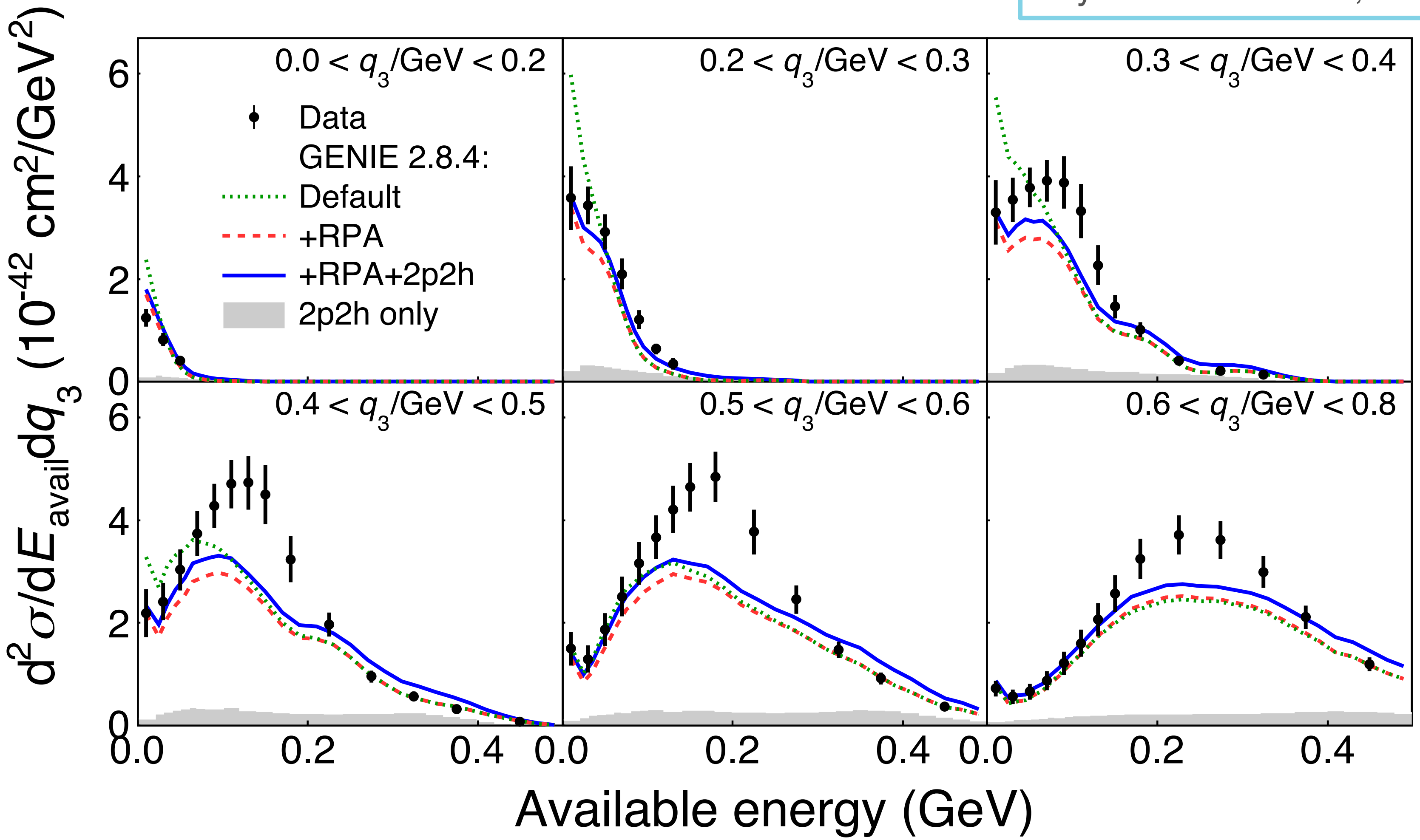
P. Rodrigues,
JETP Seminar, 11 Dec 2015

Nuclear effects at low three momentum transfer

$$E_{\text{avail}} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

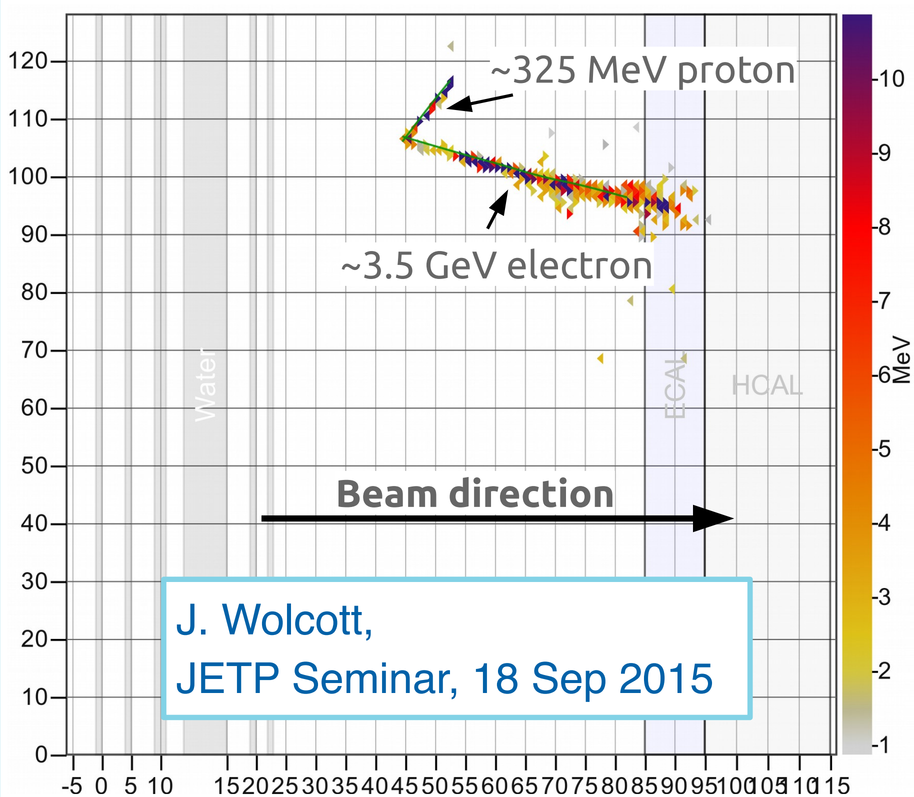
Phys. Rev. Lett. **116**, 071802

GENIE π production modified



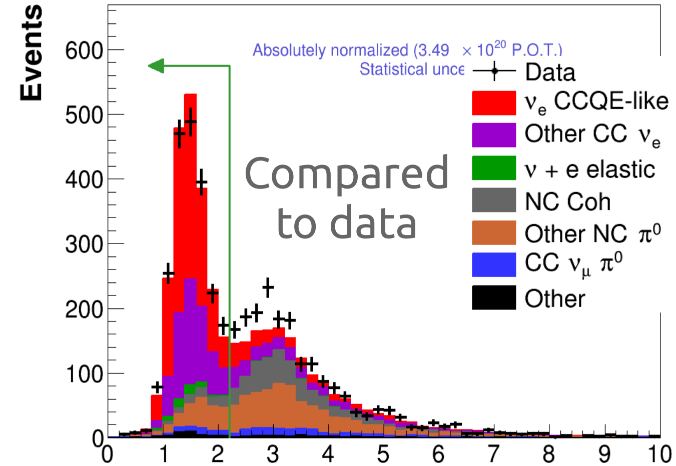
Electron-neutrinos

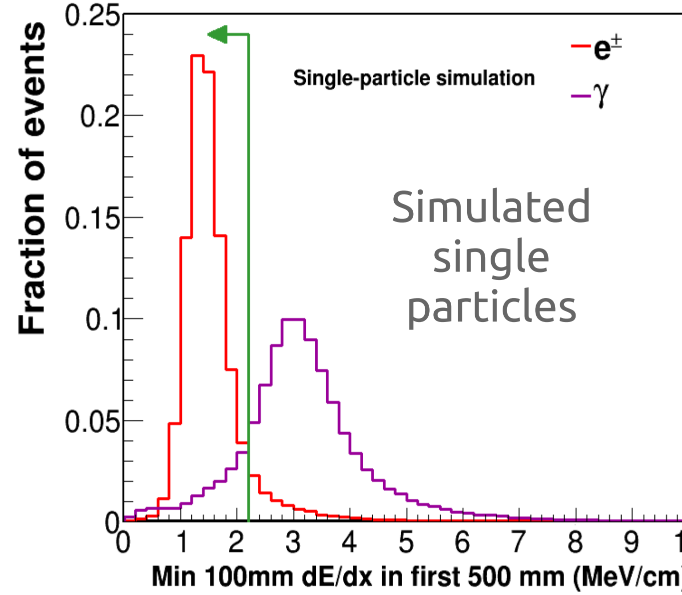
- "QE-like" (0-pion final state) electron-neutrinos.
  - Electron or position.
  - Any number of protons and/or neutrons.
  - *First* measurement ever of this channel.



J. Wolcott,
JETP Seminar, 18 Sep 2015

Event display of simulated
~4 GeV ν_e interaction in MINERvA





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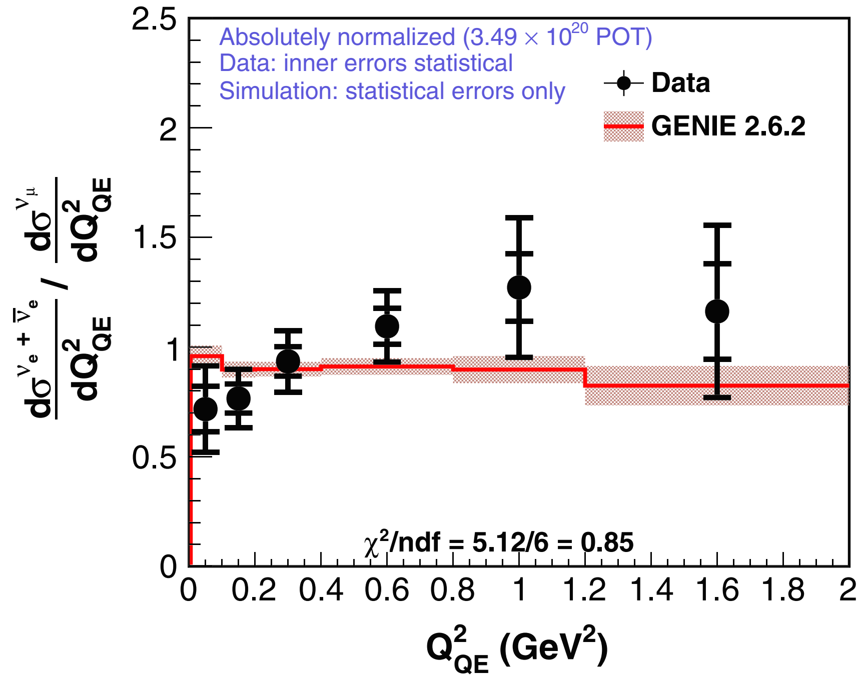
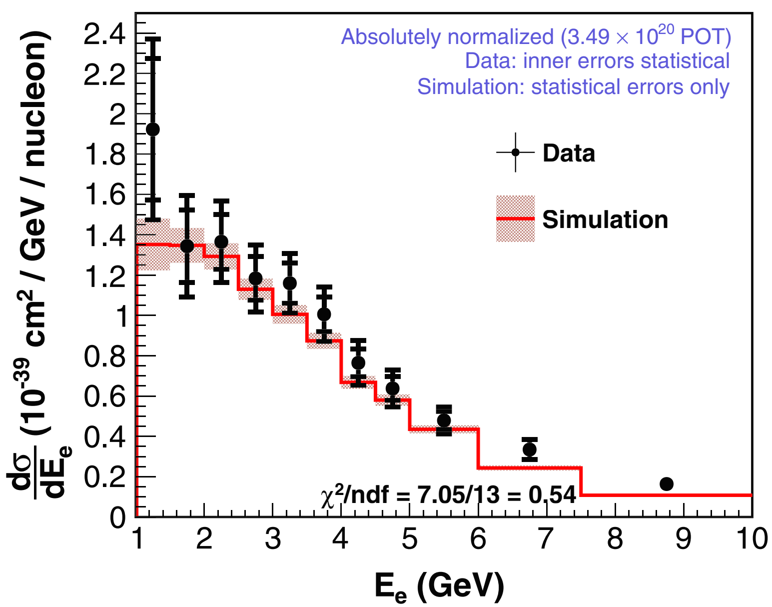
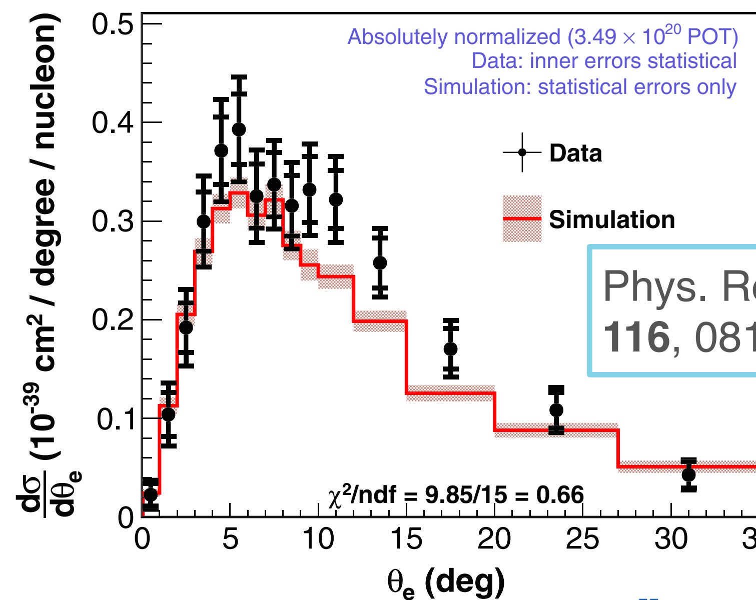
Electron-neutrinos

- Statistically consistent with the generator prediction.
- Q² (four-momentum transfer squared) consistent with MINERvA measurement for muon neutrinos.
- Nuclear and kinematic effects are consistent with their modeling.

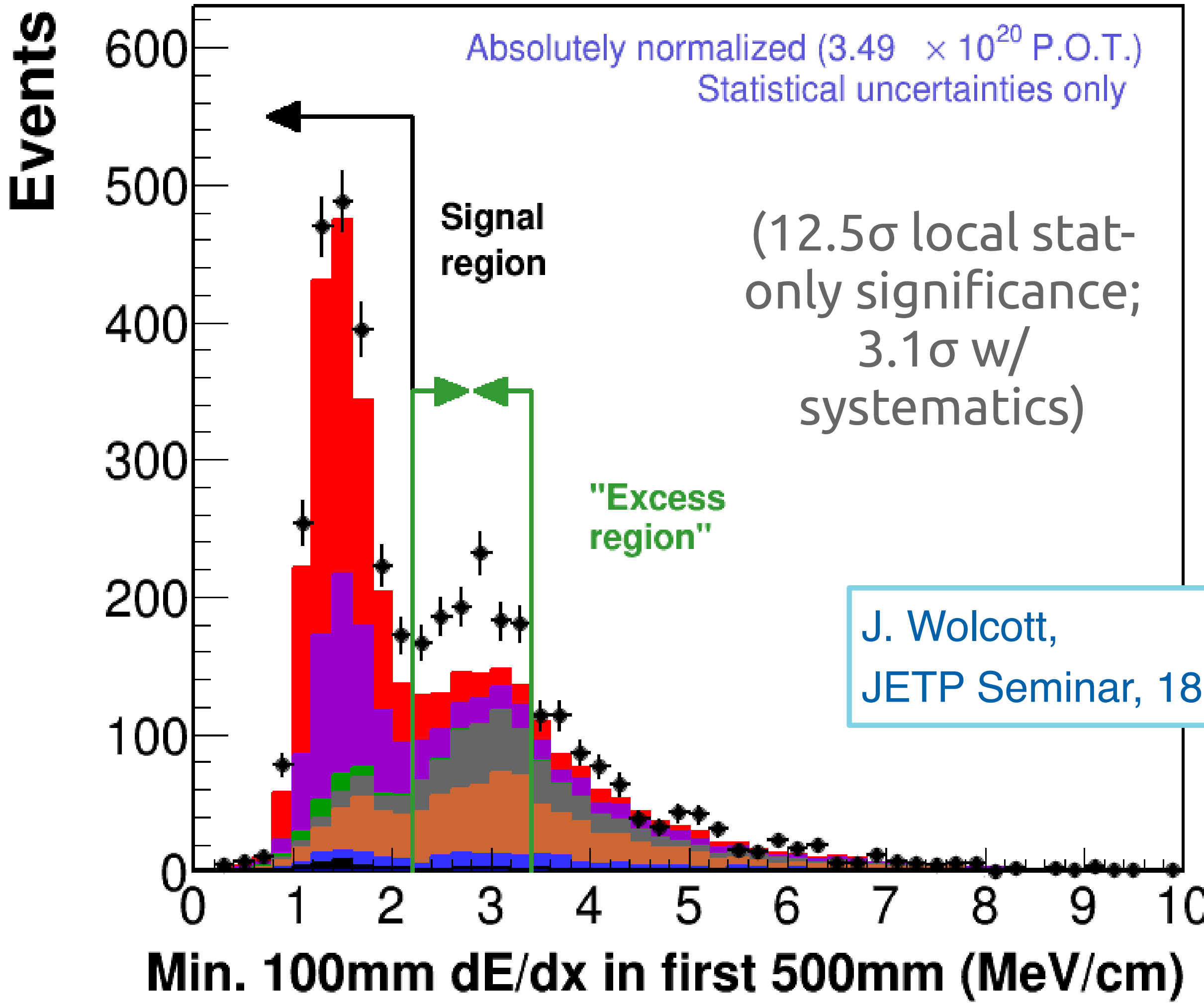






Phys. Rev. Lett. **116**, 081802

Who ordered that?

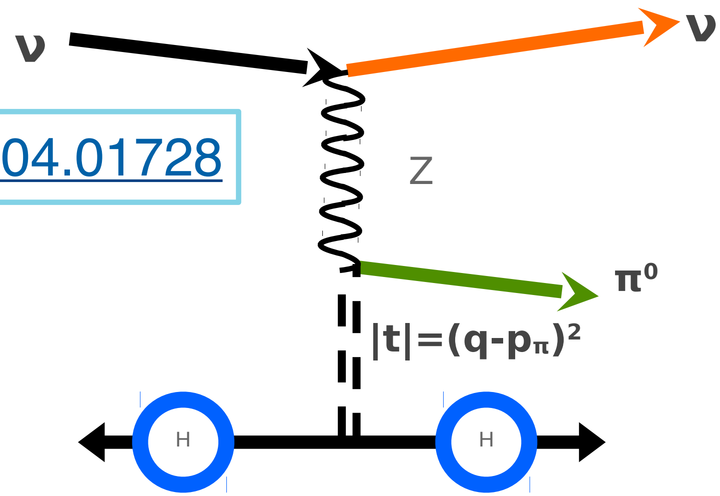


(12.5σ local stat-only significance; 3.1σ w/ systematics)

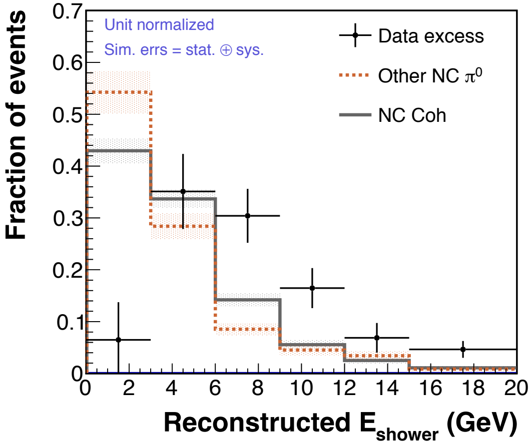
J. Wolcott,
JETP Seminar, 18 Sep 2015

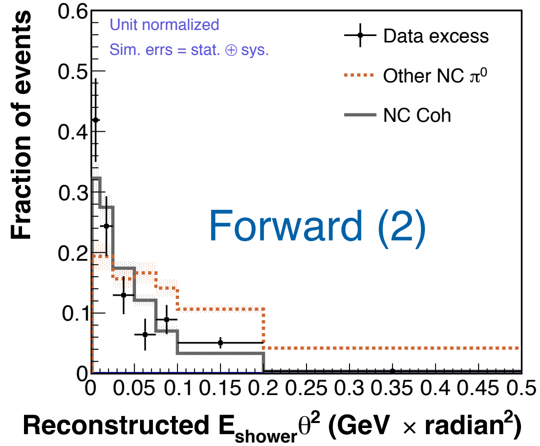
Who ordered that?

https://arxiv.org/abs/1604.01728

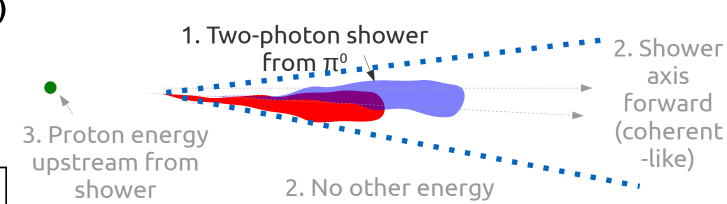


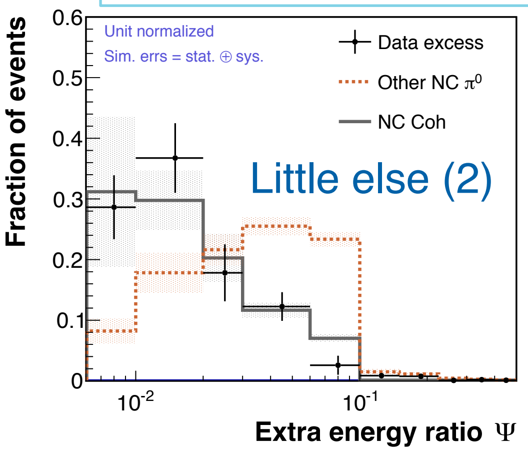
NC diffractive production from Hydrogen

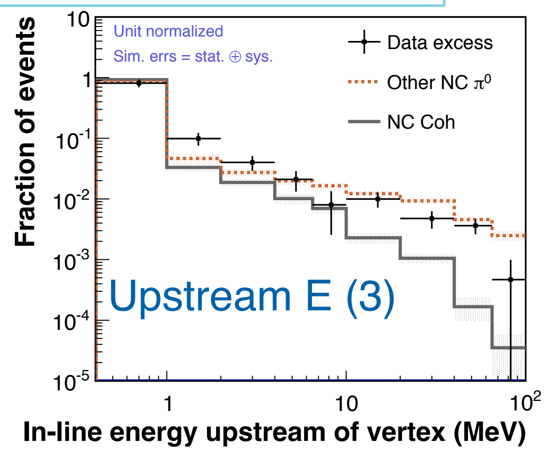




Total Cross Section for E_{shower} > 3 GeV Integrated over MINERvA flux = $0.26 \pm 0.02_{stat} \pm 0.08_{sys} \times 10^{-39}$ cm²/CH



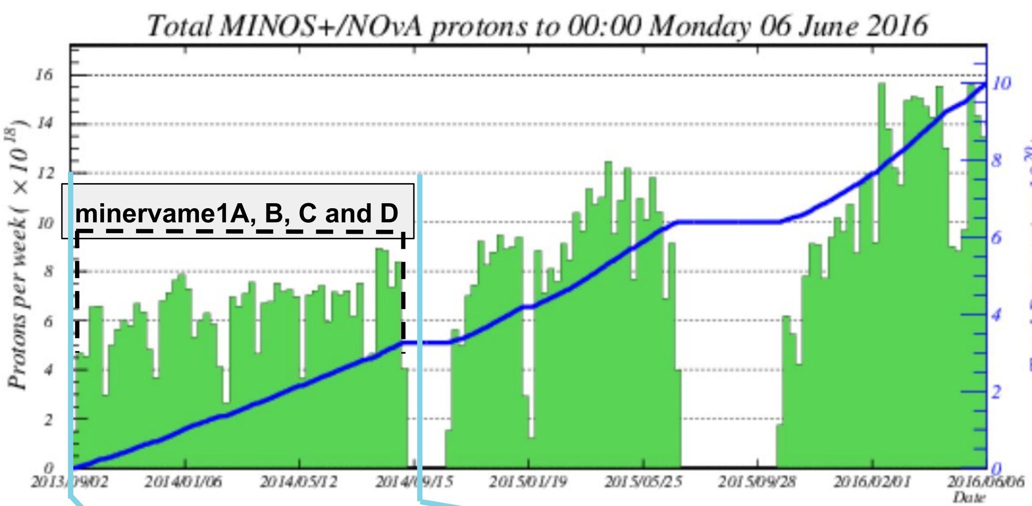




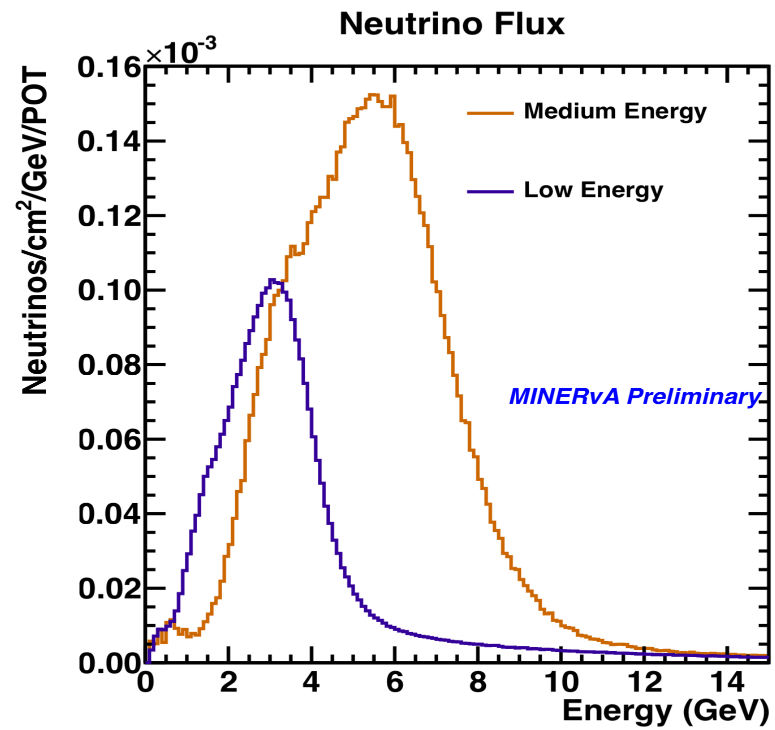
1) Two-photon π^0 shower
2) Coherent-like scattering:
   - Forward kinematics
   - Very little other energy
3) Visible proton energy

Medium Energy

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



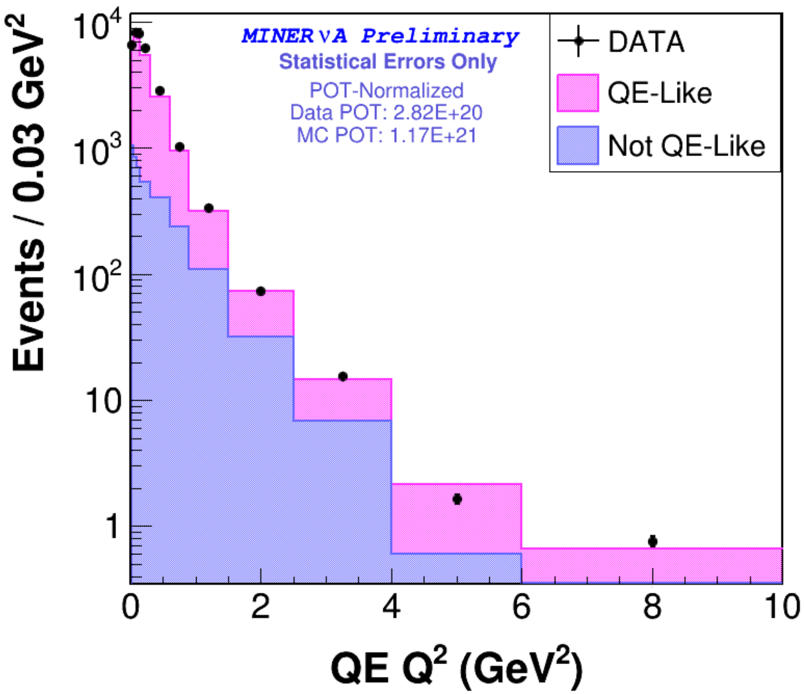
Sign-analyzed CC-muon neutrinos with a fiducial vertex in the tracker	*1,110,000*
Passing all QE-like (0-pion final state) event selection cuts	*141,000*



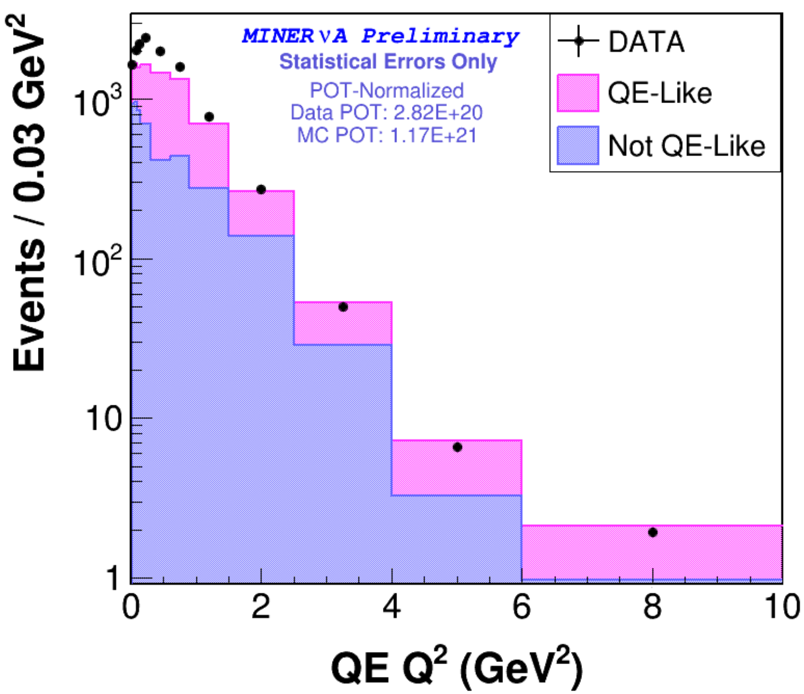
Medium Energy "QE-like" (0-pion final state)

- The higher energy beam tune gives us a much higher reach in four-momentum transfer squared (Q^2).
  - And this is only about 30% of the data for neutrinos!

1 track

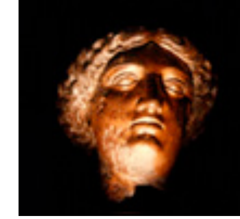


2 tracks



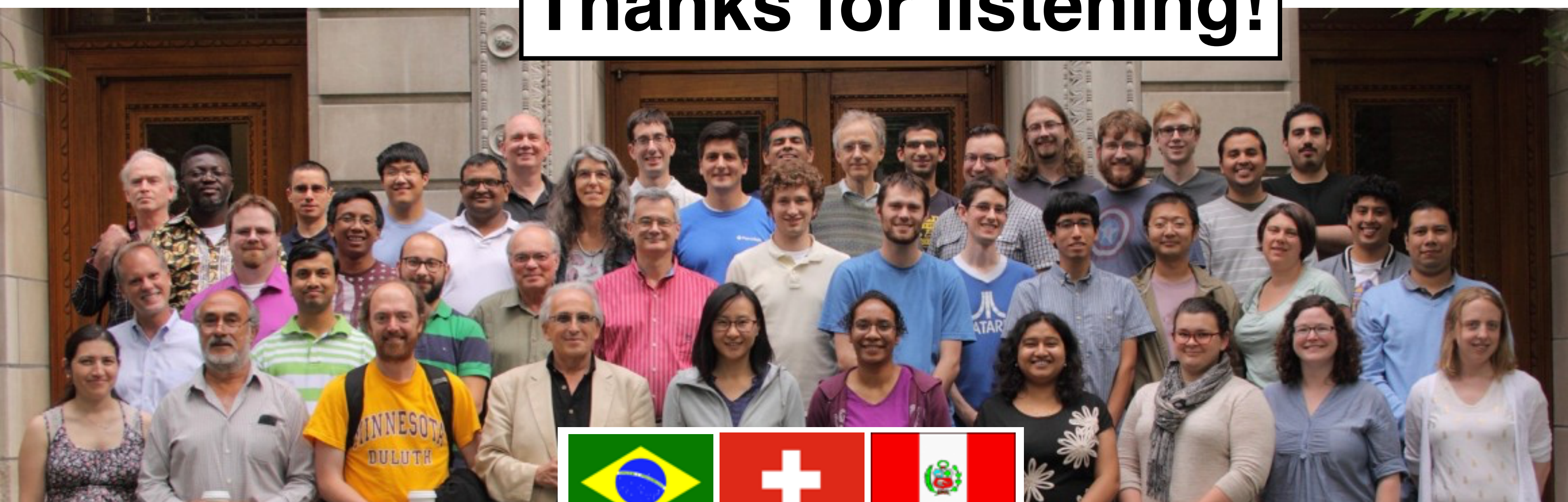
Conclusion

- MINERvA is a results factory with a busy past year and a full pipeline looking forward!
  - Maybe we'll out-do the Wine and Cheese three-peat?
    - Remember to come to the Wine and Cheese *tomorrow!*
- The detector is working well and we're stock-piling an enormous Medium Energy dataset that we've only just begun to analyze.
  - Still wrapping up our NuMI Low Energy analyses, and our new data offer substantially improved statistics for exclusive state channels.
- Ready to come back after the upcoming shutdown.
  - Looking forward to eventually integrating an antineutrino dataset.
- We're learning a great deal about neutrino-nucleus interactions and building a rich set of results that nicely span the first oscillation peak at DUNE with measurements on a variety of targets bracketing Argon in the periodic table.

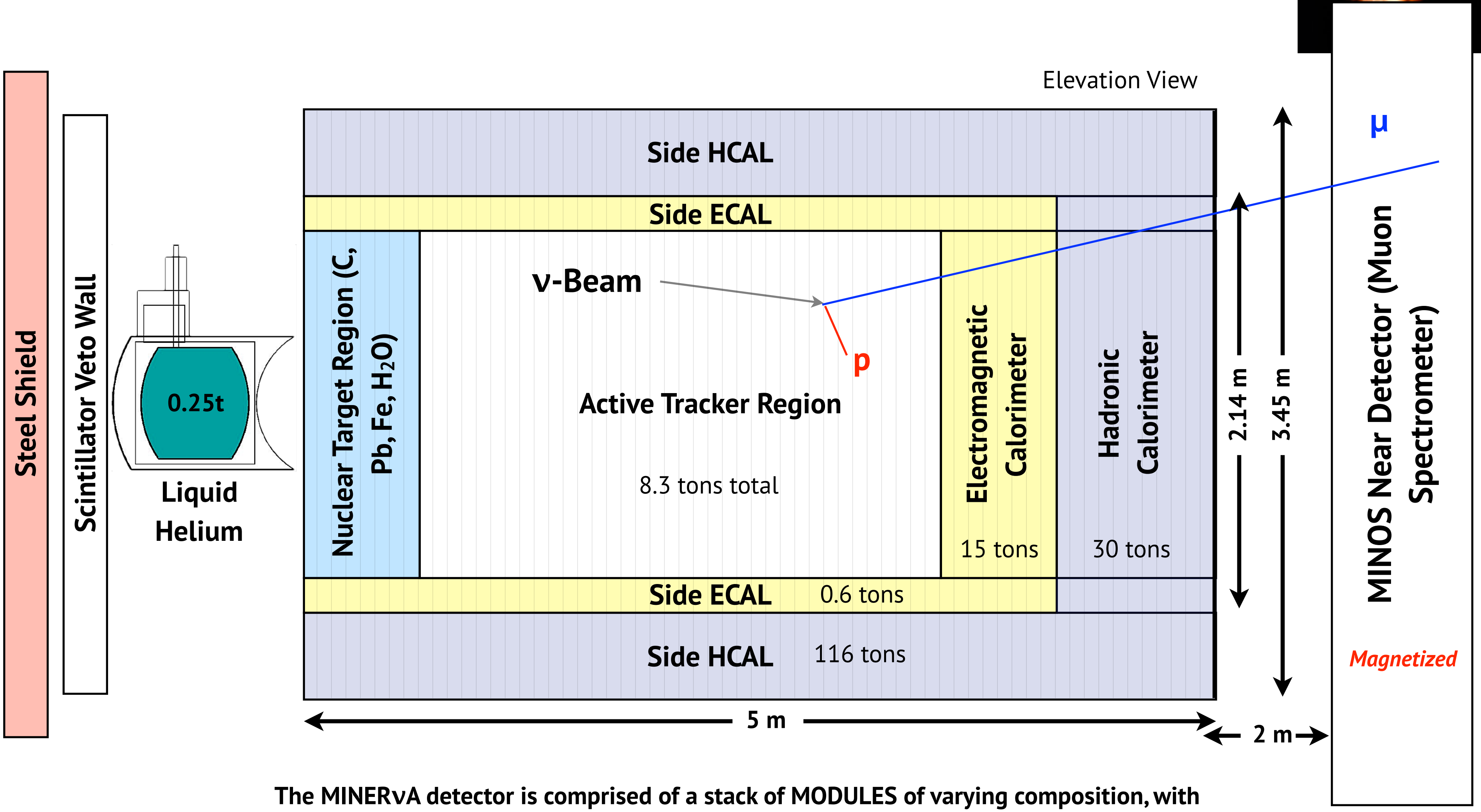


- On behalf of the whole MINERvA collaboration…
  - ~60 physicists
  - Centro Brasileiro de Pesquisas Fisicas, University of Chicago, Fermilab, University of Florida, Université de Genéve, Universidad de Guanajuato, Hampton University, Massachusetts College of Liberal Arts, Oxford University, University of Minnesota at Duluth, Universidad Nacional de Ingeniería, Northwestern University, Otterbein University, Pontifica Universidad Catolica del Peru, University of Pittsburgh, University of Rochester, Rutgers University, Universidad Técnica Federico Santa María, Tufts University, College of William and Mary

Thanks for listening!

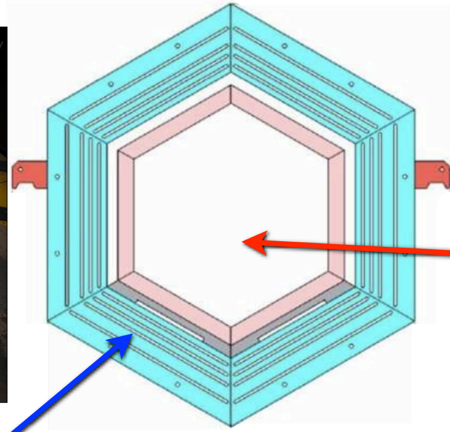


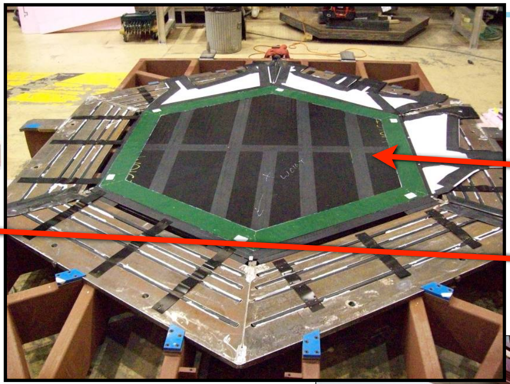
The Best Thing Since Sliced Bread…



The MINERvA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).

MINERvA Modules



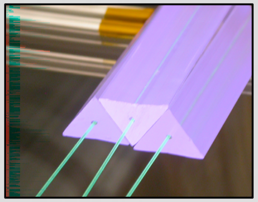


...and an inner detector element of scintillator strips and absorbers/ targets.

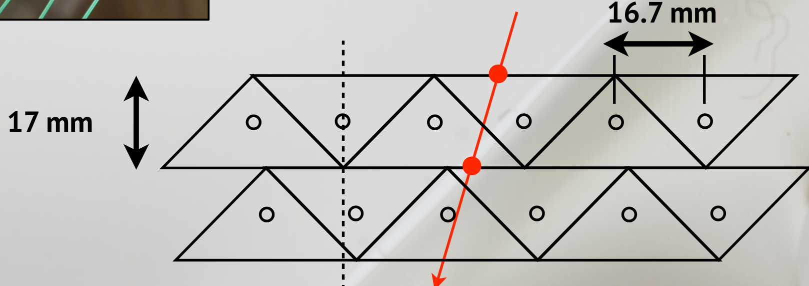
Modules have an outer detector frame of steel and scintillator...

- Four basic module types:
  - *Tracker:* two scintillator planes in stereoscopic orientation.
  - *Hadronic Calorimeter:* one scintillator plane and one 2.54-cm steel absorber.
  - *Electromagnetic Calorimeter:* two scintillator planes and two 2-mm lead absorbers.
  - *Nuclear Targets:* absorber materials (some with scintillator planes).
- Instrumented outer-detector steel frames.
- 120 Total Modules: 84 Tracker, 10 ECAL, 20 HCAL, 6 Nuclear Targets.

Plastic Scintillator Strips: The Active Detector Elements.

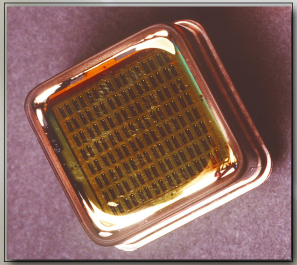


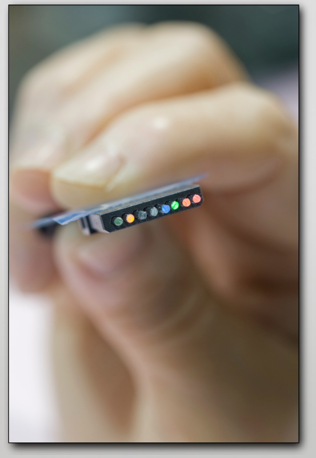
Extruded scintillator & wavelength shifting fibers.



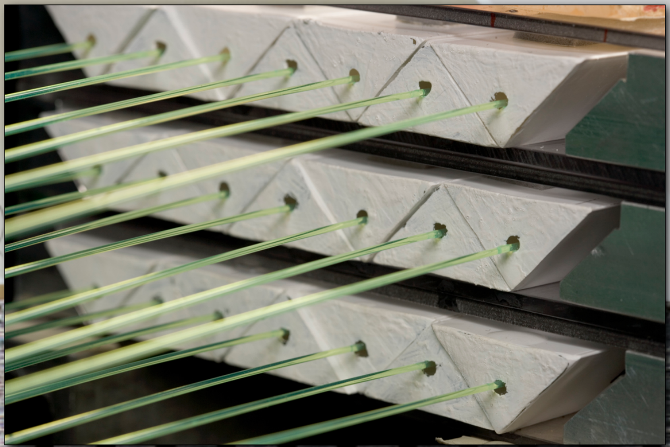
Charge-sharing for improved position resolution (~3 mm) & alignment.

Fibers bundled into cables to interface with 64 channel multi-anode PMTs.

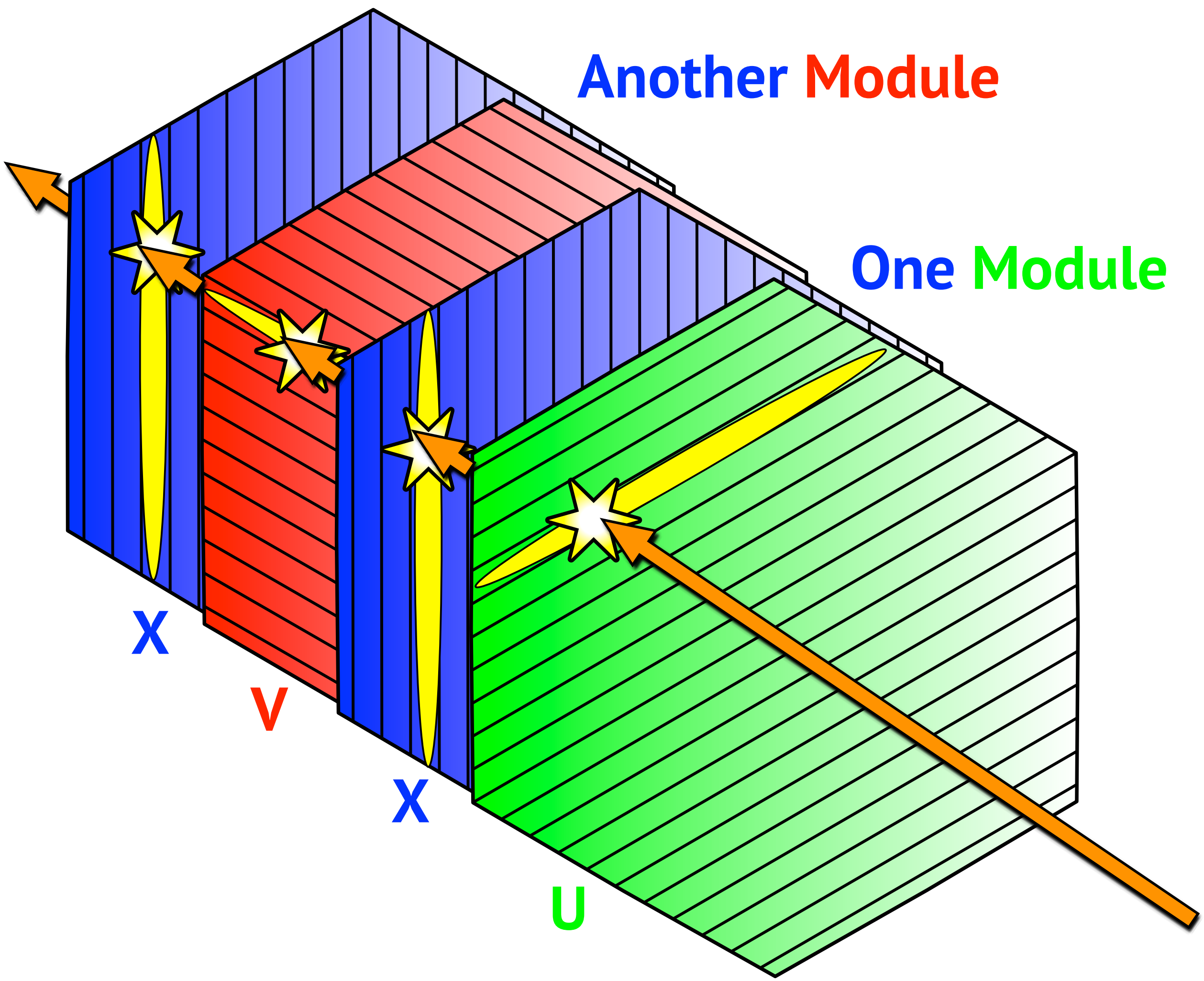


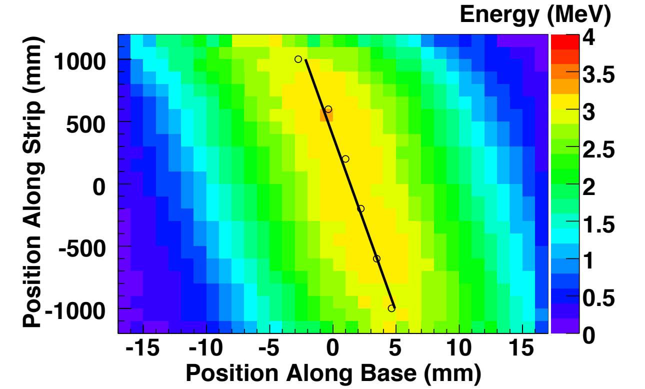


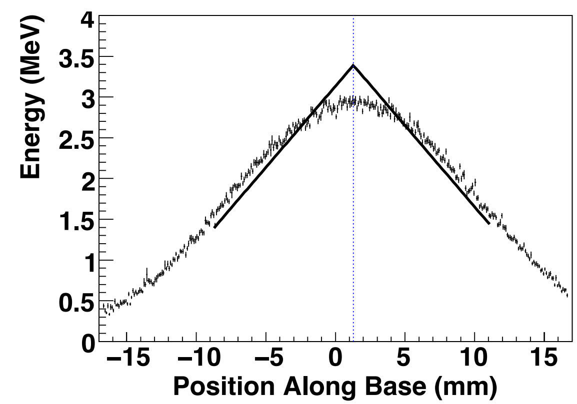
Strips are bundled into PLANES to provide transverse position location across a module.

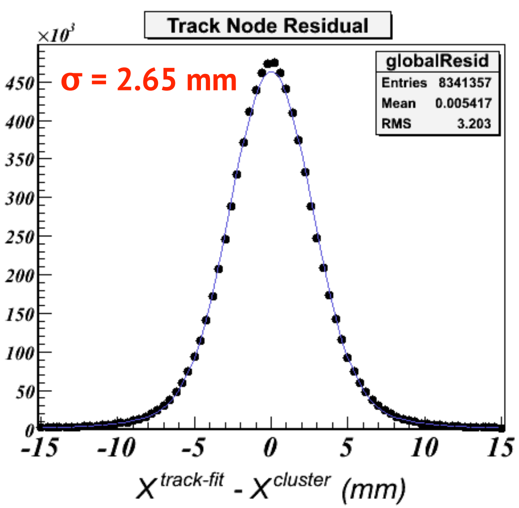


Planes are mounted stereoscopically in UX or VX orientations for 3D tracking. There are typically **two planes per module**.



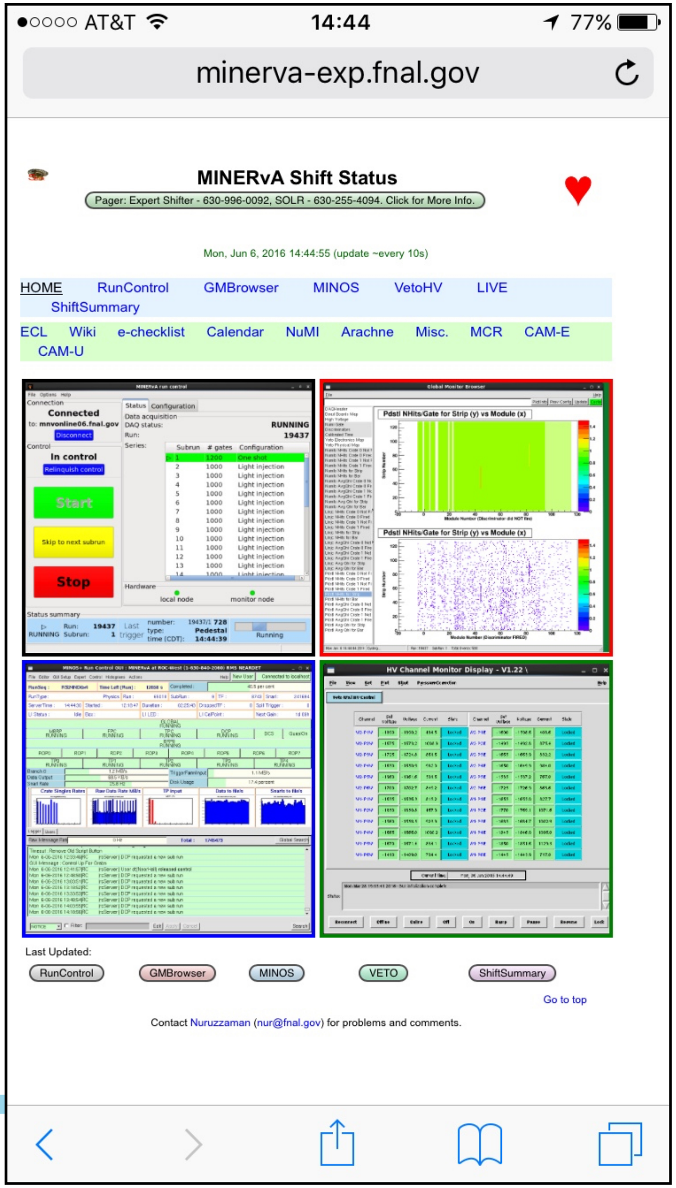






Operations updates

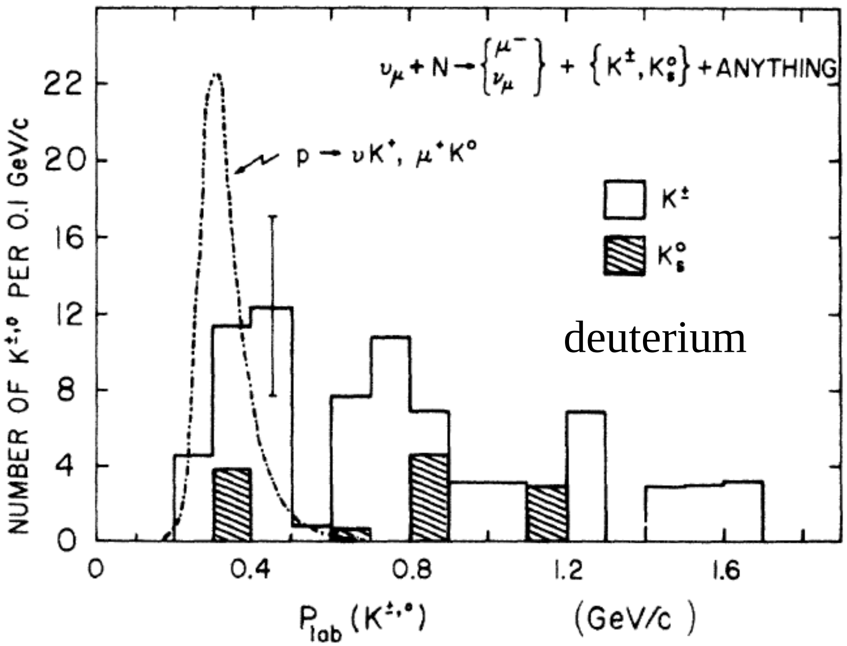
- Many improvements to remote shift and monitoring technology.
  - We can now monitor the detector via the web on a smartphone!
- Water target filled on 22 Feb 2016 (170.3 gallons).
- Busy shutdown ahead of us:
  - New firmware for front end boards and our custom VME boards (to reduce deadtime in upcoming higher intensity Medium Energy NuMI beam).
  - Preparing to take over operation of the MINOS Near Detector.
  - Building new test stands in Lab F for electronics and PMT checkout.



Existing K+ production data

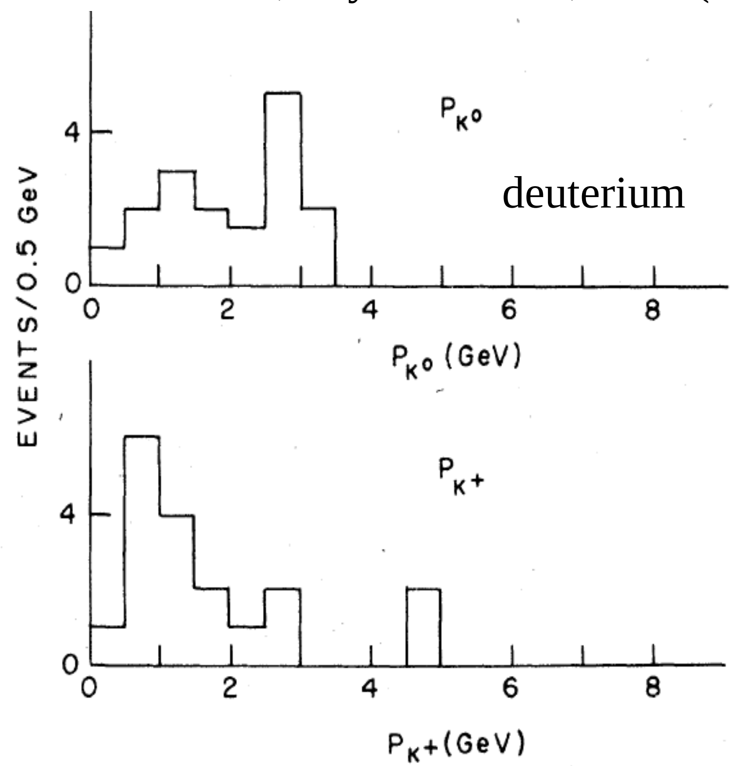
C. Marshall,
JETP Seminar, 5 Feb 2016

W. A. Mann et al., Phys.Rev. D34, 2545 (1986)



ANL 12' bubble chamber

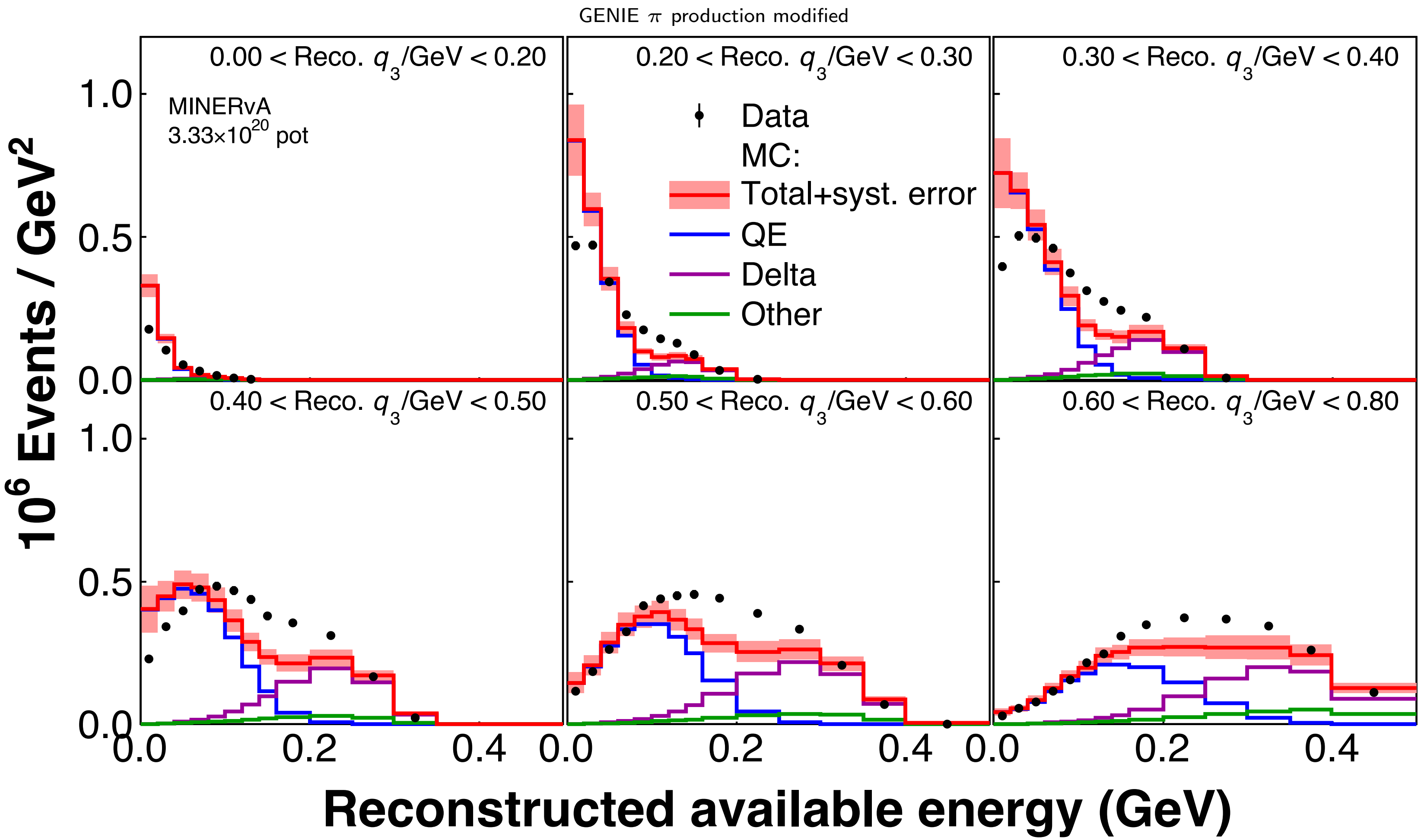
N. J. Baker et al., Phys.Rev. D24, 2779 (1981)



BNL 7' bubble chamber

Also Gargamelle: Physics Letters B 73 4-5 (1978)

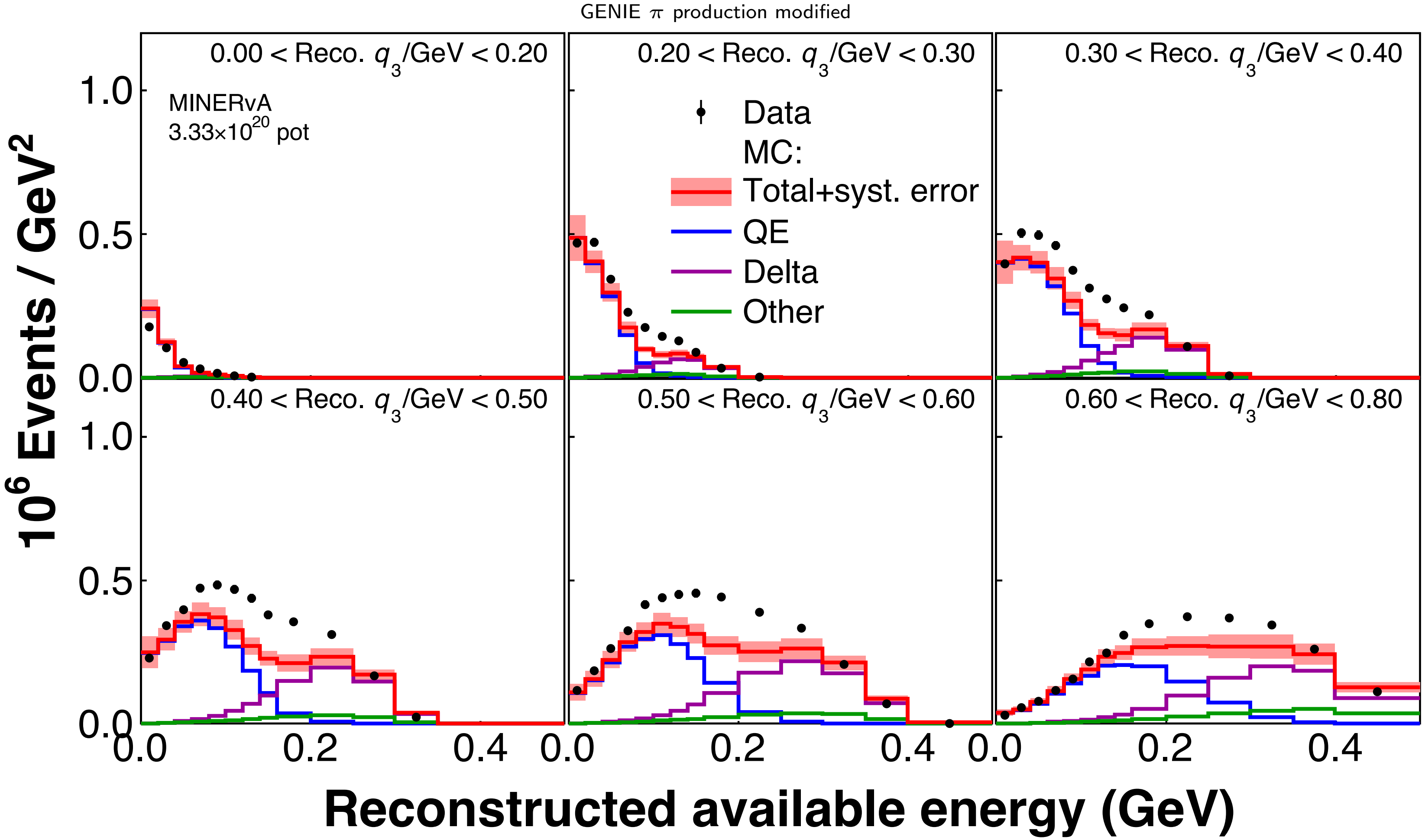
Nuclear effects at low three-momentum transfer



- $\chi^2 = 896$ (stat+syst, 62 dof)

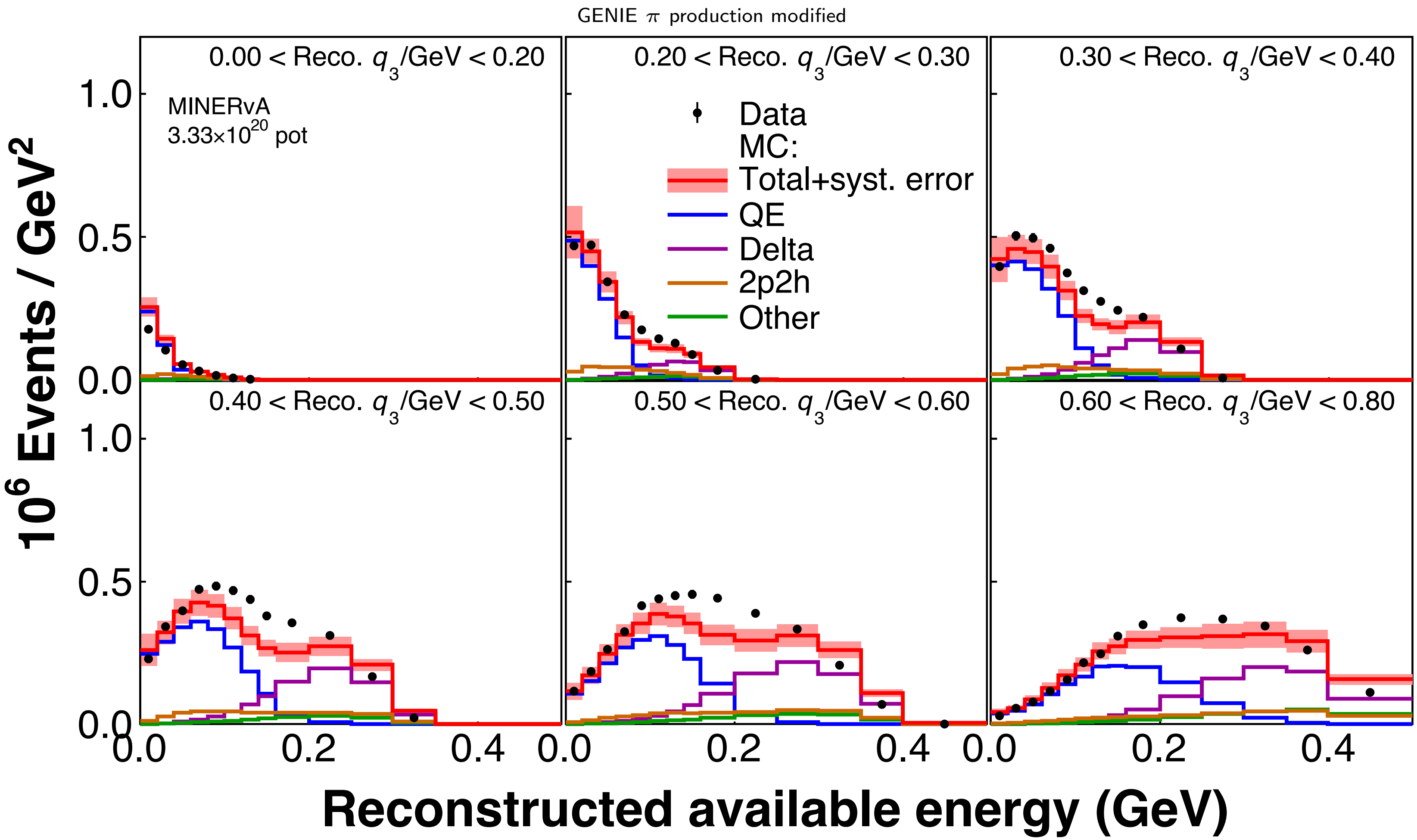
Fermilab

Nuclear effects at low three-momentum transfer



- $\chi^2 = 540$ (stat+syst, 62 dof)

Nuclear effects at low three-momentum transfer



- $\chi^2 = 498$ (stat+syst, 62 dof)

Nuclear effects at low three momentum transfer

Phys. Rev. Lett. **116**, 071802