Near Detector Optimization Task Force

Steve Brice, Daniel Cherdack, Kendall Mahn

Draft Charge to the Task Force

❑ The near detector optimization task force is charged to:

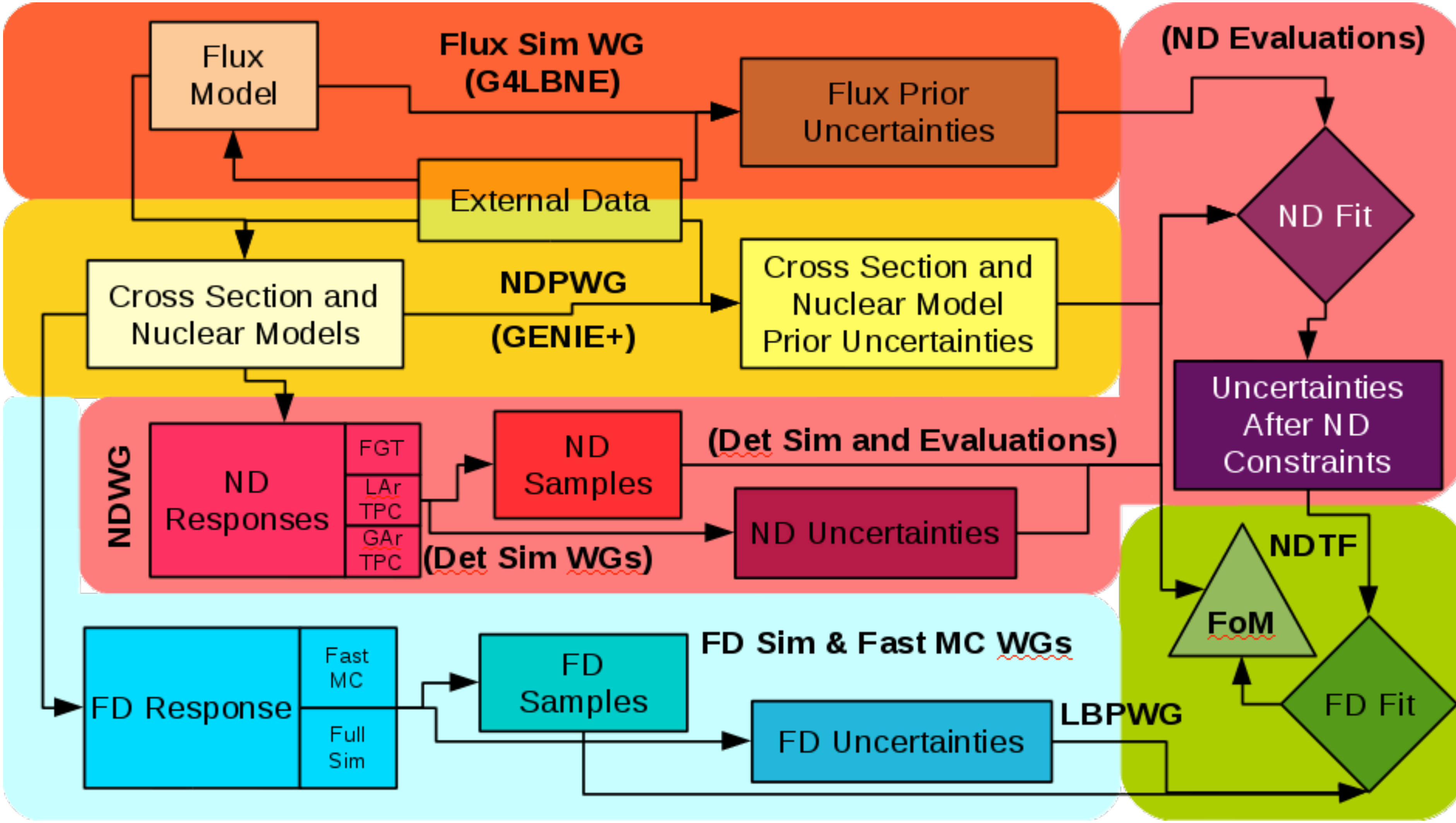
- Develop GEANT4 simulations of the reference design near detector and possible alternatives

- Perform a full end-to-end simulation connecting the measurements in the near detector to the far detector systematics using, for example, the VALOR framework

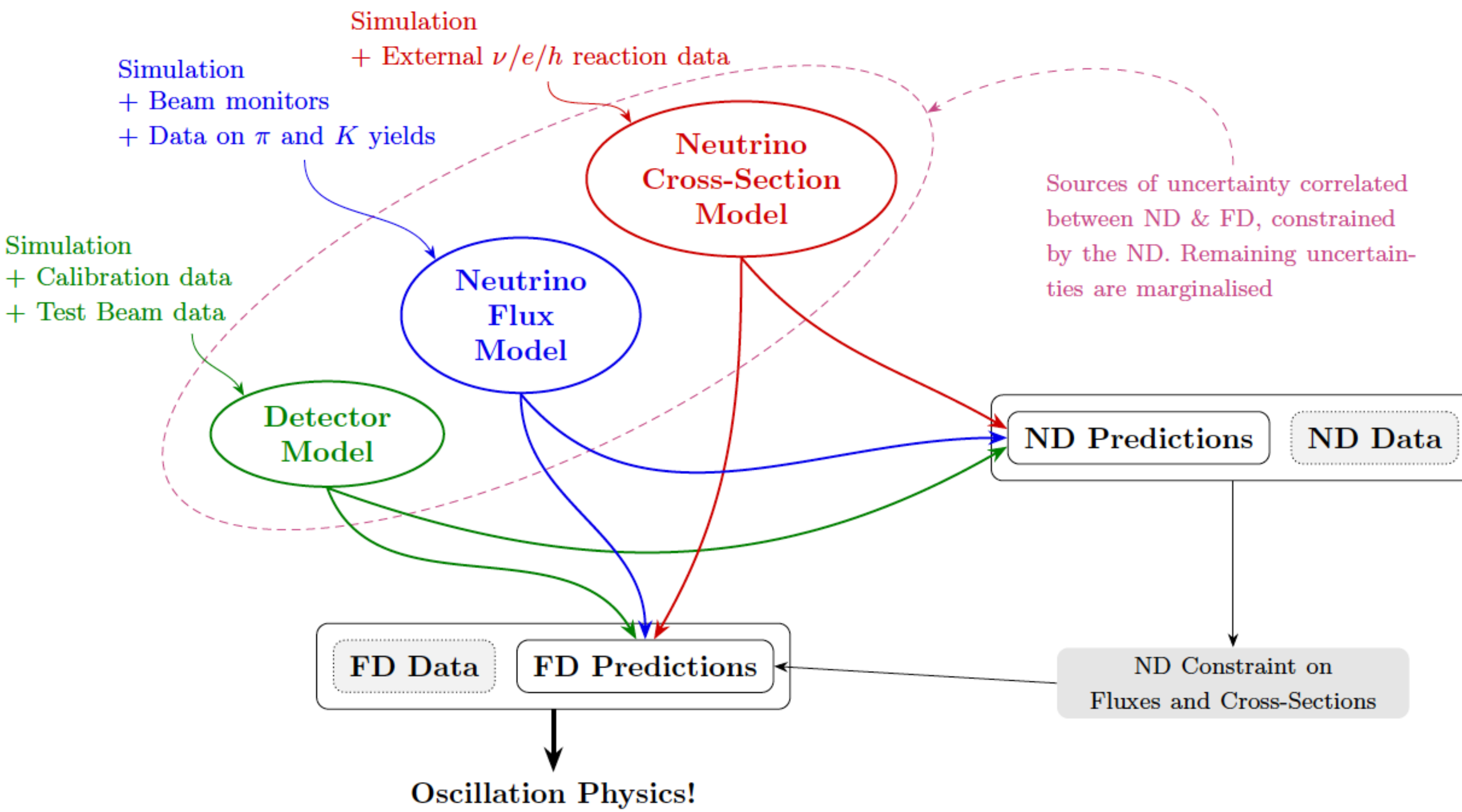
- Evaluate the potential benefits of augmenting the reference design with
  - a LAr-TPC
  - the use of a High Pressure Gaseous TPC

- Produce a first report on their findings to the DUNE Technical Board by September 2016 and a final report by March 2017.

Simulation and Analysis Path



VALOR: ND Constraints - Costas Andreopoulos



Points of Contact

Flux: Laura Fields

Infrastructure: Robert Hatcher

Cross-Section Models and Systematics: Lorena Escudero

FGT simulation: Tyler Alion & Chris Marshall

LAr simulation: Sarah Lockwitz & James Sinclair

GAr simulation: Justo Martín-Albo

VALOR: Steve Dennis & Lorena Escudero & Costas Andreopoulos

FD Simulation: Tingjun Yang & Tyler Alion

FD Fit: Daniel Cherdack

Figures of Merit: Brian Rebel

Phase 1 - focus on machinery

Sept 2015 - Jan 2016

- Milestone 1: First complete run through of the machinery (before Arlington meeting)
  - Jan 2016

Phase 2 - incrementally add the necessary physics and improve simulations

Jan 2016 - Sept 2016

- Milestone 2: 2nd run through (before SURF meeting)
  - April 2016
- Milestone 3: 3rd run through to generate material for initial report (before FNAL meeting)
  - August 2016
- Milestone 4: Initial Report
  - September 2016

Phase 3 - final improvements to the physics and simulations

Sept 2016 - Mar 2017

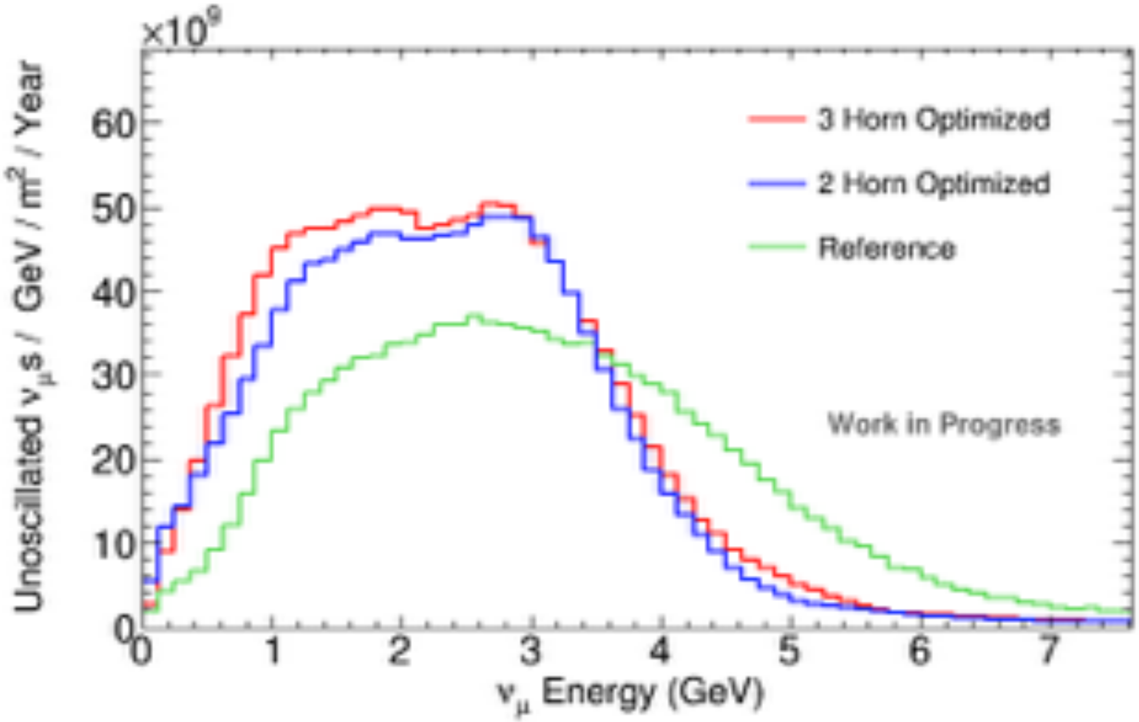
- Milestone 5: Final run through to generate material for final report (before CERN meeting)
  - December 2016
- Milestone 6: Final Report
  - March 2017

4th Run Through

- 4th Run Through almost complete

- Upgrades from 3rd Run Through
  - Significant upgrades to the reconstruction modeling in all three ND options
  - Significant upgrade to the quality of the detector uncertainties
  - Increased number of MC events generated to be ~1 year’s worth
  - Small upgrades to cross-section model

The Flux Prediction - Laura Fields



Upgraded to Laura's optimized flux for the 3rd Run Through
No change for 4th Run Through

ND Task Force Approach to Reconstruction

"Cheating but not lying"

- We have a generic problem across the 3 ND options and the FD -

  "How do you provide the best mimic of the reconstruction and PID algorithms we will have 10 years from now?"

  1) Use the best algorithms we have now
  2) Use our experience with past detectors and algorithms to appropriately smear truth quantities

- For all 4 reconstruction efforts (3ND + 1FD) we are evaluating each required observable individually, and:
  - Use 1) whenever practical, although this may be limited, esp for the 3 ND options
  - Use smearing that is well informed by studies of the full GEANT4 simulations and consistent with 2)
  - Rely upon 2) fully when extracting relevant information from the full GEANT4 simulations presents difficulties beyond the scope of the TF

A Priori Uncertainties - VALOR (Lorena Escudero)

VALOR DUNE ND+FD fit

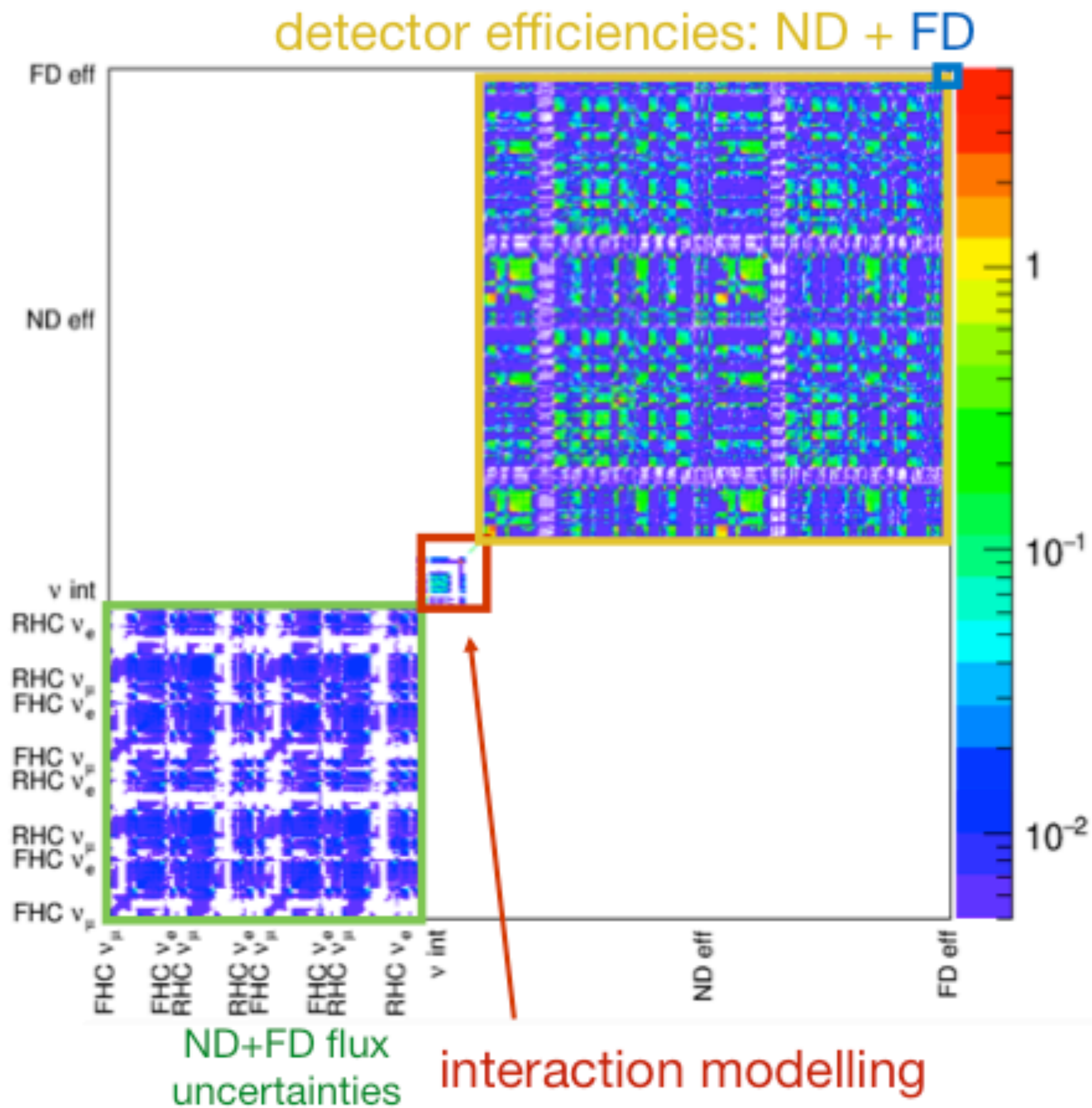
4th Pass Through

Total covariance matrix with prior uncertainties, input to the ND fit:

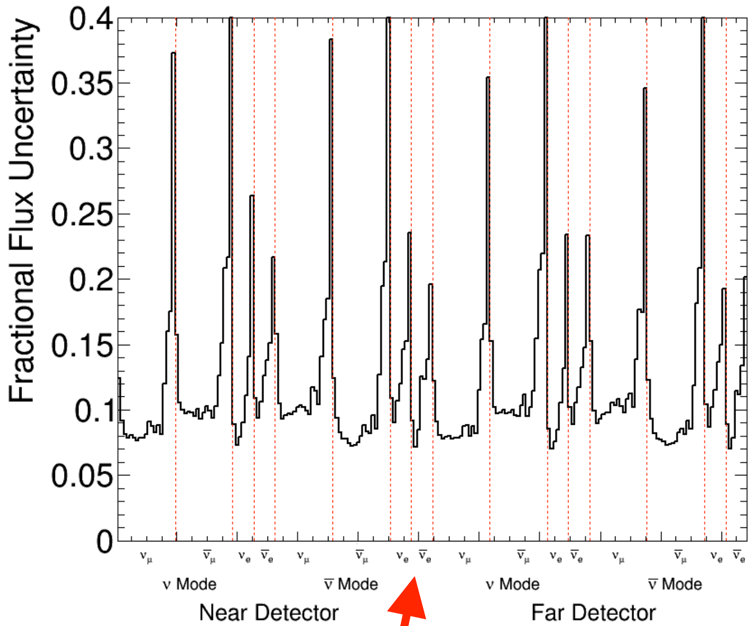
567 parameters

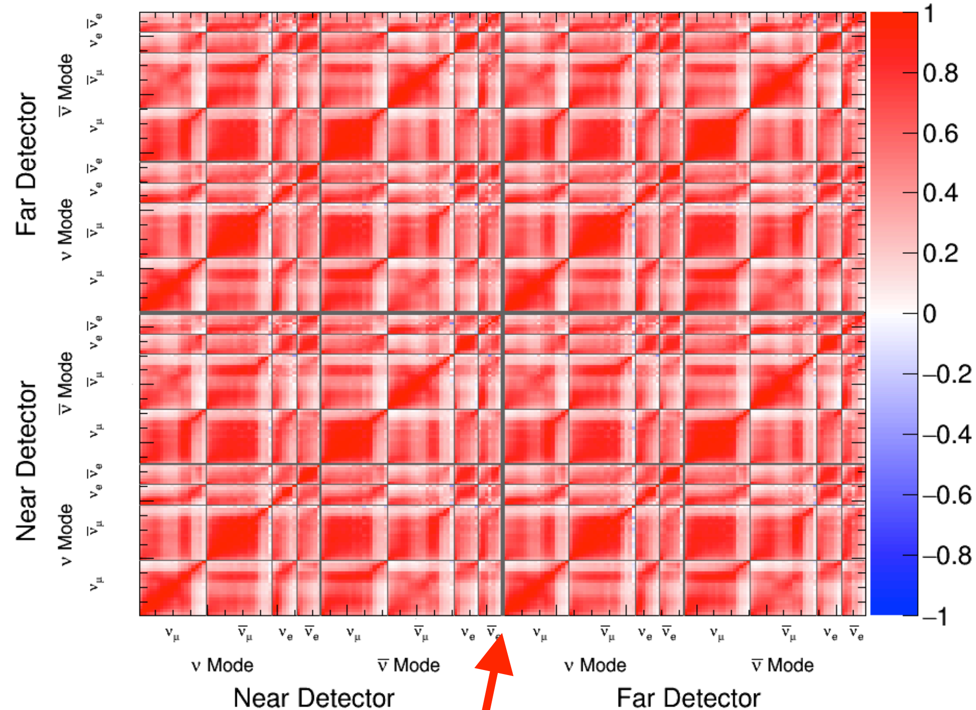
- 104+104 flux uncertainties (ND+FD)
- **45** interaction model uncertainties
- **310 ND efficiencies**
- 4 FD efficiencies

+ 6 osc parameters



A Priori Flux Uncertainties - Laura Fields





Flux Errors

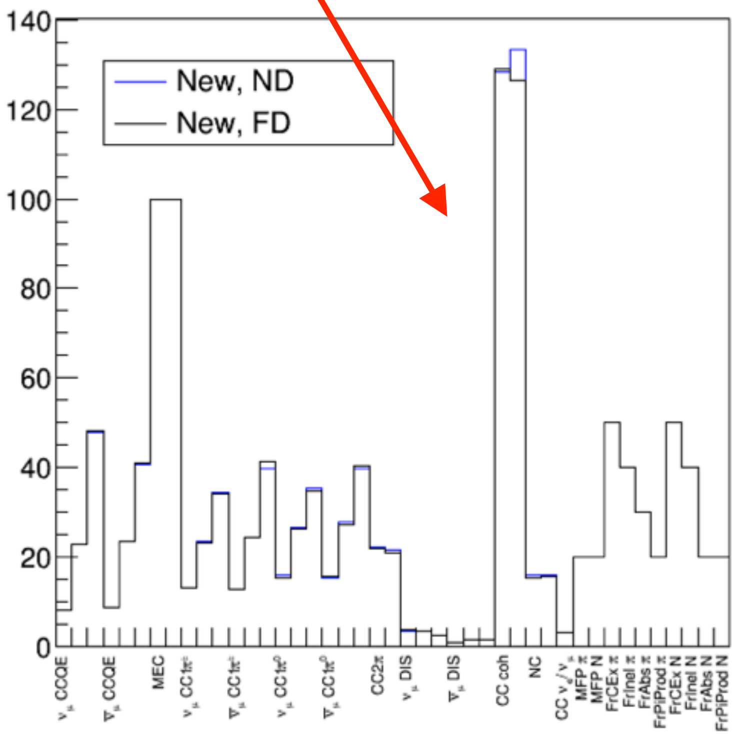
Flux Correlation Matrix

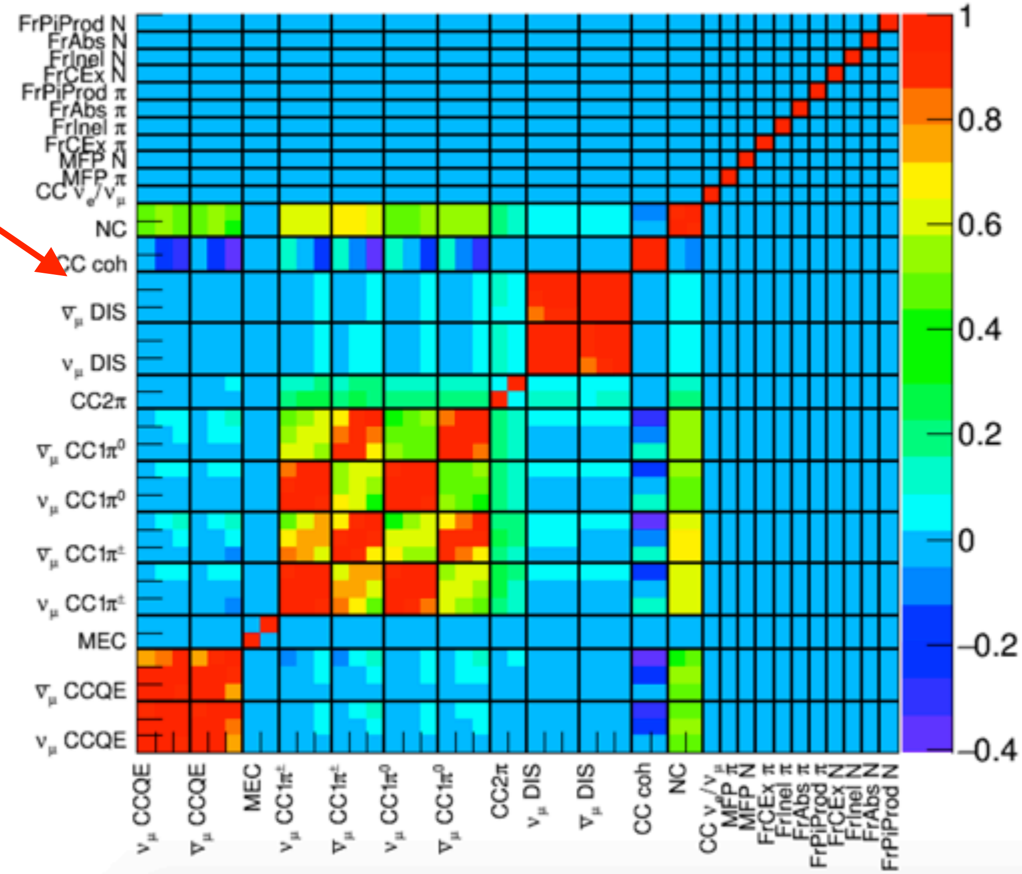
- Unchanged from 3rd run-Through

A Priori Cross-Section Uncertainties - VALOR (Lorena Escudero)

Correlation matrix

1σ uncertainties





- Unchanged form 3rd Run-Through (besides a couple of small changes)

A Priori Detector Uncertainties - VALOR (Lorena Escudero)

We want to translate the effect of the difference sources of detector uncertainties into the values of the observables measured

- VALOR fits are done in the observables E_ν and y in different samples
- Dan Cherdack developed a re-weighting code which is
    - Adding uncertainty to the measured particle momentum
        - Separately for lepton system and hadronic system
        - Then compute $E_\nu = E_{lep} + E_{had}$ and $y = E_{had}/E_\nu$
    - Applying uncertainty on particle reconstruction efficiency
        - A different number of reconstructed particles in an event will change the sample to which it is assigned
- Then by throwing different random values of these uncertainties we can build a covariance matrix for detector efficiencies

VALOR - Lorena Escudero, Steve Dennis, Costas Andreopoulos

A joint VALOR fit considers simultaneously:

- A flexibly-defined **set of detectors d**. *eg*, $d \in \{$ *FGT ND, SP-FD, DP-FD* $\}$.
- A flexibly-defined **set of beam configurations b** (for each d). *E.g.* $b \in \{FHC, RHC, ...\}$
- A flexibly-defined **set of event selections s** (for each d and b). *E.g. see page 9.*

For each (d,b,s):

- Experimental information is recorded in a number of **multi-dim. reco. kinematical bins r** *E.g.* $r \equiv \{ E_{\nu;reco} \}, \{ E_{\nu;reco}, y_{reco} \}, \{ p_{\ell;reco}, \theta_{\ell;reco} \}, \{ E_{vis;reco} \}, ...$

Our predictions for

- a set of **interesting physics params** $\vec{\theta}$ (*e.g.* $\{\theta_{23}, \delta_{CP}, \Delta m^2_{31}\}$), and
- a set of O(10^2)-O(10^3) **systematic (nuisance) params** $\vec{f}$

are constructed as follows:

systematics

physics

true interaction mode

true kinematics

$$\boxed{n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f})} = \sum_m \sum_t \boxed{P_{d;b;m}(t;\vec{\theta})} \boxed{R_{d;b;s;m}(r,t;\vec{f})} \cdot \boxed{T_{d;b;s;m}(r,t)}$$

Predicted number of events

reconstructed kinematics

Oscillation probabilities

Systematic parameters variations

Nominal unoscillated number of events

VALOR Samples - Steve Dennis

A simultaneous oscillation and systematics constraint fit

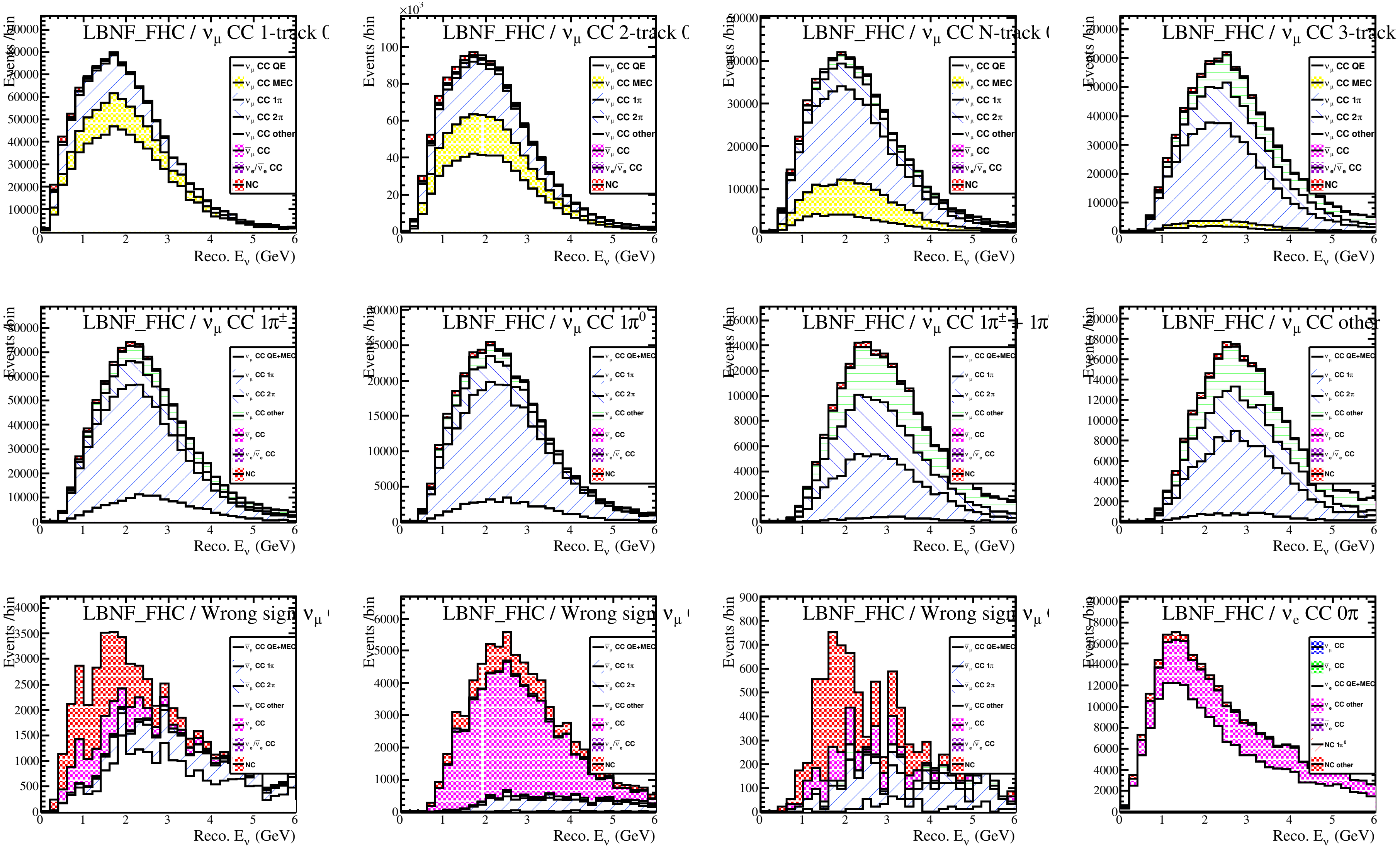
VALOR is a **multi-channel analysis** - The current version considers **46 ND samples** and **8 FD samples**:

- ν_μ CC
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π (μ^- + ($>$1) nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+ +$ p, $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm + X$)
  6. $1\pi^0$ ($\mu^- + 1\pi^0 + X$)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0 + X$)
  8. Other
- **Wrong-sign** ν_μ **CC**
  9. 0π ($\mu^+ + X$)
  10. $1\pi^\pm$ ($\mu^+ + \pi^\pm + X$)
  11. $1\pi^0$ ($\mu^+ + \pi^0 + X$)
  12. Other
- ν_e CC
  13. 0π ($e^- + X$)
  14. $1\pi^\pm$ ($e^- + \pi^\pm + X$)
  15. $1\pi^0$ ($e^- + \pi^0 + X$)
  16. Other
- **Wrong-sign** ν_e **CC**
  17. Inclusive
- **NC**
  18. 0π (nucleon(s))
  19. $1\pi^\pm$ ($\pi^\pm + X$)
  20. $1\pi^0$ ($\pi^0 + X$)
  21. Other
- ν**-e**
  22. $\nu_e + e^-$ elastic
  23. Inverse μ decay $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$ and annihilation channel $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

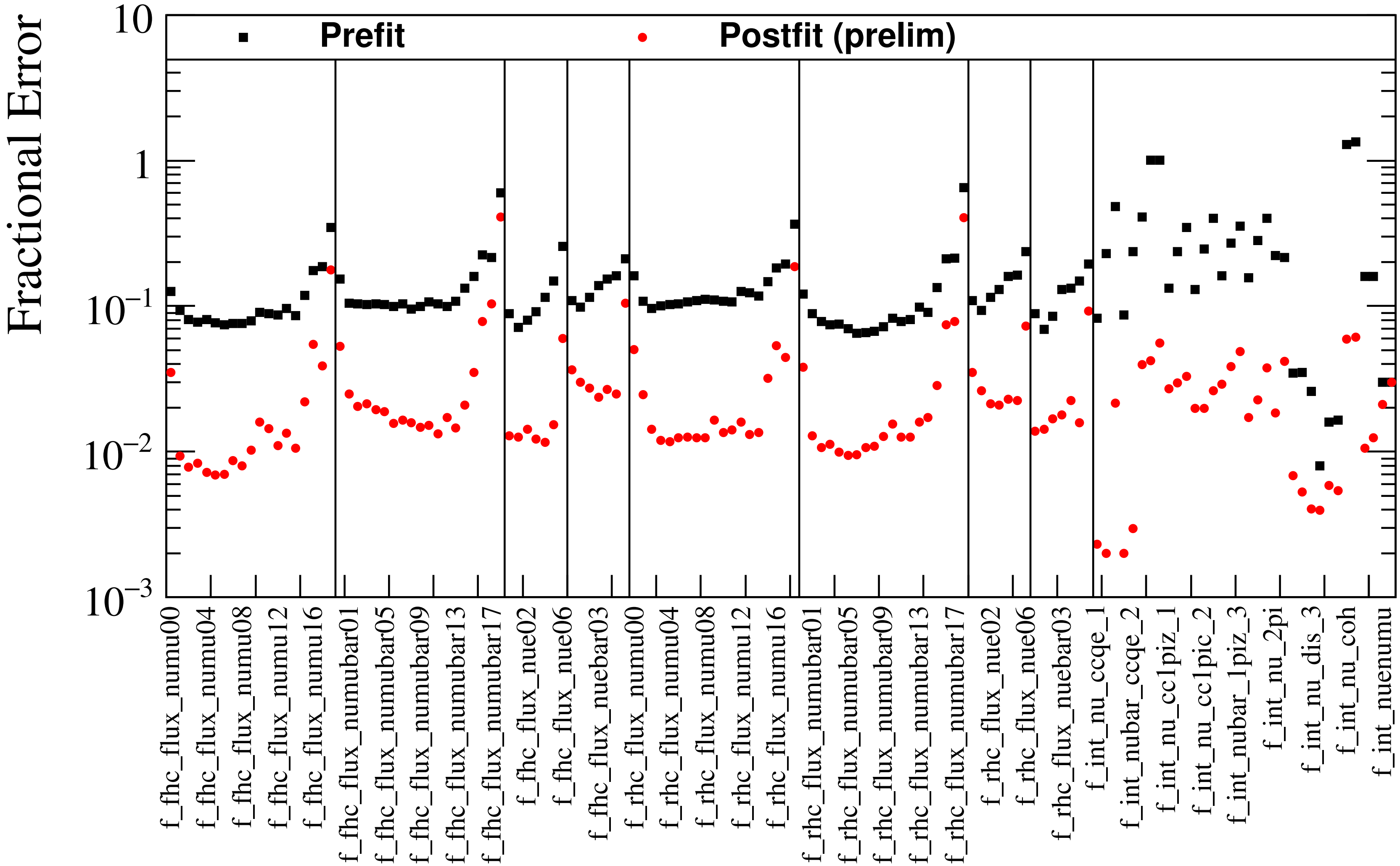
and a similar set of 23 samples for the RHC (antineutrino enhanced) beam configuration.

The utility of additional samples in reducing systematic uncertainties is being investigated in tandem with the development of improved systematic error / physics parameterizations.

Example of VALOR Samples: FGT, Neutrino Mode

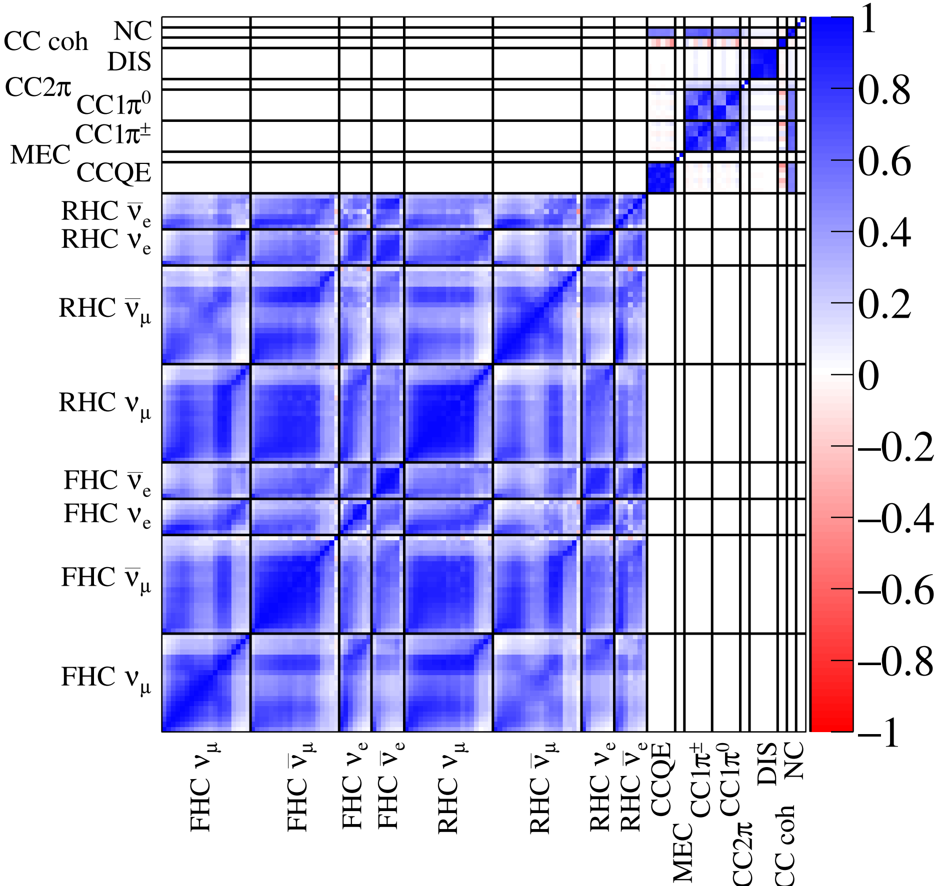


The FGT Output Uncertainties - Steve Dennis

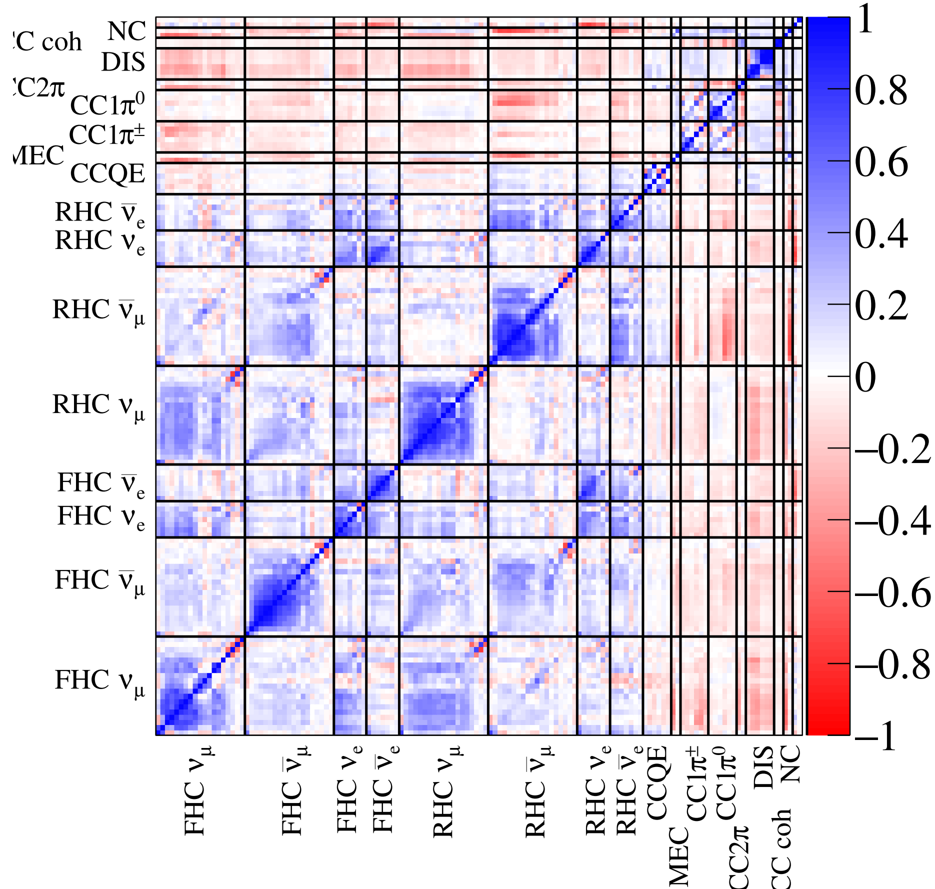


Preliminary

The FGT Output Correlation Matrix - Steve Dennis



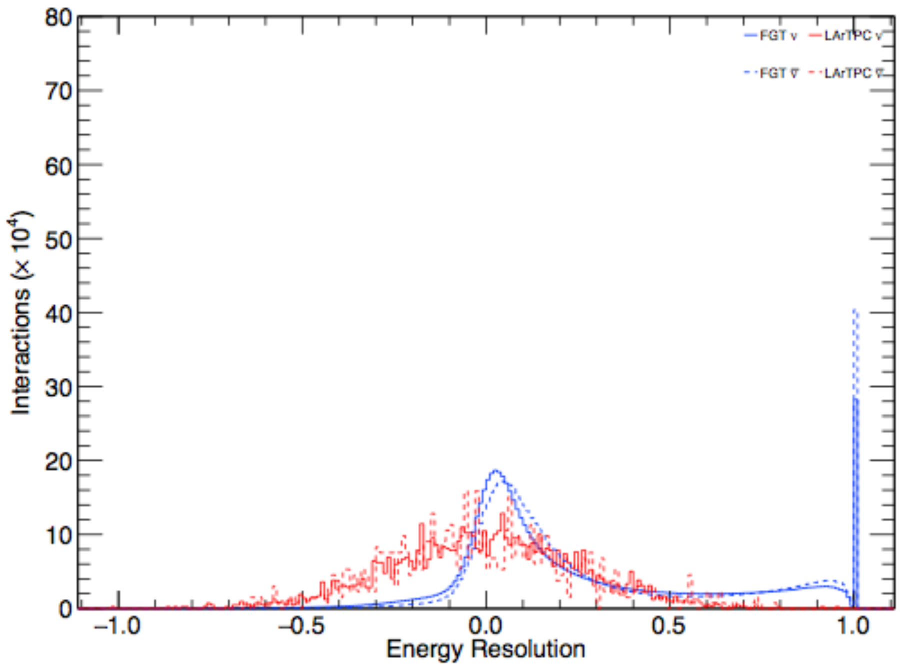
Pre-fit
correlation matrix



Post-fit FGT
correlation matrix

Very Preliminary!

Figures of Merit - Brian Rebel



How the Detectors Enable Oscillation Physics

- Sensitivity to δCP using each of the ND options

How the Detectors Perform in the Beam

- Number of interactions per POT
- Pile-up in detector due to beam intensity
- Fraction of energy shared between neutrino interactions in the same beam spill
- Fraction of energy shared between cosmic rays and neutrino interactions

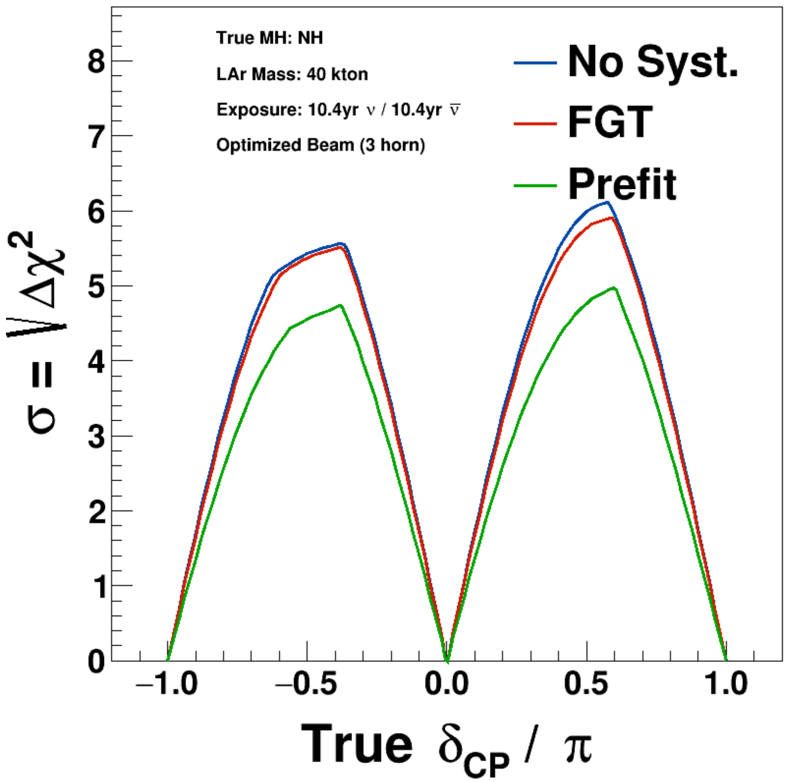
How the Detectors Enable Physics Generally

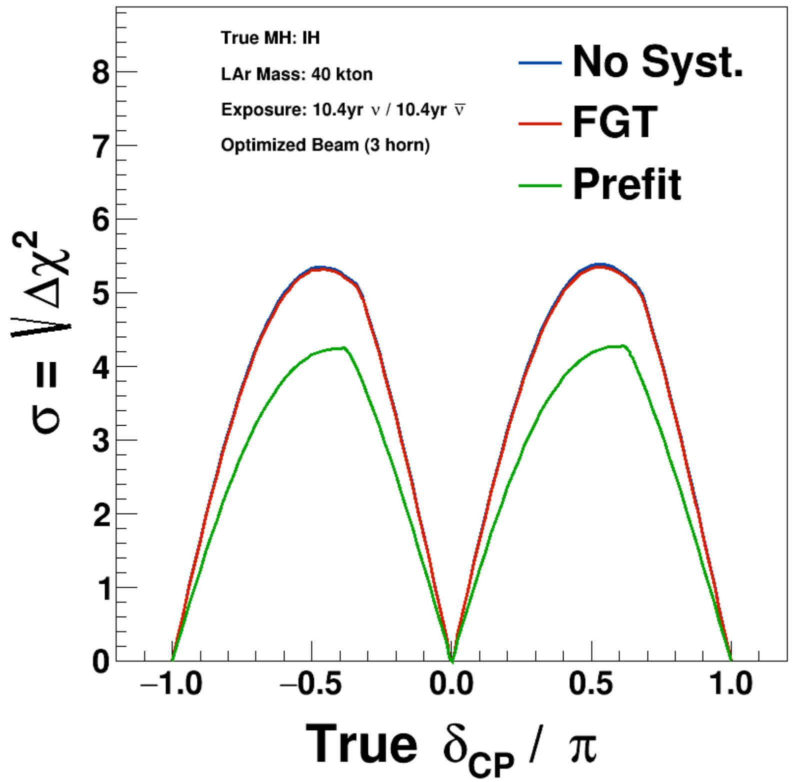
- Vertex position resolution of the detector (can we tell which nuclear target was struck)
- Energy resolution for
    - EM & Hadronic showers
    - Minimum ionizing particles
    - Total neutrino interaction
- Acceptance of final state particles as a function of energy and direction
- Fraction of neutrino interactions on each species of nuclear target
- Fraction of energy contained in the detector as a function of the vertex distance from detector edge
- Purity for distinguishing different interaction types as a function of energy
- Energy thresholds for observing different particle species (p, n, π)

Fit Results – Dan Cherdack, Steve Dennis

- ND inclusion is better than just prior knowledge on flux, cross section
- Fit done to FD with LOAF, and combined ND+FD done in VALOR

Preliminary





Practical next steps for ND TF

- The task force report is almost complete

- The work of the task force will be continued by
  - The Long Baseline WG with Dan Cherdack added as a new leader
  - The ND simulations will be taken up by the Near Detector WG

Outstanding questions and future lines of inquiry

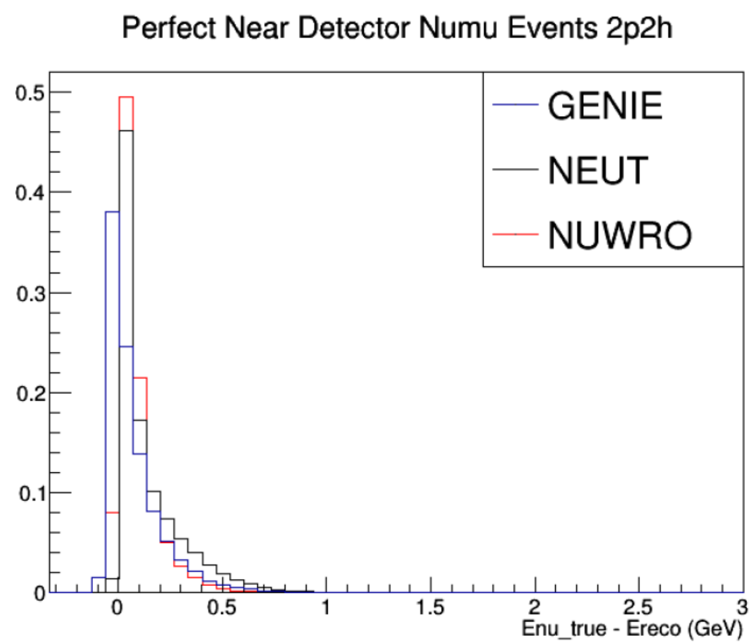
- The cheated reconstructions need to be systematically replaced by complete reconstructions

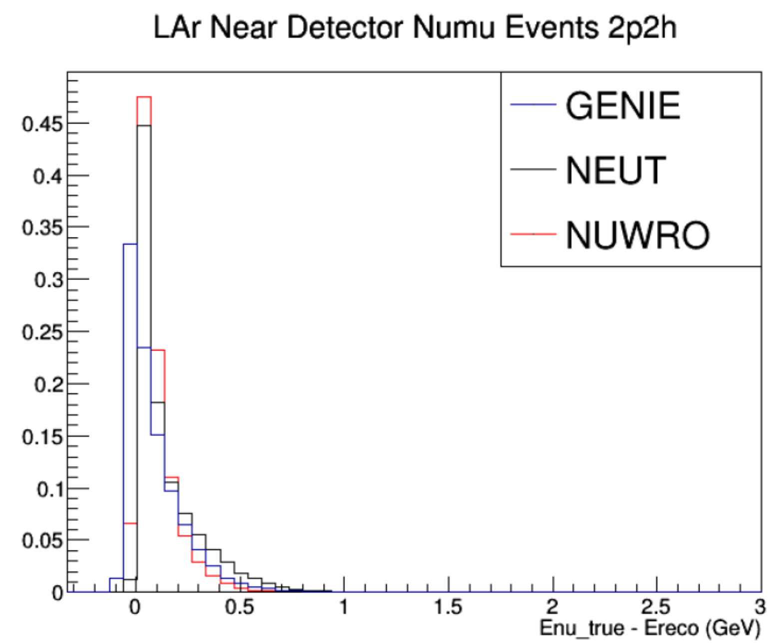
- Simple studies to validate TF results and clarify needs of ND program
  - Complexity required to address requirement of few percent level uncertainties and clarify assumptions
  - ND samples available for study thanks to TF for use!
  - Discussion of possible studies today, dedicated session

Example “simple study” of cross section model (doc 2835v1)

- Investigate current QE and 2p2h parameterization with alternate models
- Clarify the effect of acceptance on model. Example: CCQE model coverage decreases for FGT after ND TF selection
- Role of thresholds: Example: proton detection threshold not so critical for energy reconstruction

Preliminary





Summary

- 4th Run Through almost complete, along with task force report

- The work of the task force will be continued by The Long Baseline WG and Near Detector WG
  - Time to reflect, validate and question what has been learned so far
  - Ability to do this thanks to framework developed by TF

Backups

1st Run Through

- 1st Run Through completed in January 2016

- As promised not much physics, but a great deal learned about making the whole processing chain work
  - Can handle error matrices of size O(100)
  - Detector geometries up to scratch
  - Understand event simulation rates
  - Simulations able to communicate with VALOR
  - VALOR output works in Final Fit
  - Able to properly correlate systematics in near and far detector
  - ….

- 1st Run through described in detail in 18 page doc

https://docs.google.com/document/d/1TfXRqqIc2Xj4j2_GucaDqG9F30Q3xdT6Czxs30mEXXQ/edit#heading=h.sudj0au3oi0p

2nd Run Through

- 2nd Run Through completed in May 2016
- Upgrades from 1st Run Through
  - Flux and Flux errors unchanged
  - Small geometry upgrades to the 3 detectors
  - Cheated detector reconstructions implemented
  - First pass at ND sample selection defined and used
  - Cross-section uncertainties defined and *a priori* error matrix formed
  - VALOR fully run to produce output error matrices constrained by ND simulated data
  - Far detector PID improved
  - Far detector fit finished and benchmarked against CDR fits
  - Thought started on Figures of Merit
- 2nd Run Through being described in detail in

https://docs.google.com/document/d/1CNEO8xW06ooCEG3YG0AKtUdvLFuWO3GN-wGLEwdetO0/edit#

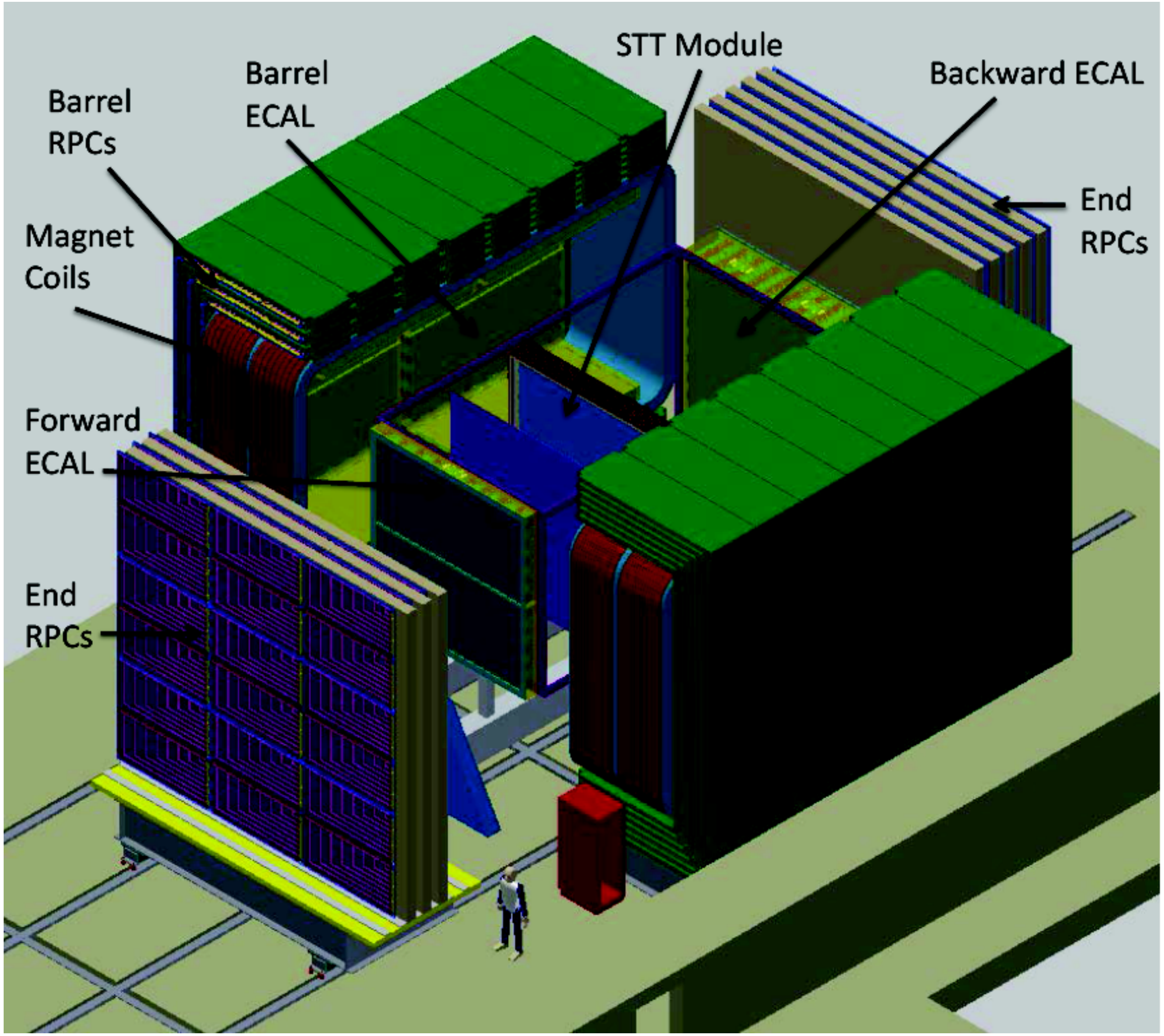
3rd Run Through

- 3rd Run Through completed in October 2016

- Upgrades from 2nd Run Through
  - Implemented Laura’s new optimized flux + flux uncertainties
  - Conducted an outside review of our approach to cross-section uncertainties (though the results of this review have yet to be incorporated)
  - Mixed cosmic ray and rock interaction events into the ND samples
  - Improved recon and cheating algorithms for all three ND options
  - Fixed the issue with 2nd run through VALOR fits
  - Produced plausible constrained error matrices from ND options (need work to move from plausible to solid)
  - Implemented almost completely full recon + PID for far detector
  - Produced a set of figures of merit

- 3rd Run Through described in detail in https://docs.google.com/document/d/1OarI91-vwgTIMS2Lm8ydLMxnISd_P0IthjkVoiqefCo/edit#

FGT Simulation – Chris Marshall



- Straw tube tracker (STT), surrounded by 4π ECAL and muon ID
- Special target modules of Ar pressurized to 140 atm
- See B. Bhuyan's talk from Sunday

FGT Reconstruction and PID – Chris Marshall

Status as of Run-Through 3

- **Simulation**
  - GENIE 2.10+GEANT4 energy deposits in active materials
  - One interaction per spill, tracker only, no pile-up
- **Reconstruction**
  - Tracks found if particle hits minimum number of straw tubes
  - “Reco” momentum smeared based on NOMAD
  - Perfect Particle ID
- **Event Selection**
  - Used full tracker (mostly Carbon)

FGT Reconstruction and PID – Chris Marshall

Status as of Run-Through 4

- **Simulation**

  GENIE 2.10+GEANT4 energy deposits in active materials

  Fixed POT per spill, pile-up in ECAL included

- **Reconstruction**

  Bug fix for improved tracking thresholds

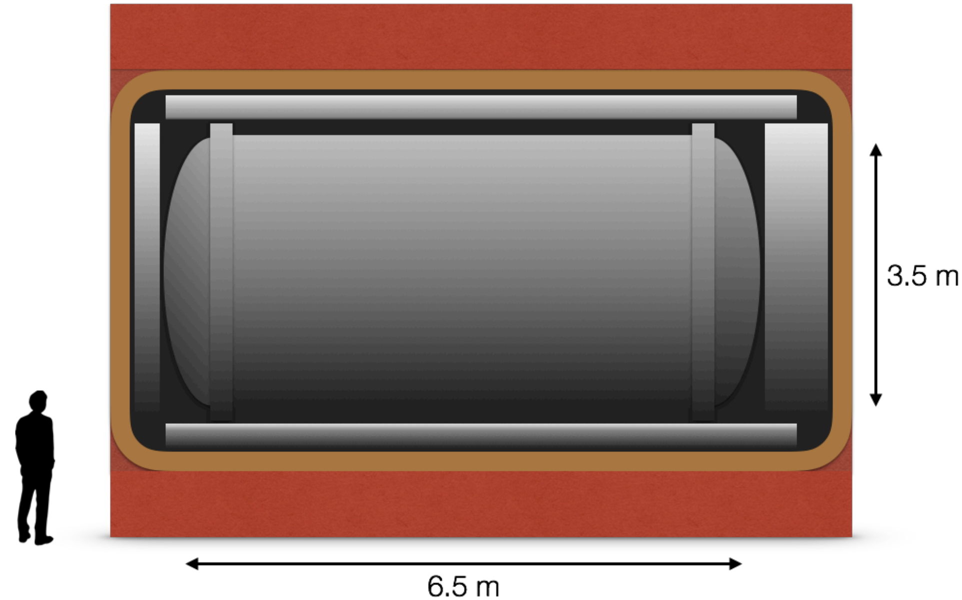
  "Reco" momentum smeared based on NOMAD

  PID based on dE/dx for hadrons, MuID and ECAL energy profile for muons, NOMAD TR table for electrons

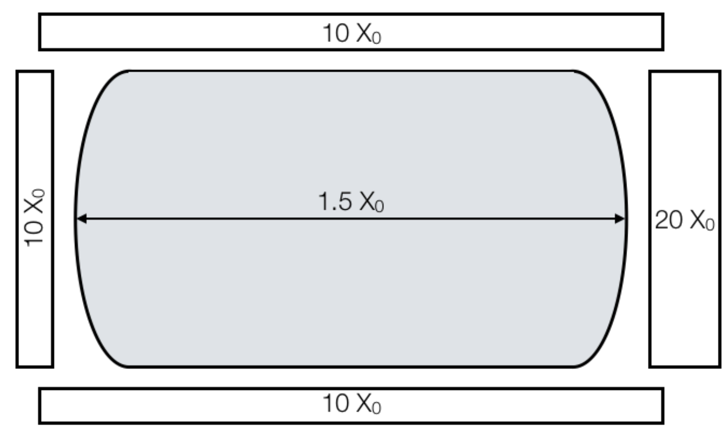
- **Event Selection**

  Used Ar only for most event categories

GAr TPC Reconstruction Scheme - Justo Martín-Albo



- **1 tonne of gaseous Argon at 10 bar**
- **Expected statistics per year:**
  nu mode: O(1M) CC events
  nubar mode: O(0.3M) CC events
- **Titanium alloy vessel (UNS-R56323)**
  thickness: barrel, 9 mm (0.25X_0),
  endcaps, 17 mm (0.5X_0)
  mass: ~13 tonnes.



X_0 (Ar) = 19.55 g/cm^2 –> 6.3 m @ 10 bar (16.11 kg/m^3): ~0.5 X_0
X_0 (Ti) = 3.6 cm –> 1.7 cm (x2) = ~0.5 X_0 (x2)

GAr TPC Reconstruction - Justo Martín-Albo

Momentum Resolution

~2.5% dominated by mult. scattering

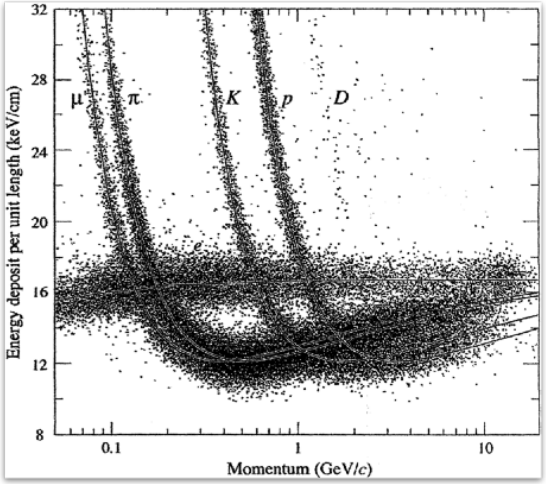
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_T\, p_T}{0.3\, B\, L^2}\sqrt{\frac{720}{N+4}} + \frac{0.05}{B\, L}\sqrt{\frac{1.43\, L}{X_0}}$$

$$\sigma_\theta = \frac{\sigma_L}{L}\sqrt{\frac{12\,(N-1)}{N\,(N+1)}} + \frac{0.015}{\sqrt{3}\, p}\sqrt{\frac{L}{X_0}}$$

$$(p_T = p\,\sin\theta)$$

For tracks of length L and with N measurements.
Resolution better than 5% for long 1-GeV tracks.

R.L. Gluckstern, NIM **24** (1963) 381



PEP-4 TPC
(~3%)

$$\sigma_E(25\ \mathrm{keV}) \simeq 10\%$$

(Energy of short, contained tracks can be measured by range.)

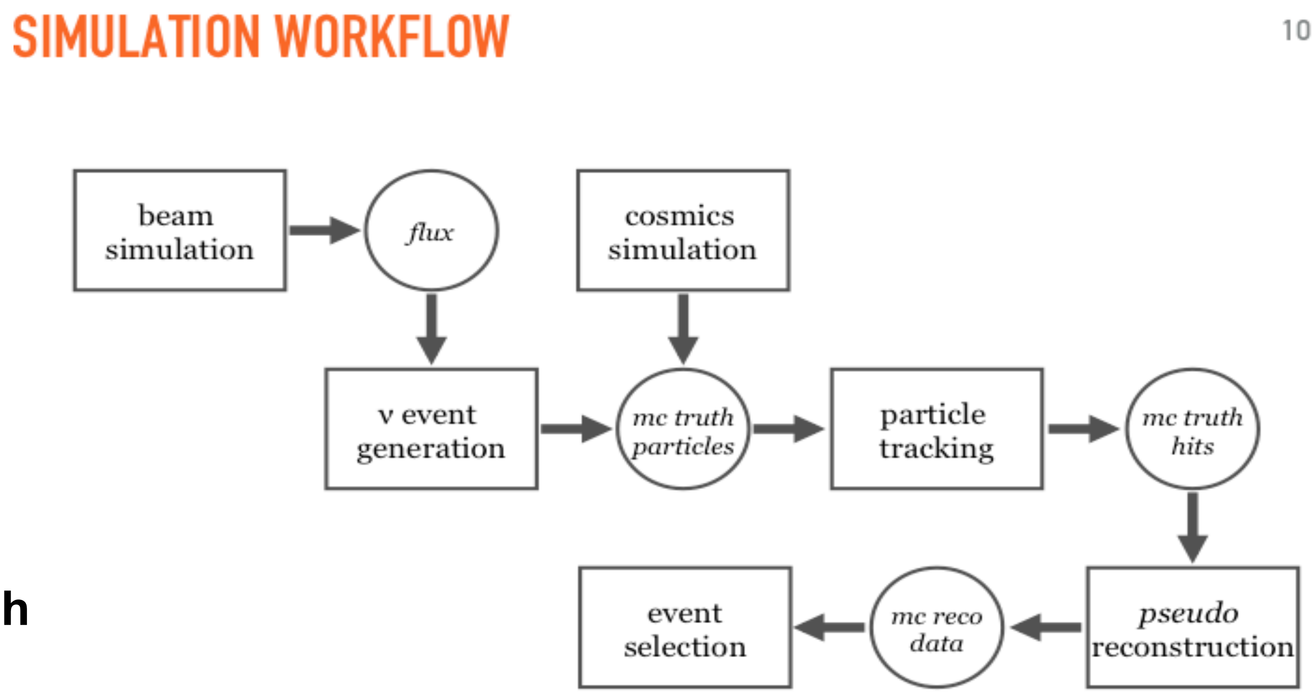
$$\sigma(\mathrm{d}E/\mathrm{d}x) = 0.41\ N^{-0.43}(N\ P)^{-0.32}$$

Empirical formula for Ar.
Resolution better than 5% for our conditions.

PID

Good separation of muons (pions), kaons, protons using dE/dx measurement in TPC.

GAr TPC Reconstruction - Justo Martín-Albo



4th Run-Through

- Changes in particle identification and track selection with respect to previous MC production to improve realism of pseudo-reconstruction.

- Several parts of reconstruction still cheated. Improving beyond this would require full, real reconstruction. Not planned for ND-TF.

LAr Simulation - James Sinclair & Joseph Zennamo

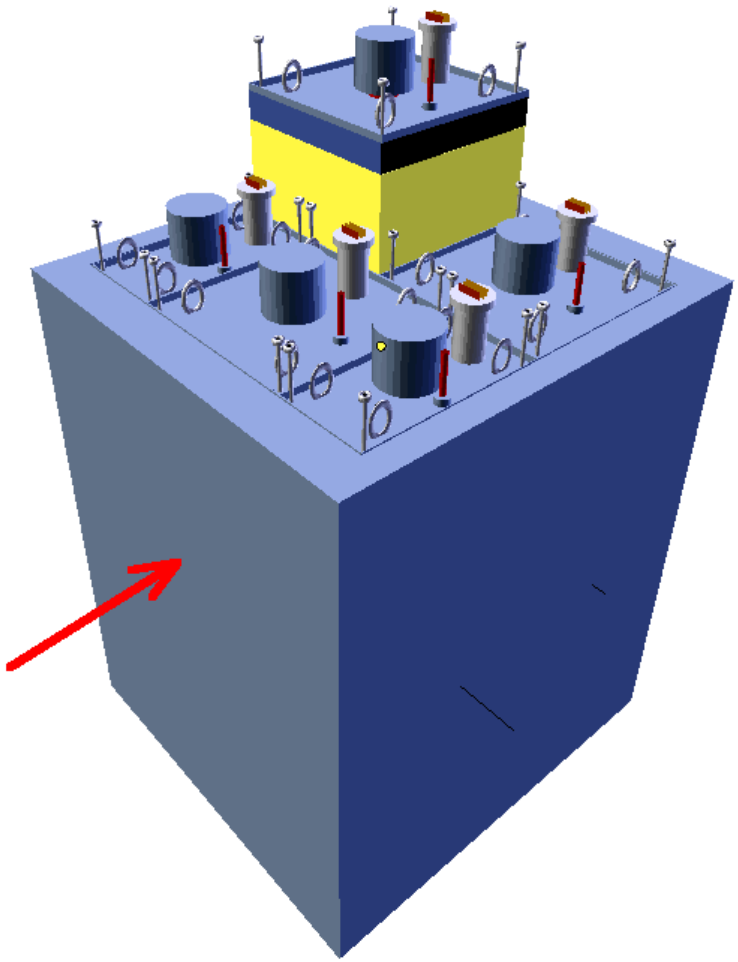
Modular TPC total 6 m x 8 m x 3 m, ~ 200 t

Each module 2 m x 2 m x 3 m.

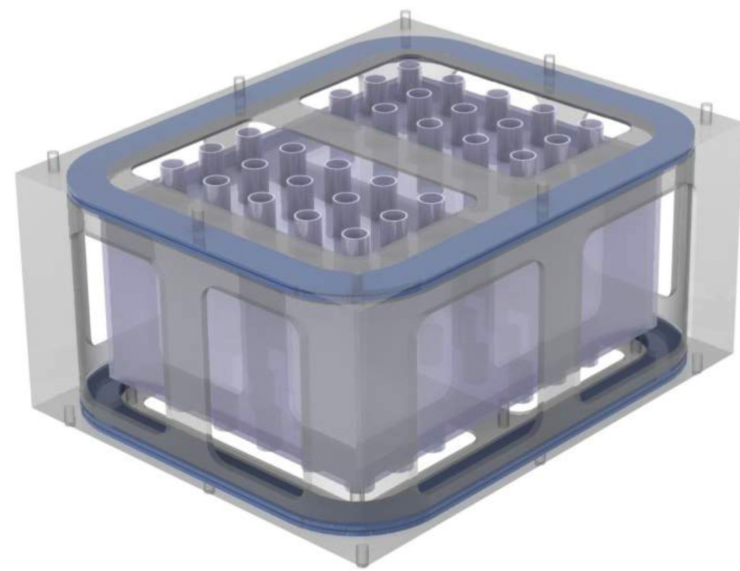
1 m drift length

E-Field 100 kV (1 kV/cm)

Superconducting Helmholtz, B-field 1T



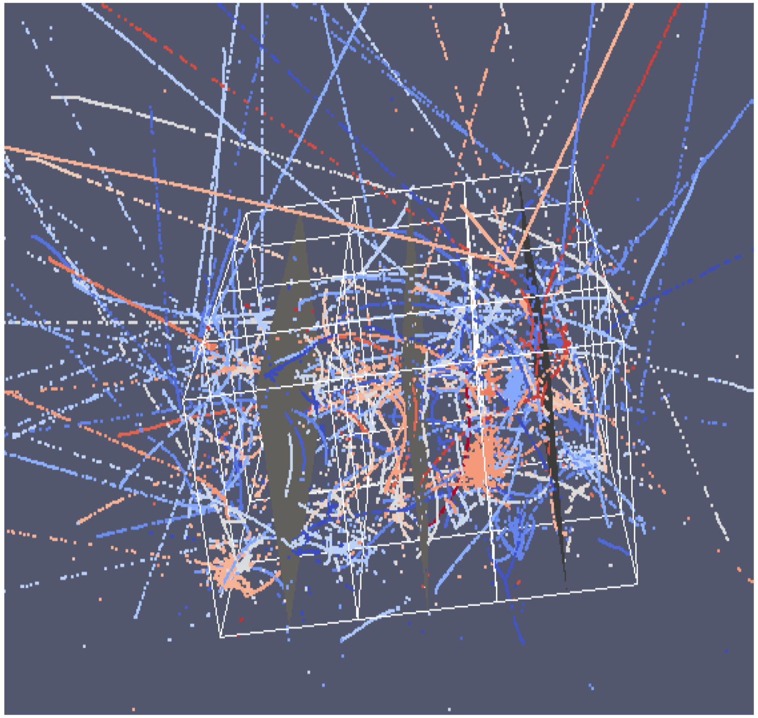
ArgonCube sketch

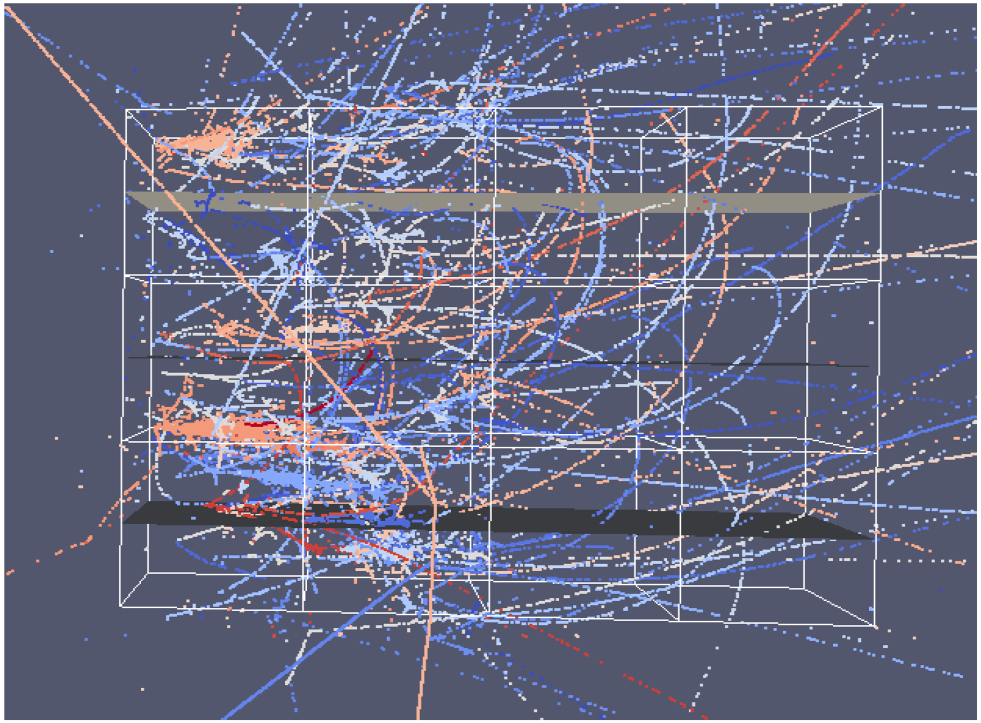


Double racetrack Helmholtz magnet

LAr Simulation - James Sinclair & Joseph Zennamo

Beam, Cosmic & Rock Events in LArND





ParaView event display of single DUNE beam spill at 7.5e13 POT (coloring by nu).

9

LAr Simulation and Reconstruction - James Sinclair and Joseph Zennamo

- Implemented magnetized modular geometry (currently only bulk material for magnets & support structure) N.B. Return yoke not required.

- Many problems observed in 3rd Run-Through. Not all yet fixed and has delayed production running for 4th Run-Through

The Reconstruction Plan

- Vertices are identified from tracks and showers start points; used for truth matching
- Track reconstruction:
  - Short track momentum uses ionization (not enough curvature); smearing on total energy deposition
  - Long track momentum uses track length and sagitta
- Energy reconstruction:
  - Assume worst case – resolution from ArgonNeuT (comparable wire spacing to pixel pitch)
- Showers reconstruction:
  - Total energy calculated from calorimetry
  - Plan to reconstruct momentum (magnitude and direction) still being implemented
- Particle ID:
  - If a final state charged lepton is present, neutrino flavor is assumed
  - Showers: dE/dx of the first few cm are used for electron photon discrimination
  - If no charged lepton is identified, recoil direction used to reject neutrons and external
  - Single protons???

FD Simulation & Reconstruction - Tingjun Yang & Tyler Alion

Simulation

- 6M events (beam, nue, nutau, both neutrino and antineutrino samples)
- Optimized flux, GENIE v2_12_2, MEC turned on.
- All events were run through hit reconstruction to provide input to CVN event selections.
- 10% of events were run through the full reconstruction chain to provide input to the MVA event selections.

Reconstruction

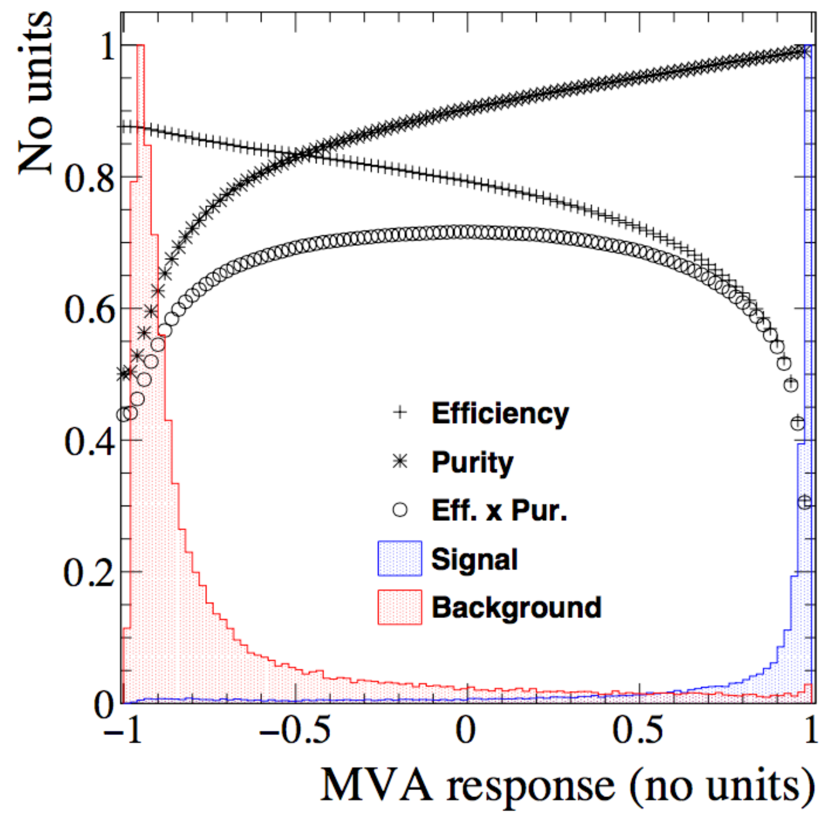
- There have been a lot of progress on reconstruction and event selection for the oscillation analysis

ν_μ selection - Dom Brailsford
ν_e selection - Mike Wallbank
CVN event selection - Alexander Radovic
Neutrino energy reconstruction - Nick Grant

FD Muon Neutrino Selection – Dom Brailsford

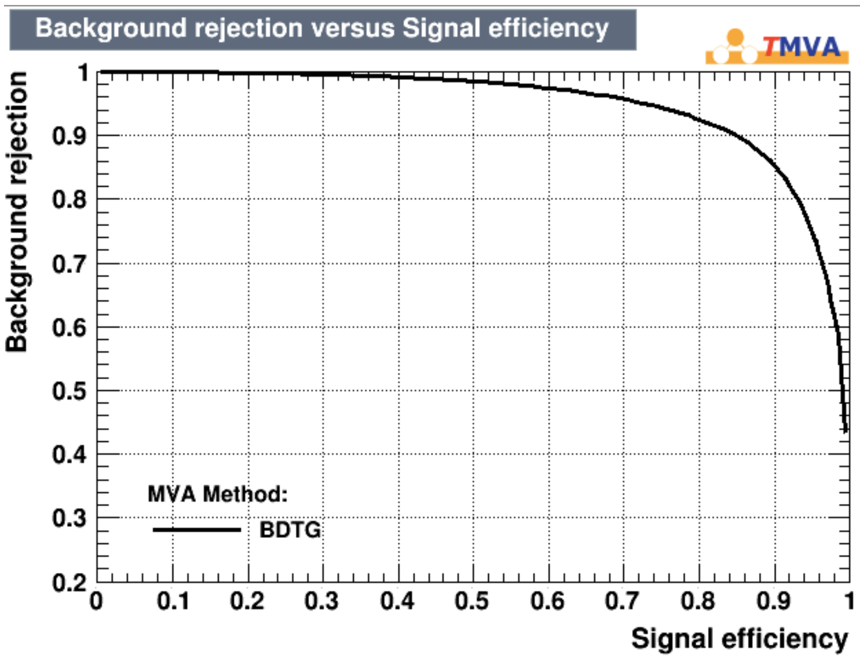
- Selection originally developed by Tyler and Tingjun.
- Uses a BDT to select CC ν_μ events using event topology, shape and charge information.
- Dom has taken over this effort and continues to make improvements.
  - Retune BDT using the latest reconstruction
  - Characterize the selection - efficiencies and purities
  - Optimize selection cut
  - Reduce selection bias

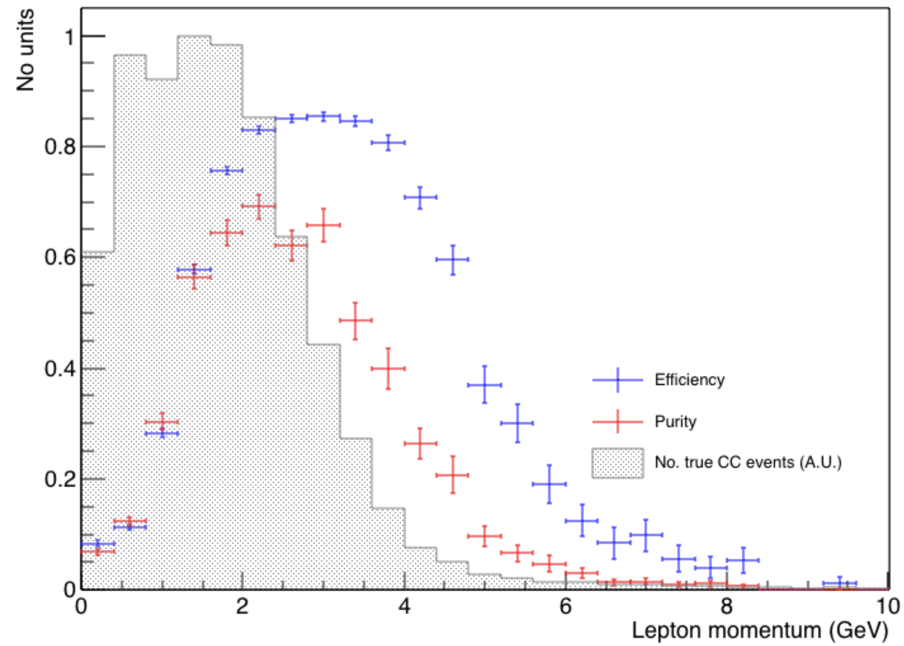
Neutrino mode



Efficiency: 79.3%
Purity: 90.3%
MVA Cut: > 0

FD Electron Neutrino Selection – Mike Wallbank





- The result looks similar to the previous one.
- A lot of lessons learned. New ideas/approaches needed.
- Lots of low energy electrons (<1GeV) where efficiency is poor. Need to focus on reconstructing low energy electrons.

A Priori Uncertainties - VALOR (Lorena Escudero)

VALOR DUNE ND+FD fit

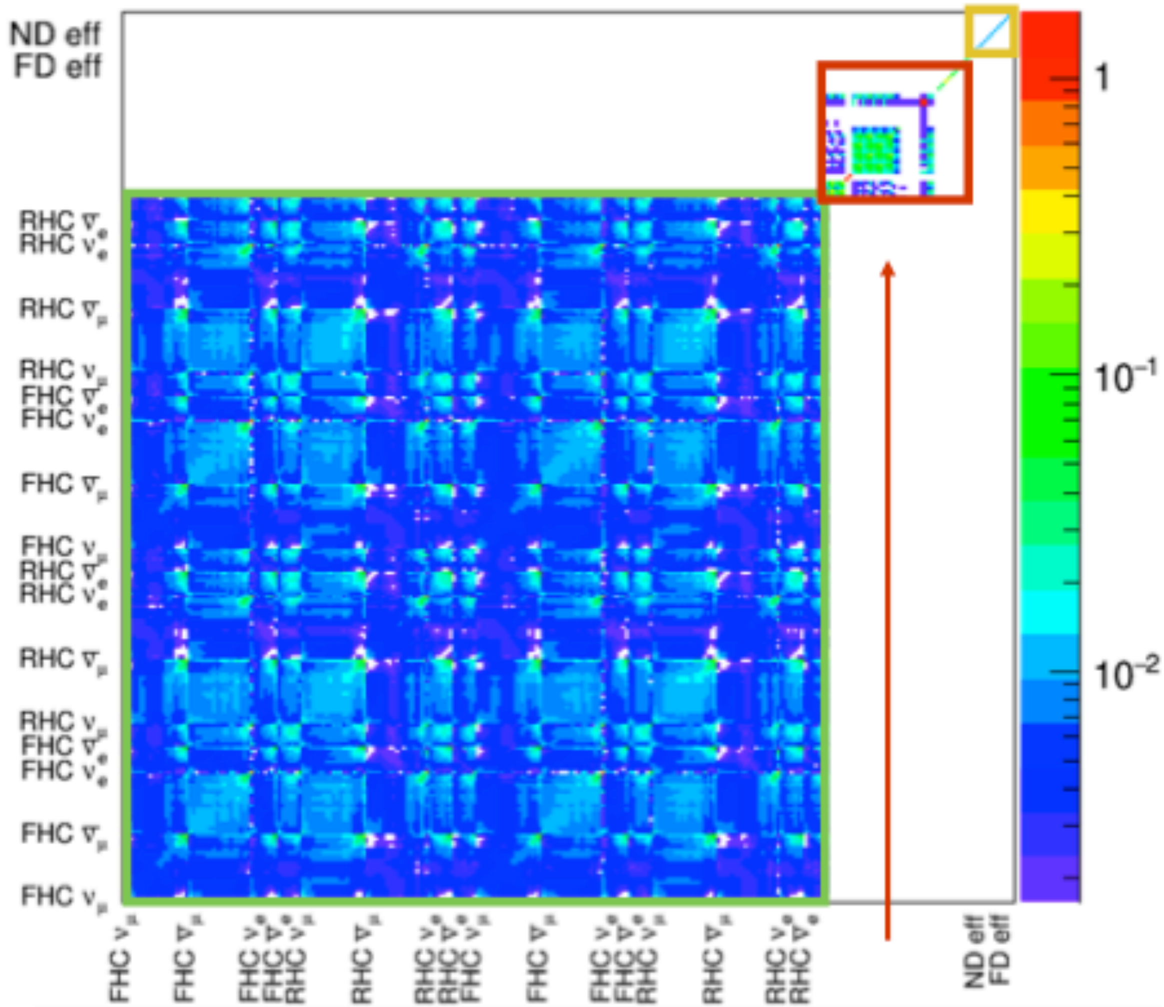
3rd Pass Through

Total covariance matrix with prior uncertainties, input to the ND fit:

264 parameters
- 104+104 flux uncertainties (ND+FD)
- 43 interaction model uncertainties
- 9+4 detector efficiencies (ND+FD)

+ 6 osc parameters

detector efficiencies



ND+FD flux uncertainties

interaction modelling

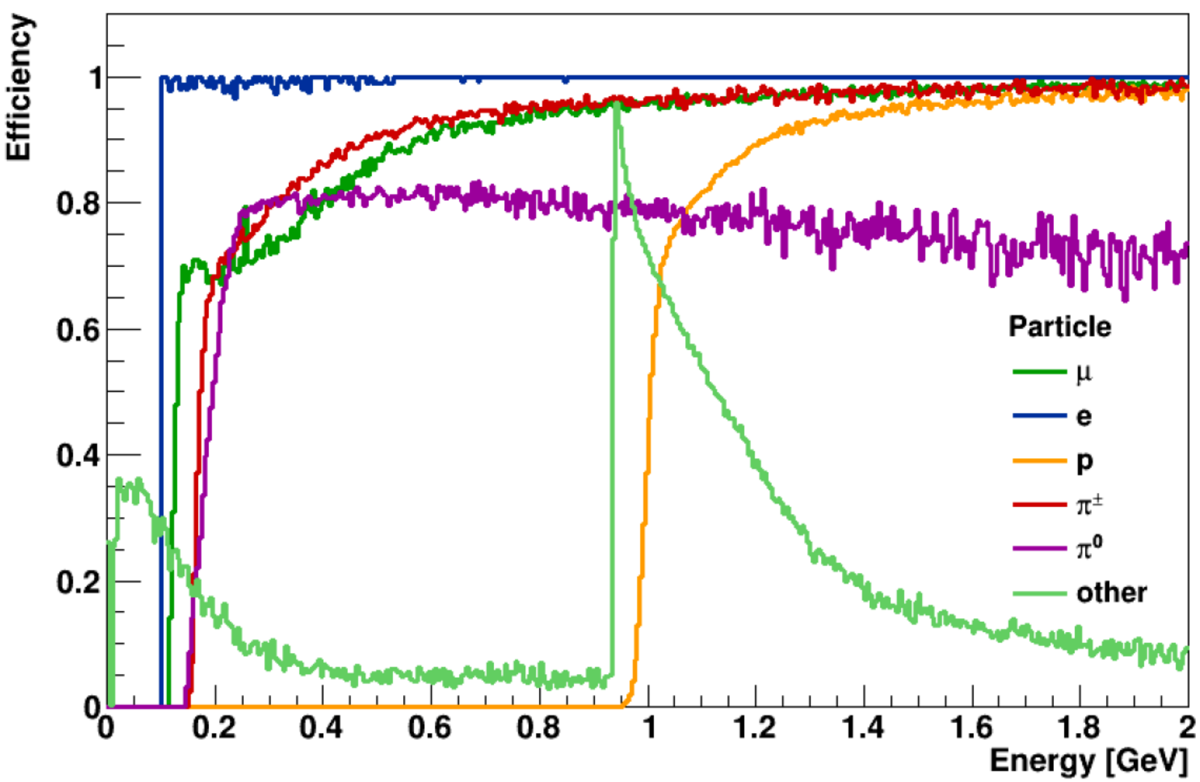
A Priori Detector Uncertainties - VALOR (Lorena Escudero)

Characterization of the FGT detector

Work by Dan Cherdack

2) Particle reconstruction efficiency

Defined as e.g. for μ:
#reconstructed μ/#total μ



Find the regions in Energy in which the efficiency goes from 0 to 1

Particle	Min E [MeV]	Max E [MeV]
μ	115	900
e	100	105
p	955	1065
$\pi^{\pm}$	145	900
π^{0}	145	300

A Priori Detector Uncertainties - VALOR (Lorena Escudero)

Correlations for the FGT detector