DUNE and DUNE-Prism concept.

FLC Long talk

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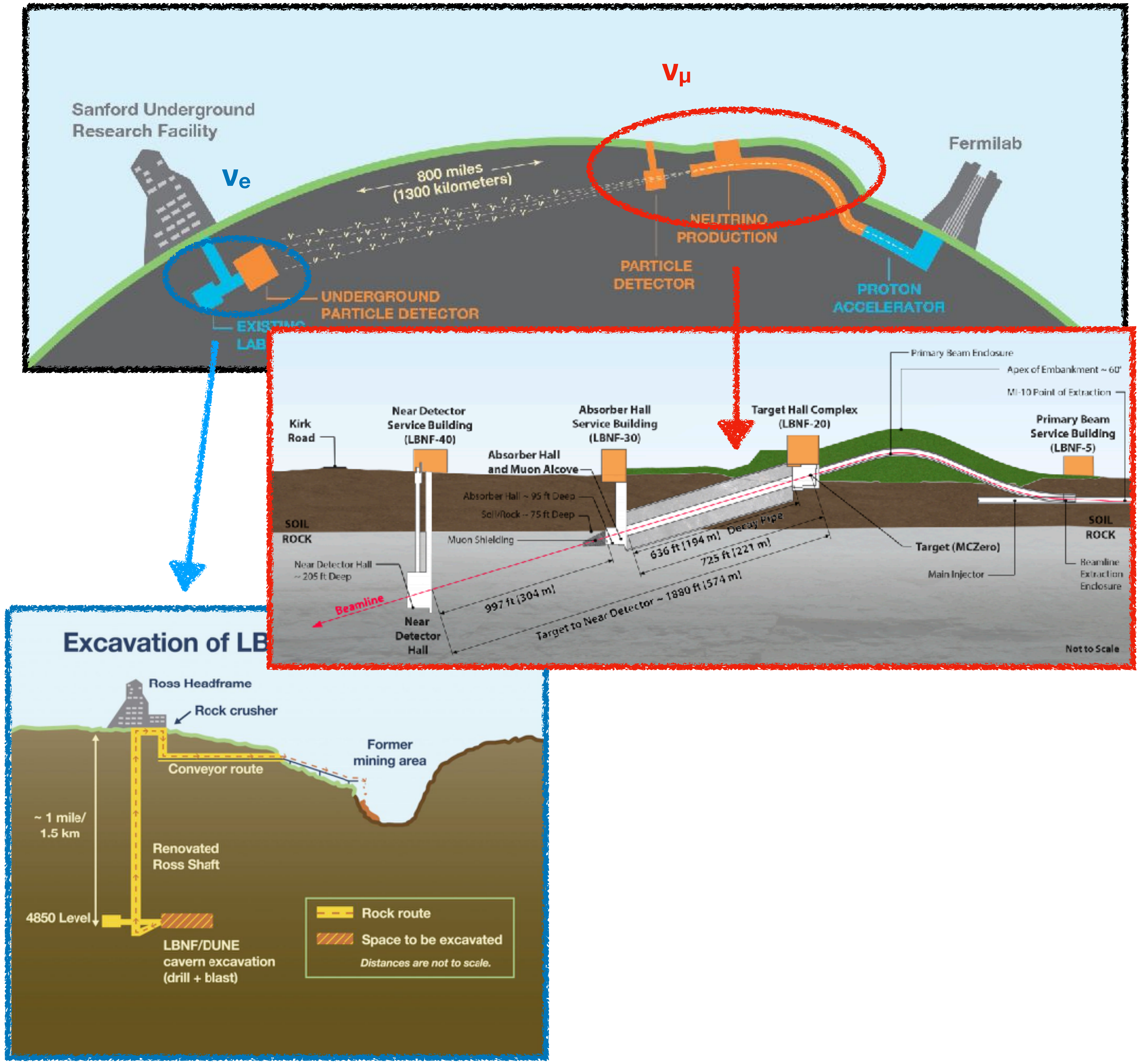
Outline.

1. The DUNE experiment
2. The Near Detector concept
3. The ND-Gar detector
4. The DUNE Prism concept
5. Outlook and Conclusion

The DUNE Experiment.

Deep Underground Neutrino Experiment

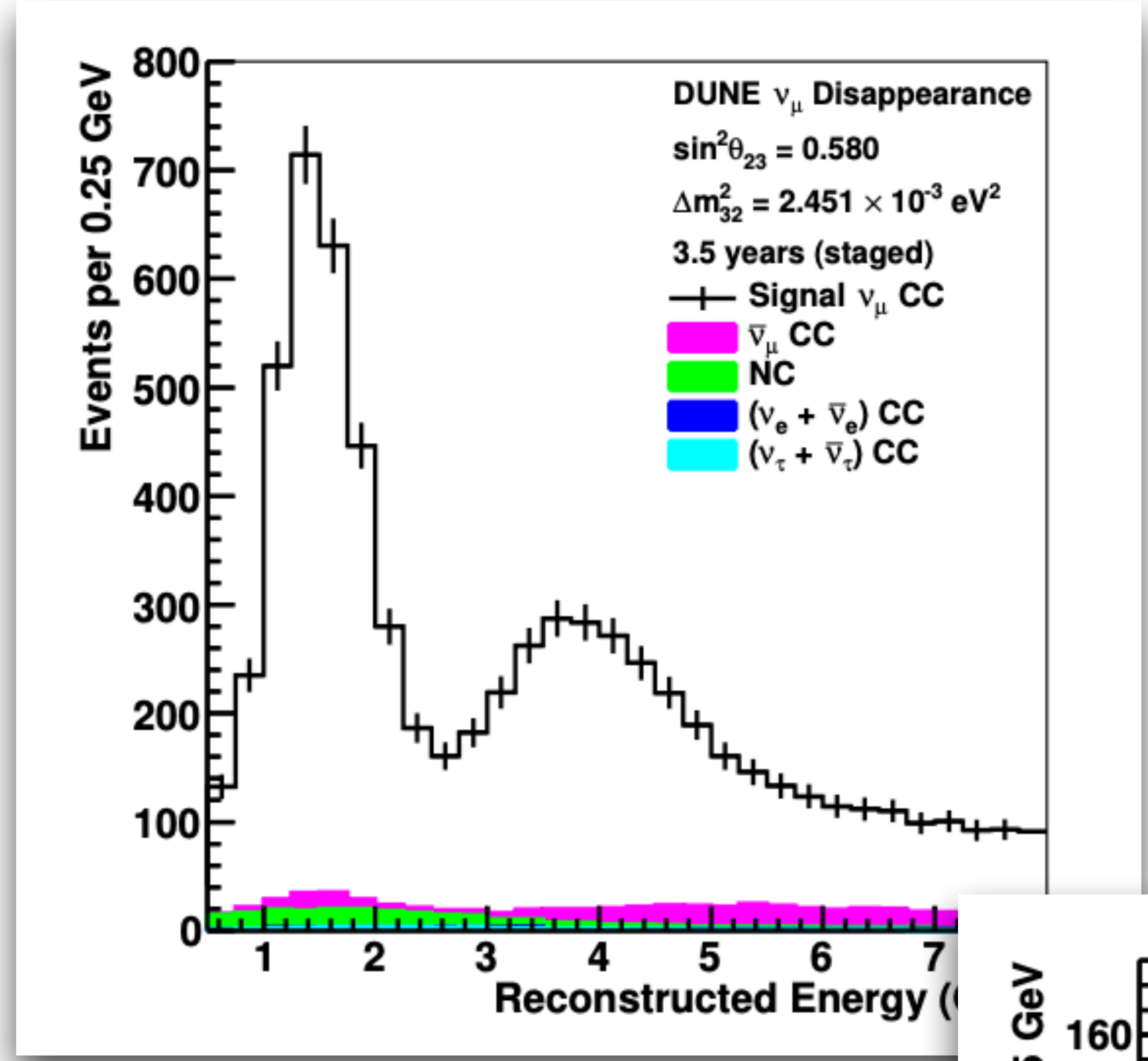
- **The next generation neutrino experiment**
  - Long Baseline Neutrino **1300 km**
  - **Wide-band** neutrino beam (GeV range, MW beam)
- Detectors
  - **Near detector** complex at 575 m from neutrino source
  - **Far Detector** made of 4 x 10 kt fiducial mass LAr detector

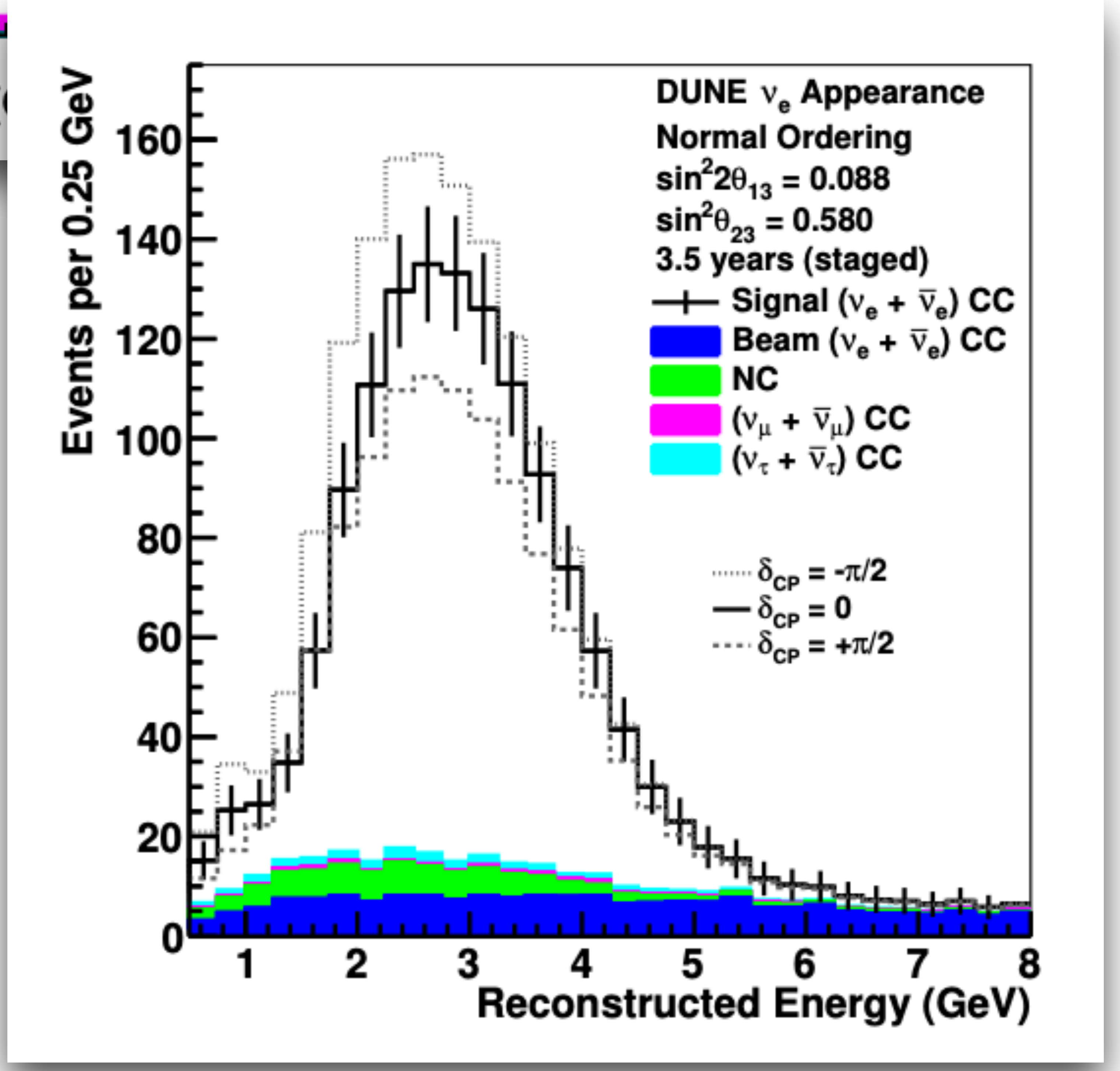


The DUNE Experiment.

Deep Underground Neutrino Experiment

- Goals:
  - **Neutrino oscillations** ➠ measure ν_μ disappearance and ν_e and ν_τ appearance (both FHC and RHC)
  - Measure δ_{cp} over 75% of the phase space with a **precision up to 5σ**, determine mass hierarchy and precise measurement of the mixing angles (θ_{23} octant)
  - *Beyond the SM physics*: neutrino tridents, DM, sterile neutrinos…
- Other searches: neutrino supernovae, proton decay…





How to measure neutrino oscillations?.

Ups and downs of neutrinos

- Want to measure oscillation probability
- However, detector effects ➠ need for unfolding / not so easy to cancel systematics
- In reality, this is not easy, need to understand
  - The neutrino flux
  - Cross-section ratios
  - Extrapolation near to far
  - Detector effects (near and far)
  - Relation true to reco neutrino energy

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu)}$$

$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}(E_\nu) * T_{\nu_\mu}^{det}(E_\nu, E_{rec})\, dE_\nu$$

$$\frac{dN_{\nu_e}^{far}}{dE_\nu} \Bigg/ \frac{dN_{\nu_\mu}^{near}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_\mu}^{Ar}(E_\nu)} * F_{far/near}(E_\nu)$$

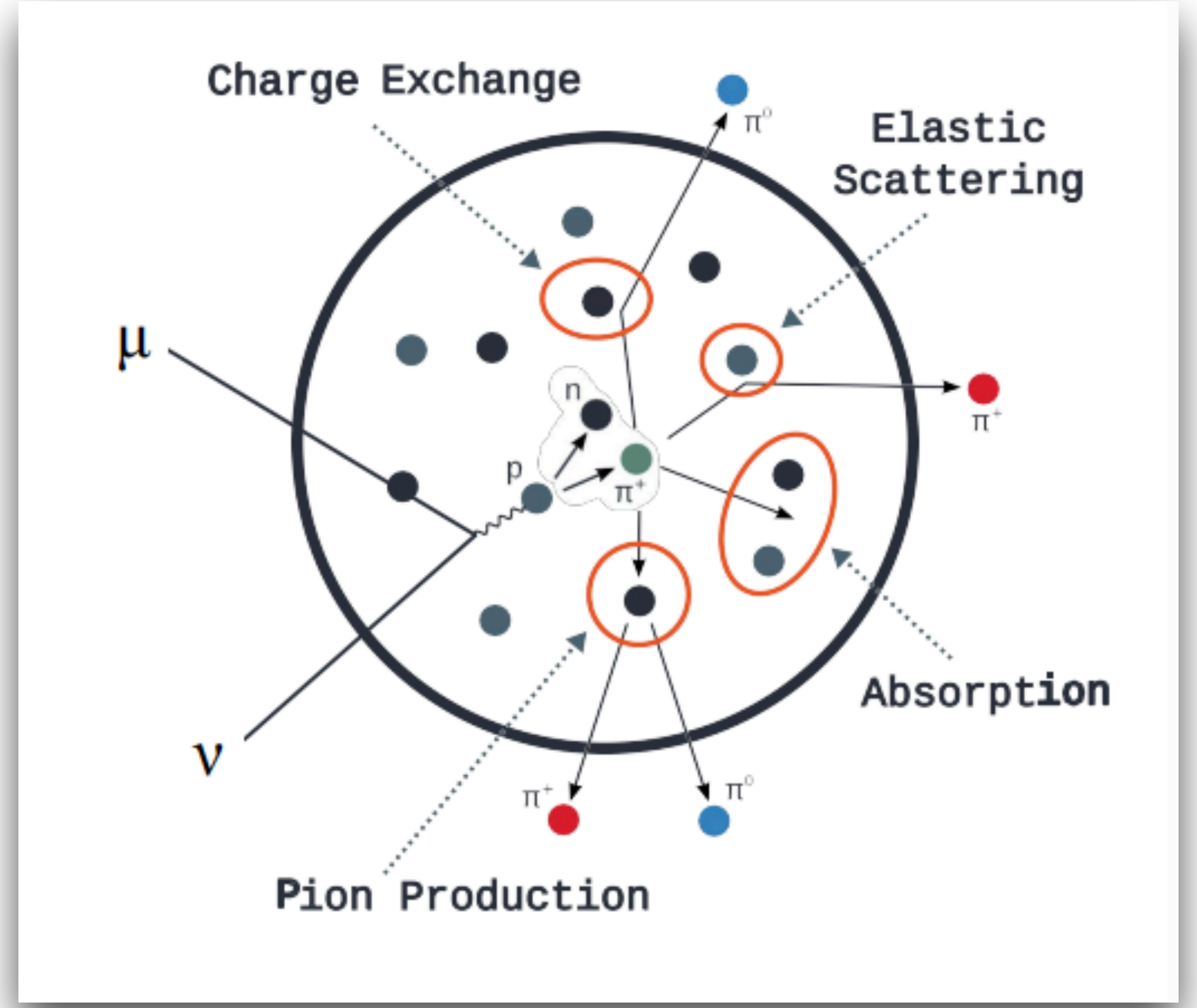
$$\frac{dN_{\nu_e}^{near}}{dE_\nu} \Bigg/ \frac{dN_{\nu_\mu}^{near}}{dE_\nu} = \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_\mu}^{Ar}(E_\nu)} * \frac{\phi_{\nu_e}^{near}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu)}$$

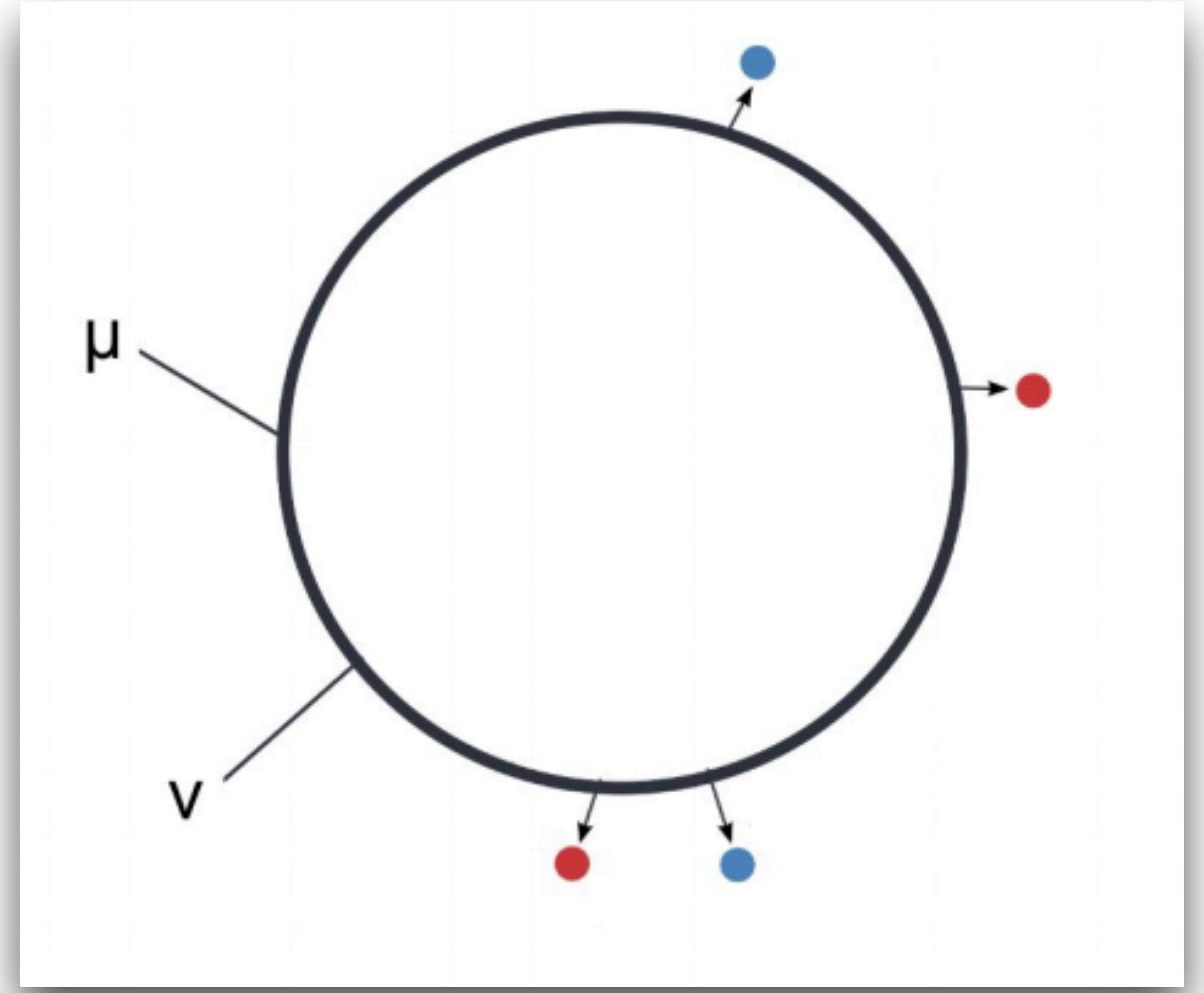
Example: Impact of cross-section measurement.

Effect on CP sensitivity

- Cross-sections are directly used to reconstruct the neutrino energy
  - **Final state interactions** (FSI) and **nuclear effects** within the nuclei can make different interaction channels with the same topology

What can happen



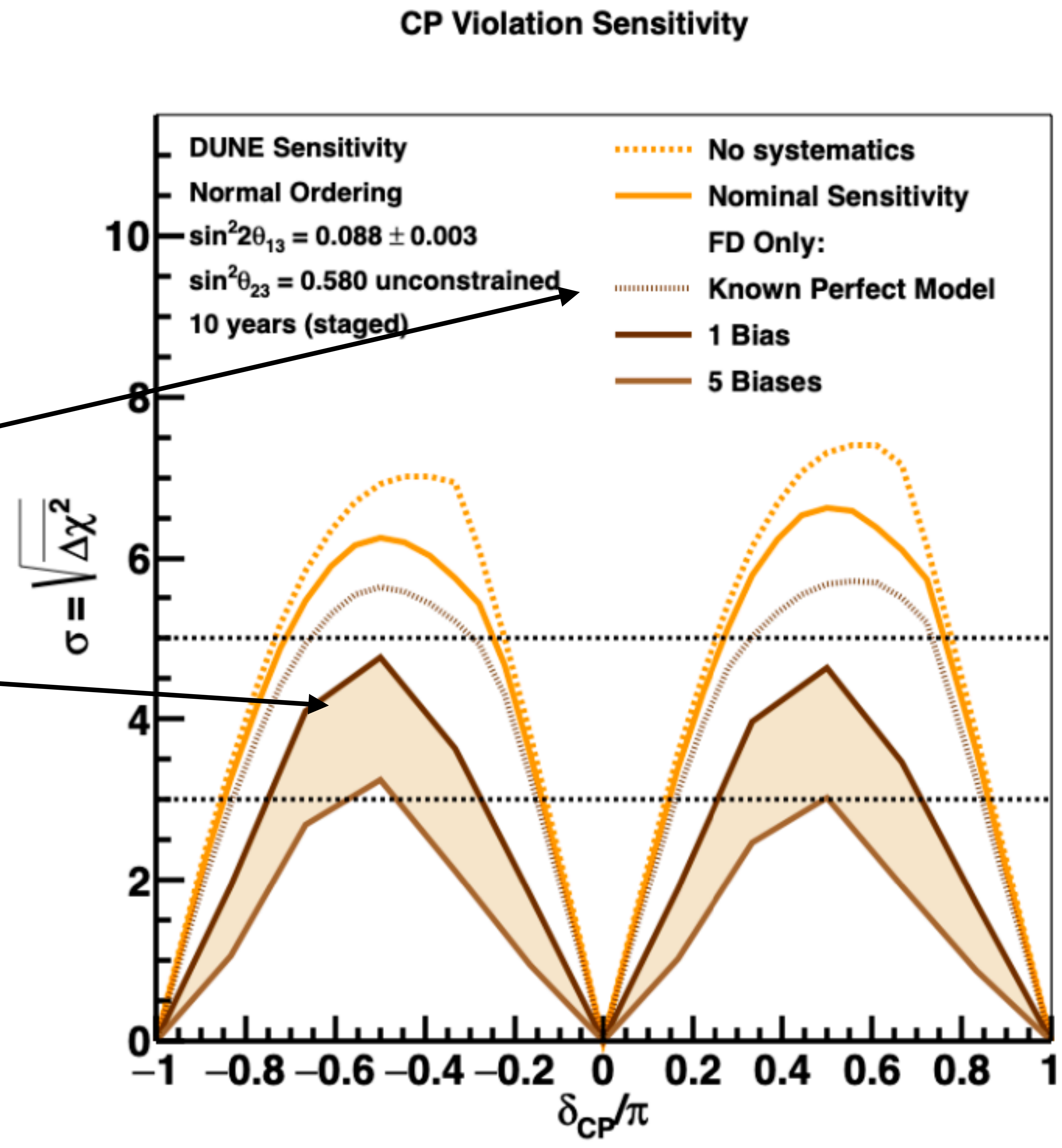


What you observe

Example: Impact of cross-section measurement.

Effect on CP sensitivity

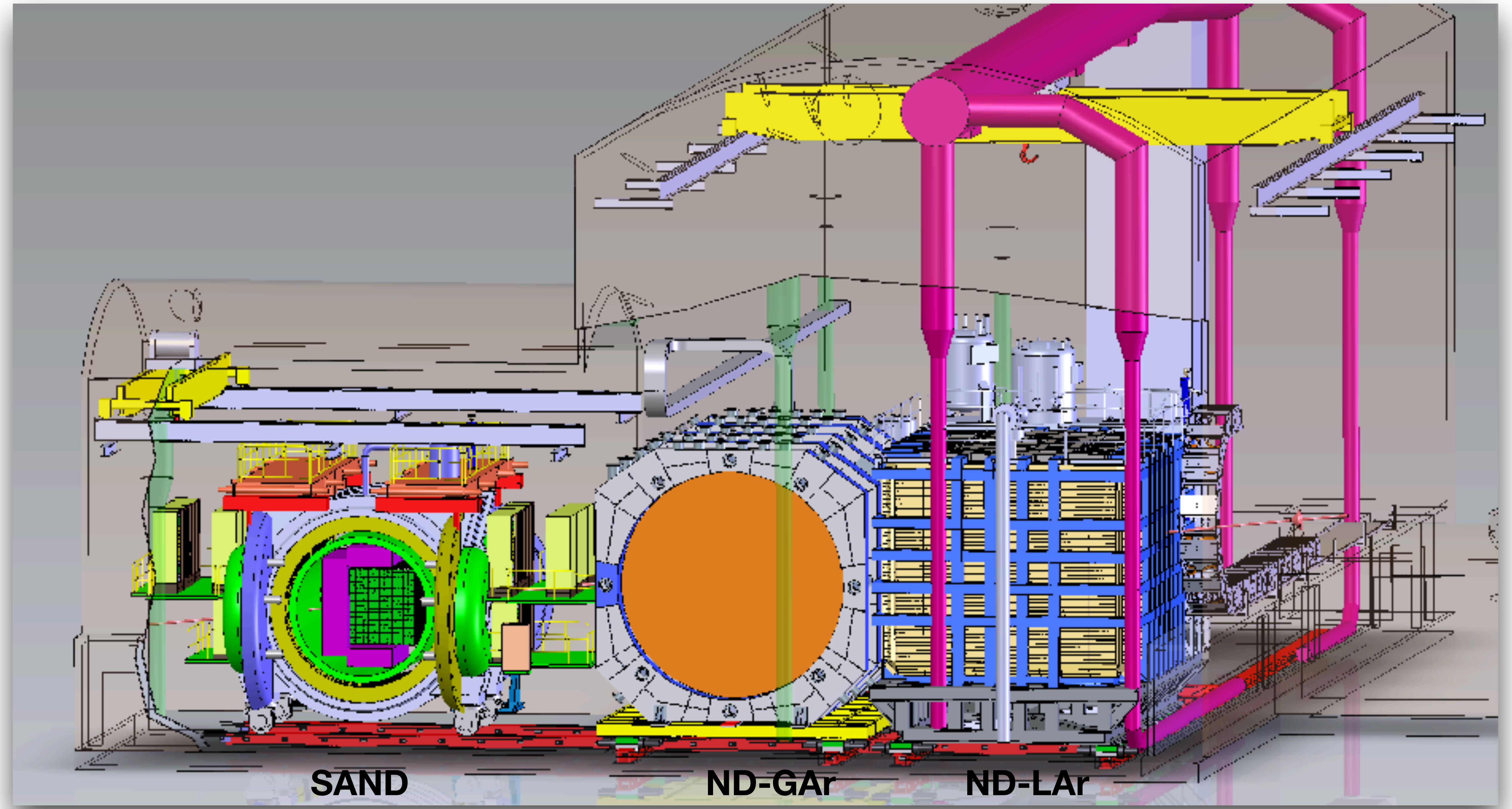
- Cross-sections are directly used to reconstruct the neutrino energy
    - **Final state interactions** (FSI) and **nuclear effects** within the nuclei can make different interaction channels with the same topology
- Cross-sections systematics are often the **dominant** contribution in the error on neutrino oscillations
    - Sensitive to the **generator model** (GENIE)
    - **Different** but plausible **model**
- Strong possibility of other viable models ➠ **more model bias** will need to be included **reducing the sensitivity** further

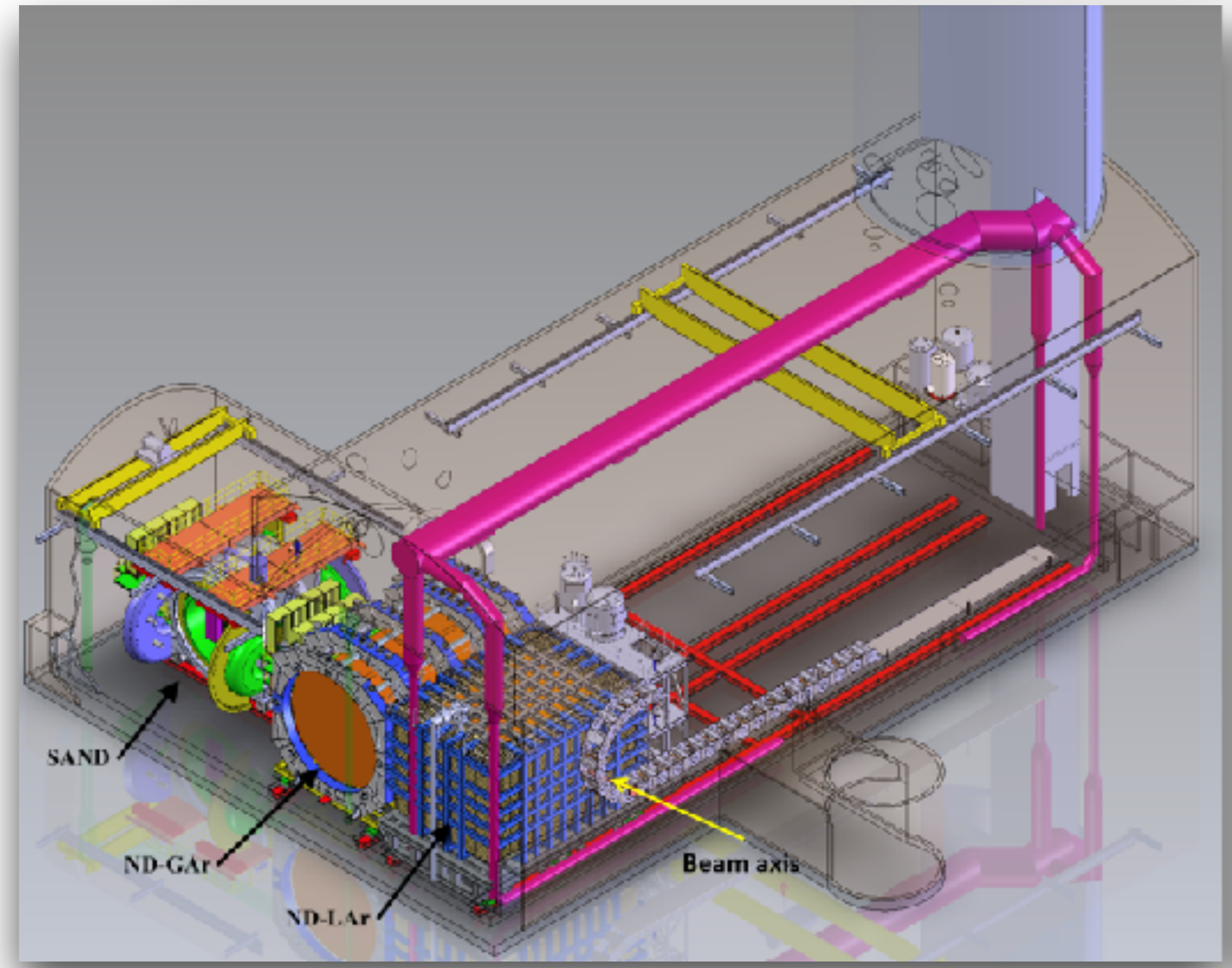


The DUNE ND Complex.

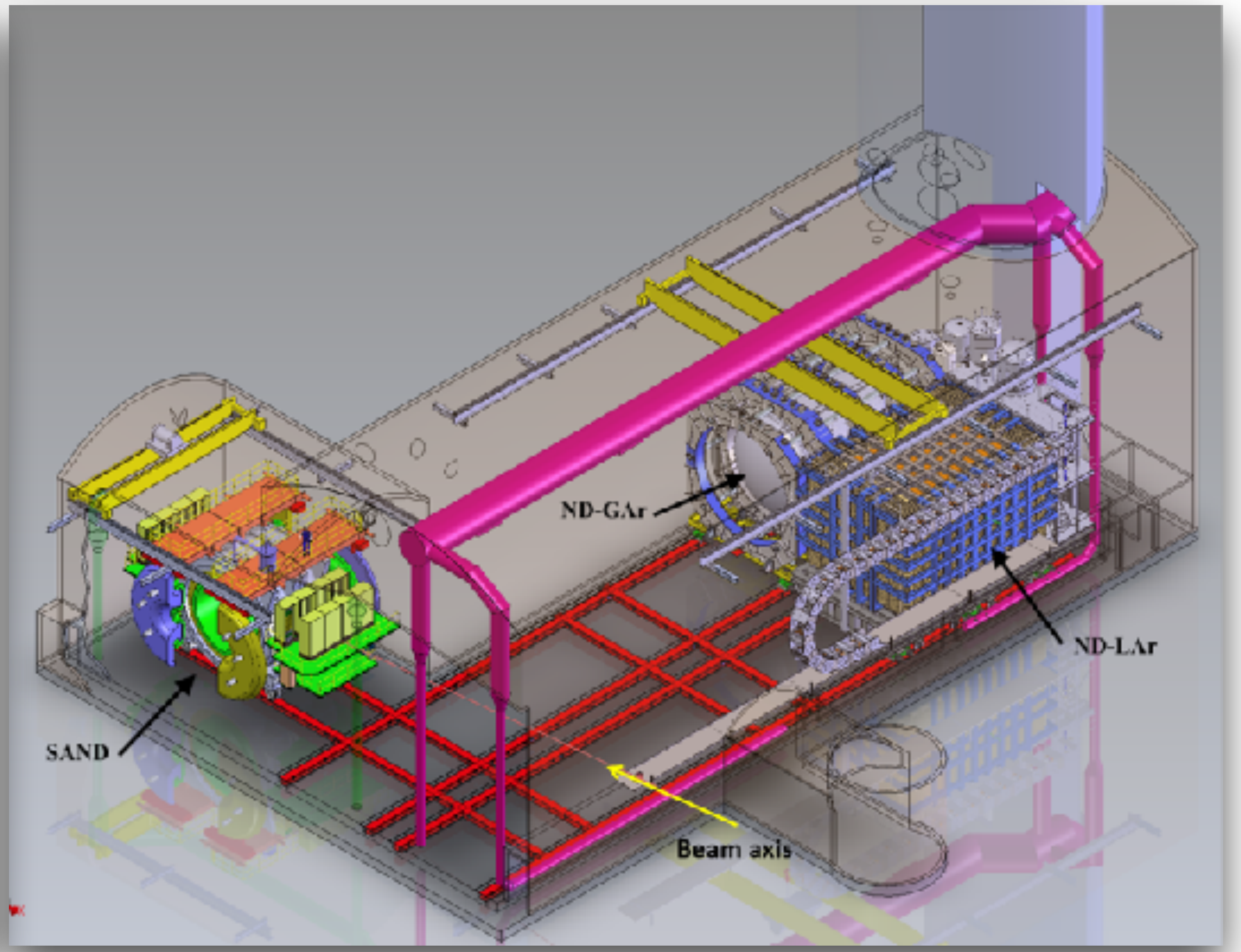
A crucial part of DUNE

- **ND-LAr**
  - Highly modular Liquid Argon Time Projection Chamber with pixelated readout (50 t), similar to FD, primary target
- **ND-GAr**
  - High-pressure gas Argon TPC (1 t) surrounded by a high performance ECAL, a magnet and a muon system, muon spectrometer and constrain nuclear modelling on Argon
- **SAND**
  - Highly granular plastic target (8 t) surrounded by trackers and ECAL inside a magnet, on-axis beam spectrum monitor
- **ND-LAr** and **ND-GAr** can move off-axis ➠ **DUNE-Prism** concept





On-axis



DUNE-Prism

ND Requirements.

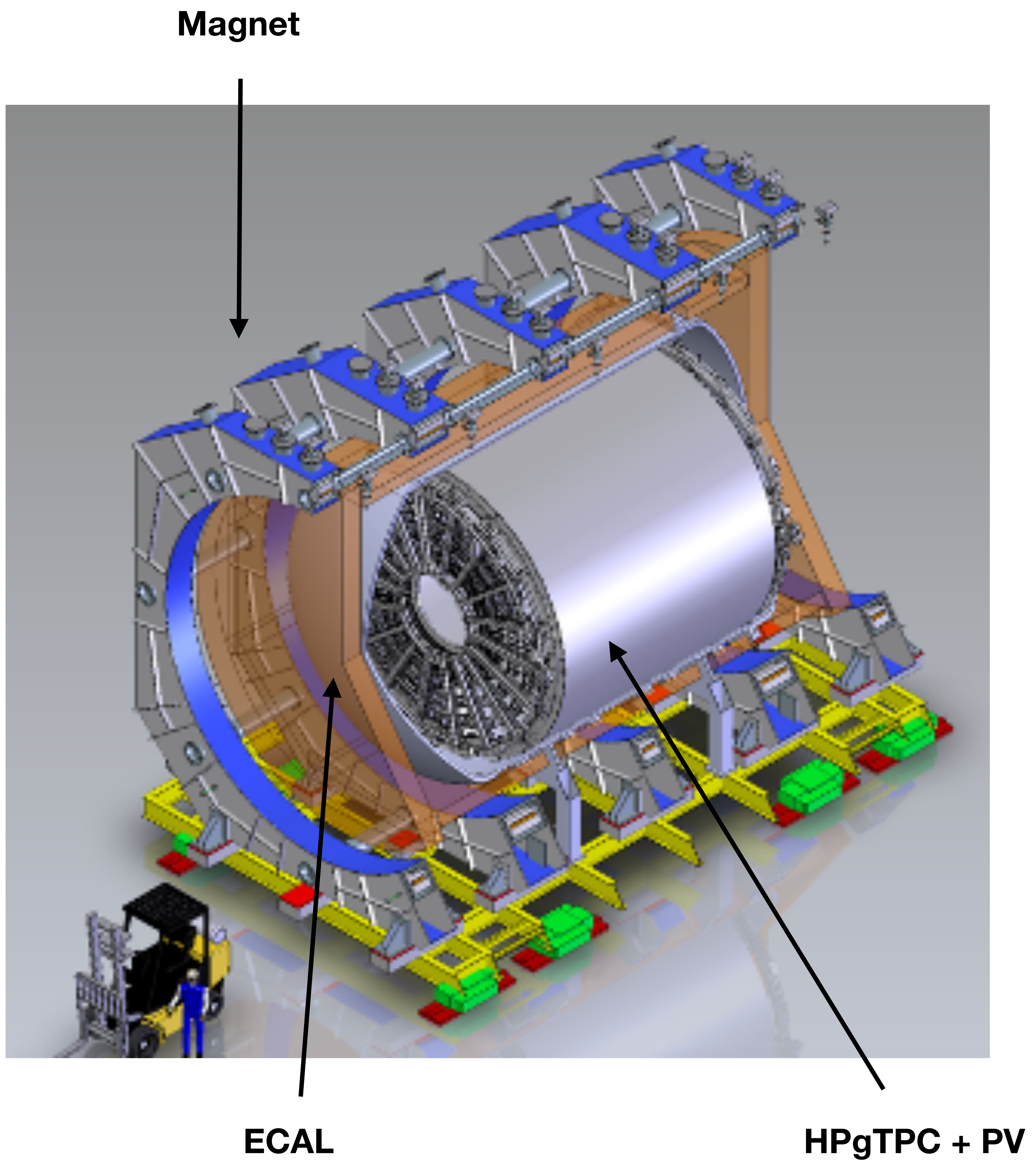
The goals of the ND

- Predict neutrino flux at the FD
    - ND must be able to **predict observable** at the FD
- Transfer measurements to the FD
    - ND measurements must be **transferable** to the FD to minimise systematics
- Constrain the neutrino cross-section model
    - **Reduces systematics** of the FD response to neutrino energy/flavor
- Measure the neutrino flux
    - Constrain the **flux modelling**
- Obtain data with different neutrino fluxes (**DUNE-Prism**)
    - ND must be able to verify the **robustness of model** predictions with different fluxes
- Monitor the neutrino beam
    - Detect **variations** in the beam flux
- Operate in a **high rate** environment

The ND-GAr detector.

The CDR baseline

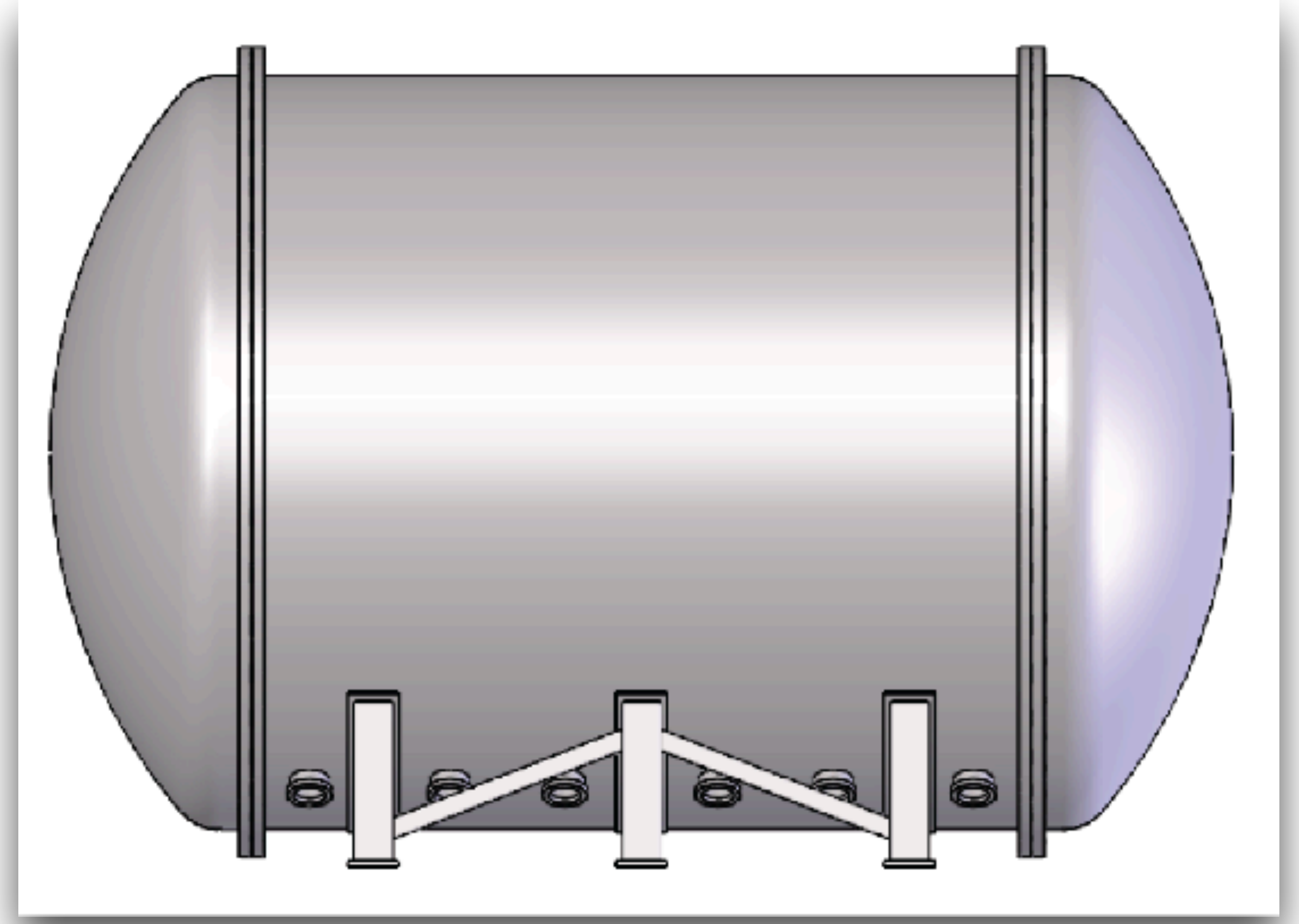
- **1 ton fiducial mass** Gas Argon TPC at 10 bar inside a pressure vessel
- High-performance **ECAL** using copper as absorber and scintillator tiles/strips with SiPM readout
- A super-conducting **magnet** and a complementary **muon system**
- Acts as a **spectrometer** for muons exiting the ND-LAr
- **Lower** target energy **threshold** (~MeV compared to ~30 MeV)
    - improve understanding of nuclear models to reduce systematics
- Key for some **channels** that are **hard to distinguish** in the ND/FD-LAr, such as multi-pi final states

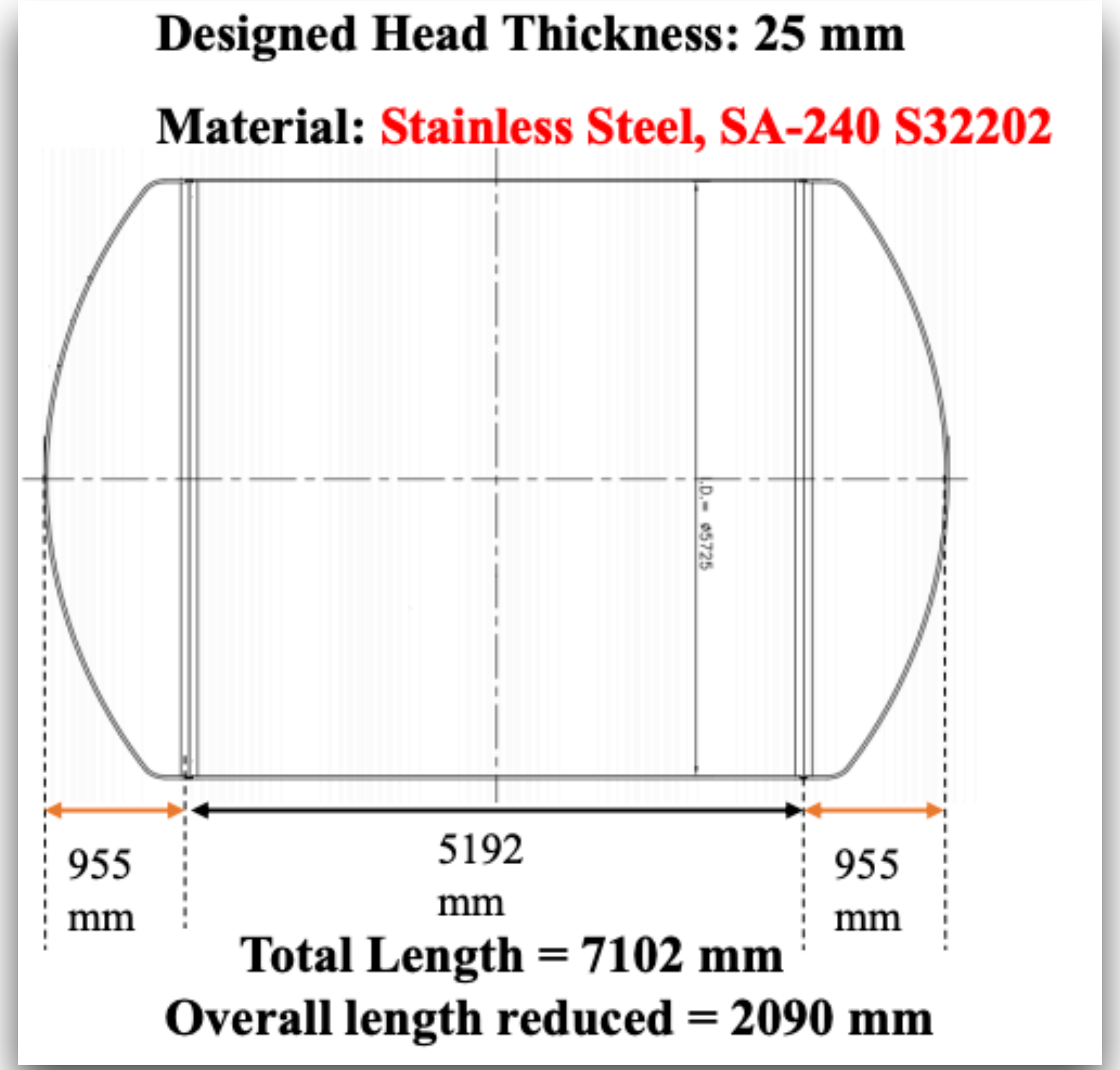


The ND-GAr detector.

Fast evolution of the concept

- Engineering design of the pressure vessel is evolving fast
  - Understand **mechanical constrains** due to pressure, welding etc…
- Barrel thickness designed to be **~0.5 X_0** (~4.4 cm Al)
  - Due to mechanical constrains ➠ pressure vessel head need to be ~1 X_0 (if using Al)
  - Stainless steel being investigated ➠ would reduce overall ND-GAr length by ~ 2m with a thickness of 25 mm (~1.4 X_0)
- This has an impact on the overall ND-GAr design especially on the **ECAL**
  - ECAL endcaps need to be **inside** the pressure vessel

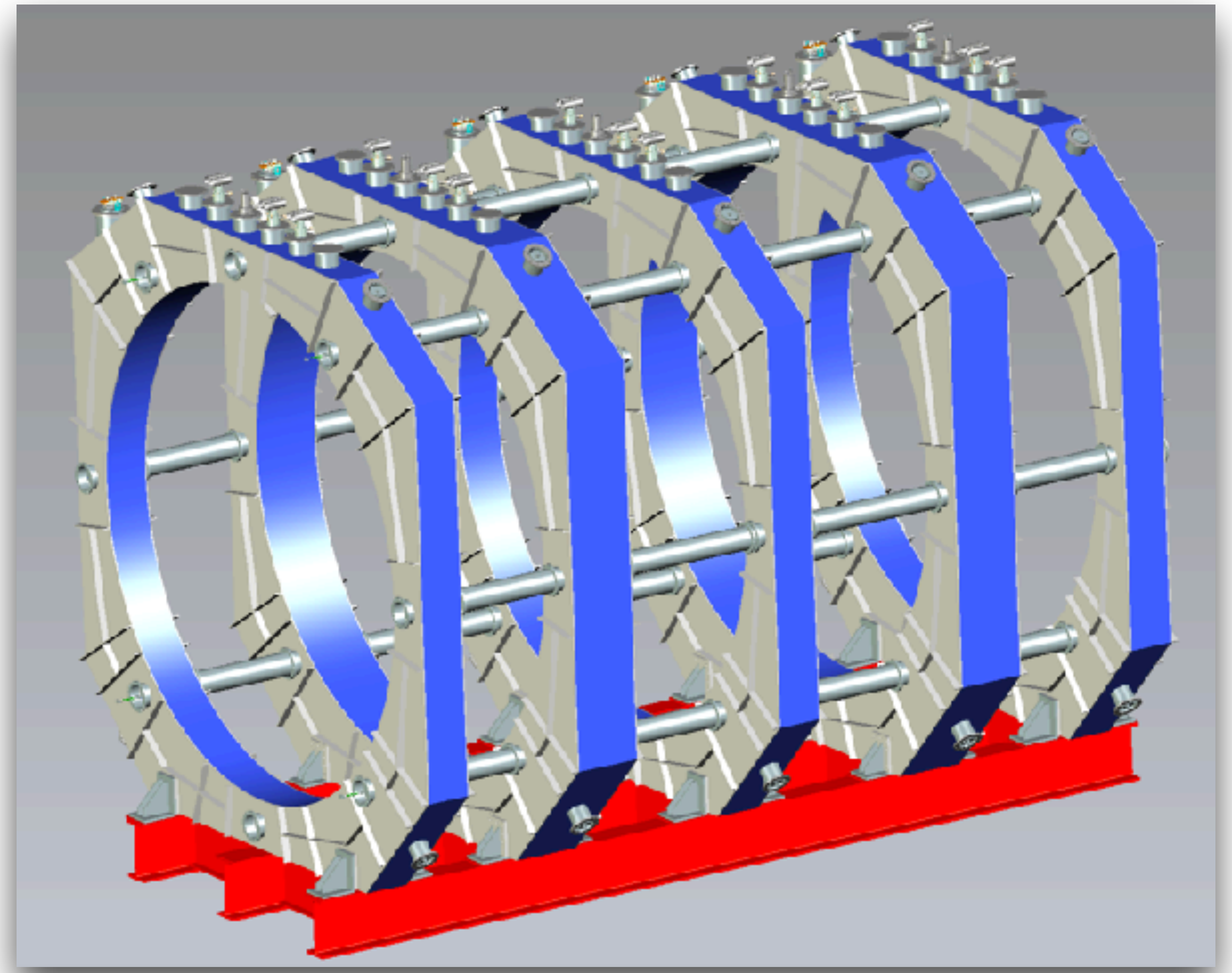


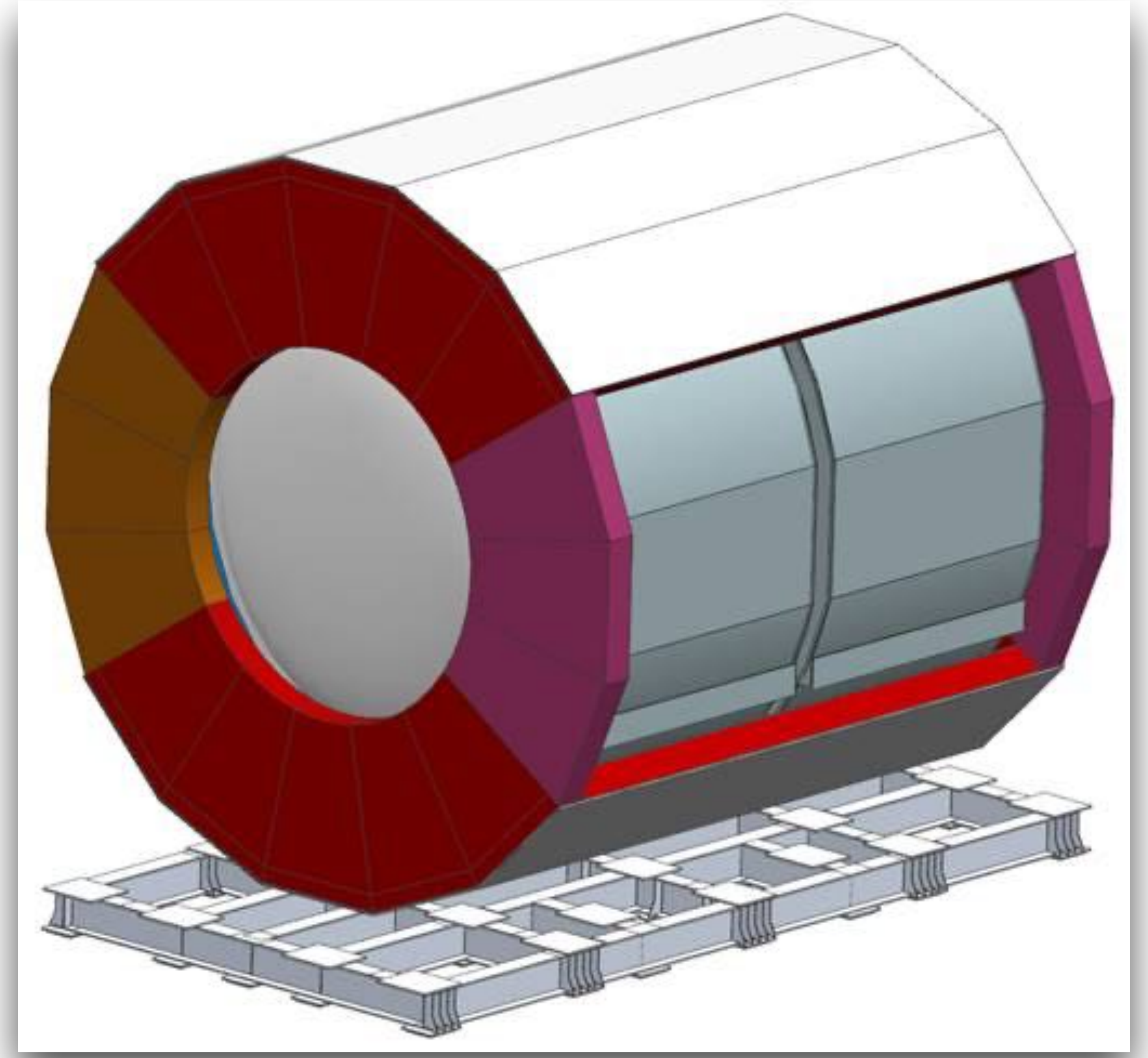


The ND-GAr detector.

Fast evolution of the concept

- Engineering design of the ND-GAr magnet has changed a lot in the past few months
  - Allowance in the overall detector radial size reduced
  - Impact of the stray B-field on SAND (forces on the SAND yoke)
  - Cost
- Original design using 3 to 5 **Helmholtz-coils**
- New design investigated using a **solenoid with a partial return yoke (SPY)**
  - Reduces **material** in front of the ND-GAr
  - Reduces **overall size** in diameter
  - Reduces **stored energy, stray field and cost**
  - Can include a **muon system** inside the yoke

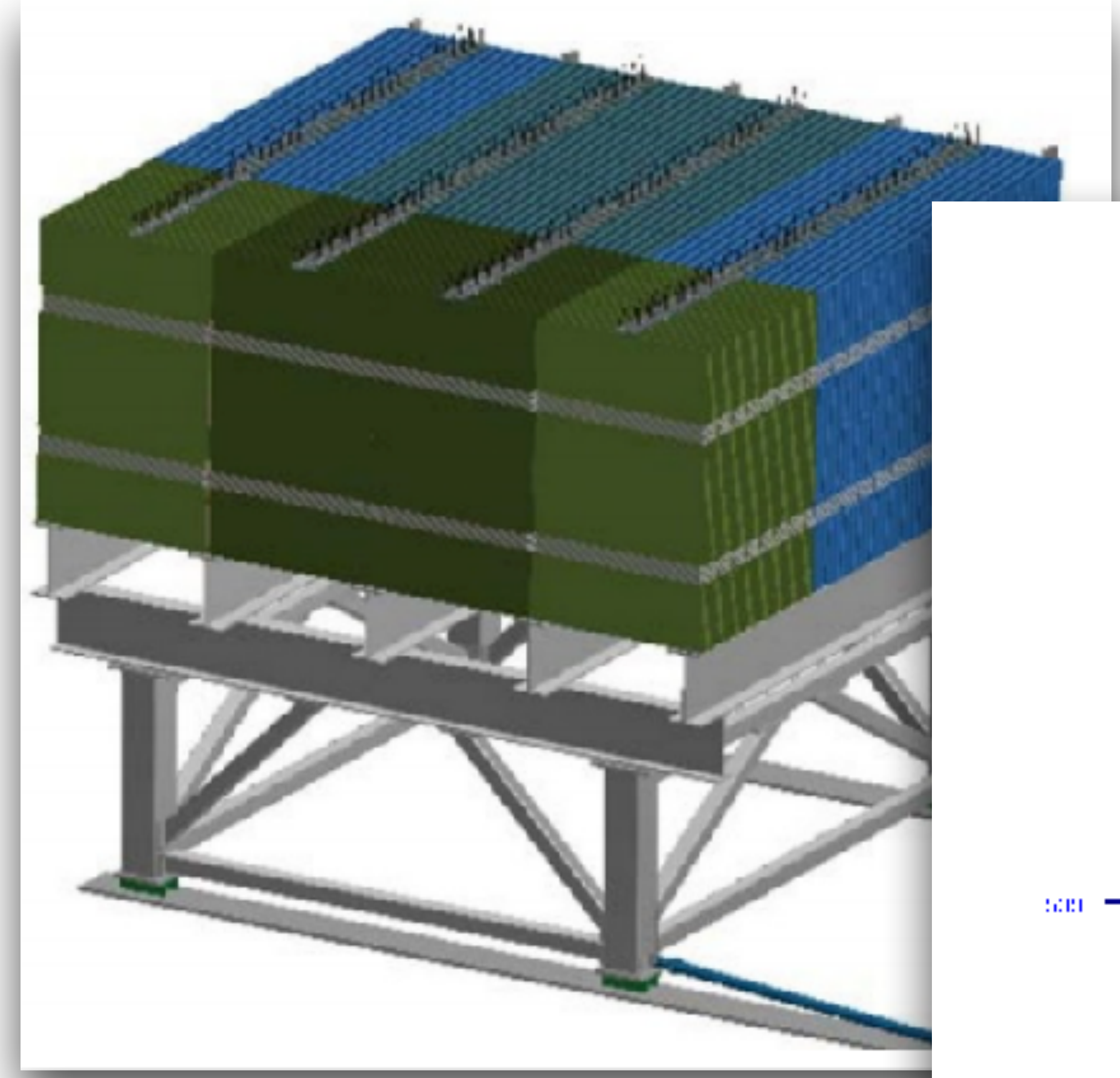


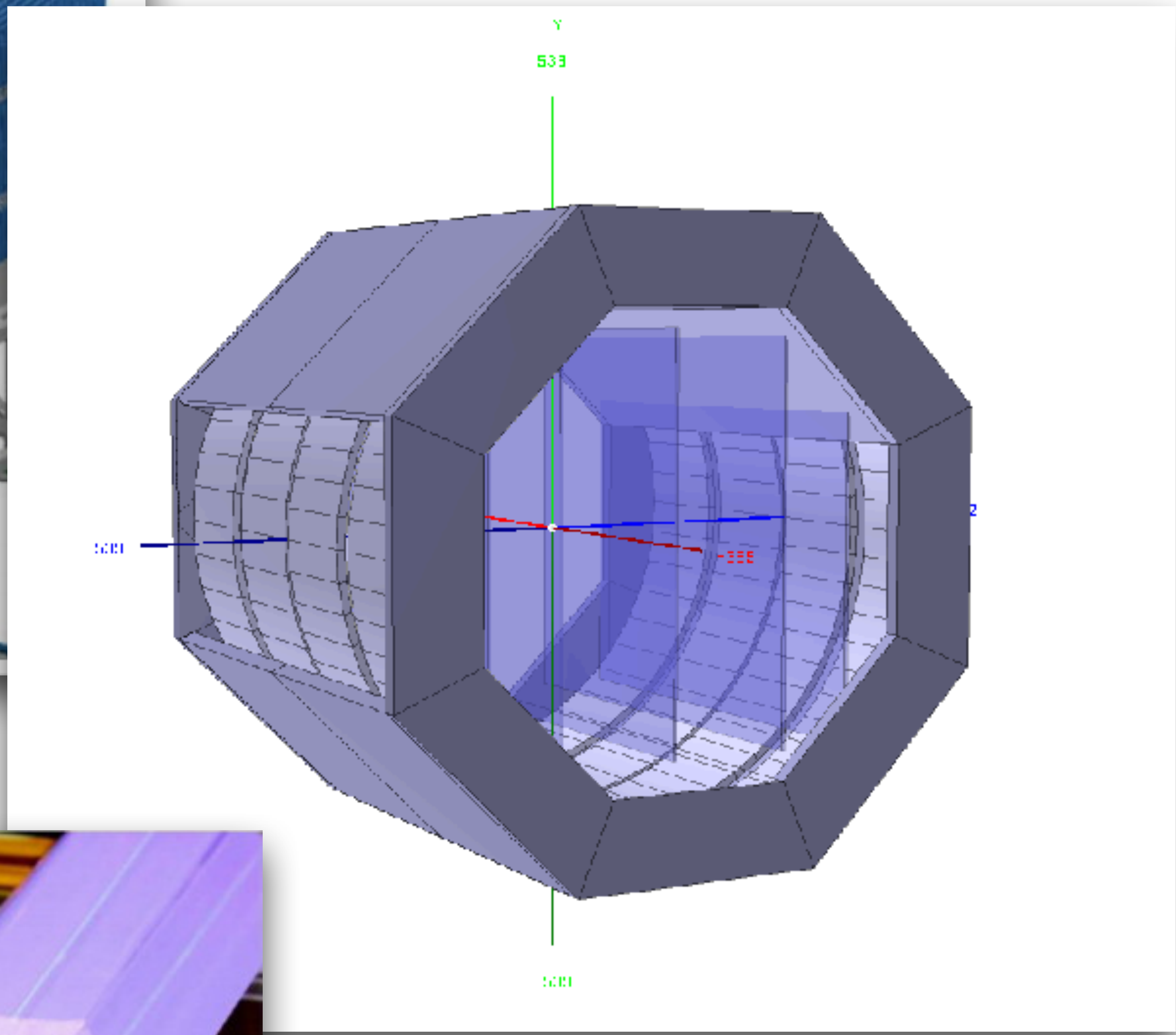


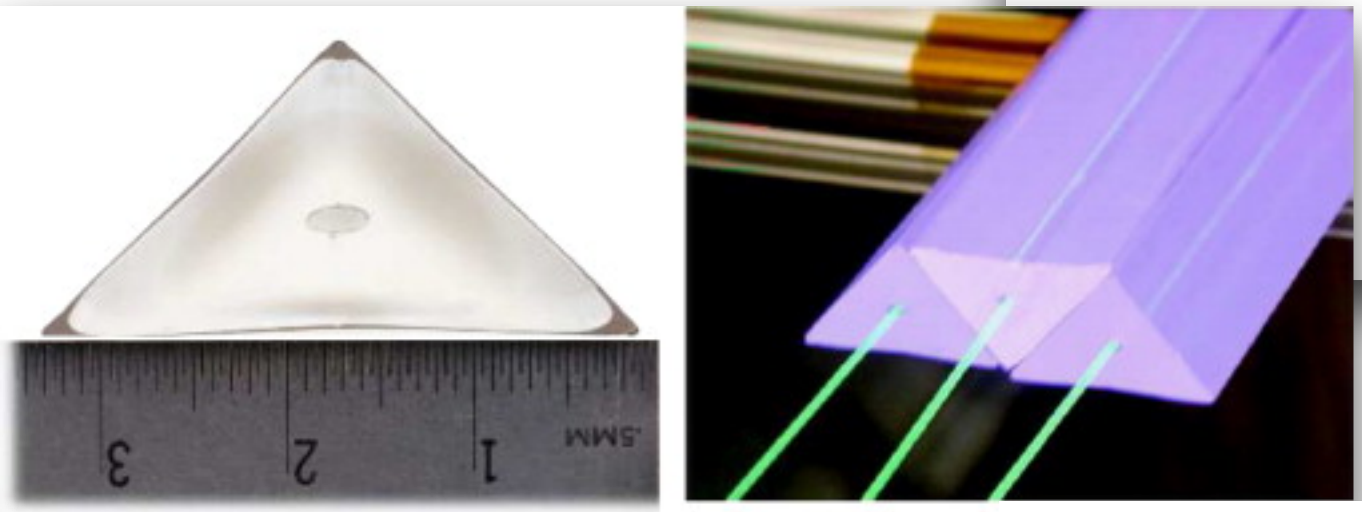
The ND-GAr detector.

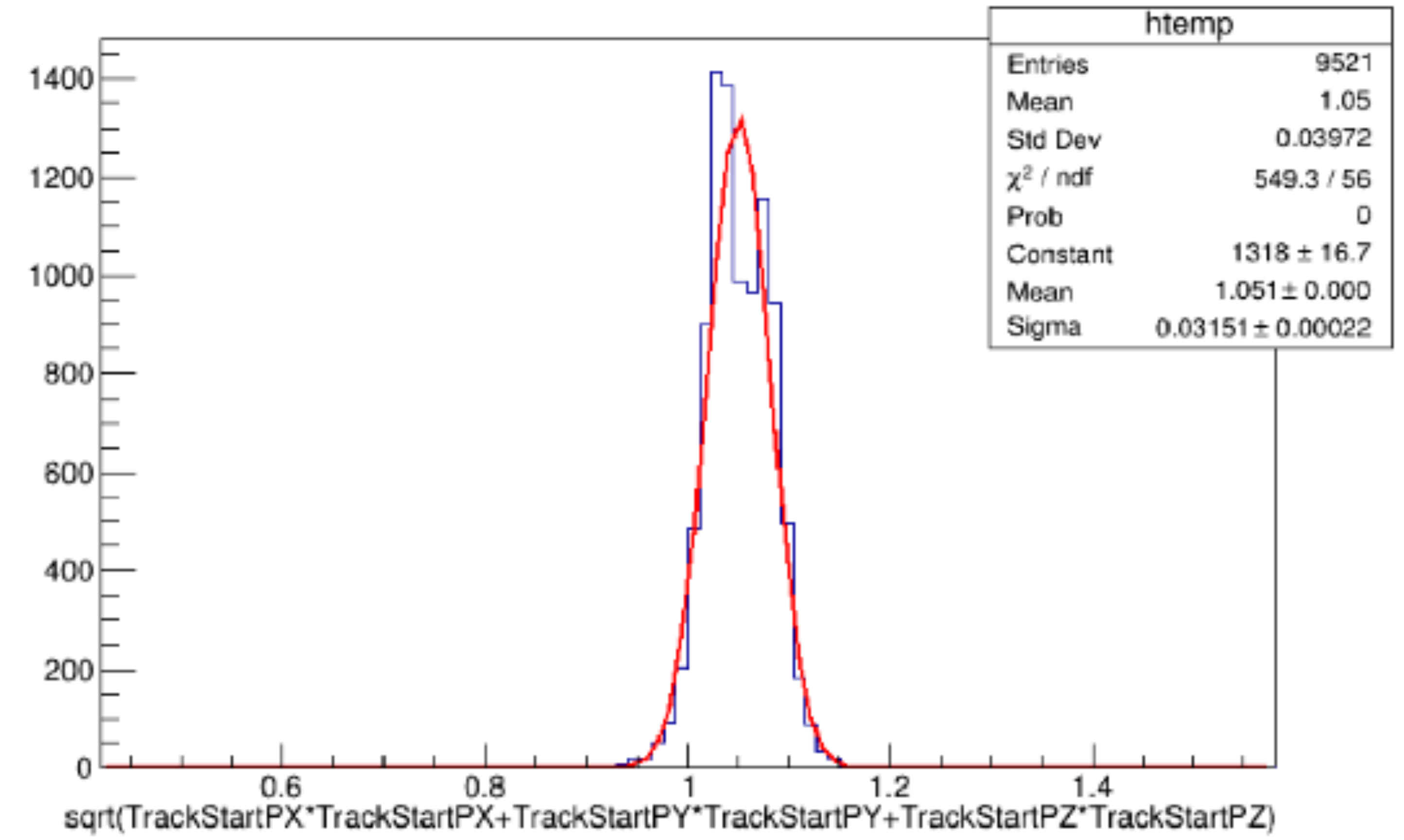
Fast evolution of the concept

- The full ND-GAr will **not** be available on day-one
- Needs to be able to measure muons exiting from the ND-LAr
- Needs to meet the DUNE **physics requirements** (3+ years running)
    - **3σ CP violation sensitivity** at $\delta = \pi/2$
    - **Mass-ordering** determination
- **Alternatives** are being investigated
    - Temporary muon spectrometer system (**TMS**) using magnetised steel and scintillator planes
    - ND-GAr with the **SPY** magnet system + 5 scintillator tracker planes (Minerva-like)





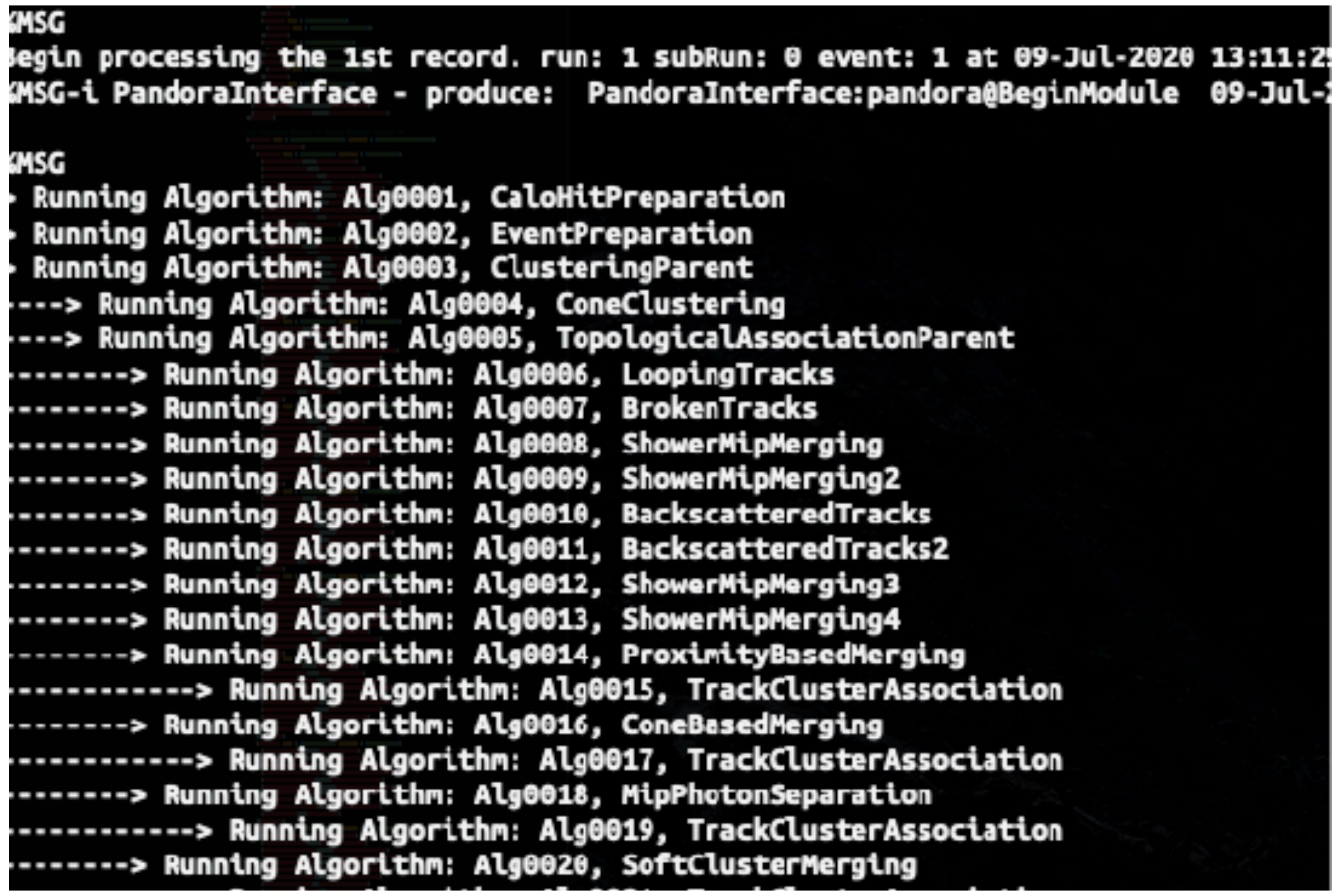


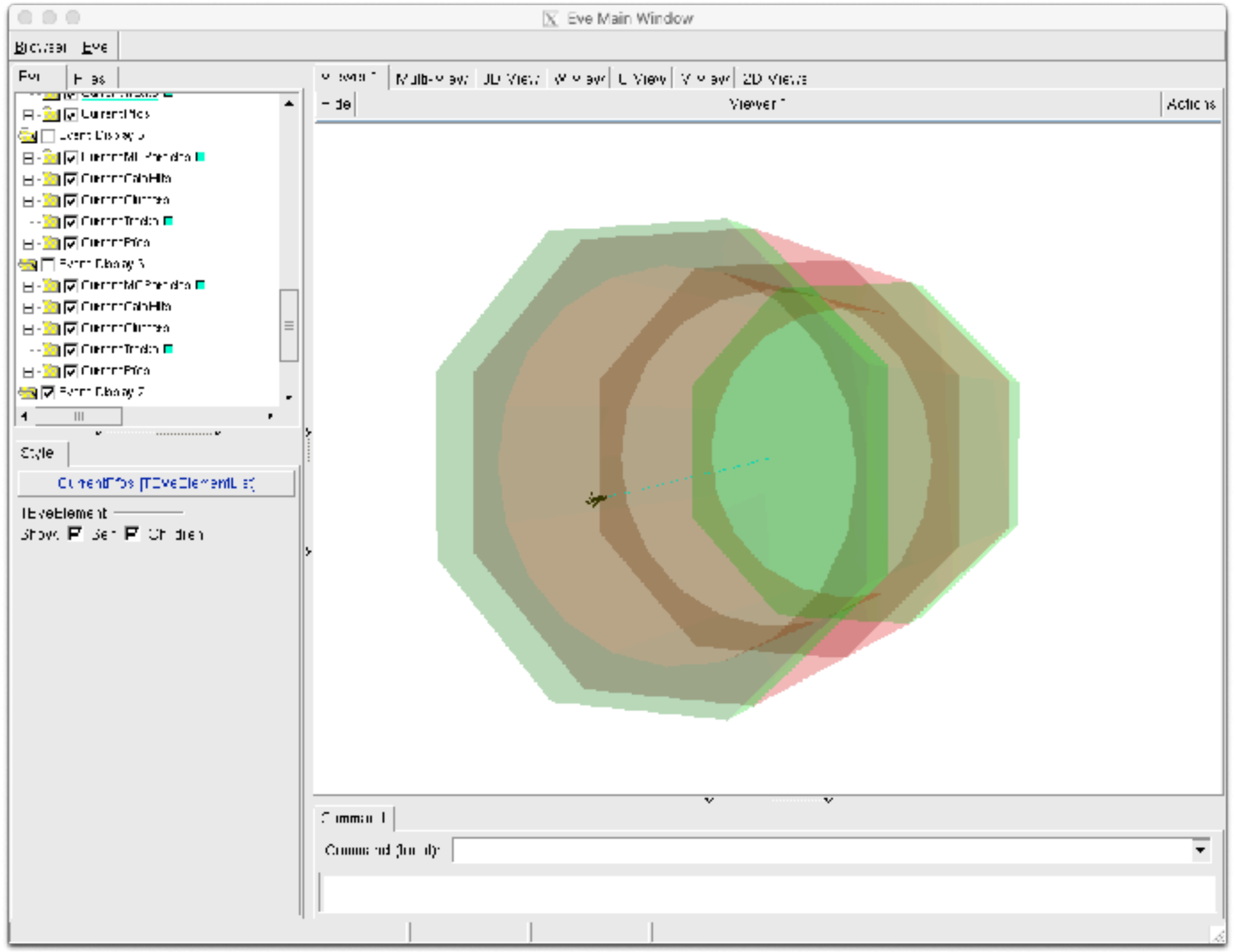


The ND-GAr detector.

Integration of Pandora

- Software framework is evolving a lot also
- Full simulation and reconstruction chain being **harmonised** within the ND groups
  - Agreements on **generator** (GENIE) and **simulation** wrapper (edep-sim)
- **PandoraPFA** algorithms are used to reconstruct the neutrino event in the FD
  - Why not also using it for the **ND**?
- ND-LAr and ND-GAr groups are interested in implementing Pandora into their reconstruction chain
  - ND-GAr ➠ PandoraPFA is now **implemented** due to large similarities with ILD (using for now LCContent algorithms)
  - Pandora group is interested in providing support into the implementation of PandoraPFA for the ND complex

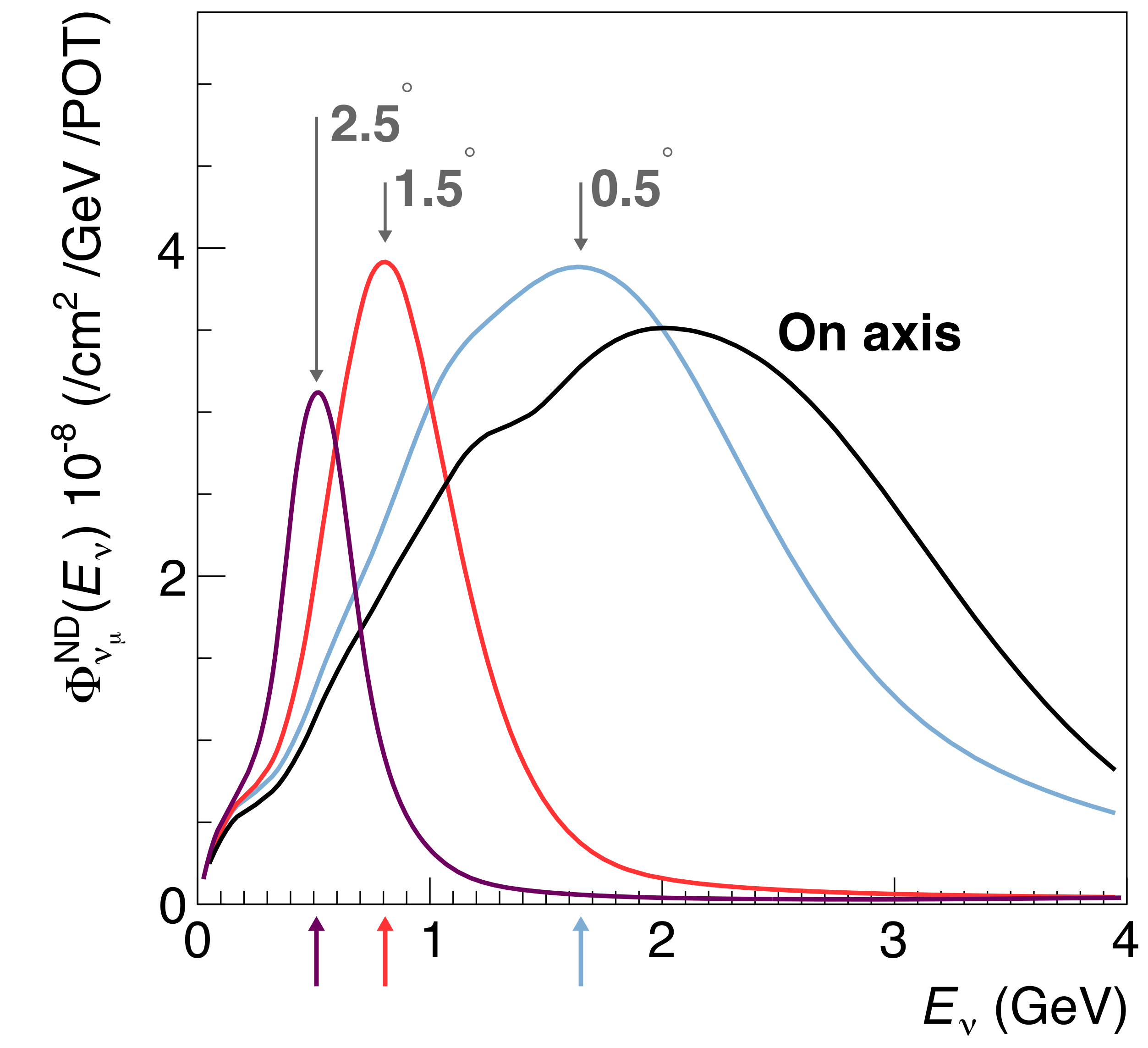


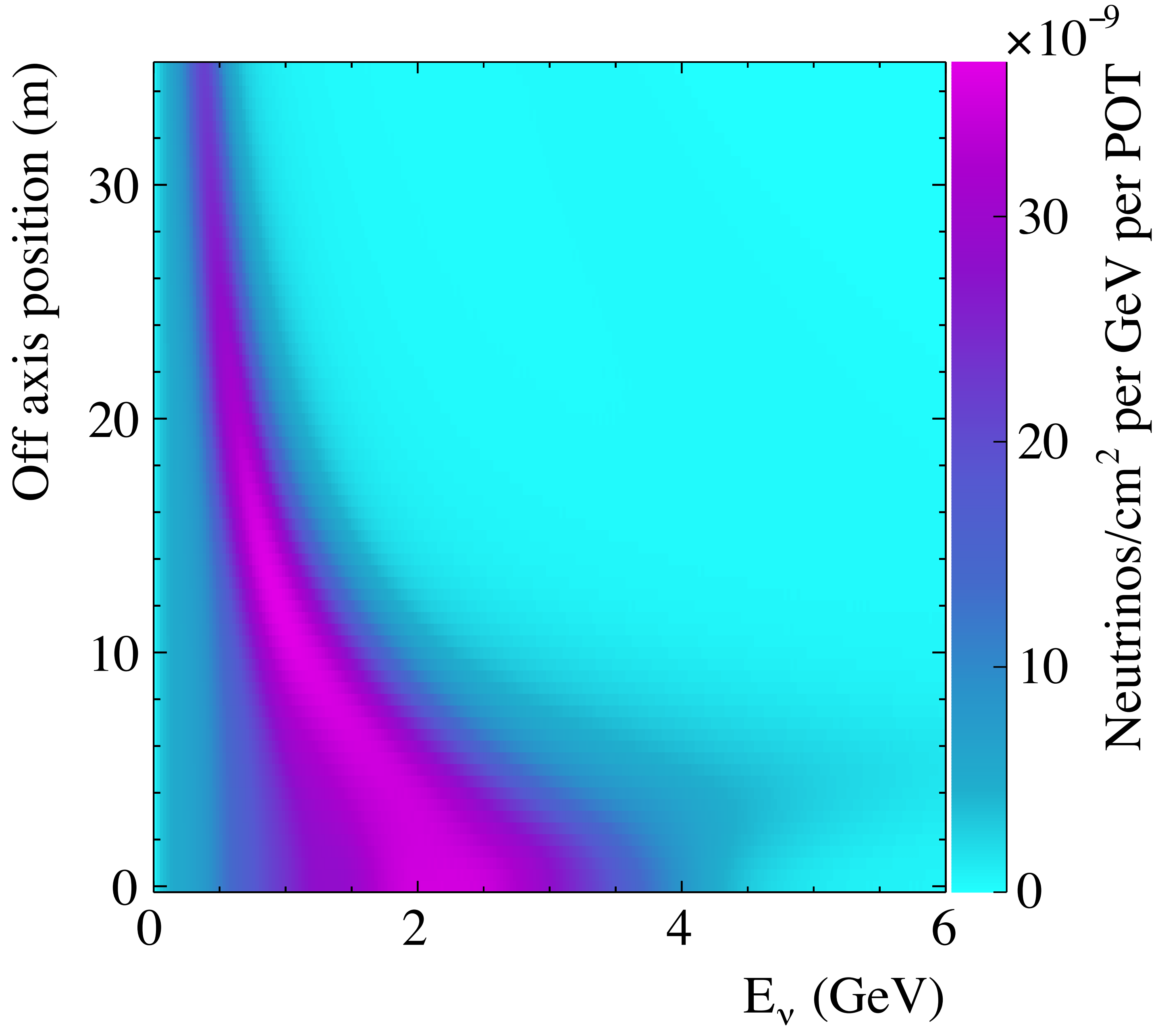


The DUNE Prism concept.

Motivation

- Neutrino energy depends on the interaction model
- Constraining neutrino interactions uncertainty is difficult due to the lack of a complete model (**unknown** biases that can be difficult to estimate)
- DUNE neutrino beam
  - Peak energy decrease as function of the angle relative to the beam ➠ generally used in **narrow-band** experiment (T2K, NOvA)
- **DUNE-Prism** concept exploits this
  - Measure various **off-axis** positions
  - Provide an **additional degree of freedom** to constrain systematics uncertainties
- Allow for **data-driven determination** of the relation E_{true} - E_{reco} (less sensitive to neutrino interaction model)

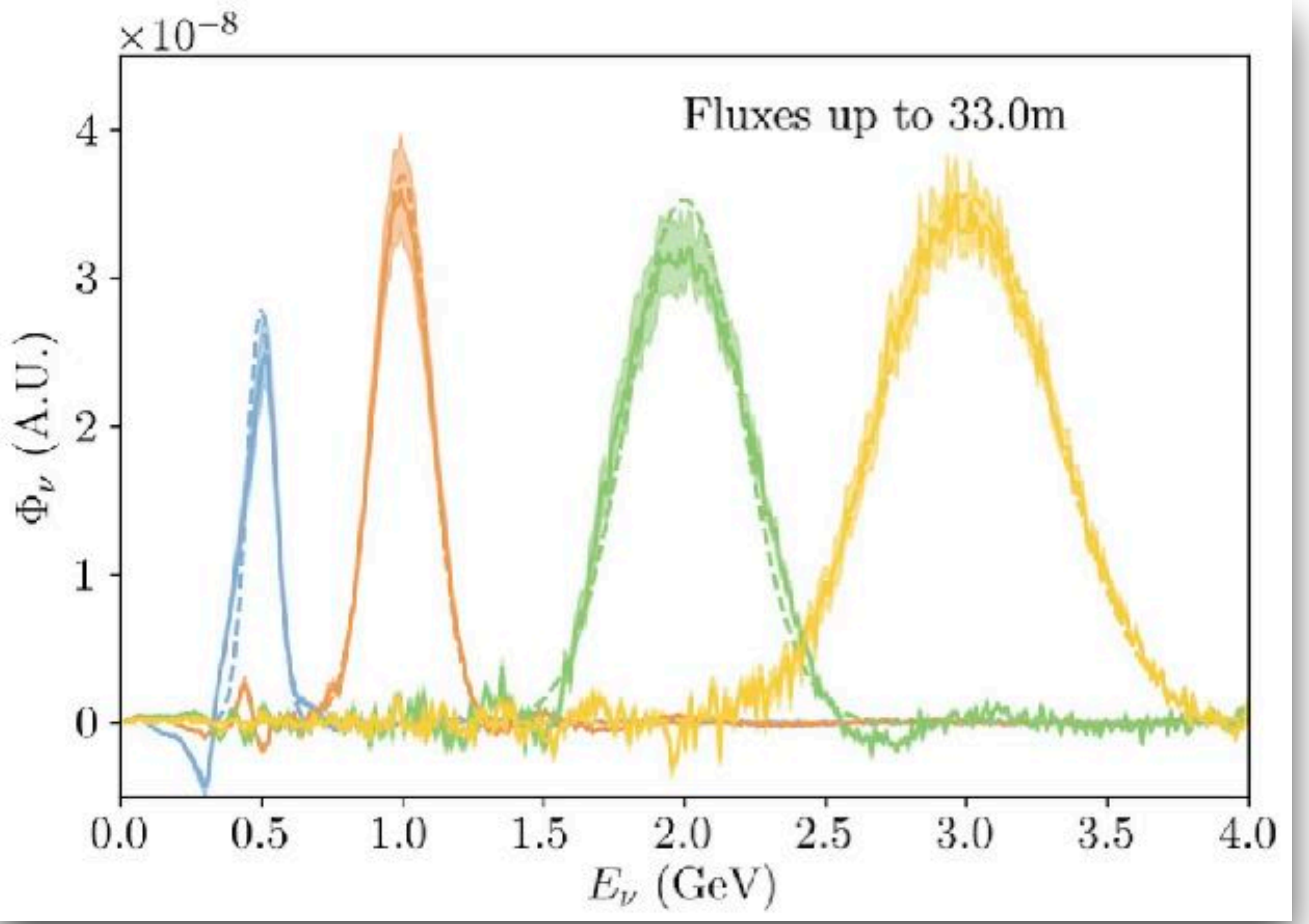


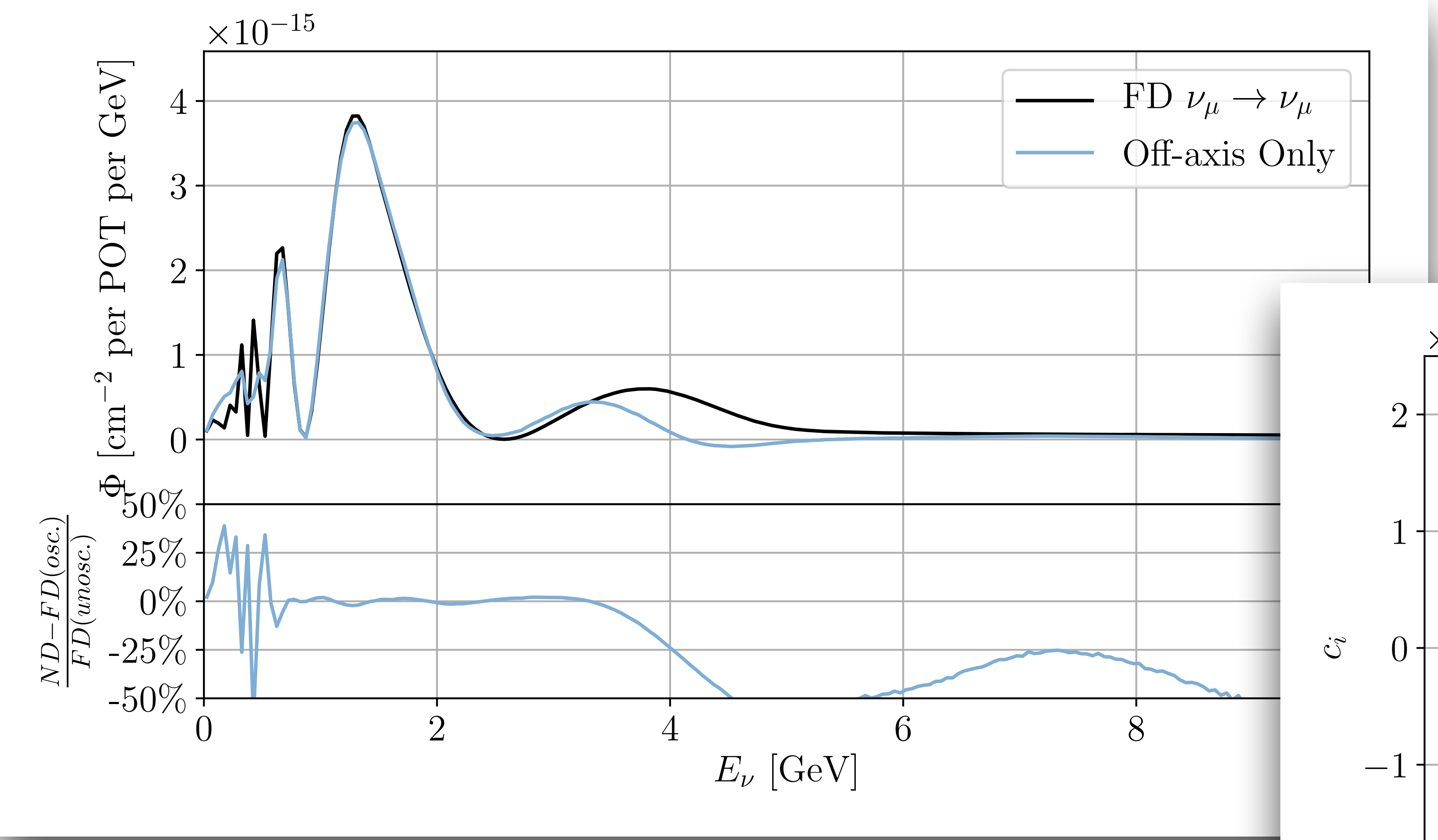


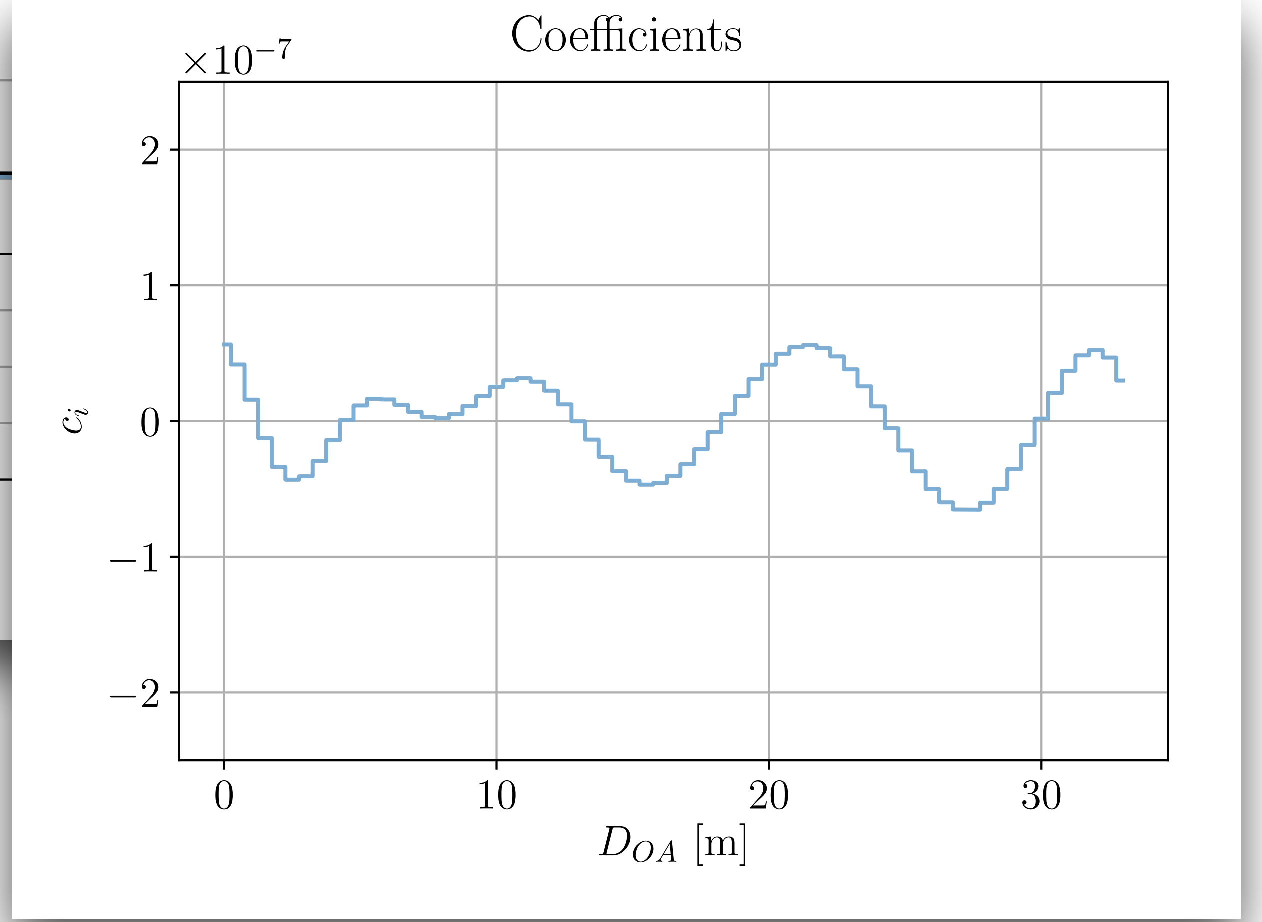
The DUNE Prism concept.

Flux matching

- Off-axis positions constitute a **set of fluxes** peaking at different energies across the DUNE neutrino energies
- Using these fluxes, one can mock-up a nearly Gaussian spectra using **linear combination** of the energy spectra
- Going even further, one can directly **construct** the oscillated energy spectrum at the FD for any oscillation parameter
  - This minimises the ND/FD flux differences and associated systematics
  - Gives a set of coefficients that can be applied to any ND observable to get the **FD prediction**
  - In the limit that the model flux is perfect, this gives a **nearly model independent** measurement







Conclusion.

A lot of progress

- The DUNE experiment is the next generation neutrino experiment that will probe the neutrino sector to great details
- The DUNE Near Detector complex is crucial to achieve DUNE's physics goals
- The ND-GAr is a necessary complementary detector to the ND-LAr
- Its conceptual design is evolving fast
- The ND group is going toward a unified software framework
- The DUNE-Prism concept is a fundamental part of the DUNE ND program, providing datasets that will enable us to understand to great details neutrino oscillations
- The DUNE ND CDR is currently under review and hopefully will be soon available publicly

Backup Slides.