A Method to Evaluate ND Optimization Options

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Introduction

- "The VALOR approach is complete but complex – it needs to be supplemented by a simple approach to validate the work."
  - Steve Brice, LBNC meeting 2017/03

- The complete problem is very complicated
  - Flux/Detector effect for Near vs. Far Detectors, Neutrino vs. Antineutrinos, ν_μ CC vs. ν_e CC vs. NC …

- It is crucial to break this complex problem into many small (hopefully simple) problems
  - Allow feedback on the inputs
  - Allow cross checks to avoid bugs
  - Build up intuitive understanding of the problem from every aspect

Method Description

- Given vectors X, Y with their mean and covariance matrix

$$\mu = \begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix}, \quad \Sigma = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix}$$

- We can calculate the conditional mean

$$\mu_{Y|X} = \mu_Y + \Sigma_{YX} \cdot \Sigma_{XX}^{-1} \cdot \left(X - \mu_X \right)$$

Expectation on Y given the measurement of X

and conditional variance

$$\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX} \cdot \Sigma_{XX}^{-1} \cdot \Sigma_{XY}$$

Uncertainties on Y given the measurement of X and X's uncertainties

E. L. Morris "Multivariate Statistics: a Vector Space Approach" 1983.

One Simple Example

- Two detectors with isotropic neutrino flux (10% uncertainty)

$$\begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix} = \begin{pmatrix} \frac{a}{L_1^2} \\ \frac{a}{L_2^2} \end{pmatrix}, \quad \Sigma = \begin{pmatrix} \left(\frac{a \cdot 10\%}{L_1^2}\right)^2 + \Sigma_{XX}^{measurement} & \frac{a \cdot 10\%}{L_1^2} \cdot \frac{a \cdot 10\%}{L_2^2} \\ \frac{a \cdot 10\%}{L_1^2} \cdot \frac{a \cdot 10\%}{L_2^2} & \left(\frac{a \cdot 10\%}{L_2^2}\right)^2 \end{pmatrix}$$

Detector Related

- Assume perfect measurement of neutrino flux at ND (X)

$$\Sigma_{Y|X} = \Sigma_{YY} \cdot \left(I - \Sigma_{YY}^{-1} \cdot \Sigma_{YX} \cdot \Sigma_{XX}^{-1} \cdot \Sigma_{XY} \right) = 0$$

Perfect constraint at FD predicted flux (Y)

- Assume 1% measurement of neutrino flux at ND (X)

$$\Sigma_{Y|X} = \Sigma_{YY} \cdot \left(1 - \frac{(10\%)^2}{(10\%)^2 + (1\%)^2} \right) = \Sigma_{YY} \cdot 0.0099$$

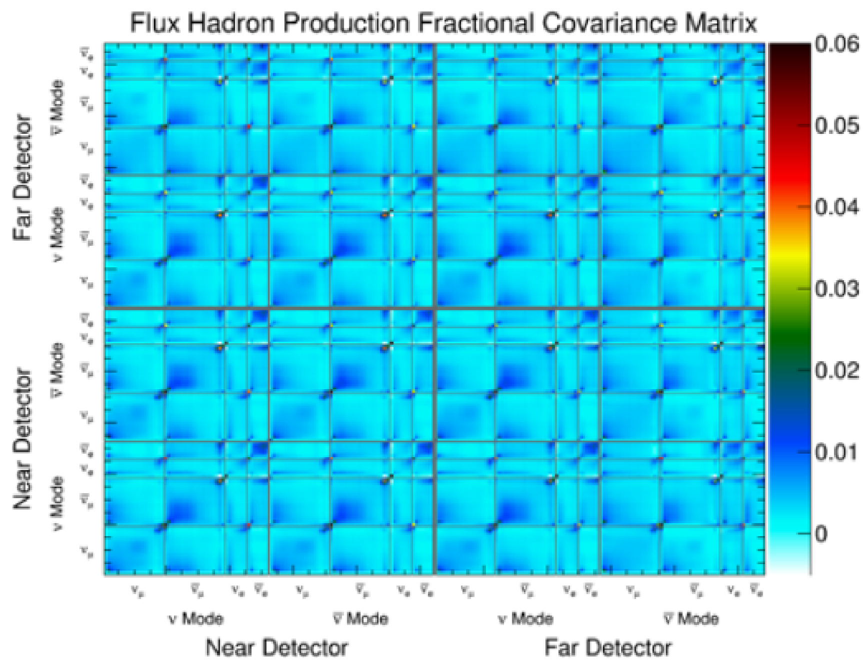
Far Detector flux (Y) is constrained to < 1%

Another Example

- Thanks Dan Dwyer & Chris Marshall for forwarding the current estimation of full covariance matrix generated by the beam group

- With this covariance matrix, many questions can be addressed

Covariance Matrices



- Covariance matrices encode all of the uncertainties on previous slides (plus similar plots not shown for near detector) and their correlations
- This is the final output to the NDTF

L. Fields et al.

Reference

14 DUNE Flux Uncertainties 12 August 16

Operation on Covariance Matrix

- Given the full covariance matrix (208x208)
  - Forward Horn Current (FHC), Reverse Horn Current (RHC), muon/electron, neutrino/antineutrino
  - We can choose any (X,Y) we want from the variable vector (F)

$$\begin{pmatrix} X \\ Y \end{pmatrix} = R \cdot \left(F_{1-208} \right) \qquad \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix} = R \cdot \Sigma_{(208\times208)} \cdot R^T$$

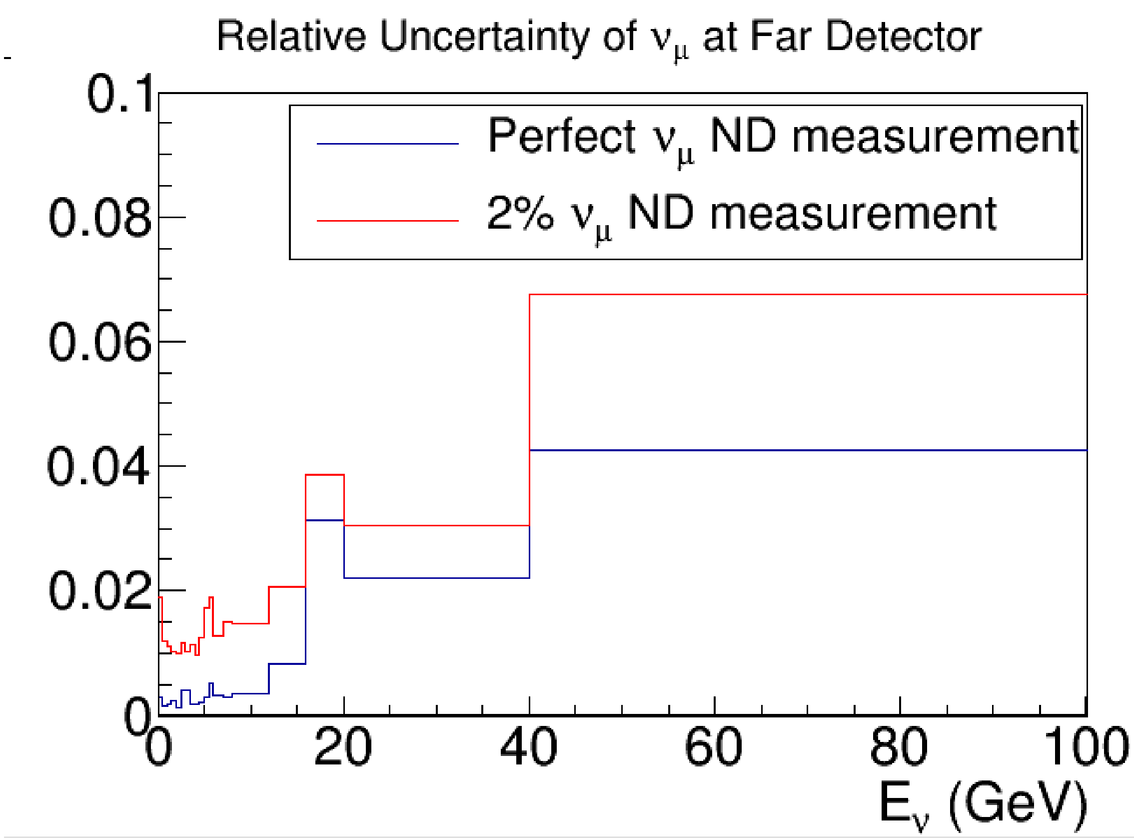
- X can be muon neutrino flux at ND in FHC mode (sub-vector of F)
- X can be summation of (3) muon neutrino and muon antineutrino flux at ND in FHC mode (no magnetic field)
- X can be the measured neutrino-electron elastic scattering rate
- Y can be the muon neutrino flux at FD in FHC mode
- Y can be the electron neutrino flux at ND in the FHC mode
- …

$$\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX} \cdot \Sigma_{XX}^{-1} \cdot \Sigma_{XY}$$

Case I: Muon neutrino flux uncertainty at Far Site

- X: muon neutrino flux at near detector in FHC mode
- Y: muon neutrino flux at far detector in FHC mode

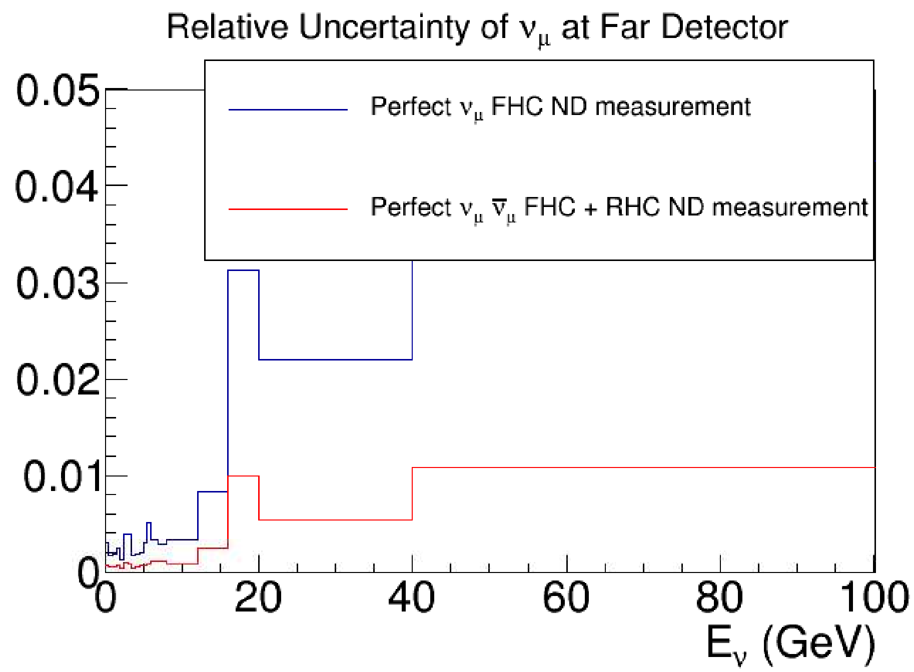
- Perfect case vs. 2% measurement case through Σ_{XX}



For each detector technology or ND proposal, what would be the expected uncertainties to constrain ND neutrino flux measurement?

Case II: Muon neutrino flux uncertainty at Far Site

- Y: muon neutrino flux at far detector in FHC mode
- X: muon neutrino flux at near detector in both FHC and RHC modes and muon antineutrino flux at near detector in both FHC and RHC modes
- Assume perfect measurements



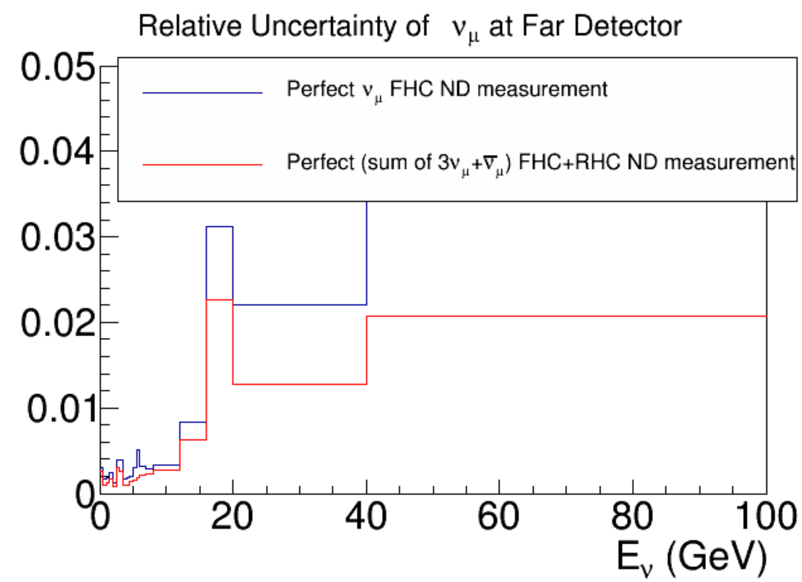
Multiple measurements are helpful in constraining the neutrino flux!

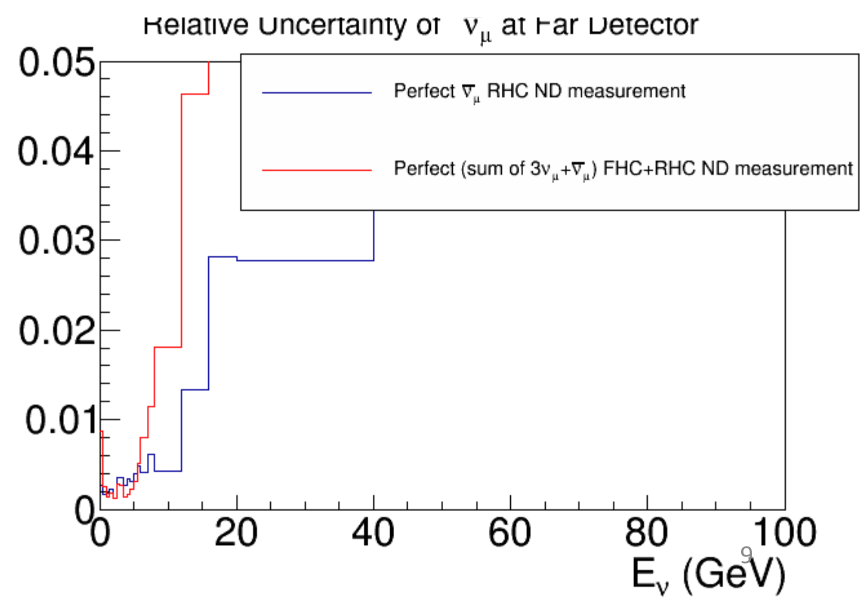
Is ~0.2% uncertainty reasonable?
Any additional beam uncertainties to be considered?

Case III: muon neutrino flux uncertainty at Far Site

- Y: muon neutrino flux at far detector in FHC mode
- X: summation of (3) neutrino and antineutrino flux at ND in both FHC and RHC mode
  - Mimic no magnetic field case

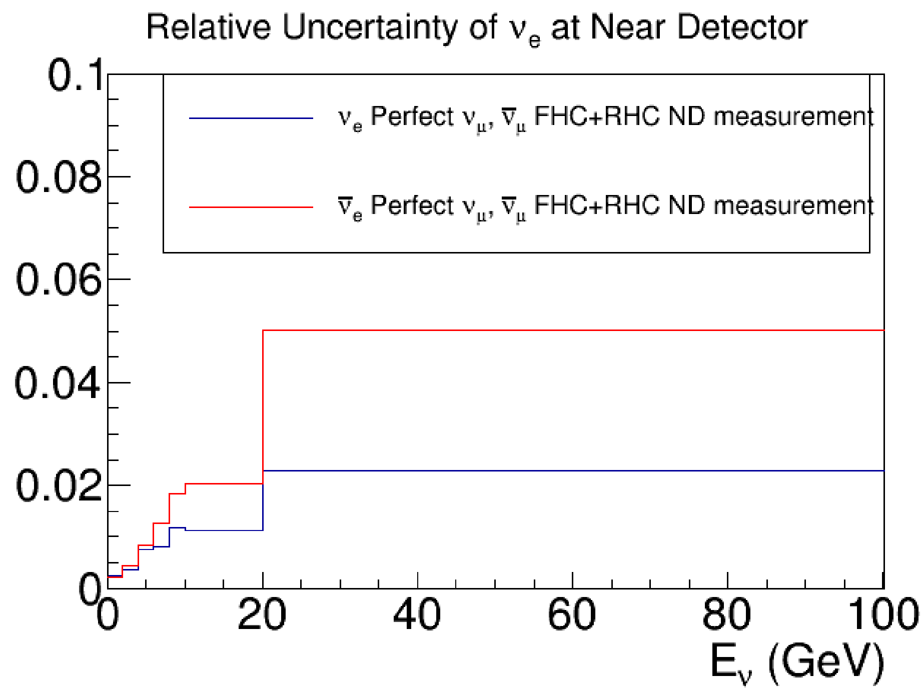
No need to have magnetic field?
Additional uncertainties to be considered in the covariance matrix?
→ Add in measurement uncertainties!





Case IV: electron neutrino flux at Near Site

- Y: electron neutrino flux at the ND
- X: muon neutrino flux at near detector in both FHC and RHC mode and muon antineutrino flux at near detector in both FHC and RHC mode



With ~ 1% uncertainty, we can measure electron neutrino + Ar CC Xs in ND and test $\sigma(\nu_e\text{+Ar})/\sigma(\nu_\mu\text{+Ar}) = 1$?
Can we achieve this for the first time?

Discussion about the Method (I)

- This method allows us to answer one (small) question at a time to build up confidence in systematics and intuition of this problem
  - This method also provides inputs to higher-level fitter to obtain CP sensitivity

- In comparison to the full fitter, this method avoids minimization, which can be challenging in practice due to complicated neutrino oscillation formula

- This method also allows for natural separation of the beam model vs. actual measurements at ND for different technologies (different working groups)

$$\Sigma_{XX} = \Sigma_{XX}^{model} + \Sigma_{XX}^{measurement}$$

Discussion about the Method (II)

- This method is also simple to implement: anybody can do the calculation, easily to test your ideas, no need to rely on 3rd party, allow for easy cross checks → avoid bugs, enable validations

- In case of non-intuitive results, people can provide feedback to relevant working groups → towards realistic systematics uncertainties

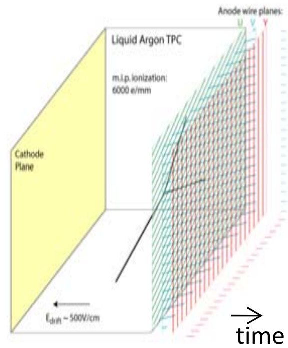
- Once we can come up/agree with a list of questions, we can use this method to achieve optimization of ND design on the basis of physics considering financial constraints

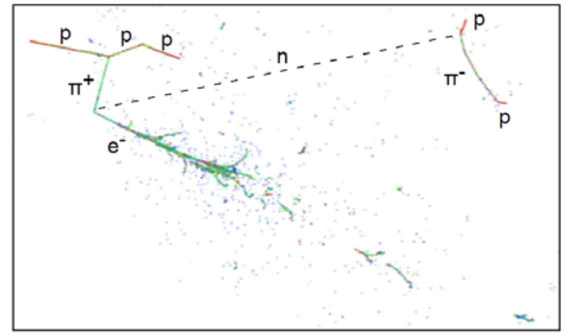
About ND detector location

- With this method, it is straight forward to evaluate the ND location choice according to physics
  - How much degradation in constraining far-detector muon neutrino flux given a detector at 360 m vs. 580 m?
    - Degradation based on beam model?
    - Gain in event rates for both muon and electron neutrinos interactions
  - How much gain do we have in having two detectors (360 m and 380 m)?
    - Can this compensate the degradation from the beam model theoretically?
    - What the situation after considering realistic measurement uncertainties?
  - How much gain do we have if we allow for additional off-axis detector locations?
    - Can this help us by allowing the ND to be movable?

About Systematic Uncertainties (I)

- There are three (major) systematics
  - Neutrino flux related uncertainties
    - Certainly complicated than reactor neutrino
  - Detector related uncertainties
    - LArTPC is powerful and complicated
  - Cross Section related uncertainties
    - QCD in non-perturbative region is (the most) complicated
  - Also background related uncertainties
    - Need in-situ measurements to constrain





Measurement of Single Spin Asymmetry in

$n^{\uparrow}(e, e'\pi^{\pm})X$ on Transversely Polarized ^{3}He

by

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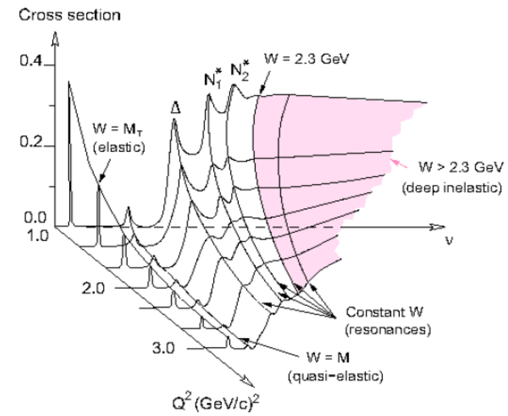
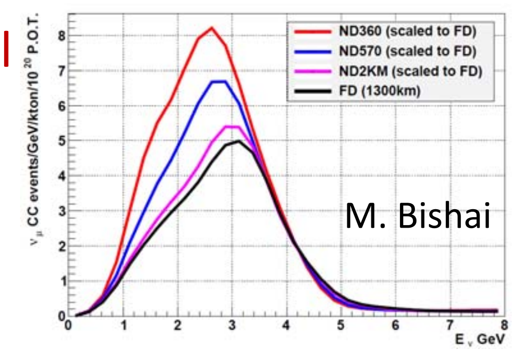
- For neutrino oscillations, "relative uncertainty" (or uncorrelated uncertainties) is **more dangerous** than "absolute uncertainties" (or correlated uncertainties)
  - Near vs. Far, neutrino vs. antineutrino …
  - Daya Bay's **0.2%** relative energy scale uncertainty is **the largest systematic uncertainty**

About Systematic Uncertainties (II)



- Although neutrino-argon cross-section is complicated, it essentially has two effects: normalization uncertainties + (neutrino to reconstructed) energy model uncertainties (energy scale + resolution)
  - With same Ar target, cross-section (Xs) related uncertainties are all **absolute** uncertainties between near and far
  - The issue is that there are **relative components** coupled to Xs
    - Relative neutrino flux uncertainties between near and far detectors (not exactly isotropic) → **need robust flux model constraint**
    - Relative detector response uncertainties between near and far detectors → Contribute to overall energy model in strong coupling with the Xs model → **need LArTPC given its complication**
    - Also relative uncertainty between neutrino and antineutrino Xs → **Continuously improve Xs model**
    - Also relative uncertainty between electron neutrino and muon neutrino Xs → **need in-situ constraint**
  - We need to design ND to minimizing relative uncertainties → optimizing sensitivity



About Potential Measurements to Constrain Neutrino Flux (I)

- Neutrino-electron elastic scattering (“only” precisely known cross section)
  - Mixture of muon and electron (anti-)neutrinos
  - How well do we need the angular resolution to select signal events (also energy reconstruction?)
    - For LAr/HPG, angular resolution is likely to be worse, but will active veto (single wire at the vertex) help to select events?
- Neutrino-nuclei “coherent” cross section with full kinematics
  - Also precisely known cross section with flavor separation
  - Can these events be successfully selected?
  - What about rho or pion production?

^{40}Ar Analog Transition as a Flux Monitor for a Near Detector

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I examine the possibility that the coherent nuclear transition

$$\nu_\mu + {}^{40}\mathrm{Ar} \rightarrow \mu^- + {}^{40}\mathrm{K}^*(4.38\ \mathrm{MeV}) \qquad (1)$$

About Potential Measurements to Constrain Neutrino Flux (II)

- Low-nu (energy transfer to hadronic system) method with CC interaction (using QE cross section to anchor the total cross section)
  - Can we do this on both electron and muon neutrinos?
  - Is there any advantages to use Argon or C or multiple nucleus?
  - For antineutrino, there is usually an energetic neutron in the final state. How efficiently can low-nu events be selected in this mode given a particular detector technology
    - What's the mean free path of neutron inside low-density fine-grain tracker?
  - What's the impact of incomplete acceptance?
    - Kinematics of QE and total cross sections are clearly different
  - What's the impact of existence of external magnetic field?

- Detector-related systematics are expected to be very important due to the requirement of spectral analysis → Important to have LArTPC

Summary

- In wall street, there are two types of jobs: Traders and Quants
  - Traders: back-of-envelope estimation of price based on experience
  - Quants: quantitative analysis on the price based on advanced mathematical tools
  - Usually more confidence in action when the conclusions from both sides are consistent → minimizing risks
- In design/optimize ND, we need both experience ("traders") and quantitative calculations ("quants")!
  - A statistical method is proposed here enabling both back-of-envelope estimation and quantitative calculations

$$\Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX} \cdot \Sigma_{XX}^{-1} \cdot \Sigma_{XY}$$

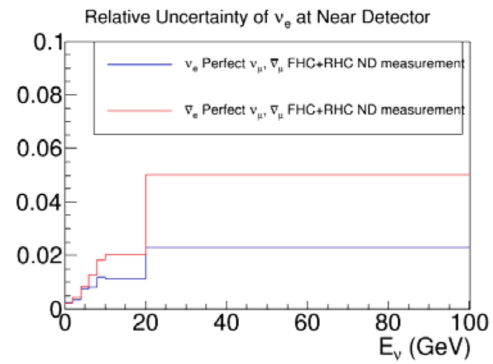
- We need to design ND to minimize relative uncertainties → maximizing neutrino oscillation sensitivity

My 2 cents

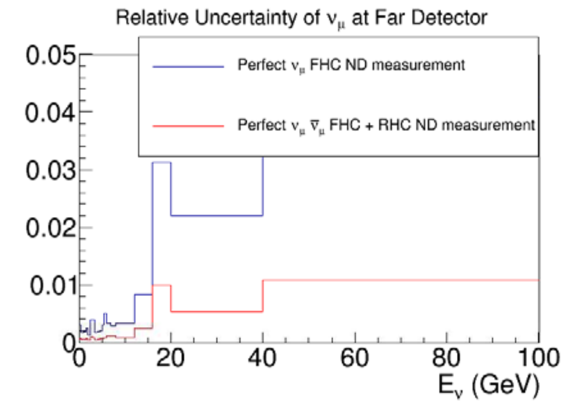
- About neutrino model
- About ND detector location
- About various systematics
- About measurements at ND

About Neutrino Flux Model

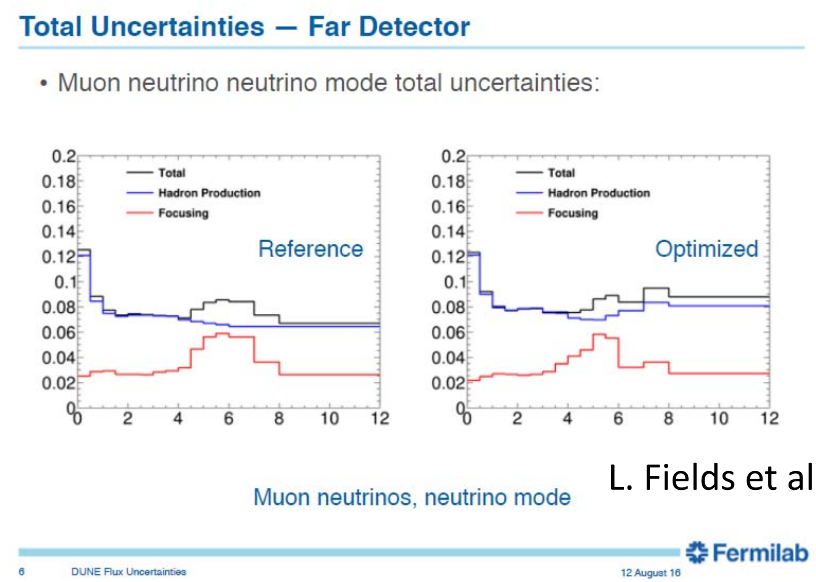
- There are many uncertainties
  - QCD part
    - Pion and Kaon production Cross Section
    - Pion/Kaon and material secondary interaction Cross Section
    - Target degradation
    - …
  - Focusing part
    - Horn Current
    - Skin depth effect
    - Alignment
    - Beam size/position
  - Geometry/Material part
    - Dimensions (thickness)
    - Decay pipe materials
    - Decay pipe geometry
  - Other contributions to be considered ?



<1% for ND ν_e flux



<0.2% for FD ν_μ flux



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Uncertainties are improved when the antineutrino mode is added