Stefan Söldner-Rembold
University of Manchester

Prague, 17 October 2022

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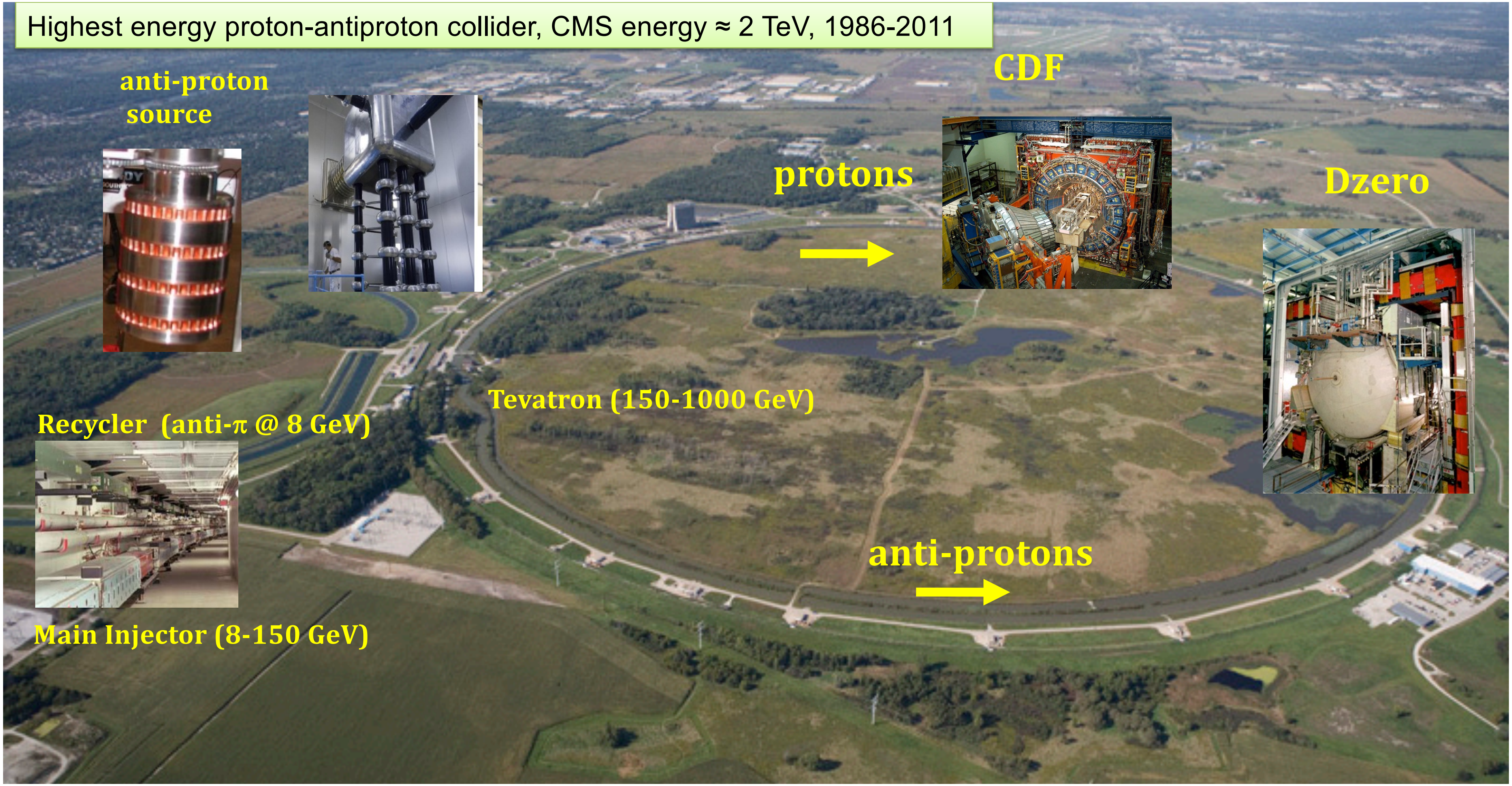
The Tevatron

Highest energy proton-antiproton collider, CMS energy ≈ 2 TeV, 1986-2011



FERMI NEWS

Volume 24 | Friday, June 8, 2001 | Number 10

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Prague Scientists Check in at Fermilab

by Chad Boutin

The particles could travel, but the particle physicists couldn't.

Czech physicists now form a lively group at Fermilab's DZero. But for many Cold War decades, scientists in Prague were isolated from their Western colleagues.

"Fermilab was like Jupiter for us," said Ivan Wilhelm, Charles University rector and himself a nuclear physicist. "We knew it existed, but we couldn't reach it."

Researchers from three Prague institutions--Charles University, Czech Technical University, and the Academy of Sciences of the Czech Republic-- are now fully engaged with the community at DZero, contributing to the experiment and to the education of future scientists.

"The Prague group has been right up to speed with us from the outset," said John Womersley, spokesman for DZero. "It's as though there had never been a barrier between us at all."

Building a Collaboration

Once the Iron Curtain was torn down, senior physicist Vladimir Simak of the Academy of Sciences saw places like Fermilab as international destinations and sources of international collaboration, instead of as interplanetary dreams. Simak made contact with a number of Western colleagues at a 1996 workshop in Padua, Italy, which led to his collaboration on experiments at CERN, the European Laboratory for Particle Physics. It was in Geneva that he first heard about the planned upgrades to Fermilab's Tevatron. For a physicist with longstanding interest in probing the structure of the proton, the possibility of contributing to Collider Run II was a great temptation.

Vladislav Simak

Many contributions from Czech groups to Dzero detector components and physics:

- Muon HV system
- Silicon and luminosity detectors
- Computing
- Jet physics

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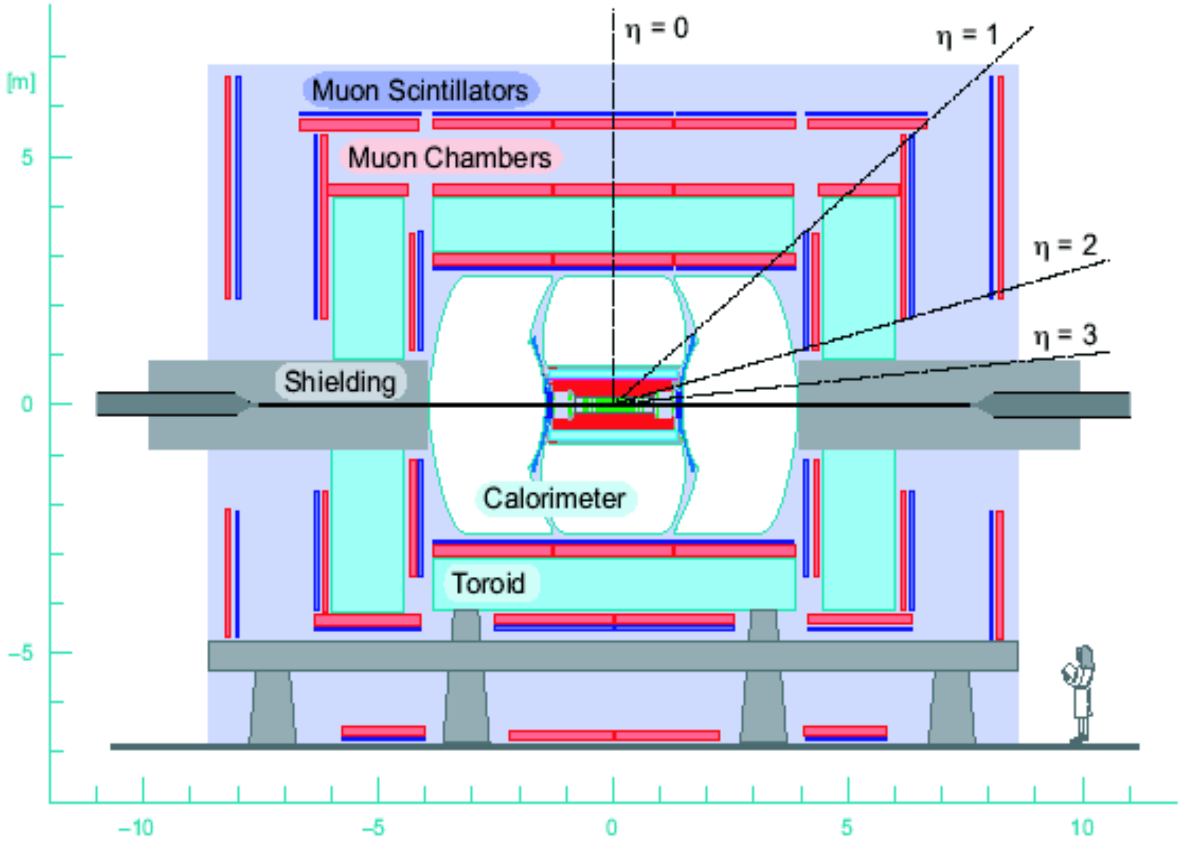
The Dzero Detector

Tracking:
Silicon Microstrip Tracker
Central Fiber Tracker
2 T Solenoid

Calorimeter:
Liquid Argon Calorimeter
Scintillator Pre-shower

Muons:
Drift Tubes
Scintillators
1.8 T Toroid



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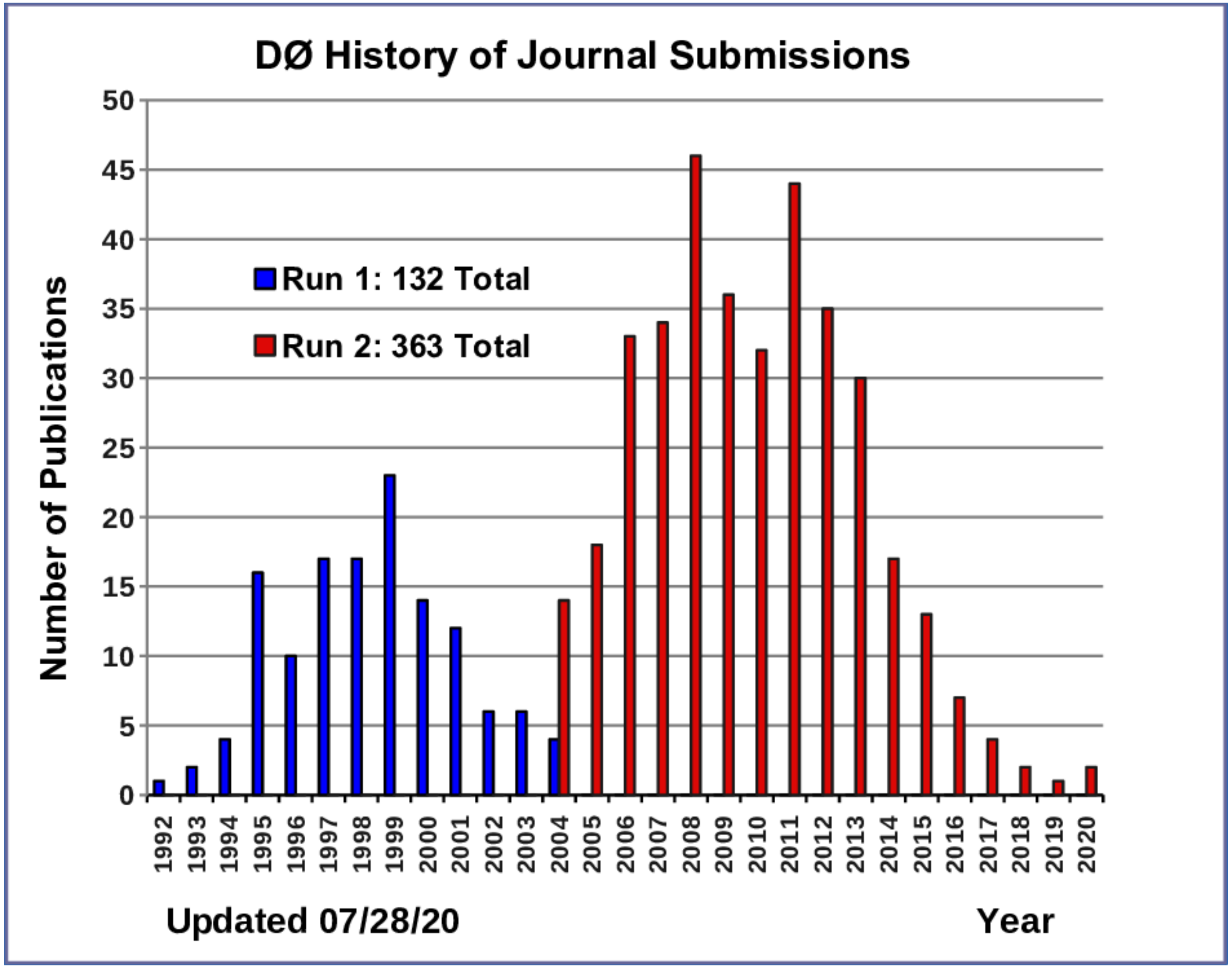
DØ History of Journal Submissions
Run 1: 132 Total
Run 2: 363 Total
Number of Publications
0
5
10
15
20
25
30
35
40
45
50
1992
1993
1994
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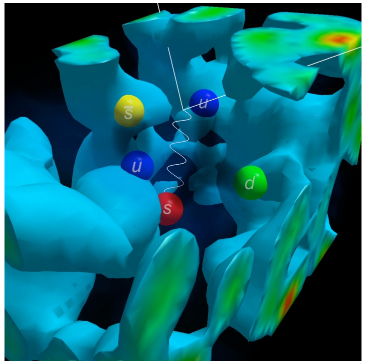
2018
2019
2020
Updated 07/28/20
Year

A rich physics programme

QCD



Top

B physics

New Phenomena

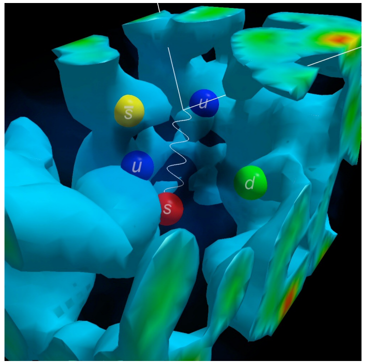
$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f(i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f\bar{\Psi}_f\gamma^\mu\Psi_f A_\mu) +$$
$$+\frac{g}{\sqrt{2}}\sum_i(\bar{a}^i_L\gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L\gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w}\sum_f \bar{\Psi}_f\gamma^\mu(I^3_f - 2s^2_w Q_f - I^3_f\gamma_5)\Psi_f Z_\mu +$$
$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$
$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig'c_w(W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$
$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig'c_w(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$
$$-\frac{1}{2}M^2_\eta\eta^2 - \frac{gM^2_\eta}{8M_W}\eta^3 - \frac{g'^2M^2_\eta}{32M_W}\eta^4 + |M_W W^+_\mu + \frac{g}{2}\eta W^+_\mu|^2 +$$
$$+\frac{1}{2}|\partial_\mu\eta + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f\Psi_f\eta$$

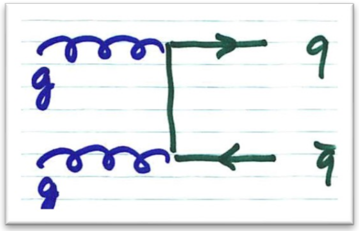
Electroweak

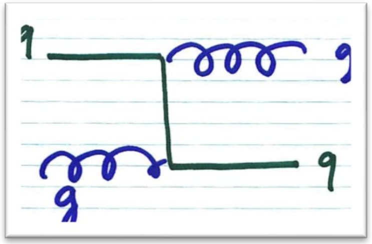
Higgs

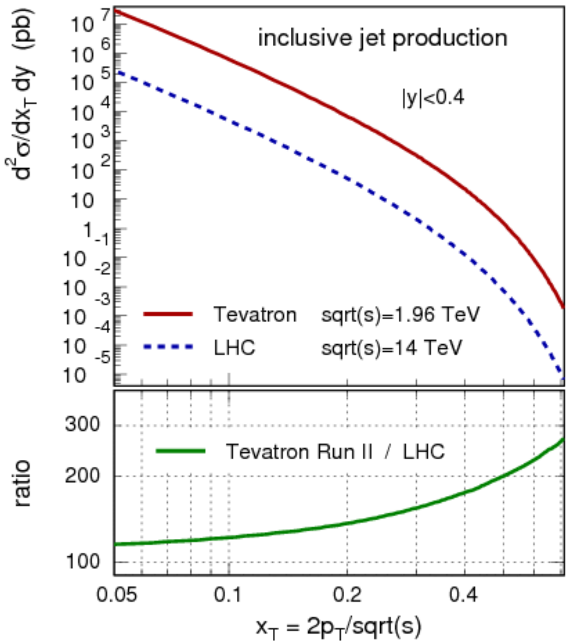
A rich physics programme

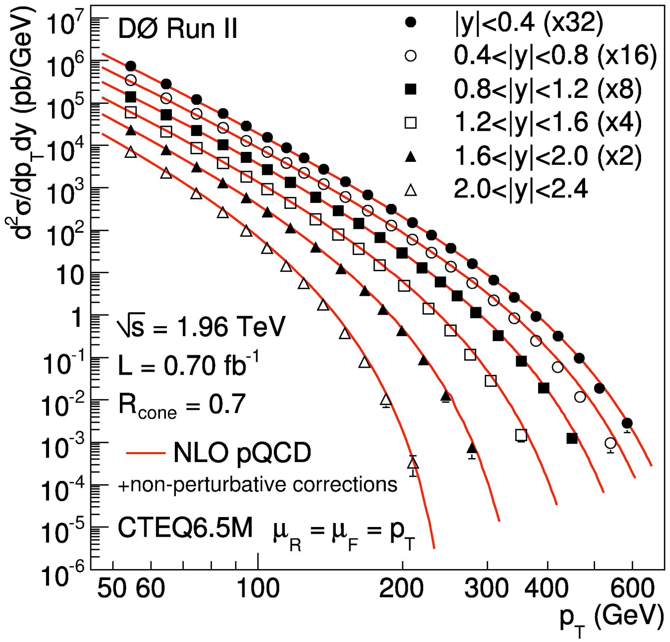
QCD





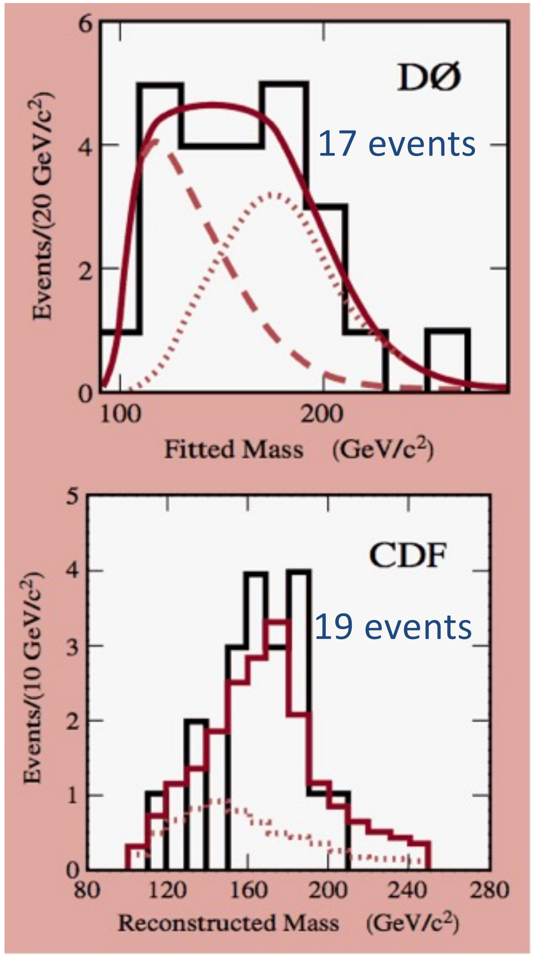




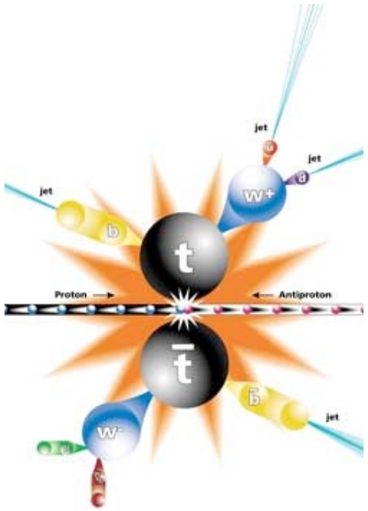


$$x_T = 2 \times 700\ \text{GeV}/1.96\ \text{TeV} = 0.7$$

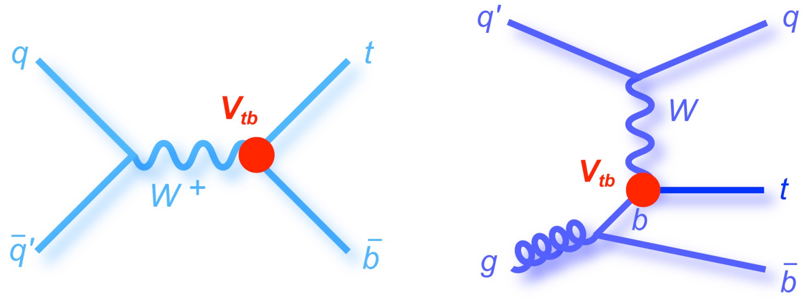
A rich physics programme

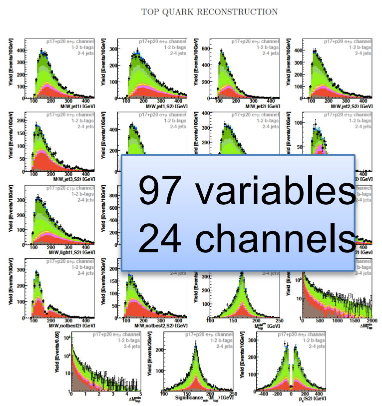


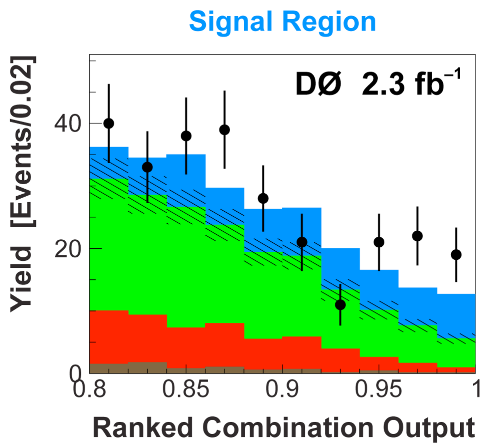
Top



Electroweak production, single top







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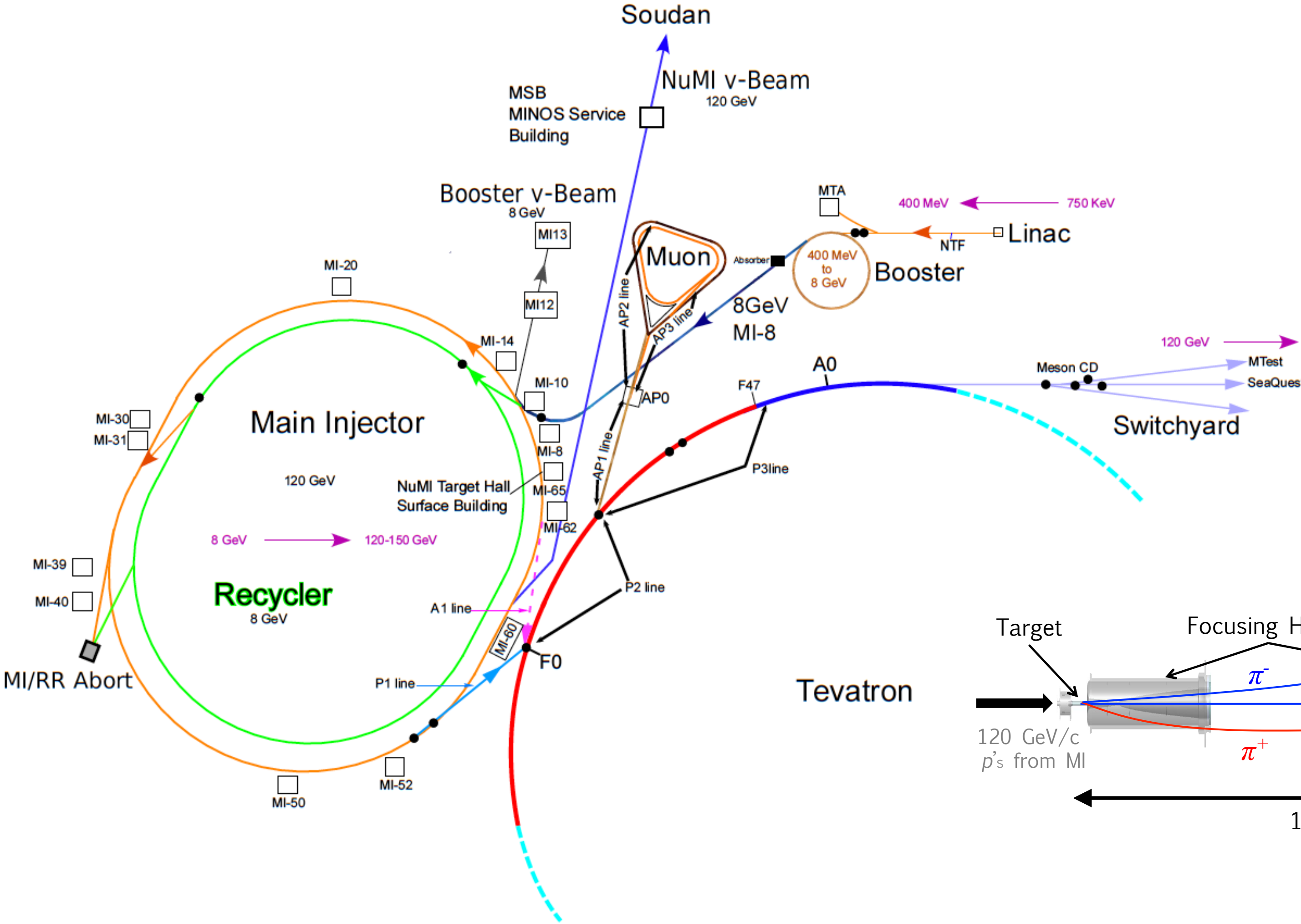
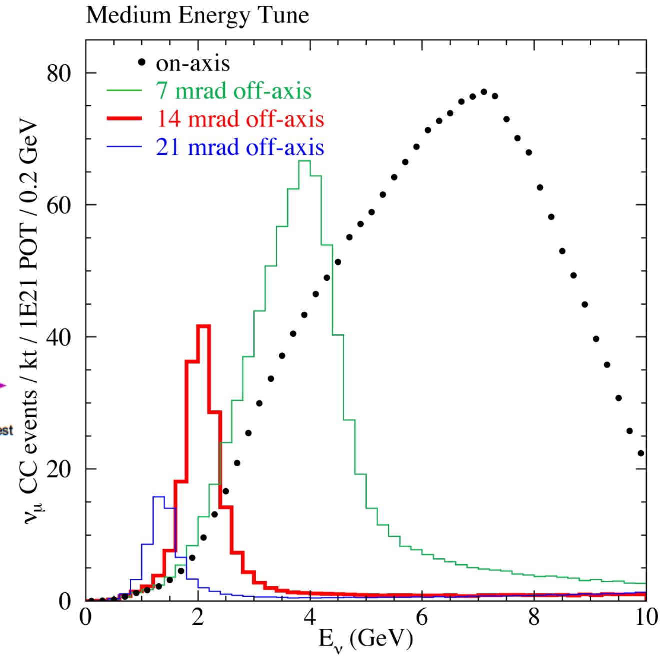
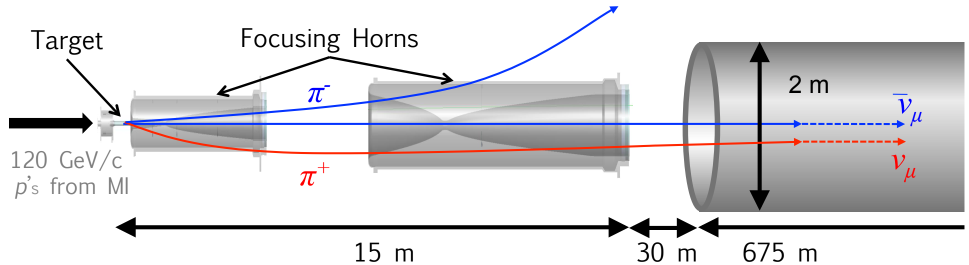
From the energy to the intensity frontier: neutrinos







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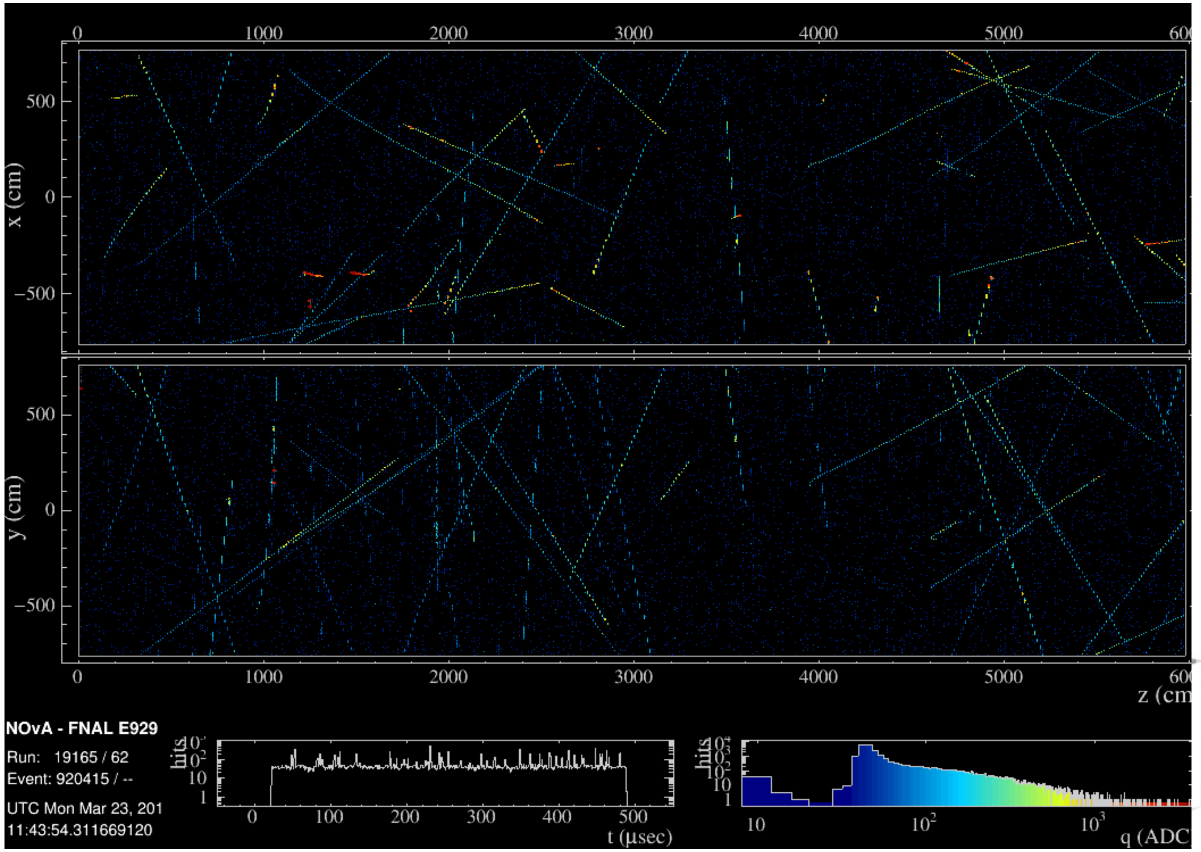
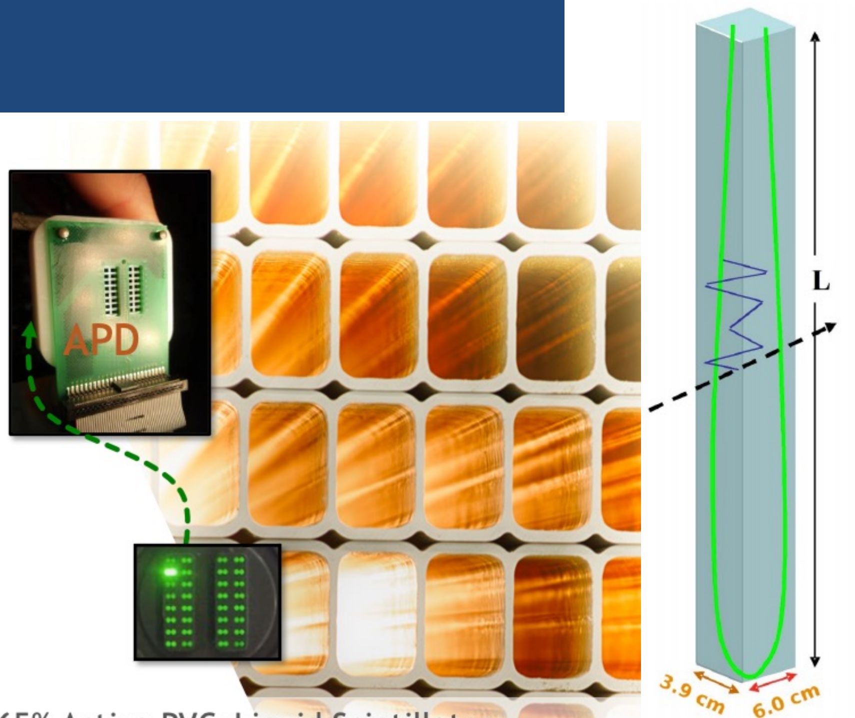
NOvA Far Detector (Ash River, MN)
MINOS Far Detector (Soudan, MN)
NuMI beam axis
810 km baseline
Wisconsin
Lake Michigan
Milwaukee
Fermilab
Chicago
A long-baseline neutrino oscillation experiment, situated 14.6 mrad off the NuMI beam axis
NOvA baseline: 810 km

NOvA Experiment

- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

NOvA is on the surface..

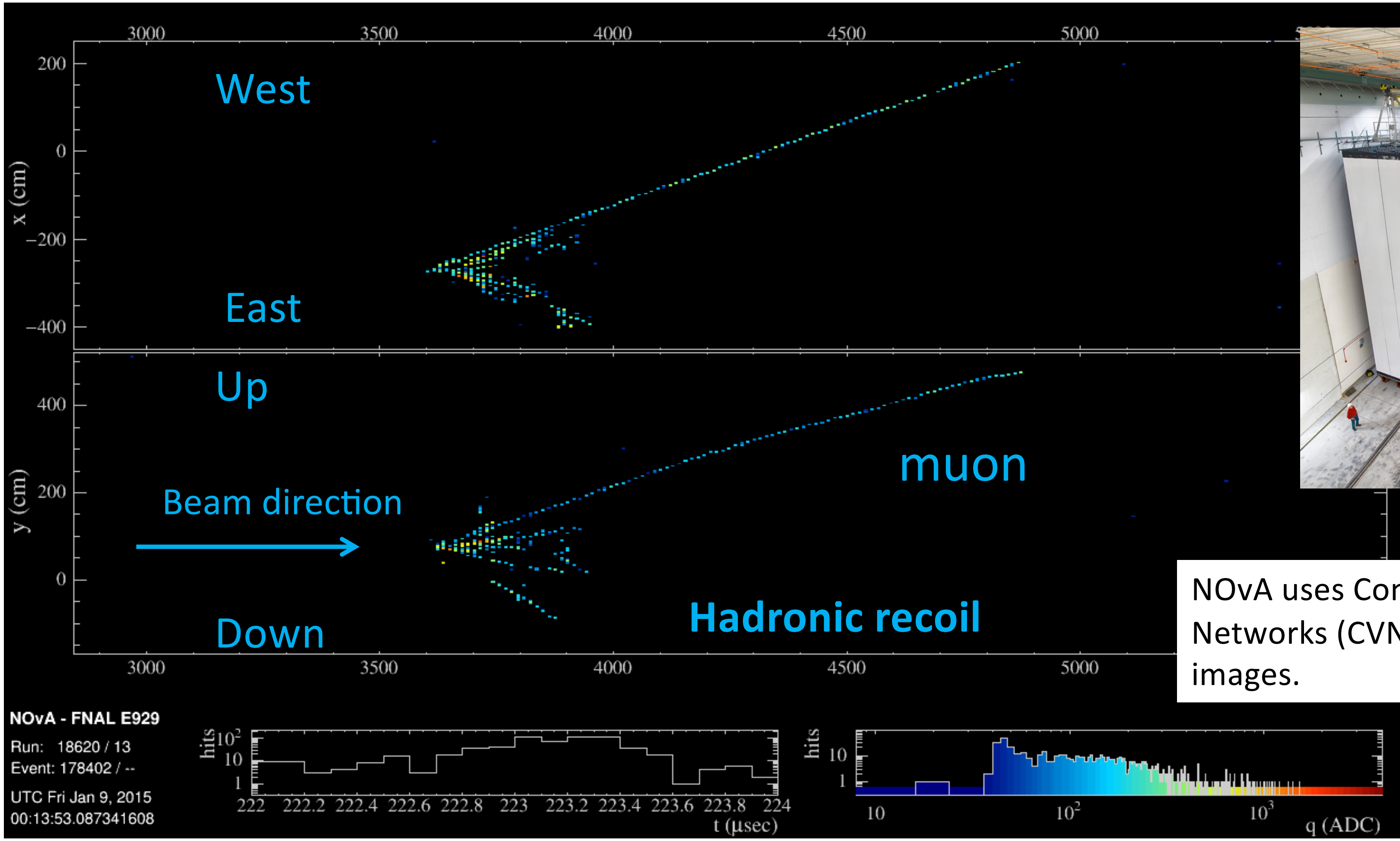




- 65% Active PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
  - Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer

- 14 kt Far Detector
- Equivalent Near Detector

NOvA Detector



NOvA uses Convolutional Neural Networks (CVNs) to reconstruct images.

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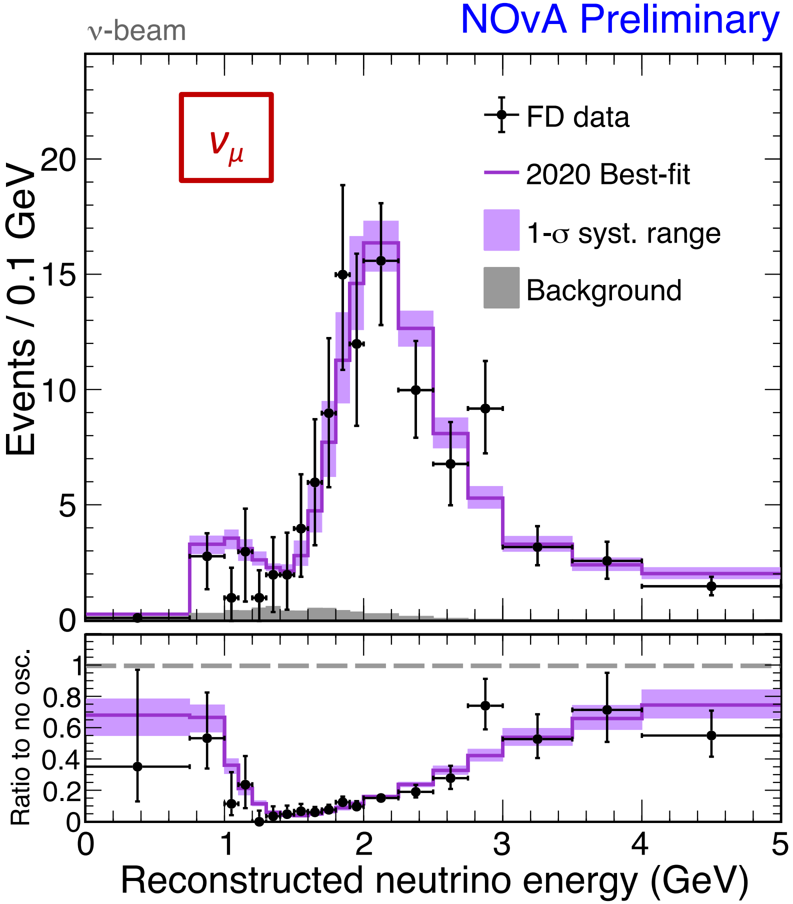
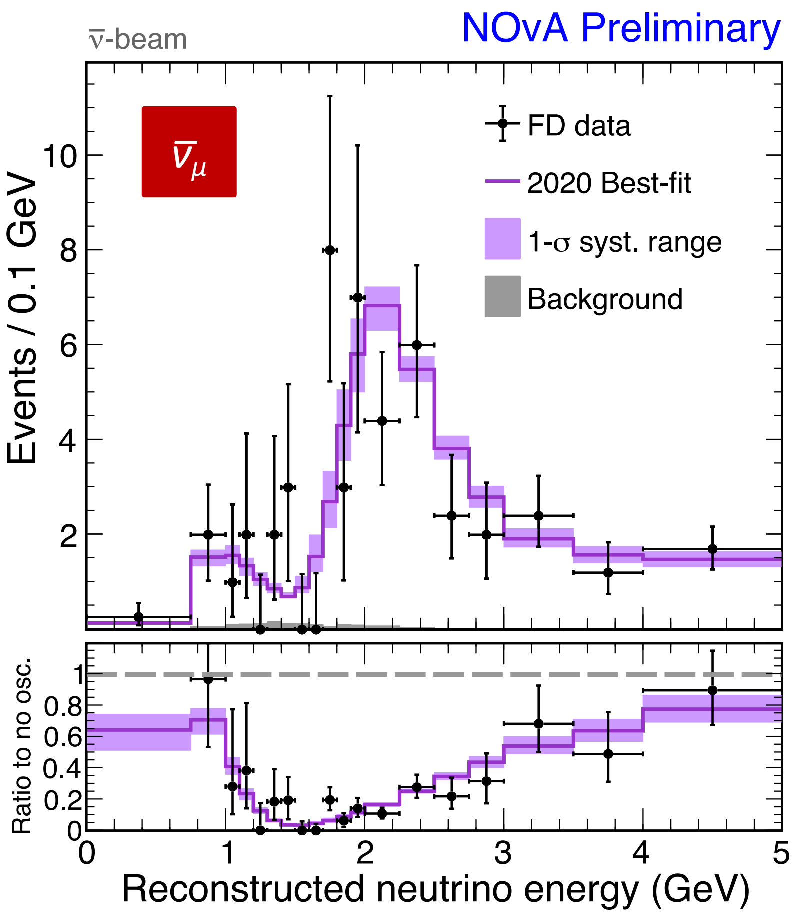
ν_μ and $\bar{\nu}_\mu$ disappearance at the NOvA Far Detector



211 events, 8.2 background



105 events, 2.1 background

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To give you a "flavour"

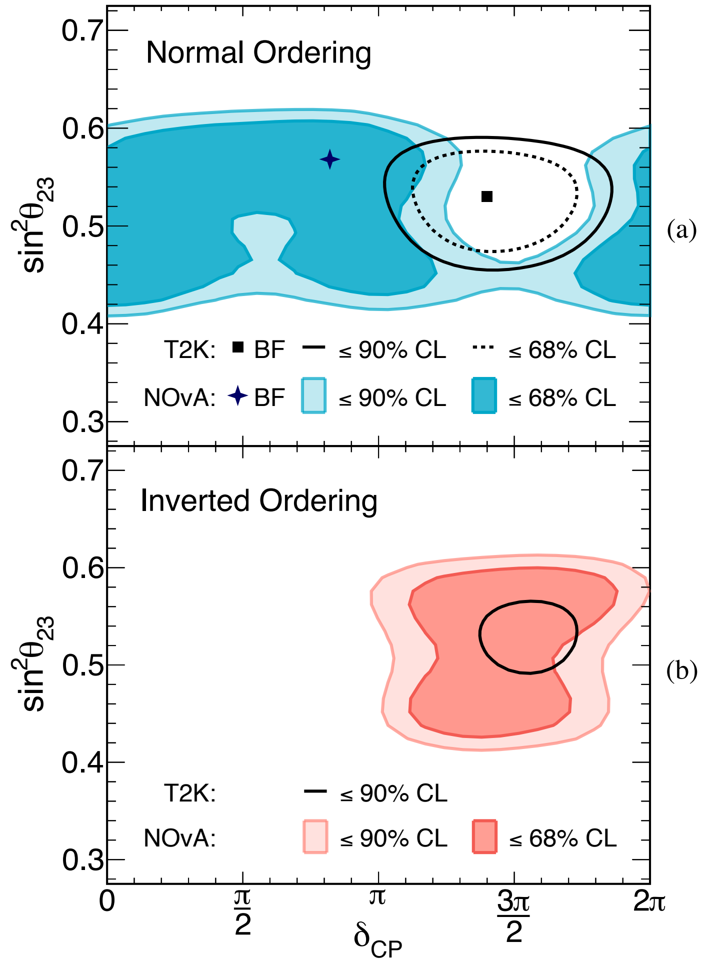
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}-\delta)$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin(aL)}{aL}\Delta_{21}^2$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

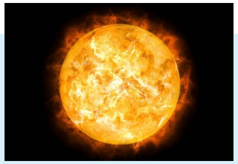
- Electron-neutrino appearance is sensitive to the CP phase.
- Mass ordering effect depends on electron density N_e.
- Simultaneous determination of mass ordering and CP phase only possible with long-baselines by fitting the energy dependence of the flux modulation.

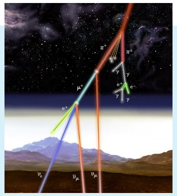
NOvA and T2K

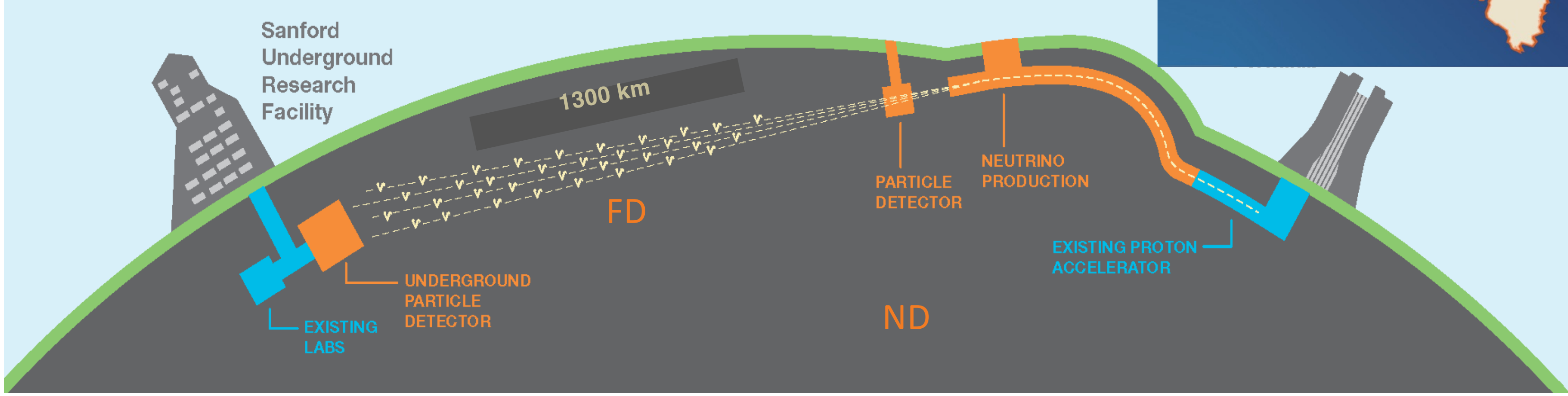
- Current data are inconclusive – expect some improvements with further running.
- Need next-generation experiments to discover CPV and resolve mass ordering.

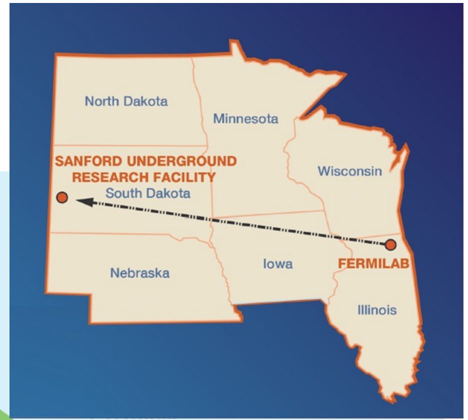


DUNE in a Nutshell









1. A high-power, wide-band **neutrino beam** (~ GeV energy range).
2. A ≈ 70 kt **liquid-argon Far Detector** in South Dakota, located 1478 m underground in a former gold mine.
3. A **Near Detector** located approximately 575 m from the neutrino source at Fermilab.

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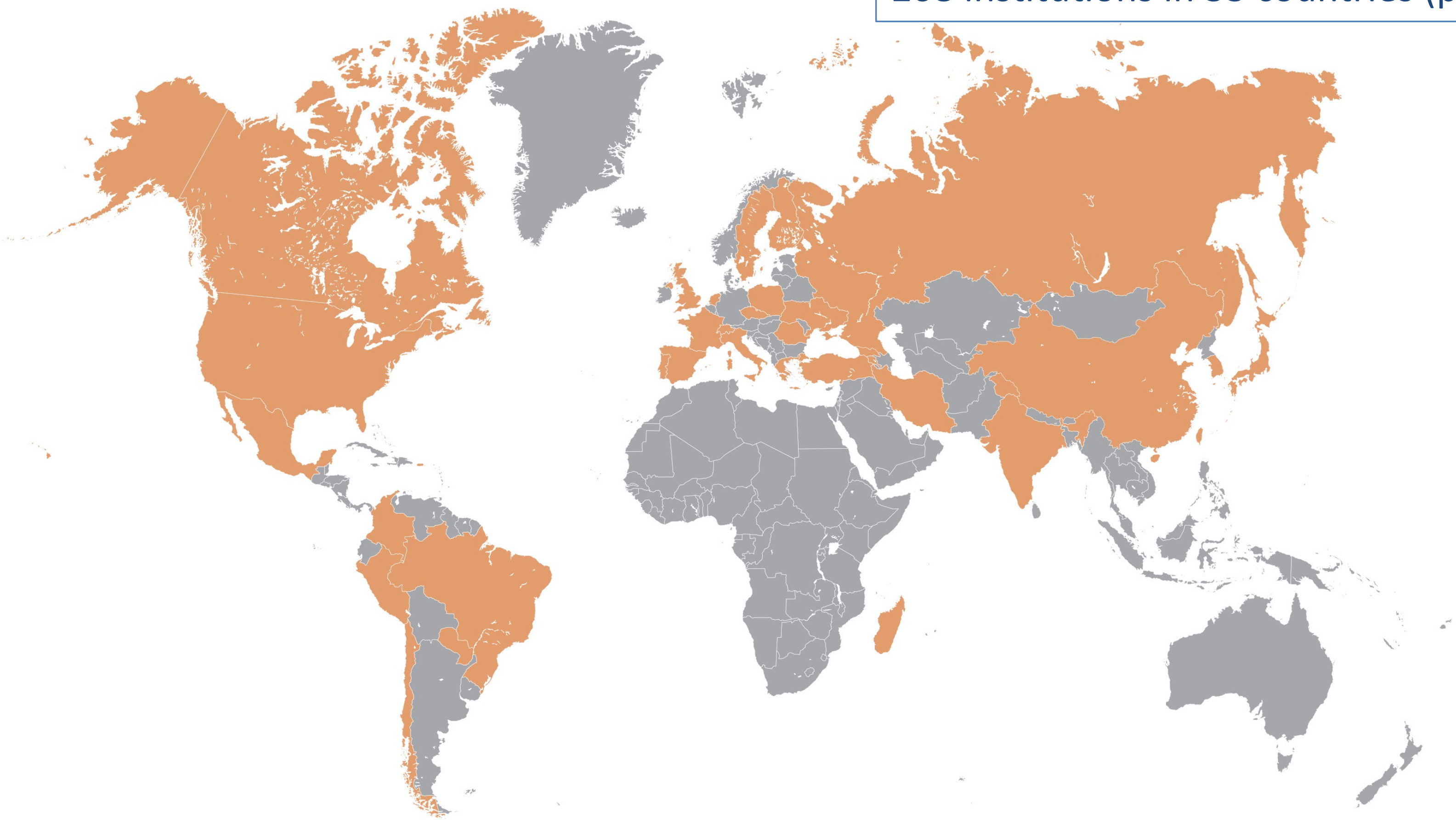
DUNE – a global collaboration

1317 collaborators from
208 institutions in 33 countries (plus CERN)



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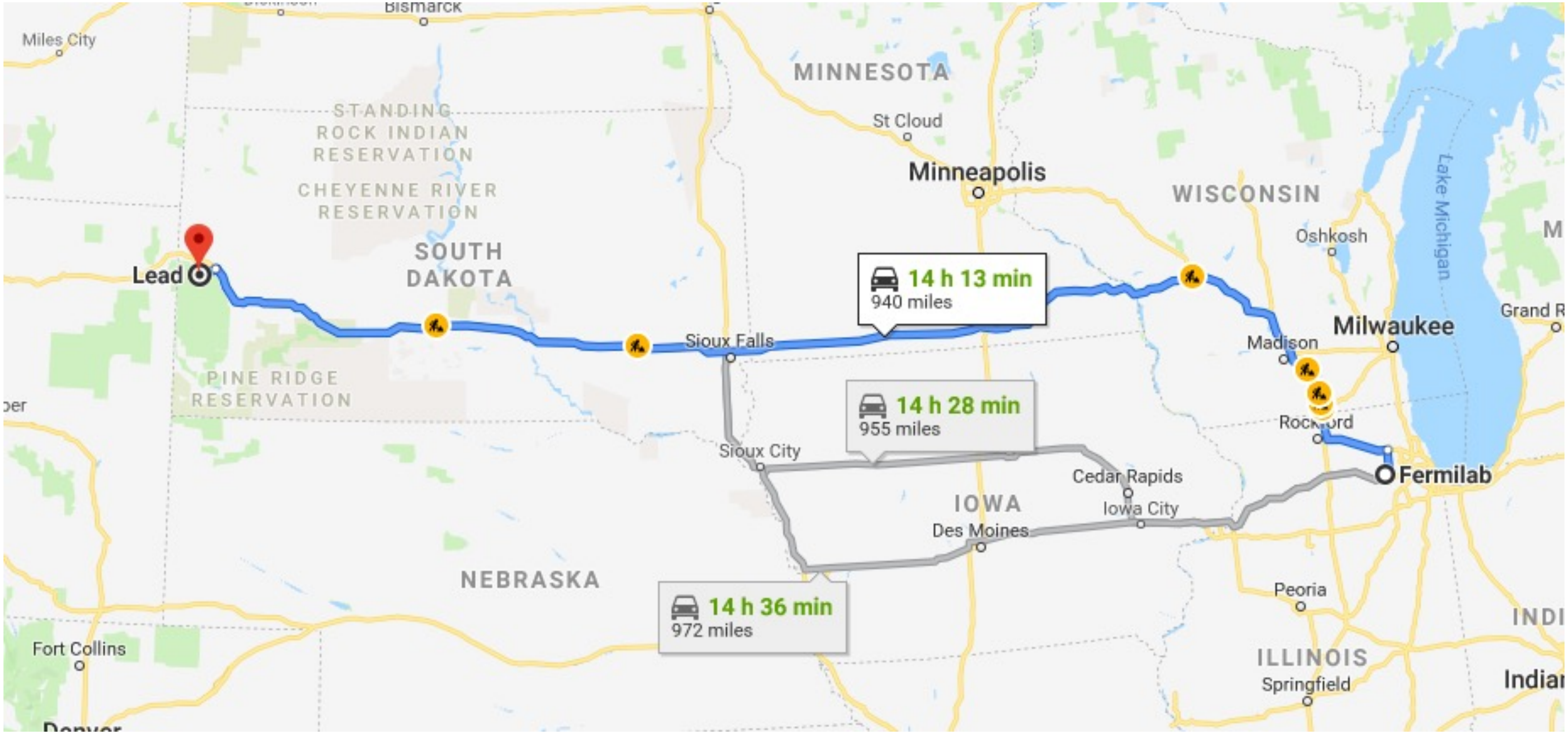
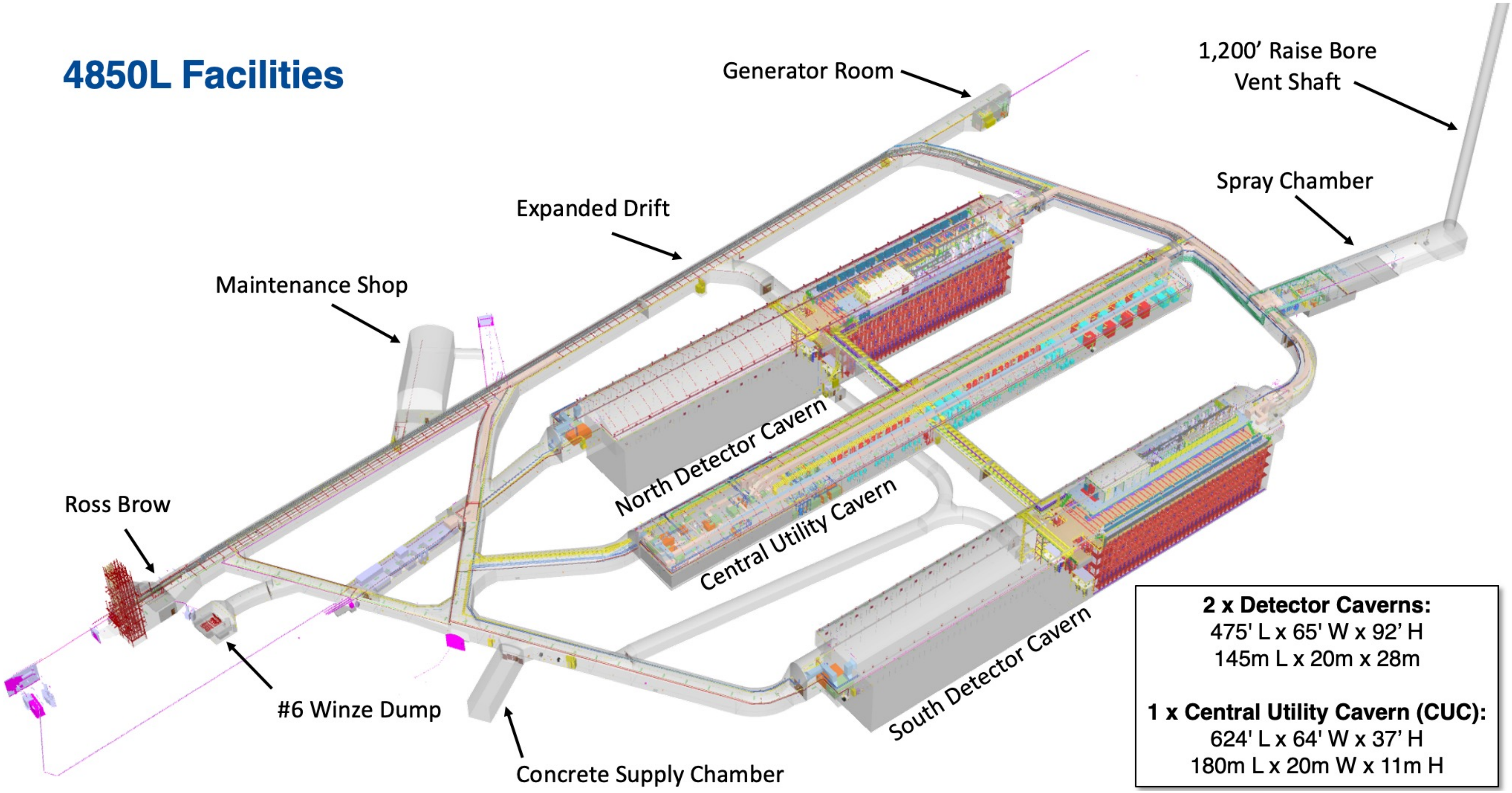
Proton Improvement Plan (PIP-II)

$L/E = 500$ km/GeV $\Rightarrow L = 1300$ km



4850L Facilities



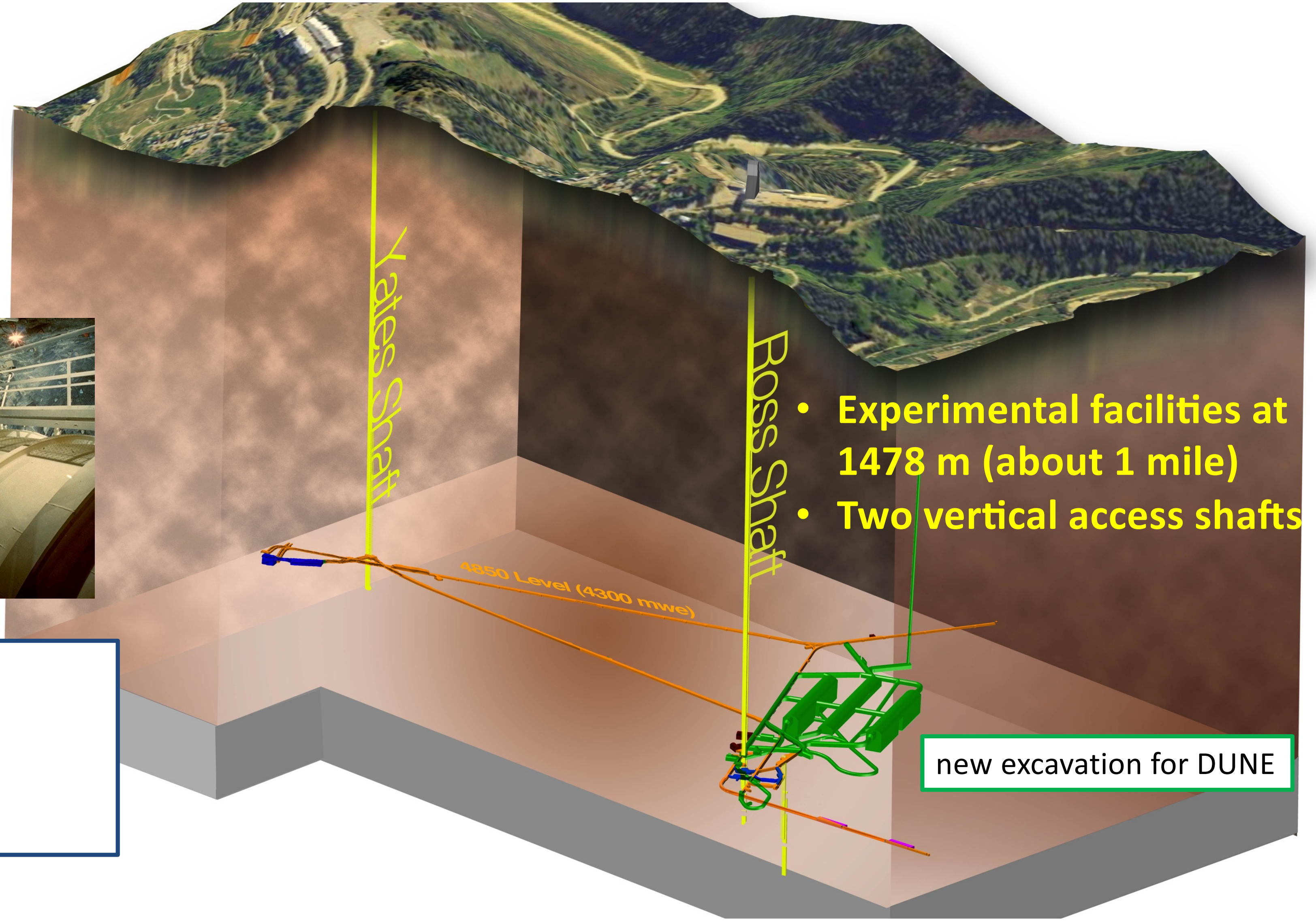
2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

12 Feb 2022

Central Utility Cavern Pilot Drift Breakthrough

Sanford Underground Research Facility (SURF)



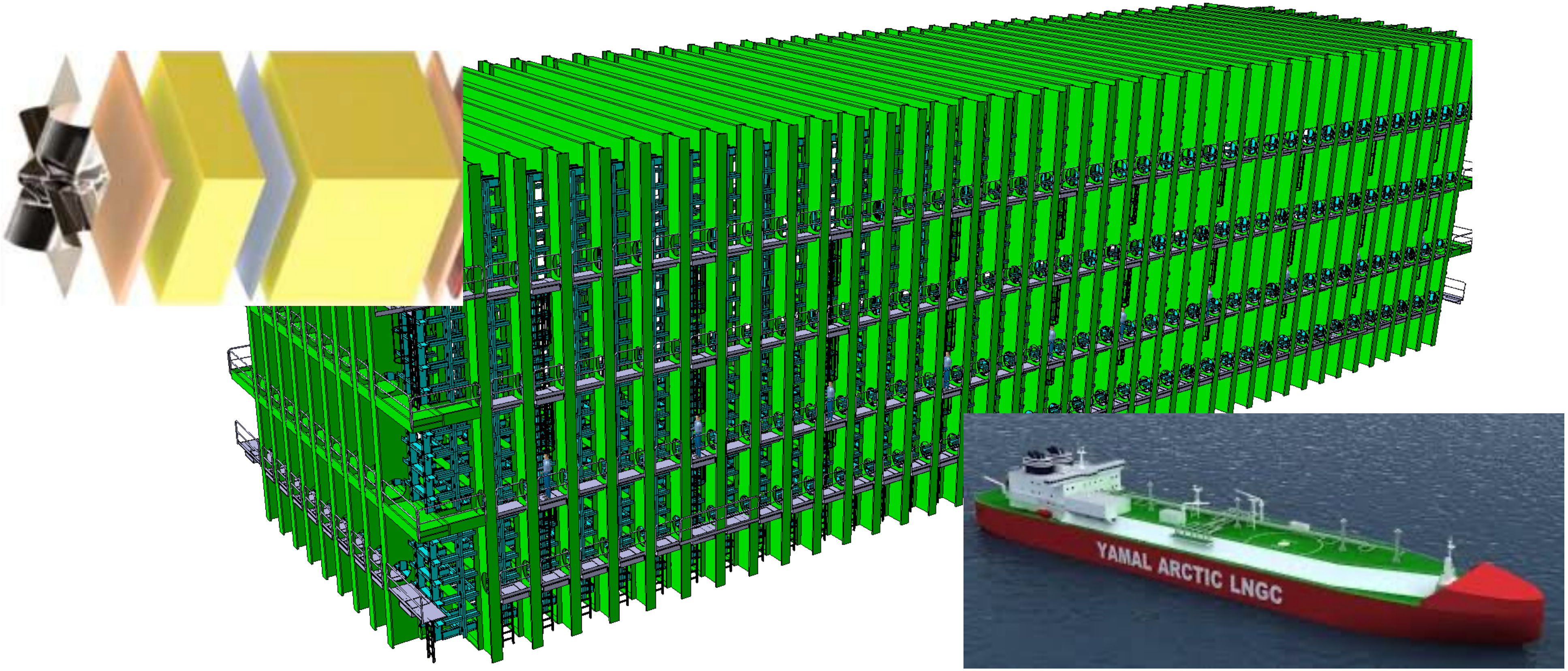
- Experimental facilities at 1478 m (about 1 mile)
- Two vertical access shafts

new excavation for DUNE

Davis Campus:
- LUX
- Majorana
- …
- LZ

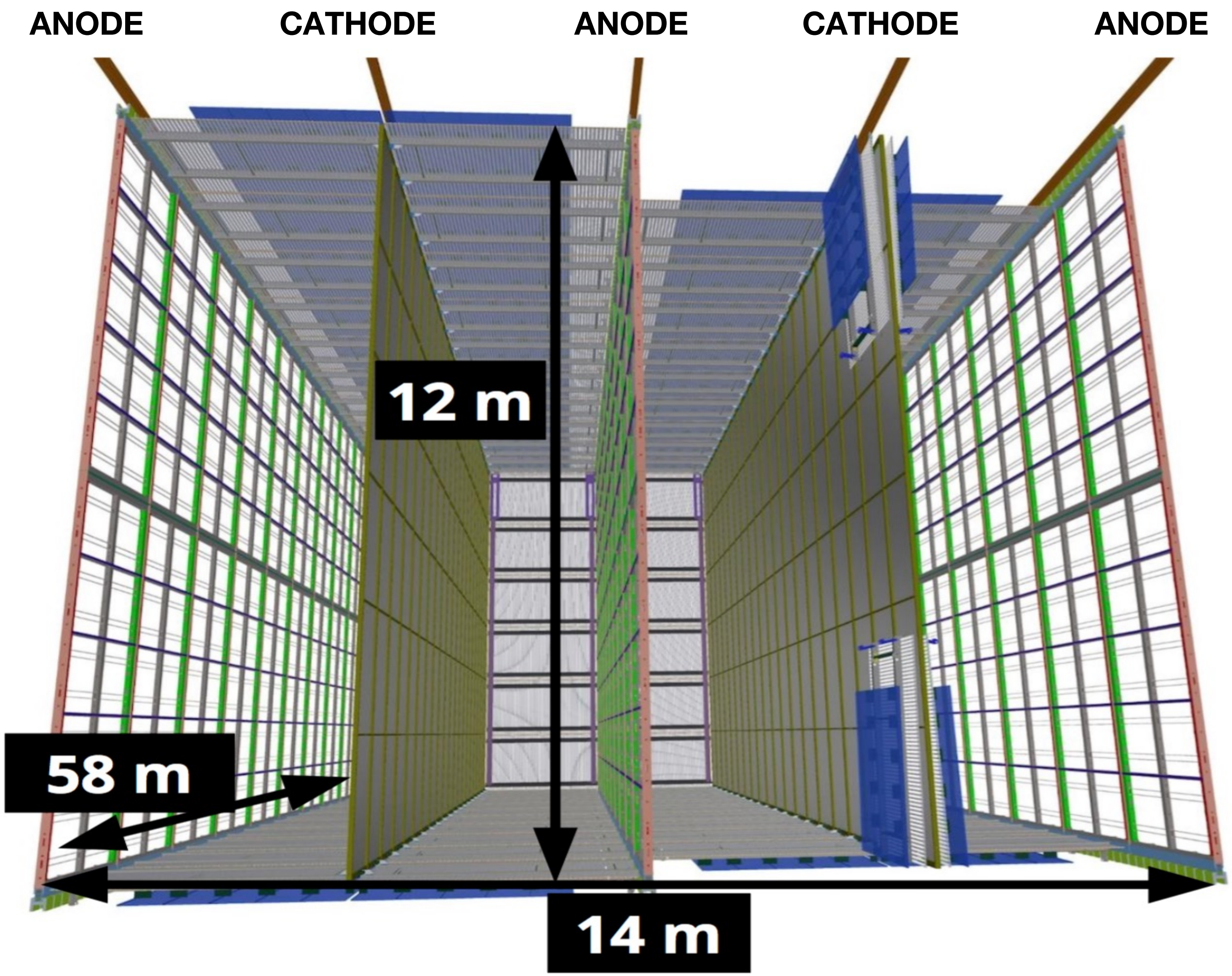
Four cryostats filled with liquid argon

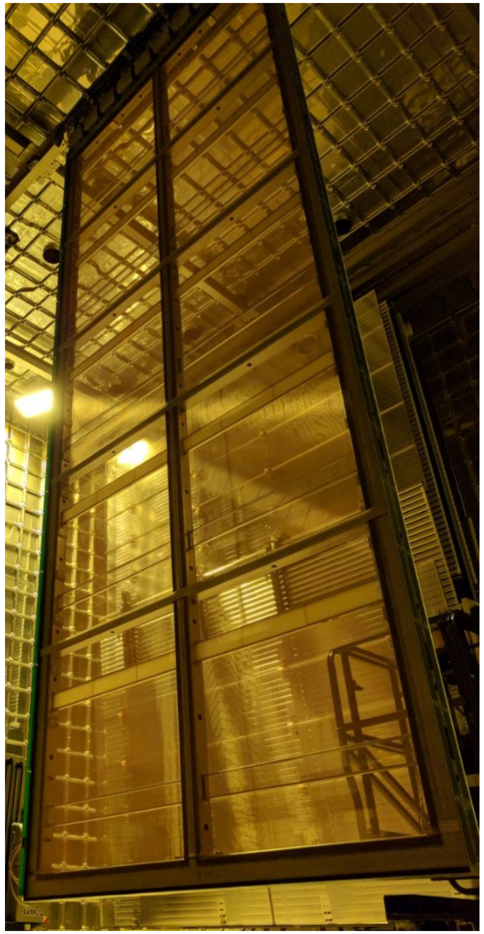
Each of the four cryostats contains 17,000 tons of liquid argon at 89 K (-184°C or -299°F)



<u>External Dimensions:</u> 19 m x 18 m x 66 m

Horizontal Drift Detector (FD Module 1)





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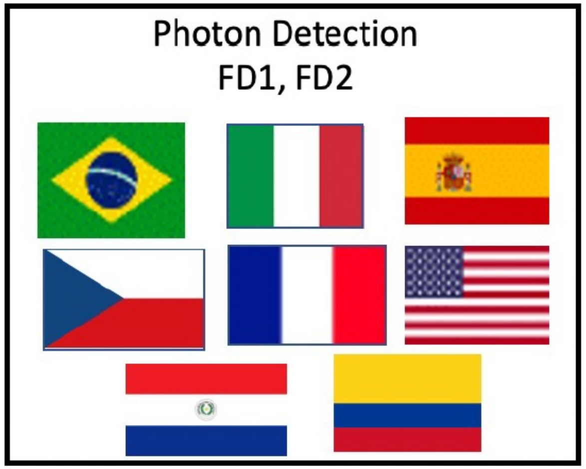
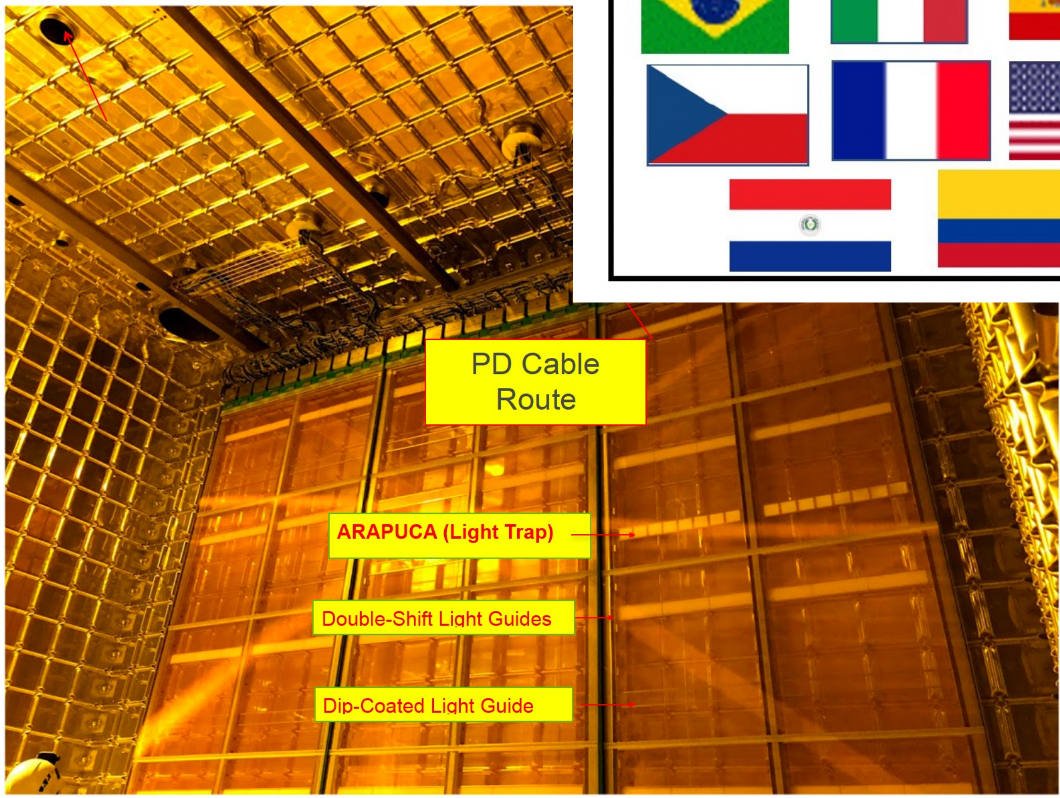
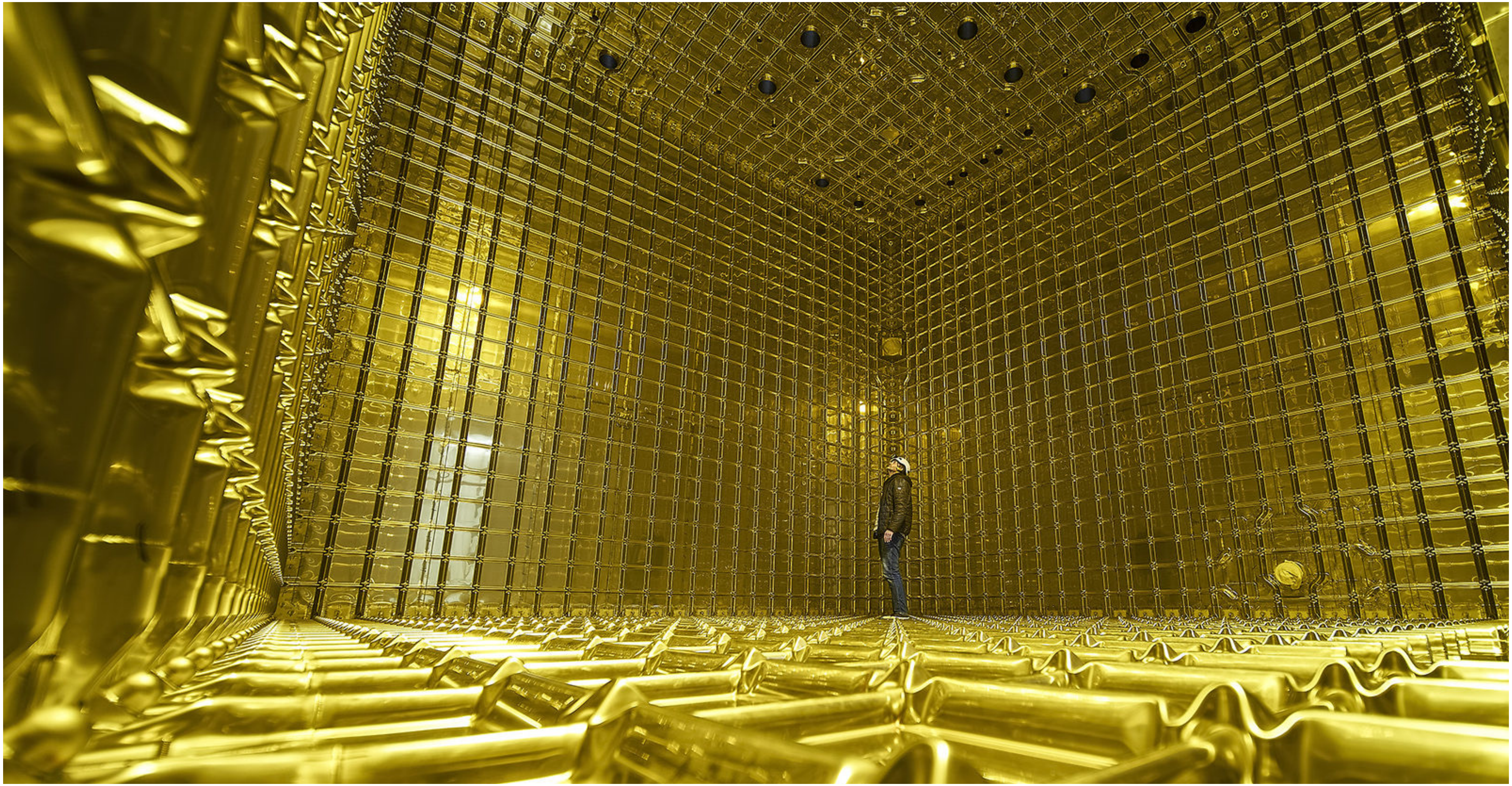
Photon Detection

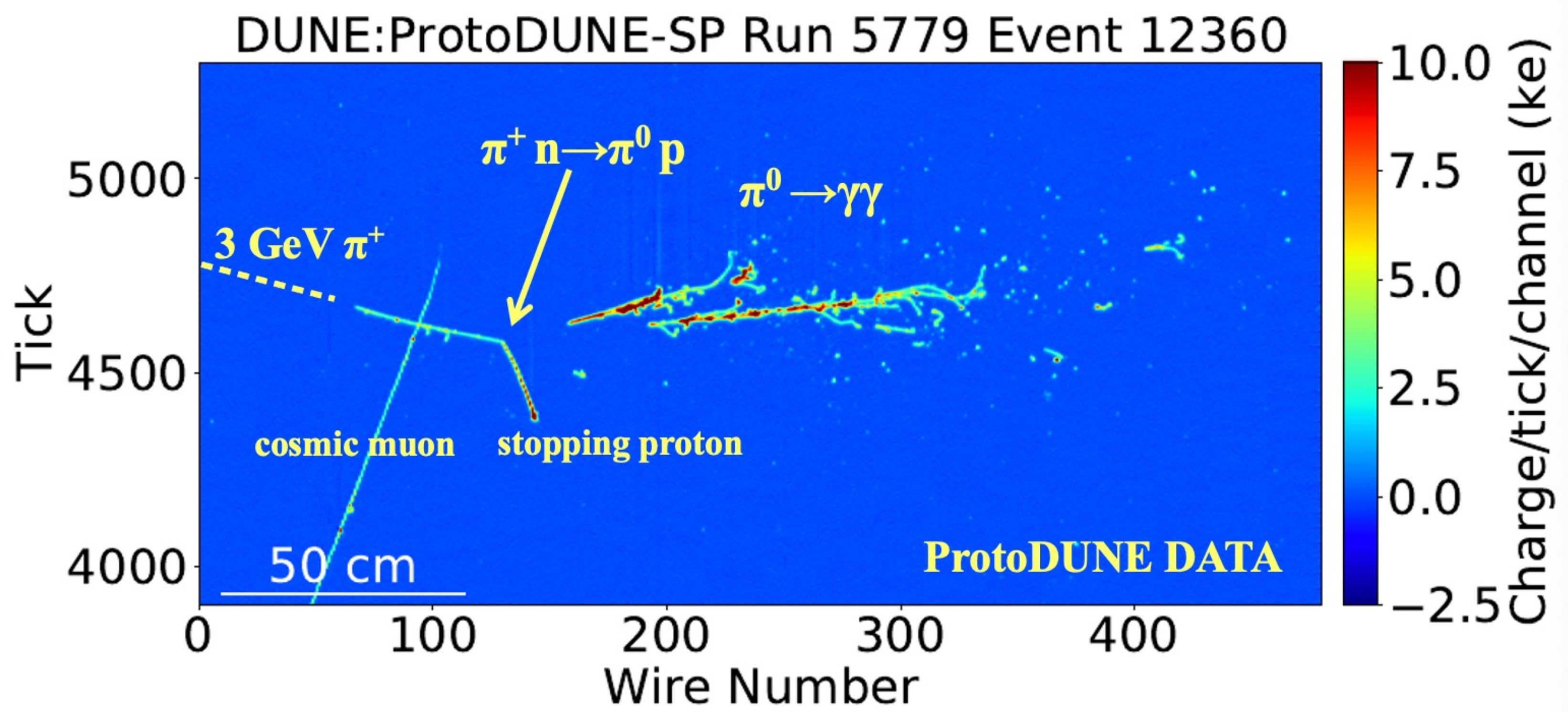




- Argon scintillation light is very abundant (40k photons/MeV)
- Arapuca technology with SiPMs for read-out
- Provides timing and event reconstruction
- Complementary to charge readout

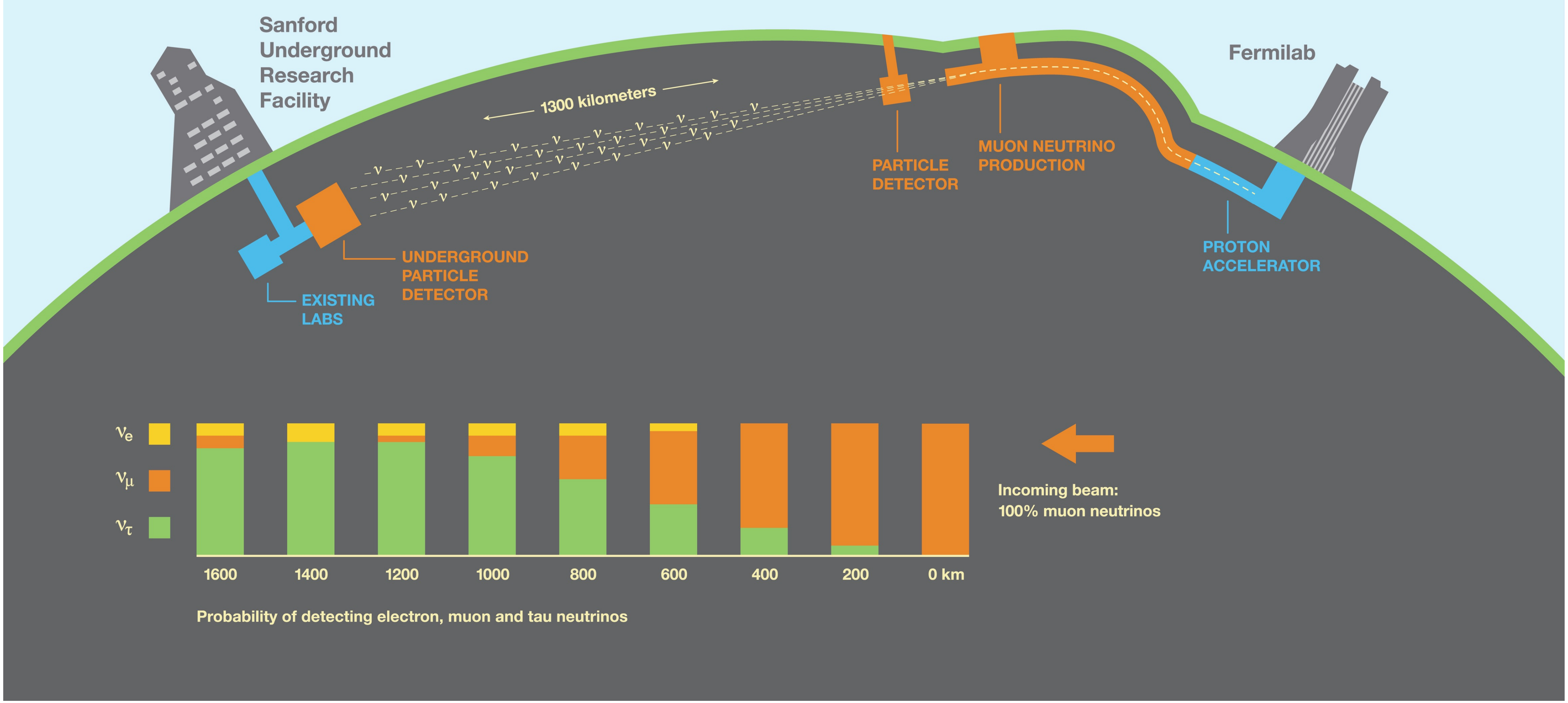


A ProtoDUNE-HD Data Event

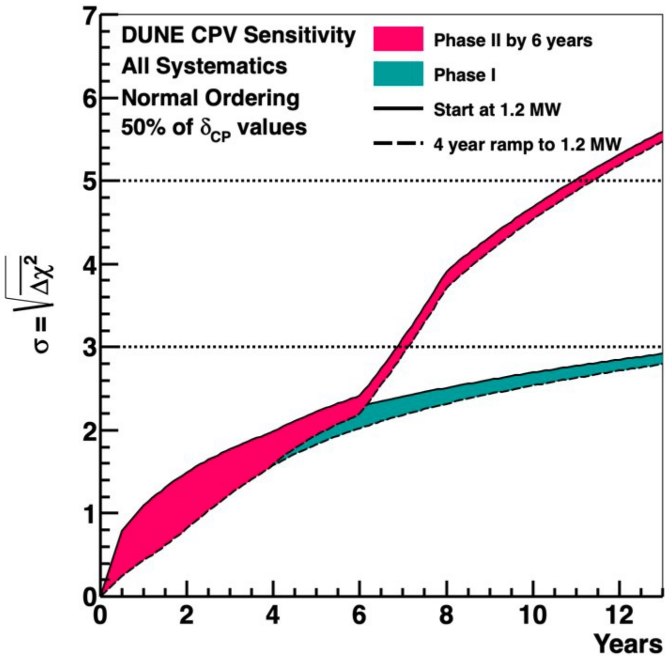


Reconstruction of events performed by PANDORA framework with the use of Grid computing resources, both areas UK-led.

Deep Underground Neutrino Experiment

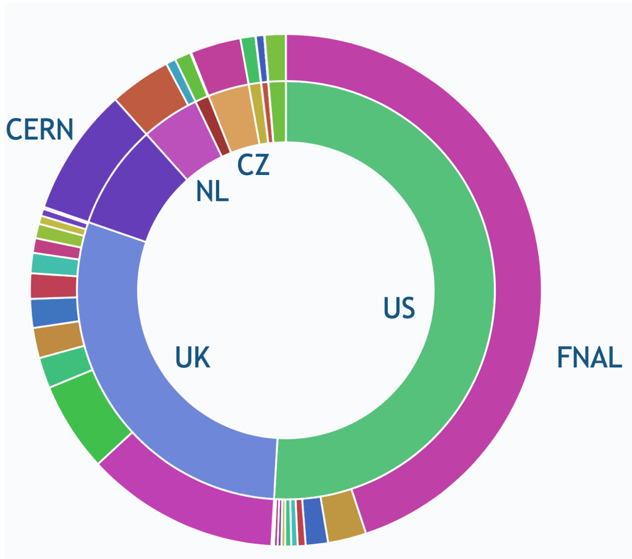


DUNE: Sensitivity to CP Violation



Phase II of DUNE will add Modules 3 and 4

DUNE production jobs 2021

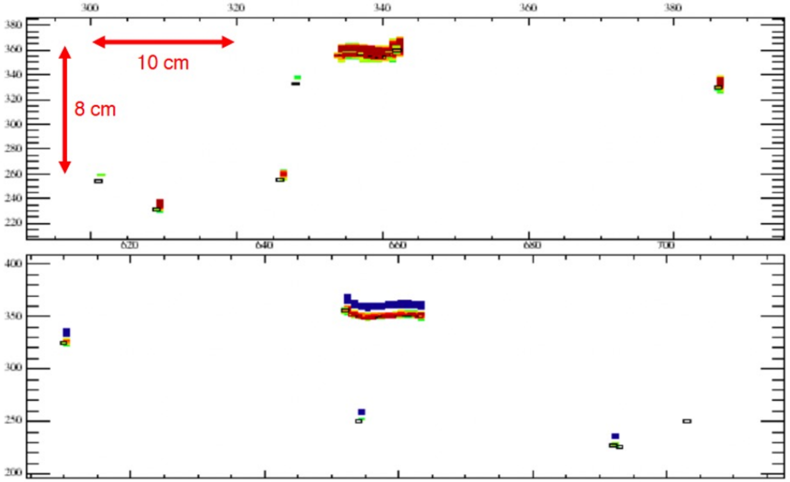


Czech institutes are major contributor to computing for NOvA and DUNE.

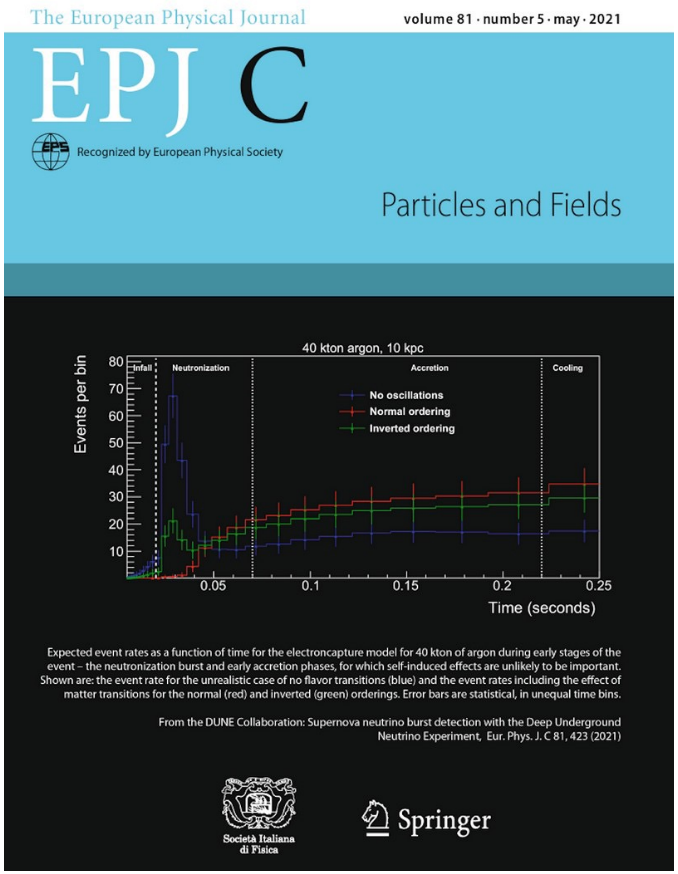
Neutrino Observatories

- Rich non-accelerator physics programme studying neutrinos from a supernova, solar, atmospheric neutrinos..
- Measurement at early times tests mass ordering and Detector requirements different from beam physics.

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



CC, 20 MeV



Fermilab – from the Tevatron to DUNE

- Czech particle physicists have made (and continue to make!) important contributions to the science programme at Fermilab.
- The Tevatron's rich physics programme included the discovery of the top quark and world-leading measurements of the W boson mass. It also made important contributions to Higgs boson physics.
- NOvA and DUNE provide pioneering measurements at the intensity frontier, searching for CPV with neutrinos. DUNE will also be an observatory for supernova neutrinos.