The NOvA Test Beam Program

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on behalf of the NOvA collaboration

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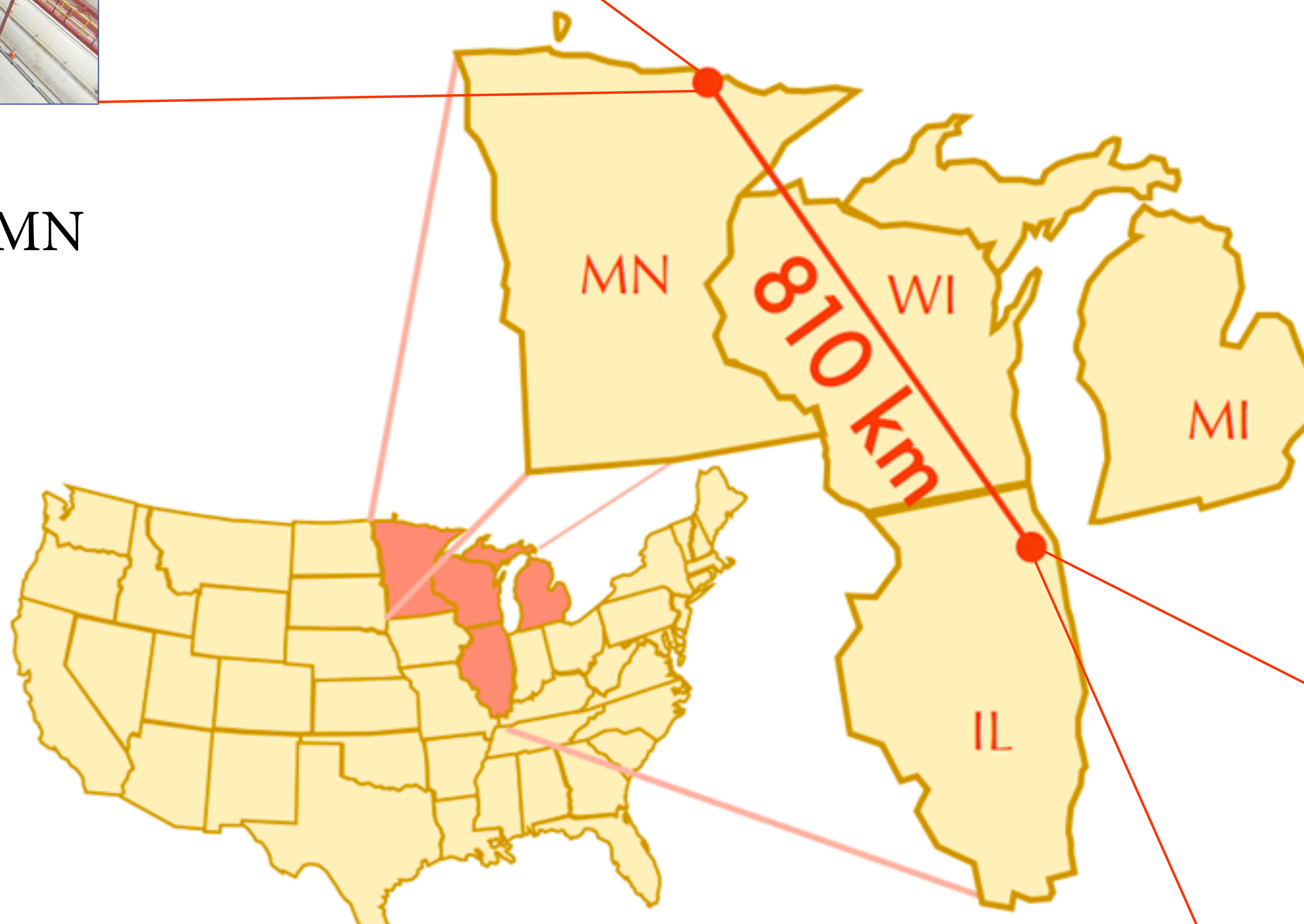
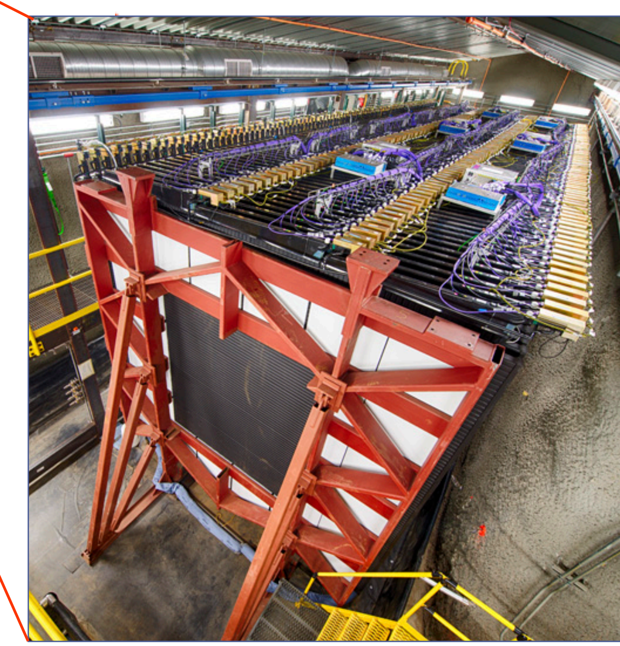
The NOvA Experiment

NOvA is a **long-baseline neutrino oscillation experiment** based at Fermilab with two functionally identical detectors placed in the NuMI beamline, the most powerful neutrino beam in the world.

Far Detector
14 kt at Ash River, MN

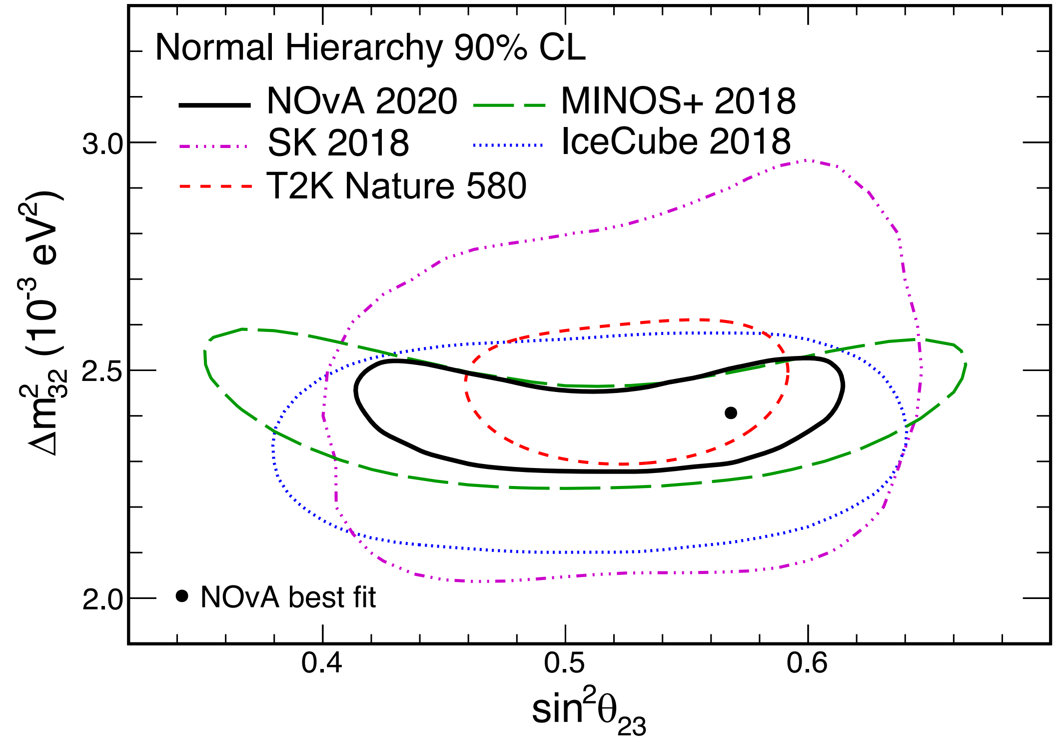


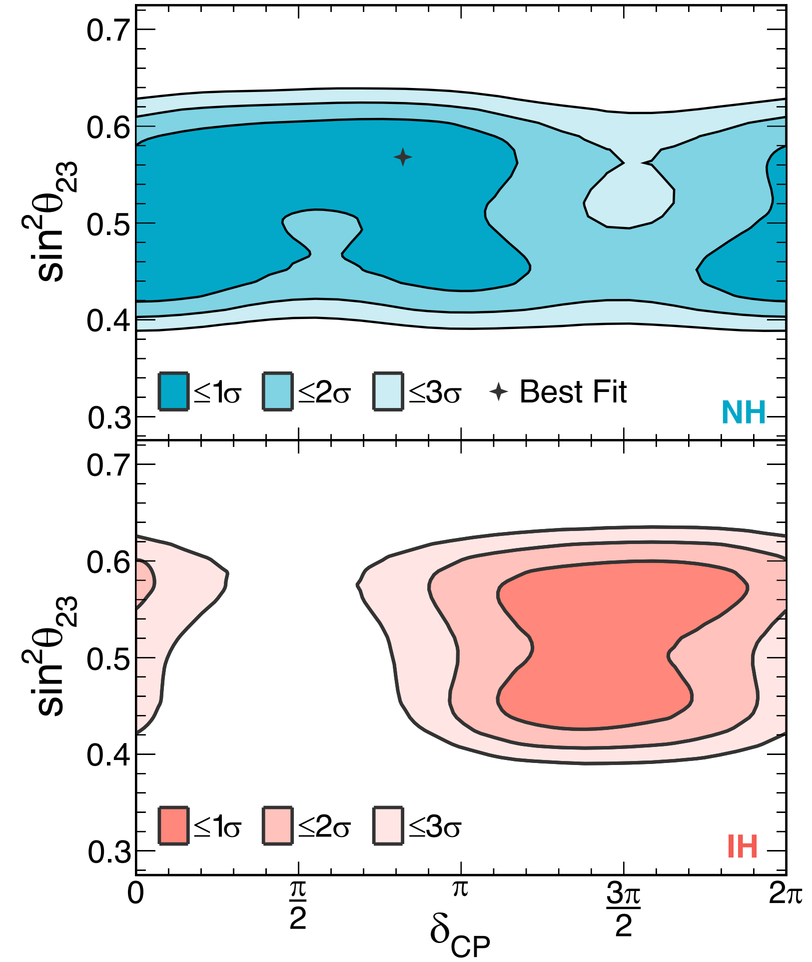
Near Detector
300 t at Fermilab, IL



NOvA Physics

- Study $\nu_\mu \to \nu_e$, $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations to:
  - resolve the neutrino mass ordering (is ν_3 the heaviest mass state?)
  - measure the octant of θ_{23} (is there an underlying ν_μ/ν_τ symmetry?)
  - search for CP symmetry violation in leptons (constrain differences between ν and $\overline{\nu}$ oscillations)
- Measure neutrino cross-sections at the Near Detector.
- Search for sterile neutrinos via non-standard oscillations.
- Other exotics and more!

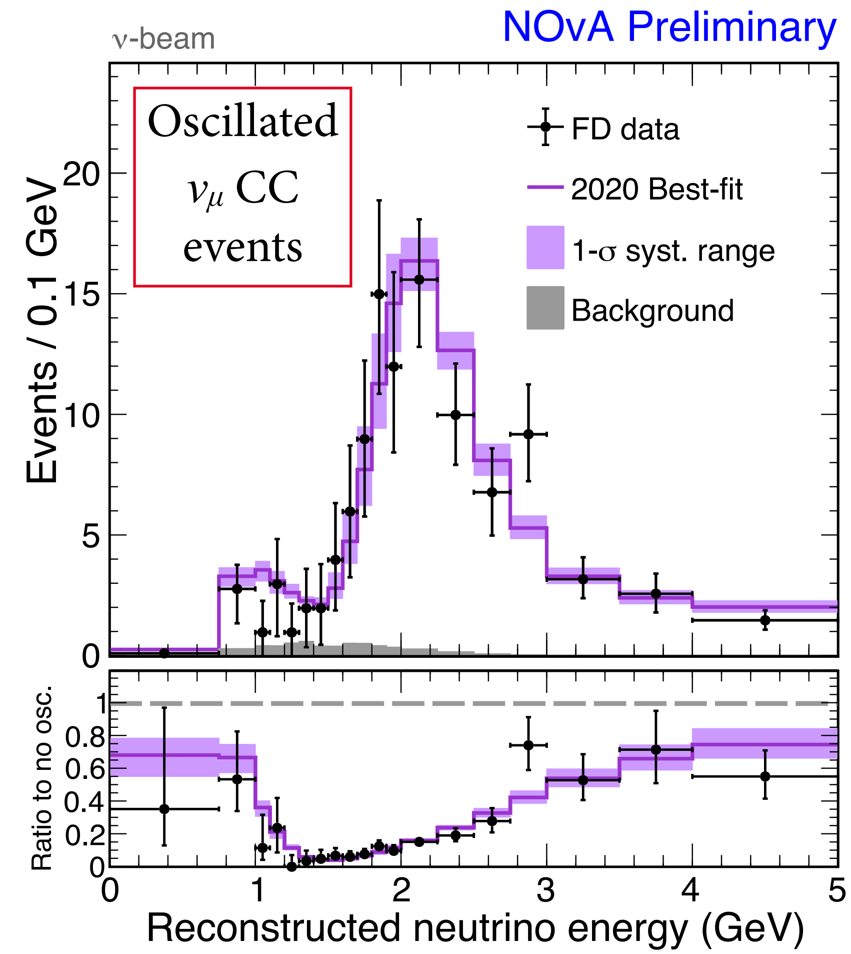




NOvA, Phys. Rev. D 106, 032004 (2022)

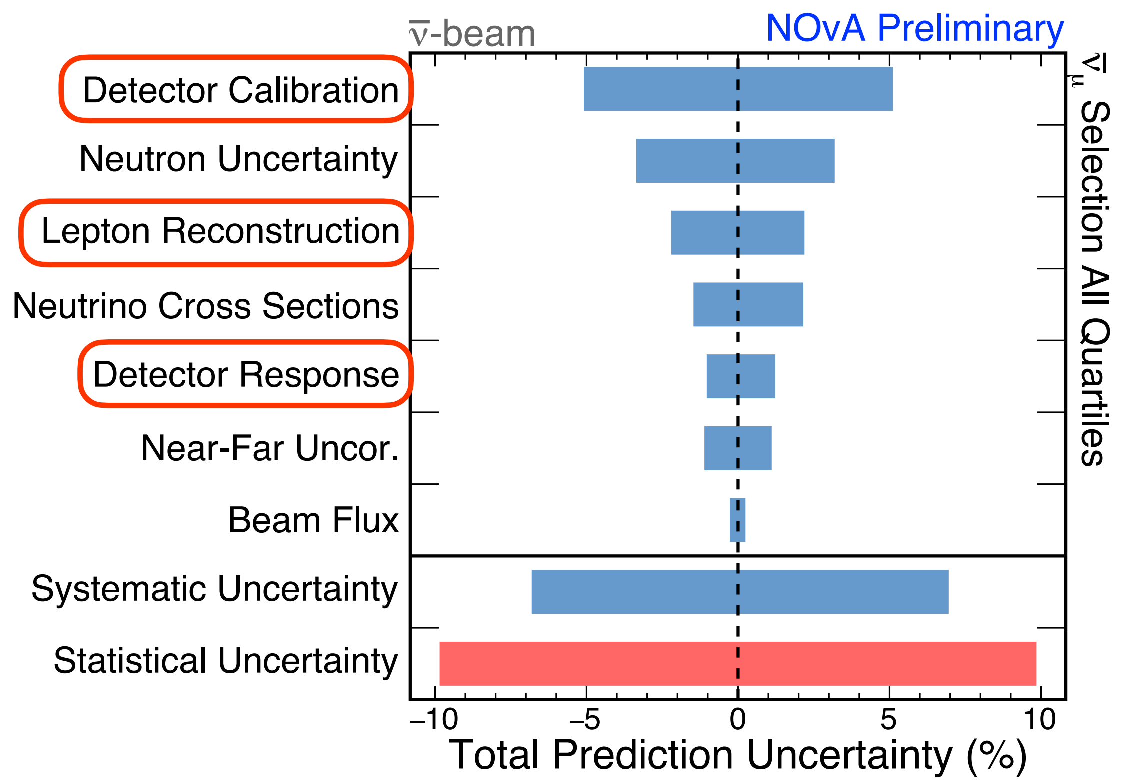
Oscillation Analyses

- Measure energy spectrum of ν_μ, ν_e, $\overline{\nu}_\mu$, $\overline{\nu}_e$ selected events and fit to oscillation models.



- As more data are collected, statistical uncertainties will decrease and systematic uncertainties will become more limiting.

- Some of the largest uncertainties can be addressed directly using a Test Beam experiment:
  - validate and improve detector calibration procedures;
  - characterize detector response;
  - collect single particle libraries for use in improving the simulation and reconstruction tools.



NOvA Test Beam

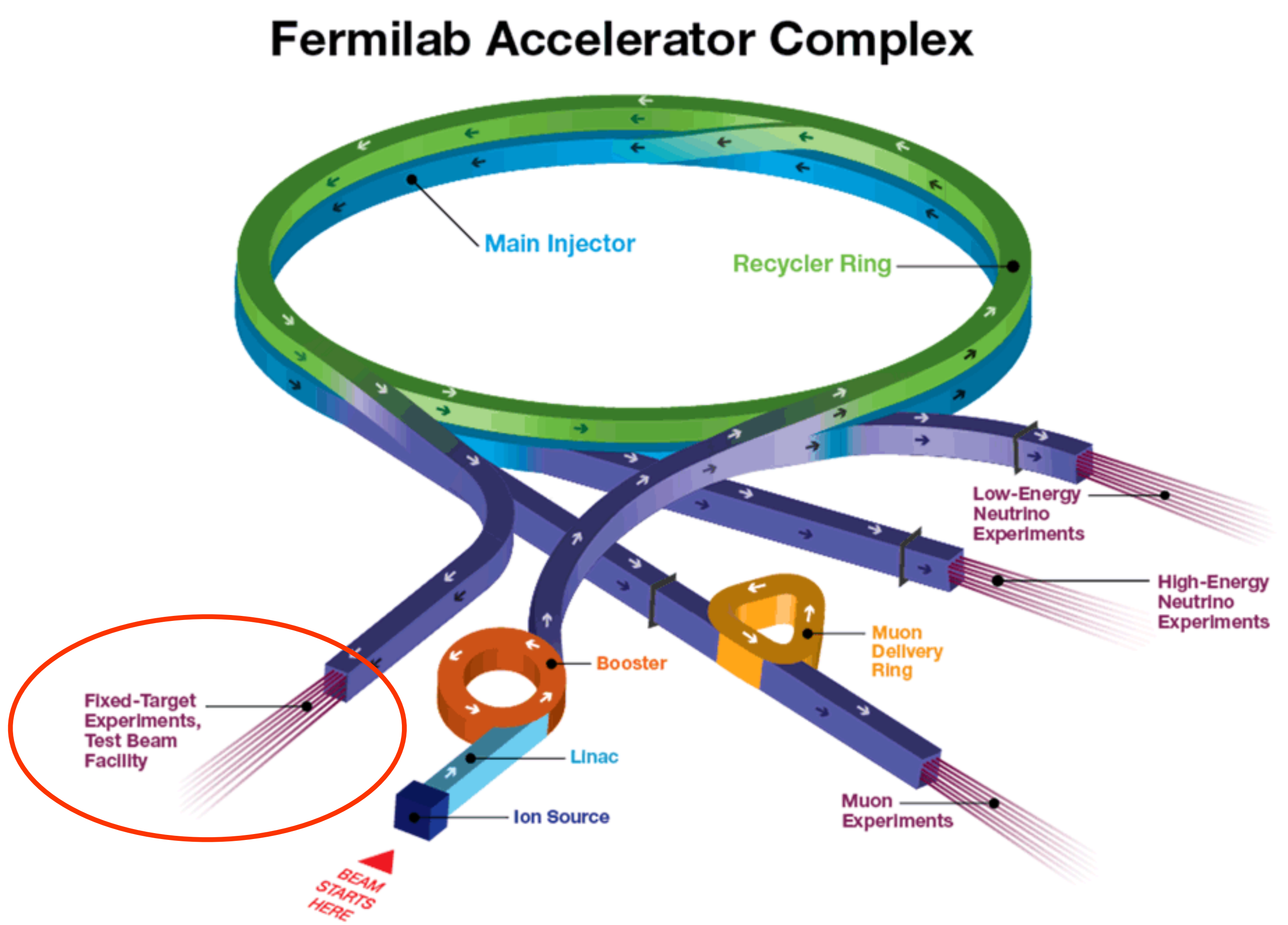
- The NOvA Test Beam Program uses a scaled-down 30-ton NOvA detector with identical technologies to the other NOvA detectors.

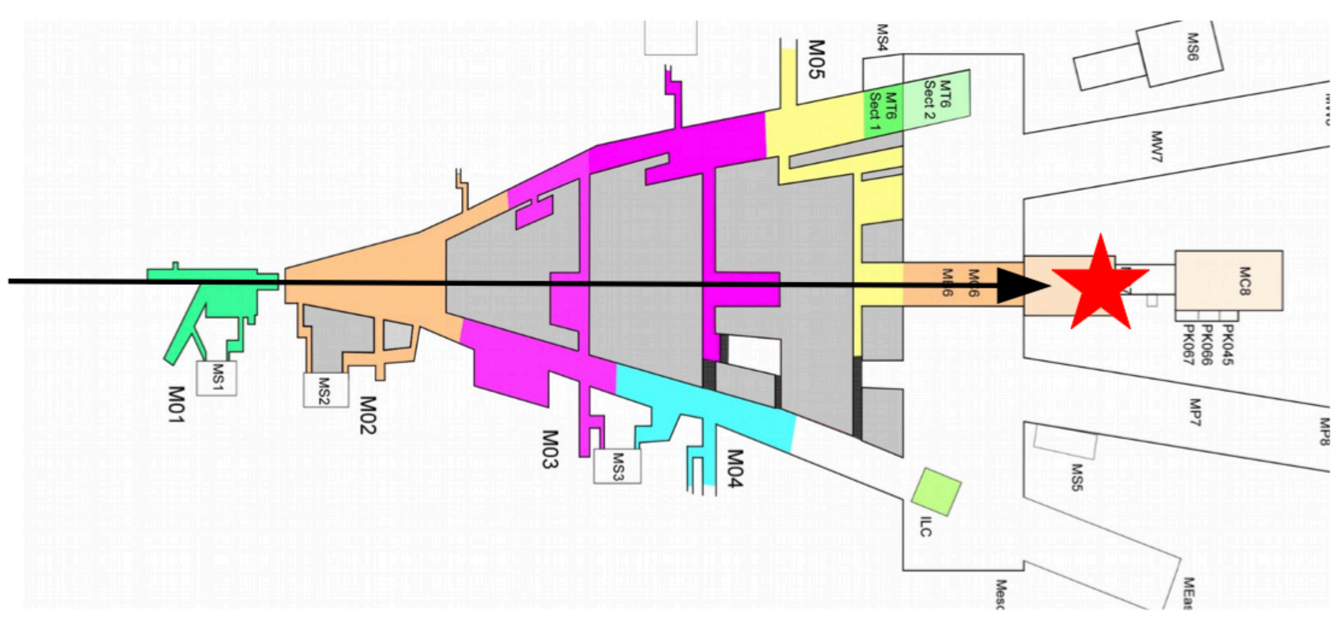
- It analyzes tagged charged particles from a tertiary beamline consisting of protons, pions, muons, electrons and kaons in the 0.2 — 2.0 GeV/c momentum range relevant to NOvA's neutrino interactions.

- Timeline:
  - Deployed at the Fermilab Test Beam Facility in from Summer 2018 — Spring 2019.
  - Commissioning: May — July 2019.
  - Data taking: December 2019 — July 2022 (3 dedicated runs).
  - Decommissioning: July 2022 — end of 2022.

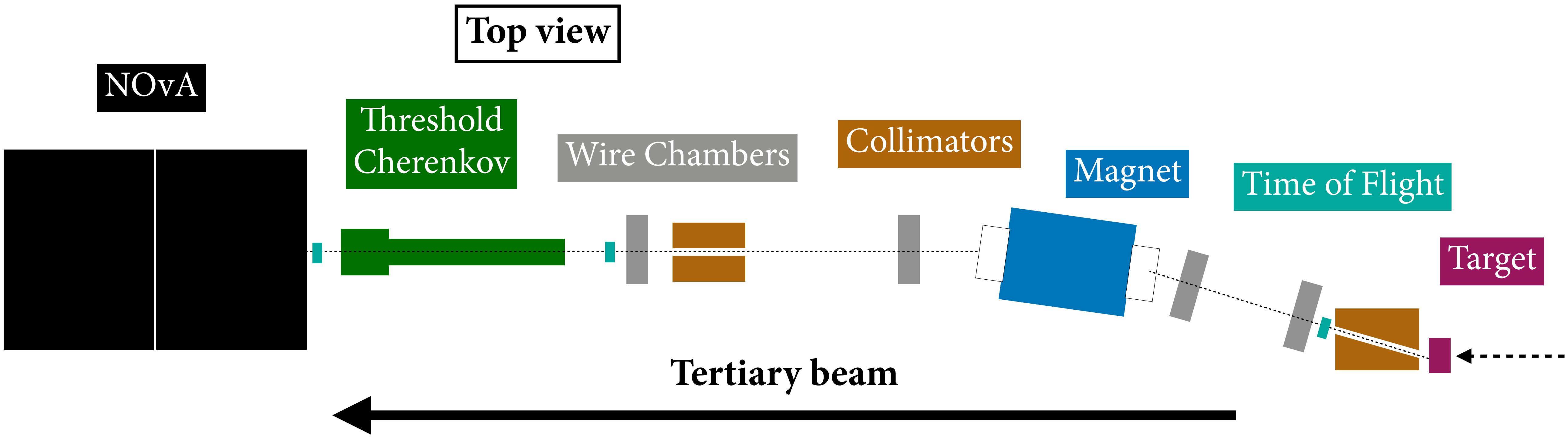
MCenter Beam

- NOvA Test Beam is located on the MCenter beamline;
    - Downstream of the the area previously used by LArIAT.
- Protons accelerated up to 120 GeV by the Main Injector are extracted in a continuous 4.2 s spill once a minute.
- A secondary beam containing 8 — 80 GeV protons and pions is created by impinging the primary protons on a Cu target.
- A second Cu target is used to produce a tertiary beam containing the particles of interest for NOvA Test Beam.



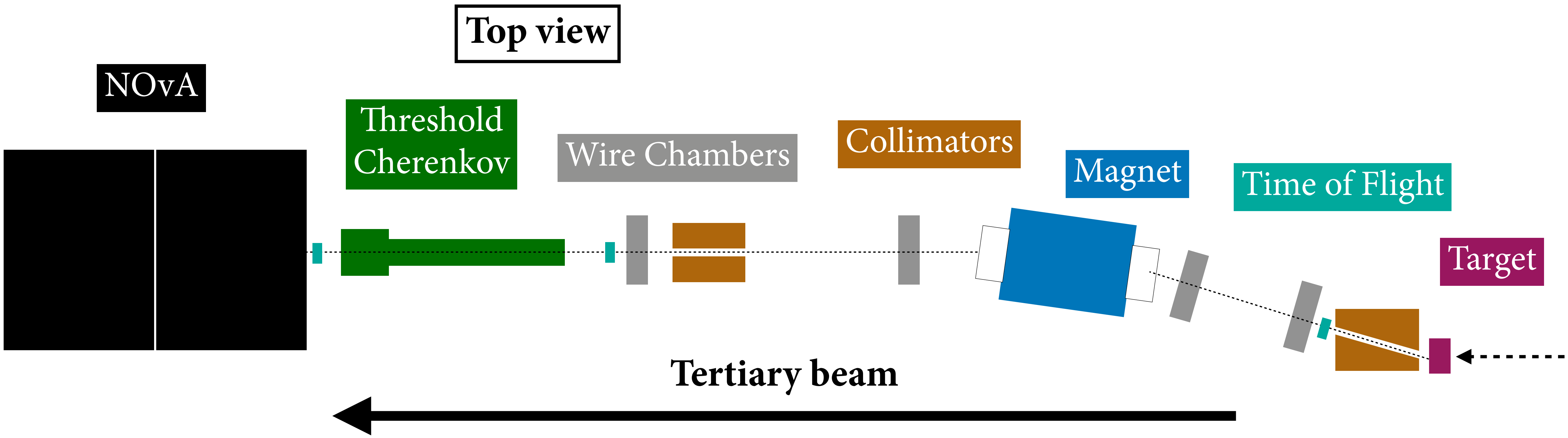


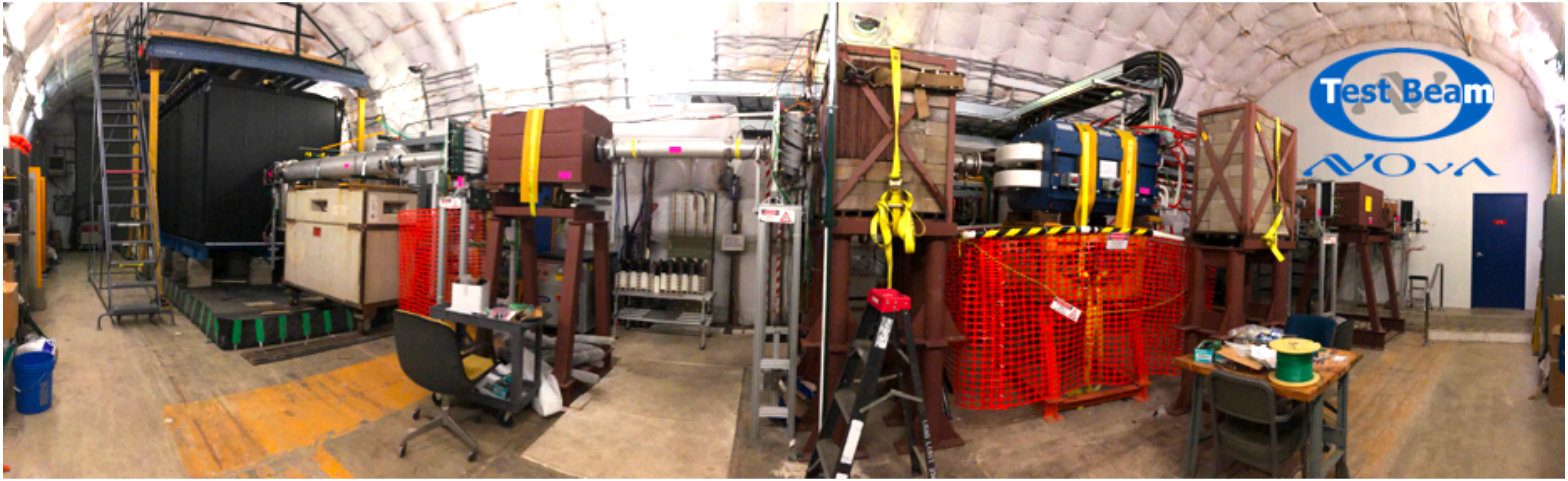
Tertiary Beamline Instrumentation



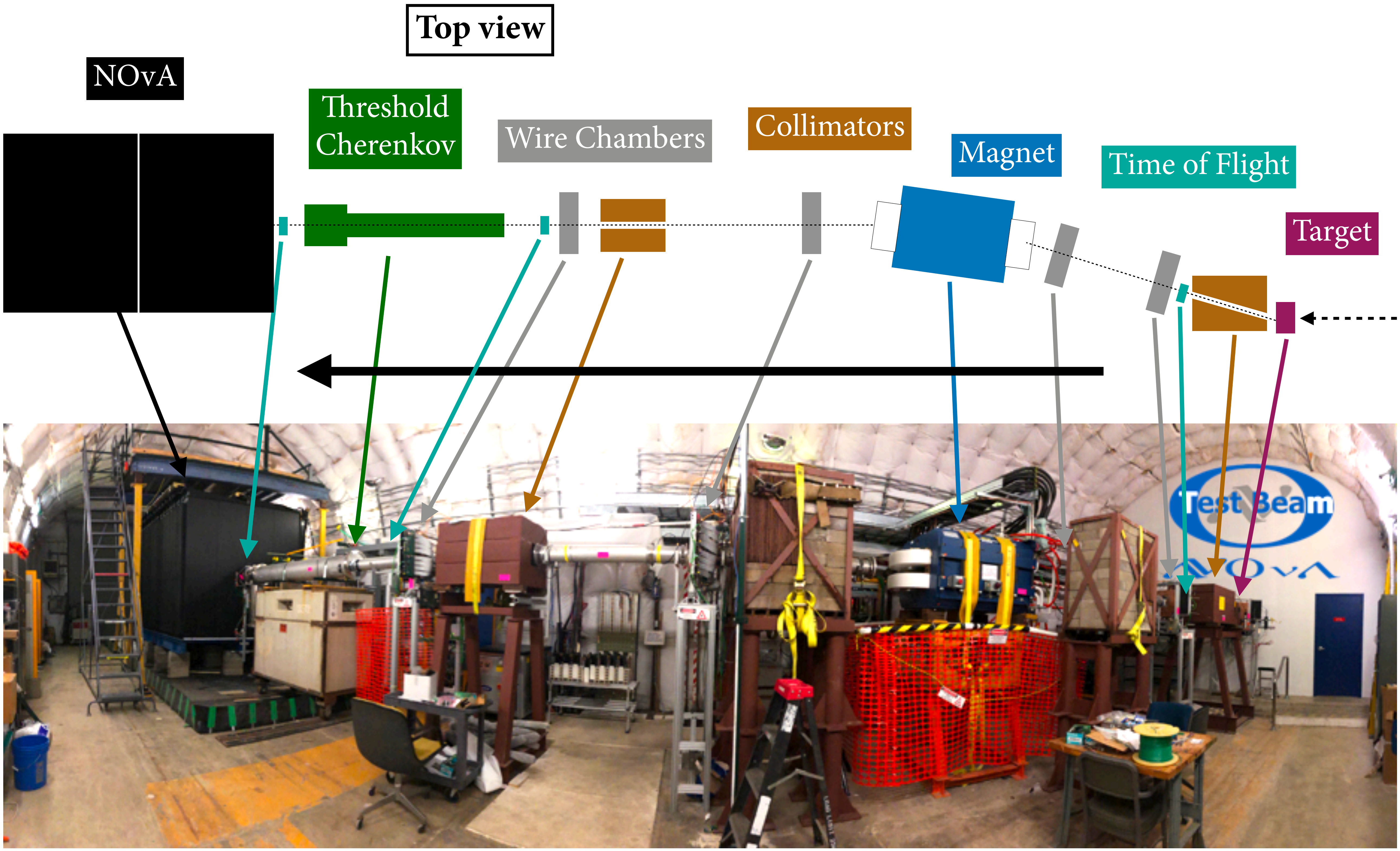
Tertiary beamline instrumentation provides **trigger**, **particle identification** and a precise **momentum measurement** for tertiary beam particles of interest before interactions in the **NOvA Detector**.

Tertiary Beamline Instrumentation



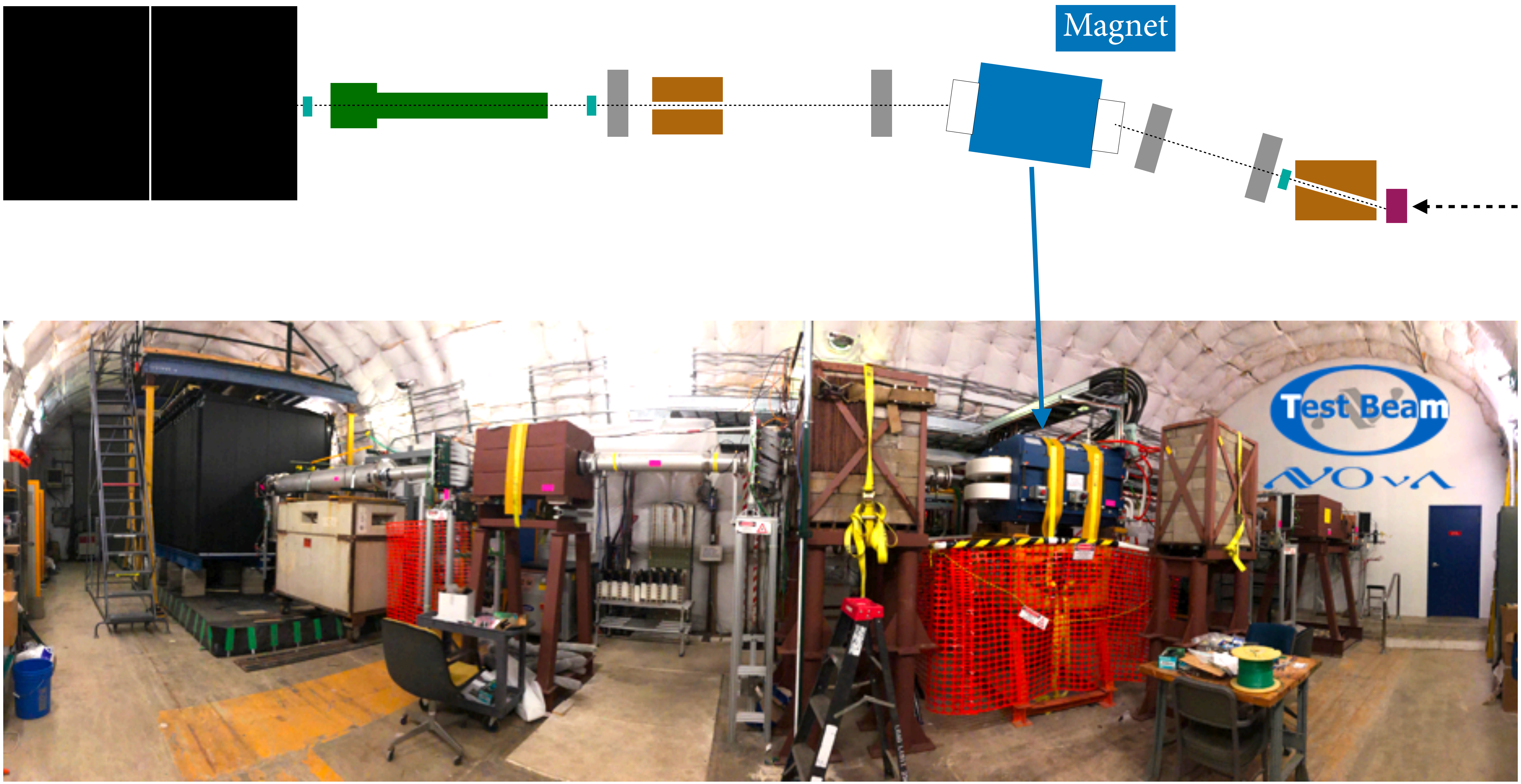


Tertiary Beamline Instrumentation



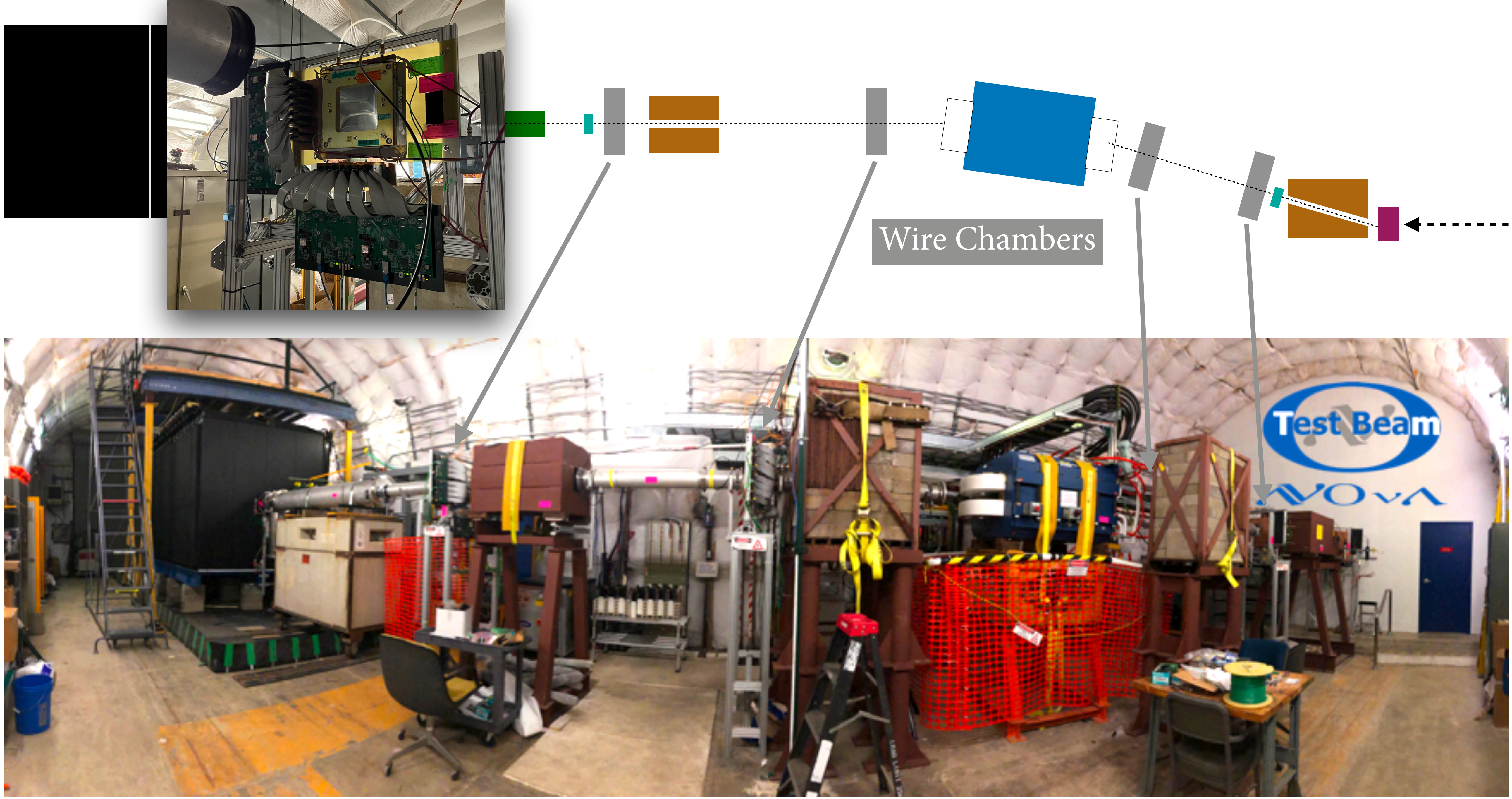
Tertiary Beamline Magnet

Analyzer magnet is used to select the tertiary beam momentum and charge of interest with a field up to 1.8 T.



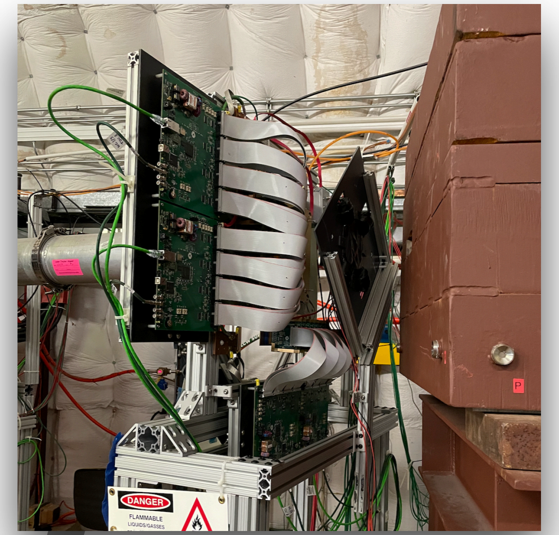
Tertiary Beamline Wire Chambers

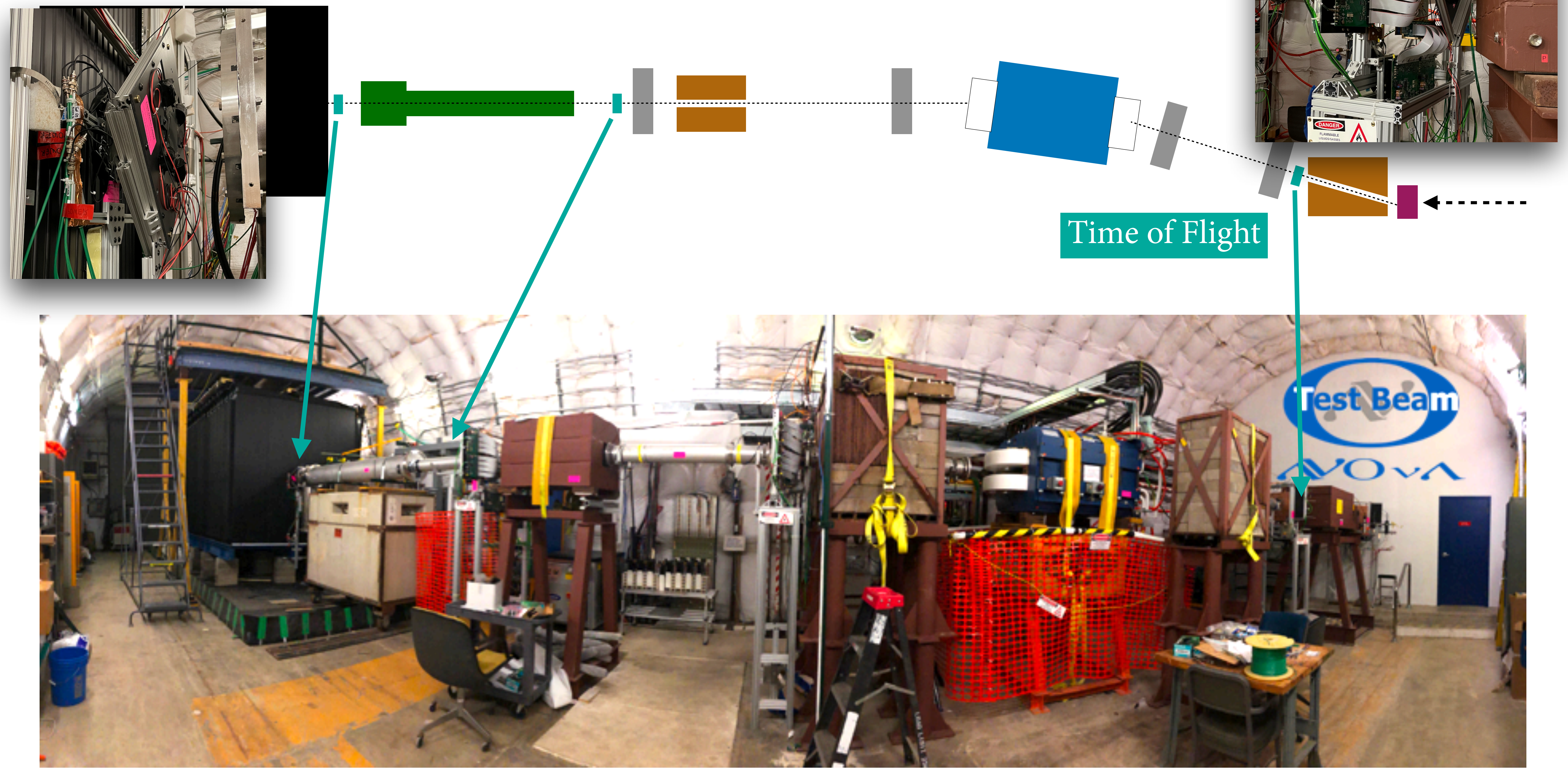
Four **wire chambers**, each with two 5.5”x5.5” planes and 1 mm wire pitch, provide particle tracking and are used to reconstruct the particle momentum with 1-3% resolution.



Tertiary Beamline Time-of-Flight

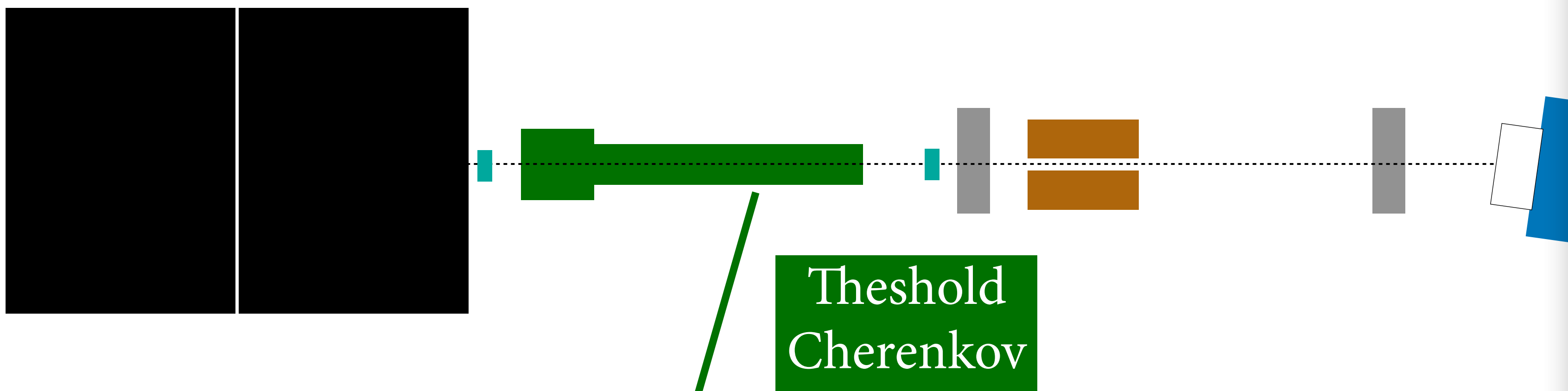
Time-of-Flight (ToF) with three arms and two path lengths, 9.7 m and 13.2 m, provides identification of heavier particles (protons and kaons).

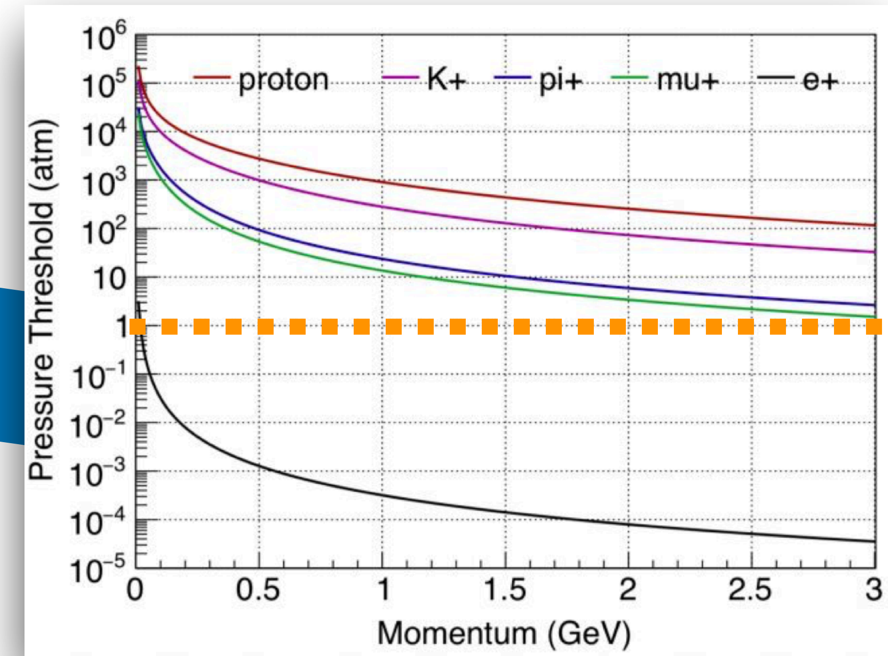




Tertiary Beamline Threshold Cherenkov

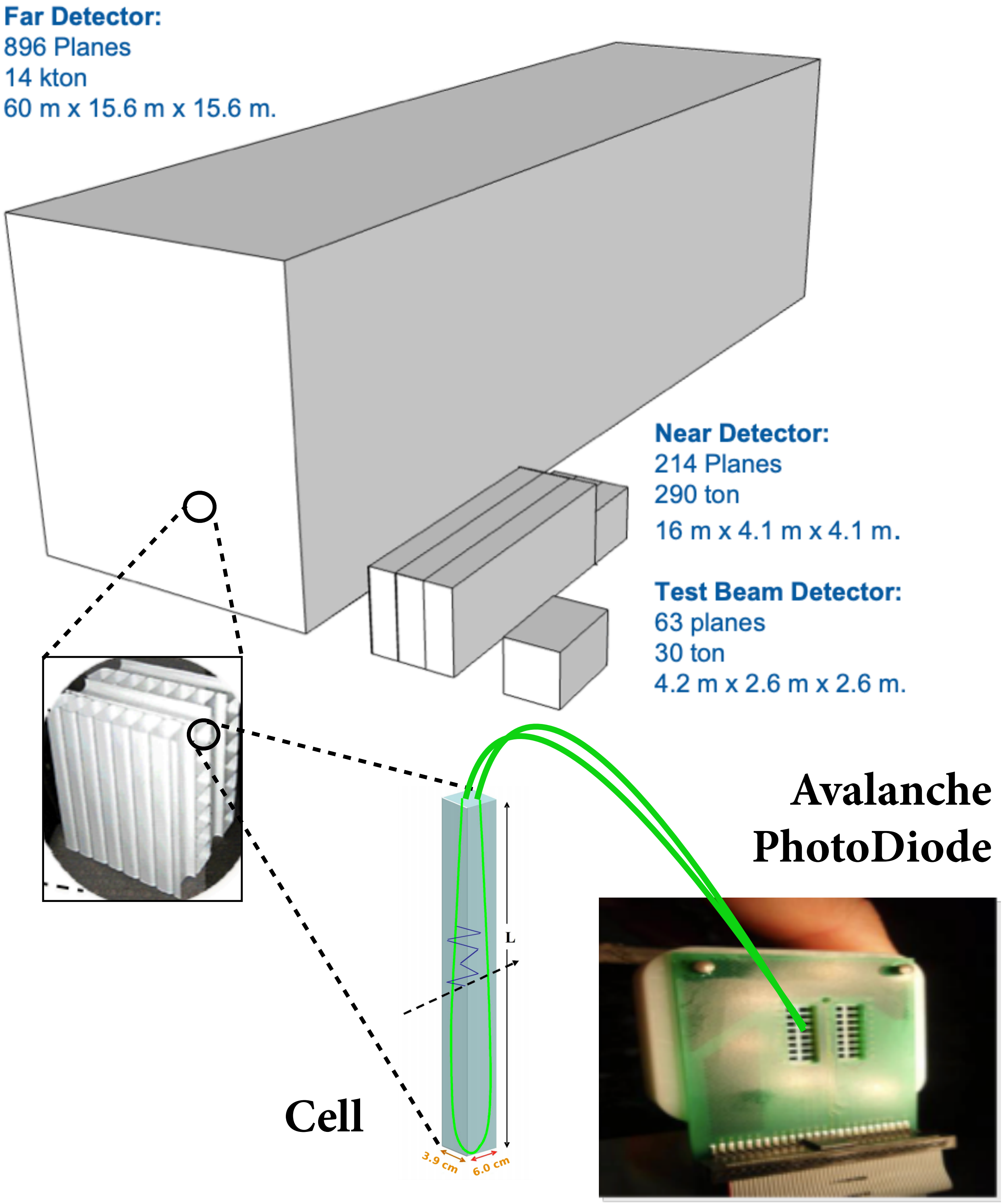
Threshold Cherenkov Counter containing 1 atm CO_2 for tagging electrons in the tertiary beam via Cherenkov light.





NOvA Detector Technology

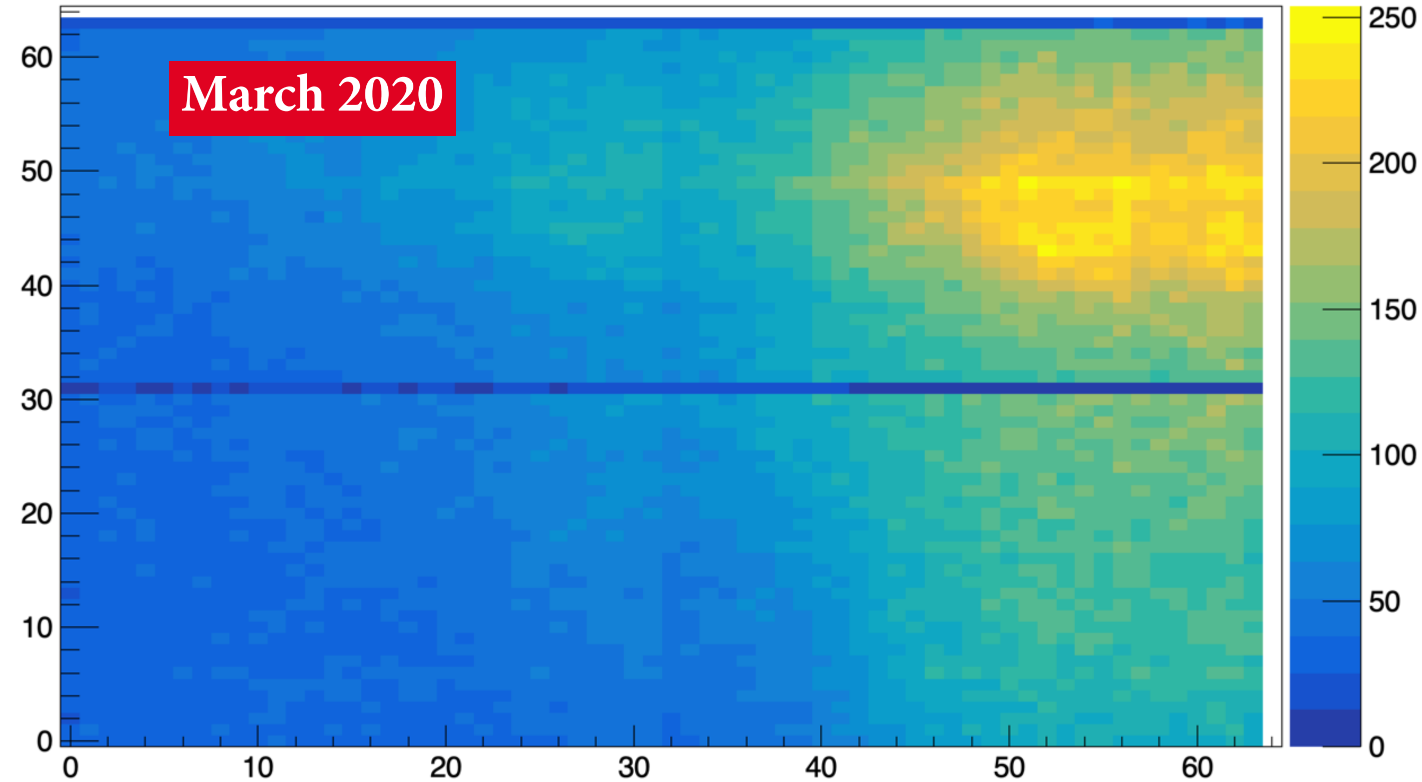
- Detectors are constructed from planes of cells, alternately oriented vertical and horizontally perpendicular to the beam direction.
- Filled with liquid scintillator and instrumented with wavelength-shifting fibers.
- Scintillation light is read out by photodiodes.
  - Different front-end electronics are used at the Far Detector and Near Detector.
  - Test Beam detector uses both types.

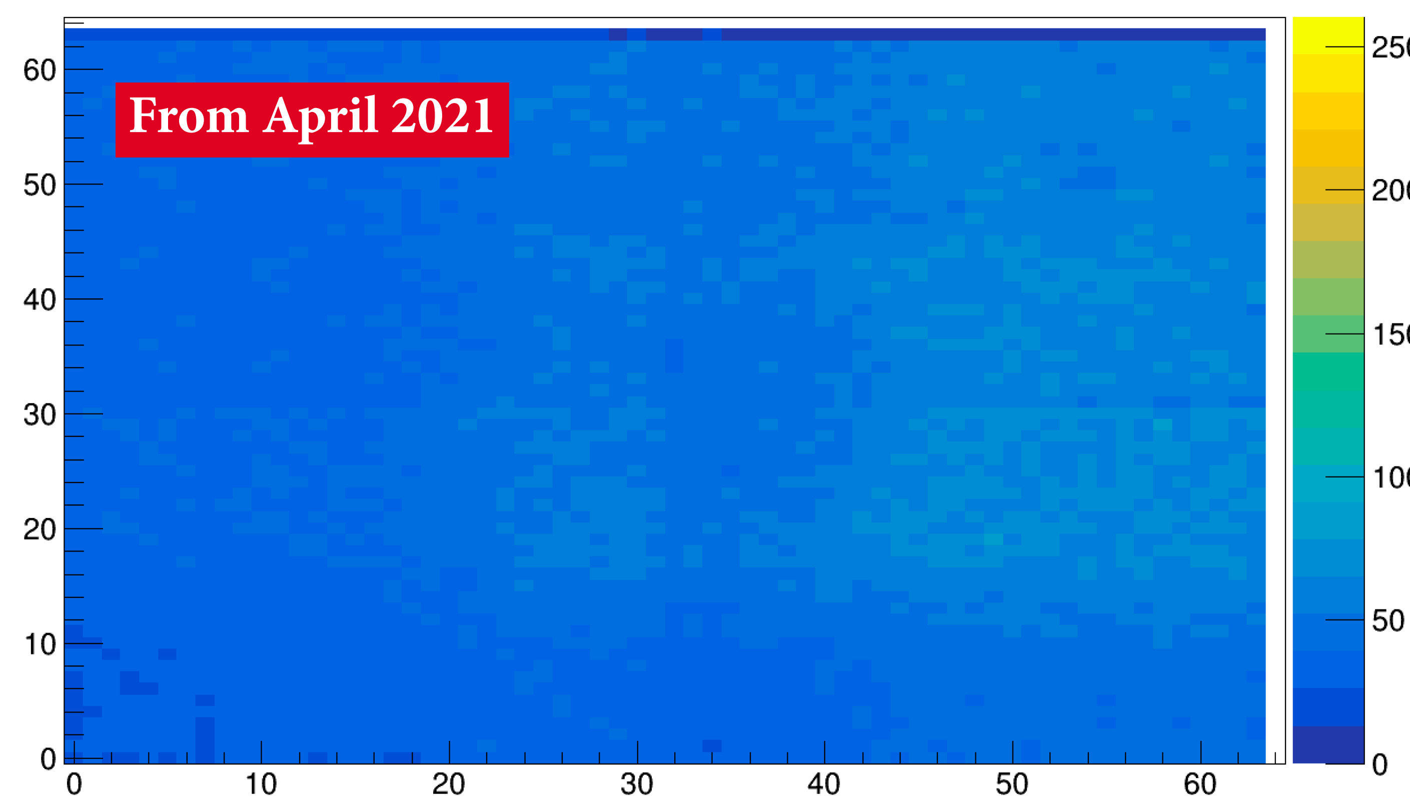


Beam Improvements

Beam profile on NOvA front face, looking upstream

- Improved understanding of our beamline over the course of our three years of operations has significantly improved our data quality and quantity.
- Significant beam-related backgrounds removed by large amount of shielding.
  - Installed in December 2020 and removed the high intensity region shown in the top plot.
- Fine tuning of our very long beamline, as upstream as the trajectory of the primary protons, enabled us to set the optimal beam configuration with maximal analysis-quality particle yield.

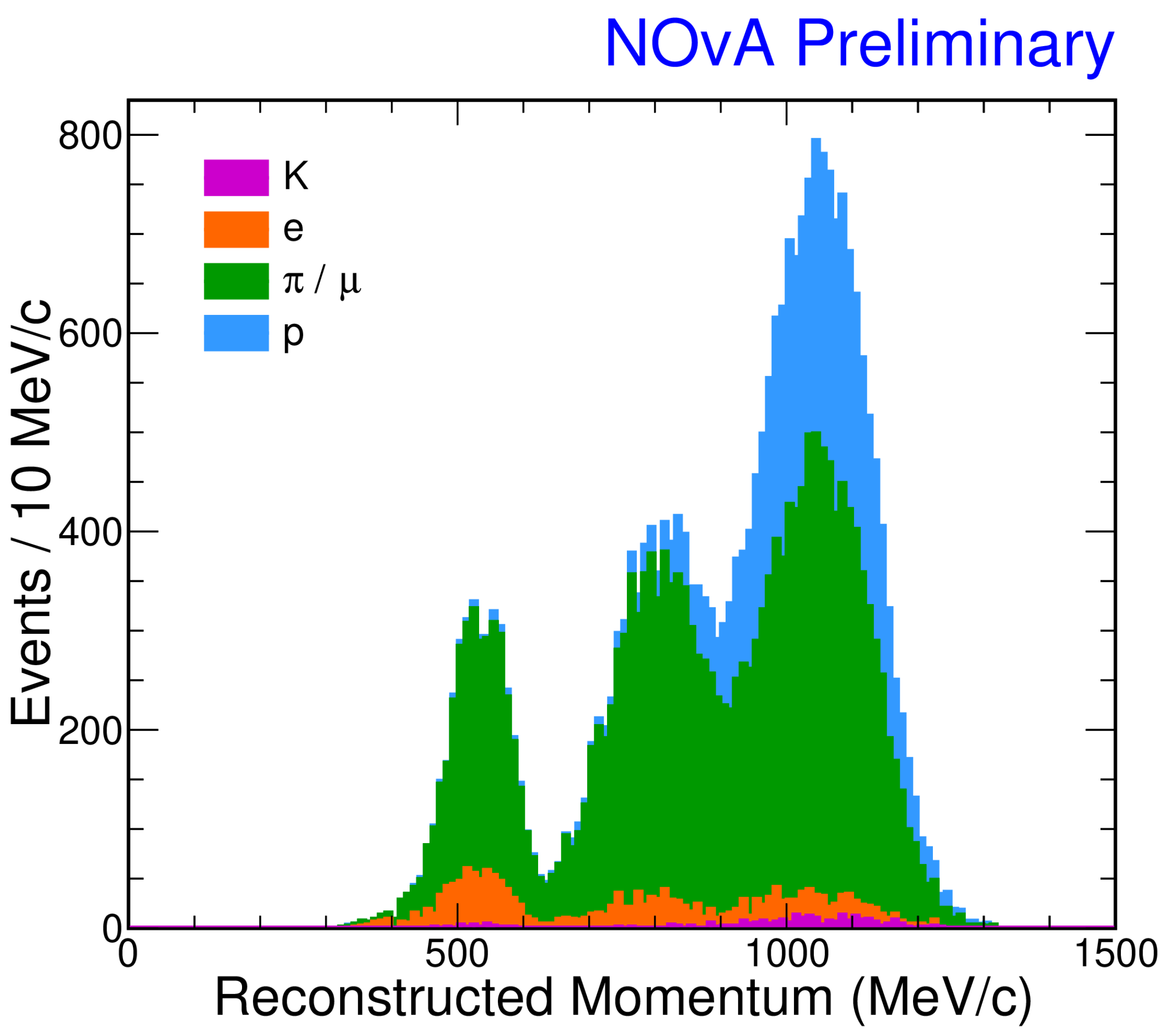


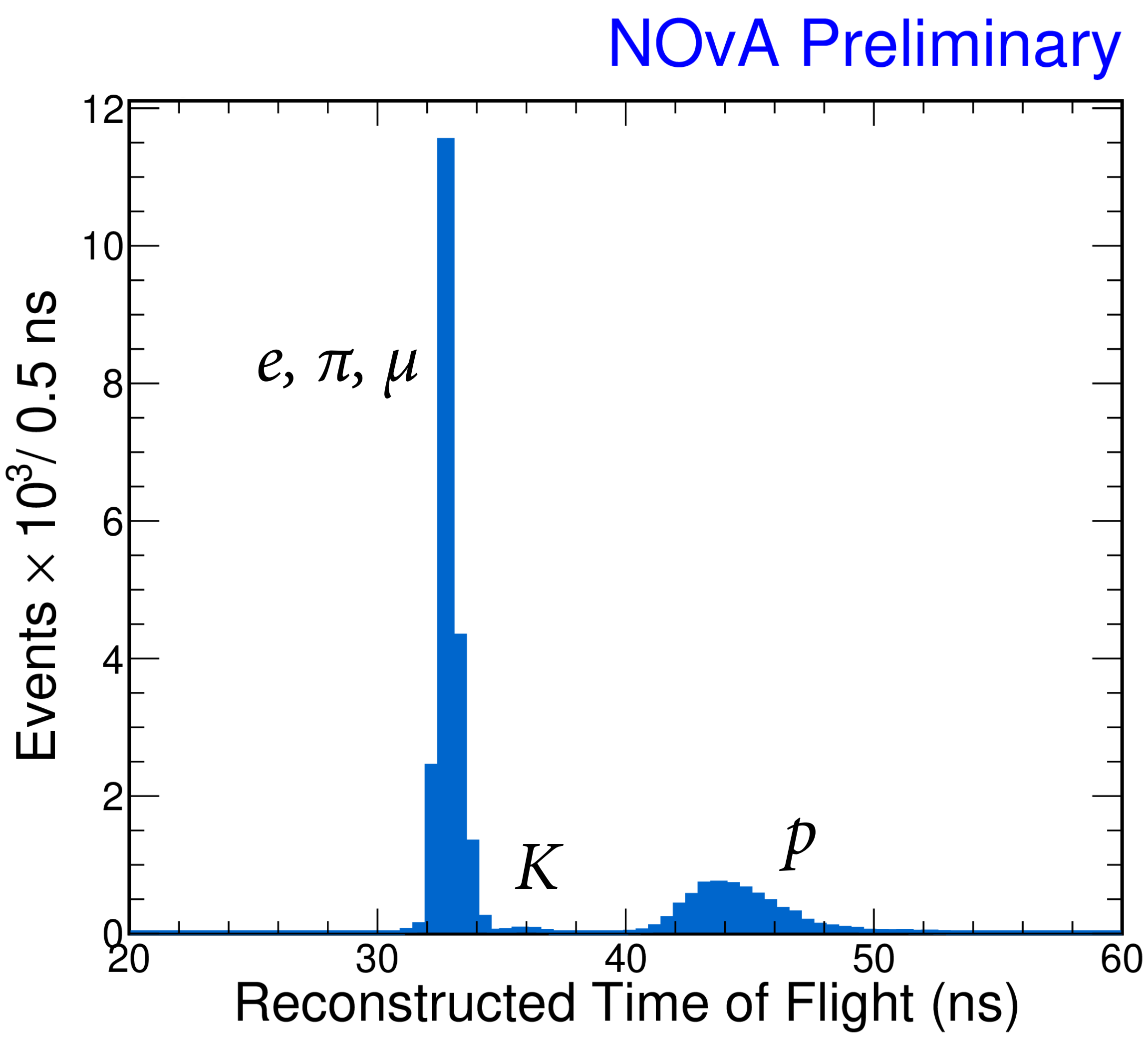


Particle Properties

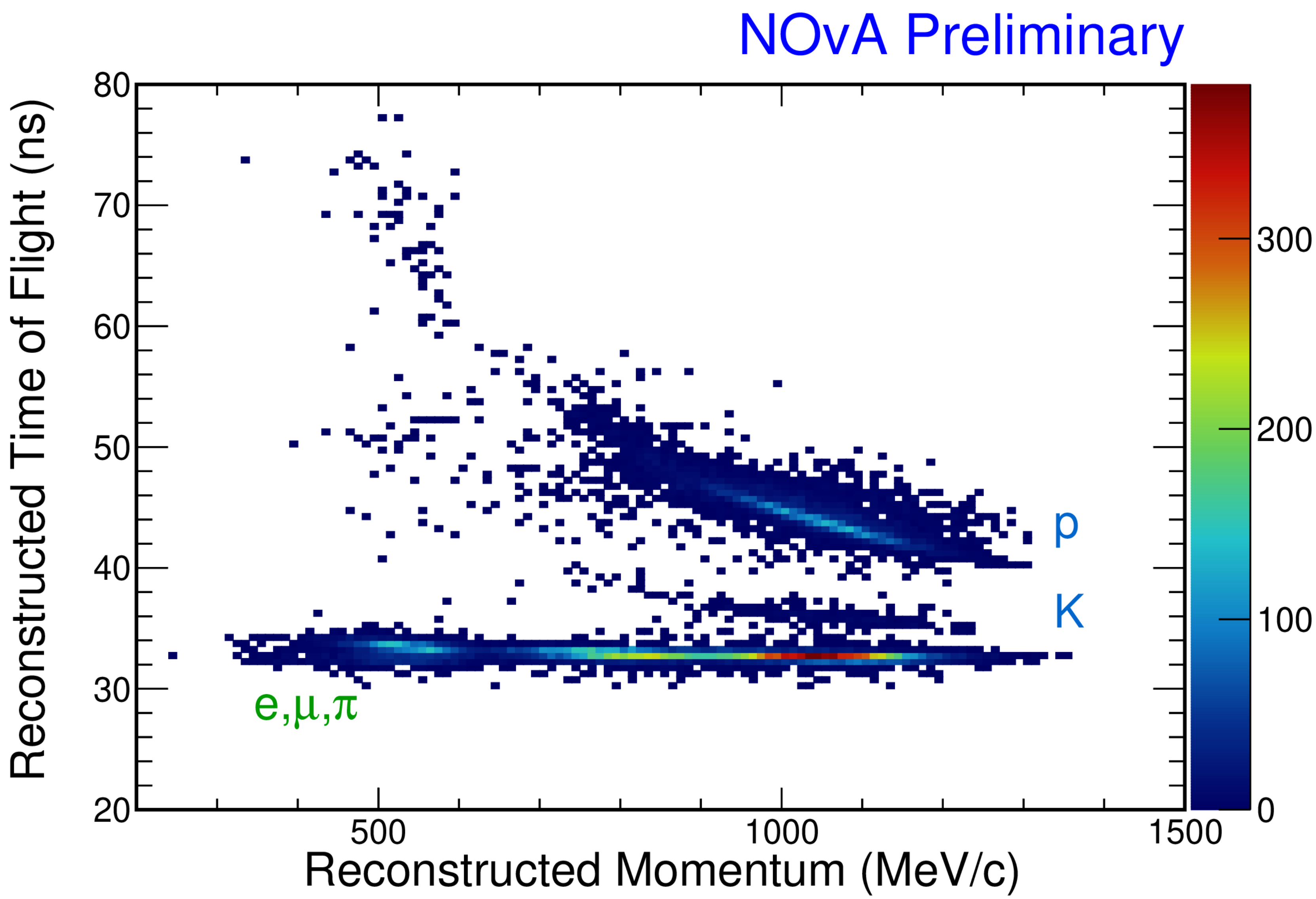
- Data from the 2021 run period using the beamline detectors, showing reconstructed momentum and time-of-flight for tertiary particle candidates.
    - Particles were collected at three different momentum tunes, ~0.5, ~0.75 and ~1.0 GeV/c.

- Analysis of 2022 data underway; included additional running configuration at ~1.25 GeV/c.



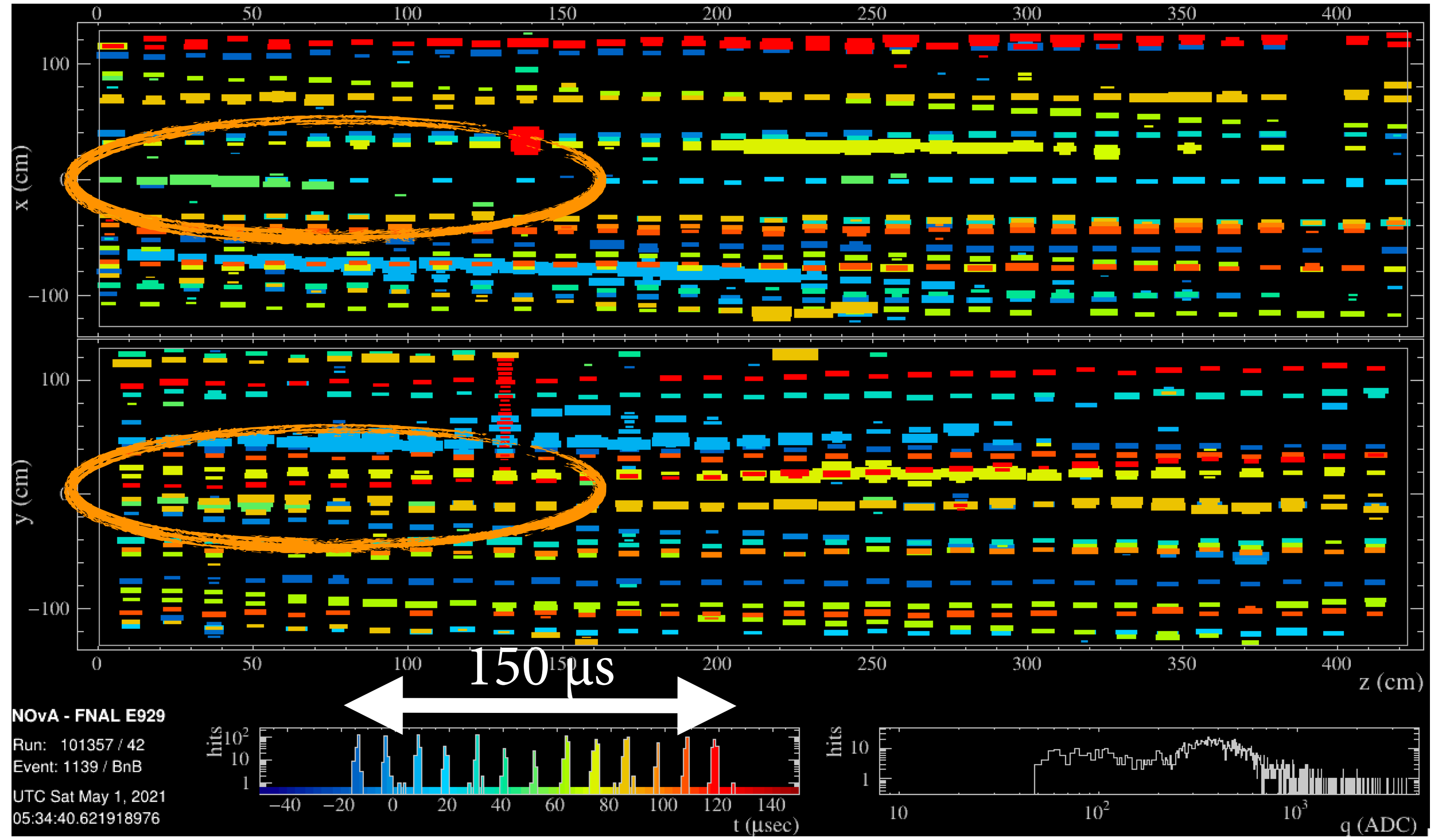


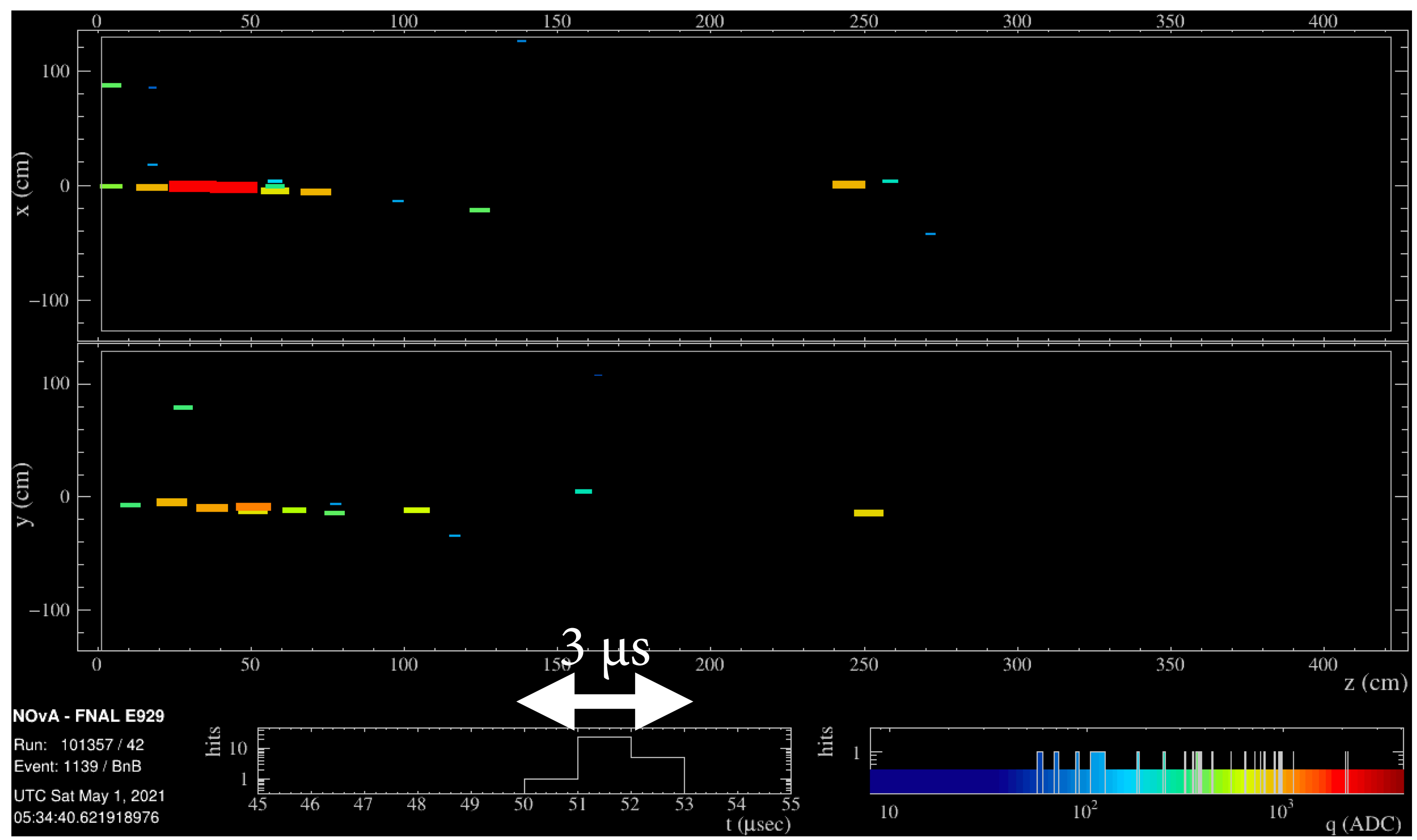
Particle Identification



- Combining information on momentum and time-of-flight gives a handle on particle mass, and therefore particle identification.
  - Light particles are difficult to distinguish with the beamline; the electrons are tagged with the threshold Cherenkov detector.

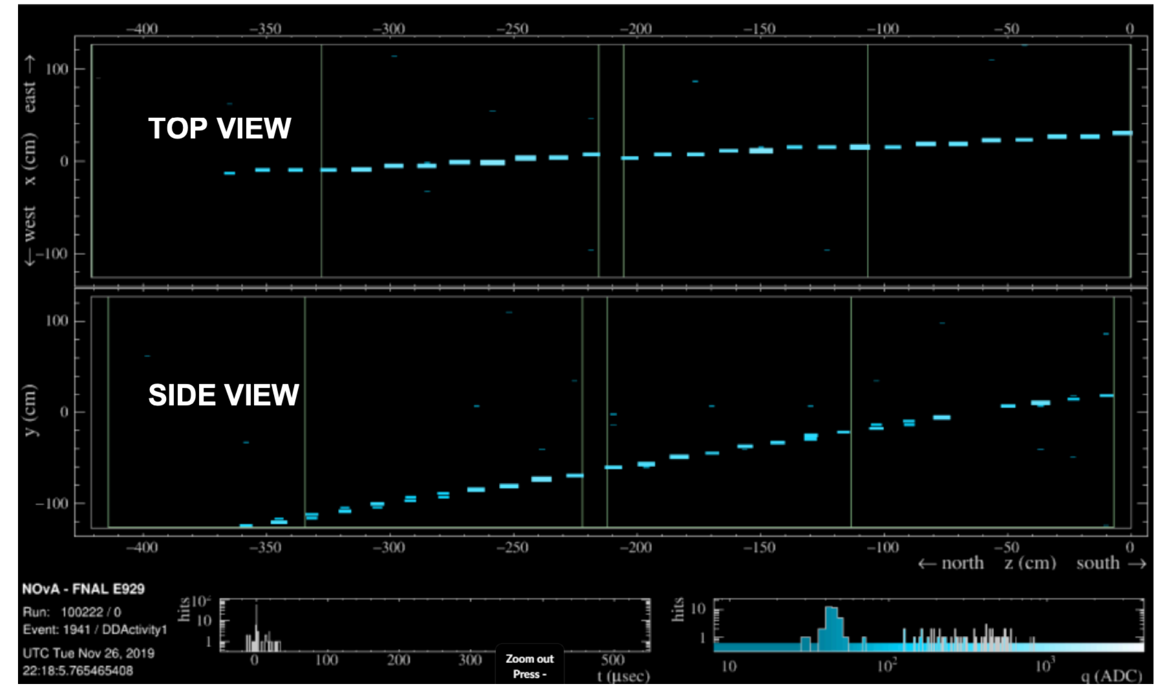
NOvA Detector



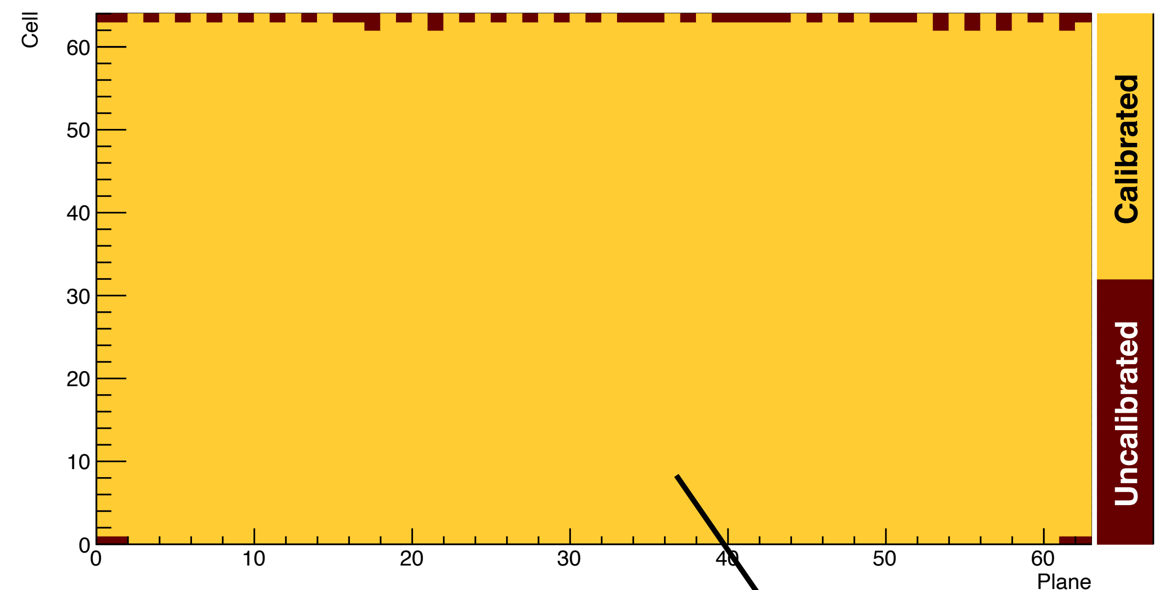


- Collect data in a 100-150 μs time window whenever a tertiary beam particle triggers the detectors in the beamline.
- The nanosecond-level timing resolution of the NOvA detector enables precise reconstruction of the particle of interest.

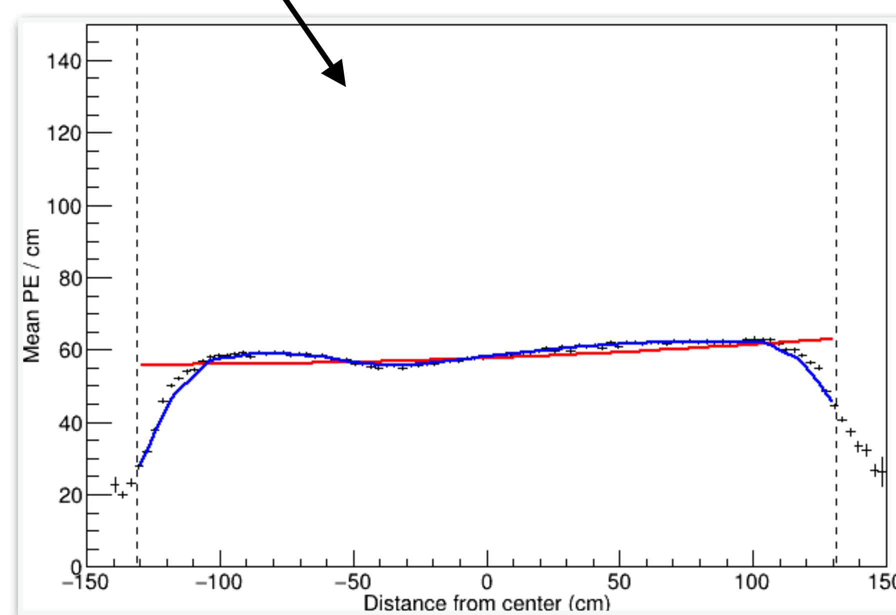
NOvA Detector Calibration



- Detector calibration uses the same technique as the NOvA neutrino detectors.
  - One of the analysis procedures which will be cross-checked by the Test Beam program.



- Uses both through-going and stopping cosmic muons to set both the relative cell-to-cell and the absolute energy scale.

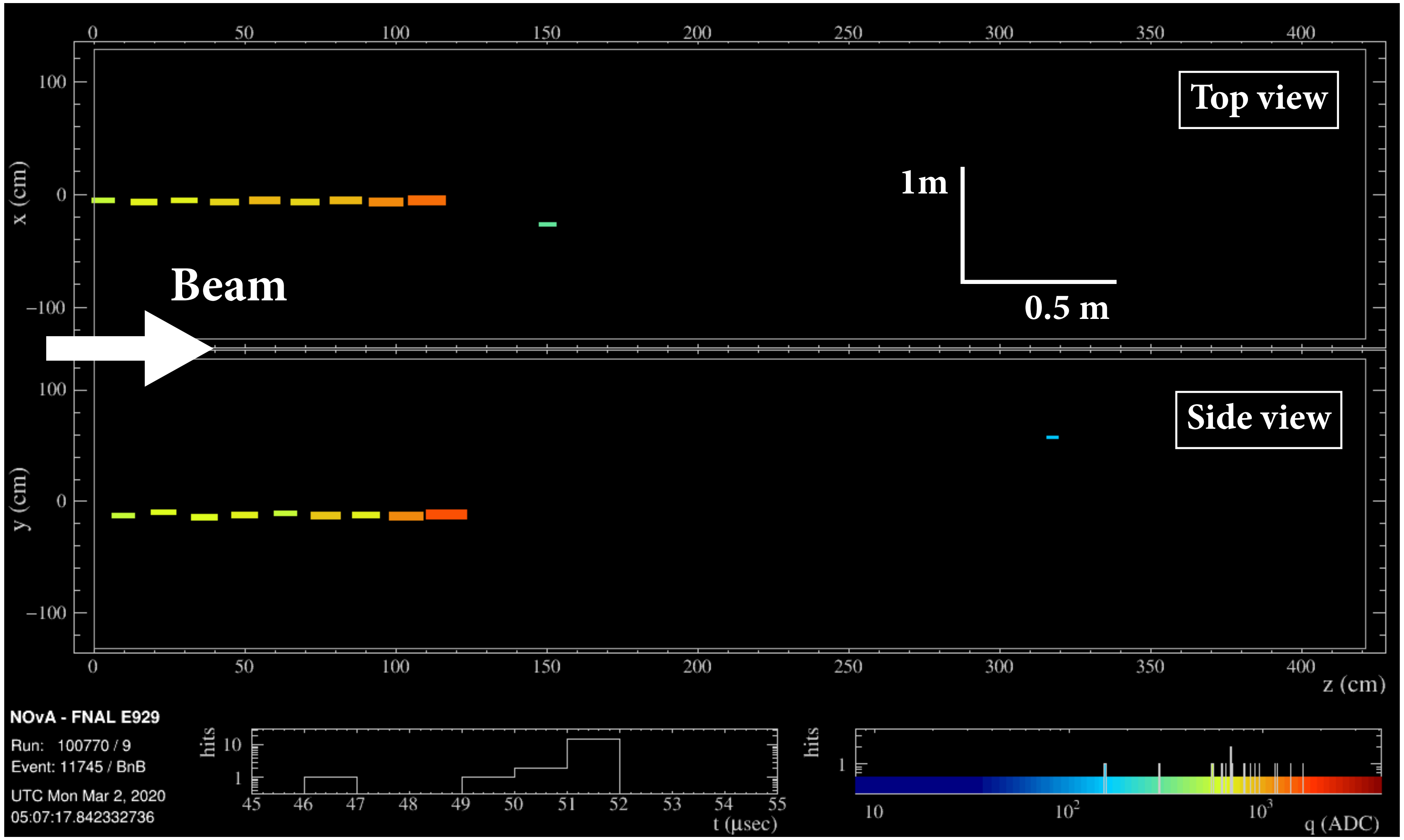


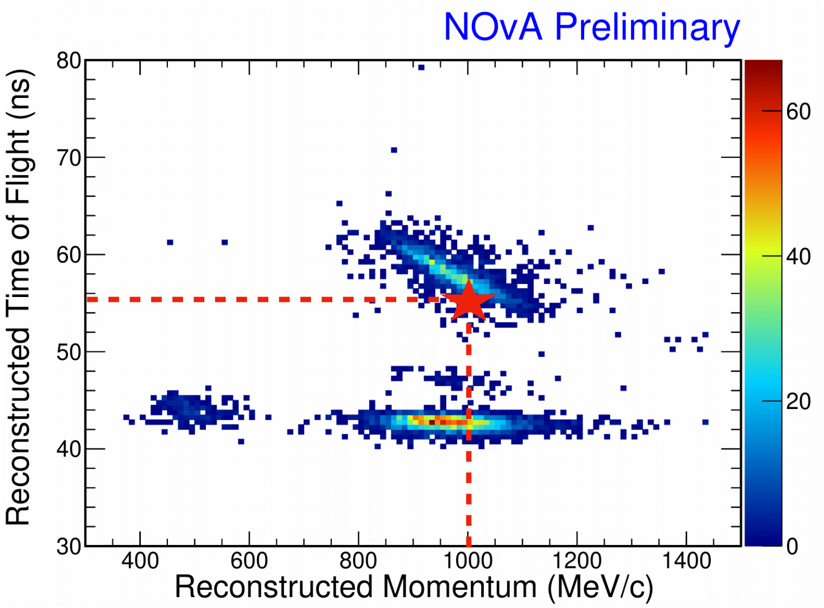
- Simulated muons sampled from similar distributions used to provide corresponding calibration of modeled detector response.

See R Králik's Neutrino 2022 poster

Particle Candidates

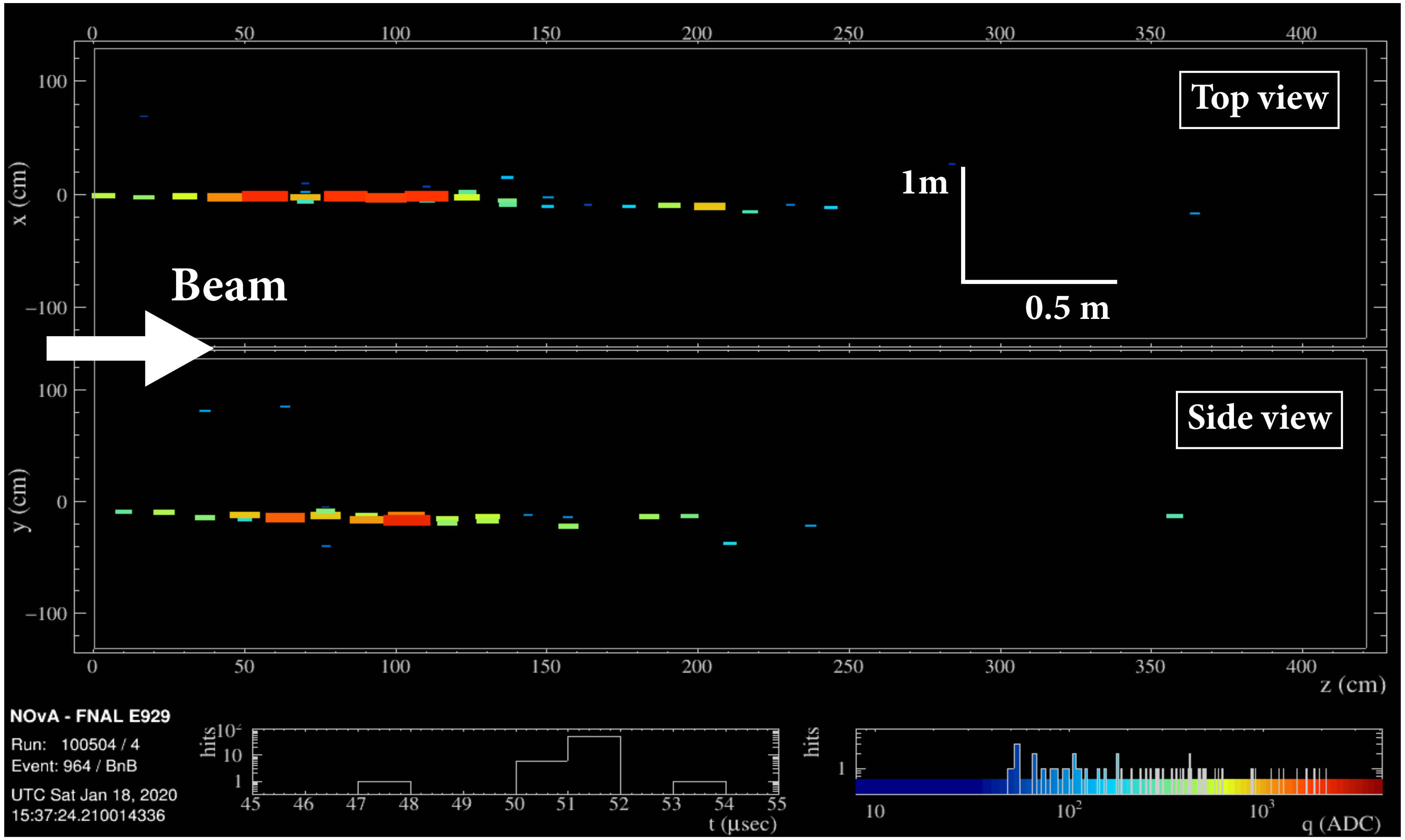
- **Proton candidate** (2020 data) matched to event in NOvA detector.
  - Reconstructed **Time-of-Flight: 55.7 ns**.
  - Reconstructed **momentum: 1.0 GeV/c**.
  - **No signal** from Cherenkov counter.

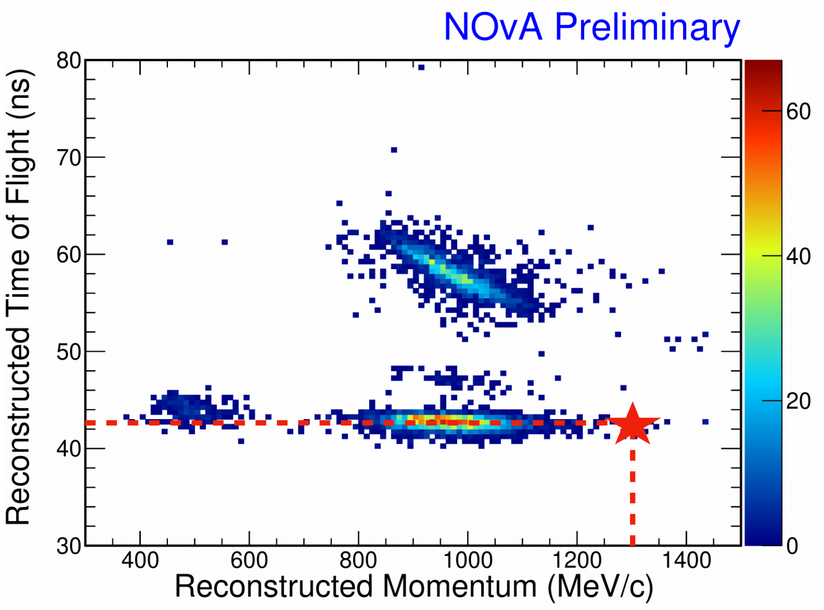




Particle Candidates

- **Electron candidate** (2020 data) matched to event in NOvA detector.
  - Reconstructed **Time-of-Flight: 42.7 ns**.
  - Reconstructed **momentum: 1.3 GeV/c**.
  - **Signal** detected from Cherenkov counter.





Datasets for Analysis

- Estimated total analysis-quality particles accumulated during physics data-taking.
  - Particles pass a data quality and particle identification selection comprising cuts from the beamline and the NOvA detectors.
- Particles collected at various momenta and both charges (see next slide).
- Dedicated analysis working group actively working on studying these data, with results expected in the coming year.
  - Aiming to incorporate improved understanding of NOvA detectors and physics into future neutrino analyses.

Preliminary	**Total**
Protons	**9003**
Electons	**2252**
Kaon	**363**
Pions/Muons	**22357**
Total	**33975**

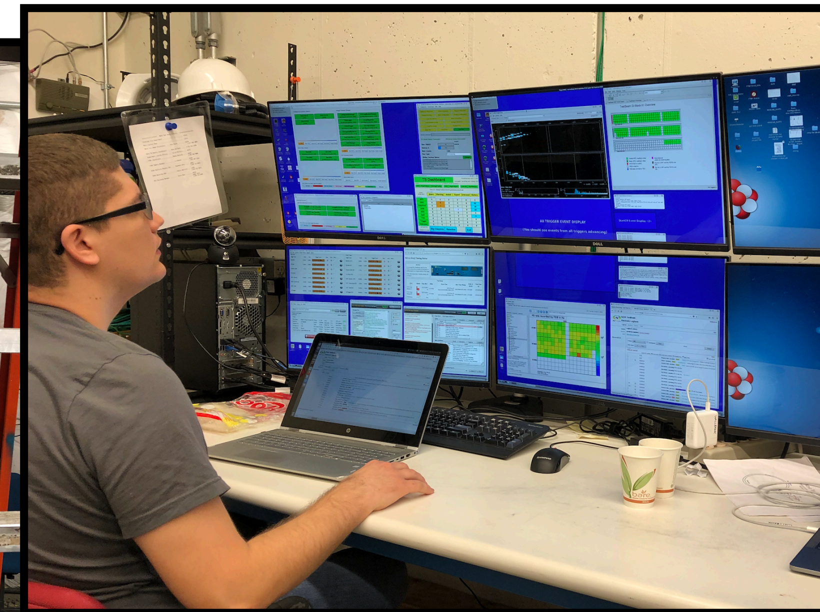
Datasets for Analysis

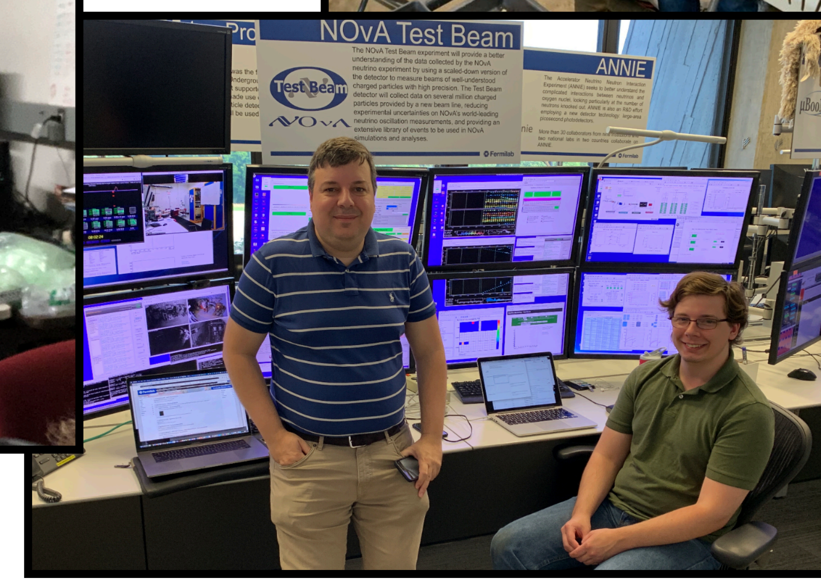
Preliminary		~0.5 GeV/c	~0.75 GeV/c	~1.0 GeV/c	~1.25 GeV/c	Total	
Protons	Positive	67	589	7544	784	8984	**9003**
	Negative	4	8	4	3	19	
Electons	Positive	578	332	545	44	1499	**2252**
	Negative	313	297	115	28	753	
Kaon	Positive	14	27	216	81	338	**363**
	Negative	4	5	11	5	25	
Pions/ Muons	Positive	2545	3184	10058	793	16580	**22357**
	Negative	814	2740	1605	618	5777	
Total	Positive	**3204**	**4132**	**18363**	**1702**	**27401**	**33975**
	Negative	**1135**	**3050**	**1735**	**654**	**6574**	

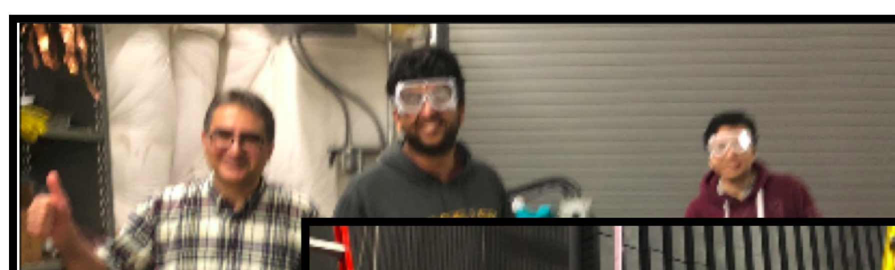
Summary & Future Plans

- Tertiary beamline and NOvA detector installed, commissioned and operated at Fermilab Test Beam Facility.
- Commissioned beam and detector in Summer 2019, and consistently improved operating conditions and particle rates in the subsequent three years of data taking.
- Dedicated a significant amount of time on the project understanding the behavior of the beam and implementing improvements to optimize running conditions for NOvA Test Beam.
- Collected analysis-quality data December 2019 — July 2022, with at over a year in our most optimal operating conditions.
- Decommissioning commenced a couple of weeks ago following the culmination of the physics run.
- Focus is now on the maturing data analyses, with a view to improving understanding of the NOvA detectors and incorporating improvements into the calibration, reconstruction and analyses.

Thanks!



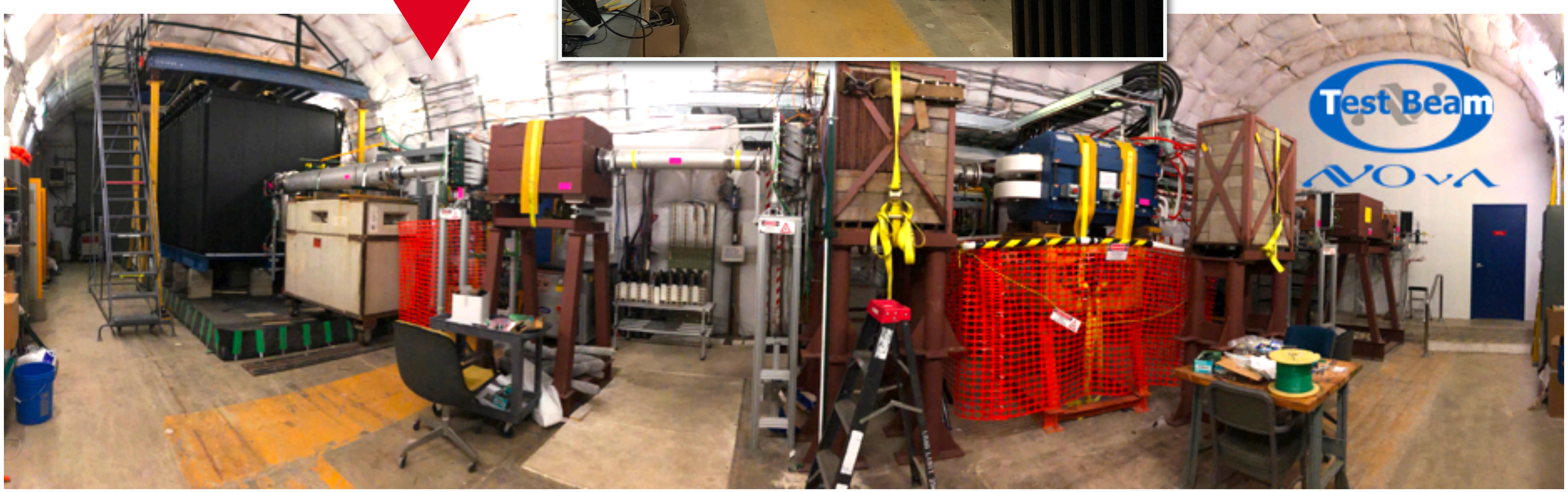




Back-Ups

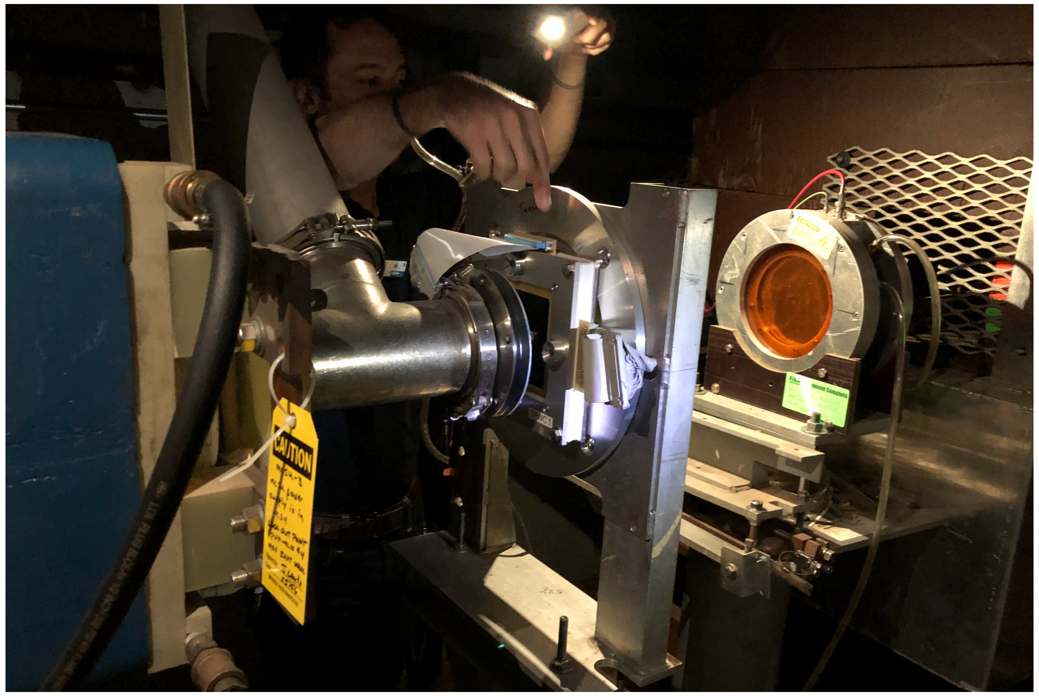
Building A Test Beam Experiment!

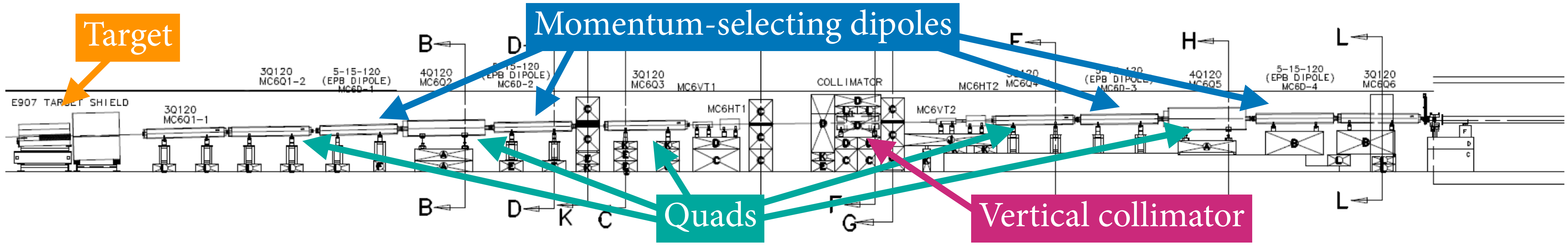
Early 2018



MCenter Secondary Beam

- A secondary beam, mostly protons and pions, is created by smashing the 120 GeV protons into a 'primary' target, ~120m upstream of NOvA.
- The beamline is directed upwards and then leveled out, allowing the momentum of the particles to be selected using dipole magnets and a vertical collimator; typically use 64 GeV/c.





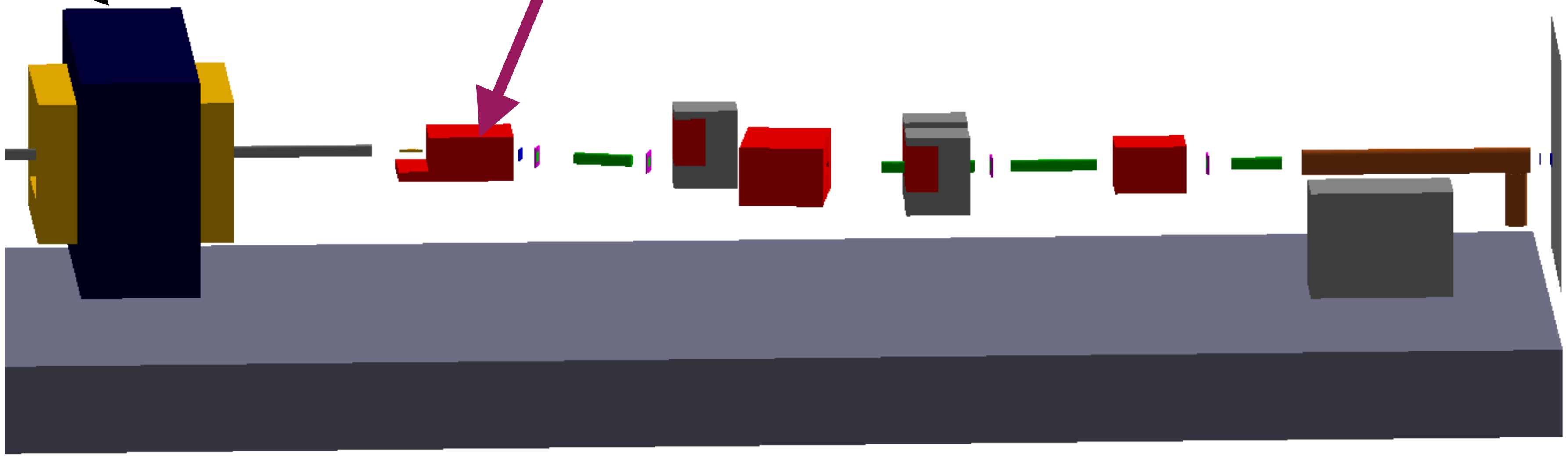
MCenter Tertiary Beam

- The 64 GeV protons/pions hit a second target in MC7, ~14m upstream of the NOvA detector.
  - The interactions in the target produce tertiary beam particles of lower momentum.

- During a 4.2s beam spill, ~O(10^6) particles hit the NOvA target.

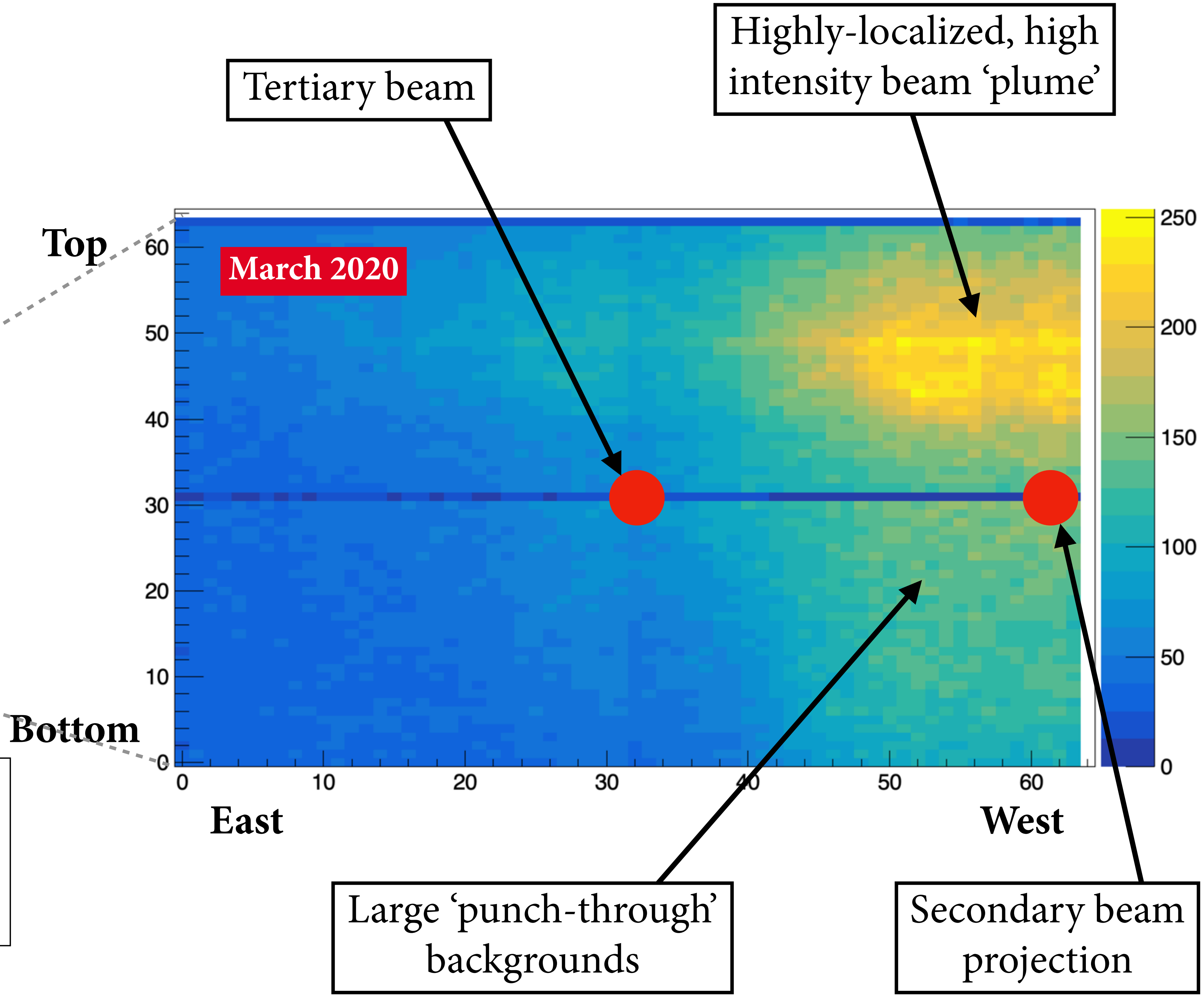
Target

ROSIE magnet



G4beamline model of tertiary beamline

MCenter Beam Characteristics

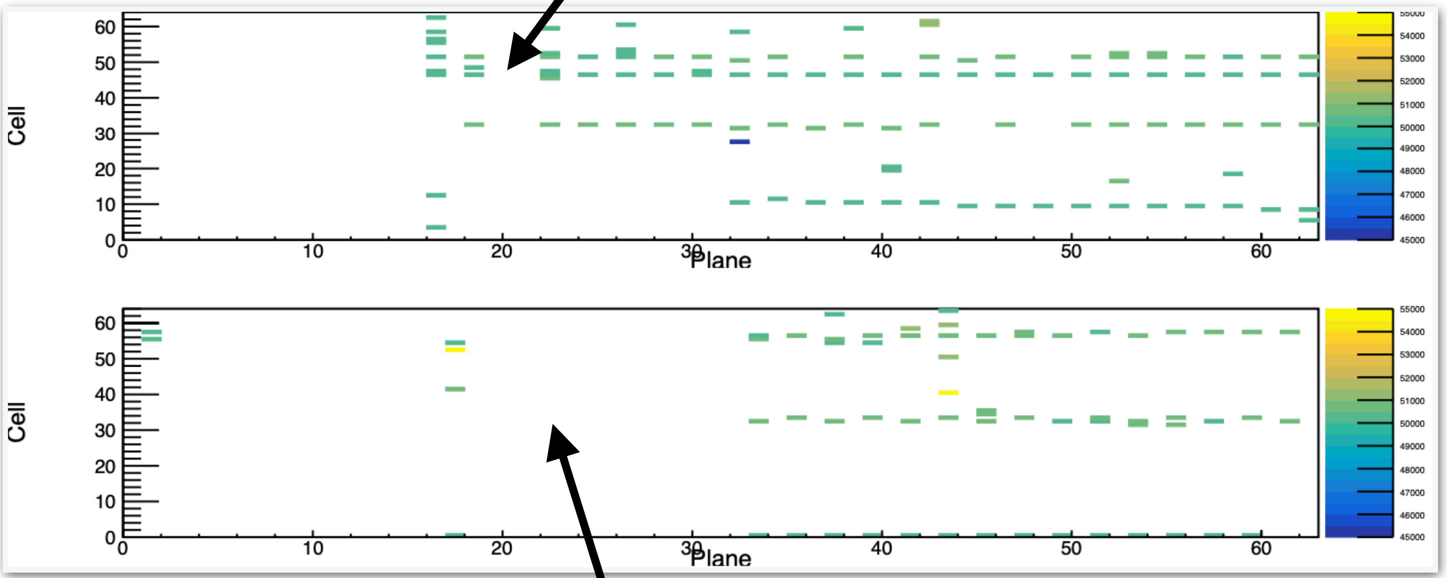


Profile of hits on the front face of the NOvA detector, looking upstream

MCenter Beam Characteristics

- Large rate of backgrounds, particularly evident as our 'plume' in the Top-West quadrant of the detector, cause significant pile-up and limit our data-taking rate.
    - Although the plume is striking, the overalls background rates (from punch-through, secondary interactions along beamline etc) are high in general.
- Causes saturation of the NOvA front-end electronics, causing missing data.
- NOvA timing is good enough to resolve and separate out background particles, assuming the data are successfully collected.

Saturation of individual front-end board buffers



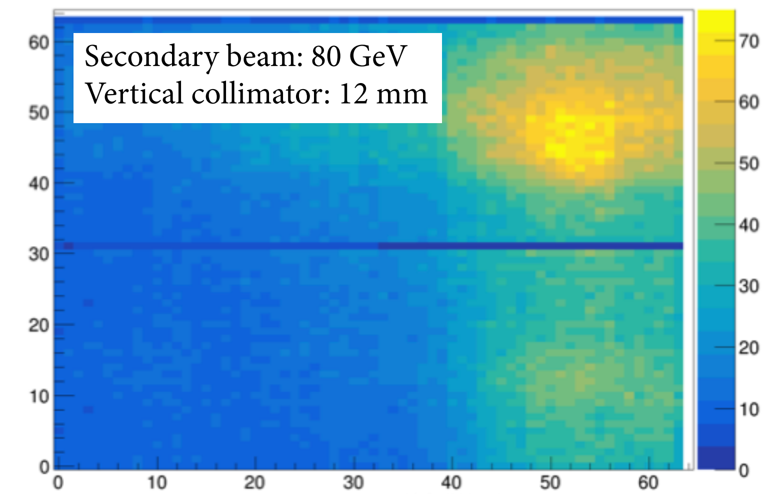
Saturation of buffers aggregating channels across multiple boards

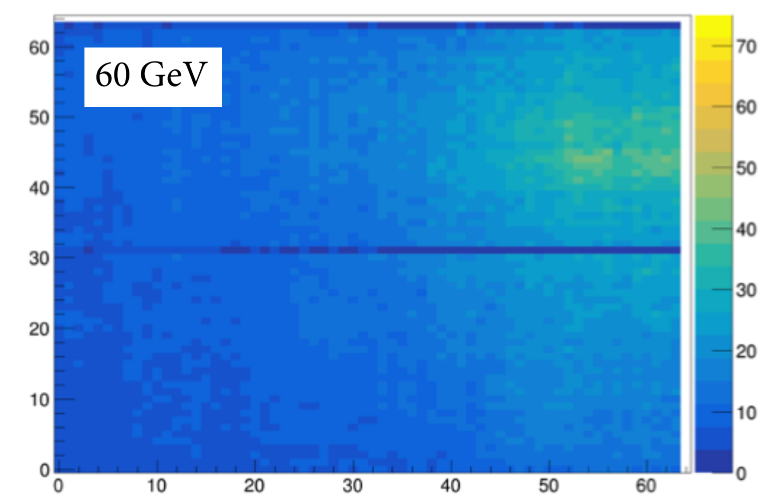
MCenter Beam Studies

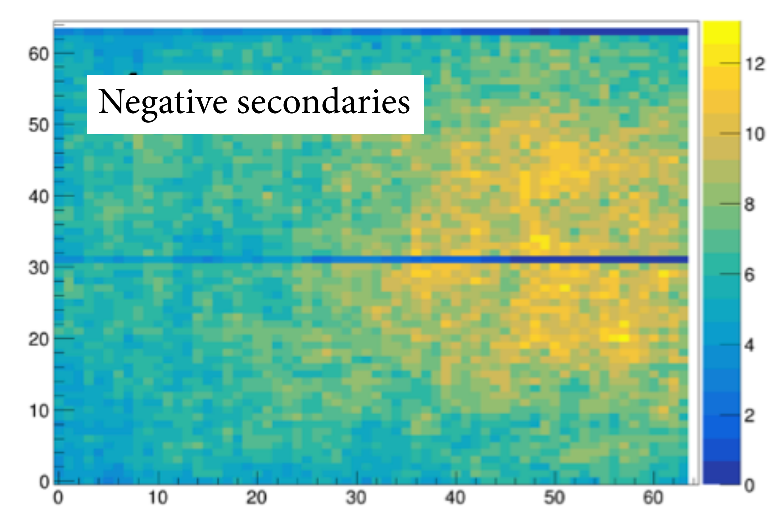
- In 2020, a concerted effort from a collaboration involving NOvA Test Beam, AD External Beams Group and FTFB dedicated a large amount of work to understanding and investigating potential improvements.
    - Huge thanks to Tom Kobilarcik, Adam Watts, Carol Johnstone and all members of the External Beams Group for their dedication to this project!

- A significant number of dedicated beam studies were carried out before the shut-down, to better understand the properties of the beam.

- During the long shut-down, we developed an improved simulation to attempt to reproduce for the first time the plume using a beamline model.
    - The previous simulation contained a simplistic model of magnet apertures and missed most of the material and a full modeling of magnetic fields.



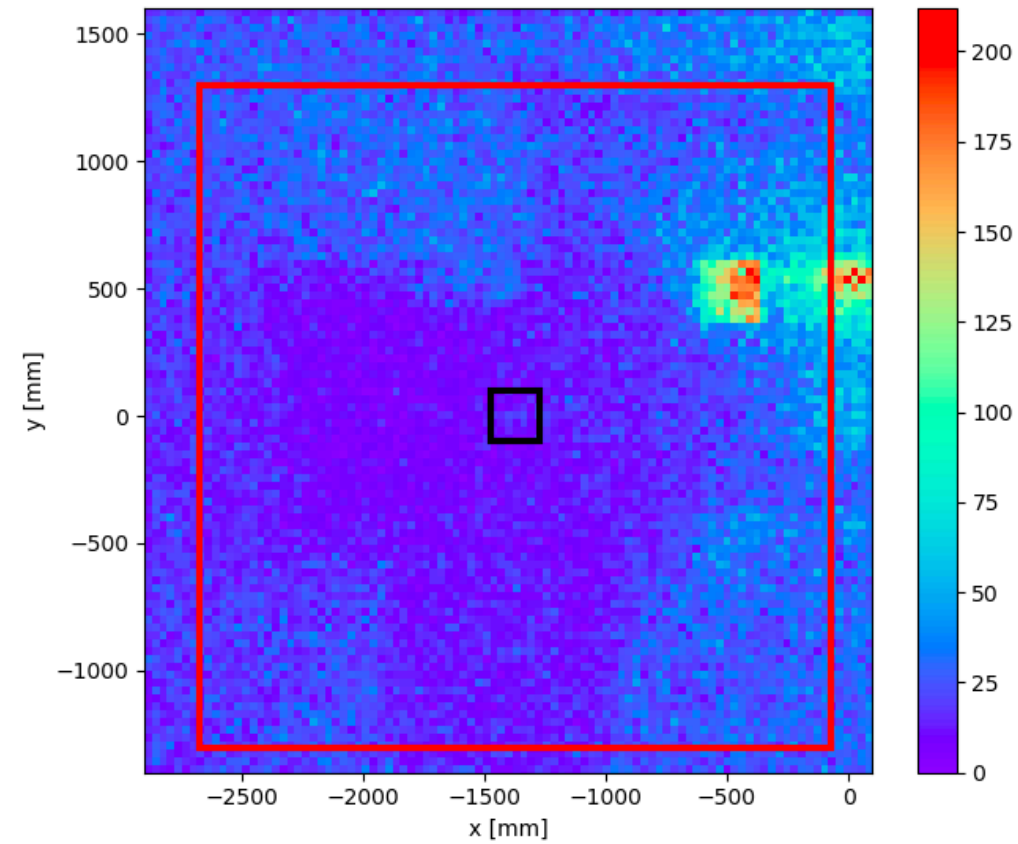




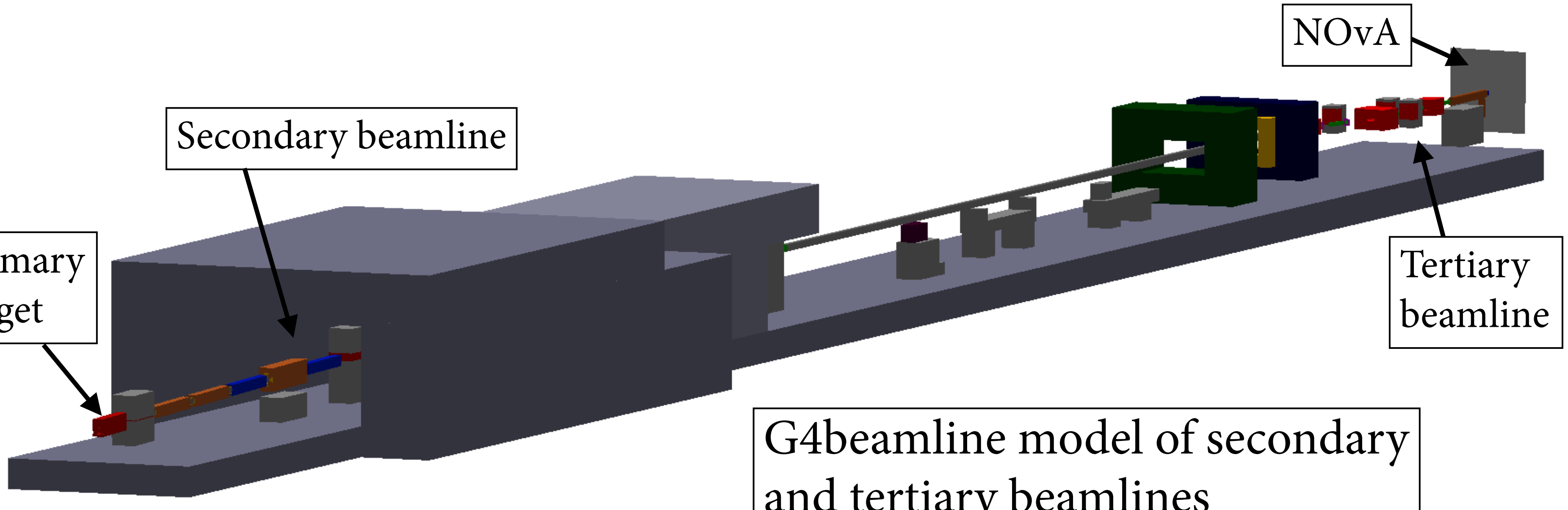
MCenter Simulation

- With the addition of all the material in the beamline, and the full magnetic fields, we were able for the first time to observe simulated plume-like characteristics in the NOvA detector.

- The aim was to qualitatively show this and then utilize the improved simulation to investigate possible mitigations.

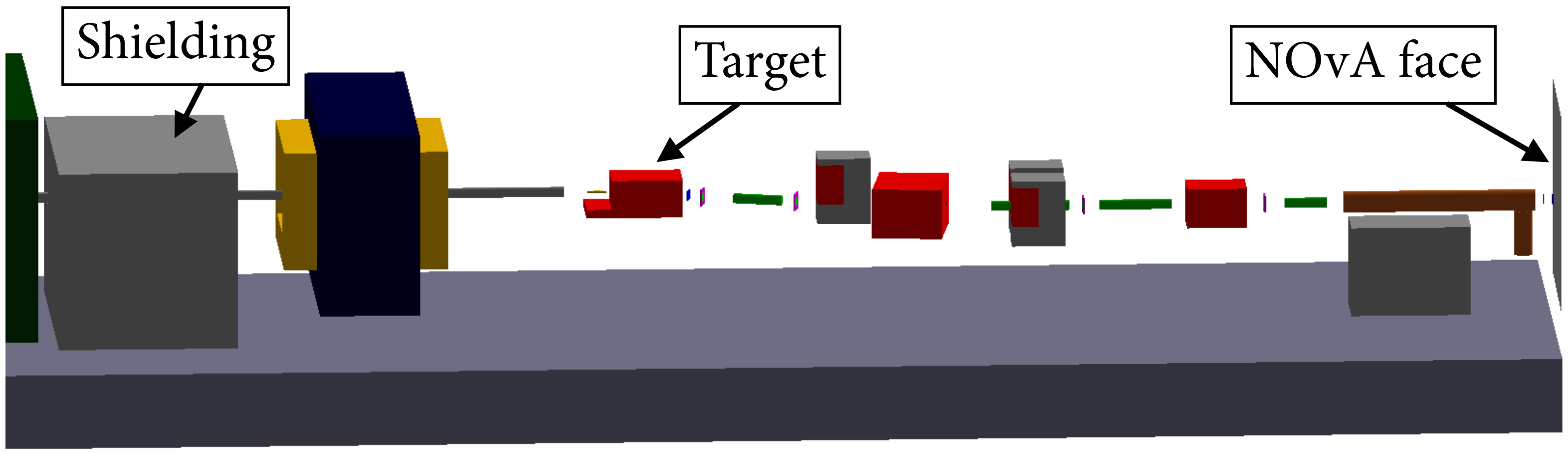


Simulated beam profile on the front face of the detector, showing the concentrated plume in the Top-West corner

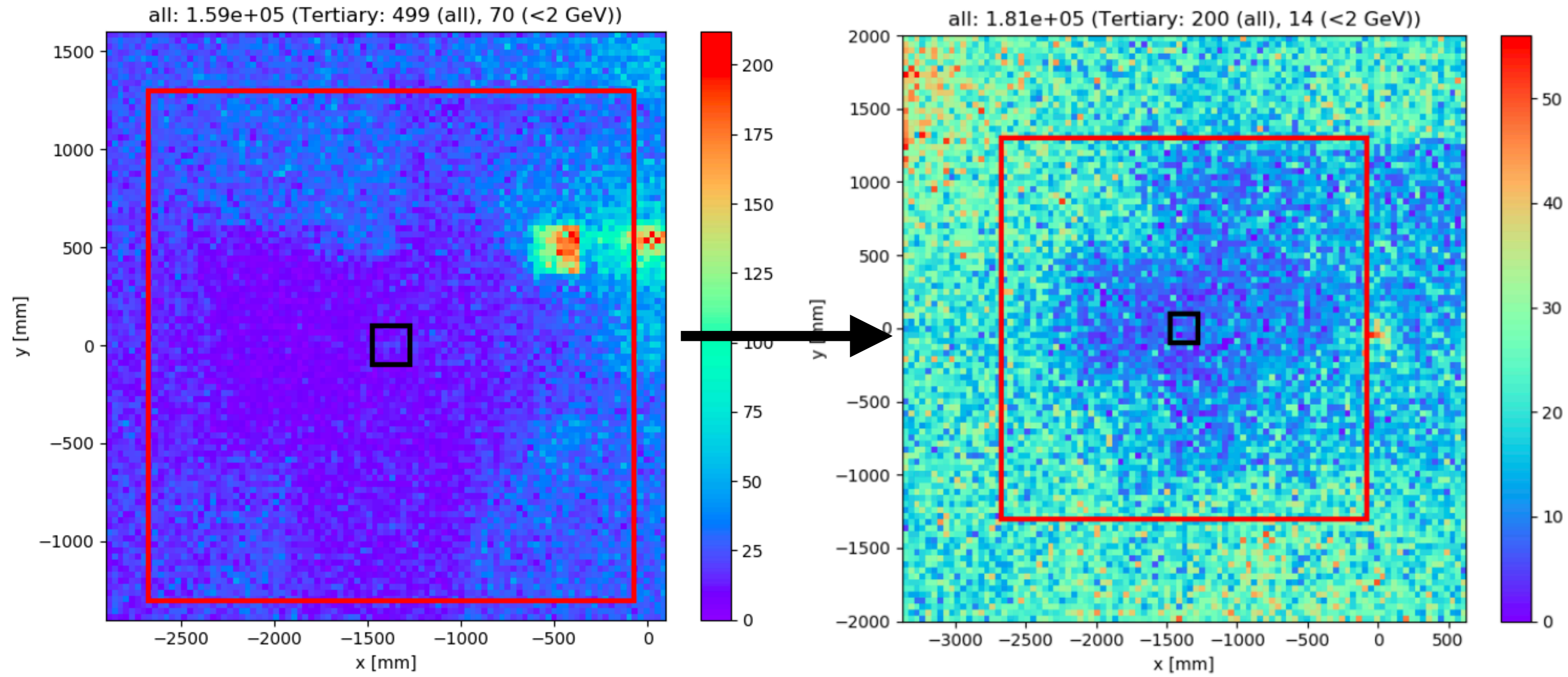


G4beamline model of secondary and tertiary beamlines

MCenter Simulation



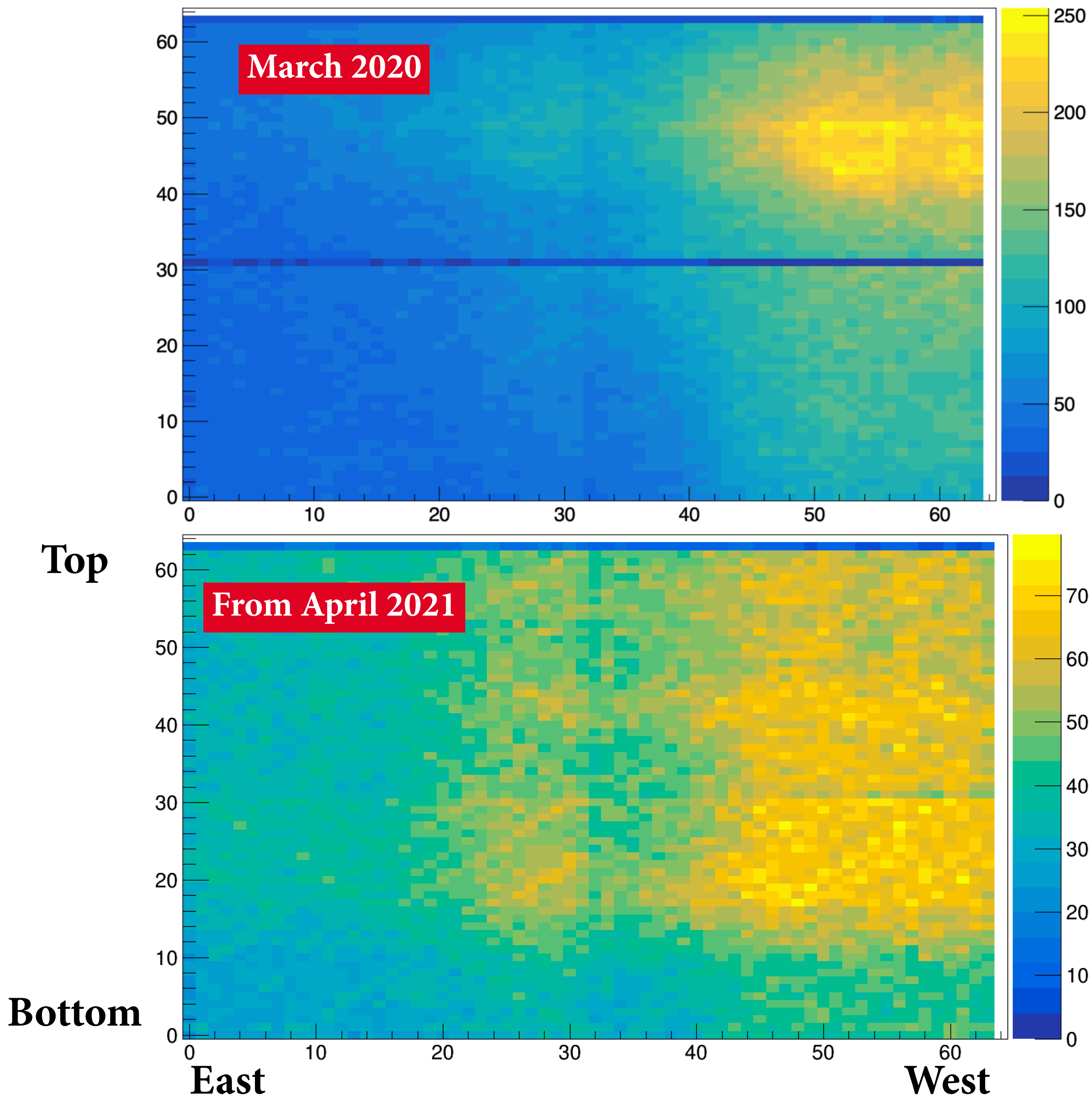
- Found a large amount of shielding was successful in reducing the off-axis backgrounds.
    - Placed just upstream of the NOvA target, since that's where the available space is!



- This was subsequently installed in December 2020 and contributed to a factor of ~5 increase in 2021 data, c.f. 2020.

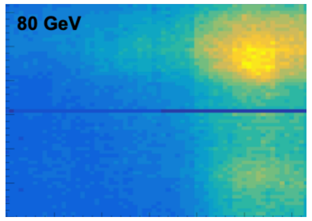
MCenter Shielding

- Note z-axis scale, which is significantly reduced.
- Still a significant amount of background from punch-through etc on the West side, but the plume is reduced (as observed in the simulation).
    - The other backgrounds are then the dominant limitation to our data-taking.



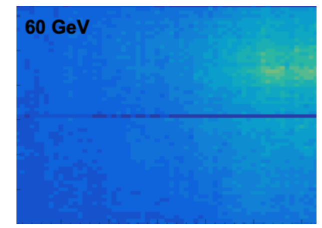
Plume Characteristics

Simulation hints at significant backgrounds made by primary and secondary beam losses, in particular around the collimator

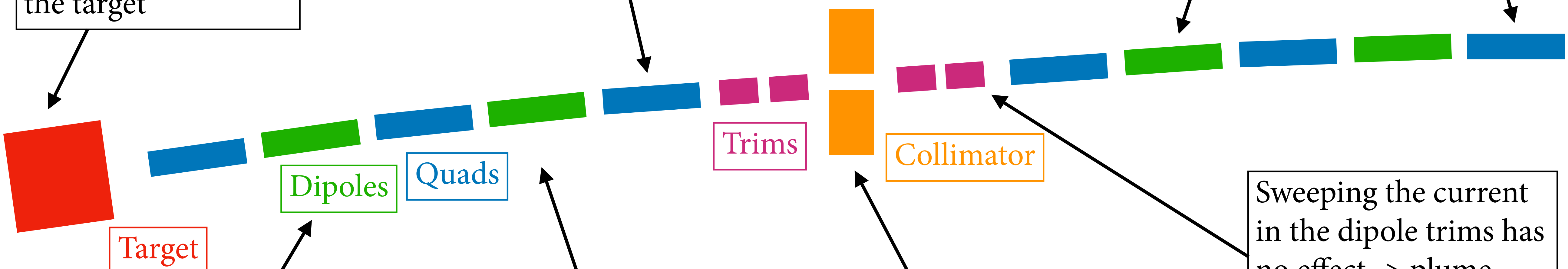


Steering on primary target doesn't affect location -> formed at or downstream of the target

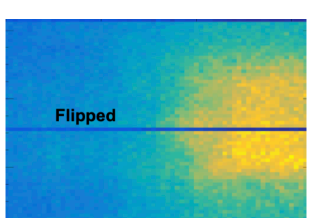
Didn't see the plume in simulation before adding the full magnet fields -> passes through beamline elements



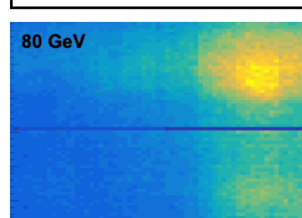
Changing momentum tune affects plume intensity, but not location



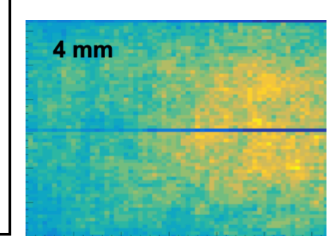
Negative polarity moves the plume -> plume origins from particles passing through dipoles



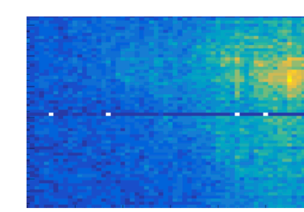
Hits detector above the center -> formed in the upward-directed region



Closing the collimator dissipates the plume



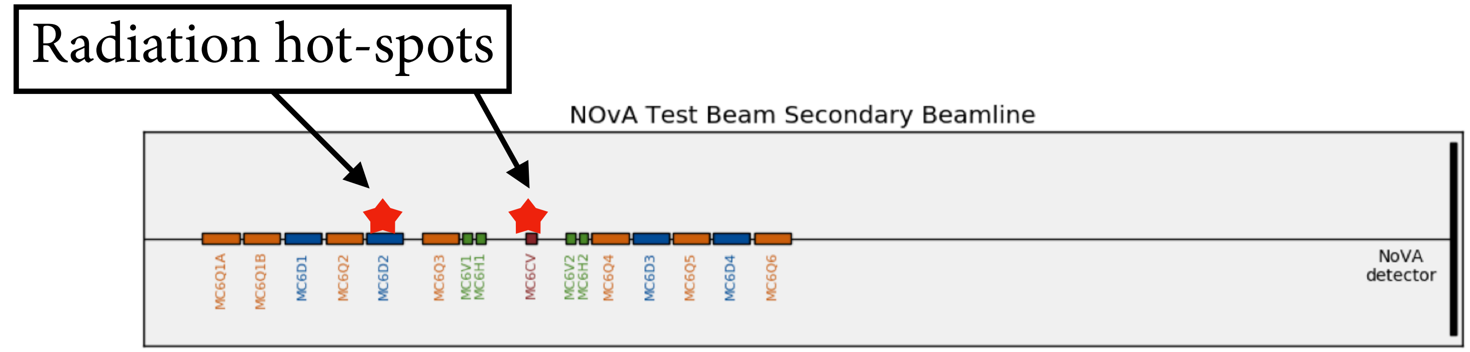
Sweeping the current in the dipole trims has no effect -> plume made upstream

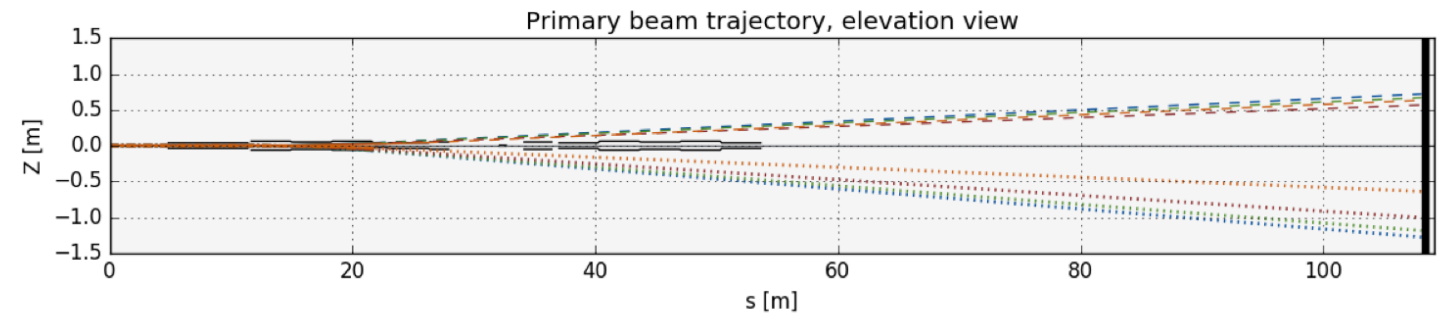


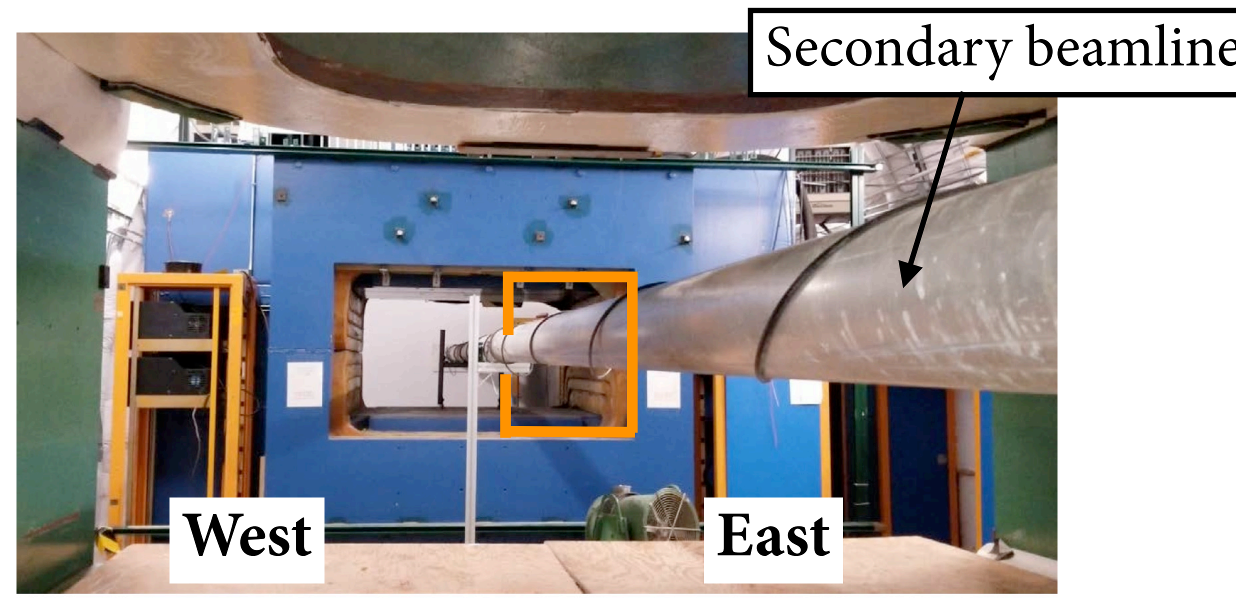
Basic secondary beamline model

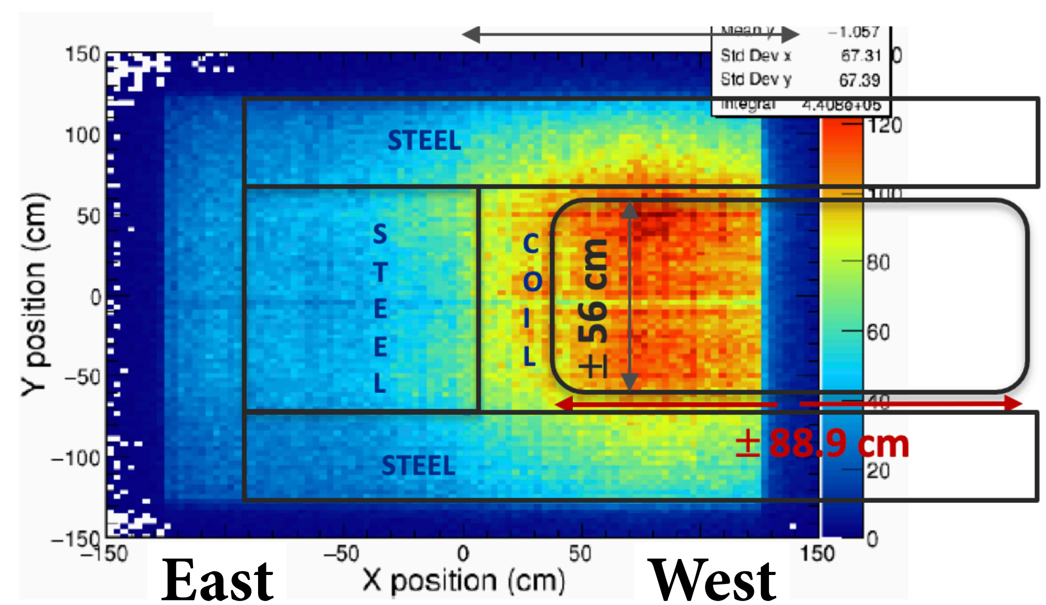
Plume Origins

- Whilst we do not have a fully verified understanding, there is good evidence about its likely origins:
  - Created from multiple-scattered primaries which dump on material in the secondary beamline, likely the momentum-selecting collimator;
  - Produces a relatively collinear beam which is transported on the East (and likely also West) side of the secondary beam;
  - The observed profile at the NOvA detector is shaped by the material in the line, particularly the ROSIE magnet steel.









Mitigating Other Backgrounds

- The major difference in these profiles is the trajectory of the primary beam onto the target.
- The NOvA Test Beam experiment is slightly unique in that reducing backgrounds is the primary way to improve data quality and useful data quantity, even at the expense of on-axis, on-momentum tertiary particles.
  - Any tune which results in fewer backgrounds in the detector is an improvement, and we consistently monitor the backgrounds we observe and feed back into the beam tune during operations.