# Hadron Production Measurements with EMPHATIC

NuFact: September 19, 2024

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(for the EMPHATIC Collaboration)

ILLINOIS TECH

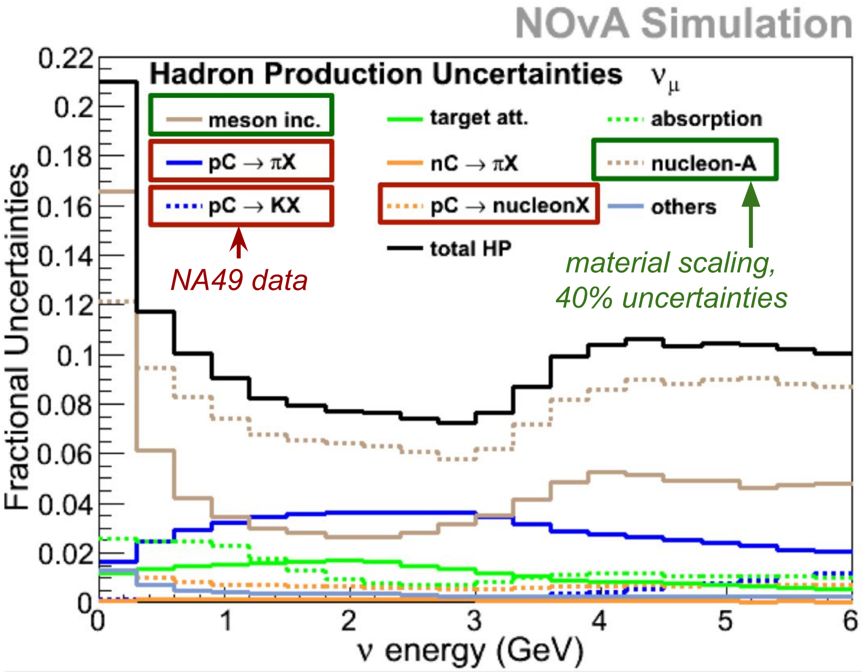
# Neutrino flux uncertainty

-Flux uncertainties for accelerator neutrino measurements are at the level of 10% → leading systematic uncertainty in neutrino measurements

-Dominant uncertainties come from secondary interactions in materials (target, horn, etc.) at low energies→ we assume 40% uncertainties

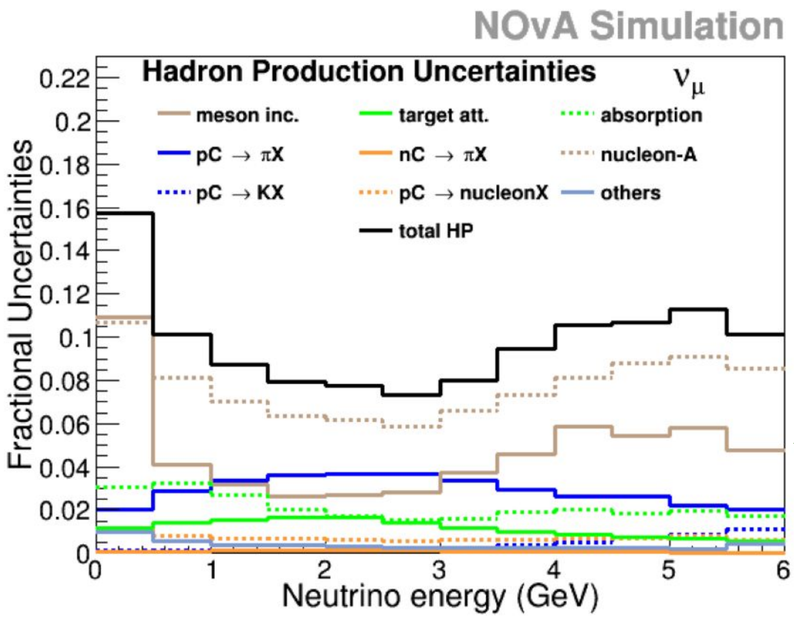
-Impacts baseline predictions for near and far detectors, single-detector measurements, and the neutrino background in BSM searches

-*We need more data to improve our knowledge of hadron production (HP) and improve the flux prediction*

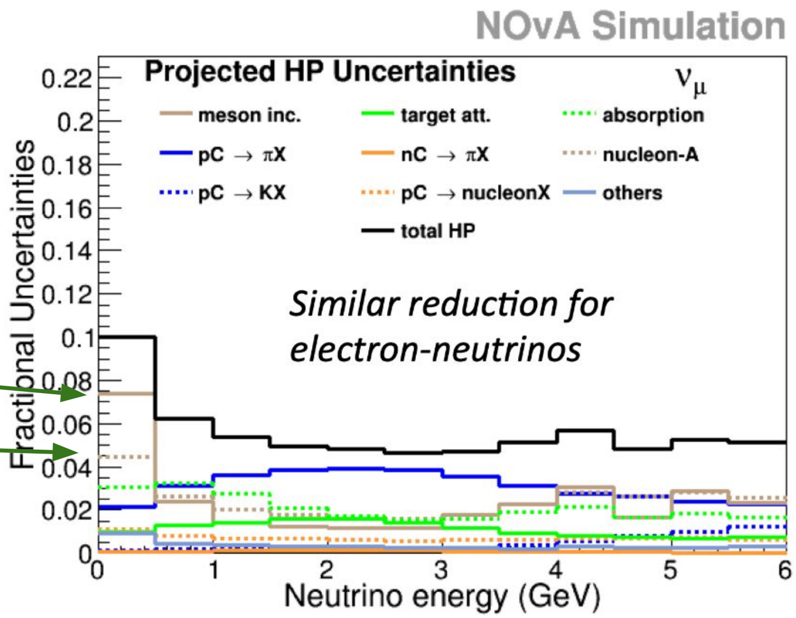



*Phys. Rev. D 94, 092005 (2016)*

# What can we gain from new data?






-New data not only will reduce the uncertainty but will also enhance the robustness of the flux prediction

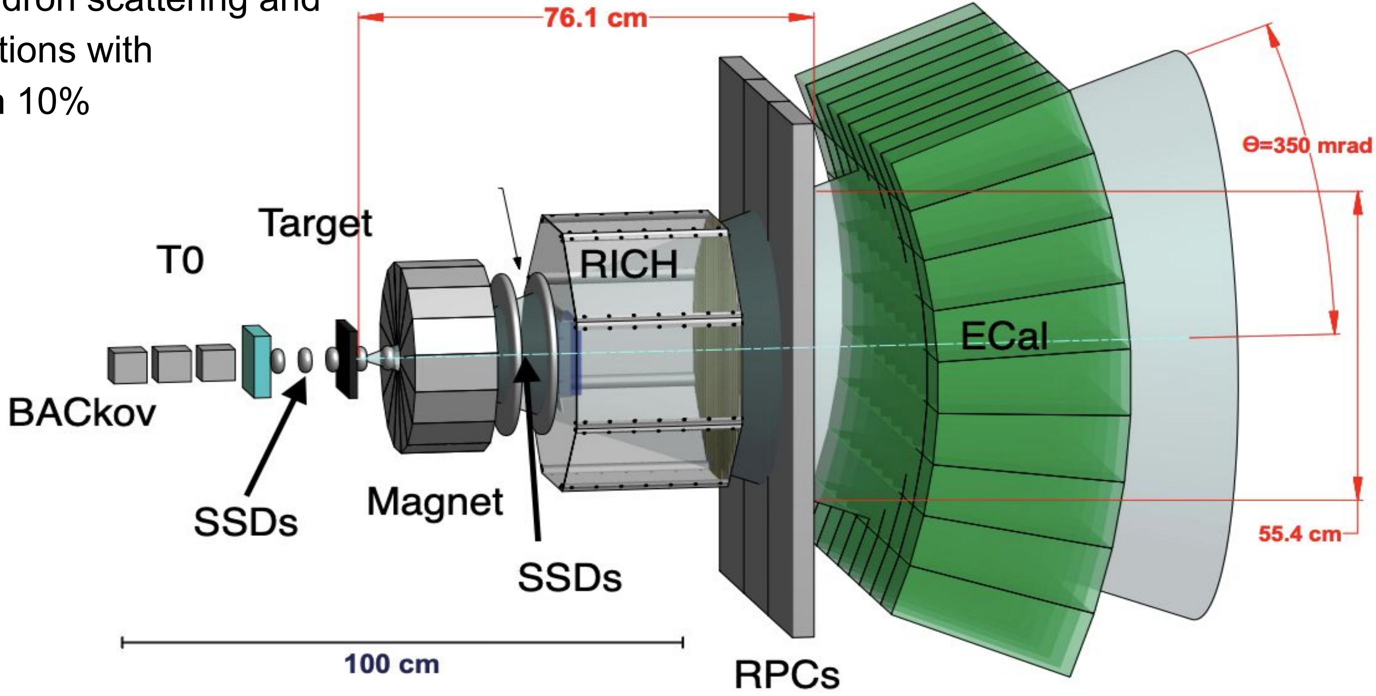
-Improved knowledge of hadron production benefits all GeV-scale neutrino experiments

# EMPHATIC overview

-**E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**est-beam **I**n **C**hicagoland

-Fill in the gaps of missing hadron scattering and hadron production cross sections with measurements of better than 10%

***Top-view***



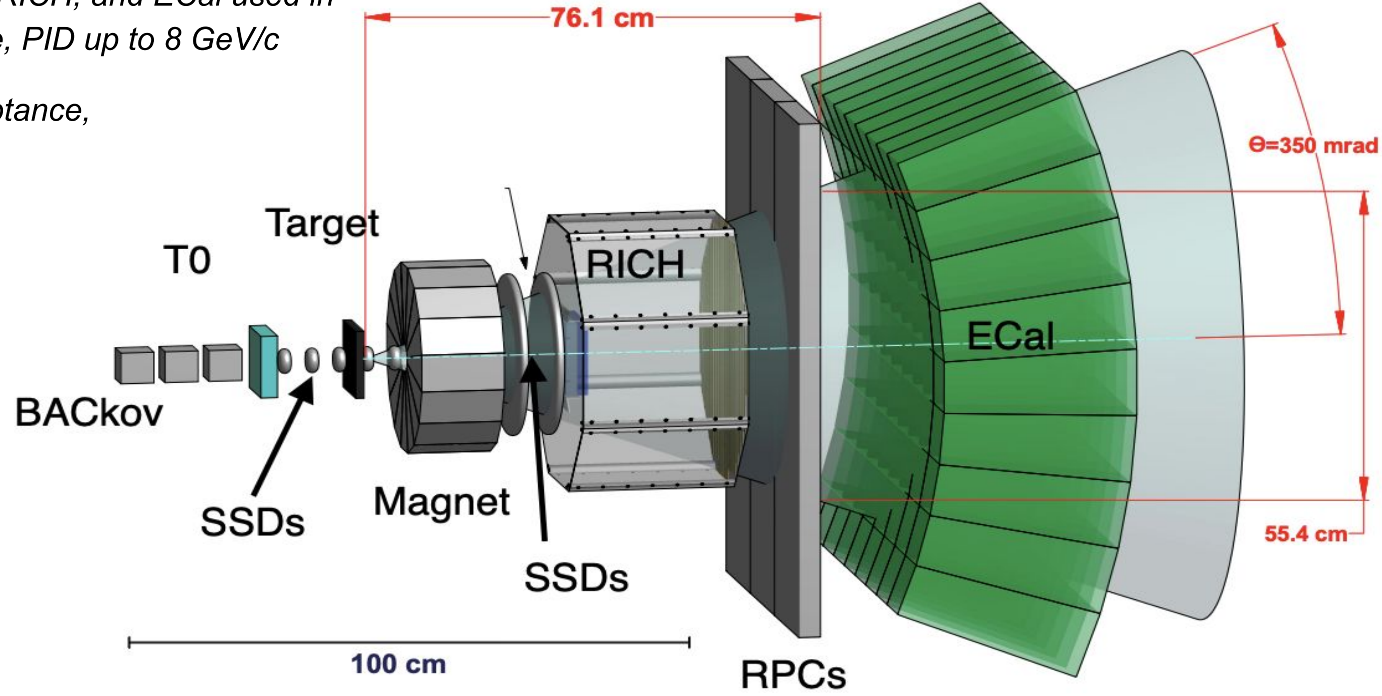
# EMPHATIC overview

-Table-top experiment (detectors fit within 4 meters) at Fermi Test Beam Facility (FTBF)

*-Smaller versions of the Magnet, RICH, and ECal used in Phase 1: ≤ 100 mrad acceptance, PID up to 8 GeV/c*

*-Ultimate design: 350 mrad acceptance, PID up to 18 GeV/c*

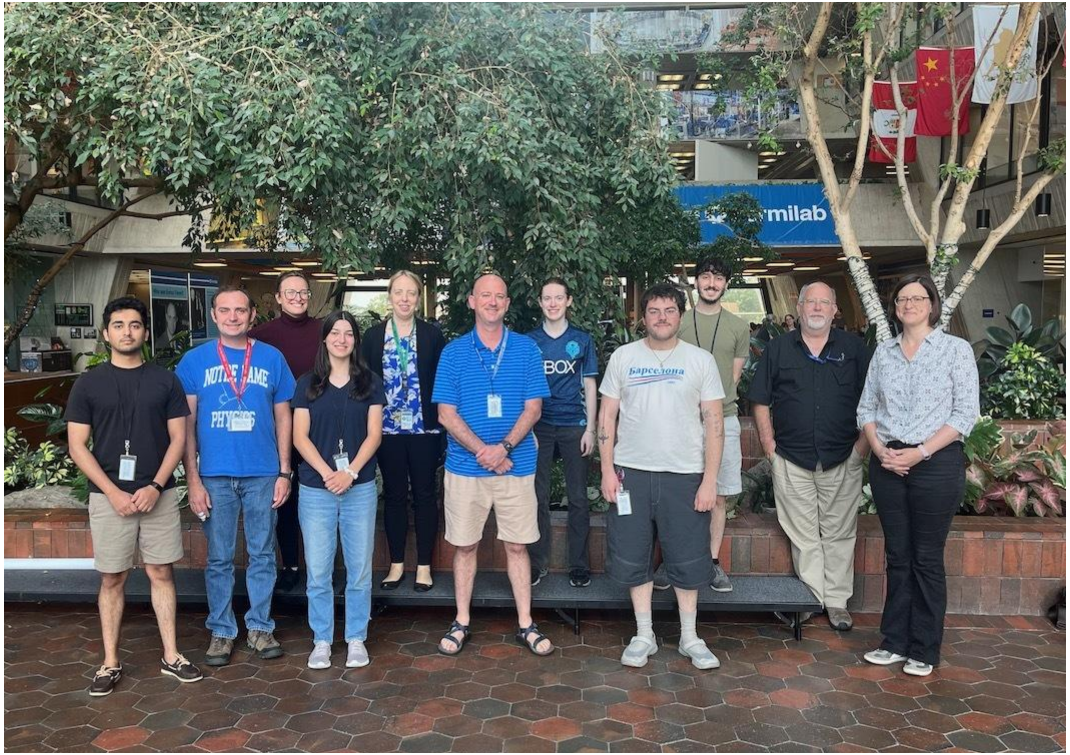
***Top-view***



# Who is EMPHATIC?

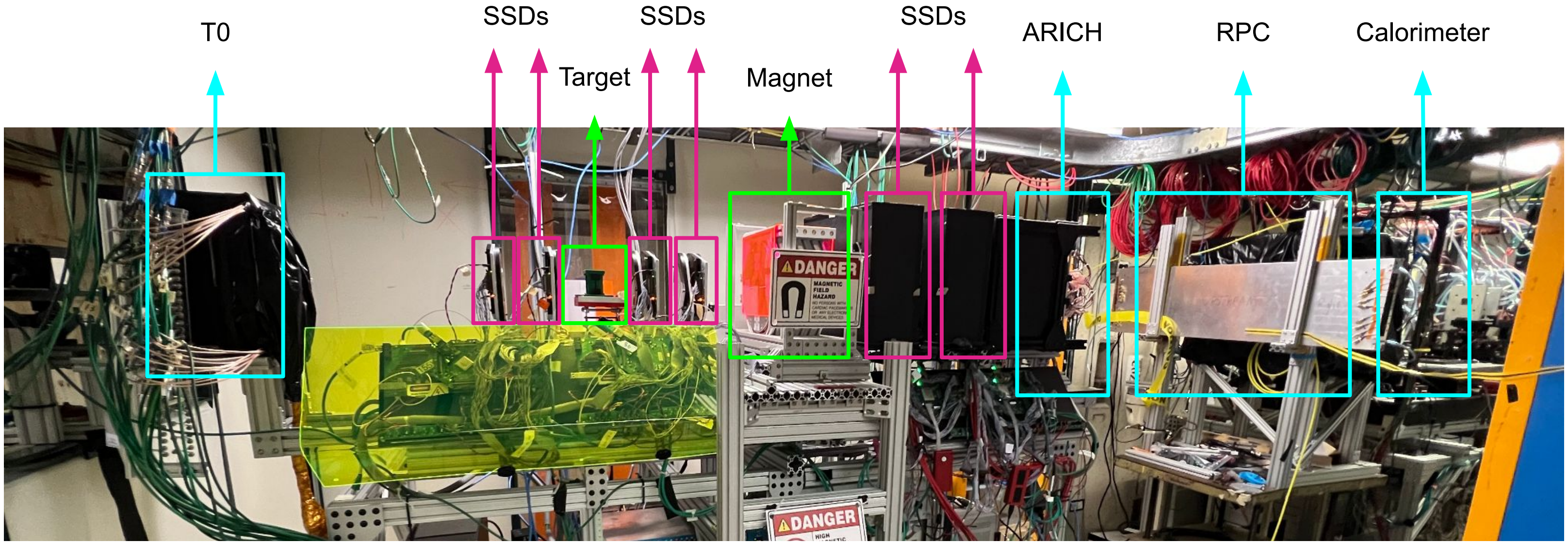
-International collaboration of about 25 institutions

-We are all neutrino experts interested in reducing flux uncertainties!



*In-person attendees at recent collaboration meeting*

# Detector layout (Phase 1)




-Focus on low-momentum beam: p < 15 GeV/c, but also collected data with beam from 20-120 GeV/c

-Our collaborators are actively updating NuMI and LBNF flux predictions with our measurements as additional constraints

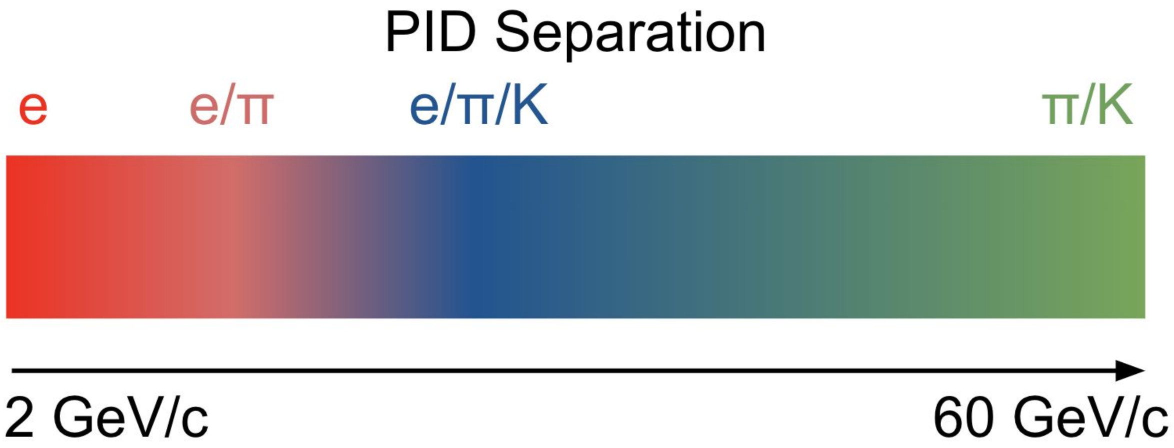
# Beam characterization

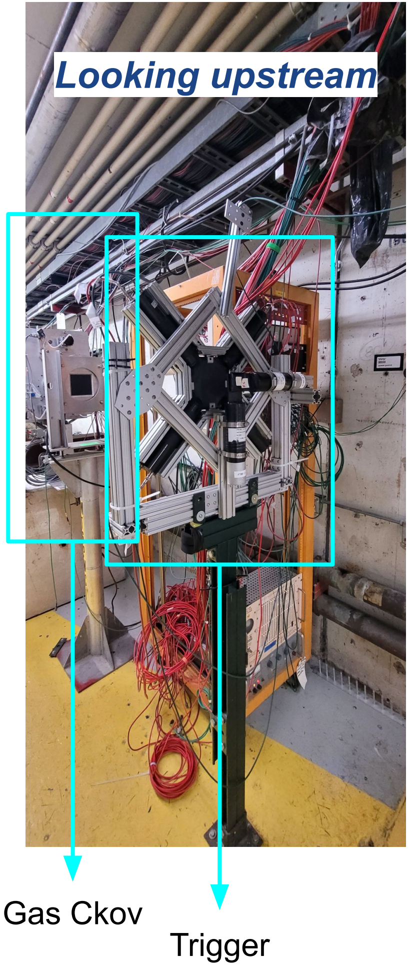
**Gas Cherenkov:**

-Facility Cherenkov detector with inner and outer mirrors

-Filled with $CO_2$, pressure varied depending on the beam momentum

-Provides upstream PID



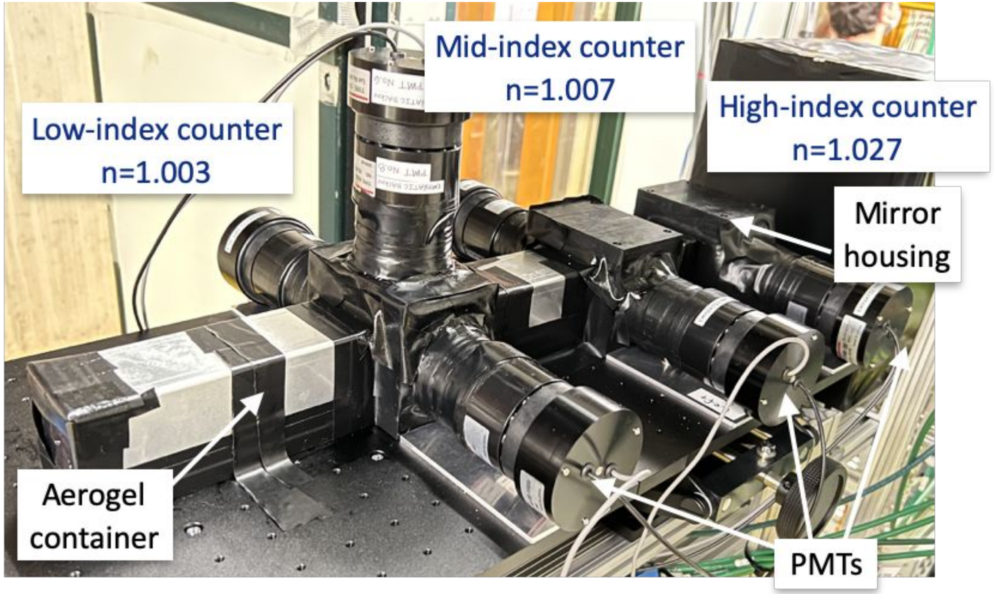



# Beam characterization

**Beam Aerogel Cherenkov (BACkov):**

-Extend the range of upstream beam particle identification to lower momenta

-Array of threshold-type Cherenkov counters where silica aerogels are used as radiators

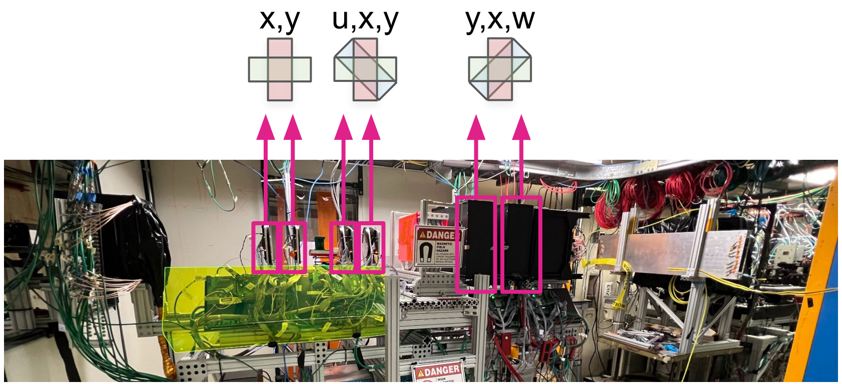



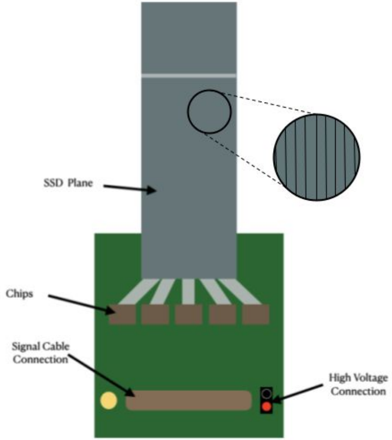
# Silicon Strip Detectors (SSDs)

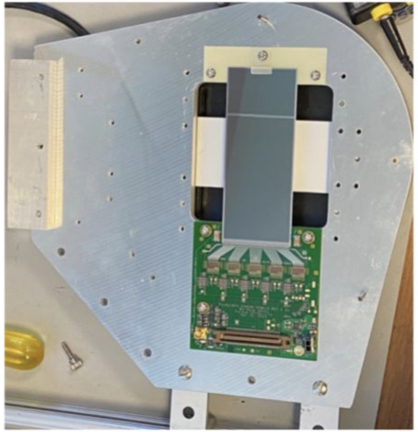
-Provides tracking for charged particles both upstream and downstream from the target

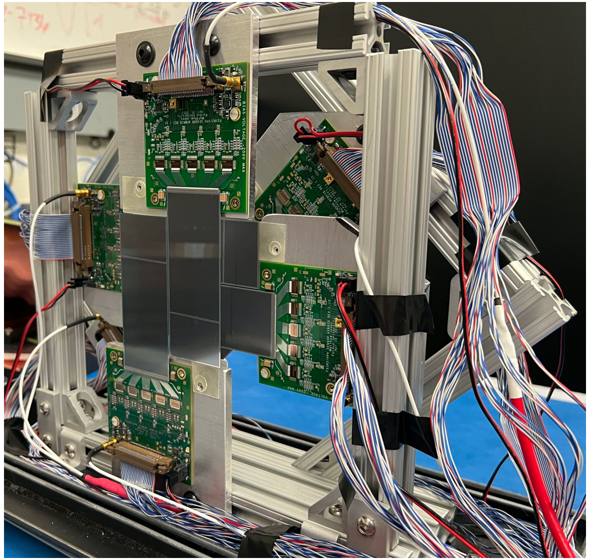
-60 μm pitch and ~17.3 μm spatial resolution

-Increase our acceptance by placing two SSDs side by side at downstream stations → ~100 mrad acceptance for Phase 1



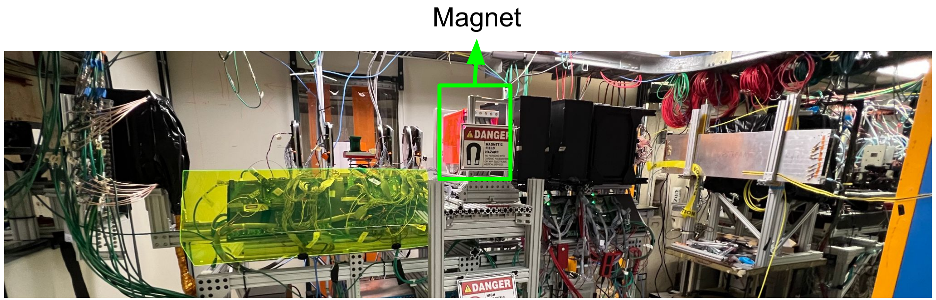


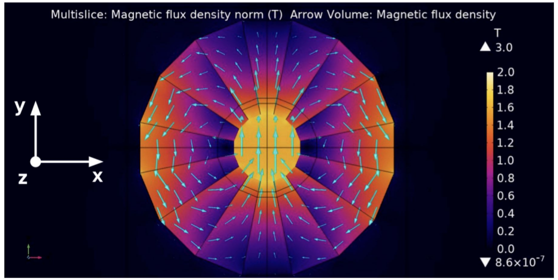
# Magnet

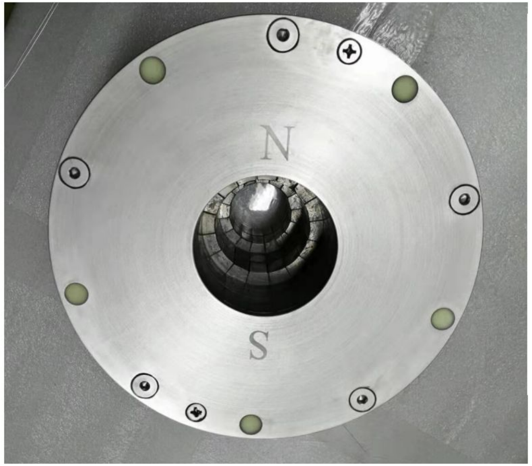
-Phase 1: prototype small-aperture compact magnet

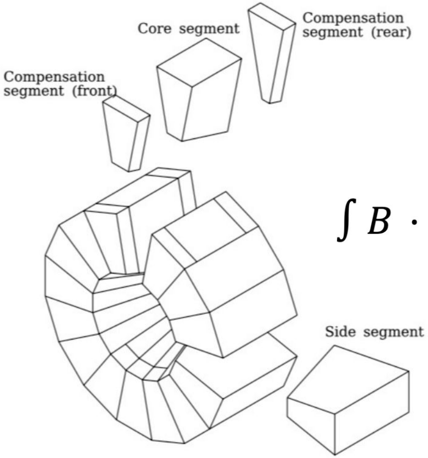
-N52-grade Neodymium permanent magnet segments provide a dipole field

-We have a 3D measured map of the field available where $B_{max}$ = 1.44 T

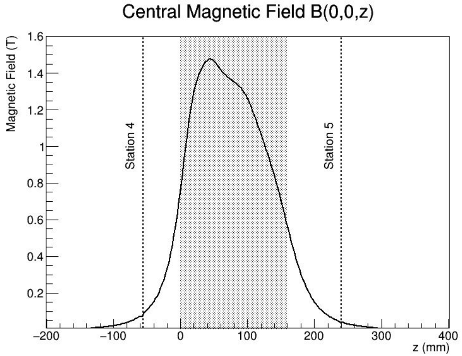



$$\int B \cdot dl = 1.2\,Tm$$



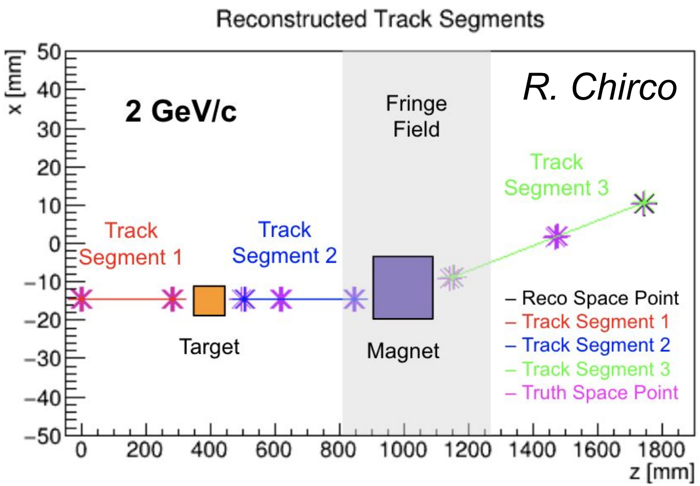
# Track Reconstruction

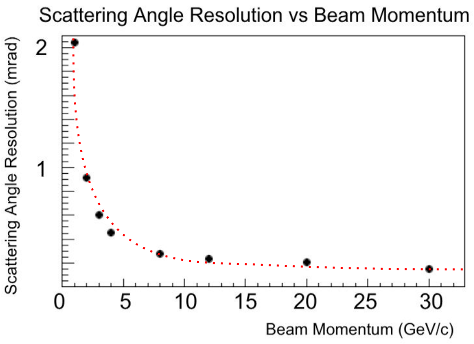
-Take SSD position information and create
 3D space points

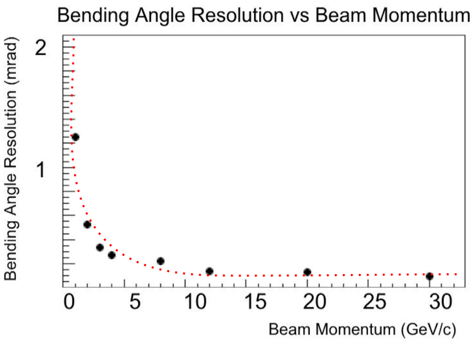
-Fit 3D space points to straight-line track segments

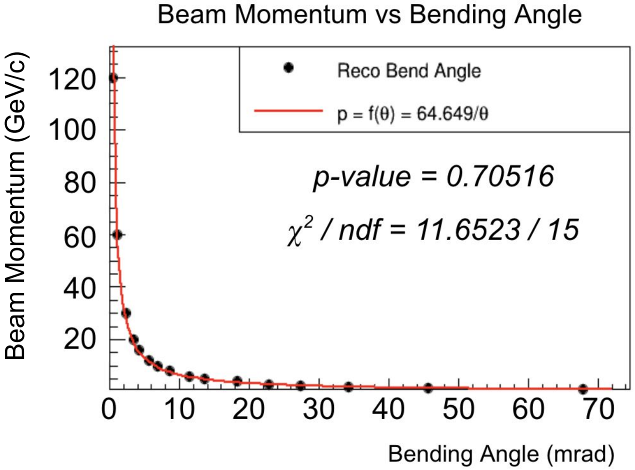
-Reconstruct scattering angle and bending angle

-Reconstruct momentum from bending angle

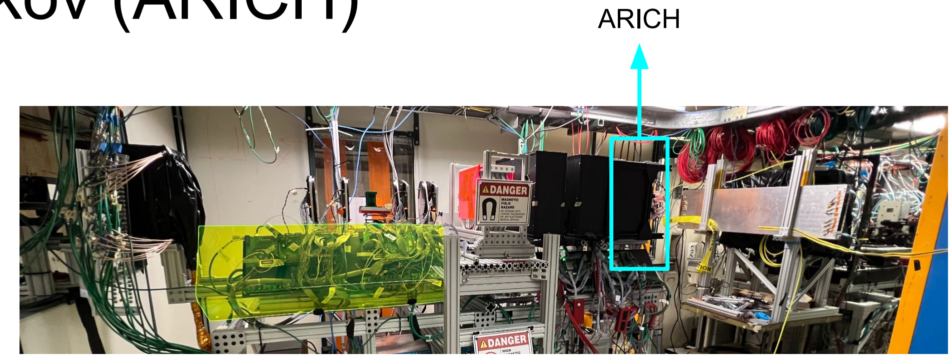


# Aerogel Ring Imaging CHerenkov (ARICH)

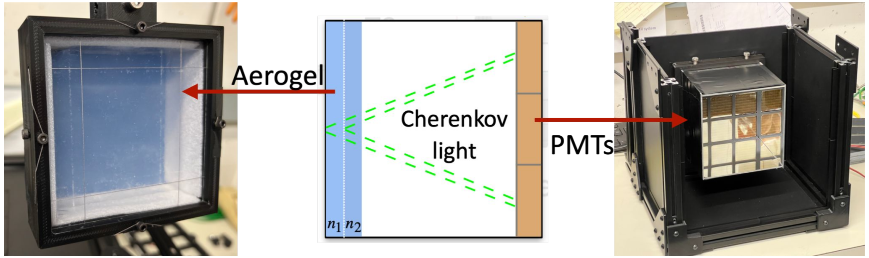


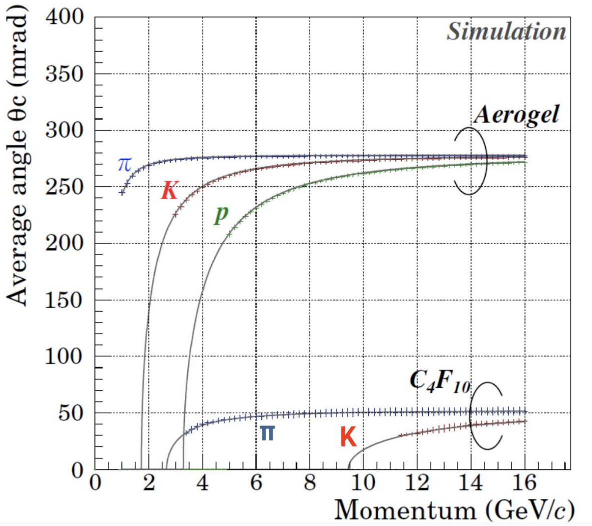

-Phase 1: prototype ARICH with 150 mrad acceptance

-2 layers of aerogel, developed for Belle II by Chiba University

-Aerogels with lower indices of refraction ($n_1$=1.02, $n_2$=1.03) and good transmittance

-Expect to achieve better than 2σ π/K separation at 7 GeV/c



# Time of flight (ToF) system


**T0:**

-x-shaped acrylic Cherenkov layered detector

-Measures the time of the incident beam particle
before it hits the target

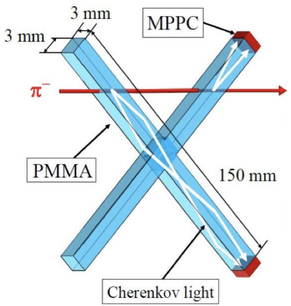
**Resistive Plate Chamber (RPC):**

-Measures the time of secondary particles downstream

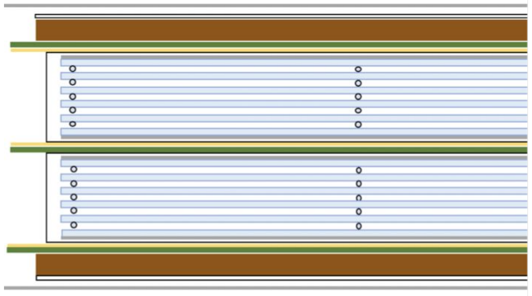
**ToF:**

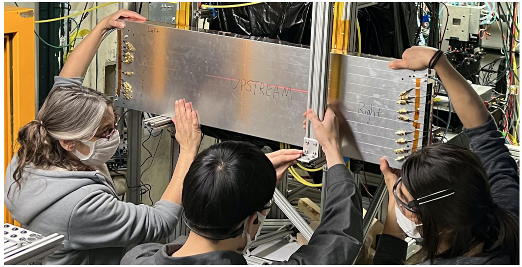
-Expected combined timing resolution of ~70 ps

-Particle separation up to ~1.5 GeV/c




PMMA: poly(methyl methacrylate)
MPPC: multi-pixel photon counter (SiPM)

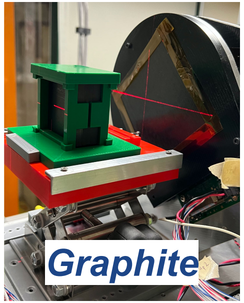


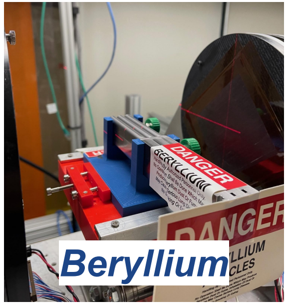


# Phase 1 data

| Target | Beam Mom (GeV/c) | # Triggers | Target | Beam Mom (GeV/c) | # Triggers |
|---|---|---|---|---|---|
| **Graphite** | 120 | 2.5M | **Beryllium** | -4 | 11M |
| | 4 | 11M | | 4 | 11M |
| | -4 | 11M | | 8 | 13M |
| | -8 | 38M | **CH2** | -20 | 14M |
| | -12 | 18M | | -8 | 8.5M |
| | 20 | 12M | | -4 | 3M |
| | -20 | 14M | **H2O** | -4 | 10M |
| | 30 | 23M | | 4 | 10M |
| | | | | -20 | 5.6M |

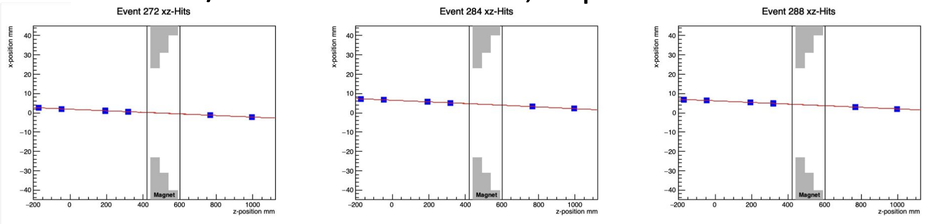
-During the 6-week data collection period (including installation and removal), we collected over 250 million triggers



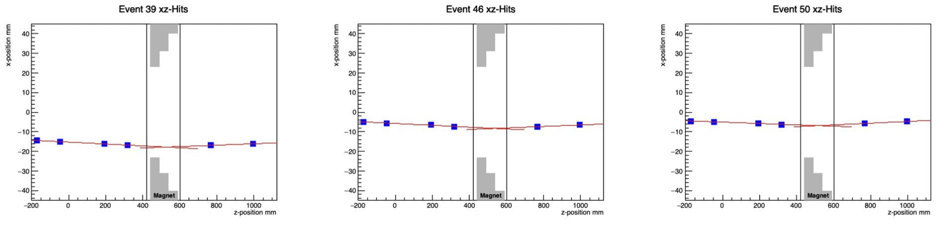




# First look at Phase 1 data

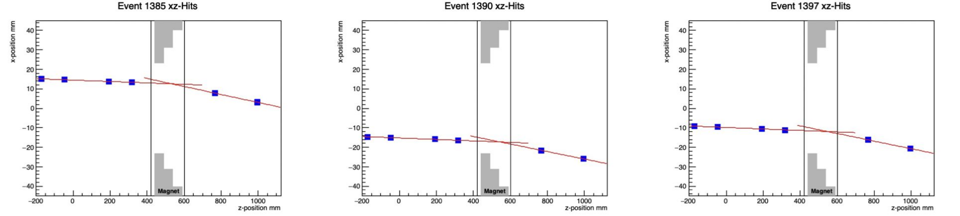
120 GeV/c Proton: XZ-PLane, Expected minimal Bending

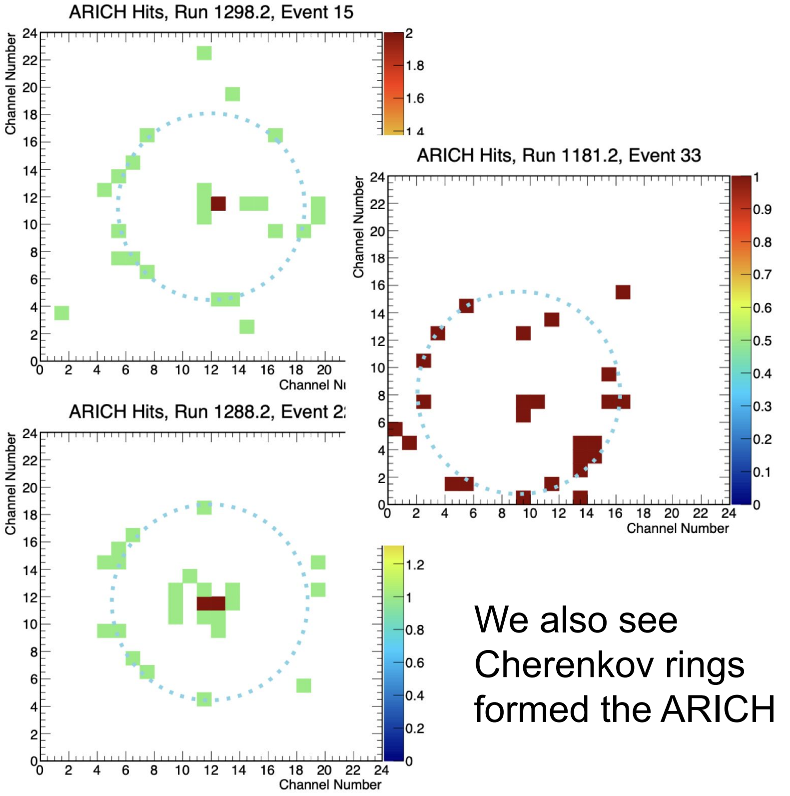



-8 GeV/c Pion: XZ-Plane, Expected Bending




We see bending tracks.




We also see Cherenkov rings formed the ARICH

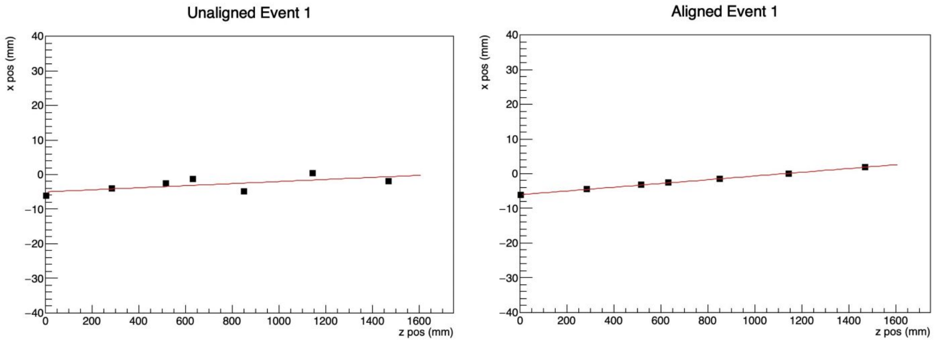
# Phase 1 simulation & analysis

-Working on detector alignment and calibration

-Developing an extensive map of the magnetic field
 region of the spectrometer

-Developing PID algorithms (ARICH)

-Writing analysis infrastructure (CAFs)

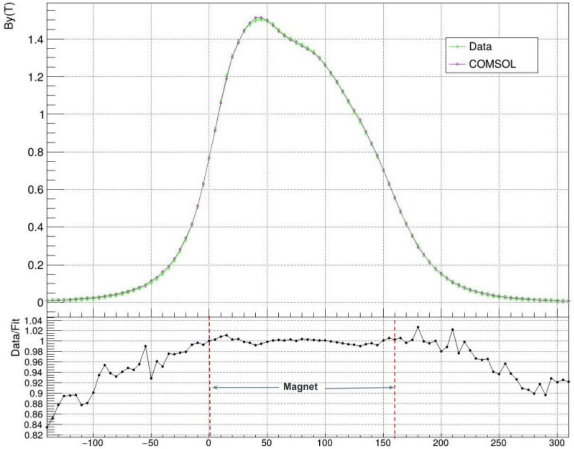



*J. Mirabito*

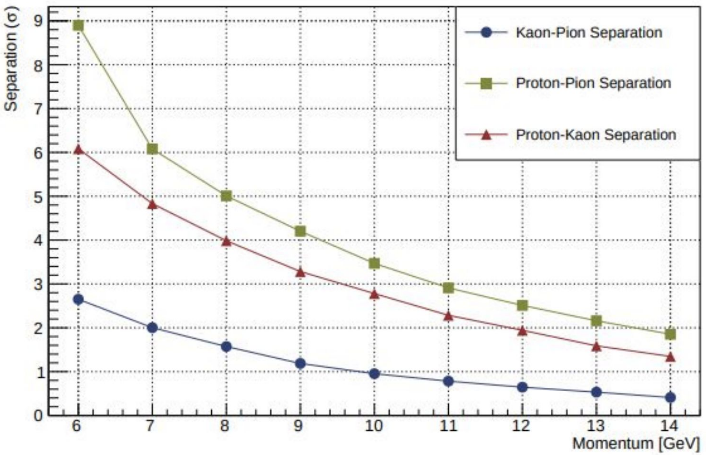
x =0, y = 0, (Center)

Uncertainty= 0.01T

*P. Sharma*




Particle Separations, Centered Beam *ARICH*



# Phase 2

-Make the first-ever measurement of the charged-particle spectrum downstream of a target + ***unpowered*** (NuMI) horn

- -More thin-target measurements

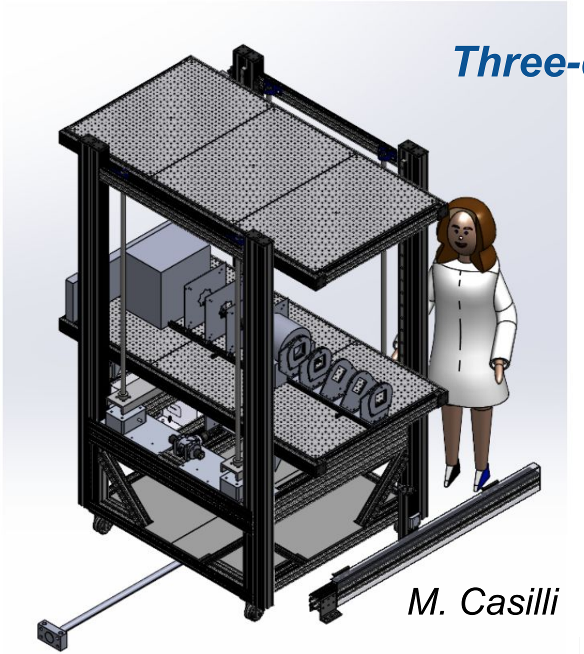
-Put the EMPHATIC Phase 1 spectrometer on a motion table that will sweep through the acceptance of the horn

-Power supply also available → hope to measure with pulsed horn in the future

-Updated beam characterization: Large Area Picosecond Photodetector (LAPPD)-based ToF system to identify particles up to 25 GeV/c

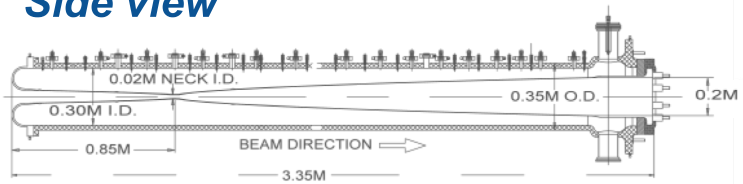
-Beam returns in late 2024 → we will begin installation soon in our new location at MCenter!

***Three-quarter view***

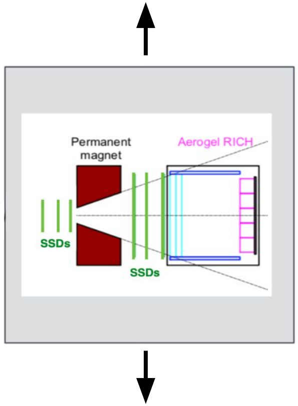


*M. Casilli*

***Side view***




NuMI target + Horn 1



# Summary

-Oscillation measurements, single-detector measurements, and BSM searches will benefit from improved neutrino flux predictions

-EMPHATIC plans to provide hadron production measurements to reduce uncertainties associated with neutrino flux

-EMPHATIC initial results, obtained during a proof-of-principle run in 2018, have been published:

*Phys. Rev. D 106, 112008* (arxiv:2106.15723)

-We currently analyzing thin-target data from Phase 1

-Preparation for Phase 2 in underway → additional thin-target data and measurements using the NuMI target and horn with a small-acceptance spectrometer

# Thank you!

# Beam

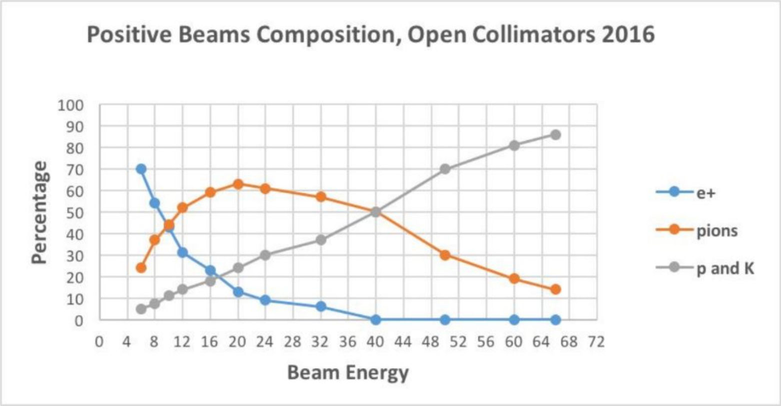
-FTBF delivers beams of particles between 2-120 GeV/c

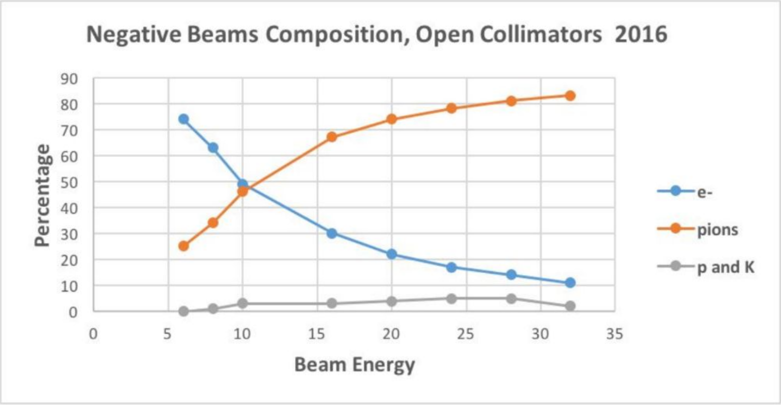
-Beam is directly extracted from the Main Injector, and is therefore a pure proton beam

-Secondary beams of pions, kaons, protons, and electrons can also be provided at momenta as low as 2 GeV

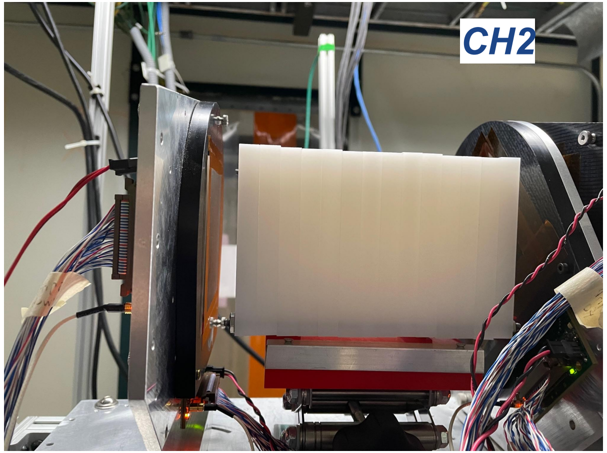
-The intensity, spot size, and momentum spread of the beam are all tunable, with the highest particle rates over 100 kHz, typical spot sizes of 1-2 $cm^2$ and $\Delta p/p$~2–3%

-Particle identification is provided using gas Cherenkov detectors → beam composition study from 2017

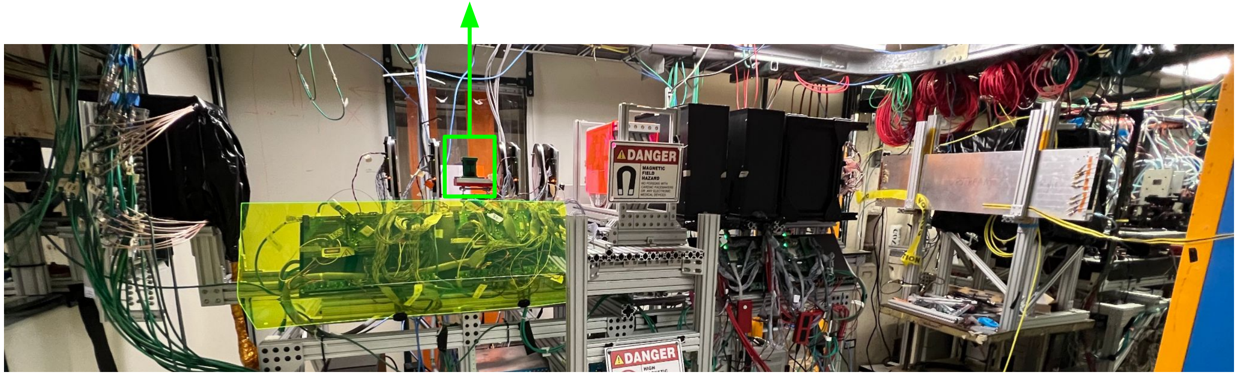


# Target




Target




-Variety of targets available, so far we have taken data with graphite, CH2, beryllium, H2O

-Target widths are about 5% of interaction length

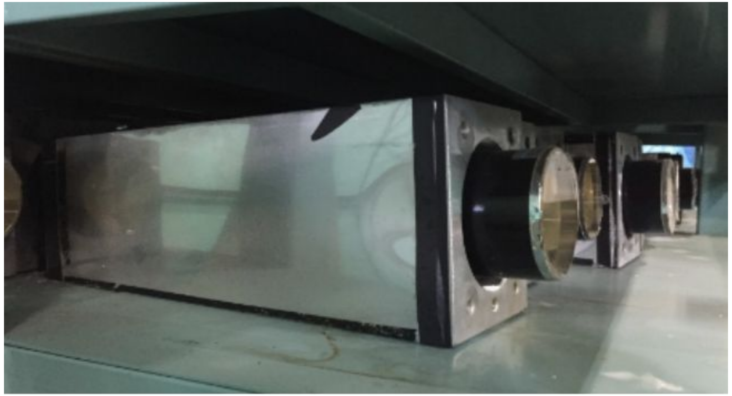
# Lead-glass calorimeter

-9 lead glass blocks with PMTs attached

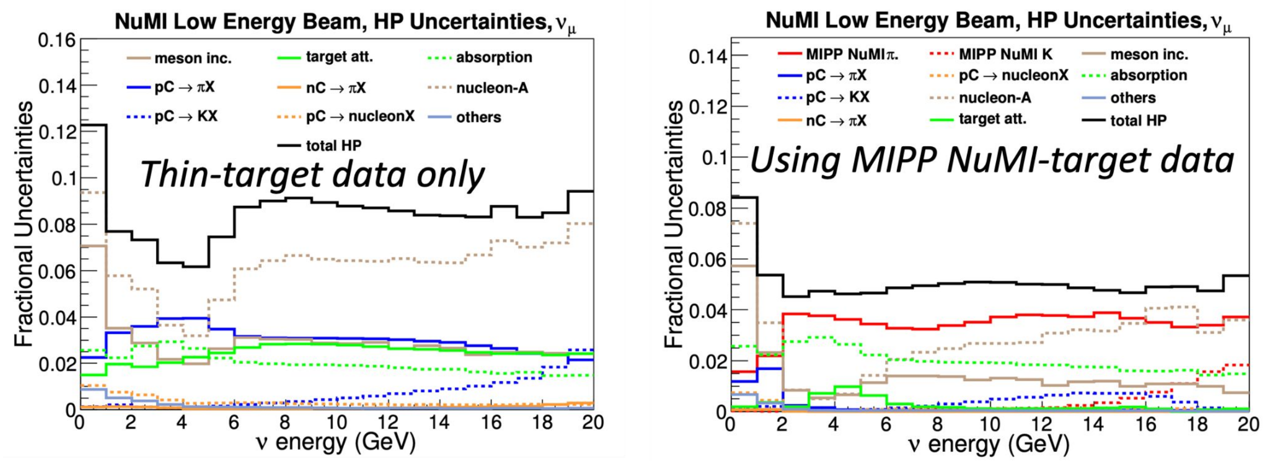
-3x3 array used in Phase 1

-Measures energy deposition

-Ultimate design uses 9x9 block array for full 350 mrad acceptance

# Phase 2 motivation




***L. Aliaga thesis***

-Measurements by MIPP and NA61/SHINE of HP off real (or replica) targets significantly reduced the HP uncertainties when compared to using only thin target measurements

*MIPP: Phys. Rev. D 90, 032001 (2014)*
*NA61: Phys. Rev. D 103, 012006 (2021)*

# Phase 2 location

-Move into MCenter: more space and can collect data for a long time

*MCenter, facing downstream*

*MCenter, facing upstream*