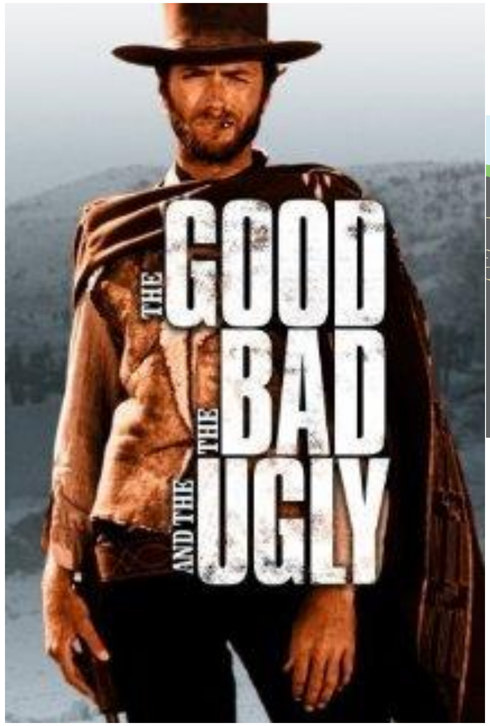
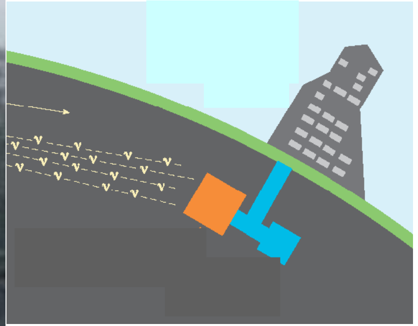
Cross-sections and systematics at DUNE:





S. Manly

University of Rochester

Neutrino platform week
CERN
Jan. 29, 2018

- *No attempt at a systematic overview ... **or** … an overview of systematics*
- *Concerns about Xsecs and systematics driving DUNE ND design*
- *Potential advances in the state-of-art which are under study/consideration*

Oscillations for the naïve optimist

Electron neutrino appearance
Ignore backgrounds (including intrinsic beam ν_e) for now

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,unosc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) F_{far/near}^{\nu_\mu}(E_\nu)}$$

Use high statistics, unoscillated, precision measurement of numu flux in ND and beam model/geometry

“You are only naïve once. Use it well.”*

*Quote from author Joyce Rachelle

$$\frac{dN_\nu^{\det}}{dE_\nu} = \phi_\nu^{\det}(E_\nu)\sigma_\nu^X(E_\nu)$$

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\dfrac{dN_{\nu_e}^{far}}{dE_\nu}\dfrac{1}{\sigma_{\nu_e}^{Ar}(E_\nu)}}{\dfrac{dN_{\nu_\mu}^{near}}{dE_\nu}\dfrac{1}{\sigma_{\nu_\mu}^{X}(E_\nu)} F_{far/near}^{\nu_\mu}(E_\nu)}$$

The Good

If use the same target material and detectors are identical and flavor differences in lepton reconstruction are negligible and/or well understood, then nuclear and detector effects largely cancel in the systematic error.

Oscillations for the realist

"The secret of happiness is to face the fact that the world is horrible, horrible, horrible."*

The Bad

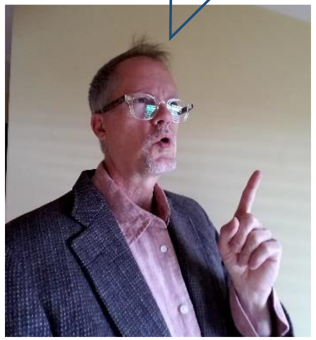
$$\frac{dN_\nu^{det}}{dE_\nu} = \int \frac{dN_\nu^{det}}{dE_{rec}} D_\nu^{det}(E_{rec}, E_\nu)\, dE_\nu$$

Detectors never perfect
Must unfold observations to get "truth"

Correct for:

- *efficiency of detection*
- *detector acceptance*
- *resolution and smearing of experimental observables, i.e, Ev*
- *mistakes in determination of morphology*

CCQE, CC1pi, 2p2h
Usually we use "topology" when describing different event types. "Morphology" is a better word.



*Quote from philosopher Bertrand Russell

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\int \frac{dN_{\nu_e}^{far}}{dE_{rec}} D_{\nu_e}^{far}(E_{rec}, E_\nu) \frac{1}{\sigma_{\nu_e}^{Ar}(E_\nu)} dE_\nu}{\int \frac{dN_{\nu_\mu}^{near}}{dE_{rec}} D_{\nu_\mu}^{near}(E_{rec}, E_\nu) \frac{1}{\sigma_{\nu_\mu}^{X}(E_\nu)} F_{far/near}^{\nu_\mu}(E_\nu)\, dE_\nu}$$

*Quote from Alfred E. Neuman (MAD magazine)

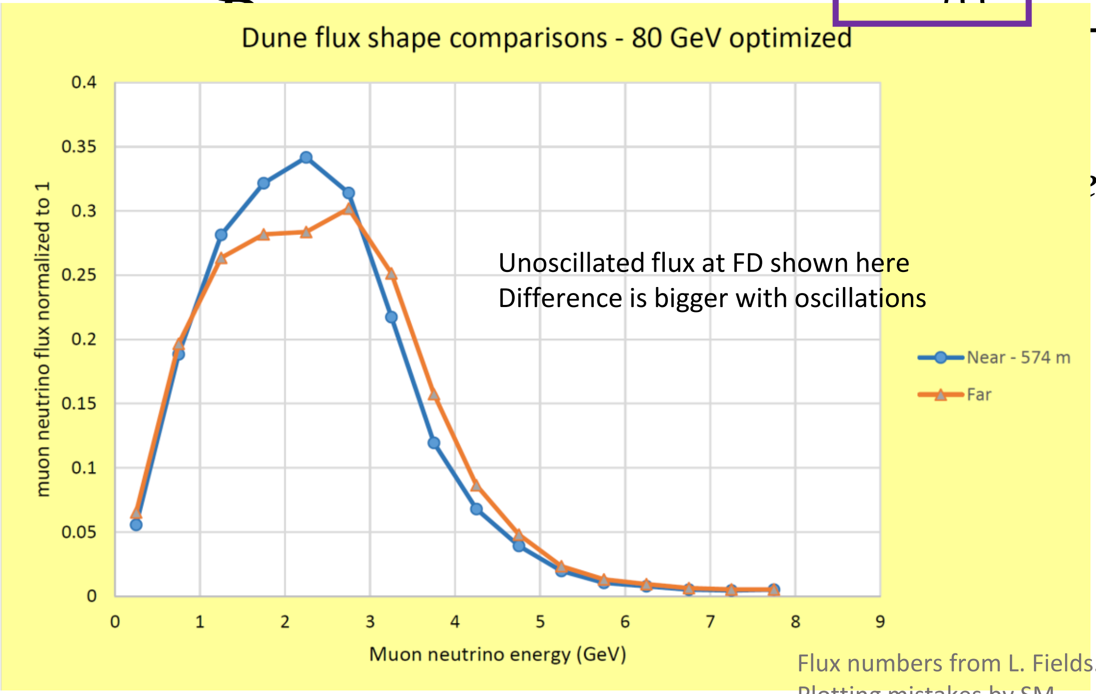
$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\int \frac{dN_{\nu_e}^{far}}{dE_{rec}} D_{\nu_e}^{far}(E_{rec}, E_\nu) \frac{1}{\sigma_{\nu_e}^{Ar}(E_\nu)} dE_\nu}{\int \frac{dN_{\nu_\mu}^{near}}{dE_{rec}} D_{\nu_\mu}^{near}(E_{rec}, E_\nu) \frac{1}{\sigma_{\nu_\mu}^{X}(E_\nu)} F_{far/near}^{\nu_\mu}(E_\nu) dE_\nu}$$

Backgrounds discussed in a moment. This is signal only.

$$\int \boxed{\frac{dN^{far}_{\nu_e}}{dE_{rec}}} D^{far}_{\nu_e}(E_{rec}, E_\nu)\frac{1}{\sigma^{Ar}_{\nu_e}(E_\nu)} dE_\nu$$

$$\ldots c, E_\nu)\frac{1}{\sigma^{X}_{\nu_\mu}(E_\nu)} F^{\nu_\mu}_{far/near}(E_\nu) dE_\nu$$

Flux ratio sensitive to beam errors



Flux numbers from L. Fields.
Plotting mistakes by SM.

Detector effects!!
Must unfold.

D corrects for:

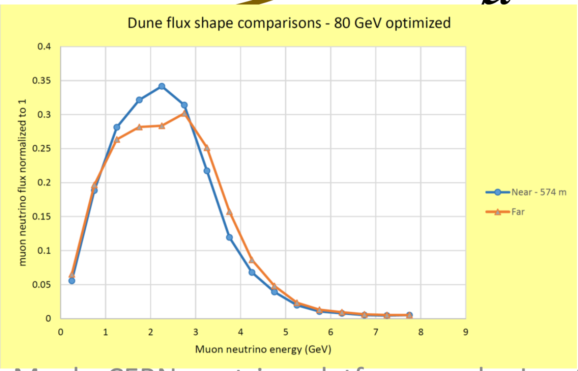
- Efficiencies
- Resolution smearing and corrections
- Acceptance
- Morphology mixing, e.g., multinucleon interaction taken as CCQE (may also contain some nuclear dependence)

Detector effects. Much of this can be validated/tuned using data. Also uses MC with associated model dependence

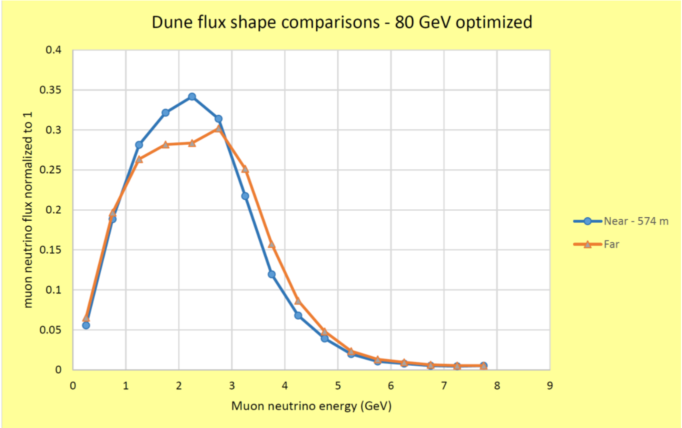
Fairly model dependent with some data driven tuning.

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\displaystyle\int \frac{dN^{far}_{\nu_e}}{dE_{rec}} D^{far}_{\nu_e}(E_{rec}, E_\nu) \frac{1}{\sigma^{Ar}_{\nu_e}(E_\nu)} dE_\nu}{\displaystyle\int \frac{dN^{near}_{\nu_\mu}}{dE_{rec}} D^{near}_{\nu_\mu}(E_{rec}, E_\nu) \frac{1}{\sigma^{X}_{\nu_\mu}(E_\nu)} F^{\nu_\mu}_{far/near}(E_\nu) dE_\nu}$$

Yikes! Muons ain't electrons.



Near detector versus far detector
Identical?? Don't bet on it.
Energy spectrum differences? For sure.



Nuclear target dependence.

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\int \frac{dN^{far}_{\nu_e}}{dE_{rec}} D^{far}_{\nu_e}(E_{rec}, E_\nu) \frac{1}{\sigma^{Ar}_{\nu_e}(E_\nu)} dE_\nu}{\int \frac{dN^{near}_{\nu_\mu}}{dE_{rec}} D^{near}_{\nu_\mu}(E_{rec}, E_\nu) \frac{1}{\sigma^{X}_{\nu_\mu}(E_\nu)} F^{\nu_\mu}_{far/near}(E_\nu) dE_\nu}$$

- Energy dependence is important
- Xsec dependence may lead to different FSI effects, i.e., different morphologies

Backgrounds for appearance measurement: intrinsic beam ν_e (on this slide) and NCpizero events and …

Detector effects!!
Must unfold.

far/near and
near ν_μ/near ν_e flux
ratios

$$\frac{dN^{far,unosc}_{\nu_e}}{dE_\nu} = \int \frac{dN^{near}_{\nu_\mu}}{dE_{rec}} D^{near}_{\nu_\mu}(E_{rec}, E_\nu) \frac{\phi^{near}_{\nu_\mu}(E_\nu)}{\phi^{near}_{\nu_e}(E_\nu)} \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{X}_{\nu_e}(E_\nu)} F^{\nu_e}_{far/near}(E_\nu)\, dE_\nu$$

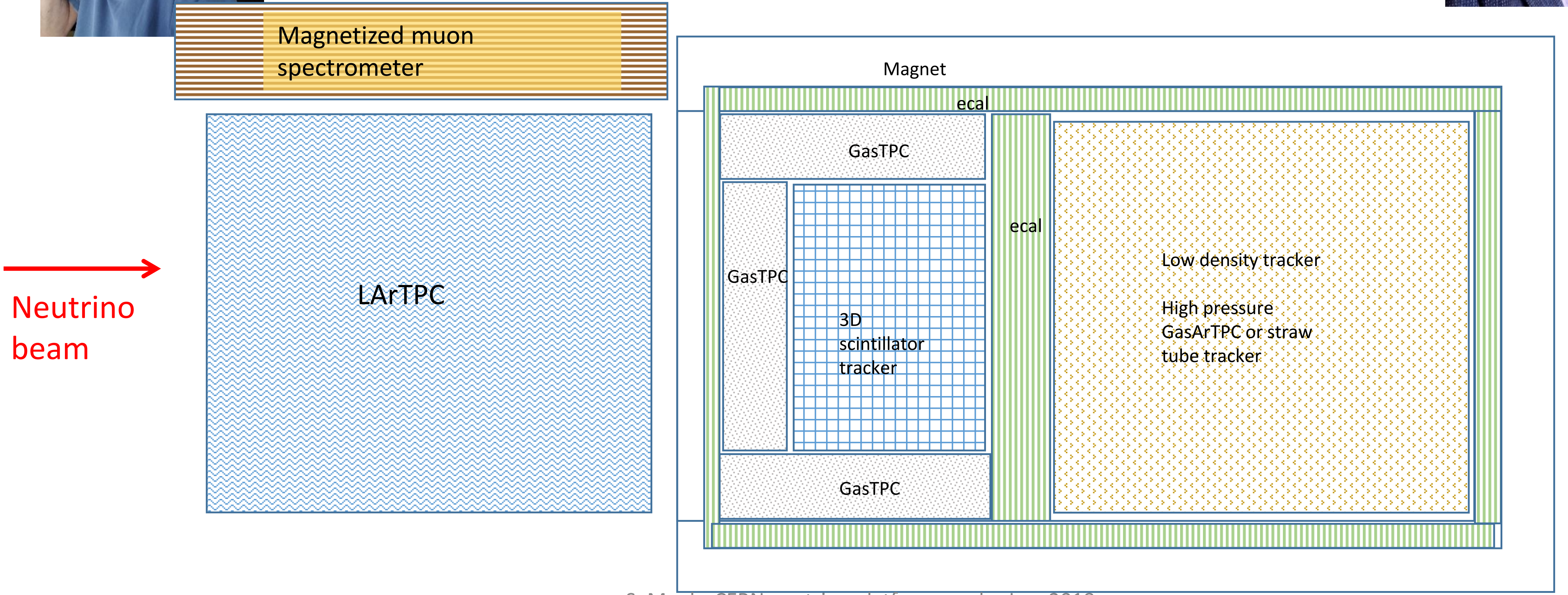
Nuclear target
dependence.

DUNE approach: optimistic realism

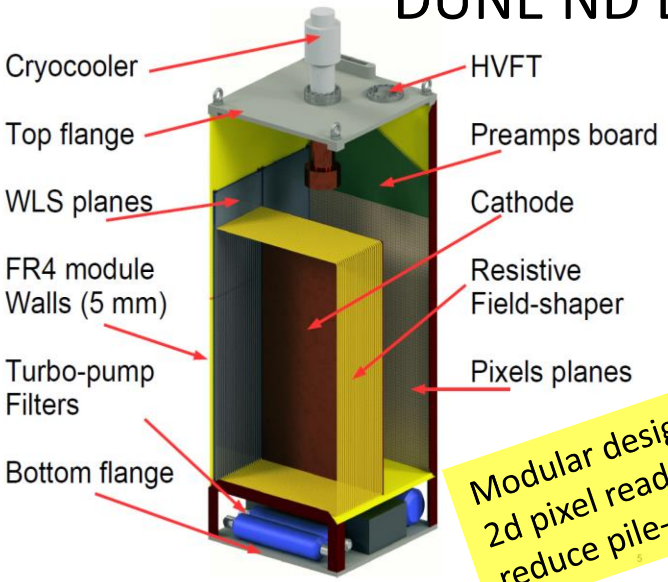
ND should be as similar to the FD as possible

One of a number of DUNE ND concepts that are under study. Hope to settle on concept in March-May time frame.

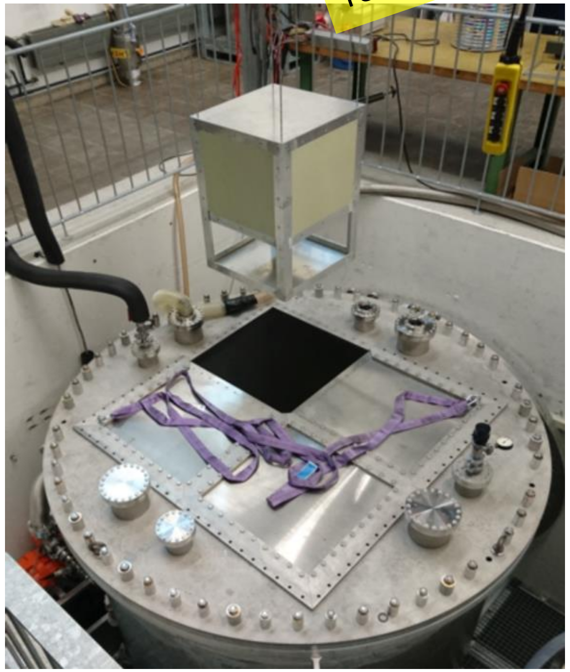
ND should have excellent resolution and ability to identify different morphologies. We'll constrain flux*xsec with uber-fit!

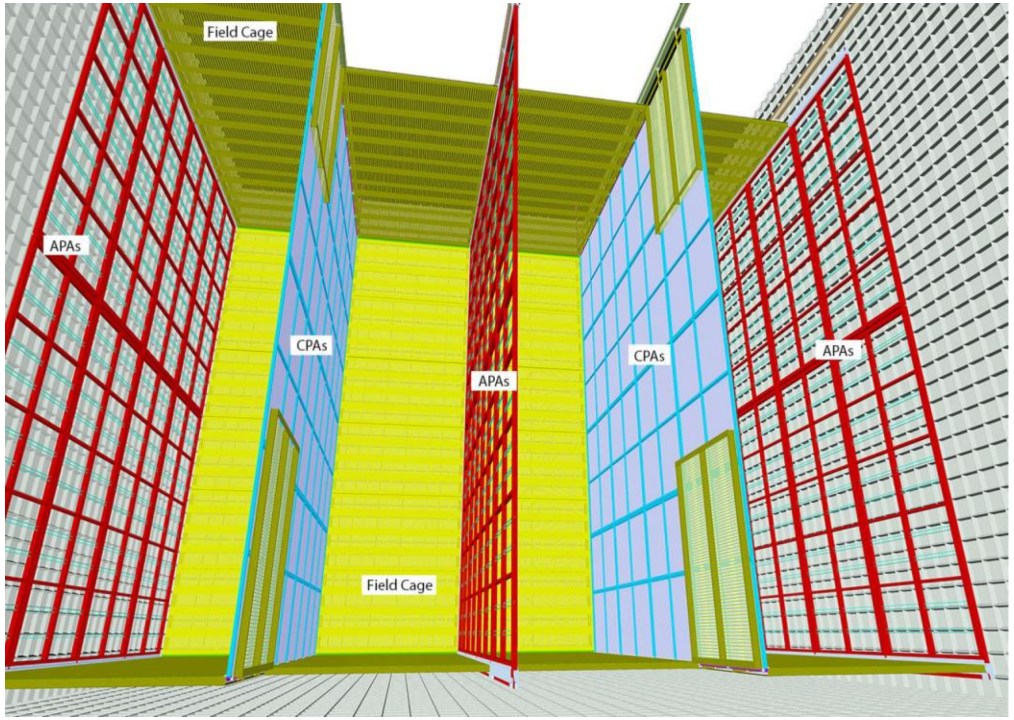


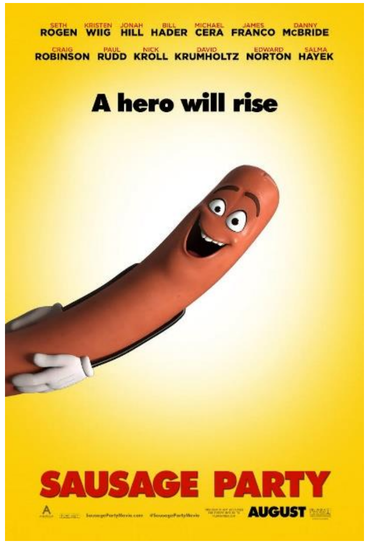
DUNE ND LArTPC option: ArgonCUBE … $\neq$ FD



Modular design
2d pixel readout
reduce pile-up issues





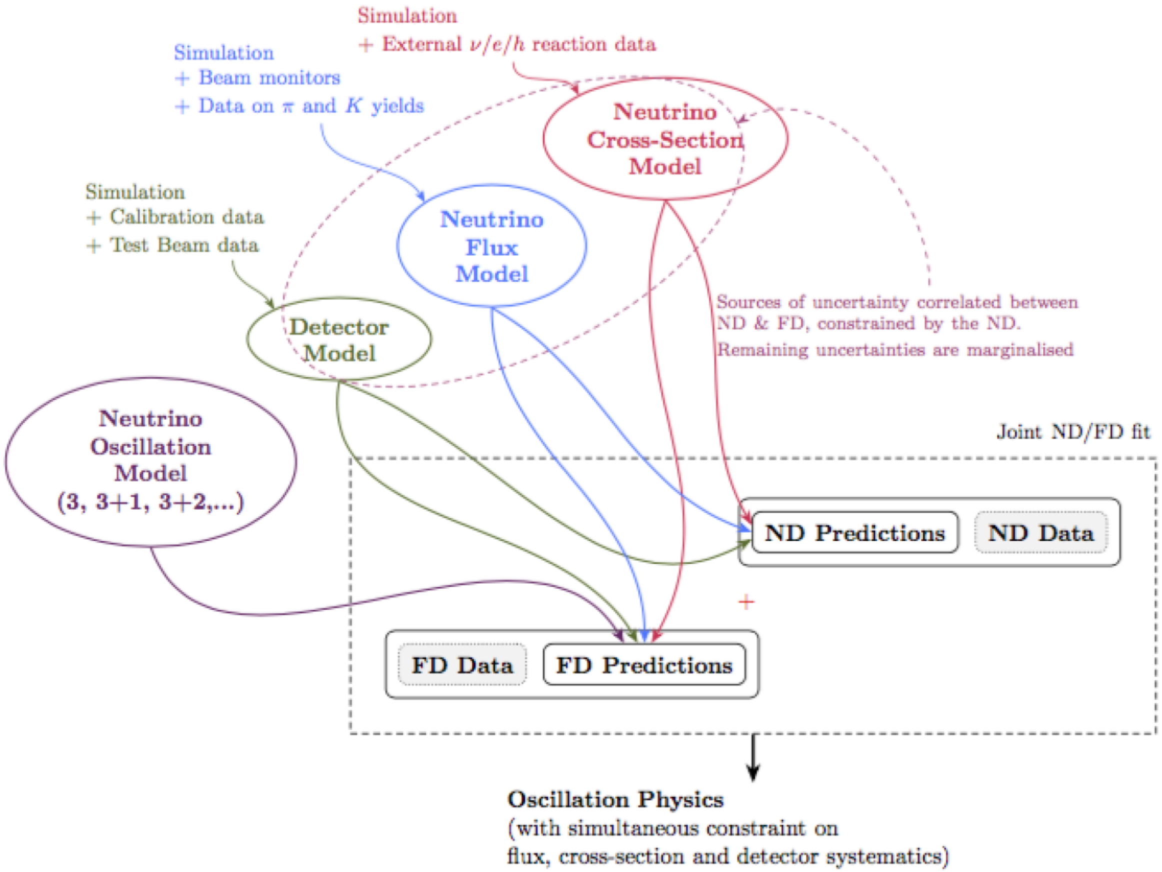


A peak at how the sausage is made

From the DUNE near detector task force studies

Final-State	Primary Hadronic System									
	$0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

Much smearing of initial state into other final states.
Information and sensitivity in this mess.



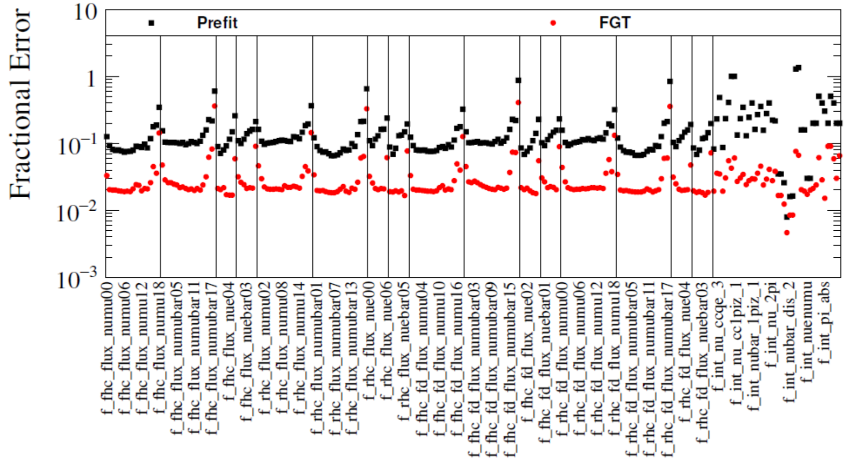
DUNE NDTF used the VALOR framework

Calculations done assuming the straw tube tracker design (FGT)

- 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 ($\mu^- + \pi^+ + \text{p}$, with $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm + \text{X}$)
  6. $1\pi^0$ ($\mu^- + 1\pi^0 + \text{X}$)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0 + \text{X}$)
  8. Other
- Wrong-sign ν_μ CC
  9. 0π ($\mu^+ + \text{X}$)
  10. $1\pi^\pm$ ($\mu^+ + \pi^\pm + \text{X}$)
  11. $1\pi^0$ ($\mu^+ + \pi^0 + \text{X}$)
  12. Other
- ν_e CC
  13. 0π ($e^- + \text{X}$)
  14. $1\pi^\pm$ ($e^- + \pi^\pm + \text{X}$)
  15. $1\pi^0$ ($e^- + \pi^0 + \text{X}$)
  16. Other
- Wrong-sign ν_e CC
  17. Inclusive
- NC
  18. 0π (nucleon(s))
  19. $1\pi^\pm$ ($\pi^\pm + \text{X}$)
  20. $1\pi^0$ ($\pi^0 + \text{X}$)
  21. Other
- ν-e
  22. $\nu_e + e^-$ elastic
  23. Inverse muon decay $\bar{\nu}_e + e^- \to \mu^- + \bar{\nu}_\mu$ (including the annihilation channel $\nu_\mu + e^- \to \mu^- + \nu_e$).

ND experimental data sets considered

Errors of fit parameters reduced with ND input



Reduction in flux errors at the FD demonstrated

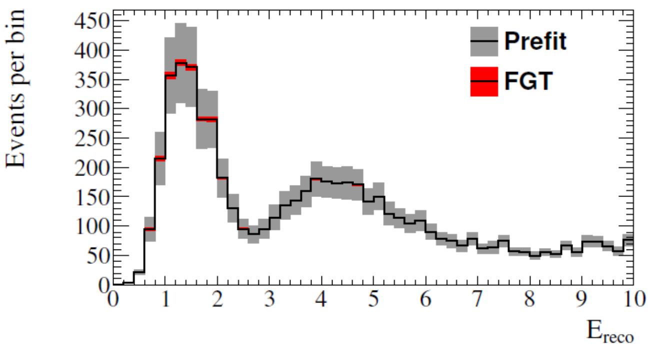


Figure 26: The far detector muon-like error envelope in the neutrino-mode beam using the FGT. The total event rate uncertainty from flux and interaction systematics in the range 1-6 GeV is 0.97%.

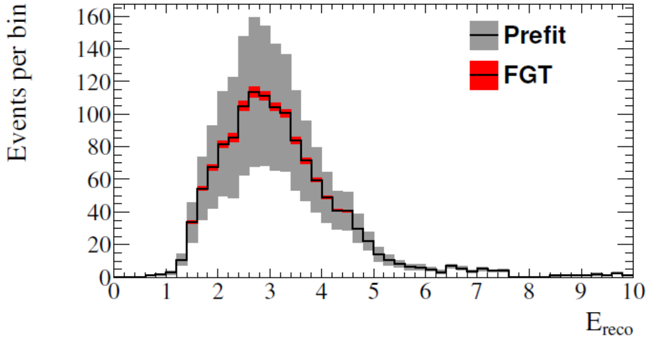
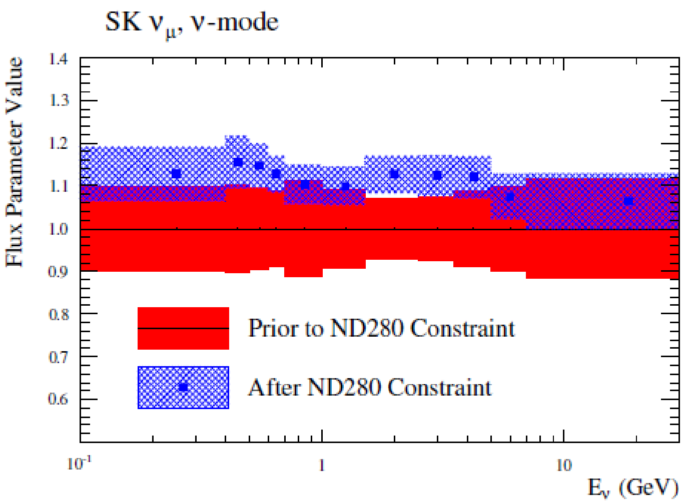


Figure 27: The far detector electron-like error envelope in the neutrino-mode beam using the FGT. The total event rate uncertainty from flux and interaction systematics in the range 1-6 GeV is 2.35%.

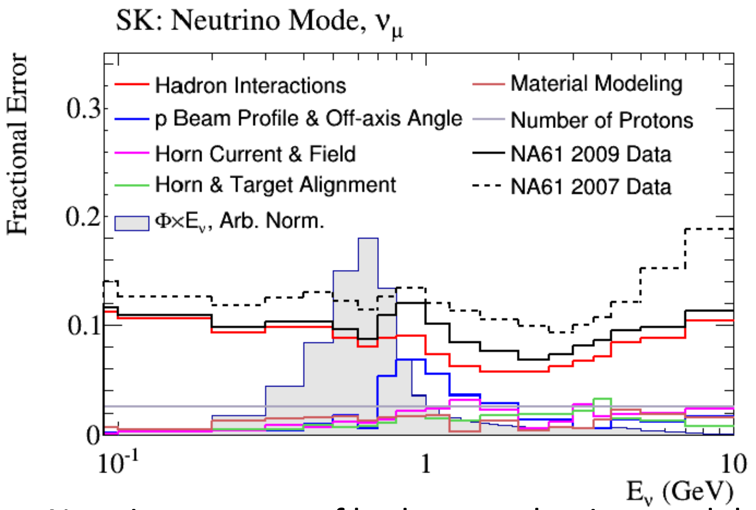
State of the art with T2K

K. Abe et al. (T2K Collaboration), Phys Rev. D **96**, 092006 (2017)



ND constraint reduces systematic error and adjusts normalization of flux

Systematics from beamline configuration and hadron production

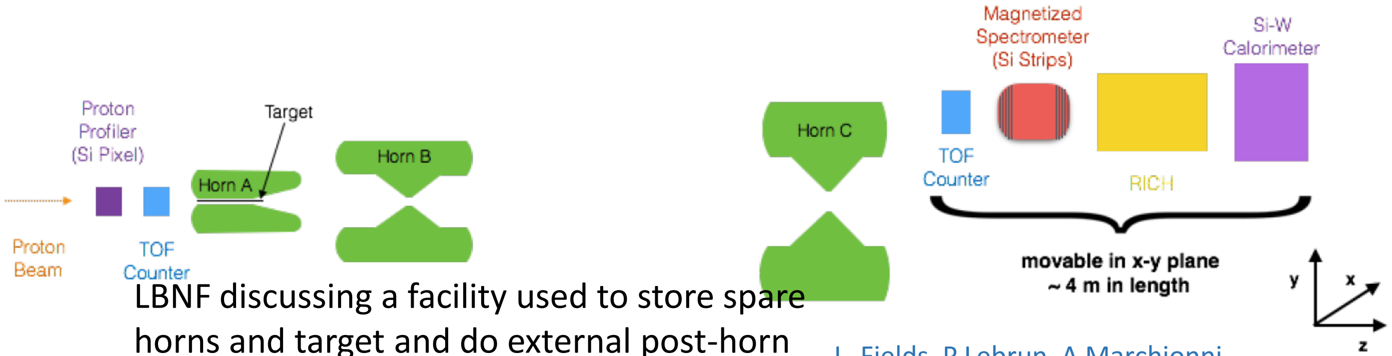


Note importance of hadron production model and input of external data from NA61 and other hadron production experiments.

ND280 sample	Total systematic uncertainty (%)
ν-mode	
FGD1 ν_μ CC-0π	1.7
FGD1 ν_μ CC-1π^+	3.3
FGD1 ν_μ CC-Other	6.5
FGD2 ν_μ CC-0π	1.7
FGD2 ν_μ CC-1π^+	3.9
FGD2 ν_μ CC-Other	5.9
$\bar{\nu}$-mode	
FGD1 $\bar{\nu}_\mu$ CC-1-Track	5.4
FGD1 $\bar{\nu}_\mu$ CC-N-Tracks	10.4
FGD1 ν_μ CC-1-Track	2.5
FGD1 ν_μ CC-N-Tracks	4.8
FGD2 $\bar{\nu}_\mu$ CC-1-Track	3.5
FGD2 $\bar{\nu}_\mu$ CC-N-Tracks	7.3
FGD2 ν_μ CC-1-Track	2.0
FGD2 ν_μ CC-N-Tracks	4.0

Systematic uncertainty of the total event rates affecting the ND samples. Current largest contribution is in the pion re-interaction rate (data-GEANT4 disagreement)

Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	ν_e CC1π^+ $\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross-section			
(w/o ND280 constraint)	11.3%	10.8%	16.4%
(w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI+SI+PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All			
(w/o ND280 constraint)	12.7%	12.0%	21.9%
(w/ ND280 constraint)	5.5%	5.1%	14.8%



LBNF discussing a facility used to store spare horns and target and do external post-horn hadron production measurements.

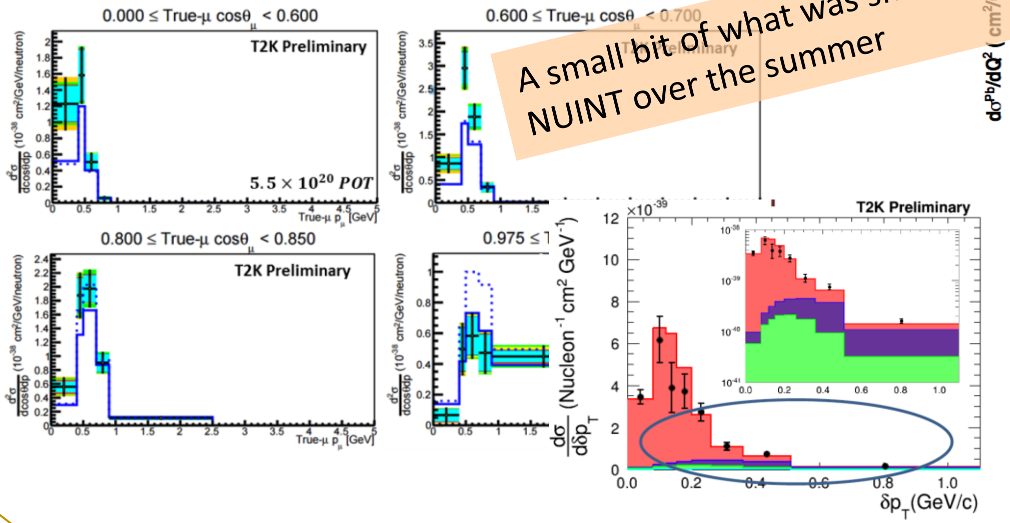
L. Fields, P Lebrun, A Marchionni

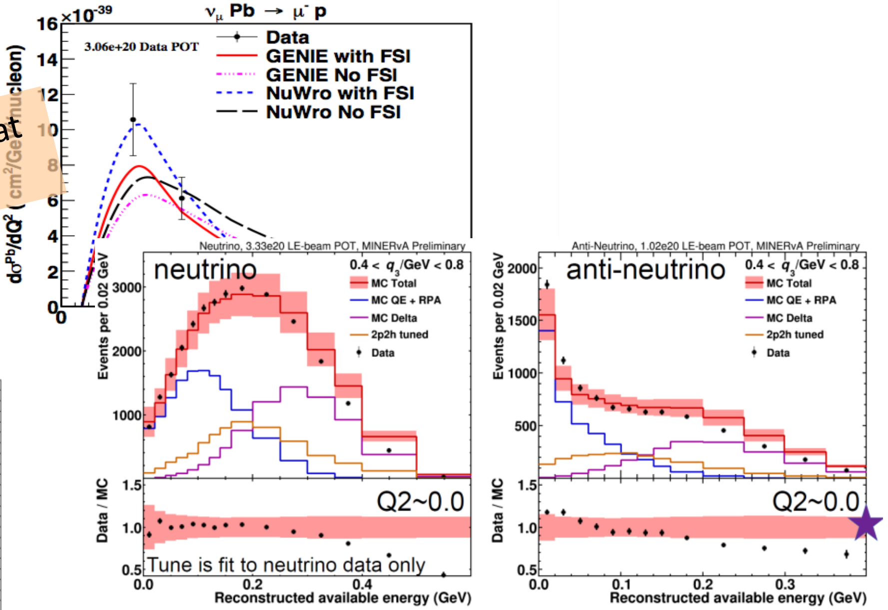
Much data, more coming!

- ANL, BNL, FNAL, CERN bubble chambers
- NOMAD
- MiniBooNE
- MINERvA
- T2K
- ARGONEUT
- MicroBooNE
- NOvA
- T2K II (upgraded ND280)
- ICARUS (at FNAL)
- SBND
- DUNE

Future

A small bit of what was shown at NUINT over the summer





- Data on CH, C, He, water, Pb, Fe, Ar
- Many differential results
- ν_μ, CC and NC, muon and proton variables, pion production
- ν_e CC measurements
- Recent progress on using transverse momentum balance variables to enhance sensitivity to nuclear and FSI effects
- Neutrons?! Really?

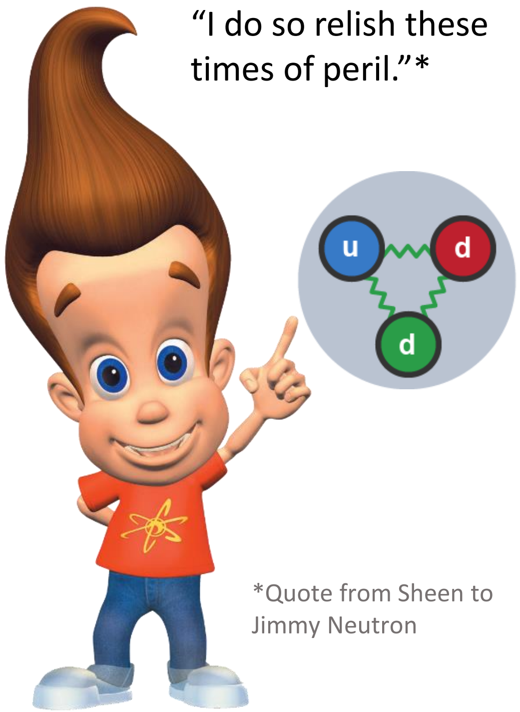
NUISANCE

Meant to provide a coherent framework for comparing neutrino generators to external data. Also useful for tuning cross-section parameters to data.

https://nuisance.hepforge.org/

The neutron problem

"I do so relish these times of peril."*



*Quote from Sheen to Jimmy Neutron

The Ugly

Neutrons are difficult.
Bounce around and then:

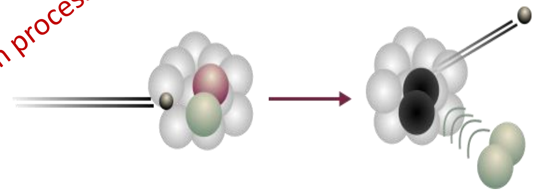
a) Deposit no energy (observable)
b) Leave a little energy
c) Leave much energy

Pick one and repeat

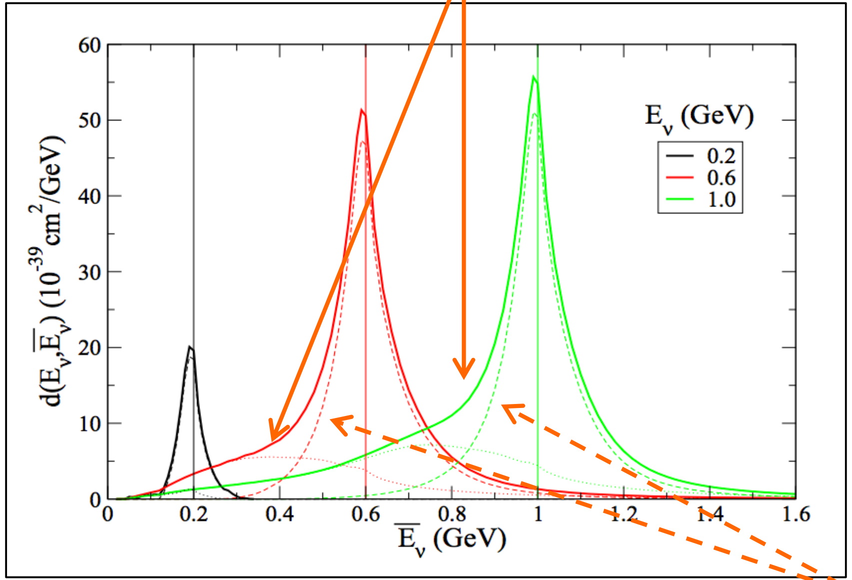
- Event morphology confusion (modeling, unfolding)
- Problems with energy reconstruction (resolution and modeling)
- Compromise use of transverse momentum balance for reconstruction
- Hurt ability to use transverse momentum balance for CC/NC separation

Can we use neutron tag to improve neutrino reconstruction in the CCQE-like sample?

Multinucleon processes



Multinucleon events reconstructed as quasielastic



Genuine quasielastic events

Martini, Ericson, Chanfray, Phys. Rev. D87, 013009, 2013

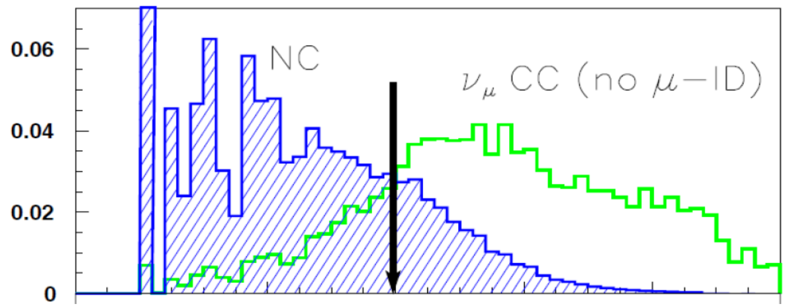
NDTF: Final states used by VALOR for the ND constraint of FD fluxes

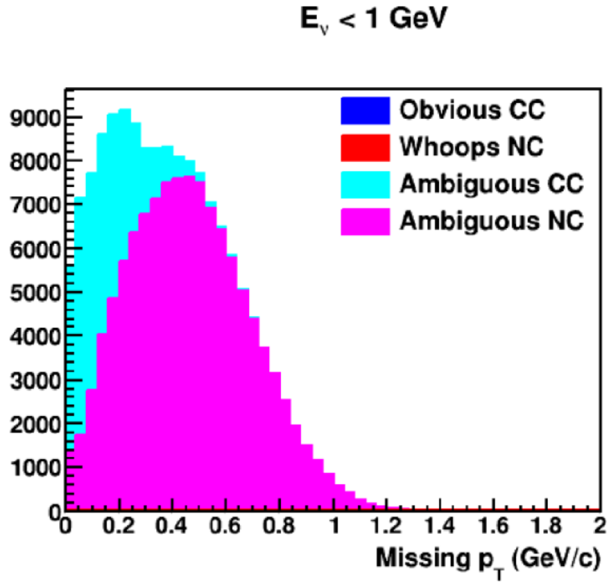
- ν_μ CC
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π (μ^- + (>1) nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+ +$ p, with $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm +$ X)
  6. $1\pi^0$ ($\mu^- + 1\pi^0 +$ X)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0 +$ 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 muon decay $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$ (including the annihilation channel $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$).

With neutron tagging, can we expand list of processes used to constrain the flux?

NC and CC separation works fairly well at NOMAD
-R. Petti

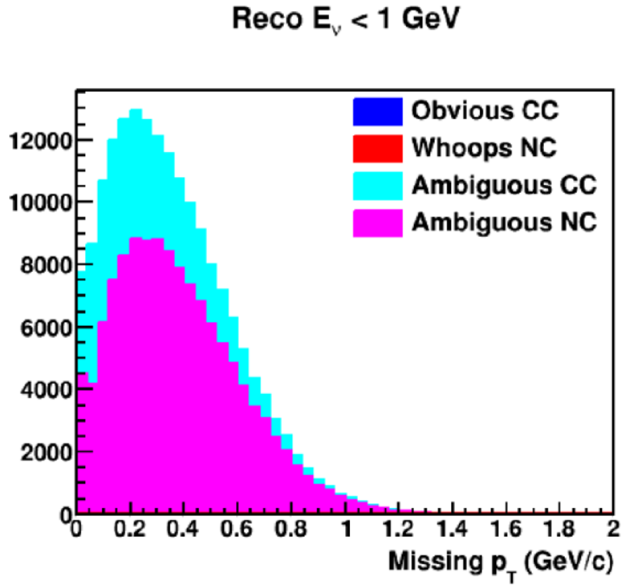
Can neutron tagging be used to improve our ability to use transverse momentum balance variables?





Perfect reconstruction

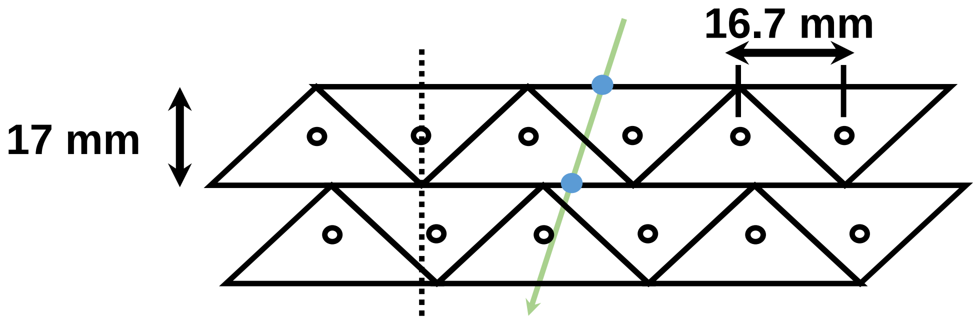
Chris Marshall, shown at March 2017 DUNE ND workshop



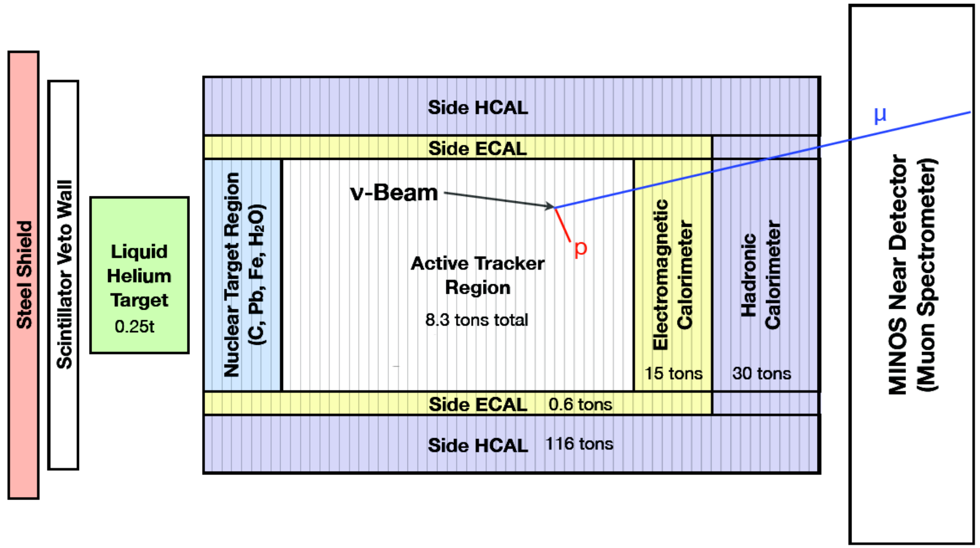
Remove neutrons

Separation between cyan (CC) and pink (NC) is reduced dramatically with missing neutrons

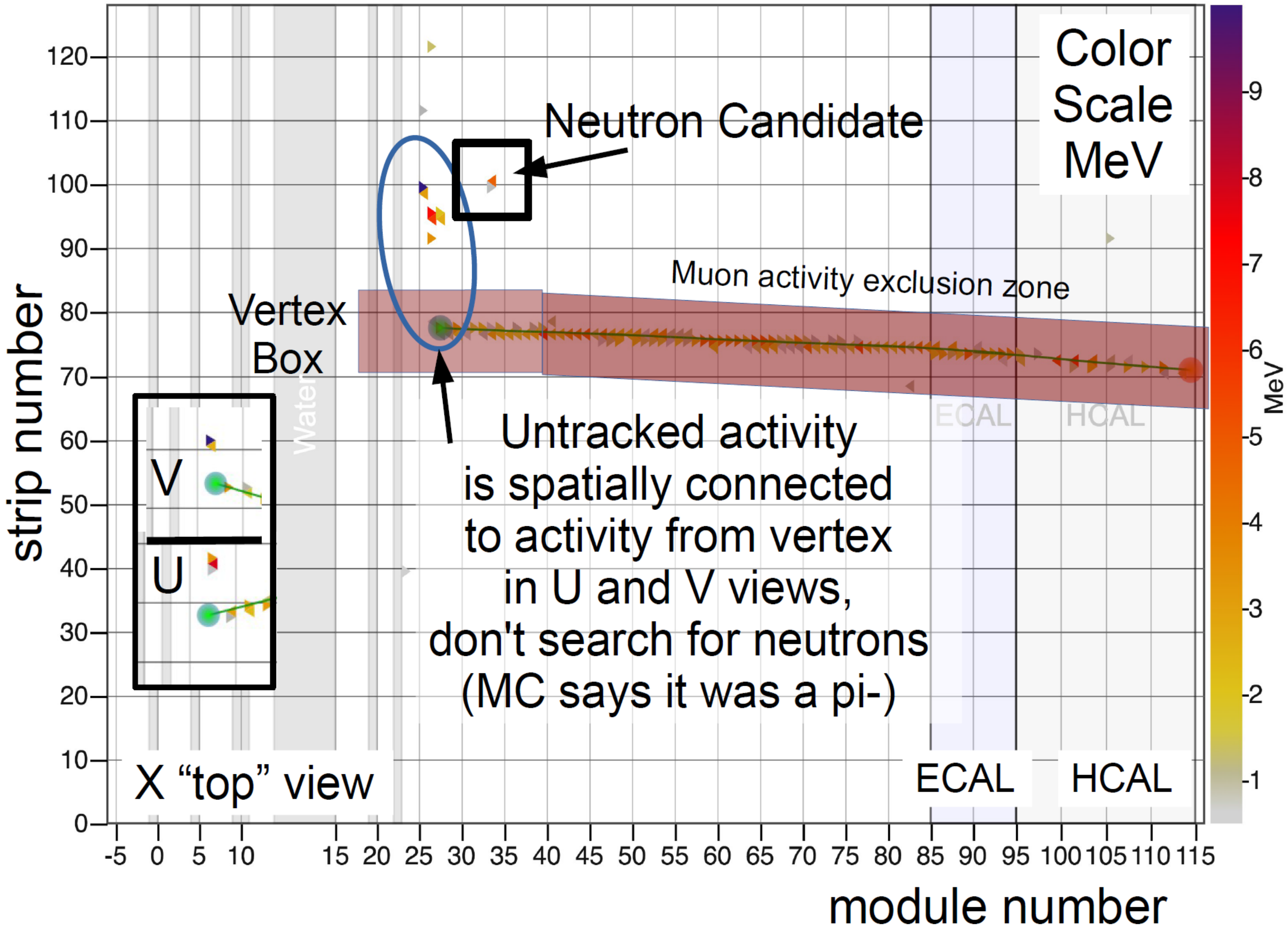
Recent MINERvA results on neutrons



presented at Fermilab Wine and Cheese talk on Nov. 3, 2017 by Rik Gran (Much progress on algorithm done as part of Miranda Elkins' MS thesis work)

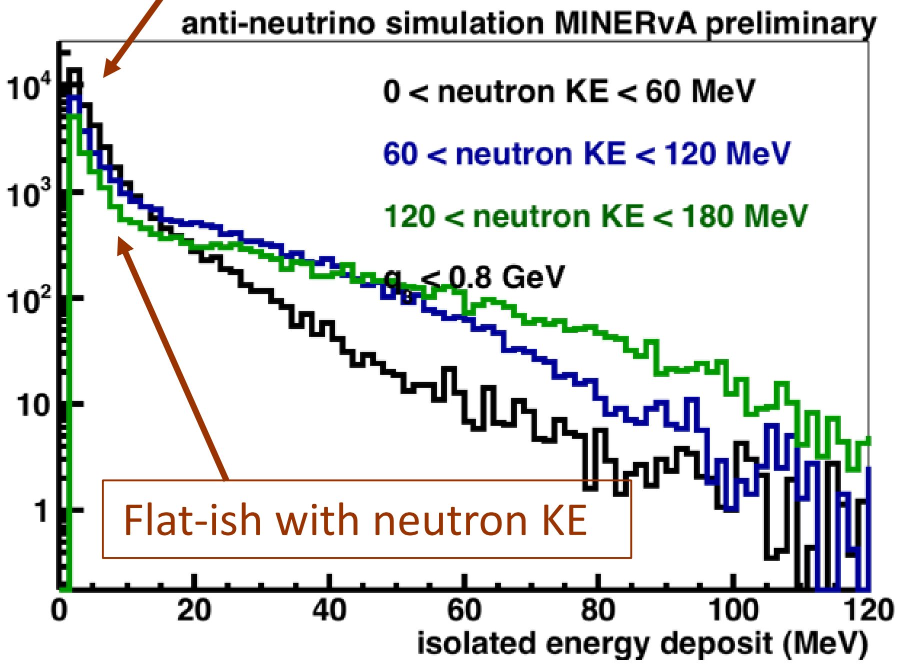


Map of where we do and do not look for neutrons

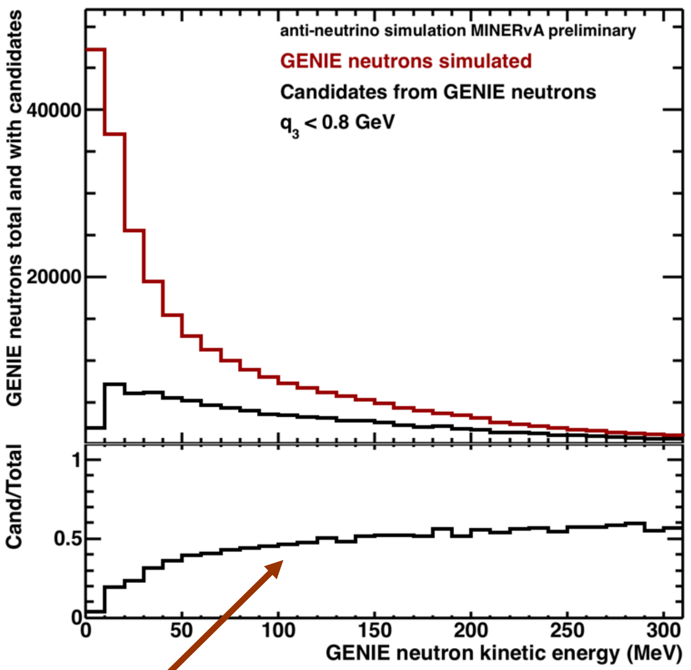


Expectation from MINERvA GENIE/GEANT simulation

Bulk of neutron energy depositions are small (2-6 MeV) – Note log scale

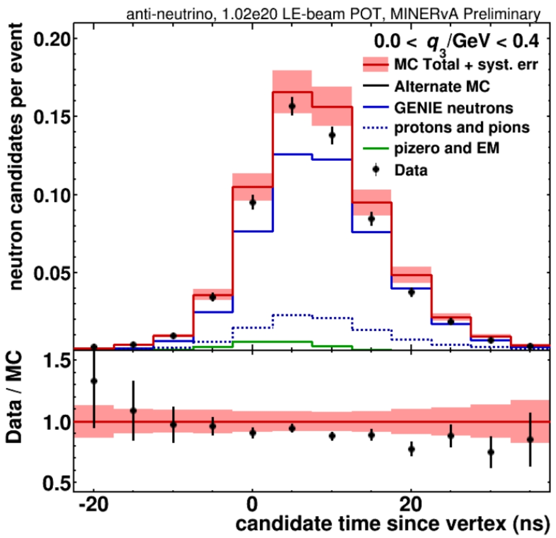


Flat-ish with neutron KE

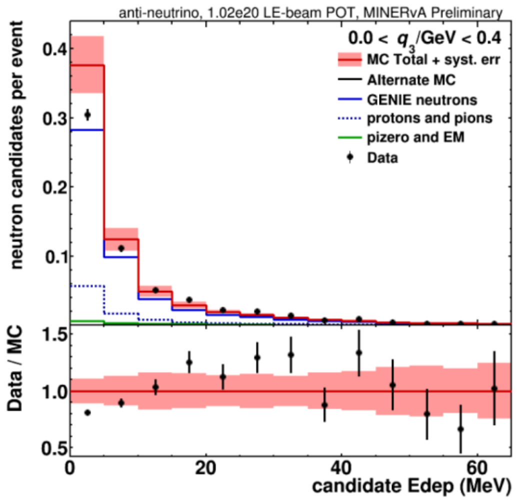


Neutron detection efficiency rises with neutron KE and reaches 50-60% for KE>50 MeV

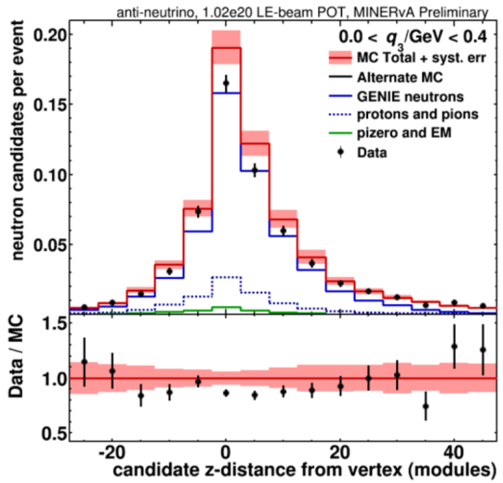
MINERvA data



Time since interaction



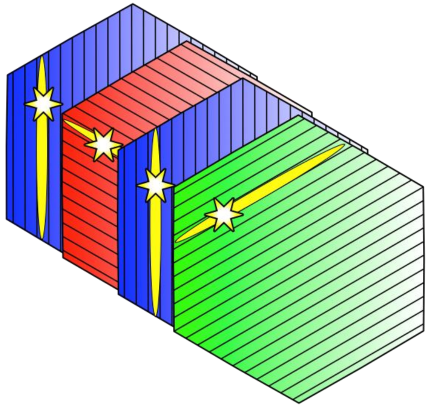
Deposited energy per candidate

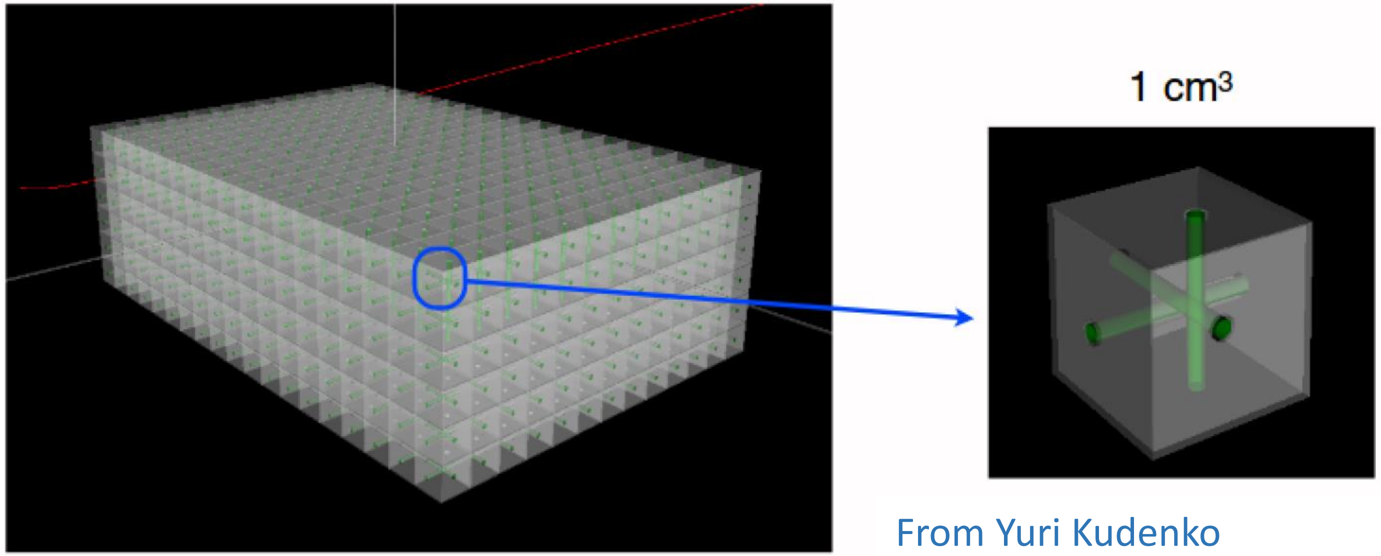


Position relative to interaction (upstream vs. downstream)

- MINERvA seems to see the neutrons.
- Dominated by the low energy (2-6 MeV) candidates in this analysis
- Data-MC agreement not so bad (surprisingly?)
- MINERvA only able to get Z position for the low energy candidates
- Can get 3D reconstruction for higher energy candidates
- 3DST expected to get 3D position for these candidates

DUNE 3DST/T2K superFGD



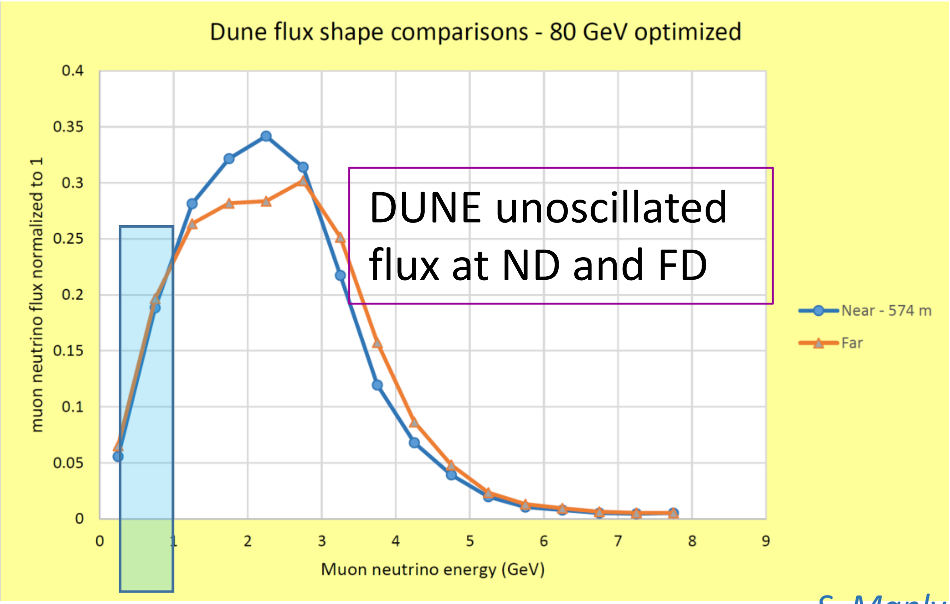


From Yuri Kudenko

- Statistics
- Timing
- 3D position
- Sensitive to small energy deposits

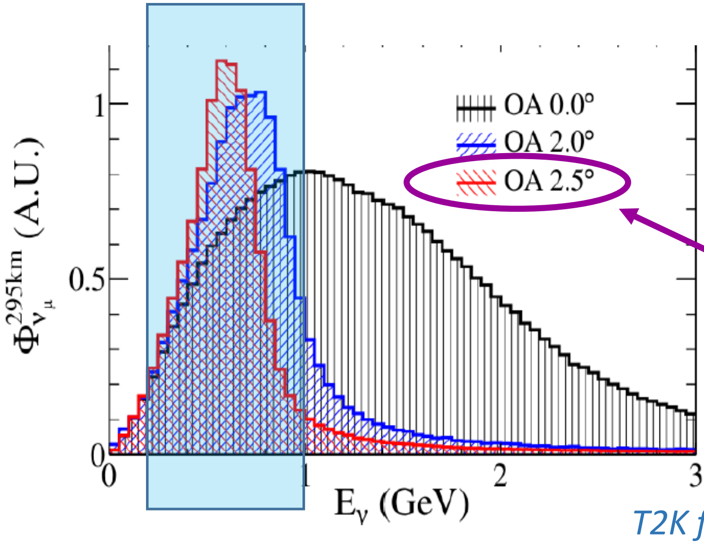
Early studies indicate 3DST should be able to tag FS neutrons with ~50% efficiency and have good resolution on the FS neutron direction. Studies in progress

- SuperFGD is “identical” to 3DST
- SuperFGD sees flux in of DUNE 2nd oscillation energy region
- DUNE has ND flux in the same region but also has higher energy flux that might confuse matters (e.g. misreconstructions and NC backgrounds



DUNE unoscillated flux at ND and FD

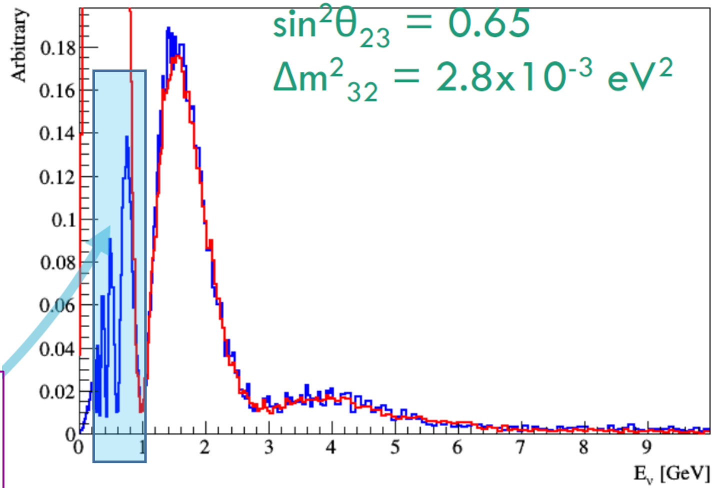
S. Manly

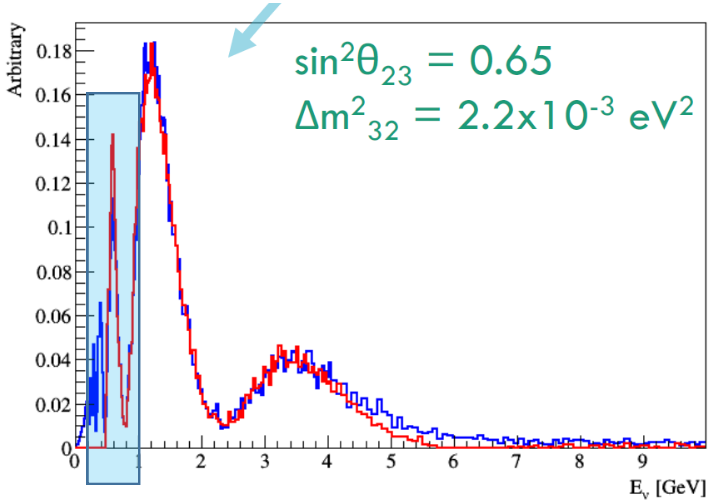


T2K unoscillated flux at ND

T2K flux paper

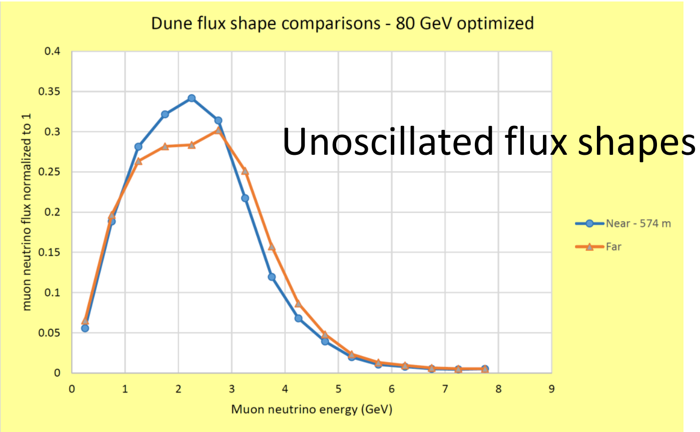
DUNE oscillated flux at FD (+ DUNEprism fit), 2 different parameter settings





The ND/FD flux shape difference problem

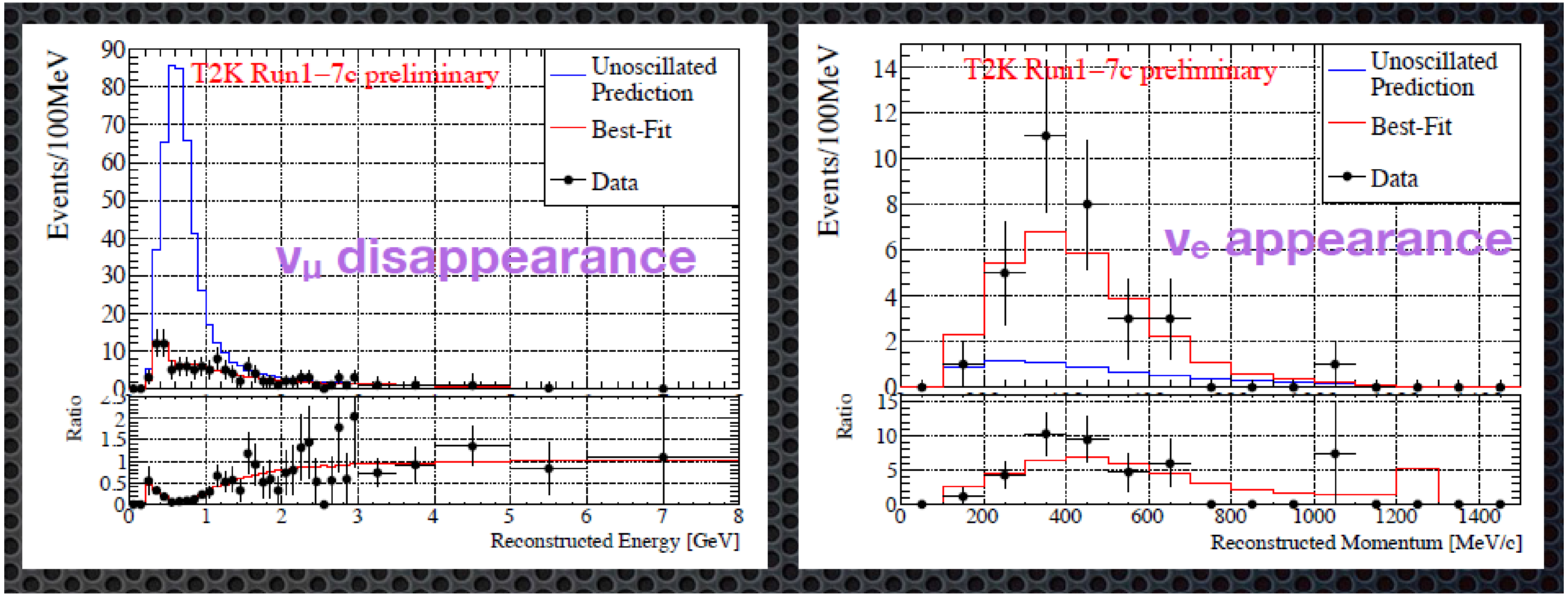
“I do so relish these times of peril.”*



- Neutrino spectra at ND and FD differ
- Leads to systematic errors arising from energy reconstruction, efficiencies, unfolding, modeling, etc.

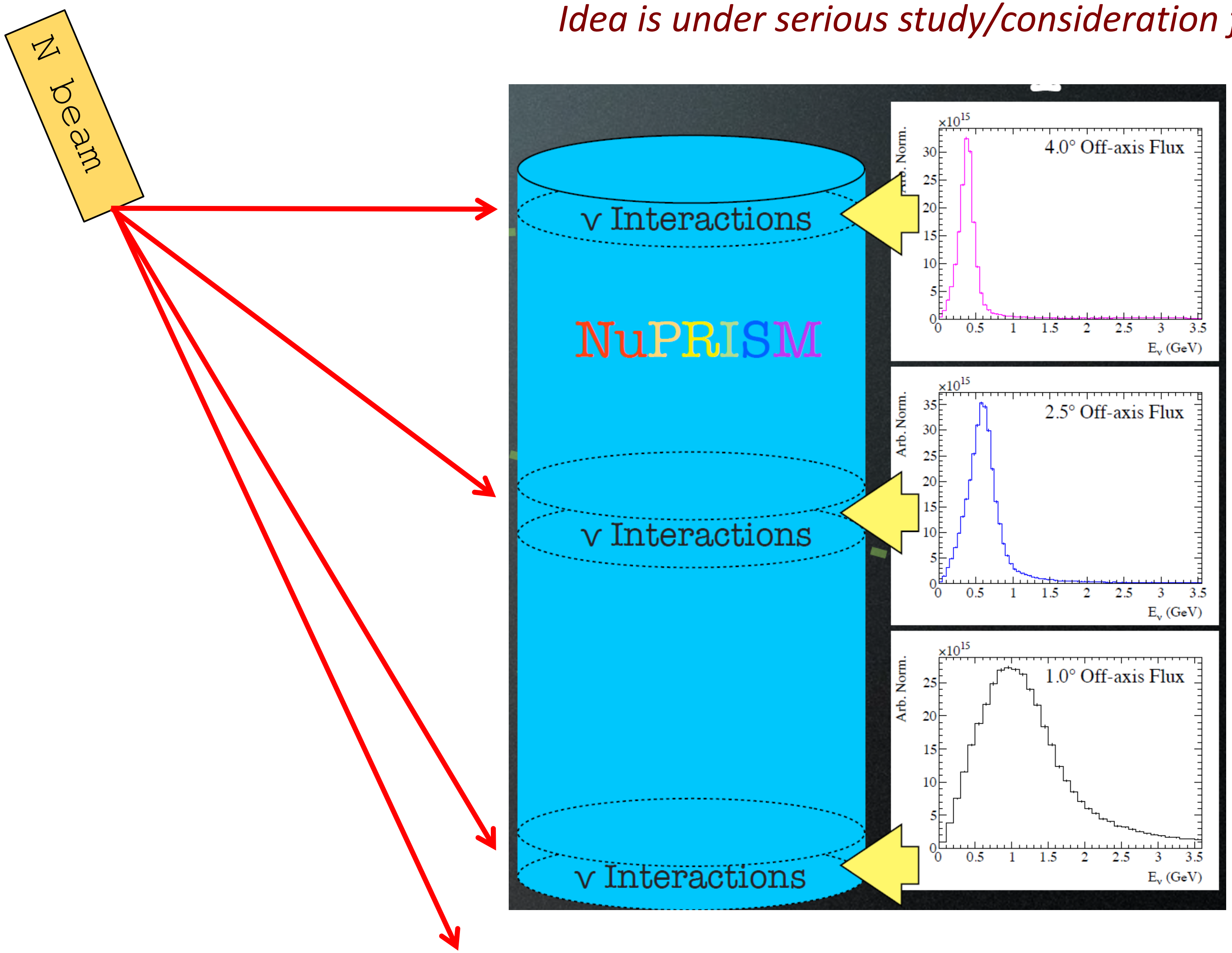
*Quote from Sheen to Jimmy Neutron

The Ugly



NuPRISM to DUNEPRISM

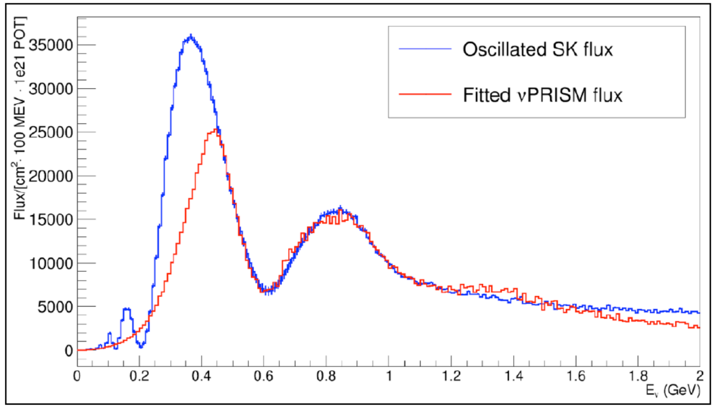
Idea is under serious study/consideration for DUNE



NuPRISM at T2K

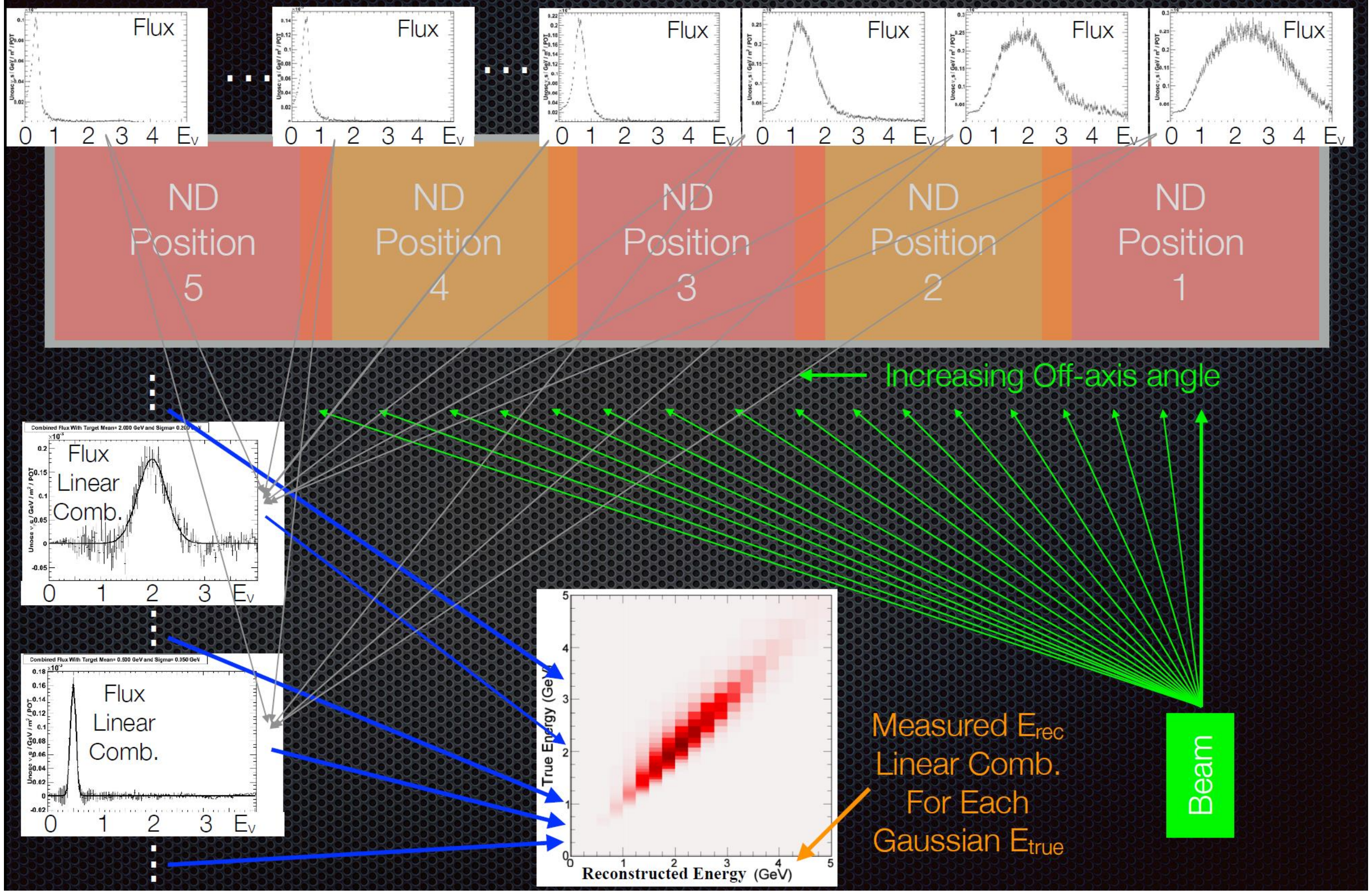
From M. Wilking

Oscillated Flux Produced at the Near Detector!



Linear combination of fluxes at differing off-axis angles can create a flux at near detector with oscillated FD flux shape

DUNE-PRISM Concept

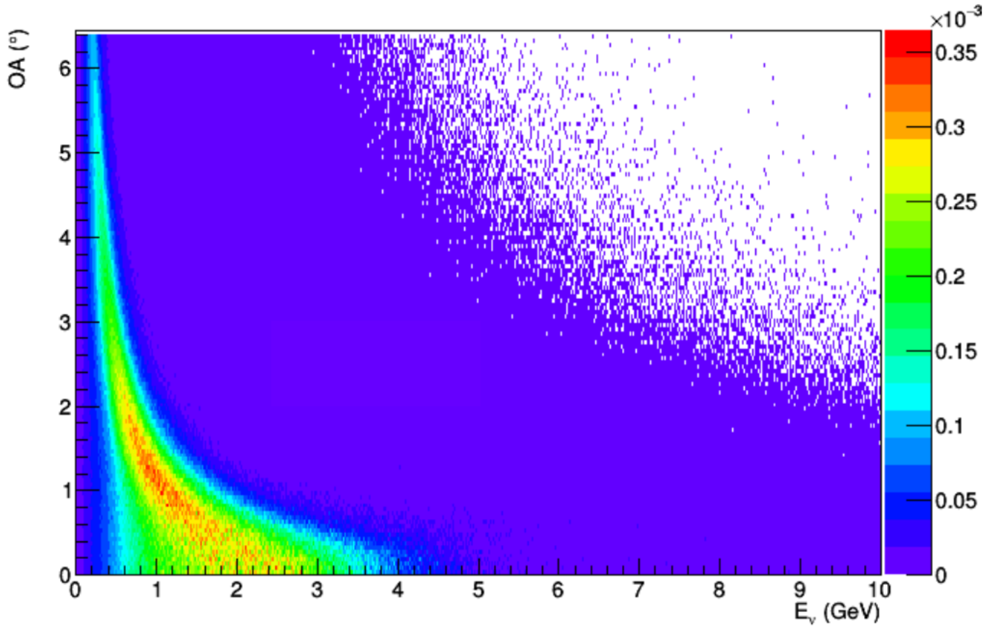


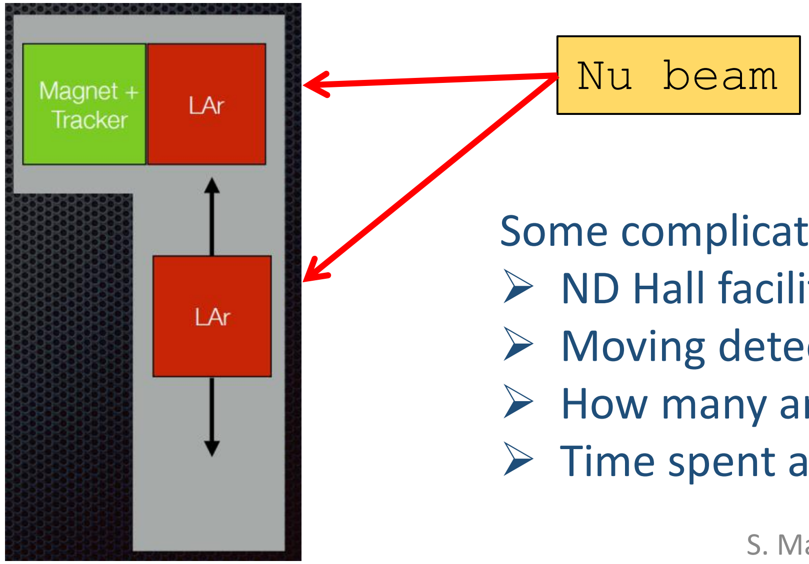
Can use linear combinations of the different fluxes to create samples of “monochromatic” beams, from which you can create the energy smearing matrix for ND

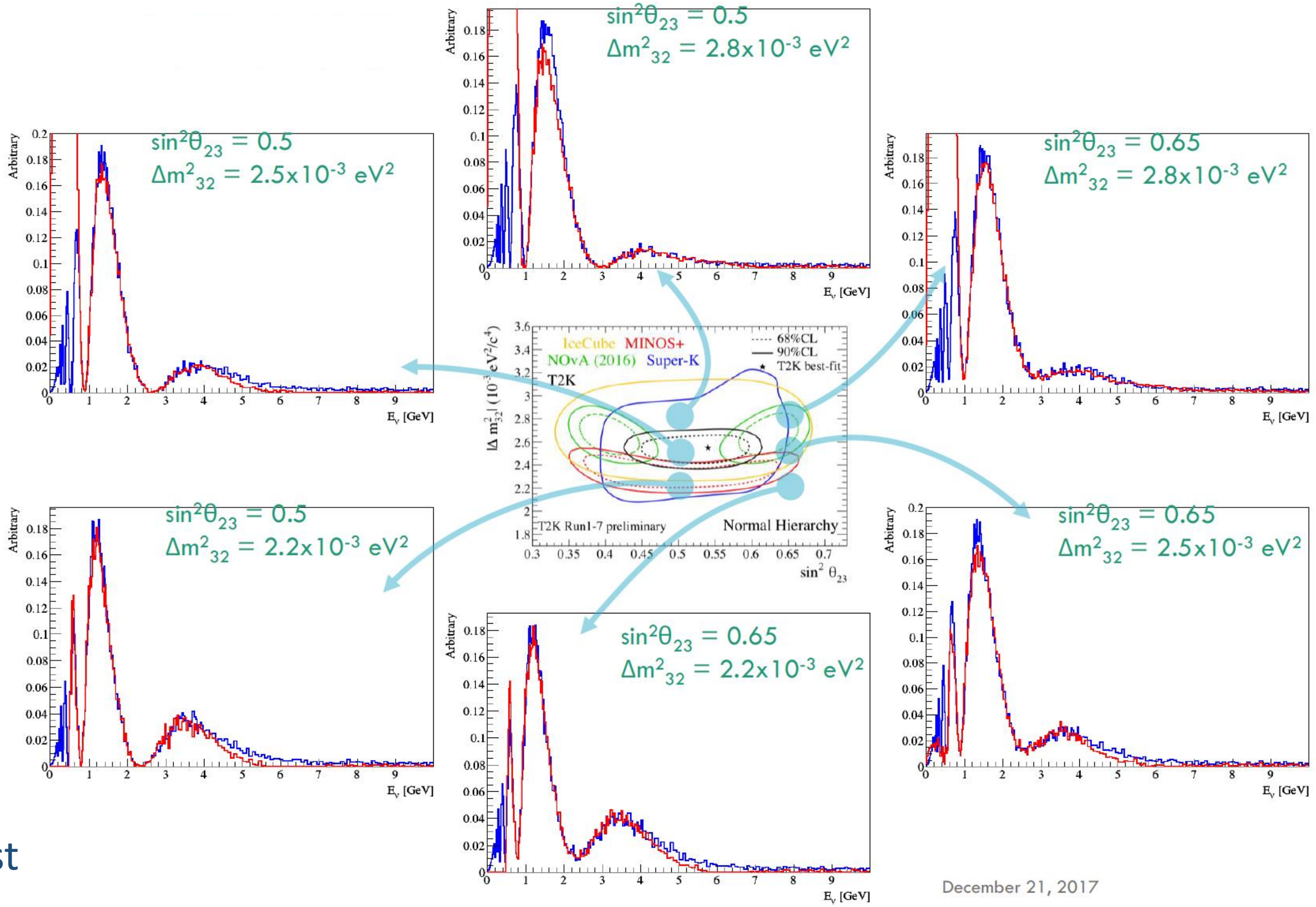
The off-axis spectra may provide indications of problems with beam or xsec model that might be missed otherwise

M. Wilking, shown at 3rd DUNE ND workshop (Nov. 2017)

DUNE ND studies underway





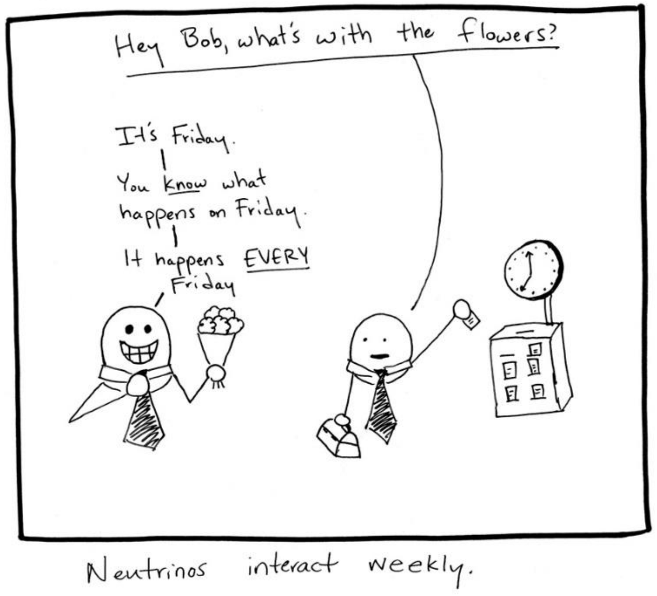


December 21, 2017

Some complications:

- ND Hall facility cost
- Moving detector
- How many angle settings
- Time spent at each angle for sufficient statistics

Conclusions/discussion



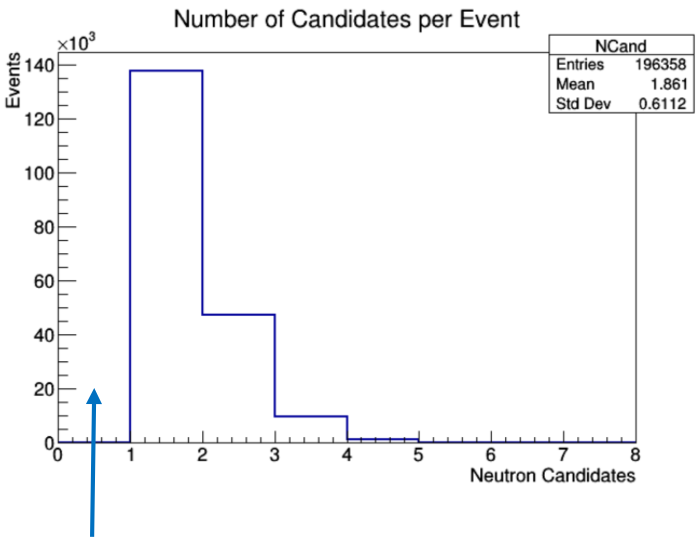
Cartoon from User's Guide to the Universe (Dave Goldberg and Jeff Blomquist)

- Neutrinos have been difficult
- Concepts under discussion for DUNE contain many elements to minimize potential systematic errors:
  - ND and FD have same target nucleus and similar-ish detectors
  - External hadron production using replica target and horns
  - Plan to include low density detector to give excellent resolution
  - PRISM concept to use map E_{recon} to E_{true} and create ND flux in same shape as FD flux
  - May include 3DST, neutrons and connection with plastic data and low energy T2K superFGD data
  - Will build on experience of T2K, NOvA
  - Will start with models consistent with (hopefully) massive data sets of MiniBooNE, MINERvA, T2K, NOvA, SBN program, etc.
- Neutrons! Multiplicity and direction measurements possible
- Neutrinos will continue to be difficult

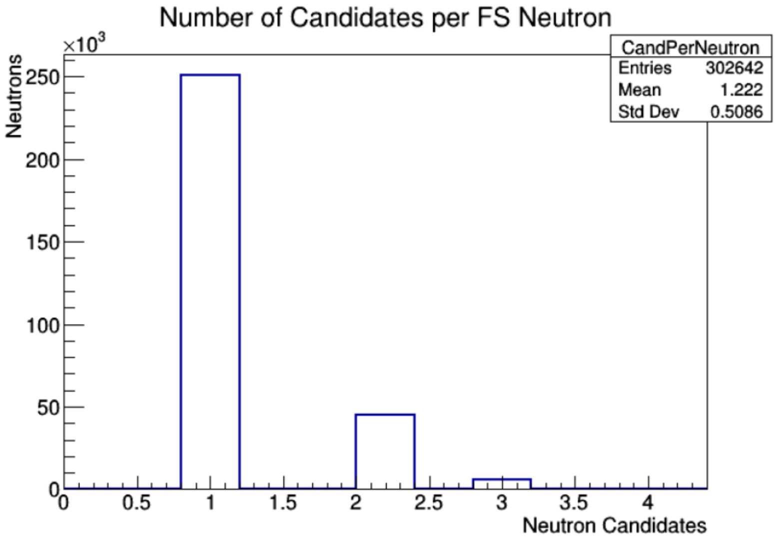
Backups

A VERY preliminary look at neutrons in 3DST simulations

- Look at MC truth (numu CC sample), neutron interactions with energy deposits > 2MeV
- Sum energy deposited in 10 cm box centered on true neutron interaction position (and >3x non-neutron energy in box)

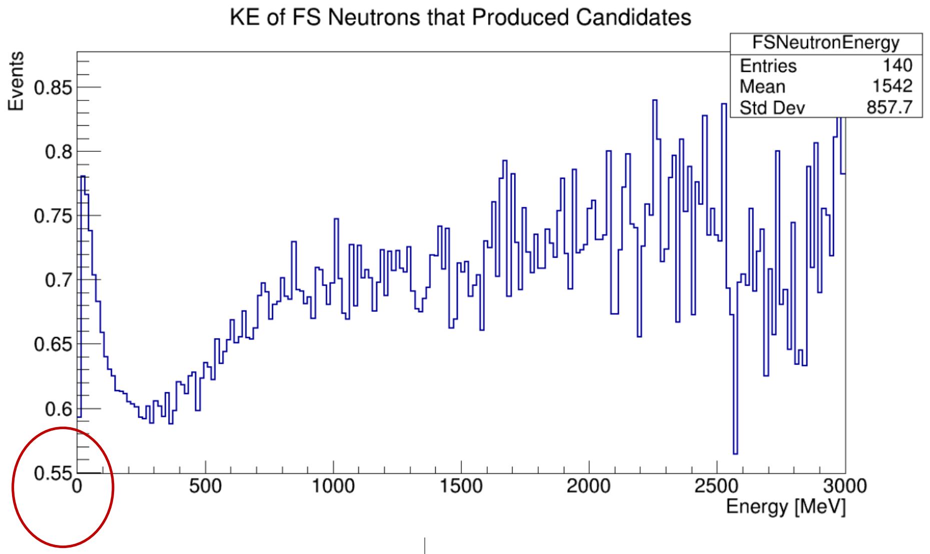


52% of events have no neutron candidates (not shown here)



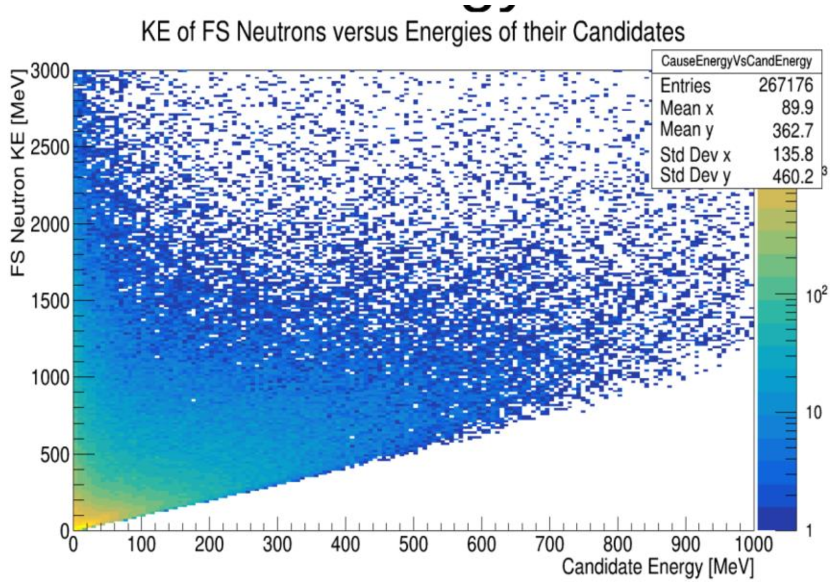
In the 48% of the events where a candidate is seen

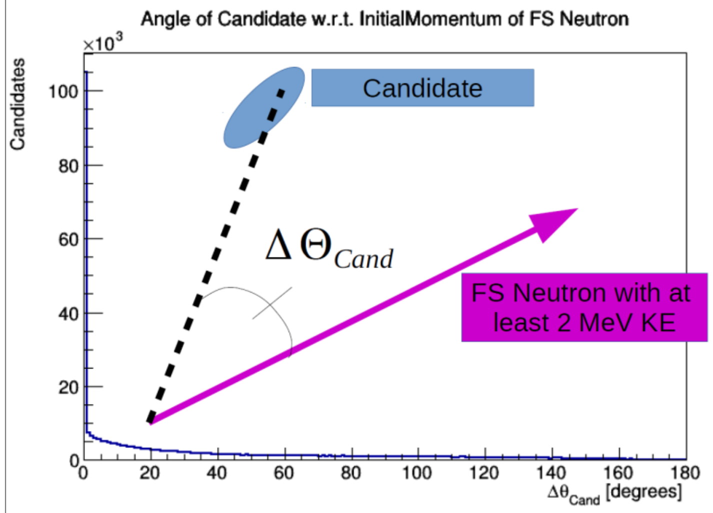
Rate at which a FS neutron is seen as a candidate per FS neutron as function of neutron KE



Note suppressed zero

Neutron candidate energy versus FS neutron KE

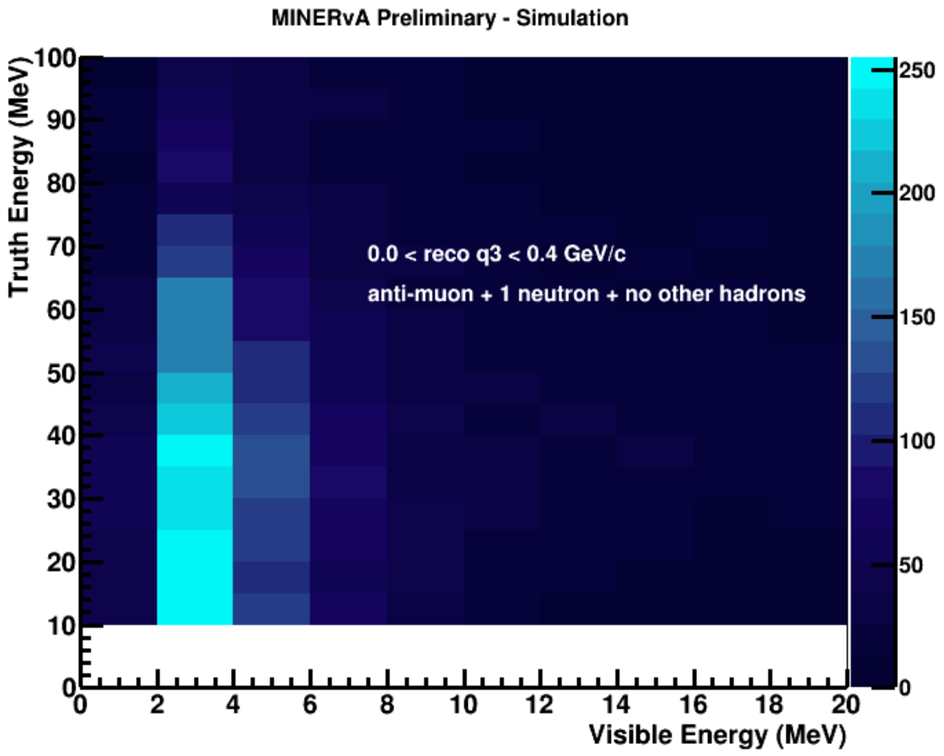


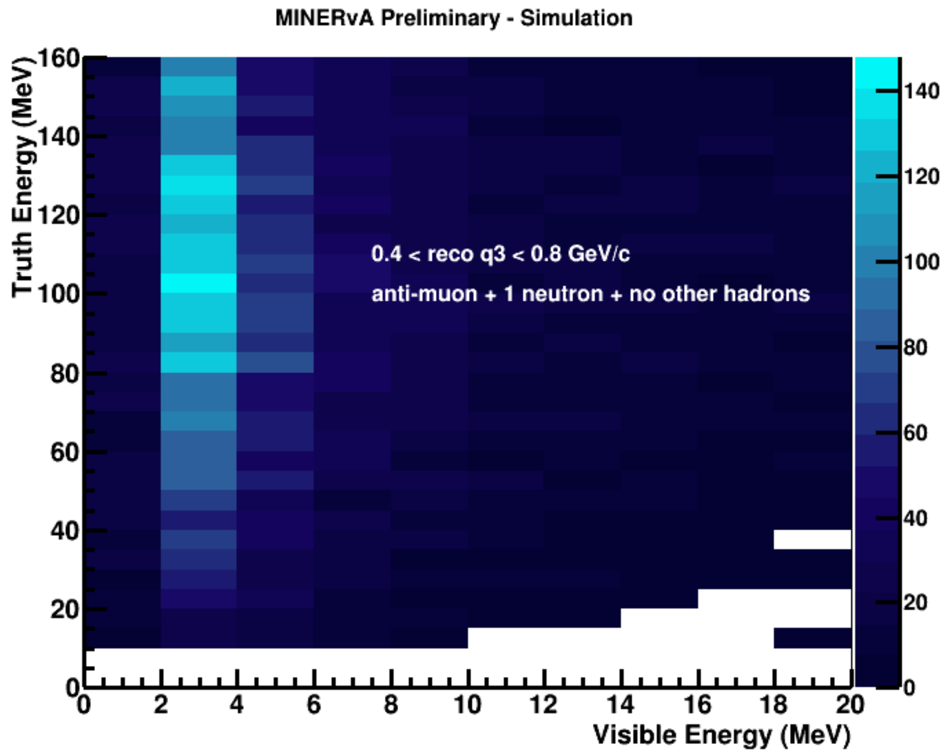


Sharp peak at zero is due to no resolution smearing and energy deposit seen is coming from first interaction of neutron

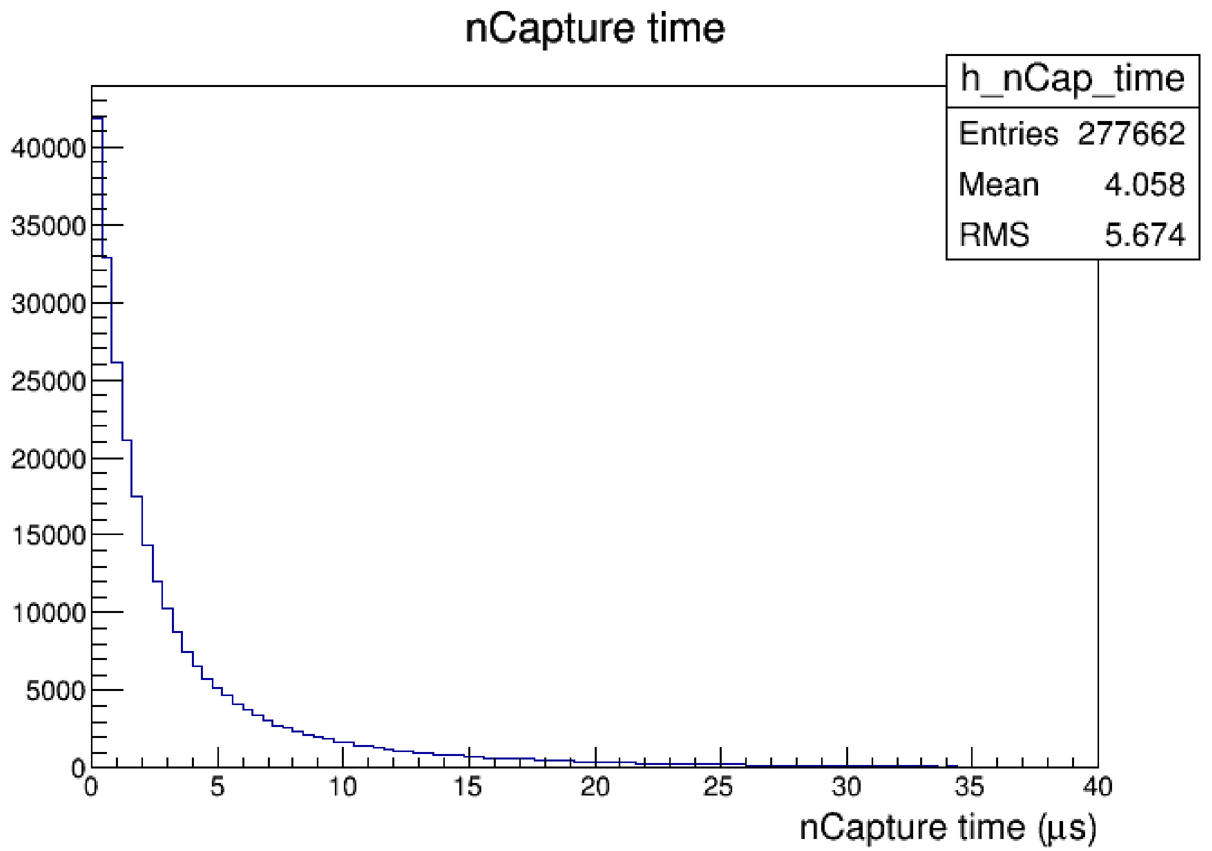
What does MINERvA see according to GEANT4?

Different bins of momentum transfer

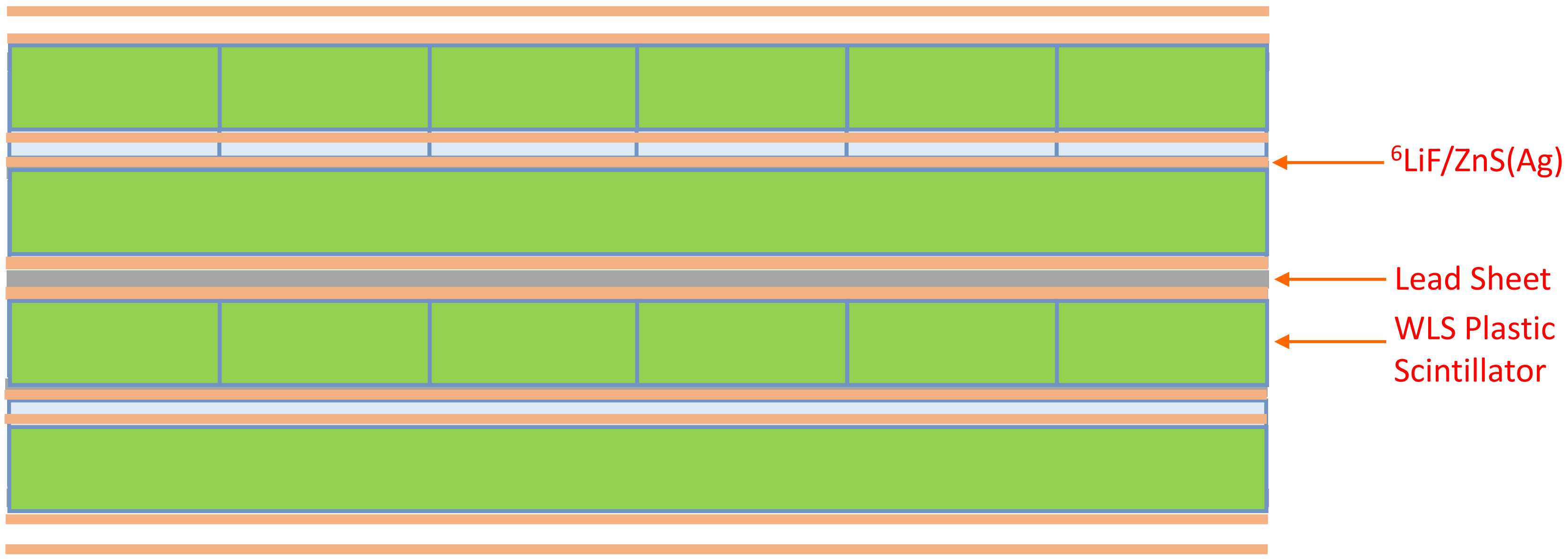




Neutrons leave deposits of 3-6 MeV, flat with neutron true energy
Recent follow-on study indicates the deposits often come from charged particles coming out of a nucleus broken up by the neutron.



$$^{6}\mathrm{Li} + n \rightarrow t\,(2.05\,\mathrm{MeV}) + \alpha\,(2.73\,\mathrm{MeV})$$



^{6}LiF/ZnS(Ag)
Lead Sheet
WLS Plastic
Scintillator

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,unosc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) F_{far/near}^{\nu_\mu}(E_\nu)}$$

$$\frac{dN_\nu^{\det}}{dE_\nu} = \phi_\nu^{\det}(E_\nu)\sigma_\nu^X(E_\nu)$$

$$\frac{dN_\nu^{\det}}{dE_{rec}} = \int \phi_\nu^{\det}(E_\nu)\sigma_\nu^X(E_\nu) D_\nu^{\det}(E_\nu, E_{rec}) dE_\nu$$

Detector effects lead to reconstructed spectrum

$$\frac{dN_\nu^{\det}}{dE_{rec}} = \int \frac{dN_\nu^{\det}}{dE_\nu} D_\nu^{\det}(E_\nu, E_{rec}) dE_\nu$$

$$\frac{dN_{\nu}^{\det}}{dE_{\nu}} = \int \frac{dN_{\nu}^{\det}}{dE_{rec}} D_{\nu}^{\det}(E_{rec}, E_{\nu}) dE_{\nu}$$

Must unfold to go from reconstructed spectrum to “truth”

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) F_{far/near}^{\nu_\mu}(E_\nu)} = \frac{\dfrac{dN_{\nu_e}^{far}}{dE_\nu} \dfrac{1}{\sigma_{\nu_e}^{Ar}(E_\nu)}}{\dfrac{dN_{\nu_\mu}^{near}}{dE_\nu} \dfrac{1}{\sigma_{\nu_\mu}^{X}(E_\nu)} F_{far/near}^{\nu_\mu}(E_\nu)}$$

If ND and FD have:
Same target
Same detector effects (even for the different leptons)

Then it simplifies to counting plus flux ratio calculation

$$P_{\nu_\mu \to \nu_e}(E_\nu) \simeq \frac{\int \frac{dN^{far}_{\nu_e}}{dE_{rec}} D^{far}_{\nu_e}(E_{rec}, E_\nu) \frac{1}{\sigma^{Ar}_{\nu_e}(E_\nu)} dE_\nu}{\int \frac{dN^{near}_{\nu_\mu}}{dE_{rec}} D^{near}_{\nu_\mu}(E_{rec}, E_\nu) \frac{1}{\sigma^{X}_{\nu_\mu}(E_\nu)} F^{\nu_\mu}_{far/near}(E_\nu) dE_\nu}$$

If ND and FD have:
Same target
Same detector effects (even for the different leptons)

Then it simplifies to counting plus flux ratio calculation

Significant irreducible ν_e appearance background is intrinsic ν_e content of beam.
Suppose we choose to constrain that via ND measurement of ν_e content of beam.

$$\frac{dN_{\nu_e}^{far,unosc}}{dE_\nu} = \frac{dN_{\nu_e}^{near}}{dE_\nu} \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} F_{far/near}^{\nu_e}(E_\nu)$$

$$\frac{dN_{\nu_e}^{far,unosc}}{dE_\nu} = \int \frac{dN_{\nu_e}^{near}}{dE_{rec}} D_{\nu_e}^{near}(E_{rec}, E_\nu) \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} F_{far/near}^{\nu_e}(E_\nu) dE_\nu$$

Significant irreducible ν_e appearance background is intrinsic ν_e content of beam. Suppose we choose to constrain that via ND measurement of ν_μ content of beam plus ν_e/ ν_μ ratio at the ND.

$$\frac{dN_{\nu_e}^{far,unosc}}{dE_\nu} = \frac{dN_{\nu_e}^{near}}{dE_\nu} \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} F_{far/near}^{\nu_e}(E_\nu)$$

$$\frac{dN_{\nu_e}^{far,unosc}}{dE_\nu} = \frac{dN_{\nu_\mu}^{near}}{dE_\nu} \frac{\phi_{\nu_\mu}^{near}(E_\nu)}{\phi_{\nu_e}^{near}(E_\nu)} \frac{\sigma_{\nu_\mu}^{X}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} F_{far/near}^{\nu_e}(E_\nu)$$

$$\frac{dN_{\nu_e}^{far,unosc}}{dE_\nu} = \frac{dN_{\nu_\mu}^{near}}{dE_\nu} \frac{\phi_{\nu_\mu}^{near}(E_\nu)}{\phi_{\nu_e}^{near}(E_\nu)} \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} F_{far/near}^{\nu_e}(E_\nu)$$

Assuming neutrino universality

$$\frac{dN_{\nu_e}^{far,unosc}}{dE_\nu} = \int \frac{dN_{\nu_\mu}^{near}}{dE_{rec}} D_{\nu_\mu}^{near}(E_{rec}, E_\nu) \frac{\phi_{\nu_\mu}^{near}(E_\nu)}{\phi_{\nu_e}^{near}(E_\nu)} \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_e}^{X}(E_\nu)} F_{far/near}^{\nu_e}(E_\nu) dE_\nu$$

Technical slide: steps to calorimetric reconstruction

We do not start knowing the energy of the neutrino, only the direction.

Measure the energy E_μ and angle θ_μ of the outgoing muon.
Measure the detected energy attributed to hadrons $E_{visible}$.

A. turn $E_{visible}$ into $E_{available}$ using detector MC, discounts neutrons
$E_{available}$ = Proton KE, $\pi^\pm$ KE, π^0, e, γ energy (plus heavier particles)
little neutrino model dependence (some anti-nu model dependence)

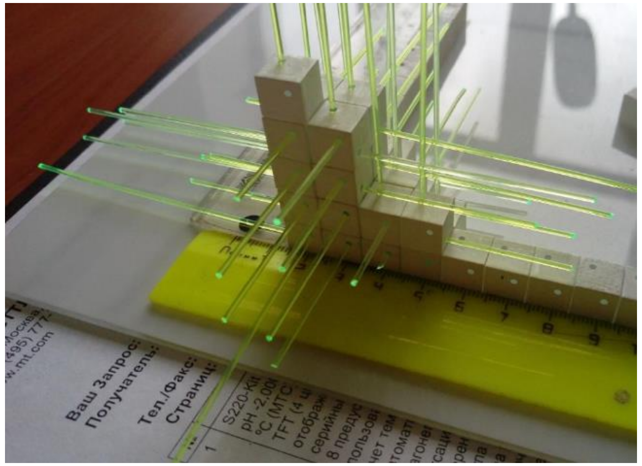
B. Use MC and correct to energy transfer q_0 (= E_{had} = ν = ω)
(unbiased, but correction has some dependence on interaction model)

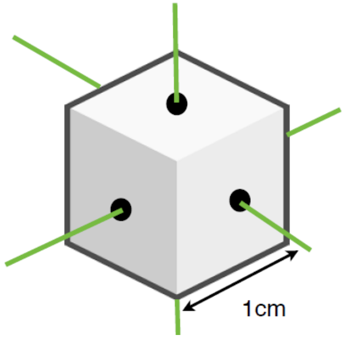
B. Estimated neutrino energy $E_\nu = E_\mu + q_0$

C. Estimated four-momentum $Q^2 = 2\, E_\nu\, (E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$

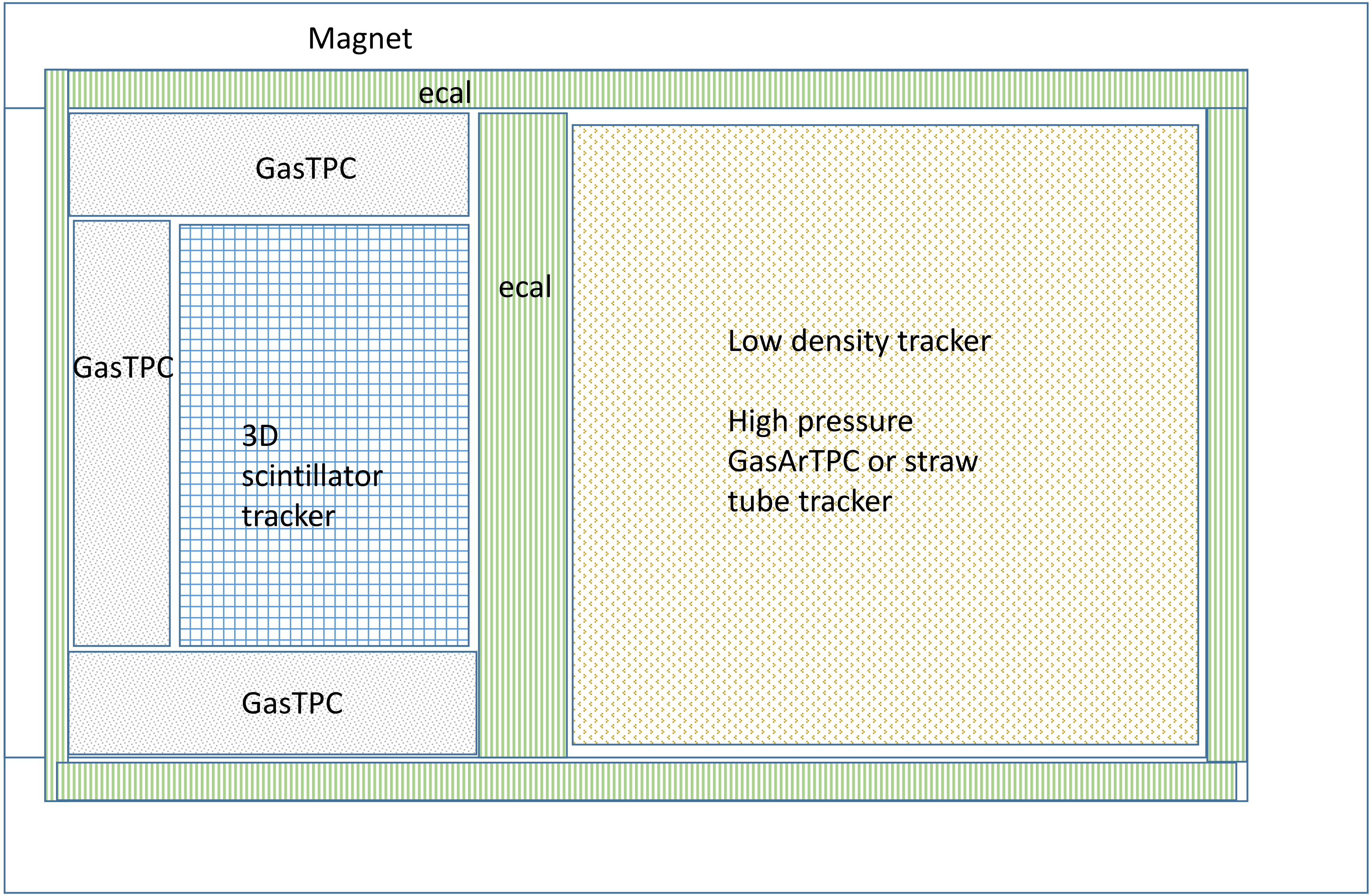
D. Estimated momentum transfer $q_3 = \mathrm{Sqrt}(Q^2 + q_0^2)$

17





Super-FGD, D. Sgalaberna, A. Longhin, Yuri Kudenko


Magnet
ecal
GasTPC
GasTPC
3D
scintillator
tracker
ecal
Low density tracker
High pressure
GasArTPC or straw
tube tracker
GasTPC