FUTURE NEAR DETECTORS

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SLAC NATIONAL ACCELERATOR LABORATORY

Overview, Main Points

- I will focus on "conventional" accelerator-based long-baseline **(LBL)** experiments
  - Similar considerations apply to other neutrino oscillation experiments
  - Energy ranges, signatures differ significantly so practically many things are different
  - Near detectors (by construction) must always be considered in the context of the overall experiment
- We are in the ~3rd generation of long-baseline experiments
  - In each generation, goals have become more ambitious
    - Discovery → several phases of precision measurement
    - Next up: CP violation and mass ordering
      - Requires control over all oscillation parameters
- Control over systematic uncertainties becomes increasingly more demanding
  - Always a crucial element of the experiment
  - Learn as much from previous experience
  - Confront new issues arising from more ambitious goals

BACKGROUND

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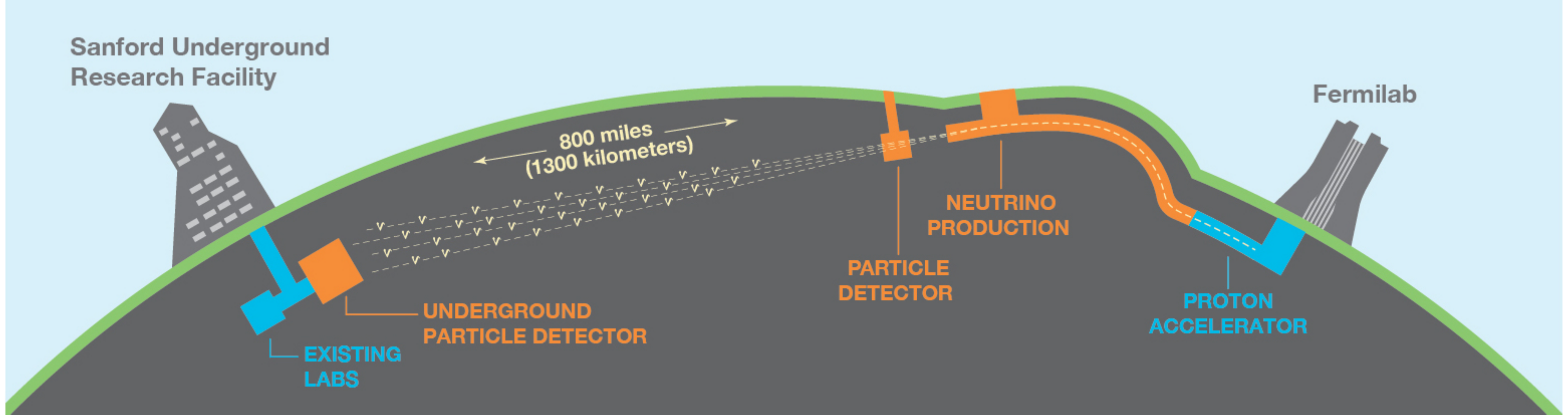
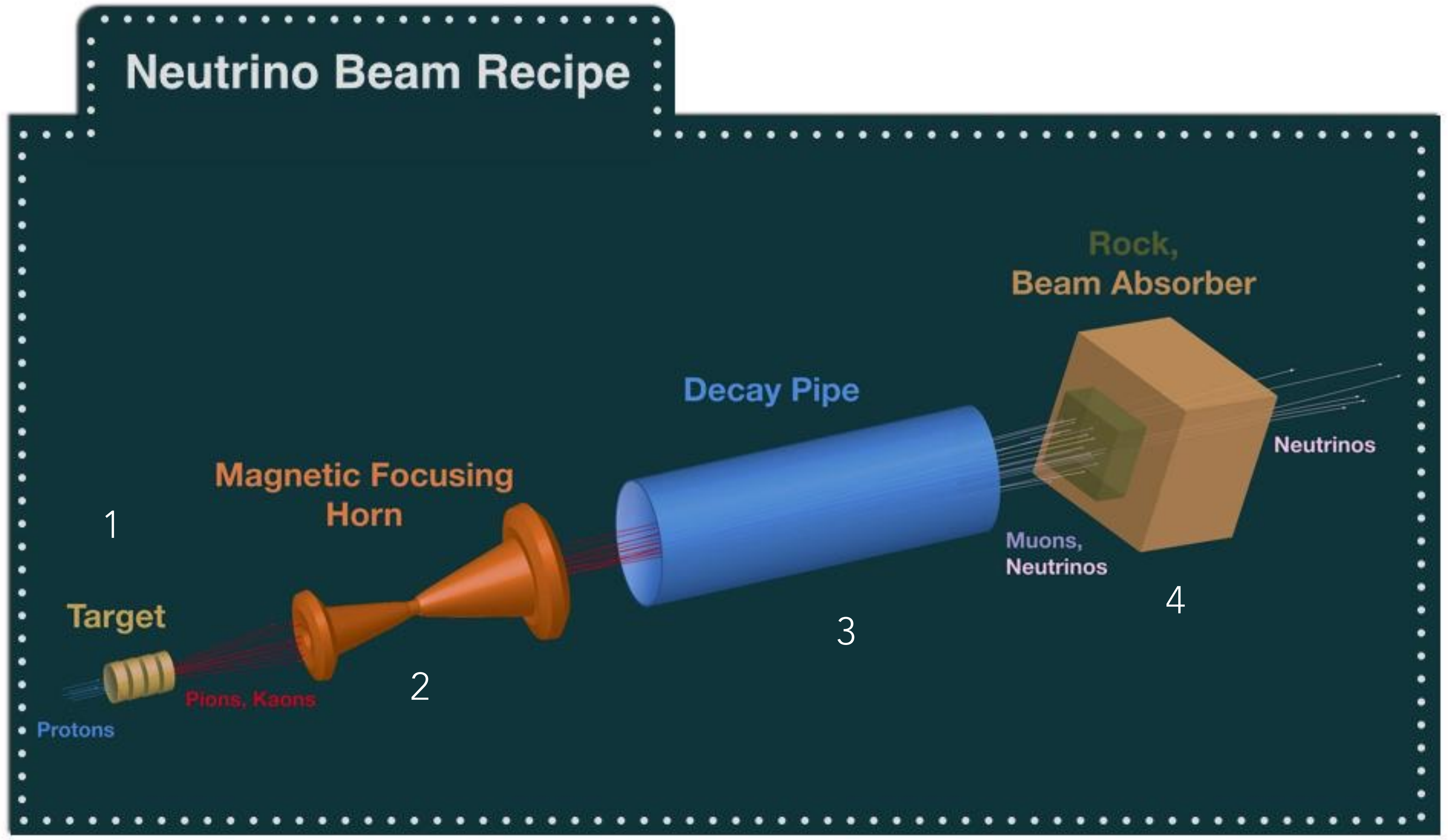
Long baseline oscillation experiment with “conventional beam”



- O(GeV) sign-selected $\nu_\mu/\bar{\nu}_\mu$neutrino beam produced from pion decays
- Intercepted by near detector ND at O(1) km before oscillation effects
- Observed O($10^{2\text{-}3}$) km at far detector (FD) where enough time has elapsed for oscillations



- Current/future experiments require tera watt-tons-years of exposure
  - O(10^6) W proton source for neutrino beam
  - O($10^{4\text{-}5}$) tons FD target mass
  - O(10^1) years of operation
- Systematic control in predicting observed FD rate/spectrum at ~percent level → ND

OBSERVABLES:

What we observe in the far detector:

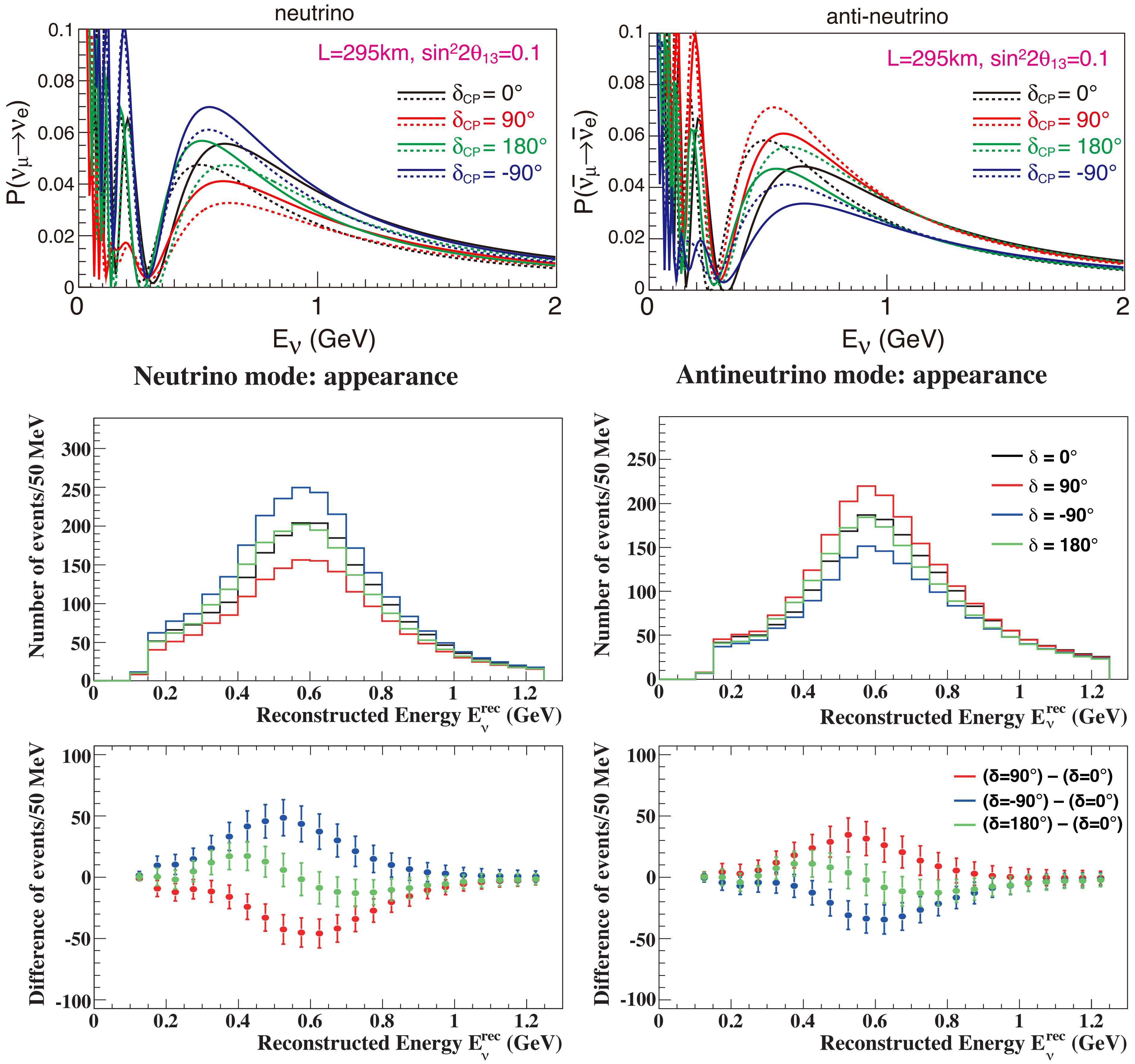
$$N_\beta(E_{REC}) = \int dE_\nu \, \Phi_\alpha(E_\nu) \times P(\nu_\alpha \to \nu_\beta, E_\nu; \Theta, L) \times \sigma_{\beta X}(E_\nu) \times R_{\beta X}(E_\nu, E_{REC})$$

- $\Phi_\alpha(E_\nu)$: Initial flux of neutrinos of flavor α, energy E_ν (~μ in case of LBL)
- $\sigma_{\beta X}(E_\nu)$: cross section for ν_β interacting via charged-current process X (~μ/e in case of LBL)
- $R_{\beta X}(E_\nu, E_{REC})$: "response" of detector to ν_β CC interaction with energy E_ν, channel X resulting in its selection and reconstructed energy E_{REC}
- $P(\nu_\alpha \to \nu_\beta, E_\nu; \Theta, L)$: probability of $\nu_\alpha \to \nu_\beta$ for energy E_ν, oscillation parameters Θ, baseline L
- $\int dE_\nu$: integral over initial ν_α spectrum

- Oscillation parameters extracted by comparing observed spectrum against prediction vs. Θ
- n.b. in a measurement era, predicting/modelling the signal for given Θ is essential
  - Understanding backgrounds is essential, but systematics in predicting the signal are just as fundamental

TARGET UNCERTAINTY

- Systematic uncertainties are extremely complicated
  - Nonetheless, useful to get a very rough sense of what is needed
- Consider observing CPV in the case where it its effect is maximal
  - At 1st oscillation max, δ_{CP} effects at most ~30% variation in $P(\nu_\mu \to \nu_e)$
  - Due to spectrum, backgrounds, etc. $\nu_\mu \to \nu_e$ rate varies by at most ~20%
- For "definitive" observation at "5 σ"
  - **total uncertainties** in predicting $\nu_\mu \to \nu_e$ candidates should be < **4%**
  - **systematic uncertainty should be considerably smaller than this**
- This would be "low hanging fruit" in the CPV program
  - **Further goals require more stringent systematics at ~2% level**
  - e.g. 5 σ significance over 50% of δ_{CP} values, 10° precision on δ_{CP}, etc.
- All this depends/varies/complicated by numerous things
  - Underlying parameter values, spectrum information, $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$, etc.
  - Like I said, it's complicated!



Expected $\nu_\mu \to \nu_e$ for $\delta_{CP} = 0(-\pi/2)$, NO

- T2K: 62 (74)
- DUNE: 1537 (1757)

SOME "PRINCIPLES" ABOUT ND

Obvious point:

- $N_\beta(E_{REC}) = \int dE_\nu \, \Phi_\alpha(E_\nu) \times P(\nu_\alpha \to \nu_\beta, E_\nu; \Theta, L) \times \sigma_{\beta X}(E_\nu) \times R_{\beta X}(E_\nu, E_{REC})$

we are talking about the far detector (FD)

- ND exists in ecosystem where it is addressing systematic uncertainties in FD
  - Hence, design/role of ND must be driven by the design of FD and its systematic uncertainties.

These uncertainties may be

- largely independent of the FD: e.g. $\Phi_\alpha(E_\nu)$
- dependent on basic features of FD: e.g. $\sigma_{\beta X}(E_\nu)$
- dependent on details of FD: $R_{\beta X}(E_\nu, E_{REC})$

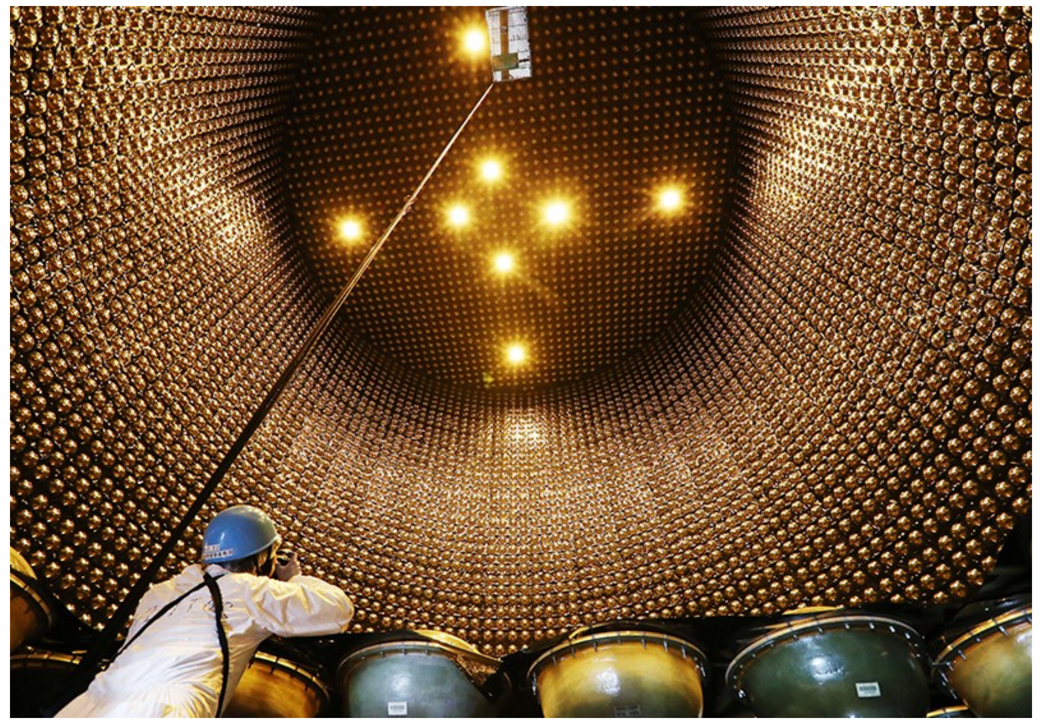
Neutrino energy (E_ν) plays a special role

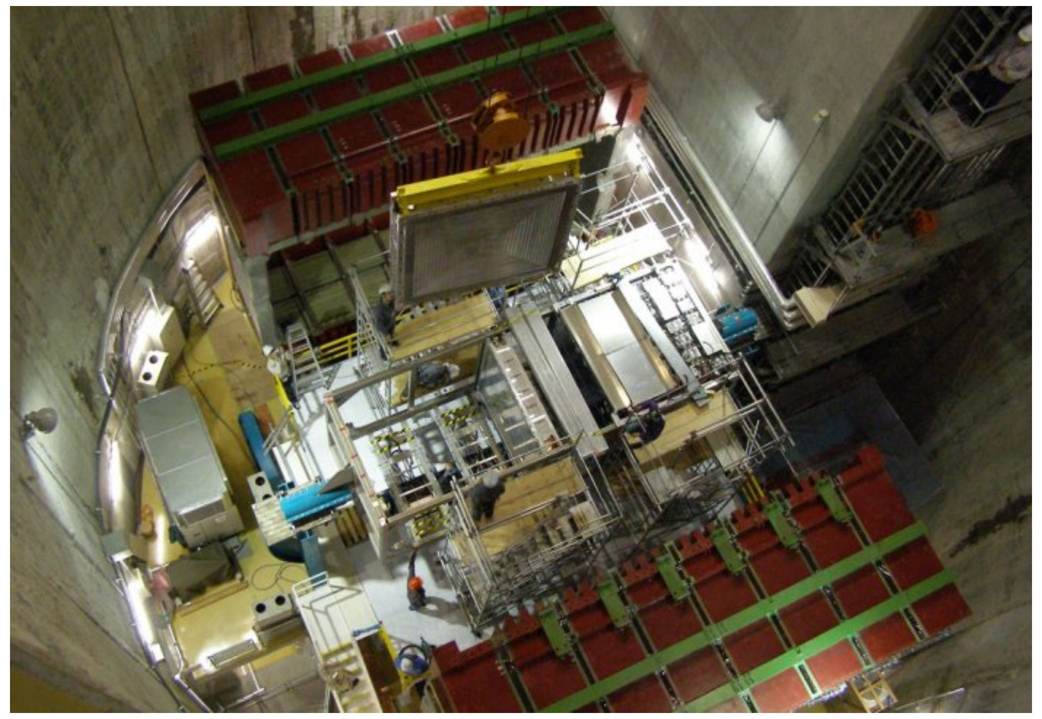
- Observables vs. true neutrino energy spectrum must be accurately understood to predict the signal

CONFLICTING CONSIDERATIONS

Addressing $R_{\beta X}(E_\nu, E_{REC})$ requires a ND that is similar to the FD

- "Identical detector" strategy: ND should be as similar as possible to FD
- Opportunities for cancellations in systematic uncertainties (e.g. backgrounds, efficiencies)



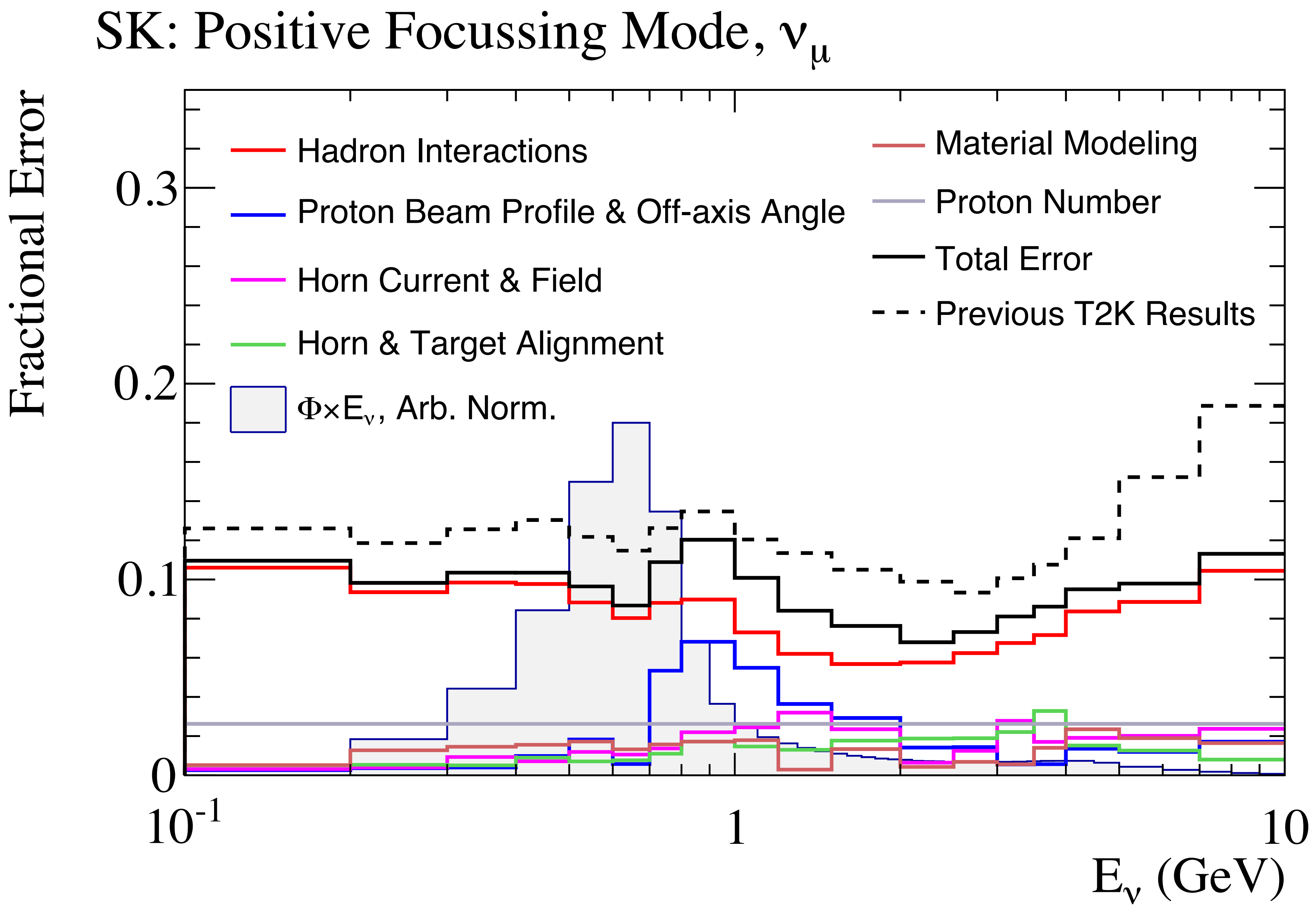


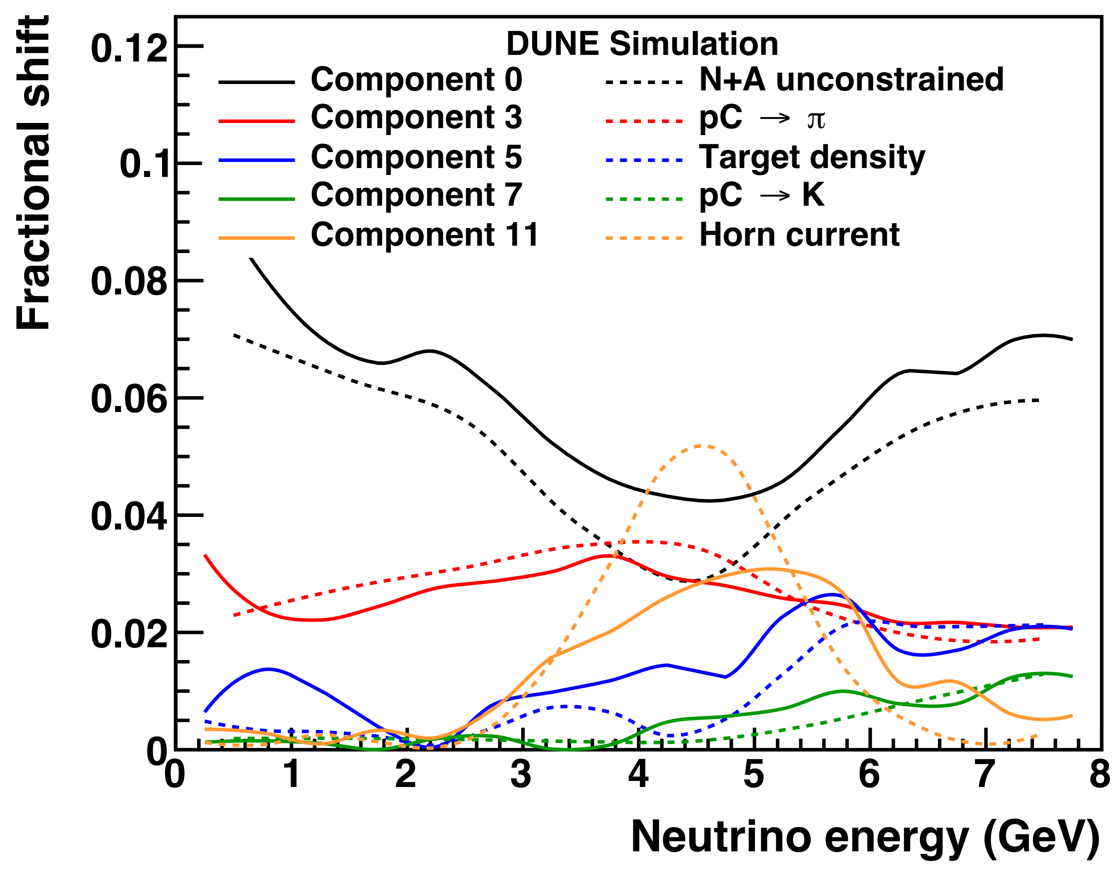
But, ND and FD cannot be identical

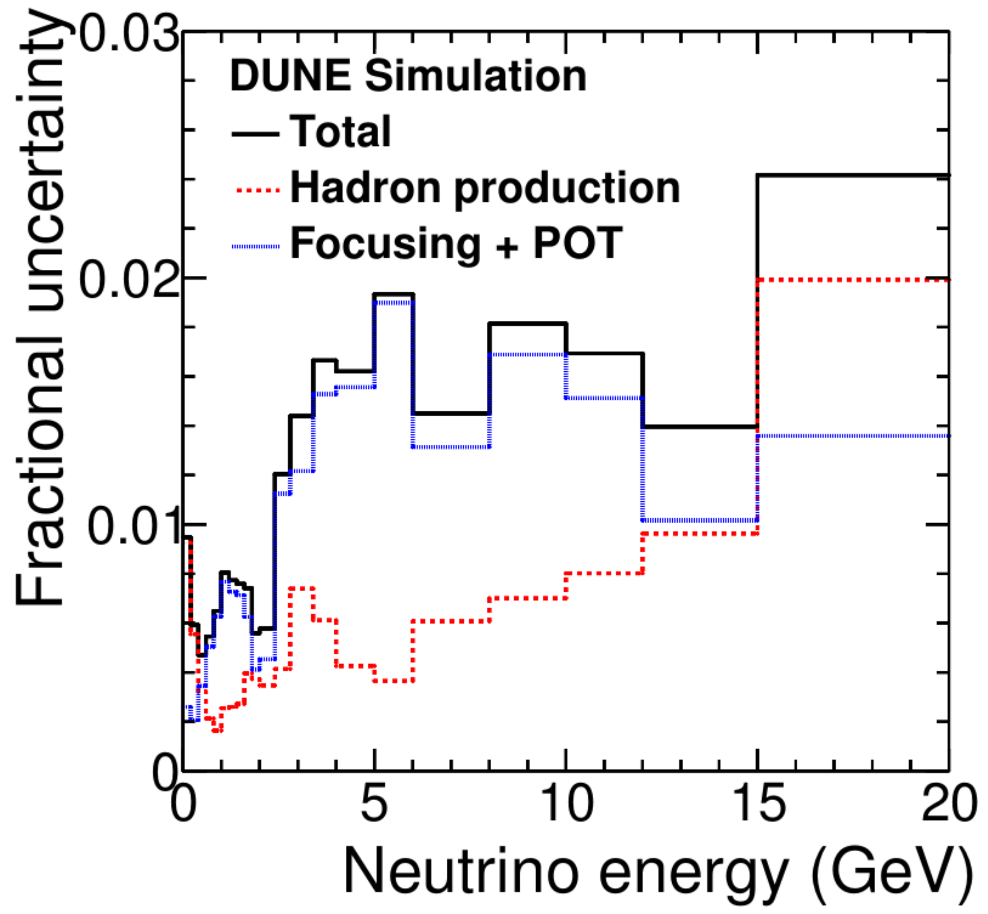
- Practical considerations
  - ND must be (much) smaller, size impacts performance (e.g. containment, sampling)
  - ND operates in a very high rate environment
- Optimization: ND and FD should not be identical?
  - FD design must be scaleable to multi-kTon scales
  - Why accept compromises that are not needed for ND especially for systematics that do not depend on details of ND?

THE NEUTRINO FLUX

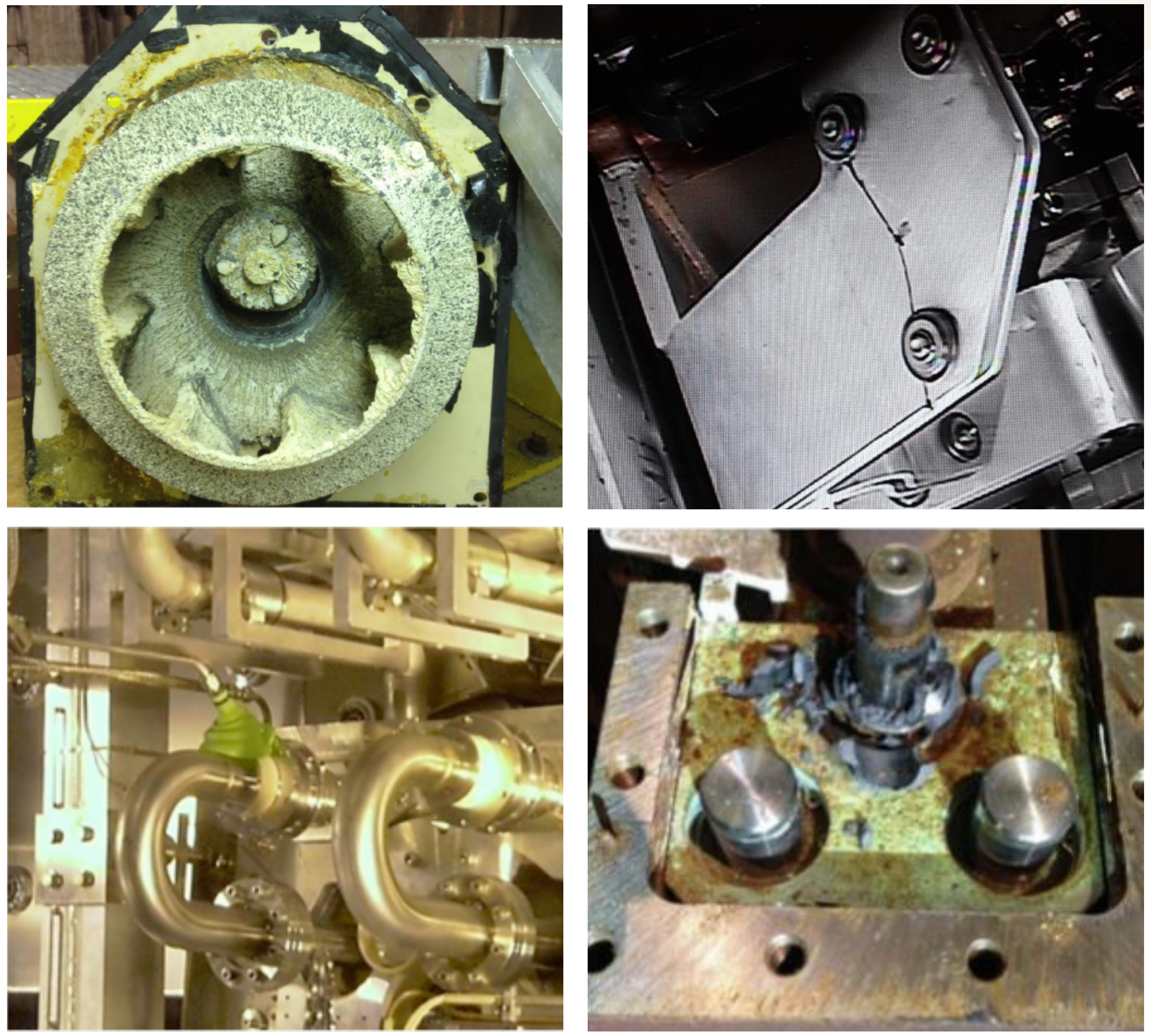
- *Ab initio* prediction of neutrino flux from conventional beams has improved enormously over the LBL era
  - Progress from "intractable" problem to ~10% or better uncertainty
  - **Thanks to hadron production experiments (e.g. NA61/SHINE)**, improved simulation frameworks, analysis
  - Relation between flux at ND and FD is nominally well understood
- However:
  - Uncertainties are still larger than desired
  - Differences between as-built vs. what is simulation
- Flux measurements at ND are desirable **(new!)**
  - Lepton channels ($\nu - e$ elastic scattering)
  - Low-ν method (low hadron transfer)
  - Identify, measure O(1%) $\nu_e/\bar{\nu}_e$, O(10%) "wrong sign"
  - May require optimization/capabilities beyond FD





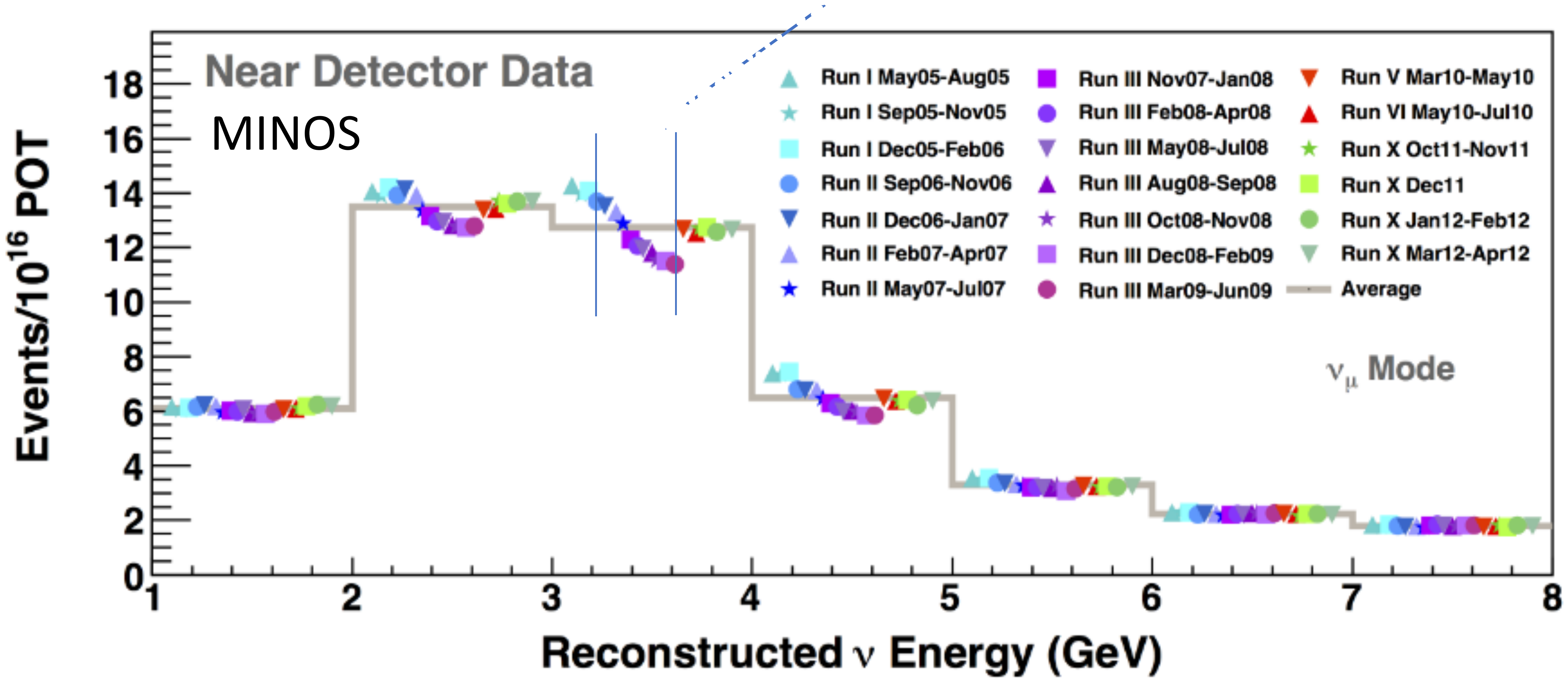


BEAM MONITORING



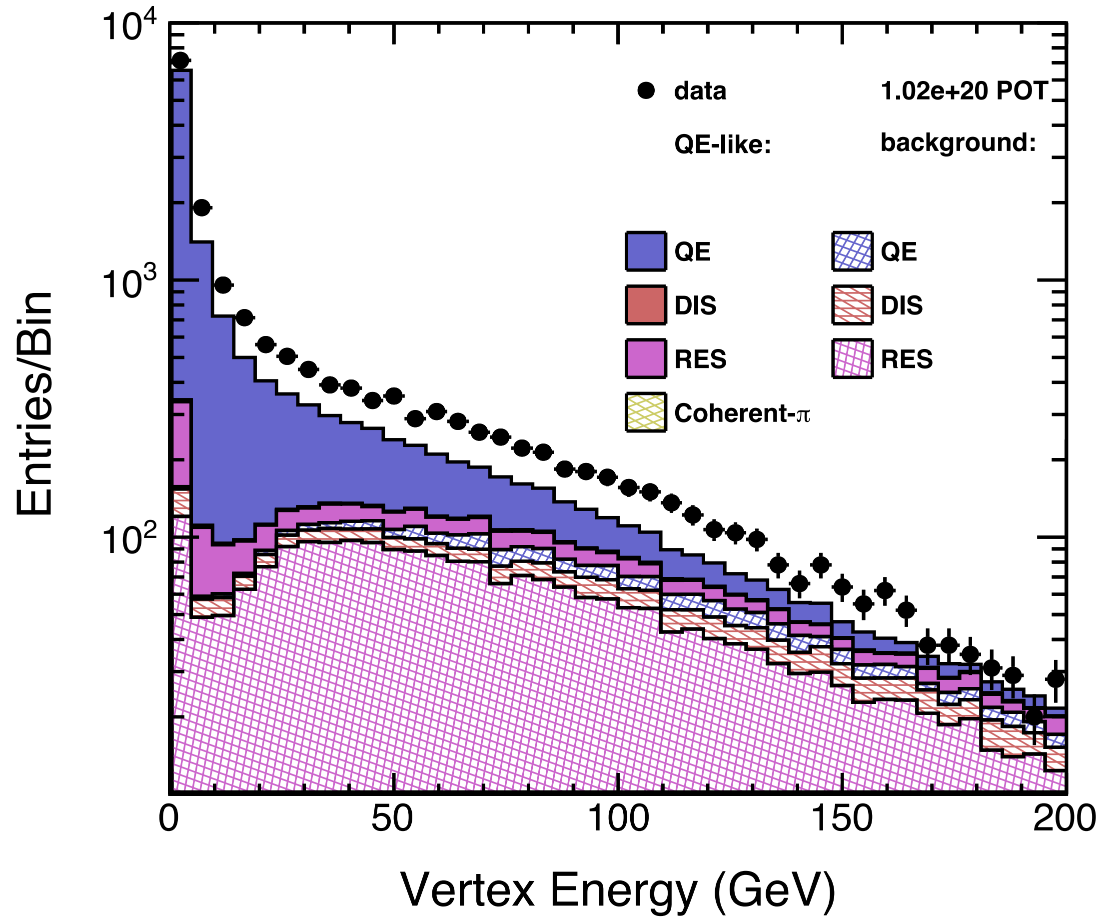
- MW neutrino beam lines are volatile environments
  - Variations range from slow (tolerable) creep to outright failure of the beam
- It is essential to:
  - Detect in short order (~day) potential variations at O(%) level
    - Large target mass (statistics) needed to quickly assess rates, profiles, spectrum
    - **On-axis** deployment optimizes rate/spectral sensitivity
  - Monitor long term stability (~years) at the same level
    - Comparable requirement on detector stability

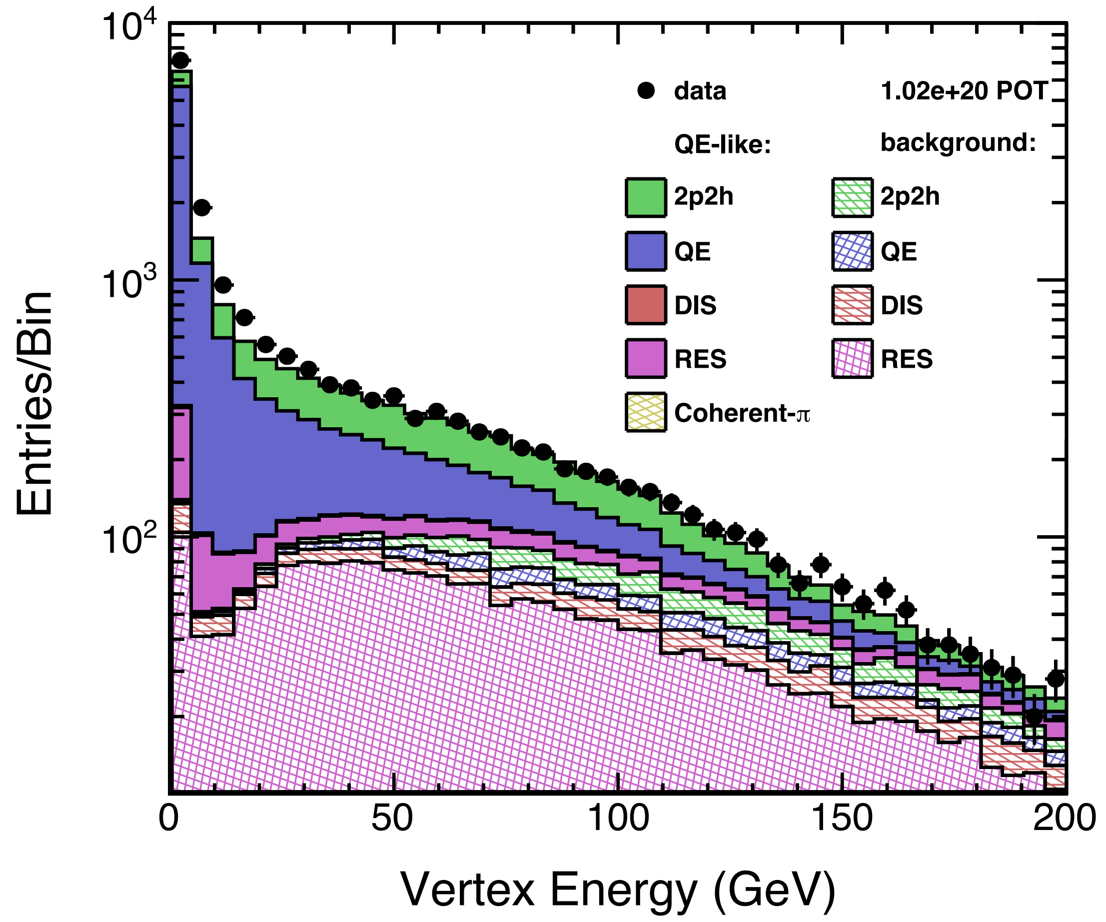
- Auxiliary monitors (e.g. muon monitors) are important and provide "real time" feedback.
- However, sensitive only to a limited range of variations
- Monitoring with neutrino interactions is essential

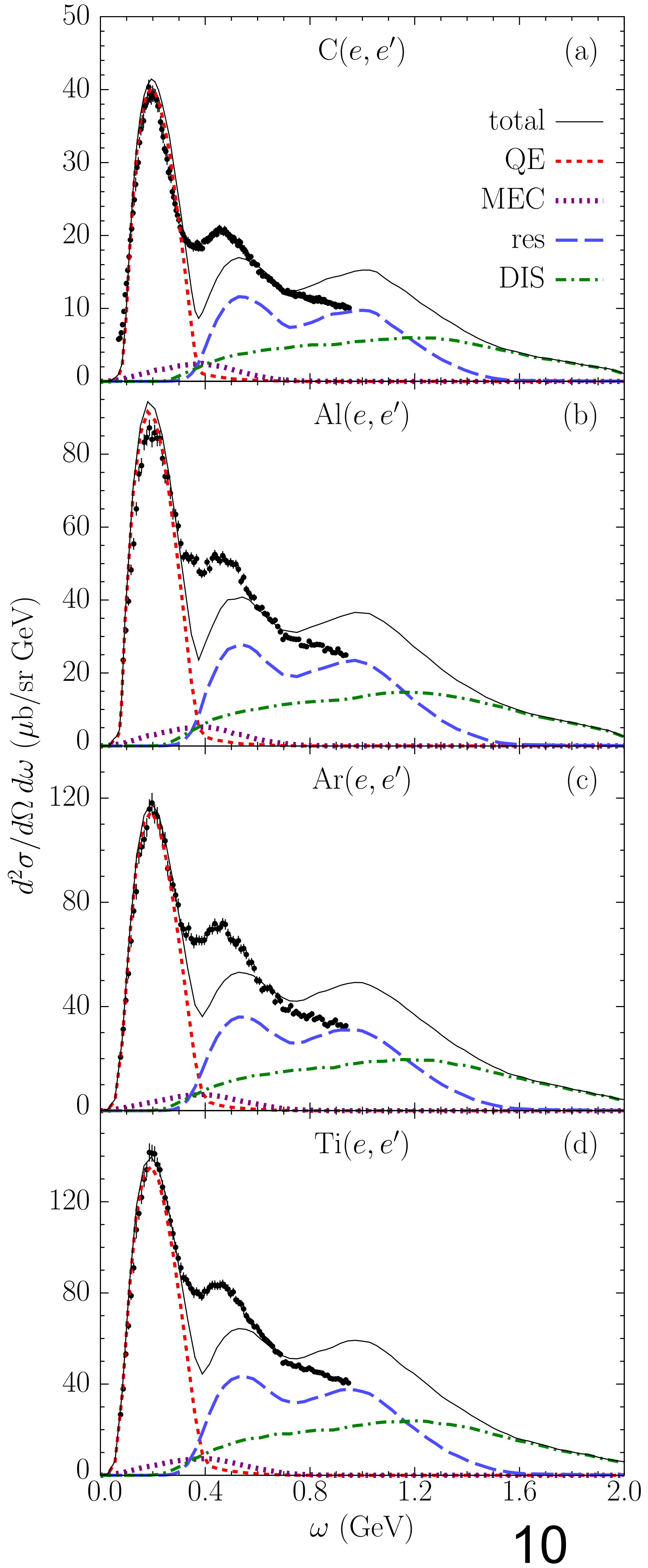


CROSS SECTIONS AND NEUTRINO REACTIONS

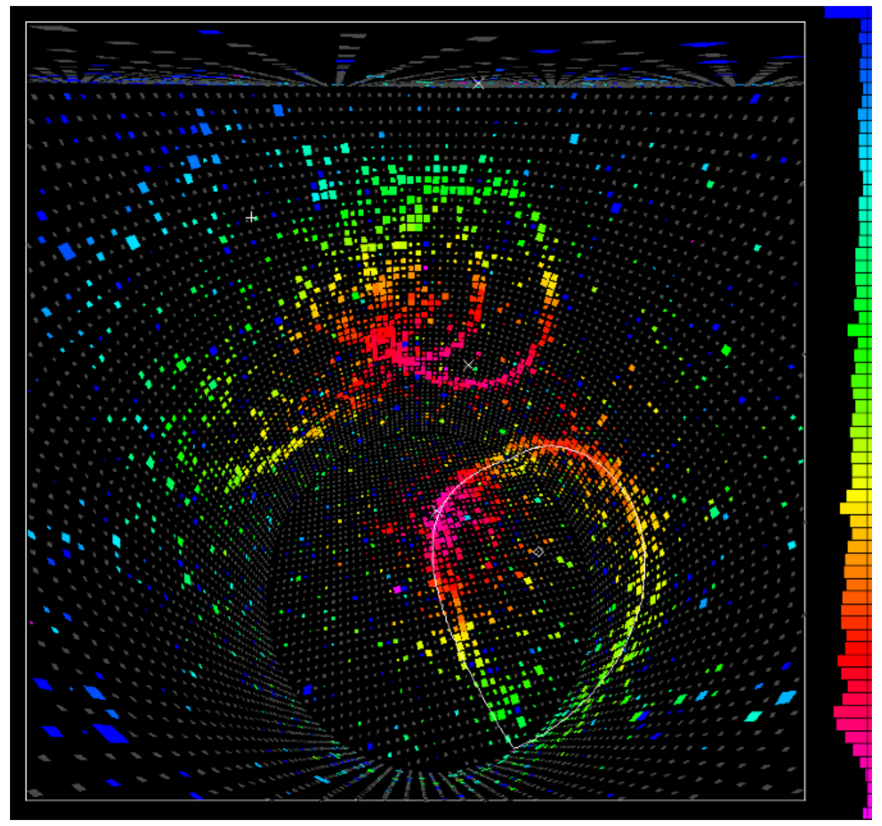
- Modeling of neutrino-nucleus $\nu - A$ interactions continue to be a potentially the most challenging aspect for the LBL program
  - More than a "cross section" issue . . details of final state matter since they couple to detector response
  - Significant progress in understanding the situation, improving fundamental modeling considerations, etc.
    - Still worry whether we are converging on the "right" (enough) physics within our generators
- Precarious situation for current/future LBL experiments that must be addressed by ND
  - Large but not particularly well-defined challenges

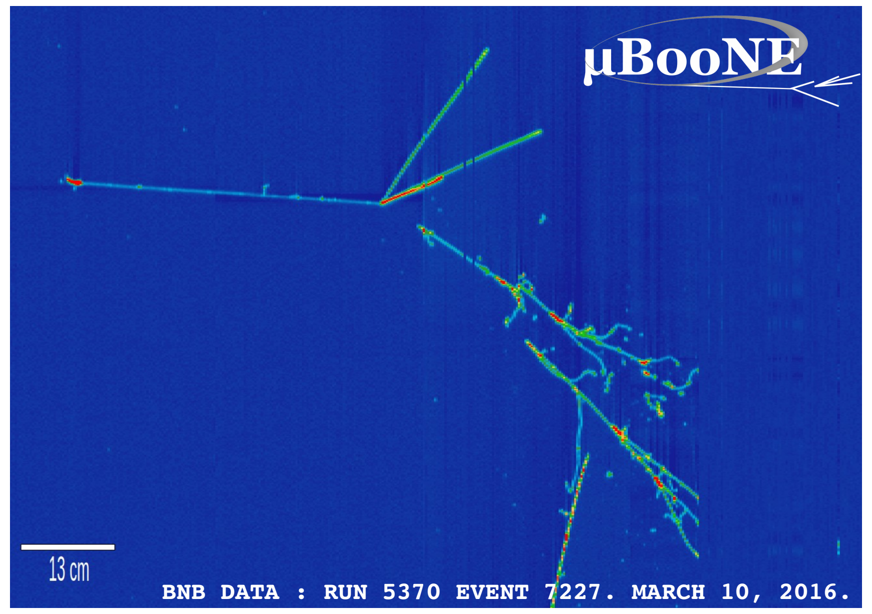






DETECTOR RESPONSE





Challenge:

$\nu - A$ interactions offer precious few calibration or control samples

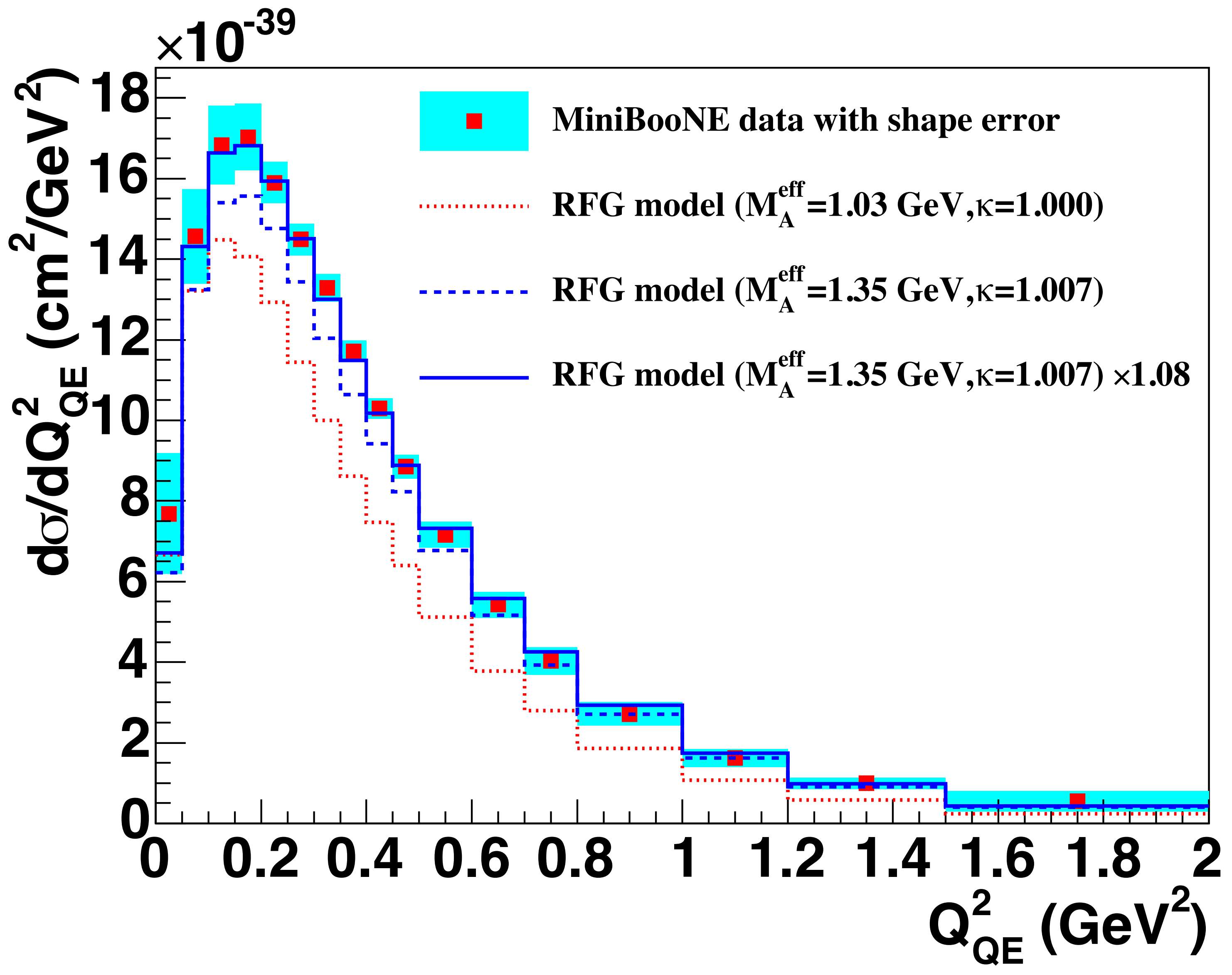
- What are the J/ψ, K^0_S, Zs, etc. of neutrino physics?
  - π^0s, MIPs, μ DAR, ...?
- Compounded by the low statistics in FD
- Heavy reliance on getting detector simulation correct with limited cross checks
- Dense medium of FD means significant secondary interaction effects (high thresholds)

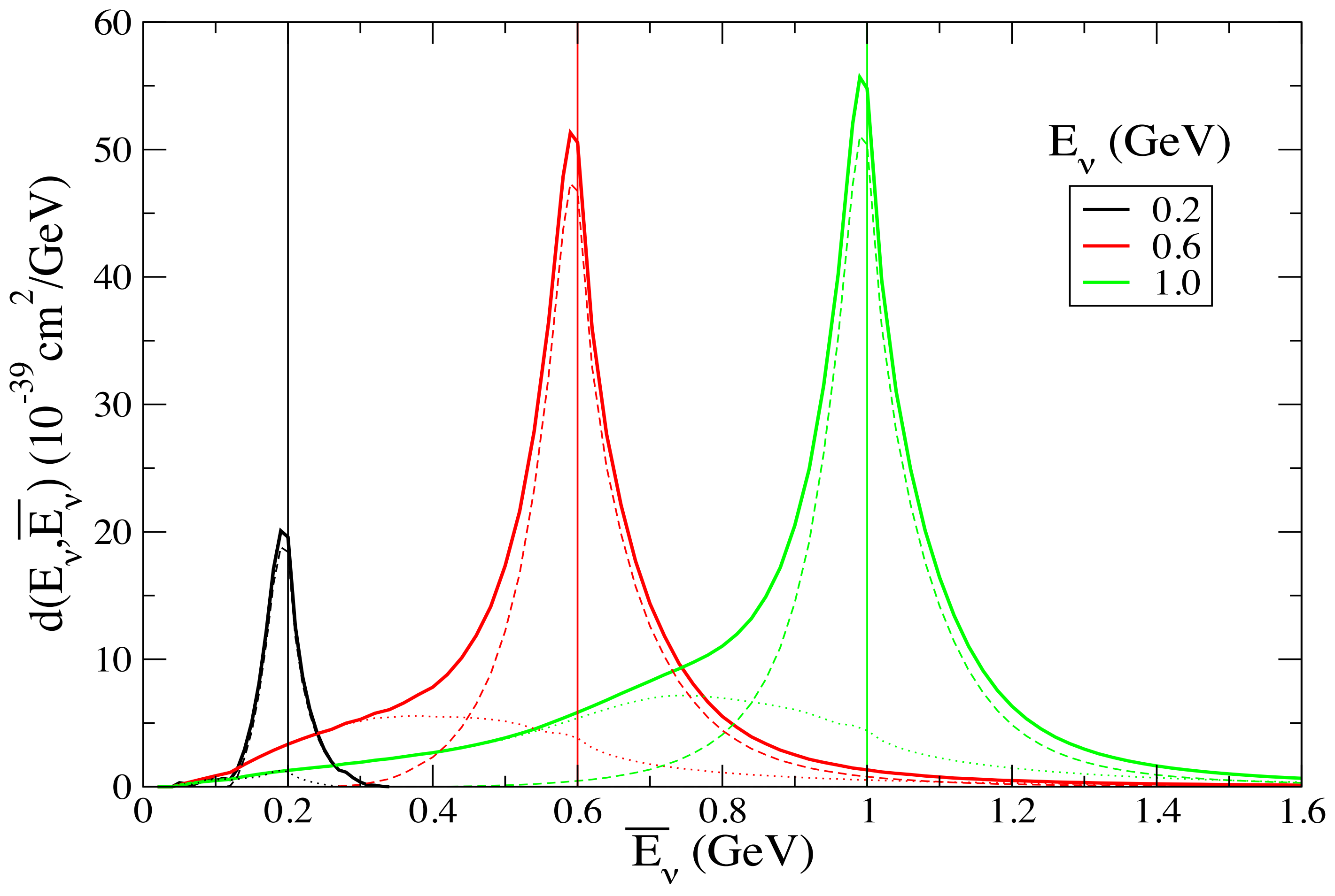
$$N_\beta(E_{REC}) = \int dE_\nu \, \Phi_\alpha(E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta, E_\nu; \Theta, L) \times \boxed{\sigma_{\beta X}(E_\nu) \times R_{\beta X}(E_\nu, E_{REC})}$$

Challenge: coupling of detector response and $\nu - A$ modeling uncertainties

- Efficiencies, resolutions, etc. depend on
  - Underlying reaction mechanisms (relation between incoming and outgoing kinematics)
  - Kinematic distribution of outgoing particles (detection/identification thresholds, re-interactions, etc.)
- It is essential to study these things in the ND that can be robustly translated into the FD
  - Suggests that a ND functionally similar/identical to FD is essential

MULTI-NUCLEON EFFECTS





Case study:

- MiniBooNE ν_μ CC "0π" distributions "explained" well by change in the form factor via dipole parametrization
  - $M_A \sim 1.0$ GeV → ~ 1.3 GeV) for CCQE events
  - Large increase in CCQE cross section and "hardening" of the interaction
- M. Martini and others pointed to overlooked multinucleon effects
  - Introduction of topologically new processes with inherently different kinematics, including neutrino energy reconstruction.
- Lessons:
  - Surprises: Basic nuclear physics, other issues can be overlooked
  - It is not sufficient to achieve "agreement" in ND observables
  - Detectors must have sufficient capability to resolve potential degeneracies in modeling
    - Suggests ND may need to have more capability than the FD

STRATEGIES/DESIGN CONSIDERATIONS

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$$N_\beta(E_{REC}) = \int dE_\nu\, \Phi_\alpha(E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta, E_\nu; \Theta, L) \times \sigma_{\beta X}(E_\nu) \times R_{\beta X}(E_\nu, E_{REC})$$

Conflicting requirements:

- "Functionally identical" ND is necessary to robustly connect ND ↔ FD observables
  - ND should be as similar as possible to FD
- Flux measurements, degeneracy resolution may not be possible with FD technology
  - ND requires additional/different capabilities than FD

$R_{\beta X}(E_\nu, E_{REC})$
Requires functional overlap between ND and FD

$\Phi_\alpha(E_\nu)$
May require special reconstruction capacities not present in FD

$\sigma_{\beta X}(E_\nu) \times R_{\beta X}(E_\nu, E_{REC})$
Requires functional overlap between ND and FD

$\sigma_{\beta X}(E_\nu)$
Requires at least same target as FD, but additional capabilities desirable/needed

ND should be "identical" to FD ⟷ ND needs additional capabilities

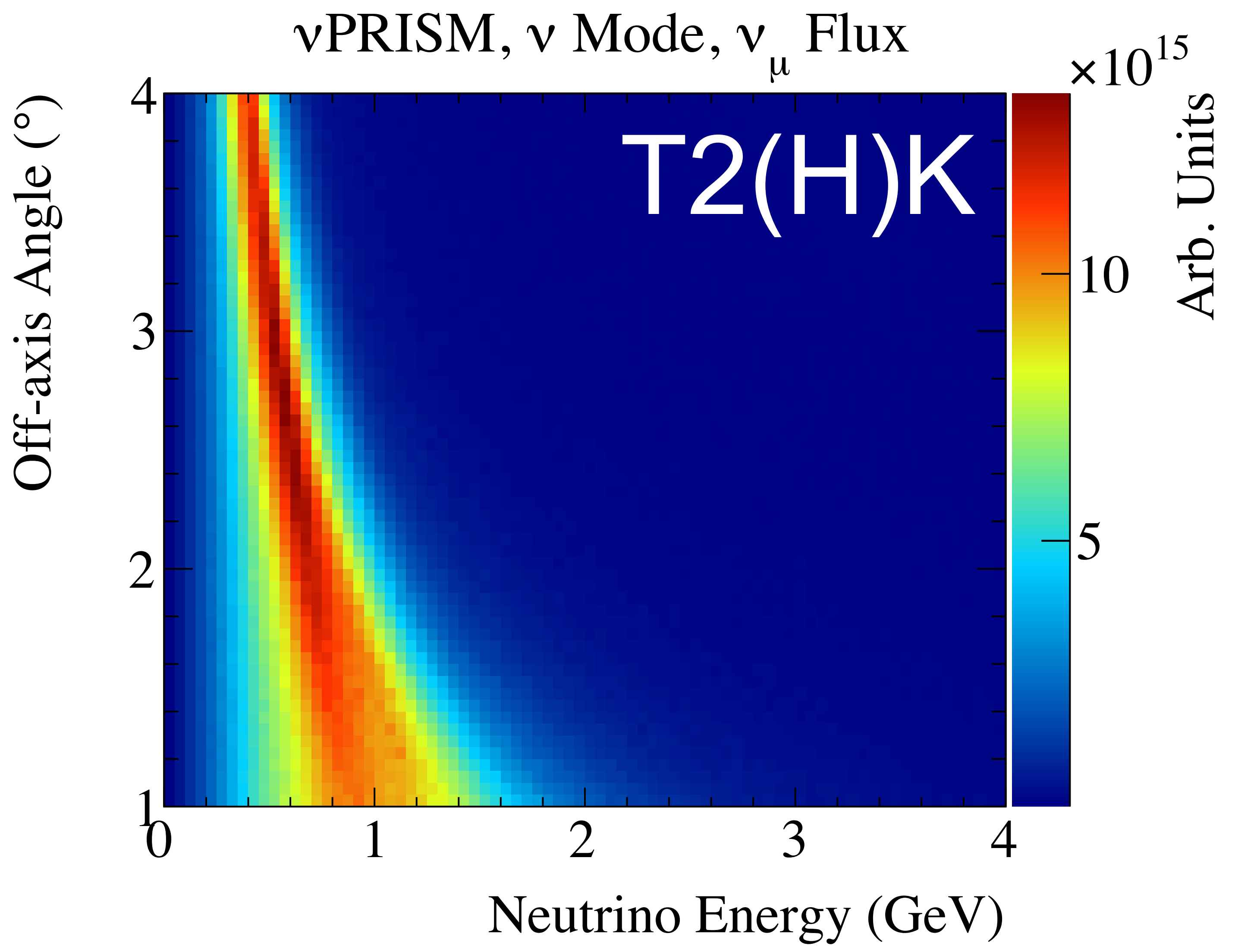
Obvious solution:

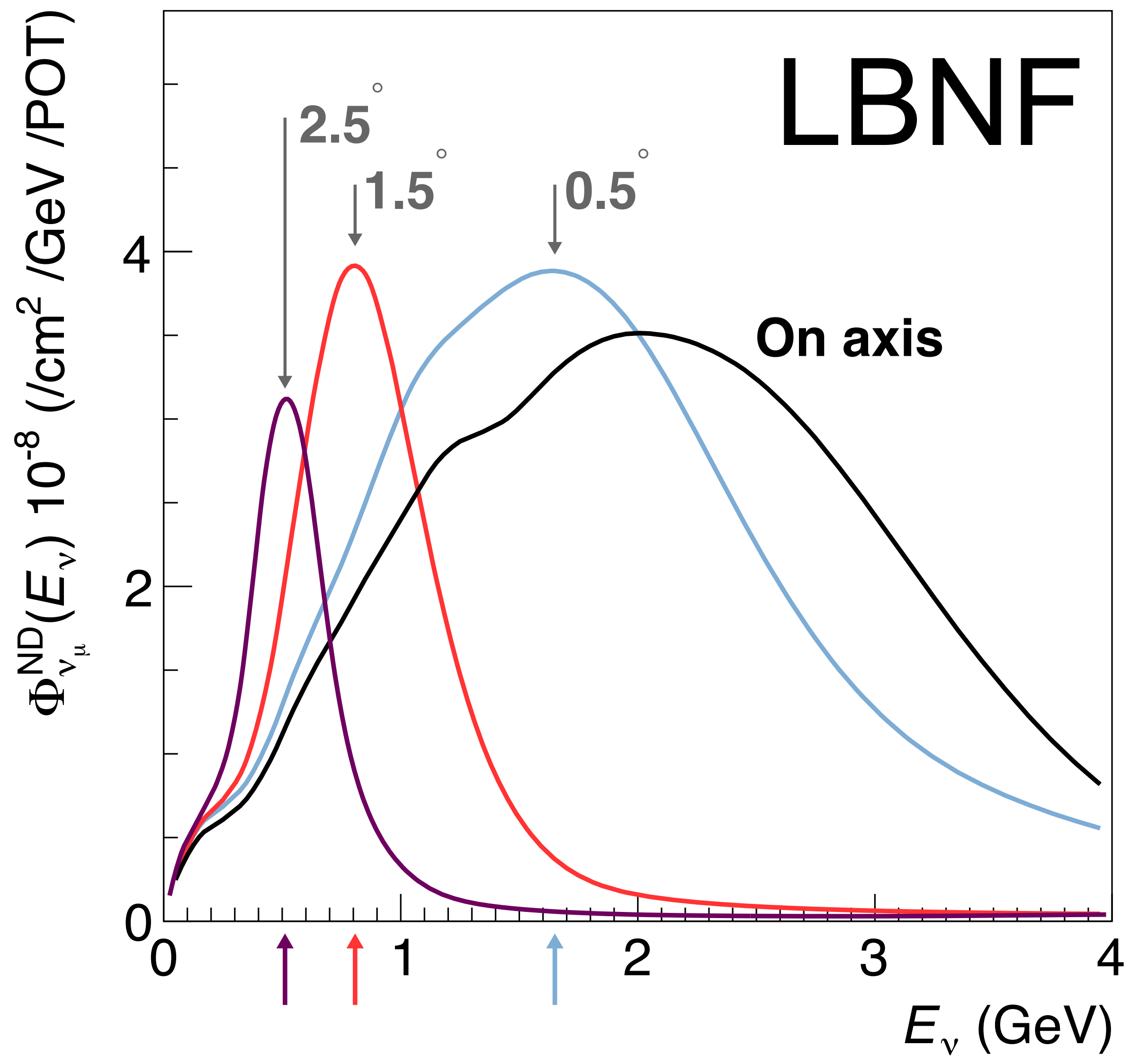
- Do not try to solve everything with one detector
- Subsystem specialization to take on part of the task as part of an overall strategy
  - One detector can perform more than one function

PRISM

- The neutrino beam spectrum changes as one moves traverse ("off-axis") from the beam center
  - Spectrum becomes narrower and lower in energy
- Moving detector can sample a continuously varying neutrino spectrum
  - Independent handle on (true) neutrino energy that can verify observables (e.g. reconstructed energy) vs. neutrino energy
  - Alternatively, distribution of observables (in the presence of oscillations) can be constructed directly by the data taken at different positions
- PRISM: "Precision Reaction Interaction Spectrum Measurement"
  - A ND system that moves transversely in the beam
  - An analysis program to combine measurements to predict FD observables

$$N_\beta(E_{REC}) = \int dE_\nu\, \Phi_\alpha(E_\nu) \times P(\nu_\alpha \rightarrow \nu_\beta, E_\nu; \Theta, L) \times \sigma_{\beta X}(E_\nu) \times R_{\beta X}(E_\nu, E_{REC})$$

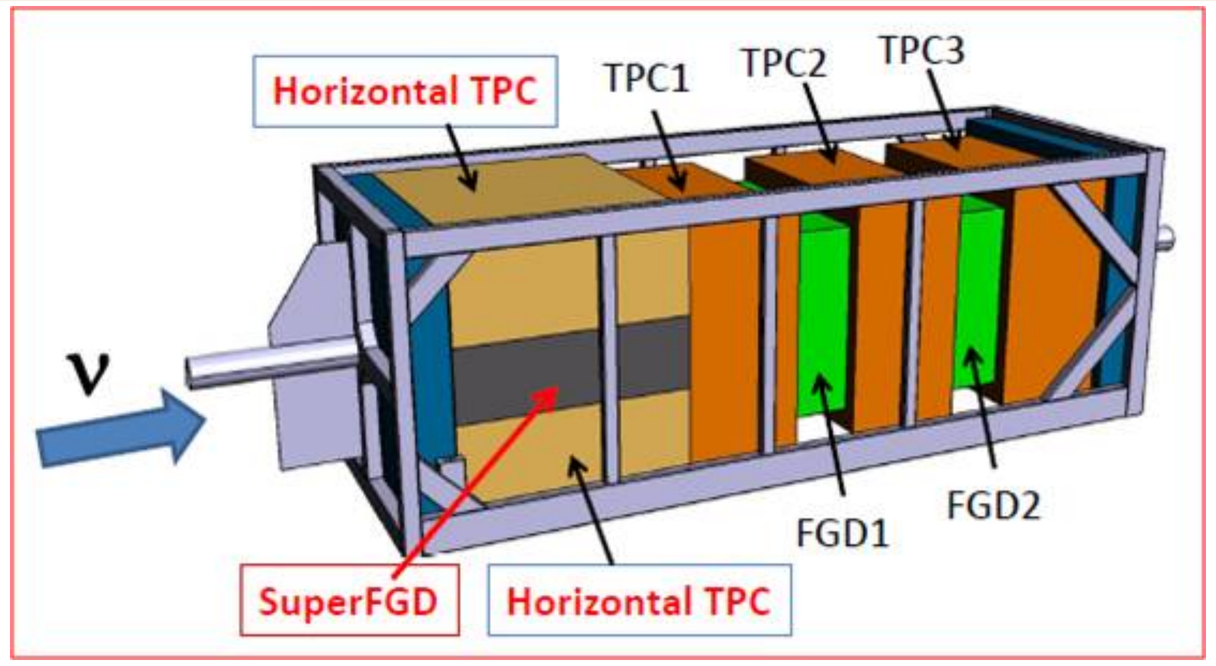


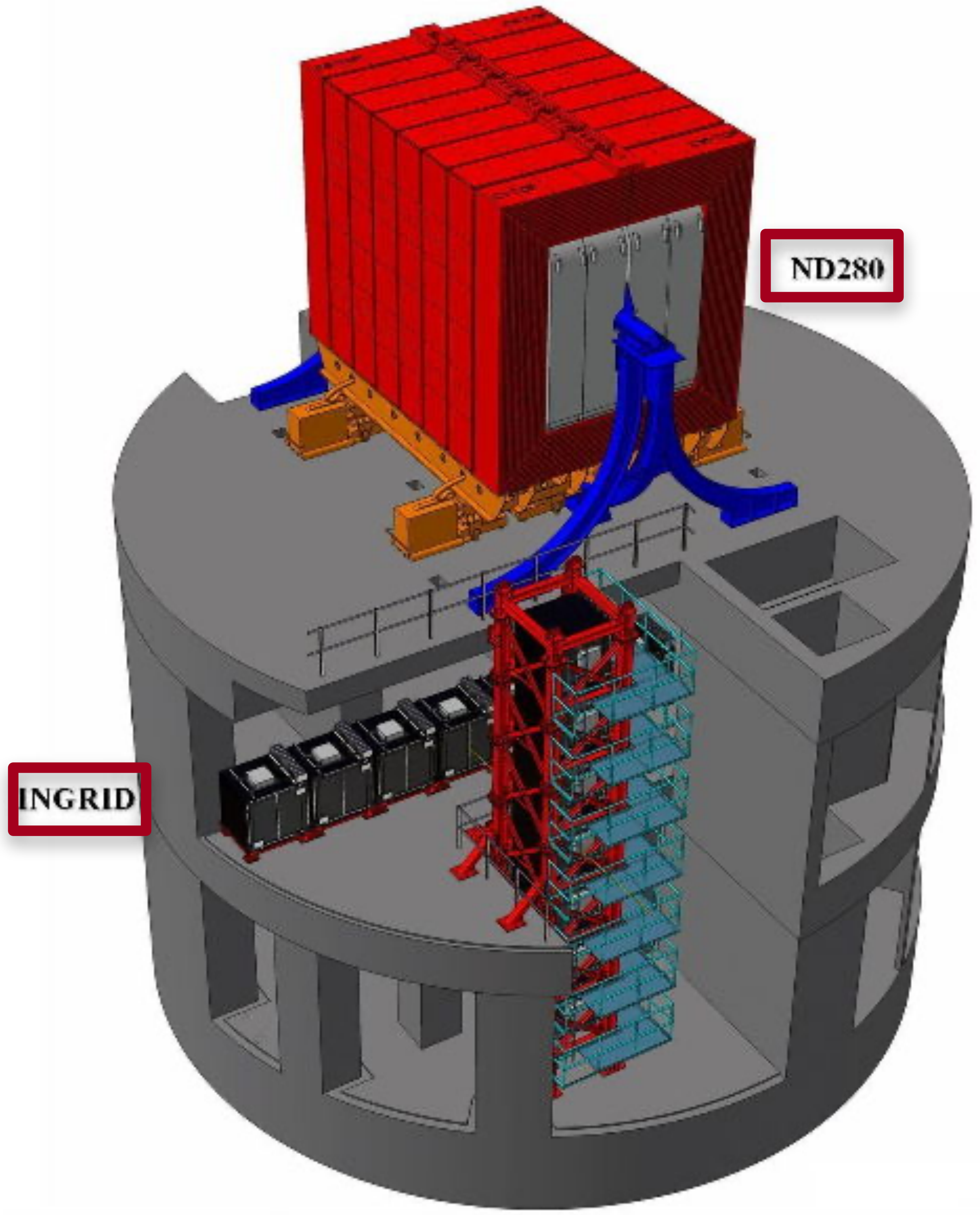


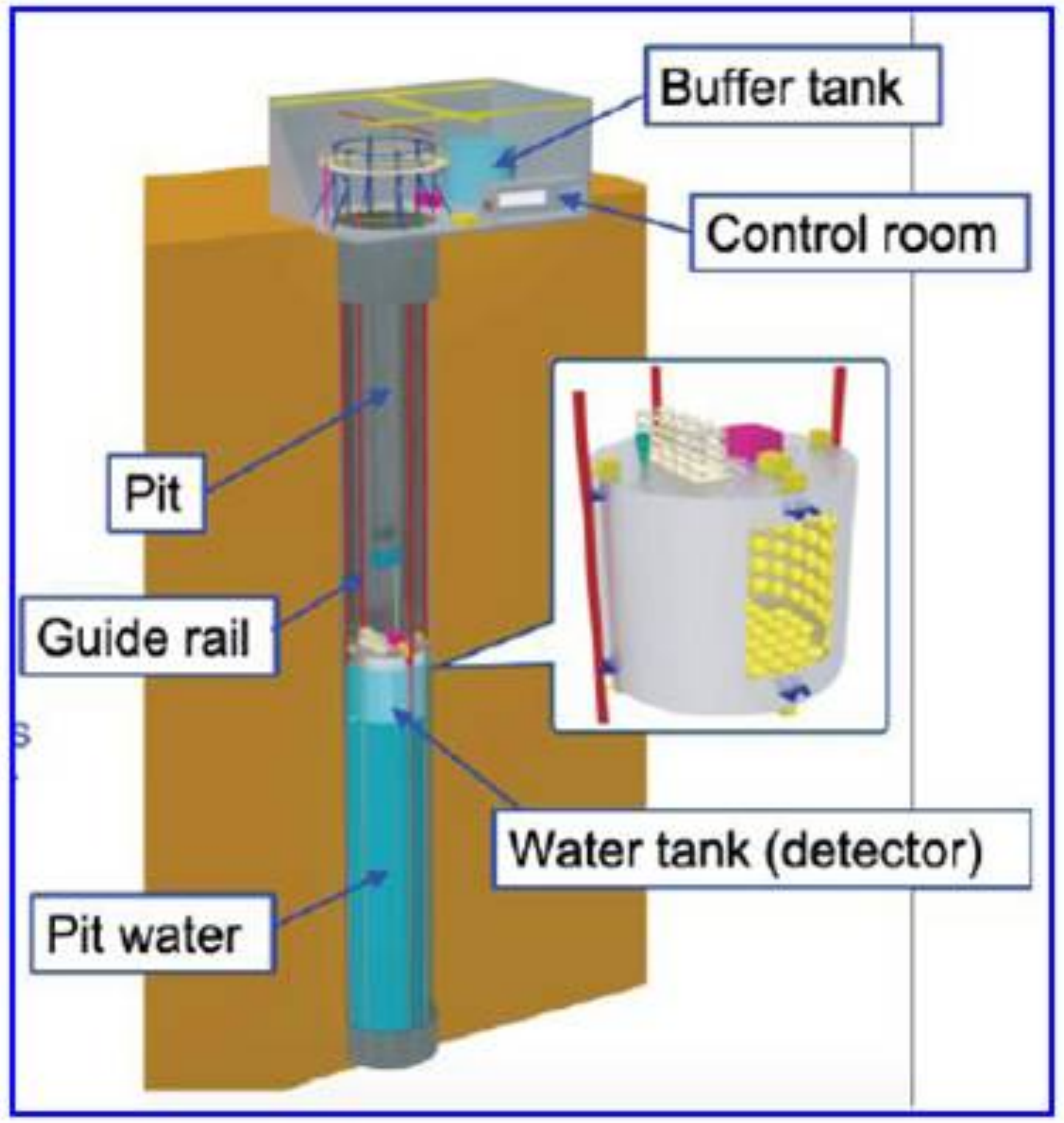
DEVELOPING CONCEPTS: T2K/HK

Three part system:

- ND280: ~280 m from target:
  - On-axis beam monitoring: INGRID
    - Transverse vertex profile
    - Rate, ~spectrum information
  - ND280: off-axis spectrometer (towards SK/HK)
    - 0.2 T field
    - Scintillator tracker/TPC/ECAL/muon system to study neutrino interactions
    - Upgrades to improve wide-angle reconstruction
- IWCD: ~1 km from target
  - Water Cherenkov detector "functionally" identical to FD (SK/HK) at ~1 km) using mPMT
  - Executes vertical PRISM movements over 50 m







CURRENT CONCEPTS: DUNE

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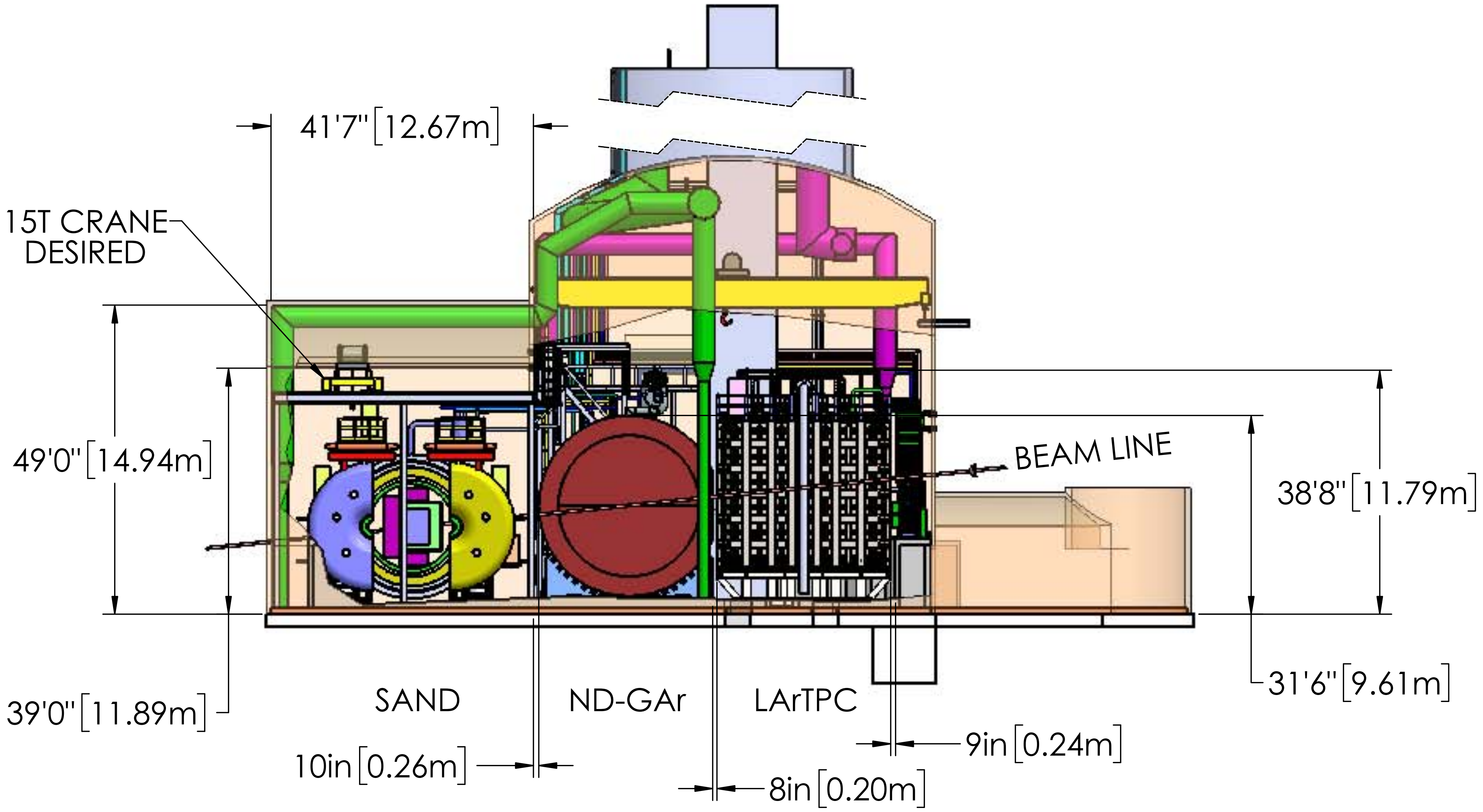


ND-LAr: LArTPC detectors

Functionally similar to FD LArTPCs, optimized for high rate

- Modular design with 7x5 array of 1x1x3 m^3 LArTPCs
- Pixel readout for "native" 3D charge response

ND-GAr: Magnetized Gaseous Argon TPC system

Low threshold, magnetized reconstruction of ν-Ar interactions

- 0.5 Tesla superconducting magnet
- High pressure (10 bar) GAr TPC
- Electromagnetic calorimeter
- Also serves as downstream μ spectrometer for ND-LAr interactions

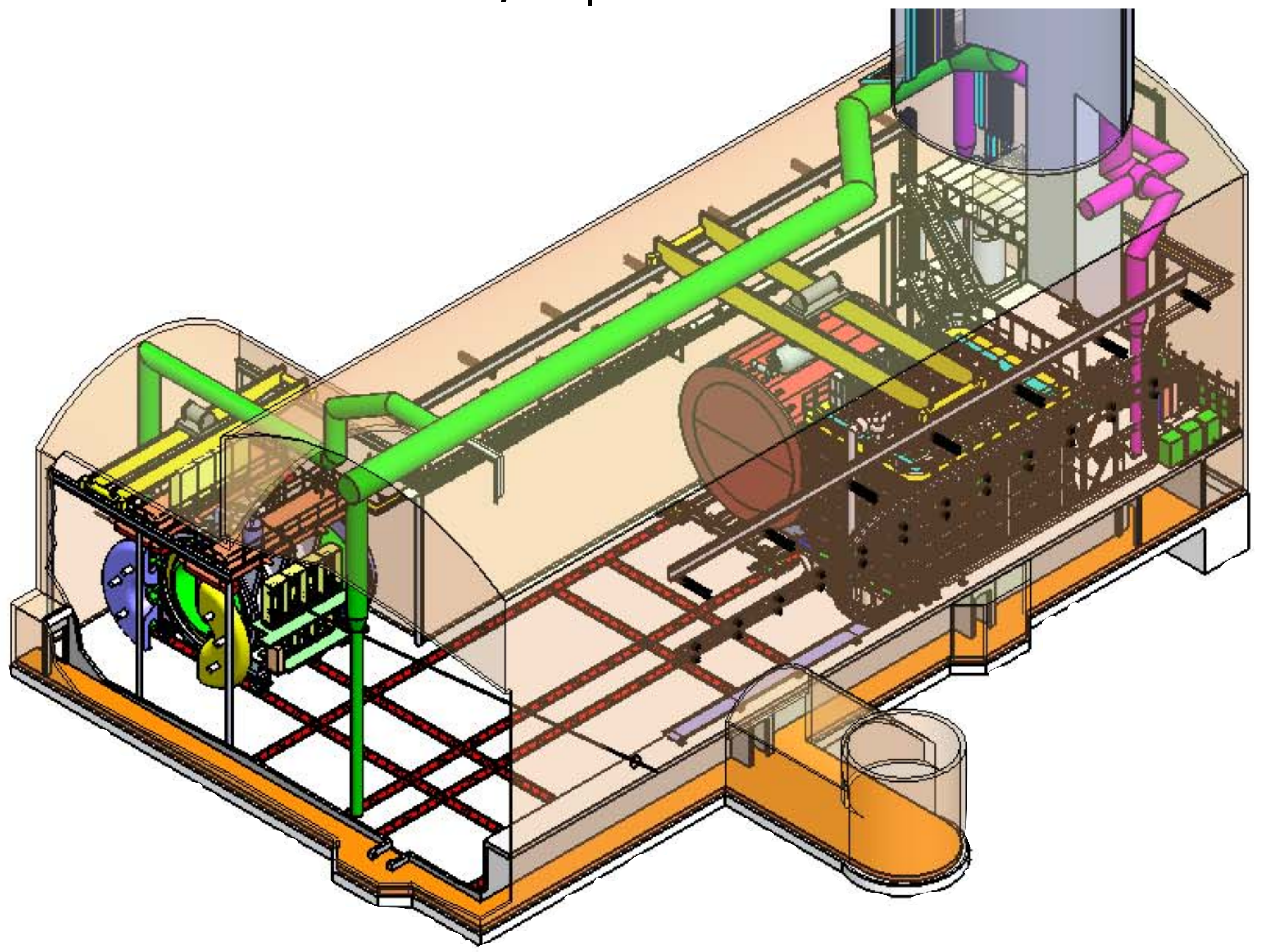
DUNE-PRISM:

- ND-LAr+ND-GAr system can move up to ~30 m off-axis
- Sample neutrino fluxes peaked down to ~0.5 GeV

SAND:

On-axis magnetized beam spectrum monitor

- 0.5 T SC magnet + ECAL from KLOE
- New inner tracking system including LAr target



LORE:

NDs have come a long way and evolved with our understanding of neutrino oscillations.

Some considerations I have heard in the past:

- *The purpose of ND is to measure the flux*
  - That is one purpose of the near detector. It must do many other things
- *ND must be as identical as possible to FD*
  - ND must address detector systematics at FD , but it needs to do more than that.
- *ND should see the same neutrino flux as FD*
  - In LBL, by construction ND will see a different flux as FD . . . .
  - While flux uncertainties are still large, near/far fluxes are better understood
- *We should choose the ND with the best performance (resolution, efficiency, etc.)*
  - By construction, “performance” for ND is in the context of a LBL experiment.
  - It should be optimized to address systematics at the far detector

We are asking more than ever of NDs and our understanding must continue to be improved and refined

MORE BROADLY

The primary purpose of the ND is to reduce systematics in a LBL experiment

- It exists within an ecosystem of approaches, methods, etc.
- We shouldn't lose sight of them.

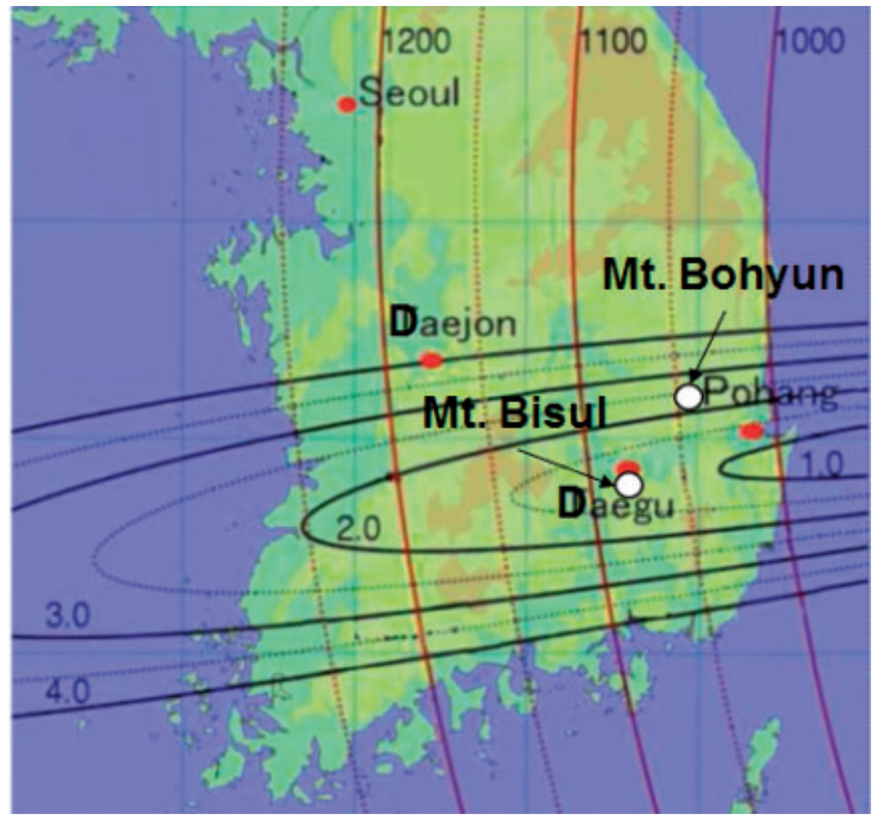
A few examples

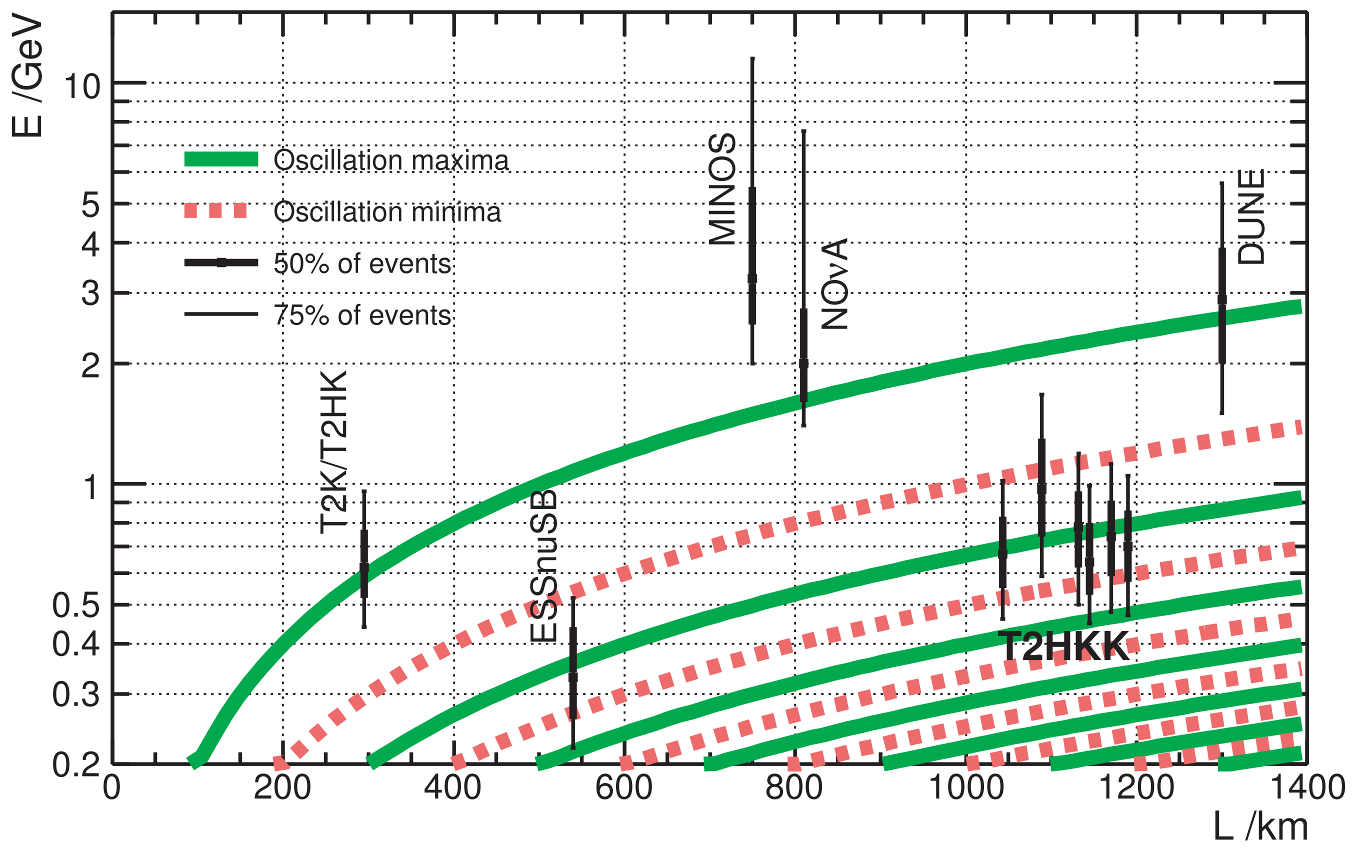
- Hadron production/scattering experiments
  - Continue to improve our understanding of the neutrino beam
- Test beam
  - Improve our understanding of detector response
  - n.b neutrino interactions are a very difficult environment in which to understand a detector
- $\nu - A$ theory:
  - Connect measurements with fundamental physics

Billions of (CHF, $, €, £, 百円) at stake over the coming decades in LBL

- These efforts will leader to more robust results from LBL experiments and a richer science program

OUTLOOK

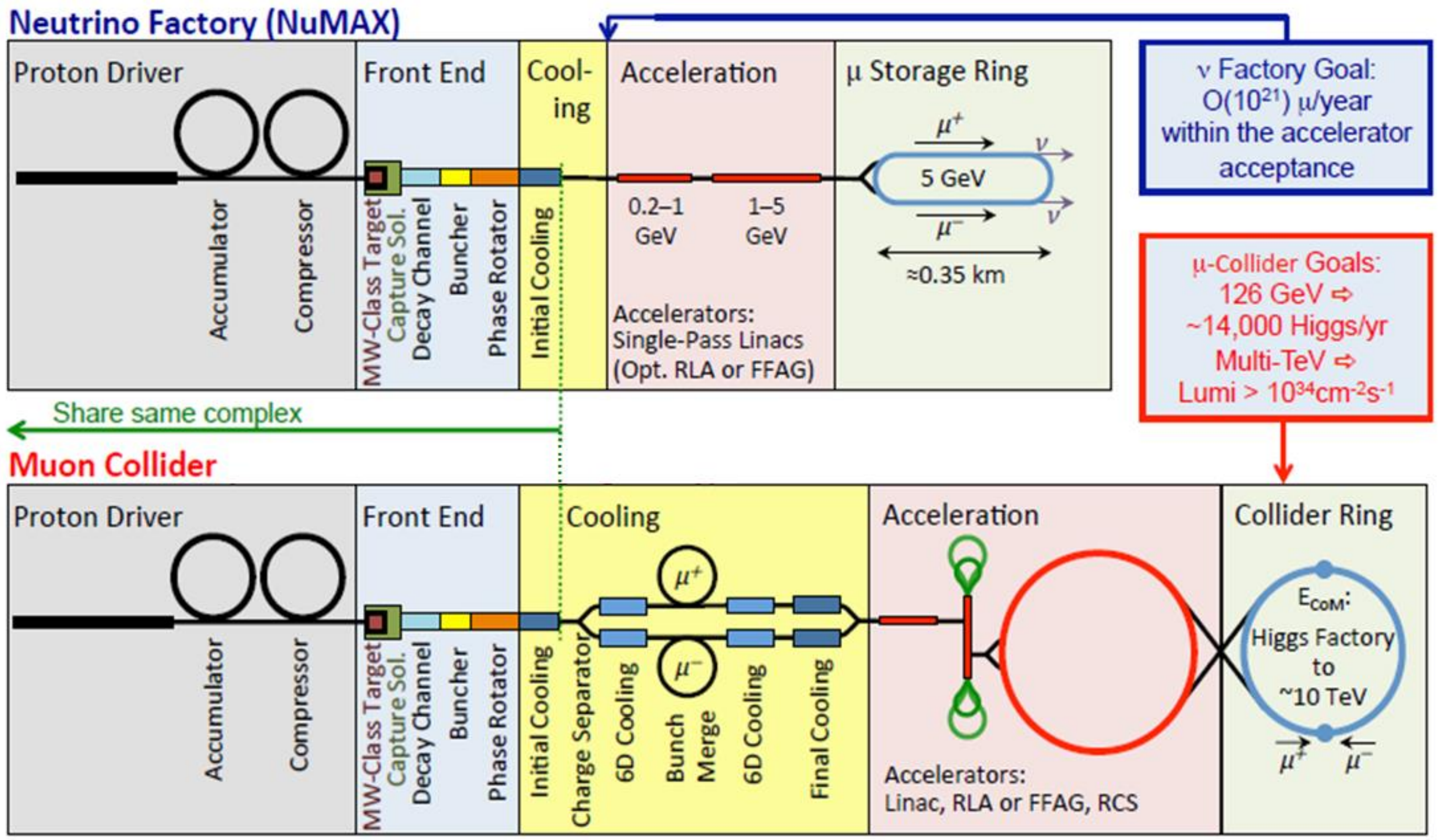


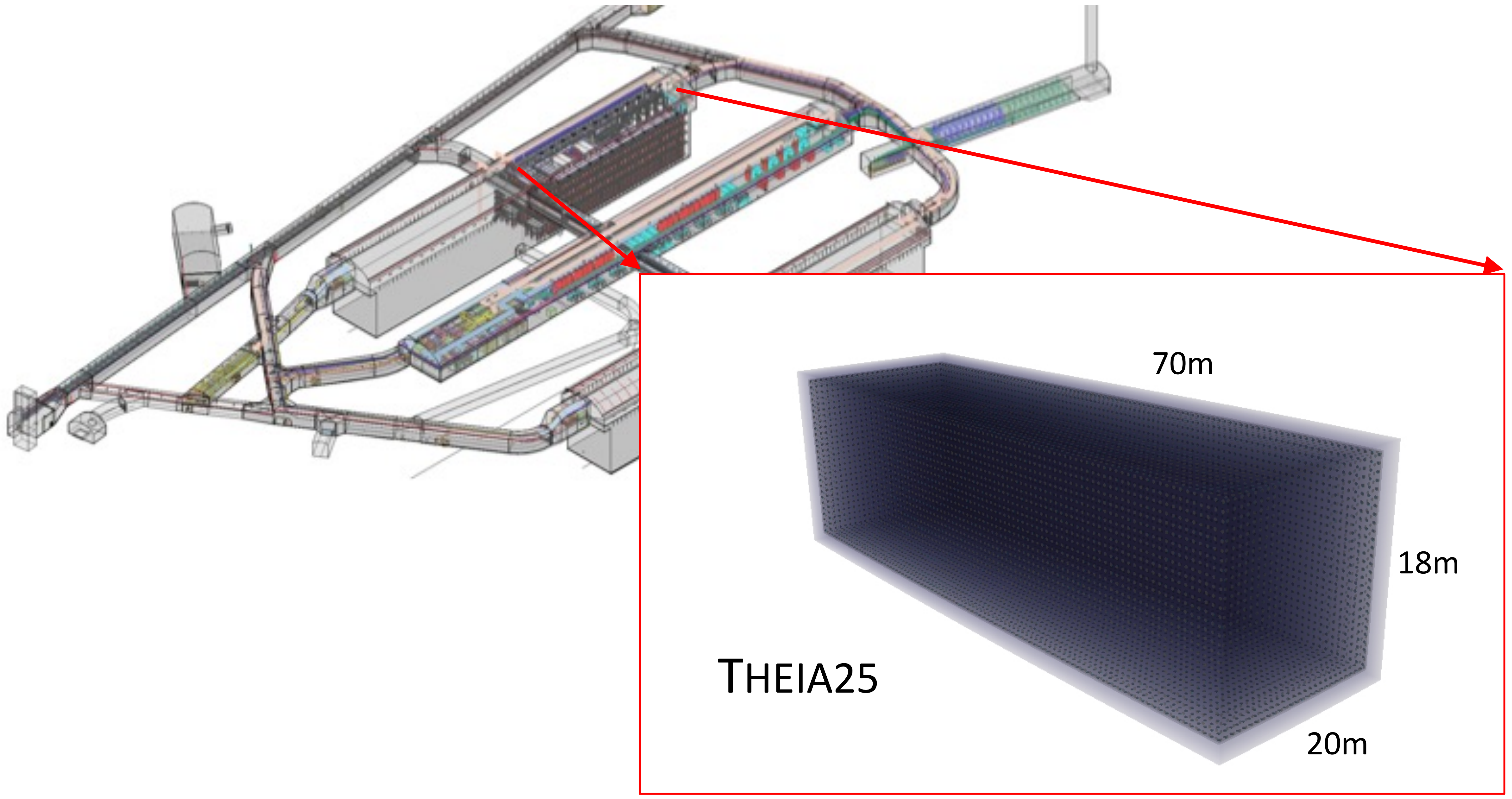


Beyond the "immediate/planned" future?

- 2nd oscillation maximum
- Additional detectors in LBNF beam?
- Muon-based neutrino beams?

When the next step are clear, it seems like a good time to think beyond them!





CONCLUSIONS

- It's a golden age for neutrino experiments
  - it's been a "golden age" for neutrinos for a while . . .
  - Answers to old questions → fascinating new ones
- Experimentally, we are in a very exciting place
  - Mature experiments (NOvA, T2K) moving towards ultimate goals
  - Next generation experiments (LBNF/DUNE, HK) on the way
    - Will pose unprecedented demands on systematic uncertainties and ND strategy
- We should continue to think about how to optimize this stage of discovery and beyond.
- ***The golden age continues with new experiments and opportunities***

Thank you to the organizers!
I wish I were there!