Experiences with Geant4 at MINERvA

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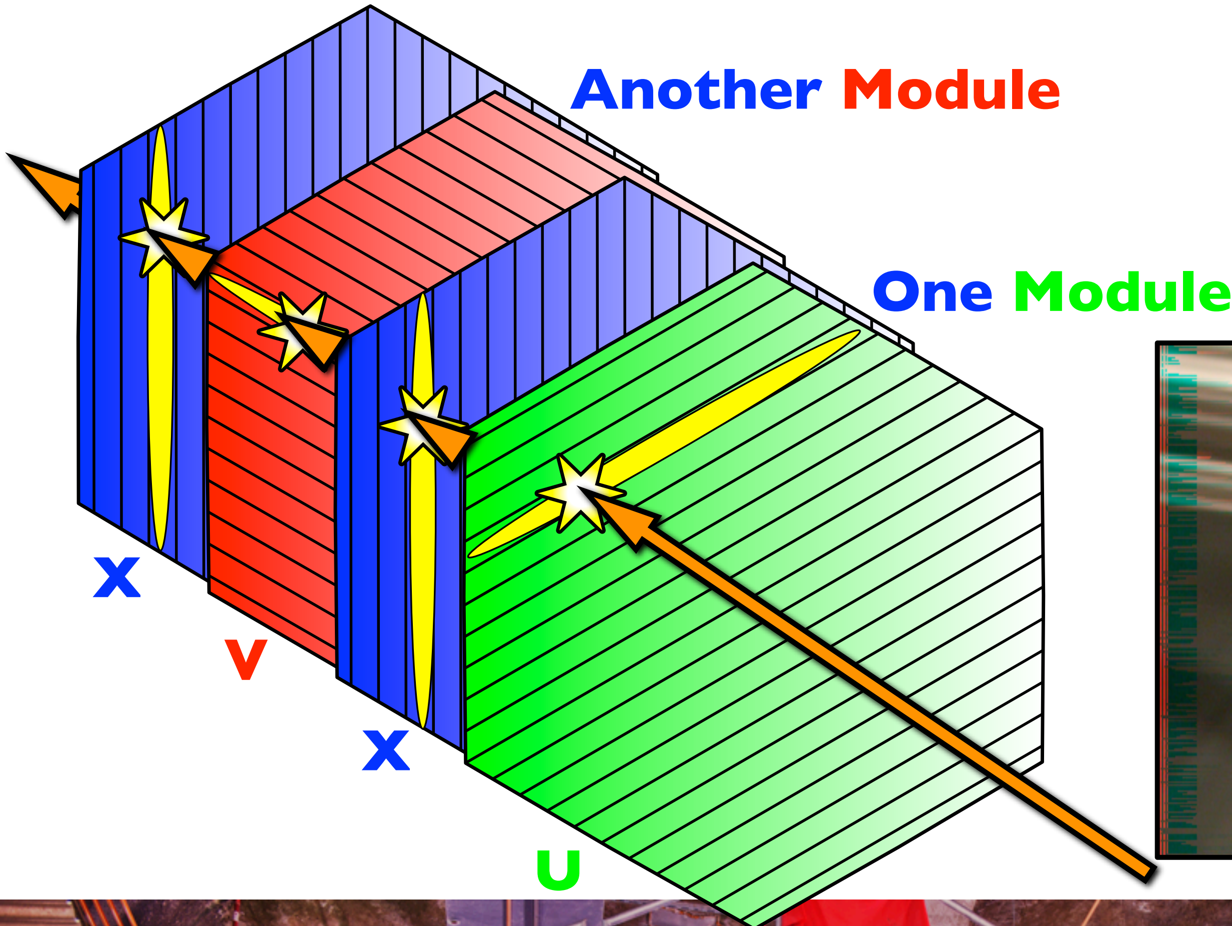
Geant4 Technical Forum

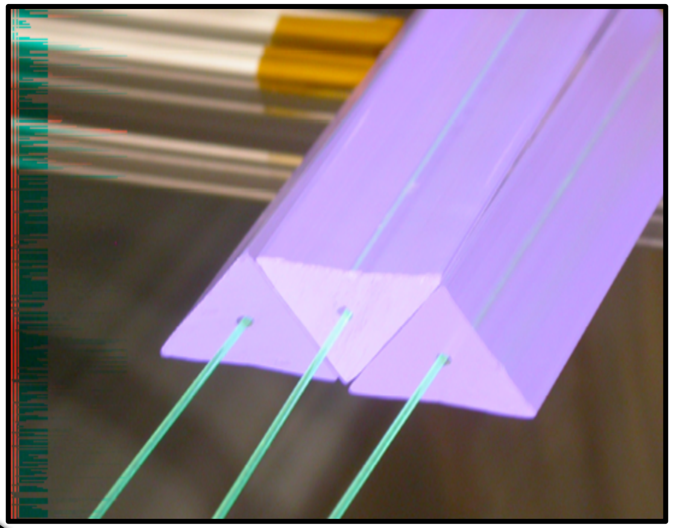
Overview

- How MINERvA uses Geant4:
  - Neutrino flux central values & re-weighting (correction to data & uncertainties)
  - Detector response & estimating systematic uncertainties on detector response
- Proposal for Geant4 model parameters: *estimating systematics is easier if, where appropriate, the parameters are **exposed**, **configurable**, and **explained**.**

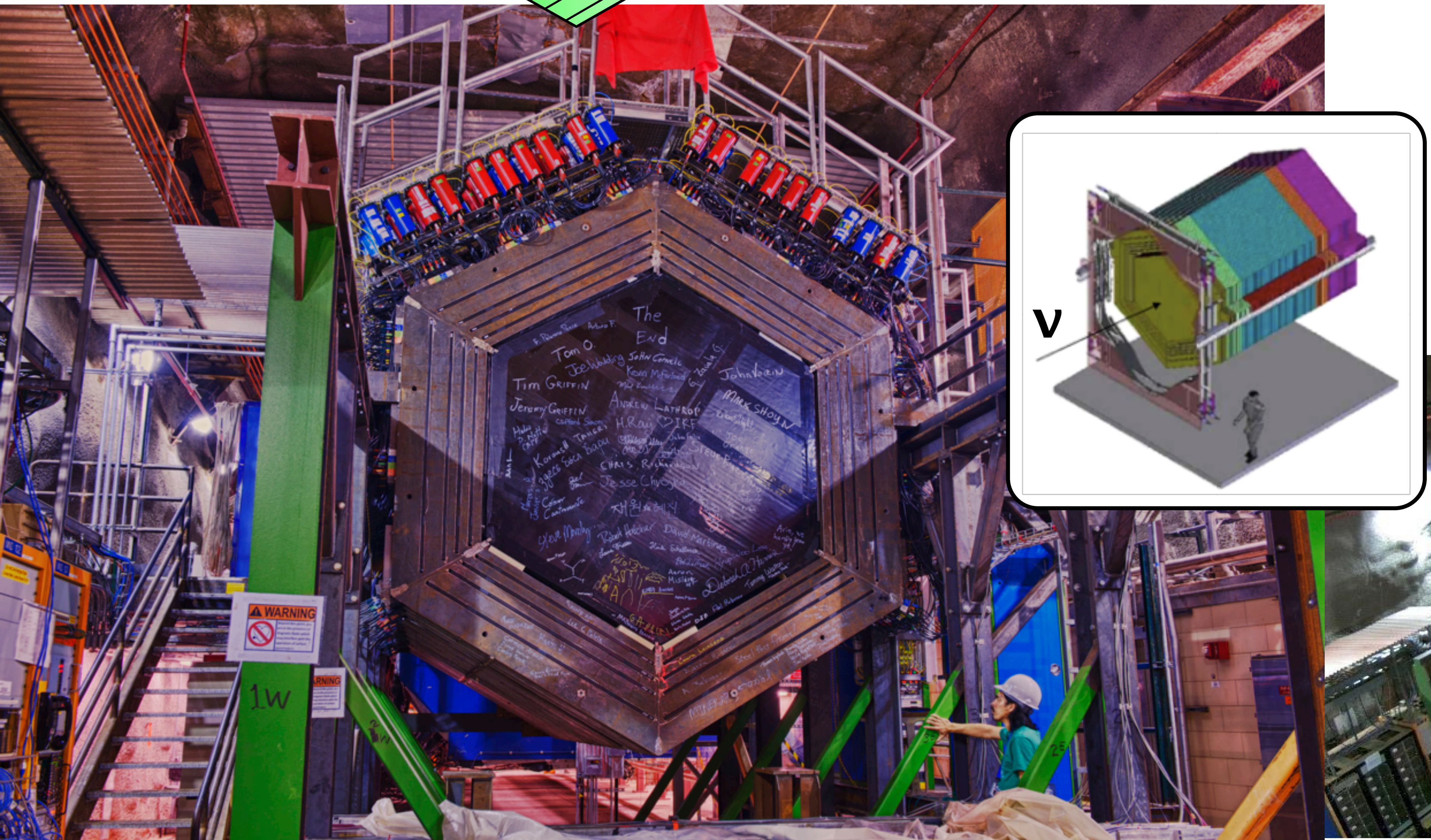
*Note: There is an implicit assumption that at least some of the parameters have meaningful uncertainties themselves.

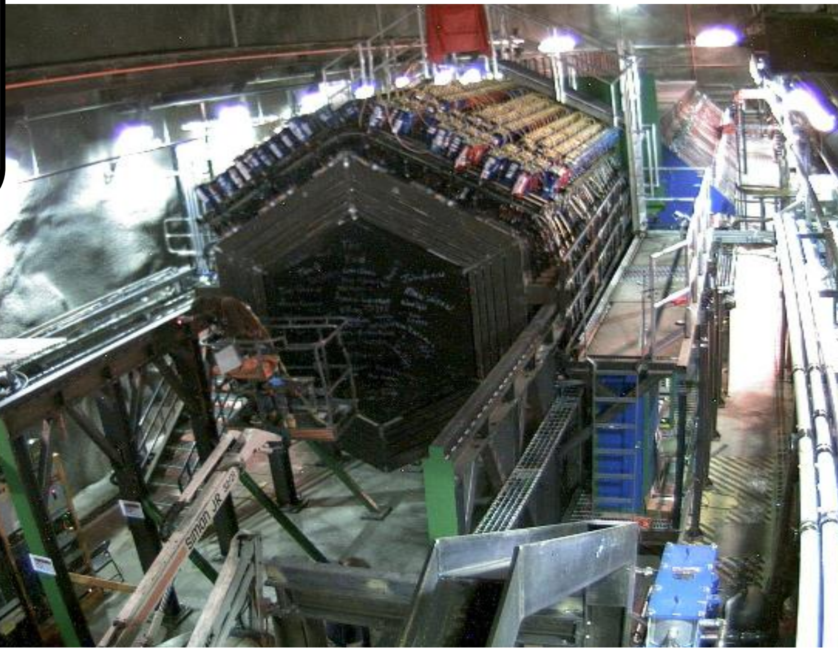
MINERνA





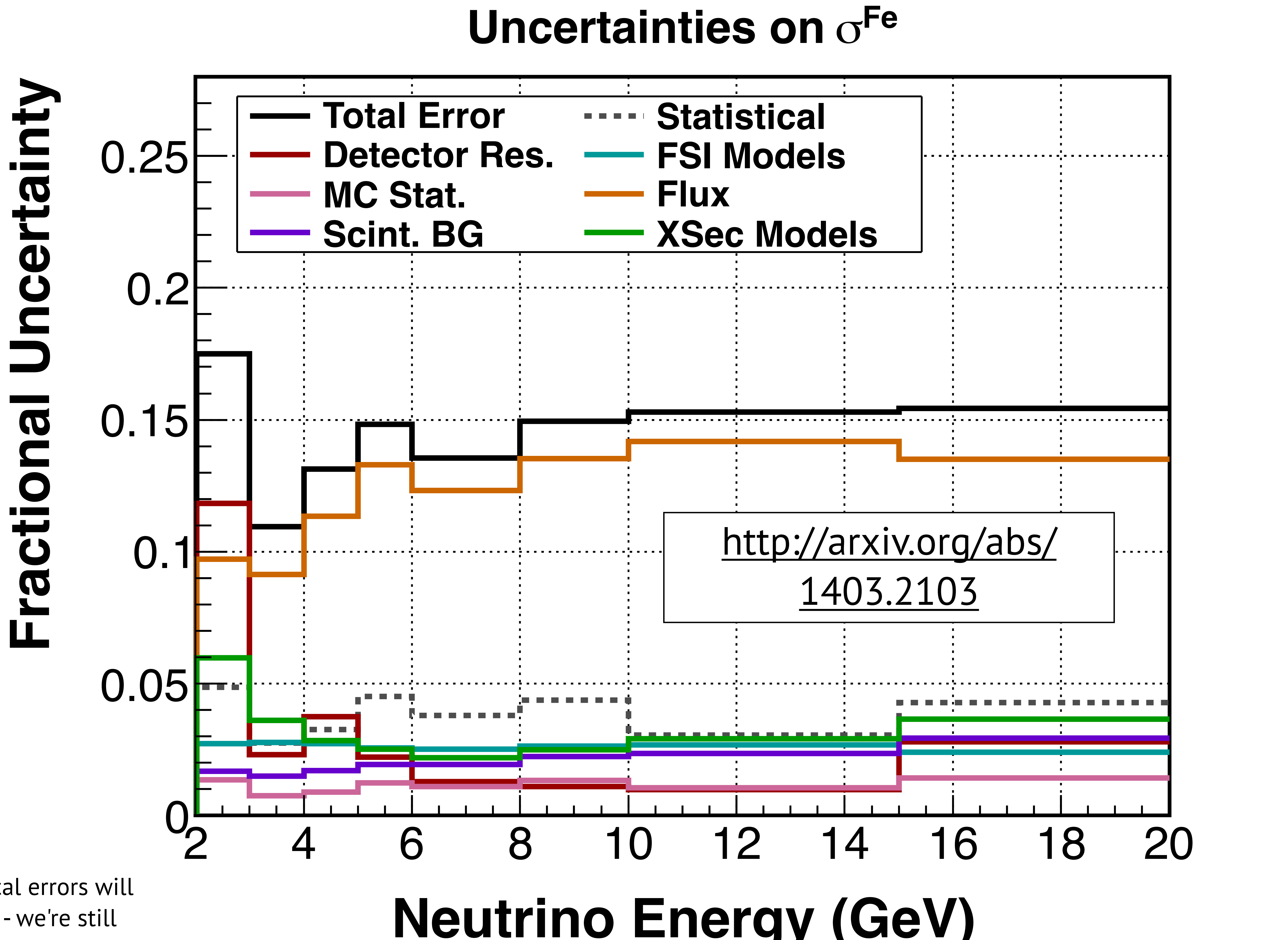
- Neutrino interaction cross sections, structure functions, and kinematics in the few to few tens of GeV neutrino energy range.
- Fine-grained resolution for excellent kinematic measurements.
- Nuclear effects with a variety of target materials ranging from Helium to Lead.





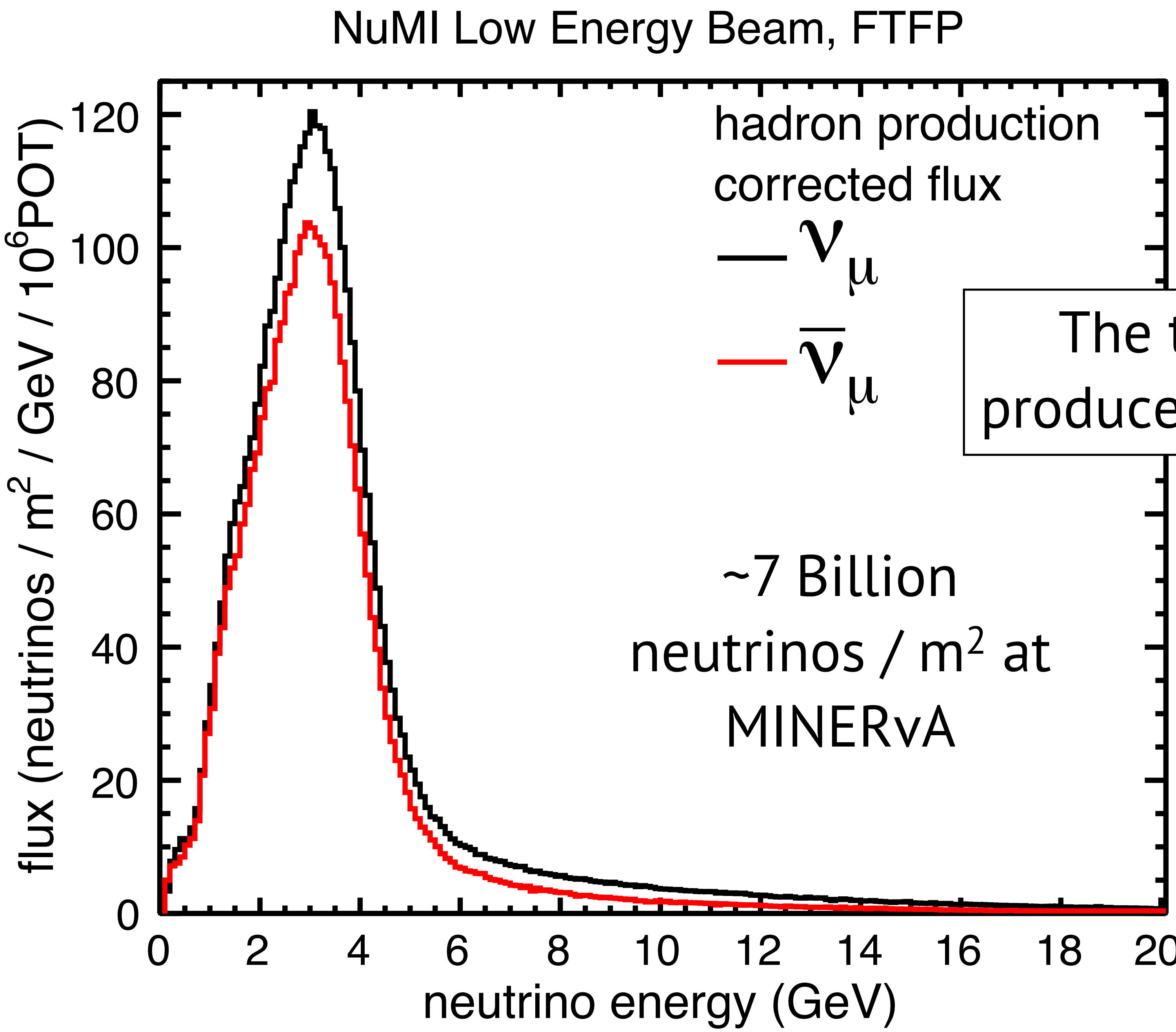
Geant4 and MINERvA

- Geant4 is a critical part of MINERvA's simulation software stack.
  - g4NuMI: beamline simulation (primary protons @120 GeV on Carbon target through secondary and tertiary interactions in the target, meson focusing horns, and beamline, basically stopping with meson decay)
  - MINERvA test beam detector (small-scale replica used to study hadronic response)
  - Main MINERvA detector simulation (largest concerns are ~hundreds of MeV to ~GeV hadrons)

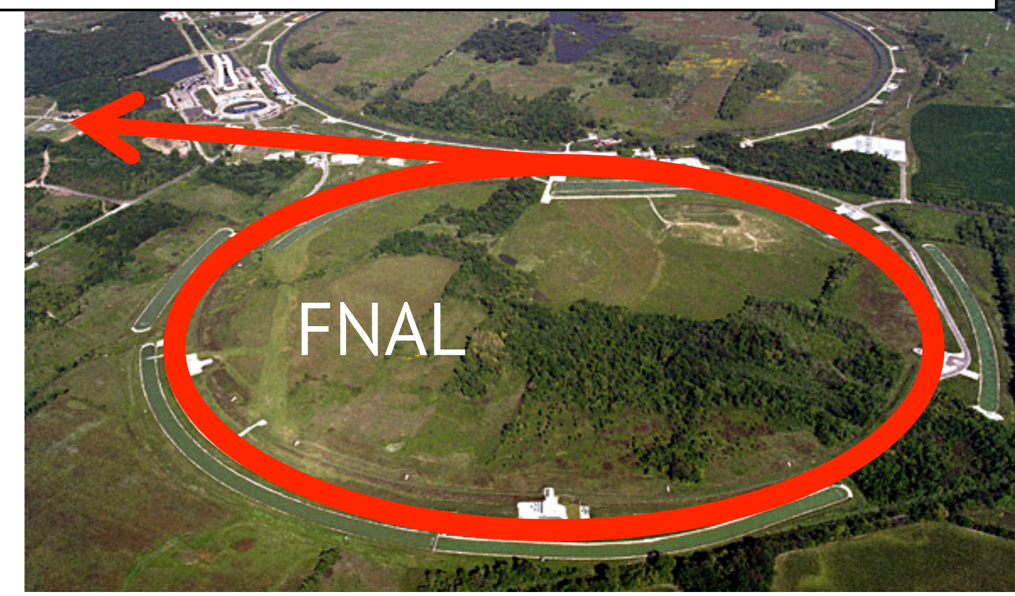


Statistical errors will shrink - we're still recording data.

Neutrino Beam



The target position is configurable to produce "Low" and "Medium" Energy beams.



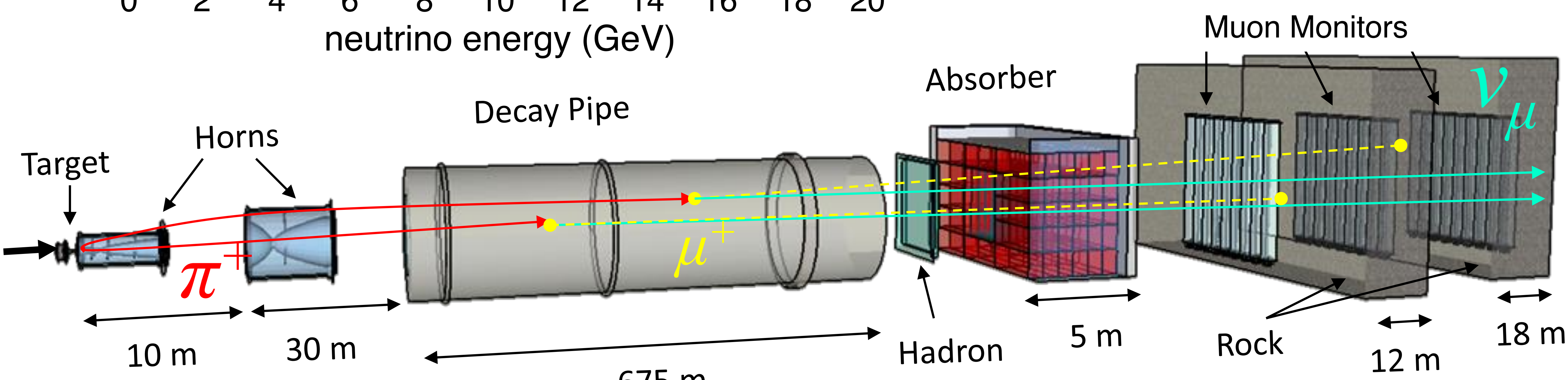
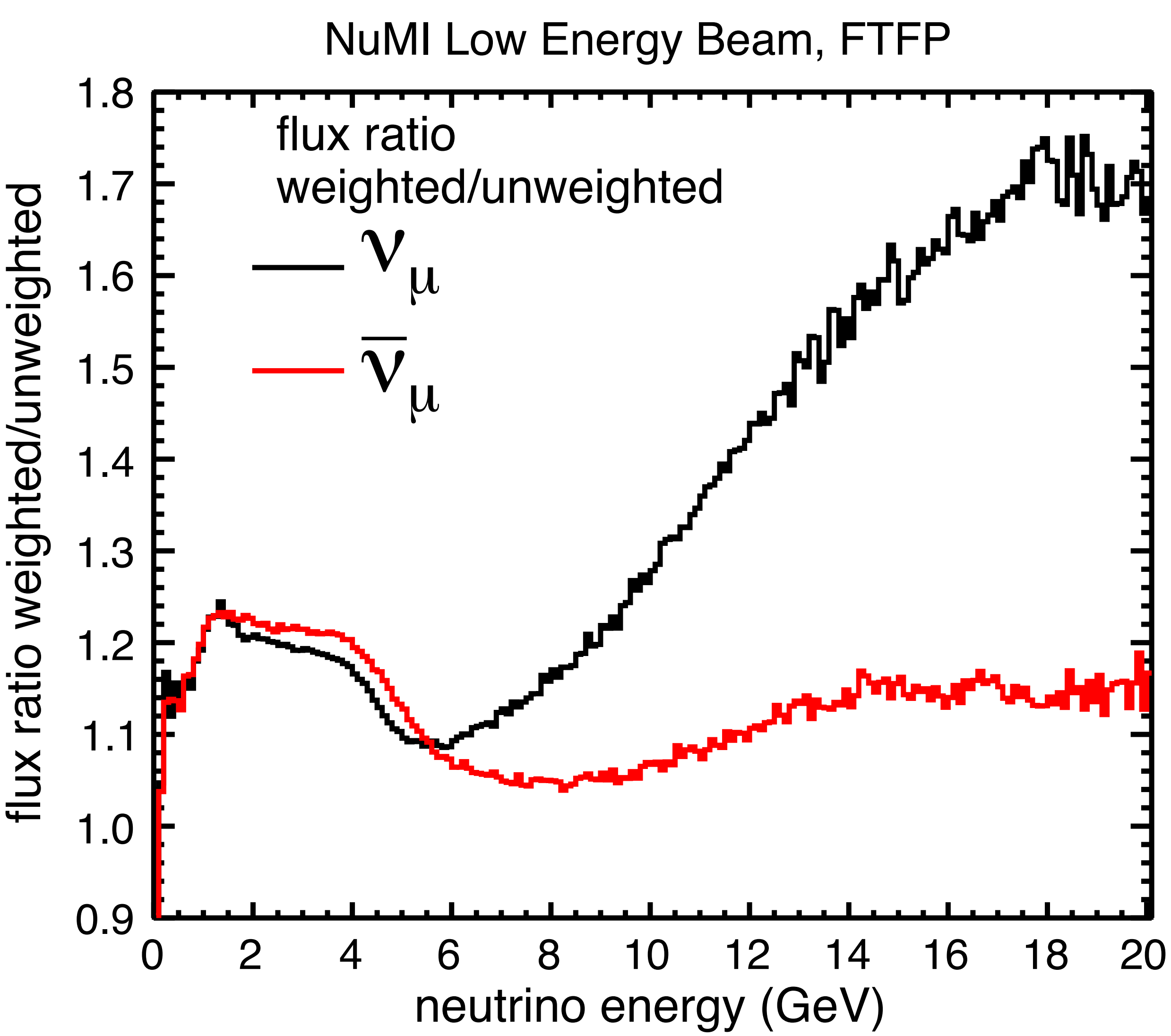
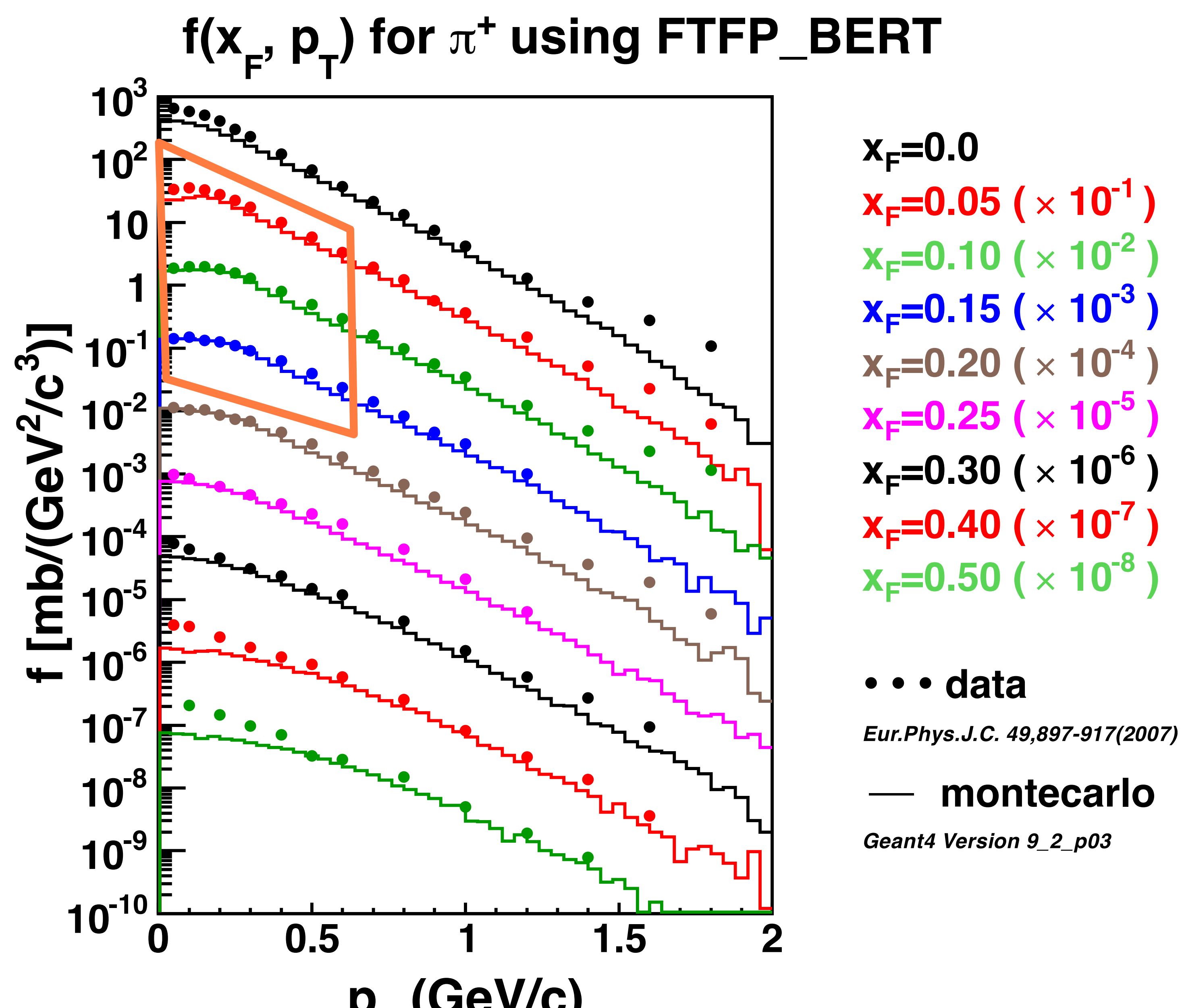
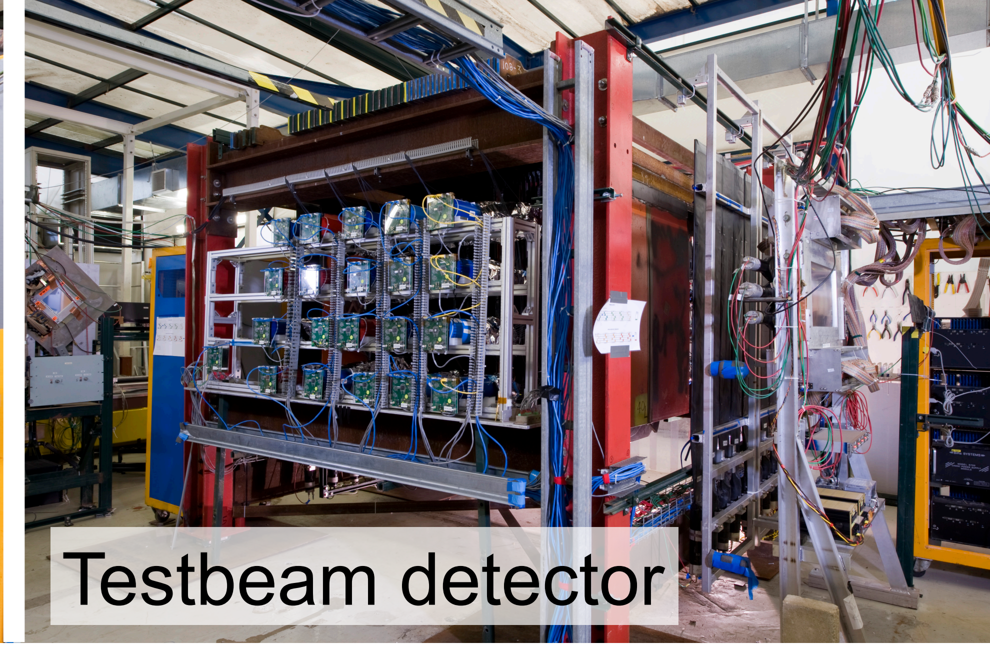


figure courtesy Ž. Pavlović

- Tune the hadron production spectrum (FTFP) to world data (mostly NA49 for MINERvA) and use experimental uncertainties in those regions. But, we cannot re-weight events with no matching (x_F, p_T) hadron production data.
  - The weights are the ratio of measured (NA49) cross sections to Geant4 predictions. Uncertainties outside this region are driven by model spread and are very large.
- Ideally we would tune the model to get agreement in the (x_F, p_T) region where we have data and this would likely provide better agreement in regions with no data.
  - *This would enable us to drive down uncertainties to the level reported by hadron production experiments.*



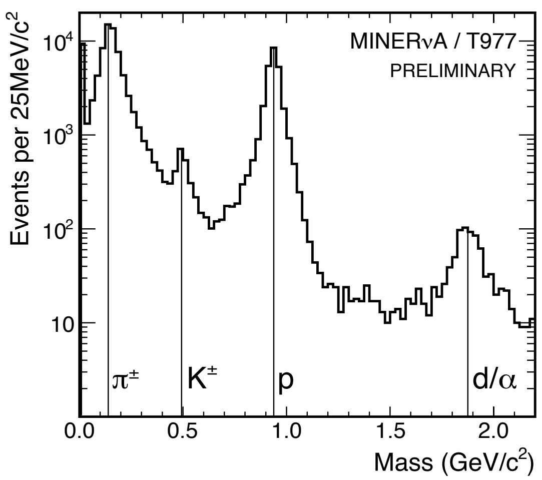


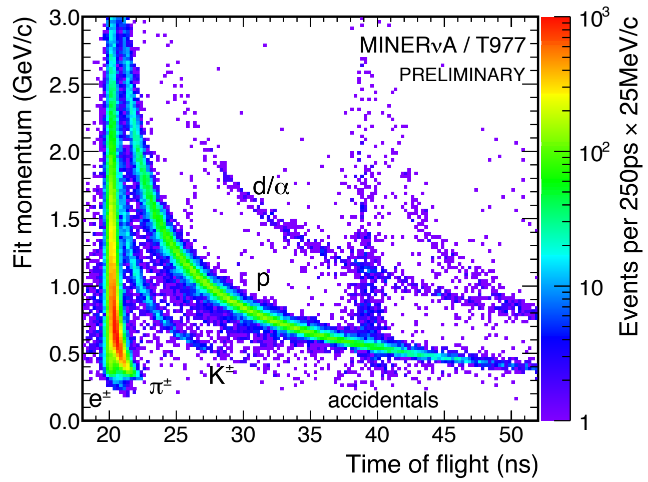


Detector Response

New tertiary beam at Fermilab Test Beam Facility

Delivers 400 < momentum < 2000 MeV/c hadrons,
designed and built by us and FTBF, available for future users.

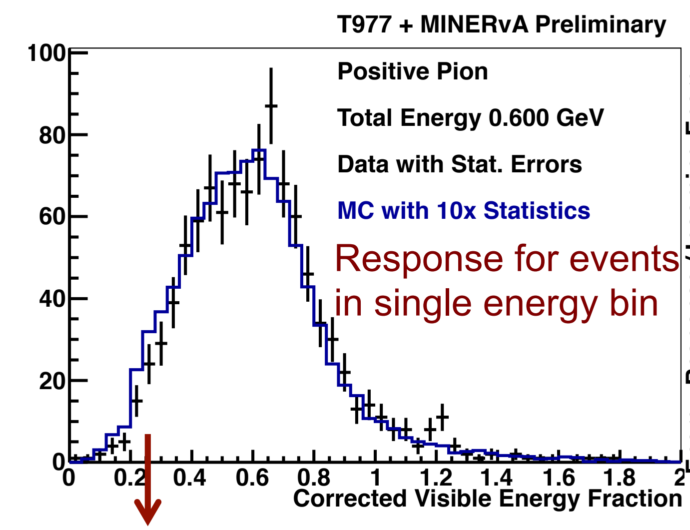


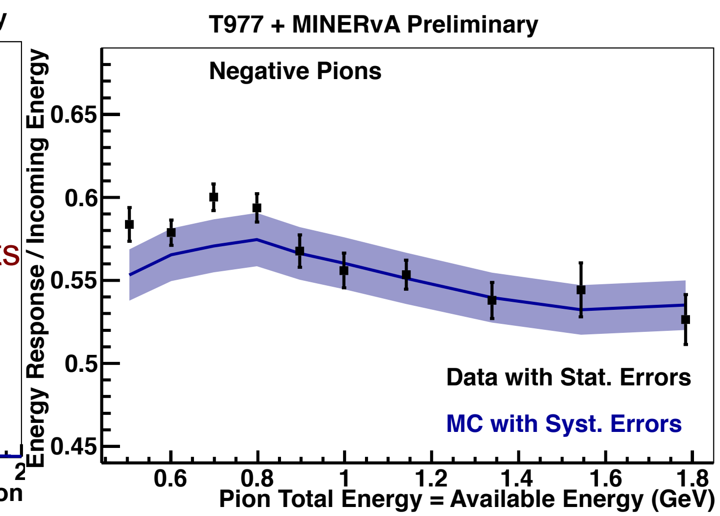


We ran a beam configuration that matched our large detector, wide in energy and wide in aperture.
This beam can be configured for narrow spectrometer beam
Design precision is 1% beamline 2% detector.
The as-measured particles also become input to our MC.

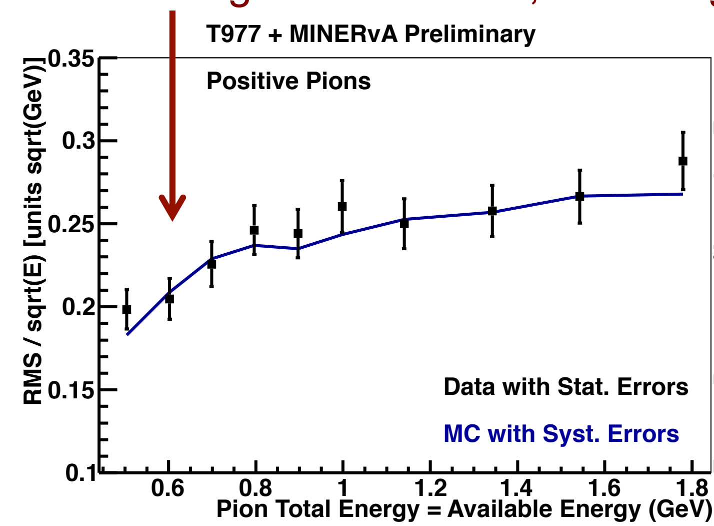
R. Gran, NuInt 2012

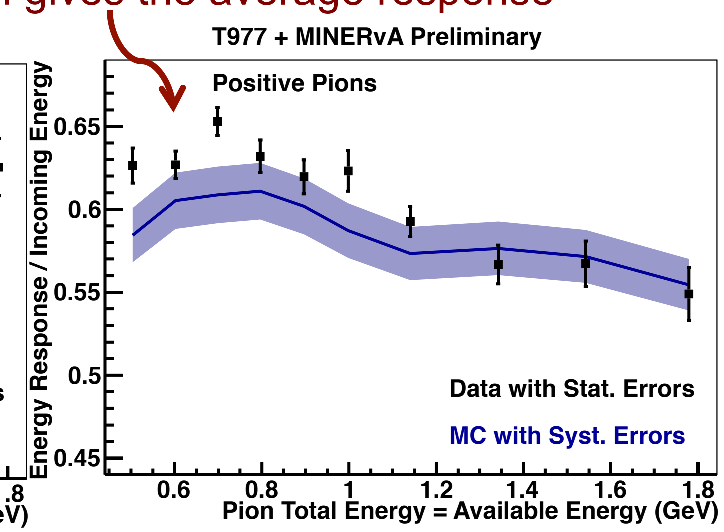
Pion calorimetry preliminary results





Width gives resolution, mean gives the average response

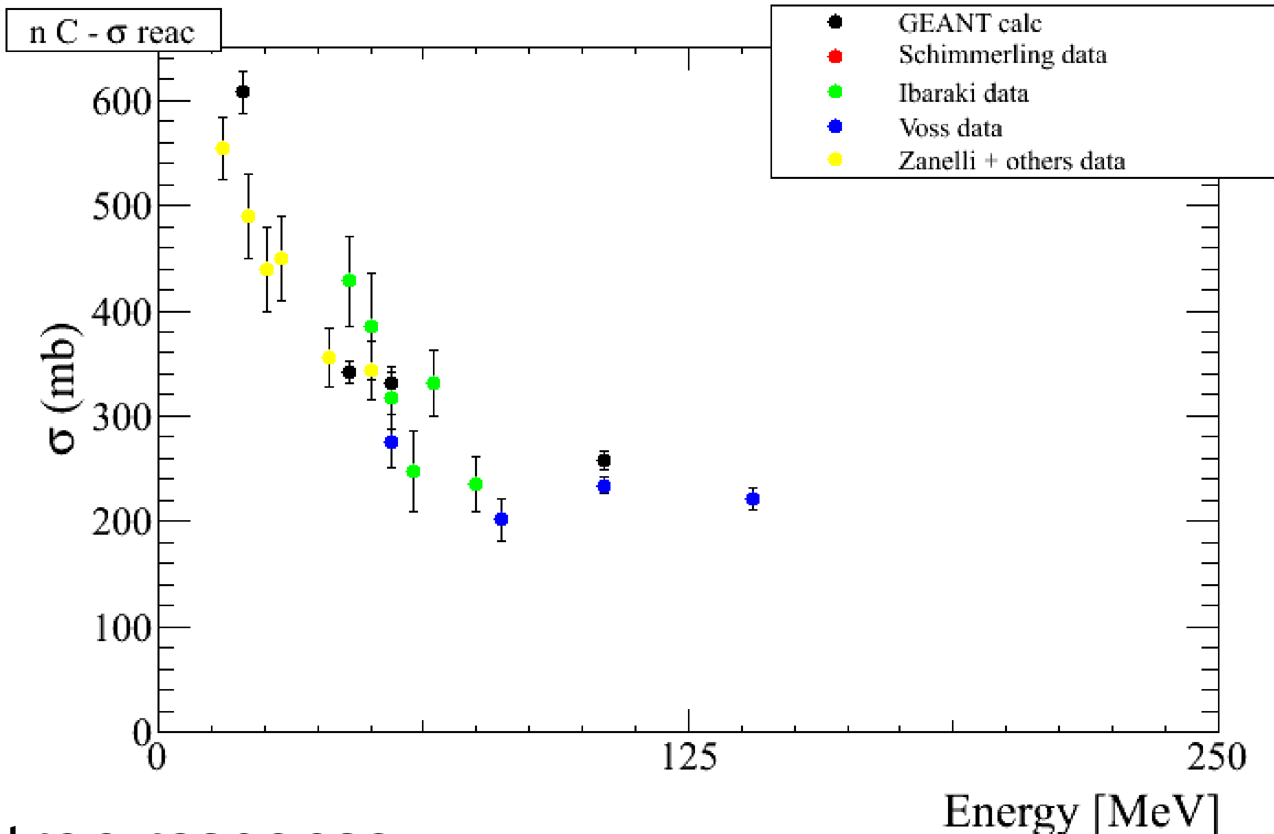


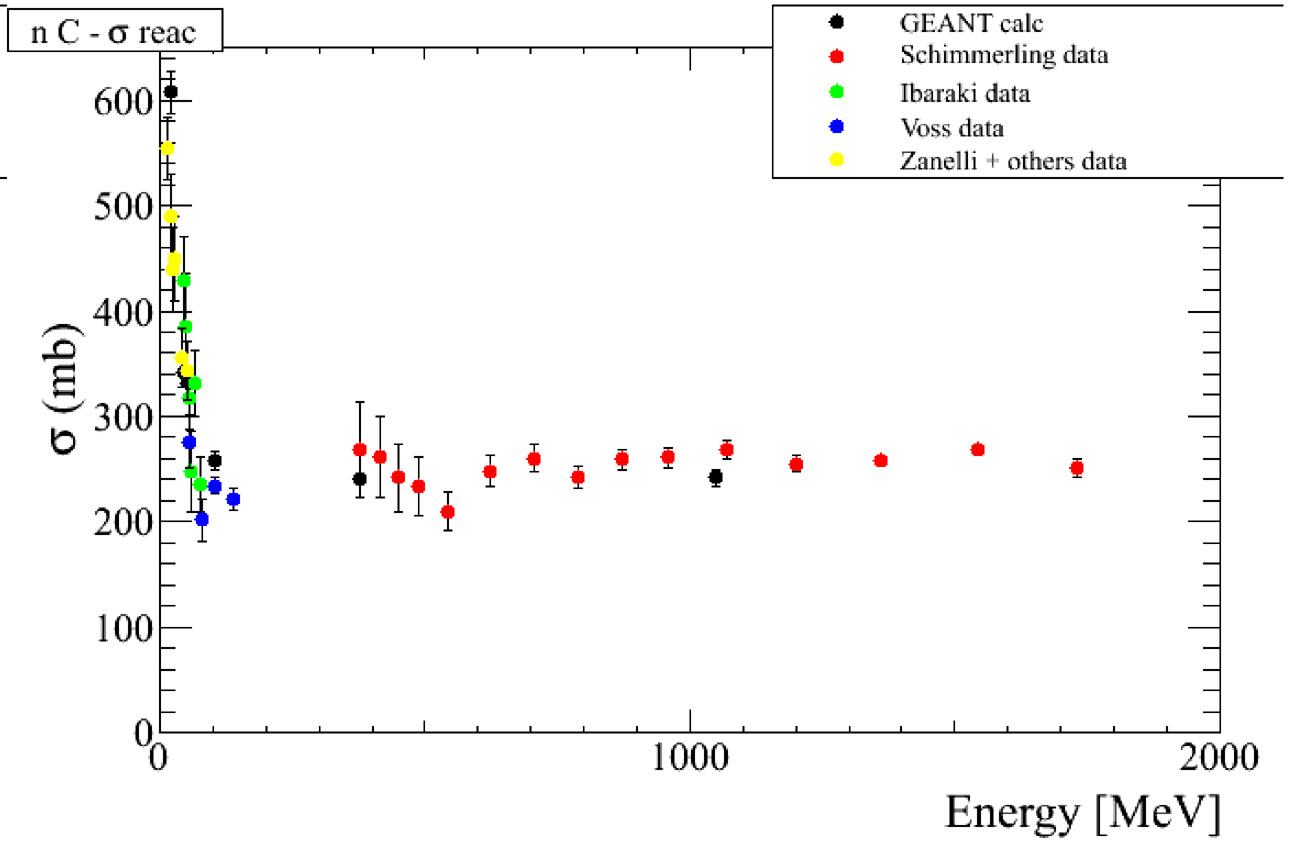


Status: preliminary result already part of neutrino analysis uncertainties,
finishing final calibrations of beamline and detector,
Also finishing proton calorimetry constraints.

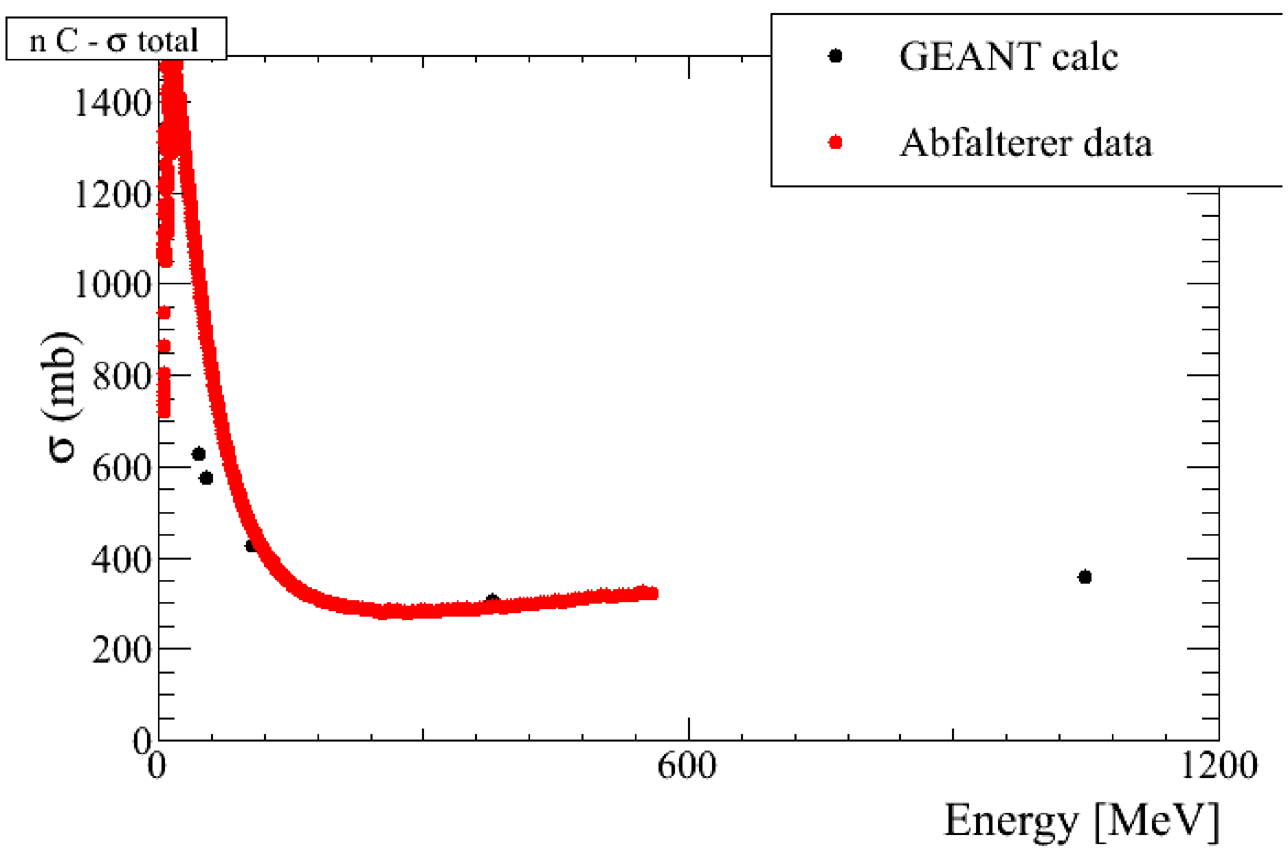
Gabriel N. Perdue

Detector Response: Neutrons





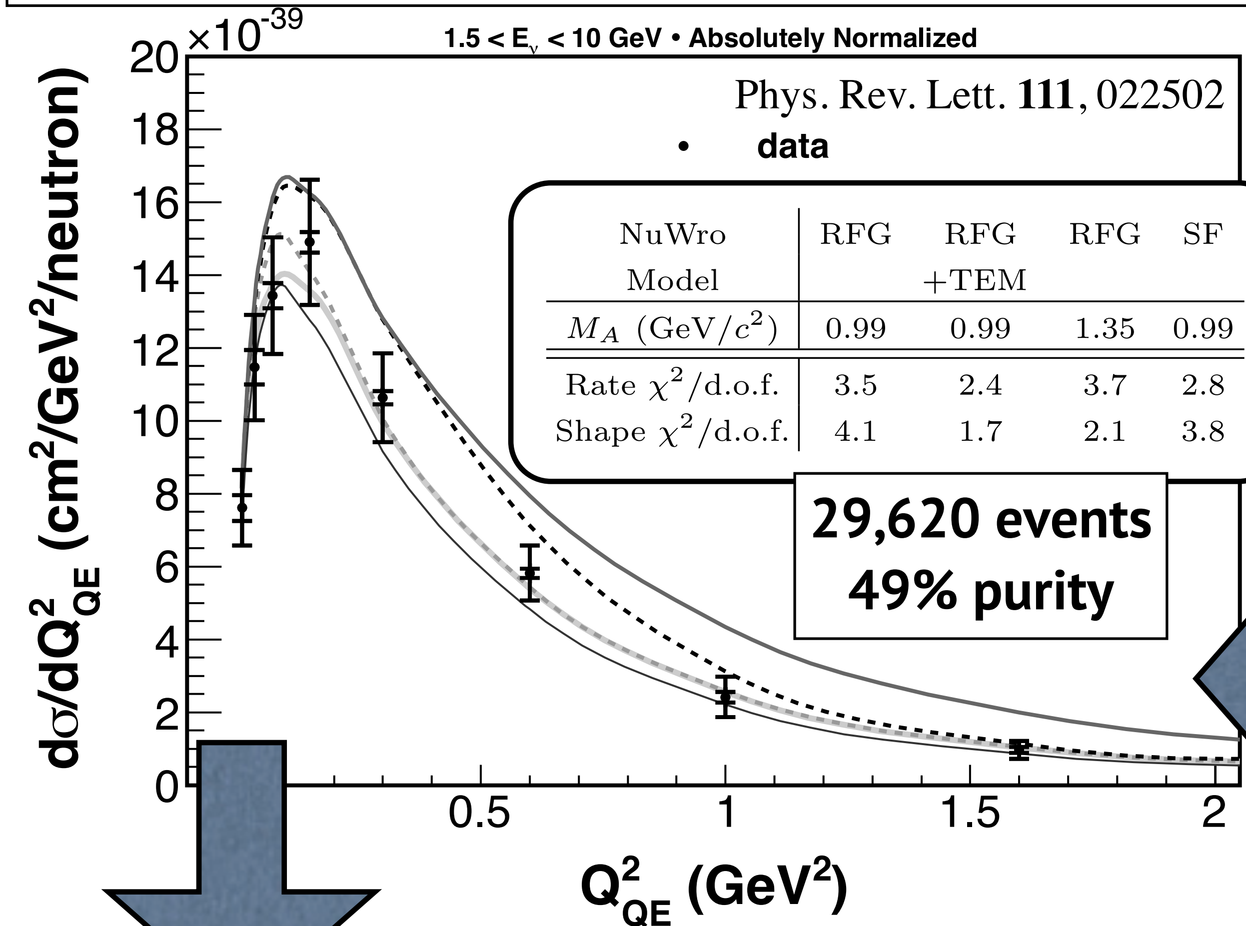
Neutron response uncertainty driven by comparison of GEANT4.9.4.p02 (MINERvA Official Version) and Data. (differences in the elastic cross-section at low energy; inelastic (top) looks quite close.)



Estimating Uncertainties on Detector Response

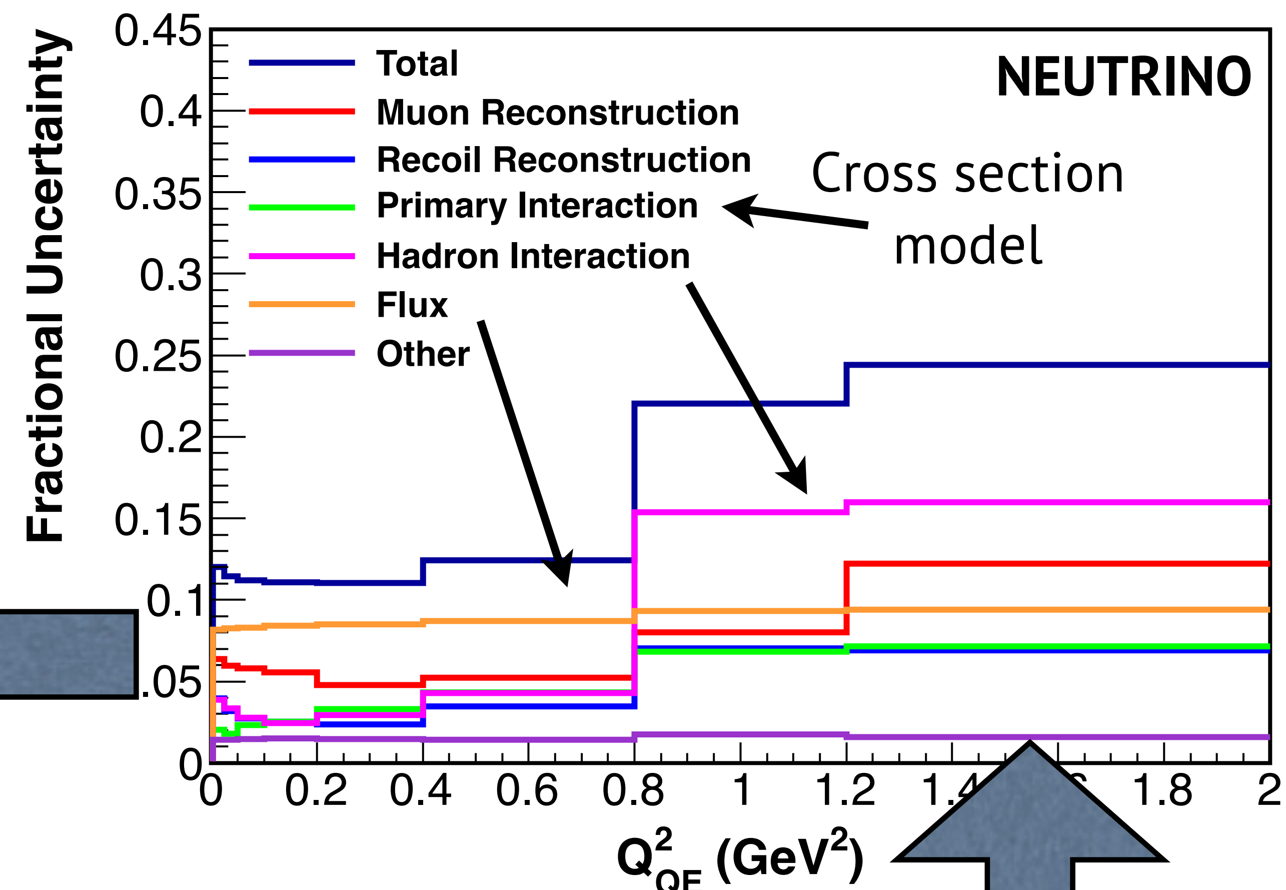
- Detector response uncertainties affect every aspect of constructing a signal sample.
- "Experiments are sometimes more concerned with uncertainties on the model than the central value of the model." (S. Oser, INT 2012, paraphrased)
- MINERvA detector uncertainties are driven by inspection of the disagreement between the simulation prediction and data (re-weighting obviously very difficult in this case).
- Questions we ask ourselves: *If we varied model parameters, would we be able to cover the discrepancies? Could we tune them away?* We are forced to err on the side of conservatism.

Cross Section Model Uncertainties: Background Subtraction (experiences with GENIE)

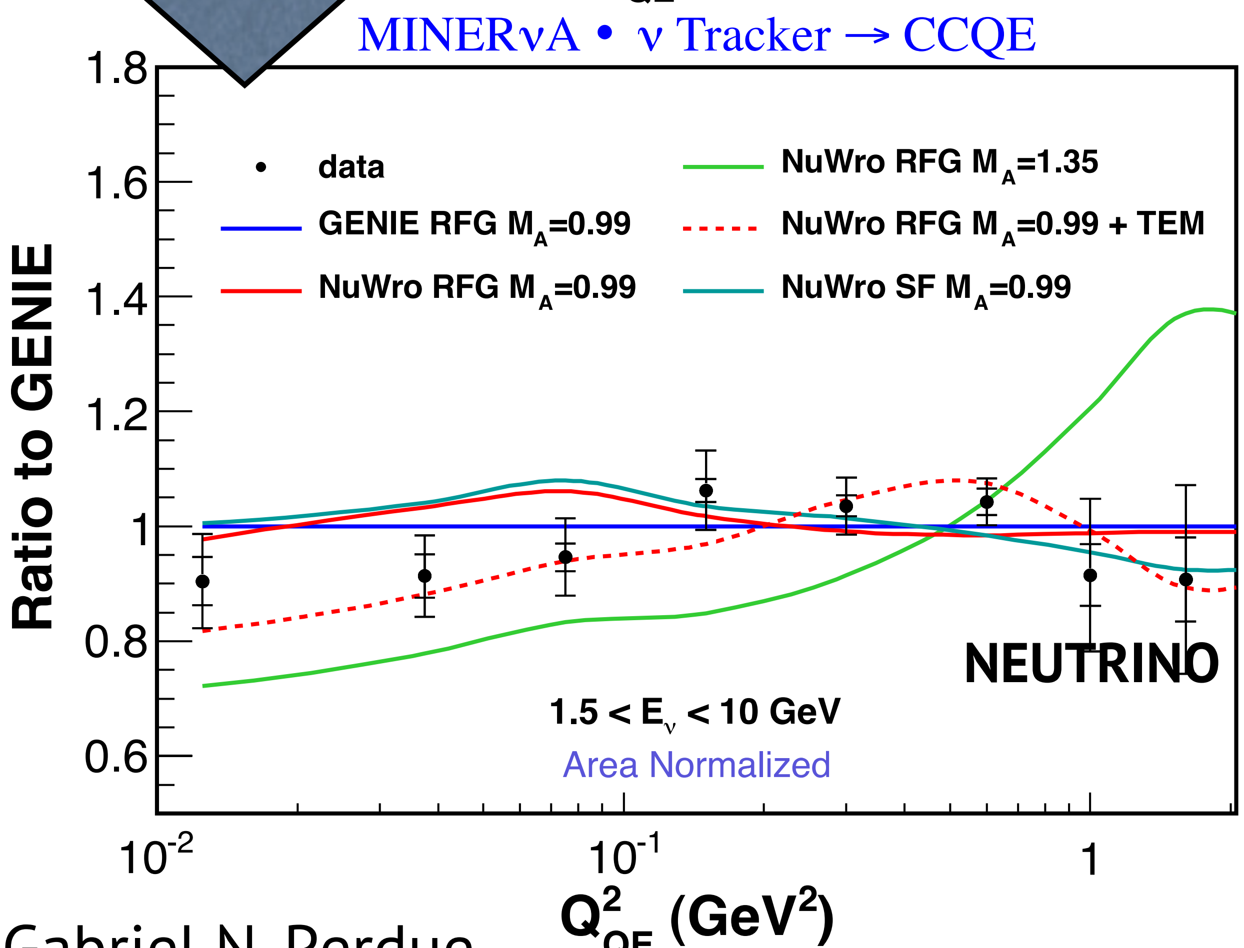


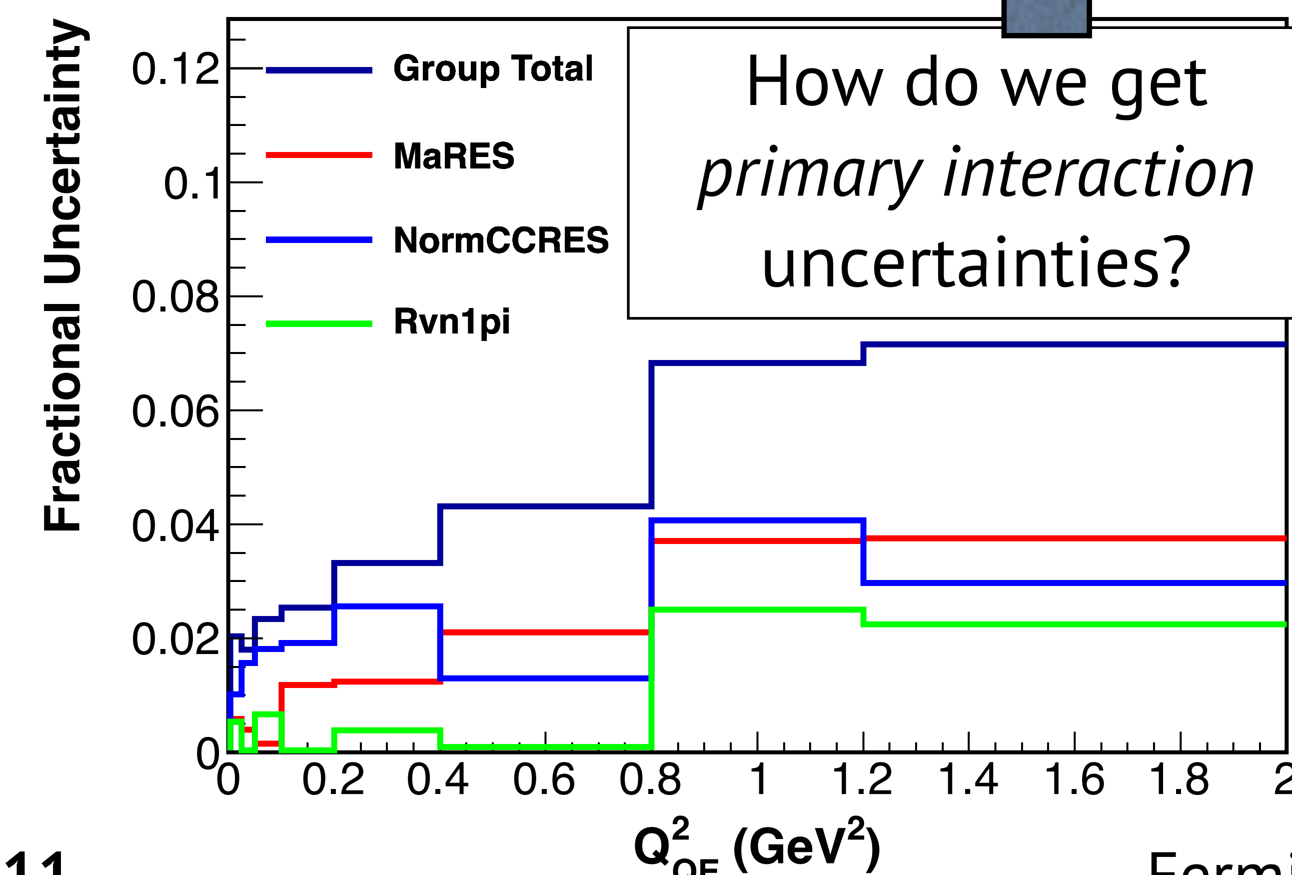
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

29,620 events
49% purity



Cross section model





How do we get *primary interaction* uncertainties?

Estimating Uncertainties on the Event Generator Predictions: An Example of Exposed Model Parameters

- It is the classic way:
  - We vary the MC (in this case, our event generator, GENIE) and "repeat the experiment."
  - For generators we can often "cheat" and re-weight directly (e.g., if we are changing a single cross section). Usually this means randomly varying a model parameter within its experimental uncertainties (or a range provided by theorists).
- For many uncertainties (e.g. hadronization model, formation zone, etc.), re-weighting won't work. *But exposed model parameters allows us to produce sensible "varied samples" which are used to build uncertainty bands.*

Conclusions

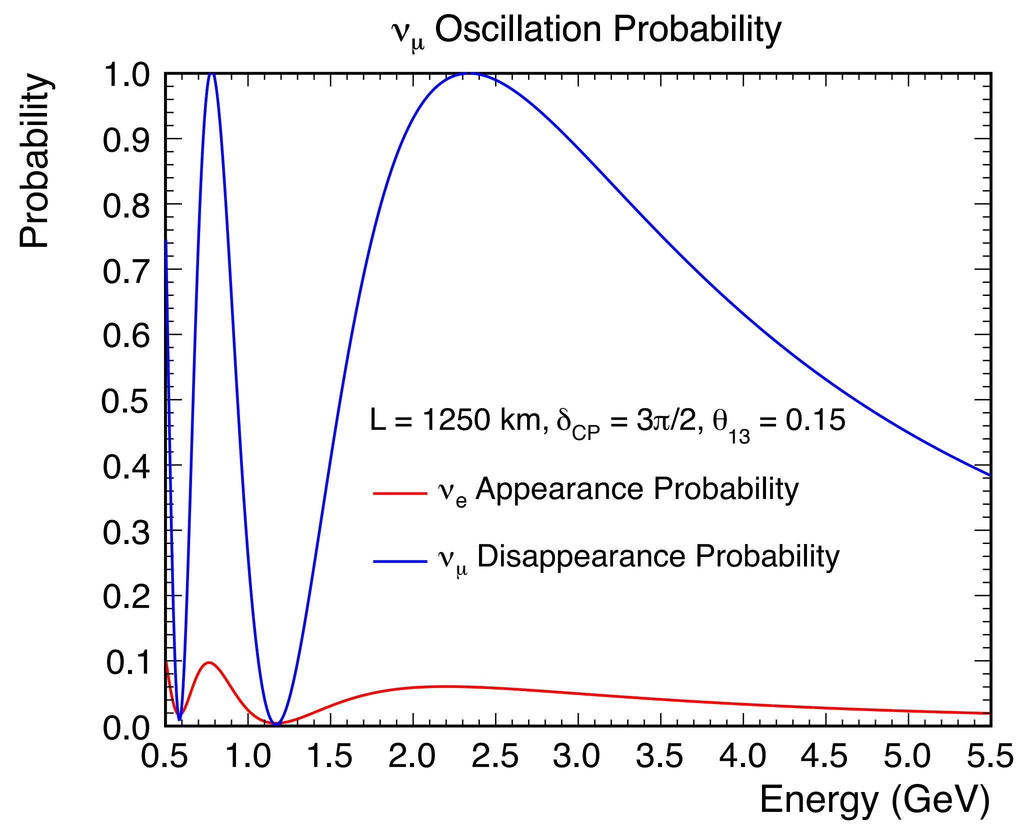
- Geant4 is an extremely important tool for neutrino experiments and the intensity frontier program.
- Neutrino experiments require very fine control over their systematic uncertainties, e.g. for cross sections, sterile neutrino searches, and attempts to measure CP violation, etc.
- Exposing Geant4 model parameters, where appropriate, providing guidance about their meaning, and making it simple for experiments to tune them can help experiments achieve these goals.

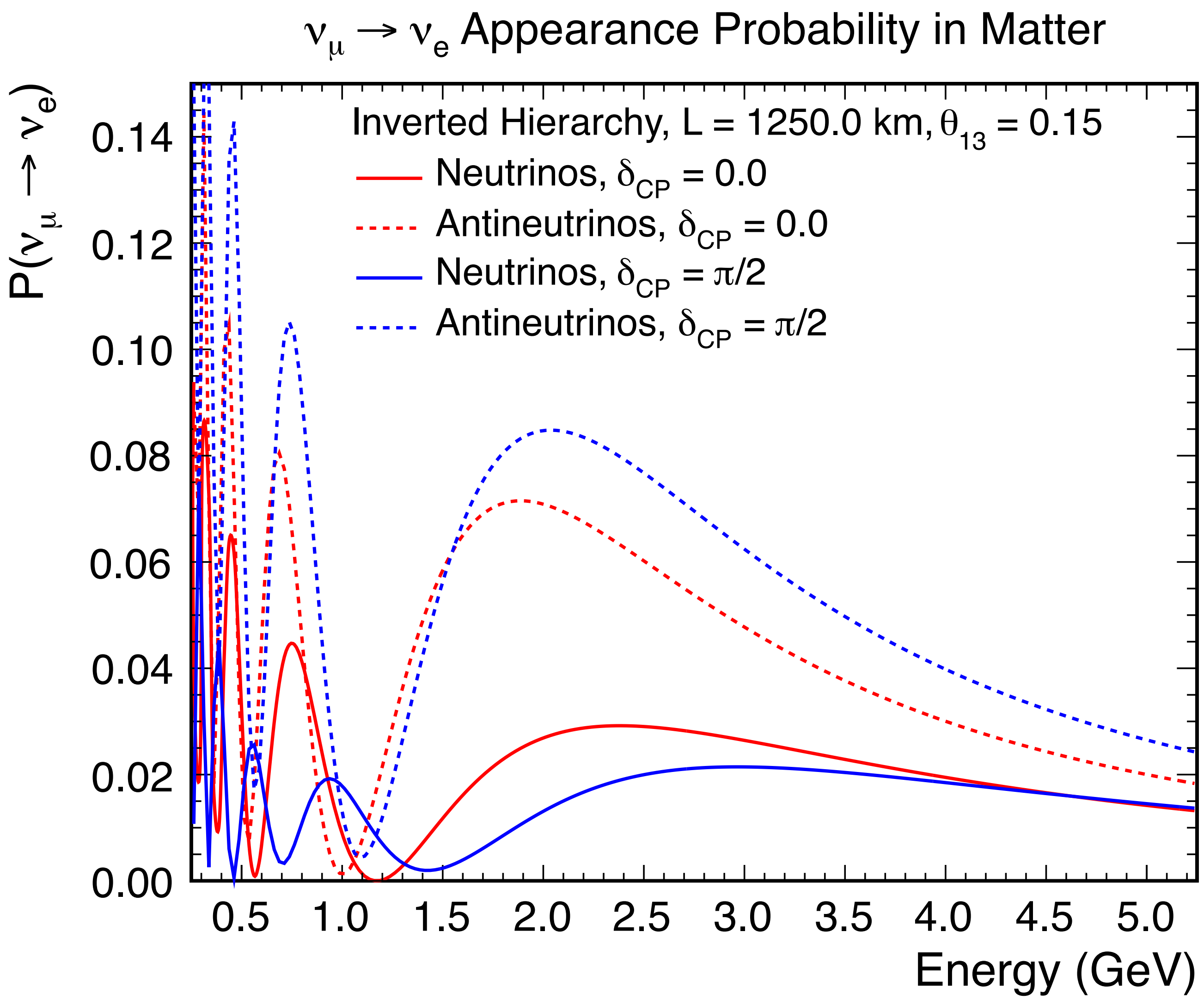
Thank you for listening and thanks for Geant4!

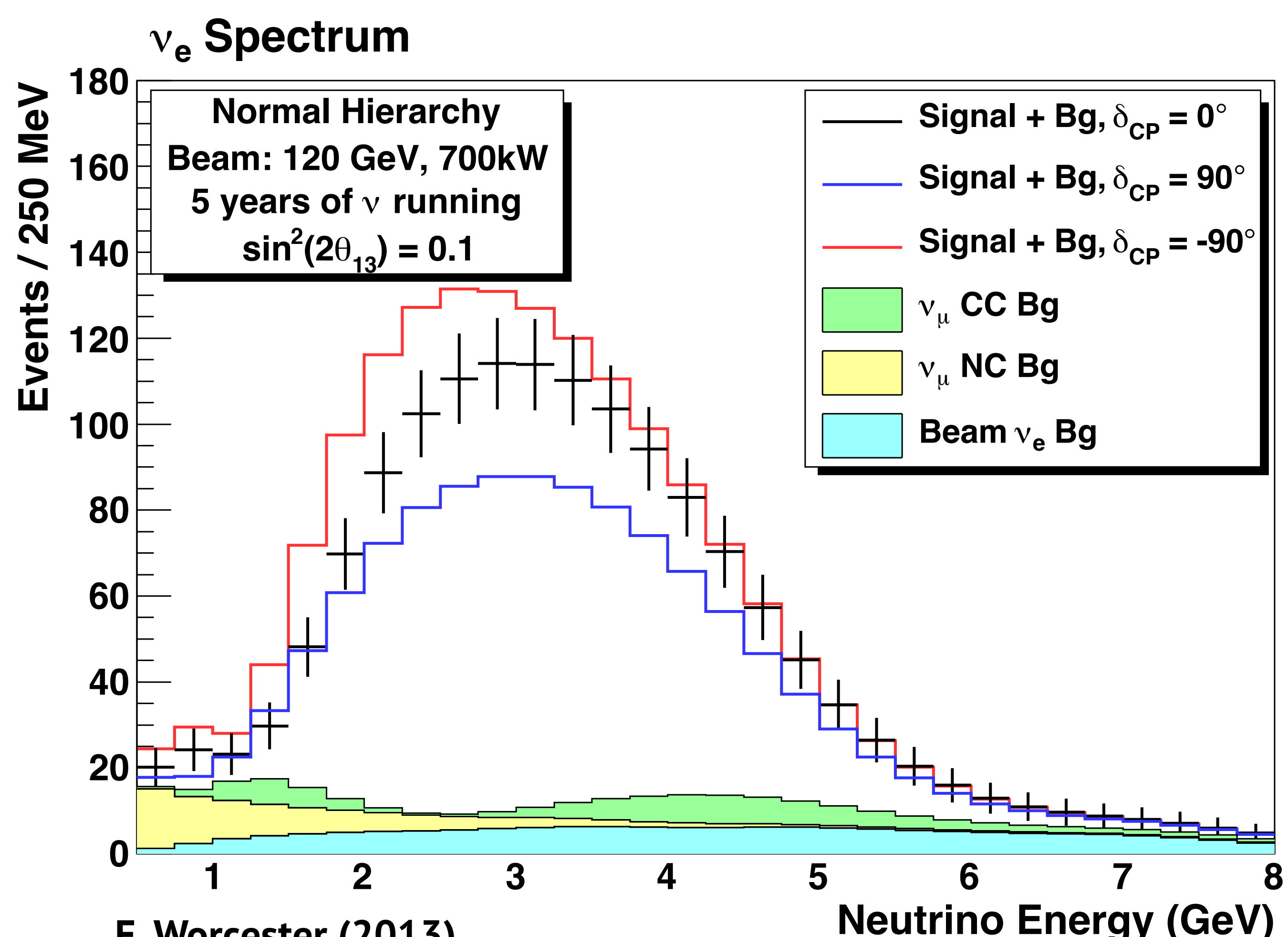
Back-Up

How much do these uncertainties matter?

- For neutrino CP-violation measurements, they are important.
- Neutrino and antineutrino measurement are not completely independent efforts, but there are important flux and final state differences.







E. Worcester (2013)

TABLE XVI: Summary of the contributions to the total uncertainty on the predicted number of events, assuming $\sin^2 2\theta_{13}$=0 and $\sin^2 2\theta_{13}$=0.1, separated by sources of systematic uncertainty. Each error is given in units of percent.

Error source	$\sin^2 2\theta_{13}$= 0	0.1
Beam flux & ν int. (ND280 meas.)	8.5	5.0
ν int. (from other exp.)		
$x_{CCother}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
x^{CCcoh}	0.2	0.2
x^{NCcoh}	2.0	0.6
$x^{NCother}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
W_{eff}	1.9	0.8
$x_{\pi-less}$	0.5	3.2
$x_{1\pi E_\nu}$	2.4	2.0
Final state interactions	2.9	2.3
Far detector	6.8	3.0
Total	13.0	9.9

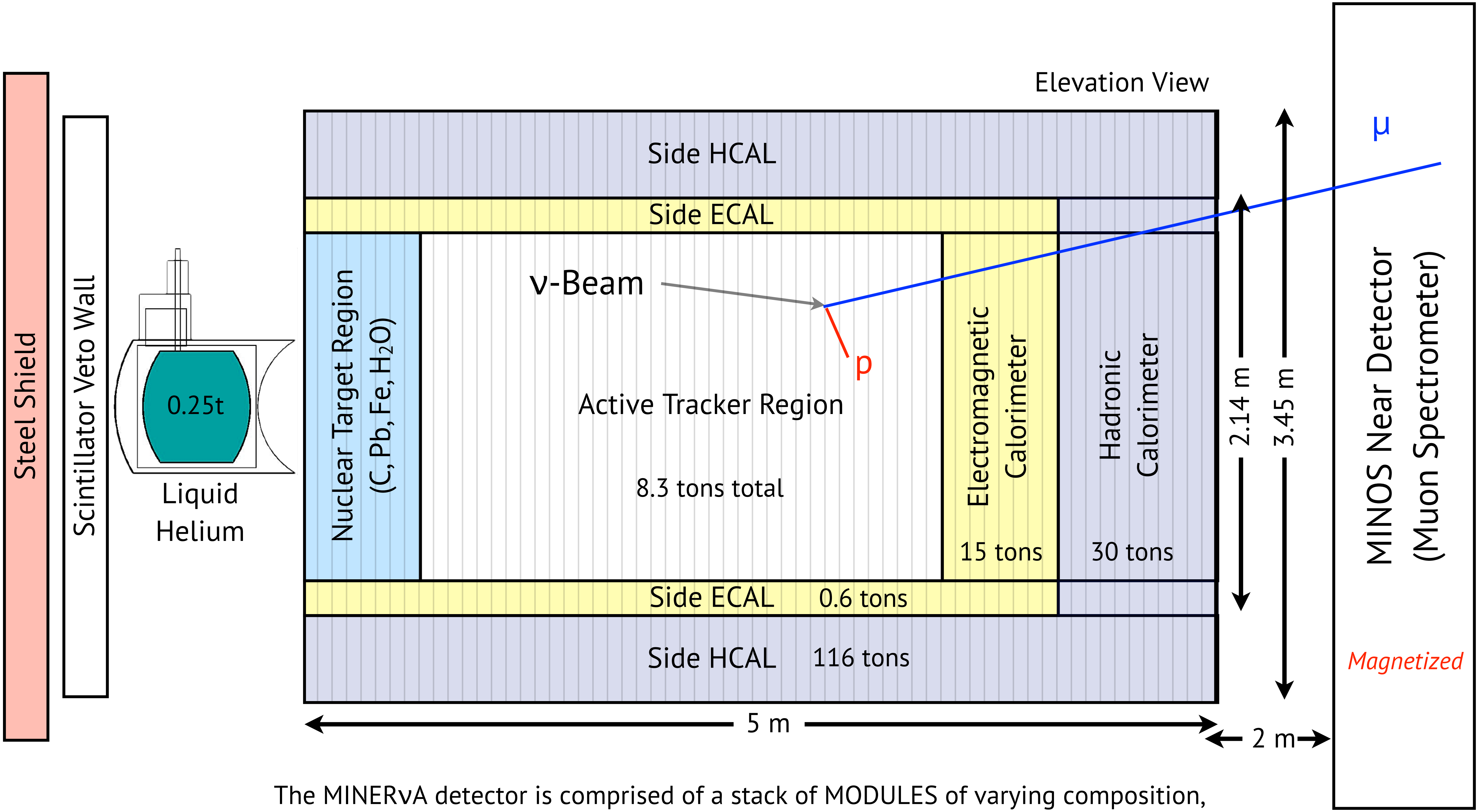
K. Abe et al, arXiv 1304.0841

Overview of the T2K experiment, where a high intensity beam of ν_μ is created at Tokai and sent 300 km under ground to the water Cherenkov detector Super-Kamiokande.

CCQE Cross Section	
M_A^{QE}	The mass parameter in the axial dipole form factor for quasi-elastic interactions
x_1^{QE}	The normalization of the quasi-elastic cross section for $E_\nu < 1.5$ GeV
x_2^{QE}	The normalization of the quasi-elastic cross section for $1.5 < E_\nu < 3.5$ GeV
x_3^{QE}	The normalization of the quasi-elastic cross section for $E_\nu > 3.5$ GeV
Nuclear Model for CCQE Interactions (separate parameters for interactions on O and C)	
x_{SF}	Smoothly changes from a relativistic Fermi gas nuclear model to a spectral function model
p_F	The Fermi surface momentum in the relativistic Fermi gas model
Resonant Pion Production Cross Section	
M_A^{RES}	The mass parameter in the axial dipole form factor for resonant pion production interactions
$x_1^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu < 2.5$ GeV
$x_2^{CC1\pi}$	The normalization of the CC resonant pion production cross section for $E_\nu > 2.5$ GeV
$x^{NC1\pi^0}$	The normalization of the NC1π^0 cross section
$x_{1\pi E_\nu}$	Varies the energy dependence of the 1π cross section for better agreement with MiniBooNE data
W_{eff}	Varies the distribution of $N\pi$ invariant mass in resonant production
$x_{\pi-less}$	Varies the fraction of Δ resonances that decay or are absorbed without producing a pion
Other	
$x^{CCcoh.}$	The normalization of CC coherent pion production
$x^{NCcoh.}$	The normalization of NC coherent pion production
$x^{NCother}$	The normalization of NC interactions other than NC1π^0 production
$x_{CCother}$	Varies the CC multi-π cross section normalization, with a larger effect at lower energy
$\vec{x}_{FSI}$	Parameters that vary the microscopic pion scattering cross sections used in the FSI model
x_{ν_e/ν_μ}	Varies the ratio of the CC ν_e and ν_μ cross sections

- Cross-section and interaction uncertainties (especially the nuclear physics model) are a significant part of the total error budget, even with constraints from a Near Detector!

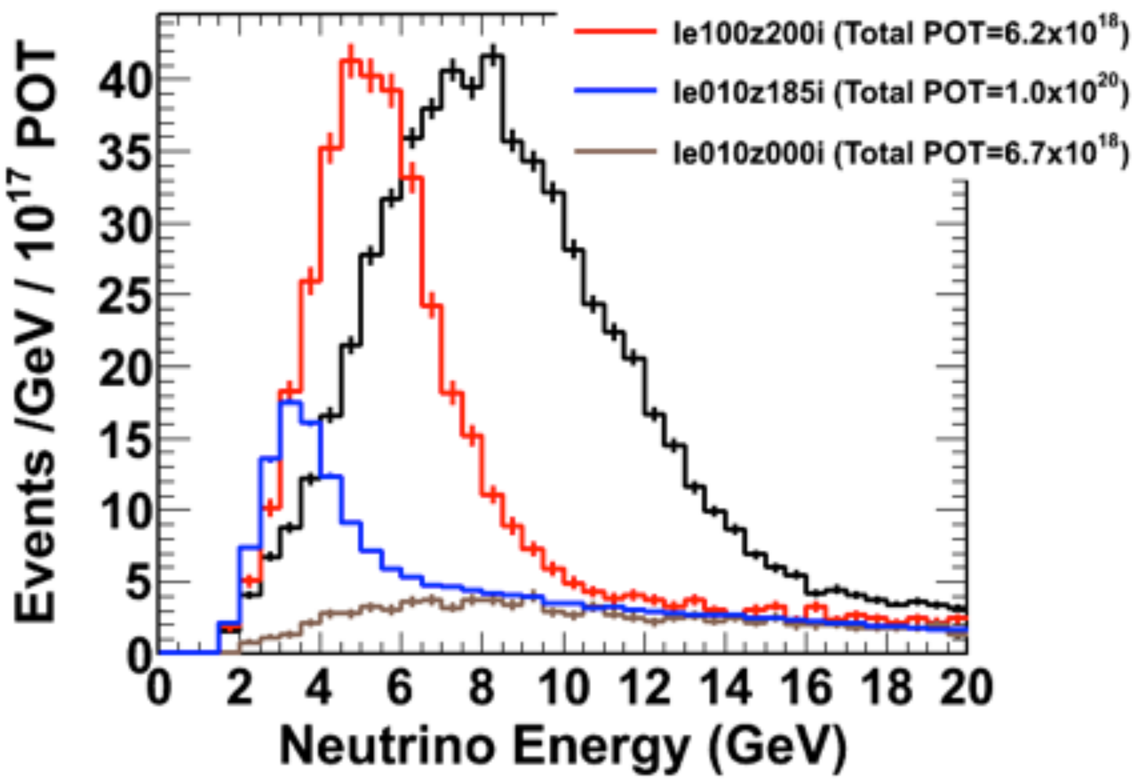
The Best Thing Since Sliced Bread...

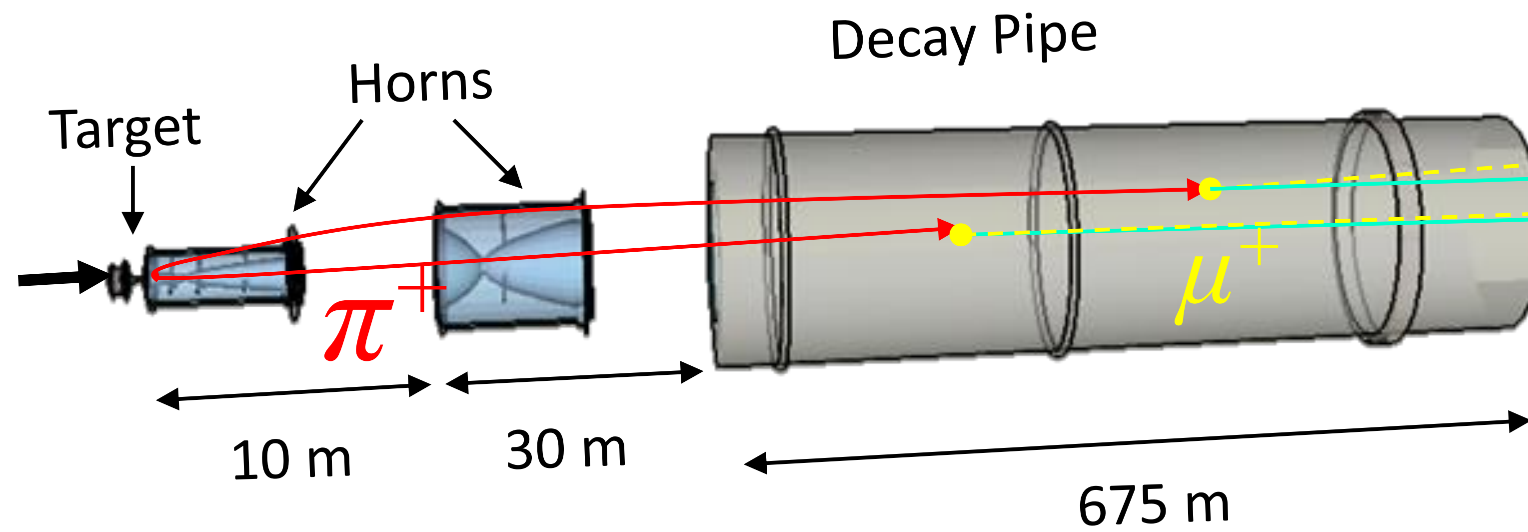


The MINERνA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).

Beam Flux

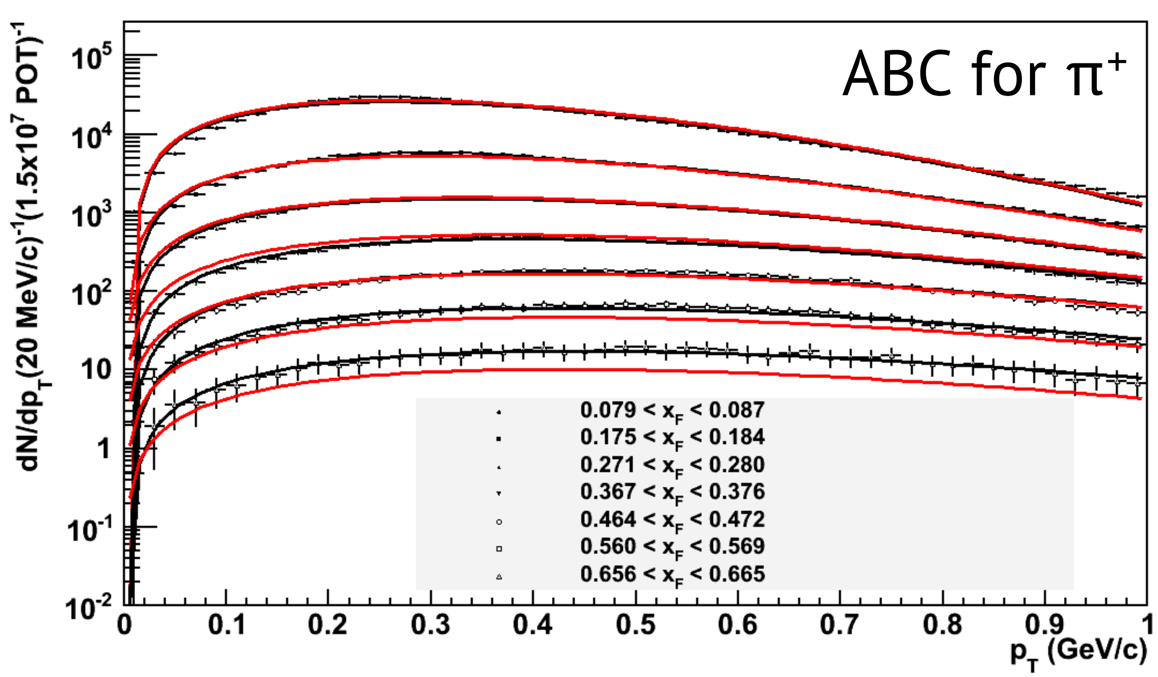
"Special Runs"





Vary target position and horn current.

$$\frac{d^2N}{dx_F\,dp_T}=[A(x_F)+B(x_F)\,p_T+D(x_F)\,p_T^2]\,e^{-C(x_F)\,p_T^{E(x_F)}}$$



Dots: FTFP
Solid: ABC
Solid: Parameterized ABC