Flux and cross-section measurements in MINERvA

- How to predict the flux from a wideband neutrino beam...
- and what that buys you!

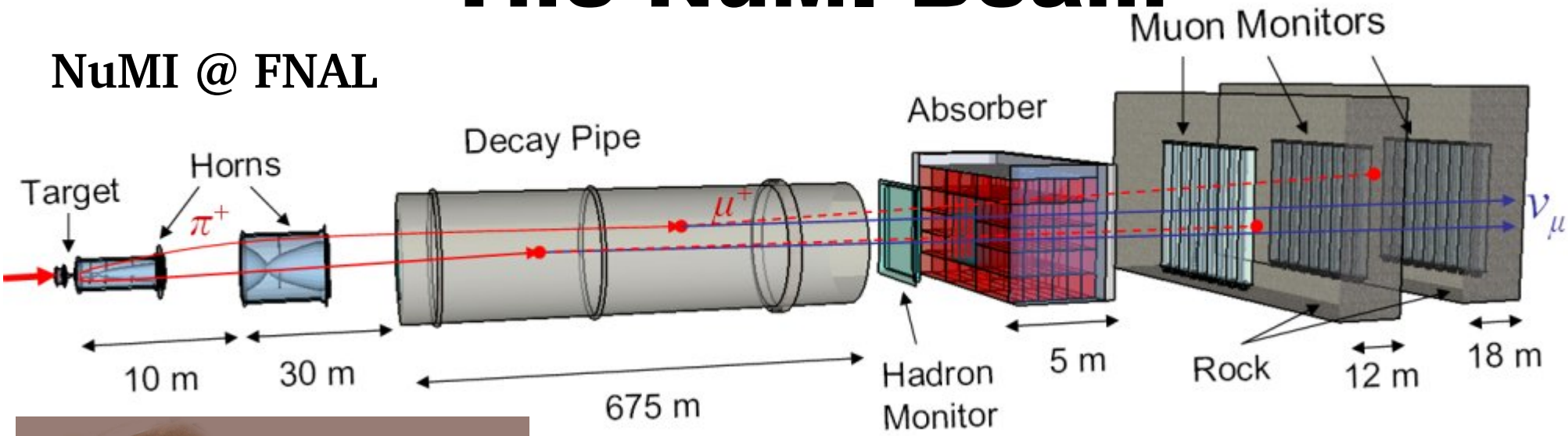
Mike Kordosky

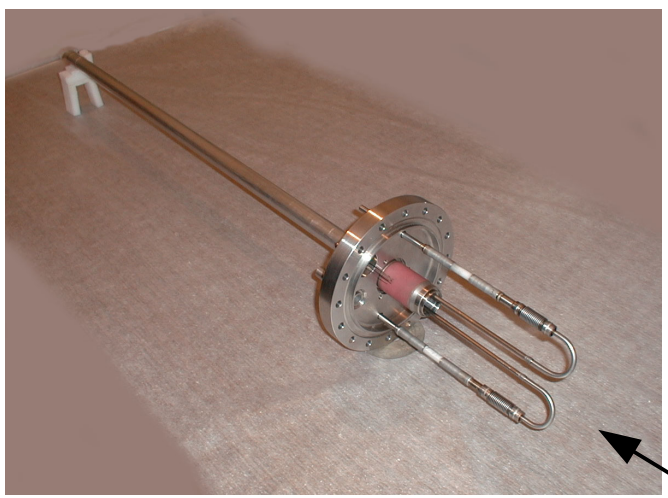
WILLIAM & MARY
CHARTERED 1693

ICHEP2016CHICAGO

The NuMI Beam

NuMI @ FNAL





- π,K production off a graphite target
- Wide range of p_T, p_z
- Cross-sections not well known

Important decay modes

$\pi^+, K^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$

$\rightarrow \pi^0 e^+ \nu_e$

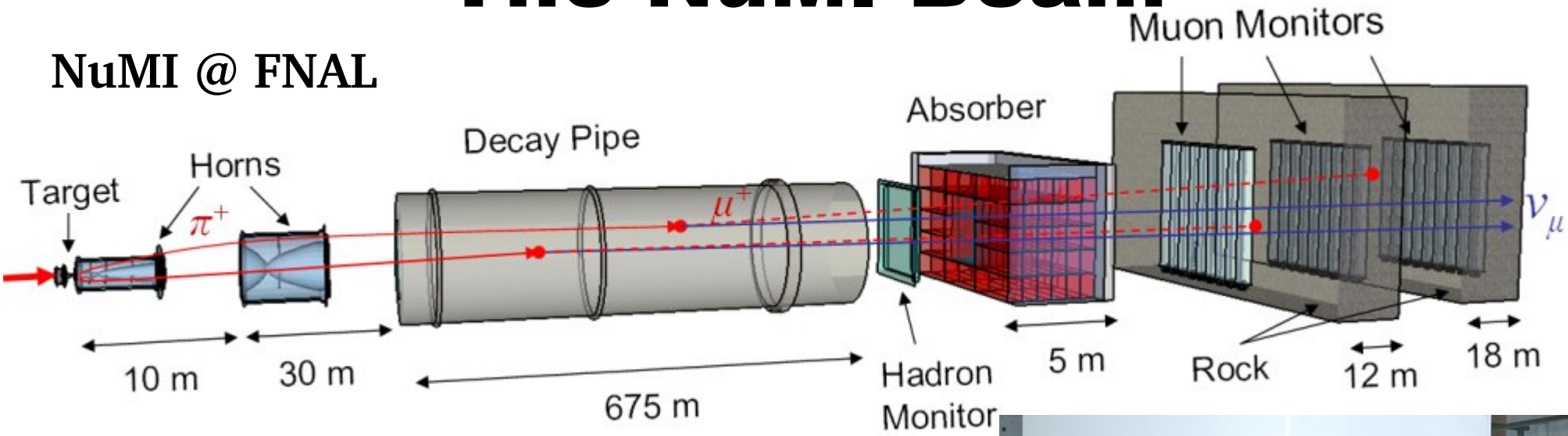
$K^0_L \rightarrow \pi^- e^+ \nu_e$

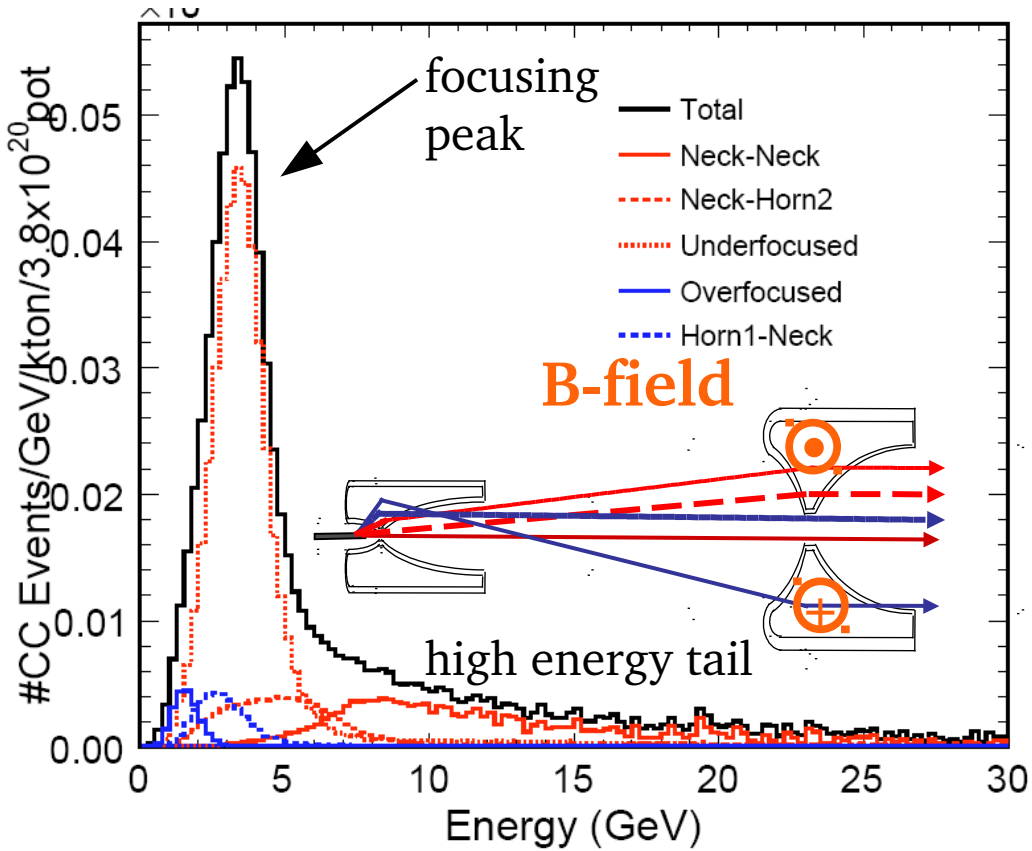
$\rightarrow \pi^- \mu^+ \nu_\mu$

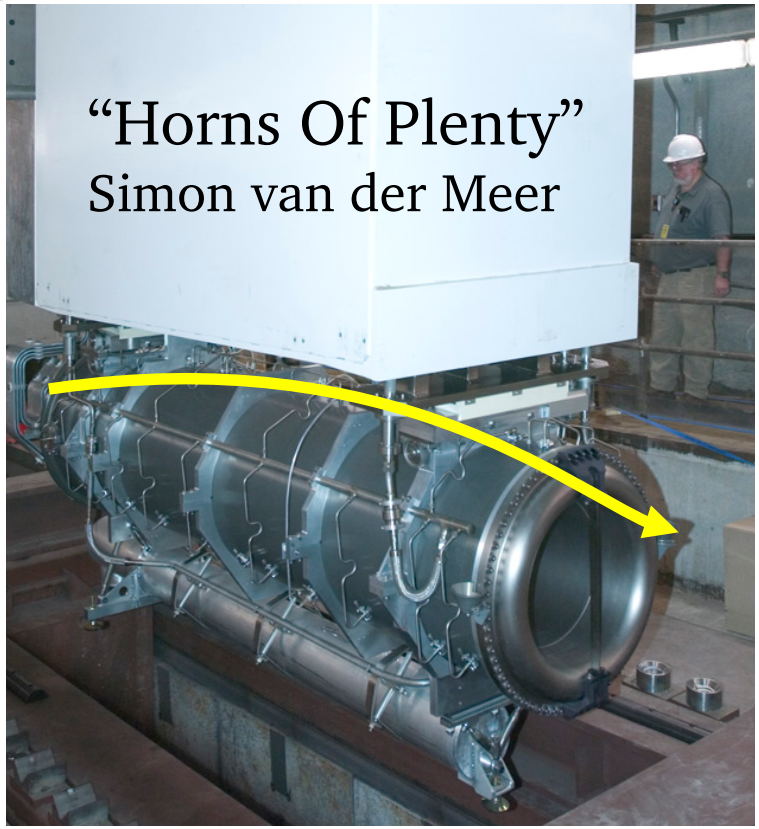
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

The NuMI Beam

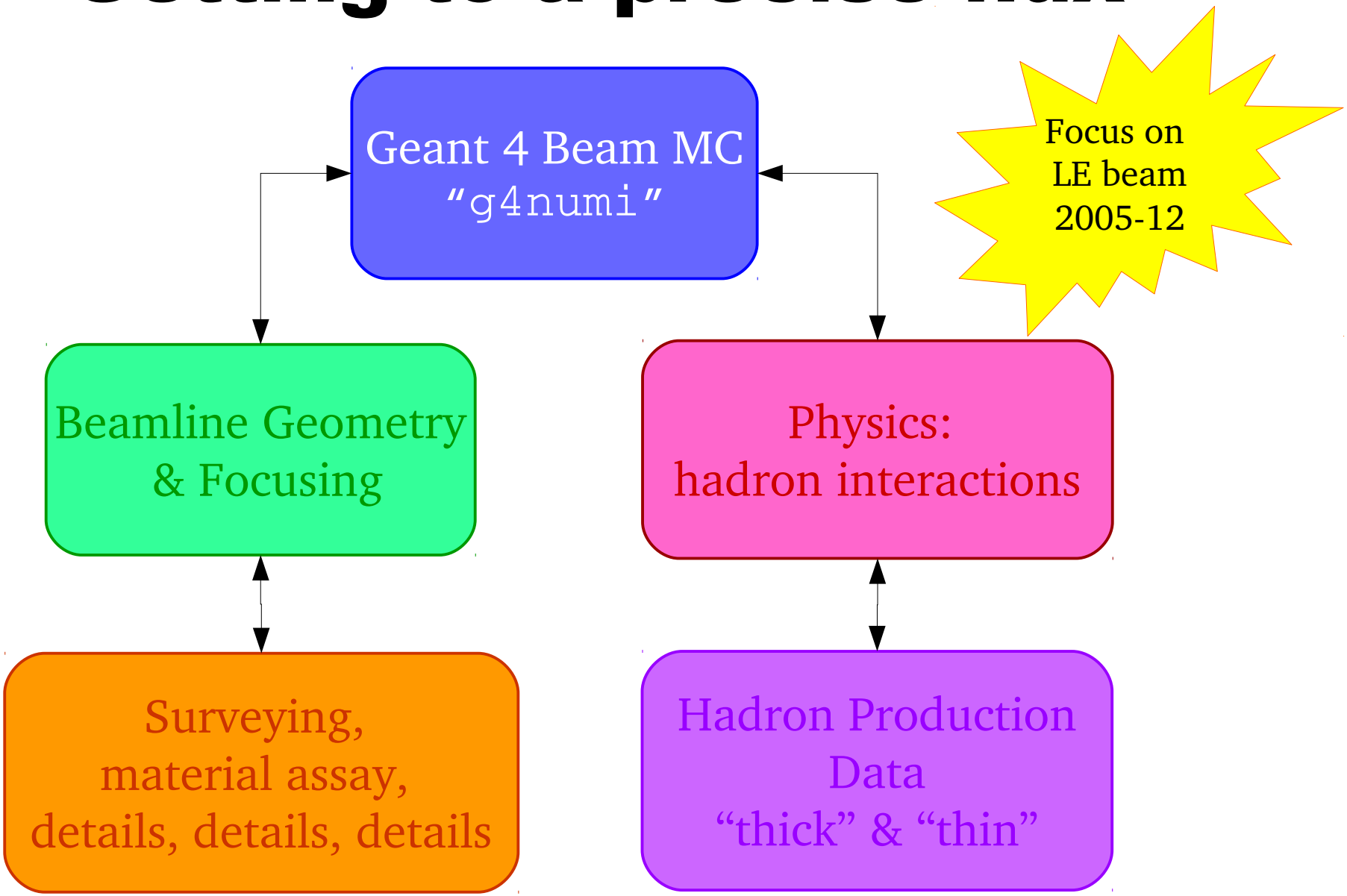
NuMI @ FNAL



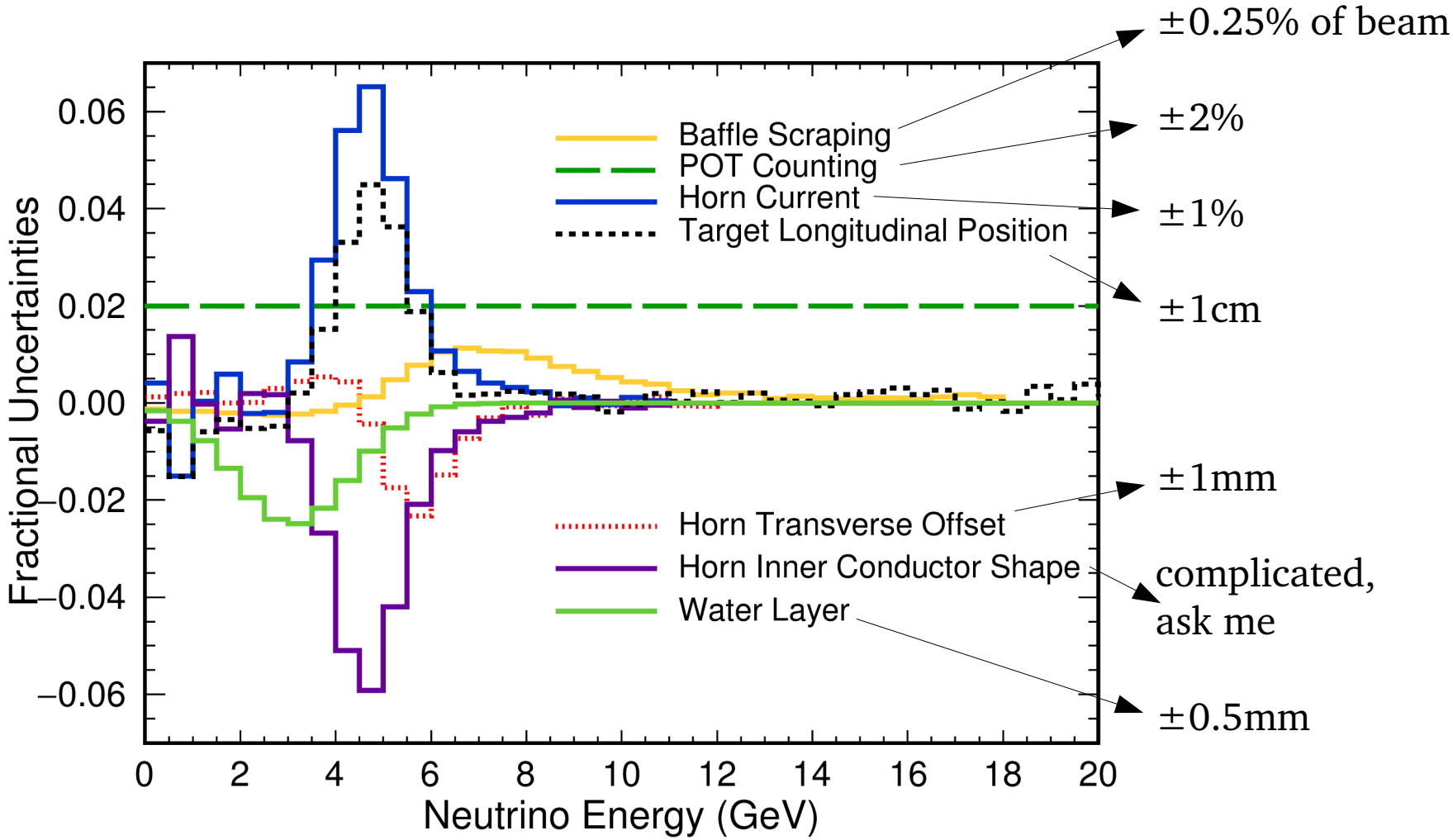




Getting to a precise flux



Focusing uncertainties

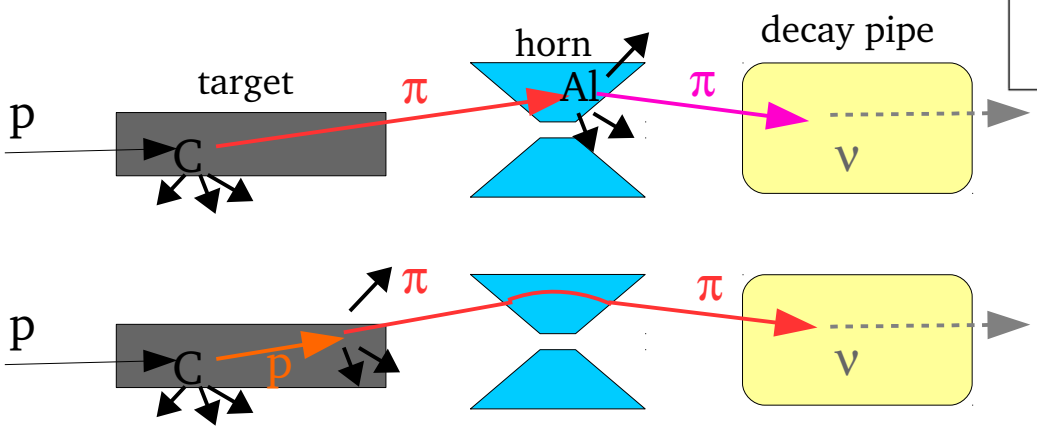


Small details matter!

Hadronic interactions

What a mess!

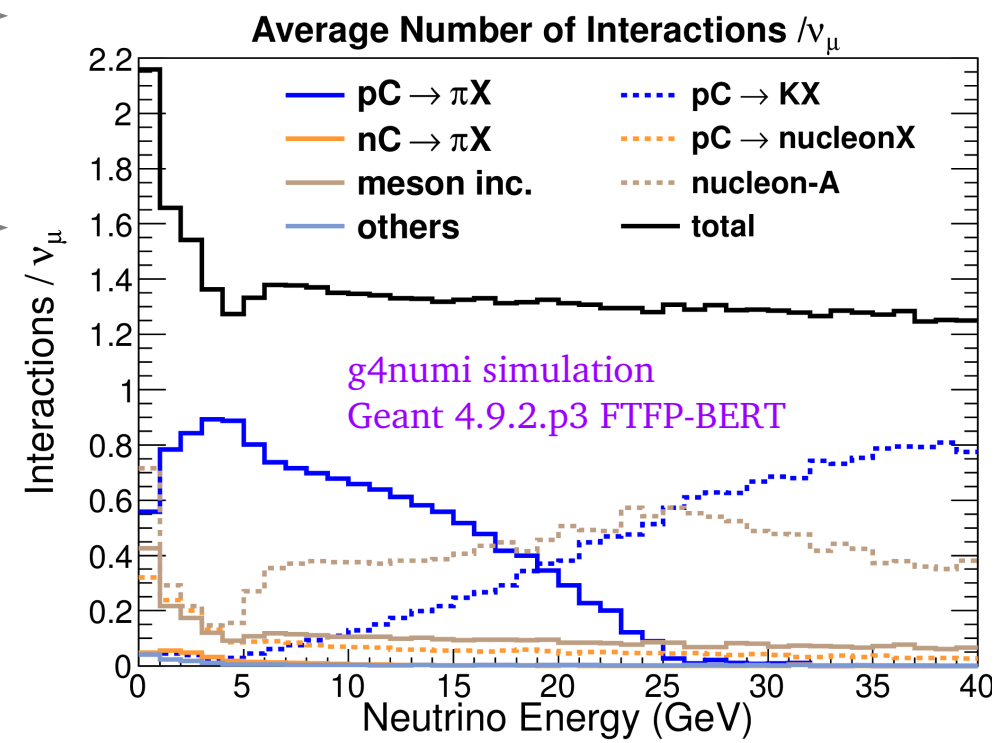
- Many neutrinos have multiple interactions in their "ancestry"



- Strong interactions & hadronization at low Q^2 in nuclei. Don't expect the MC to get it right!

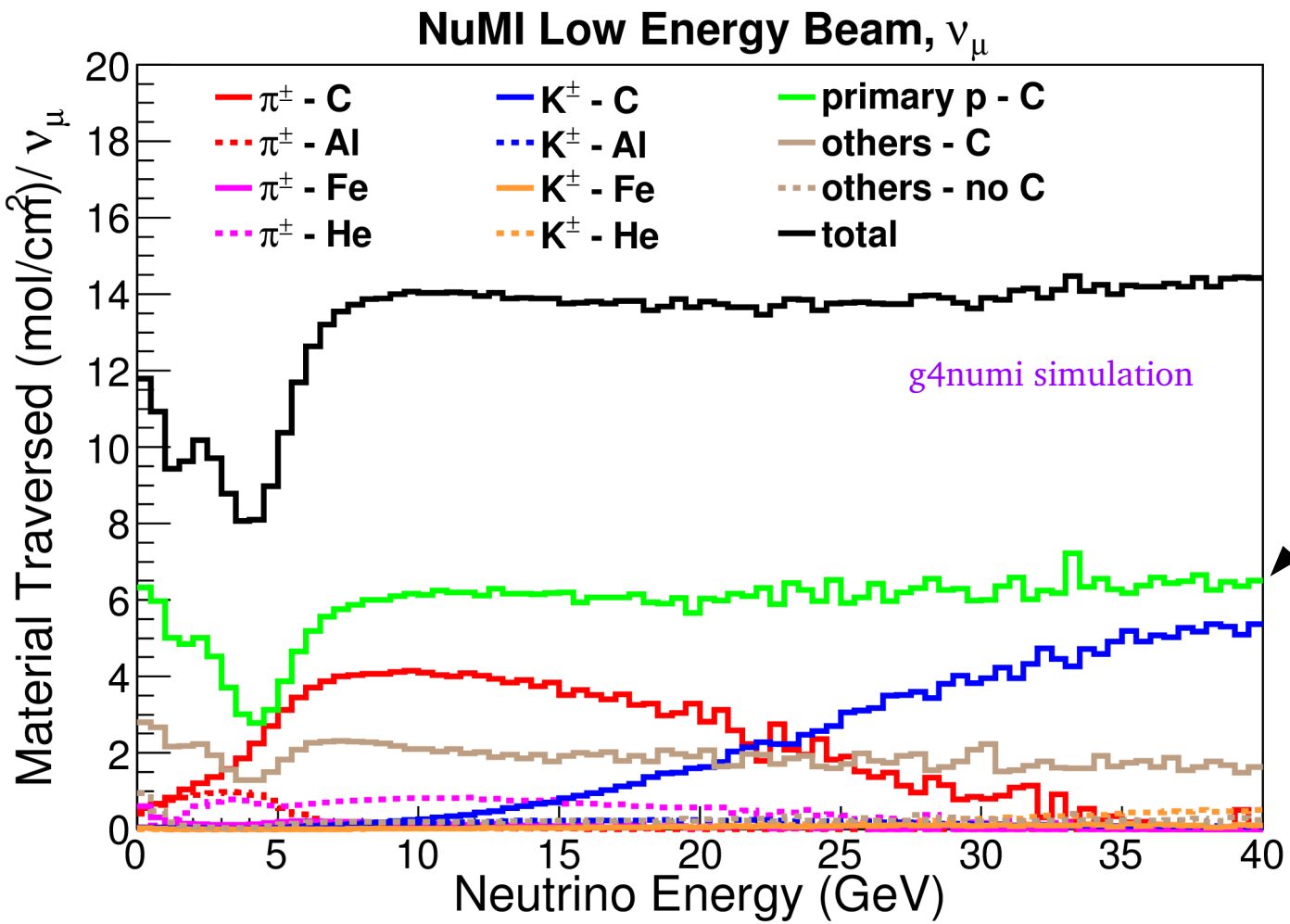
# of interactions per ν_μ (x100)

	Material						
Projectile	C	Fe	Al	Air	He	H_2O	Be
p	117.5	2.9	1.0	1.1	1.5	0.1	0.1
π^+	8.1	1.3	1.8	0.2	–	0.4	–
π^-	1.3	0.2	0.2	–	–	–	–
$K^\pm$	0.6	0.1	0.1	–	–	–	–
K^0	0.6	–	–	–	–	–	–
Λ/Σ	1.0	–	–	–	–	–	–



Absorption in the beamline

Particles traverse a significant amount of material



6 mol/cm^2 of graphite ≈ 40cm

Constraining the simulation

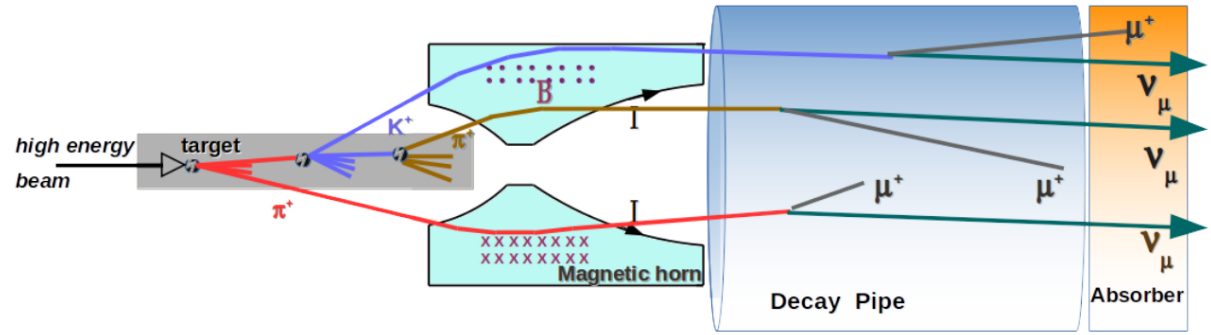
Our Strategy

1) Carefully tabulate interactions and material in each ν's ancestry

2) Find some relevant hadron production data

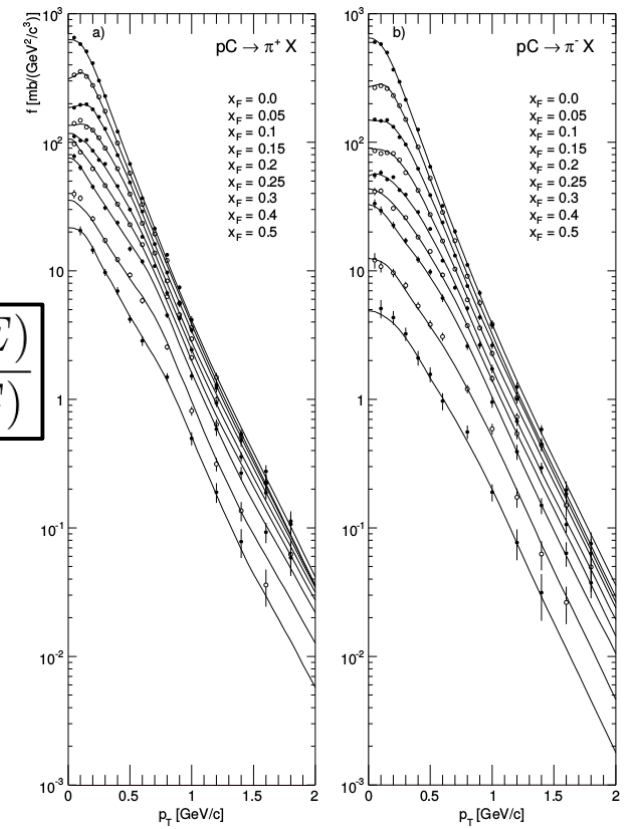
3) Weight interactions

4) Assign and propagate uncertainties



$$f_{Data} = \frac{1}{\sigma_{\text{inel}}} E \frac{d^3\sigma}{dp^3}$$

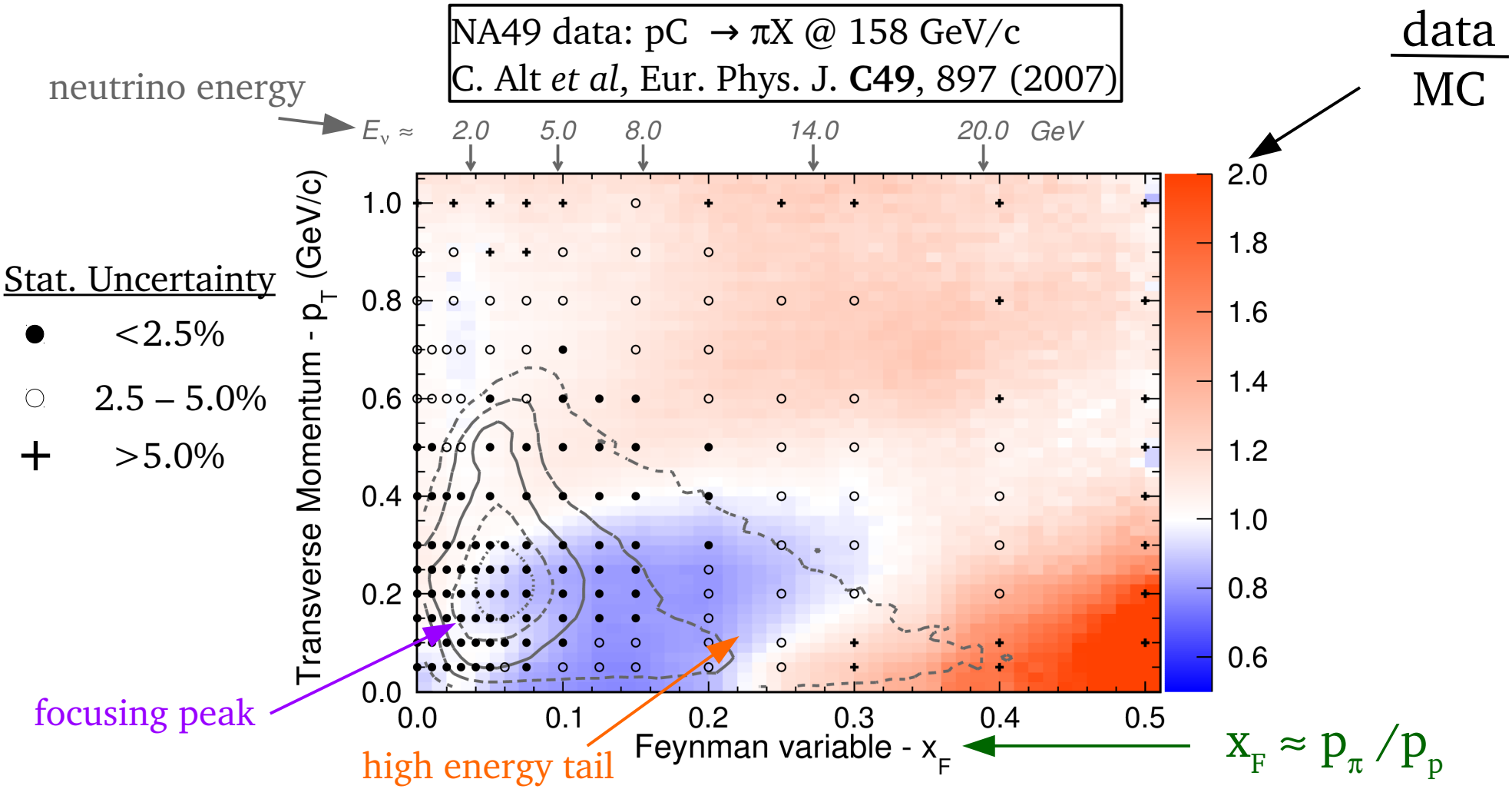
$$w(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$



data from NA49 @ CERN

Thin target π production data

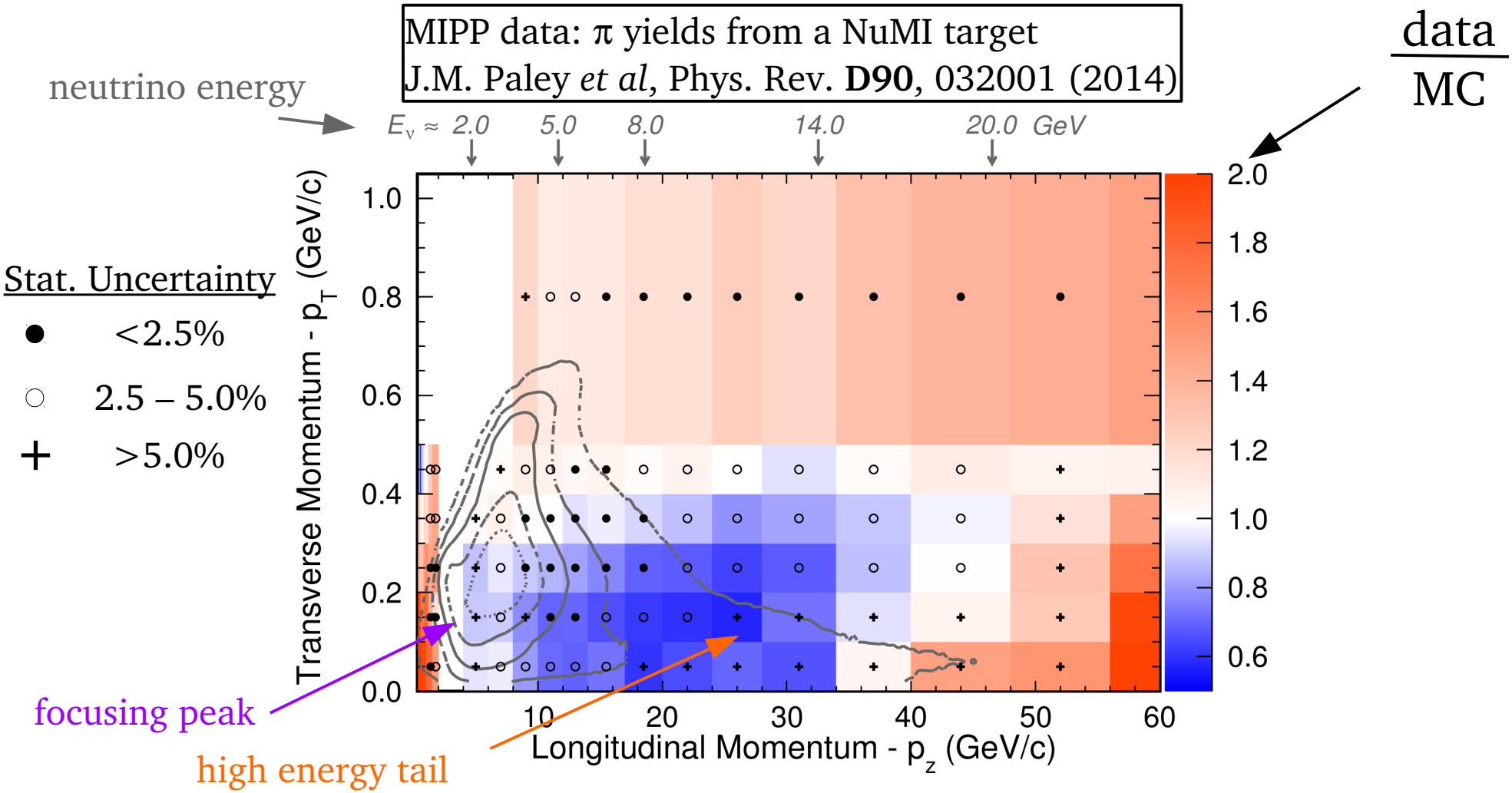
NA49 data: pC → πX @ 158 GeV/c
C. Alt *et al*, Eur. Phys. J. **C49**, 897 (2007)



This is the major data-set used to make a "thin target" flux prediction

NuMI target π production data

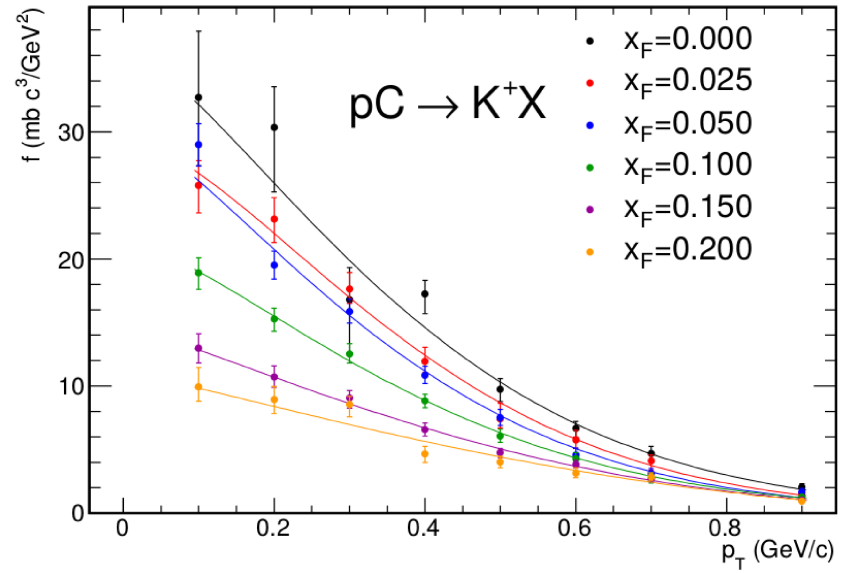
MIPP data: π yields from a NuMI target
J.M. Paley *et al*, Phys. Rev. **D90**, 032001 (2014)

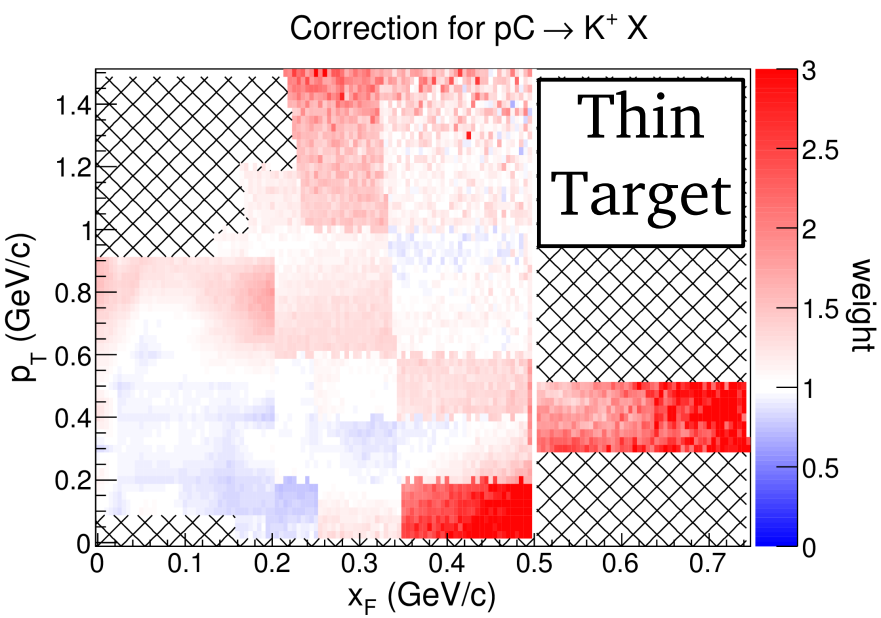


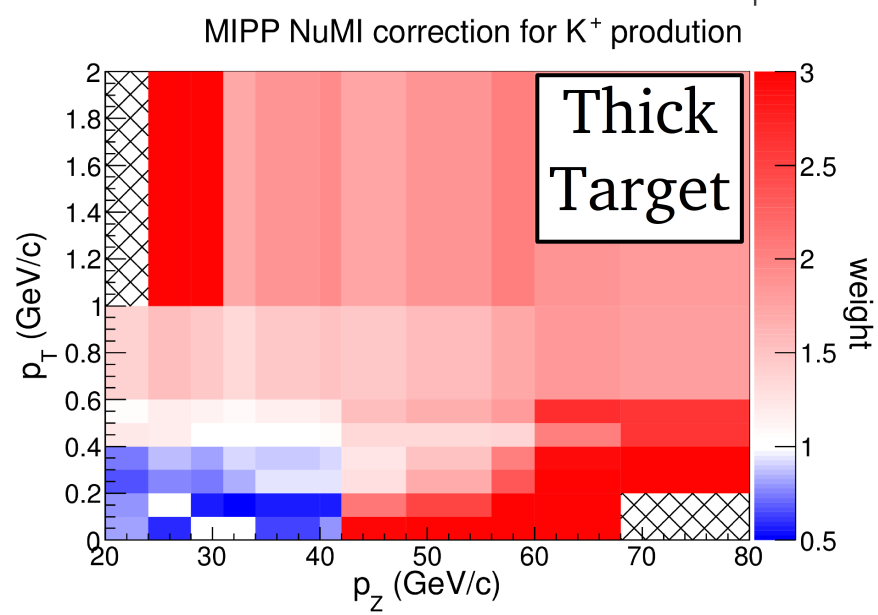
This is the major data-set used to make a "thick target" flux prediction

Constraining Kaons

- Thin target: pC → $K^{\pm}X$ data from NA49 (G. Tinti PhD Thesis, Oxford 2010) and K/π ratio from MIPP (A. Lebedev PhD thesis, Harvard 2007) cover most of the region $x_F<0.5$
- Thick Target: MIPP's measurements of the K/π yield from a NuMI target (S. Seun PhD thesis, Harvard 2007).







We account for everything

Additional constraints applied to both thin and thick target predictions

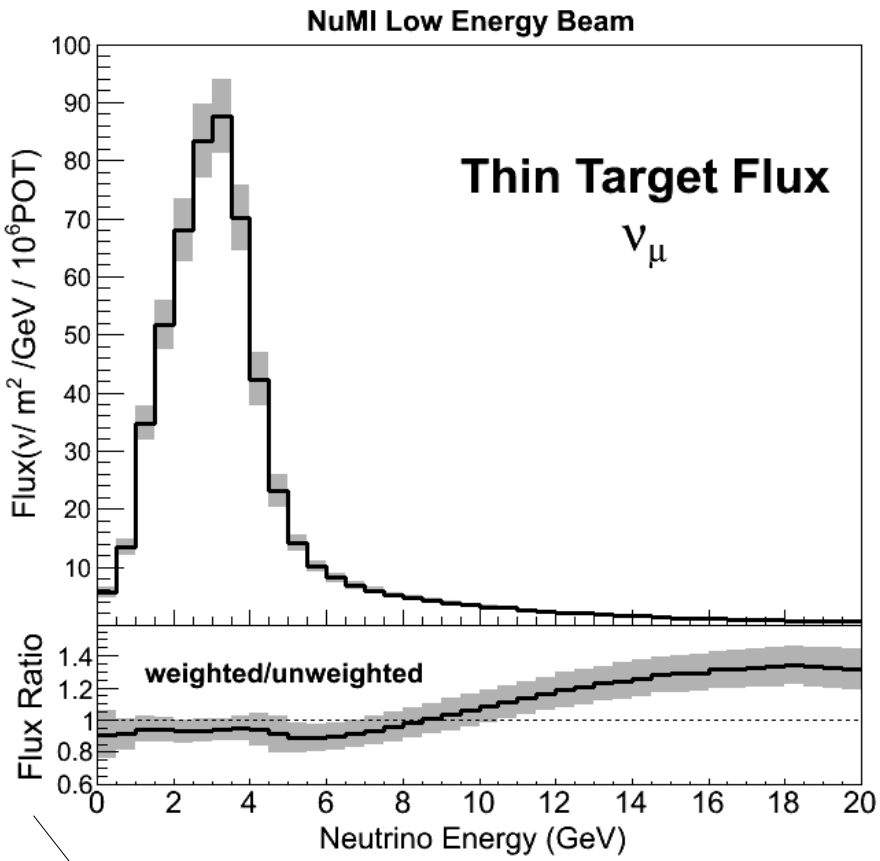
- Neutral K production predicted from charged K data via quark counting

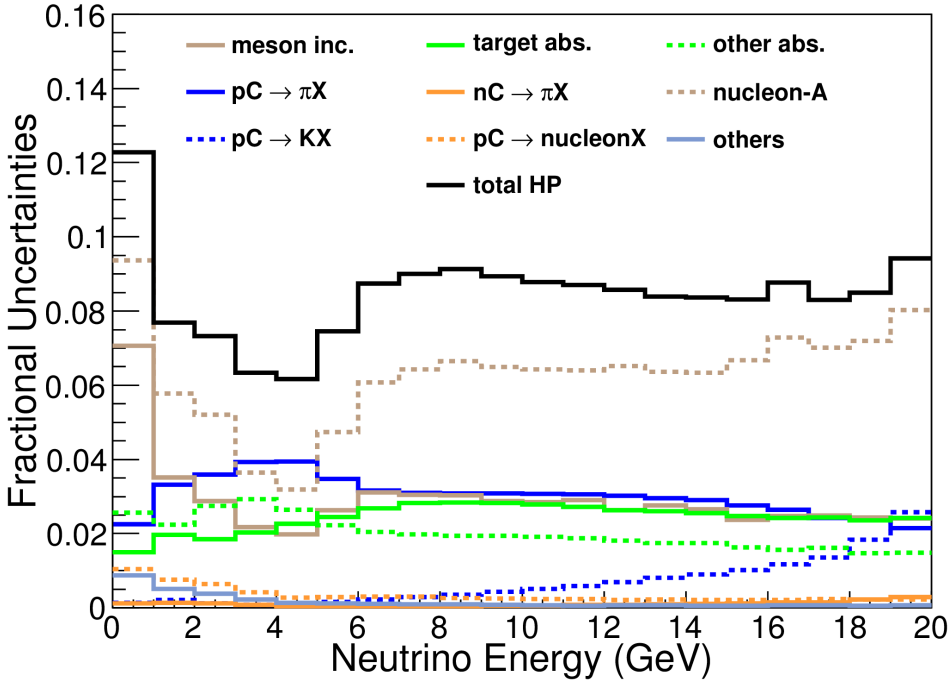
$$N(K^0) = \frac{1}{4}N(K^+) + \frac{3}{4}N(K^-)$$

- We use pC → pX, nX data from NA49 [B.Bataar *et al*, Eur. Phys. J. C73,2364 (2014)]
- nC → π^-X data corrected with pC → π^+X data and vise versa.
- We use FLUKA to scale data to lower projectile energies.
- We compare measured absorption cross-sections with the MC to derive corrections and uncertainties for p,n,π,K projectiles
- We constrain pA → π,K X interactions with pC data, adding 10-30% uncertainty
- Processes without data constraints are characterized by projectile and produced particle. Assign a 40% uncertainty to each in 4 xF bins from 0 to 1

More details in arXiv:1607.00704 & L. Aliaga PhD thesis (FNAL-2016-03)

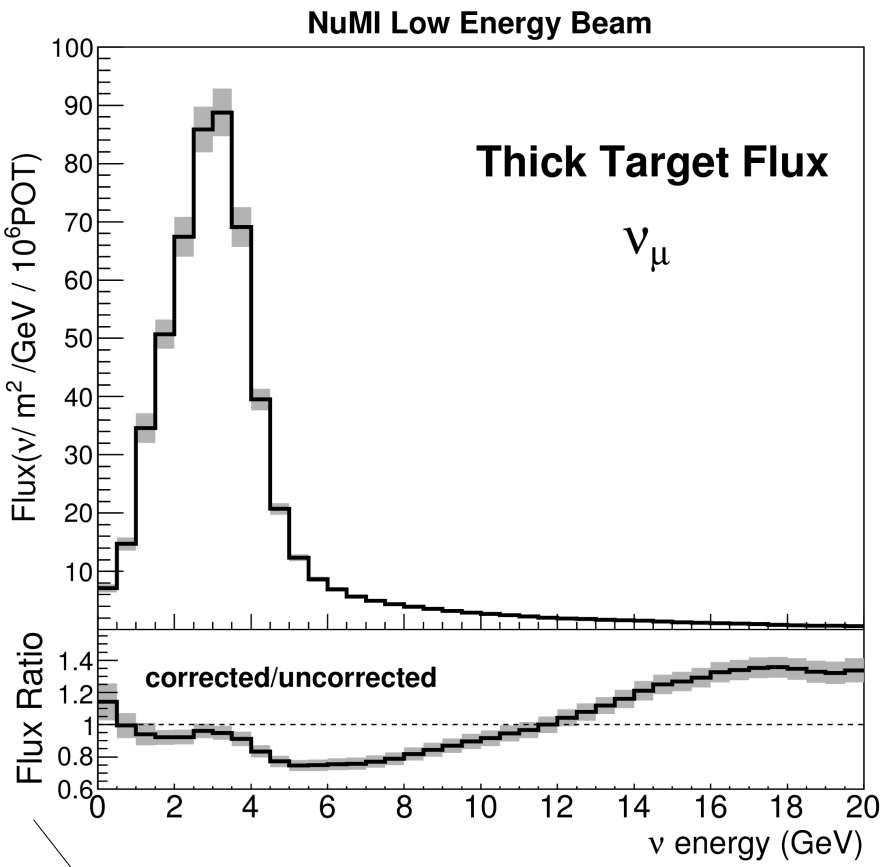
Thin target results

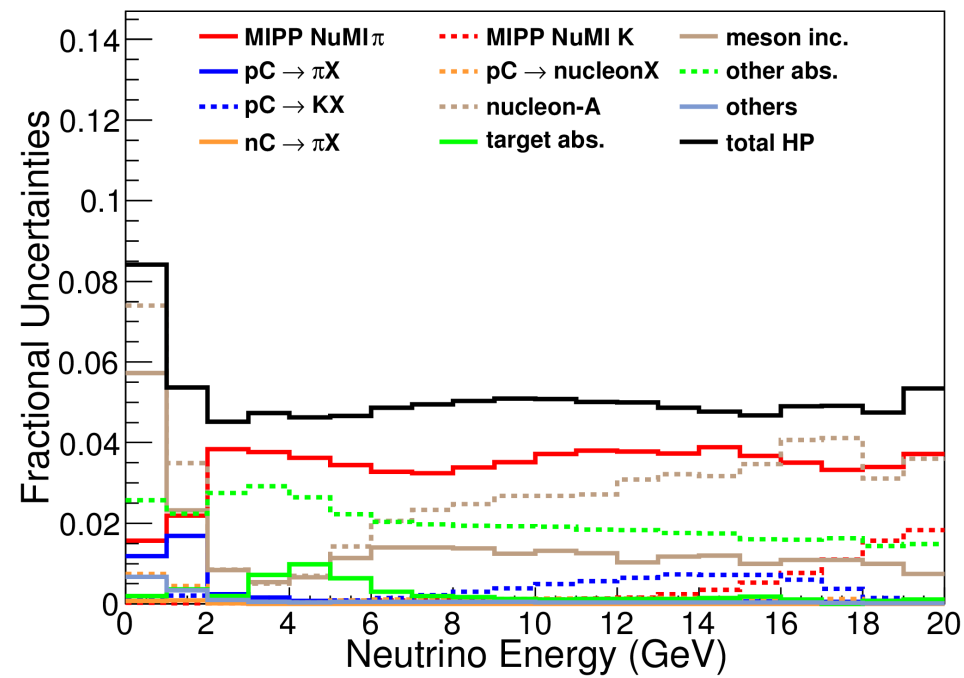




ratio to g4numi uncorrected prediction

Thick target results

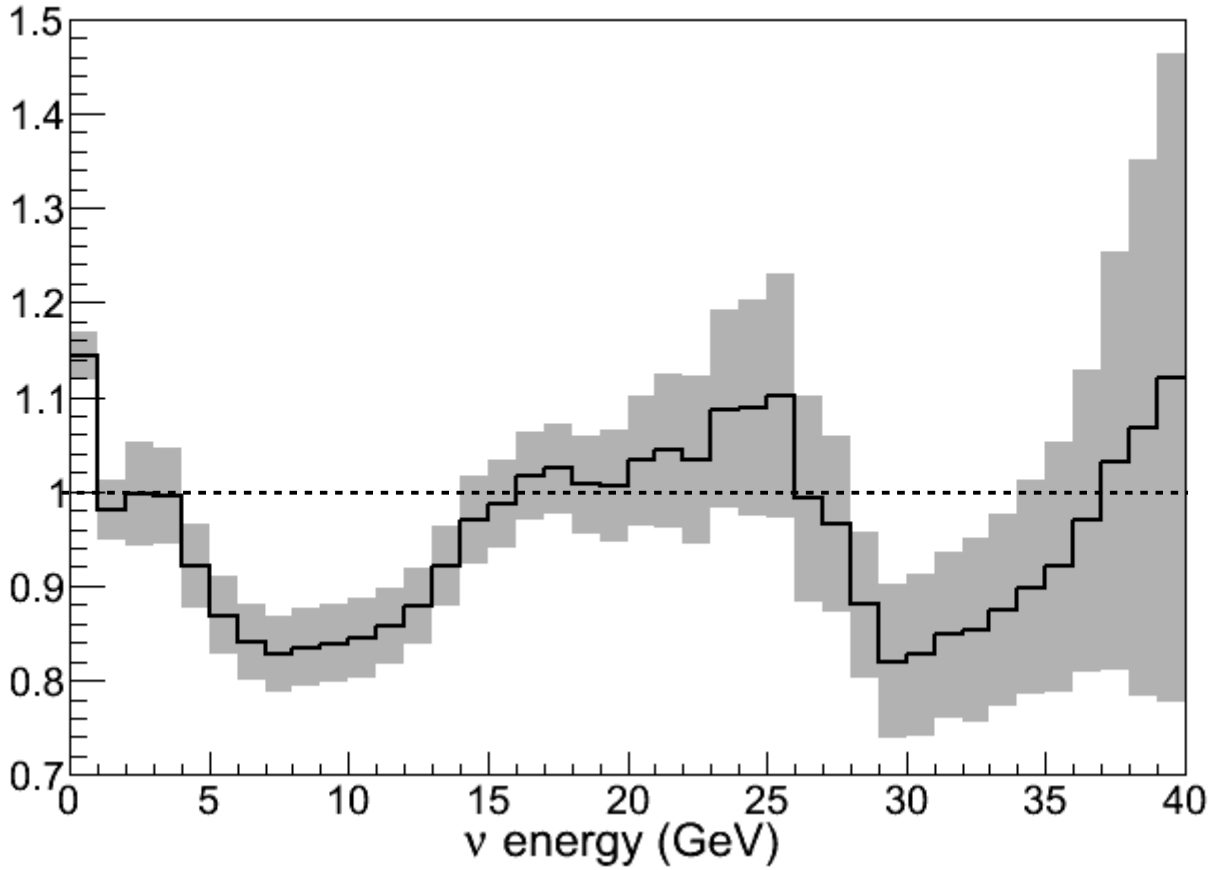




ratio to g4numi uncorrected prediction

A conundrum

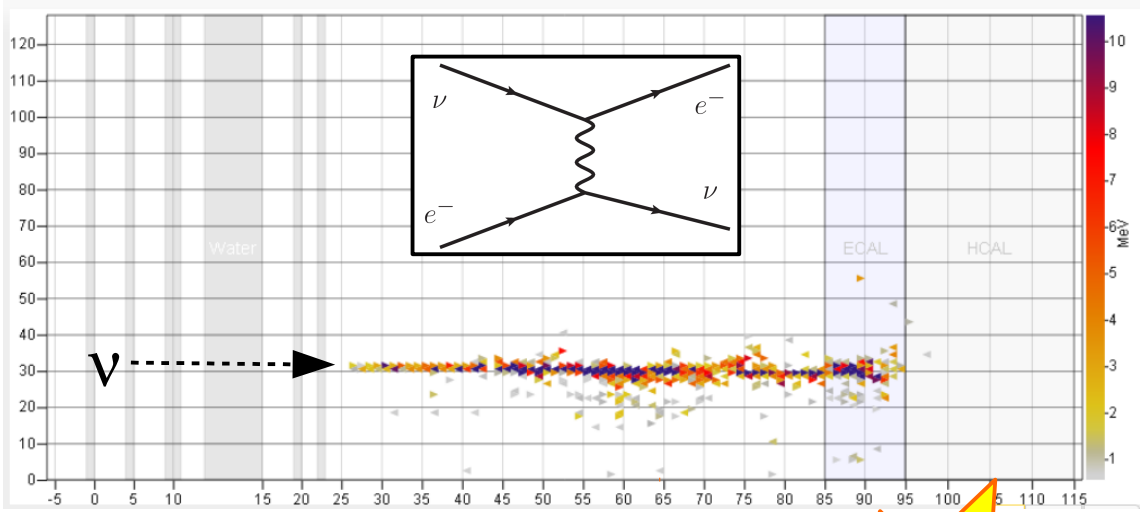
Thick / Thin
ν_μ flux ratio



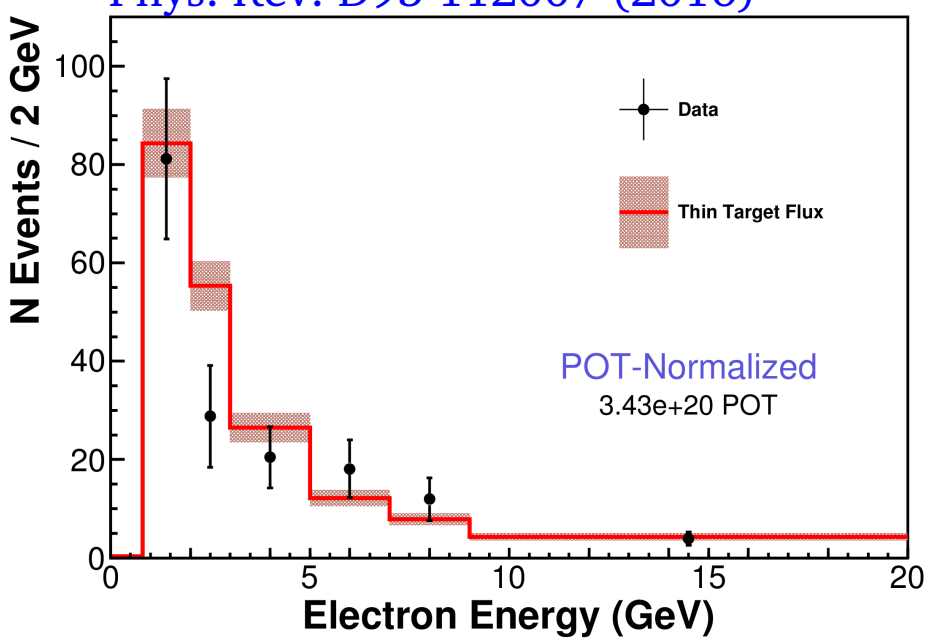
The curve ought to agree with 1

Comparison to *in situ* data

<u>ν e → ν e scattering</u>
Well known cross-section.
2000x smaller than νN.
Cleanly identified events.



J. Park Ph.D (FNAL-thesis-2013-36)
Phys. Rev. D93 112007 (2016)



<u>Thin:</u> 106 events
<u>Thick:</u> 105 events
<u>Data:</u> 96.6 events

10x better in ME beam

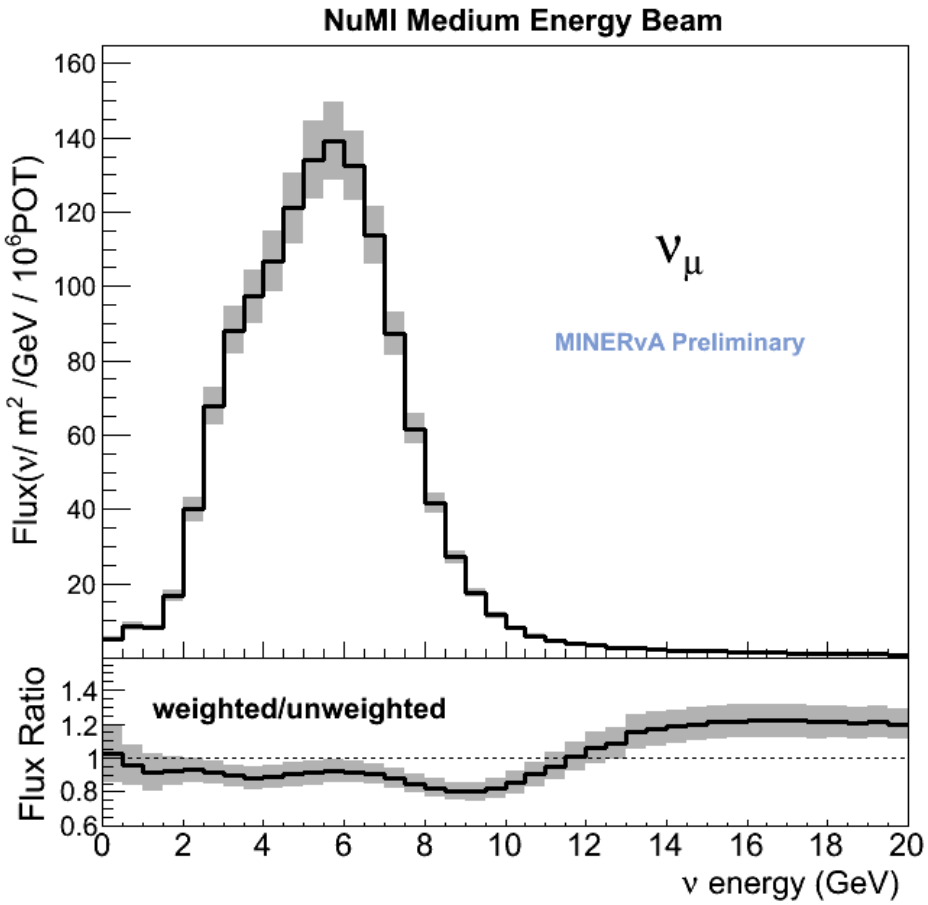
Good agreement seen for both flux predictions.

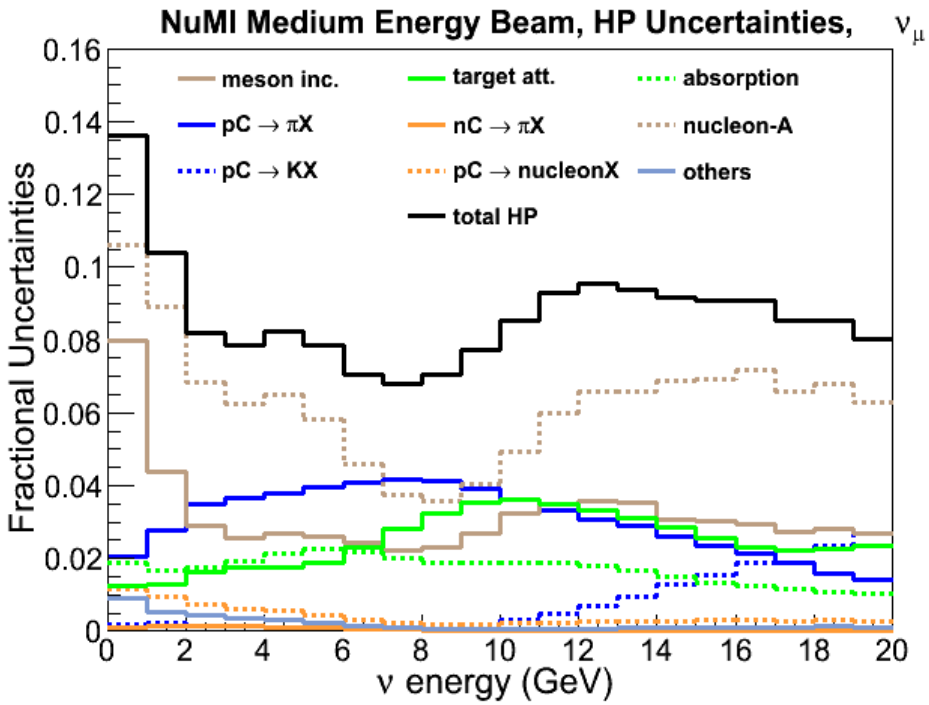
Used to tune our final flux prediction.
Reduces flux and unc. by ~1%

Medium Energy Flux

An aside….

2013 – present





Now, carrying on with the LE beam…

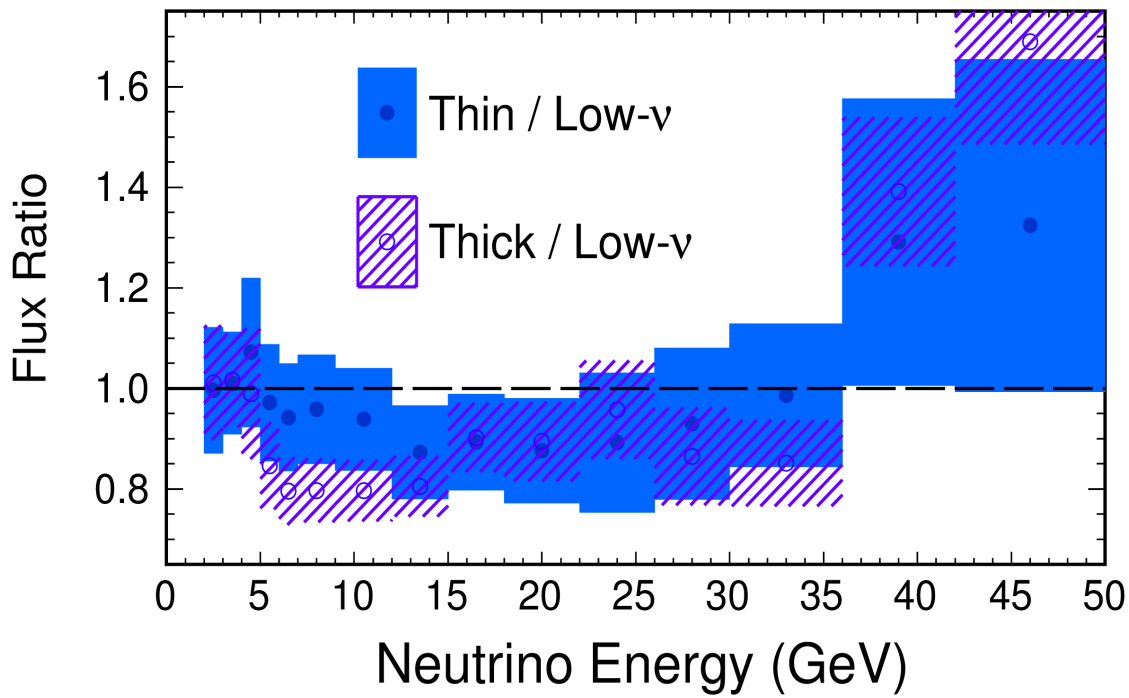
Comparison to *in situ* data

Cross-section as a function of the energy transfer ν

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

Becomes constant for small ν/E resulting in a measurement of the flux shape.

Normalized to well measured high energy neutrino CC cross-section

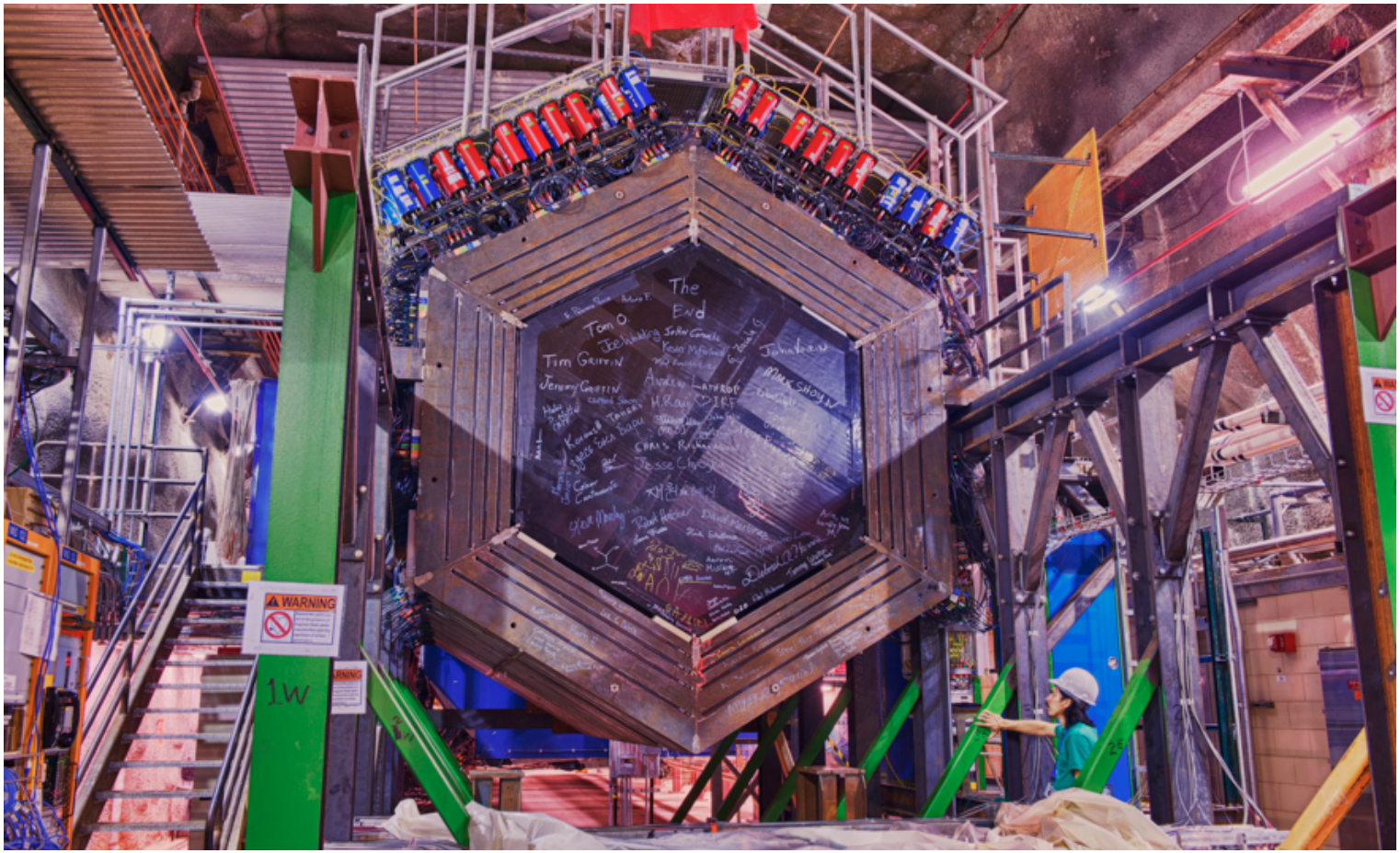


Result agrees with the thin target flux prediction (χ^2/NDF = 7.3/15) better than the thick target prediction (61.3/15)

We have adopted the thin target flux, corrected by ν e → ν e, as the official prediction

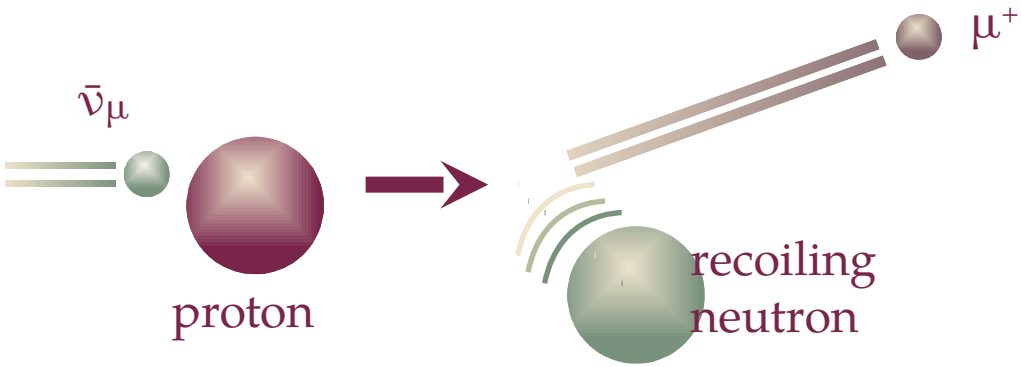
MINERvA

Selected cross-section results: quasi-elastics



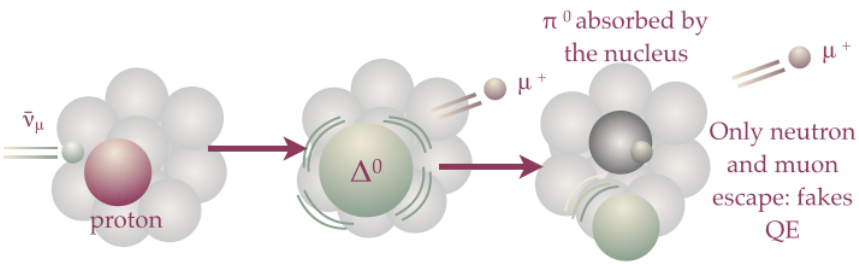
Quasi-elastic scattering

CC = charged current



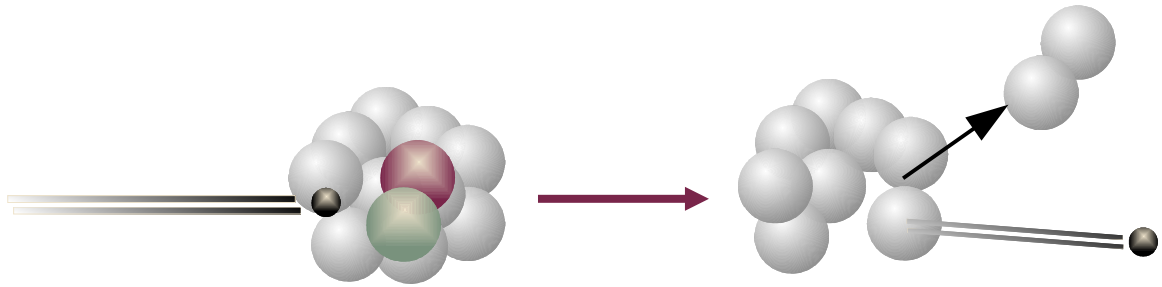
Quasi-elastic (QE) CC scattering dominates charged-current (and therefore oscillation signals) at ~1 GeV.

QE on nucleons is thought to be well understood.



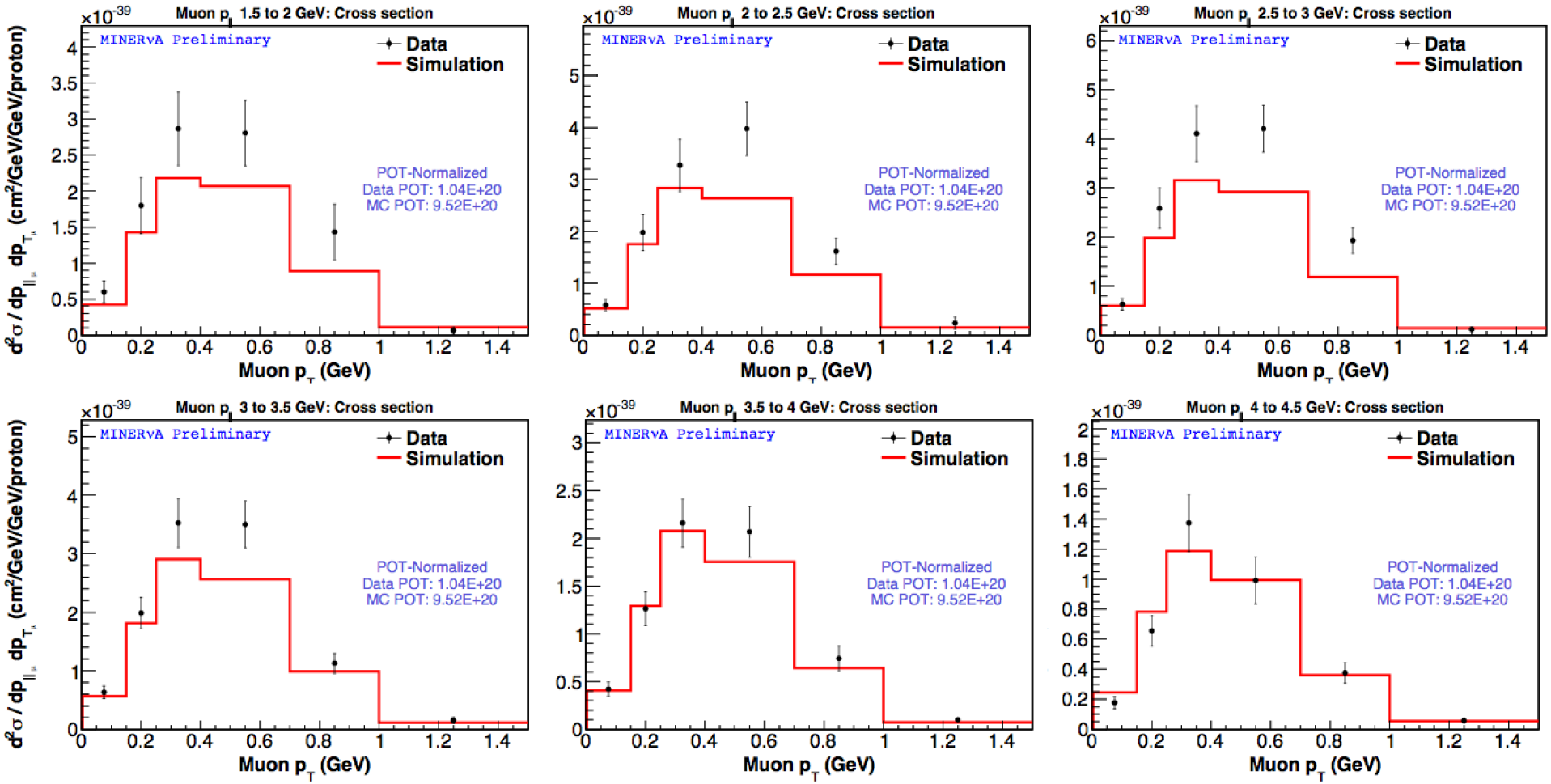
But scattering on nuclei is complicated by final state interactions that introduce "quasielastic-like" zero-pion final states

And by the possibility of interactions with multi-nucleon bound states (frequently called 2p2h interactions).



QE-like = 0 pions $\bar{\nu}_\mu$ QE-like update

C. Patrick PhD thesis, Northwestern, (2016)



New measurements are in dimensions of muon p_T and p_Z

Improved systematics and reconstruction

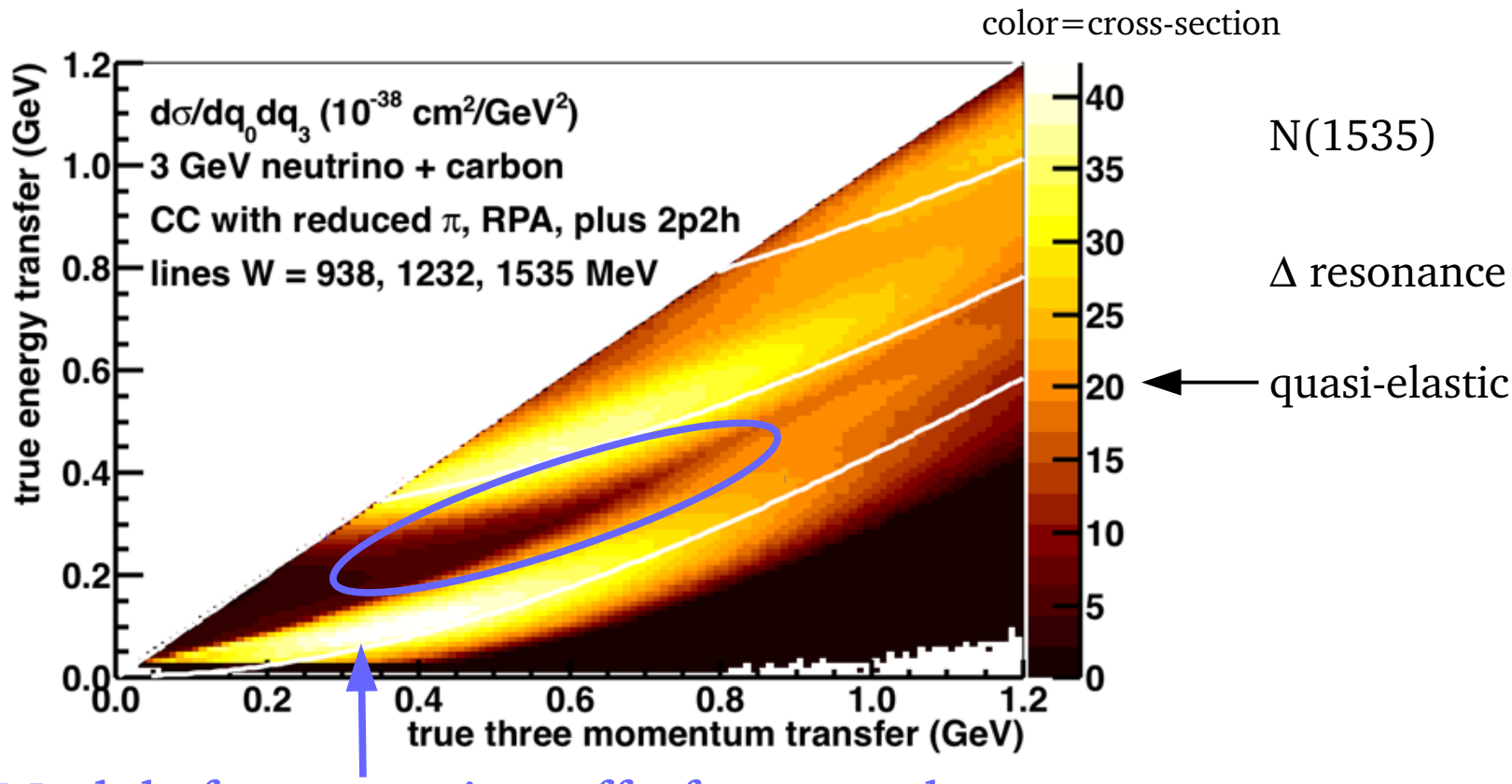
Data indicates extra strength in cross section at moderate transverse momentum

A new way of studying QE

Idea: Look at inclusive scattering in 2 kinematic dimensions.

Split Q^2 into energy transfer q_0 and 3 momentum transfer $\mathbf{q_3}$

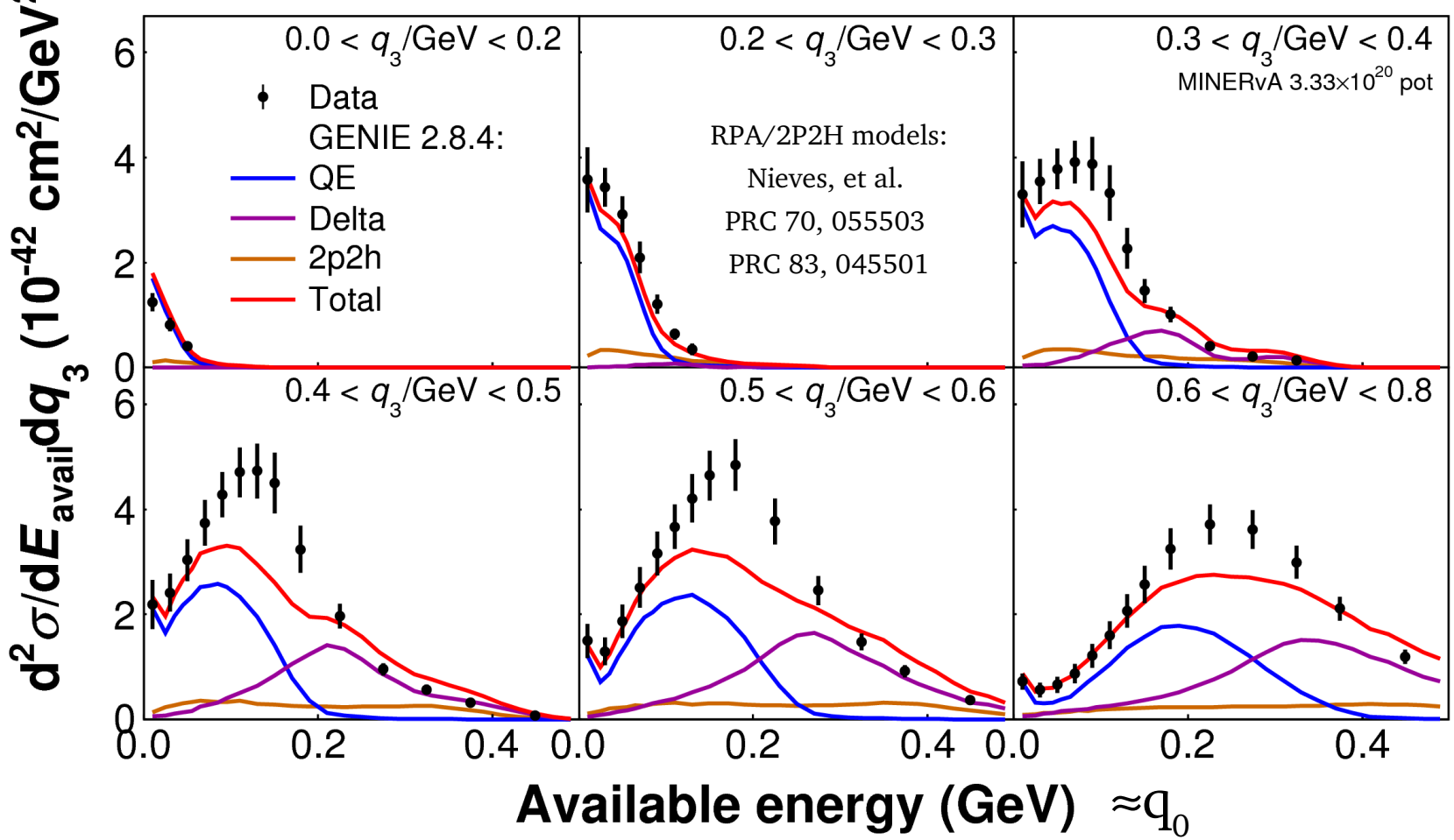
Different scattering channels appear as bands



Models for scattering off of two nucleons tend to increase the cross-section in this area

ν_μ data in the (q_0,q_3) plane

Phys. Rev. Lett. 116 (2016) 071802

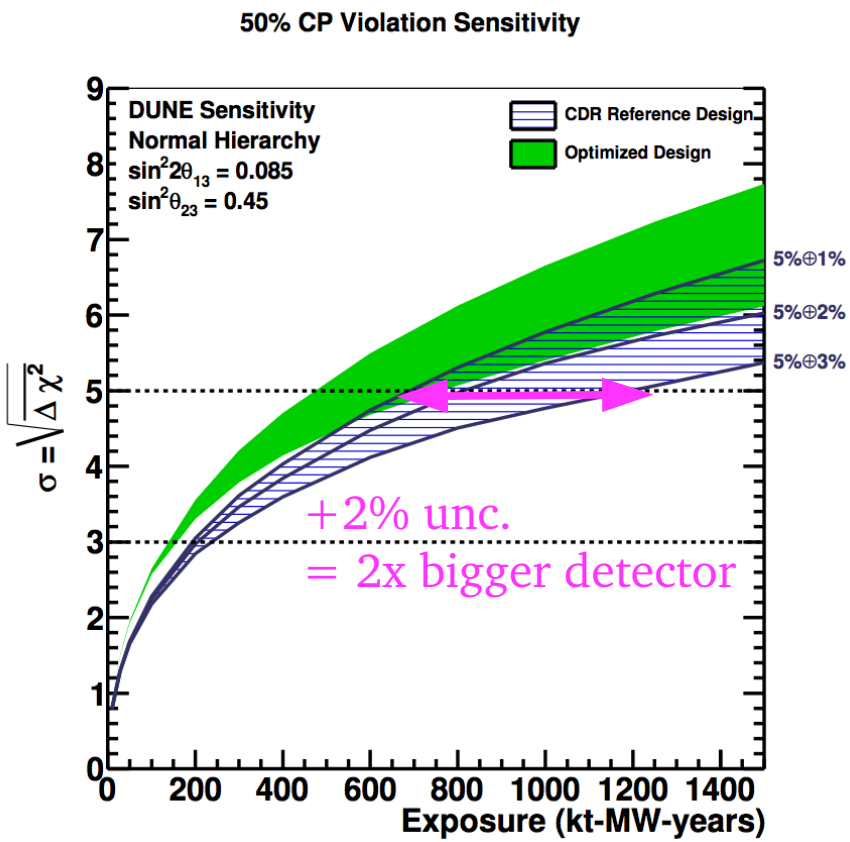


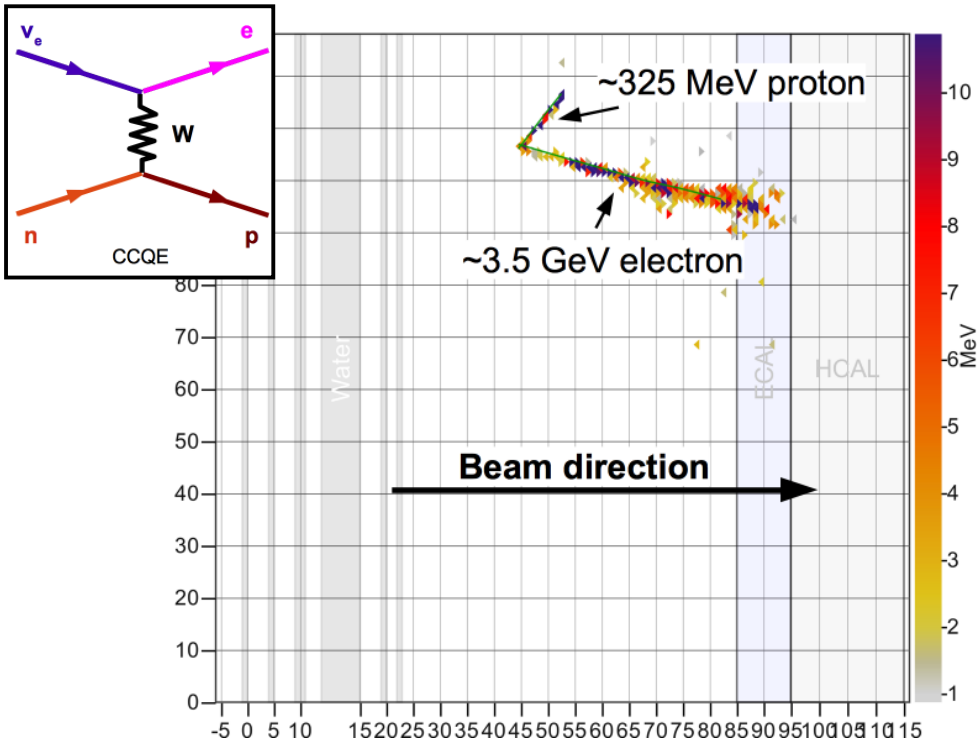
Adding in models of RPA (a charge screening effect) and 2p2h improves agreement in some regions, but not in others — excess in similar kinematic region to excess in antineutrino QE

$$E_{\text{avail}} = \sum \text{p and } \pi^{\pm} \text{ K.E.} + \text{total energy of all other particles except n}$$

ν_e QE-like

Uncertainty on ν_e CC cross-section relative to ν_μ has a strong impact on DUNE's physics reach



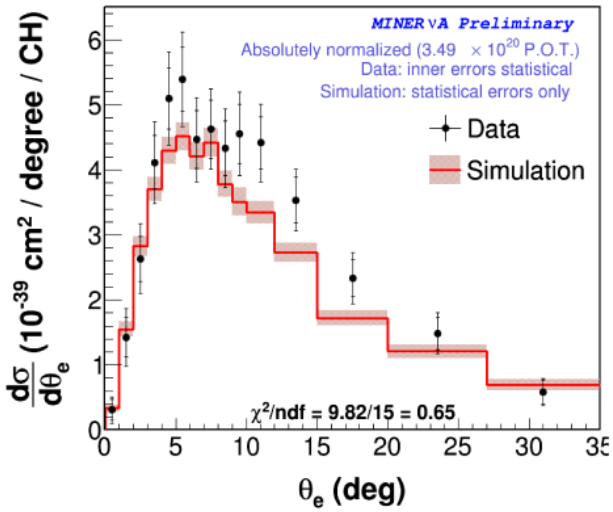


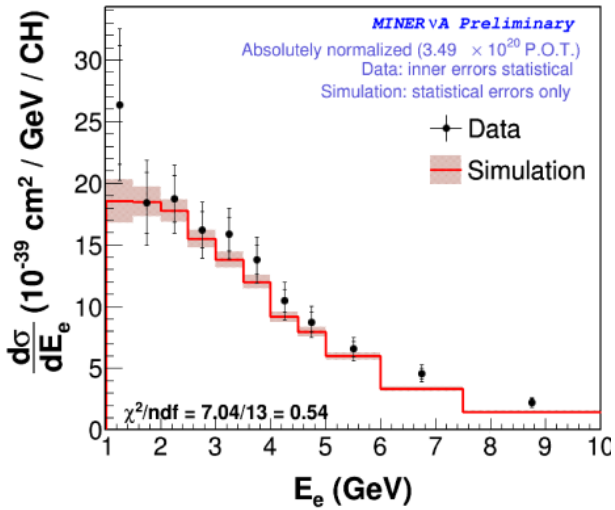
ν_e makeup only ~1% of the NuMI beam but can be readily identified.

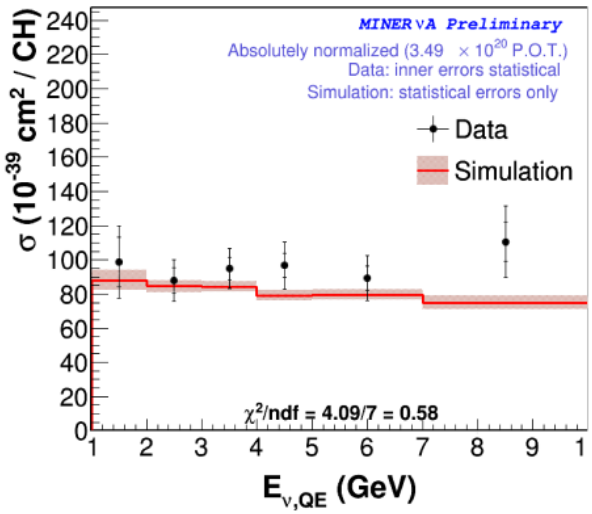
Goal: measure ν_e QE and compare to ν_μ

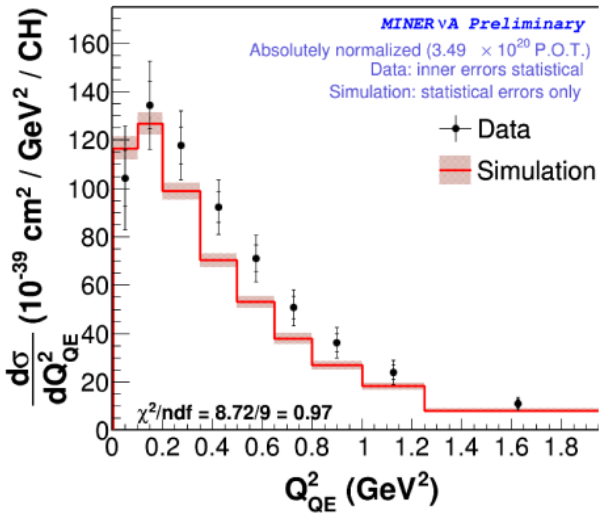
ν_e QE-like

J. Wolcott PhD (Rochester, 2015), Phys. Rev. Lett. 116, 081802 (2016)

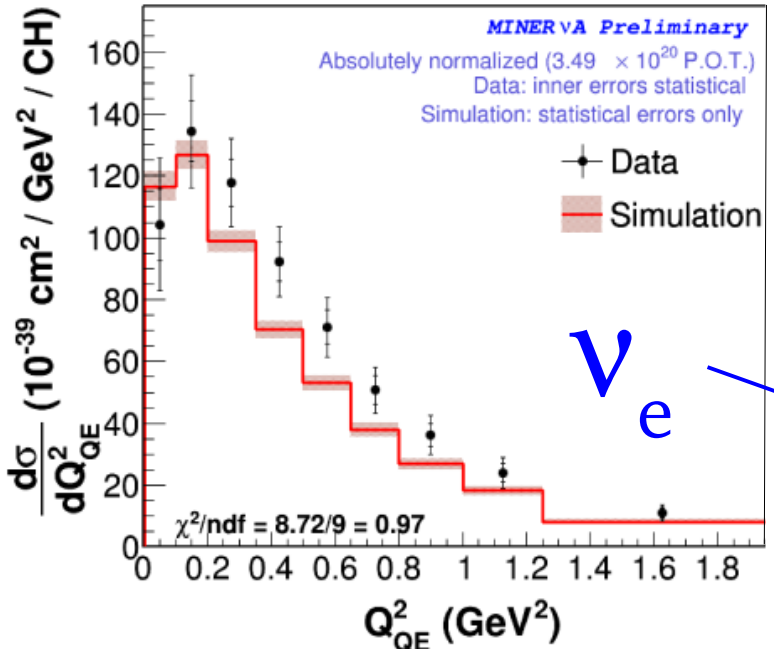






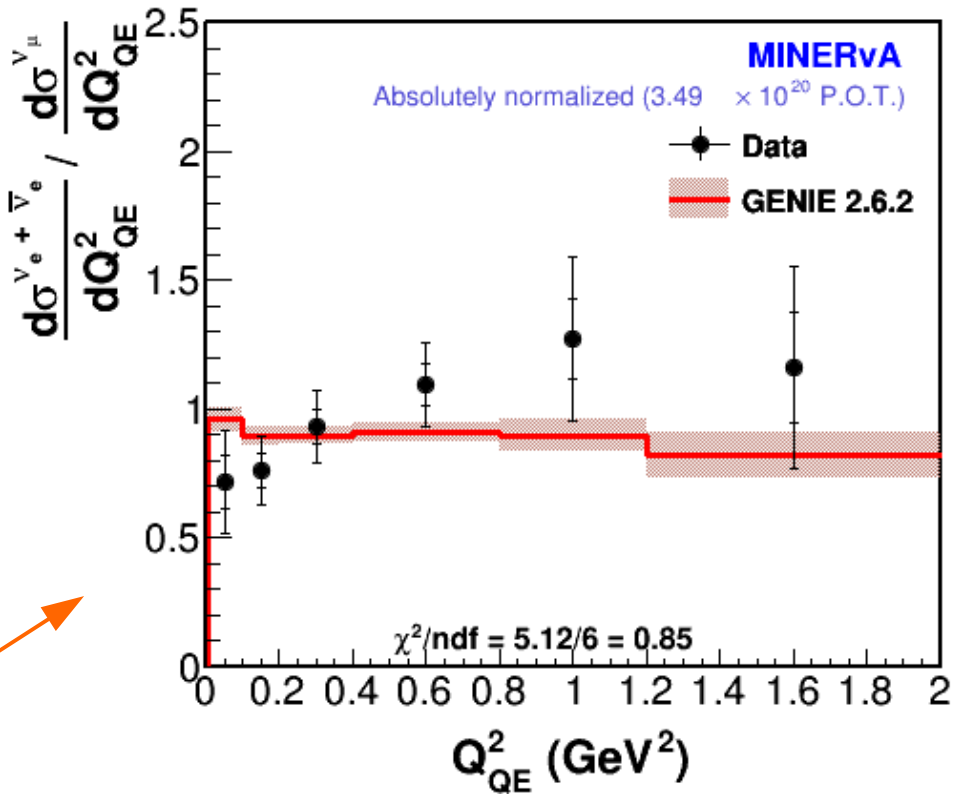


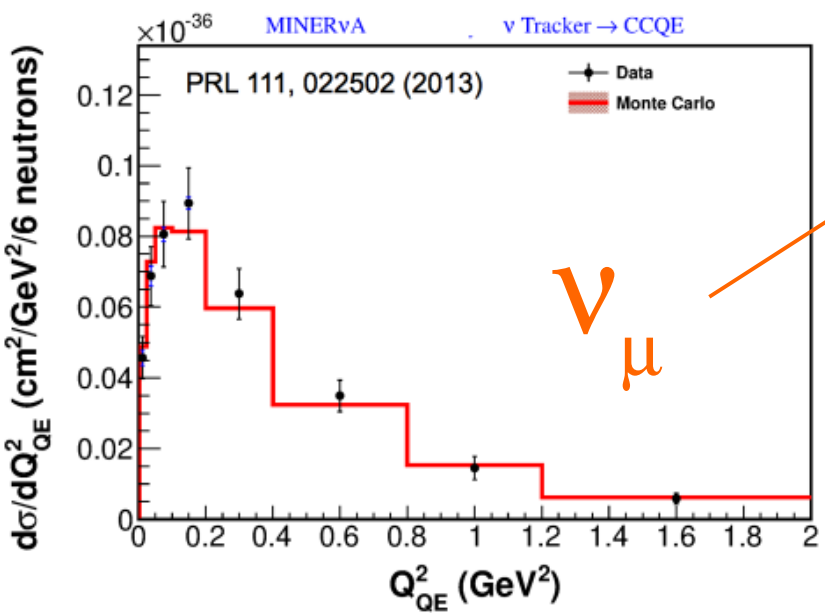
ν_e vs ν_μ



ν_e

Phys. Rev. Lett. 116, 081802 (2016)





ν_μ

Summary

- MINERvA's flux prediction is as precise as has ever been made for a wide band beam like NuMI.
- That prediction enables precision absolute cross-sections
- A multi-faceted study of QE and other low recoil channels is now bearing significant fruit.
- Many other exclusive channels I couldn't cover! (Single $\pi^{\pm,0}$ production, CC and NC K production, coherent p production, diffractive π^0 production). Plus inclusive scattering on different nuclear targets!
- Next talk → Meson production

Backups

MINERvA Publications

MINERvA Physics Publications so far:

"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 Eν of 3.6 GeV", PRL 116, 081802 (2016).

"**Single neutral pion production** by charged-current anti-νμ interactions on hydrocarbon at average Eν of 3.6 GeV", Phys.Lett. B749 130-136 (2015).

"Measurement of **muon plus proton final states** in νμ Interactions on Hydrocarbon at average Eν of 4.2 GeV" Phys. Rev. D91, 071301 (2015).

"Measurement of **Coherent Production of π±** in Neutrino and Anti-Neutrino Beams on Carbon from Eν of 1.5 to 20 GeV", Phys. Rev.Lett. 113, 261802 (2014).

"**Charged Pion Production** in νμ Interactions on Hydrocarbon at average Eν of 4.0 GeV" , Phys.Rev. D92, 092008 (2015).

"Measurement of ratios of νμ charged-current **cross sections on C, Fe, and Pb** to CH at neutrino energies 2–20 GeV", Phys. Rev. Lett. 112, 231801 (2014).

"Measurement of **Muon Neutrino Quasi-Elastic Scattering** on a Hydrocarbon Target at Eν~3.5 GeV", Phys. Rev. Lett. 111, 022502 (2013).

"Measurement of **Muon Antineutrino Quasi-Elastic Scattering** on a Hydrocarbon Target at Eν~3.5 GeV", Phys. Rev. Lett. 111, 022501 (2013).

"Measurement of **K+ production in charged-current** νμ interactions" **accepted for publication, in press**

"Evidence for **neutral-current diffractive neutral pion production** from hydrogen in neutrino interactions on hydrocarbon", **accepted for publication, in press**

"First evidence of **coherent K+ meson production** in neutrino-nucleus scattering", **accepted for publication, in press**

Two more recently went to the arXiv

Cross sections for **neutrino and antineutrino induced pion production** on hydrocarbon in the few-GeV region using MINERvA

Neutrino Flux Predictions for the NuMI Beam

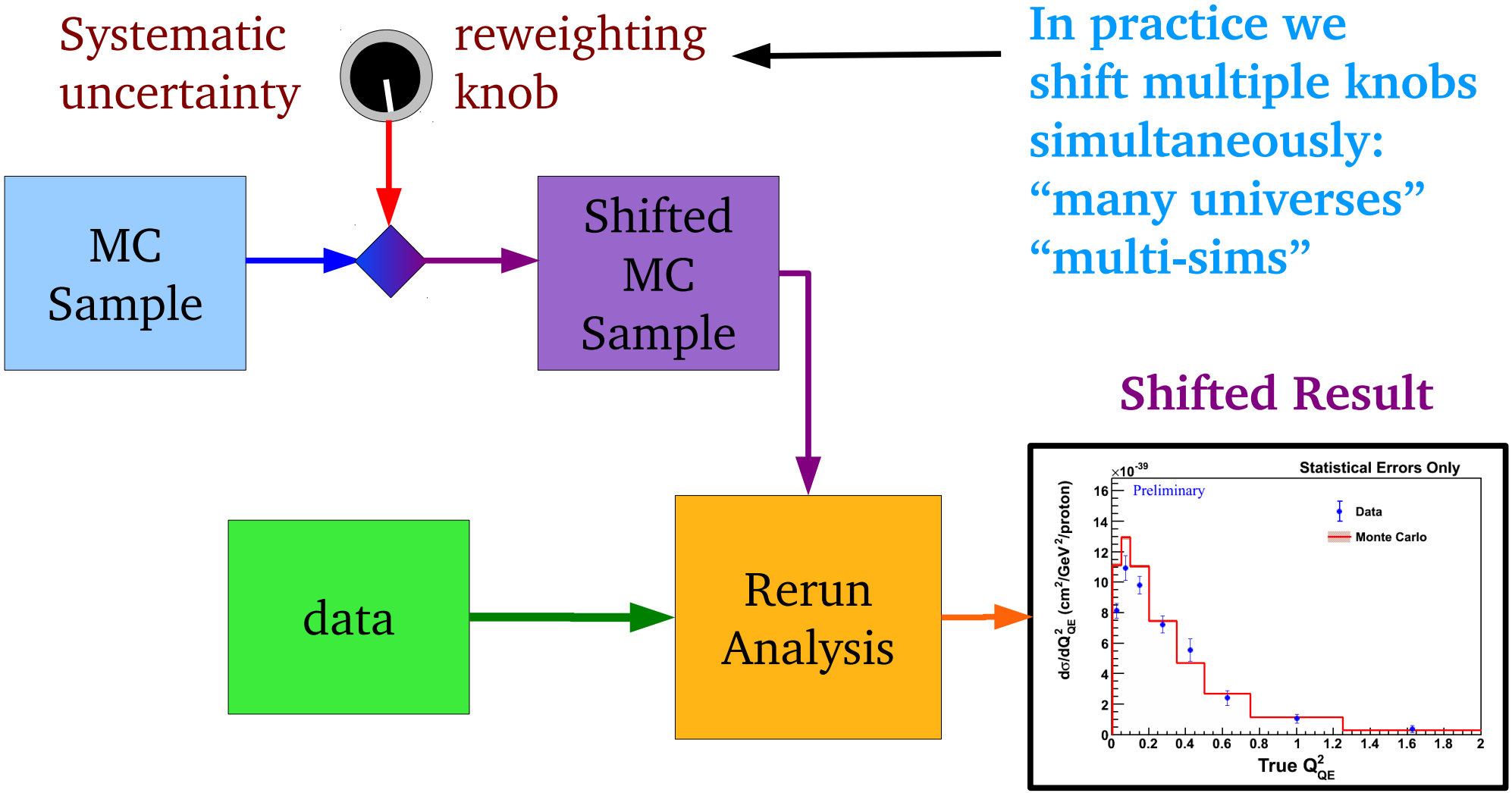
Several public results in paper preparation

Antineutrino Quasielastic Scattering

Neutrino Quasielastic Scattering

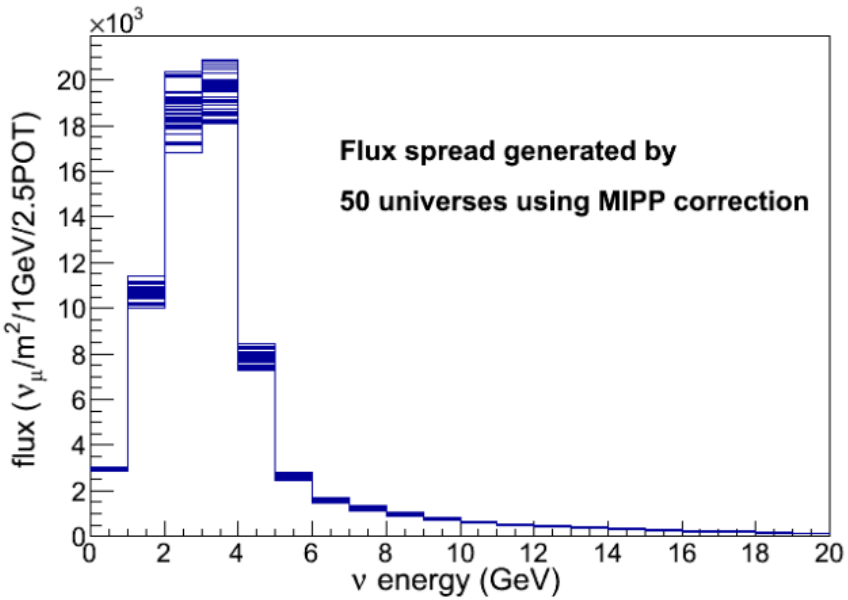
Charged current neutrino and antineutrino inclusive cross sections via **the "Low-nu" method**

Systematic Uncertainties



The "Many Universes" method

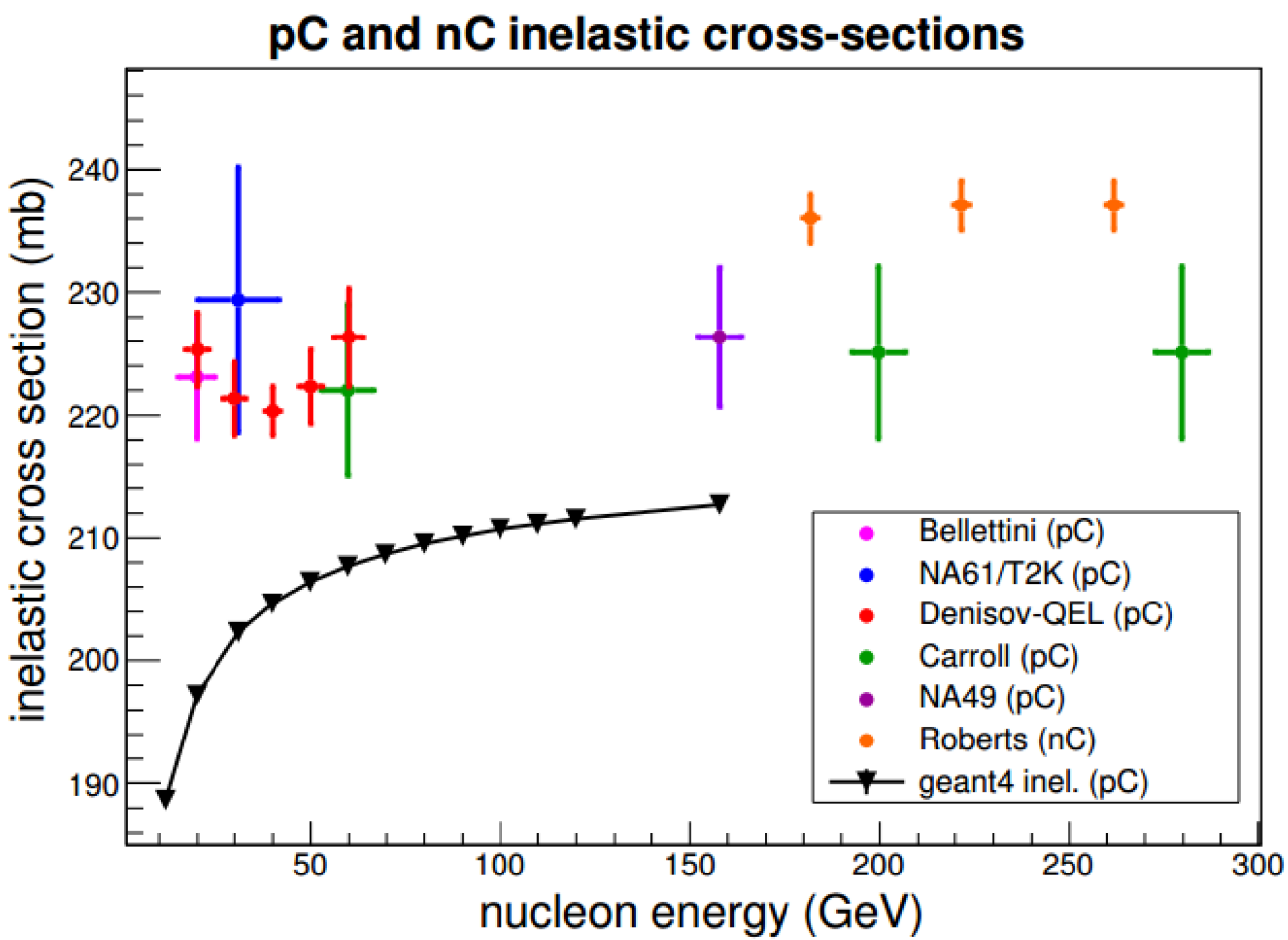
- Each hadron production data point, including absorption cross-sections, is treated as a random variable with a central value and uncertainty.
- Points can be correlated.
- Random MC universes created by throwing new values for the data points, recomputing weights.
- For any distribution, can compute the bin-to-bin covariance matrix.



Applying pC to pA

- Subdominant portion of the ancestry is interactions on nuclei that are not carbon. Most common are He, Fe and Al.
- We constrain these interactions with pC data when possible.
- An additional uncertainty was derived:
  1) Measurements of K^0, and Λ^0 production off Be, Cu and Pb targets by a 300 GeV proton beam are used to derive an A-dependent scaling in bins of momentum and angle
  2) The scaling is applied to pA → pX and pA → KX data collected at 100 GeV on C, Al, Cu, Ag, and Pb targets. Agreement at ~10% level.
  3) The scaling is then applied to the MC, and unscaled vs scaled MC are compared
  4) The level of agreement for both scaled data and MC is used to assign the eventual error.
- Results in an additional 10-30% error

p absorption



Inelastic = meson or heavy baryon production

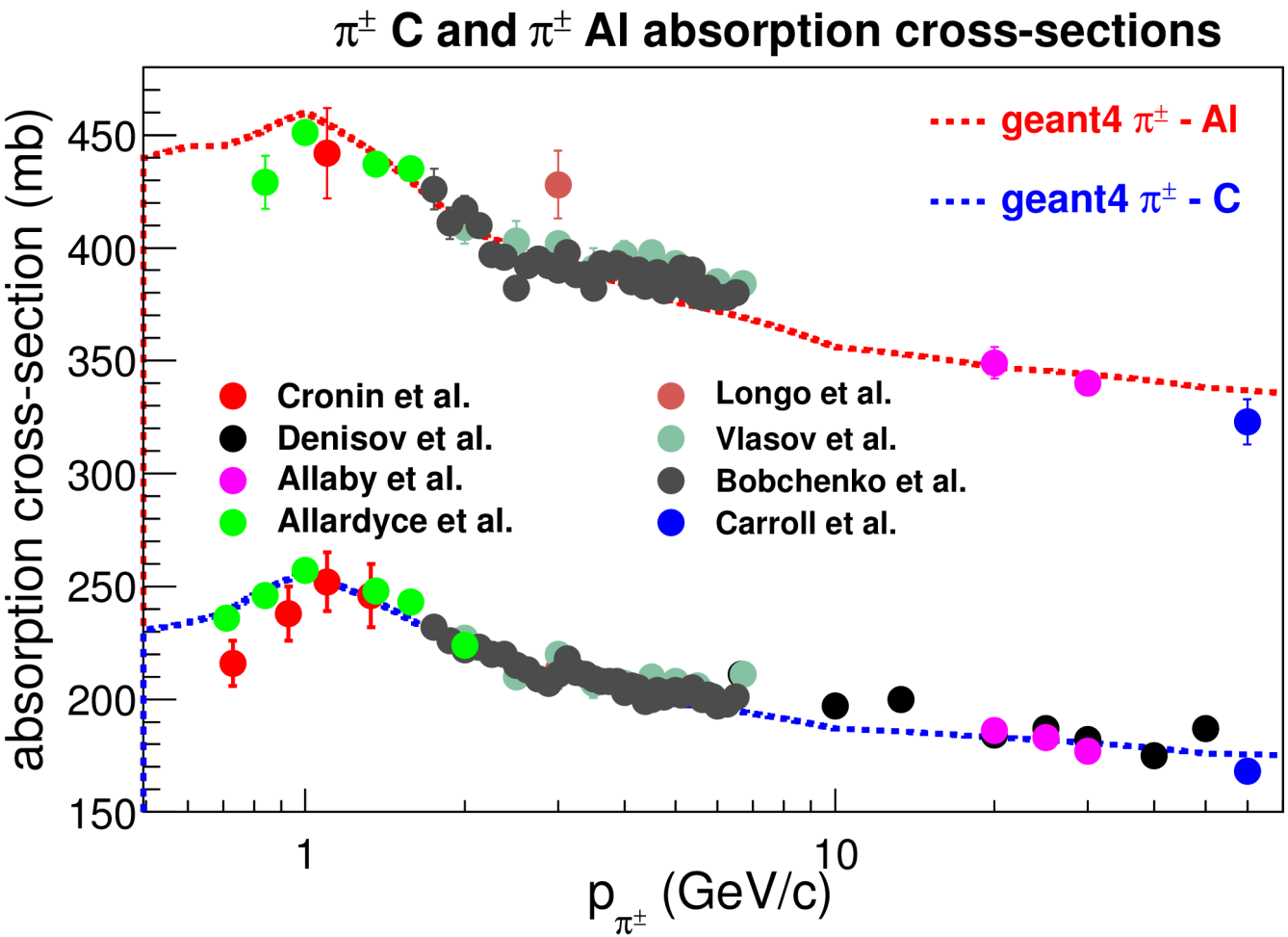
Absorption = inelastic + quasi-elastic

MC underestimates inelastic by ~5%. We correct and take 5% as the error.

The QEL cross-section is taken to be 29±4 mb

For neutrons, and for protons colliding with He, Al, Fe we assume a 40% uncertainty. No other materials are relevant.

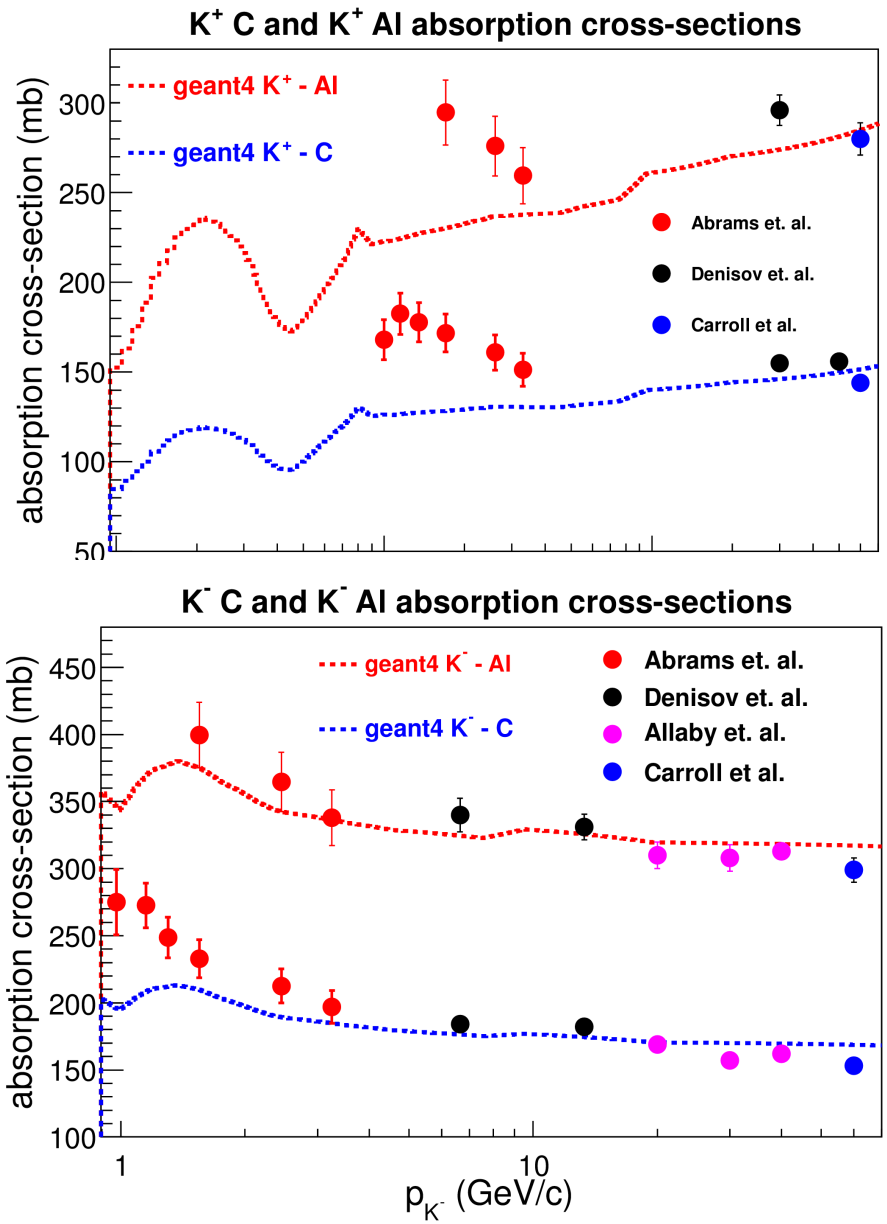
π absorption



MC agrees well with the data. Error set by residuals.

C: 10 mb (~5%)
Al: 24 mb

K absorption



MC agrees not-so-well with the data. Error set by residuals.

<u>K+ with p<2 GeV</u>
C: 68 mb
Al: 83 mb

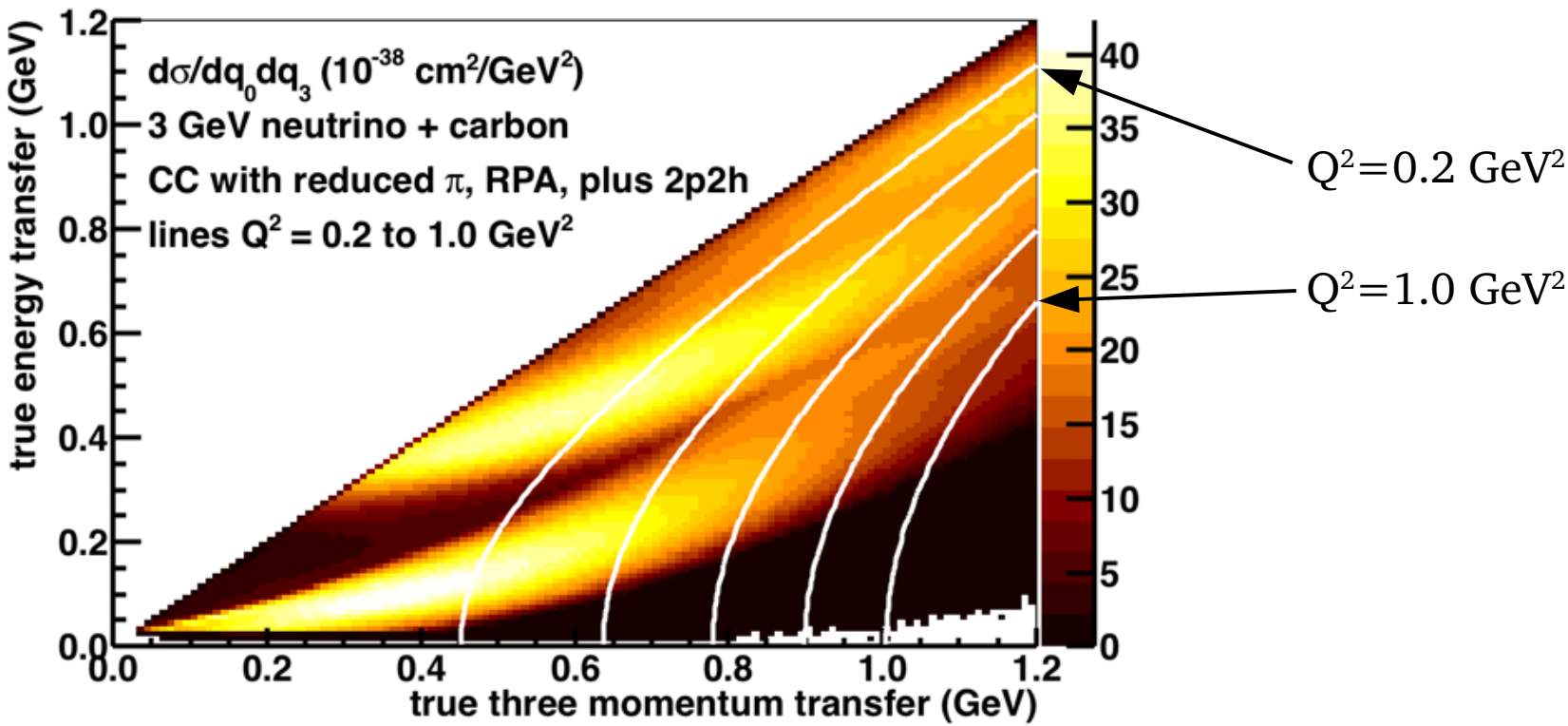
<u>K- with p<2 GeV</u>
C: 80 mb
Al: 49 mb

<u>K+ with p>2 GeV</u>
C: 13 mb
Al: 31 mb

<u>K- with p>2 GeV</u>
C: 20 mb
Al: 31 mb

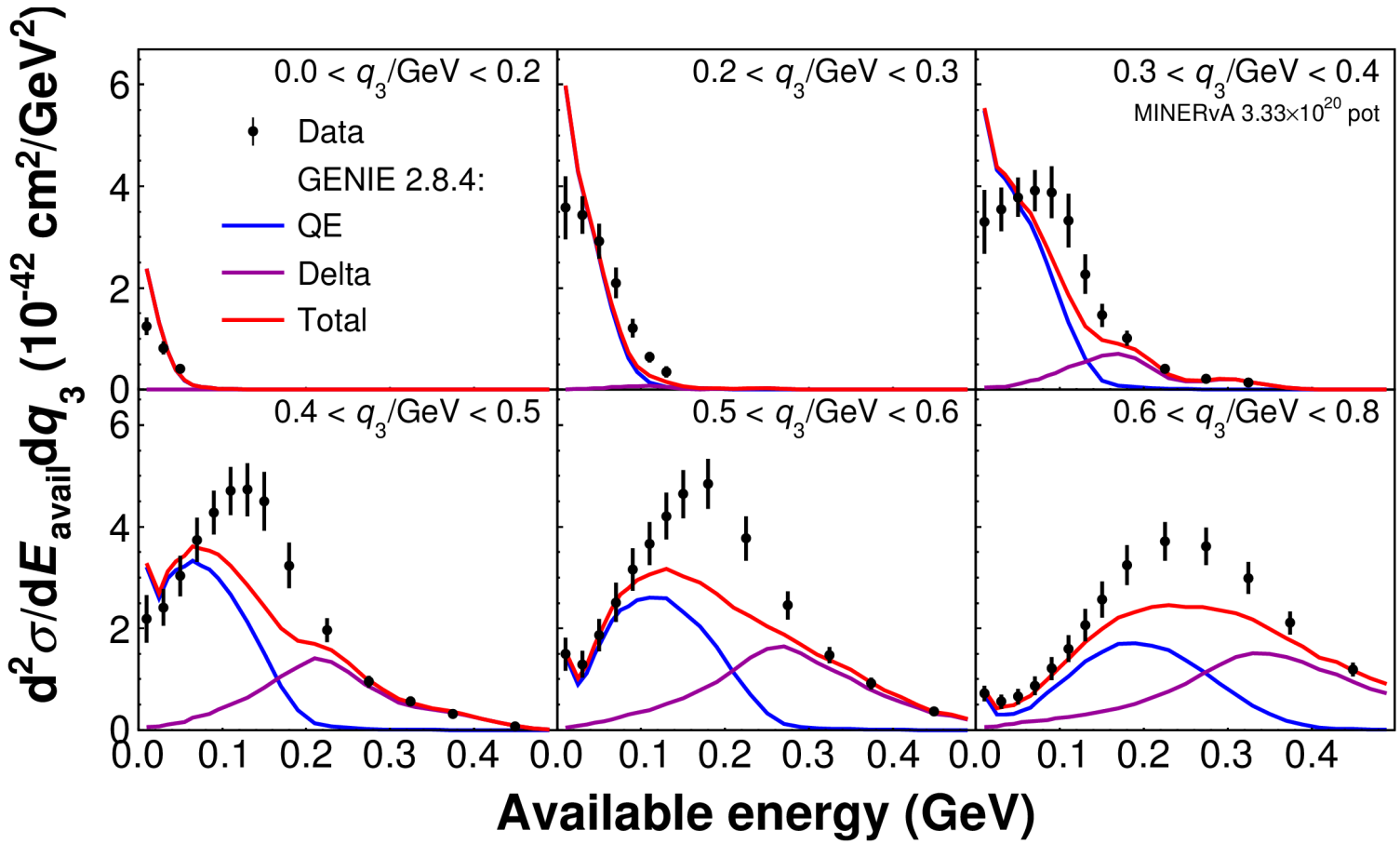
A new way of studying QE

Just looking at $d\sigma/dQ^2$ integrates across the bands, obscuring things



GENIE vs low recoil data

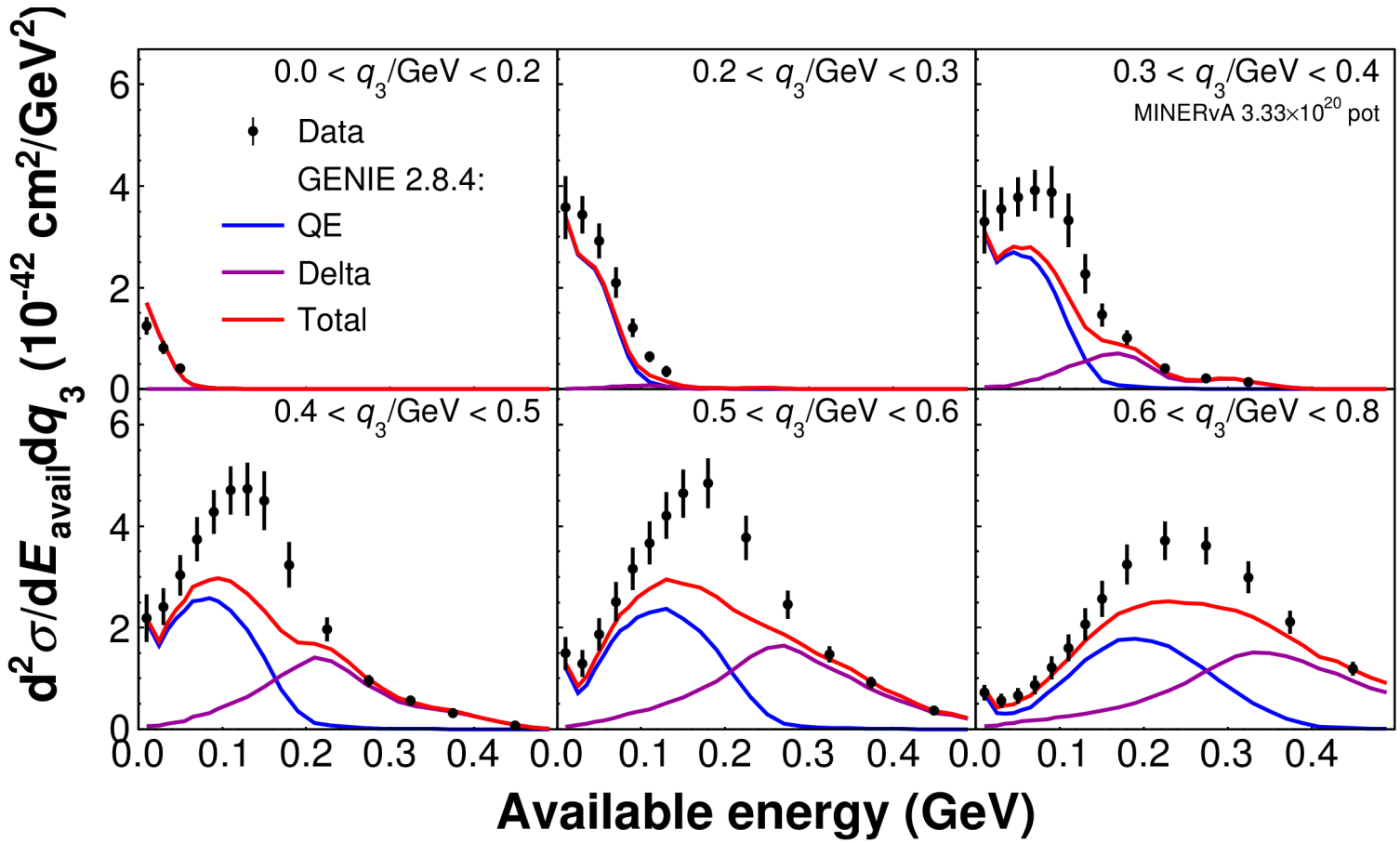
Default* GENIE



* includes a MINERvA tune which lowers non-resonant ν_μ n → 1π +nucleons production by 76% and the total rate of π production for W<1.8 GeV by an additional 10%. Coherent $\pi^\pm$ production also lowered by 50% for E_π < 450 MeV.

GENIE vs low recoil data

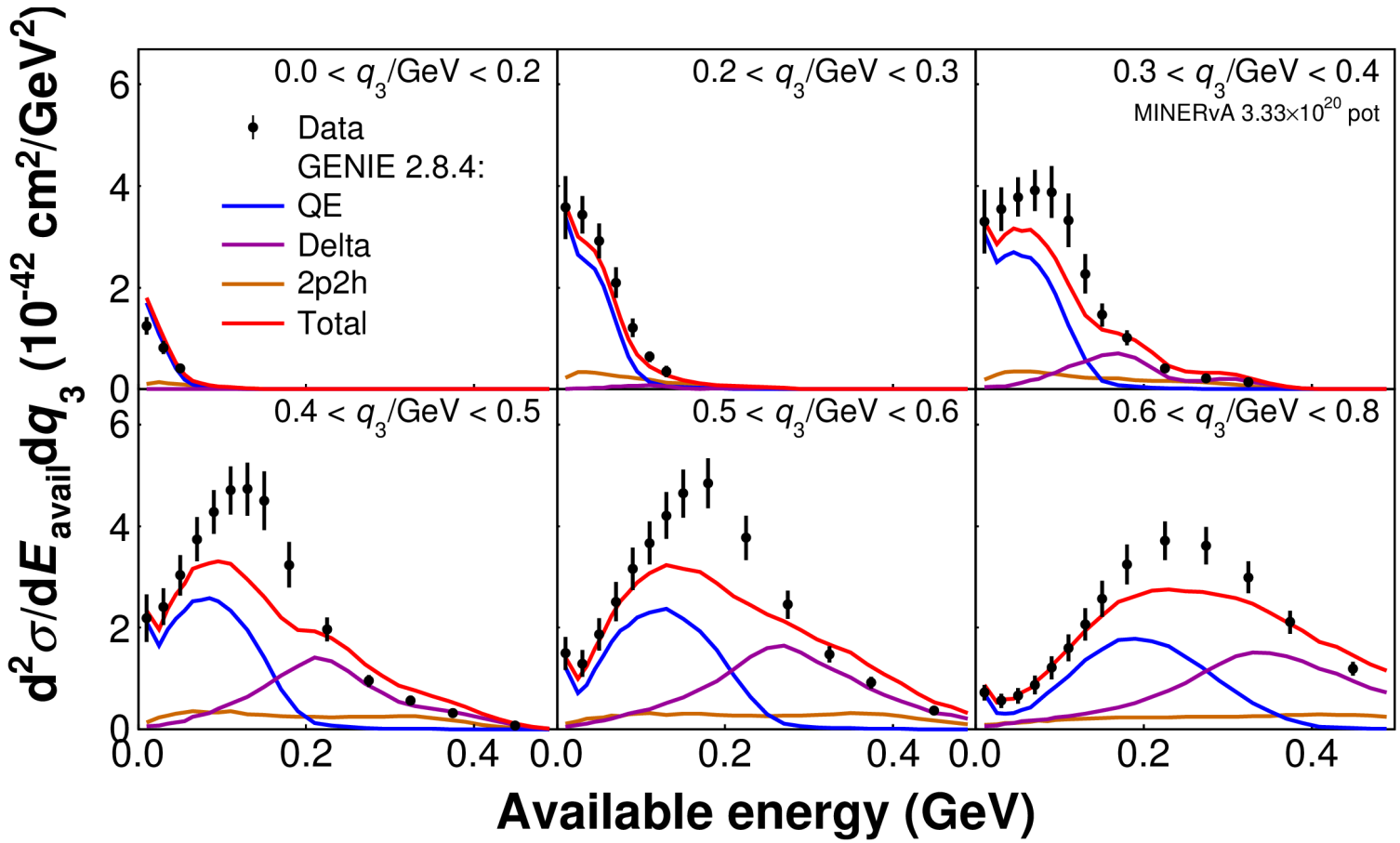
Default* GENIE + RPA correction



* includes a MINERvA tune which lowers non-resonant ν_μ n → 1π +nucleons production by 76% and the total rate of π production for W<1.8 GeV by an additional 10%. Coherent $\pi^\pm$ production also lowered by 50% for E_π < 450 MeV.

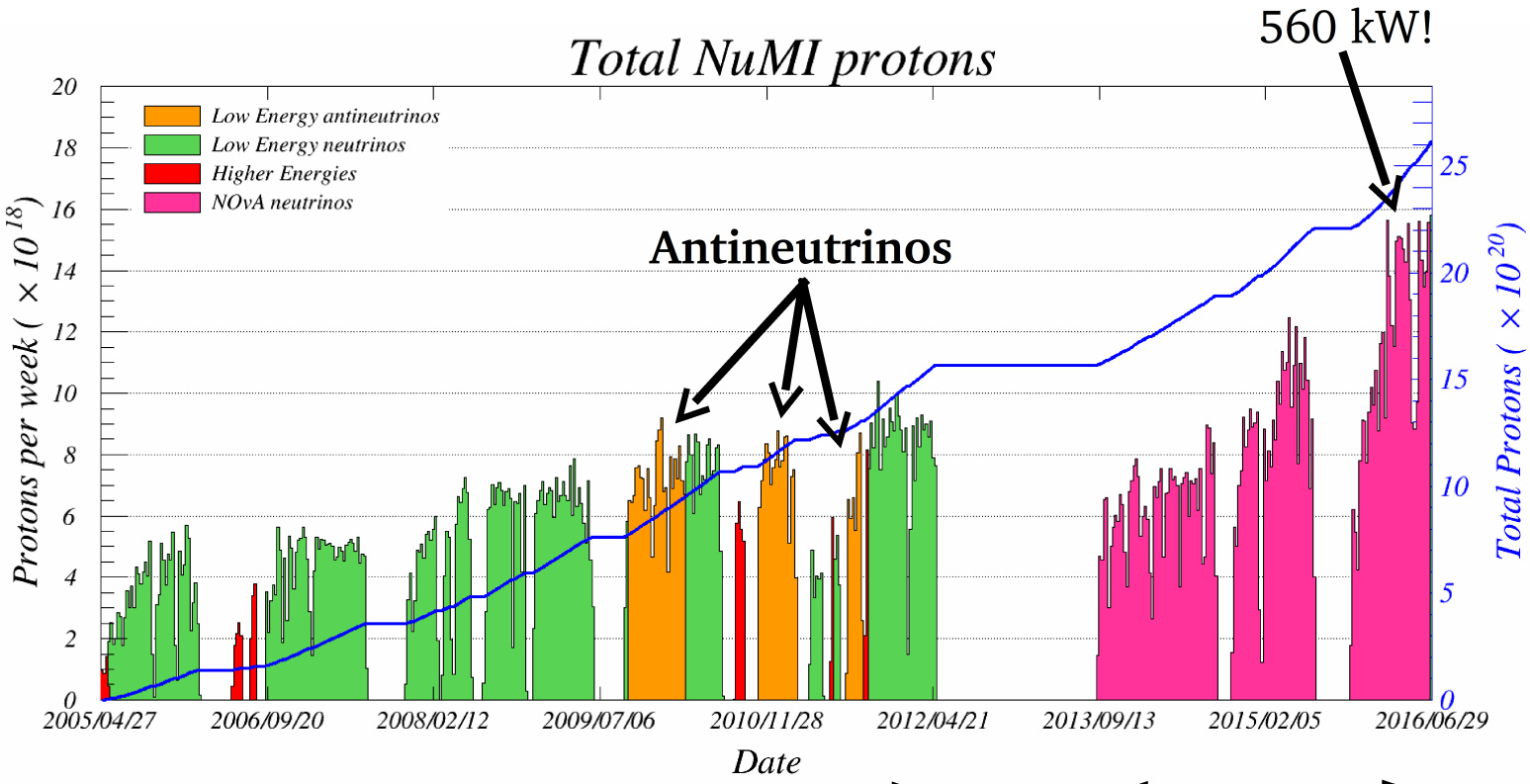
GENIE vs low recoil data

Default* GENIE + RPA correction + MEC

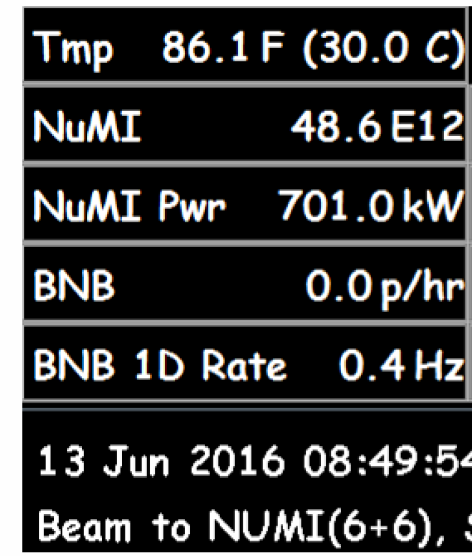


* includes a MINERvA tune which lowers non-resonant ν_μ n → 1π +nucleons production by 76% and the total rate of π production for W<1.8 GeV by an additional 10%. Coherent $\pi^\pm$ production also lowered by 50% for E_π < 450 MeV.

NuMI Running



Major Milestone!



MINOS

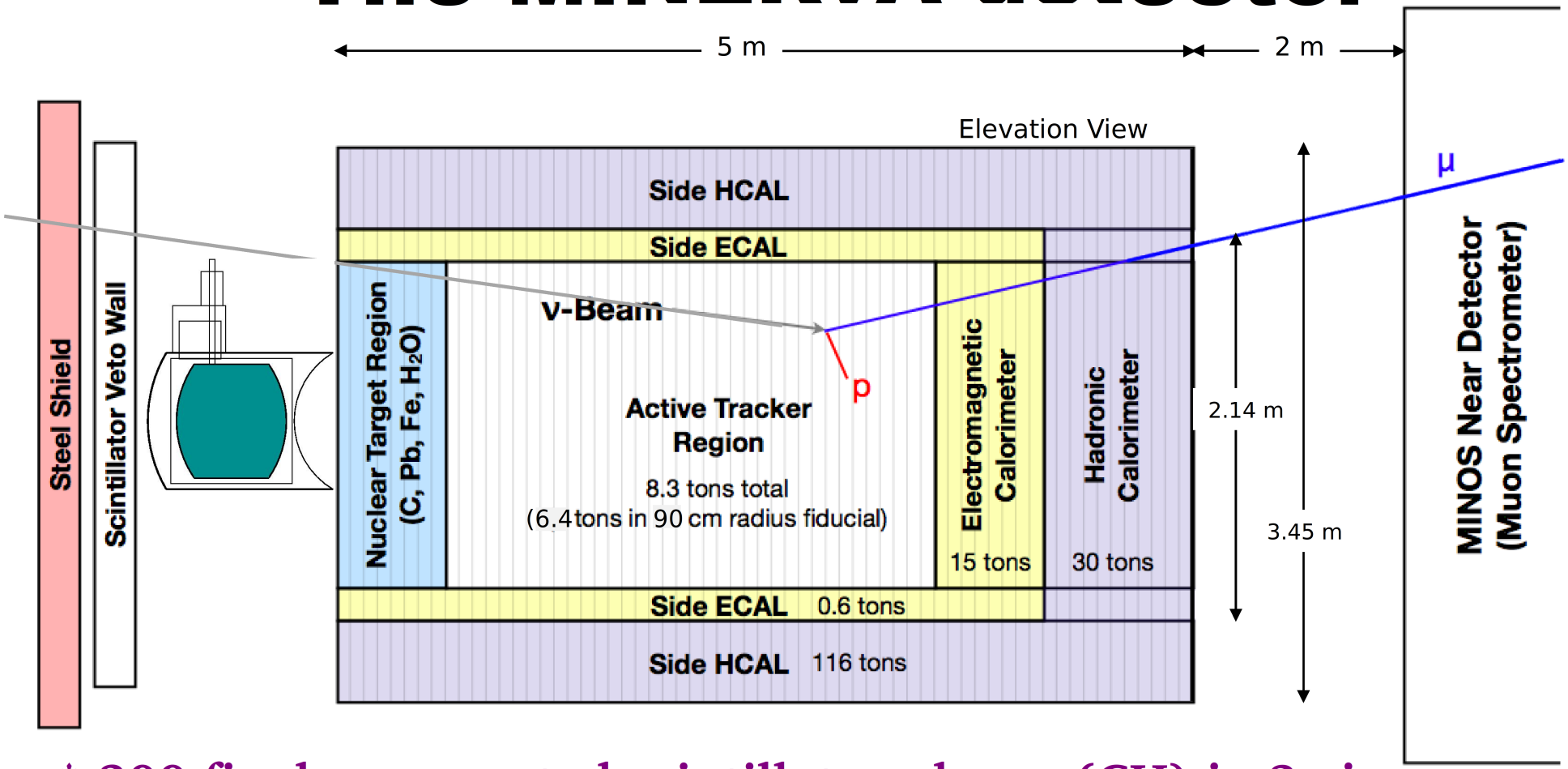
MINOS+

MINERvA

NOvA

10.56×10^{20} PoT MINOS neutrino-mode
5.80×10^{20} PoT MINOS+ neutrino-mode
3.36×10^{20} PoT MINOS antineutrino-mode

The MINERvA detector



* 200 finely segmented scintillator planes (CH) in 3 views
* Calib: FEB bench tests, source mapper, LI, rock μ, Michel electrons, test-beam
* 4% channel to channel variations after calibration