H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF)

NEAR DETECTORS

CURRENT AND UPCOMING CHALLENGES

GUIDANCE:

- *"Should cover the potential near detector technologies for the experiments presented in the previous talk, with focuses on the challenges of neutrino interactions and systematic error constraints."*
- Known knowns:
  - near detectors for current and past experiments
- Known unknowns:
  - near detector concepts for upcoming experiments like DUNE and Hyper-Kamiokande
- Unknown unknowns:
  - will current near detector concepts for DUNE/HK accomplish their goals?

OVERVIEW

- Near detector design is intimately tied to systematic errors
    - what are the systematic errors?
- How does one optimize near detector design?
- Over the year I've heard several very general "mantras", "rules", etc. regarding near detectors
    - Revisit these statements? What motivates them?
    - Are they true? Have things changed?
    - important to know what the ND is supposed to do in order to sensibly design one
- Evaluate current challenges
- Focus on accelerator-based experiments

REMINDER: LBL PHYSICS

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Delta m^2_{31}\frac{L}{4E}$$

- Measurement of $\sin^2 2\theta_{23}$ and Δm^2_{31} **Precision of ~1% needed**

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$
$$- \alpha\sin\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+ \alpha\cos\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+ \mathcal{O}(\alpha^2)$$

~30% max. effect

~10%-50%

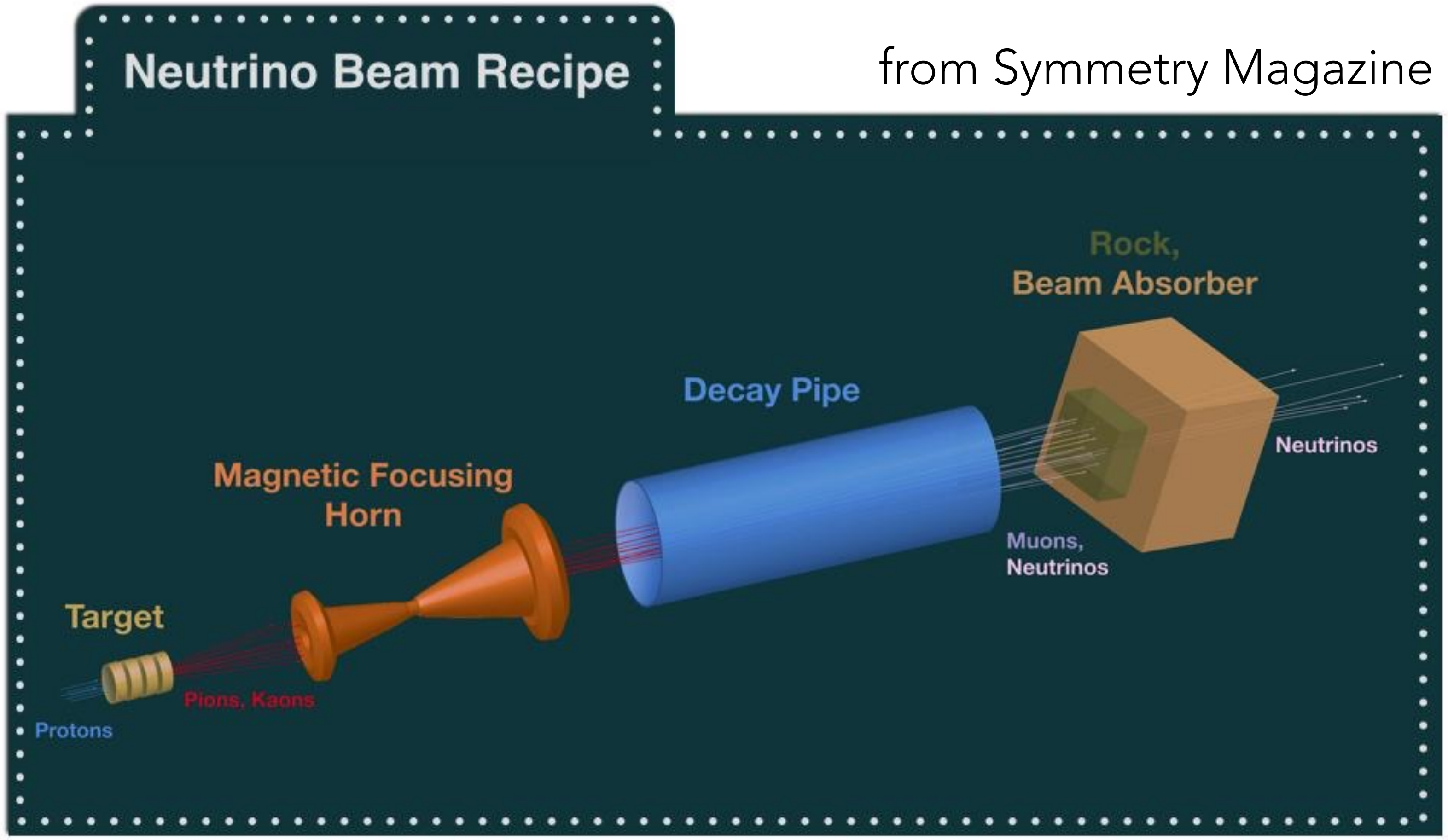
$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31}L}{4E} \qquad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

M. Freund, Phys.Rev. D64 (2001) 053003

- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if sin δ ≠ 0
- Matter effect through x: ν_e ($\bar{\nu}_e$) enhanced in normal (inverted) B

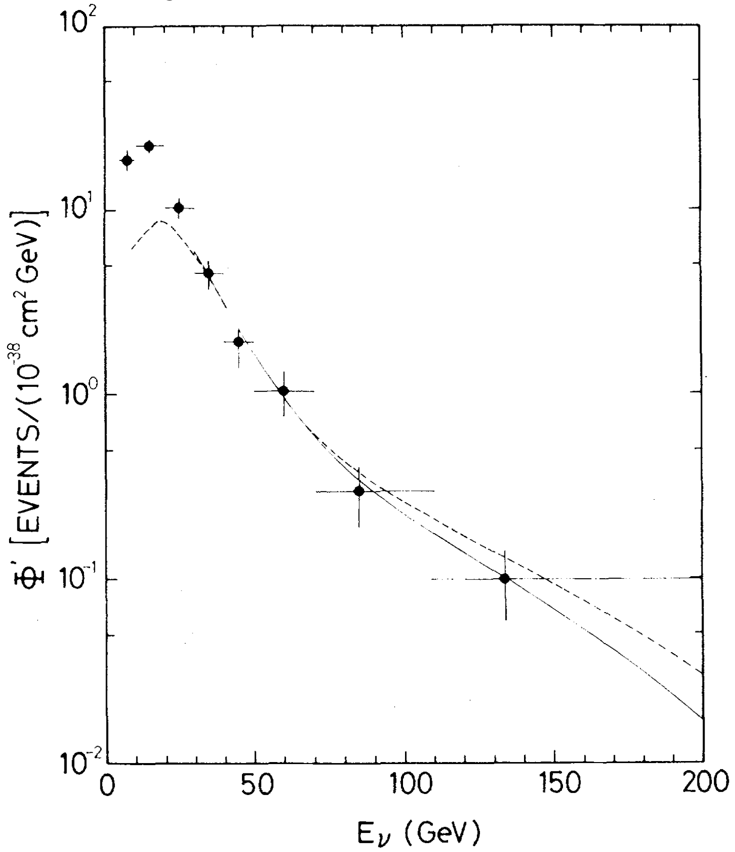
Bottom line: it's complicated!

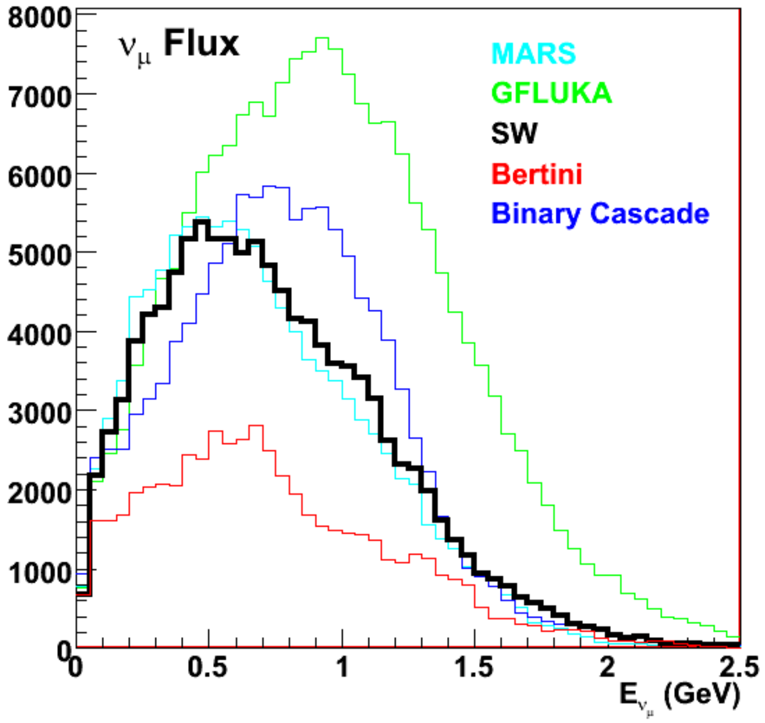
NEUTRINO FLUX



from Symmetry Magazine

T. Kitagaki et al.
Phys.Rev.Lett. 49, 98





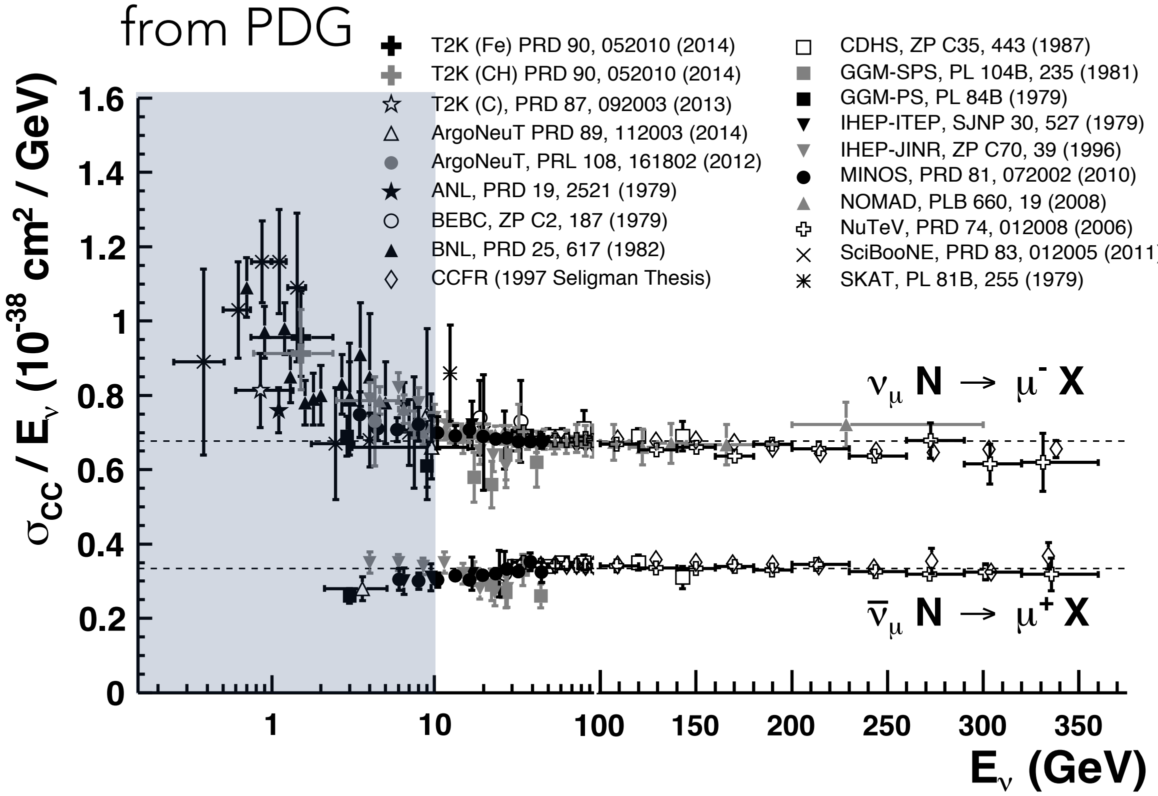
from MiniBooNE

- (absolute) neutrino flux estimates considered a very difficult proposition
    - reflected in large and “unreliable” errors, lots of “difficult” physics
    - “neutrino flux cannot be predicted” >30% uncertainty typical in the past

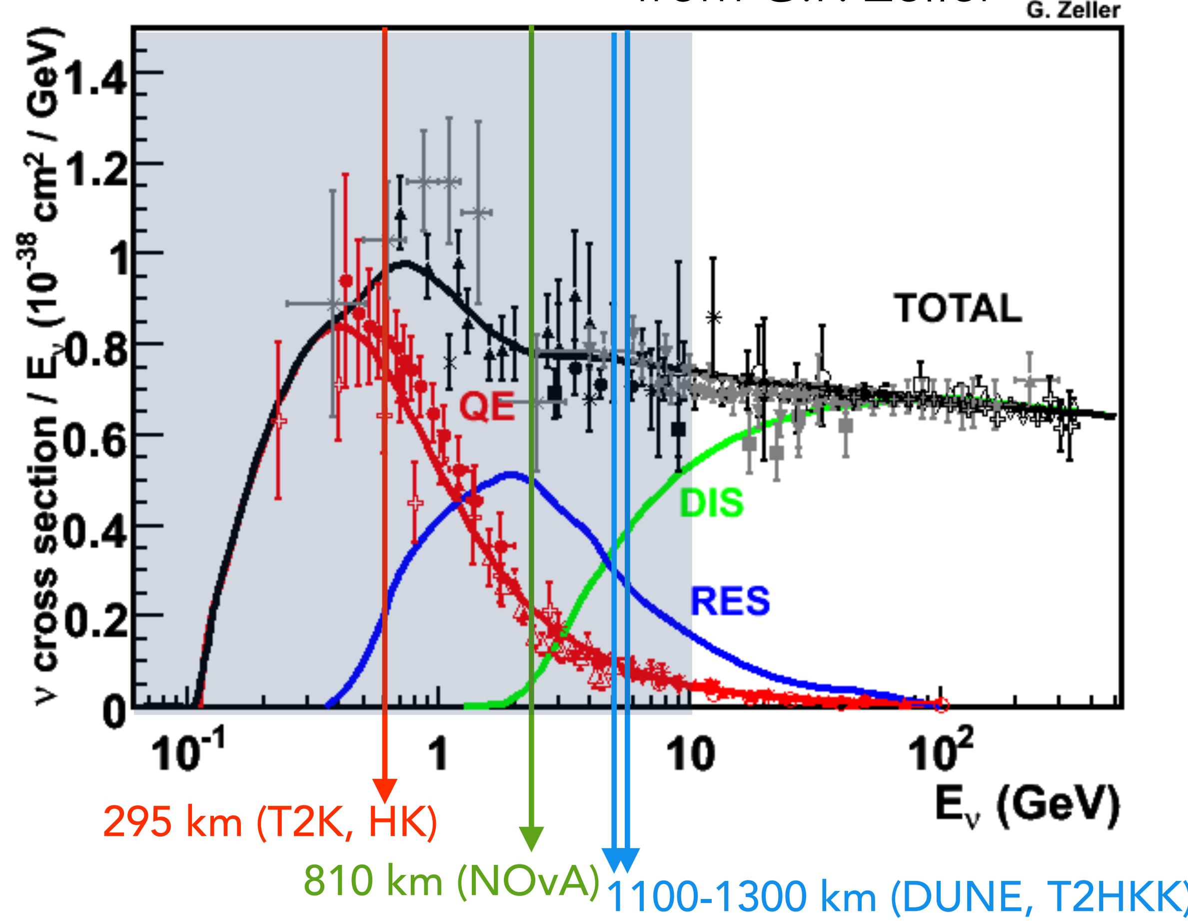
Bottom line: it’s complicated!

NEUTRINO CROSS SECTION:

from PDG



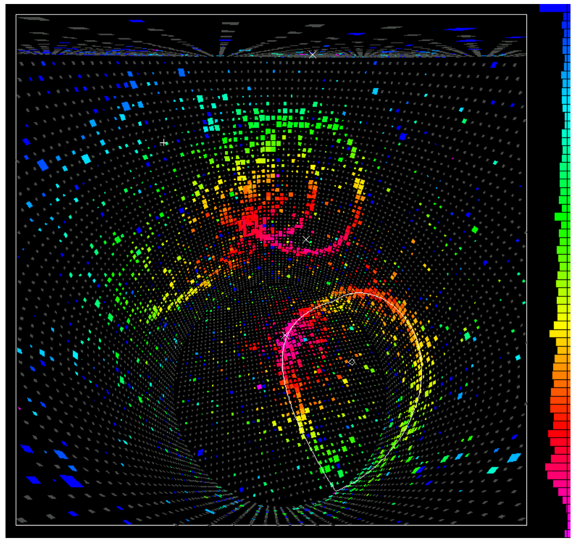
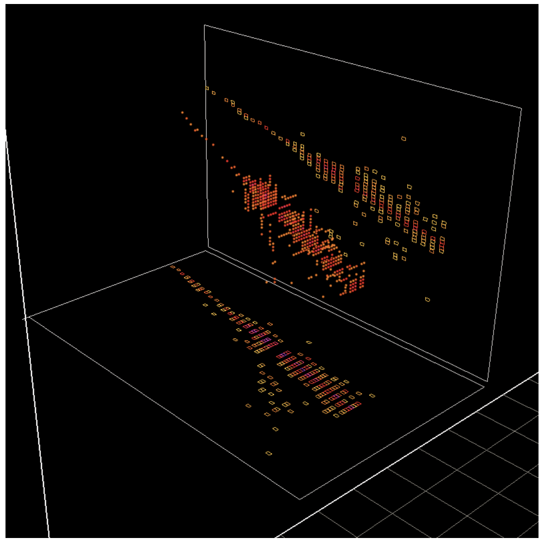
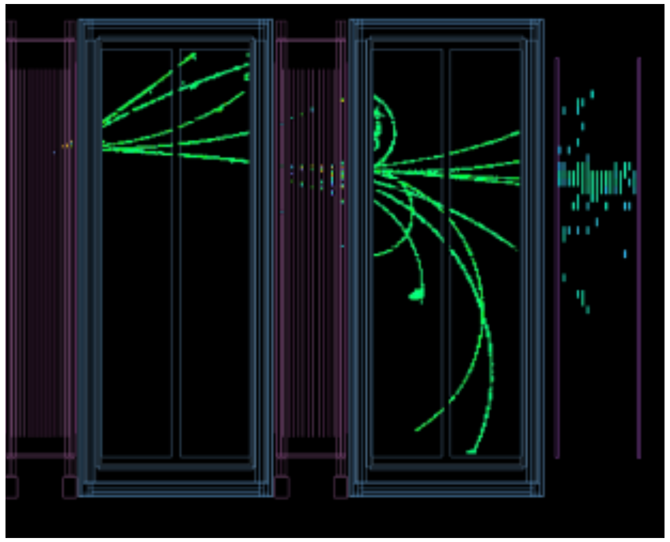
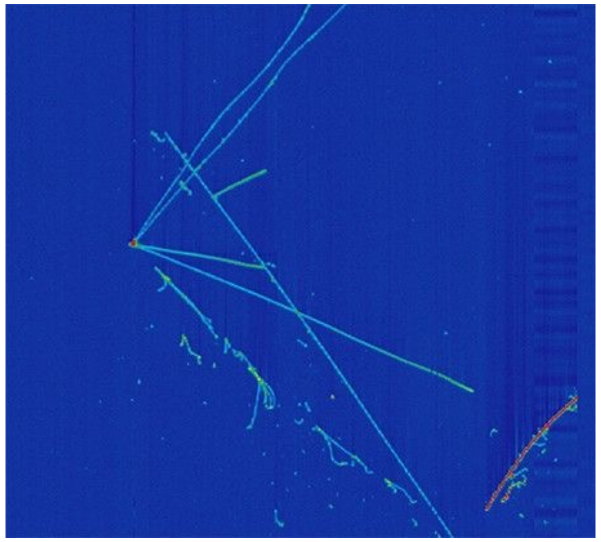
from G.P. Zeller



- At high energies, interactions well understood experimentally and theoretically
  - parton-level deep inelastic scattering dominates the cross section
- Nature has given us a miracle and a curve ball:
  - neutrino oscillations can be probed with accelerator-based beams on a terrestrial scale
  - oscillation maximum occurs at O(1 GeV) where there is a "**rich**" mix of nucleon (resonance production, etc.) and nuclear effects (multibody effects, etc.).

Bottom line: it's complicated!
and much of it isn't particle physics!

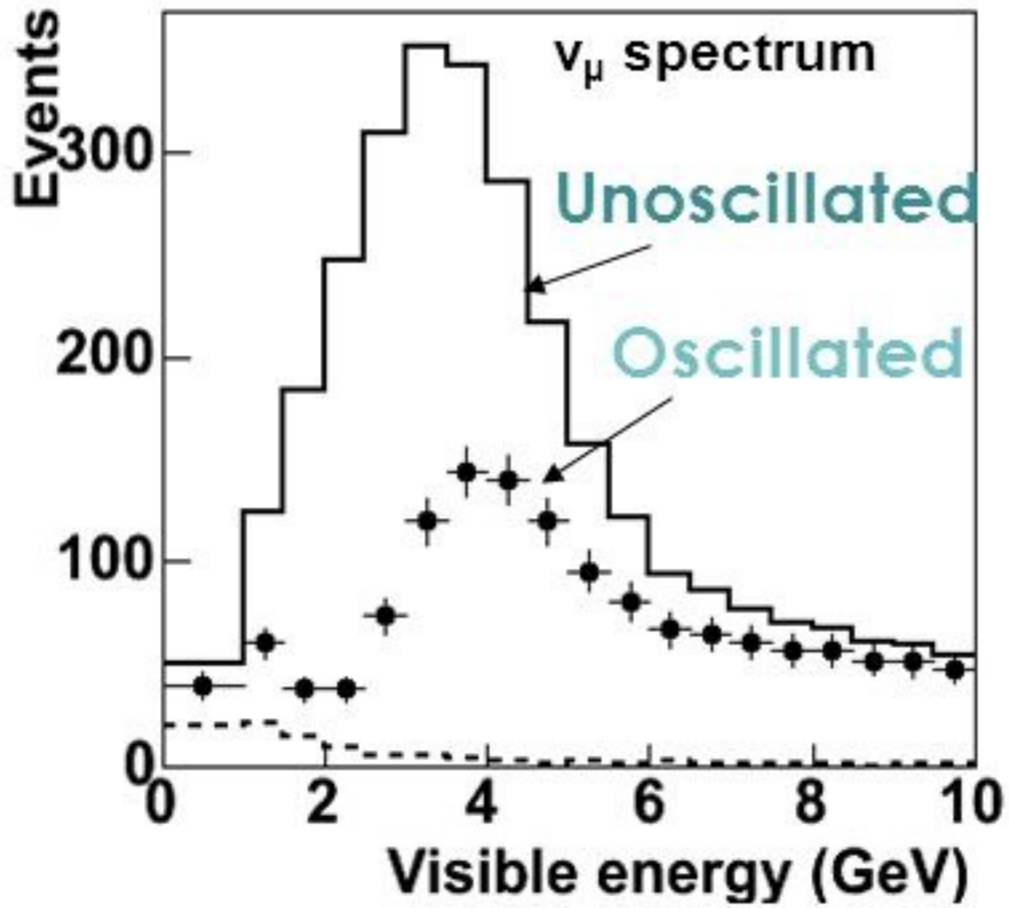
DETECTOR SYSTEMATICS:

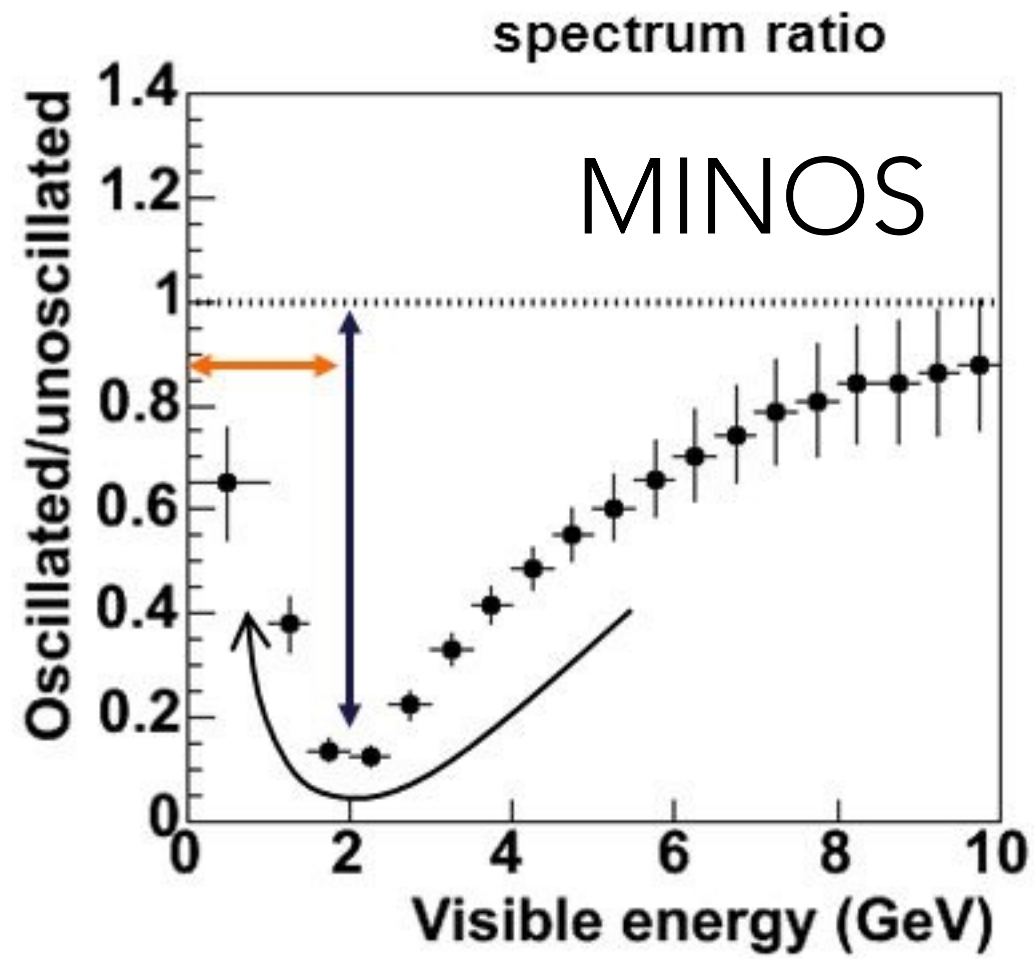





- top down: systematic for each piece of information you want from your detector
    - kinematics (energy/momentum scale, resolution, sign) and overtaxing
    - particle identification,etc.
- bottom-up: systematic for each aspect of your detector
    - water transparency, reflectivity, scattering, PMT response . ….
    - alignment, material composition, particle interactions (EM, hadronic interactions, etc.) .
- drift lifetime, diffusion, etc.
- efficiency/resolution of active elements
- etc., etc.

D. J. Griffiths: *Introduction to Elementary Particles*
"neutrino experiments are notoriously difficult"

BASIC NEAR DETECTOR STRATEGY





$$N_{FD} = \Phi_\nu \times \sigma_\nu \times \epsilon \times P_{osc}(\theta, \Delta m^2)$$
$$N_{ND} = \Phi_\nu \times \sigma_\nu \times \epsilon$$

- Systematic uncertainties can be cancelled by measurements of the unoscillated neutrinos

"ONLY DISAPPEARANCE EXPERIMENTS"

- **. . . . need near detectors**"
- Basic idea:
  - as before, detectors observe

$$N = \Phi_\nu \times \sigma_\nu \times \epsilon$$

  - if there are large uncertainties in

$$\Phi_\nu \times \sigma_\nu$$

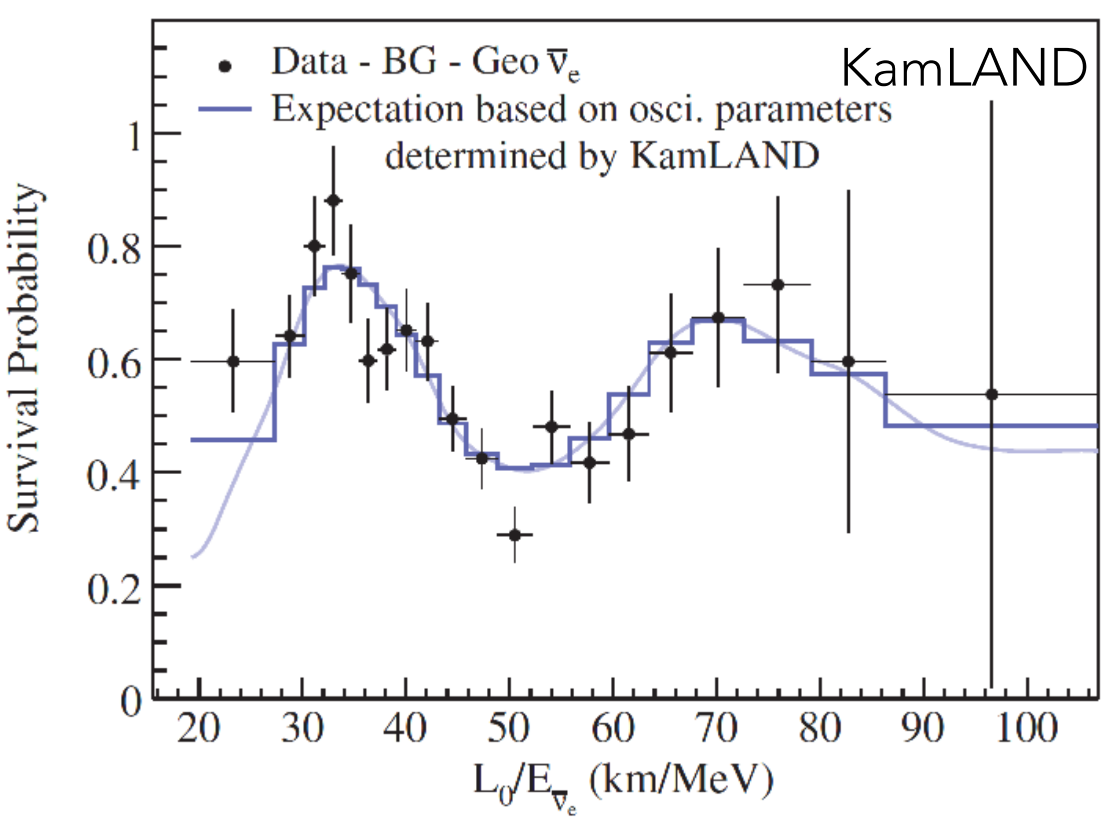
  - it is difficult to make "disappearance measurement" which has as its primary signal a deficit of events.
  - If definitive spectral distortions are visible, than one can circumvent this "rule".

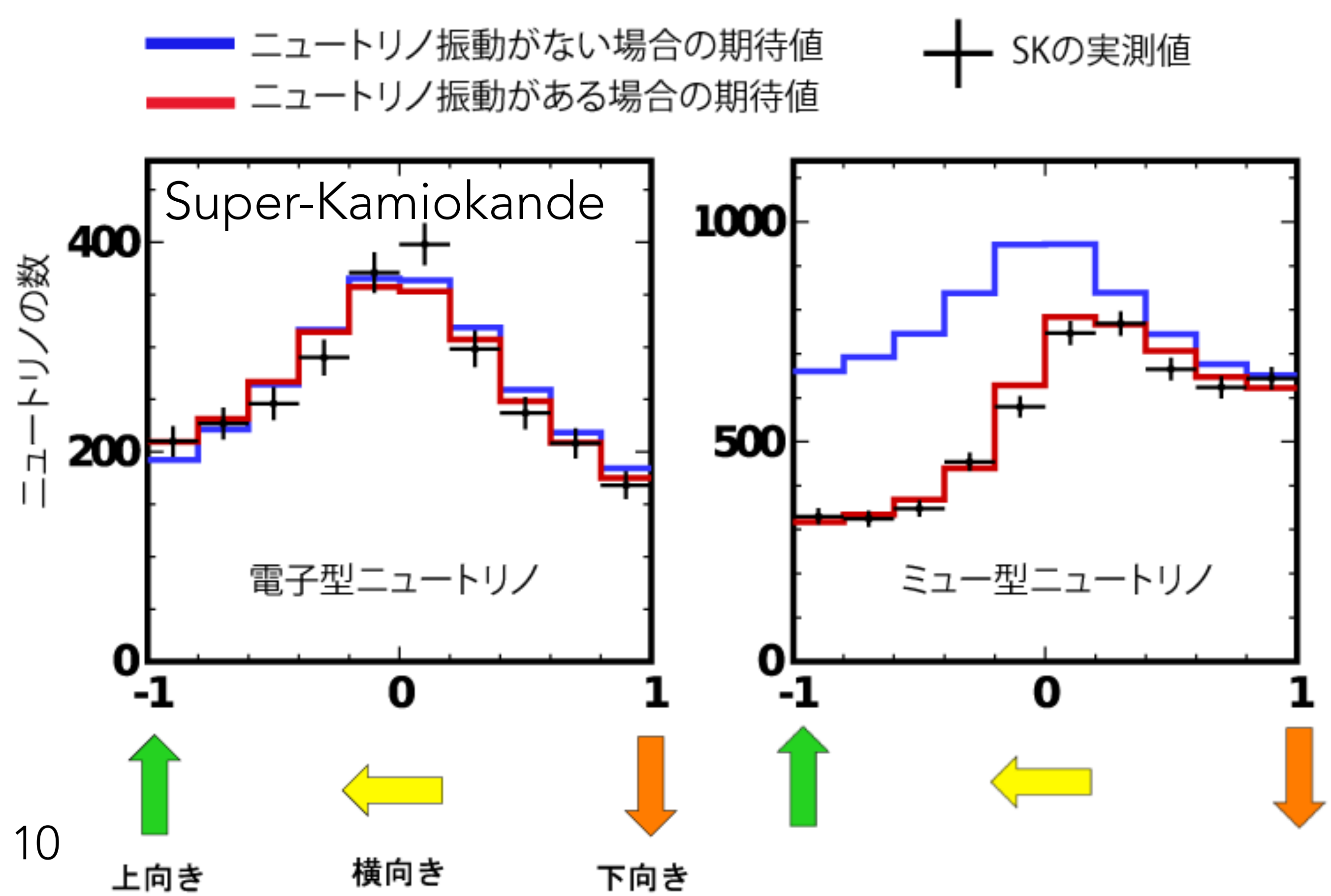
EXAMPLES: DISAPPEARANCE

K2K

MINOS

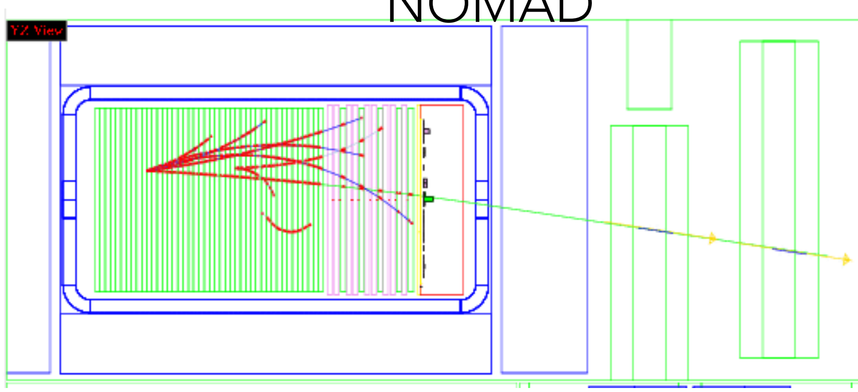
- K2K, MINOS
  - disappearance experiments with NDs
- SK atmospheric., KamLAND
  - disappearance experiments without NDs
  - SK is “its own near detector”
  - reactors: better known flux, cross section
    - range of L/E allows shape to be used



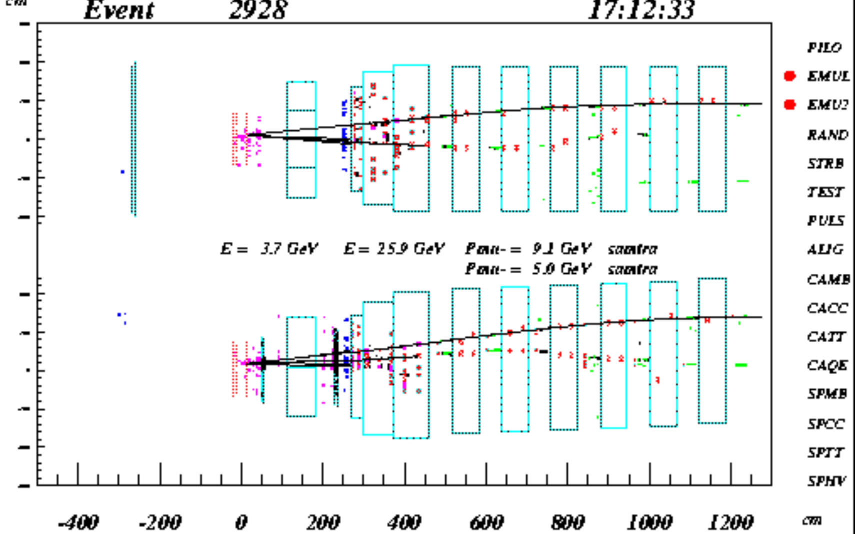


EXAMPLES: APPEARANCE

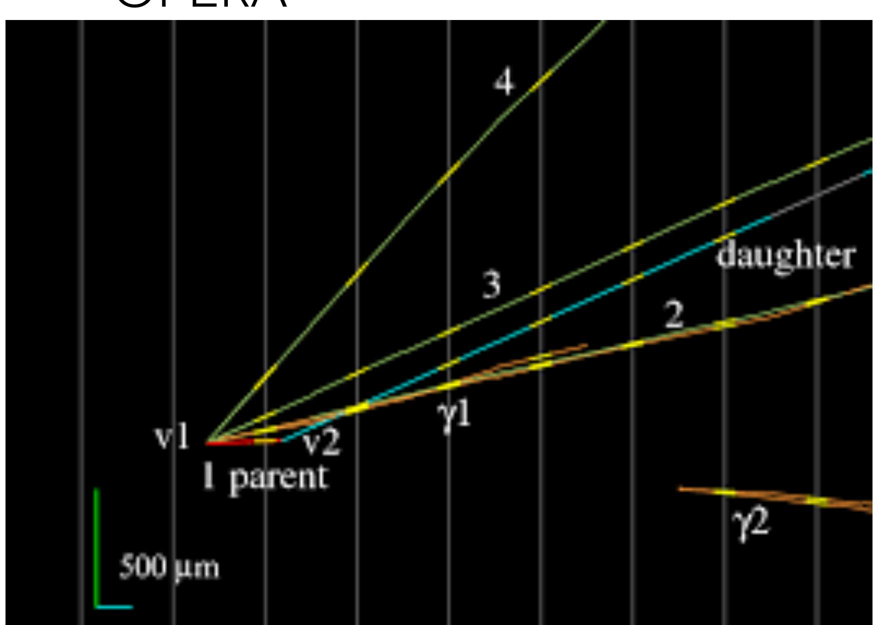
NOMAD



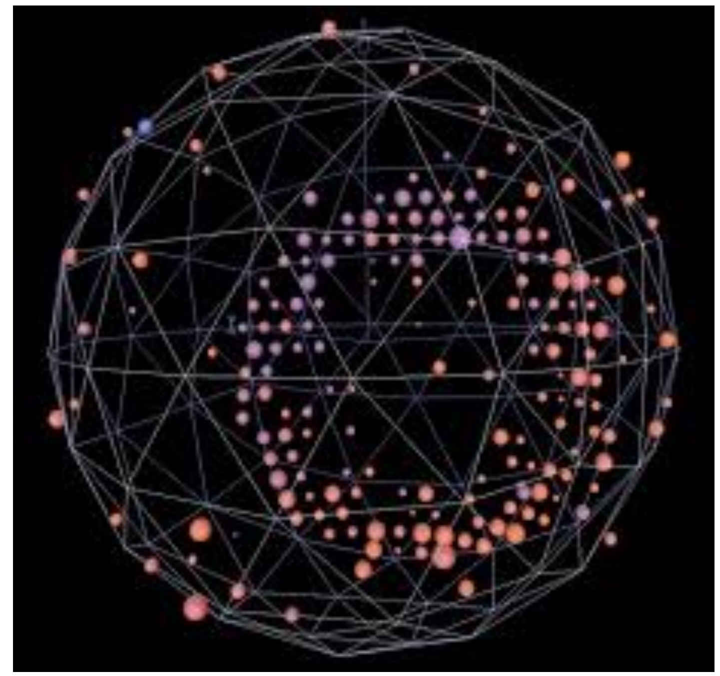
CHORUS



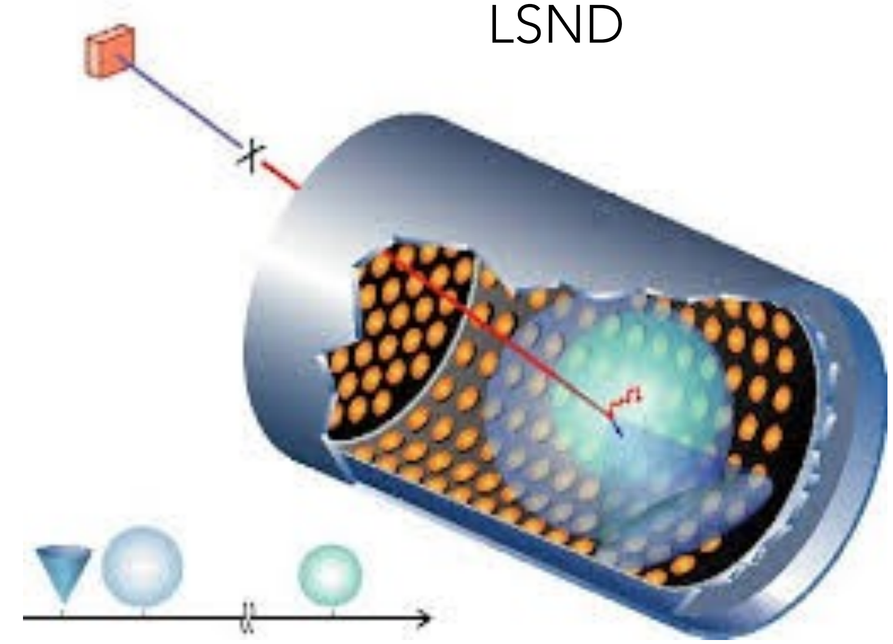
OPERA



MiniBooNE



LSND

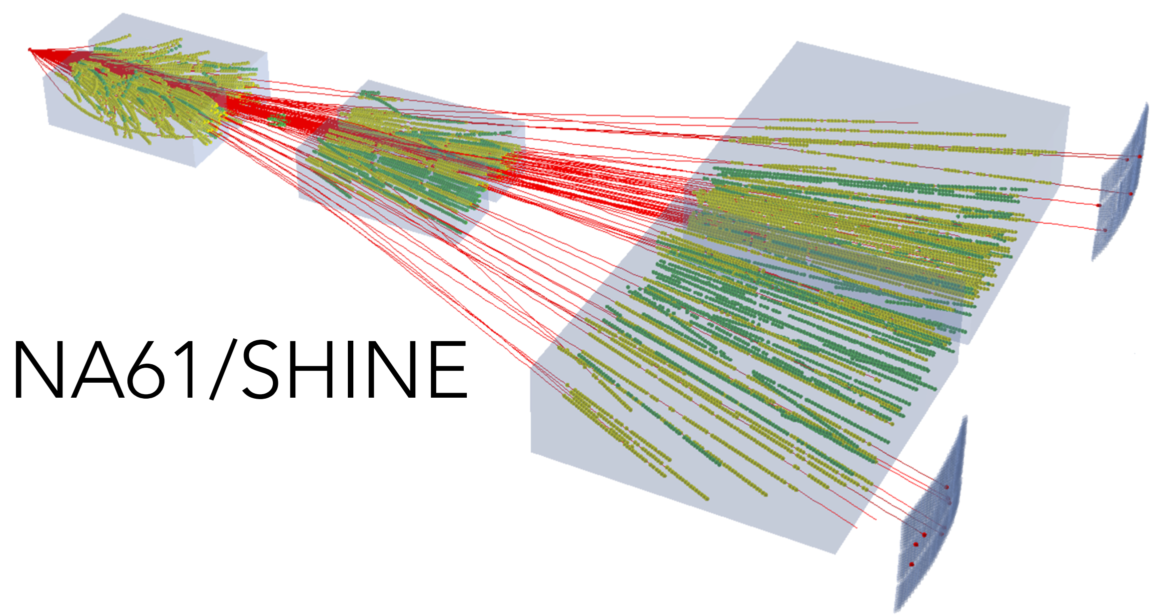


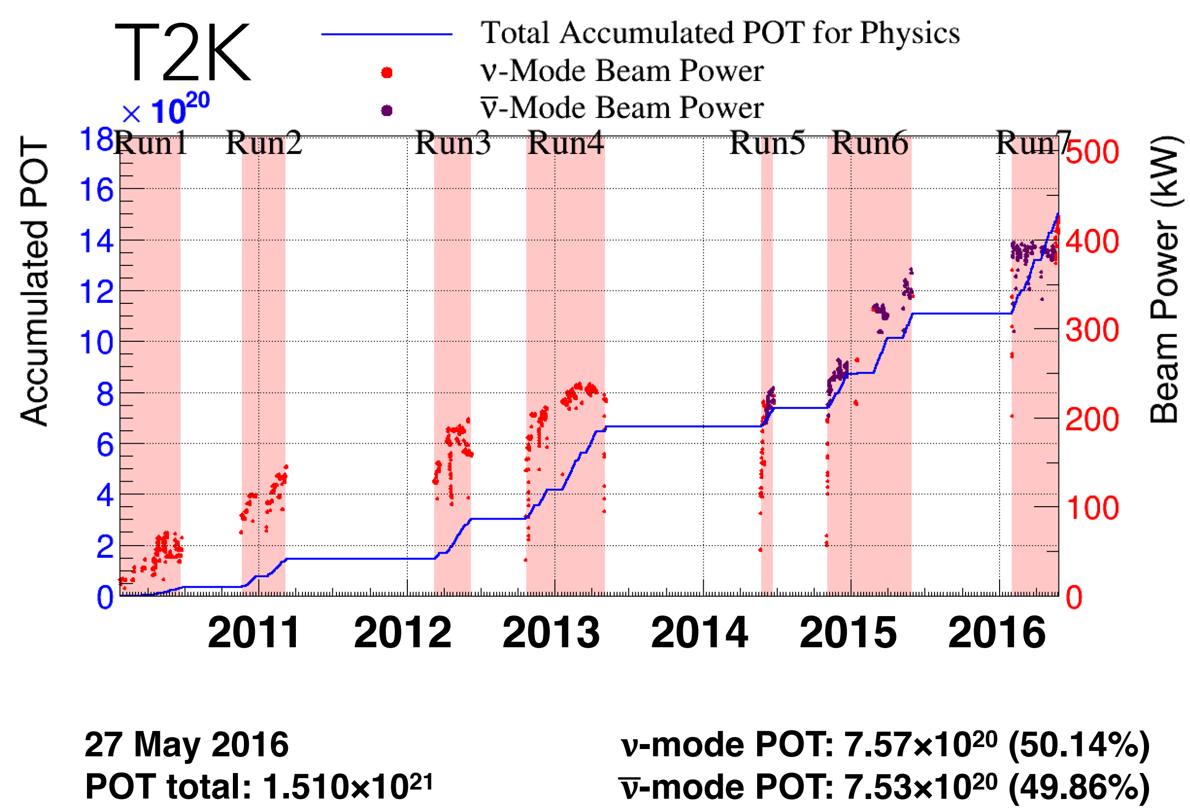
- If potential signal can be cleanly extracted with small expected background, large uncertainty are tolerable
- Last two generations of $\nu_\mu \rightarrow \nu_\tau$ appearance experiments did not near detectors
- Recent $\nu_\mu \rightarrow \nu_e$ experiments also did not have near detectors
- We are now beyond the phase of "establishing" appearance
  - we are moving into the measurement phase . . . .

"UNDERSTAND YOUR FLUX . .. "

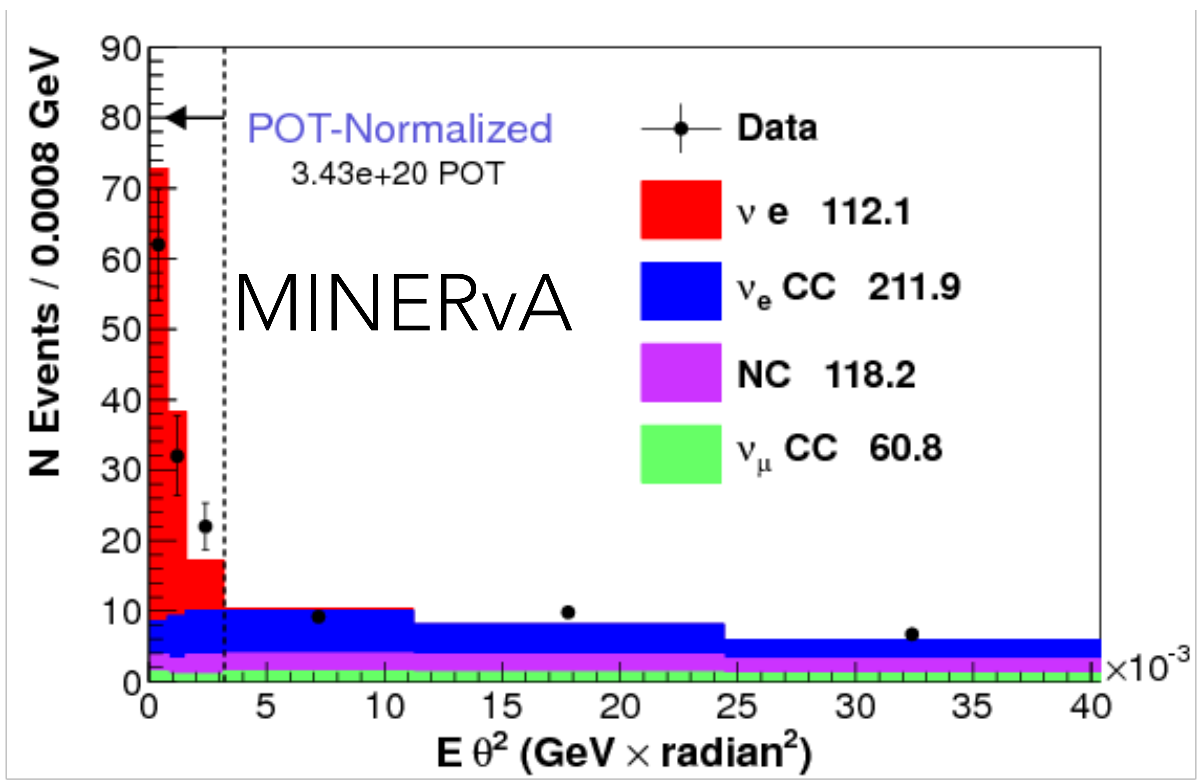
- **" . . . and you can do wonderful things. "**
  - sounds obvious, who could disagree?
  - understanding (half) of the initial state of an interaction seems beneficial.
  - other kinds of experiments (colliders, etc.) make a significant effort to understand initial state (luminosity, etc.) even if normalization factors, etc. come from elsewhere
- However, I have encountered a lot of resistance:
  - there's a near detector so I don't care
  - understanding neutrino flux is difficult; is it worth it?

NEUTRINO FLUX PREDICTION

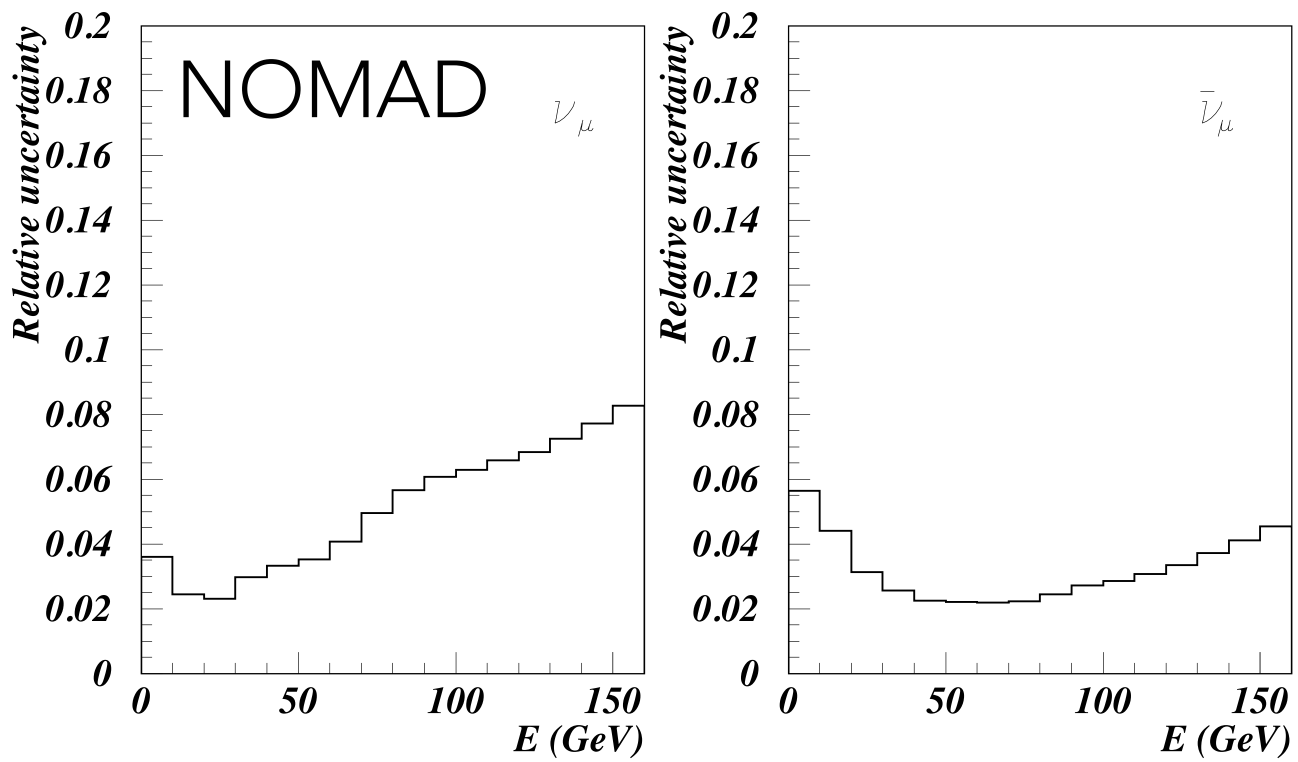


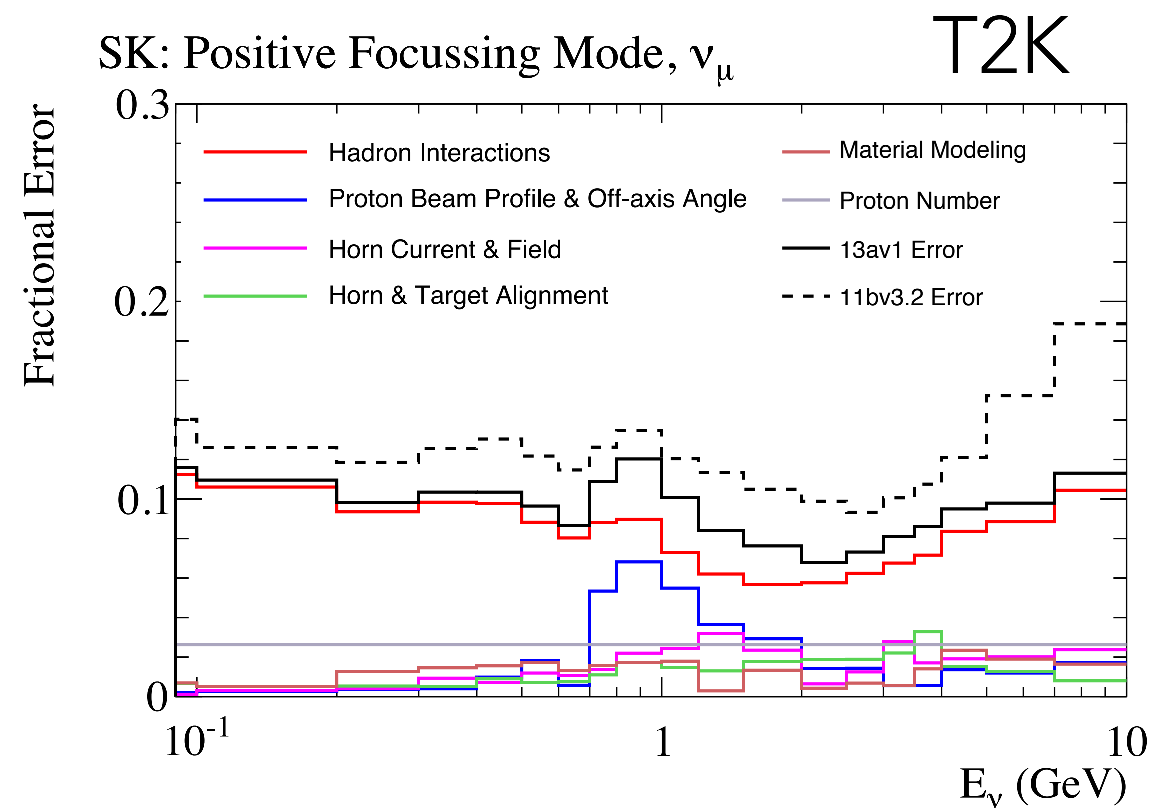


- **Hadron production from the target**
  - usually dominant uncertainty
  - followed by subsequent interactions
- **Precise monitoring of beam**
  - accelerator variations (primary protons)
  - beam line variations (horn current, alignment, etc.)
  - more dramatic/drastic changes . . . .
- **"Standard candles"**
  - ν-e elastic scattering, inverse muon decay, etc.
  - obvious challenges (statistics, energy range, etc.)



RECENT EXAMPLES:





- **NOMAD**
  - ~4% energy dependent uncertainties with ~4% overall normalization uncertainties
- **T2K**
  - with dedicated effort, 2009 NA61/SHINE thin target measurements, uncertainties reaching ~10% level
  - with NA61/SHINE replica target, uncertainties of ~5% are within reach
- **My opinion:**
  - these efforts are important and sometimes under-appreciated (particularly dedicated efforts)
  - something as important as the incident neutrinos should be understood as well as practically possible.

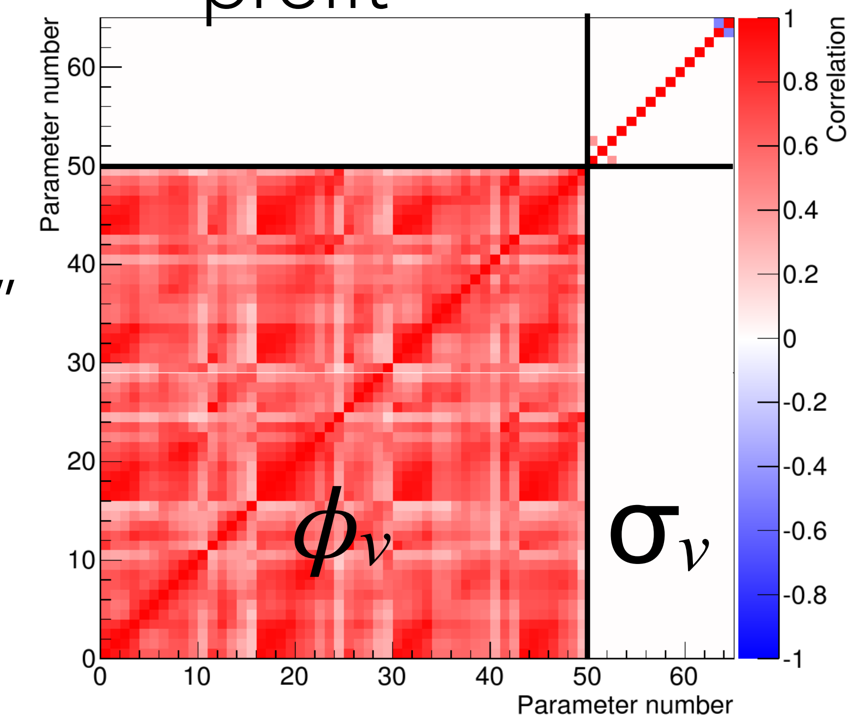
“THE PURPOSE OF THE NEAR DETECTOR”

- **“ . . . is to measure the flux.”**
- Neutrino detectors cannot measure the flux directly:

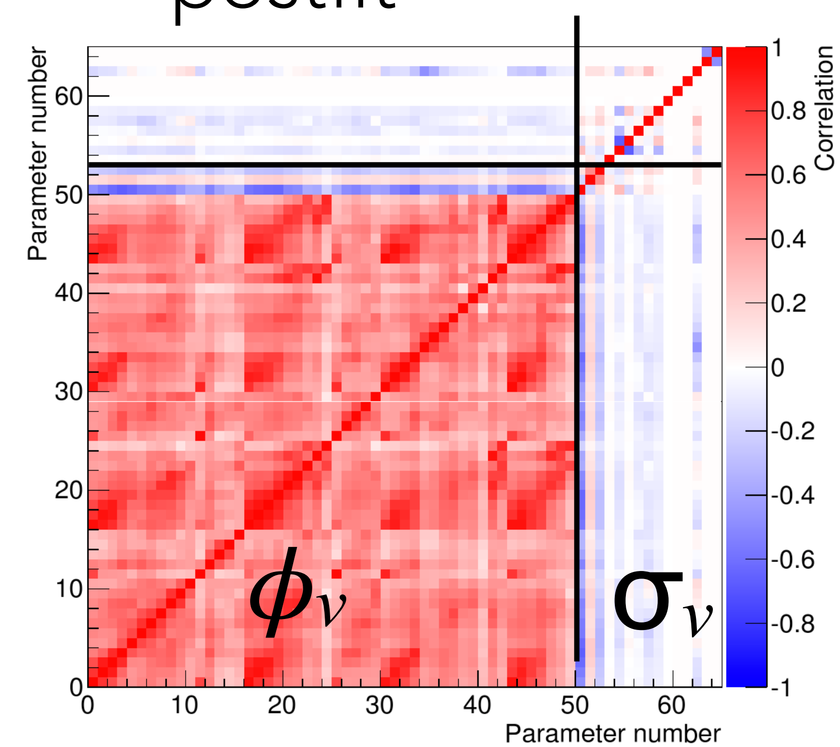
$$N = \Phi_\nu \times \sigma_\nu \times \epsilon$$

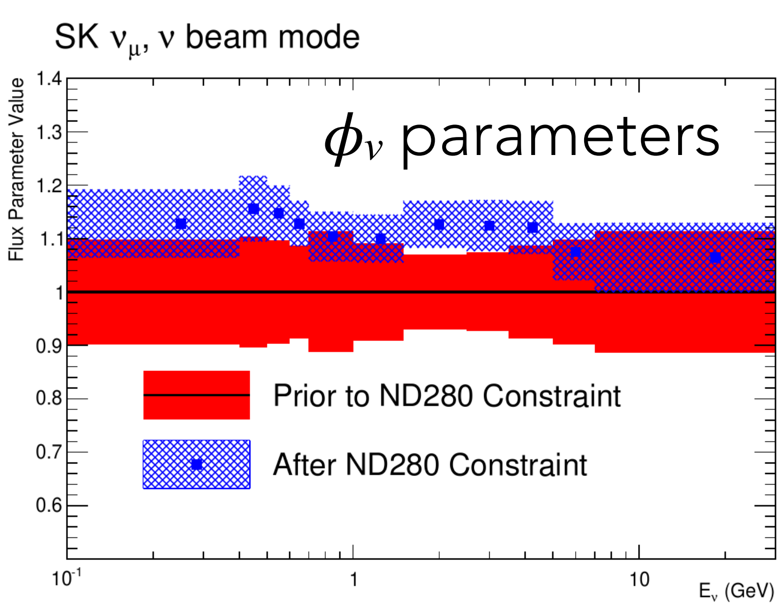
- if σ_ν is well understood (“standard candle”) can “measure ϕ_ν”
  - However, this appears not to be the case.
  - covariances of ϕ_ν / σ_ν may constrain the flux further
- in my opinion:
  - not incorrect . .but maybe not relevant to current/next LBL

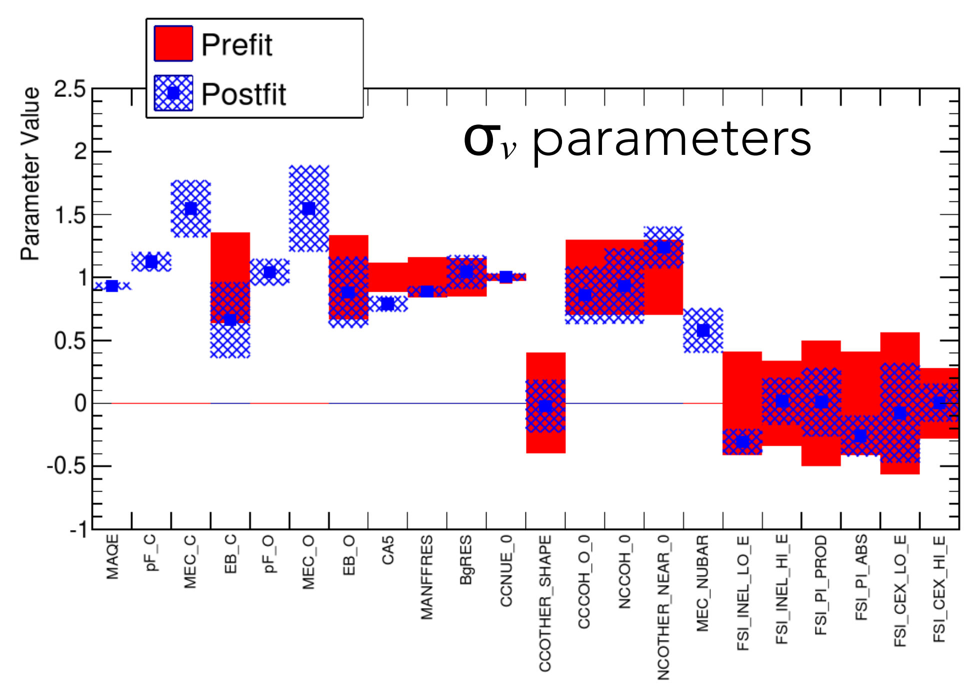
“prefit”



“postfit”







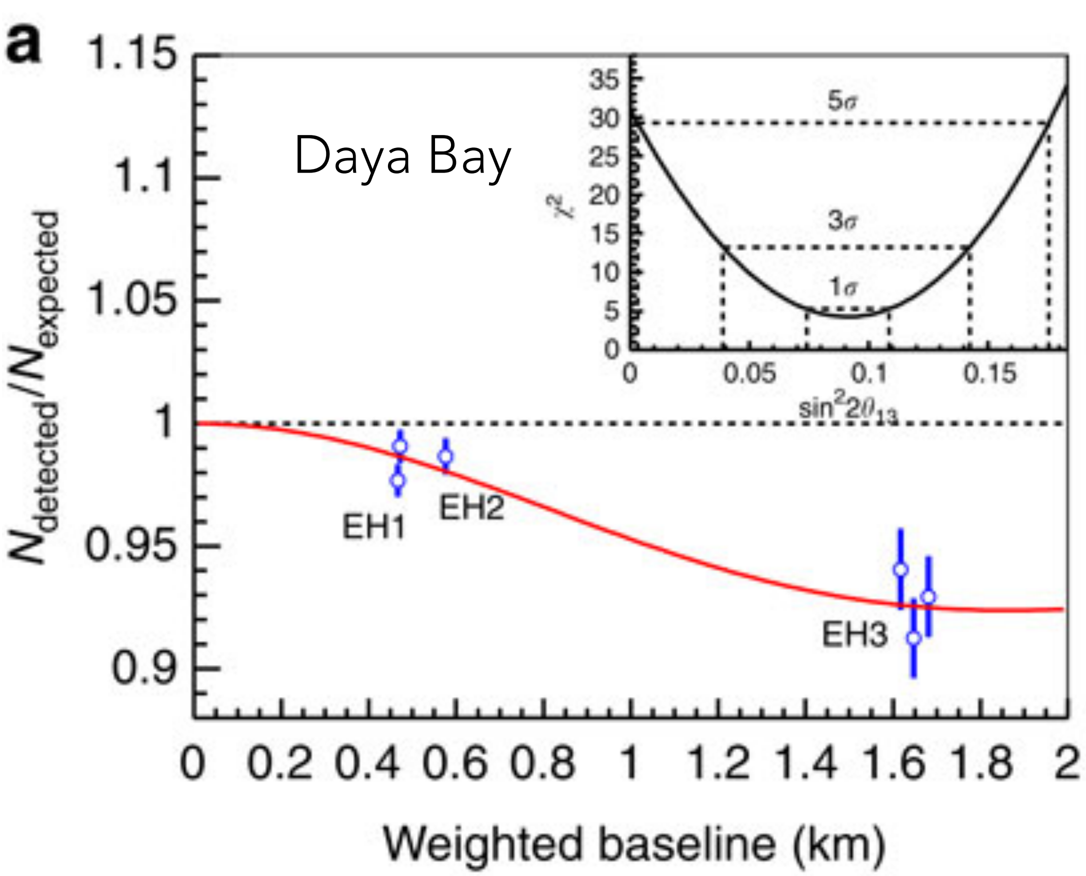
PRELIMINARY

"NEAR AND FAR DETECTOR . . . ."

- **" . . . . should be identical"**
- Obvious strategy when one considers

$$N_{FD} = \Phi_\nu \times \sigma_\nu \times \epsilon \times P_{osc}(\theta, \Delta m^2)$$
$$N_{ND} = \Phi_\nu \times \sigma_\nu \times \epsilon$$

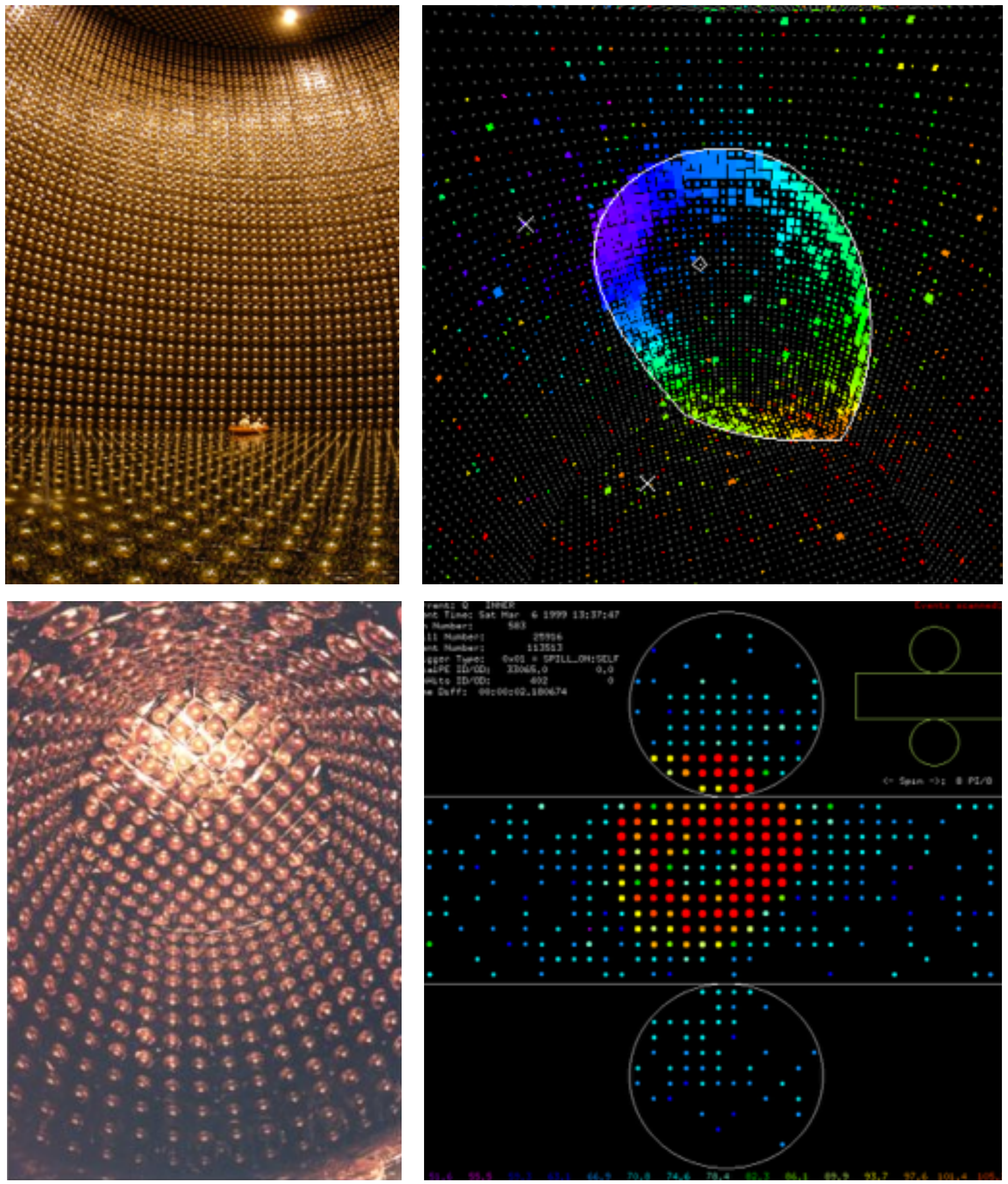
- cancel ϵ by maximizing correlation between near and far.




MINOS


NOvA

"IDENTICAL DETECTORS"

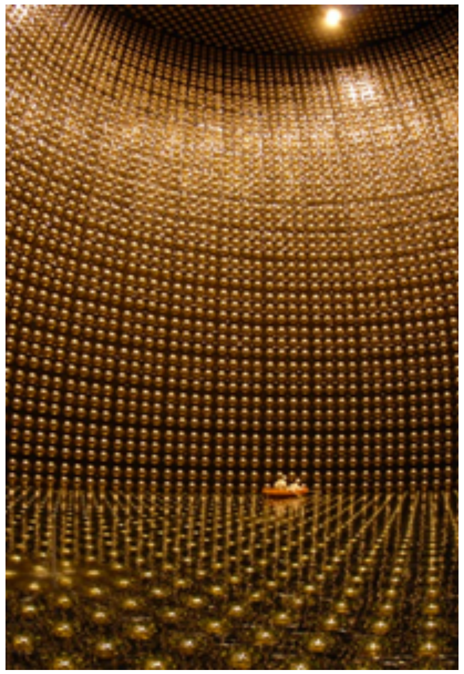


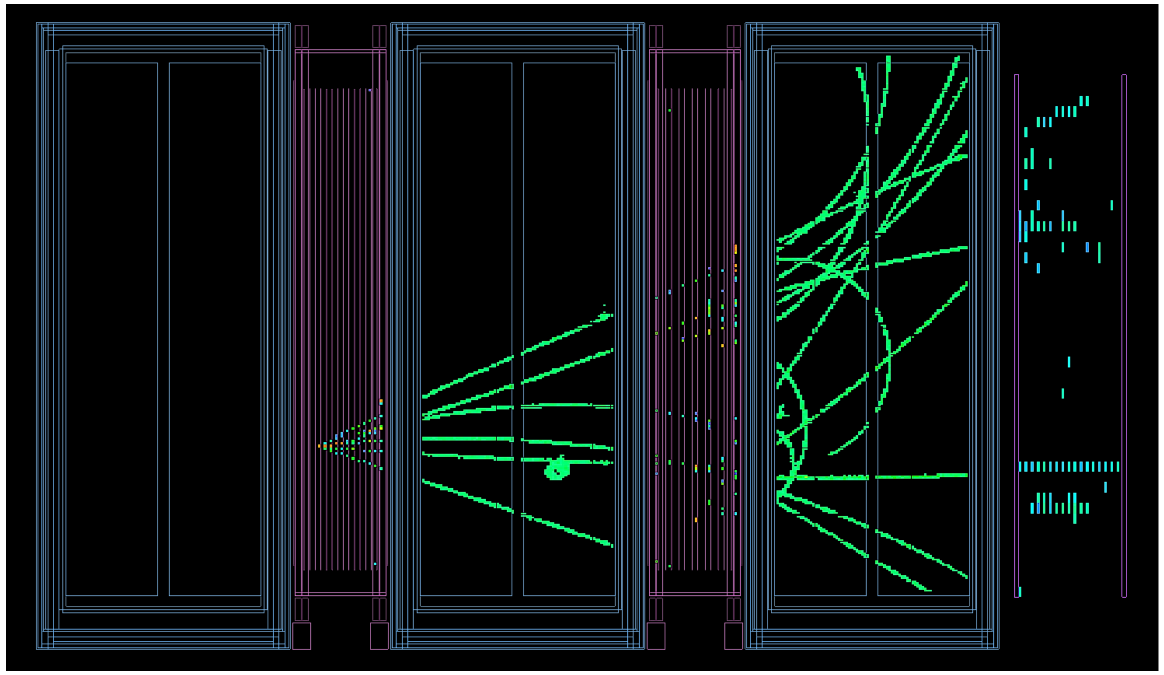
- What does it mean to be "identical" when they cannot be identical?
- Often the case for LBL:
  - no way to replicate far detector (multi-kT)
  - How to achieve "practically identical"?
- K2K 1 kTon WČ detector
  - use same overall method, components
    - 20" PMTs, readout electronics, etc/
  - as far detector (SK)
- size is an intrinsic aspect for some detectors
- Further consideration led to:
  - T2K 2km proposal: 5" PMTs
  - NuPRISM: 3" PMTs
  - to achieve greater effective granularity

OTHER ISSUES

- Pile up:
  - interaction rates very different in near/far detector
  - near detectors may not be deep underground;
    - significant cosmic ray rate
- Containment:
  - smaller detectors may not contain muons, photons, etc.
  - need cost-effective means to measure outgoing muons, escaping photons over large volume
- Information:
  - unexpected systematics, data/MC discrepancies may arise
  - complementary/additional capability with far detector may be needed to resolve issues (scintillation, magnetization, etc.)

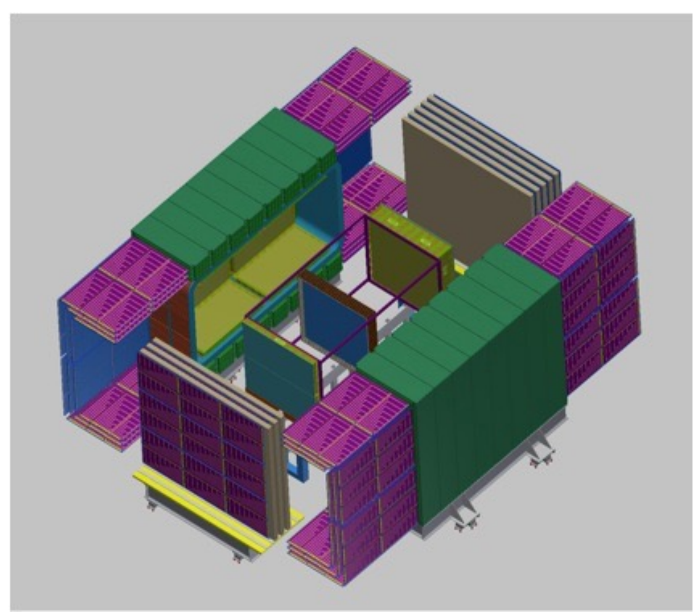
EXAMPLES

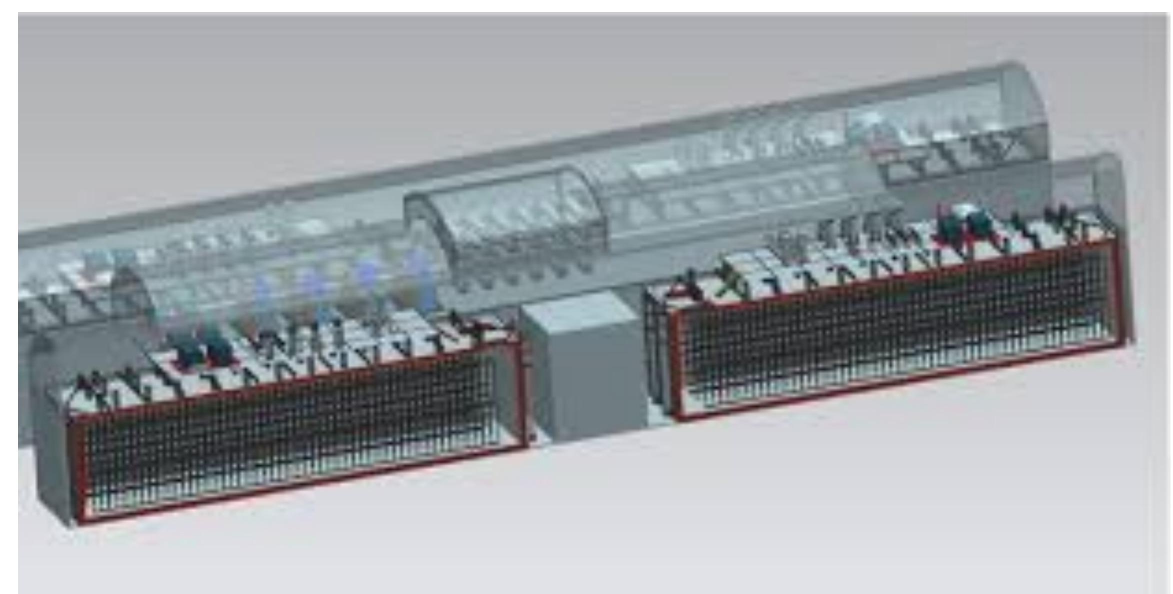




- ND280: Tracking near detector for T2K (SK far detector)
- Sign selection, lower particle detection threshold, particle detection capability.
- Challenges: planar geometry with wide angle particle production.

- DUNE "reference" near detector design with straw-tube tracker
  - magnetized
  - low-density





NEUTRINO ENERGY RECONSTRUCTION

- **Kinematic:**
  - target reaction hypothesis, e.g.

    $$\nu + n \rightarrow \ell^- + p$$

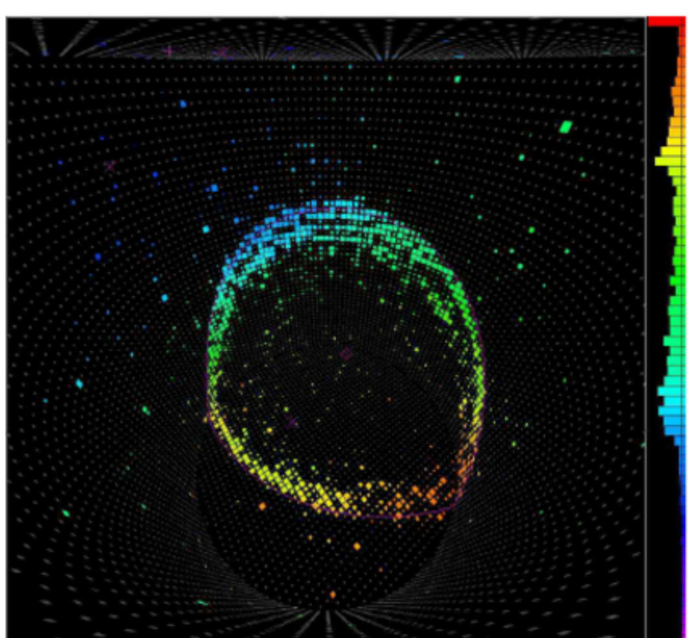
    $$\nu + p \rightarrow \ell^- + \pi^+ + p$$

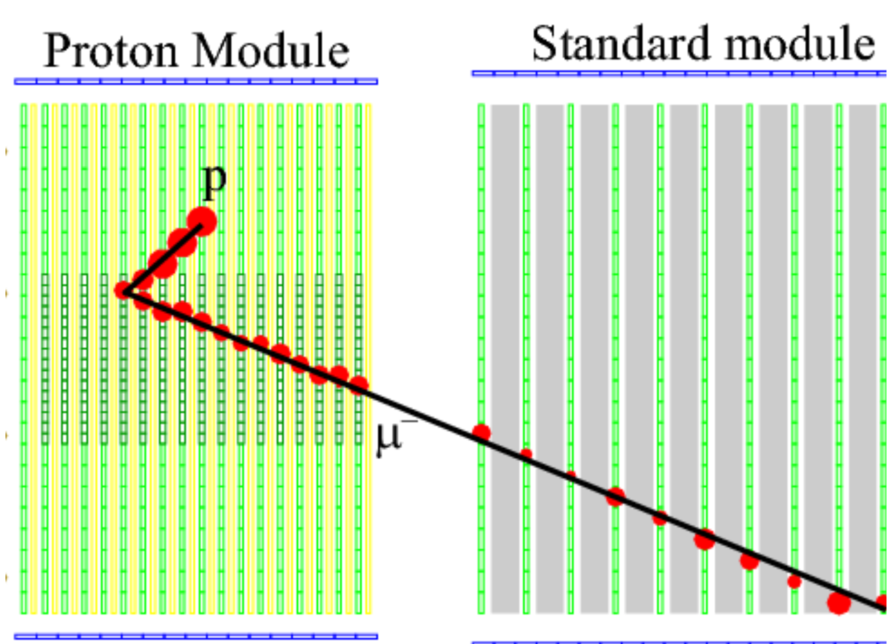
  - identify events consistent with hypothesis
  - e.g. CC events with no pions
  - exclusive selection (e.g. μ+p+(π))

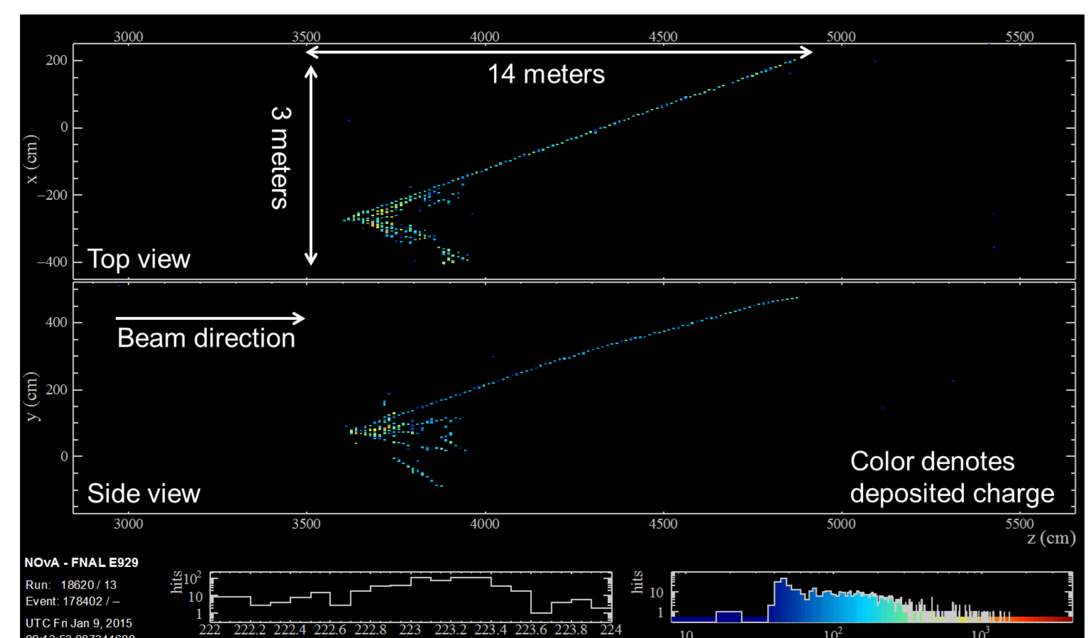
- **Calorimetric**
  - sum energy in the event
  - typically:

    $$E_\nu = E_{lep} + E_{had}$$

    - calorimetric reconstruction of hadron shower
    - particle-by-particle

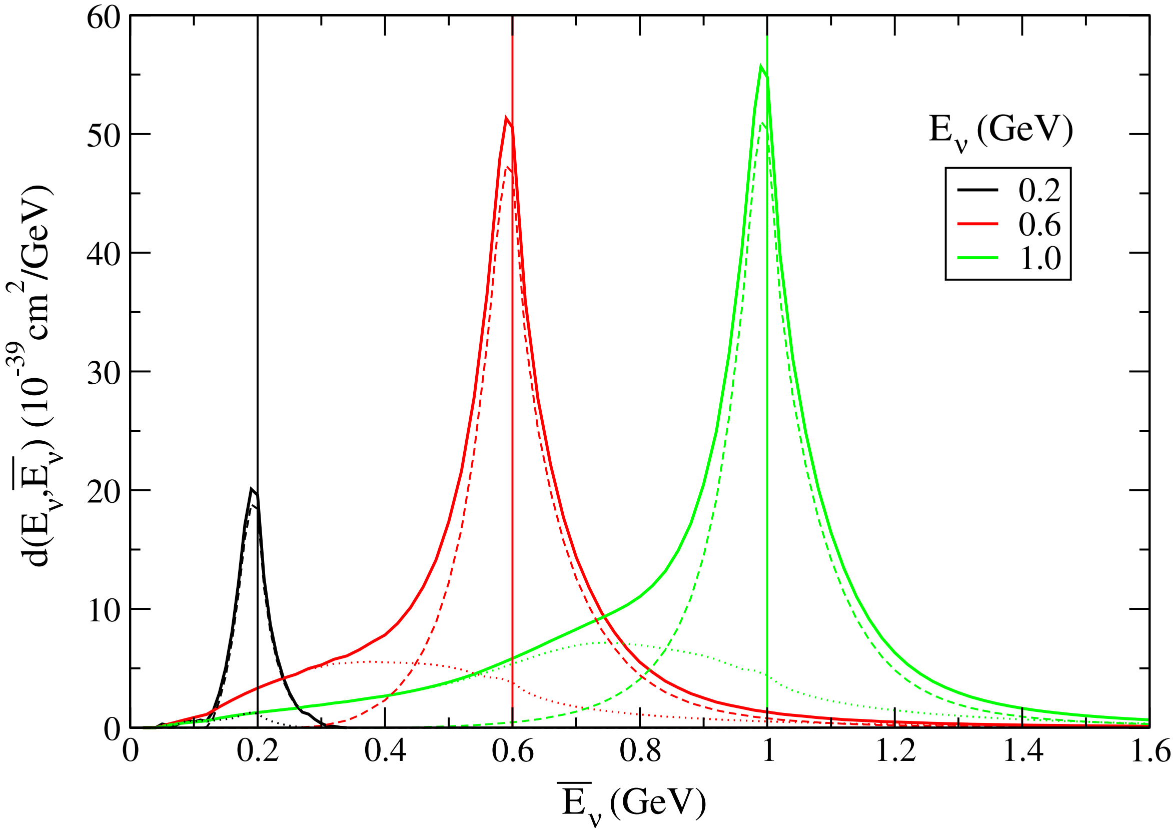




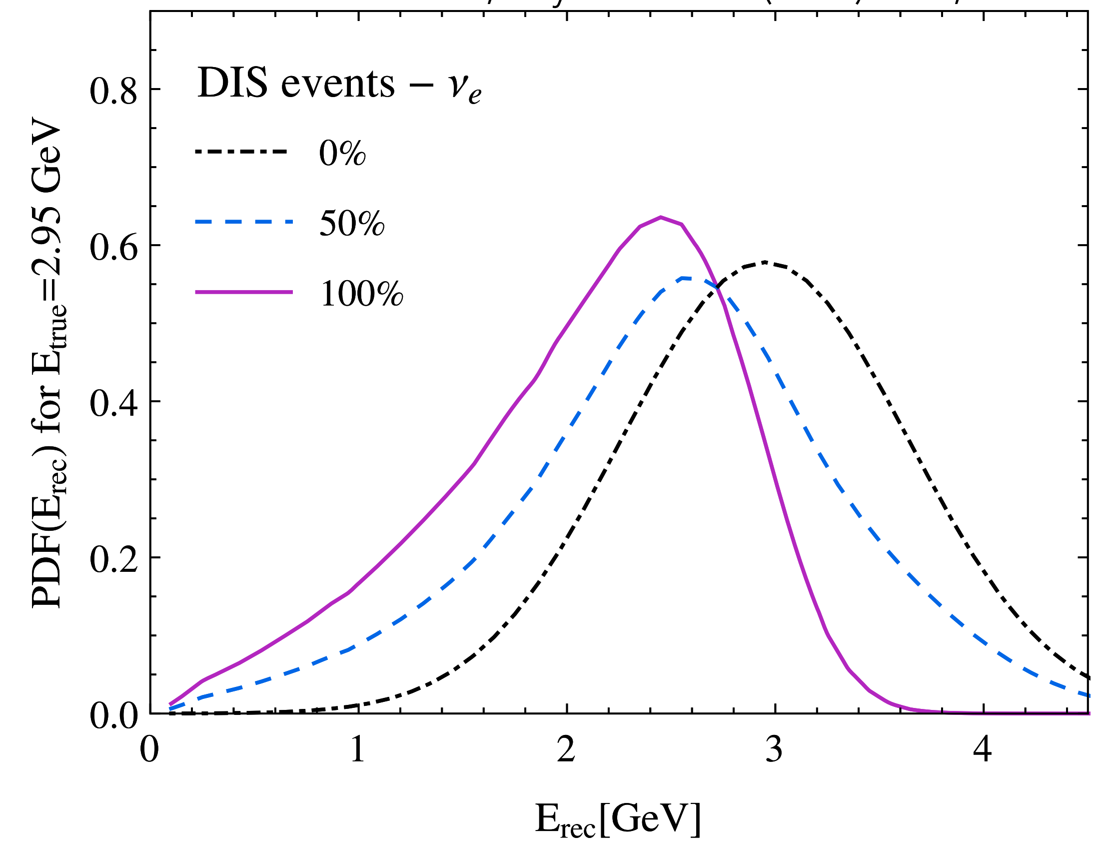


ENERGY RECONSTRUCTION ISSUES

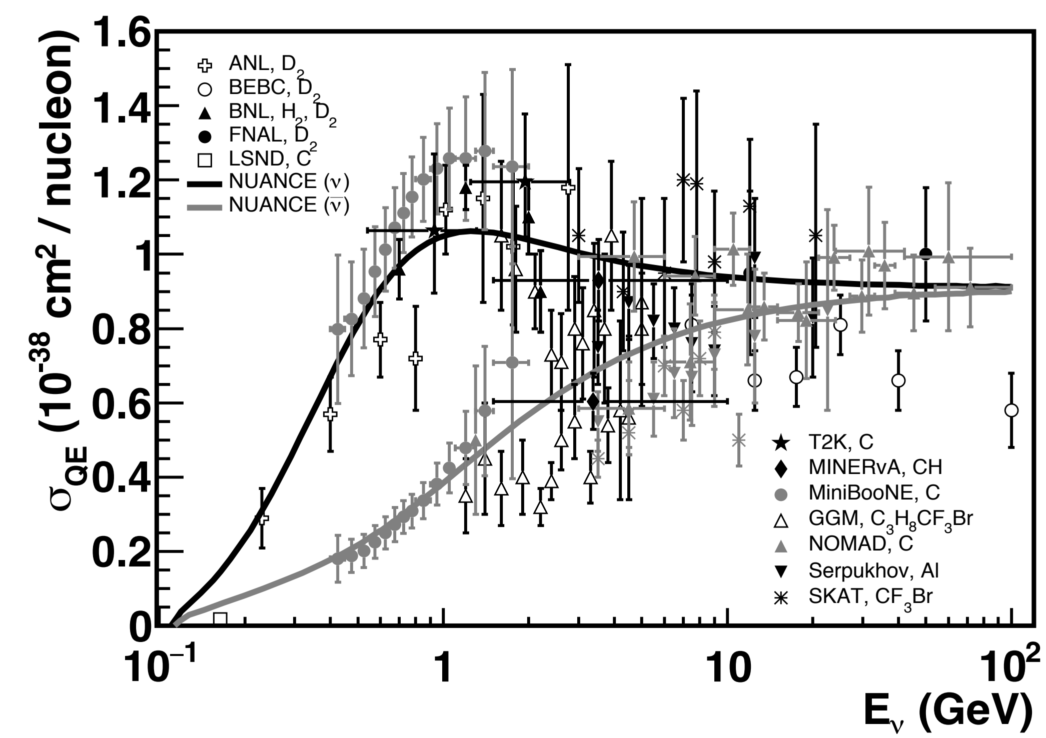
M. Martini, et al. Phys.Rev. D87 (2013) no.1, 013009



A. Ankowski et al., Phys.Rev. D92 (2015) no.9, 091301

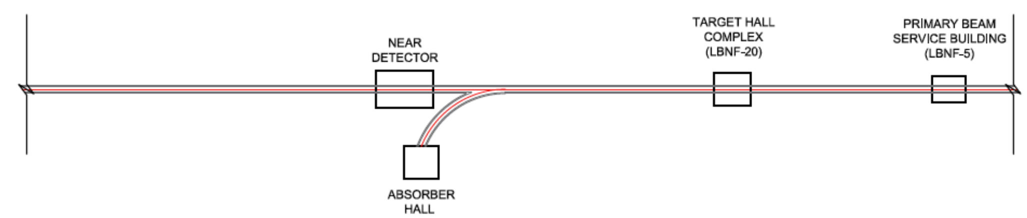


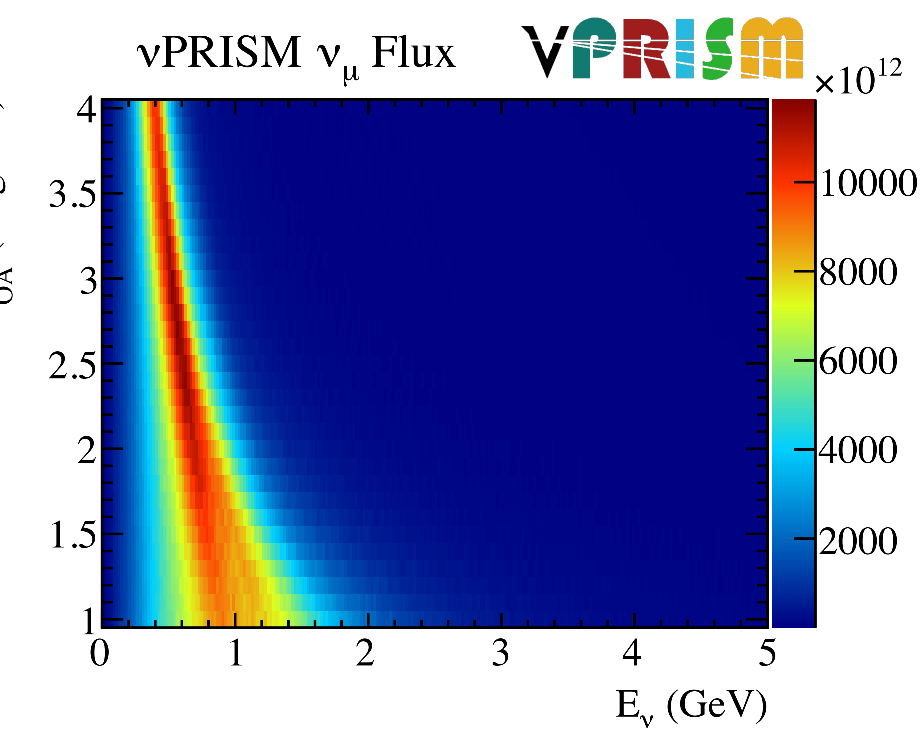
- Kinematic: kinematically different channels with potentially indistinguishable final states
  - how to measure: predicted final states rely on nuclear model (large uncertainty), final state interactions
- Calorimetric: amount of energy going into undetectable particles
  - relies on getting final state content correct through underlying reaction, final state interactions, and secondary interactions

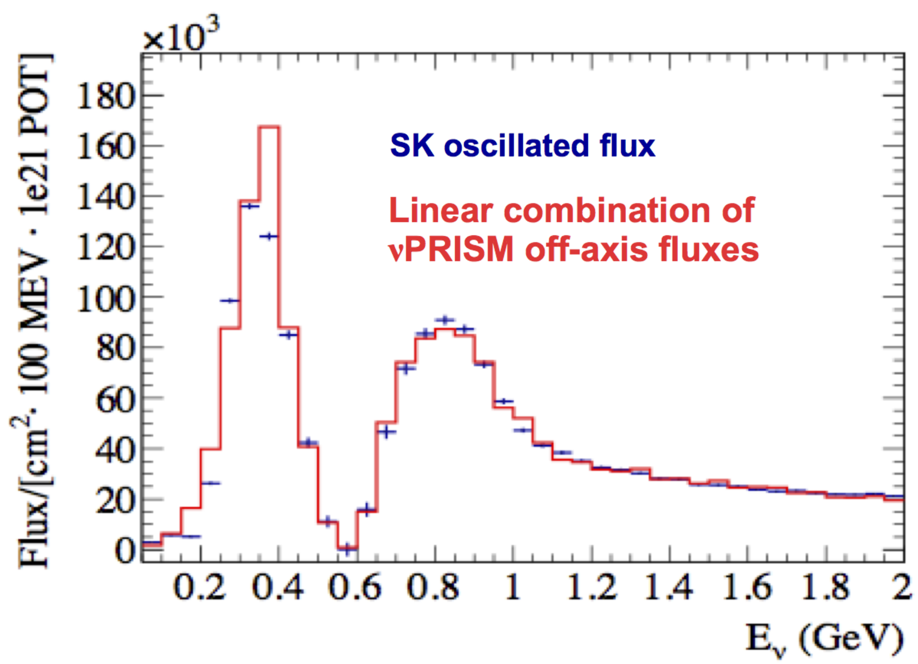


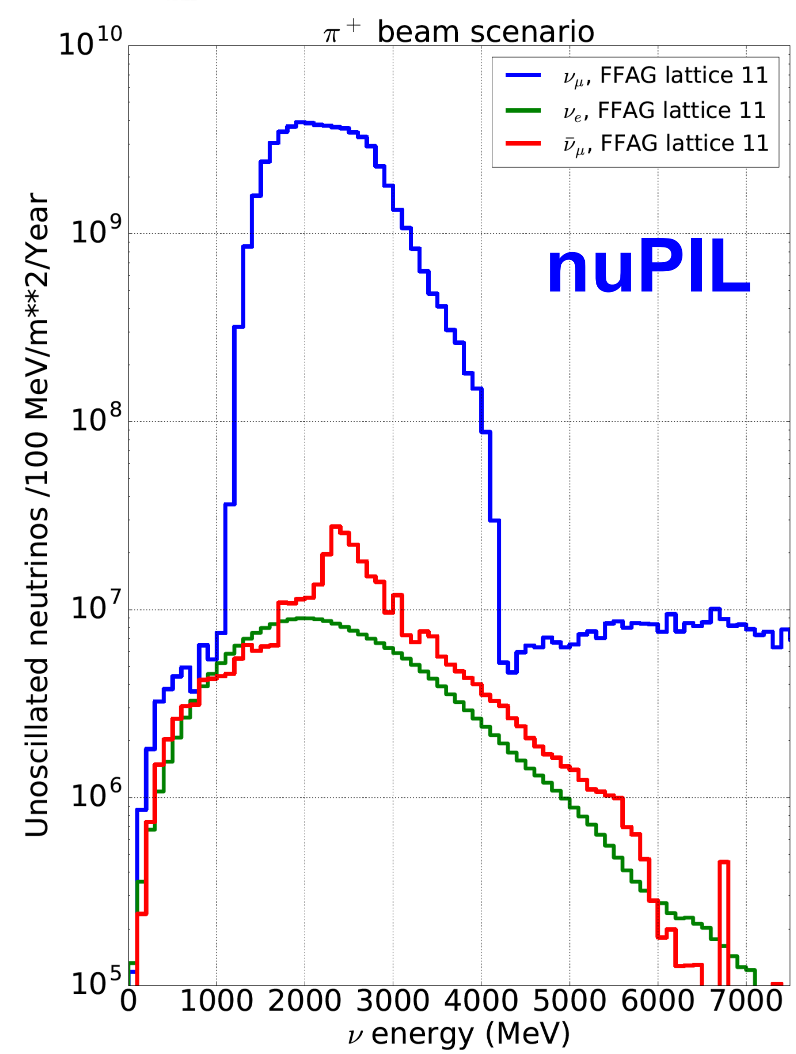
THE CHICKEN AND THE EGG

- Ideally: measure neutrino interaction final states as a function of neutrino energy
- However, we use the final state to infer the neutrino energy
  - the neutrino doesn't tell us its energy other than through its interaction products
  - we can only measure properties inclusively over the entire energy spectrum
- Several possibilities
  - employ more than one energy reconstruction strate
    - e.g. both kinematic and calorimetric
  - find other ways to control neutrino energy





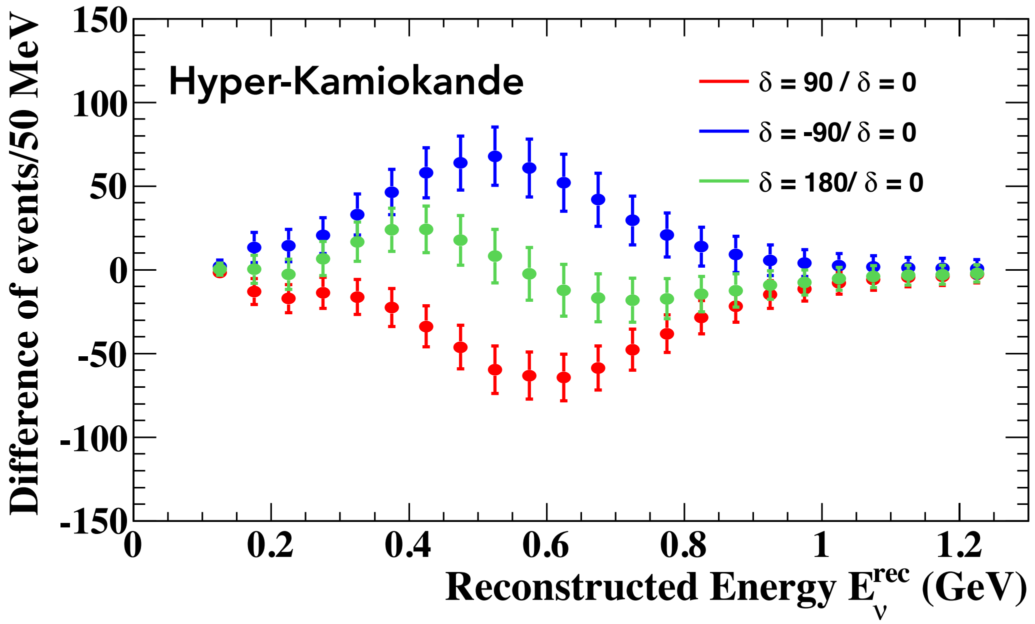




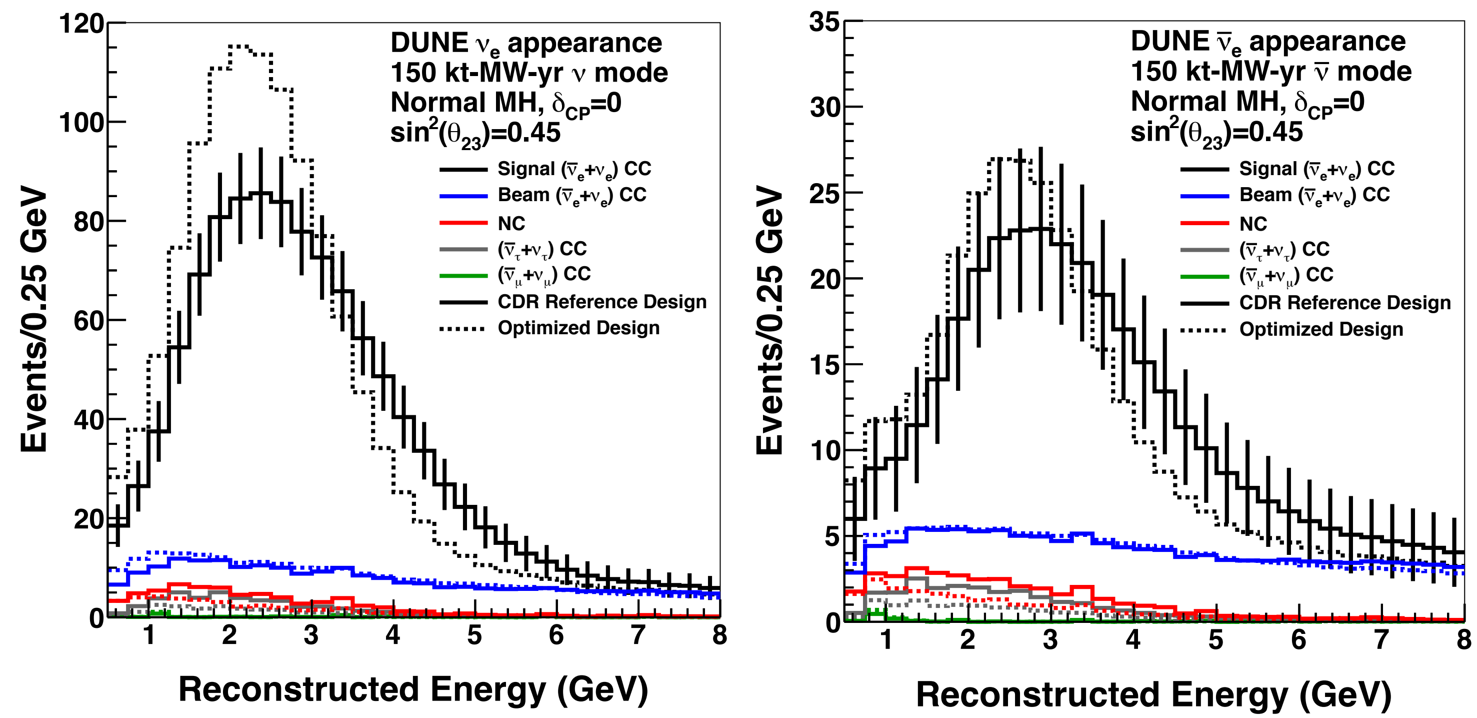
CHALLENGES FOR THE FUTURE:

Hyper-Kamiokande

	SIGNAL $\nu_e/\bar{\nu}_e$	WS $\nu_e/\bar{\nu}_e$	ν_μ CC	BEAM ν_e	NC
ν MODE	2300	21	10	362	188
$\bar{\nu}$ MODE	1656	289	6	444	274



DUNE



- Next generation need precision to ensure:
  - systematic errors don't limit the sensitivity from high statistics
  - exploit spectral information

- Recall: neutrino oscillation are driven by true energy
  - correct E_ν spectrum essential to predict oscillation signature (including rate), extract parameters
  - this relies on an accurate understanding of how we reconstruct E_ν
- Large "wrong sign" contribution in antineutrino mode: ~25% in each experiment
  - need measurements in near detector to understand this "background"

CONCLUSIONS:

- Near detectors are needed for the next generation of oscillation experiments
  - they are a central aspect of the measurement strategy
  - please don’t do a LBL (or a SBL) neutrino oscillation experiment without one and without a careful consideration of its design.
  - as we “up" the game, revisit the “identical detector” strategy
- Past experience is always valuable
  - however, we are playing a new game
  - don’t accept existing rules-of-thumb/dogma for granted
- Please support:
  - hadron production measurement and flux estimation efforts
  - neutrino interaction modelling and measurement efforts
- We should be prepared for surprises
  - there is a very well defined paradigm for the physics . . . . .
  - but it’s very complicated, relies on challenging modelling of ν production, interaction, detection
  - **and** there is a significant chance for physics beyond this paradigm
  - we should build near detectors that are up for the challenge

NUINT(INTNU?) 2017

- 26 June-1 July
- Fields Institute at the University of Toronto
- See you there!