The DUNE Near Detector

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on behalf of the DUNE collaboration

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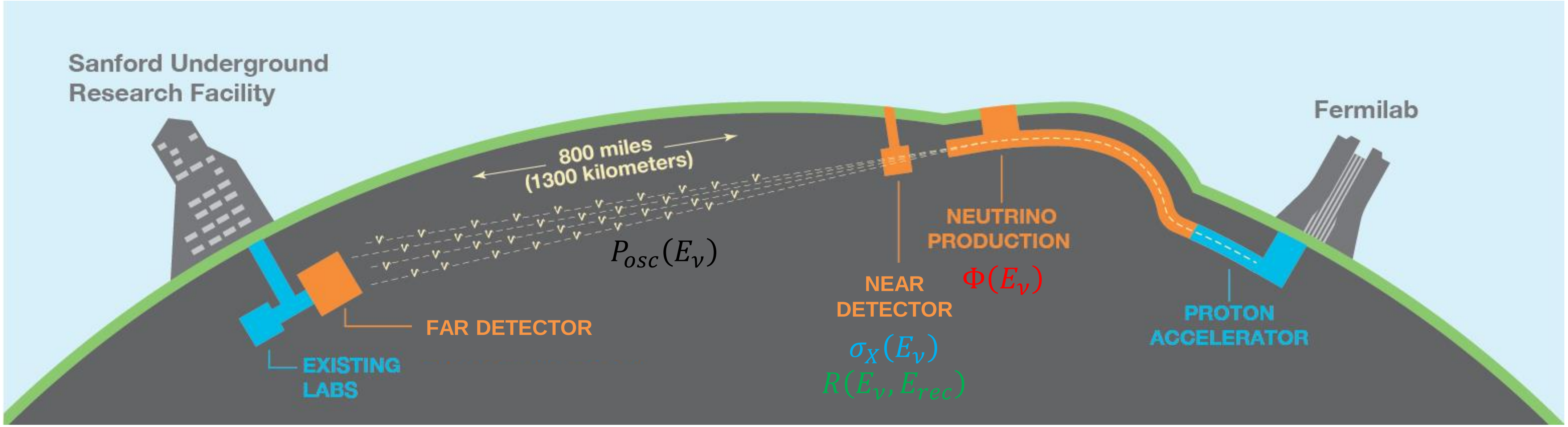
DUNE: new generation long baseline experiment

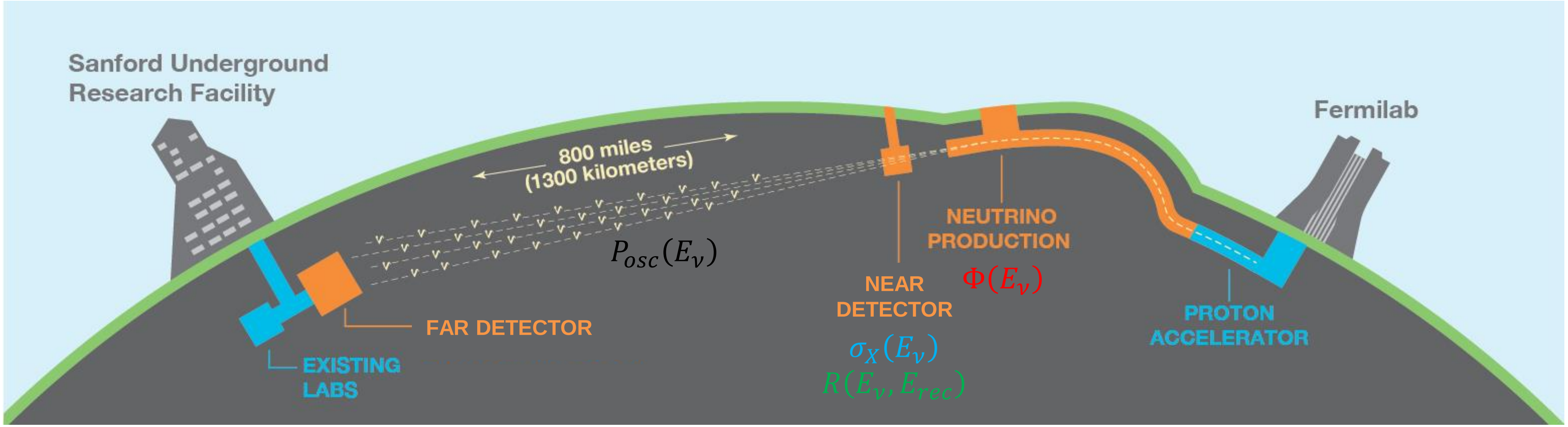


- DUNE long baseline neutrino experiment: main goal measure neutrino oscillation parameters ($\delta_{CP}, \theta_{13}, \theta_{23}, \Delta m^2_{32}$, etc.)
  1. Measure flavor-tagged neutrino spectra at the Far Detector
  2. Make prediction for both signal and background at the FD as function of oscillation parameters and compare

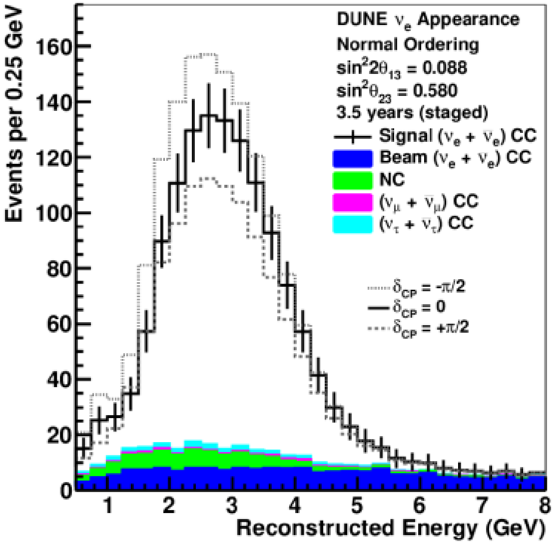
- To make predictions at Far Detector one must know:
  - Neutrino flux at production $\Phi(E_\nu)$
  - Interaction cross sections $\sigma_X(E_\nu)$
  - Detector Response $R(E_\nu, E_{rec})$

All factors are essential in producing the prediction and are affected by systematics that need to be constrained

The role of the Near Detector



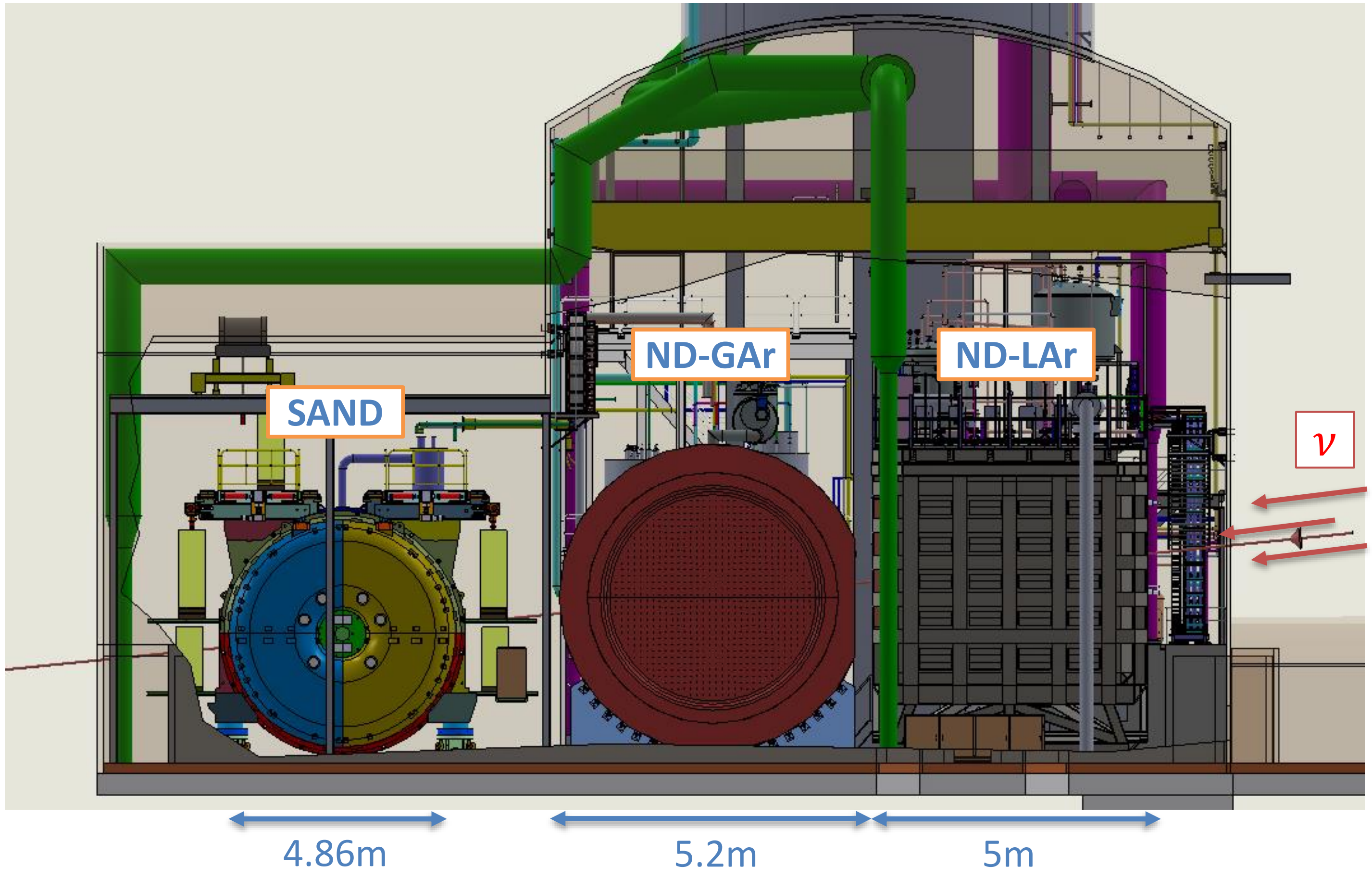
https://arxiv.org/abs/2002.03005



- To reach desired precision in the prediction at FD, the ND must address each element:
  - Measure initial flux of neutrinos from beam and predict the one at FD (different energy fluxes needed)
  - Improve neutrino interactions modeling (Cross sections/final states)
  - Model detector response (Neutrino energy dependence)
- Note: The ND will have to perform in high-rate environment, which will provide high statistics allowing to cover full phase space

DUNE ND: Main components

DUNE-ND Preliminary
https://arxiv.org/abs/2103.13910



- Three main components:
  - ND-LAr: LArTPC similar to FD
  - ND-GAr: Gas Argon TPC detector
    - TMS to replace ND-GAr at day one (see back-up for more detail)
  - SAND: on-axis magnetized beam monitor
- ND-LAr and ND-GAr movable off-axis for the DUNE-PRISM program
- Each element specifically designed to fulfill requirements of oscillation measurement

ND-LAr motivations and limitations

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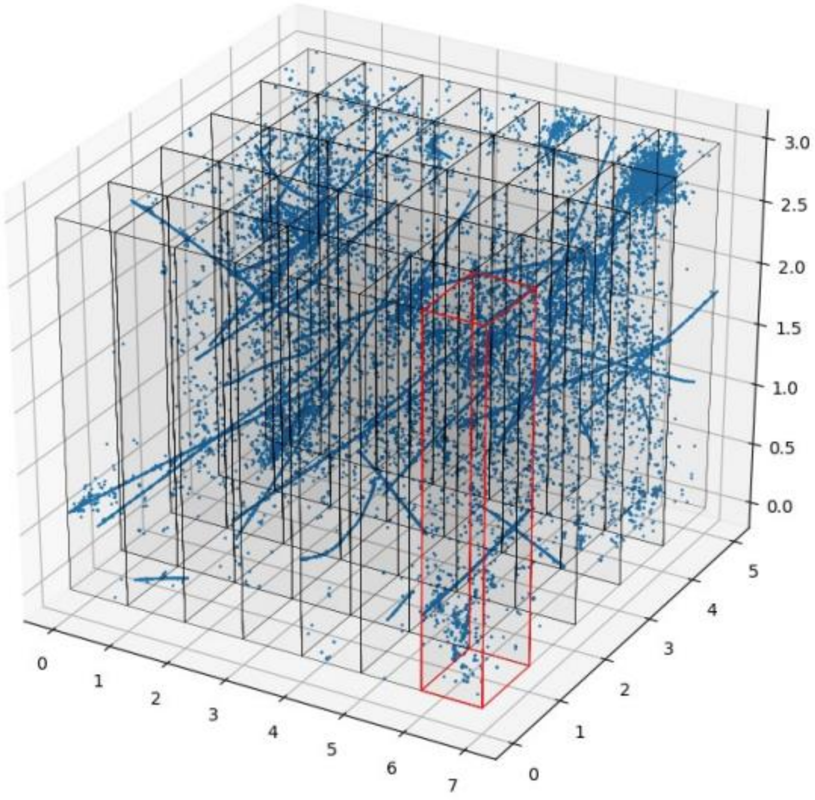
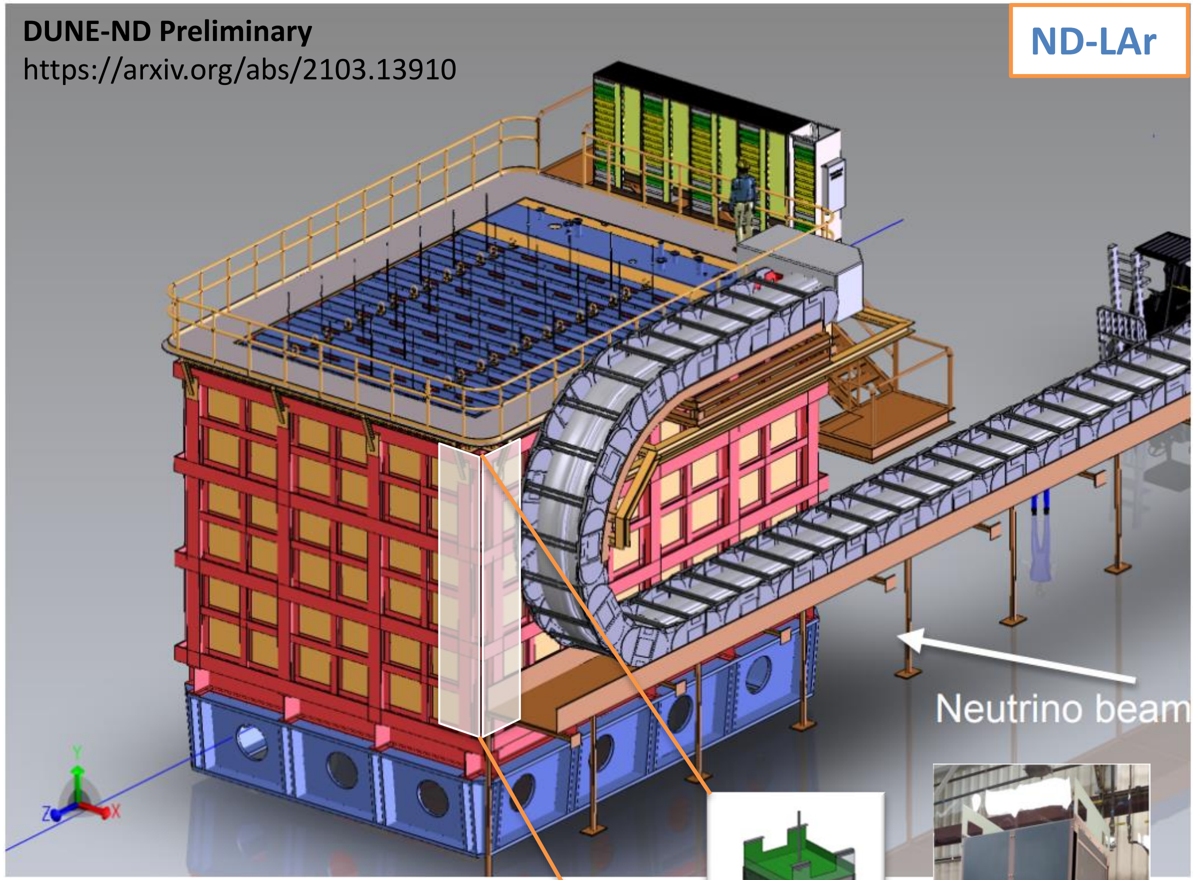
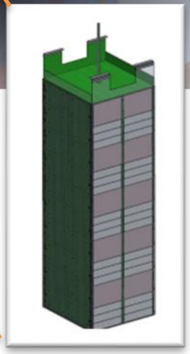


DUNE neutrino beam spill with pile-up in ND-LAr. Modular segmentation allows for optical reconstruction and vertexing

- ND-LAr designed to be as similar as possible to the Far detector:
  - ➢ Same nuclear target (Argon) → Same σ
  - ➢ Have similar detector technologies (LArTPC) → $\sim R(E_{rec}, E_{\nu})$
- Differences in design motivated by ND's specific needs :
  - ➢ Modular TPC design→ needed to deal with high rate of interactions (smaller drift, light separation, pixelation)
  - ➢ ND-LAr much smaller than FD → Cannot contain muons (external muon spectrometer needed → ND-GAr)

ND-LAr





(Top) External view on ND-LAr (Right) Zoom on one of the TPC modules (Far Right) Module prototype from ArgonCube

- Modular LArTPC based on ArgonCube technology (Concept developed in University of Bern https://cds.cern.ch/record/1993255)
- 7 × 5 optically separated LArTPC modules (~150 tons of LAr in total)
  - Charge Readout: 2 pixelated custom LArPix anode tiles per TPC (10,240 pixels, 4 mm spacing)
  - Light Readout: Fast timing information from the prompt scintillation light
  - Field Structure: low electro-static field non-uniformity < 1 % in the entirety of the active volume
- Detector movable Off-Axis

ND-GAr as a cross section laboratory

- Nuclear effects in ν -nucleus interactions (Fermi motion, FSI (Final State Interaction) breaking up nucleus, 2p2h) limit quality of cross-section models

- To correctly model these interaction, need to be able to reconstruct final state particles: liquid medium very limiting compared to gas

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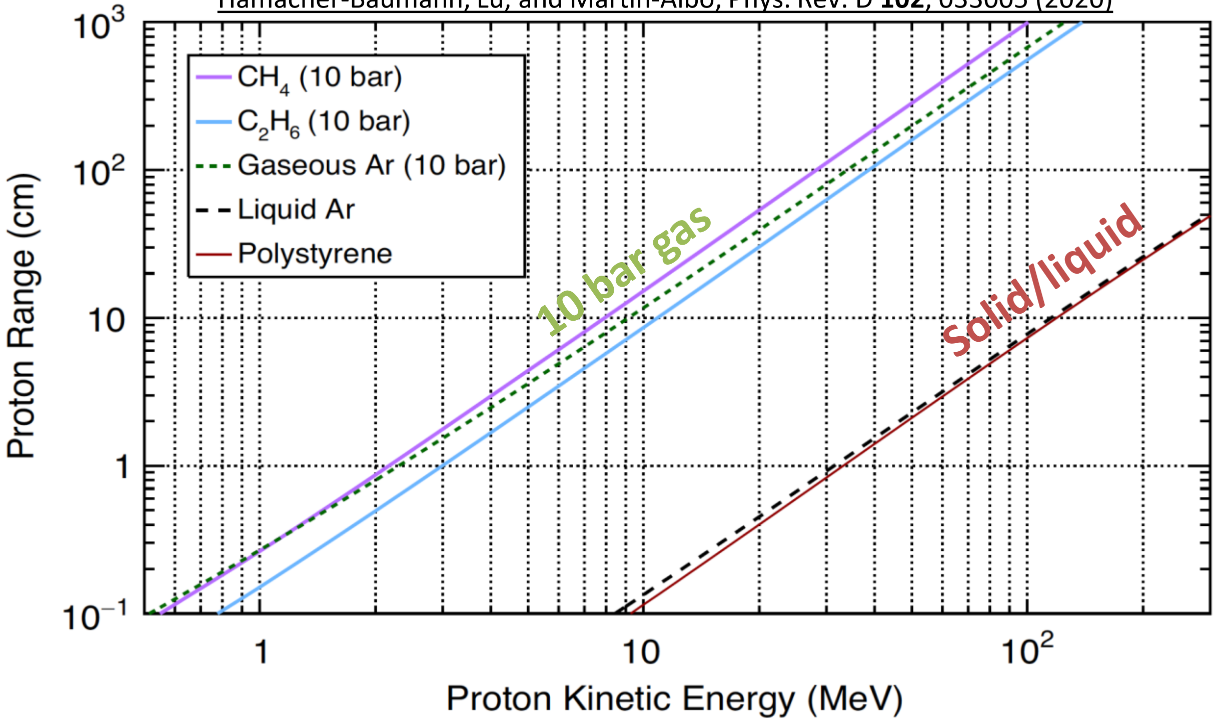
Proton Range VS Kinetic Energy

Hamacher-Baumann, Lu, and Martín-Albo, Phys. Rev. D **102**, 033005 (2020)



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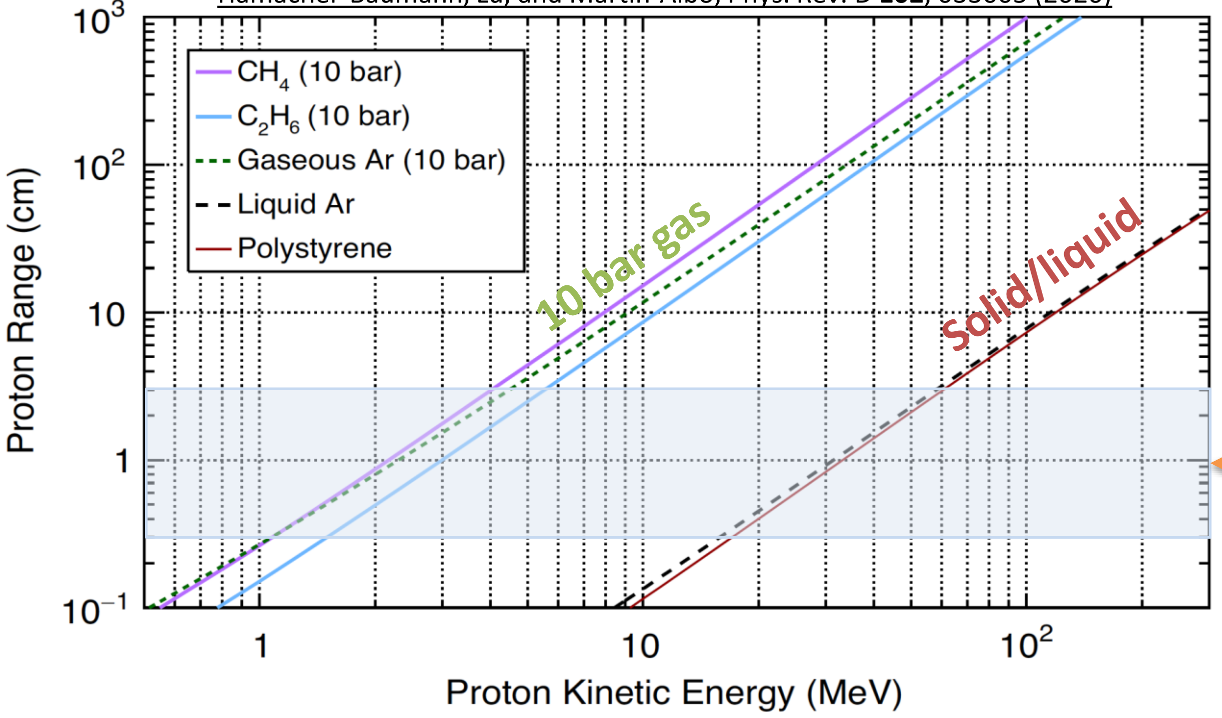

Sensor granularity ~ mm-cm

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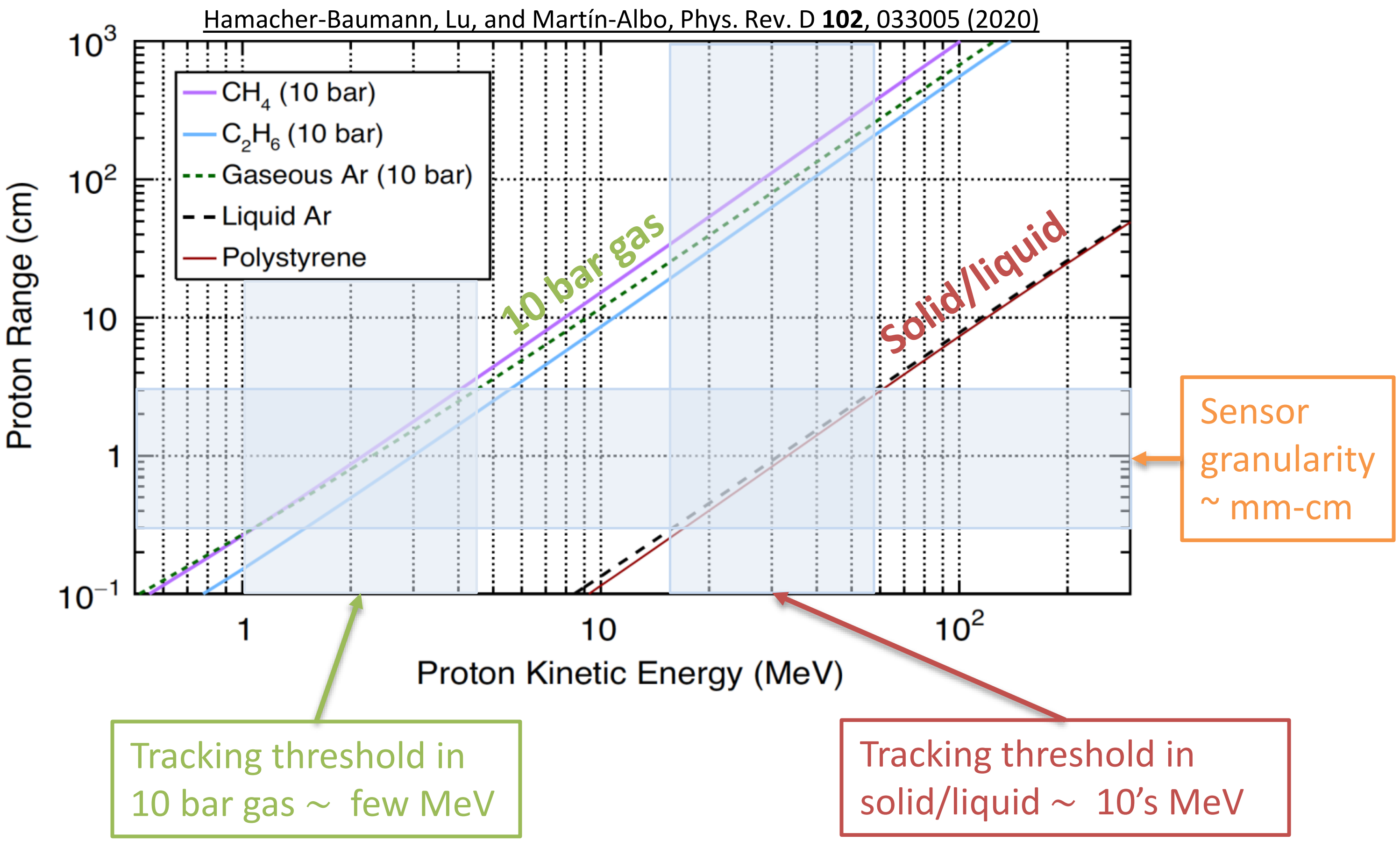

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Gas TPC such as ND-GAr provides ideal medium and granularity to study nuclear effects in neutrino interactions on Argon

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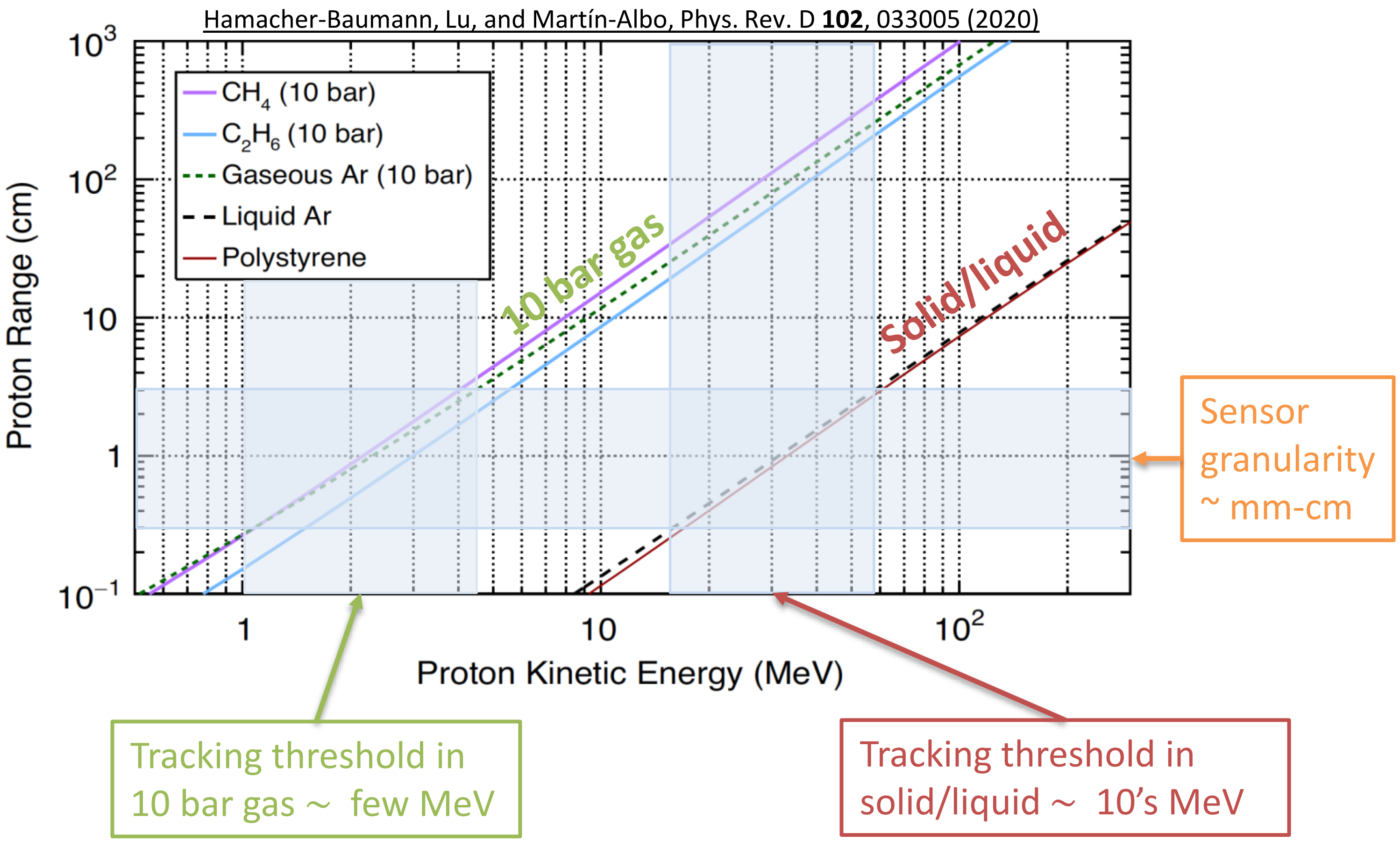
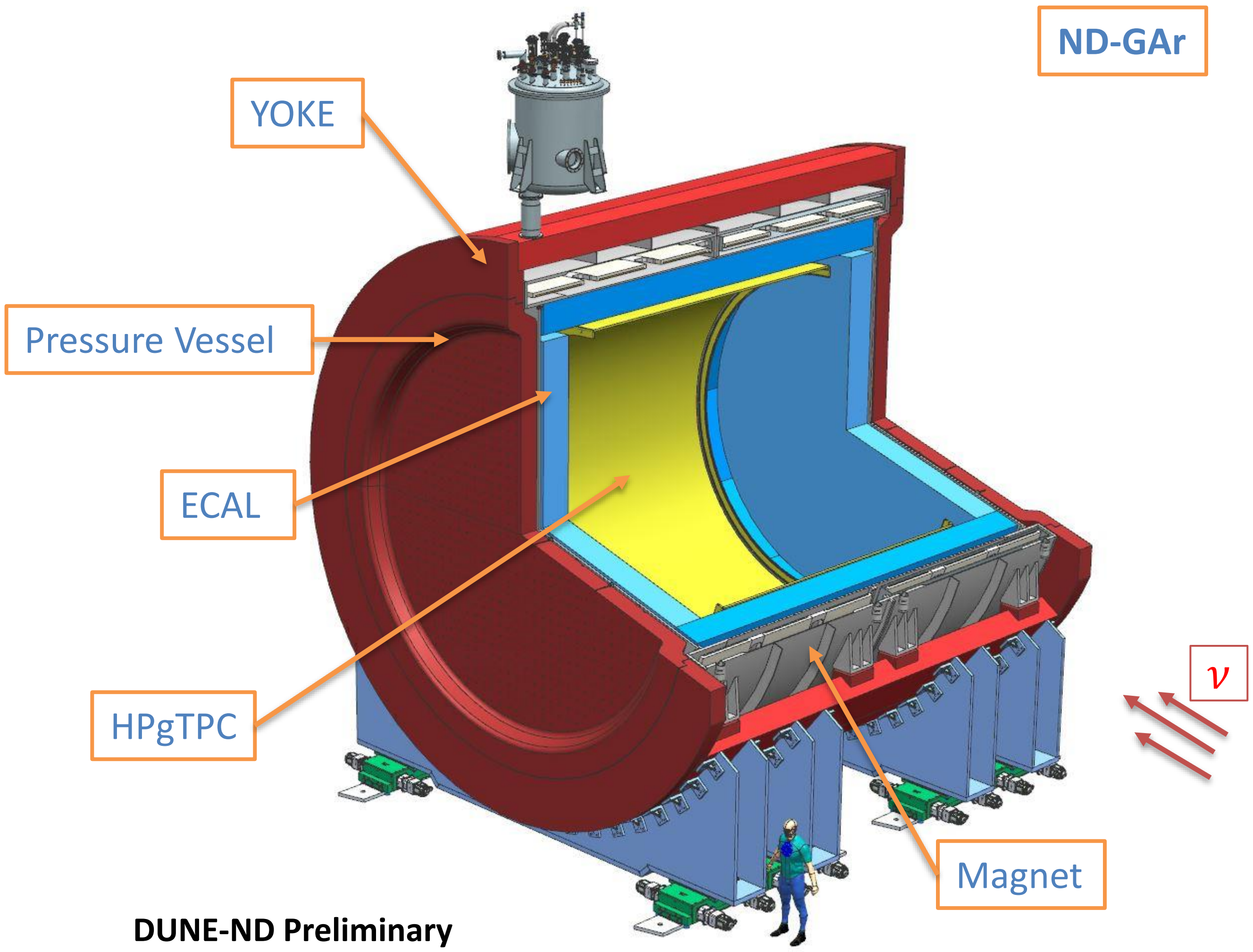


ND-GAr



DUNE-ND Preliminary
https://arxiv.org/abs/2103.13910

- ND-GAr (Gas argon) : HPgTPC (High Pressure Gas TPC) based on ALICE's, filled with Argon gas mixture (such as Ar-CH_4) at 10 atm (pressure vessel) surrounded by an ECAL in a 0.5 T superconducting magnet

- ND-GAr will offer:
  - Very low momentum threshold for charged particle tracking (π, p)
  - Excellent tracking resolution and sign selection
  - Nearly uniform angular coverage

- Main objectives:

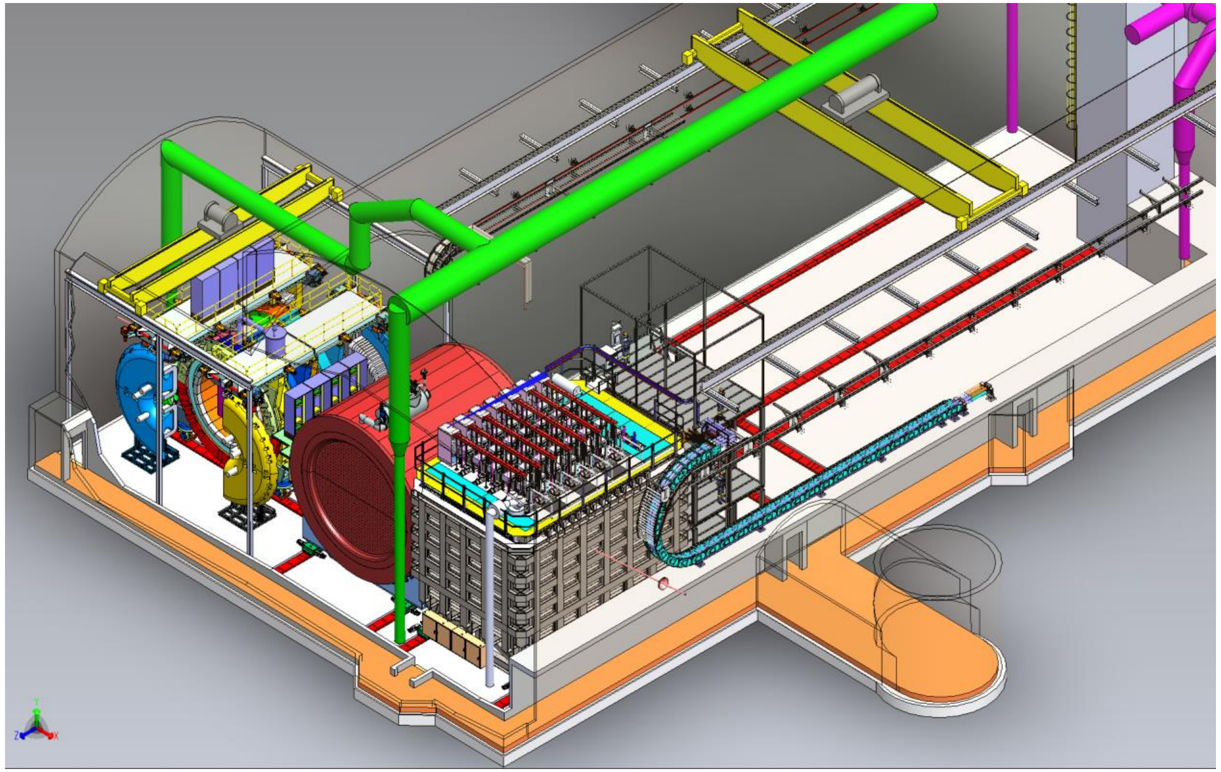
1. Improve ν-nucleus interaction model on Argon in full phase-space where MC neutrino generators struggle
2. Act as muon spectrometer for ND-LAr
3. Provide own program of BSM searches

- Detector movable Off-Axis

DUNE PRISM: flux at the FD

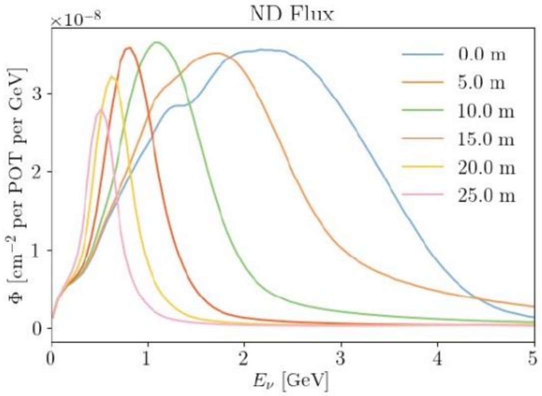
- ND-LAr & ND-GAr movable up to ~30 m off axis 574 m from beam source (0°-3° off-axis angle)

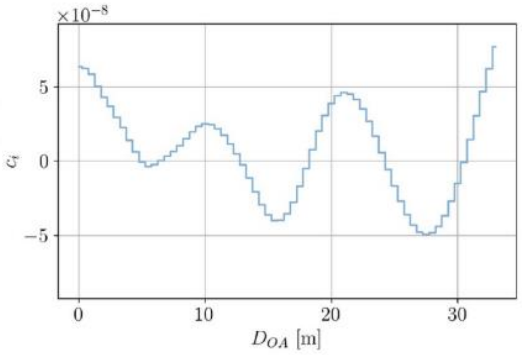
DUNE, instruments **5**, 31 (2021)

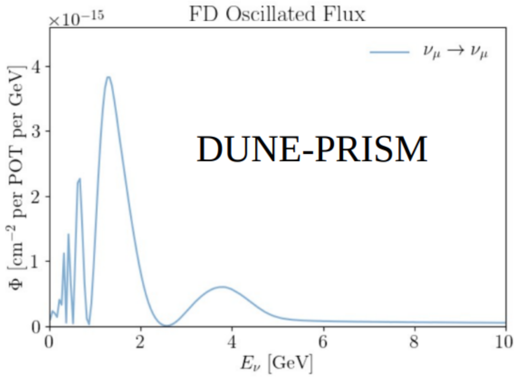


DUNE PRISM: flux at the FD

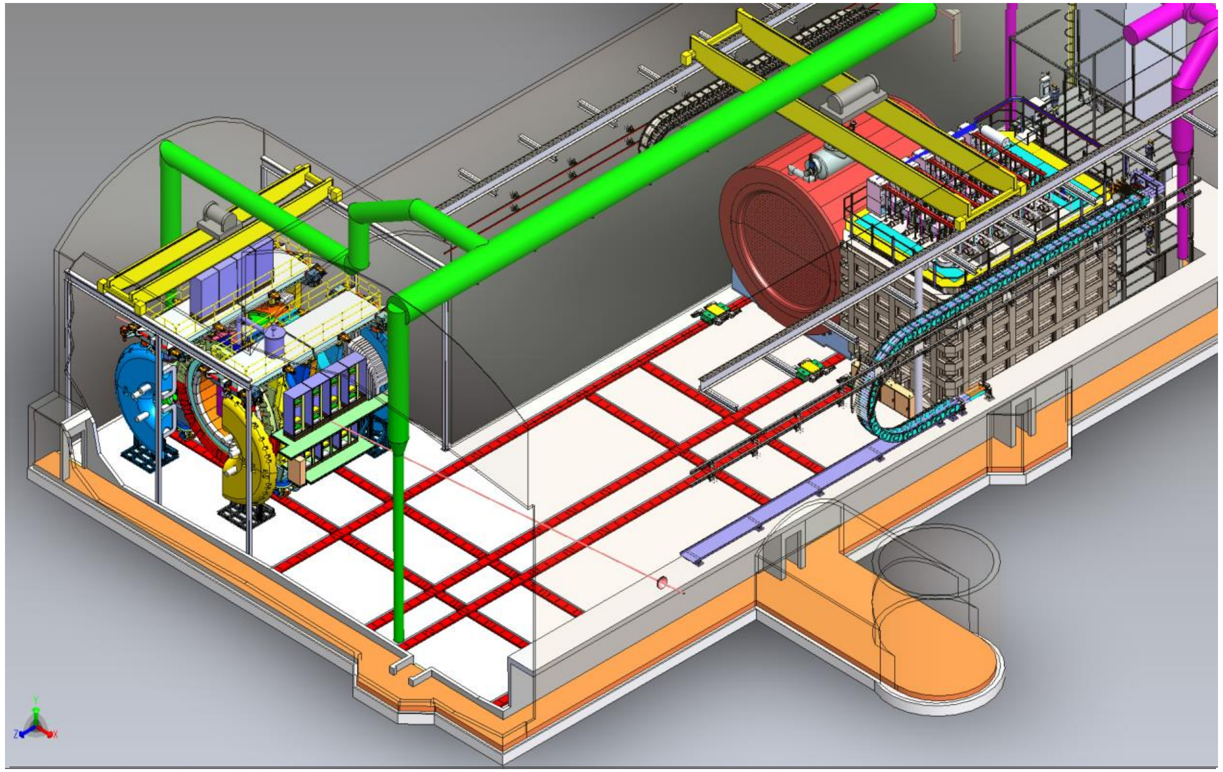
- ND-LAr & ND-GAr movable up to ~30 m off axis 574 m from beam source (0°-3° off-axis angle)
  - ➢ ND flux changes with angle due to pion decay kinematics
  - ➢ **PRISM:** Take ND data in different fluxes → Build linear combination to match FD oscillated spectra







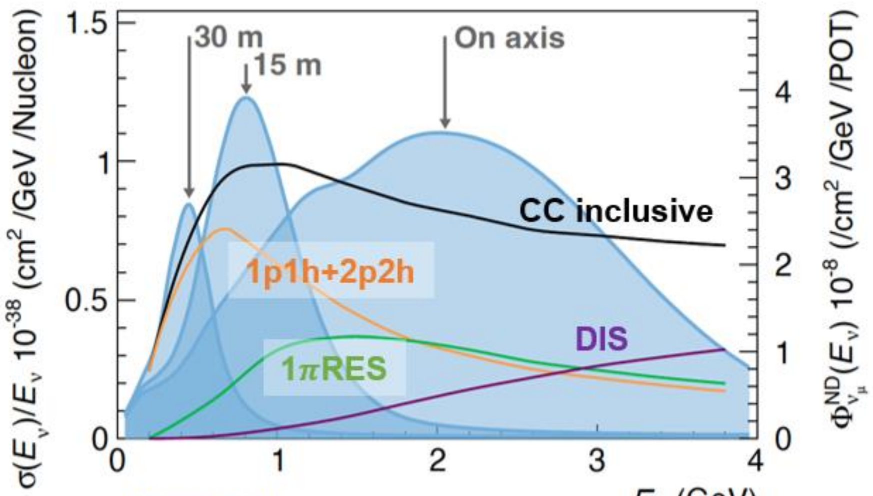
DUNE, instruments **5**, 31 (2021)



DUNE PRISM: flux at the FD

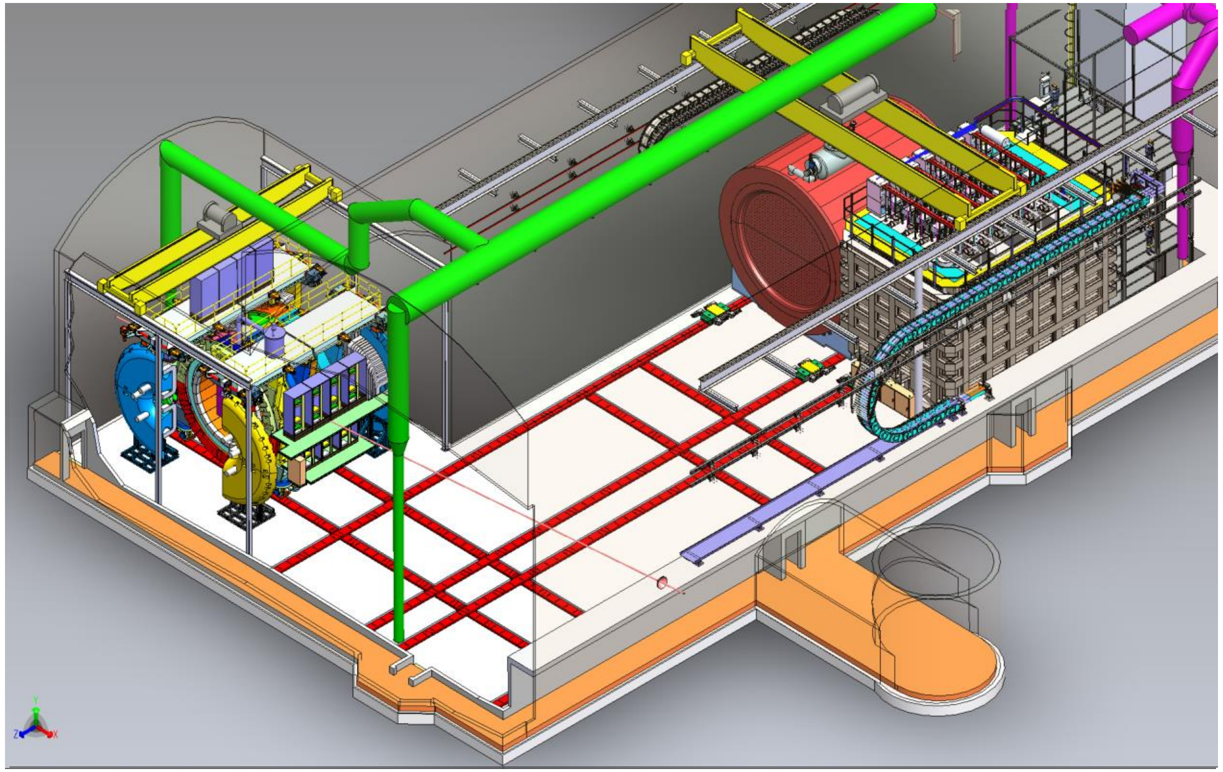
- ND-LAr & ND-GAr movable up to ~30 m off axis 574 m from beam source (0°-3° off-axis angle)
  - ➢ ND flux changes with angle due to pion decay kinematics
  - ➢ **PRISM:** Take ND data in different fluxes → Build linear combination to match FD oscillated spectra
  - ✓ E_ν up to ~3 GeV, covering different interaction dynamics
  - ✓ Probe energy-dependent medium effects

DUNE, instruments **5**, 31 (2021)



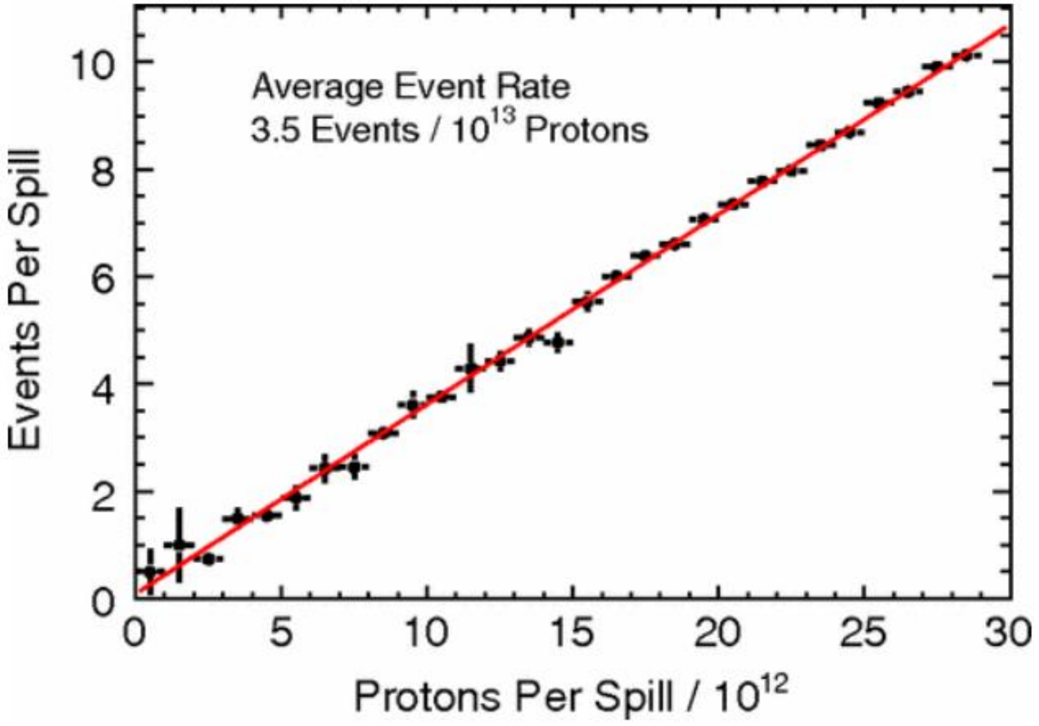
Channel mix evolves with OA location

DUNE, instruments **5**, 31 (2021)



SAND: Beam monitoring and beyond

P. Adamson et al. (MINOS), Phys. Rev. D 77, 072002 (2008)
APS License number: RNP/22/JUN/055116



Mean number of reconstructed events per Near Detector spill (at MINOS) as a function of spill intensity

- Monitor on-axis is very sensitive to flux and focusing effects
- Past experiences from NuMI (like MINOS) demonstrated importance of dedicated beam monitor
- SAND will also have rich physics program:
  - Combination of $\mathrm{CH_2}$ and C targets provides sample of clean neutrino on hydrogen (i.e. single proton) interactions by "subtraction"
  - ν on proton interactions are free from nuclear effects → directly probe nuclear medium effects by comparing with other targets

SAND: System for on-Axis Neutrino Detection

- SAND's main components:
  - ➢ Superconducting Solenoid Magnet + Cryostat from KLOE experiment
  - ➢ Electromagnetic Calorimeter (ECAL) from KLOE experiment
  - ➢ Inner STT (Straw Tube Tracker) Polypropylene/CH_2 tuneable (passive) targets interleaved with 5 mm diameter tube tracking layers
  - ➢ Thin active LAr target (GRAIN)
- SAND fixed On-Axis to monitor the neutrino beam

DUNE-ND Preliminary
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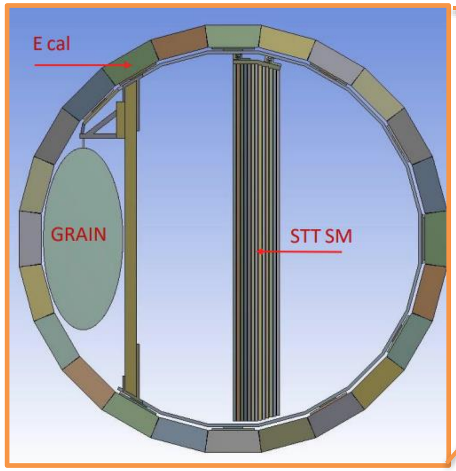
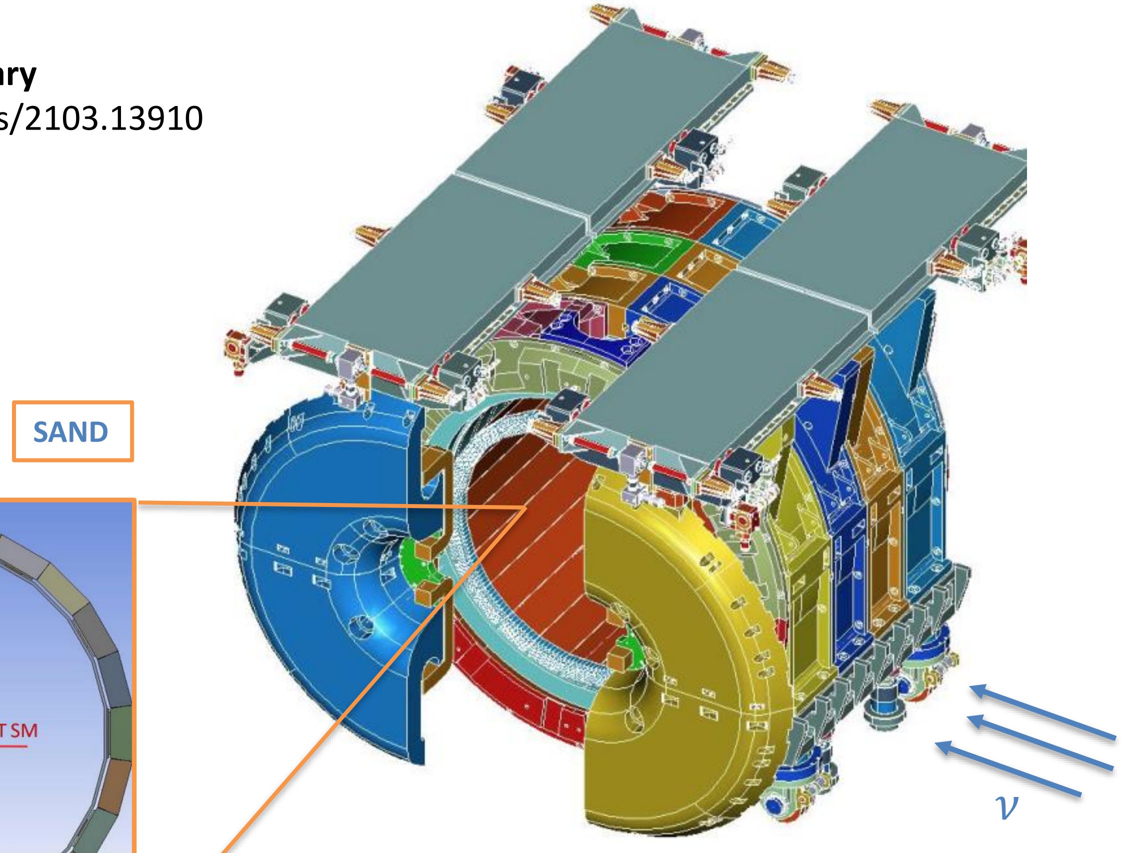




(Up) Schematic view of SAND's cryostat, ECAL and external structure (Left) Inside view of STT Tracker + LAr target (GRAIN) +ECAL

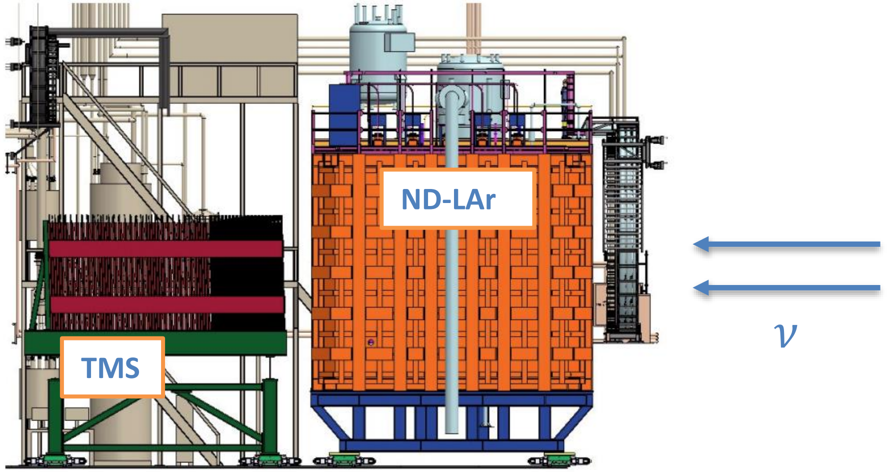
Summary

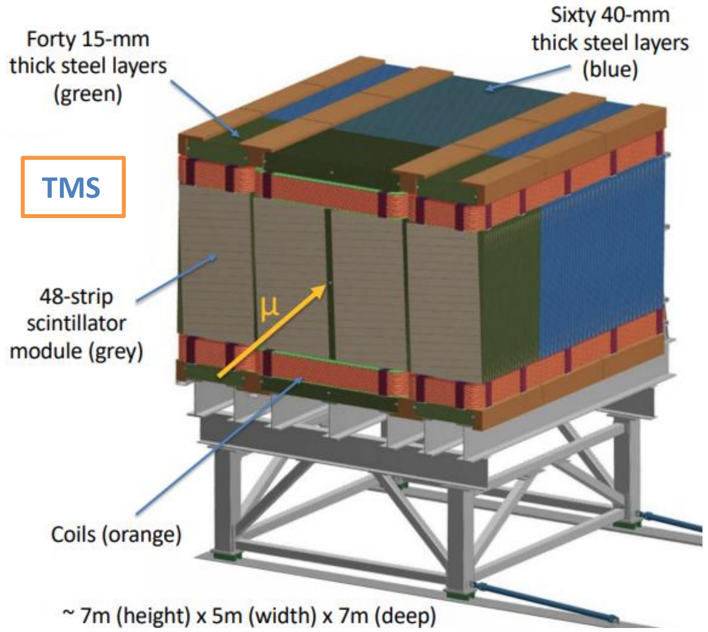
- The DUNE Near Detector will be composed of three robust and complete detector systems all capable and necessary to achieve the experiment's physics goals:
  - ND-LAr : liquid Argon target + detection technology comparable to Far Detector
  - ND-GAr : cross section measurements in low density environment + muon spectrometer for ND-LAr + BSM searches
  - PRISM: flux matching and cross section analyses across the beam spectrum
  - SAND: monitor beam flux + sample of neutrino on hydrogen interactions (baseline for the study of nuclear effects)

THANK YOU!

BACK-UP

TMS: Temporary muon spectrometer



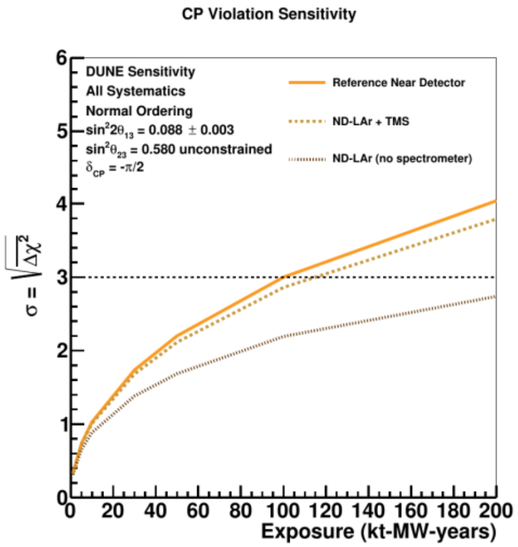


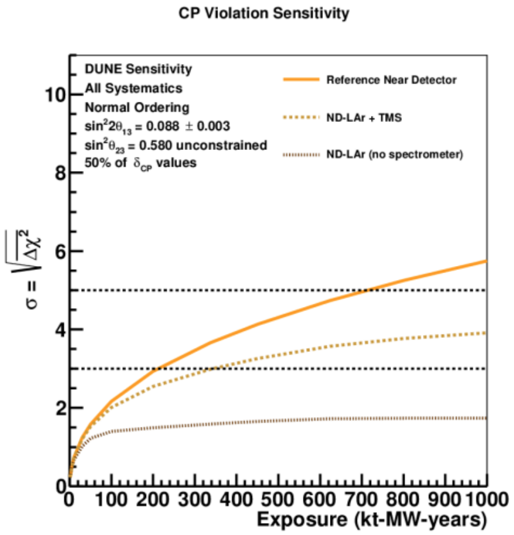
- TMS (Temporary Muon spectrometer): muon catcher for forward muons not contained in ND-LAr
  - Reconstruct momentum by range with ~5% resolution up to ~5 GeV
  - Capable of reconstructing charge sign
  - Combined of ND-LAr provides FD-like reconstruction over the full 4π in the oscillation region

- Simple design heavily inspired by MINOS:
  - Magnetized steel range stack: 100 planes of 192 scintillator strips each + steel
  - Cheap and easy to build

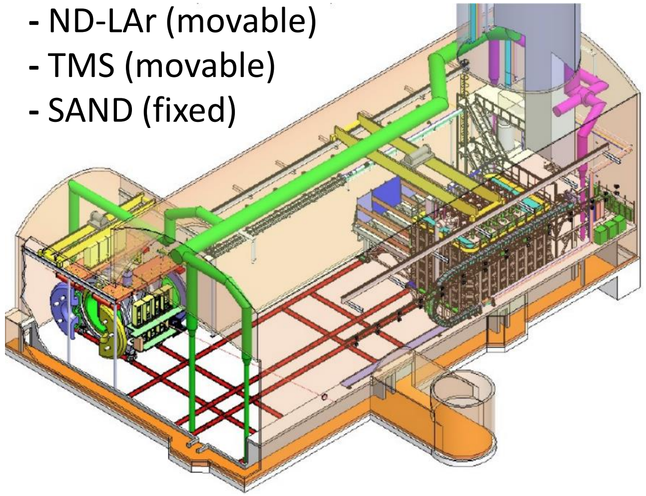
- TMS will be the ND's muon spectrometer on day one, but won't be enough for the full oscillation measurement

ND Phase I and II

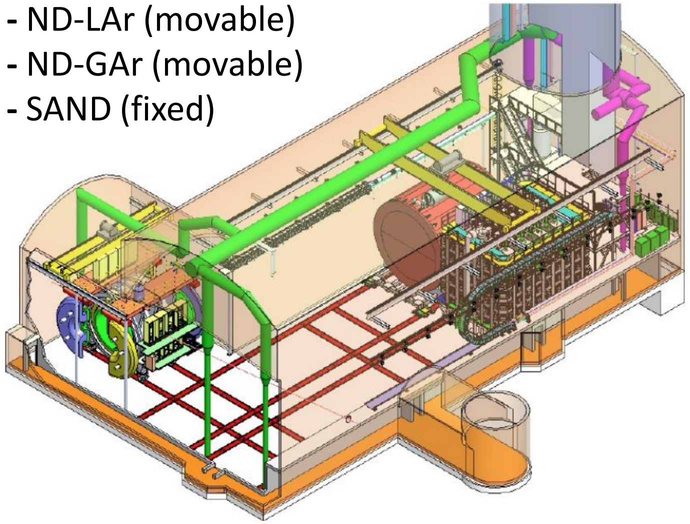




Phase I:
- ND-LAr (movable)
- TMS (movable)
- SAND (fixed)



Phase II:
- ND-LAr (movable)
- ND-GAr (movable)
- SAND (fixed)



- ND's data taking divided in Phase I (TMS muon spectrometer) and II (ND-GAr) due to cost reduction necessities
- Phase I ND, with TMS instead of ND-GAr, sufficient for the early physics goals
- Beyond that dominated by systematics without a more capable ND (also many physics opportunities lost)