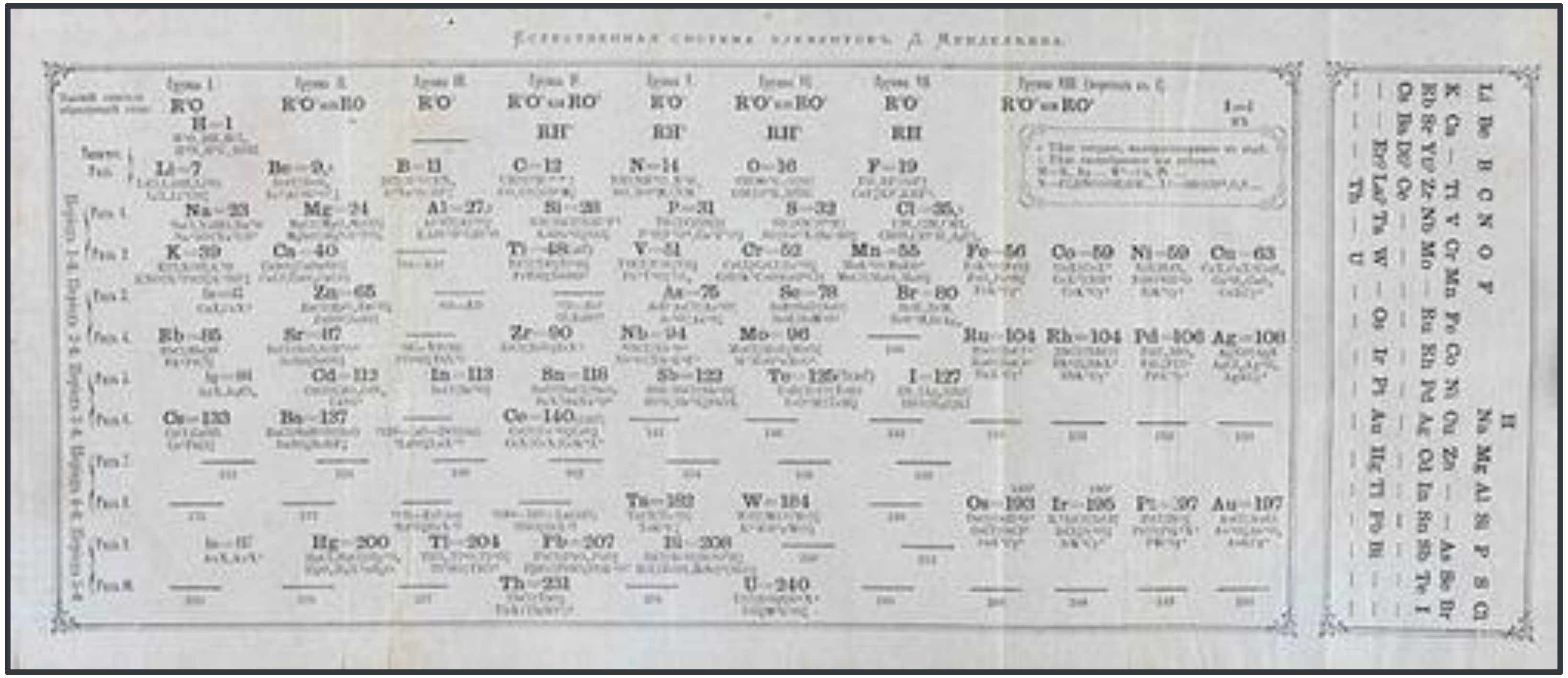
The Short Baseline Near Detector at Fermilab: First data and the exciting neutrino physics program ahead

Michelle Stancari

	No.		No.		No.		No.		No.		No.		No.		No.
H	1	F	8	Cl	15	Co & Ni	22	Br	29	Pd	36	I	42	Pt & Ir	50
Li	2	Na	9	K	16	Cu	23	Rb	30	Ag	37	Cs	44	Os	51
G	3	Mg	10	Ca	17	Zn	24	Sr	31	Cd	38	Ba & V	45	Hg	52
Bo	4	Al	11	Cr	19	Y	25	Ce & La	33	U	40	Ta	46	Tl	53
C	5	Si	12	Ti	18	In	26	Zr	32	Sn	39	W	47	Pb	54
N	6	P	13	Mn	20	As	27	Di & Mo	34	Sb	41	Nb	48	Bi	55
O	7	S	14	Fe	21	Se	28	Ro & Ru	35	Te	43	Au	49	Th	56



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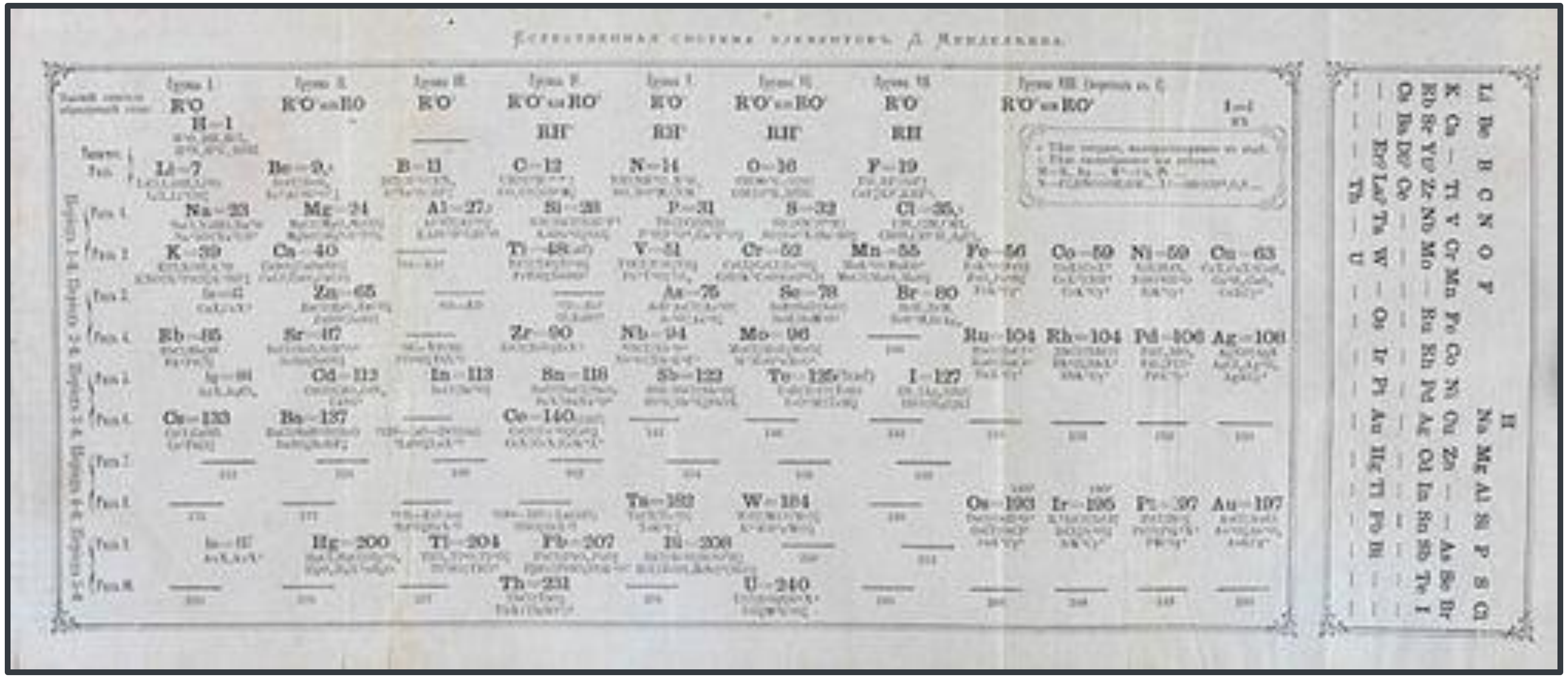
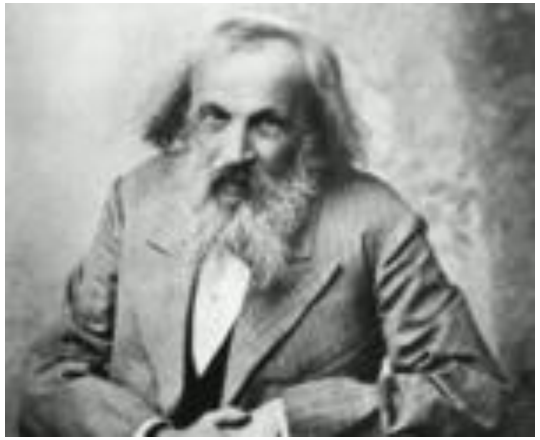
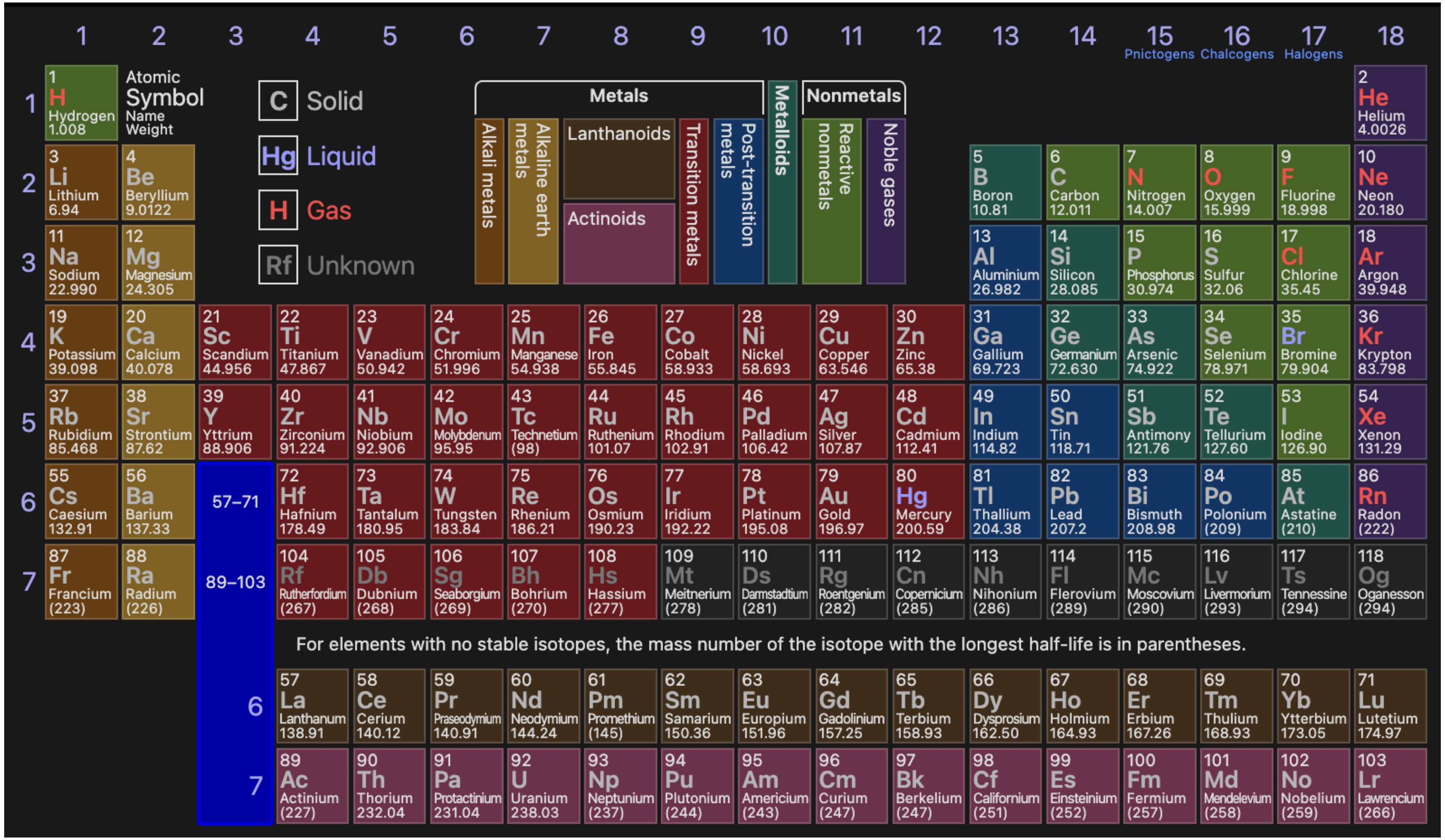
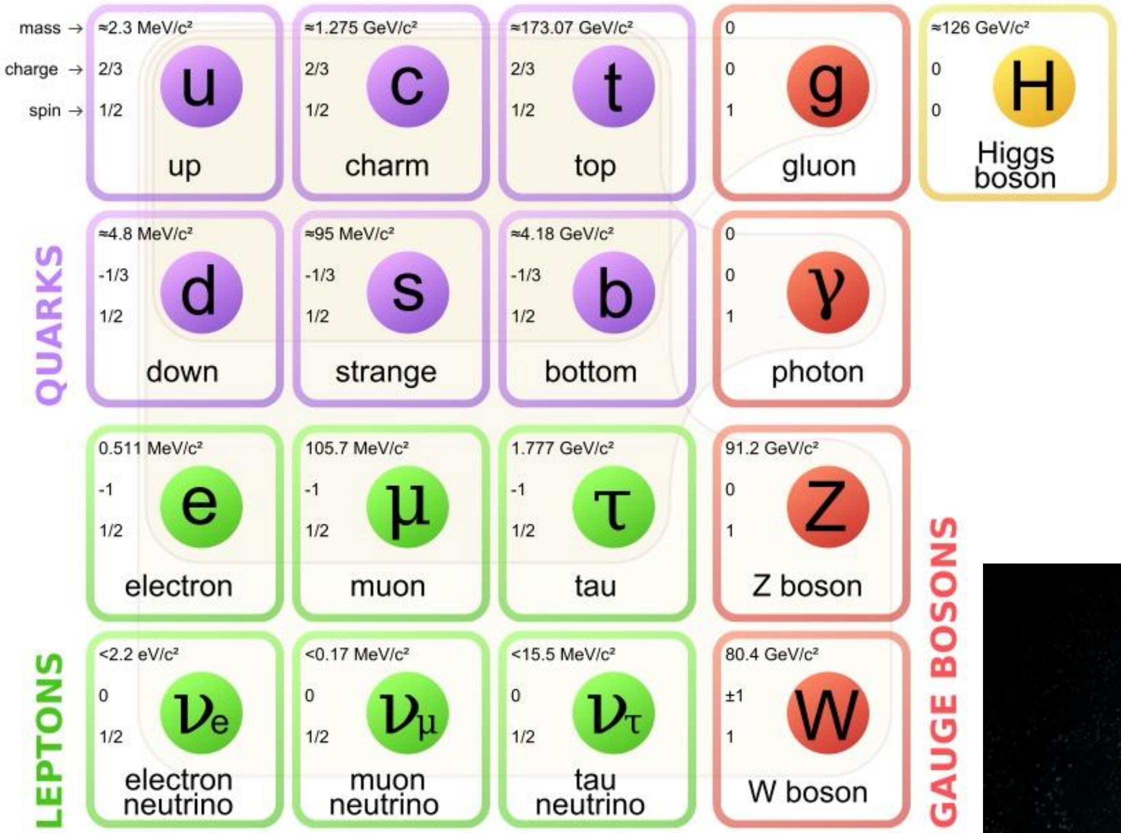
The first periodic tables (1866, 1871)






1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Pnictogens
Chalcogens
Halogens
1 2 3 4 5 6 7
Atomic
Symbol
Name
Weight
C Solid
Hg Liquid
H Gas
Rf Unknown
Metals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Post-transition metals
Metalloids
Nonmetals
Reactive nonmetals
Noble gases
1 H Hydrogen 1.008
2 He Helium 4.0026
3 Li Lithium 6.94
4 Be Beryllium 9.0122
5 B Boron 10.81
6 C Carbon 12.011
7 N Nitrogen 14.007
8 O Oxygen 15.999
9 F Fluorine 18.998
10 Ne Neon 20.180
11 Na Sodium 22.990
12 Mg Magnesium 24.305
13 Al Aluminium 26.982
14 Si Silicon 28.085
15 P Phosphorus 30.974
16 S Sulfur 32.06
17 Cl Chlorine 35.45
18 Ar Argon 39.948
19 K Potassium 39.098
20 Ca Calcium 40.078
21 Sc Scandium 44.956
22 Ti Titanium 47.867
23 V Vanadium 50.942
24 Cr Chromium 51.996
25 Mn Manganese 54.938
26 Fe Iron 55.845
27 Co Cobalt 58.933
28 Ni Nickel 58.693
29 Cu Copper 63.546
30 Zn Zinc 65.38
31 Ga Gallium 69.723
32 Ge Germanium 72.630
33 As Arsenic 74.922
34 Se Selenium 78.971
35 Br Bromine 79.904
36 Kr Krypton 83.798
37 Rb Rubidium 85.468
38 Sr Strontium 87.62
39 Y Yttrium 88.906
40 Zr Zirconium 91.224
41 Nb Niobium 92.906
42 Mo Molybdenum 95.95
43 Tc Technetium (98)
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.91
46 Pd Palladium 106.42
47 Ag Silver 107.87
48 Cd Cadmium 112.41
49 In Indium 114.82
50 Sn Tin 118.71
51 Sb Antimony 121.76
52 Te Tellurium 127.60
53 I Iodine 126.90
54 Xe Xenon 131.29
55 Cs Caesium 132.91
56 Ba Barium 137.33
57–71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.95
74 W Tungsten 183.84
75 Re Rhenium 186.21
76 Os Osmium 190.23
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.97
80 Hg Mercury 200.59
81 Tl Thallium 204.38
82 Pb Lead 207.2
83 Bi Bismuth 208.98
84 Po Polonium (209)
85 At Astatine (210)
86 Rn Radon (222)
87 Fr Francium (223)
88 Ra Radium (226)
89–103
104 Rf Rutherfordium (267)
105 Db Dubnium (268)
106 Sg Seaborgium (269)
107 Bh Bohrium (270)
108 Hs Hassium (277)
109 Mt Meitnerium (278)
110 Ds Darmstadtium (281)
111 Rg Roentgenium (282)
112 Cn Copernicium (285)
113 Nh Nihonium (286)
114 Fl Flerovium (289)
115 Mc Moscovium (290)
116 Lv Livermorium (293)
117 Ts Tennessine (294)
118 Og Oganesson (294)
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
6
57 La Lanthanum 138.91
58 Ce Cerium 140.12
59 Pr Praseodymium 140.91
60 Nd Neodymium 144.24
61 Pm Promethium (145)
62 Sm Samarium 150.36
63 Eu Europium 151.96
64 Gd Gadolinium 157.25
65 Tb Terbium 158.93
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93
68 Er Erbium 167.26
69 Tm Thulium 168.93
70 Yb Ytterbium 173.05
71 Lu Lutetium 174.97
7
89 Ac Actinium (227)
90 Th Thorium 232.04
91 Pa Protactinium 231.04
92 U Uranium 238.03
93 Np Neptunium (237)
94 Pu Plutonium (244)
95 Am Americium (243)
96 Cm Curium (247)
97 Bk Berkelium (247)
98 Cf Californium (251)
99 Es Einsteinium (252)
100 Fm Fermium (257)
101 Md Mendelevium (258)
102 No Nobelium (259)
103 Lr Lawrencium (266)

ptable.com



<u>"Recent" Discoveries</u>

Charm quark – 1974

Tau lepton – 1978

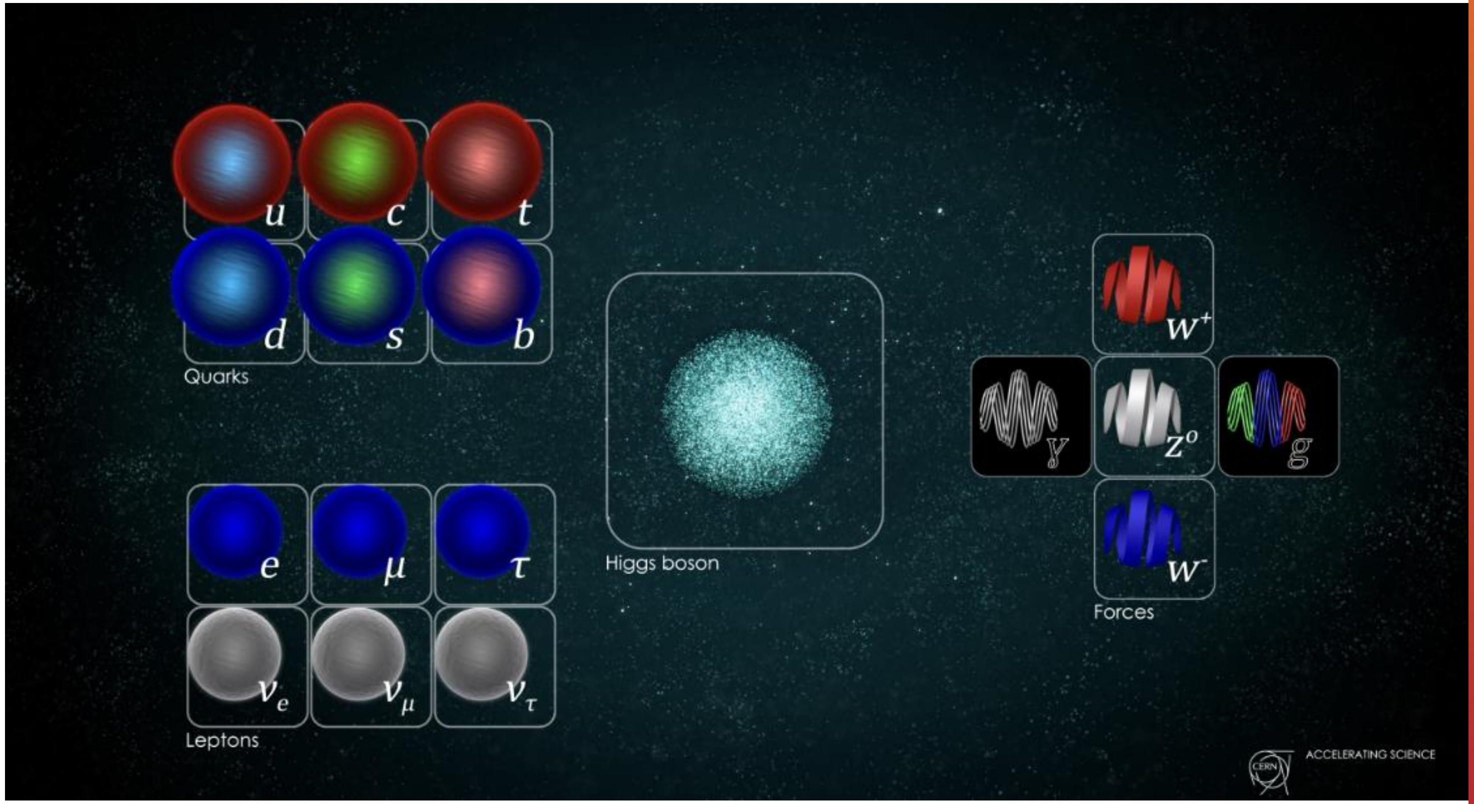
Bottom quark – 1977

W,Z bosons - 1983

Top quark – 1995

Tau neutrino – 2000

Higgs boson – 2012



Intriguing properties of neutrinos

- Tiny cross section – interact only through the weak force
- Mass so tiny that it has not yet been measured
- Oscillate from one flavor to another

Studying oscillations with experiments

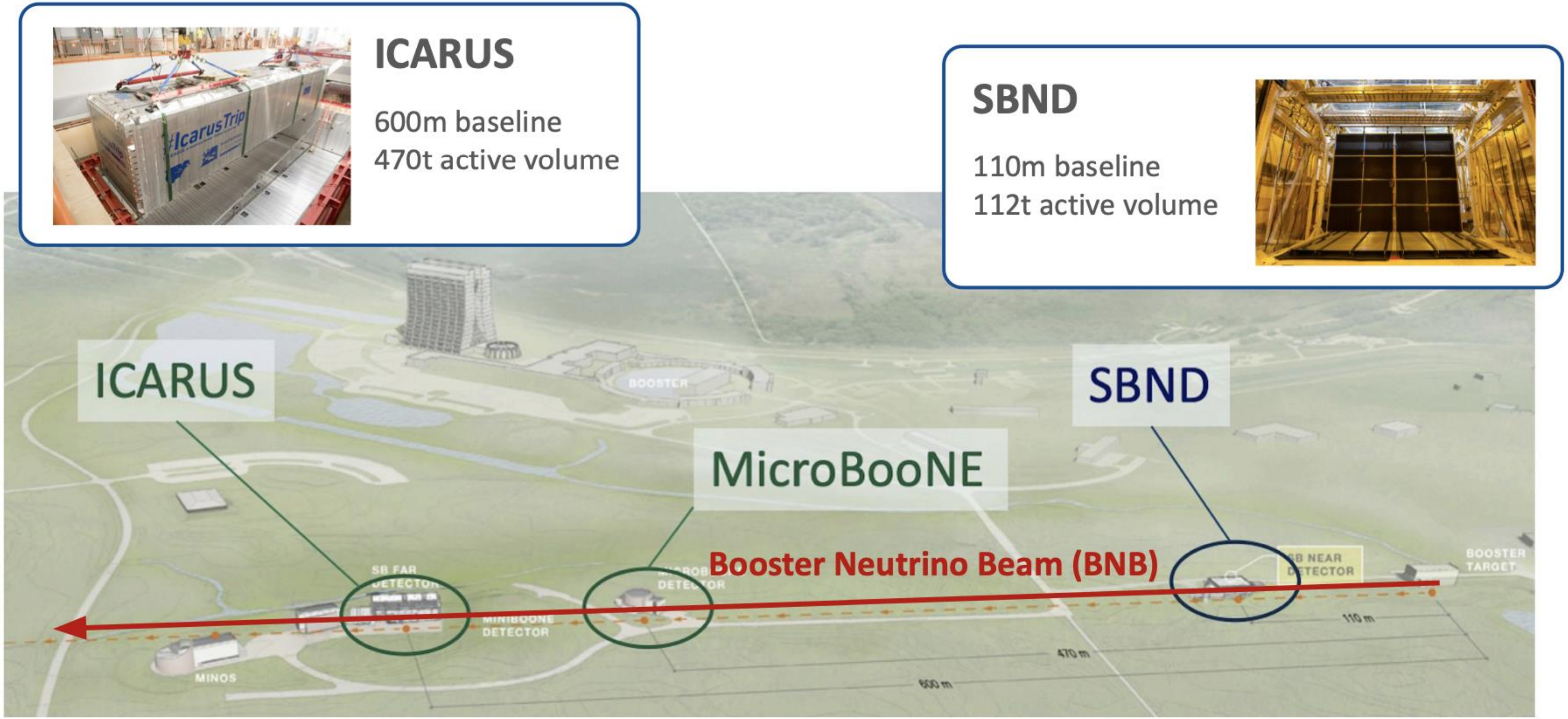
CONCEPT: Find or make a neutrino source. Get two detectors. Just count leptons in each!

However . . .

- Oscillation probability depends on neutrino flavor and energy
- Nuclear target complicates extracting the neutrino energy from the observed final state particles
- Preferred final states . . . a hadron leaving the interaction improves vertex resolution and background rejection.

REALITY: precision oscillation measurements require exquisite understanding of BOTH the neutrino source and the neutrino-nucleus interactions

The Short Baseline Neutrino Program at Fermilab



SBN will perform a robust measurement in the search of sterile neutrinos, while also investigating a broad spectrum of other new physics beyond the standard model.

Strategy to reduce uncertainties:
- Three detectors sampling the **same neutrino beam at different distances** (BNB)
- **Same nuclear target** (Ar) and **detector technology** (LArTPC: liquid argon time projection chambers)

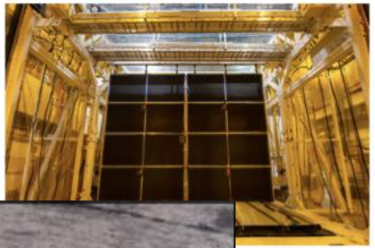
The Short Baseline Neutrino Program at Fermilab

ICARUS

600m baseline
470t active volume

SBND

110m baseline
112t active volume



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Strategy

- Three detectors sampling the **same neutrino beam at different distances** (BNB)
- **Same nuclear target** (Ar) and **detector technology** (LArTPC: liquid argon time projection chambers)

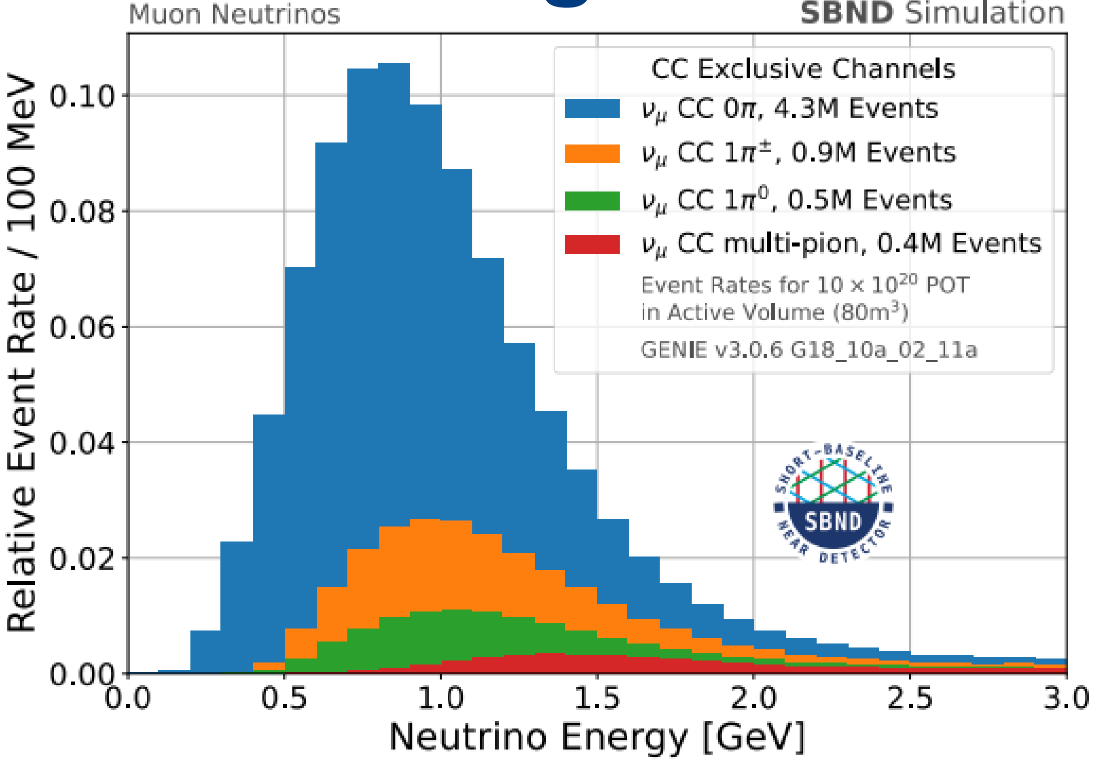
Near Detector – only 110 m from the target!

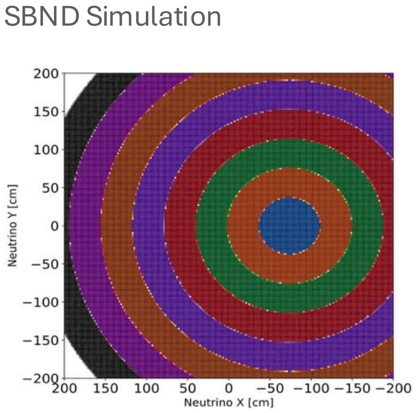
Unique opportunities:

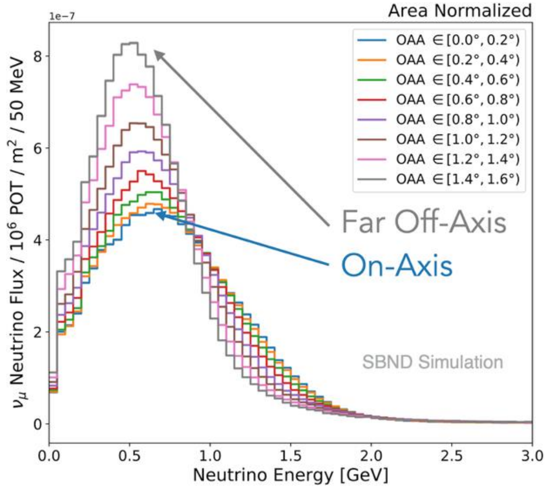
- Up to 7000 neutrino interactions per day – unprecedented statistics
    - Cross sections, cross sections, cross sections
    - rare process/BSM searches
- Prism effect – sample off axis fluxes

Unique challenges:

- Neutrino pile-up
- Backgrounds from the beam
- Sheer data volume ~100 MB/event



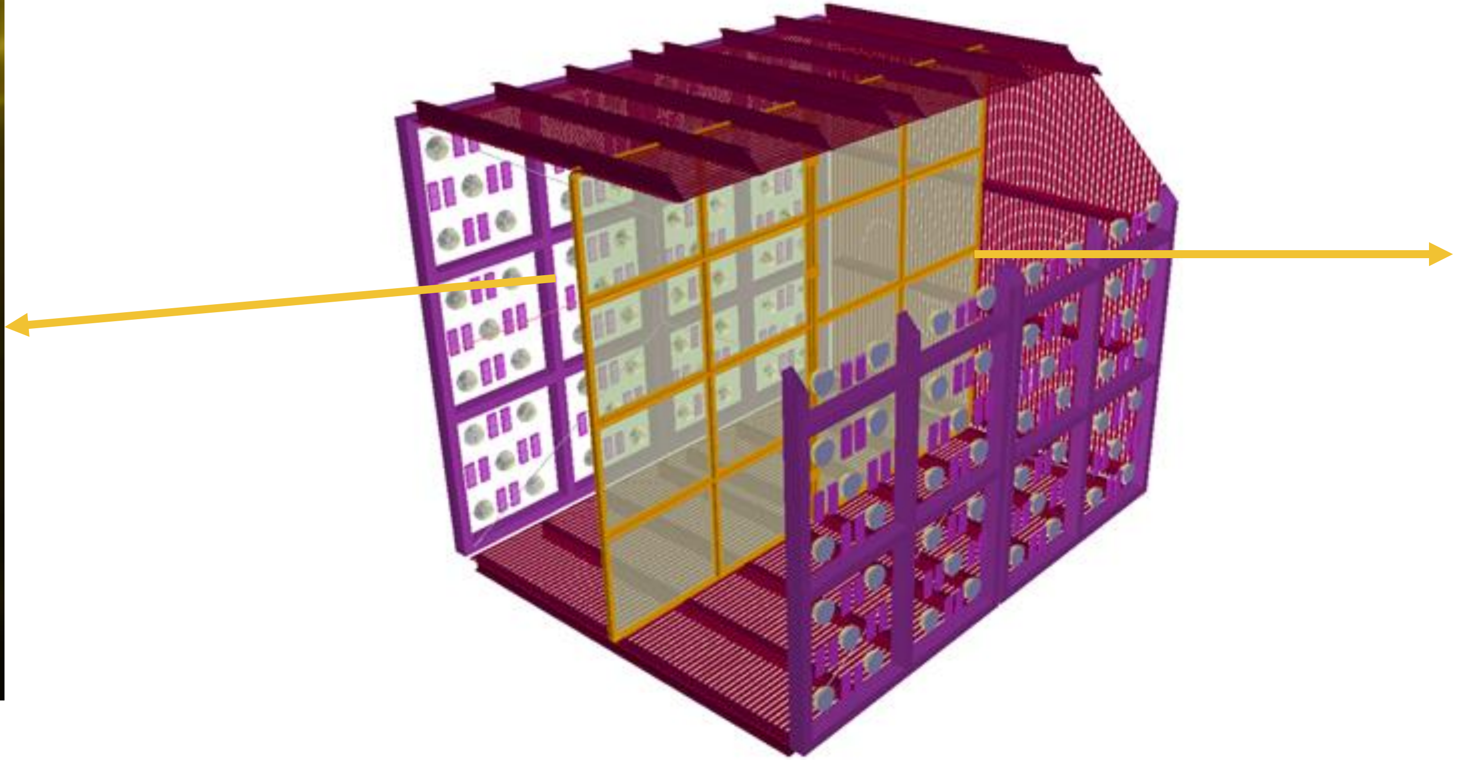




SBND TPC

2 drift volumes

[total 4 X 4 X 5 m]



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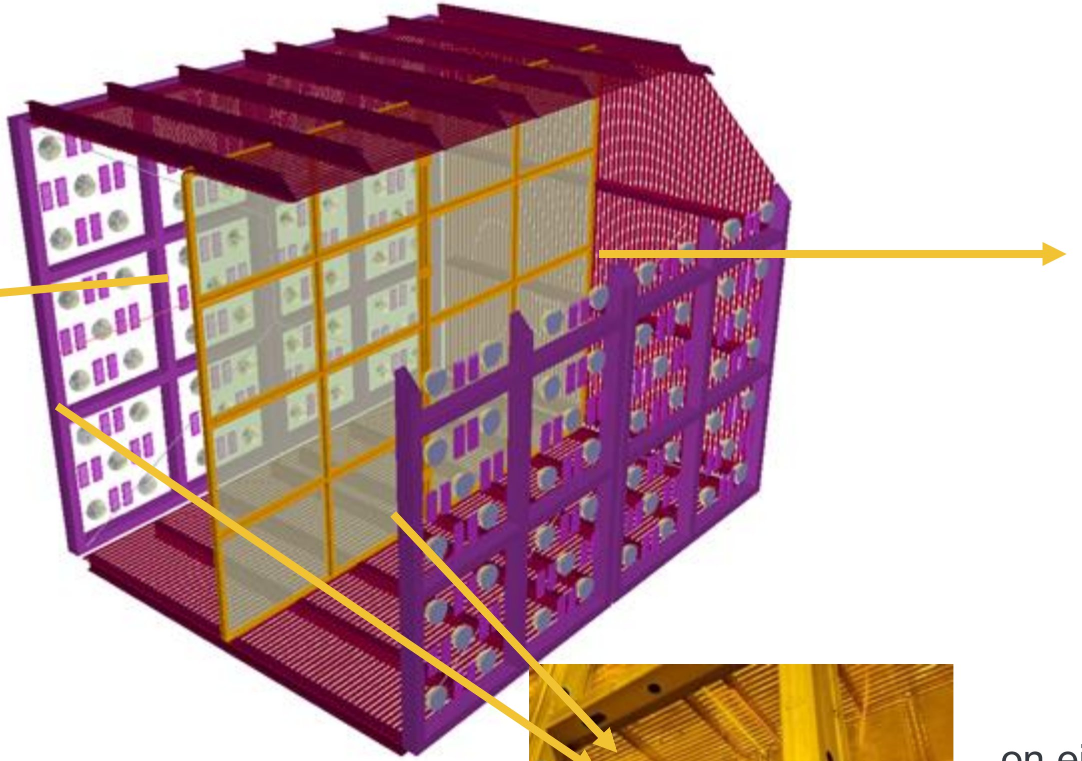
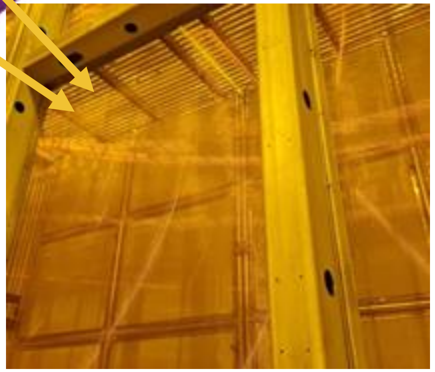
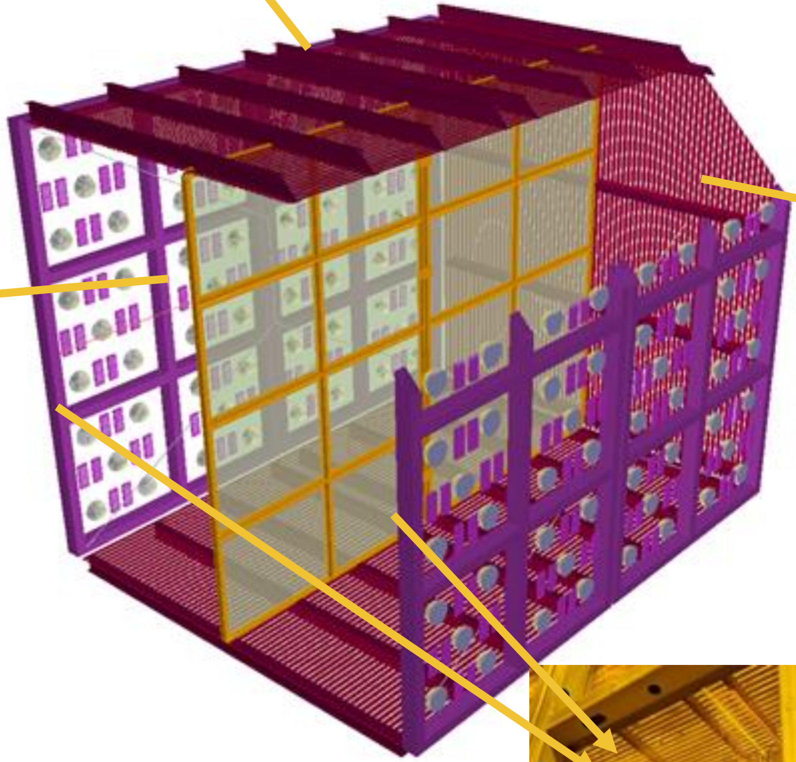


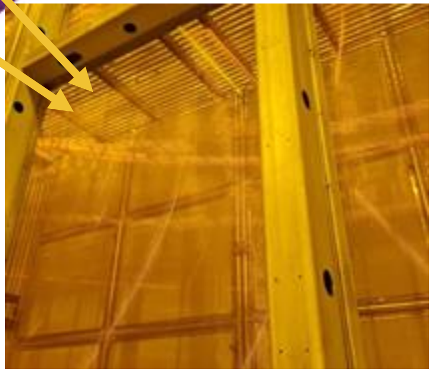


Anode Plane
on either side. Each consists of 3 planes of wires with 3 mm spacing and different angle per plane. Total of 11,260 wires

SBND TPC
2 drift volumes
[total 4 X 4 X 5 m]

Cold (89K) Electronics to pre-amplify and digitize signals





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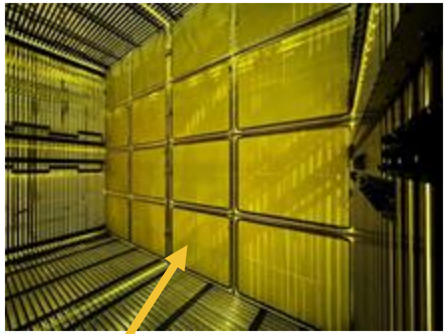
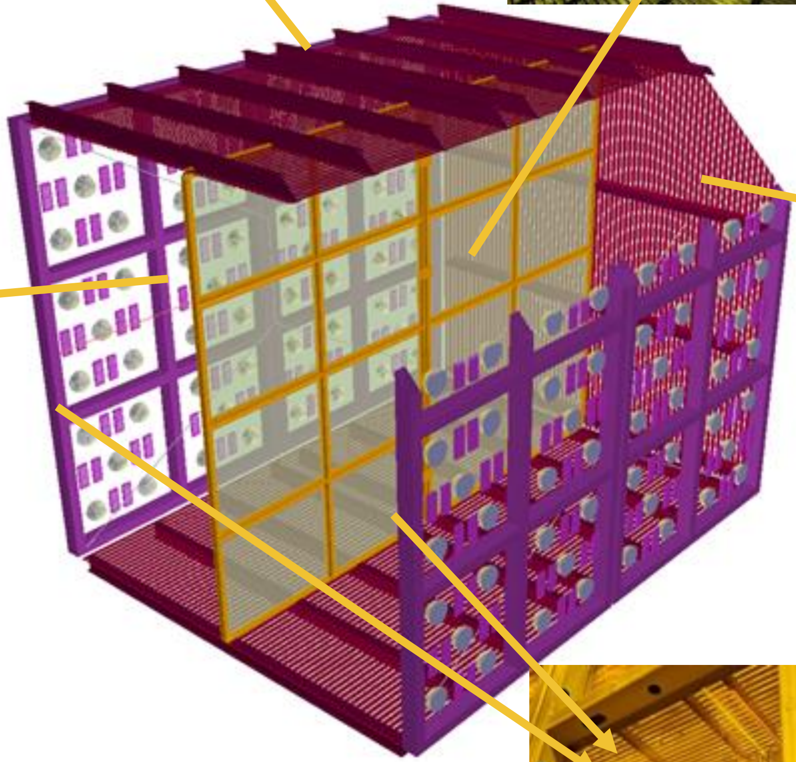
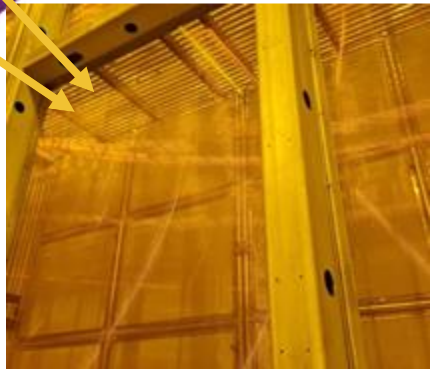


Cathode Plane
in the middle; divides the detector into 2 TPCs. Will be supplied with -100 kV.





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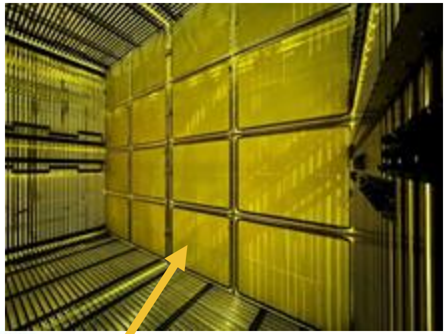

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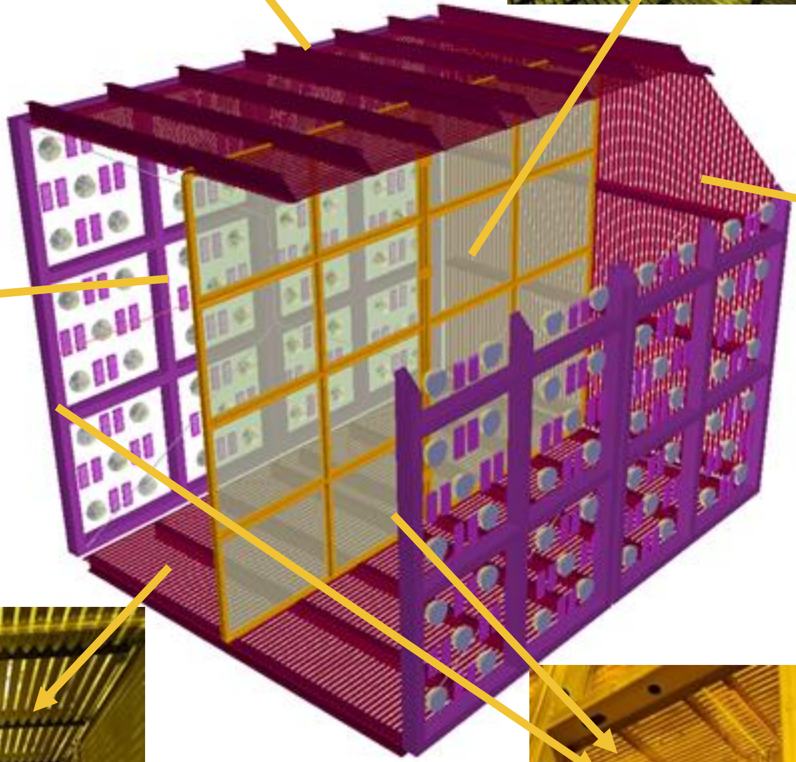
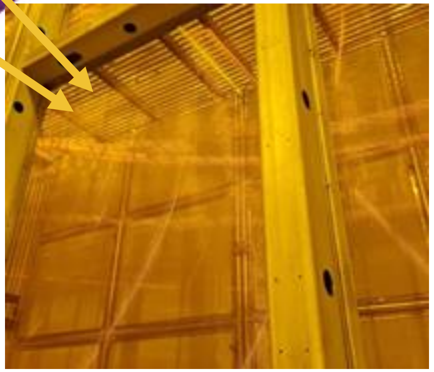


Field Cage
that wraps around the 2 LArTPCs to step down the voltage & ensure uniform electric field of 500 V/cm.



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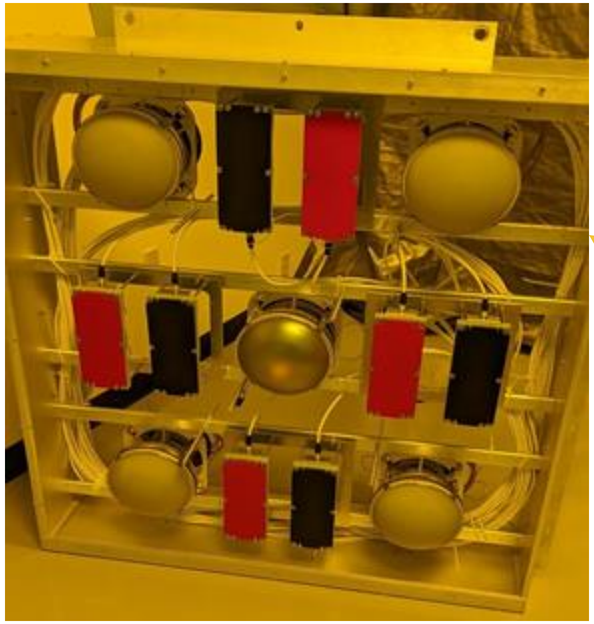
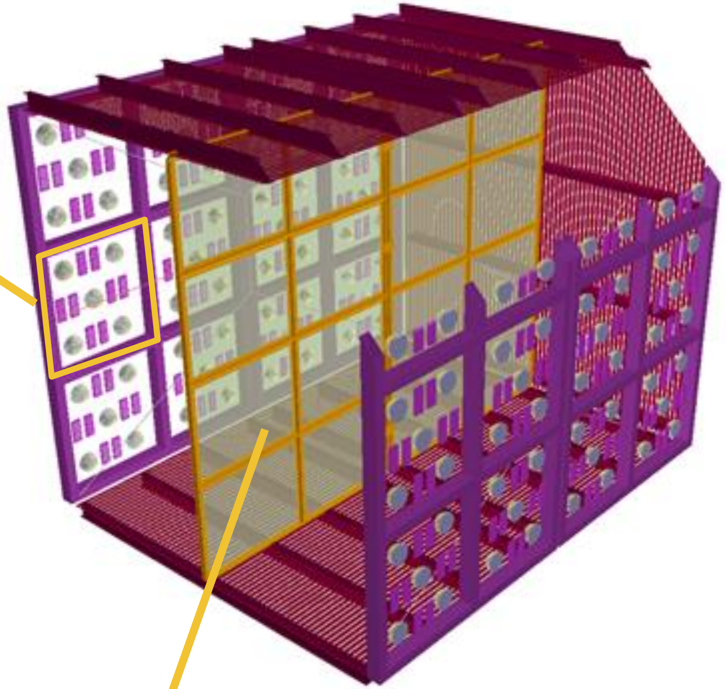
SBND Photon Detection System





24 Anode Plane boxes

4x24 = 96 **PMTs** (TPB coated)
1X24 = 24 **PMTs** (uncoated)

8x24 = 192 **X-ARAPUCAs***

*sensitive to UV
+ visible light

Cathode Plane
with TPB coated reflective foils mounted between mesh panels.

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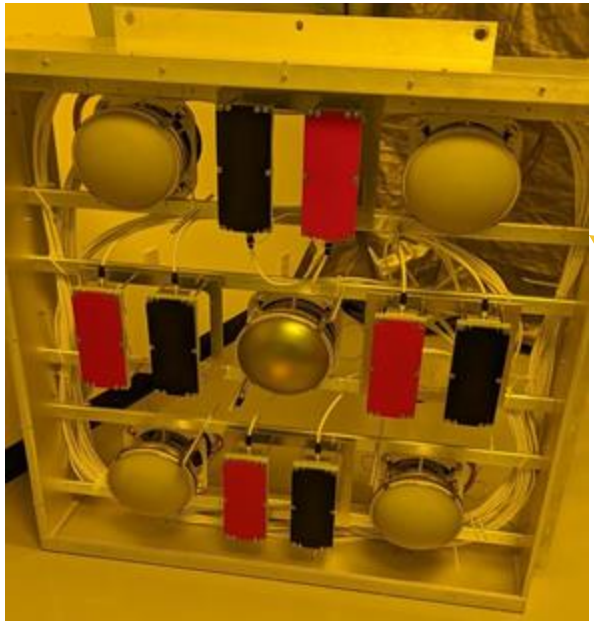

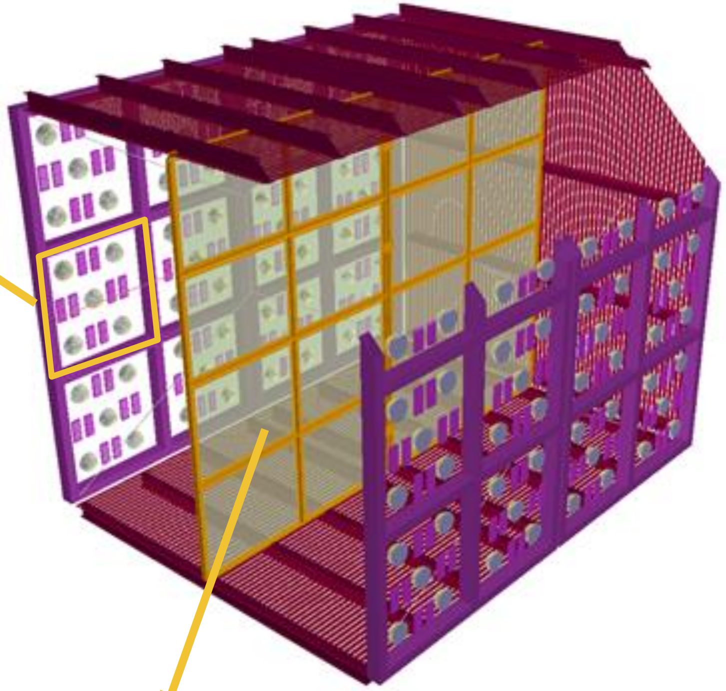

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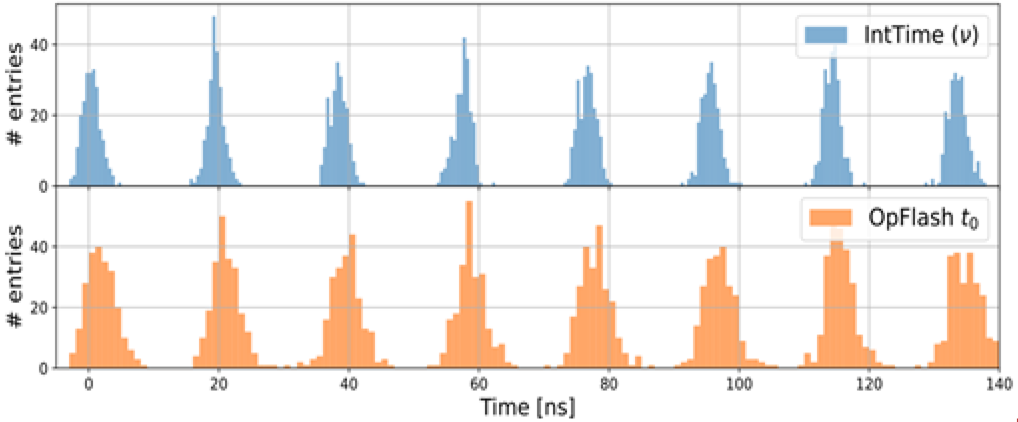
Cathode Plane with TPB coated reflective foils mounted between mesh panels.

While ionization electrons drift slowly at ~1.6 mm/us, scintillation light is fast.

- triggering
- cosmic background rejection

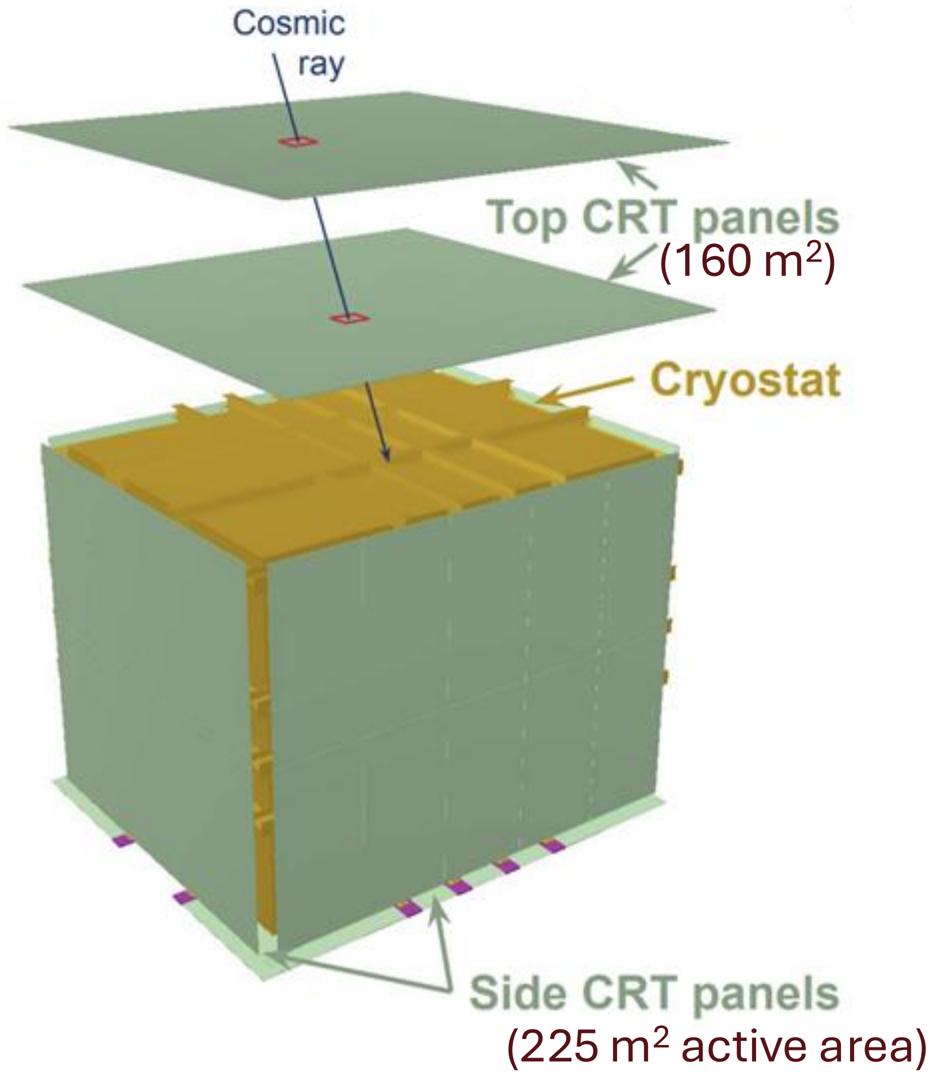
Unprecedented coverage enables SBND to explore using light for calorimetry

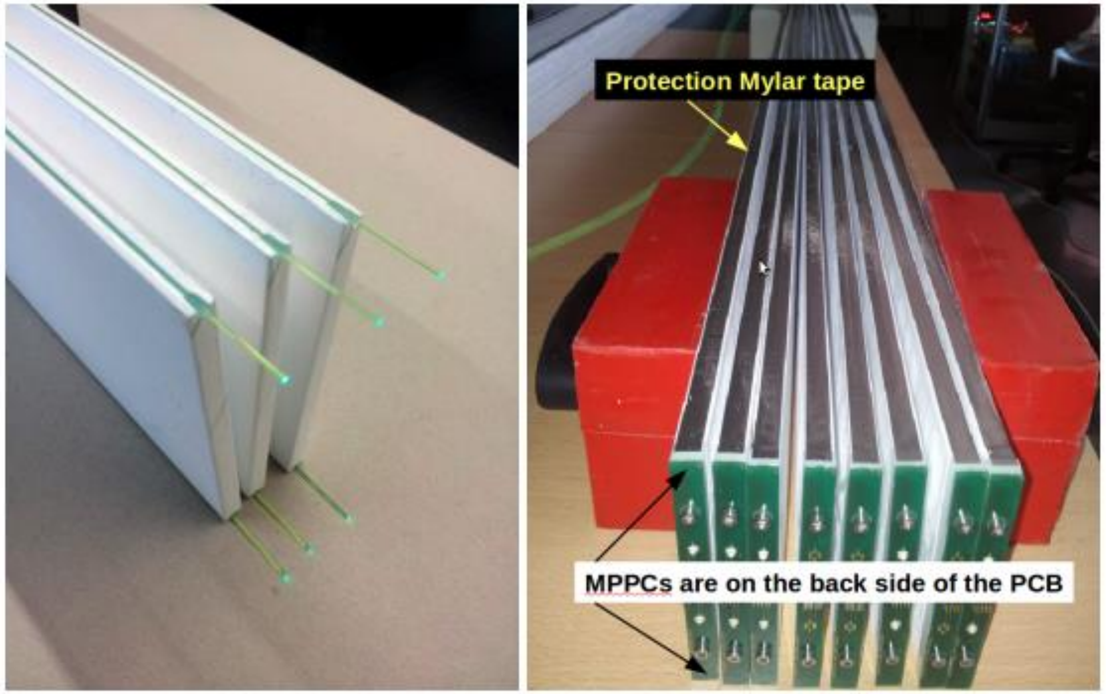
Experiment	Average light yield (PE/MeV)	Uniform light collection?
MicroBooNE	~ 5	no
LArIAT	~ 18	yes
pDUNE-SP	1.9 at 3.3m	no
SBND	~ 80 ($>$ 50 min)	yes
DUNE: Vertical Drift	~ 38 ($>$ 16.5 min)	yes



Simulated (top) and reconstructed (bottom) light flashes showing the neutrino beam structure.

SBND Cosmic Ray Tagger





Designed to tag muons . . . .

- Each plane has two layers: one “x” strips and one “y” strips
- Each strip has 2 SiPMs, one per fiber
- Single strip (1 cm thick) absorbs radiological decays
- Readout triggered by 4-fold time coincidence of one “x” strip and one “y” strip
- Strips are 1 cm x 11 cm x 2.5-4.5 m
- position resolution: <3 cm
- time resolution: < 2 ns

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SBND Trigger System

Two custom electronics boards.

- "MTC-A" - Analog summer
- "PTB" - FPGA-based Gating and Logic

Trigger inputs

- PMT multiplicity
- Beam "early warning" signals
- CRT activity per wall/plane

Why do we need a trigger?

- Beam spill rate is 5 Hz
- There is 1 neutrino interaction every ~20 beam spills at SBND
- Events are large (~100 MB). Data management and processing isn't trivial.

Only save events when scintillation light is detected during the beam spill*

*plus other trigger streams for calibration, monitoring, background evaluation and modeling

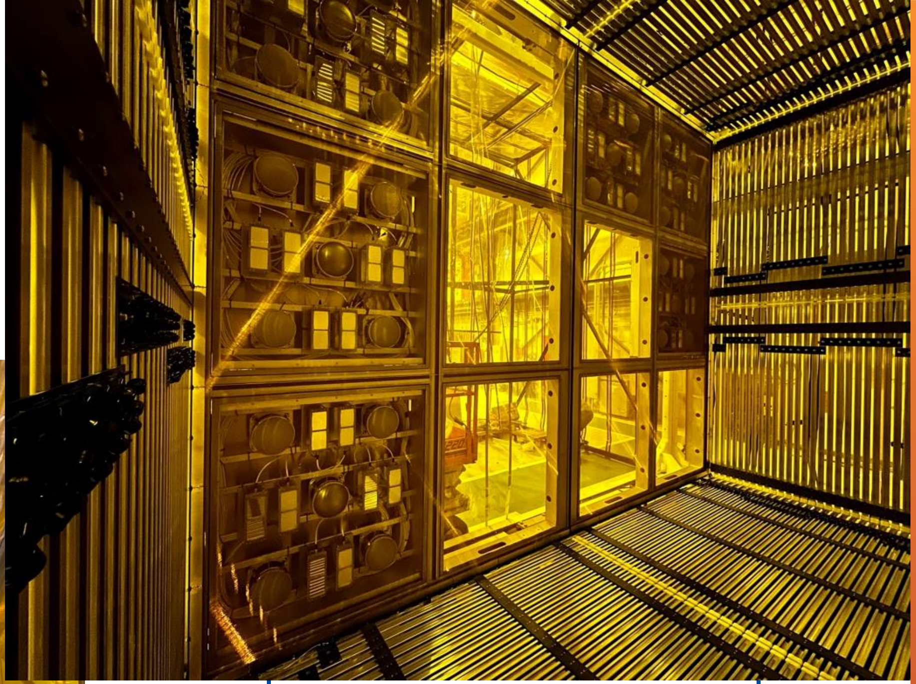
- "Flash" triggered PDS waveform acquisition, roughly 14 flashes in 3 ms window per event

SBND Installation Photos

March 2019

October 2019

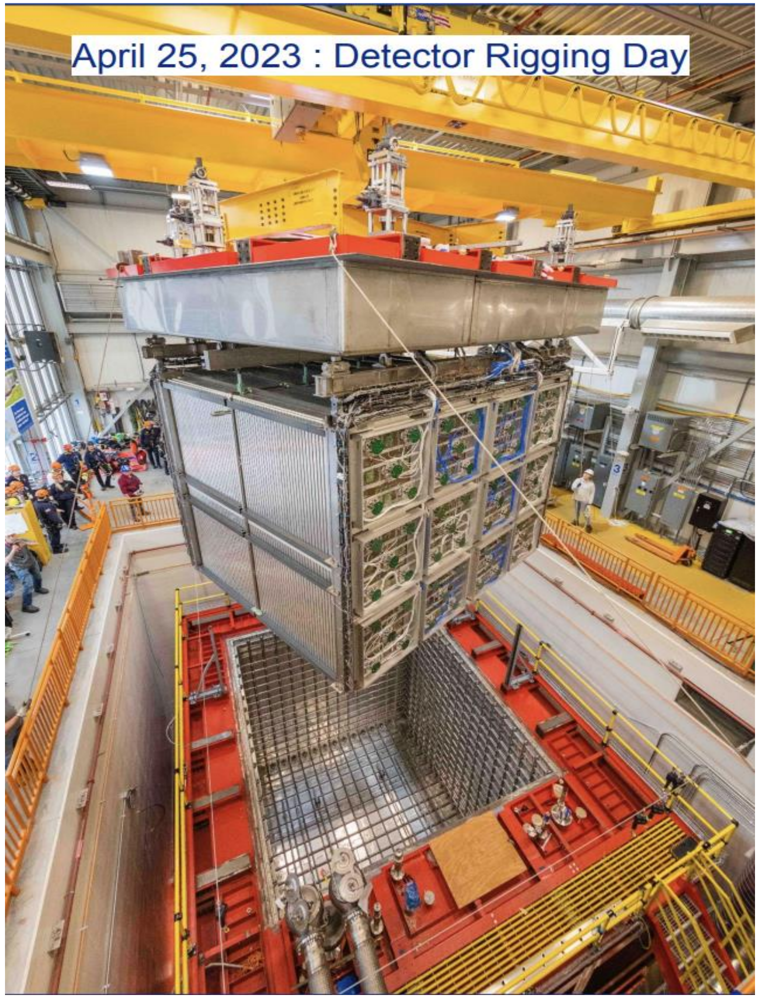
January 2022



Summer 2022

SBND Installation Photos

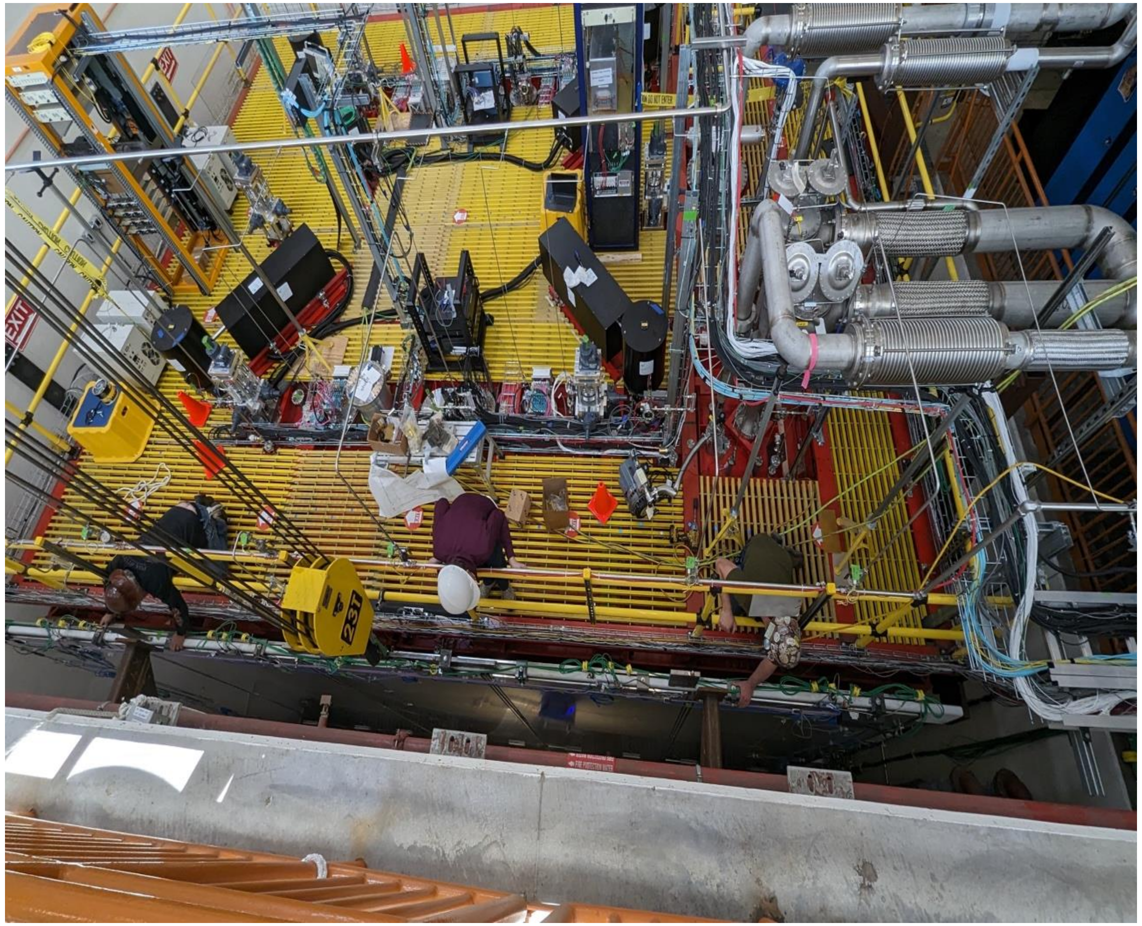
December 2022



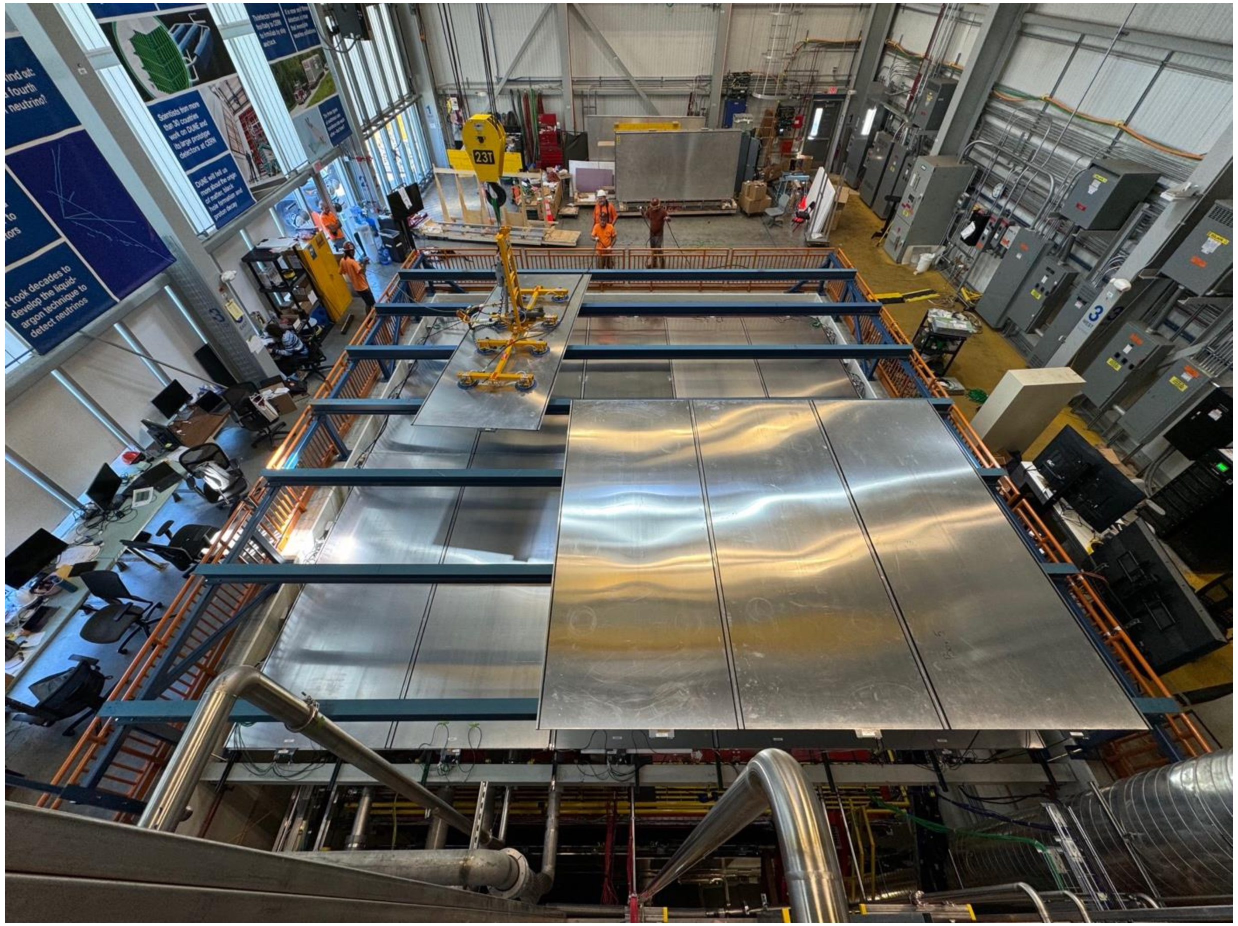
April 2023

February 2024

SBND Installation Photos

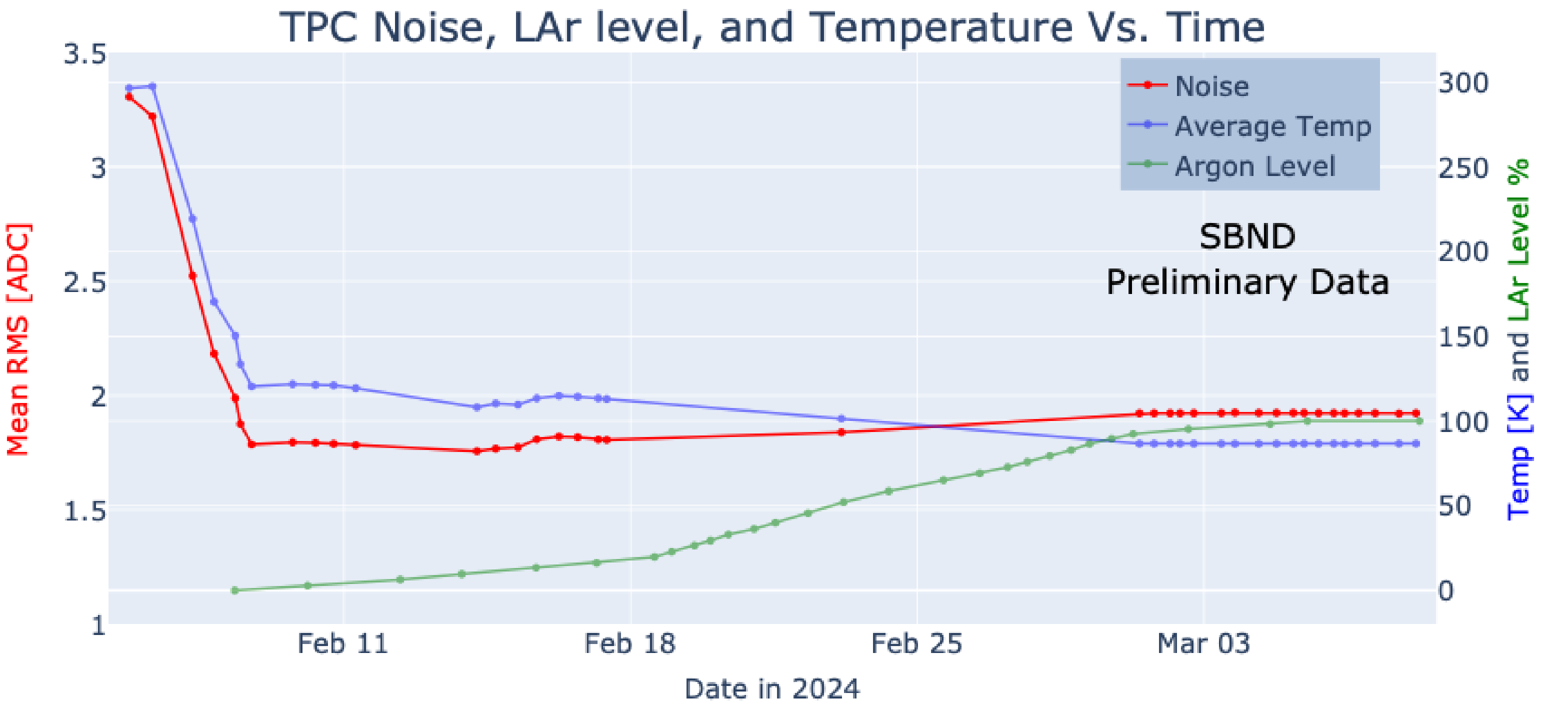


~May 2024



August 2024

TPC performance - noise

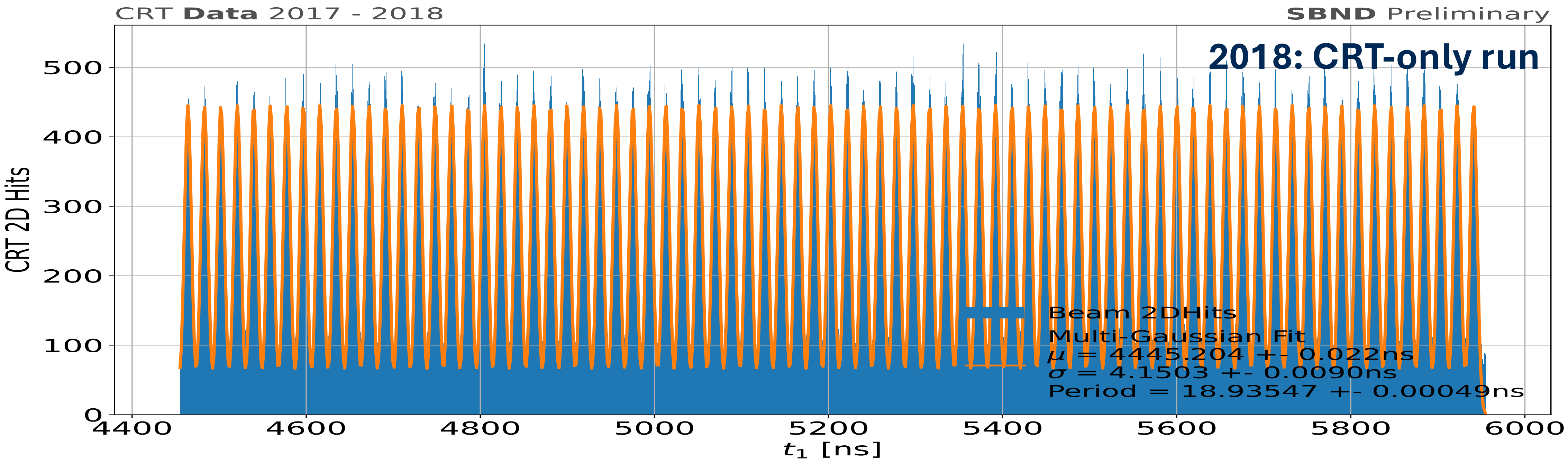


- **Raw waveform RMS from 4 m long collection plane wires**
- **From bench testing: lowest achievable is 380 ENC / 1.96 ADC with no external or coherent noise**

LArTPCs have no electron multiplication for ionization electrons, thus low noise is essential. For 3 mm path length, MIP muon signal is ~15,000 collectable electrons per wire, 2-4 nA current pulse

- Low noise grounding strategy started with the SBND building design
- Grounding monitored throughout installation and cryo commissioning with active mitigation
- Additional filters added to wire bias voltage connections after protoDUNE-VD lesson learned

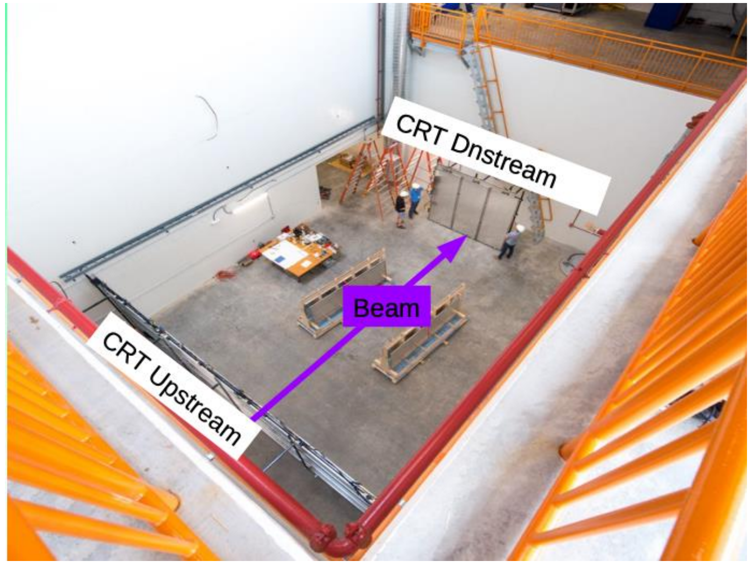
Beam substructure measured by the CRT



CRT detects muons from neutrino interactions in the dirt upstream of the detector

The beam spill substructure can be seen

- 81 bunches with 19 ns spacing
- spill duration of 1.6 μs



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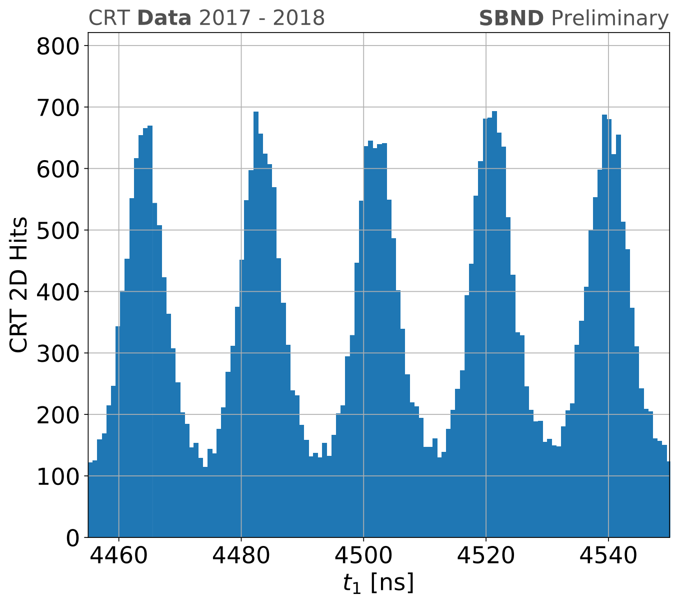

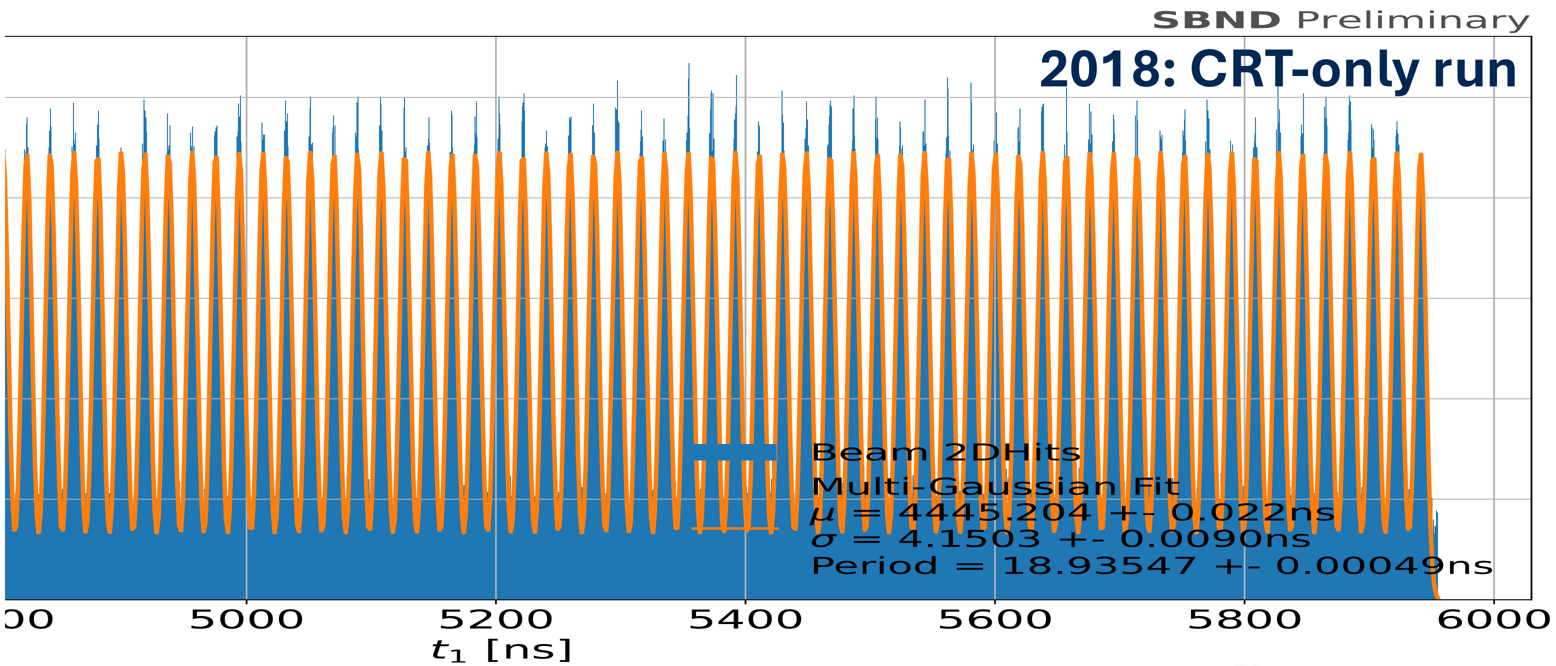

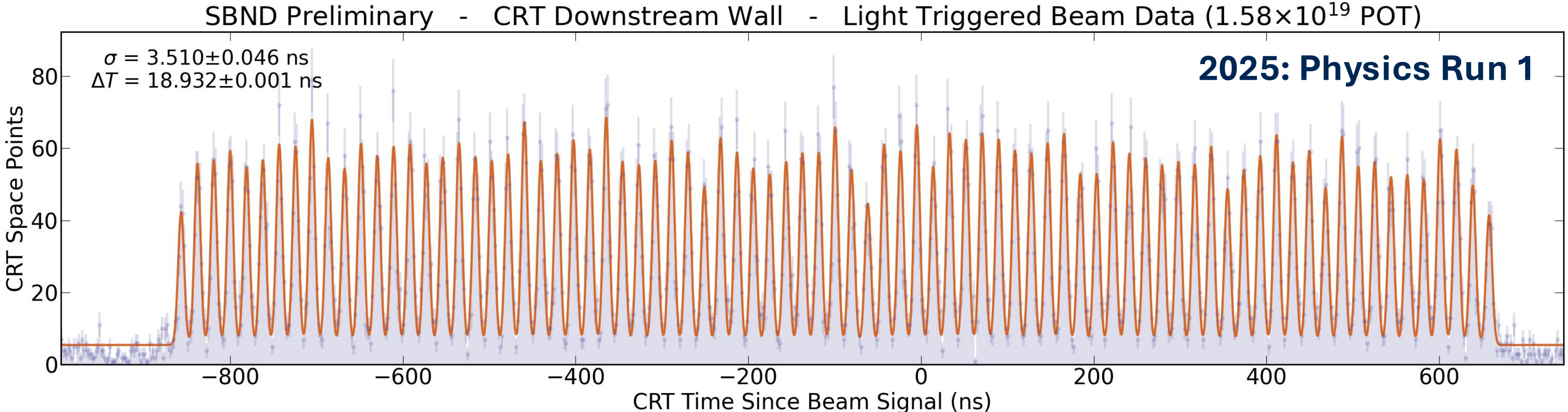

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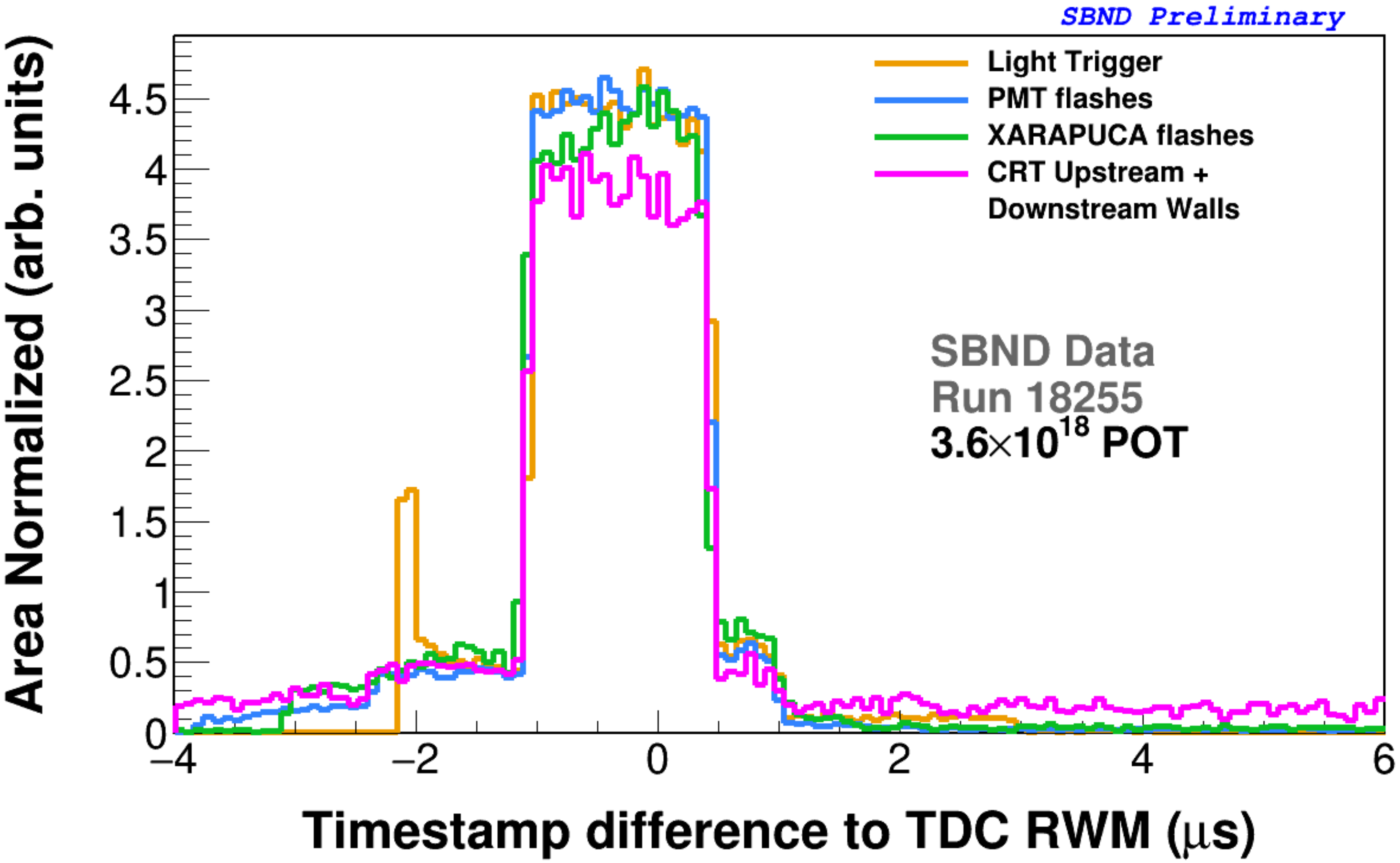
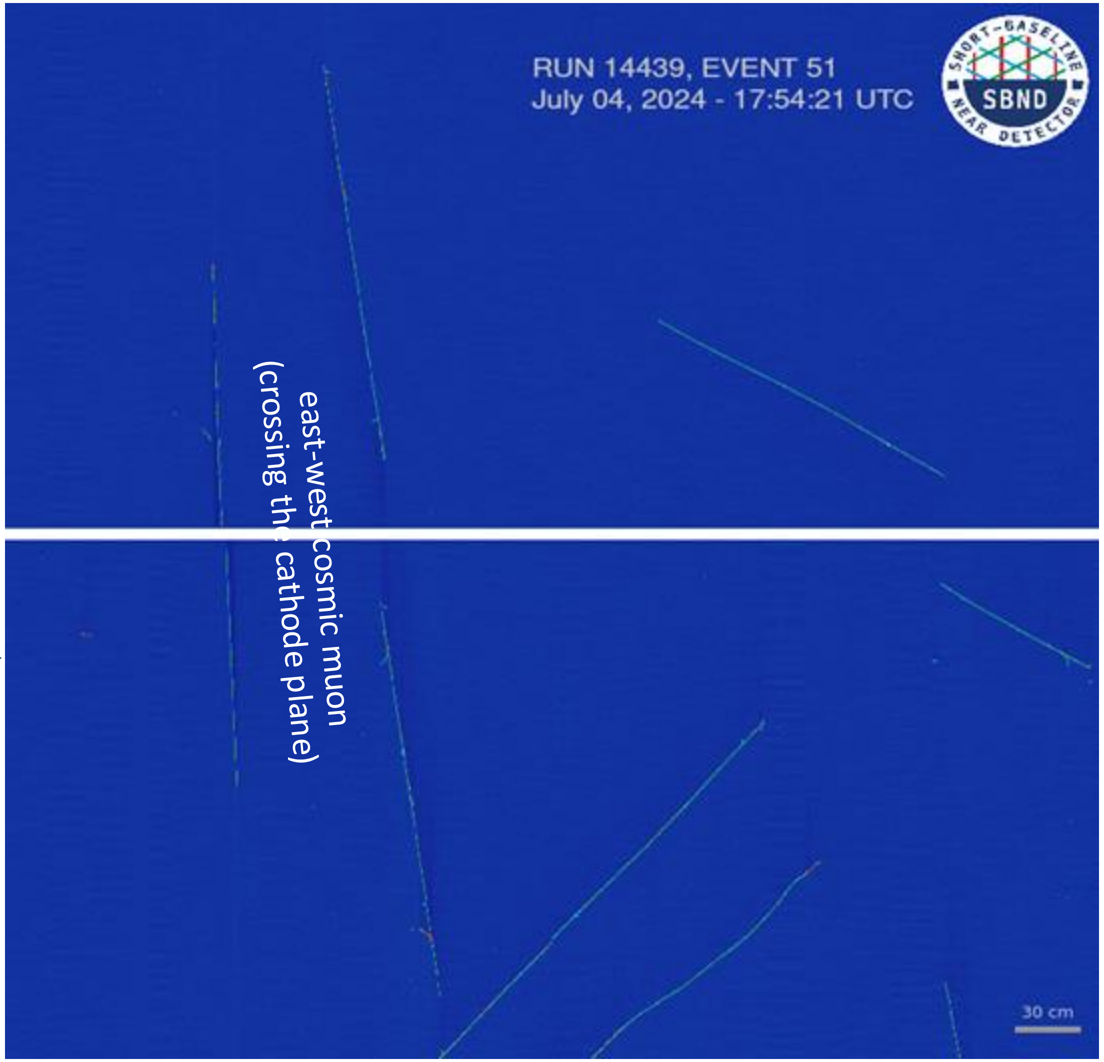
Data synchronization and timing validation



Remember . . . light is fast, charge is slow

- Independent TPC reconstruction of beam spill timing is in progress.
- 1 TPC clock tick = 0.5 μs

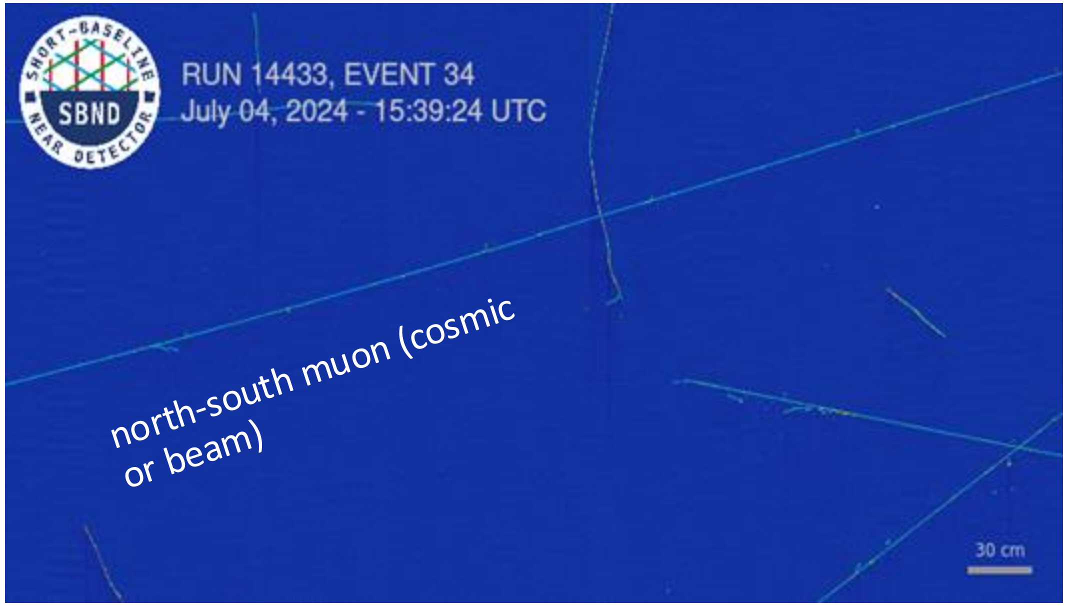
Data synchronization and timing validation



Time tick

BNB beam

Collection plane wire number

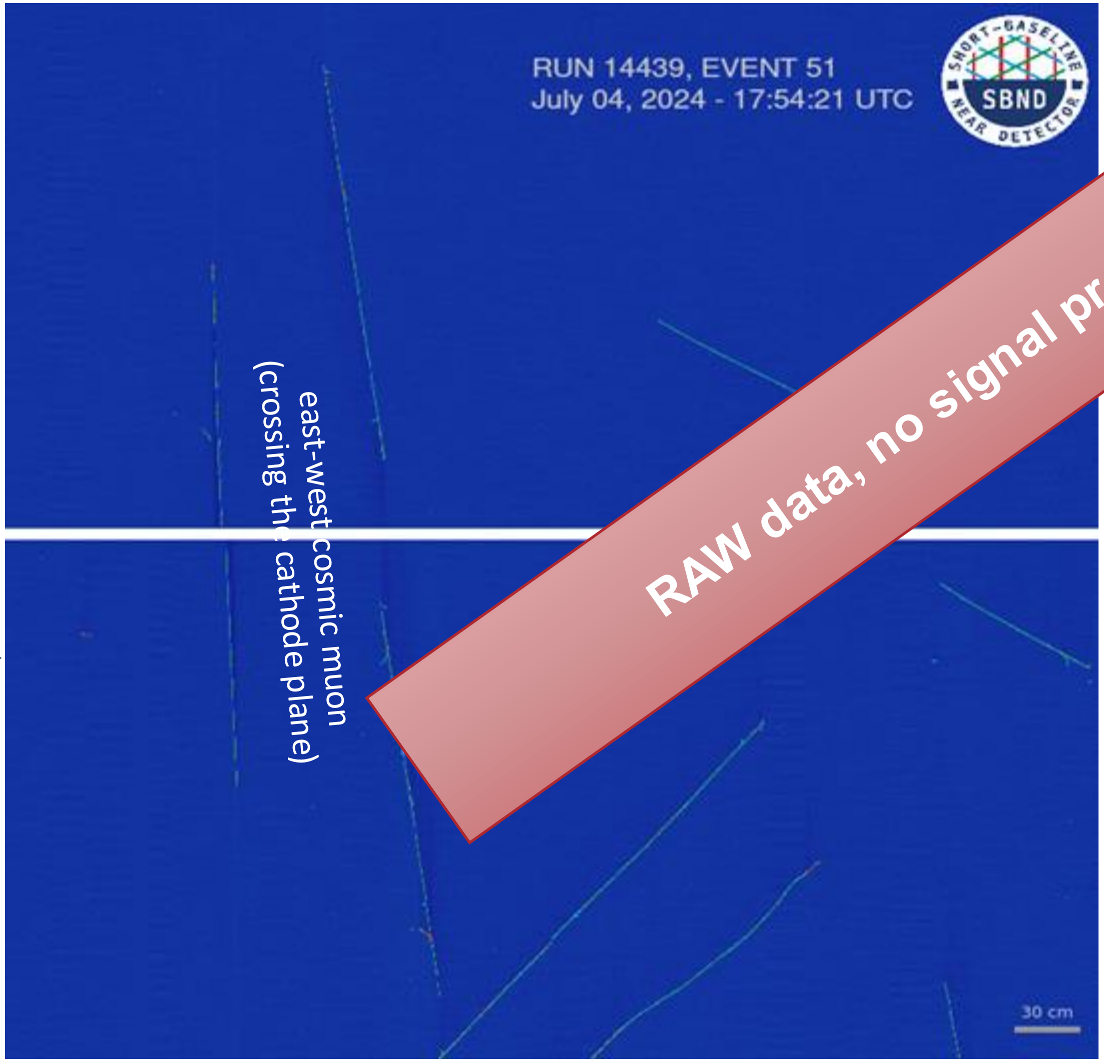


Time tick

Collection plane wire number

Trigger on opposite side CRT walls enables
- rapid confirmation of timing during commissioning TPC, CRT and PDS synchronization verified visually with event display
- efficient acquisition of calibration data samples during physics running

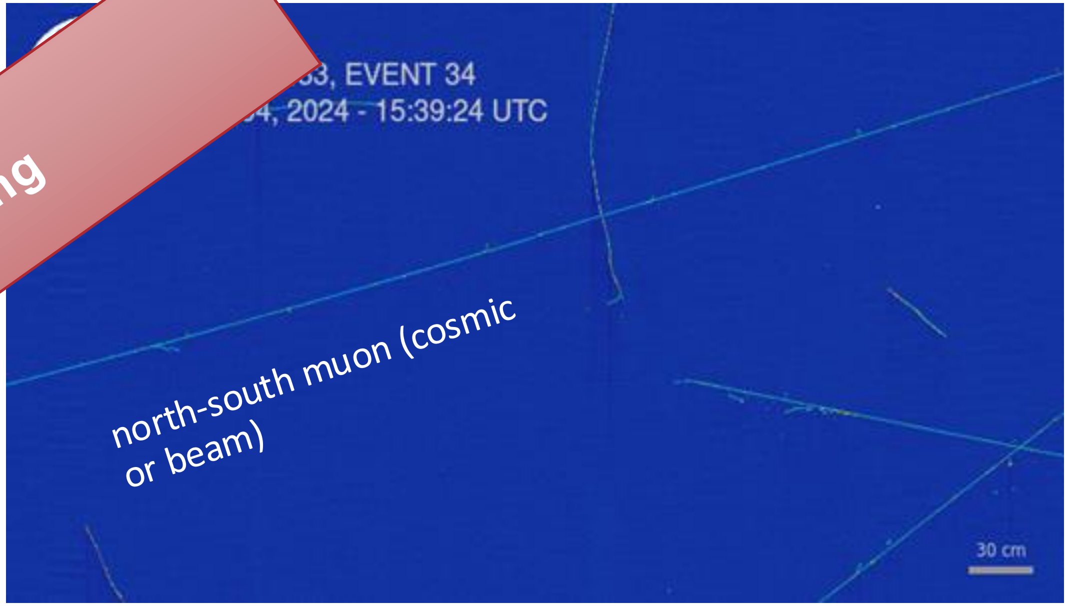
Data synchronization and timing validation



Time tick

BNB beam

Collection plane wire number



tick

Collection plane wire number

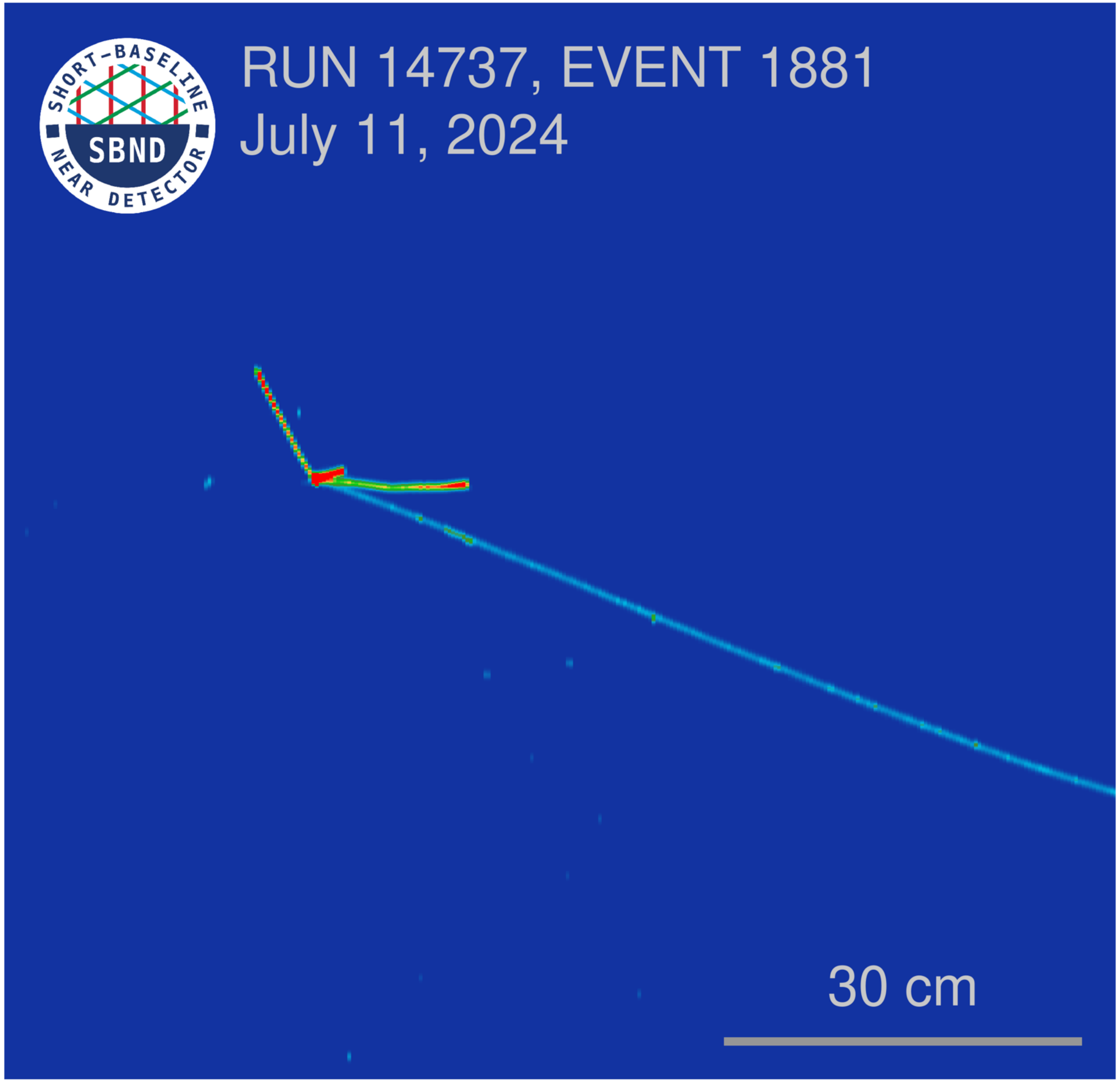
Trigger on opposite side CRT walls enables

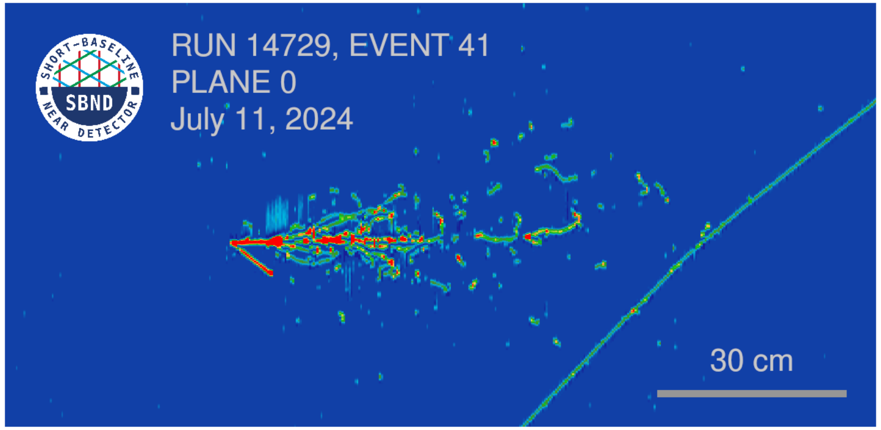
- rapid confirmation of timing during commissioning TPC, CRT and PDS synchronization verified visually with event display
- efficient acquisition of calibration data samples during physics running

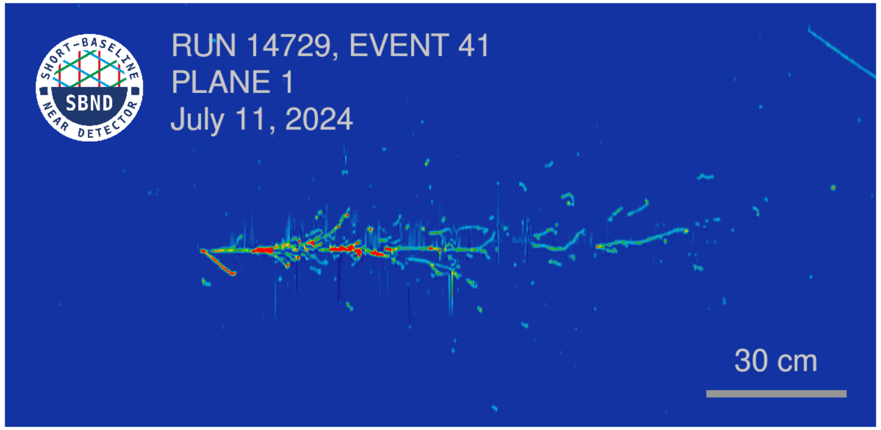
July 4-11
Initial physics run

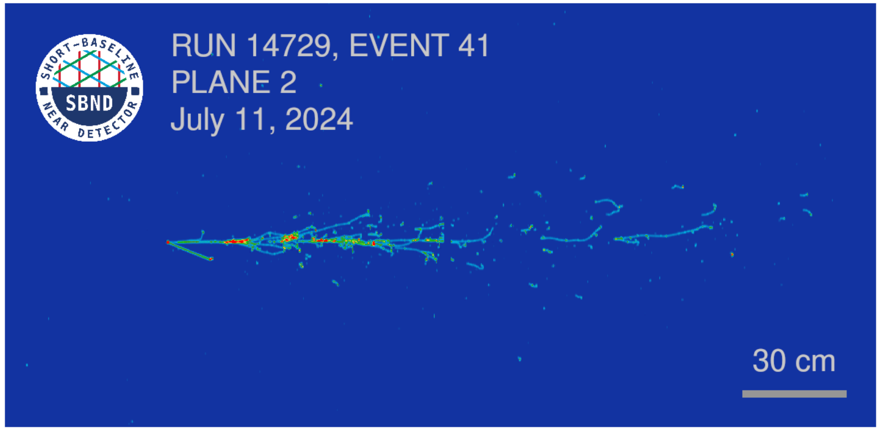
Time tick

Wire number



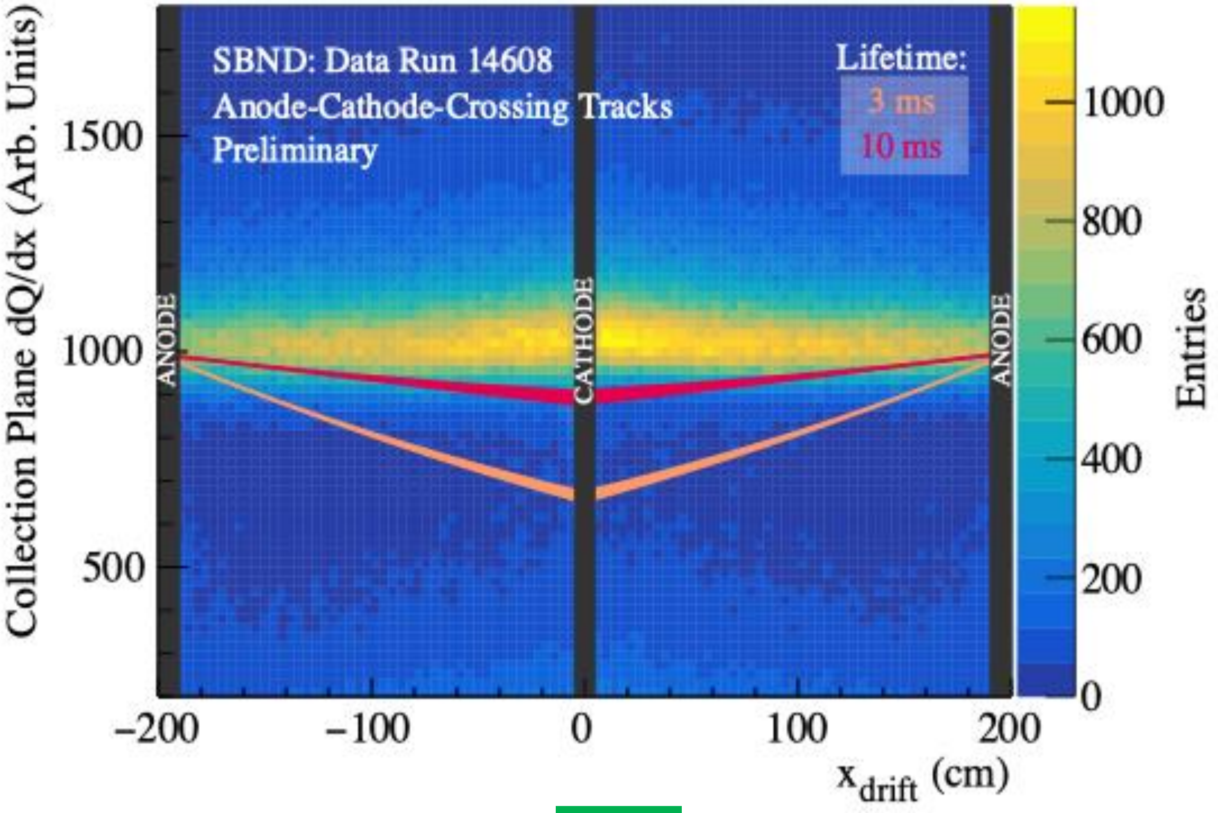


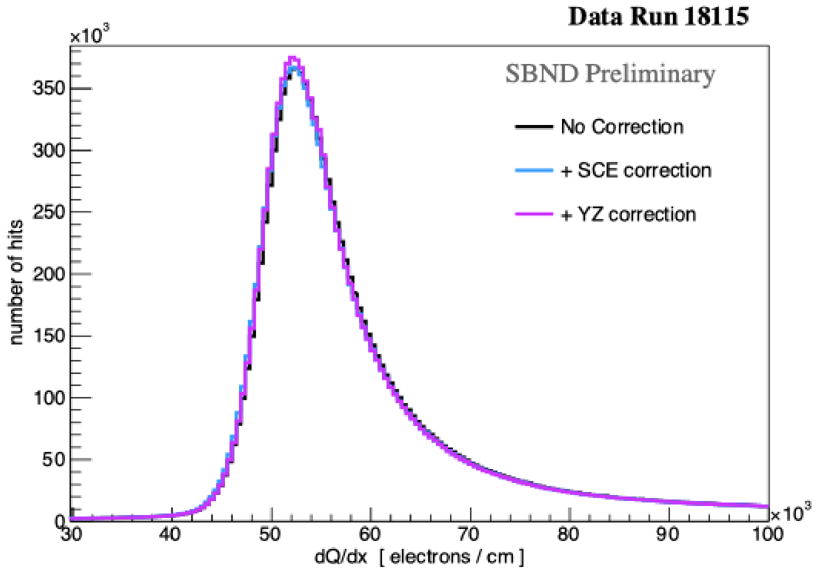


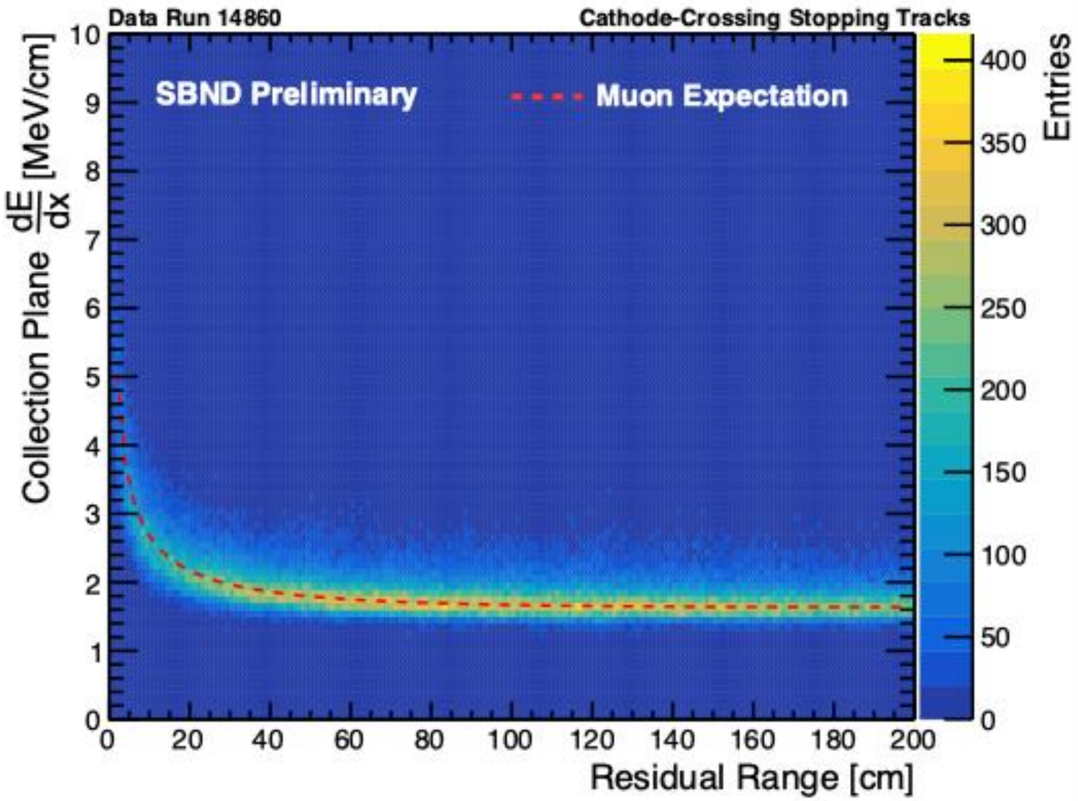


FERMI NATIONAL ACCELERATOR LABORATORY

Argon Purity and TPC calorimetry



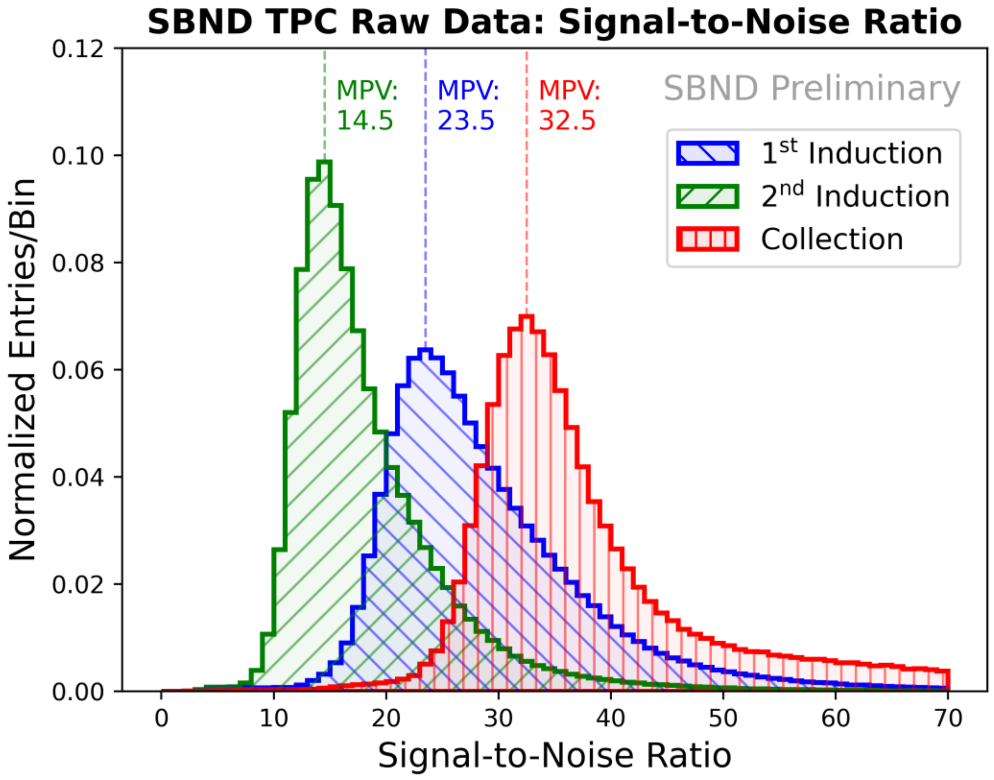


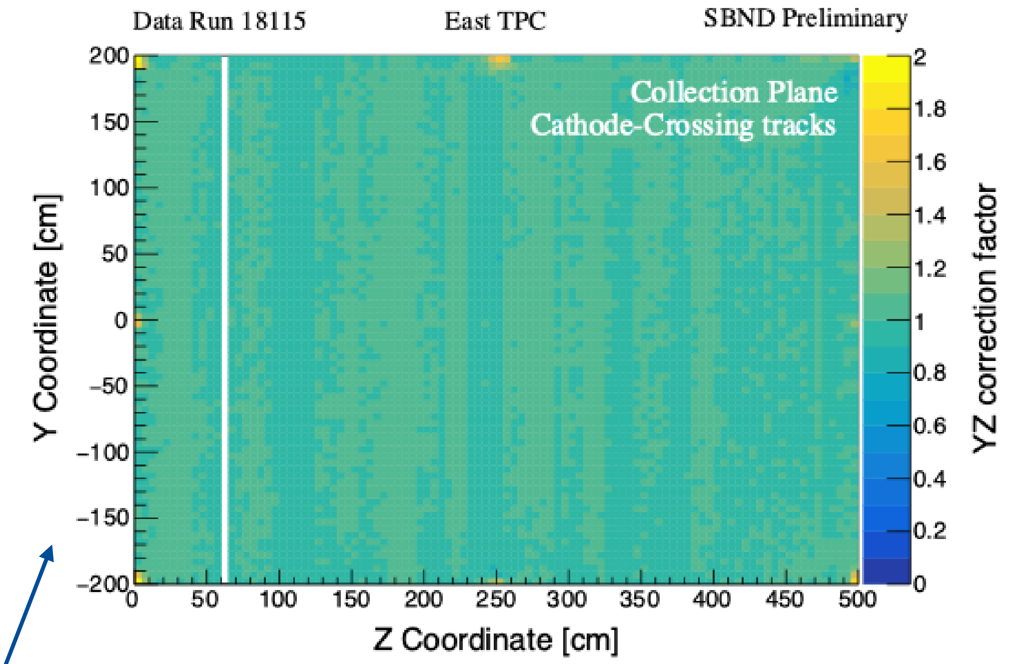


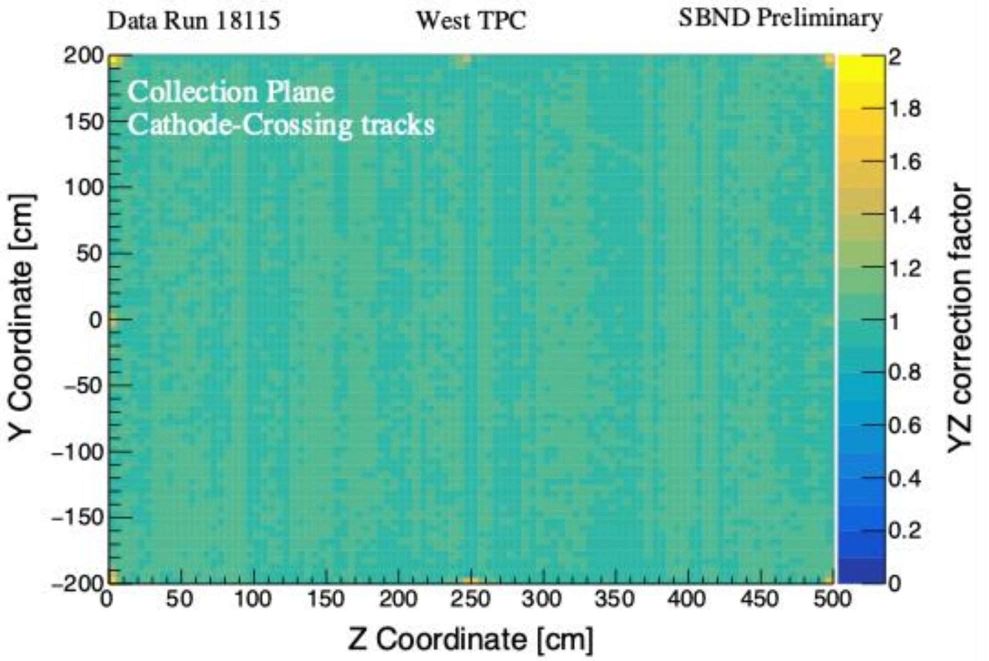
Electron lifetime (ms)	3	10	25	125
Surviving fraction after 1.25 ms drift	66%	88%	95%	99%

DESIGN REQUIREMENT

TPC performance

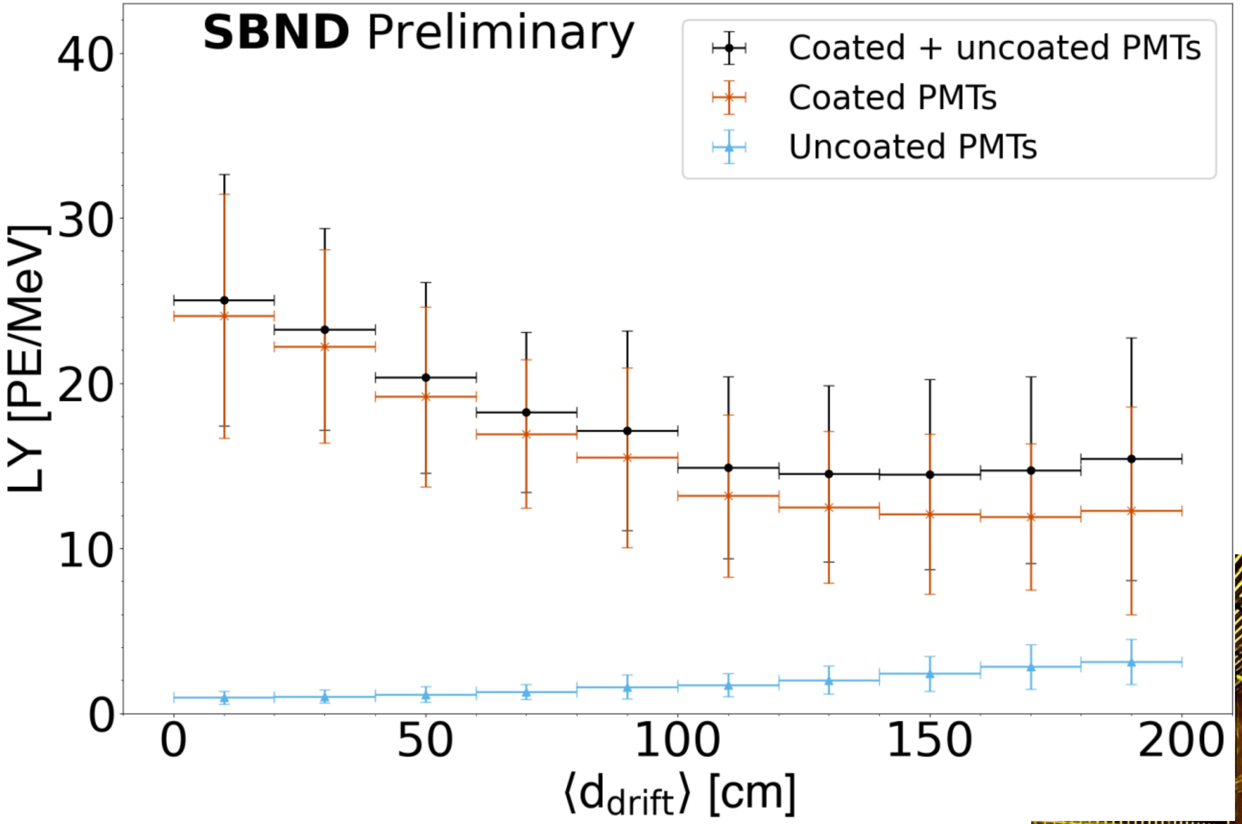


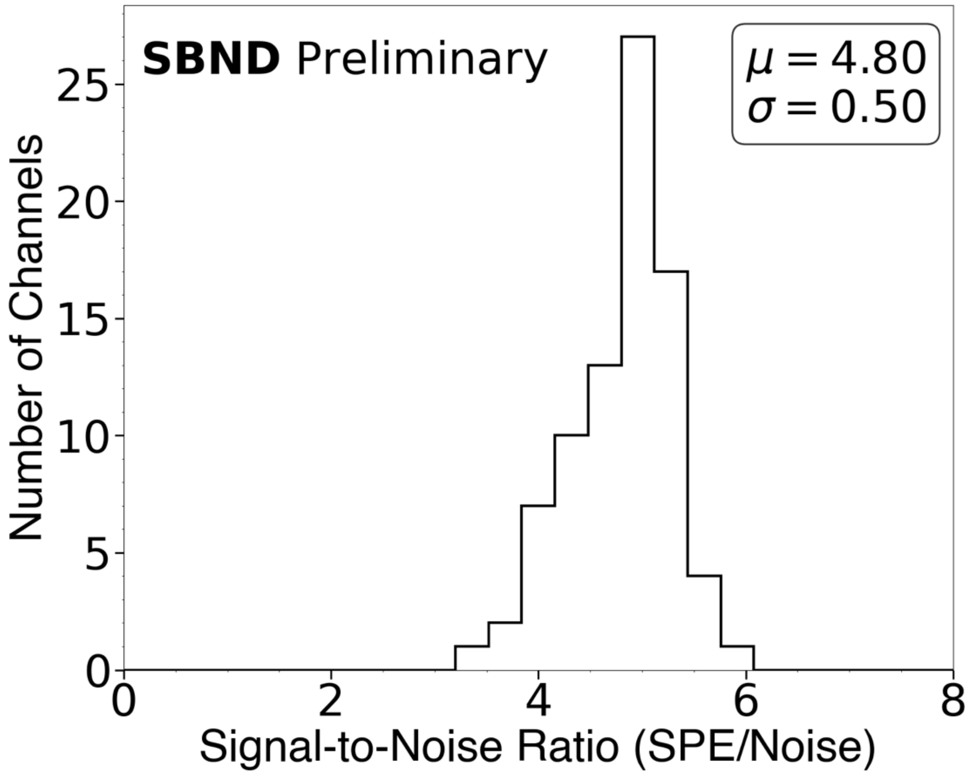




Current uniformity of detector response to MIP muons across both wire planes

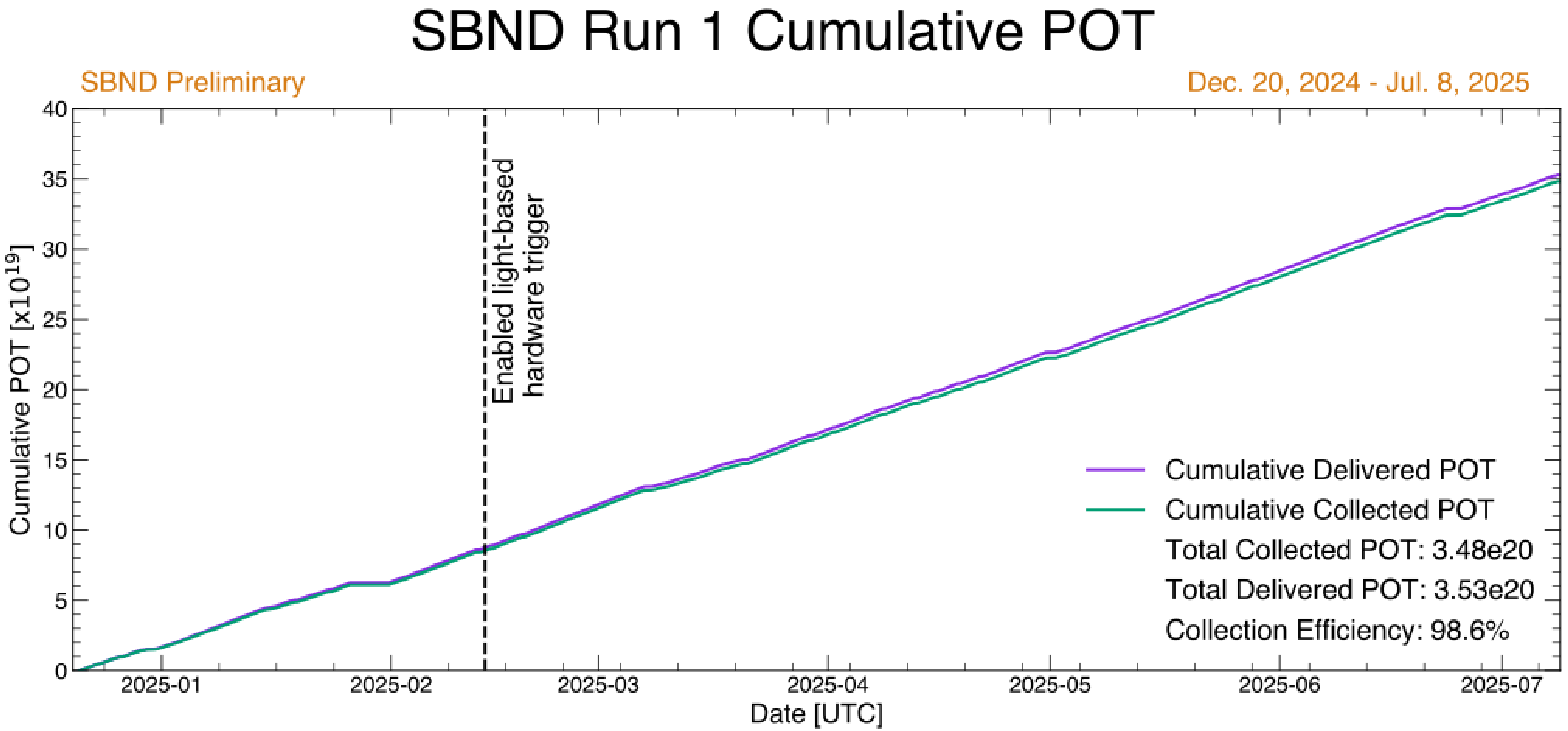
PMT performance





XArapuca readout installation ongoing this summer shutdown

6+ months of BNB data so far . . .



. . . two more years of running ahead!

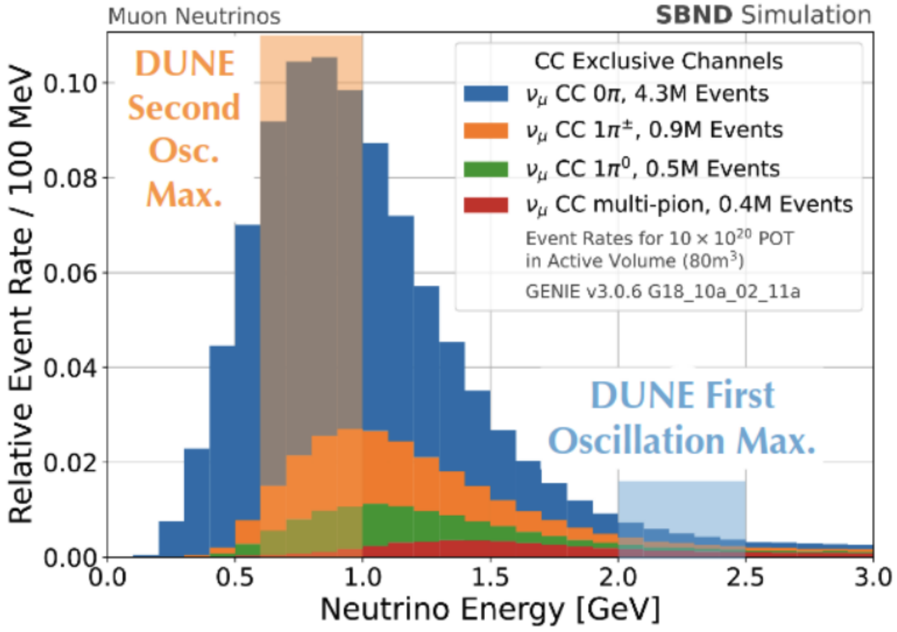
Where is SBND pushing the envelope?

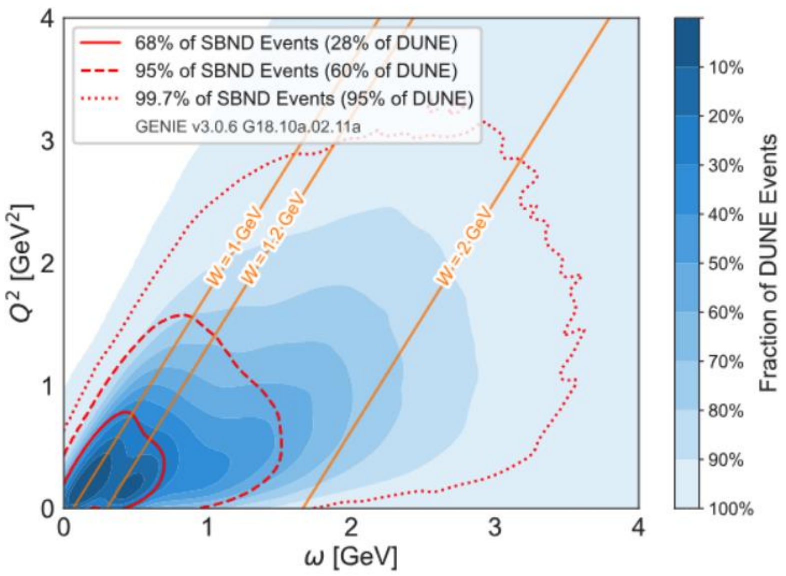
On the road to DUNE

- 3^{rd} iteration of DUNE cryostat design – instrumented with strain gauges and temperature sensors to evaluate performance
- 5^{th} generation of TPC cold electronics
  - Low noise without software mitigations/removal
  - Important for DUNE far detector "triggering"
- Side by side PMTs and XArapucs for detailed studies of performance
- Neutrino-Ar cross section measurements
- PRISM

Near detector challenges

- Tools for addressing modest neutrino pileup in light system and exposure accounting
- Tools to understand beam-related backgrounds





Conclusions

- The high statistics and exceptional performance of the SBND detector will deepen our understanding of neutrino-argon interactions
- A robust search for sterile neutrinos is on the horizon, combining data from all three detectors in the SBN program

Watch the fall conferences for exciting new results from SBND!

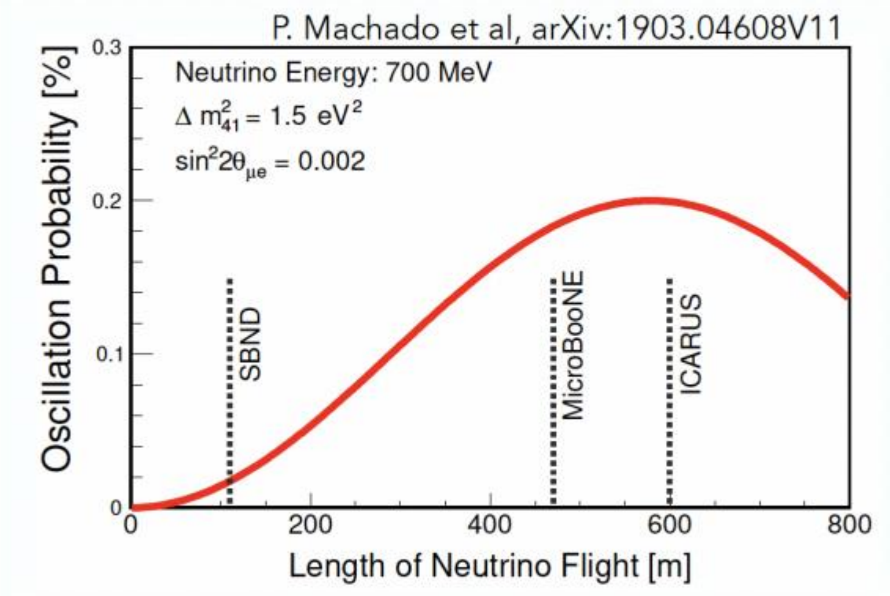
02

Backup Slides

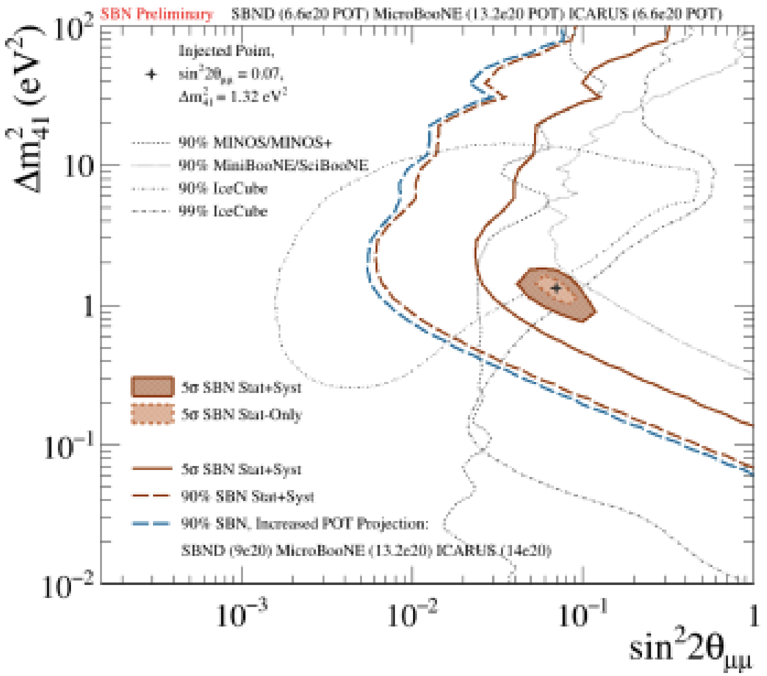
SBN Oscillation Program

The SBN program tests the sterile neutrino hypothesis by covering the parameter regions allowed by past anomalies at 5 significance.

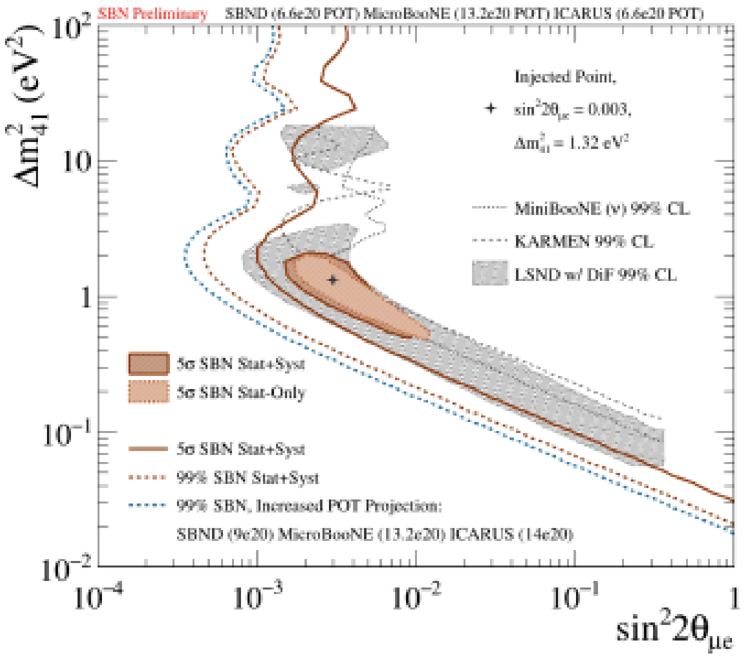
Complementary measurements in different modes are important for interpretation in terms of sterile neutrino oscillation



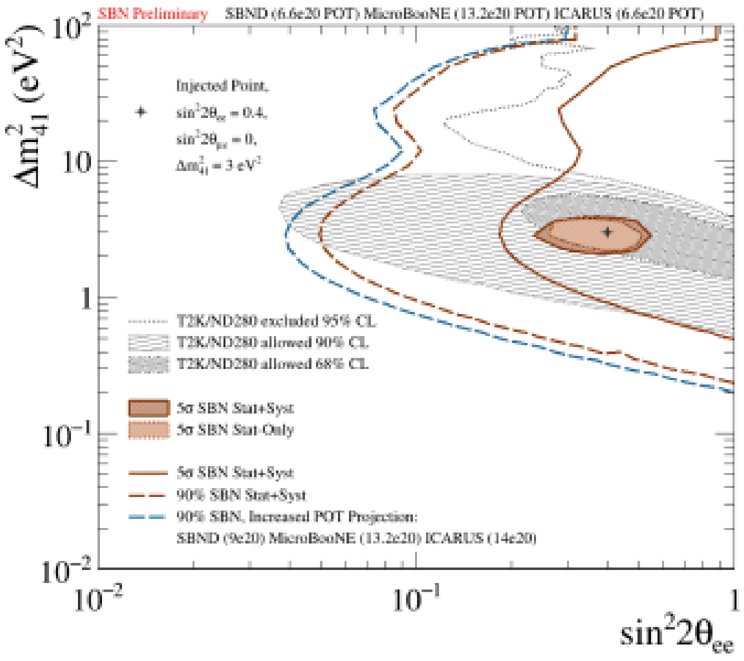
ν_μ disappearance



ν_e appearance



ν_e disappearance

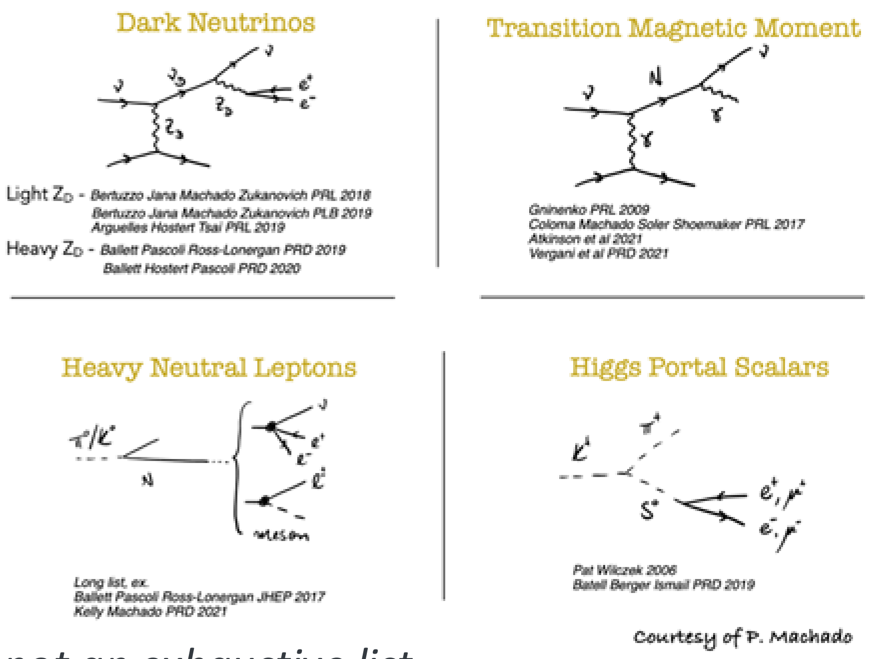


Alternative Explanations

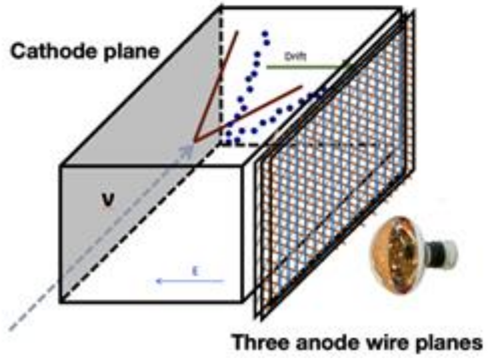
- There are many alternative models to explain the MiniBooNE excess that are not in tension with experimental results (including MicroBooNE)
- SBN can exploit these and other BSM scenarios using the strengths of each detector

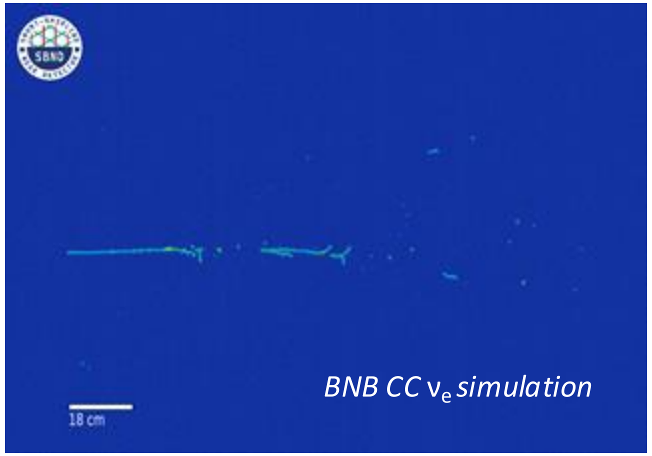
  SBND: proximity to beam target

  ICARUS: observing the off-axis NuMI beam in addition to the BNB



not an exhaustive list





Investigating such models uses the unique capabilities of the LArTPC technology, with *high track and shower kinematic resolution, very good particle ID, calorimetric information on electro- magnetic & hadronic activity*

Slide Credit: Anne Schukraft

Why do we need a trigger? (the beam rate is only 5 Hz after all)

- There is 1 neutrino interaction every ~20 beam spills at SBND
- Events are large, processing the data offline isn't trivial.

Only save events when scintillation light is detected during the beam spill

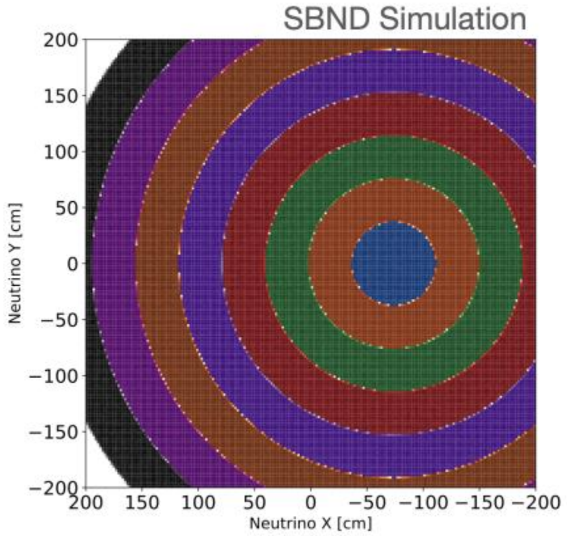
Aside on why events are so large and what we can do about it

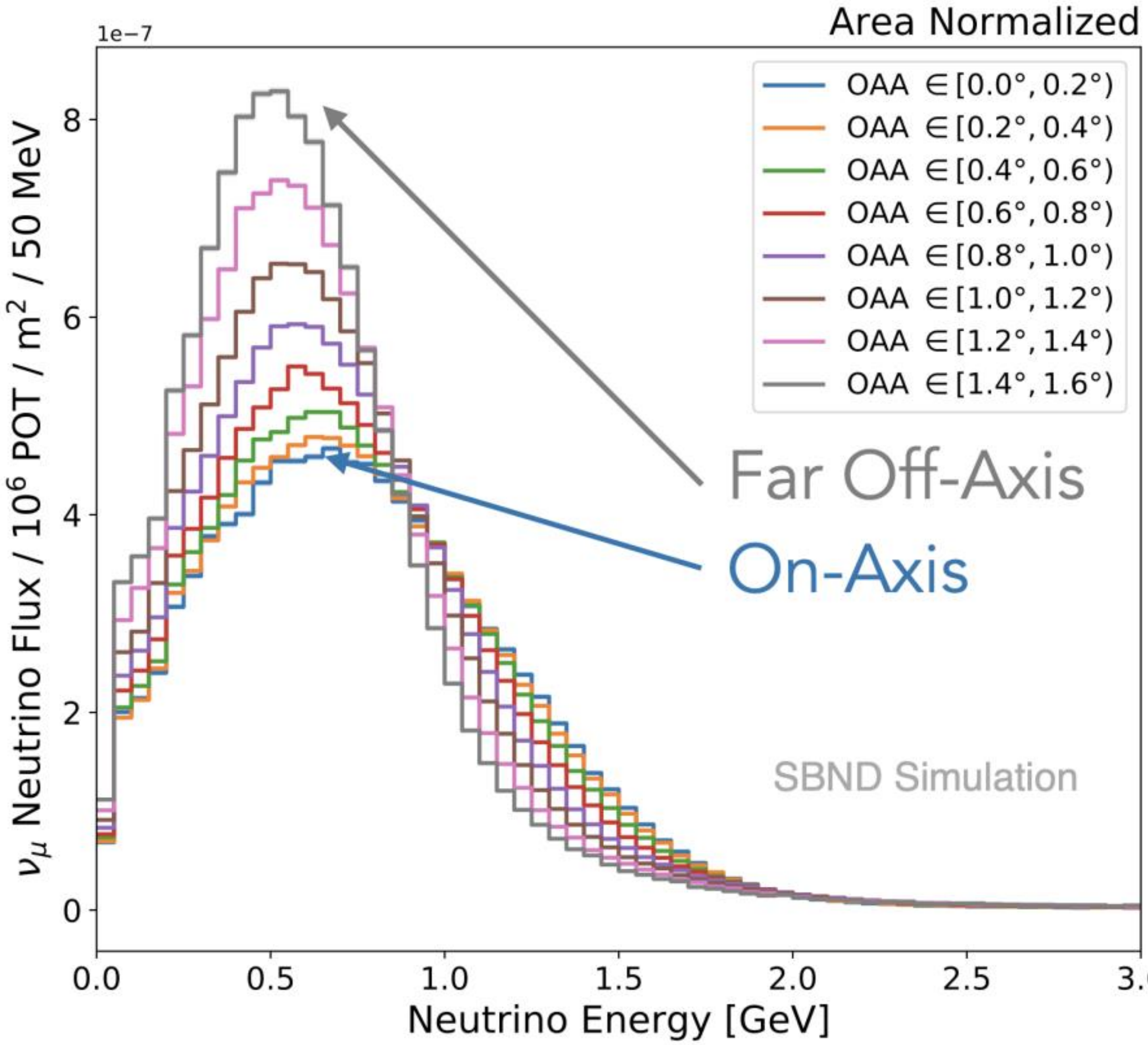
- LArTPCs are slow, the detailed 3D image is a lot of numbers. SBND drift time is 1.25 ms and the TPC waveforms are sampled at 2 MHz
- Precision calorimetry without electron multiplication requires signal processing on raw waveforms.
  - with 3mm wire spacing, MIP muons deposit only 25,000 collectable electrons per wire in 1-2 us -> O(1) nA signals 😳
- New tools such as real time signal processing/ROI finding are in development across the community . . . exciting!
- Today's pixel (instead of wires) anode planes integrate hit charge on the chip . . . game changing!

SBND-PRISM

nuPRISM proposal: arXiv:1412.3086

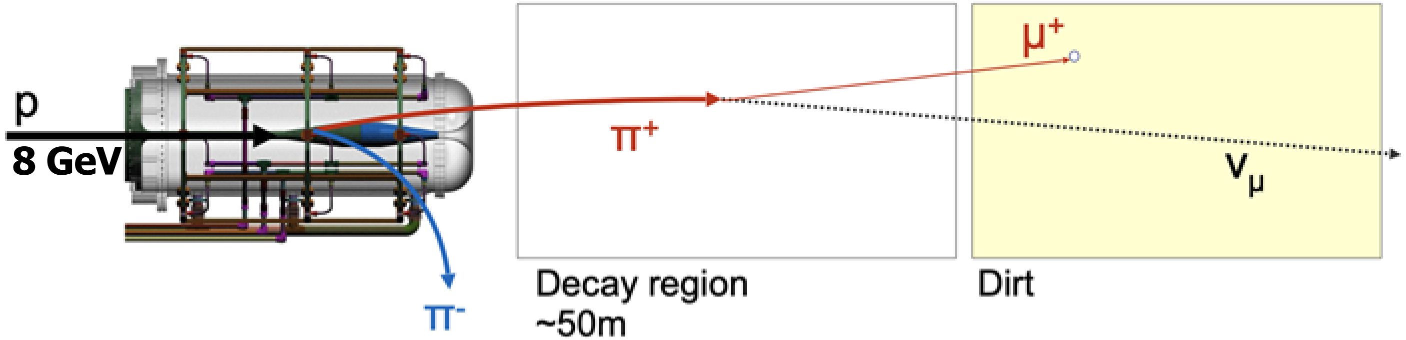
- Off-axis angle directly corresponds to the neutrino interaction vertex position
- The flux spectrum evolves as a function of the off-axis angle
  - Further off-axis fluxes peak lower and tighter
- Allows SBND to leverage PRISM concept





The Booster Neutrino Beam @ SBND

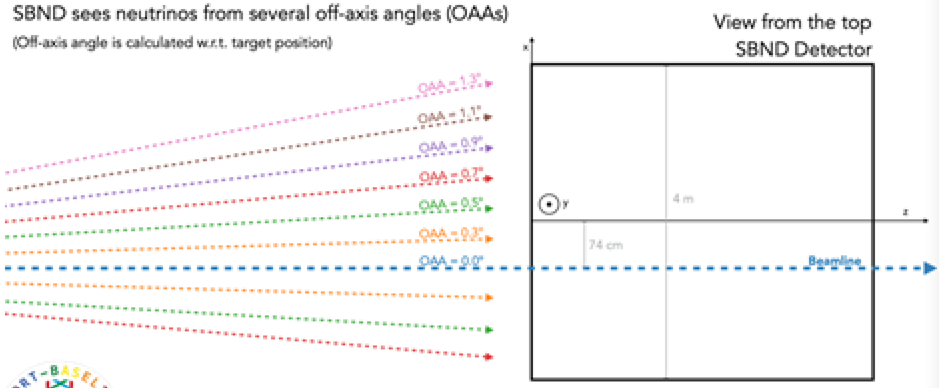
Image credit: Zarko Pavlovic

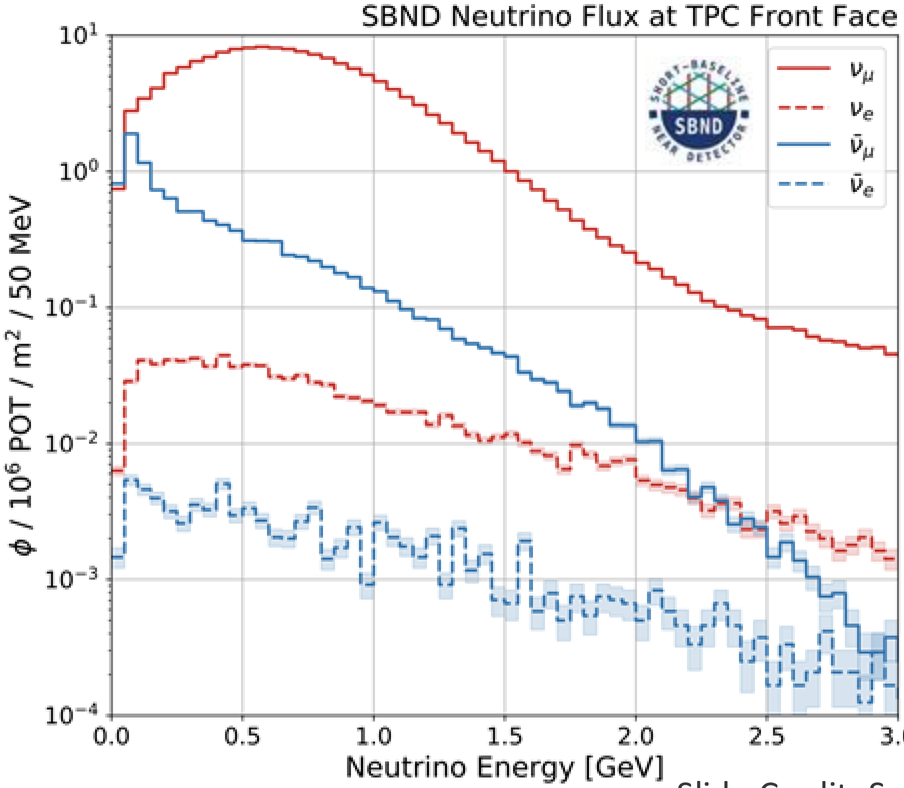


Beam Composition:

$\bar{\nu}_\mu$ = 93.6%
ν_μ = 5.9%
ν_e + ν_e = 0.5%

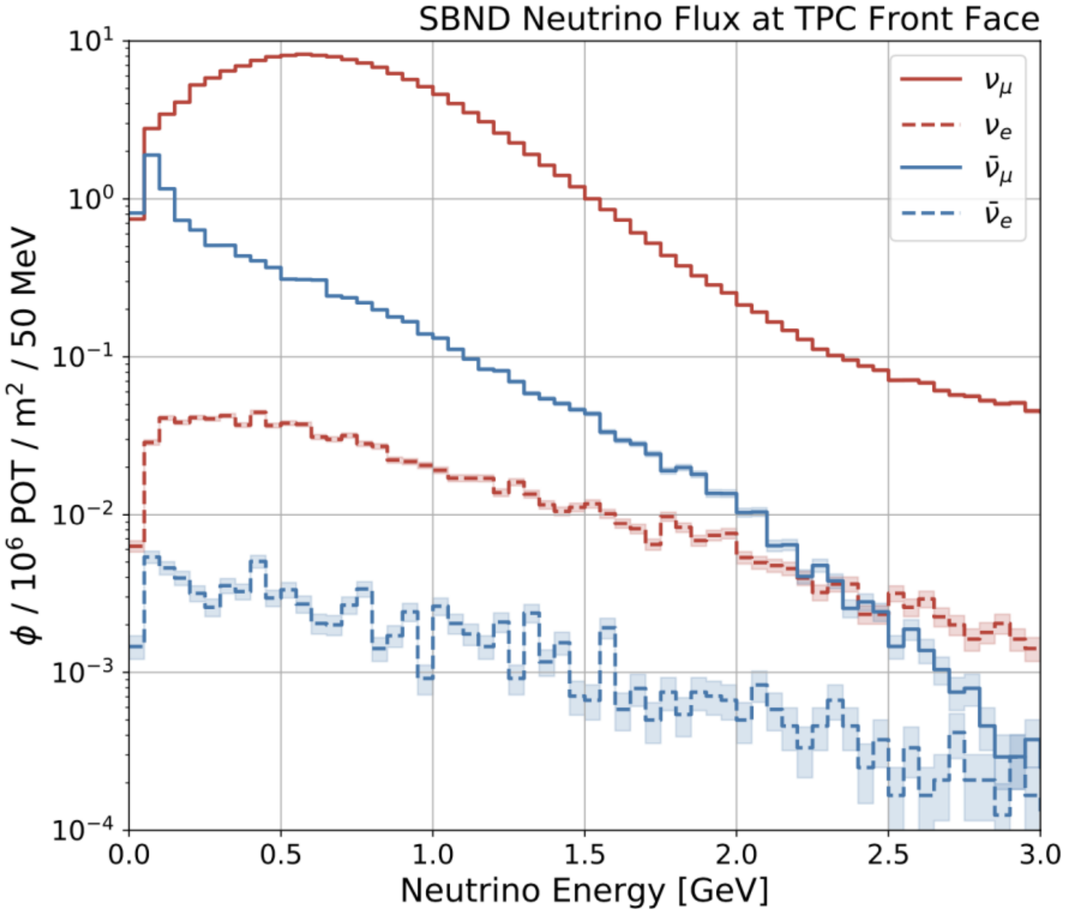
- <E_ν> ~ 800 MeV.
- Projected to take **10-18 X 10^{20} POT** of data in total => large statistics on Argon.
- Close to the target + slightly off-axis => SBND can sample **off-axis fluxes** (hear more about this in the next talk by Lauren Yates).





Slide Credit: Supraja B

Booster Neutrino Beam Flux at SBND

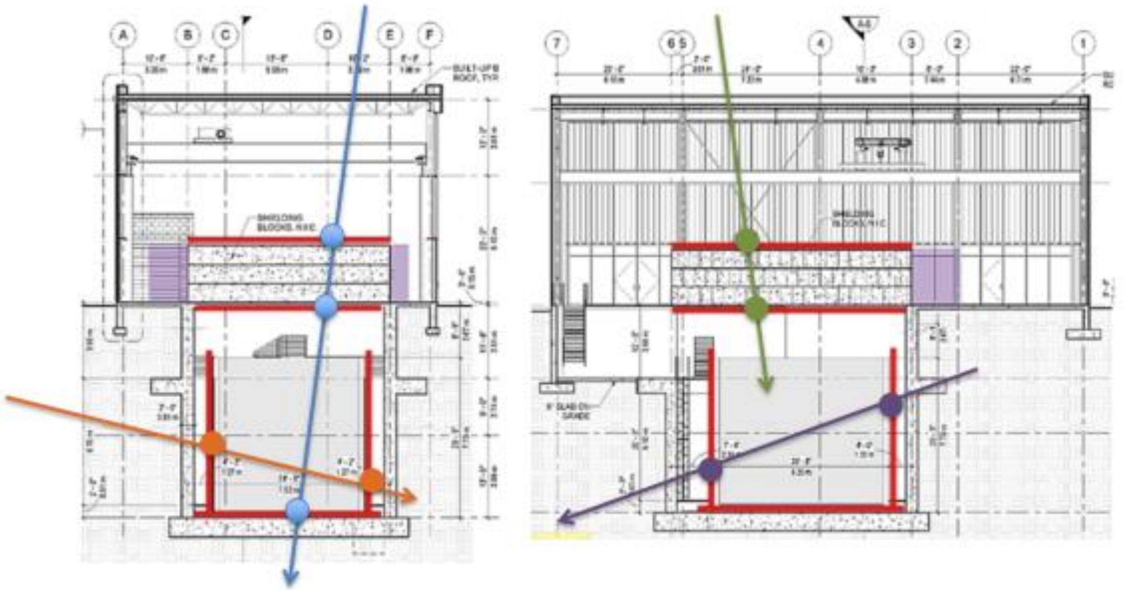


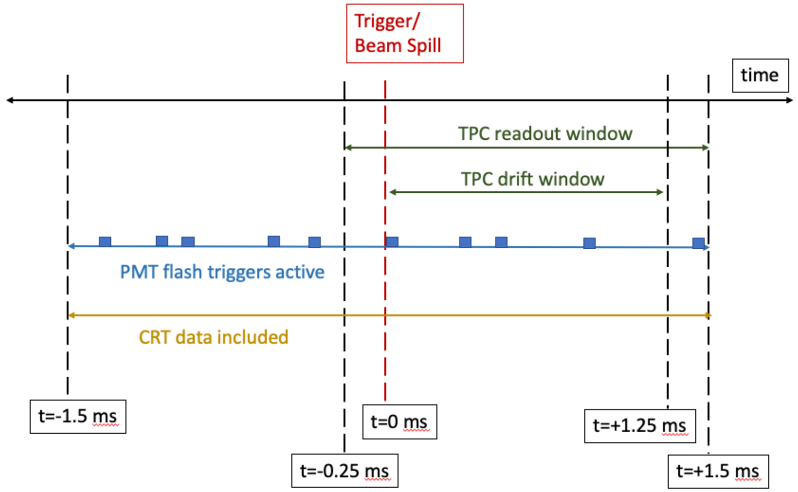
- The primary beam of interest at SBND is the Booster Neutrino Beam (BNB)
- The mean energy for muon neutrinos is about 0.8 GeV
- Beam composition by neutrino flavor:
  - 93.6% ν_μ
  - 5.9% $\bar{\nu}_\mu$
  - 0.5% ν_e+$\bar{\nu}_e$
- Plan to collect data corresponding to 10e20–18e20 protons on target (POT) over the course of a 3–4 year run

CRT based triggers

Long muon tracks are a critical commissioning tool and the basis of many calibration measurements.

The ability to trigger on the presence of muon tracks means that pure calibration samples can be acquired quickly and/or written to separate data streams. The calibration process is considerably faster when processing calibration data is decoupled from processing physics data



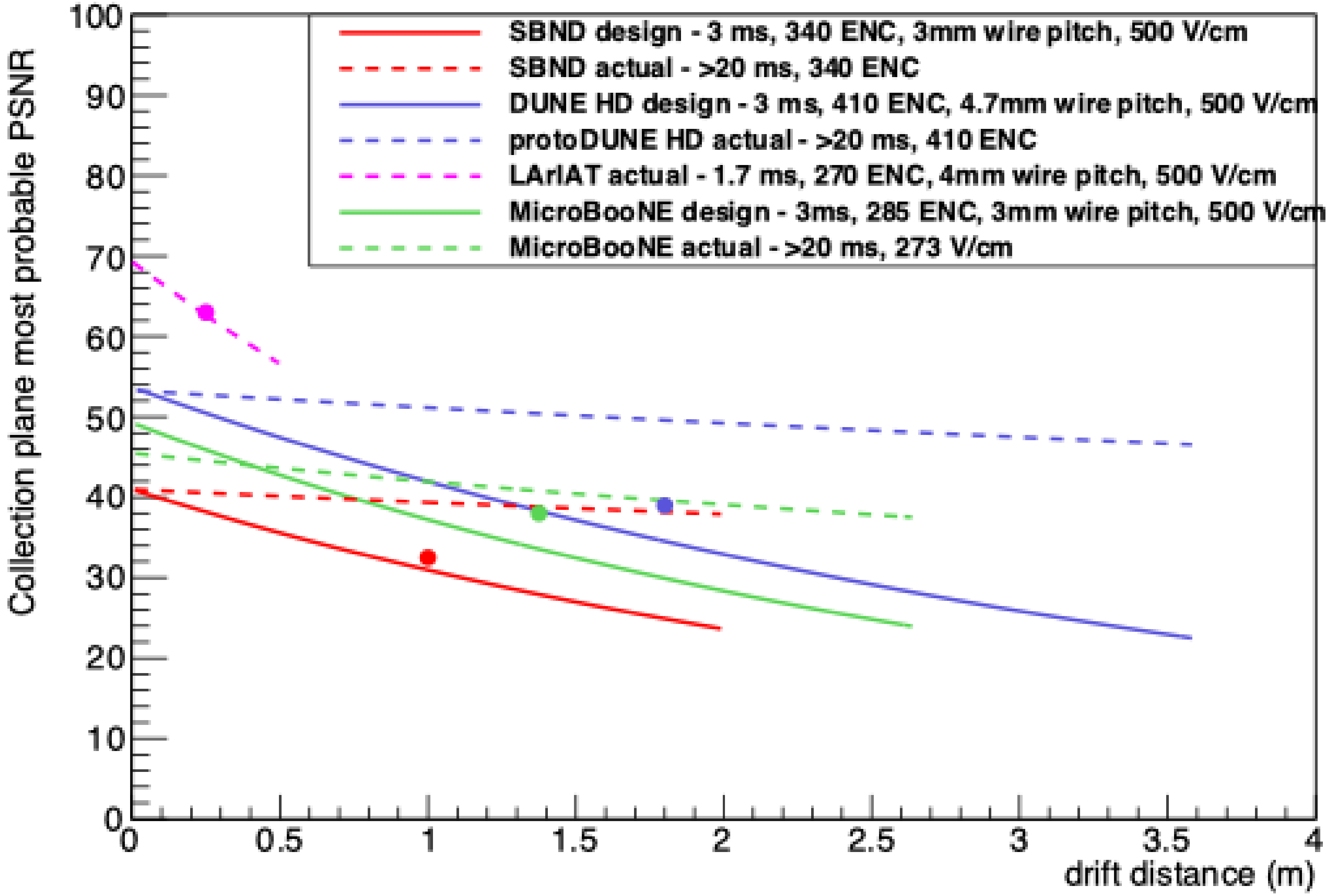


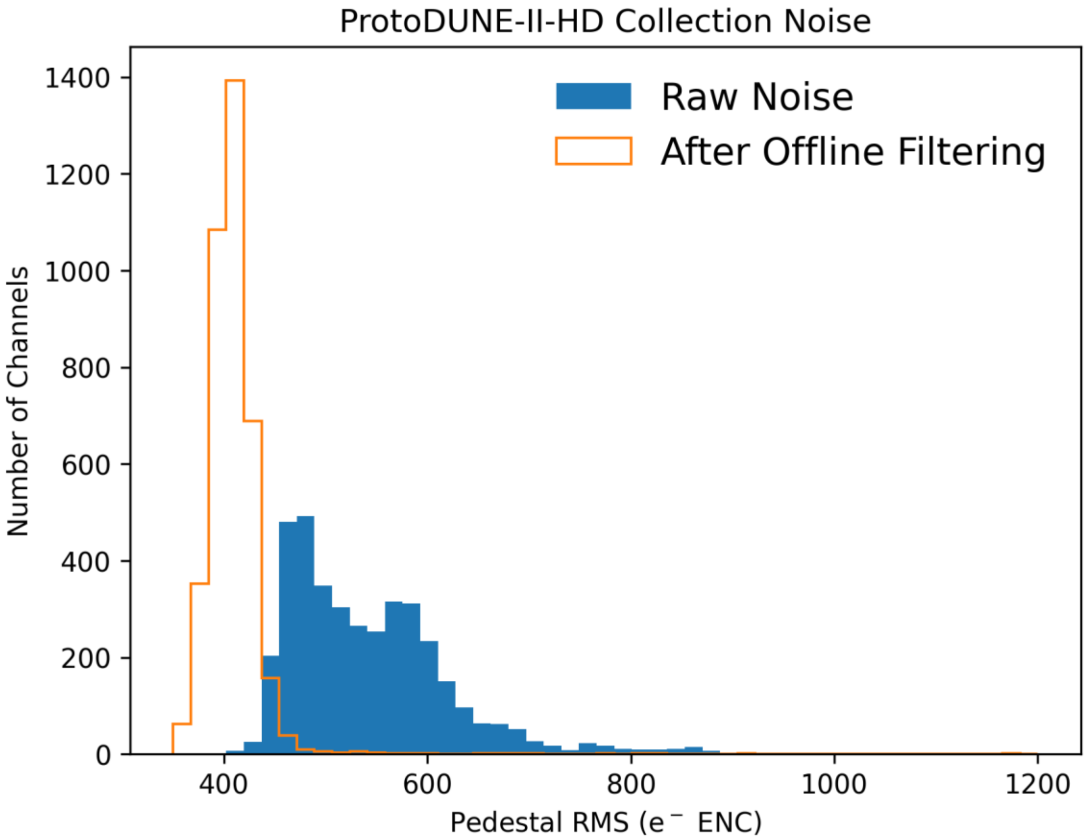
- CRT-A: Vertical through-going
- CRT-B: Stopping muons (Michel sample)
- CRT-C: Horiz. through-going Anode-Cathode crossing muons
- CRT-D: Horiz. through-going "parallel" muons

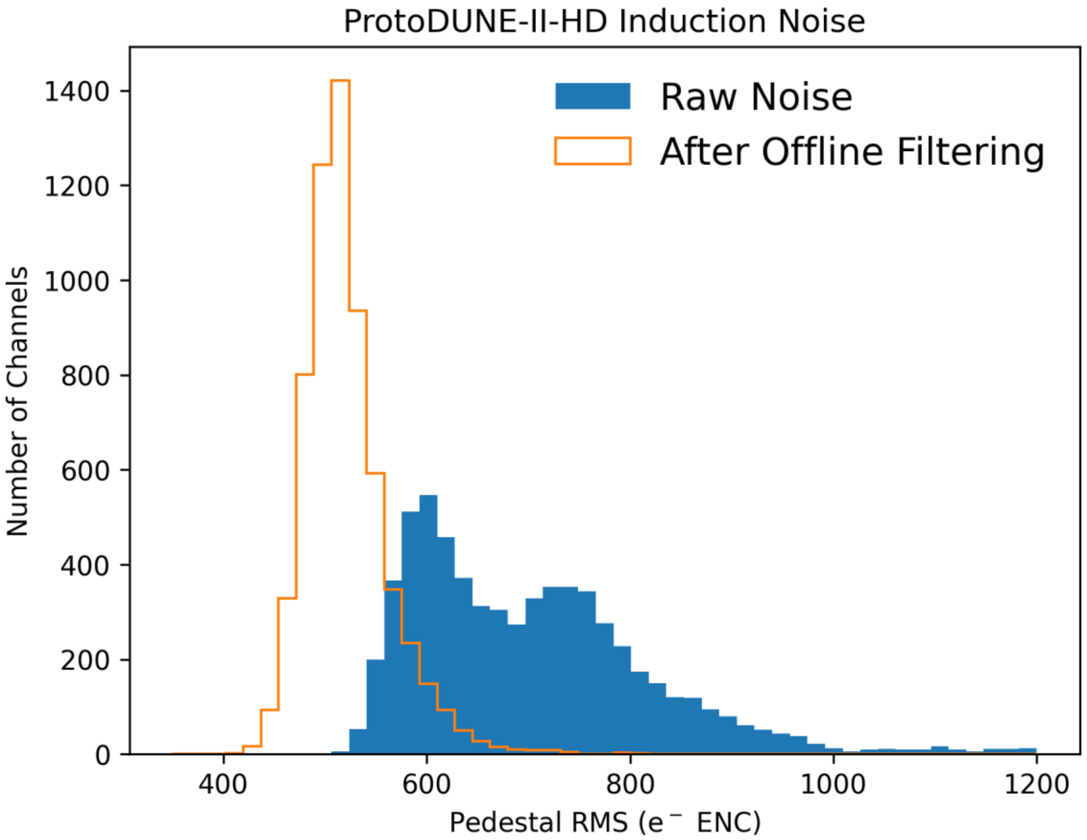
All triggers shown here also require high PMT multiplicity to ensure the muon track enters the active TPC volume

For dedicated runs, a subset of the CRT strips can be activated, restricting the trigger to certain track angles/topologies

Evolution of LArTPC cold electronics




ProtoDUNE-II-HD Collection Noise
Raw Noise
After Offline Filtering
Number of Channels
Pedestal RMS (e⁻ ENC)
0
200
400
600
800
1000
1200
1400
400
600
800
1000
1200

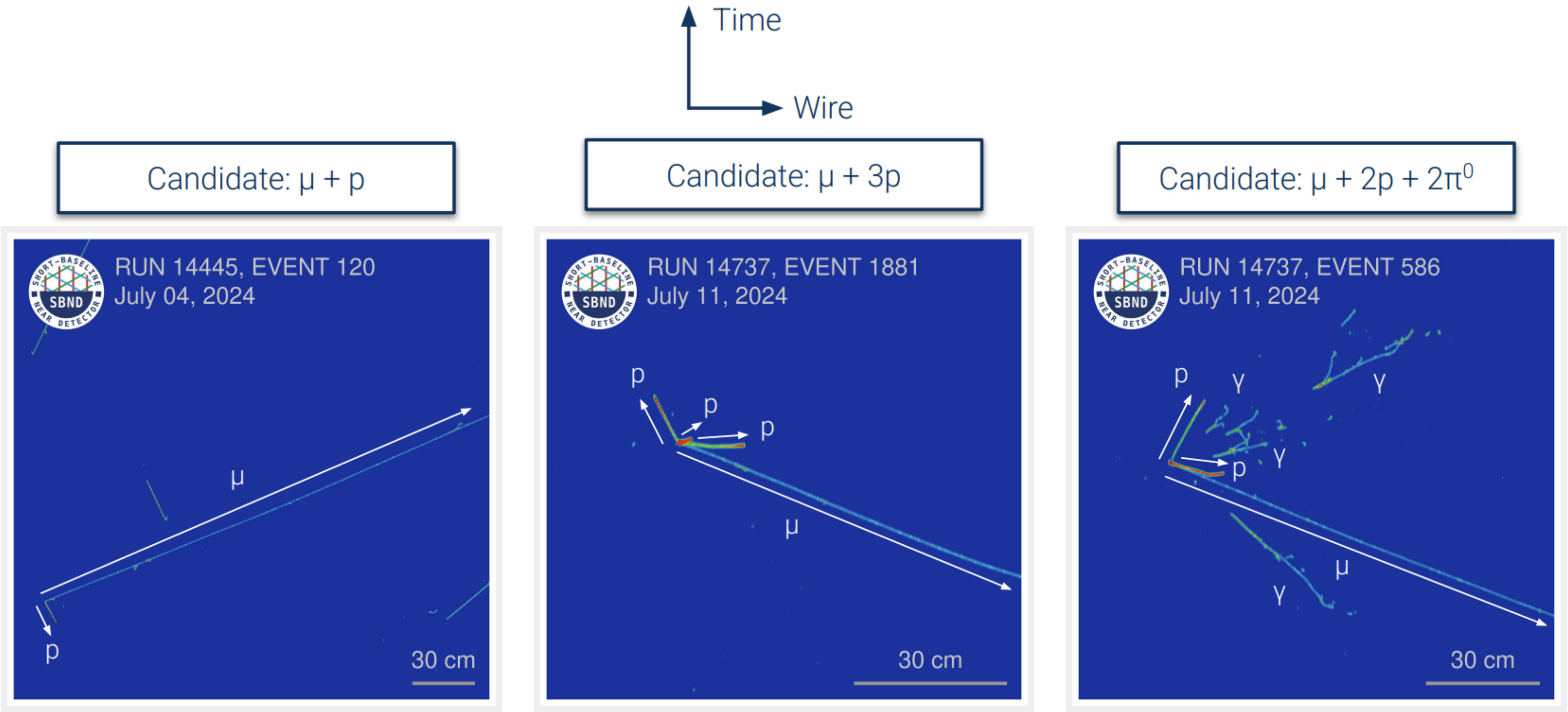

ProtoDUNE-II-HD Induction Noise
Raw Noise
After Offline Filtering
Number of Channels
Pedestal RMS (e⁻ ENC)
0
200
400
600
800
1000
1200
1400
400
600
800
1000
1200

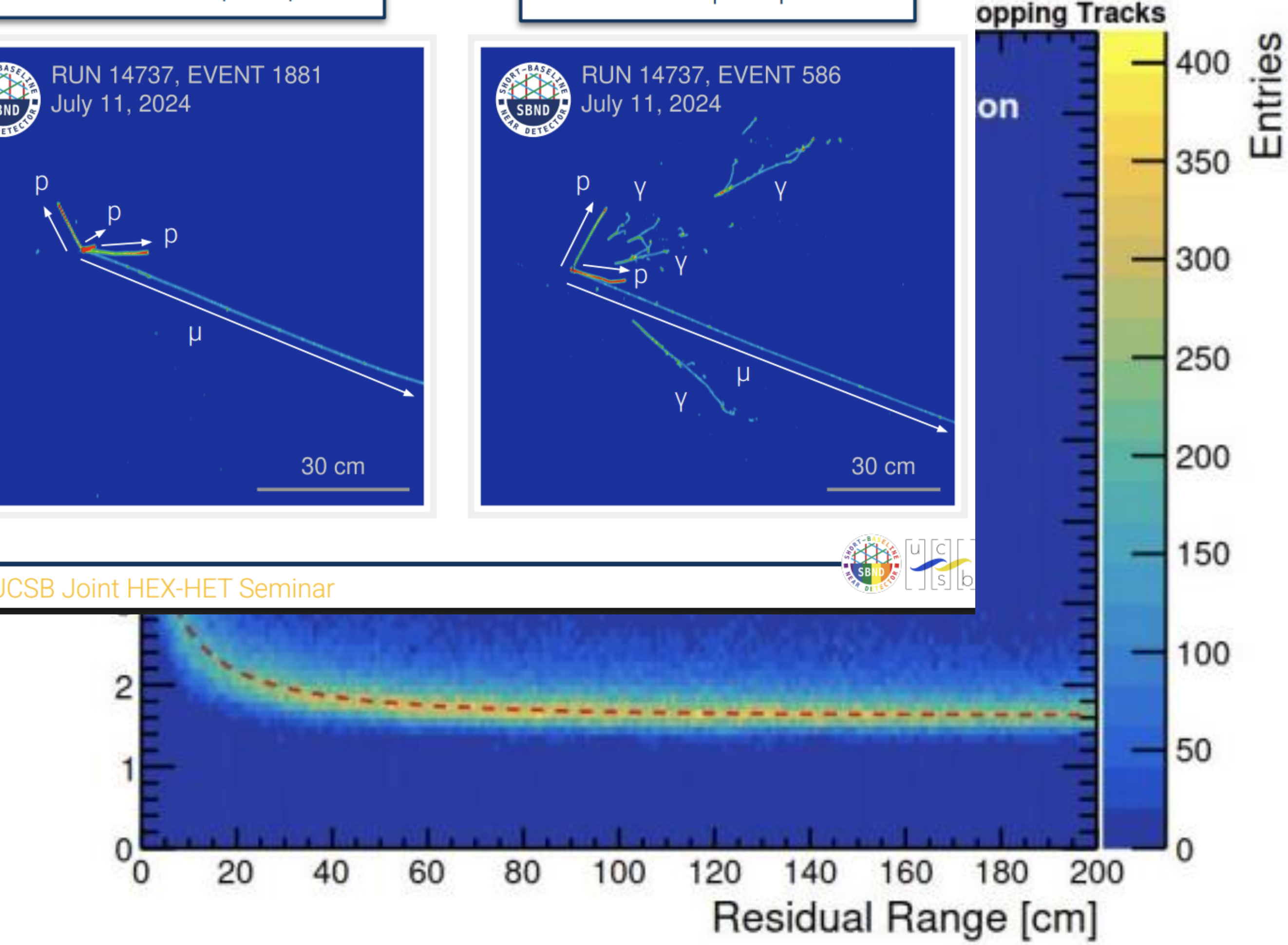
Captured First Neutrinos in July 2024

Candidate: μ + p

Candidate: μ + 3p

Candidate: μ + 2p + 2π^0





CRT Only Run in 2018

Will we be able to see the beam spot in the upstream CRT wall?
YES!