ProtoDUNE

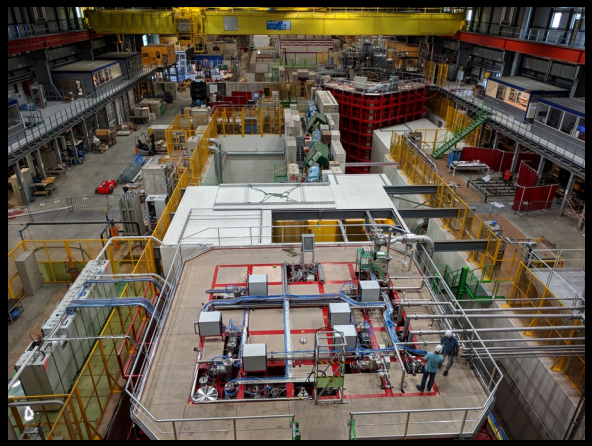
Roberto Acciarri – Fermilab
on behalf of DUNE collaboration

GSSI - NuInt18 - October 15th–19th, 2018

ProtoDUNE

We went from this →

To this →



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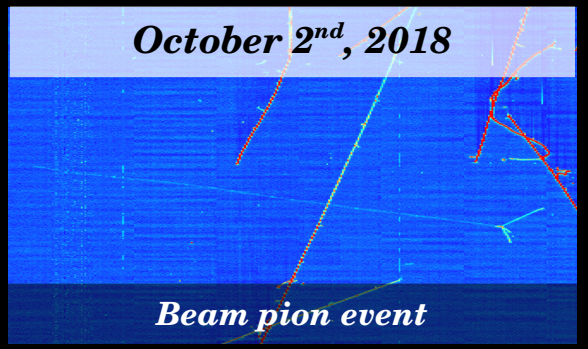


In less than two years.

This talk is about why, what for, and how

A step back to the future: DUNE

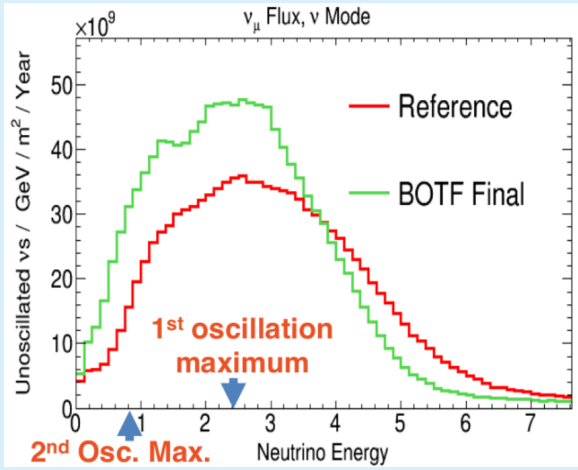
DUNE consists of:

Wide band neutrino beam

$\nu_\mu/\bar{\nu}_\mu$ beam

1300 km baseline, from Fermilab to SURF

1.2 MW power (2026), up to 2.4 MW (II phase, 2032)



Far Detector (FD)

Hosted at SURF, South Dakota

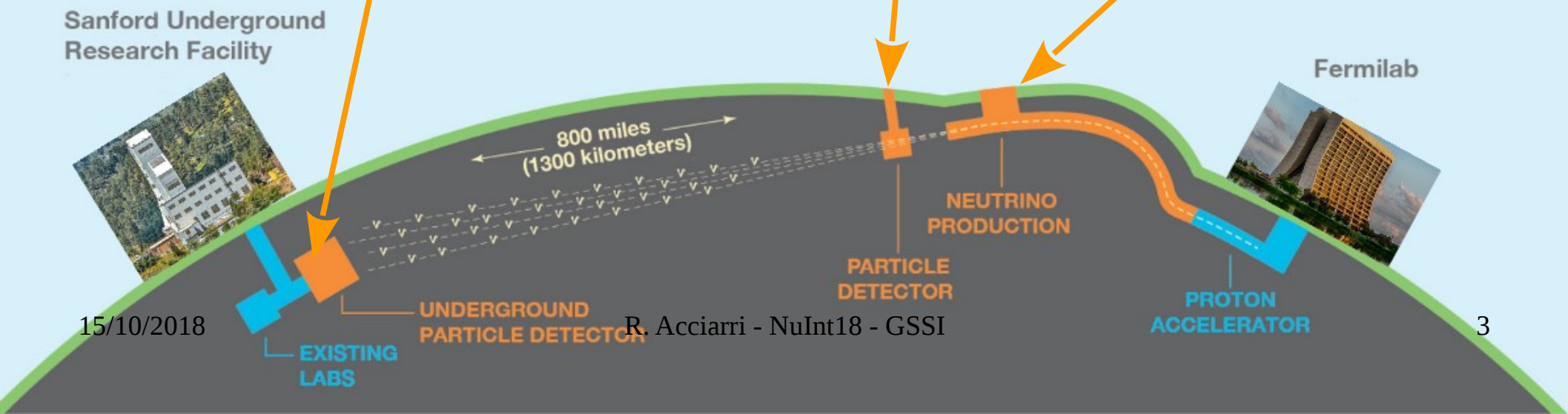
New hall, 1.5 km depth (4300 mwe)

4 LArTPC, 40 kton fid. vol. (70 kton tot.)

1st module operational in 2024

Near Detector (ND)

Hosted at Fermilab



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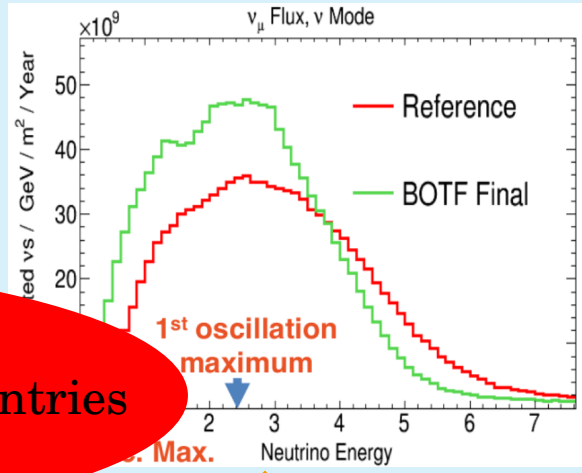


Far Detector (FD)

Hosted at SURF, South

New hall, 1.5 km d

4 LArTPC, 40 kton

1st module operational in 20

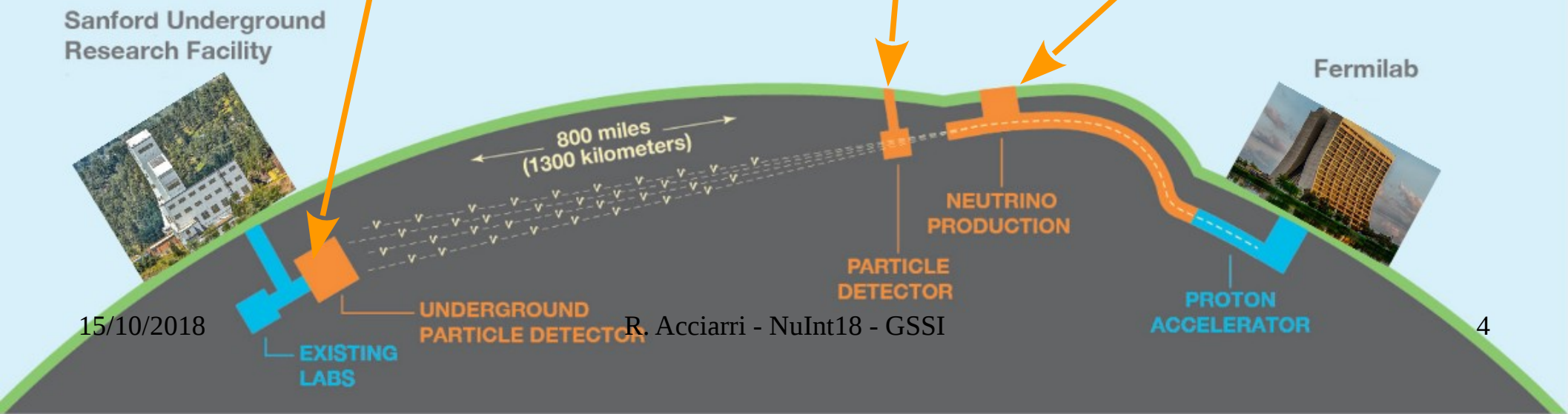
Strong international collaboration

1100+ collaborators /178+ institutions / 32+ countries

"LHC – size" neutrino experiment!

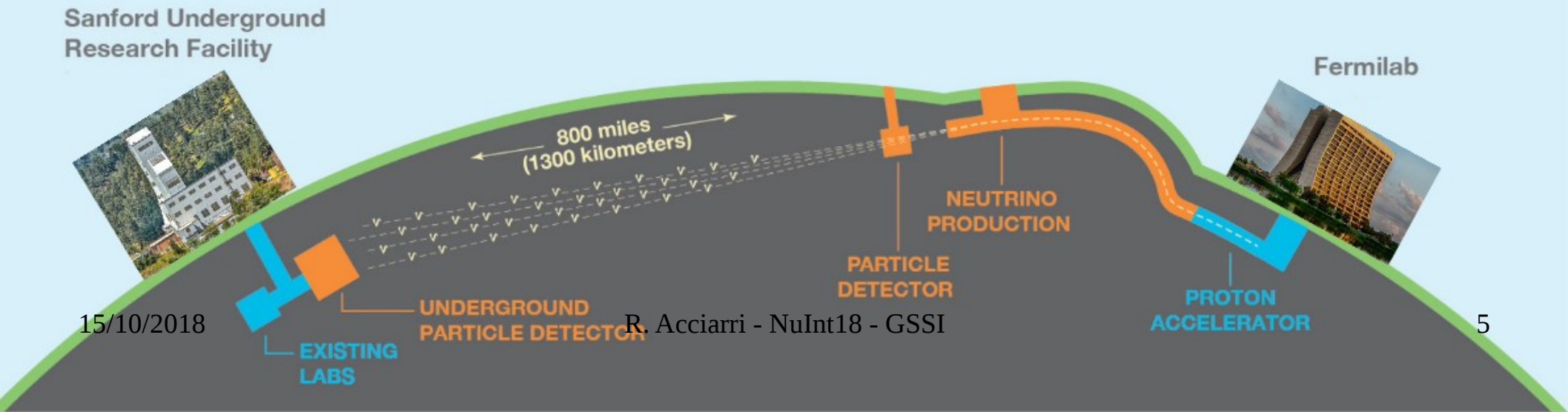
Near Detector (ND)

Hosted at Fermilab



DUNE physics

- Precise measurement of neutrino oscillations parameters ($\nu_\mu/\bar{\nu}_\mu$ disappeareace, $\nu_e/\bar{\nu}_e$ appearance), in particular δ_{CP} violation phase
- Detection of galactic-core supernovae neutrinos
- Proton decay, especially in the K-production modes ($p \rightarrow K^+\bar{\nu}$; $p \rightarrow K^0\mu^+$; $p \rightarrow K^+\mu^-\pi^+$)
- Search for NSI (Non Standard Interactions)



DUNE physics

Ambitious program, achievable with an ambitious detector!

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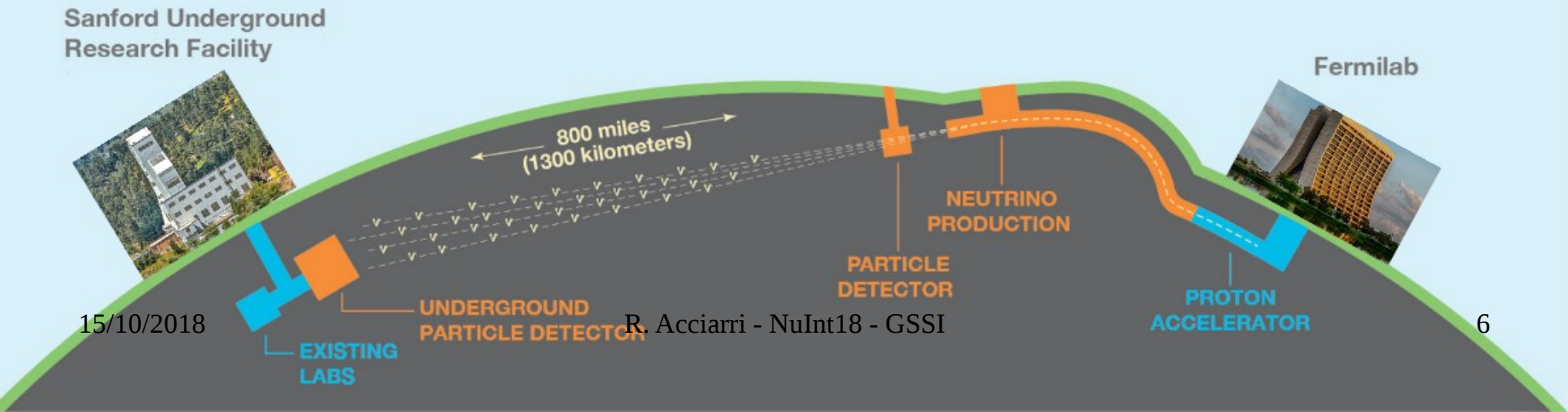

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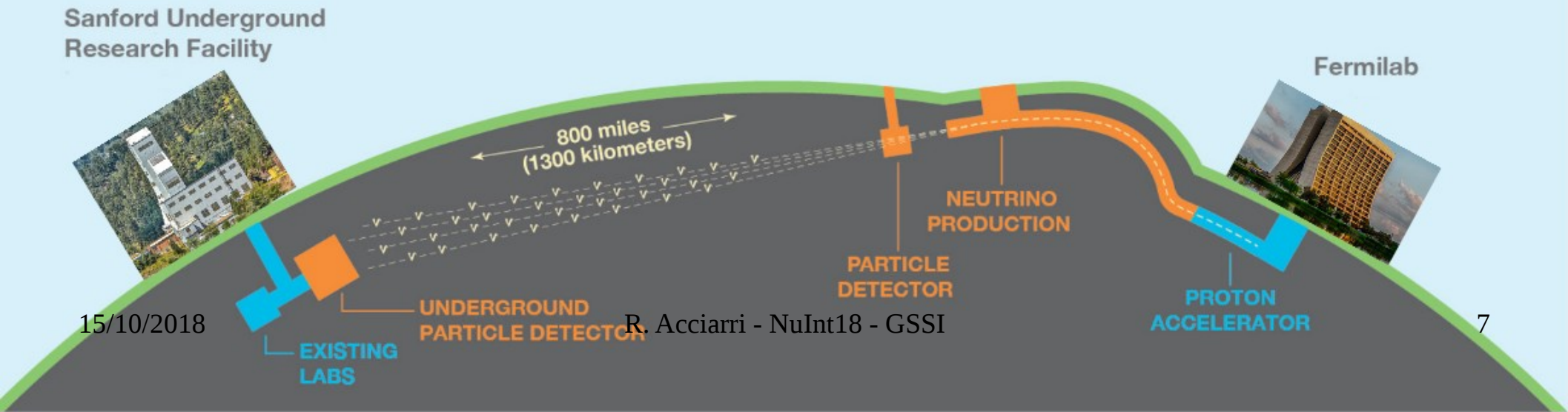
Largest LArTPC operated before 2018 was ICARUS (600 ton).
Moving from 0.6 kton to 4X17 kton requires brand new engineering and technology solutions



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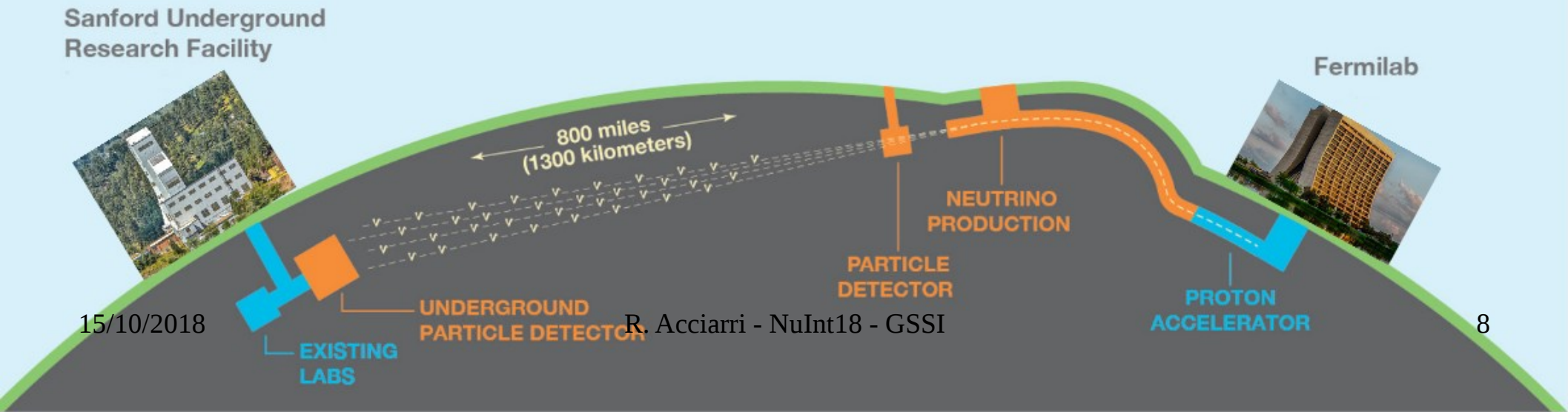

DUNE physics

Ambitious program, achievable with an ambitious detector!

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Unusual giant size (of detectors, collaborators, computing needs) for a neutrino experiment. Requires further development of both people's expertise and DAQ/analysis softwares

core supernovae neutrinos

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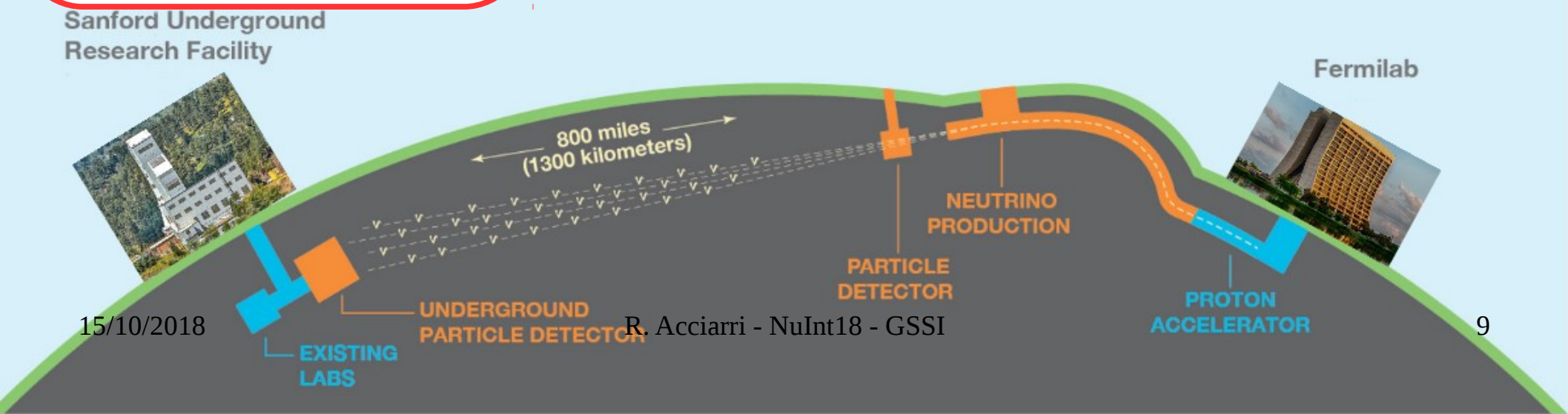

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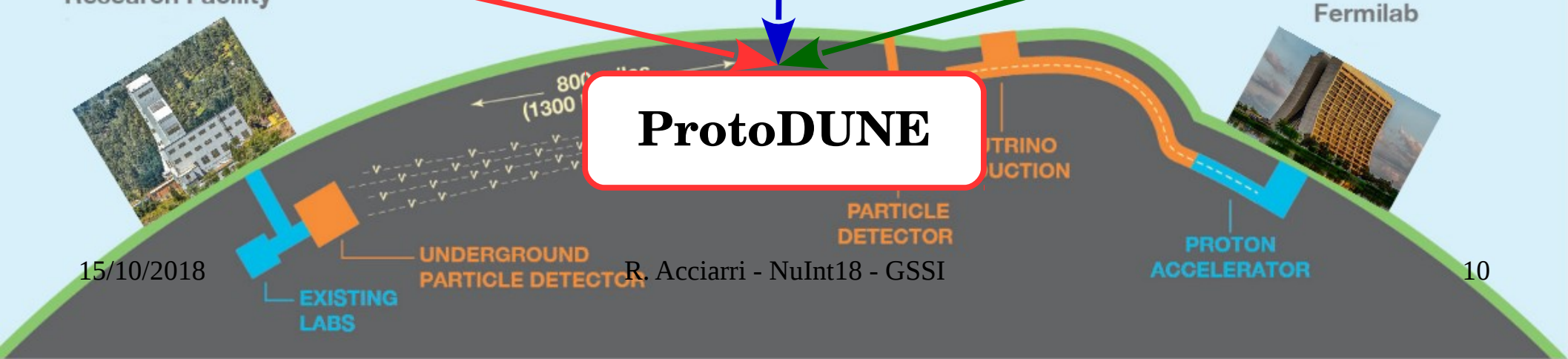


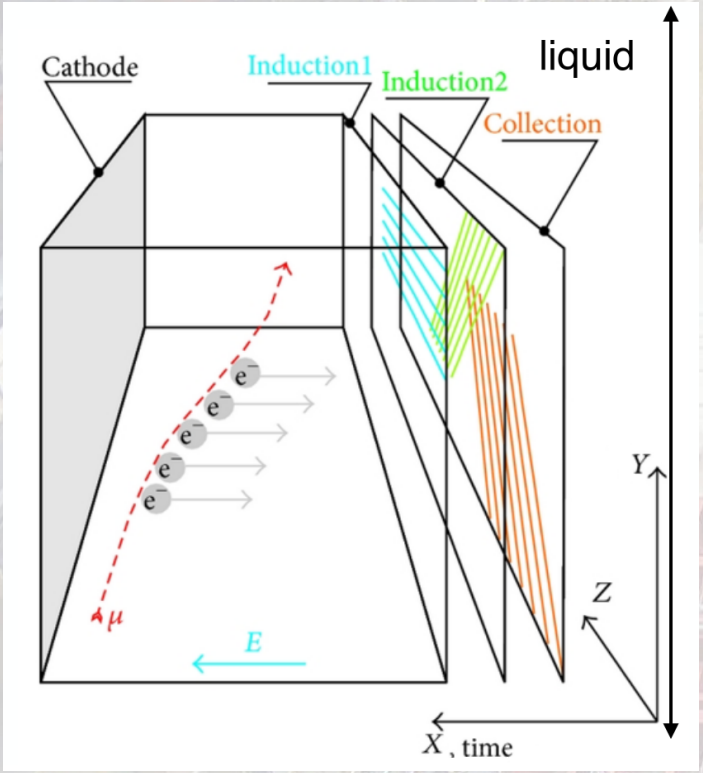
ProtoDUNE

The biggest small prototype

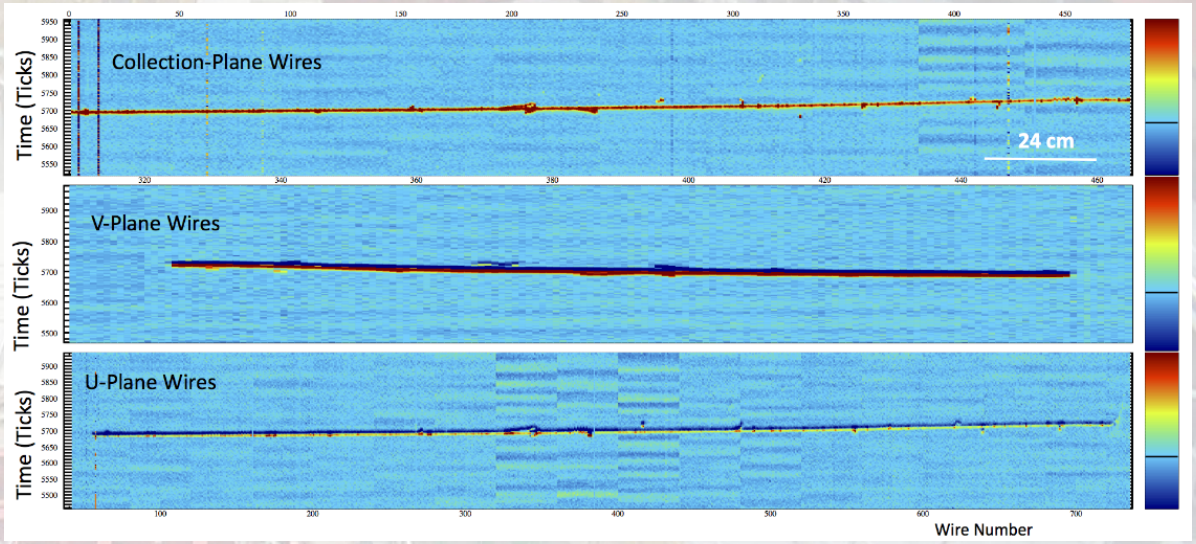
ProtoDUNE – a set of two LArTPC operated at the CERN Neutrino Platform facility – is:

- **Big!** Two identical cryostats ~12m x 12m x 11m dimensions, holding ~800 ton of LAr each. Detectors are made with full scale elements designed for DUNE FD → **test of FD engineering solutions and installation procedures**
- **Small!** Each detector is 1/20 of one module, ~ 1% of DUNE! → **optimal size for effective tests within the DUNE timeline**
- **Double!** Two detectors with similar technologies: standard "single phase" LArTPC – planned for the first DUNE FD module –, and the alternative "dual phase" LArTPC design → **validation of LArTPC tecnology, detector response and long-term stability for DUNE FD optimization**
- **Beamy!** Detectors exposed to two independent low energy beam lines → **characterization of LArTPC response to charged particles in the same energy range (1 – few GeV) of neutrino interactions in DUNE**
- **International!** Strong collaboration between the involved countries → **building the community and forming the expertise for DUNE**

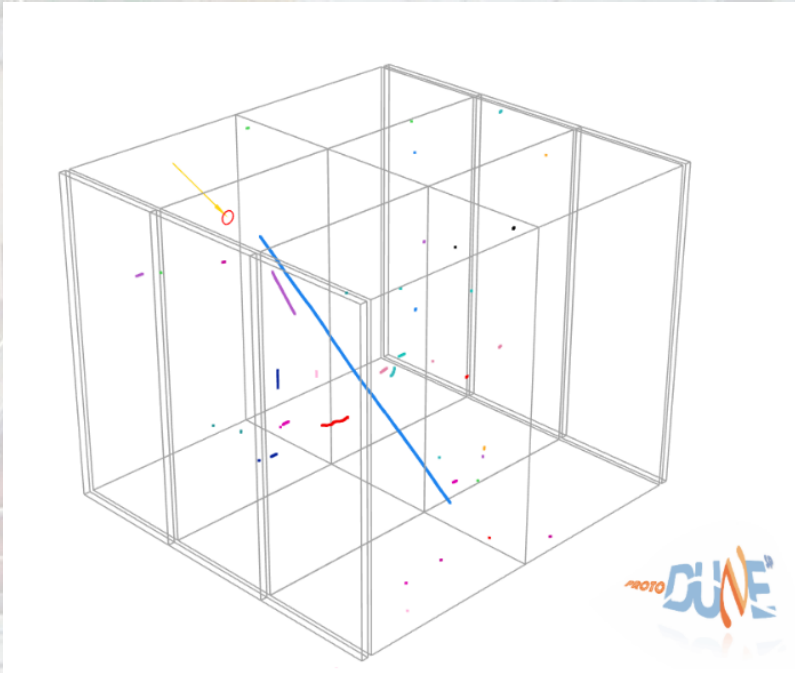
ProtoDUNE-SP: How does it work?



ProtoDUNE-SP real data



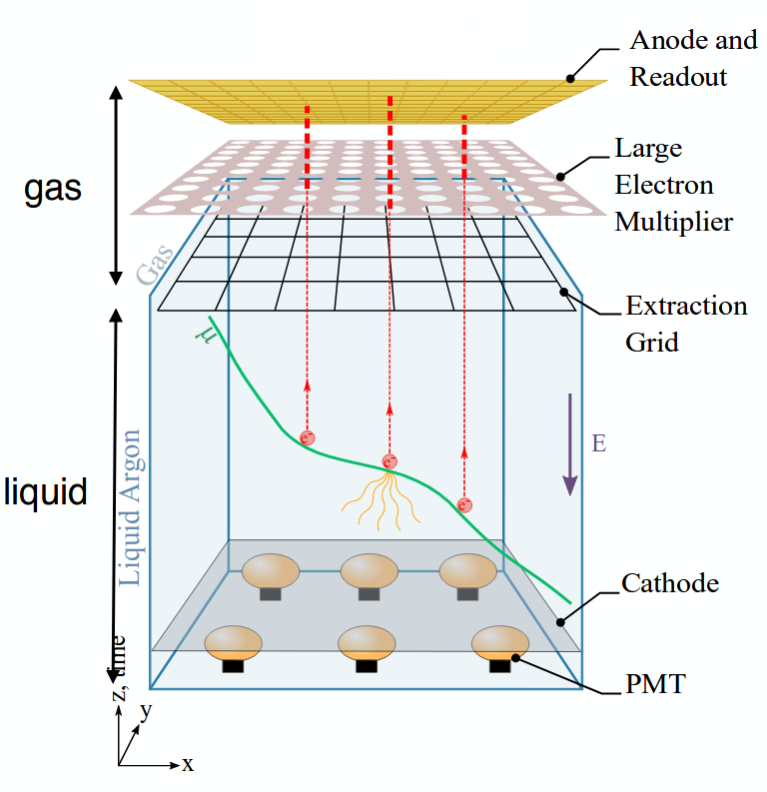
2D Reconstruction



3D Reconstruction

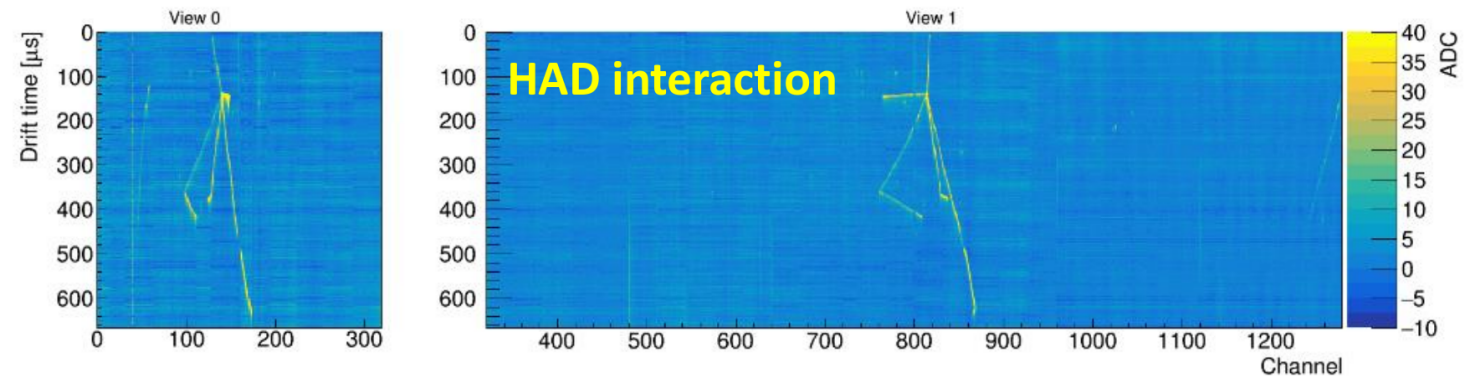
- Ionization charges drifted horizontally and read out by a set of 3 wireplanes for 3D reconstruction and calorimetry
- LAr scintillation light collected by photon detection system behind wireplanes for event triggering
- No signal amplification in liquid (expected S/N ratio between 15 and 70)

ProtoDUNE-DP: How does it work?



- Ionization charges drifted vertically, transported into the gas phase by means of an extraction grid, amplified in the Large Electron Multiplier (LEM), and readout via 2D segmented anode for 3D reconstruction and calorimetry
- LAr scintillation light collected by PMTs below the cathode for event triggering
- Signal amplification in gas with LEMs (expected S/N ratio between 80 and 100)

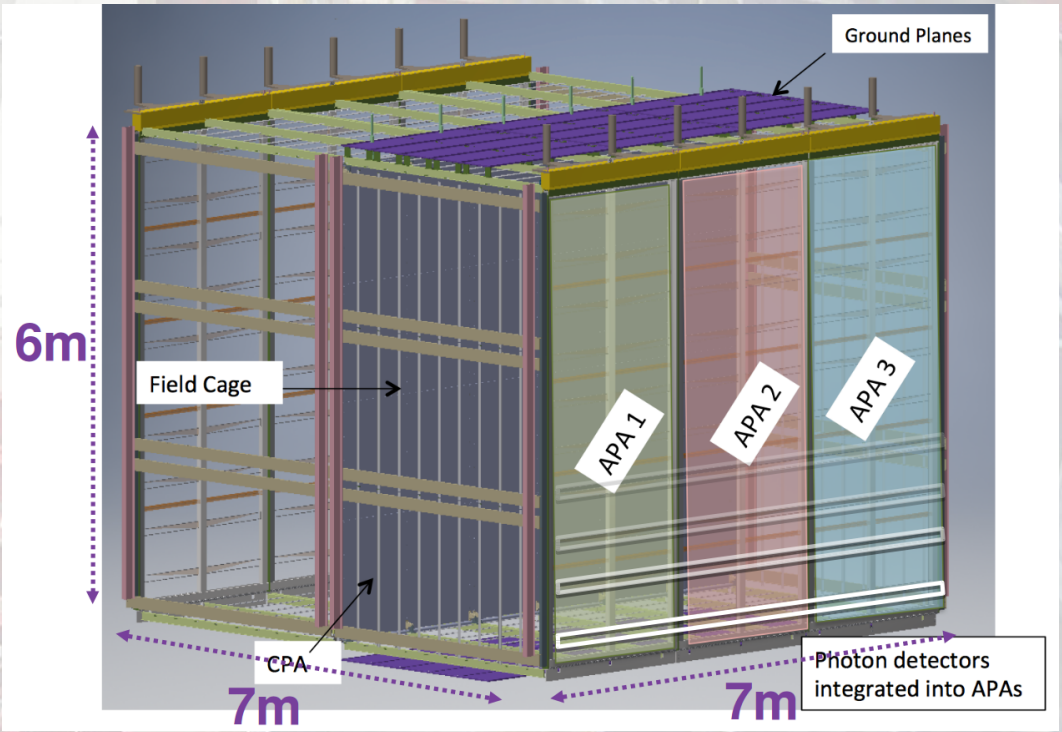
Dual Phase TPC real data (3x1x1 m³ prototype @ CERN)



ProtoDUNE-SP overview

2 TPCs 6 m high, 7 m wide, 3.6 m deep, sharing the cathode

- ***6 Anode Plane Assembly***
  - ✔ 4 wire planes installed on SS frame
  - ✔ Cold electronics (preamplifier+digitizer) installed on the APA top
- *3 **C**athode **P**lane **A**ssembly*
  - ✔ Resistive Kapton laminated on dielectric panels
  - ✔ 180 kV nominal (3.6 m drift @ 500 V/cm): **same as for DUNE FD**
- *16 Field Cages*
  - ✔ Aluminum profiles on dielectric frame, provides constant 500 V/ cm electric field
  - ✔ Top and bottom elements equipped with perforated SS ground planes to ensure null field outside active volume

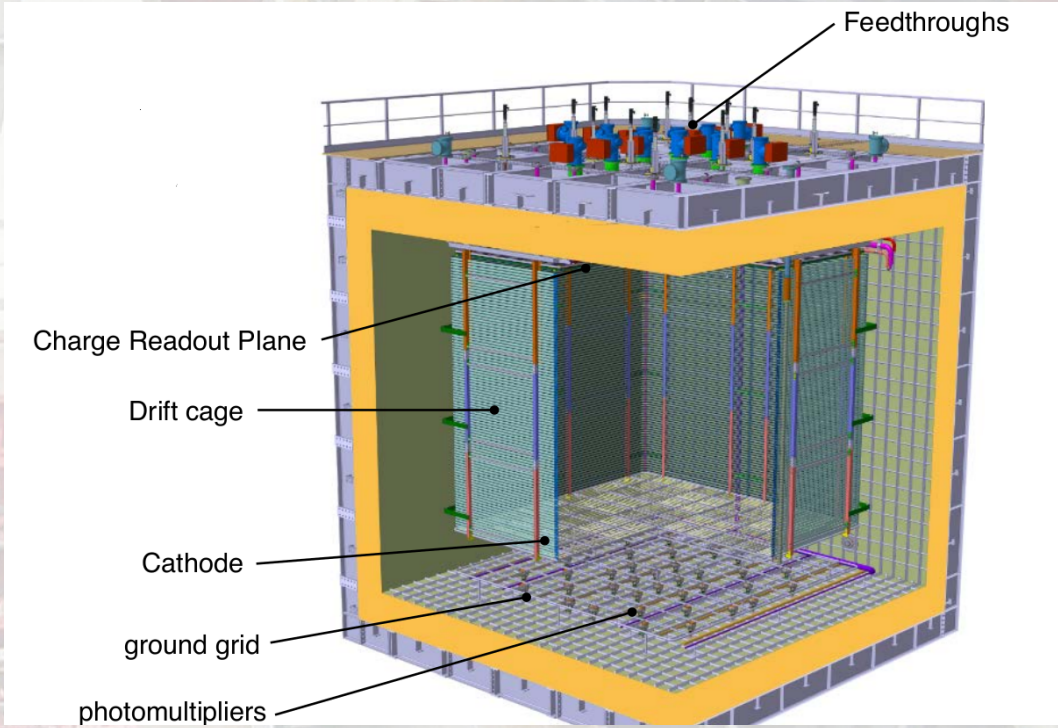


- *60 Photon Detectors*
  - ✔ Light collecting bars read out by SiPMs installed in the APA frame (10 detectors/APA)
  - ✔ high coverage with small number of channels, no HV needed
  - ✔ 3 distinct versions installed → testing solutions for DUNE

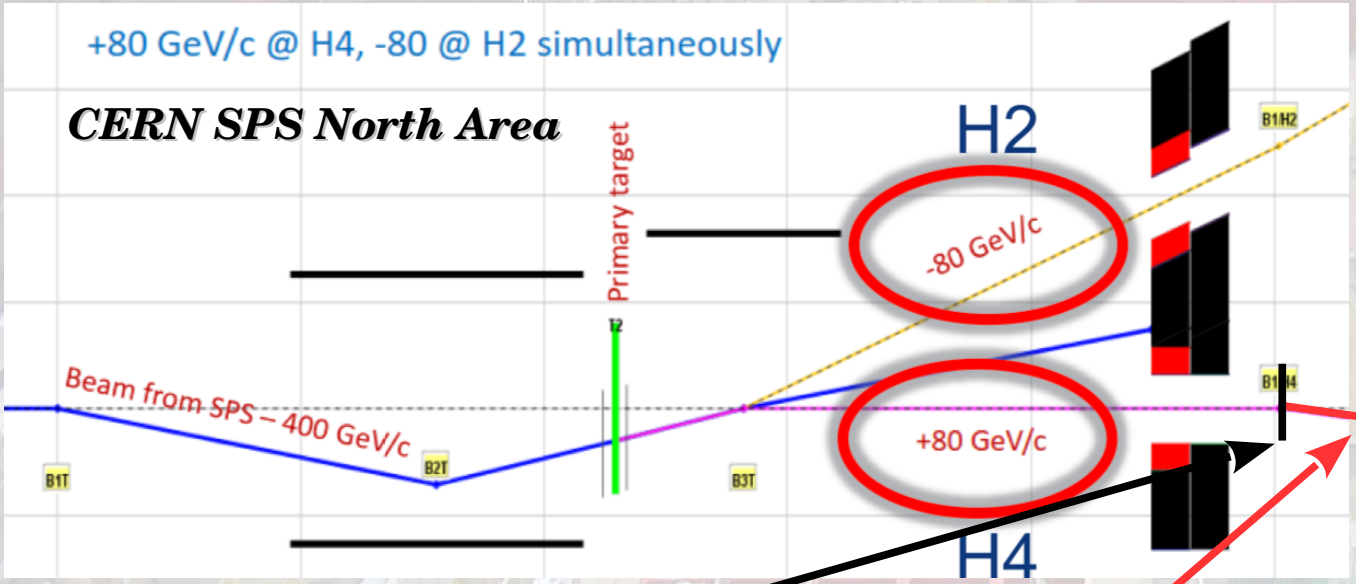
ProtoDUNE-DP overview

1 TPC 6 m high, 6 m wide, 6 m deep

- ***4 Charge Readout Plane***
  - ✔ Readout plane containing extraction grid, LEM and anode
- ***Cathode***
  - ✔ Grid of SS tubes to allow collection of light by PMTs placed below
  - ✔ 300 kV nominal (6 m drift @ 500 V/cm): **half as for DUNE FD**
- *8 Drift Cages*
  - ✔ Similar design to single phase field cages, covers vertical sides of the detector
  - ✔ No ground planes protecting HV region
- *36 Photon Detectors*
  - ✔ 8” PMTs, photocathode evaporate with TPB (Tetraphenyl Butadiene) to convert VUV LAr scintillation light into visible spectrum



The H2/H4 VLE beam line @ the Neutrino Platform



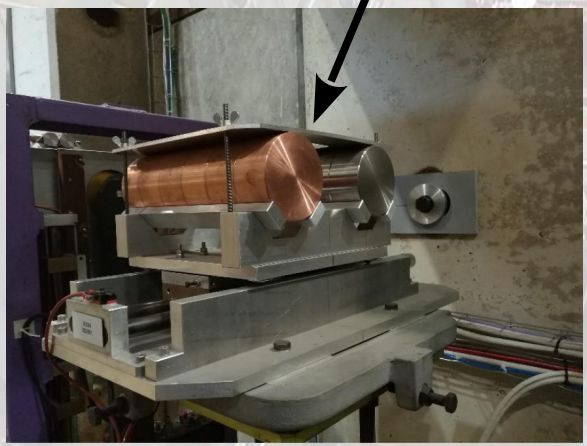
400 GeV/c P beam from SPS

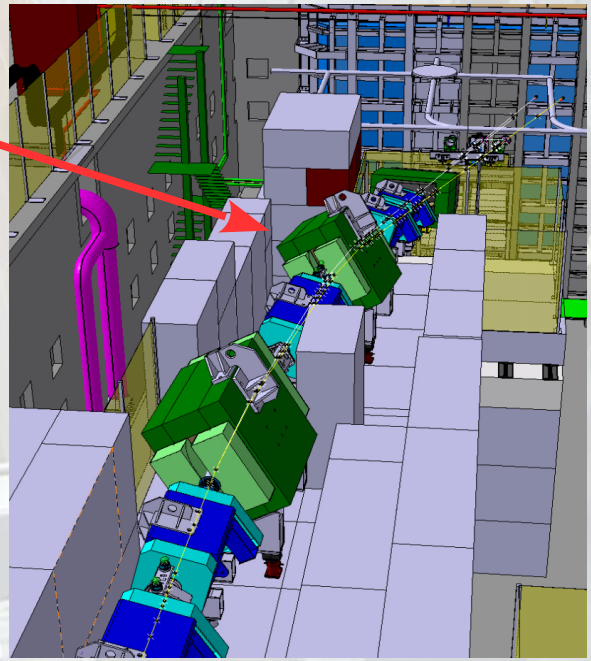
80 GeV/c secondary π^+ beam

~0.5 – 7 GeV/c tertiary e^-,p,μ^+,π^+ beam

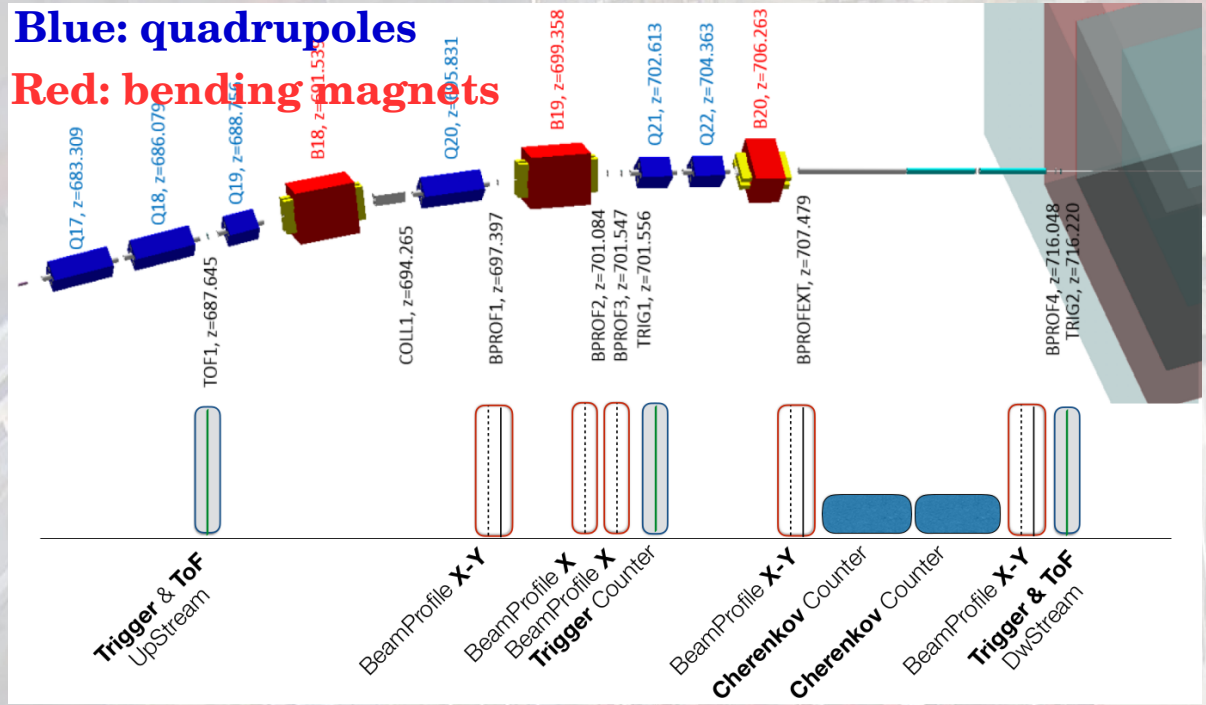
ProtoDUNE-SP (secondary) target

H4 VLE beam line





H4 VLE Beam line elements

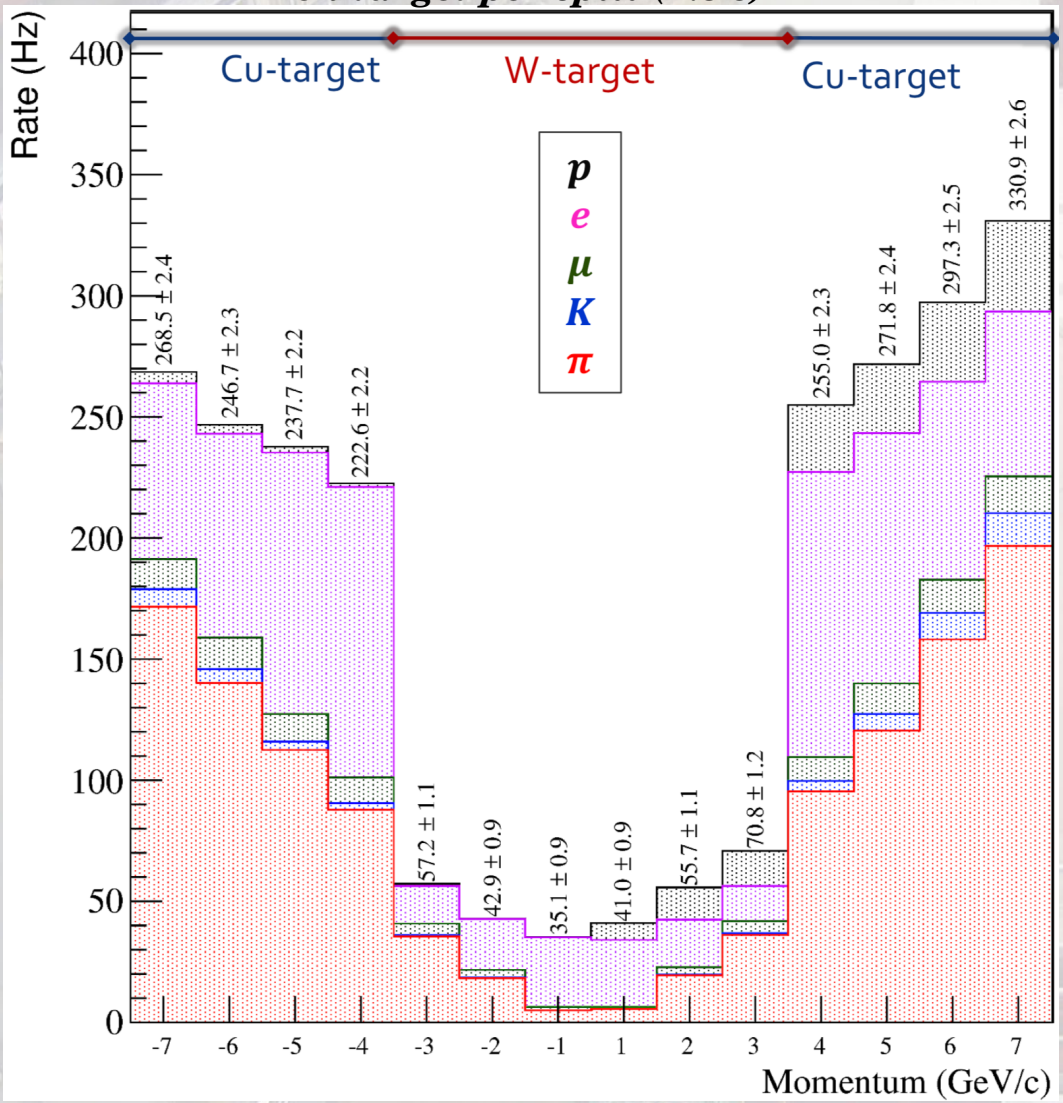


- Dipoles for bending and momentum selection
- Quadrupoles for focusing the beam
- Scintillators for trigger and TOF
- Scintillating fibers as beam profilers
- Cherenkov detectors in front of the cryostat for particle tagging (along with TOF)

Beam profilers

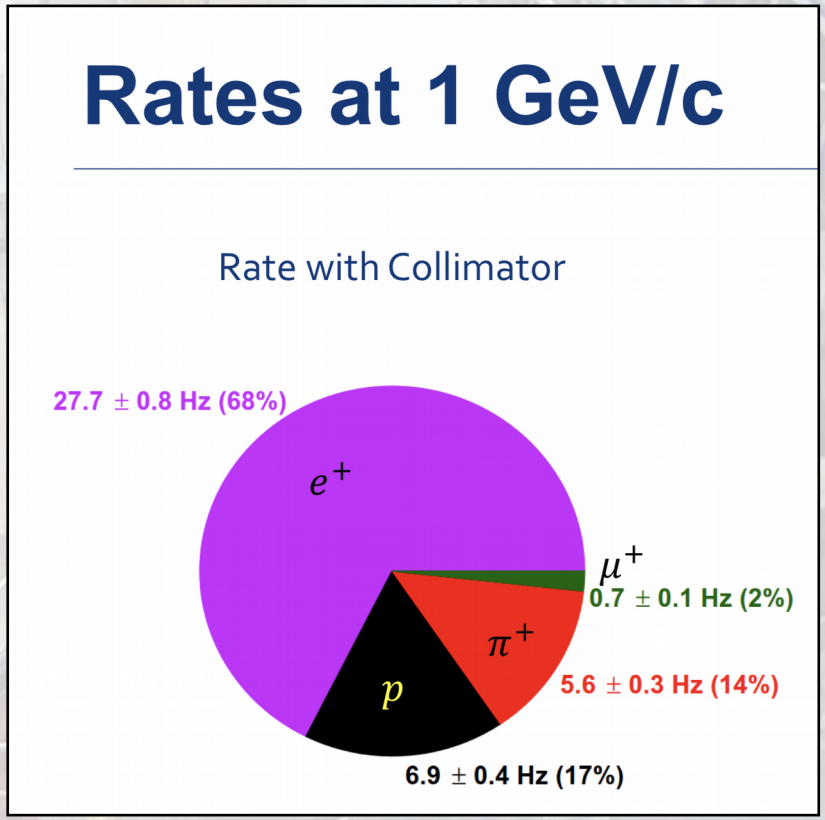
H4 VLE beam

Expected Rates (MC Calculation): normalized to 10^6 π^+ on target per spill (4.8 s)



Two beam configurations:

- hadron beam with electron contamination (W/Cu target)
- Pure electron beam (Pb target)



ProtoDUNE-SP next (beam) events

Ottobre 2018

Lunedì	Martedì	Mercoledì	Giovedì	Venerdì	Sabato	Domenica
1	2	3	4	5	6	7
8	9	10 Beam off 8am - 6pm 6pm-midnight: 7 GeV all trigger	11 7 GeV all trigger	12 1 GeV Pi and proton veto on electron	13 1 GeV Pi and proton veto on electron	14 1 GeV Pi and proton veto on electron
15 1 GeV Pi and proton veto on electron	16 1 GeV Pi and proton veto on electron	17 Beam off 8am - 6pm 6pm-midnight: 6 GeV all trigger	18 6 GeV all trigger	19 2 GeV Pi and proton veto on electron	20 2 GeV Pi and proton veto on electron	21 2 GeV Pi and proton veto on electron
22 2 GeV Pi and proton veto on electron	23 2 GeV Pi and proton veto on electron	Beam off				
Beam off		31 Beam off 8am - 6pm 6pm-midnight: 4 GeV all trigger				

- Beam available until November 11th, with beam-off weeks for detector development
- Priority given to pion and proton runs at 1 GeV and 2 GeV, followed by hadron runs at higher energies
- Goal: > 300k pion events and >100k proton events at each momentum

Novembre 2018

Lunedì	Martedì	Mercoledì	Giovedì	Venerdì	Sabato	Domenica
Beam off		Beam off 8am - 6pm 6pm-midnight: 4 GeV all trigger	1 4 GeV all trigger	2 4 GeV all trigger	3 4 GeV all trigger	4 3 GeV Pi and proton veto on electron
5 3 GeV Pi and proton veto on electron	6 3 GeV Pi and proton veto on electron	7 Beam off 8am - 6pm 6pm-midnight: 3 GeV no electron	8 Electron only trigger 1 GeV	9 Electron only trigger 1 GeV	10 Electron only trigger 2 GeV	11 Electron only trigger 2 GeV
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

- Possibility to collect Kaons at high (4 GeV and above) energies
- Electrons collected both through dedicated runs (1 GeV and 2 GeV) and general runs (at higher energies)

ProtoDUNE physics

ProtoDUNE-SP beam data will allow to:

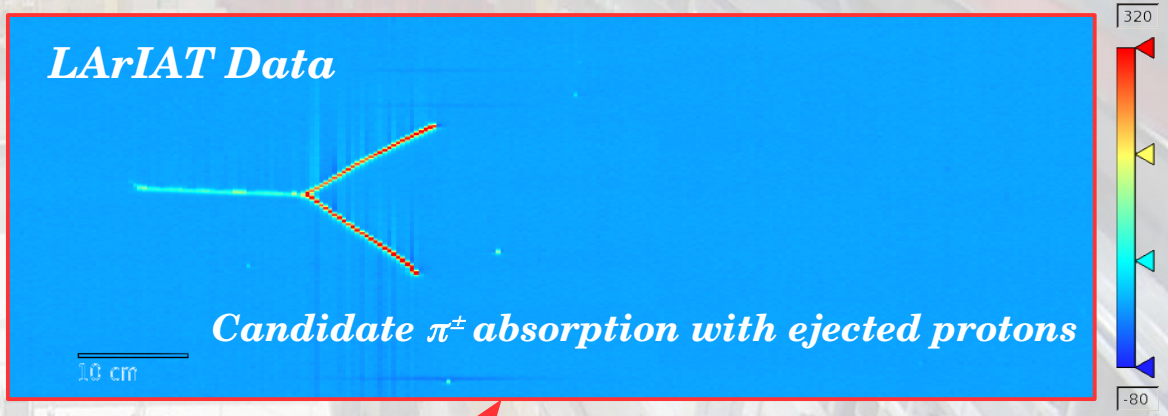
- Perform cross section measurements of hadrons on Argon
  - of interest for the entire LAr community (SBN)
  - knowledge of π-Ar interactions are key to control systematics for DUNE
- Validate on data the reconstruction algorithm performances
  - energy scale for both hadrons and electromagnetic showers
  - e-γ separation

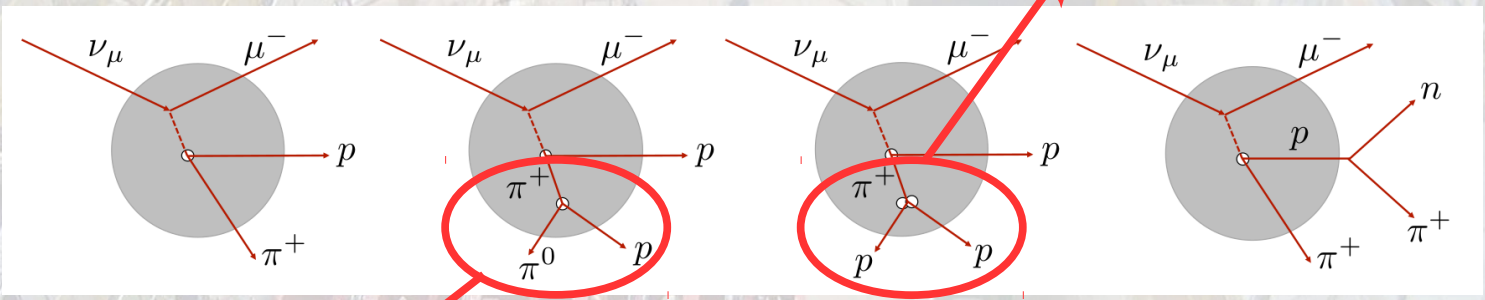
Data from cosmic runs (ProtoDUNE SP and DP) will be useful too:

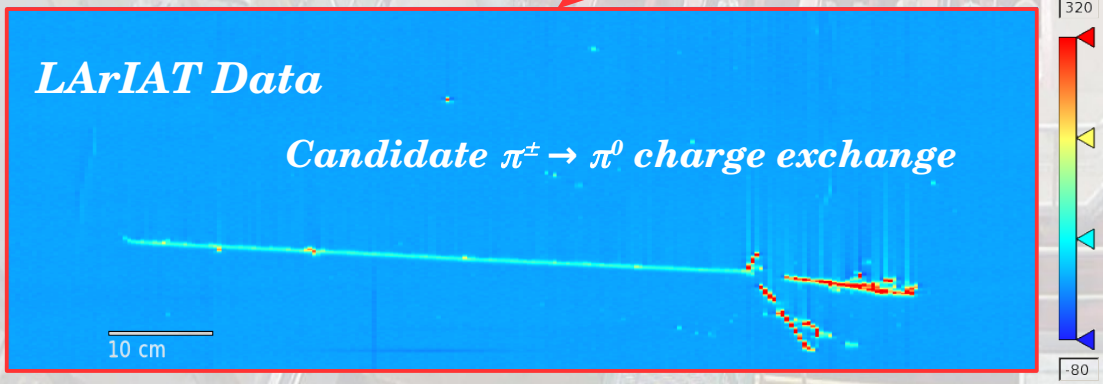
- Provide 3D map of detector response for space charge and E field distortion studies
- Run at different E field settings to test dE/dx, dQ/dx, and charge recombination models
- Identify and reconstruct Michel e^- in order to use their energy spectrum (10 – 60 MeV) to test the calibration of the detector in the energy range interesting for Supernova ν

ProtoDUNE-SP: π – Ar interaction cross section

Tune hadron – nucleus interaction and nuclear structure models through inclusive and exclusive cross section measurements





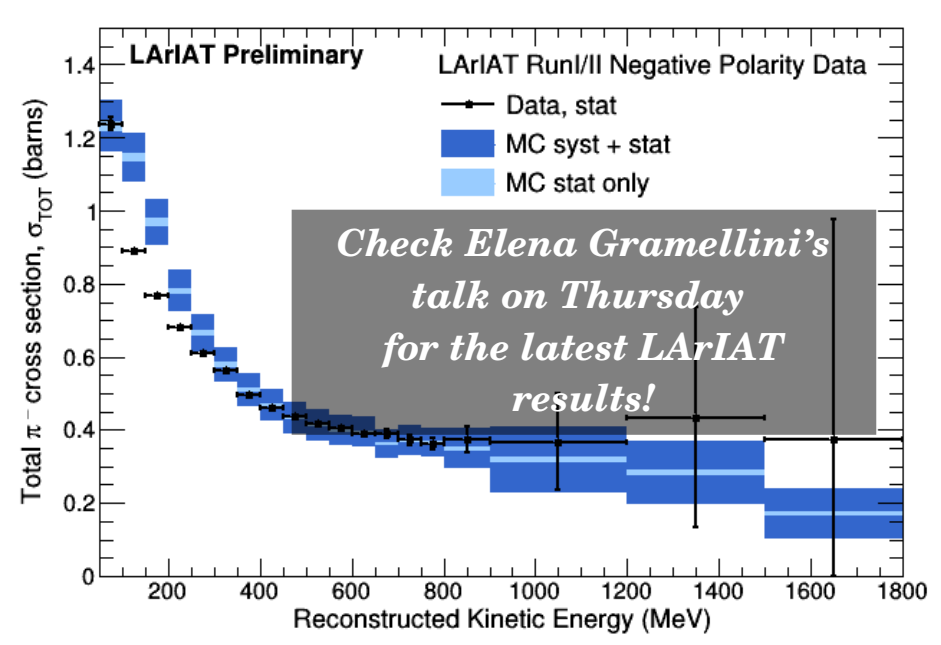


Neutrino interactions in the few GeVs energy range produce many pions, some of which won't escape the nucleus:

π – Ar cross sections play an important role in the systematics of neutrino measurements!

ProtoDUNE-SP: π – Ar interaction cross section

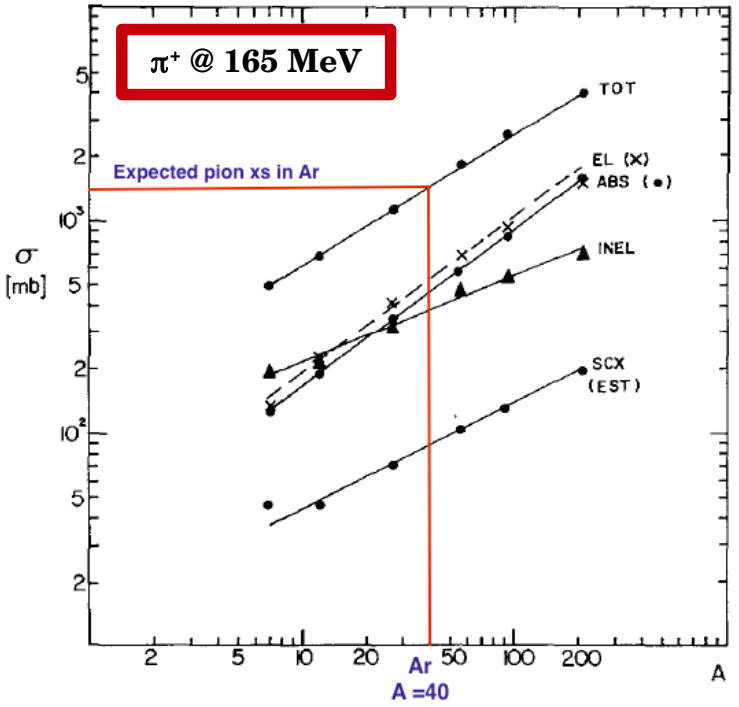
LArIAT π – Ar cross section measurement



Almost no measurement of π – Ar cross sections

- First measurements from LArIAT for momentum range 0.2 – 1.2 GeV/c
- Previous prediction come from interpolation between lighter and heavier nuclei

D. Ashery et al. Phys. Rev. C23, 2173 (1981)



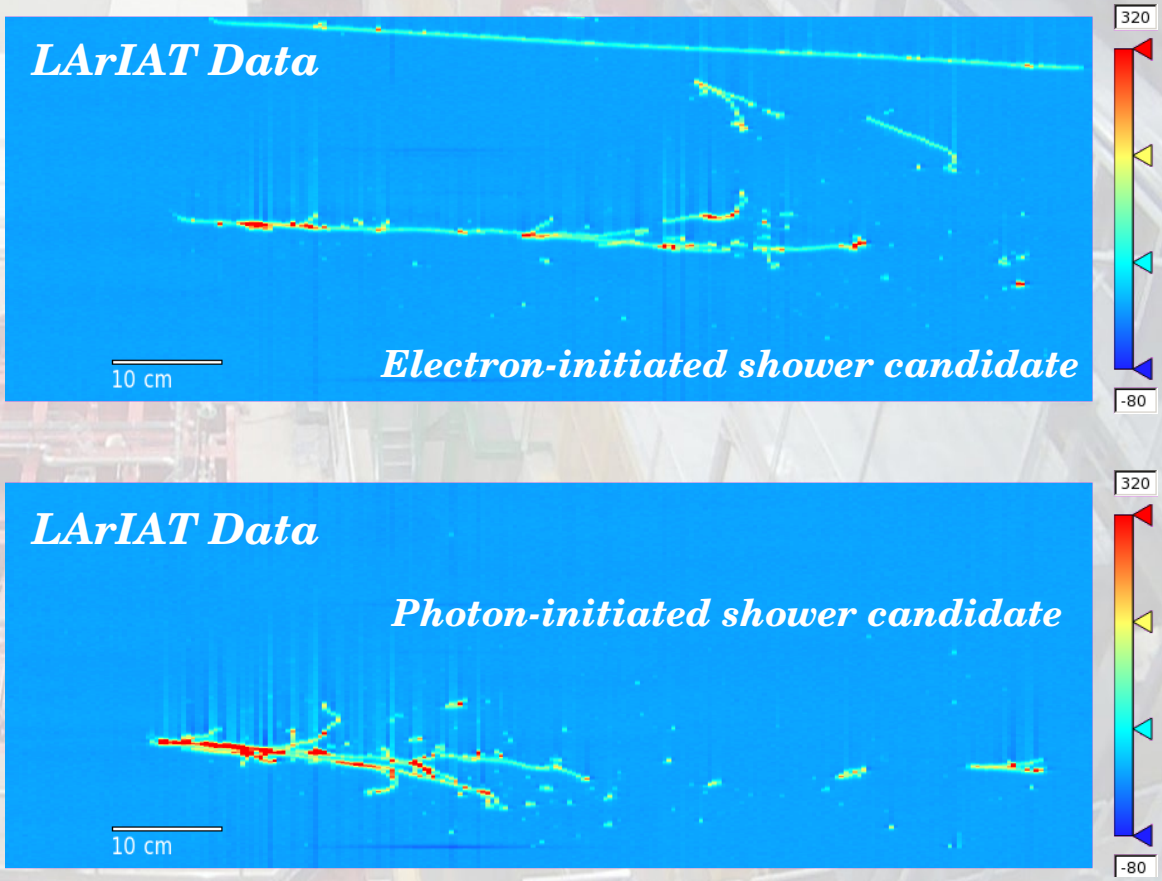
ProtoDUNE aims at reproducig LArIAT measurement enlarging the range to a few GeV/c, as well as performing a similar measurement for protons

ProtoDUNE-SP: e/γ discrimination

First few cm of the track are used to separate electron-initiated from photon-initiated showers (single vs. double ionization)

A set of pure electron beam runs at various momenta (1 – 7 GeV/c) will allow:

- direct experimental measurement of the (MC-estimated) e / γ separation efficiencies and purities as a function of energy
- development of reliable separation criteria/algorithms in the LArSoft offline reconstruction code, important to all the LAr community

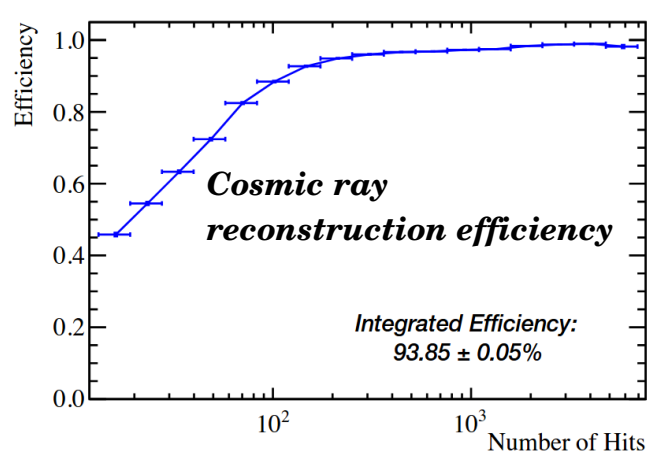


Important in DUNE for the separation of ν_e CC signal from NC π^0 background!

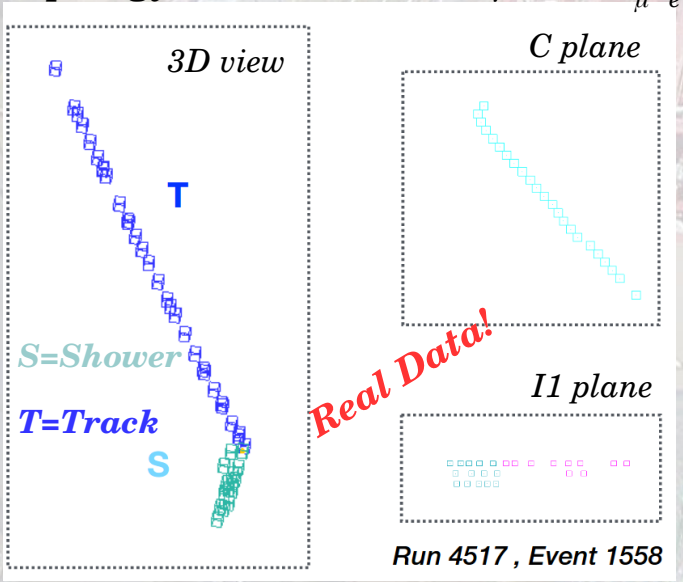
ProtoDUNE-SP: event reconstruction

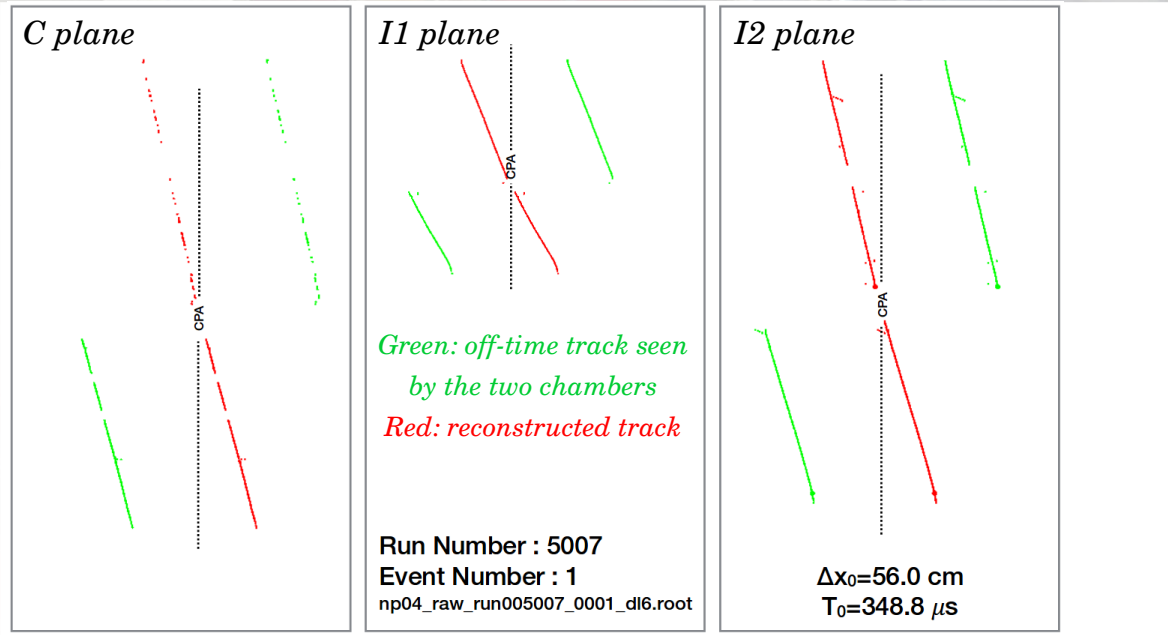
ProtoDUNE provides a test bed to develop the LAr event reconstruction algorithms to be used in DUNE

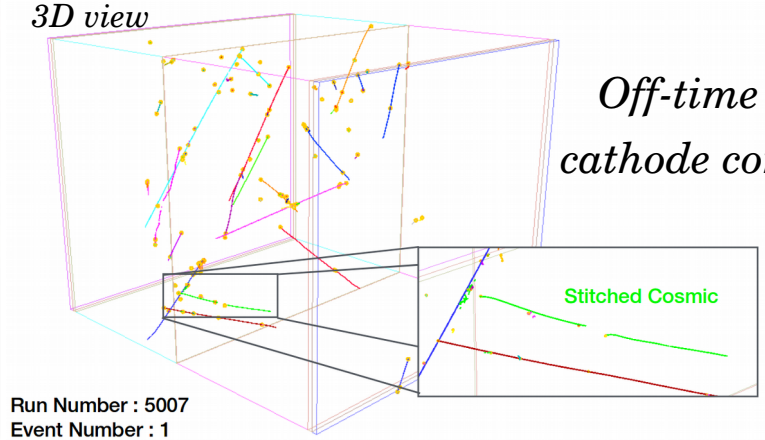
Cosmic rays background



Topology consistent with $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$







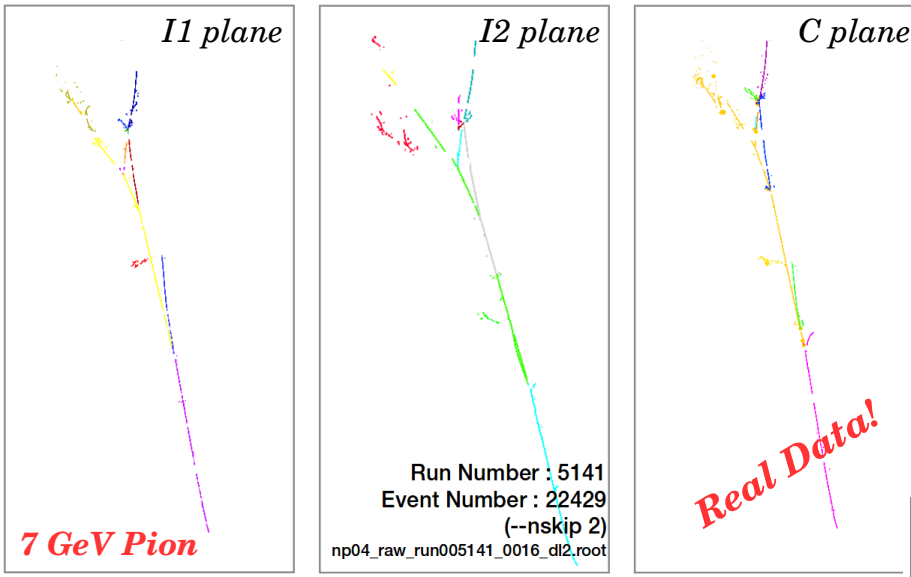
Off-time muon crossing the cathode correctly reconstructed

Real Data!

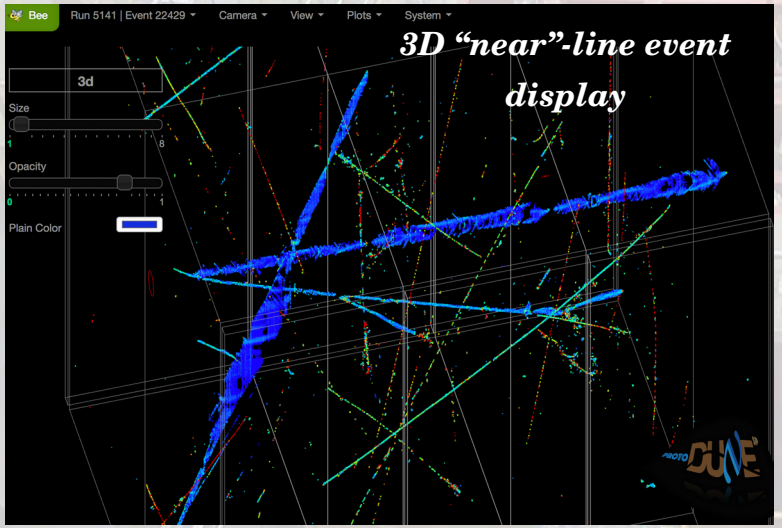
ProtoDUNE-SP: event reconstruction

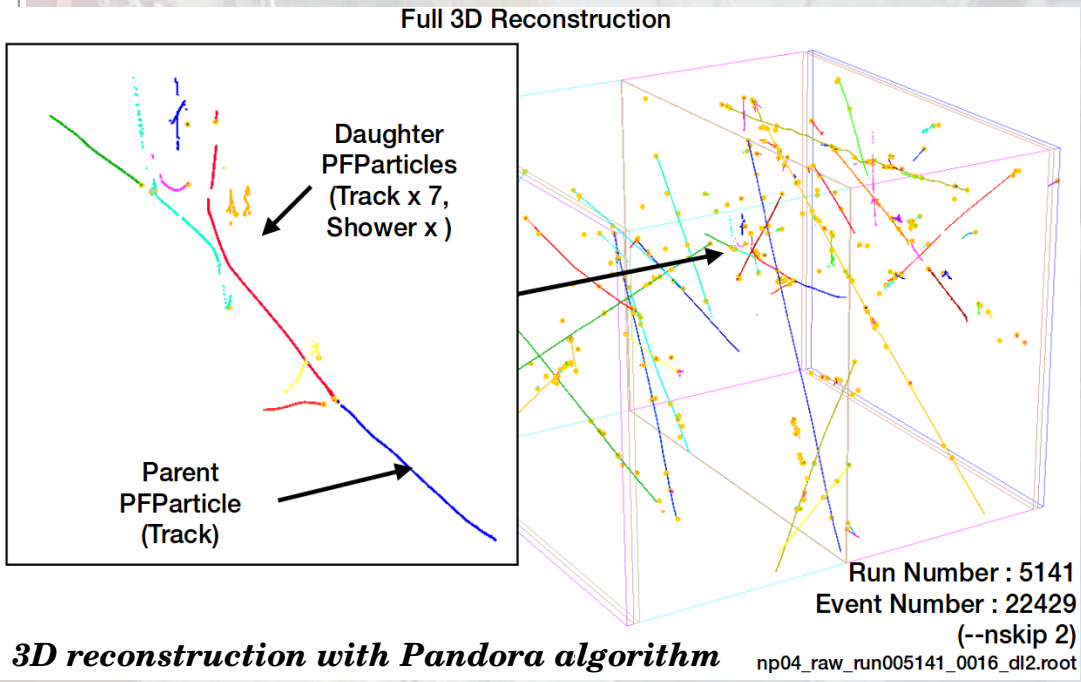
ProtoDUNE provides a test bed to develop the LAr event reconstruction algorithms to be used in DUNE

Test Beam Data



- 7 GeV Pion from beam reconstructed with Pandora algorithm both in 2D and 3D
- The algorithm correctly distinguish parent from daughter particle and identify it as a beam event…





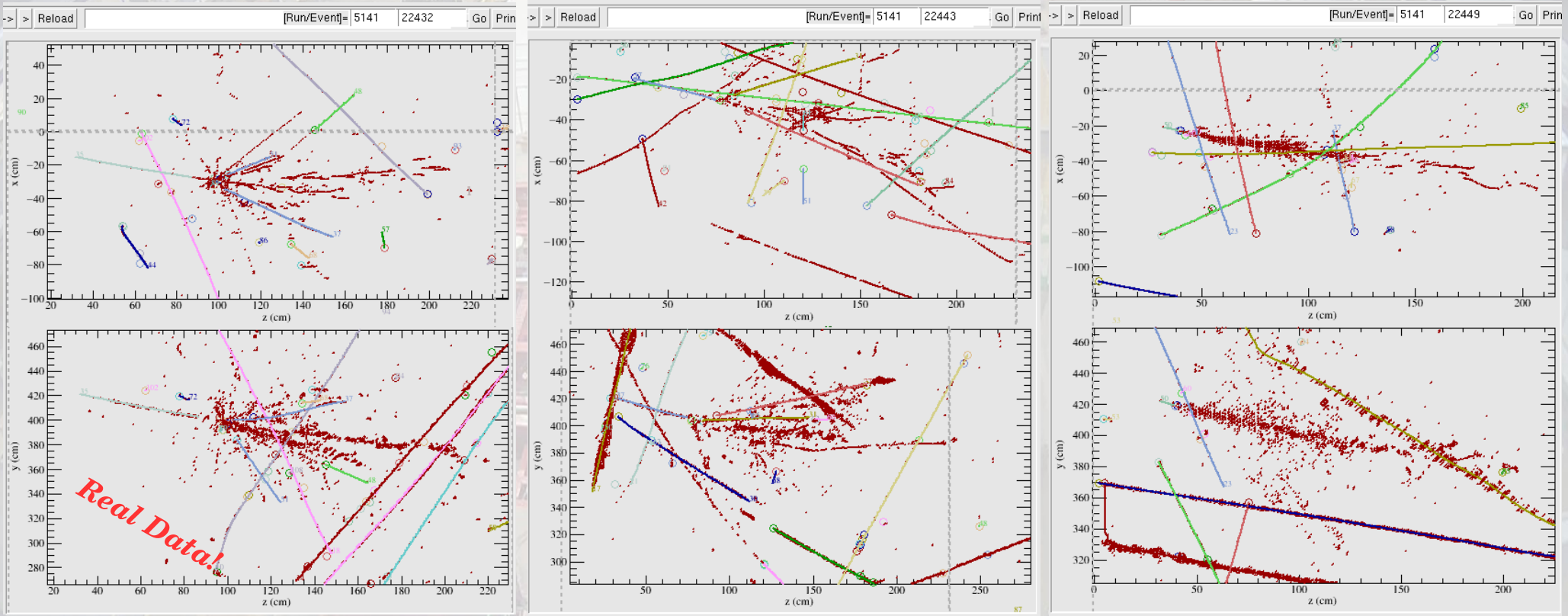
3D reconstruction with Pandora algorithm

ProtoDUNE-SP: event reconstruction

ProtoDUNE provides a test bed to develop the LAr event reconstruction algorithms to be used in DUNE

Test Beam Data

…Even in more crowded events!

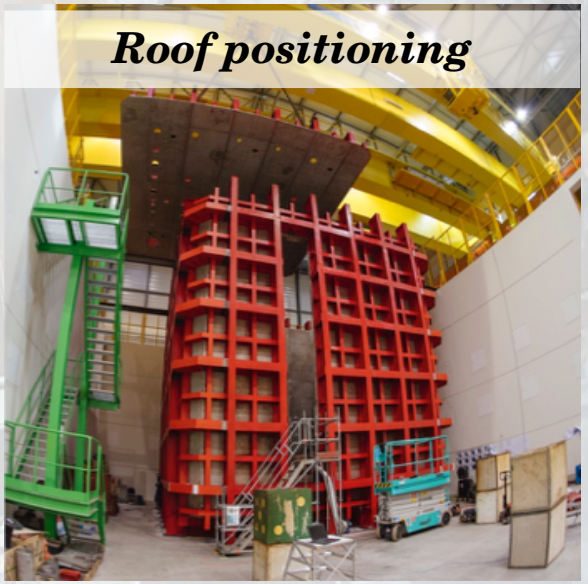


ProtoDUNE status

- ProtoDUNE-SP detector was completed at the end of June, filling of the cryostat completed on September 13th, TPC activated and on data taking since September 21st
- ProtoDUNE-SP will take beam data until mid-November, followed by an endurance run with cosmics to assess the stability and performances of the detector
- ProtoDUNE-DP installation ongoing, with cryostat closure foreseen for January 2019
- Once filled, ProtoDUNE-DP will go for an extended cosmic run to assess the stability and performances of the detector

ProtoDUNE-SP in pictures

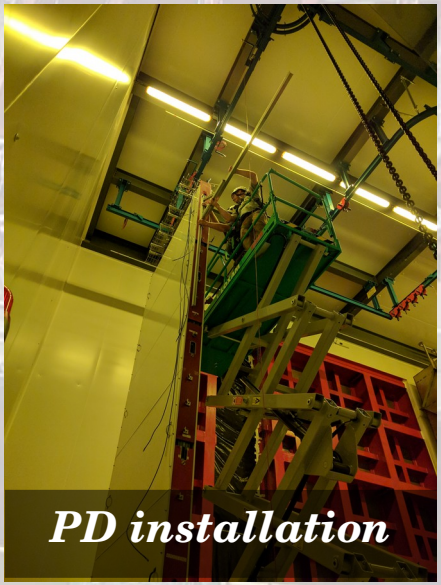
Cryostat construction



ProtoDUNE-SP in pictures

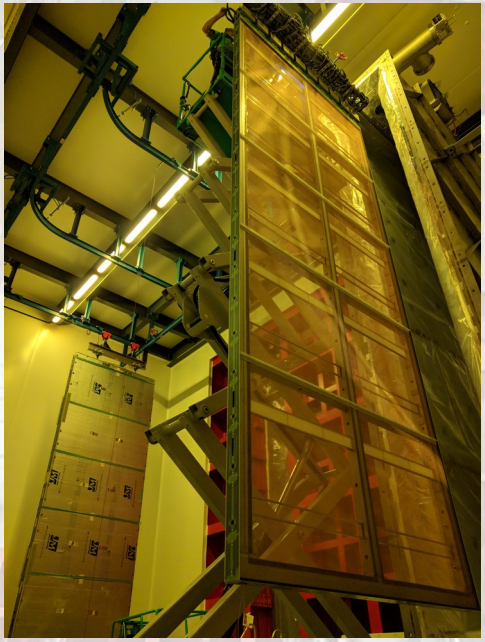
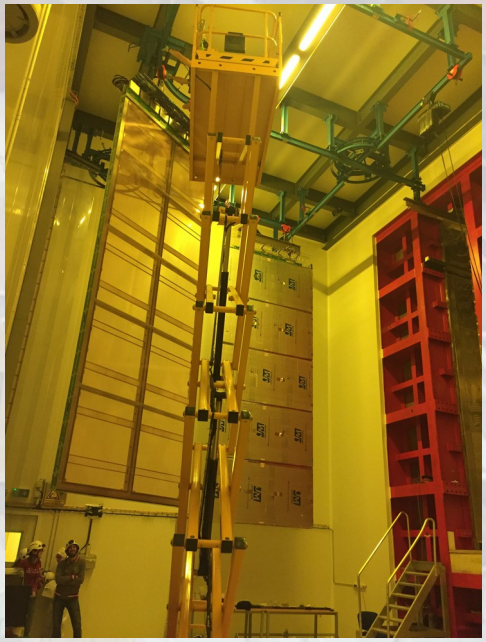
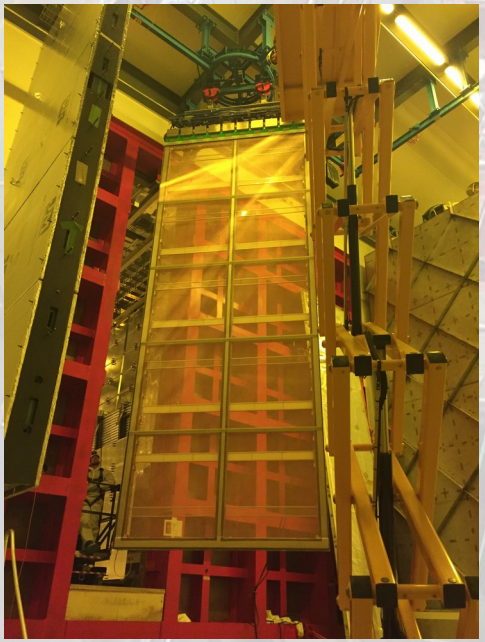
APA integration and test

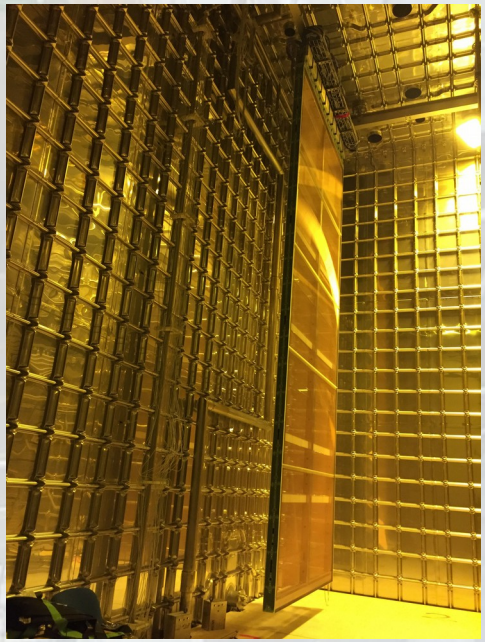
Wire tension measurement and visual inspection



Cold Electronics installation

ProtoDUNE-SP in pictures



Moving APAs around

ProtoDUNE-SP in pictures

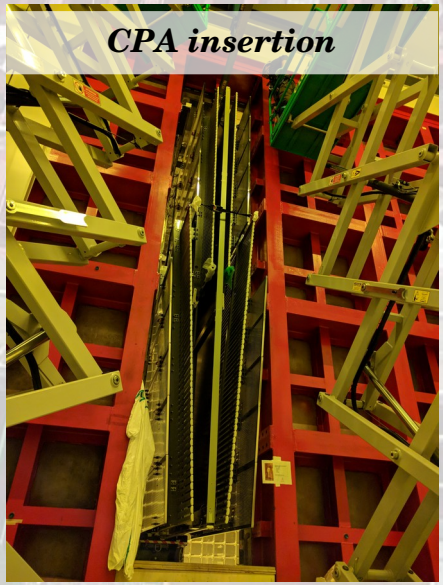

CPA half module assembly

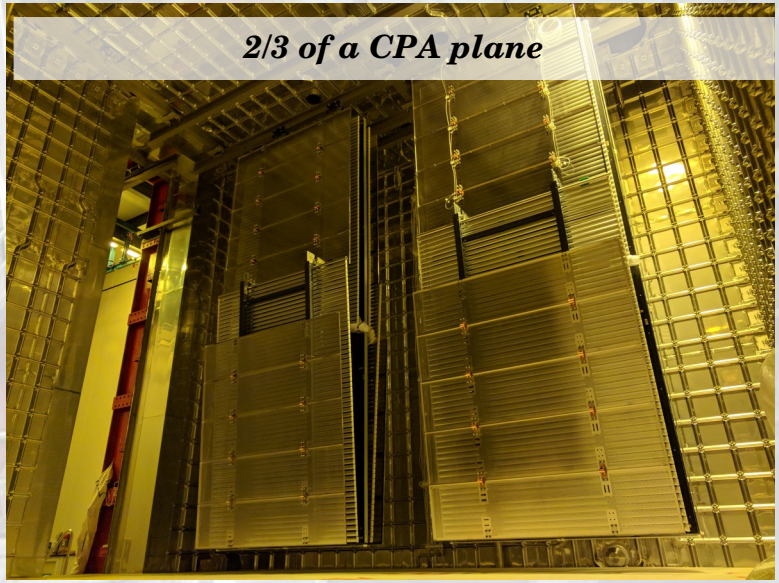

CPA continuity test


Full CPA module

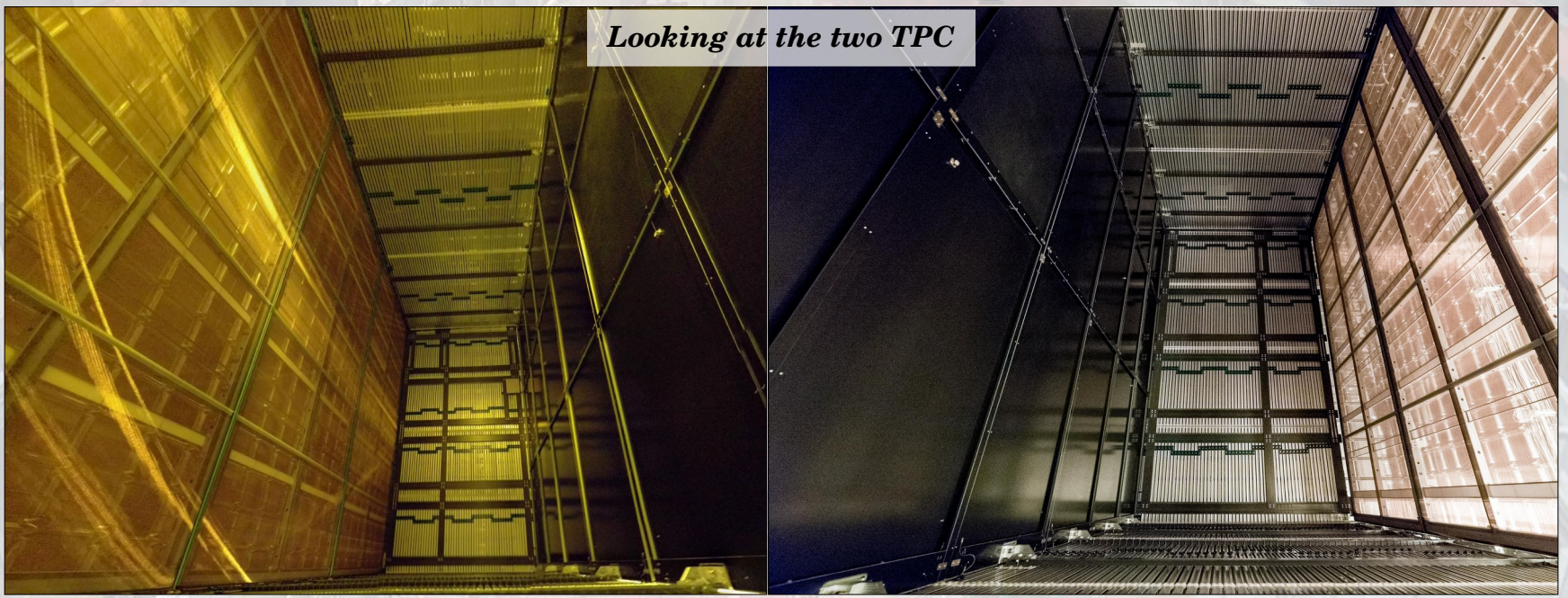
CPA assembly and installation


Field cage installation

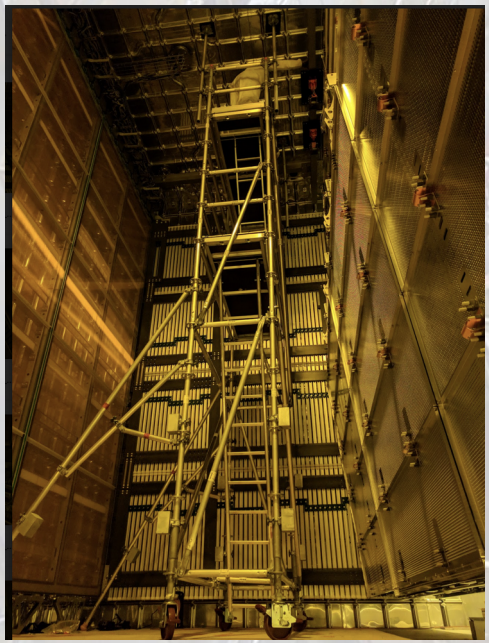

CPA insertion


2/3 of a CPA plane

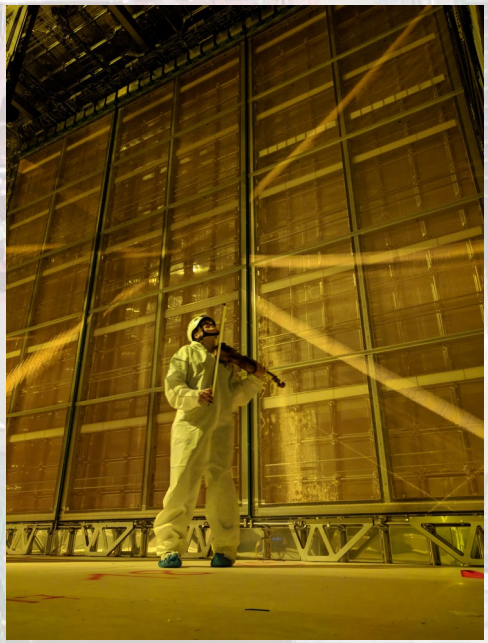
ProtoDUNE-SP in pictures



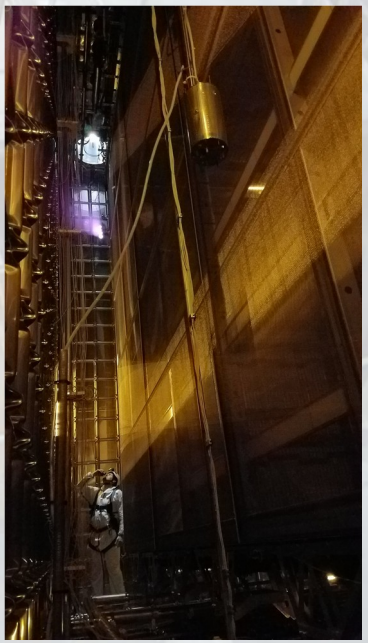
Looking at the two TPC



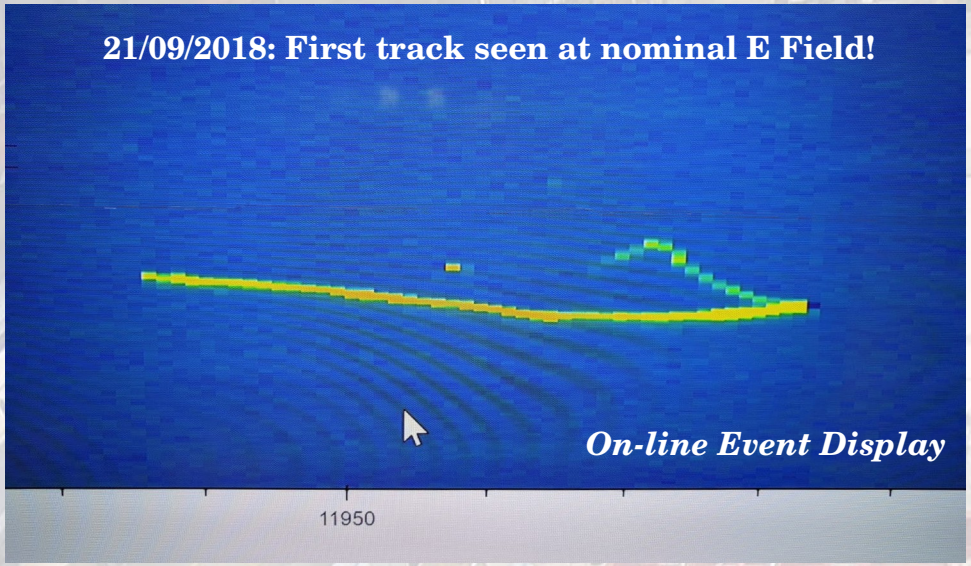
From

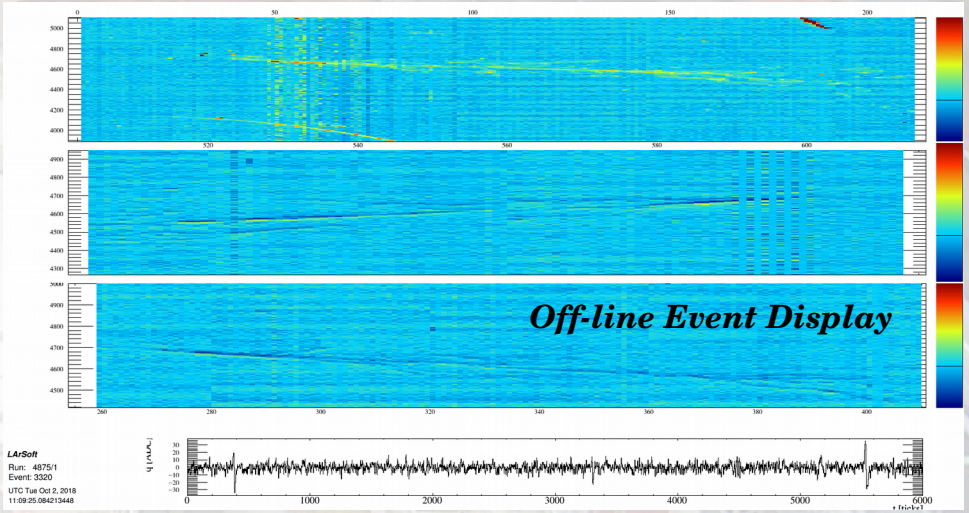


the inside

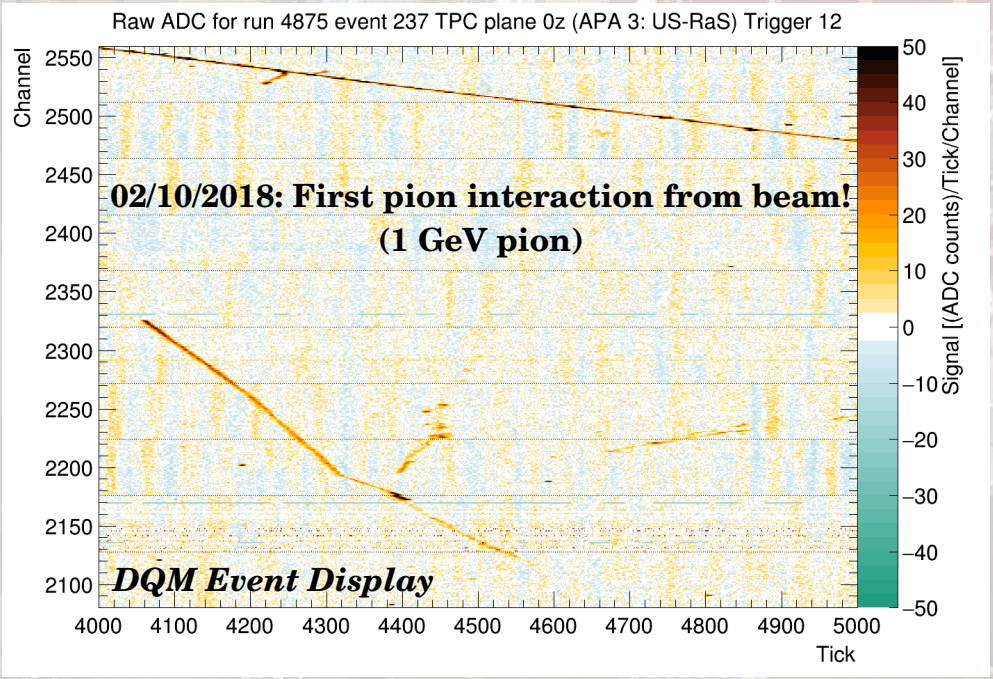


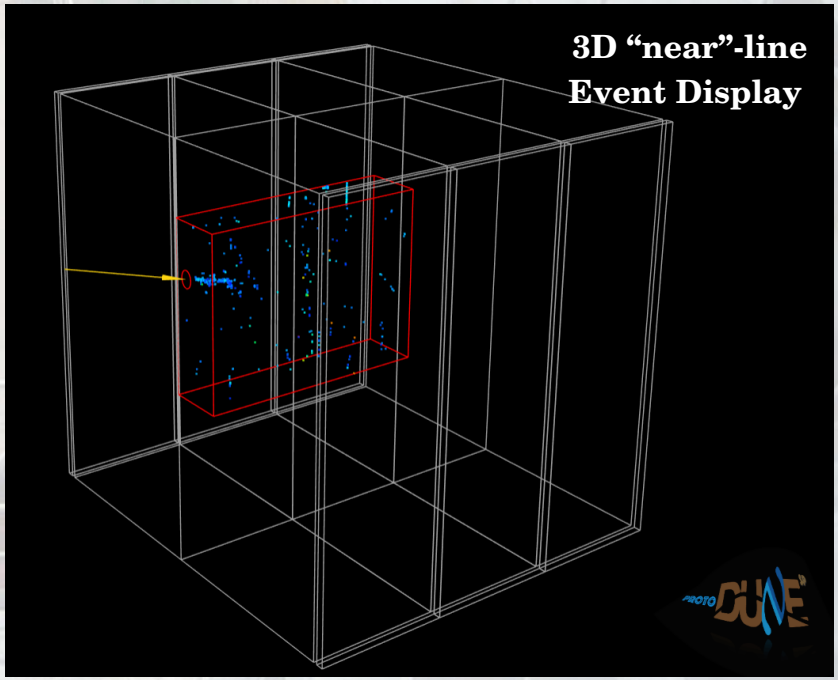
ProtoDUNE-SP first events



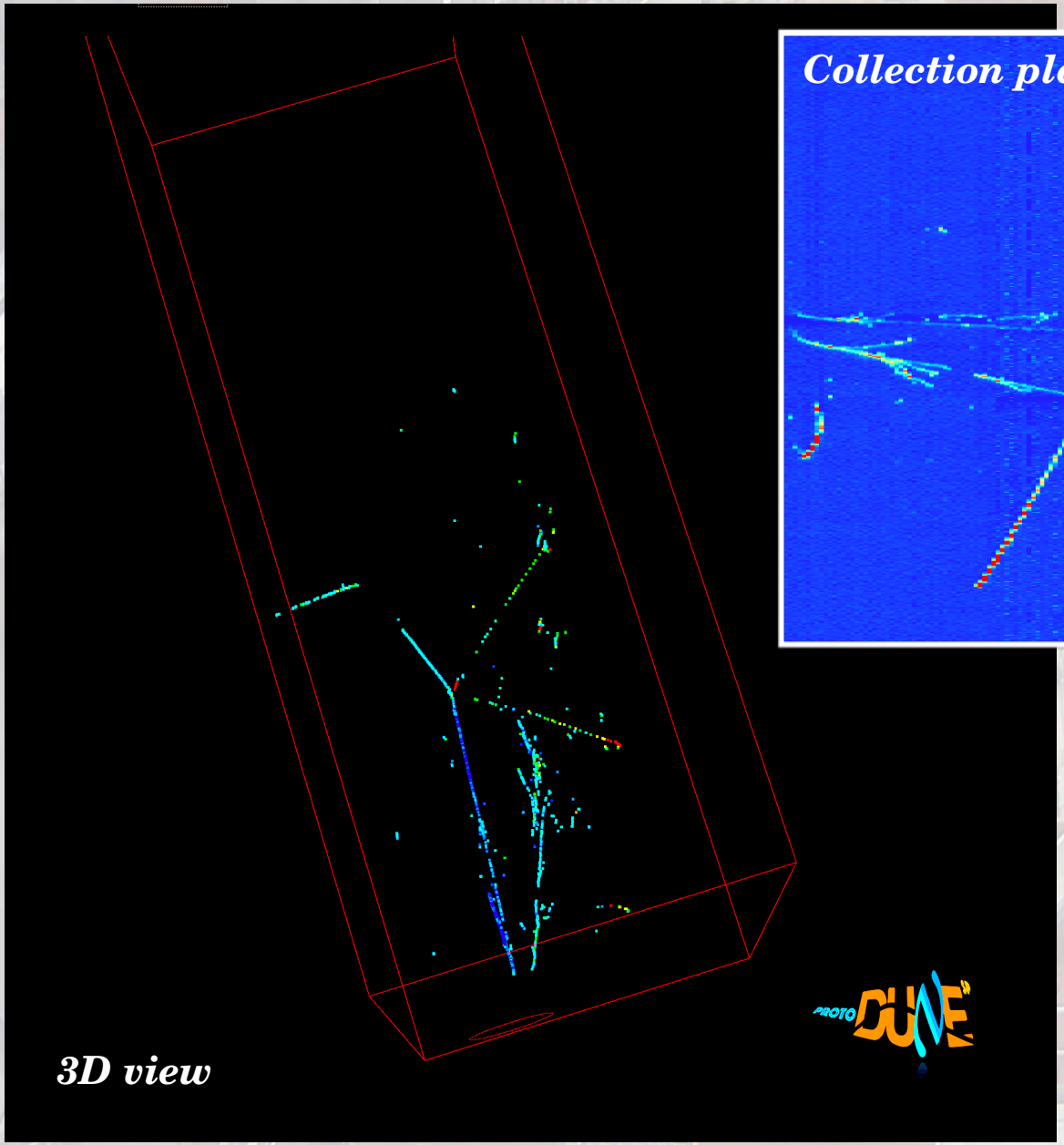


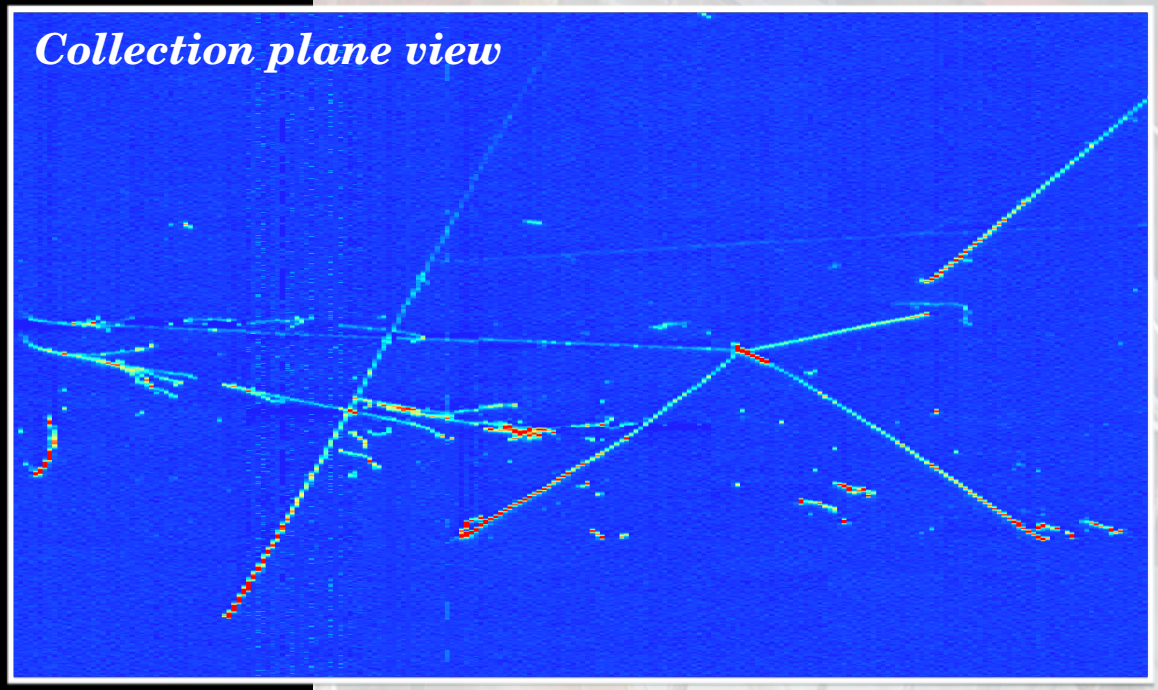
02/10/2018: First event seen from beam!
(1 GeV electron)





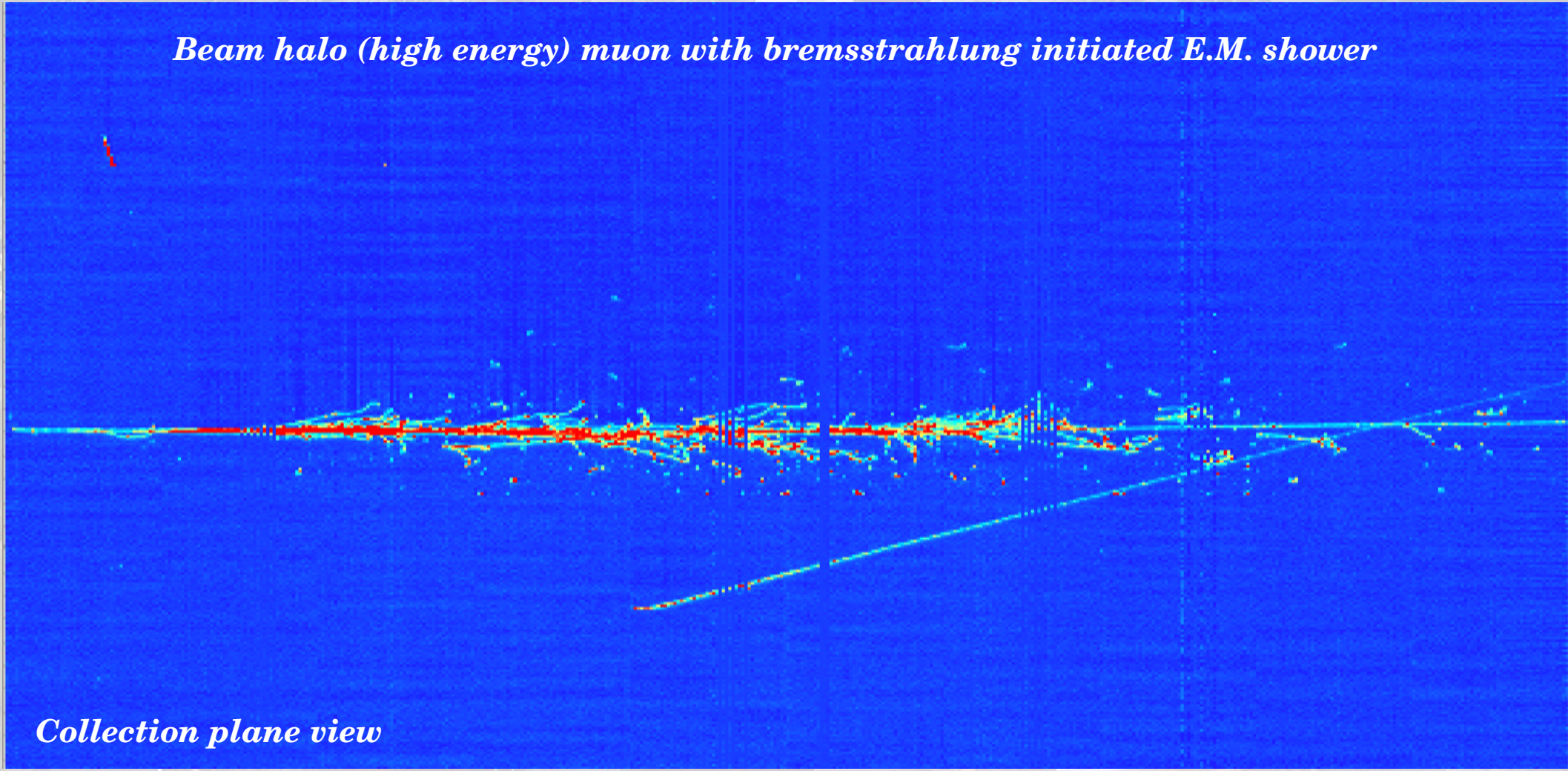
ProtoDUNE-SP first events



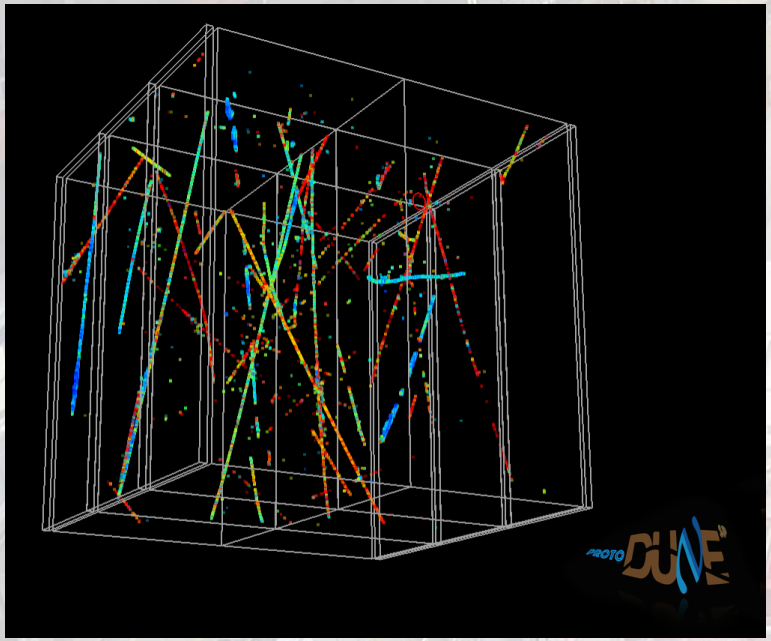


Run 4696, Ev 103:
2 EM showers and a pion interaction with 4 outcoming particles

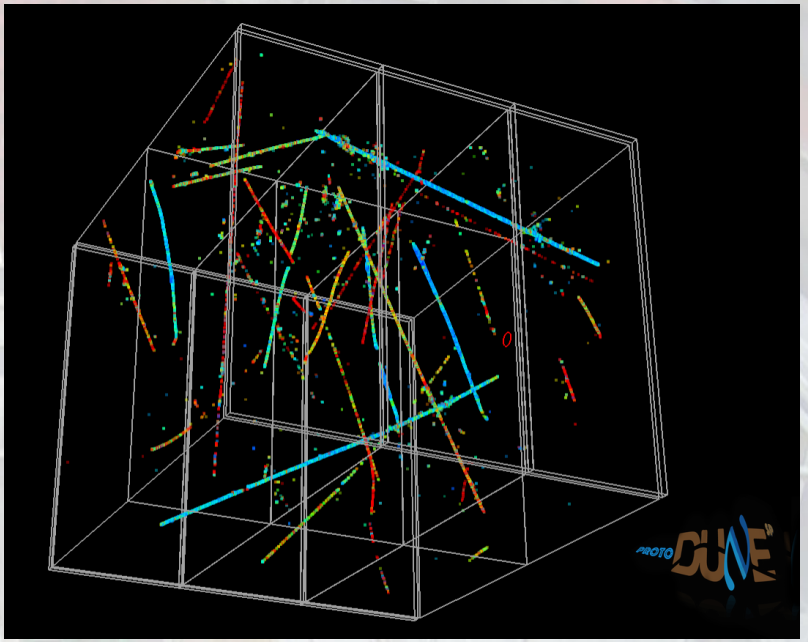
ProtoDUNE-SP first events

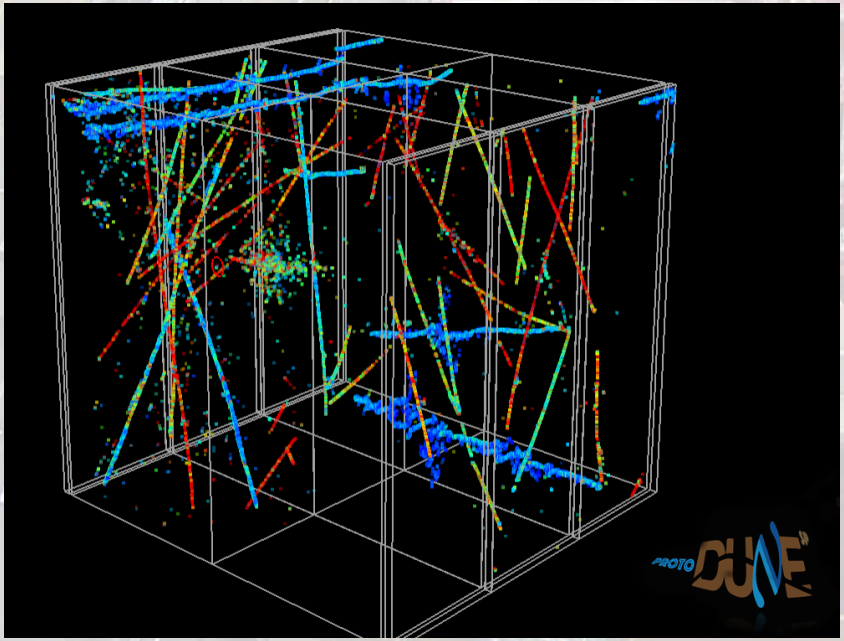


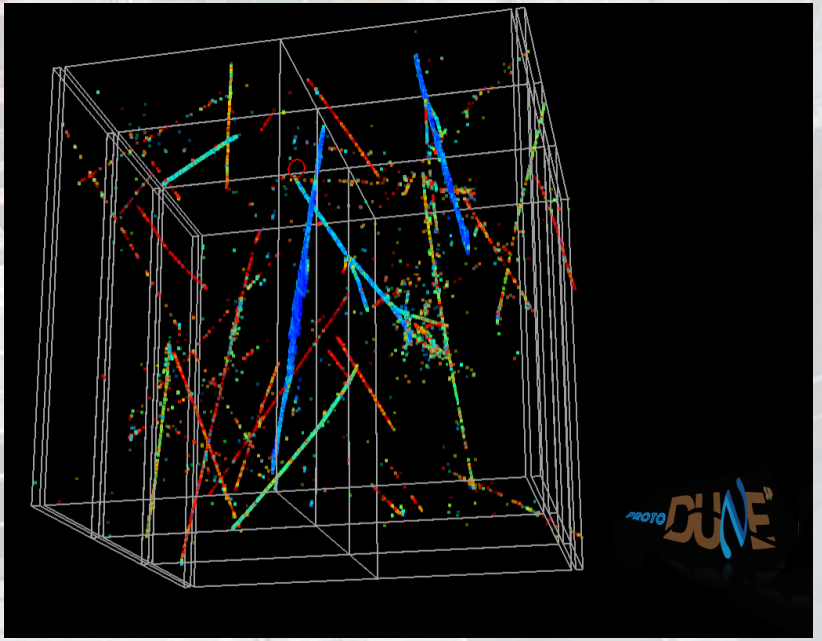
ProtoDUNE-SP first events



3D cosmic ray and beam events

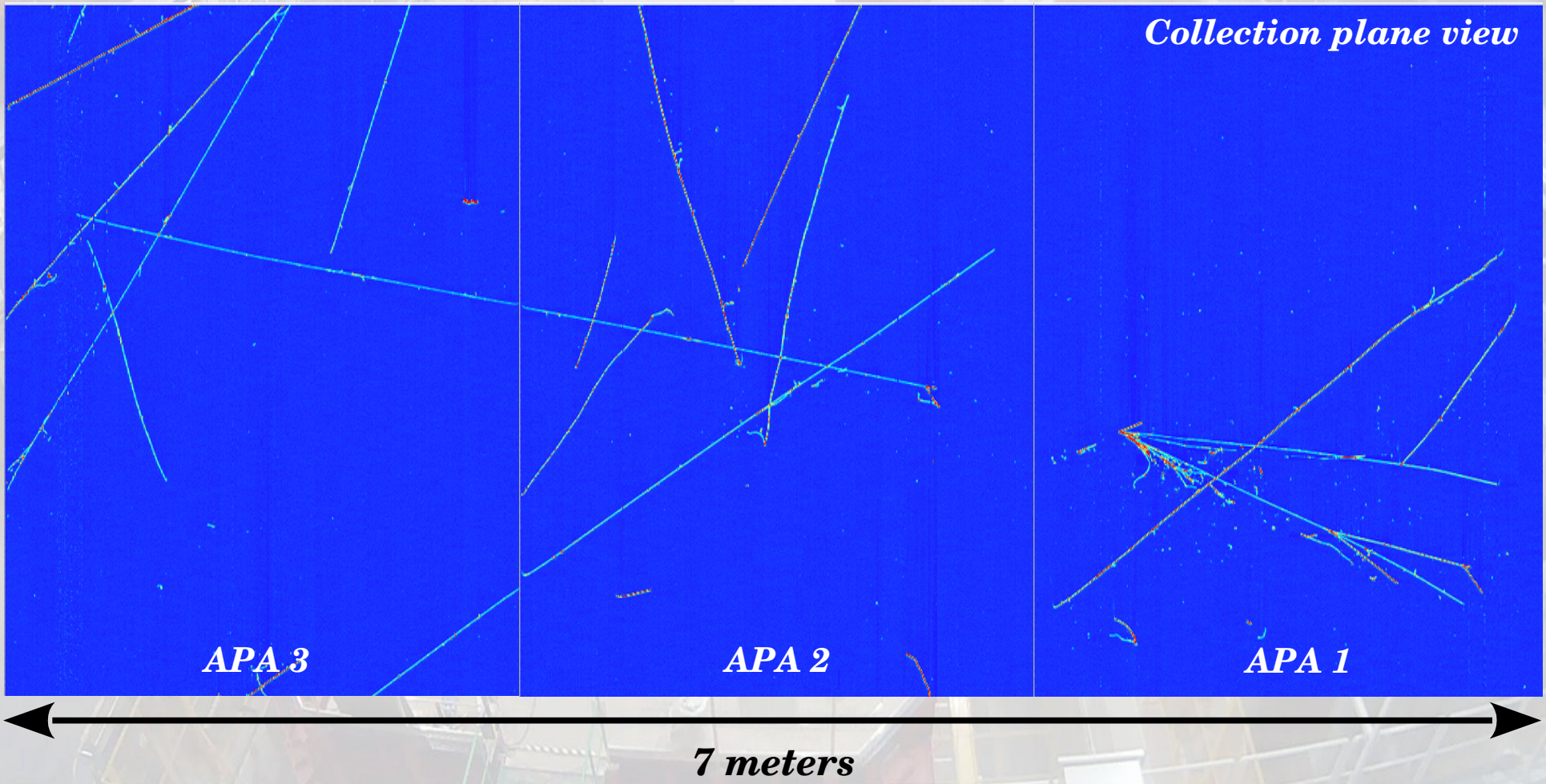




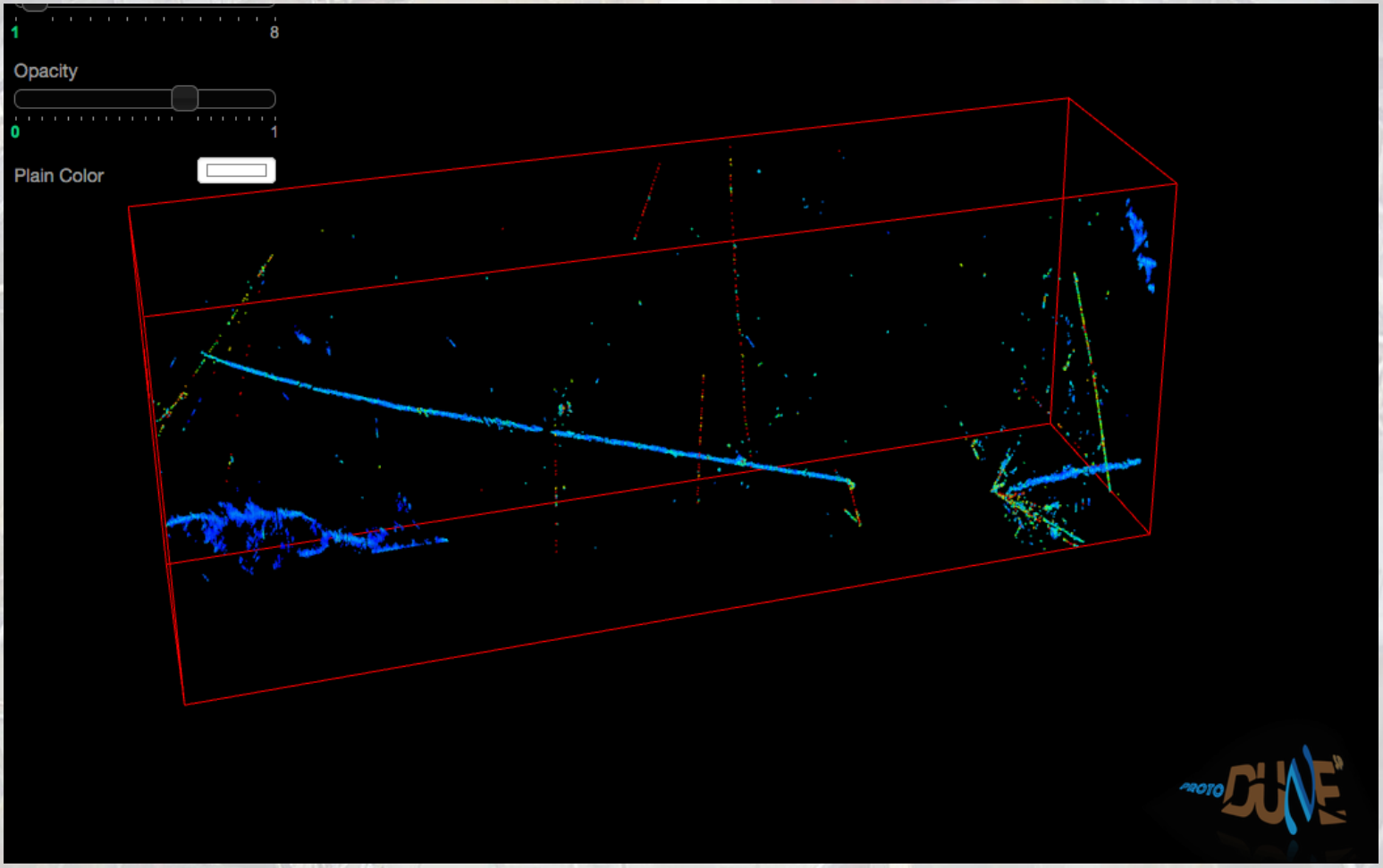


ProtoDUNE-SP first events

What a 7 GeV beam pion does in LAr?

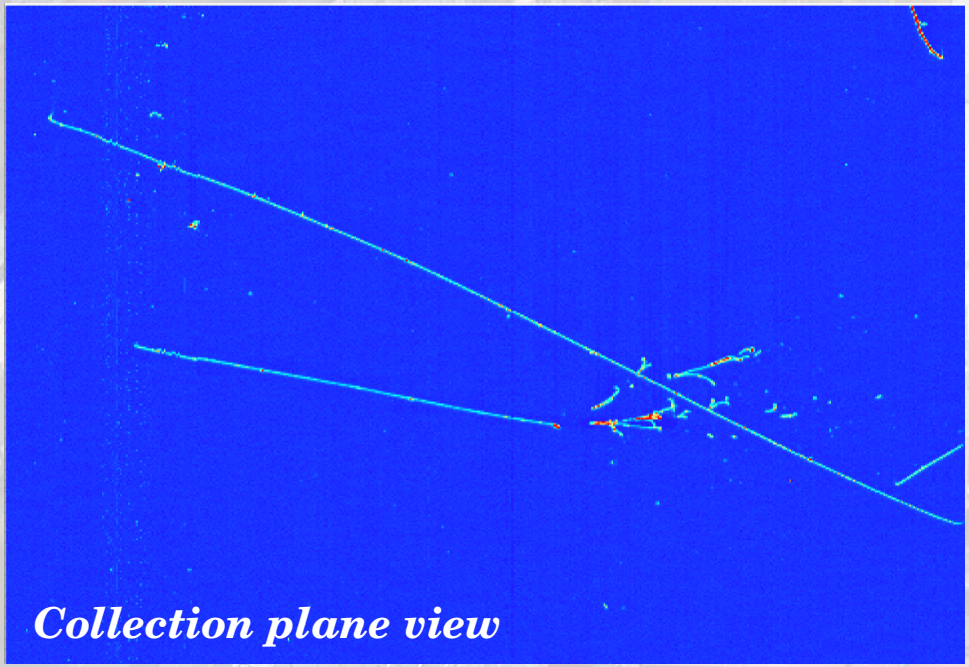


ProtoDUNE-SP first events



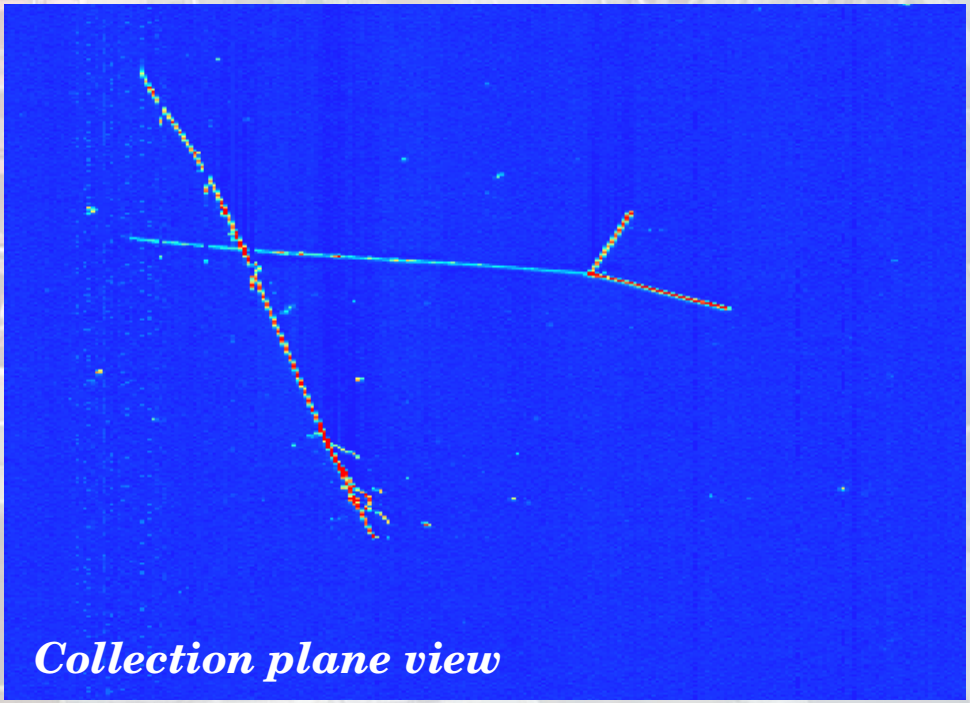
Nice things!

ProtoDUNE-SP first events



And 1 GeV beam pions?

Nice things as well!!!



In conclusion

- DUNE is a leading-edge, international experiment for neutrino science and proton decay. Its ambitious physics program requires a careful prototyping of the engineering solutions envisaged for the scale-up of the LArTPC technology, as well as a careful control of the systematics through the acquisition of a deep knowledge of the detector response and performances: ProtoDUNE

- The beam and cosmic data which will be collected by the two detectors will be extremely important to address and define the systematic uncertainties of DUNE measurements

- ProtoDUNE-SP has been successfully completed and is in full data taking mode, while ProtoDUNE-DP is expected to come online as well in early 2019


Thank you!

BACKUP SLIDES

ProtoDUNE-SP next (beam) events

Ottobre 2018

Lunedì	Martedì	Mercoledì	Giovedì	Venerdì	Sabato	Domenica
1	2	3	4	5	6	7
8	9	10 Beam off 8am - 6pm 6pm-midnight: 7 GeV all trigger	11 7 GeV all trigger	12 1 GeV Pi and proton veto on electron	13 1 GeV Pi and proton veto on electron	14 1 GeV Pi and proton veto on electron
15 1 GeV Pi and proton veto on electron	16 1 GeV Pi and proton veto on electron	17 Beam off 8am - 6pm 6pm-midnight: 6 GeV all trigger	18 6 GeV all trigger	19 2 GeV Pi and proton veto on electron	20 2 GeV Pi and proton veto on electron	21 2 GeV Pi and proton veto on electron
22 2 GeV Pi and proton veto on electron	23 2 GeV Pi and proton veto on electron	Beam off				
Beam off		31 Beam off 8am - 6pm 6pm-midnight: 4 GeV all trigger				

- Currently on a "beam on" week
- Priority given to collect pions and protons events at 1 GeV and 2 GeV, then at higher energies
- Possibility to collect Kaons at high (4 GeV and above) energies
- Electrons collected both through dedicated runs (1 GeV and 2 GeV) and general runs (at higher energies)

Novembre 2018

Lunedì	Martedì	Mercoledì	Giovedì	Venerdì	Sabato	Domenica
Beam off		Beam off 8am - 6pm 6pm-midnight: 4 GeV all trigger	1 4 GeV all trigger	2 4 GeV all trigger	3 4 GeV all trigger	4 3 GeV Pi and proton veto on electron
5 3 GeV Pi and proton veto on electron	6 3 GeV Pi and proton veto on electron	7 Beam off 8am - 6pm 6pm-midnight: 3 GeV no electron	8 Electron only trigger 1 GeV	9 Electron only trigger 1 GeV	10 Electron only trigger 2 GeV	11 Electron only trigger 2 GeV
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

Present beam run (SP only)

- CERN accelerator complex will stop operations at the end of 2018 for a 2-year shutdown (LHC luminosity upgrade) → beam available only until end of this year, then again in 2021
- 7.5 weeks of beam approved for SP between August 29th and November 11th, with beam-off weeks in between for detector development
- Hadron runs at several momentum settings between 1 and 7 GeV/c, plus an electron run
- Data collection goal (with a 25 Hz trigger rate/3000 spill day):
  - ✔ > 300k pion events per momentum setting
  - ✔ > 100k proton events per momentum setting
  - ✔ > 900k electron events total

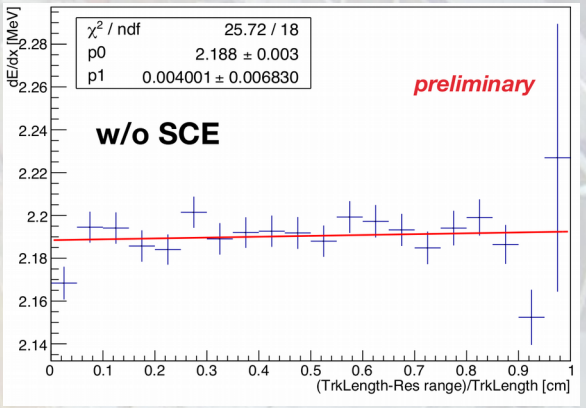
ProtoDUNE-SP: event reconstruction

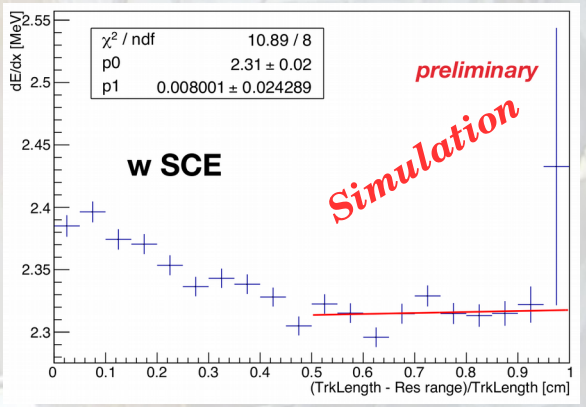
ProtoDUNE provides a test bed to develop the LAr event reconstruction algorithms to be used in DUNE

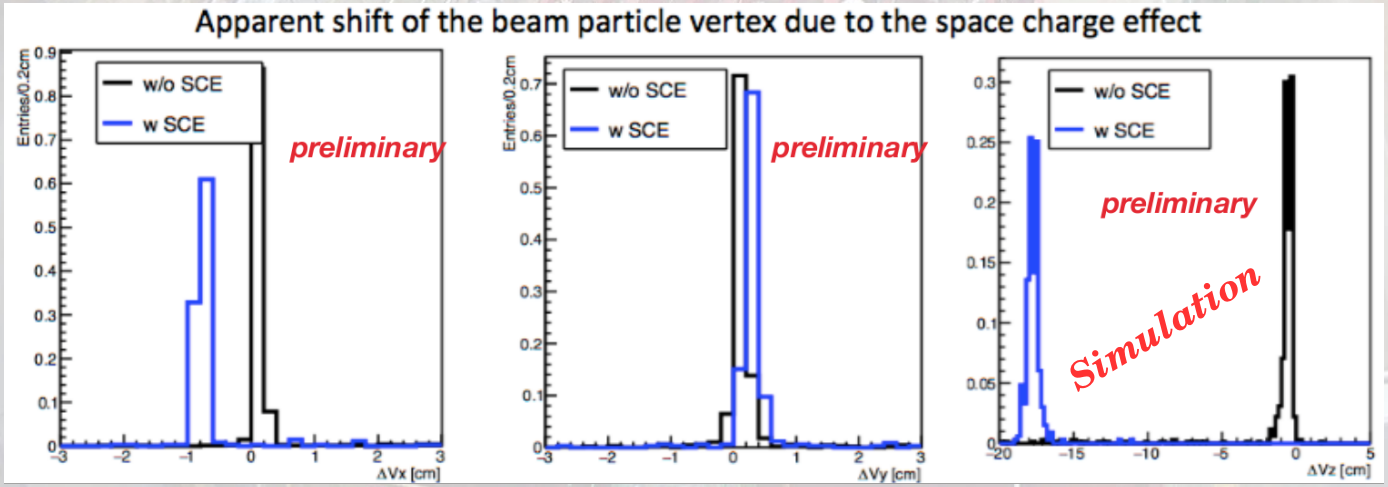
Space Charge Effect

- Space charge given by slow drifting Ar^+ ions distorts the E field, impairing the dE/dx and vertex reconstruction
- Important for large LArTPC on surface
- ProtoDUNE cosmic data can be used to measure the SCE and develop algorithms to account and correct for it

3 GeV Pions dE/dx



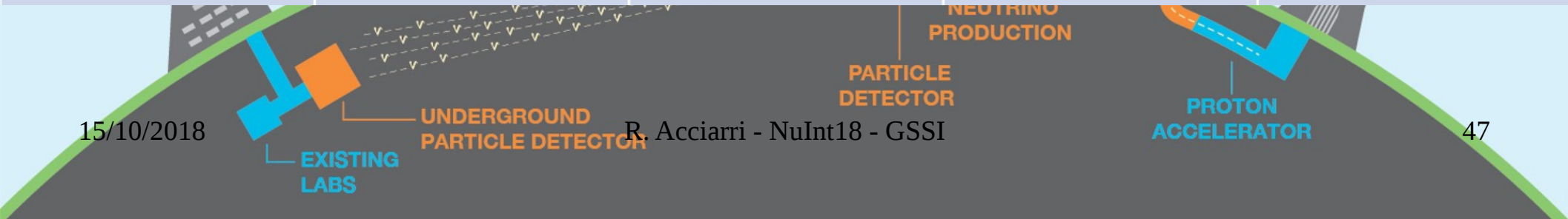




DUNE FD staging scenario

- Assumes equal ν and $\bar{\nu}$ running time
- The starting year (Year 1) is assumed to be 2026

Year	Number of FD modules	Total FD target mass (kt)	LBNF beam power (MW)	Exposure at year end (kt MW yr)
1	2	20	1.2	21
2	3	30	1.2	54
4	4	40	1.2	128
7	4	40	1.2	300
10	4	40	2.4	556



Neutrino Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor/Accelerator}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

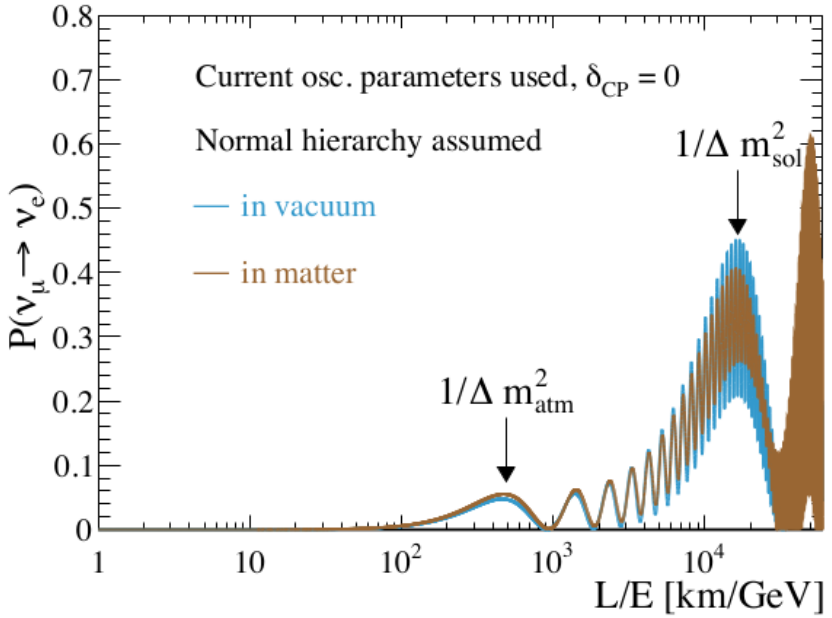
$$s_{ij} = \sin\theta_{ij}$$
$$c_{ij} = \cos\theta_{ij}$$

In the 3 ν flavor case, the oscillation phenomena is described by:

- 3 mixing angles: θ_{12}, θ_{23} and θ_{13}
- 2 mass splittings: Δm^2_{sol}, Δm^2_{atm}
- 1 CP violation phase δ
- Oscillation probabilities are modified in matter

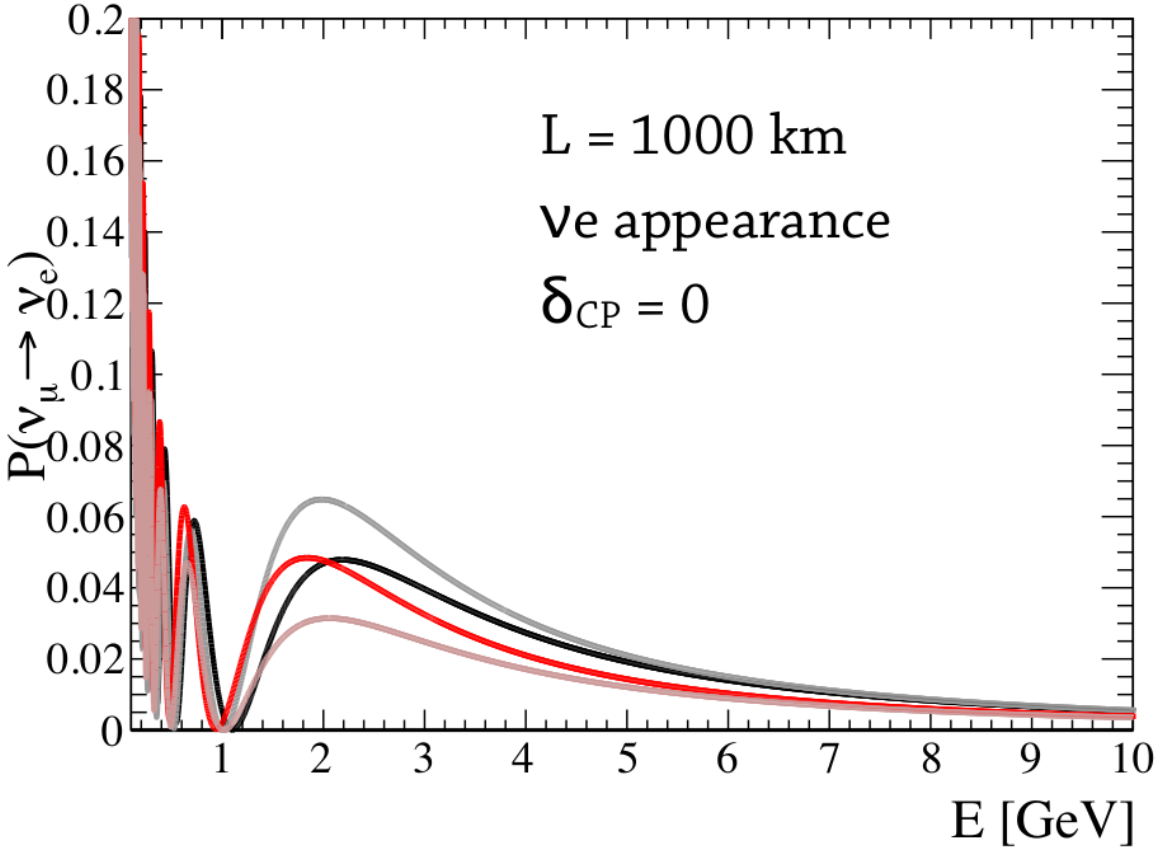
ν oscillation experiments do not have access to:

- the absolute mass scale of the neutrinos
- their profound nature (Dirac or Majorana)



DUNE oscillation parameters measurement

Oscillation amplitude variation from vacuum to matter case probes the mass ordering

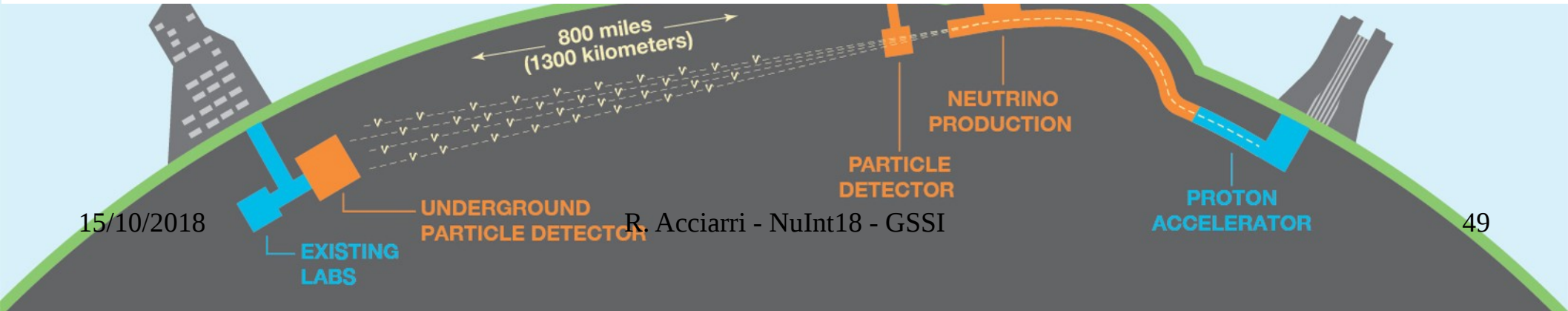


Normal hierarchy, vacuum

Normal hierarchy, matter

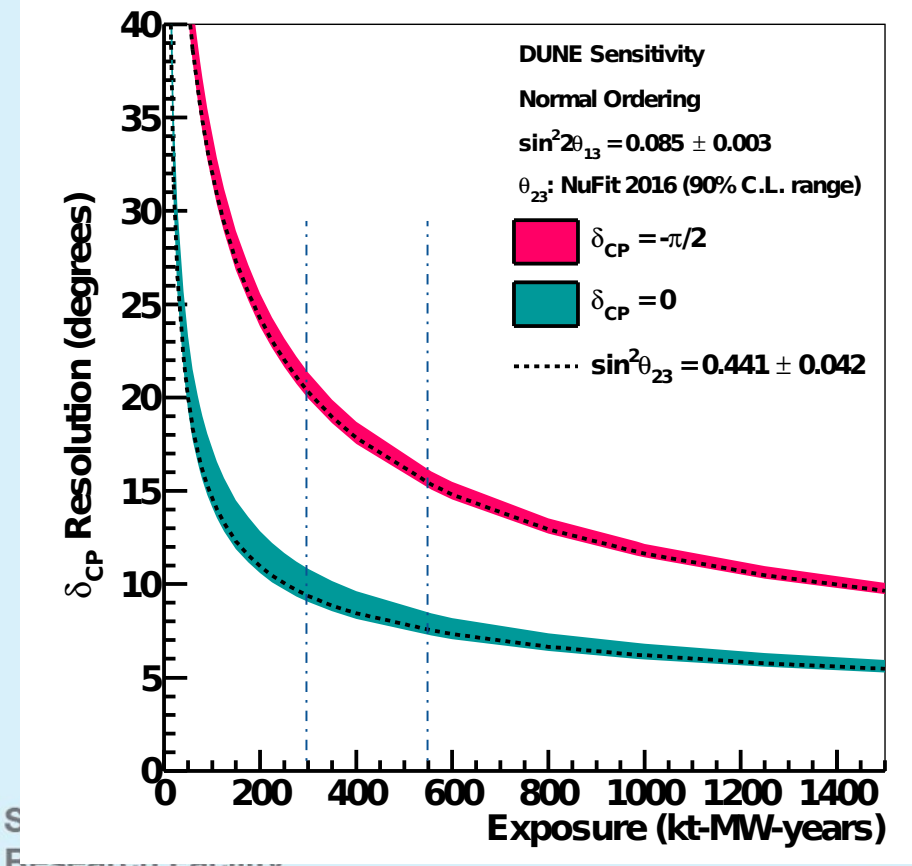
Inverted hierarchy, vacuum

Inverted hierarchy, matter

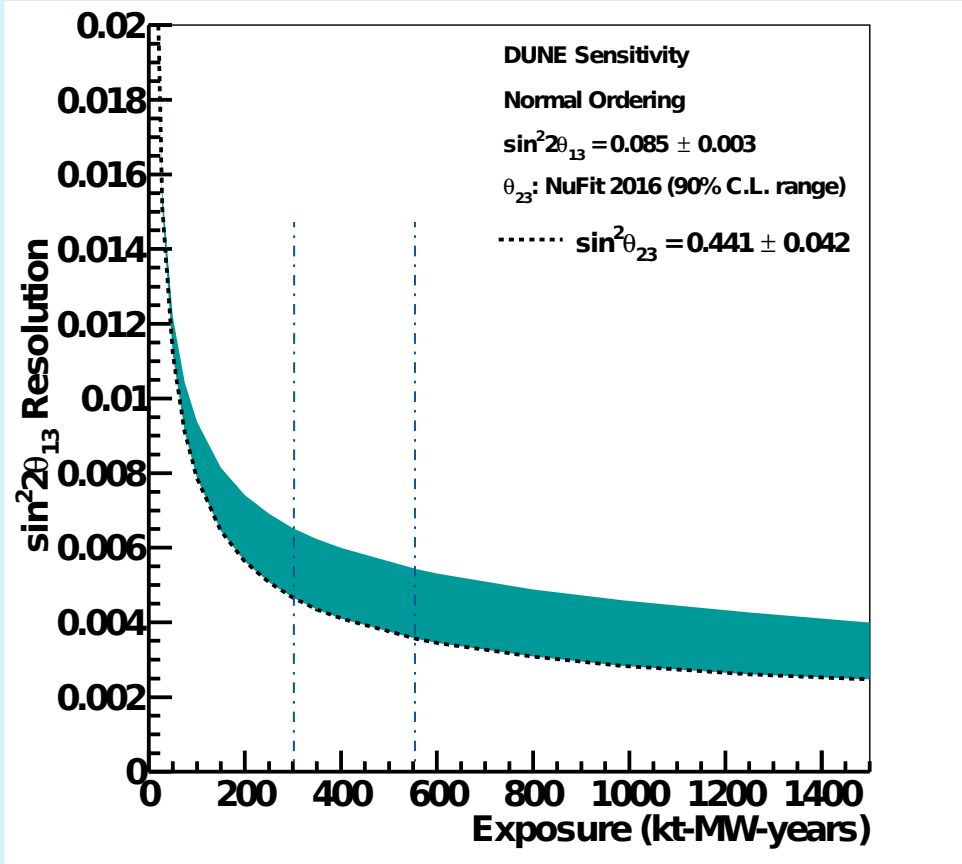


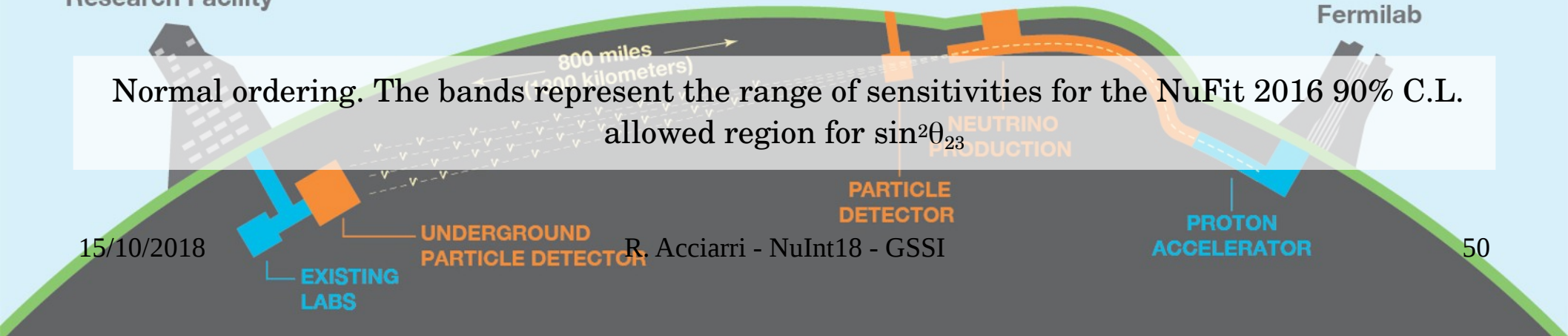
DUNE oscillation parameters measurement

δ_{CP} resolution



$\sin^2 2\theta_{13}$ resolution

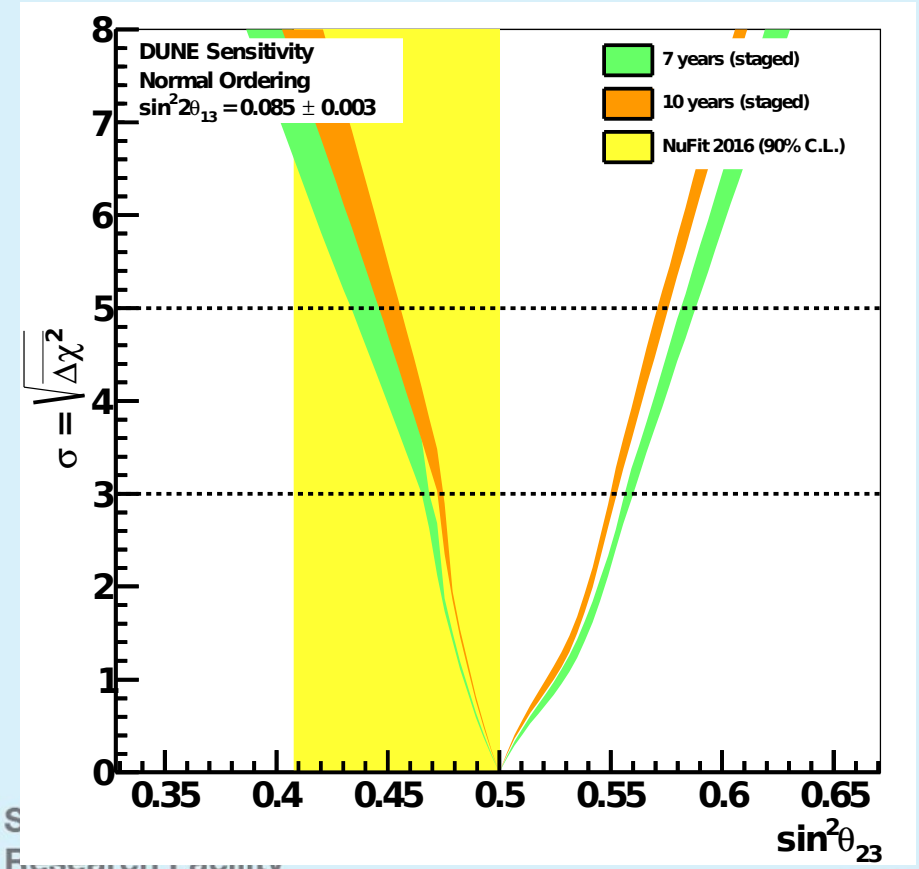




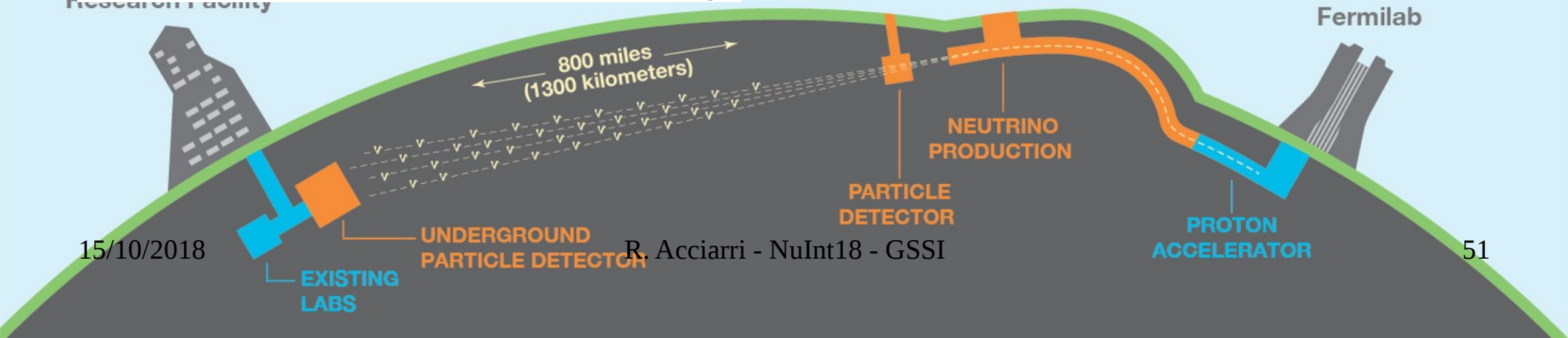
Normal ordering. The bands represent the range of sensitivities for the NuFit 2016 90% C.L. allowed region for $\sin^2\theta_{23}$

DUNE oscillation parameters measurement

Sensitivity to θ_{23} octant

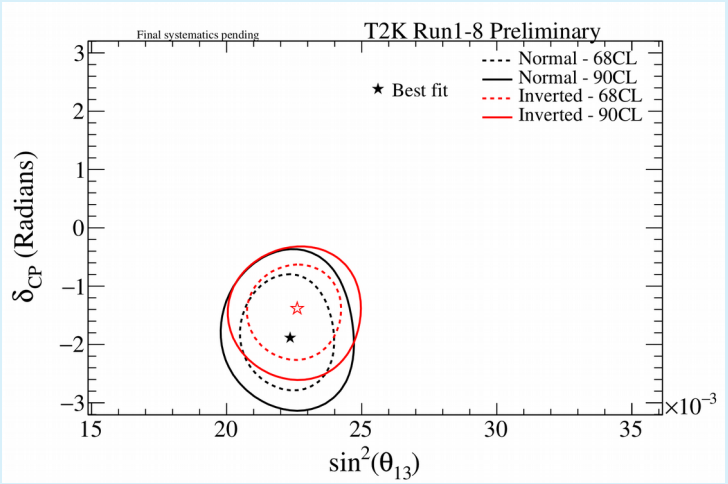


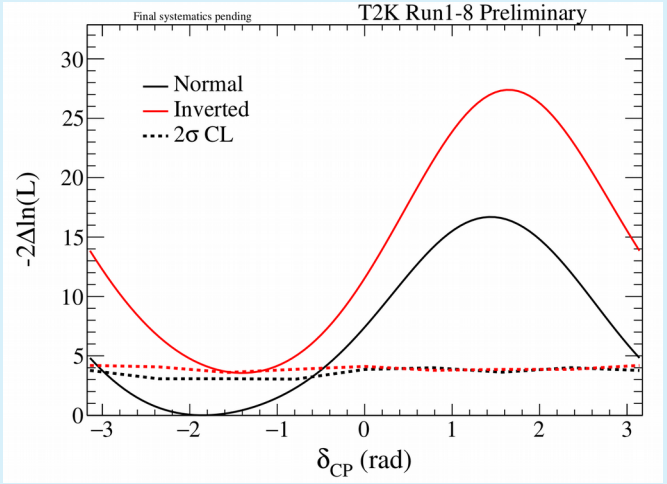
- Example sensitivity for 7 (green) and 10 years (orange) staged exposure
- Width of bands represents 80% of least extreme δ_{CP} values (best and worst 10% sensitivities not shown)
- Yellow shaded region shows 90% C.L. allowed region for $\sin^2\theta_{23}$ from NuFit 2016



ν oscillation parameters: status of the art

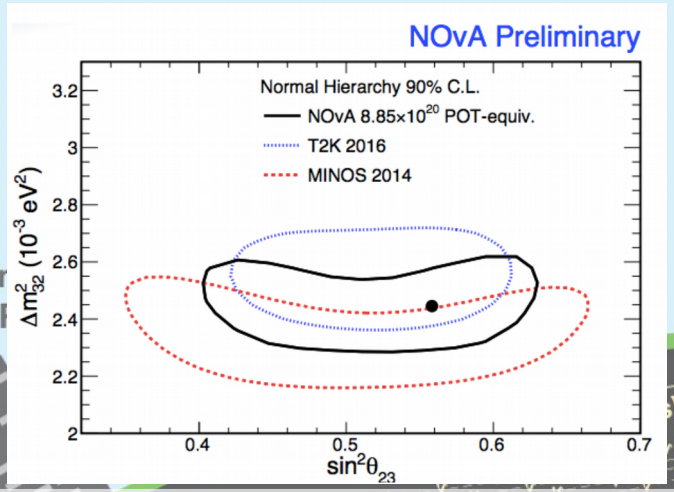
T2K results presented at KEK on summer 2017

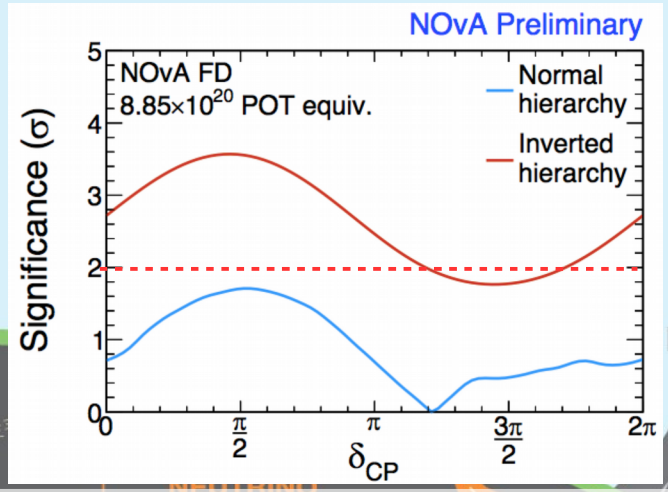




δ_{CP}=0 excluded at 2σ!

Nova results presented at CERN in January 2018



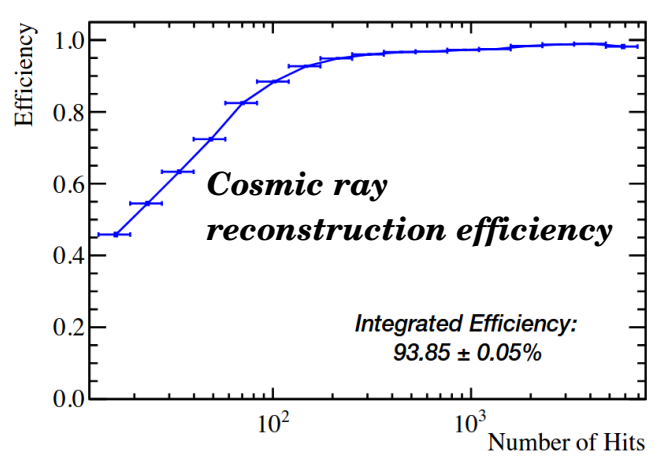


T2K and NOvA have already some sensitivities to δ_{CP} and MH with part of the foreseen final statistic, but still not enough to provide a final answer

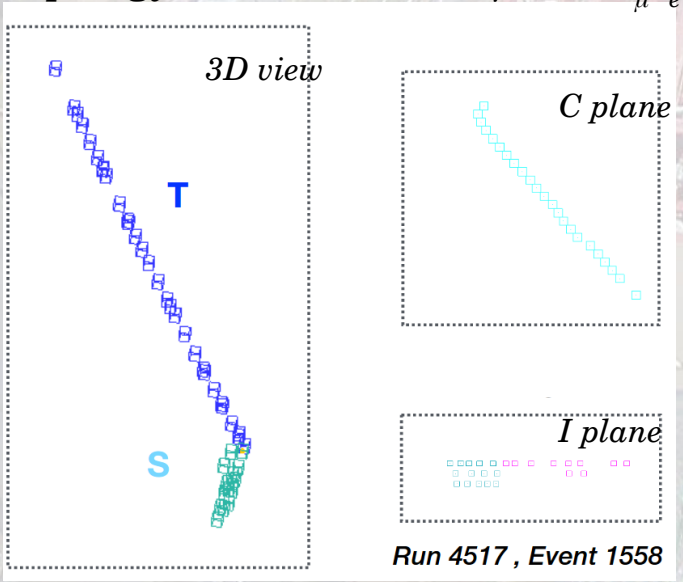
ProtoDUNE-SP: event reconstruction

ProtoDUNE provides a test bed to develop the LAr event reconstruction algorithms to be used in DUNE

Cosmic rays background



Topology consistent with $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$



Test Beam Data

Topology consistent with $\pi^0 \rightarrow \gamma\gamma$