Neutrino Experiment Simulation Overview

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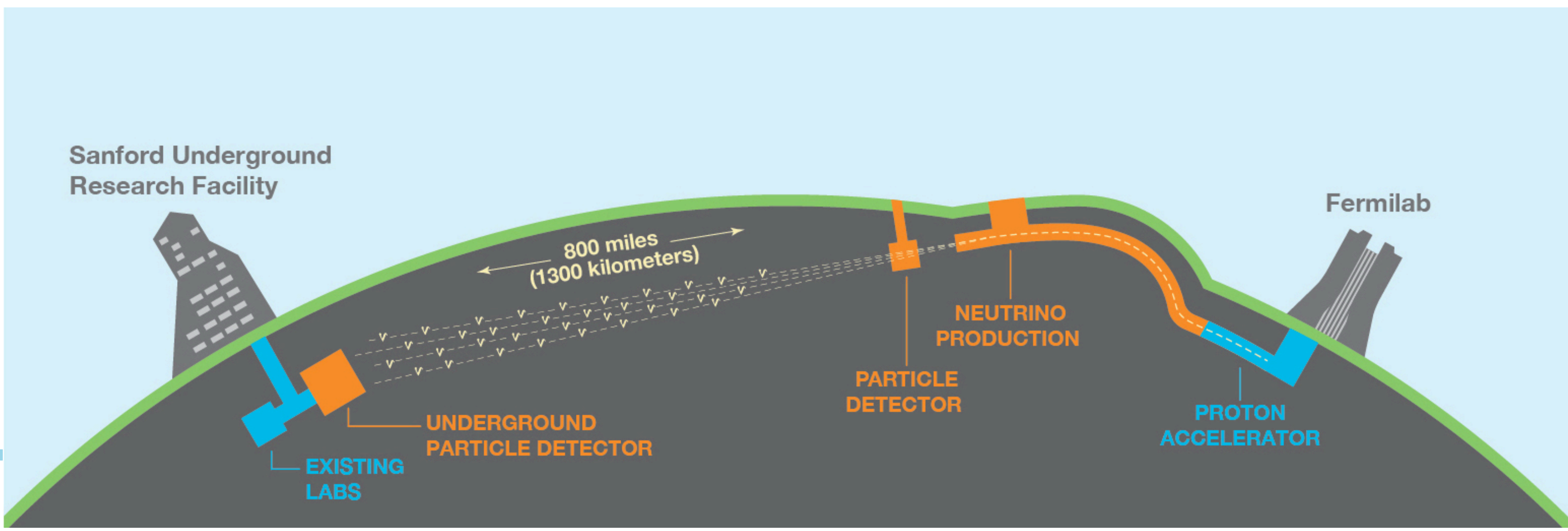
Mar 20, 2019

Thomas Jefferson National Accelerator Facility

Outline

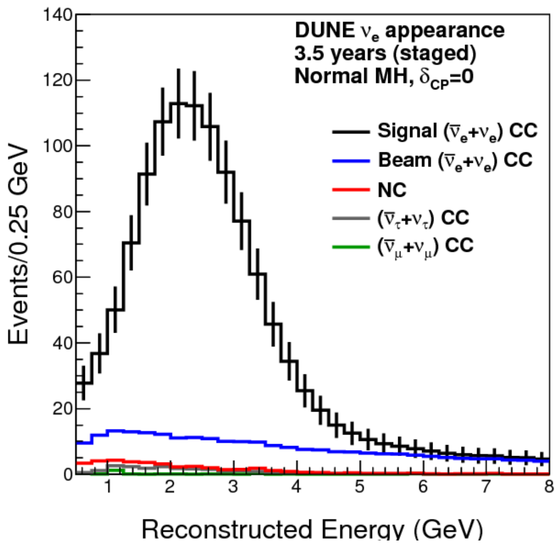
- outlook on precision measurements in neutrino oscillations
- where simulations come into the picture
- simulation of neutrino beam fluxes and systematics
- neutrino interaction event generators and cross sections
- detector simulation with GEANT4
- slight diversion about other IF experiments at Fermilab

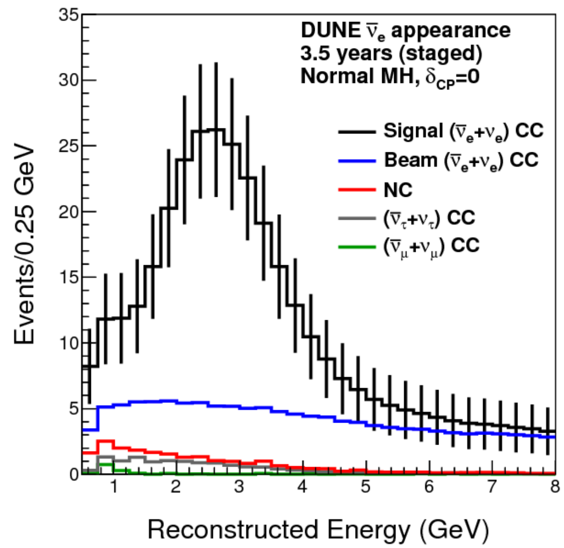
Big thanks to Laura Fields, Alex Himmel, Mary Bishai, Tao Lin, Rob Kutschke, Krzysztof Genser, Jen Raaf, Gabe Perdue, Renee Fatemi, and Leah Welty-Reiger for help with this talk. They deserve the credit. All mistakes are mine.



Neutrino Simulations in the era of oscillations

- Many neutrino experiments have measurement of neutrino oscillation parameters as their primary goal





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

Oscillation Probability

Neutrino Flux

Interaction Cross Section

Efficiency / Smearing Function

Neutrino Simulations in the era of oscillations

- Mass ordering, CP-violation, mixing matrix unitarity
- precision measurements of oscillation parameters requires accurate simulation of detector response and efficiency

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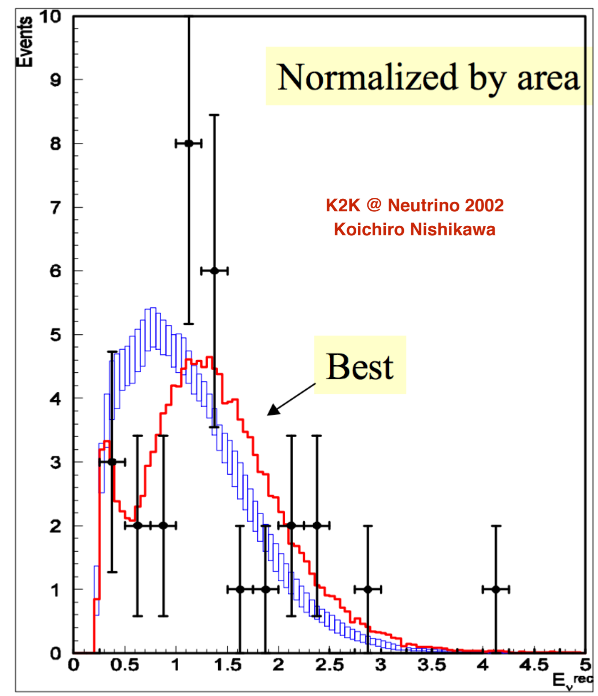
- interaction cross sections & detector uncertainties have significant impact on the potential reach of oscillation experiments
- beam fluxes dominant uncertainty for measurements of interaction cross sections and event yields



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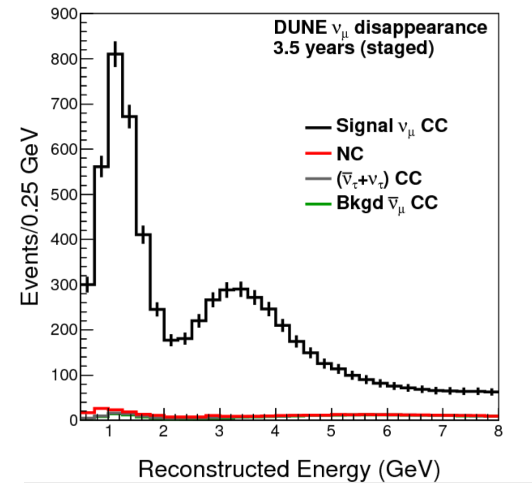

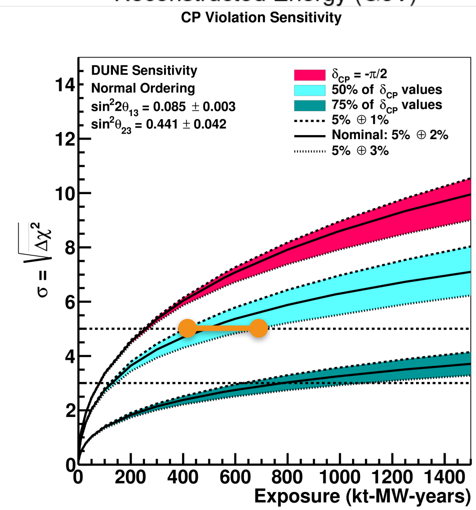

Laura Fields

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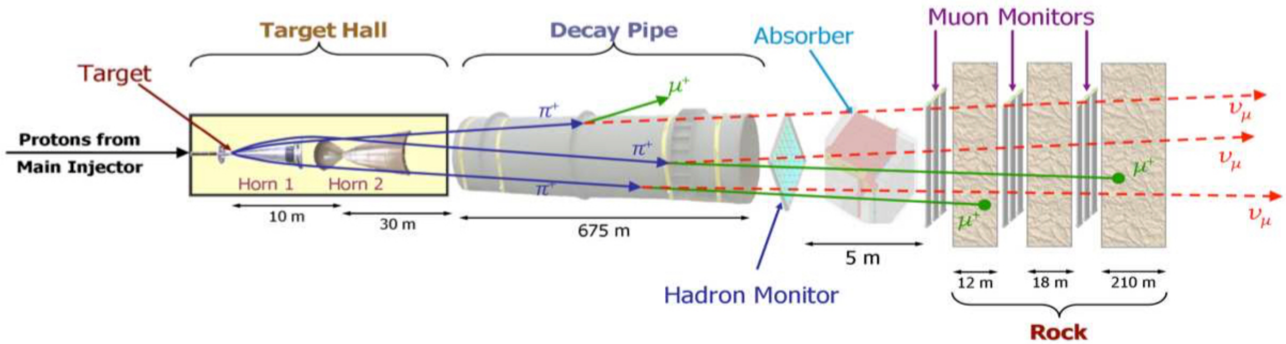
Beam simulations and neutrino flux

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

NuMI Beam

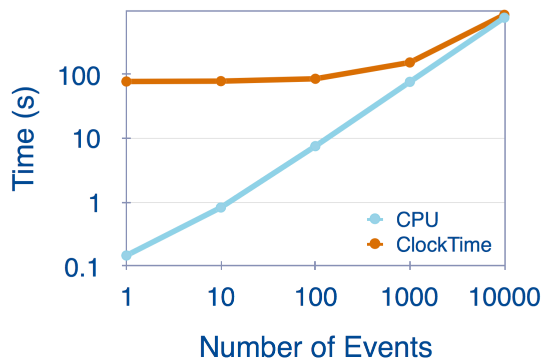


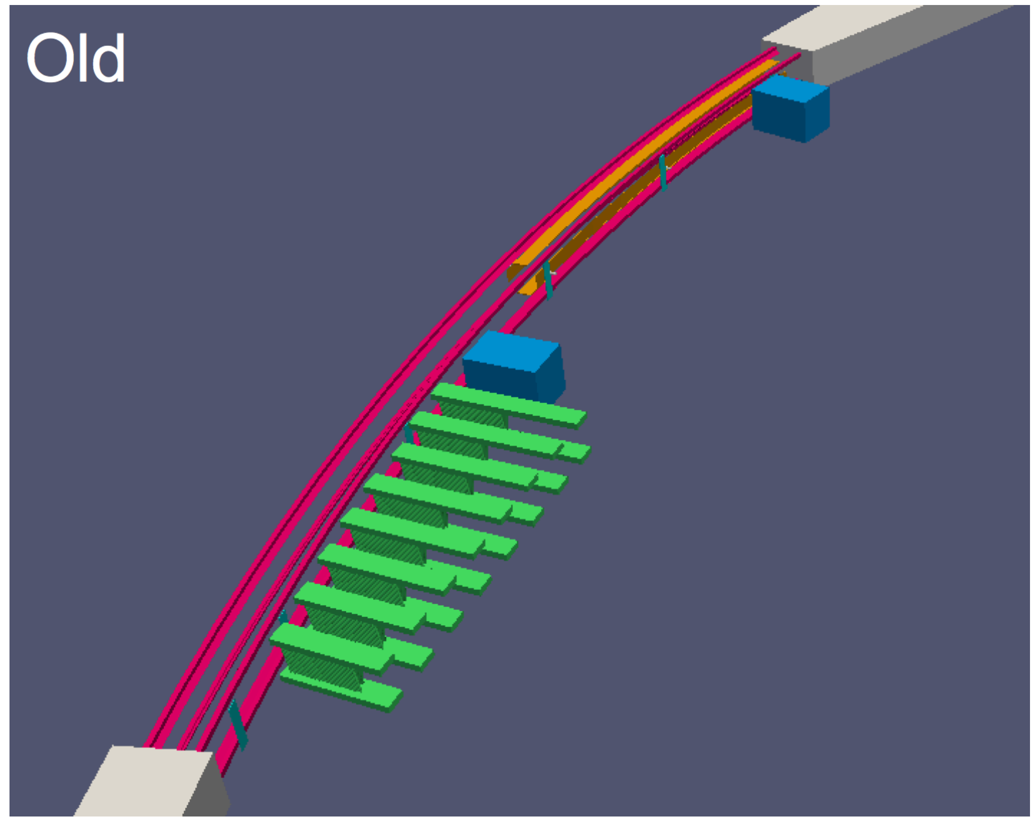
- simulate proton beam (8-120 GeV) incident on targets (thin, thick, C, Be)
- T2K Beam Simulation: FLUKA 2011.2c -> GEANT3+GCALOR
- MINERvA Beam Simulation: GEANT4 for production and simulation
  – developed the ppfx package for hadron production uncertainties
- Booster Neutrino Beam: GEANT4 based tools developed by MiniBooNE used by MicroBooNE, SBND, ICARUS
- near detectors help minimize uncertainty for oscillation measurements - not a silver bullet

- Hadron production: based up production models from hadrons exiting the targets and from secondary and tertiary interactions in the horn, decay pipe, etc
- horn focusing: particle propagation through magnetic fields and alignment of the horn elements
- other subdominant effects: gas in the decay pipe, absorber material, decay pipe windows

CADMesh utilized by the Muon g-2 Experiment

- Translates CAD files into GDML for simulation in GEANT
- allows for precise shape and location of detector components without recreation in GDML by hand
- does require greater precision than engineers are sometimes focused on
- gaps in volumes and overlapping volumes can be serious problems in GEANT





Leah Welty-Reiger, Renee Fatemi

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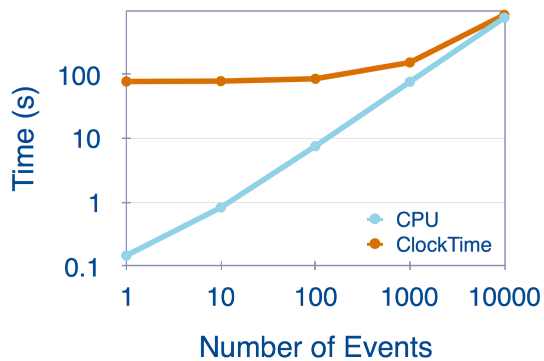
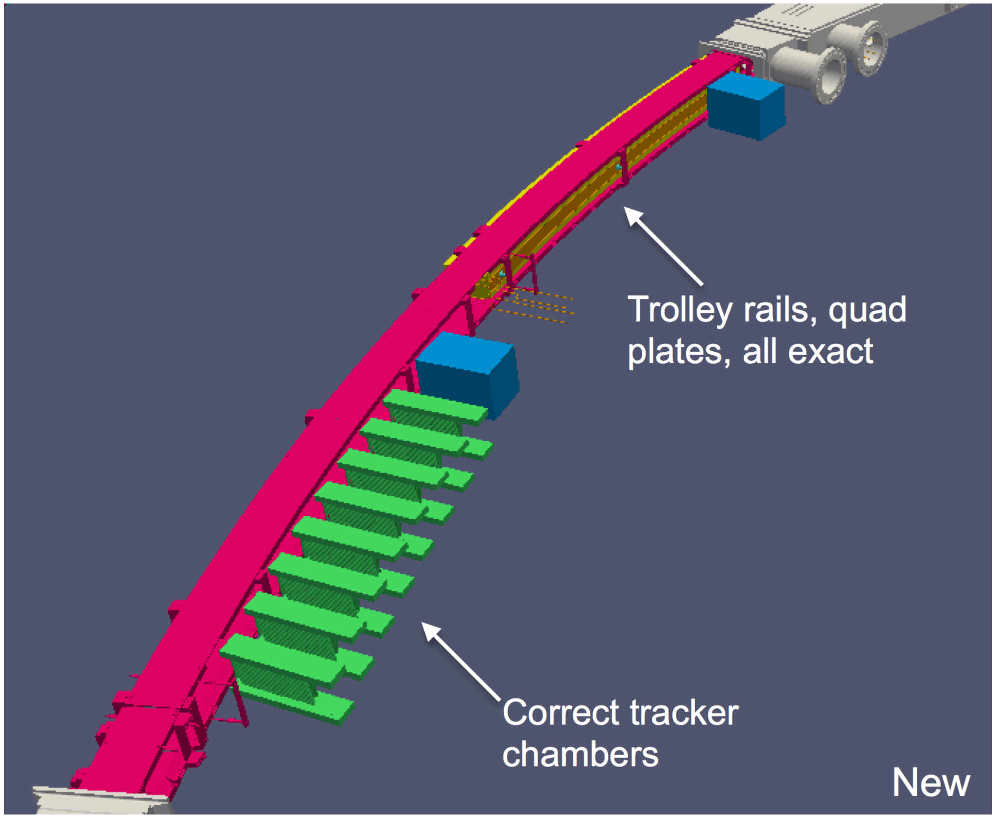
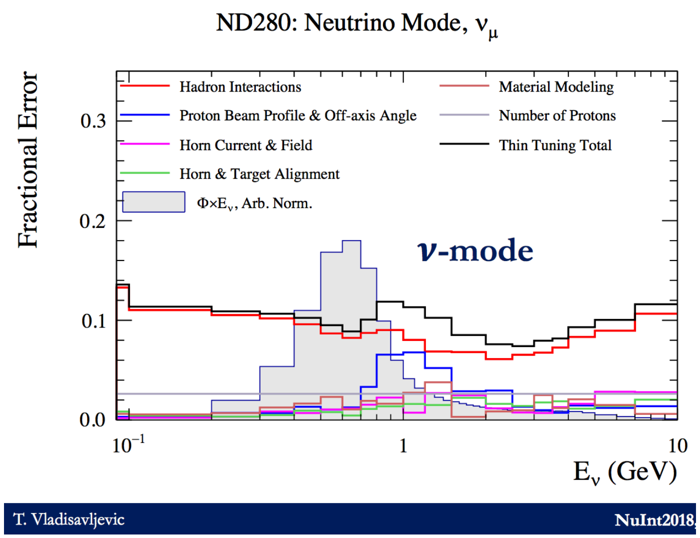


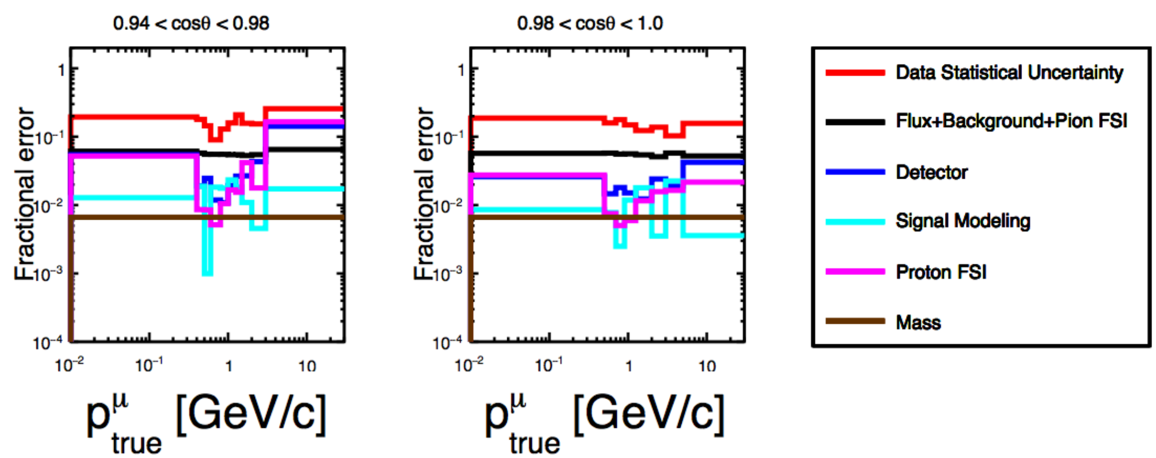


Leah Welty-Reiger, Renee Fatemi

T2K Beam simulation

- hadron interactions are the greatest source of uncertainty for the flux prediction
- constrain the pion production using NA61/SHINE, HARP datasets





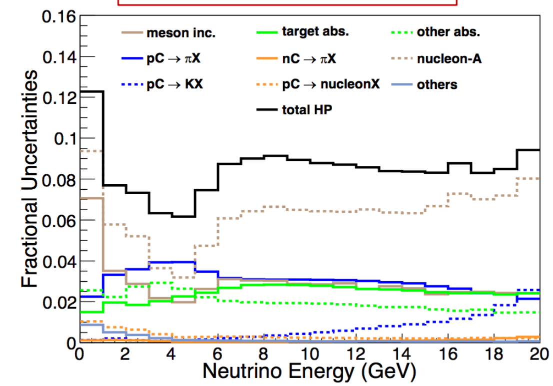
- neutrino flux uncertainty dominates the measurement of CC0π production
- this is the golden channel for measuring oscillation parameters - cleanest incident neutrino energy determination

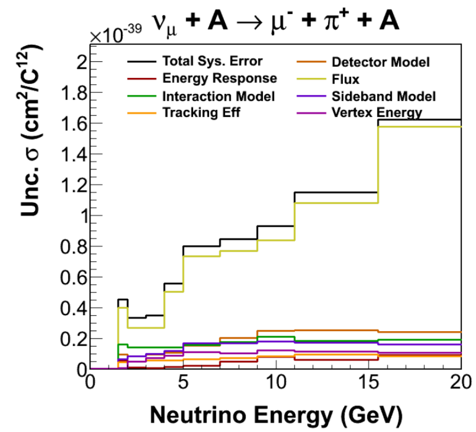
MINERvA Beam Simulation

- Hadron production model variation dominant effect for determining the uncertainty
  - use data from NA49, MIPP to tune the flux
  - scale 158 GeV proton data to 120 GeV using FLUKA
  - incorporated into Package to Predict the Flux (PPFX)
- still dominate uncertainty in most of the MINERvA measurements
- pioneering measurements to constrain the flux using neutrino scattering off electrons measurements - but suffers from limited statistics
- cross sections measurements important inputs for improving neutrino interaction models and predictions

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

Phys. Rev. D 94, 092005 (2016)





Deepika Jena, NuINT 2018

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Neutrino Interactions Simulation

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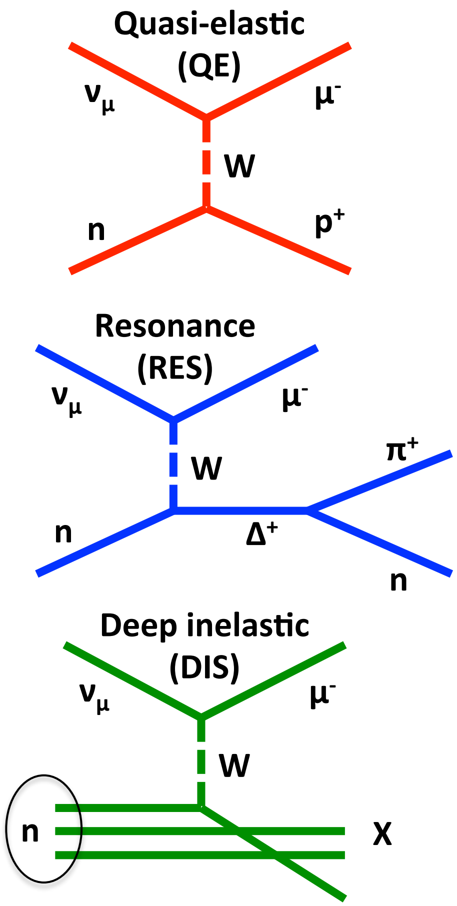
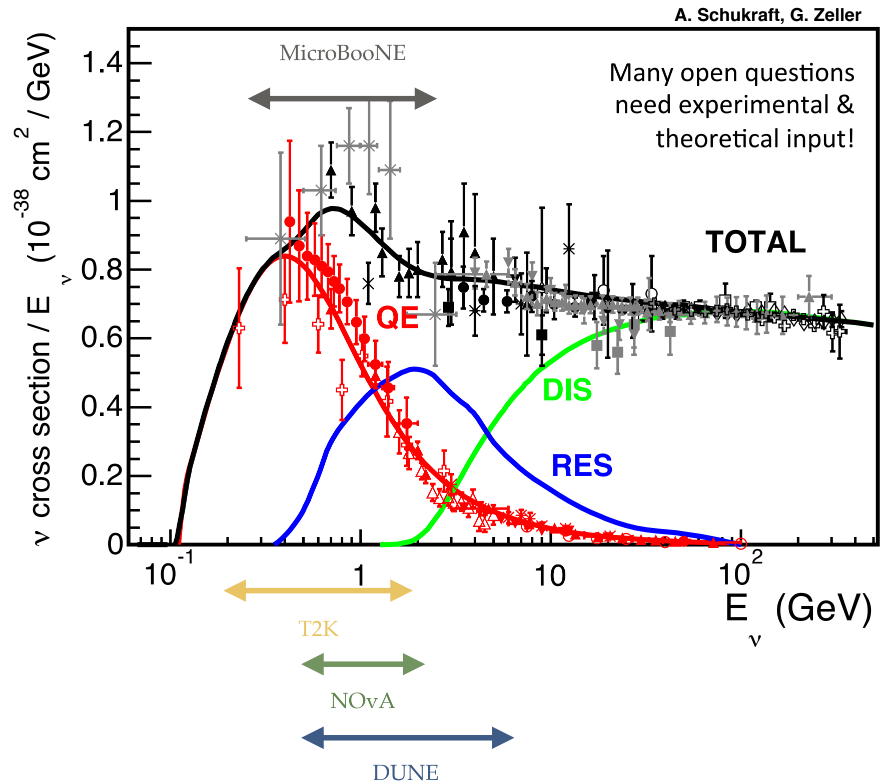


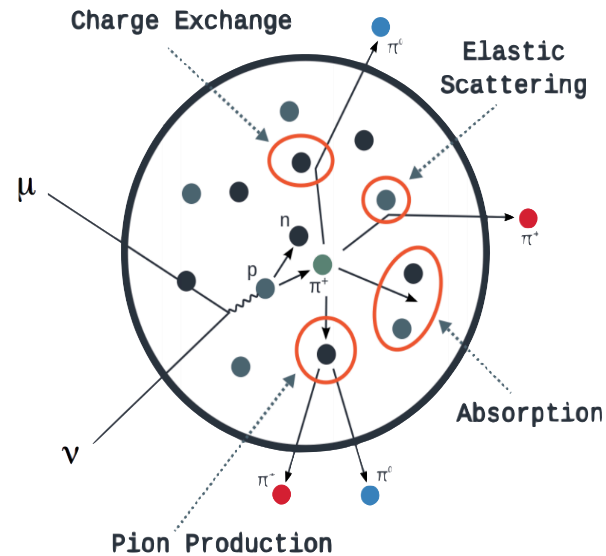
Lots of interesting (nuclear) physics over all energy ranges.



Neutrino Interactions Simulation

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

- Determination of the incident neutrino is based upon interpretation through nuclear model of reconstructed final-state objects - but there is no complete theory from first principles that describes the interaction and subsequent states
- the weak interactions at same scale as the final state strong interactions
- various nuclear models
- potential nucleon correlations
- final-state interactions
- GENIE, NEUT vs NuWRO, GiBUU
- Tuning models to data samples is a common goal for many experiments but limited ability to turn the knobs within generators and models



Gollapini, arXiv:1602.05299

- understanding systematic uncertainty from the model is a critical component to using these models and need tools to determine those uncertainties

https://hepsoftwarefoundation.org/cwp/hsf-cwp-017-CWP_neutrino_event_generators.pdf

Neutrino Interactions Simulation

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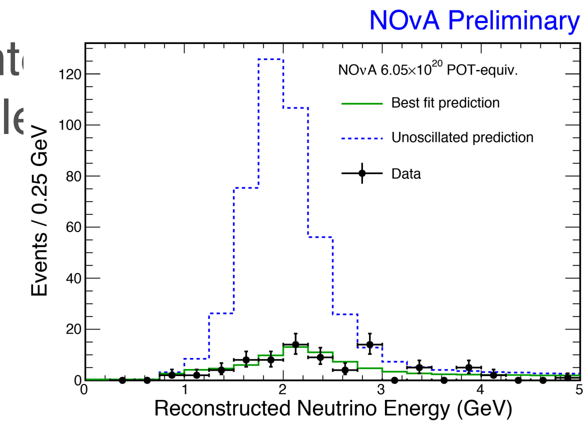

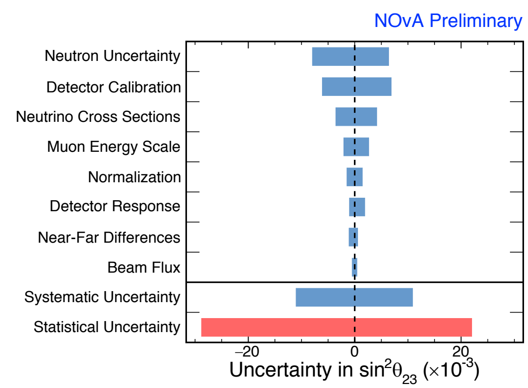

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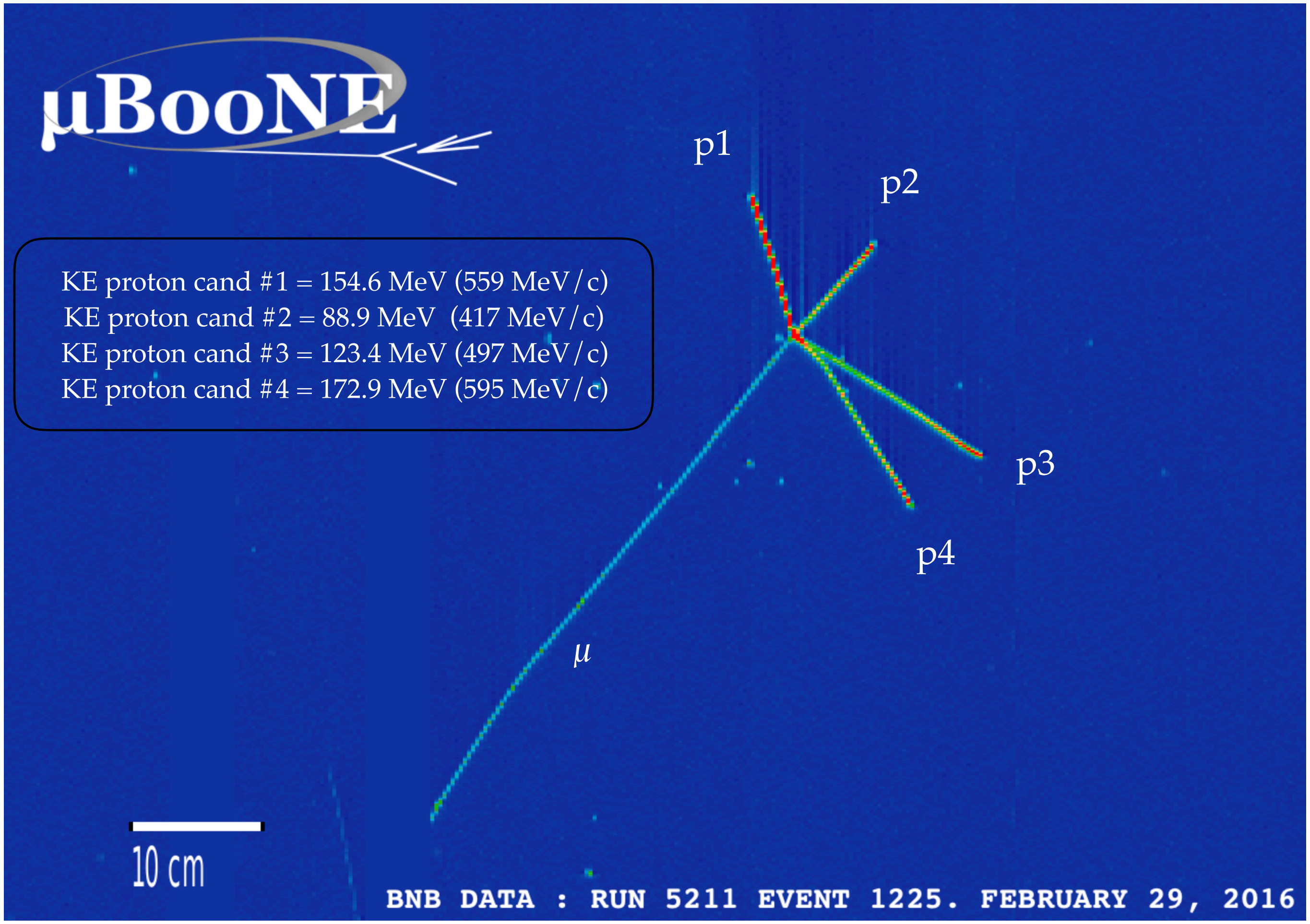
https://hepsoftwarefoundation.org/cwp/hsf-cwp-017-CWP_neutrino_event_generators.pdf

Tuning model to match interactions like this and determine neutrino energy



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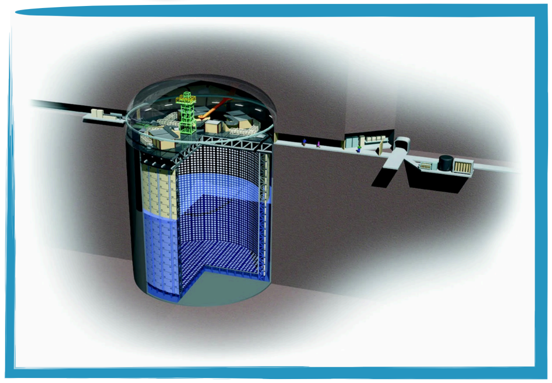
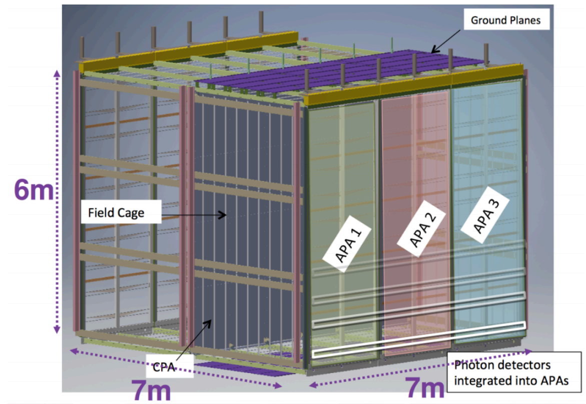
Neutrino Detector Simulations

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

- Vast array of detector designs, materials, and energy scales
- Liquid Argon Time Projection Chambers, Liquid Scintillator, Water Cherenkov, Lead, Steel, Scintillator
- Based mostly upon GEANT4 simulation with various different physics lists used for both tuning and systematic uncertainties
- detector response needed to determine response and efficiency along with uncertainties
- modeling particle response important:
  – non-static detector simulation
  – primary electron vs primary photon separation
  – scintillation photon propagation
  – neutron propagation and response



Super-Kamiokande

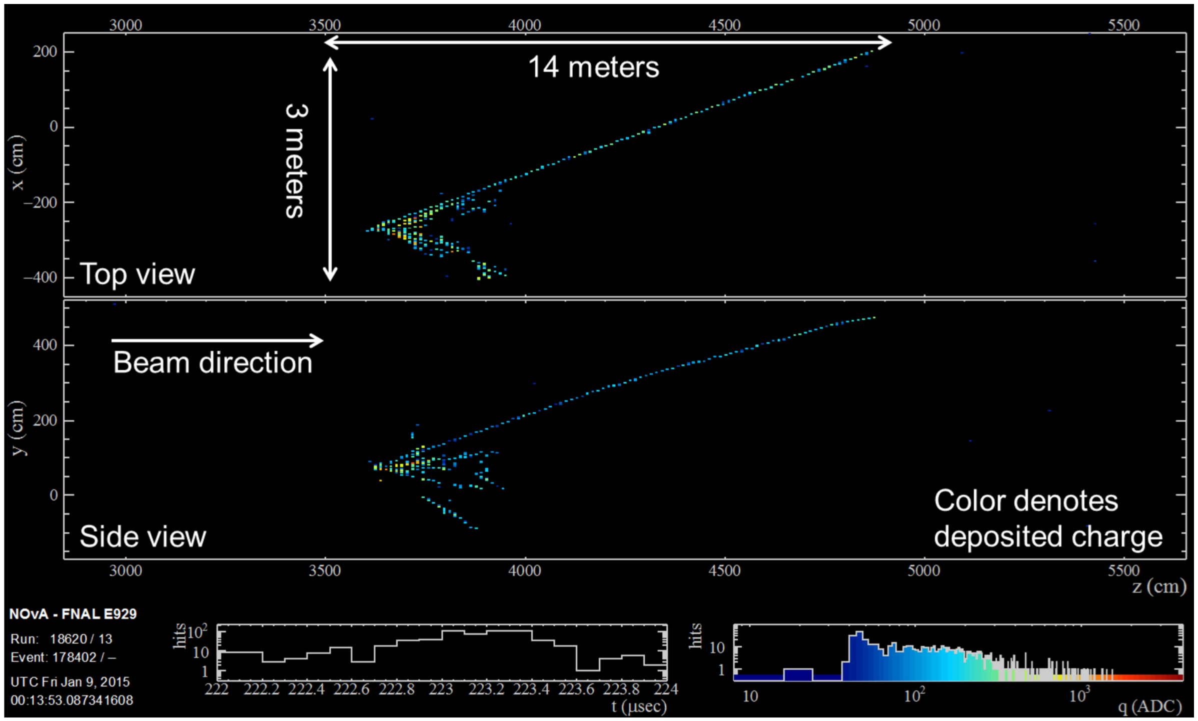


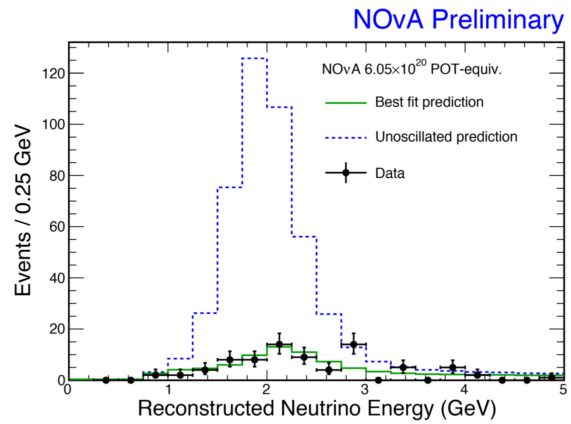
ProtoDUNE

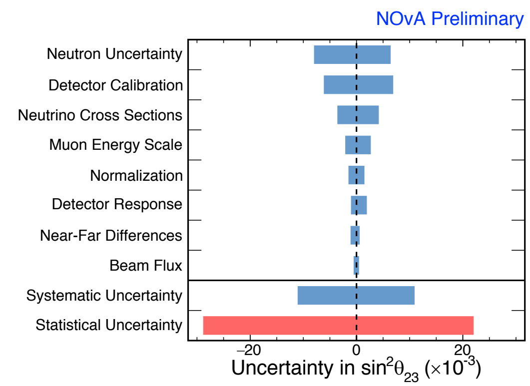
NOvA Oscillation Measurements

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

- GEANT simulation of efficiency and energy smearing important to estimation of energy reconstruction





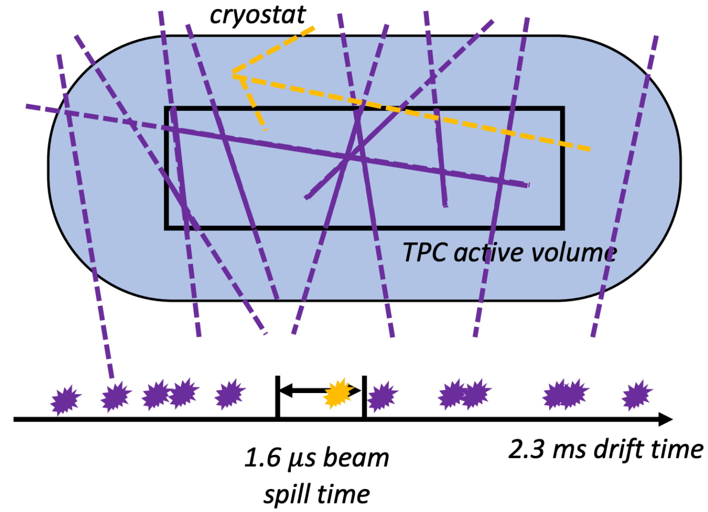


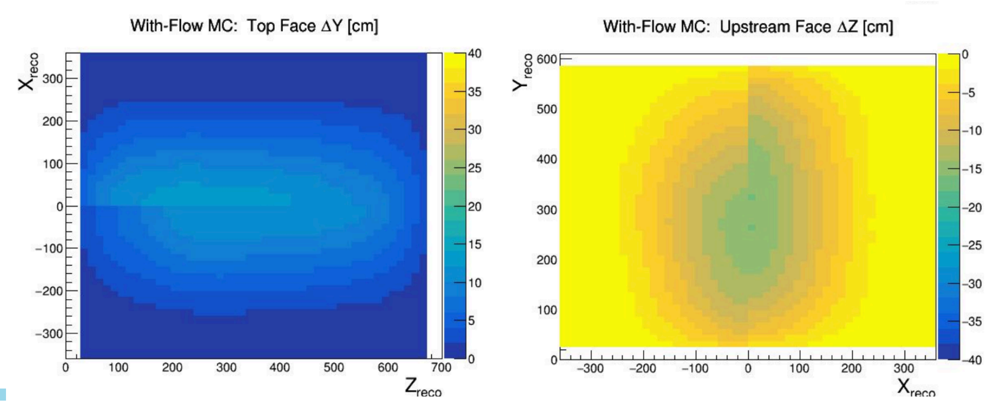
Alex Himmel, FNAL JETP

LAr detector modeling

- Modeling important for LBL and SBL - muons, pions, protons, neutrons, electrons, photons at < GeV scale
- LAr TPCs on the surface have occupancy dominated by cosmic rays generates space charge effect (SPE)
- flow model of the liquid combined with electron recombination needed to model the generation of areas of static charge
- important for alignment, calorimetry, and muon momentum measurements
- Muon g-2 experiment has injection/kicker magnets that generate varying magnetic fields inside the detector volume - tracking spin-dependent particles over 100km of path length (one of first exp to use G4EqEMFieldWithSpin) with precision greater than 1 mm

“Neutrinos + cosmics”



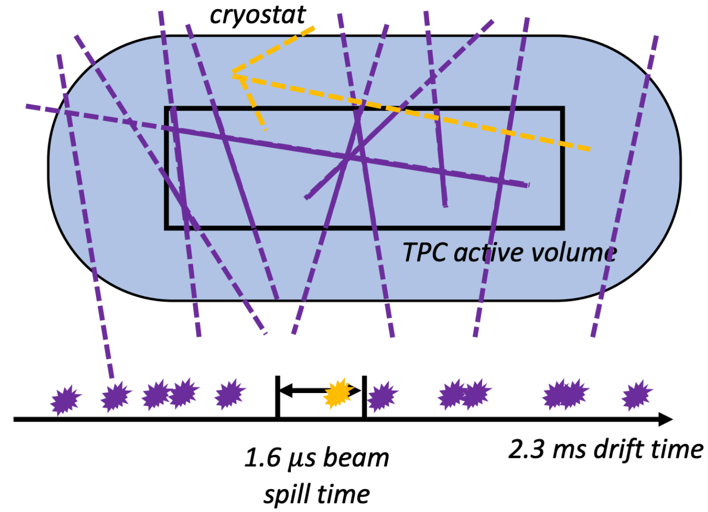


ProtoDUNE simulation SPE

Photon Simulation in Neutrino Detectors

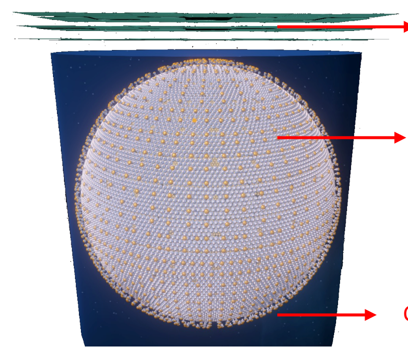
- scintillation in LAr is 10000 photons/MeV
- 2.2 MeV/cm for a MIP
- 20000 photons for every cm a muon traverses
- simulating 6000000 photons in FD on a CPU
- resorted to using photon lookup tables from dedicated photon bomb simulations (memory problems)
- DUNE - development of trigger, final detector design, shower reconstruction, and energy resolution depends upon photon simulations
- DUNE wants “natively GPU-accelerated optical photon tracking built into a fully-featured detector simulation”

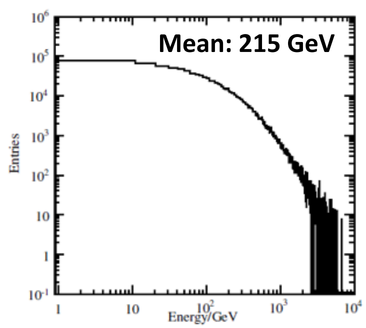
“Neutrinos + cosmics”

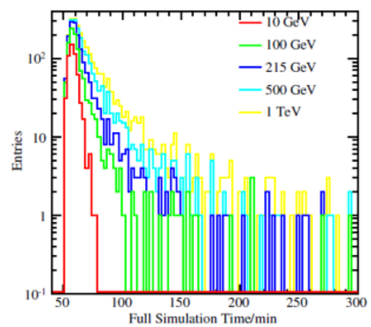


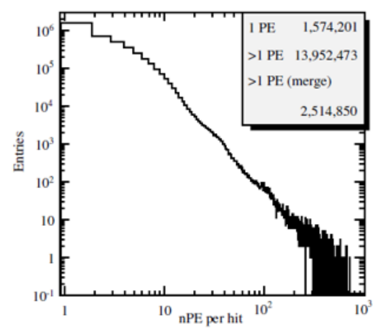
Simulation challenges in JUNO

- JUNO: Jiangmen Underground Neutrino Observatory
- ***Measuring Mass Hierarchy with Reactor neutrinos***
- ***Nominal experiment setup***
  - 700 m deep underground
  - 53 km baseline; 36 GW reactor power
  - 20 kton LS detector; 18,000 20inch PMTs
  - 3% energy resolution@1MeV
- ***Major backgrounds: Cosmic ray Muons (3 Hz)***
  - dE/dx: 2 MeV/cm, Light Yield: 10,000/MeV
    => Need to simulate millions of photons.
    => Several hours per event. Need >4GB memory.









Note: The photoelectrons in the same 1 ns time window are merged in order to save memory.

Thanks Tao Lin for slides

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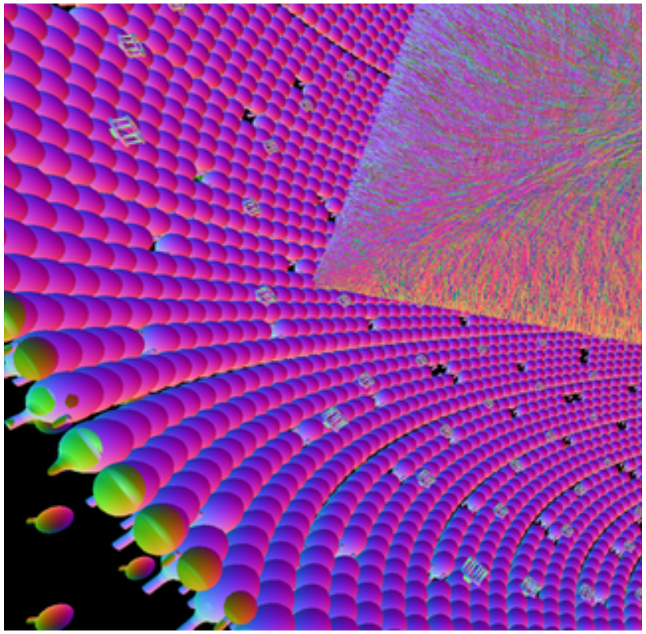
Opticks: GPU-based full simulation

- ***State-of-the-art GPU ray tracing (NVIDIA OptiX) applied to optical photon simulation***
  - replace Geant4 optical simulation with GPU equivalent
  - translate G4 geometry to GPU without approximation, (CSG implemented on GPU)
  - port G4 optical physics to CUDA
- ***Optical photons generated + propagated entirely on GPU, highly parallel***
  - only photons hitting PMTs require CPU memory
  - expected speedup : *Opticks* > 1000x *Geant4*
  - eliminates memory + time bottlenecks
- ***Status : validation iteration ongoing***
  - validation by direct comparison of random sequence aligned GPU and CPU simulations

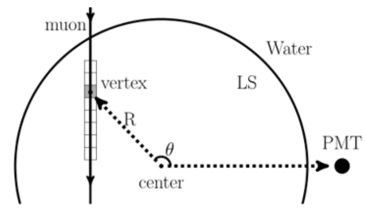


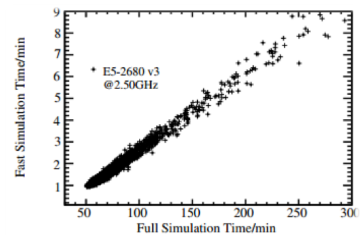
http://bitbucket.org/simoncblyth/opticks

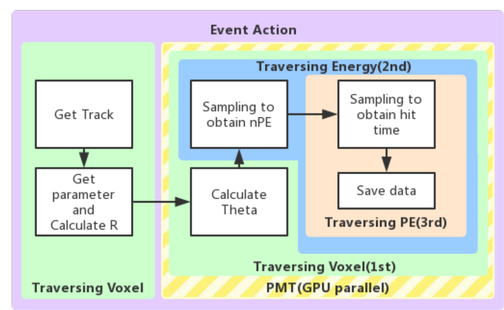
Thanks Tao Lin for slides

Voxel method: parameterized fast simulation

- ***Parameterized PMT's response for the scintillation photons.***
  - Generate scintillation photons in a certain voxel.
  - Simulate the response with Geant4.
  - Save the histograms of nPE and hit time.
  - Use the response into simulation at runtime.
- ***Speed up the optical photons' propagation in LS by a factor of 50 using CPU.***
  - Several minutes per event.
  - I/O is not included in the measurement.
- ***Status: a GPU version is under development.***
  - Speedup: ~200x CPU version.
  - The pre-generated response are loaded into GPU global memory only once.
  - The collected steps information are copied to GPU memory in each event.
  - The results are copied back to CPU memory.

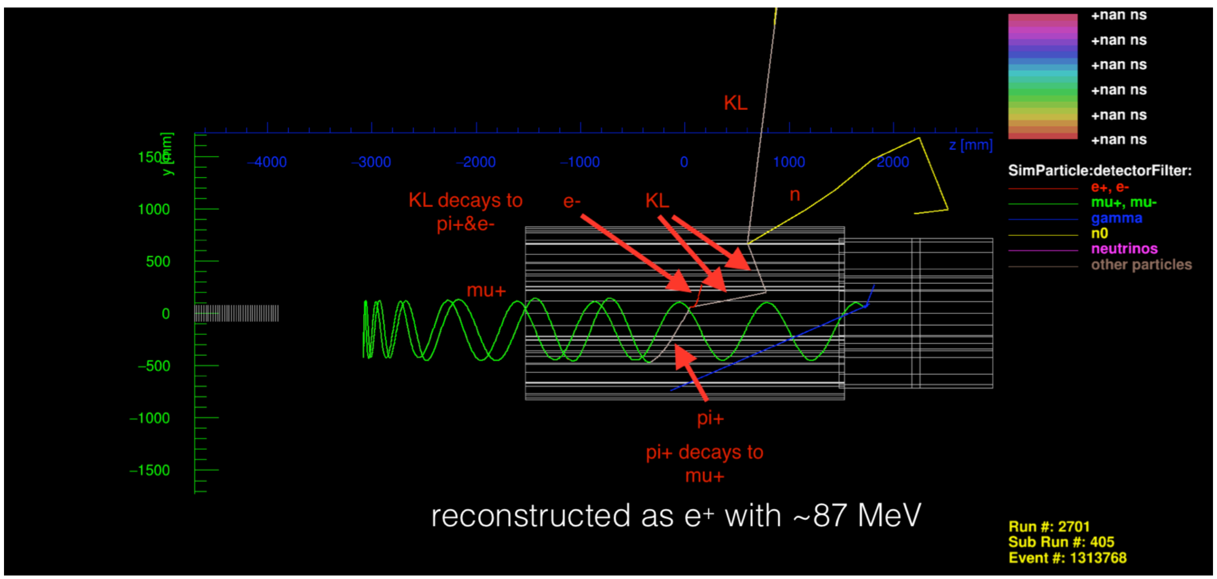






Mu2e is Using G4MT

- *Pilot project: look at cosmic ray air shower events that produce signal like tracks (with loose cuts)*
  - *Use the CRY air shower event generator*
  - *What is the rate of events that cannot be vetoed because the particle crossing the cosmic ray veto system is neutral?*

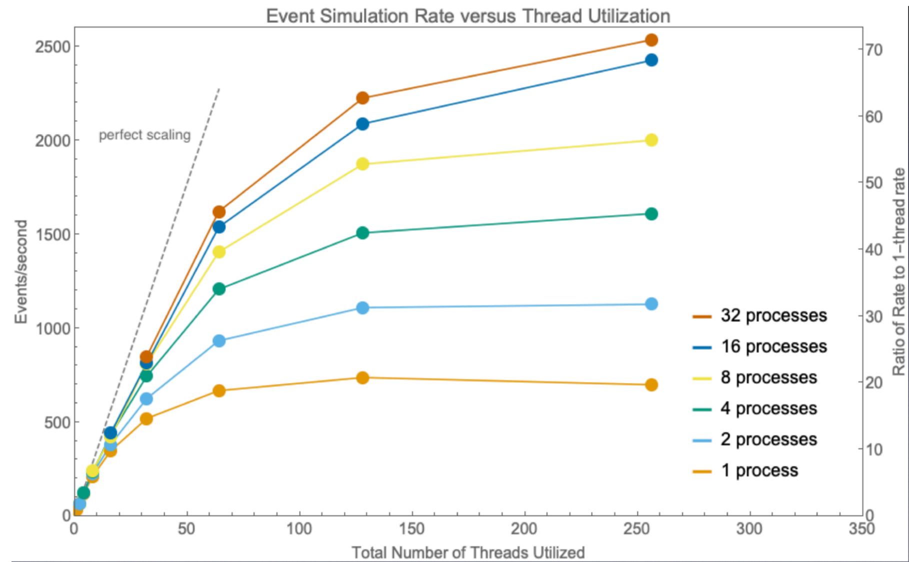


Rob Kutschke

Mu2e G4MT Technology Roadmap

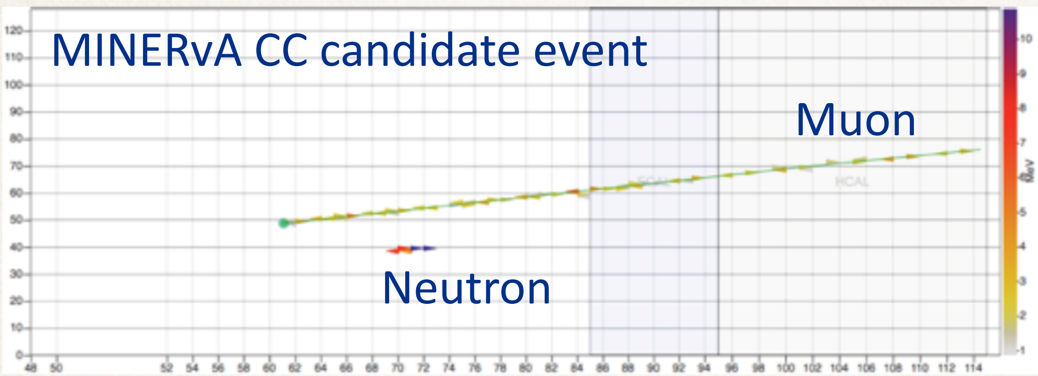
- Pilot project:
  - Runs within single threaded art v2
  - Event generator produces ~50K events
  - G4 processes all of the events MT and saves interesting ones
    - Most events are small
  - Drain the stash of processed events into art events
  - Late 2018: 750K hours on ANL BeBop (KNL and Haswell)
  - Now: now running 2.5 M hours on ANL BeBop and Theta
- Starting April
  - Port art v3 which supports MT
  - Use G4MT within art using cmssw as a model
  - Have requested 100M hours on Theta at ANL to do 3 studies one of which is the CRY cosmic ray air shower study

Scaling with Pilot Technology (~35% serial)

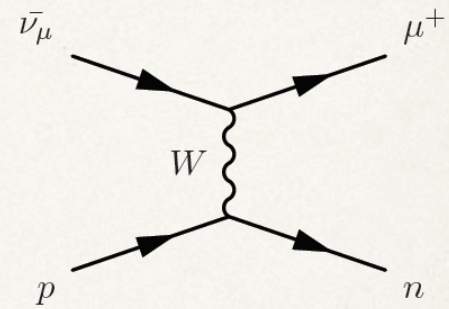


simulation of neutron response in detectors

Laura Fields



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



- one of the biggest challenges facing neutrino experiments
- final-state neutrons produced in most anti-neutrino charged current interaction
- energy deposit displaced from interaction vertex, separate de-excitation photons, inelastic scatters, etc.
- as important as proton identification for complete event reconstruction and incident neutrino energy determination - typically deposit only a fraction of their energy

Neutron simulation detectors

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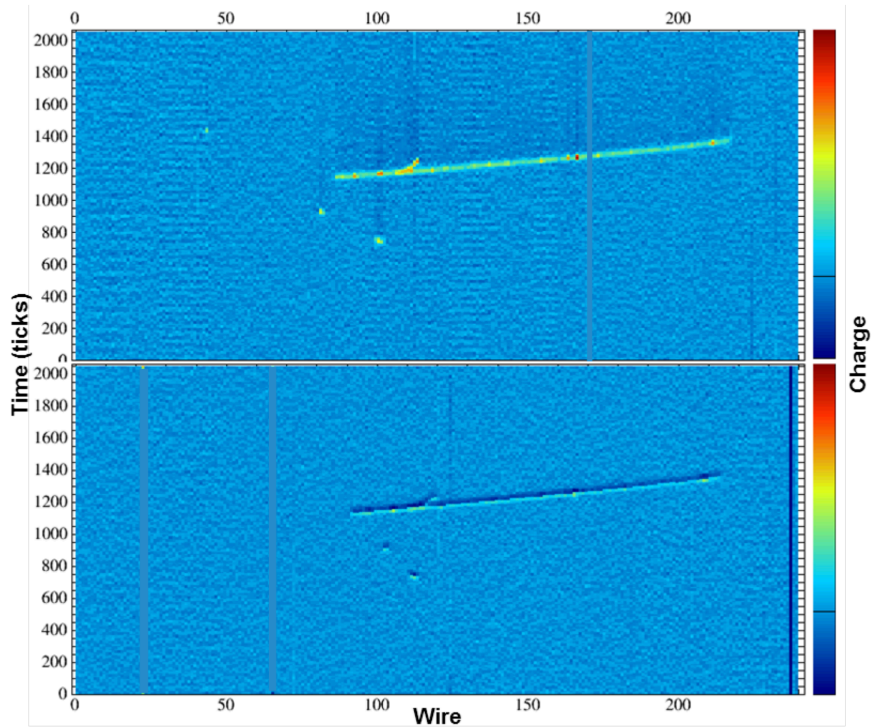
Ivan Lepetic, FNAL JETP



AgroNeuT arXiv:1810.06502v1

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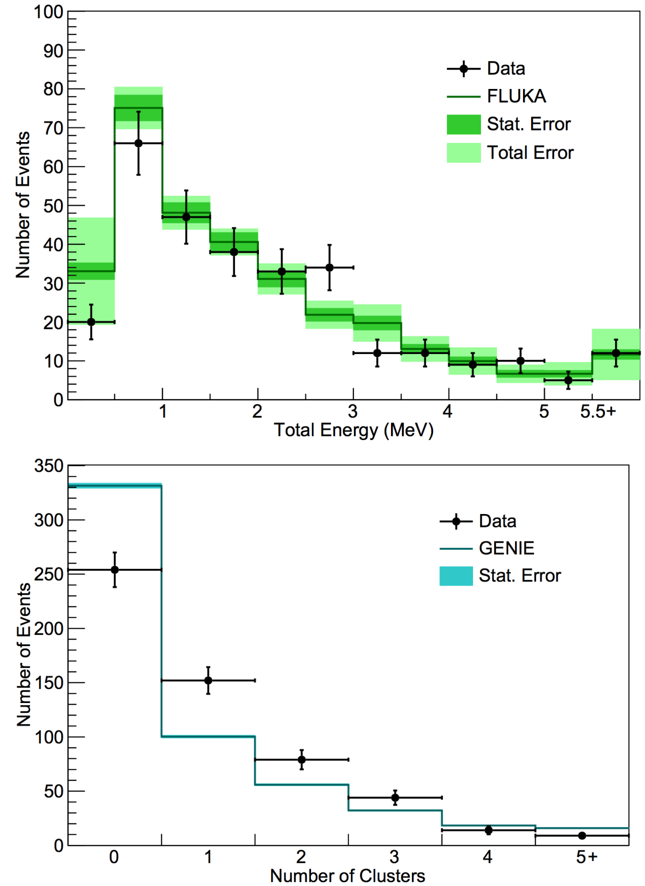
- as important as proton identification for complete event reconstruction and incident neutrino energy determination - typically deposit only a fraction of their energy

Ivan Lepetic, FNAL JETP



AgroNeuT arXiv:1810.06502v1

Conclusions

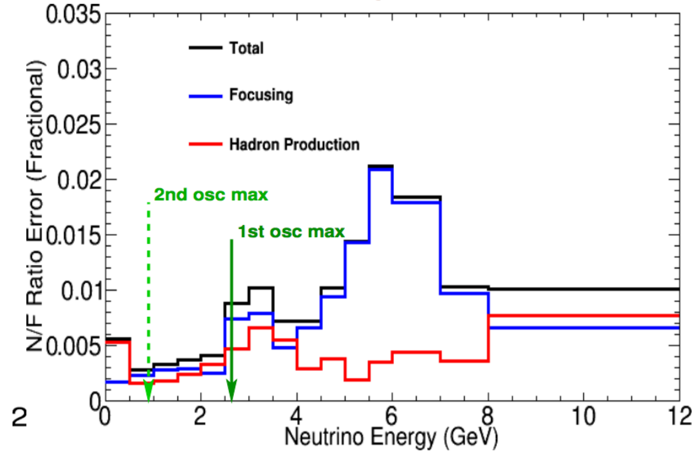
- Neutrino simulations have impact on neutrino oscillation measures at various levels and through multiple analysis pathways
- Drive to precisely measure oscillation parameters have driven increases in the beam intensity and detector size, but strong need for improvements in determination of systematic uncertainties - lean heavily on simulation with no “standard candle”
- event generation is based upon multiple models with limited ability to tune or establish uncertainties since there is no complete theory
- simulation involves wide range of scales from 100 keV to 10 GeV
- overwhelming reliance on GEANT4 tunes and physics lists that are tuned to external data (mostly designed for collider experiments)
  - branching of custom versions of GEANT4 and tunes can create difficulties for new versions
  - need to understand how we can systematically vary GEANT4 to give confidence in detector response
- need to utilize vectorized algorithms to tackle several specific problems (scintillation photons) and want to build upon the experiences and tools of other experiments

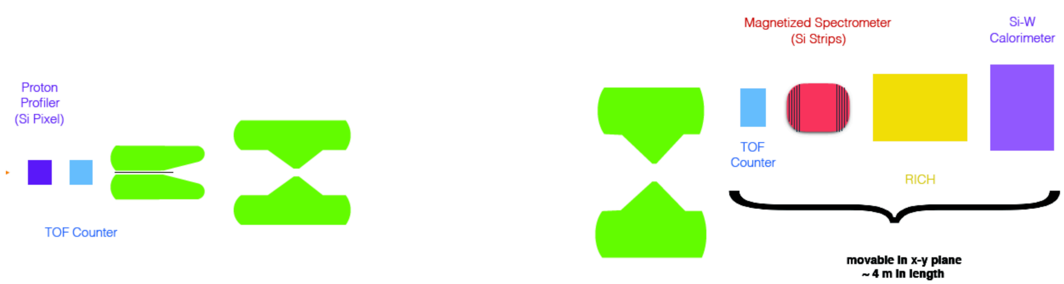
Backup

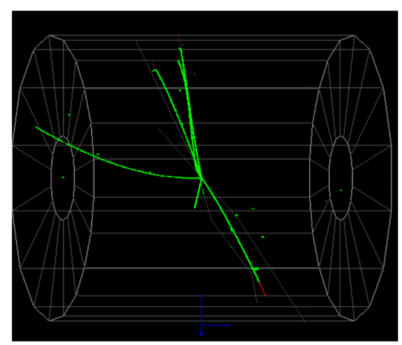
DUNE Beam simulation and Near Detector Designs

- DUNE using the PPFX for flux predictions and optimization of the horn tunings
- proposal for measuring the hadron production with replica horns at Fermilab test beam
- multiple near detector designs exist and will be an important part of the DUNE experiment

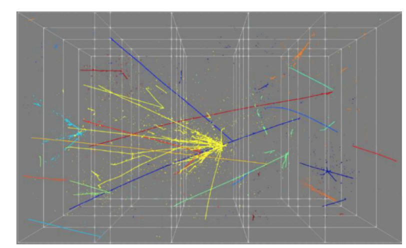
Residual uncertainty on flux at FD







ND GArTPC simulation



ND LArTPC simulation