Fermilab

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Physics Modeling: FNAL Neutrino Experiments

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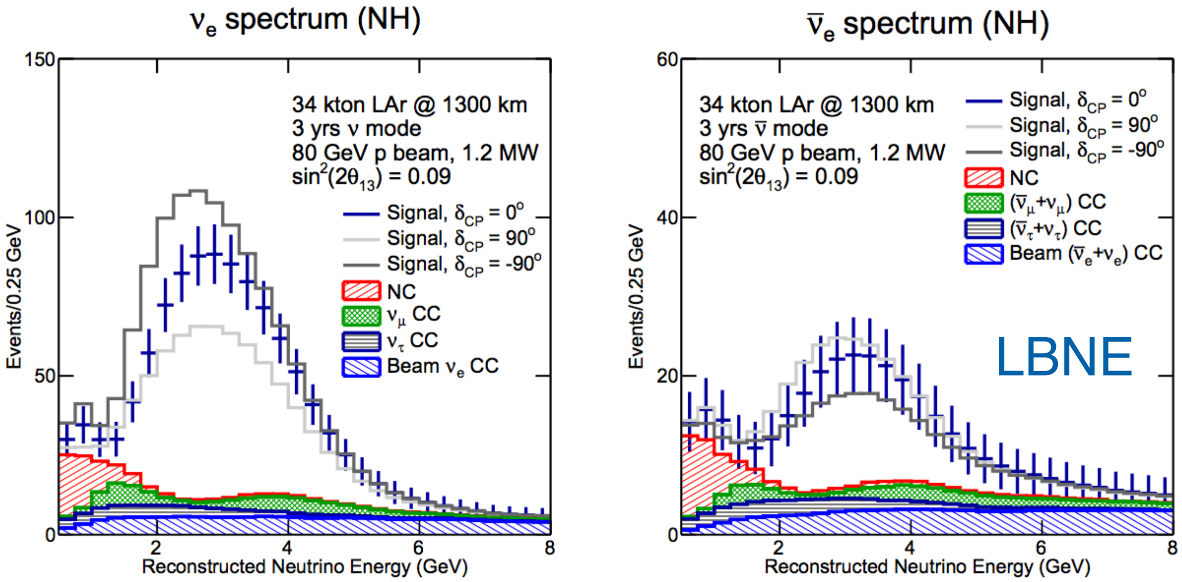
HEP CWP Detector Simulation Working Group Meeting

22 May 2017

Introduction

- Many of the goals of the Fermilab neutrino program involve measuring neutrino oscillations:



Measuring oscillations involves comparing observed spectra with predictions given different oscillation scenarios

$$N_{\nu_e}(E_\nu) = \phi_{\nu_\mu} \times \sigma(\nu_e) \times \epsilon(\nu_e) \times P\left(\nu_\mu \to \nu_e\right)$$ ← **Oscillation Probability**

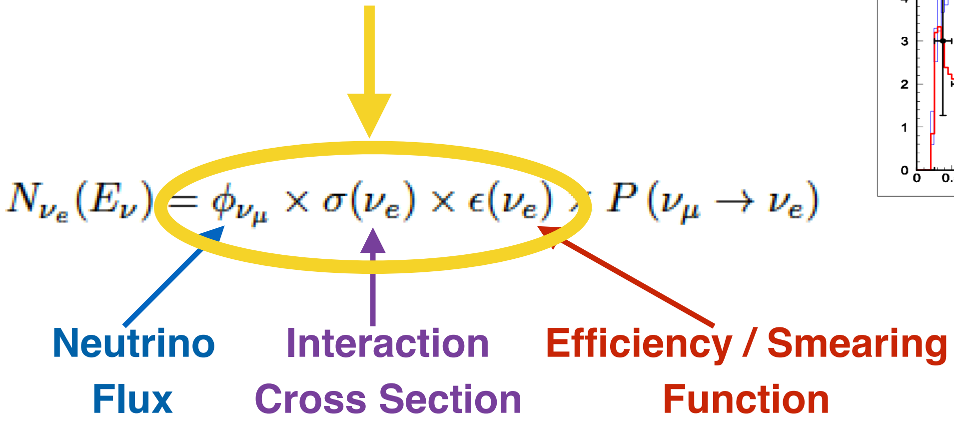
Neutrino Flux

Interaction Cross Section

Efficiency / Smearing Function

Introduction

An accurate "detector" physics modeling is needed for all of these



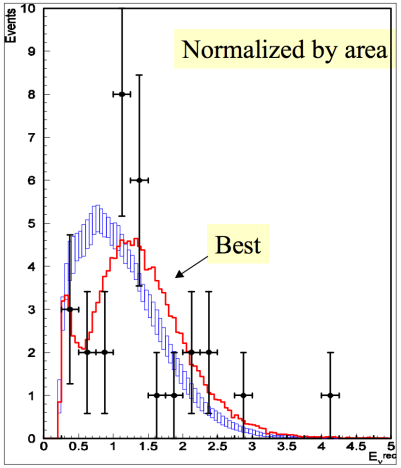
$$N_{\nu_e}(E_\nu) = \phi_{\nu_\mu} \times \sigma(\nu_e) \times \epsilon(\nu_e) \times P(\nu_\mu \to \nu_e)$$

Neutrino Flux

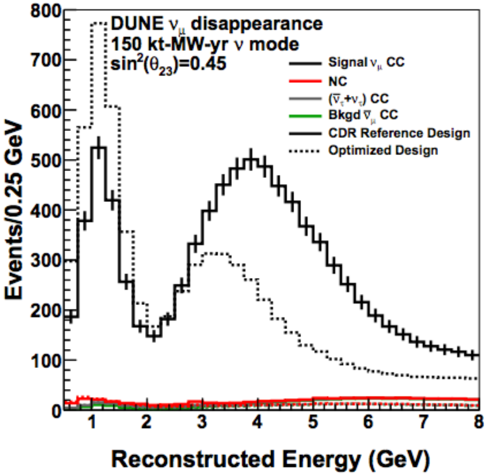
Interaction Cross Section

Efficiency / Smearing Function

And the required accuracy is changing as accelerator-based oscillation experiments become systematics dominated



K2K @ Neutrino 2002
Koichiro Nishikawa

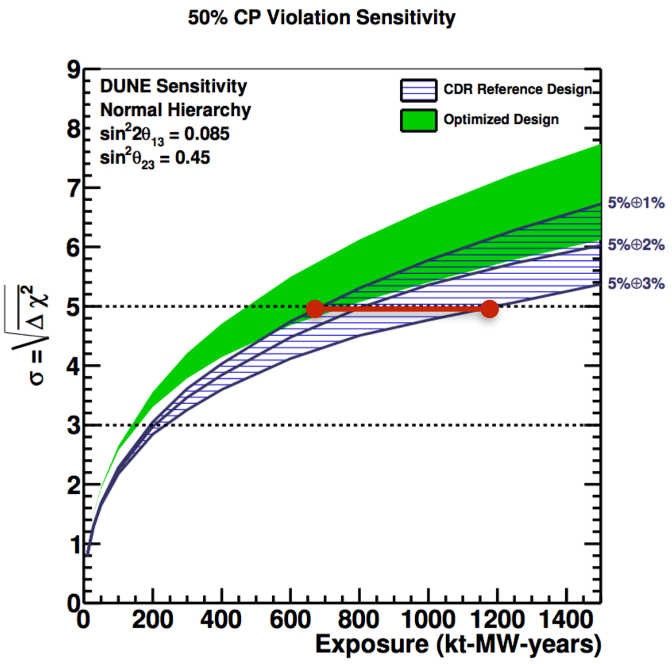


DUNE in ~2030

arXiv:1512.06148

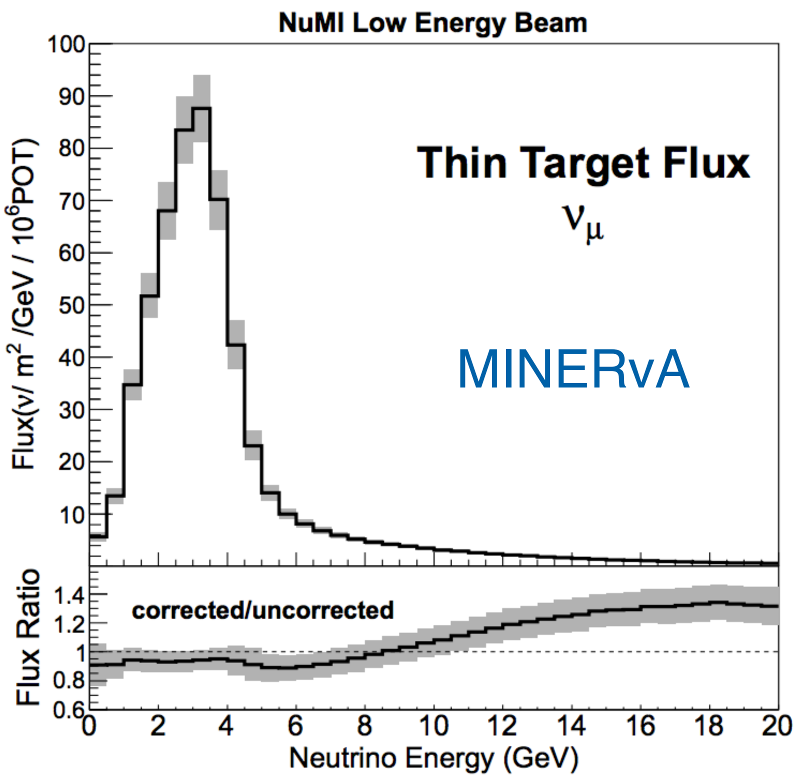
Introduction

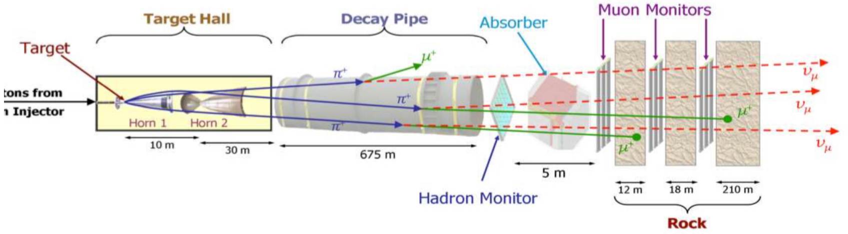
- For DUNE, difference between 3% vs 1% relative signal normalization uncertainty **equivalent to nearly doubling exposure** time for some figures of merit
- We will **need unprecedented precision in models** of beams, physics, and detectors



DUNE's physics reach will strongly depend on how low we are able to push systematic uncertainties, many of which will come from Detector/Beam modeling

Beam Simulation



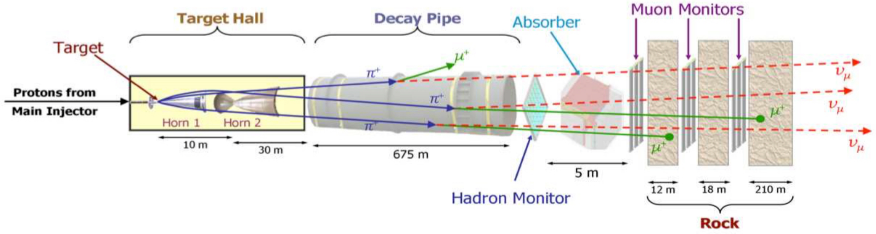


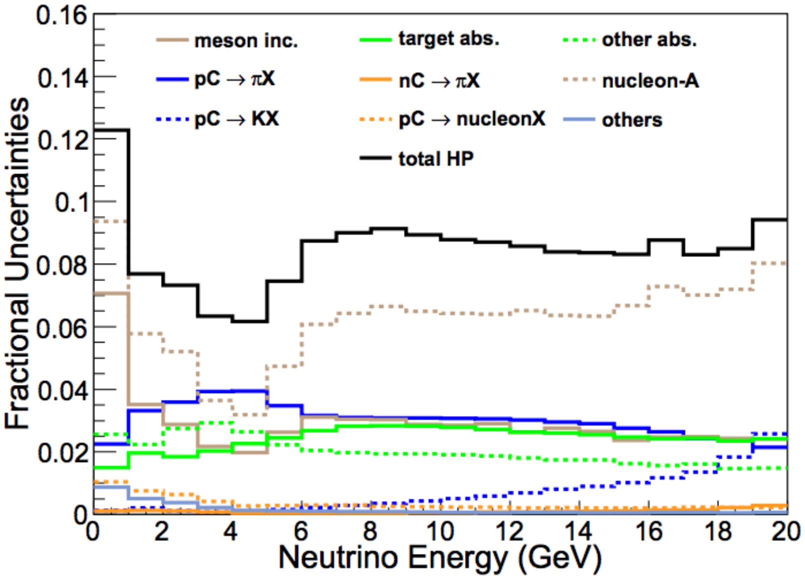
- neutrino flux simulations require very detailed simulations of neutrino beamline
- Critical processes: 8-120 GeV proton interactions on carbon
- Reinteractions of pions, protons, neutrons, kaons in Carbon and other beam materials (Al, Be, Fe, …)

$$N_{\nu_e}(E_\nu) = \phi_{\nu_\mu} \times \sigma(\nu_e) \times \epsilon(\nu_e) \times P(\nu_\mu \to \nu_e)$$

Neutrino Flux

Beam Simulation



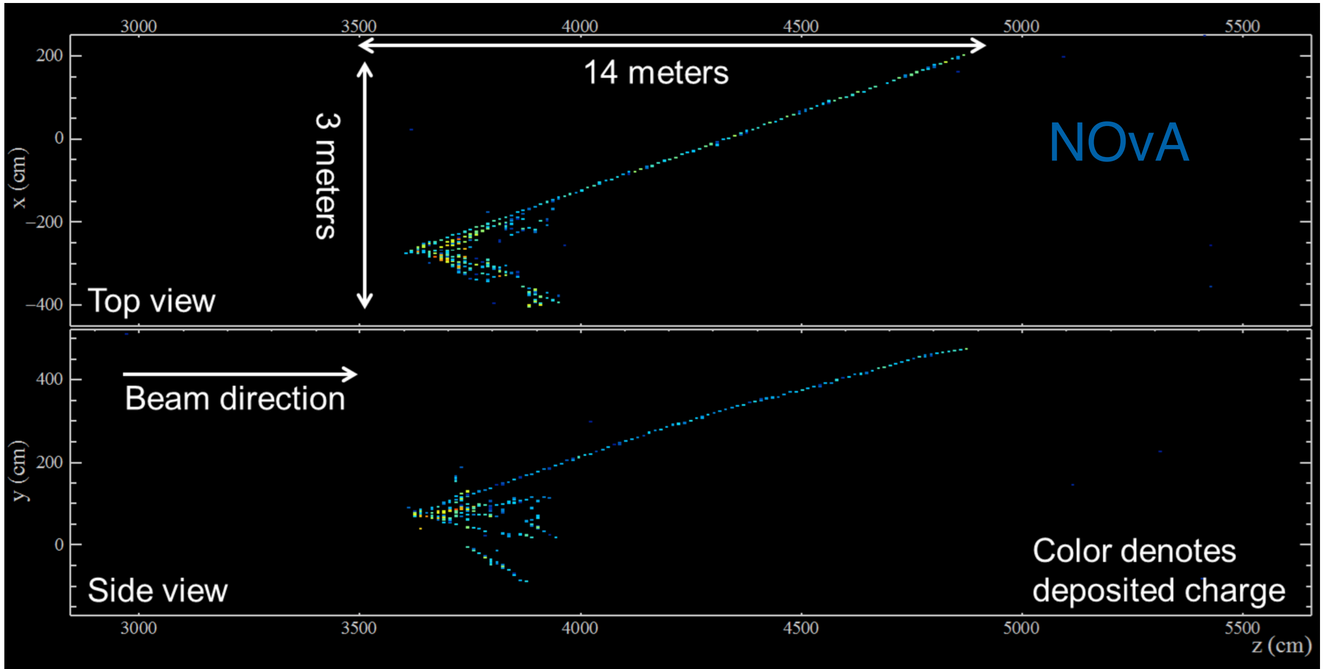


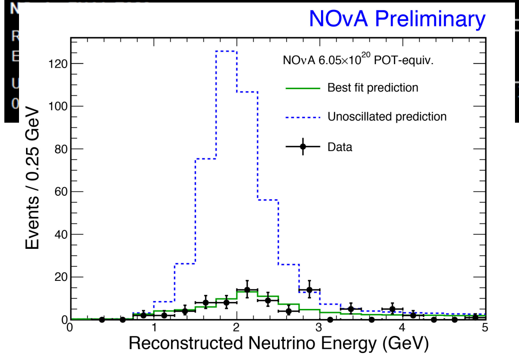
- Geant simulations require corrections to neutrino flux of up to 40% based on external data
- After correction, flux uncertainties are ~10%

$$N_{\nu_e}(E_\nu) = \boxed{\phi_{\nu_\mu}} \times \sigma(\nu_e) \times \epsilon(\nu_e) \times P(\nu_\mu \rightarrow \nu_e)$$

Neutrino Flux

Detector Simulation



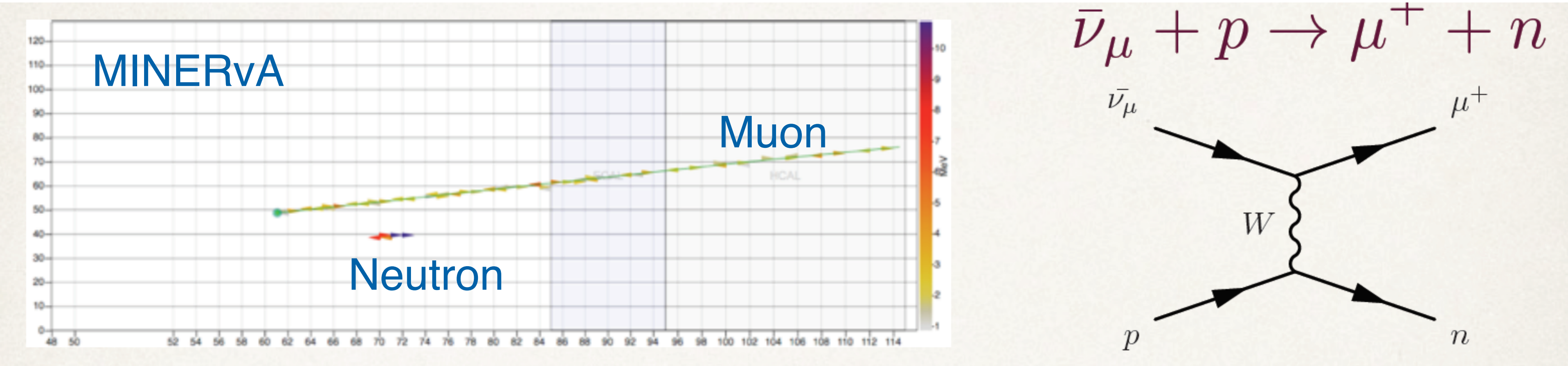


We depend on Geant modeling of our detectors to estimate efficiency and smearing; extremely important to neutrino energy reconstruction

$$N_{\nu_e}(E_\nu) = \phi_{\nu_\mu} \times \sigma(\nu_e) \times \epsilon(\nu_e) \times P(\nu_\mu \to \nu_e)$$

Efficiency / Smearing Function

Detector Simulation

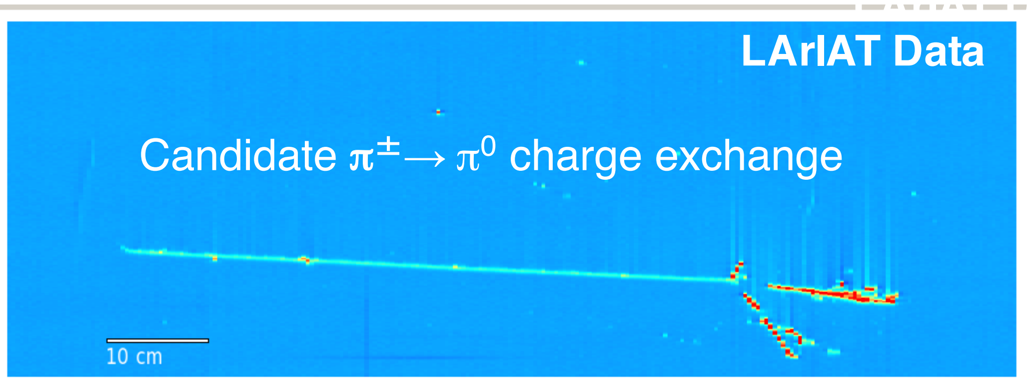


$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

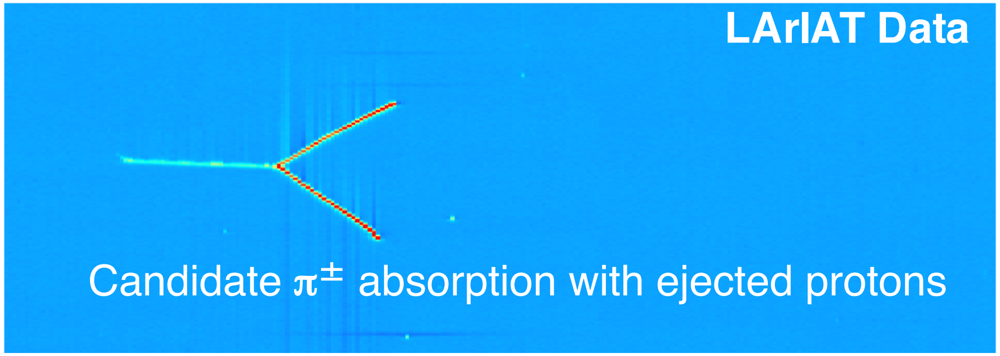
Modeling of neutrons is one of our biggest challenges to neutrino reconstruction. They are displaced in space from the rest of the interaction and typically only deposit a small fraction of their energy -> a big source of missing energy in neutrino reconstruction

Neutrons are present in all charged-current antineutrino interactions

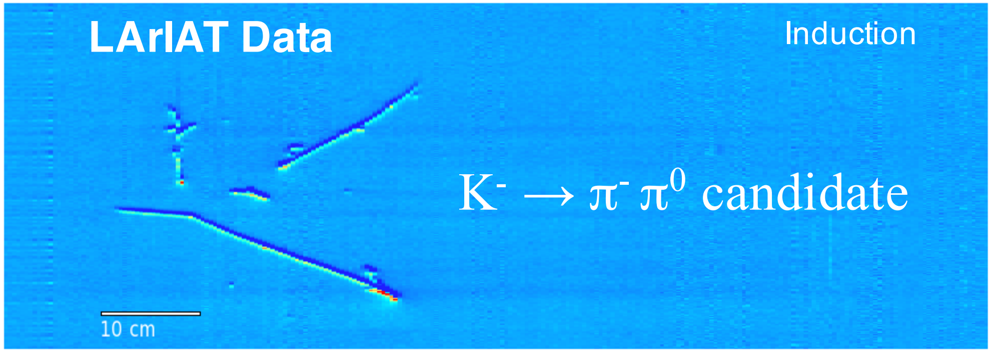
Detector Simulation



Candidate $\pi^{\pm} \rightarrow \pi^{0}$ charge exchange



Candidate $\pi^{\pm}$ absorption with ejected protons



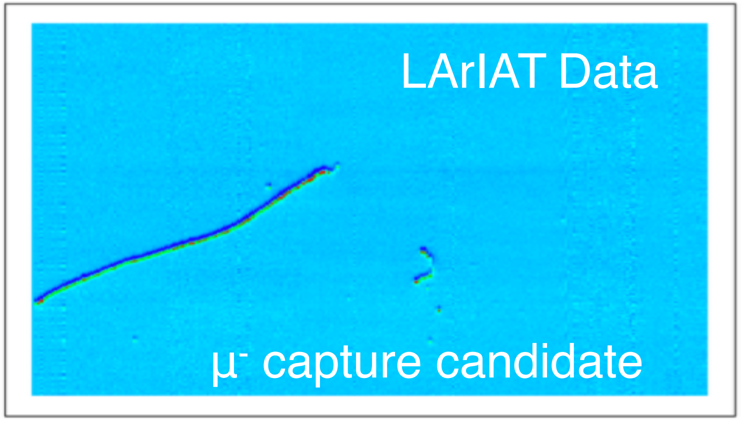
$K^{-} \rightarrow \pi^{-} \pi^{0}$ candidate

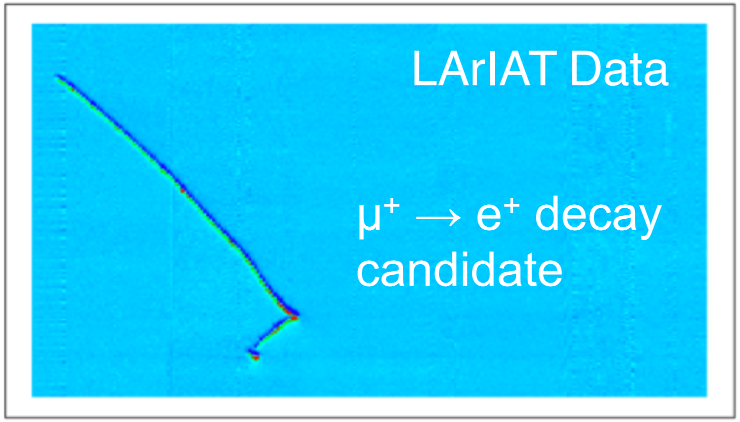
Modeling of liquid Argon Detectors is critical, as many new LAr detectors come online.

Important processes for oscillation physics: inelastic interactions/ response of < few GeV pions, protons, neutrons, photons, electrons

Kaons also important for nucleon decay analyses

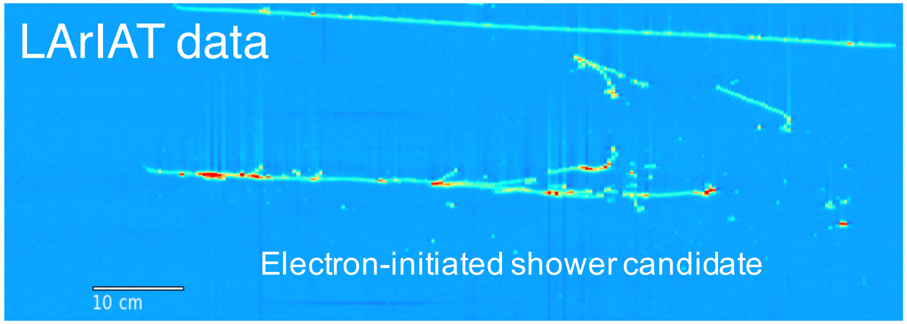
Detector Simulation

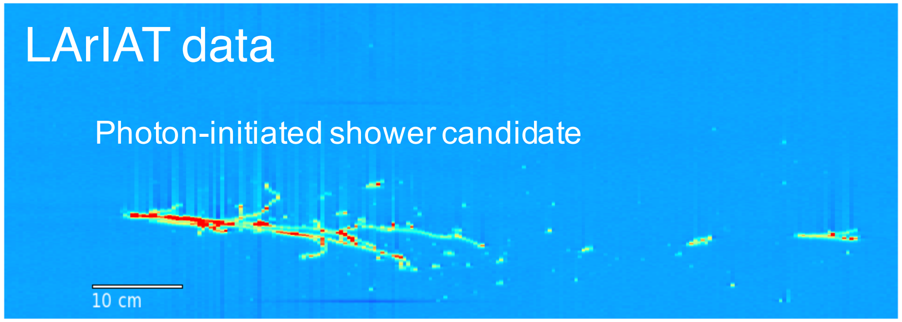




- Sign selection in detectors without a magnetic field is important
- Allows separation of neutrinos and antineutrinos (needed because observation of differences between neutrino and antineutrinos is a central physics goal)
- μ+ only decay, with e+ emission of known energy spectrum
- μ- capture on nuclei followed by γ/n emission (76%) or decay (24%)
- Capture rate higher in Argon than in lighter elements

Detector Simulation





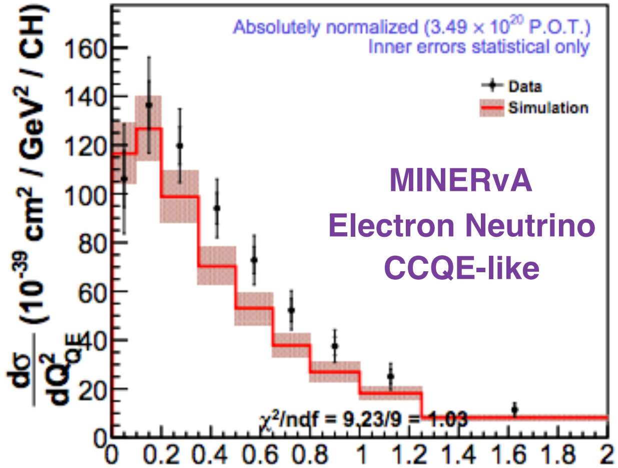
- e/γ separation also critical for oscillation measurements
- Separates electron neutrino appearance from backgrounds such as Neutral Current π^0 production

Neutrino Interaction Cross Sections

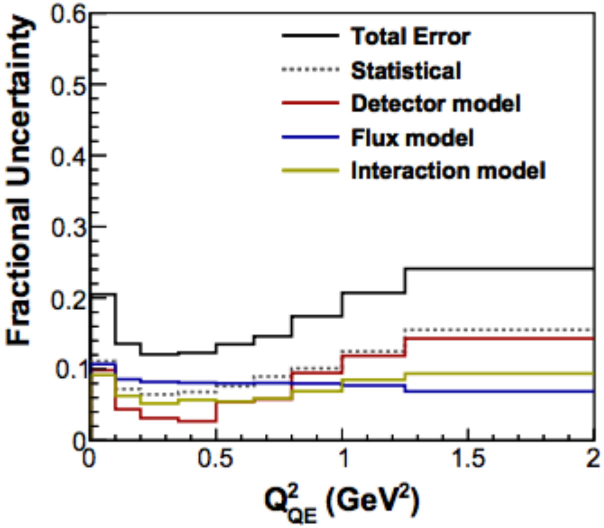
- Neutrino interactions are modeled by event generators such as GENIE, NuWro and NEUT
- Therefore, they are seemingly not relevant to this talk
- Except! that they are tuned to data from near detectors or dedicated experiments (MINERvA), whose systematic uncertainty budgets are dominated by detector and beam modeling uncertainties

$$N_{\nu_e}(E_\nu) = \phi_{\nu_\mu} \times \boxed{\sigma(\nu_e)} \times \epsilon(\nu_e) \times P(\nu_\mu \rightarrow \nu_e)$$

Interaction Cross Section



MINERvA Electron Neutrino CCQE-like



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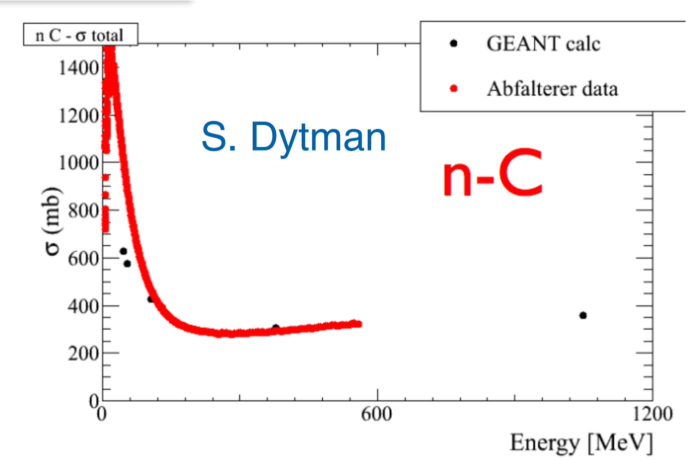
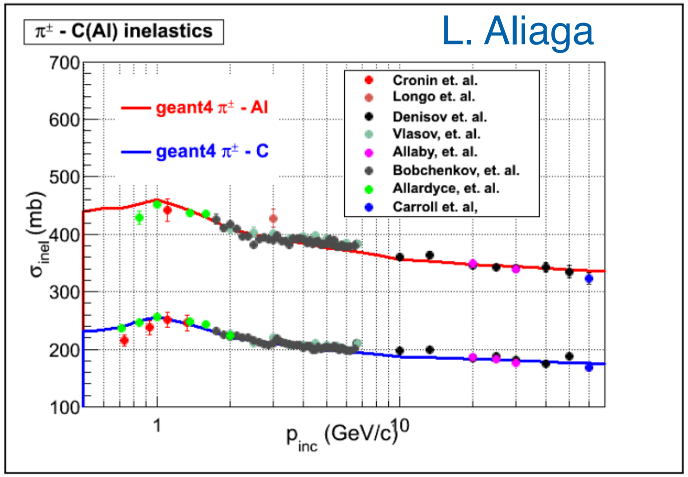
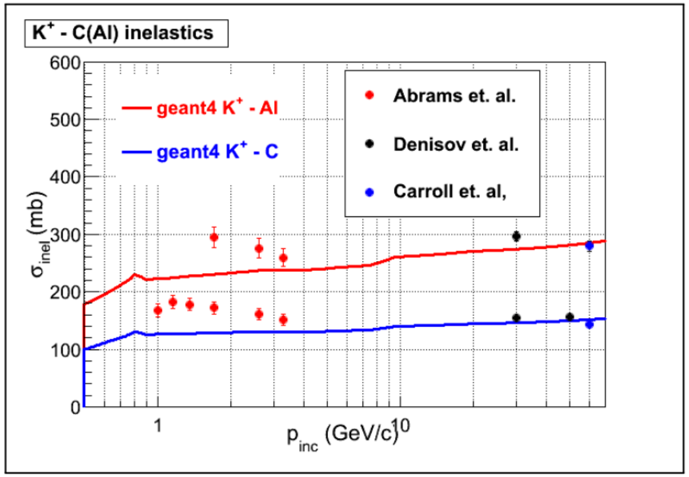
Systematic Uncertainties

- For neutrino experiments, knowing the level of inaccuracy of our simulations is as important as having accurate simulations
- Detector/beam modeling are significant sources of uncertainties and must be propagated to systematic uncertainties on measured quantities

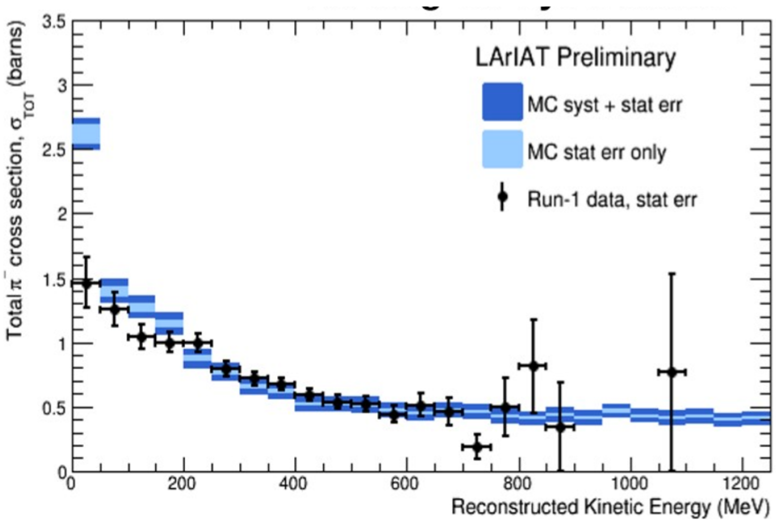






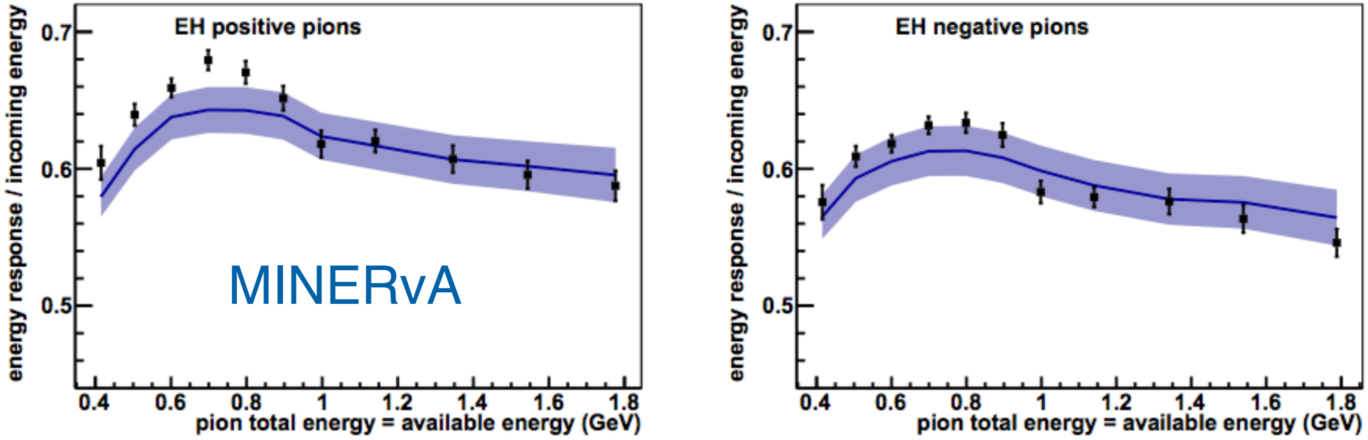
This is frequently done by comparing G4 to external data

Systematic Uncertainties



Or by making dedicated measurements in a test beam;

Work is often done separately by each (small) collaboration and makes moving to new versions of Geant4 difficult



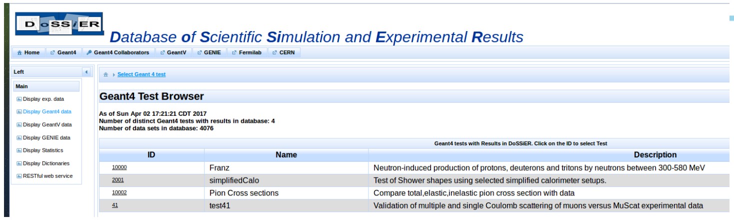
MINERvA

Liquid Argon Validation Project

- The **LAr Validation Project** is a first step towards combining the work of G4 validation across neutrino experiments
- See Fermilab **redmine** for presentations and write up:
  - https://cdcvs.fnal.gov/redmine/projects/liquid-argon-validation-project?jump=welcome
- The **goals of this project** are:
  - identify **physics processes of particular interest** for liquid Argon TPC experiments.
  - Provide **a set of tests** that can be used to simulate the processes and establish how well these are described by the Geant4 simulation (compared to experimental data).
  - **Provide guidance** about how to set up Geant4 in an optimal way (geometry, physics list, cuts...).
  - Collect test **results and experimental data in DoSSiER** (Database of scientific simulated and experimental results).

DoSSiER Database

Select Pion Cross Sections in Geant 4 test browser



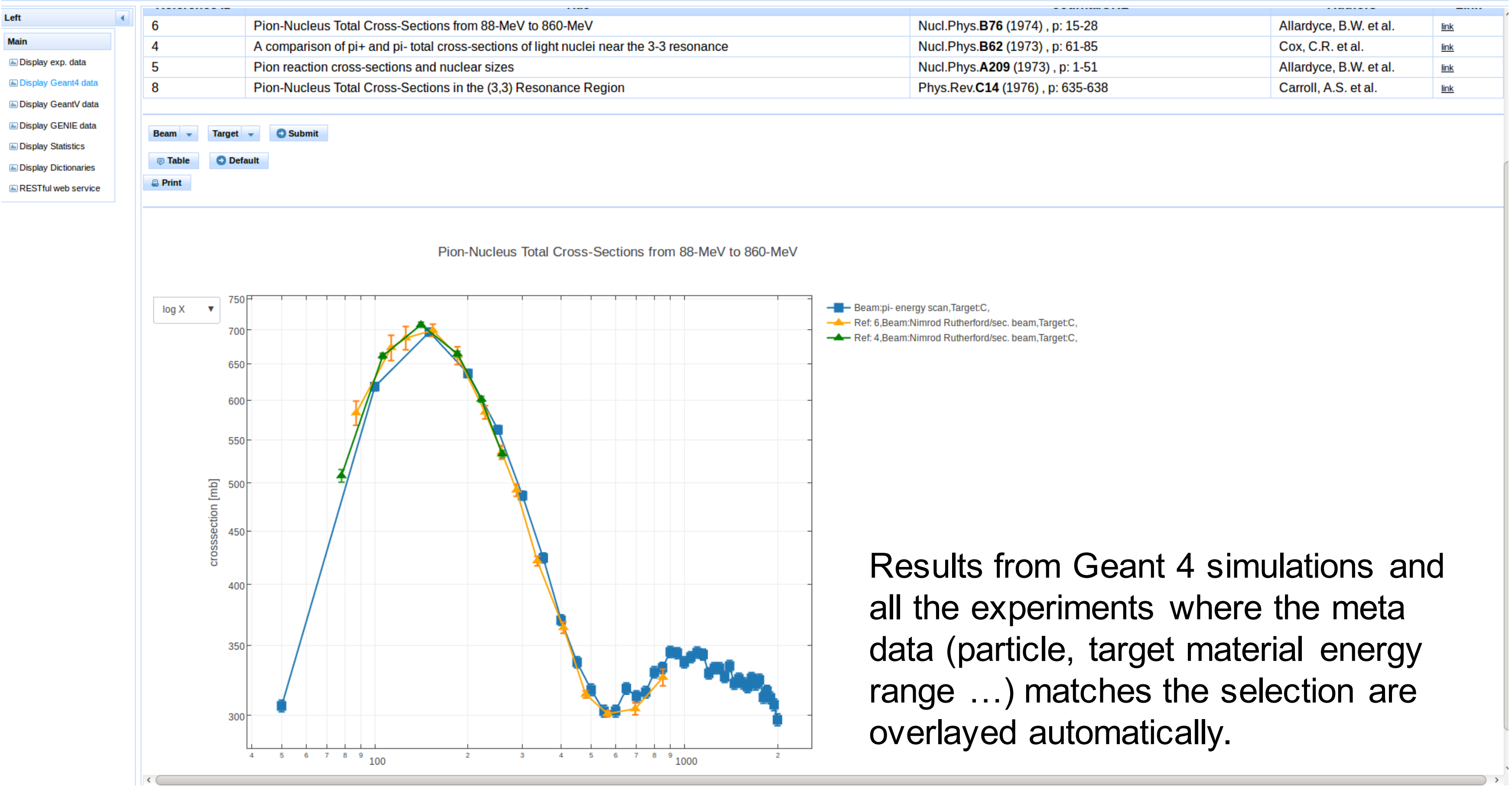
Database of Scientific Simulation and Experimental Results

Geant4 Test Browser

As of Sun Apr 02 17:21:21 CDT 2017
Number of distinct Geant4 tests with results in database: 4
Number of data sets in database: 4076

Geant4 tests with Results in DoSSiER. Click on the ID to select Test

ID	Name	Description
10000	Franz	Neutron-induced production of protons, deuterons and tritons by neutrons between 300-580 MeV
2001	simplifiedCalo	Test of Shower shapes using selected simplified calorimeter setups.
10002	Pion Cross sections	Compare total,elastic,inelastic pion cross section with data
41	test41	Validation of multiple and single Coulomb scattering of muons versus MuScat experimental data

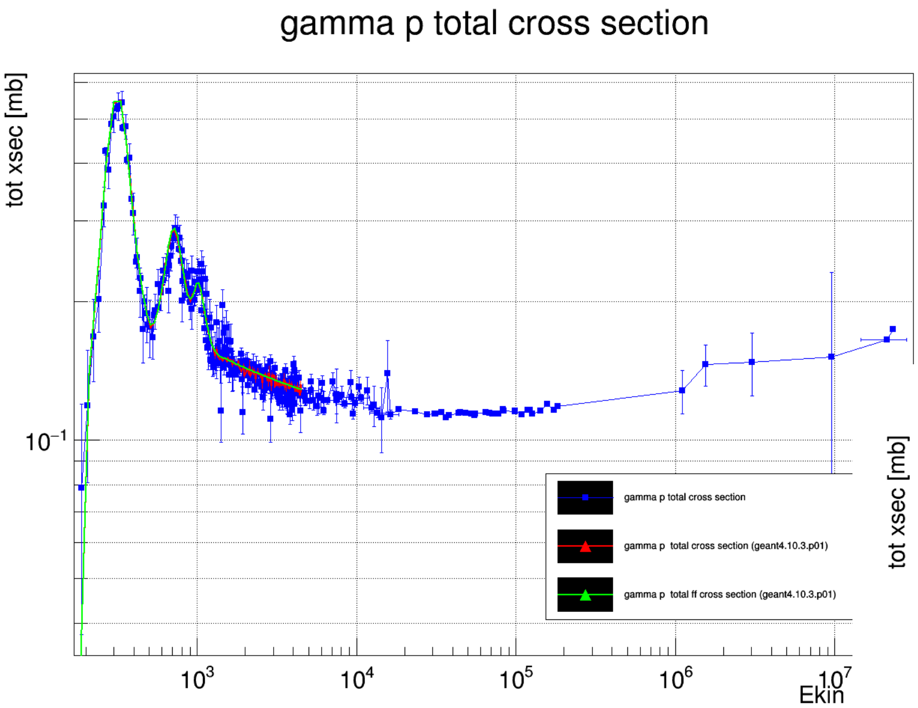


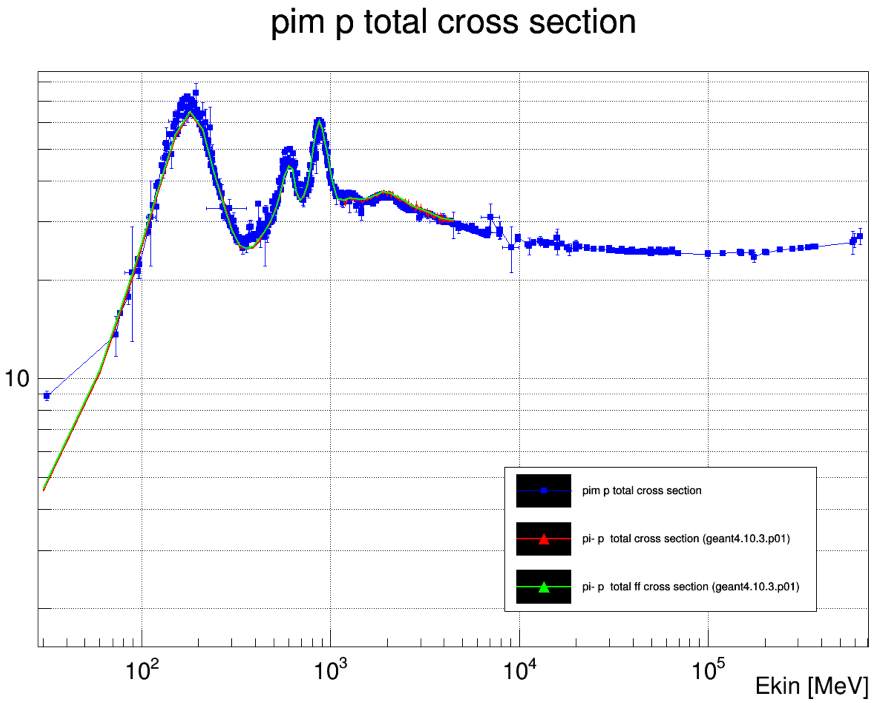
6	Pion-Nucleus Total Cross-Sections from 88-MeV to 860-MeV	Nucl.Phys.**B76** (1974) , p: 15-28	Allardyce, B.W. et al.	link
4	A comparison of pi+ and pi- total cross-sections of light nuclei near the 3-3 resonance	Nucl.Phys.**B62** (1973) , p: 61-85	Cox, C.R. et al.	link
5	Pion reaction cross-sections and nuclear sizes	Nucl.Phys.**A209** (1973) , p: 1-51	Allardyce, B.W. et al.	link
8	Pion-Nucleus Total Cross-Sections in the (3,3) Resonance Region	Phys.Rev.**C14** (1976) , p: 635-638	Carroll, A.S. et al.	link

Pion-Nucleus Total Cross-Sections from 88-MeV to 860-MeV

Results from Geant 4 simulations and all the experiments where the meta data (particle, target material energy range …) matches the selection are overlayed automatically.

DoSSiER Database


gamma p total cross section


pim p total cross section

Some agree very nicely!
Others (not shown) e.g.
K cross sections need
some work

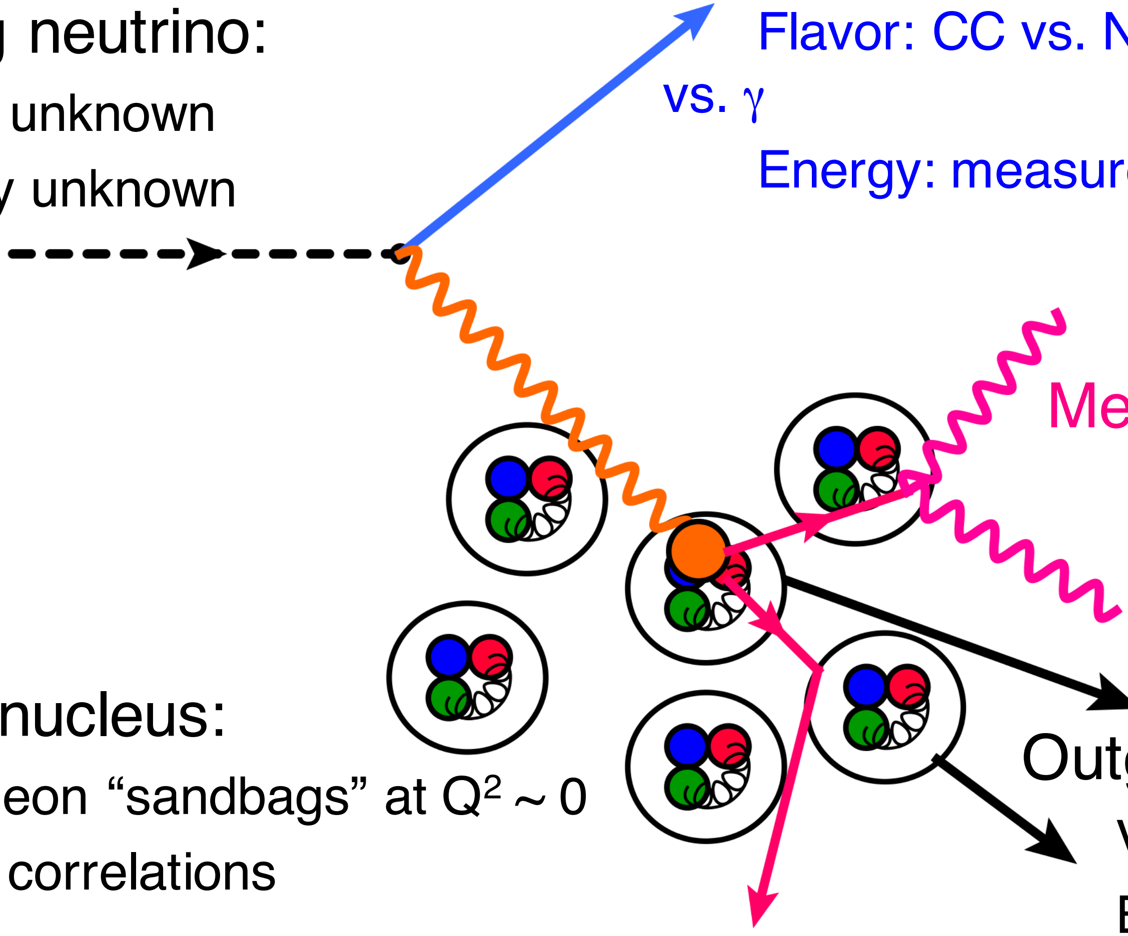
Conclusion

- Detector (and beam) simulations **affect neutrino oscillation measurements in many ways** and are a major source of systematic uncertainty
  - Wide variety of physics processes, from 100 GeV to MeV level are important
- Needed **accuracy of experiments will increase** over the next decade
- We use G4 **physics lists tuned primarily to the needs of LHC** experiments
  - This is increasingly leading us to make **private modifications** of G4 to meet our needs
  - This in turns **limits our ability to move to new** (more accurate) versions of Geant4
- Efforts (e.g. the LAr Validation Project) are beginning to identify areas of **physics modeling need across experiments** and quantify uncertainties in simulations

Backup

Introduction

Typical neutrino event



Incoming neutrino:

Flavor unknown

Energy unknown

Outgoing lepton:

Flavor: CC vs. NC, μ^+ vs. μ^-, e vs. γ

Energy: measure

Mesons:

FSI!

Energy? Identity?

Target nucleus:

Nucleon “sandbags” at $Q^2 \sim 0$

N-N correlations

Outgoing nucleons:

Visible?

Energy?