Techniques for TPC calibration: application to liquid and dual-phase Ar-TPCs

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Topical Workshop on New Horizons in Time Projection Chambers
Santiago de Compostela + Online
October 8, 2020

REPÚBLICA PORTUGUESA
FCT Fundação para a Ciência e a Tecnologia
LIP
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

My own biases…

- My experience is in large Neutrino Physics and HEP detectors
  - DUNE, SNO+, SNO, Borexino, ATLAS
  - Currently my (TPC-related) role is Calibration and Cryogenic Instrumentation Consortium Leader at DUNE

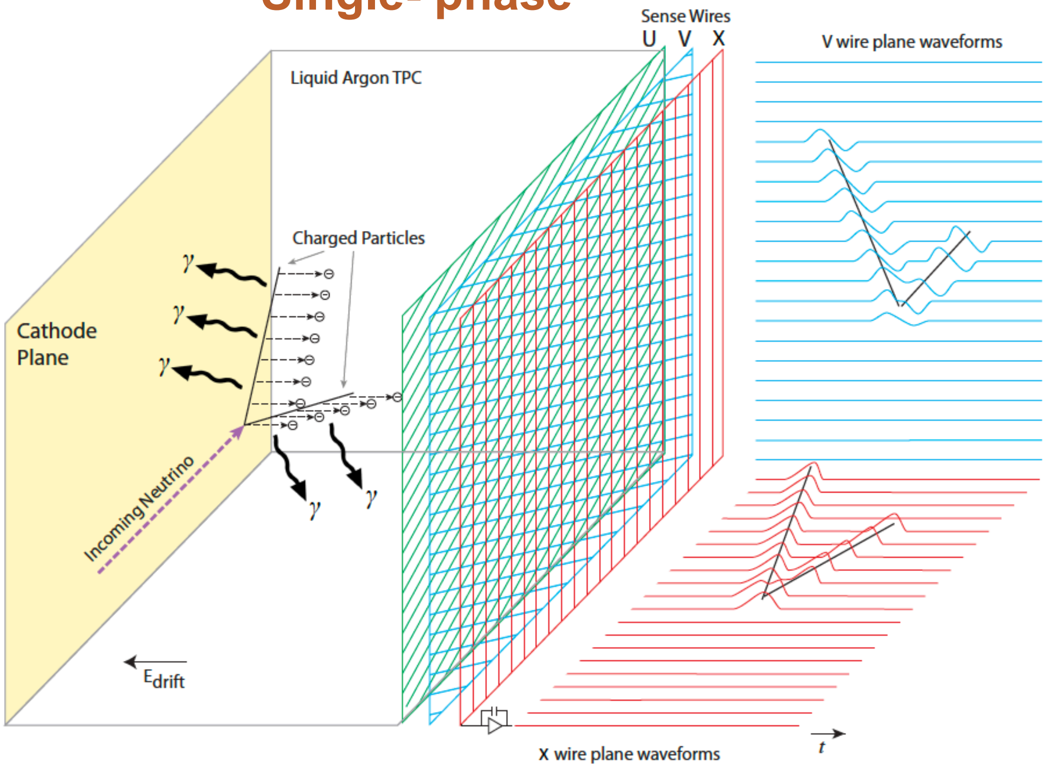
Outline

- Introduction
- Measurements with natural and intrinsic sources
- Ionization with UV lasers
  - Early systems for gas detectors, R&D towards usage in liquids
  - The first laser system in a large detector: MicroBooNE
  - Plans for DUNE and ProtoDUNE, single and dual-phase
- Pulsed neutron source, a new idea for DUNE
  - Neutron transmission and capture in argon
  - How to calibrate large detectors from outside
- Outlook

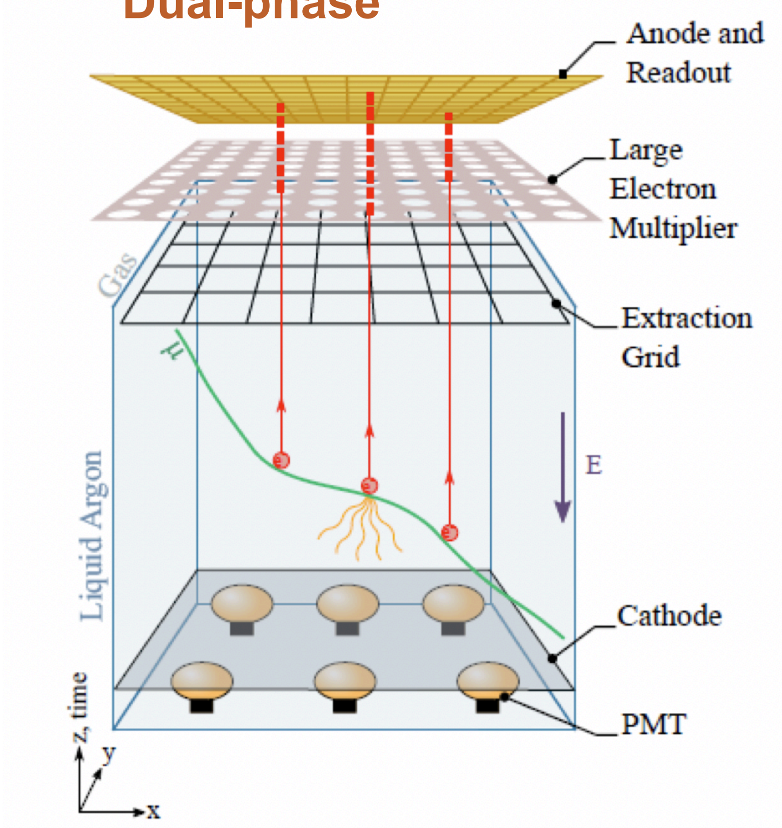
Introduction

Liquid Argon TPC

Single- phase

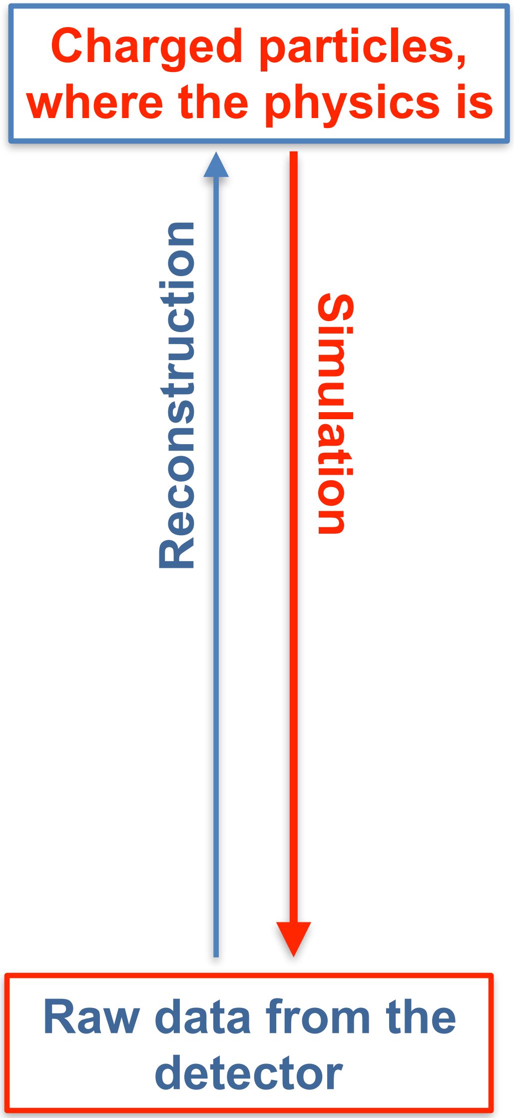


Dual-phase



Drift in liquid
No amplification
Collection in liquid

Vertical drift in liquid
Amplification and collection in gas



Object	Process	Parameters
Charged particles		
	Interaction of particles in LAr	Cross-sections dE/dX
Tracks Hit clusters		
	Recombination	Work function Birks, Box model
Electron clouds		
	Electron transport	drift velocity lifetime diffusion coeff.
Electron clouds after drift		
	Detection in wires	transparency
Charge in wires		
	Digitization	FE gain
ADC/TDC counts		

Two Types of Calibration

Low-Level

- Measure model parameters
  - Wire collection efficiency, etc.
  - Detector geometry
  - HV system defects
  - Drift velocity/E-field maps
  - Purity/lifetime
  - Recombination model
  - Work function
- Spatial uniformity, time stability
- Input to both simulation and reconstruction

High-Level

- Check performance of reconstruction
  - Overall energy scale factor
  - Energy/momentum scale and resolution
  - Position offsets/resolution
  - Particle ID algorithm biases
- Contribute to determine correlations and systematic uncertainties and
- Input to physics analyses fits

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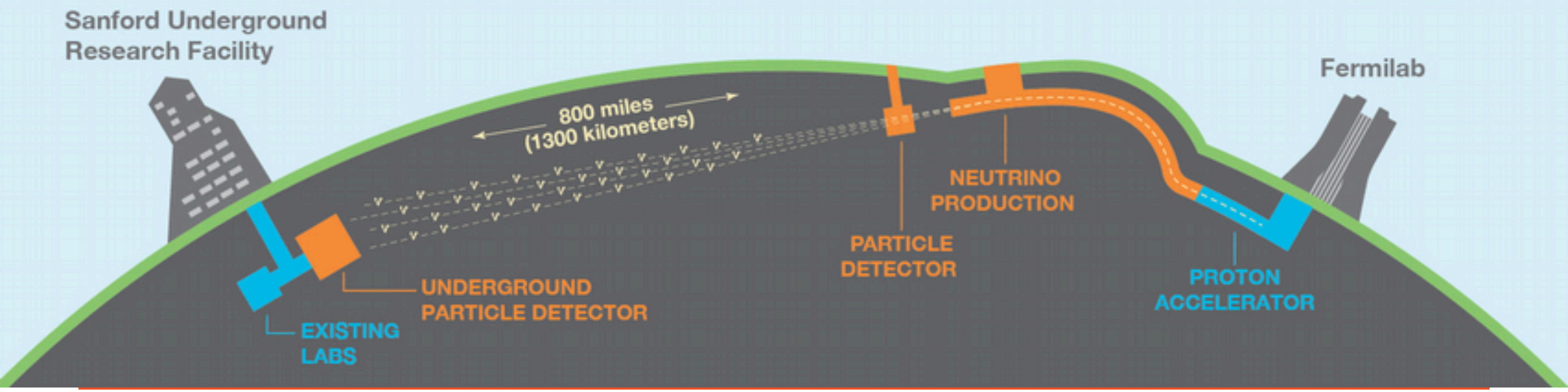
How well we need to know these?

Driven by physics goals. Example: DUNE

- Oscillation physics: CP-violation and neutrino mass ordering
  - Energies O(GeV)
  - Uncertainty on energy scale < 2% (5%) for leptons (hadrons)
- Supernova neutrino burst
  - Energies O(MeV)
  - Energy resolution 20-30%

DUNE FD Technical Design Report
Vol.II:Physics arXiv:2002.03005



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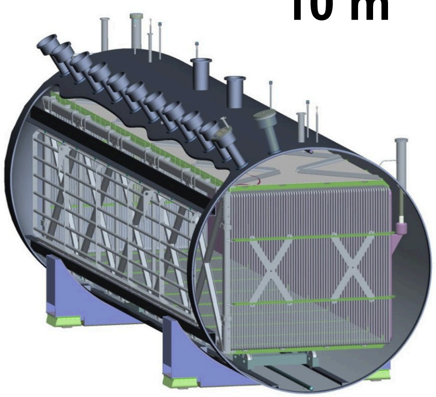
Large LAr detectors mentioned in this talk

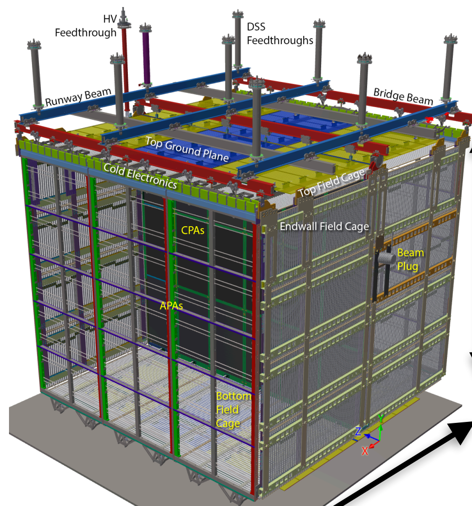
(approx. dimensions of TPC in all cases)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

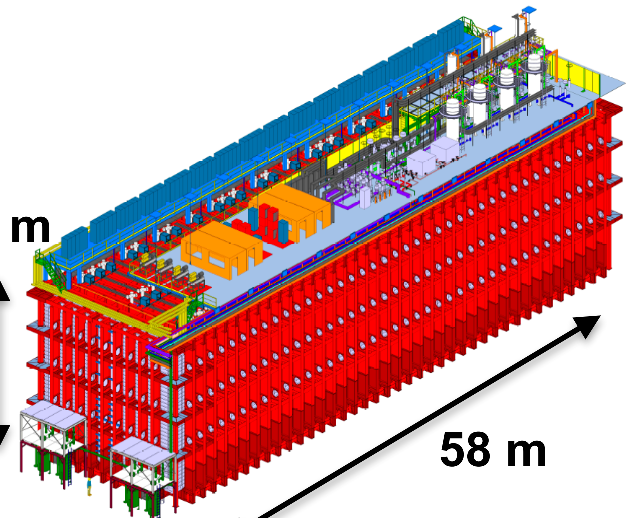
µBooNE



MicroBooNE @ FNAL
90 tons (active)
at surface

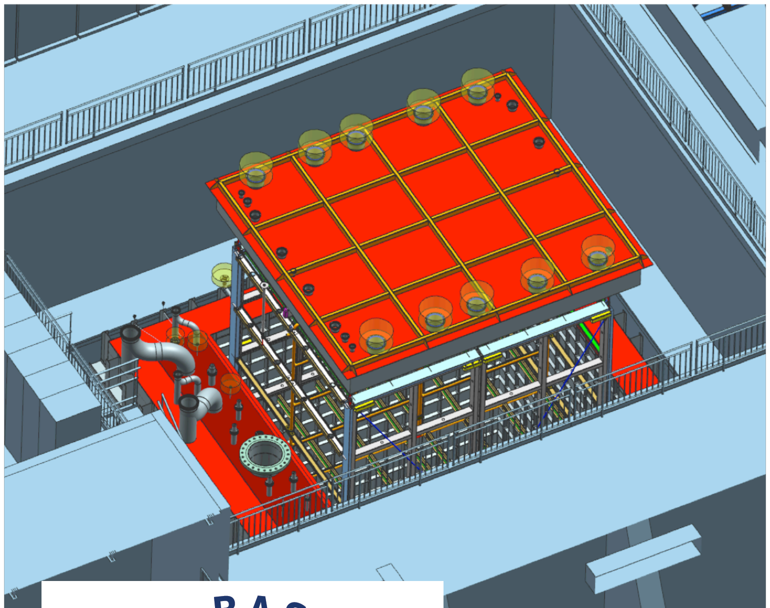


ProtoDUNE @ CERN
420 tons (active)
at surface



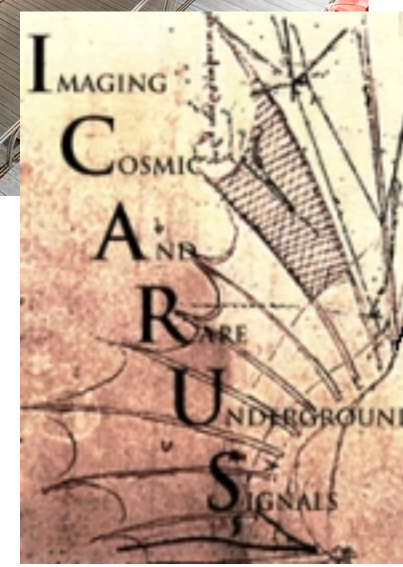
DUNE far detector module @ SURF (1 of 4)
13 ktons (active)
1.5 km underground

Other large LAr detectors



SHORT-BASELINE
SBND
NEAR DETECTOR

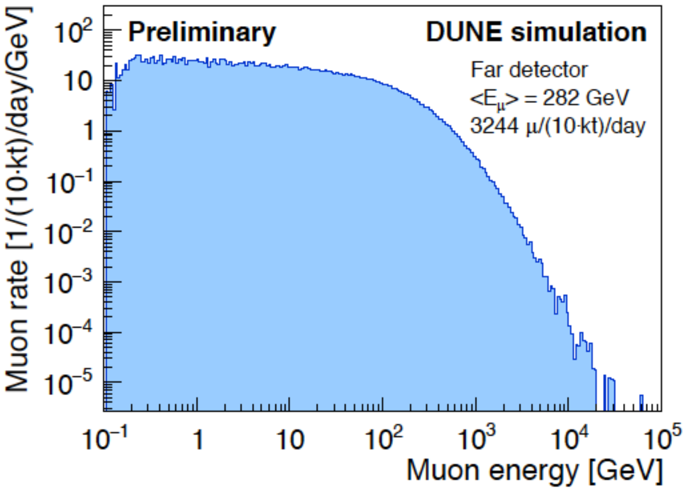
- The near and far detectors of the FNAL short-baseline program
- ICARUS is the pioneer LAr experiment moved to FNAL from Gran Sasso via CERN



Natural and intrinsic sources

- Cosmic muons
- Natural radioactivity (e.g. ^{39}Ar)
- Atmospheric neutrinos
- Neutrino beam events
- Muons from neutrino beam interactions in rock

Cosmic muons



- Advantages
  - Many possible measurements
  - Free
- Challenges
  - Low statistics if deep UG

Advantageous to have an independent position/direction

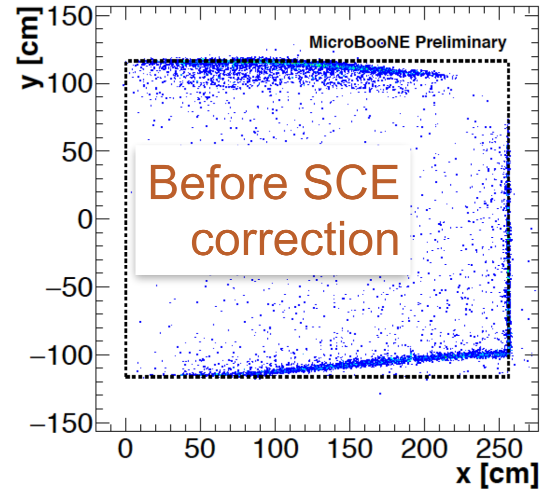
ProtoDUNE Cosmic-Ray Tagger

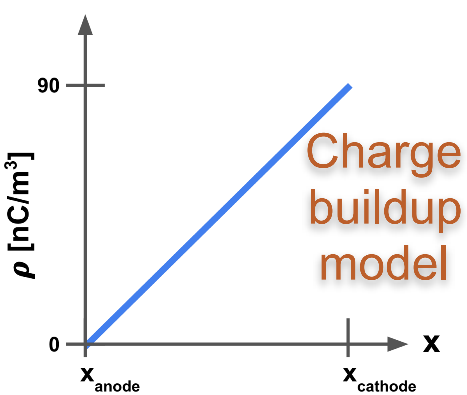
- Measure parameters
  - Space charge effect/drift
  - Lifetime
- Detector response to "standard candles"
  - through-going and stopping muons
  - Michel and Delta-ray electrons
  - π^0 decay

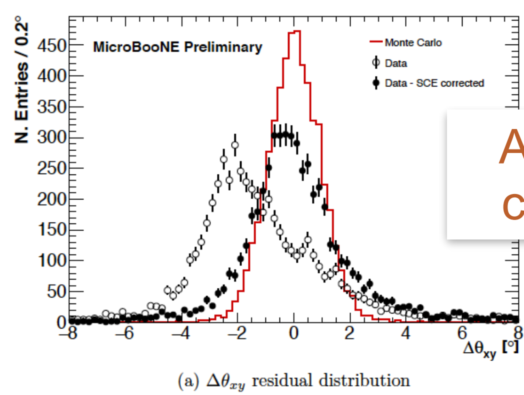
Space-charge effect (SCE) Study in MicroBooNE

MICROBOONE-NOTE-1018-PUB

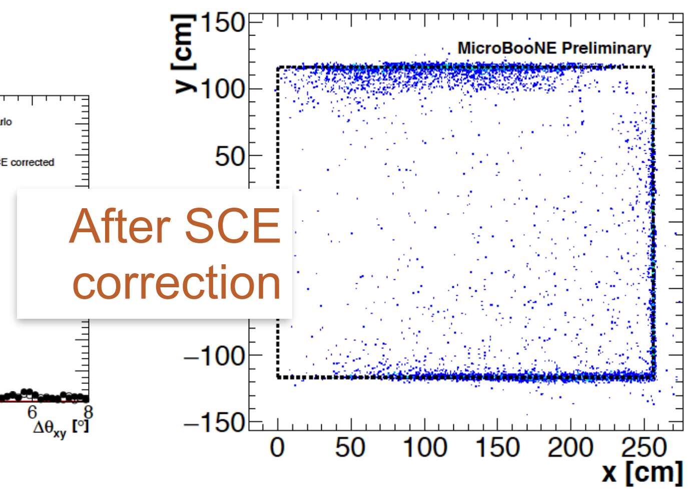
- Ion drift velocity much lower ($2x10^5$) than for electrons
- Charge buildup (cosmics) distorts E-field and drift velocity, worse with fluid flow
- Impacts position and recombination
- Distortions of tracks observed with end-points of externally tagged muons







(a) $\Delta\theta_{xy}$ residual distribution



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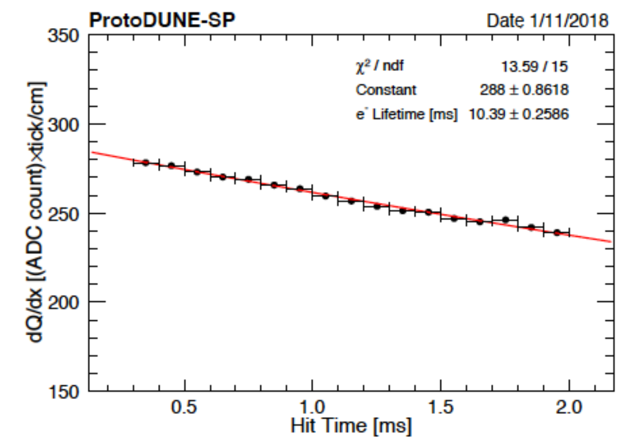
Electron lifetime

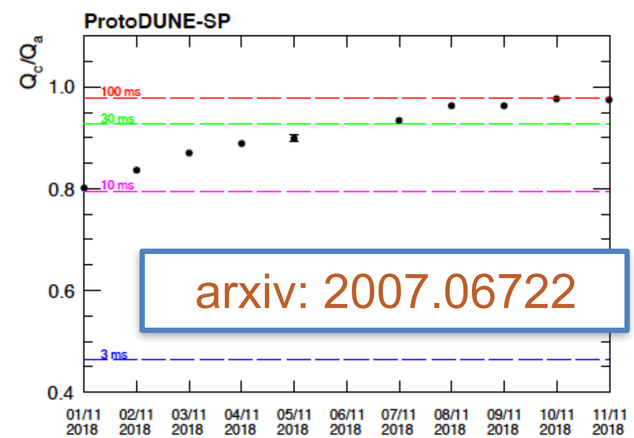
$$dQ'_e = dQ_e e^{-t/\tau}$$

$$N_{O_2} = \frac{1}{k_a \tau} = \frac{300\,\text{ppt ms}}{\tau}$$

NO_2: Oxygen contamination

- Crucial for good charge/energy response
- Directly related to purity, so can change fast and be non-uniform across detector
- ProtoDUNE performance
  - Measured with tagged cosmics, high statistic
  - Extremely high purities and good agreement with purity monitors
  - Q ratio (C_t) at Cathode: **precision of 0.5%** (stat) achieved

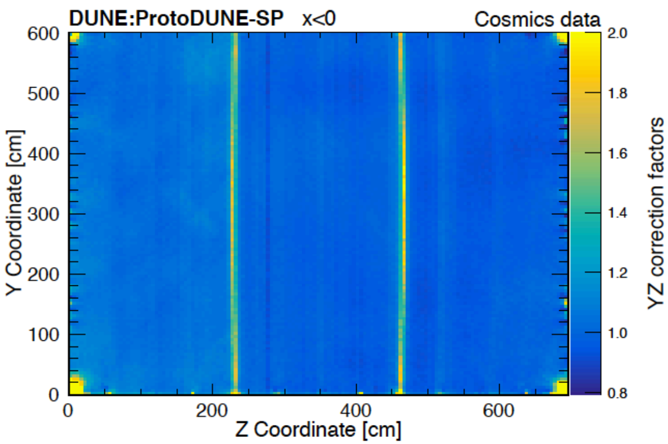


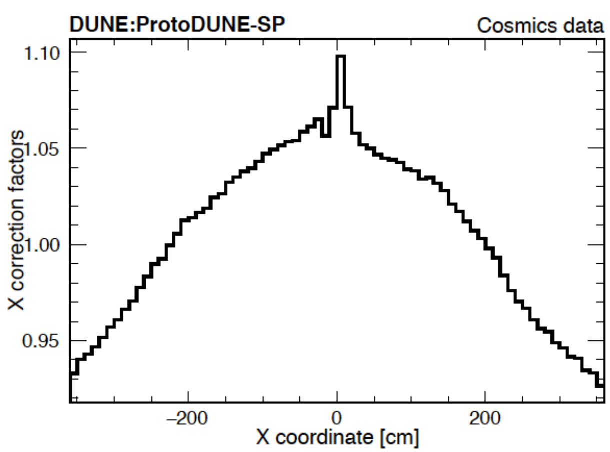


arxiv: 2007.06722

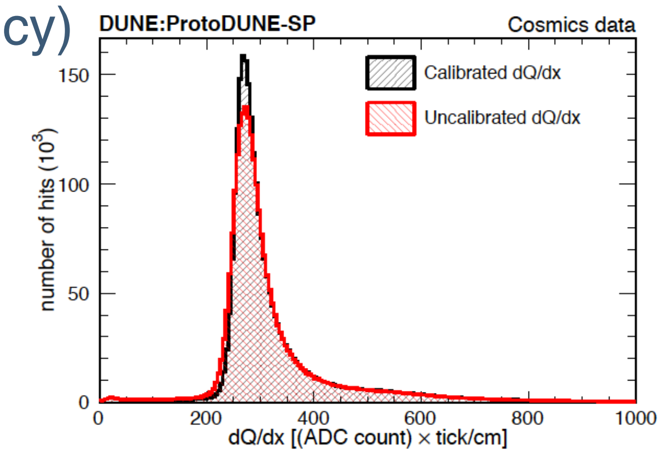
Energy response maps

arxiv: 2007.06722



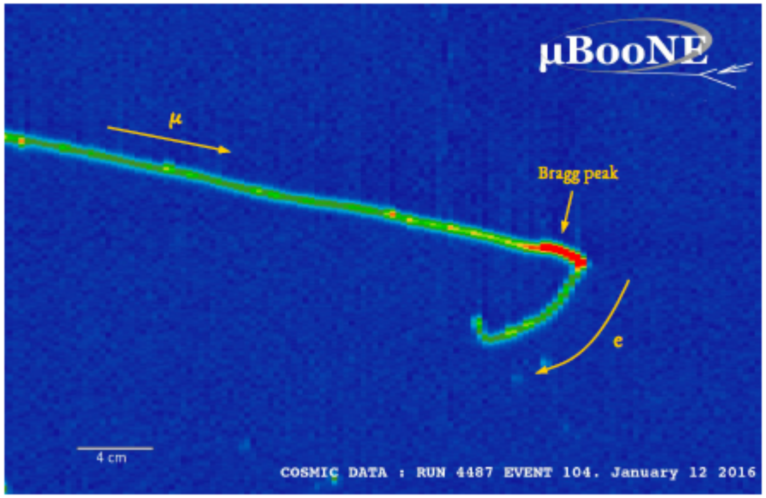


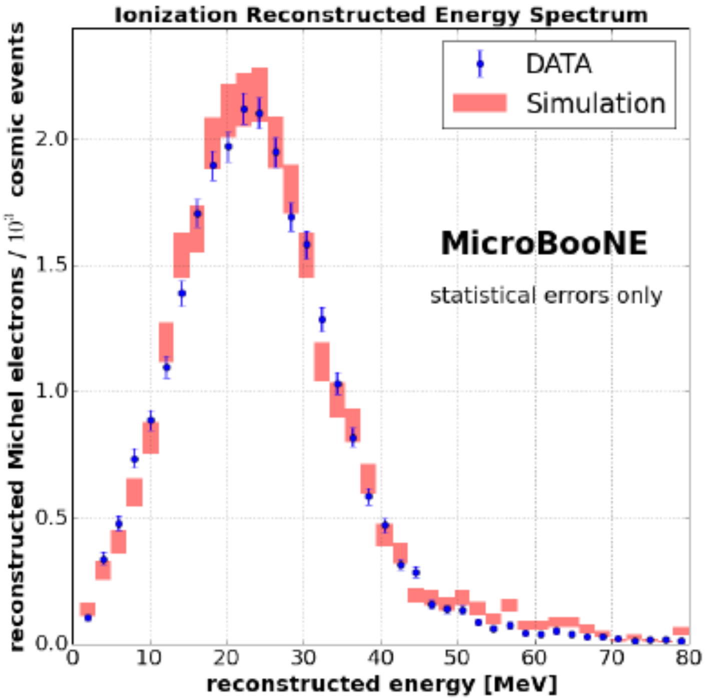
- After gain/SCE corrections, equalization of charge collection efficiency using cathode crossing cosmic ray tracks
  - Stopping muons for absolute energy scale
- ~100 k tracks for 2% precision and fine map
- How long to do the same deep UG?
  - Anode crossing-tracks? ~ 15 years
  - All tracks? At least **14 months** (w/ 50% selection efficiency)



Michel electrons

- Wide electron spectrum from stopping muon decay
- Helps constrain energy scale at low energies

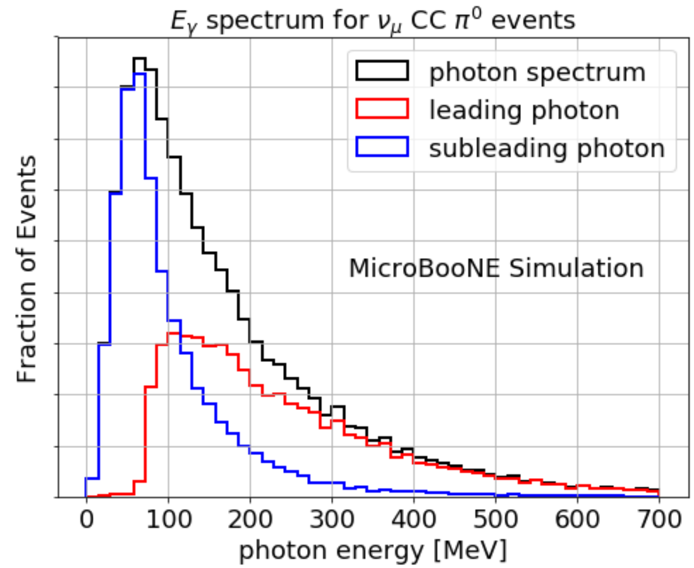


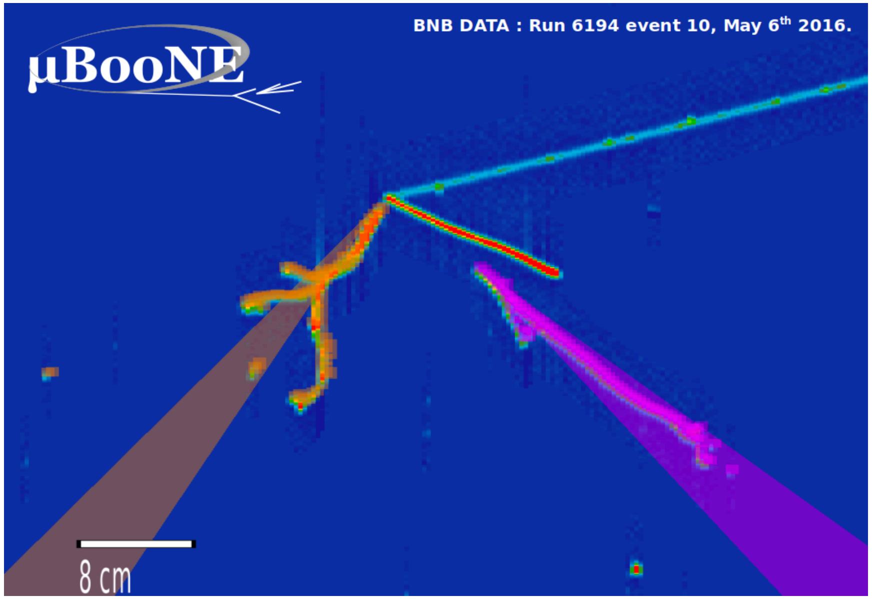


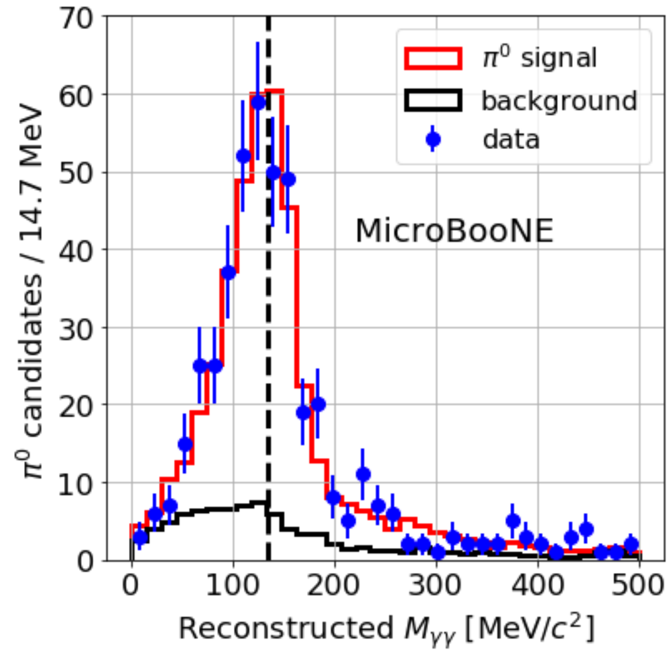
R. Acciarri et al. 2017 *JINST* **12** P09014

Beam events: $\pi^0 \rightarrow 2\gamma$

- Invariant mass of pi0 decay provides energy calibration in a wide range







C. Adams *et al* 2020 *JINST* **15** P02007

Ionization with UV laser

Calibration via ionization (gas)

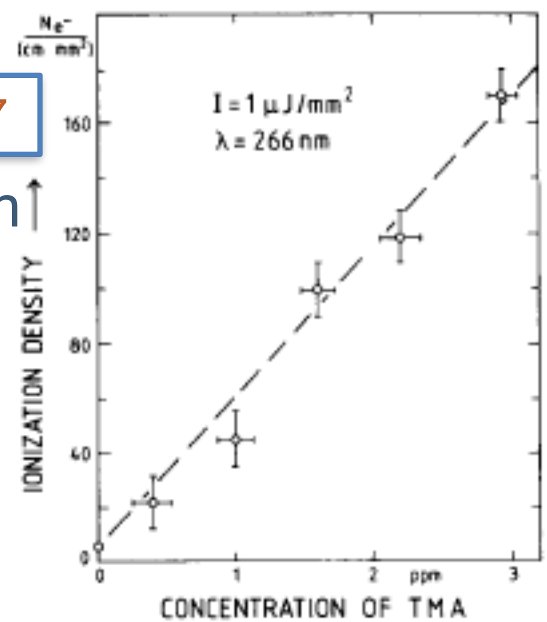
- Use lasers to "simulate" particle tracks
  - Advantages: narrow beam, well defined position and timing, independent of magnetic fields

H. Anderhub et al. 1979 *NIMA* **166** p. 581

  - Idea proposed in 1979 for drift chambers. Gas mixture with ionization potential of 6.5 eV so that two-photon absorption can occur with N_2 laser (337 nm, 3.7 eV)

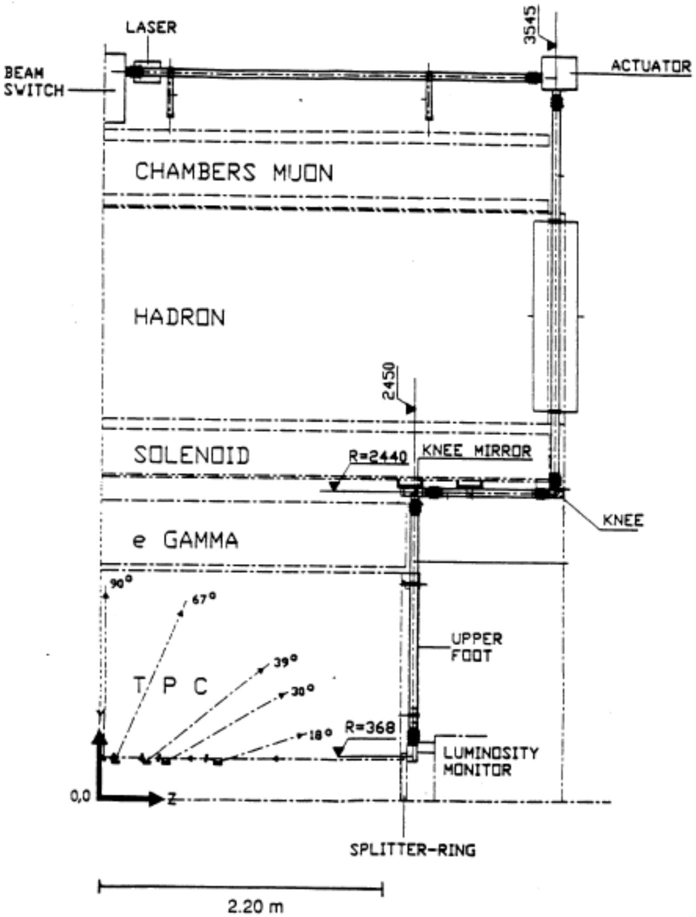
G. Hubricht et al. 1985 *NIMA* **228** p. 327

- Studies of energy density vs mixture, wavelength
  - Using also Nd:YAG laser 4th h. (266 nm, 4.67 eV)
  - With additives (e.g. TMA), can reach ionization densities higher than particles
  - Needs only moderate intensities (1µJ/mm²)

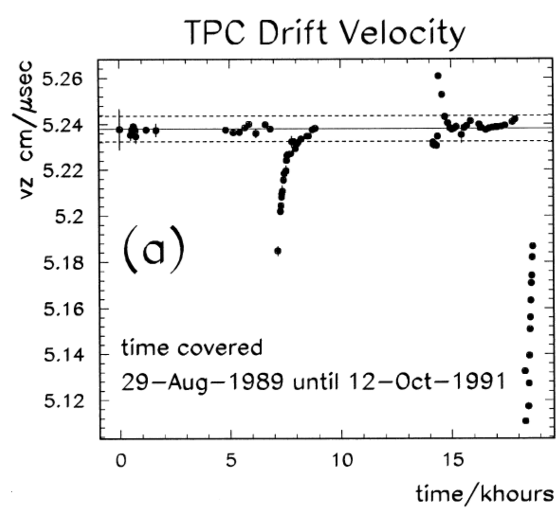


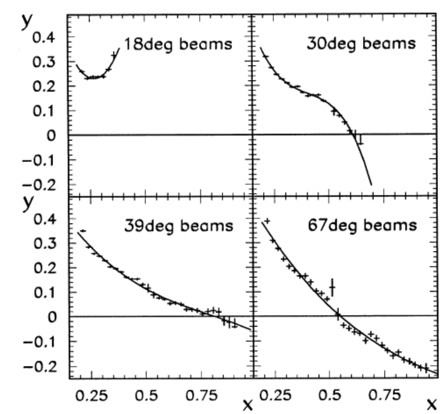
Application: calibration of ALEPH

ALEPH 91-150
TPCGEN 91-004
M. Schmelling & B. Wolf
7.11.1991



- Idea applied to the calibration of the ALEPH (LEP/CERN) gas TPC
- Ingenious system of mirrors simulates beam from e^+e^- interaction point
- Used to monitor drift velocity and misalignments





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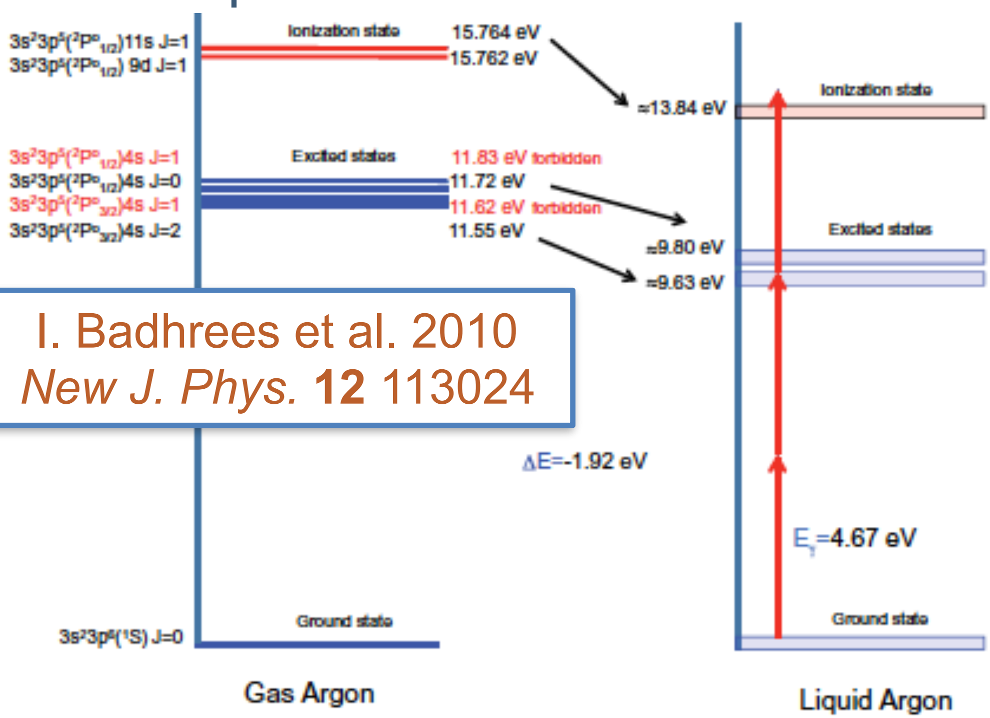
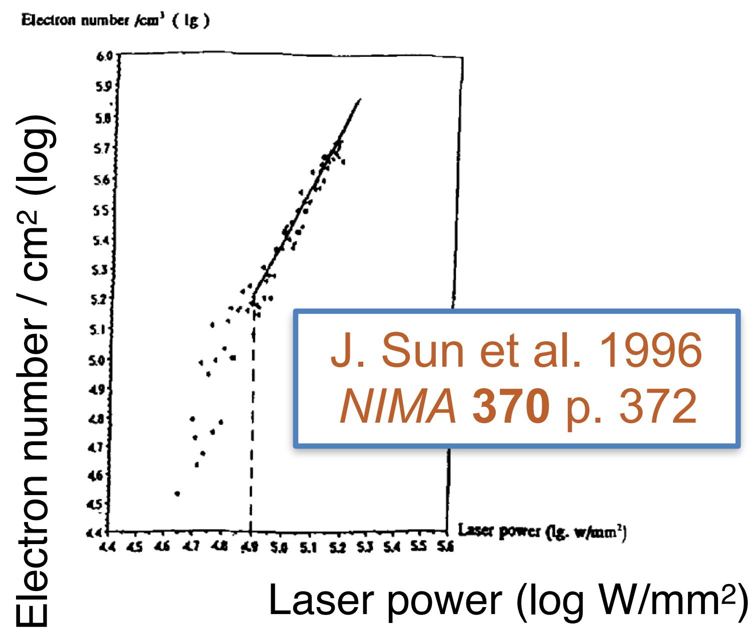
Ionization of liquid argon

- LAr ionization potential = 13.84 eV
- In purified liquid argon, there are no low ionization potential states from impurities or additives



I. Badhrees et al. 2010
New J. Phys. **12** 113024

- Absorption of two (266 nm, 4.67 eV) photons only capable of excitation, need a third one to ionize
- First measurements in 1996, at CERN, for ICARUS
- Much higher laser intensities needed, ~0.5 mJ/mm²

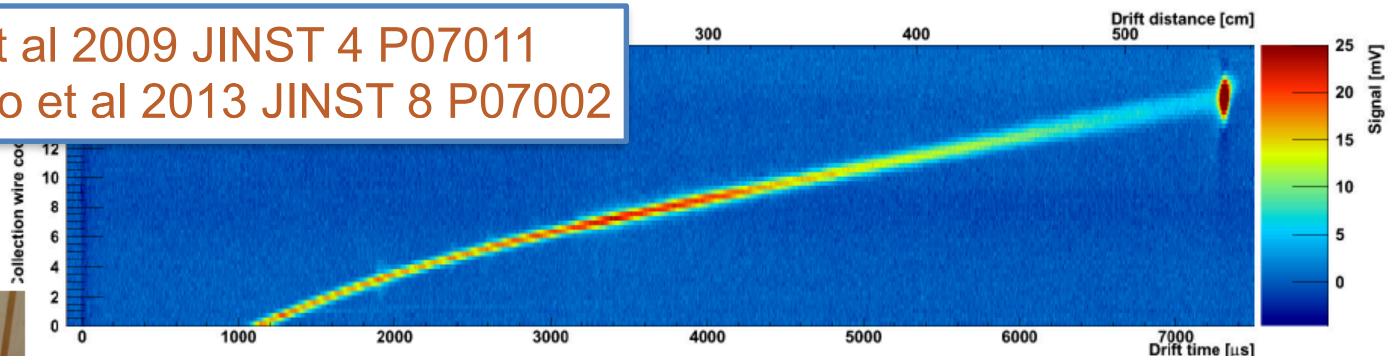


J. Sun et al. 1996
NIMA **370** p. 372

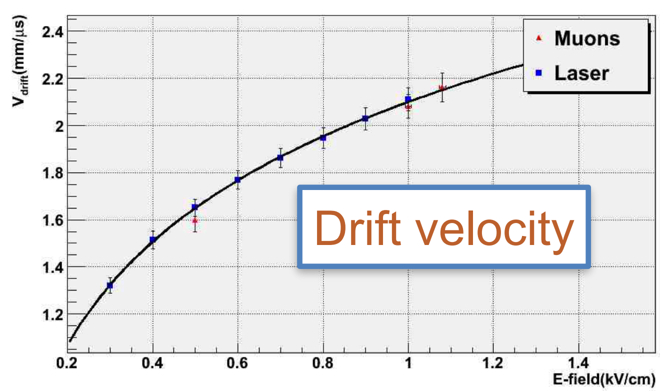
R&D on LAr laser ionization

- Test setups with up to 5 m drift @Bern
- Nd:YAG laser (266 nm), steerable with cold mirror

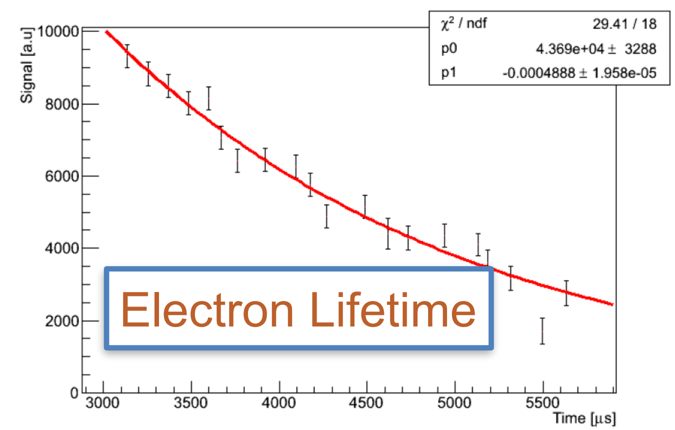
B Rossi et al 2009 JINST 4 P07011
A Ereditato et al 2013 JINST 8 P07002



- Extensive R&D, inc. measurements of:



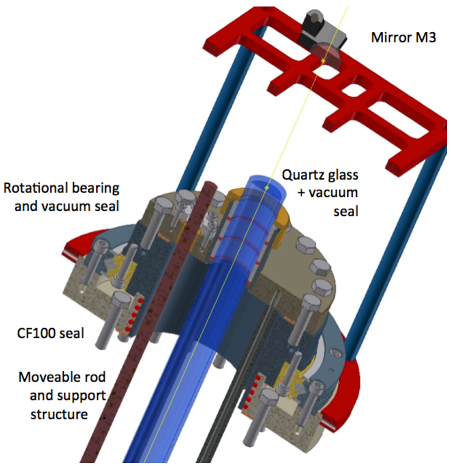
Drift velocity

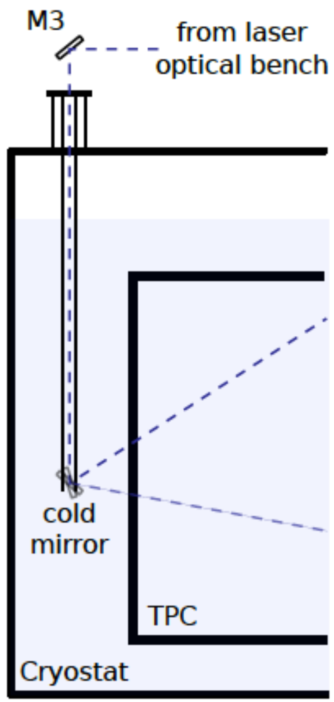


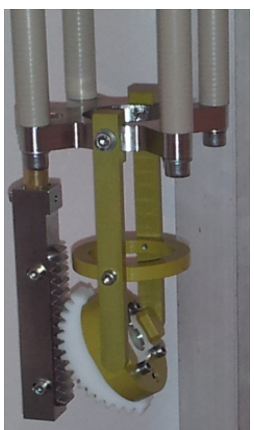
Electron Lifetime

ArgonTube,
LHEP Bern

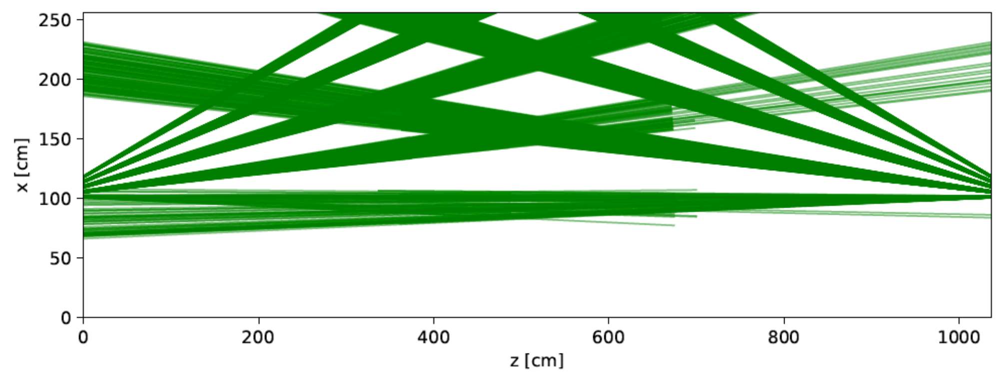
MicroBooNE laser calibration system







- First implementation in a large detector, with two laser benches + periscopes
- Coverage pattern due to shadows from field cage

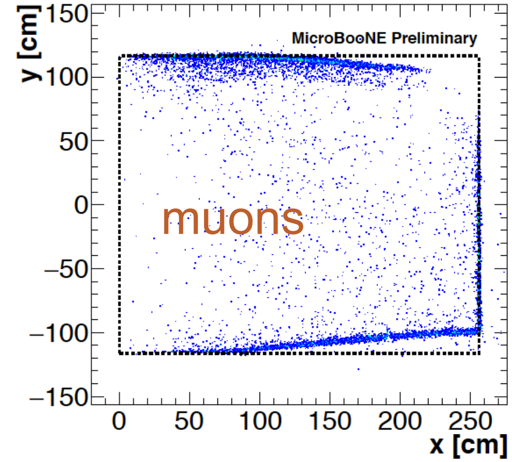


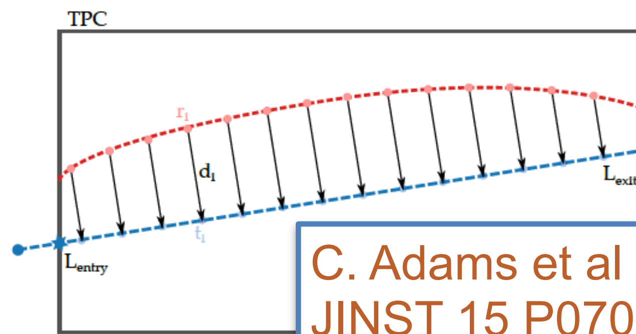
A. Ereditato et al 2014 JINST 9 T11007
C. Adams et al 2020 JINST 15 P07010

SBND also building a laser system

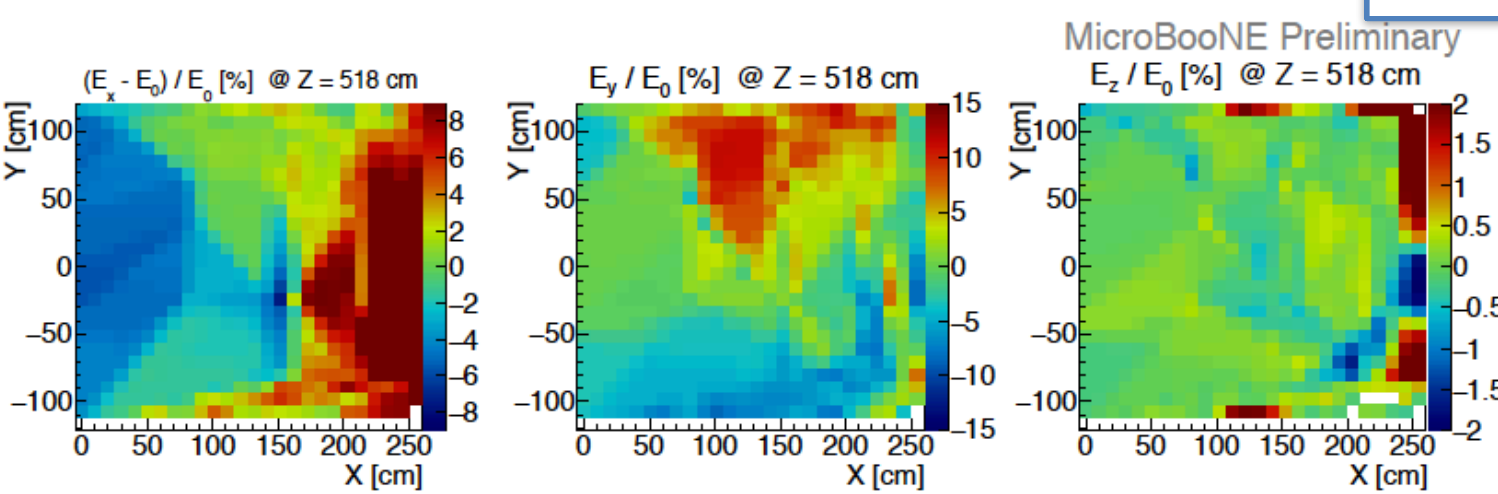
MicroBooNE results

- Compare TPC **reconstructed track** with **“true" track** (given by mirror position)
- Combine two tracks from opposite lasers to cancel displacement ambiguities
- Fit displacement map to obtain map of E-field distortions - up to 15%
- Stat. / Syst unc. each ~ 2%





C. Adams et al 2020
JINST 15 P07010



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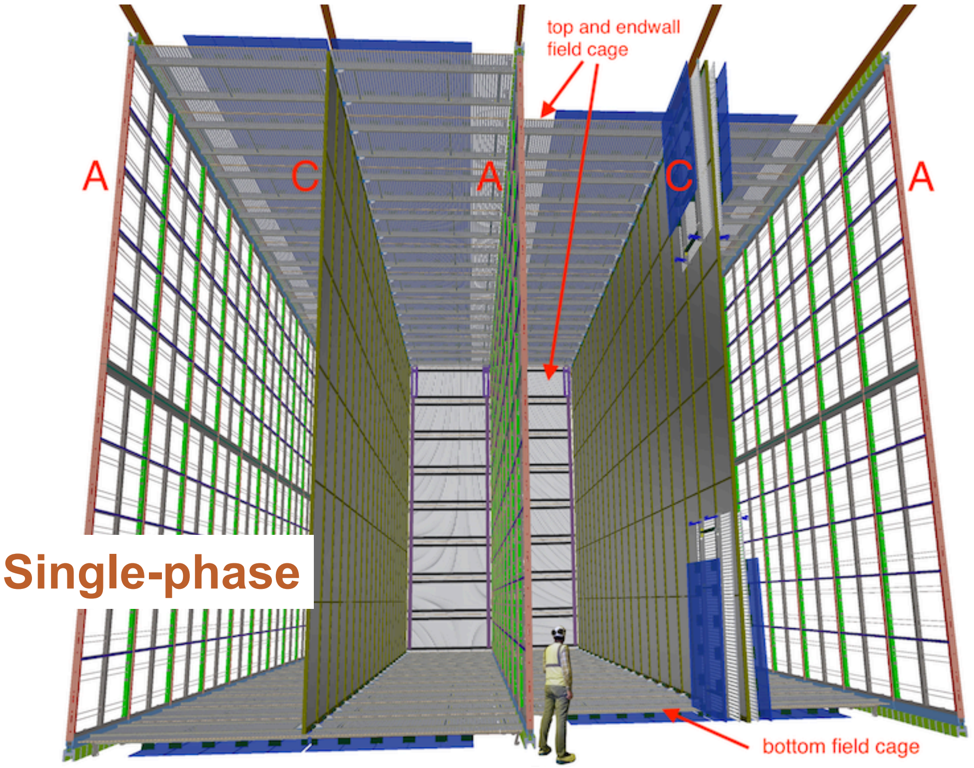
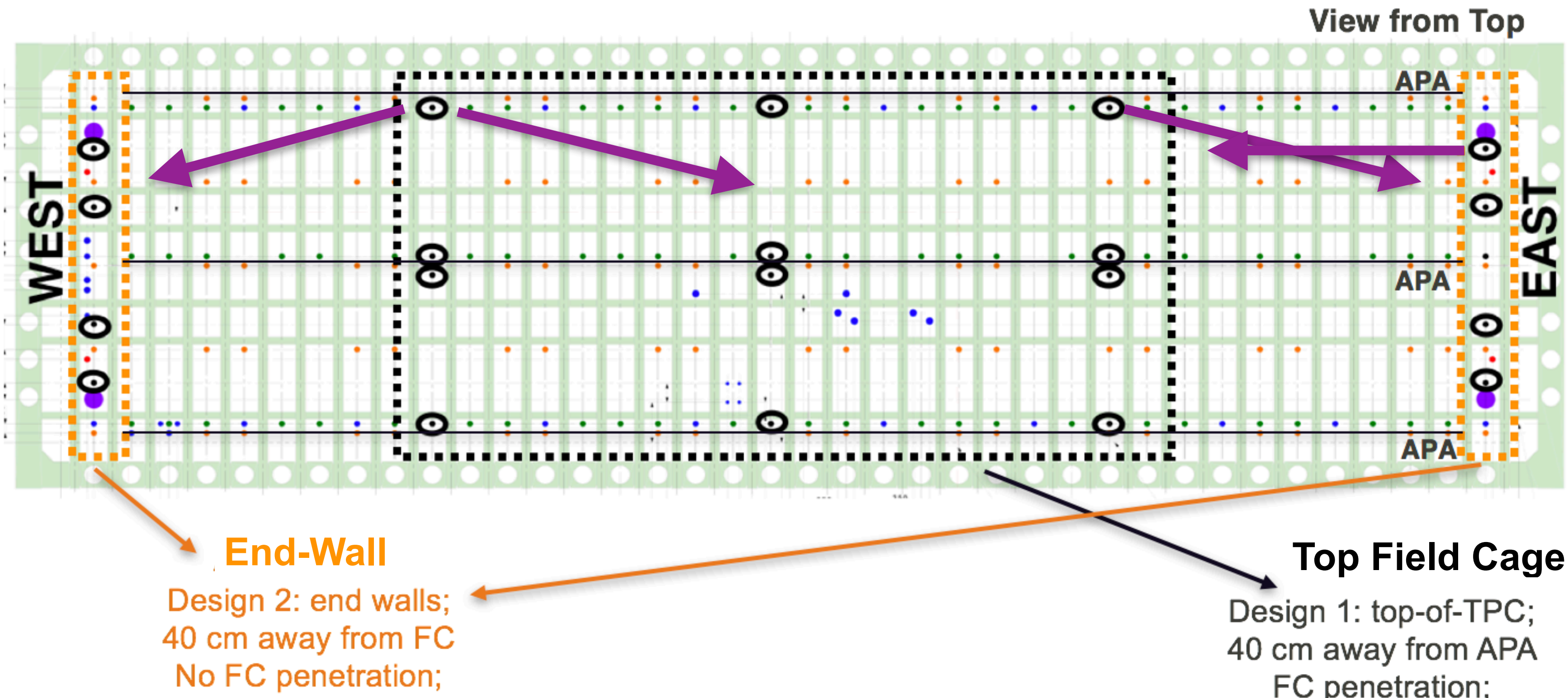
Laser calibration for DUNE

- Stringent physics requirements ~2% energy scale, and low statistics of cosmics deep UG
- Need dedicated calibration systems
  - position shifts of anode, cathode, HV system
  - various QC checks for wires, gaps, HV system
  - drift velocity/E-field
  - electron lifetime (under study)
  - photon detection system
- Challenge due to huge size (100x MicroBooNE !)



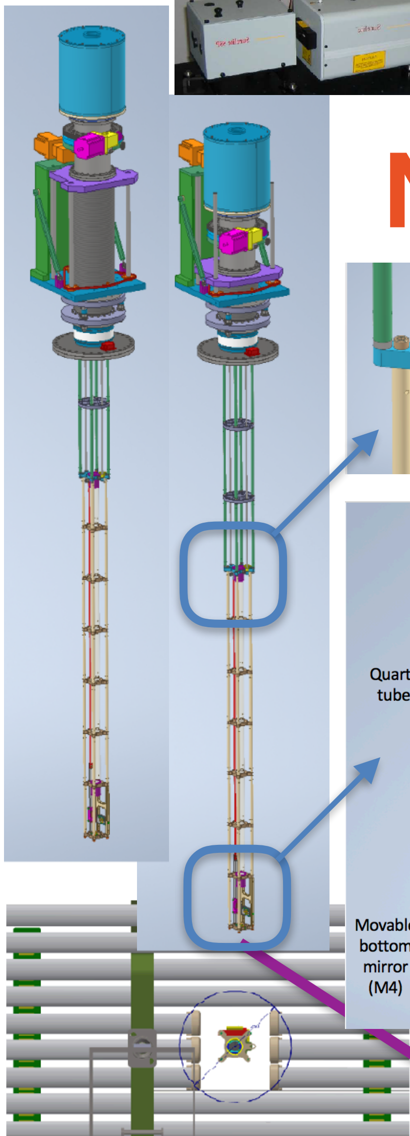
SP Calibration access ports

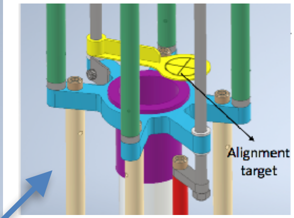
- Plan to have at least two lasers per drift volume. Range needs to be about 20m (MicroBooNE showed > 10m)
- New designs to avoid shadowing, improve alignment and checking direction

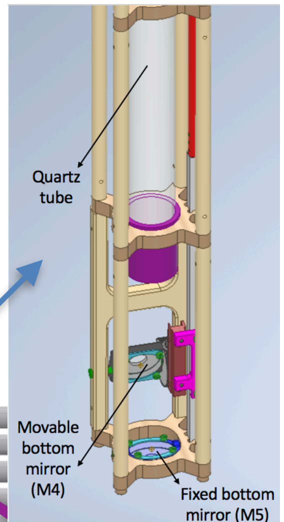


DUNE TDR
B. Abi et al 2020 JINST 15 T08010

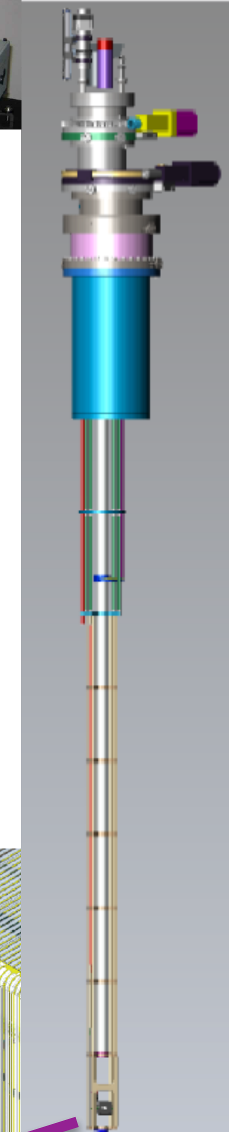
New designs for DUNE

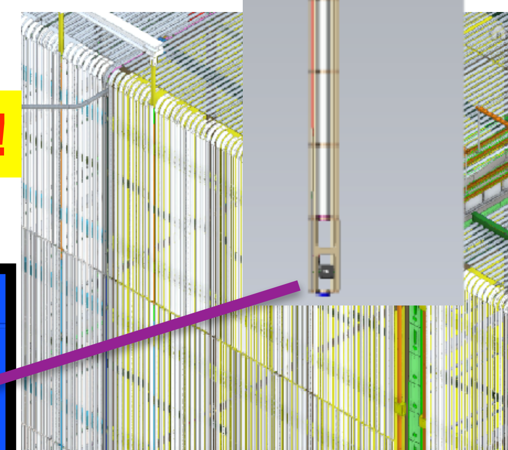






- Better coverage of TPC volume
  - opening on top FC (SBND also)
  - dual rotation for ports on the side
- Alignment system
  - target+camera+visible laser
- Beam location systems
  - fixed to Field Cage

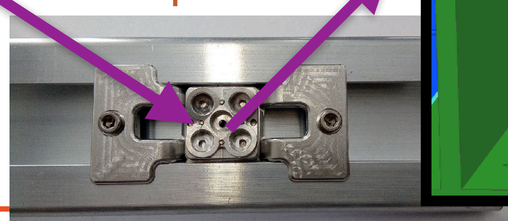




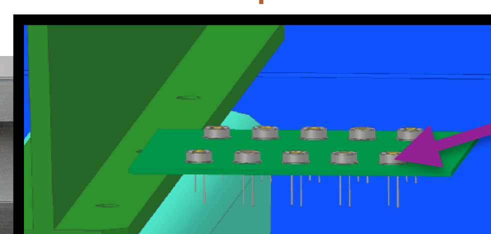
All drawings: Preliminary!

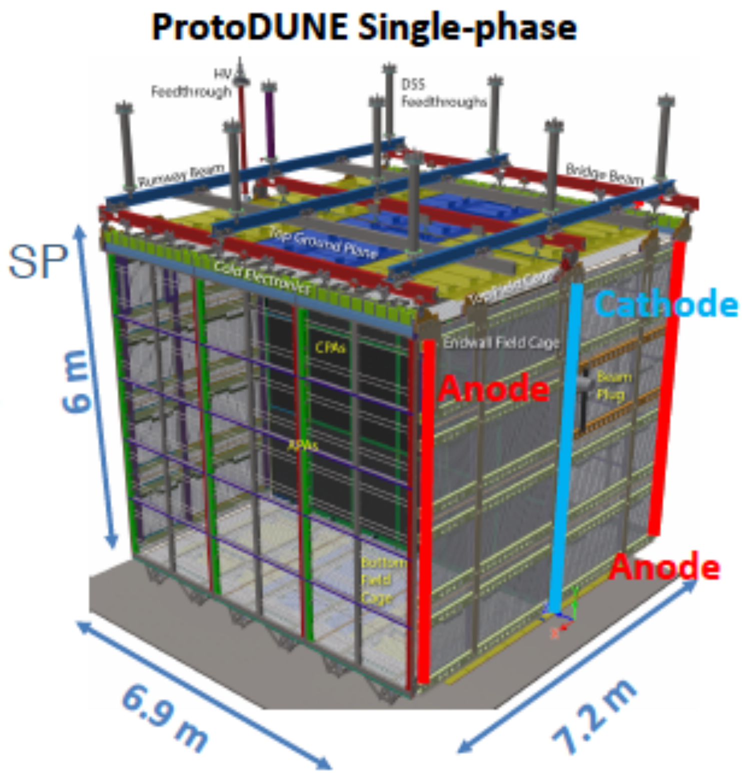
Vertical Retraction
Opening in top Field Cage

mirror pad



PIN diode pad



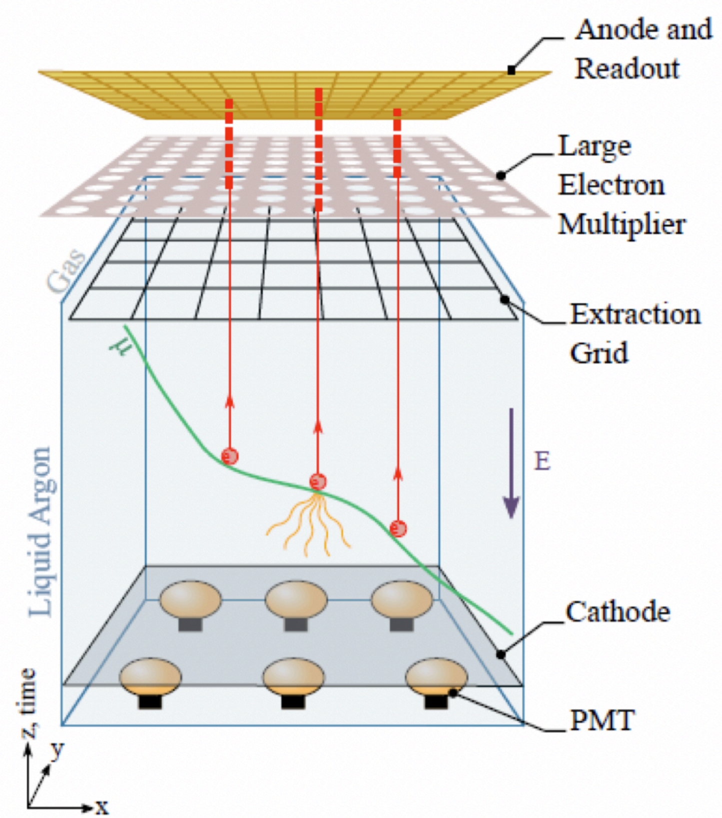


Upcoming: ProtoDUNE-II

- ProtoDUNE-I (just ended) has no dedicated TPC calibration systems
- All these new systems will be installed and tested in ProtoDUNE-II soon!

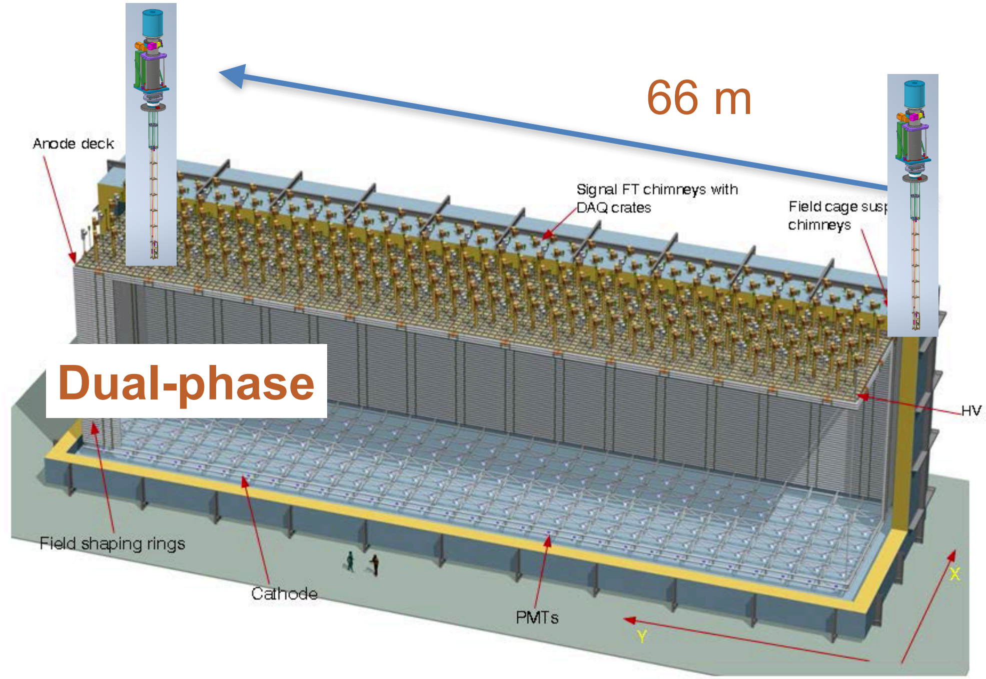
Dual-phase

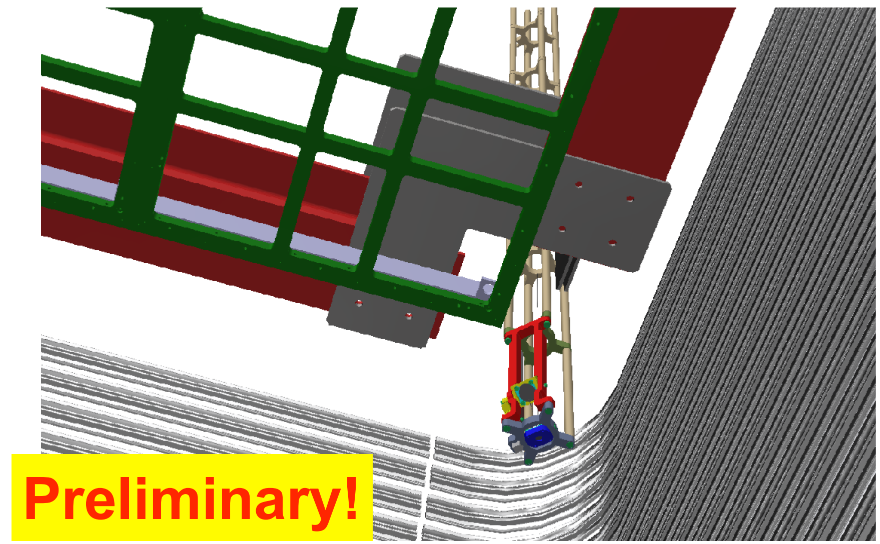
- Dual-phase has better S/N than SP, but larger SCE
- Dual-phase has a longer drift length: 12 m instead of 3.6 m.
- Due to amplification, ions produced in gas phase are much more than in the liquid and can drift back into the liquid causing much more SCE
- SCE in DUNE SP expected to be low (<1%) but in DP could be up to 15%, similar to SP detectors at surface
- Even more crucial to measure this effect in Dual-Phase



Dual-phase

- Design for calibrations in dual-phase less advanced than in SP
- Current idea is to use the same type of periscopes, inserted in gap between anode readout and field cage
- Should be possible to deploy 12 periscopes in a single module of DUNE DP





Source Calibrations

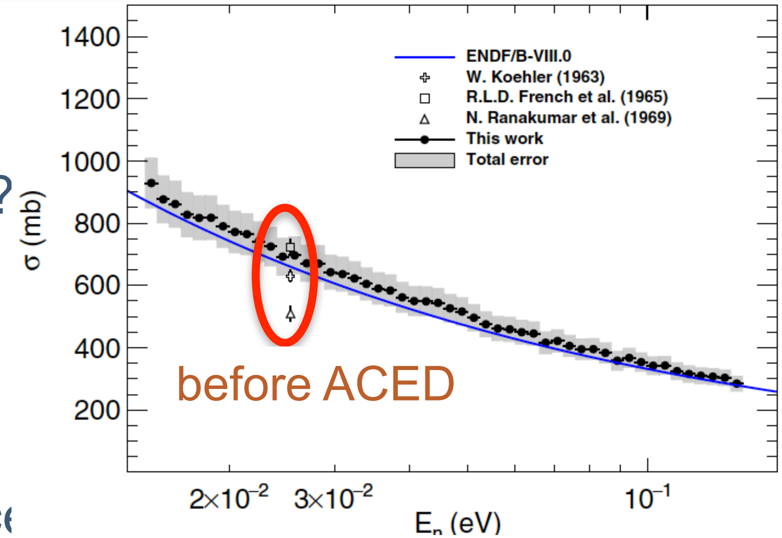
- Pulsed neutron source
- Radioactive source deployment

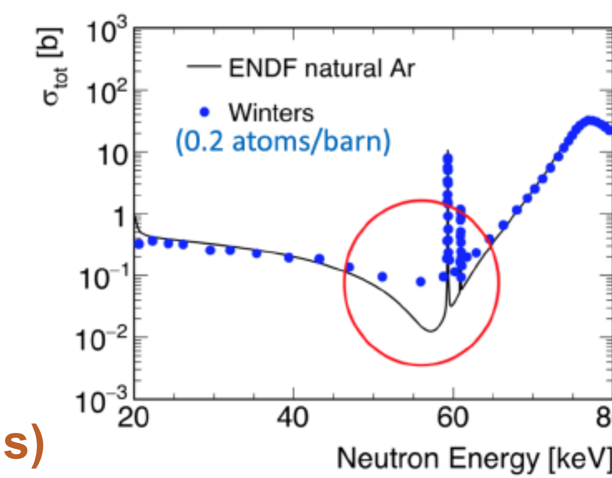
Neutron interactions in argon

$n + {}^{40}Ar = {}^{41}Ar + 6.1$ MeV

V. Fisher et al., Phys. Rev. D 99, 103021

- Measurements at Los Alamos answering these questions:
  - Thermal neutron capture cross section? [ACED, published]
  - Correlated gamma cascade? [ACED, ongoing]
  - Neutron-argon scattering anti-resonance @ 57 keV? [ARTIE, ongoing]
- Idea: use an external neutron source to calibrate DUNE
  - 6.1 MeV events calibrate low energy response (SNB, solar)

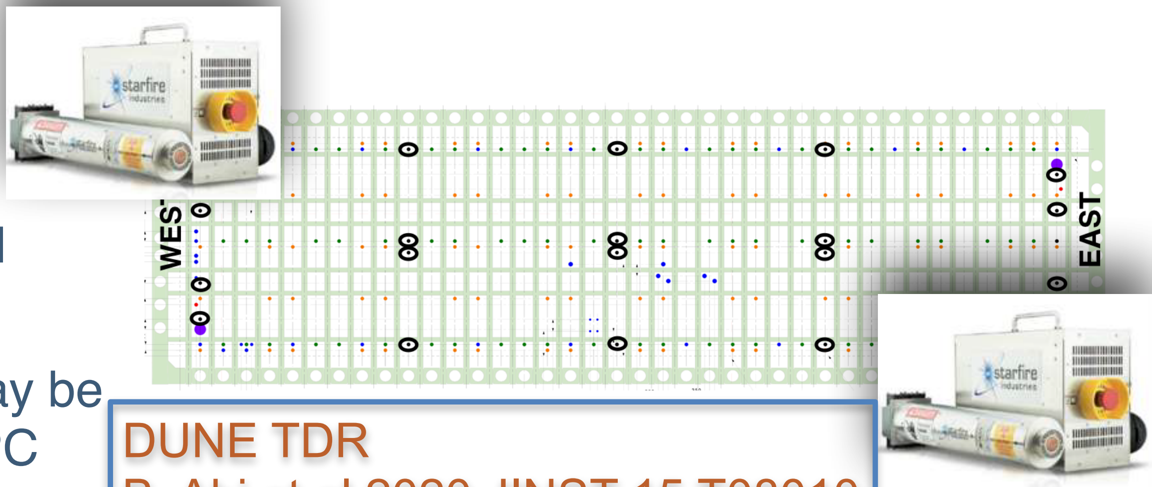




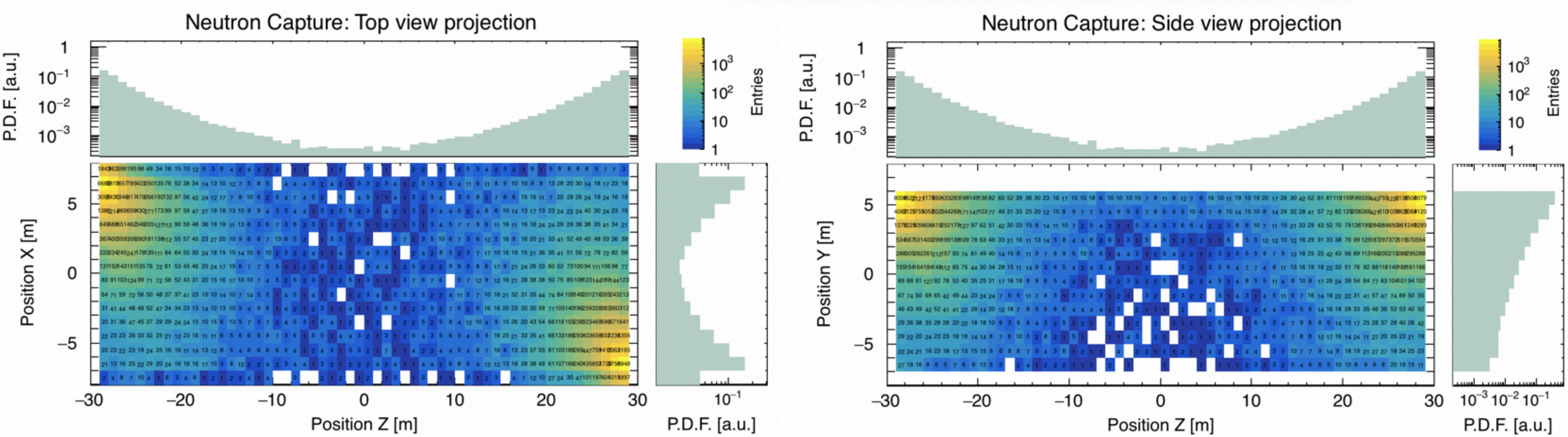
Proposed by Bob Svoboda (UCDavis)

Neutron Calibrations in DUNE

- Source: commercial DD generators, 2.5 MeV
- At a cryostat port, just to avoid absorption in insulation layer
- Two locations at both ends may be enough to cover 58 m long TPC



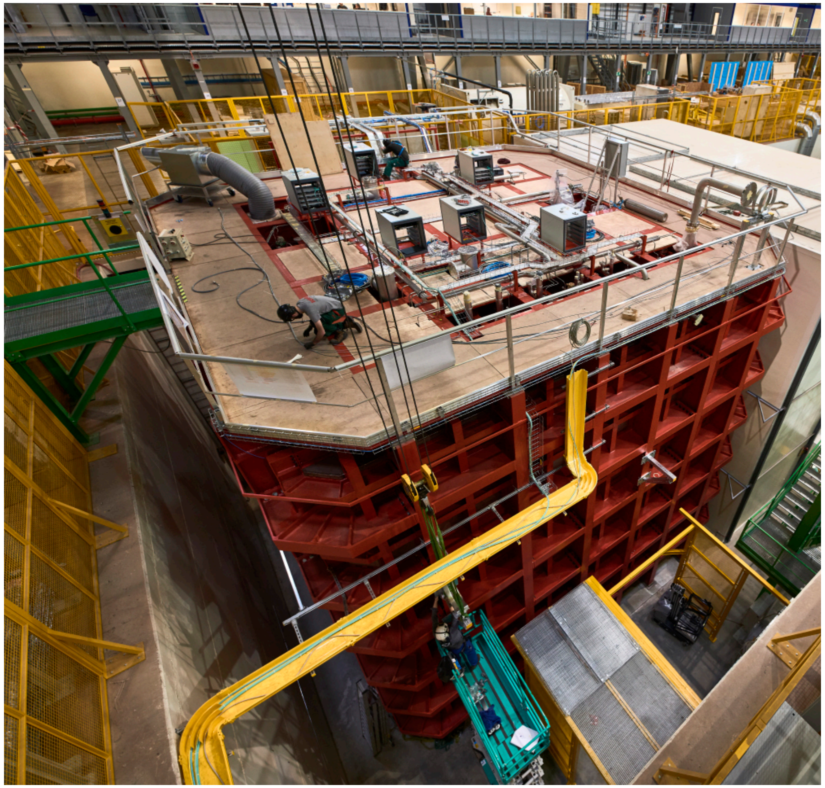
DUNE TDR
B. Abi et al 2020 JINST 15 T08010



Tests in ProtoDUNE

- Neutron (DD) generator sent from LANL to CERN this year
- Well-shielded and placed at a port on ProtoDUNE-SP
- Tests over a few days this July, just before turning detector off
- Valuable operational and physics data taken, analysis ongoing

Stay tuned!



Outlook

- Calibrations of TPCs from a combination of natural and dedicated sources
    - Many efforts over the years in ICARUS, LArIAT, ArgoNeuT, MicroBooNE, ProtoDUNE, SBND
- Dedicated sources more necessary for deep underground detectors
- Integrated plan for DUNE far detector
    - Long history of developments in laser calibration will have its next step in ProtoDUNE
    - New ideas with a neutron source
    - Plans for near detector starting to form. Gas and liquid argon TPCs

Acknowledgements

This work is funded by Portuguese national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., in the framework of project CERN/FIS-PAR/0012/2019

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Extra slides

^{39}Ar

- Naturally present ~1 Bq/kg
  - high statistics, uniform
- β-decay with Q = 565 keV
  - well defined spectrum, but very low energy
- Sensitive to:
  - e lifetime
  - Recombination
  - Electronics noise
- Challenges
  - unknown position in drift direction
  - triggering hard

MICROBOONE-NOTE-1050-PUB