EMPHATIC
Hadron production experiment

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(on behalf of the **EMPHATIC Collaboration**)
University of Texas at Arlington

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University of Texas at Arlington

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April 14-20, 2024

Neutrino flux uncertainties

Flux uncertainties in accelerator neutrino experiments are still large:

- *Impacts baseline predictions for near and far detectors, single-detector measururements and neutrino background in BSM searches*
- *Dominant uncertainties come from interactions in materials (target, horn, etc) or energies or phase spaces that have never been measured.*

We need more data to improve our knowledge of the hadron production and improve the flux prediction

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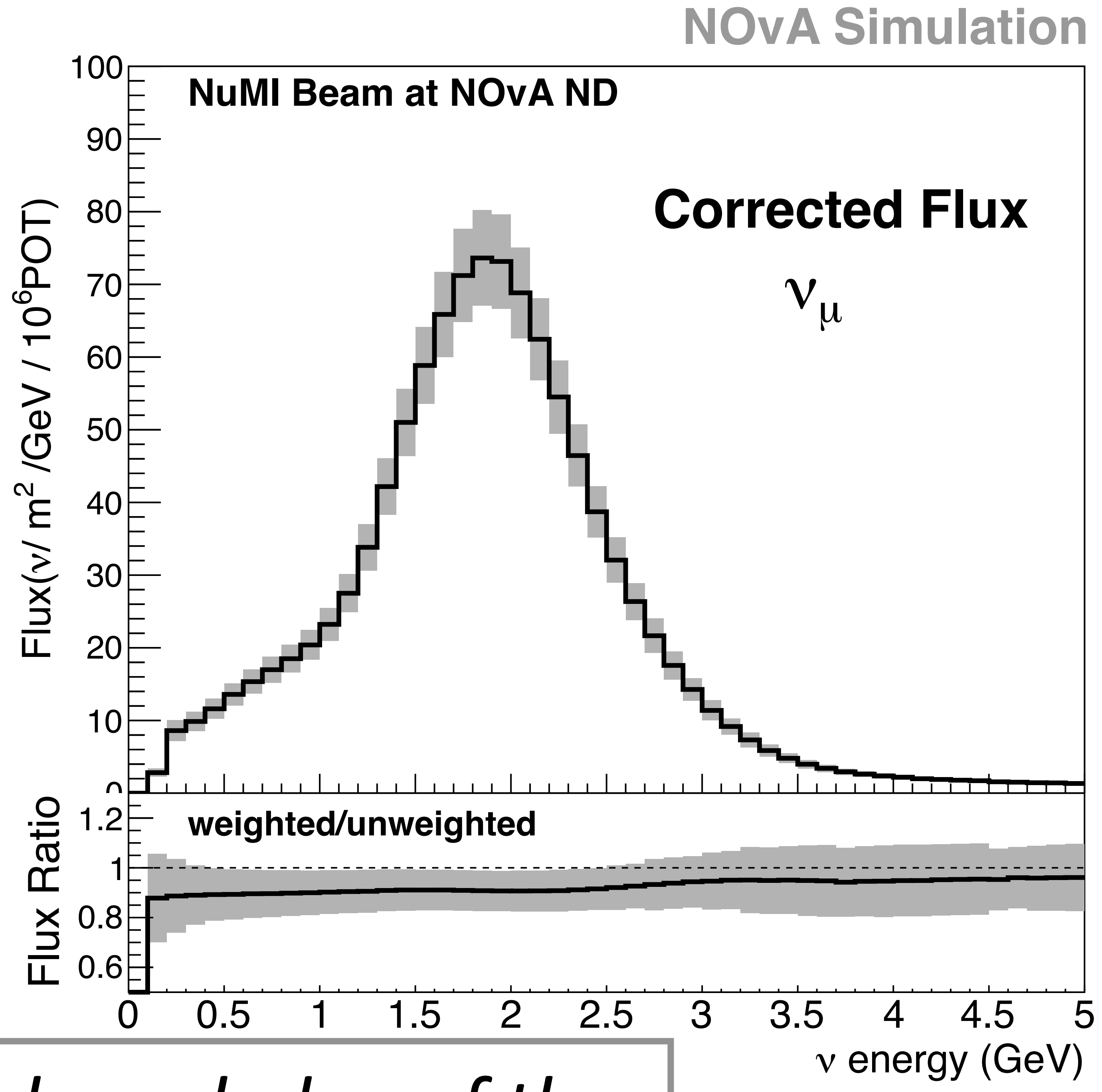
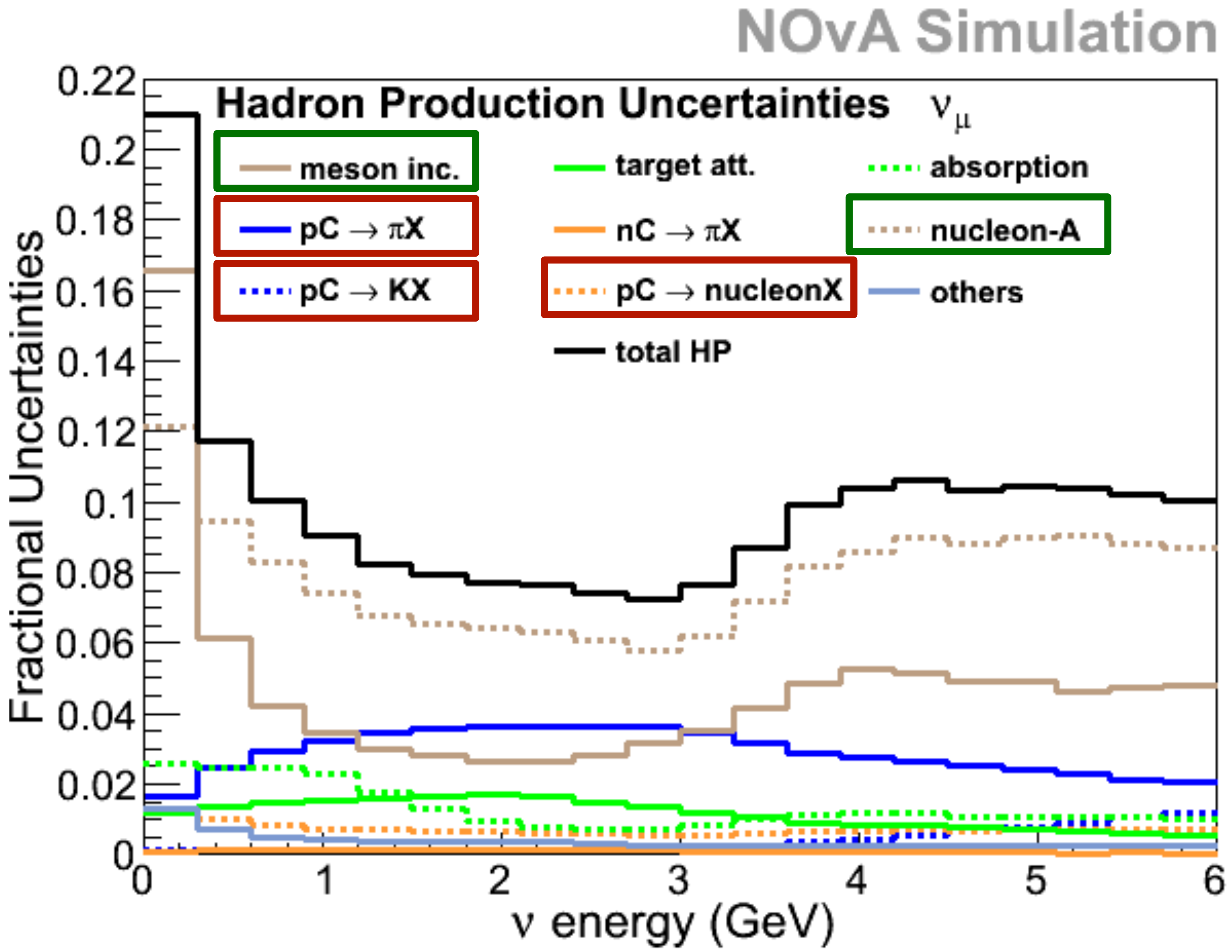
Flux prediction for NuMI (or LBNF) is based on:

- NA49 p-C at 158 GeV/c using xF-scaling to 12-120 GeV/c
- A-depending scaling uncertainty to extend carbon data
- A large 40% when there is not direct or indirect data.

Phys. Rev. D 94, 092005 (2016)





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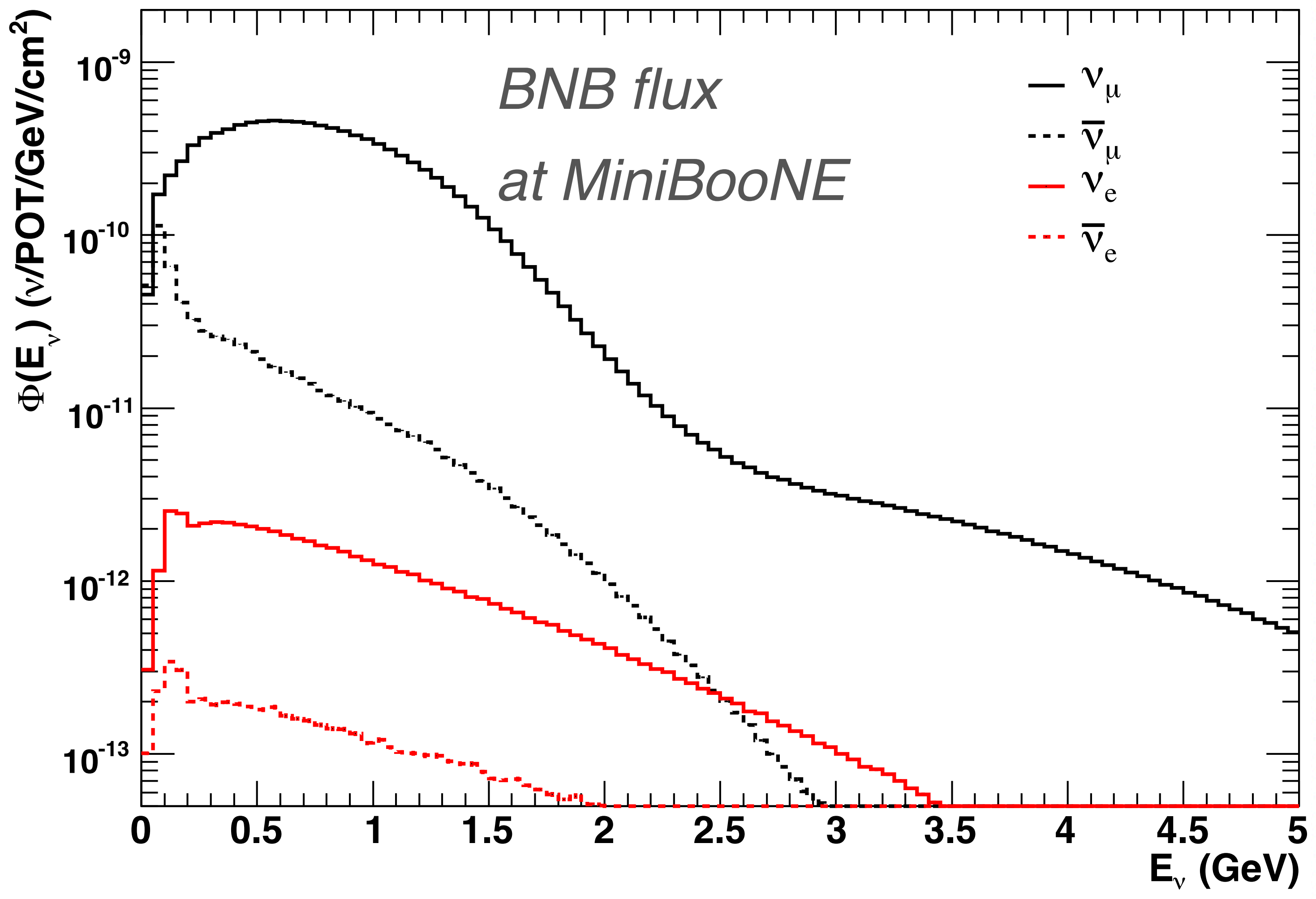
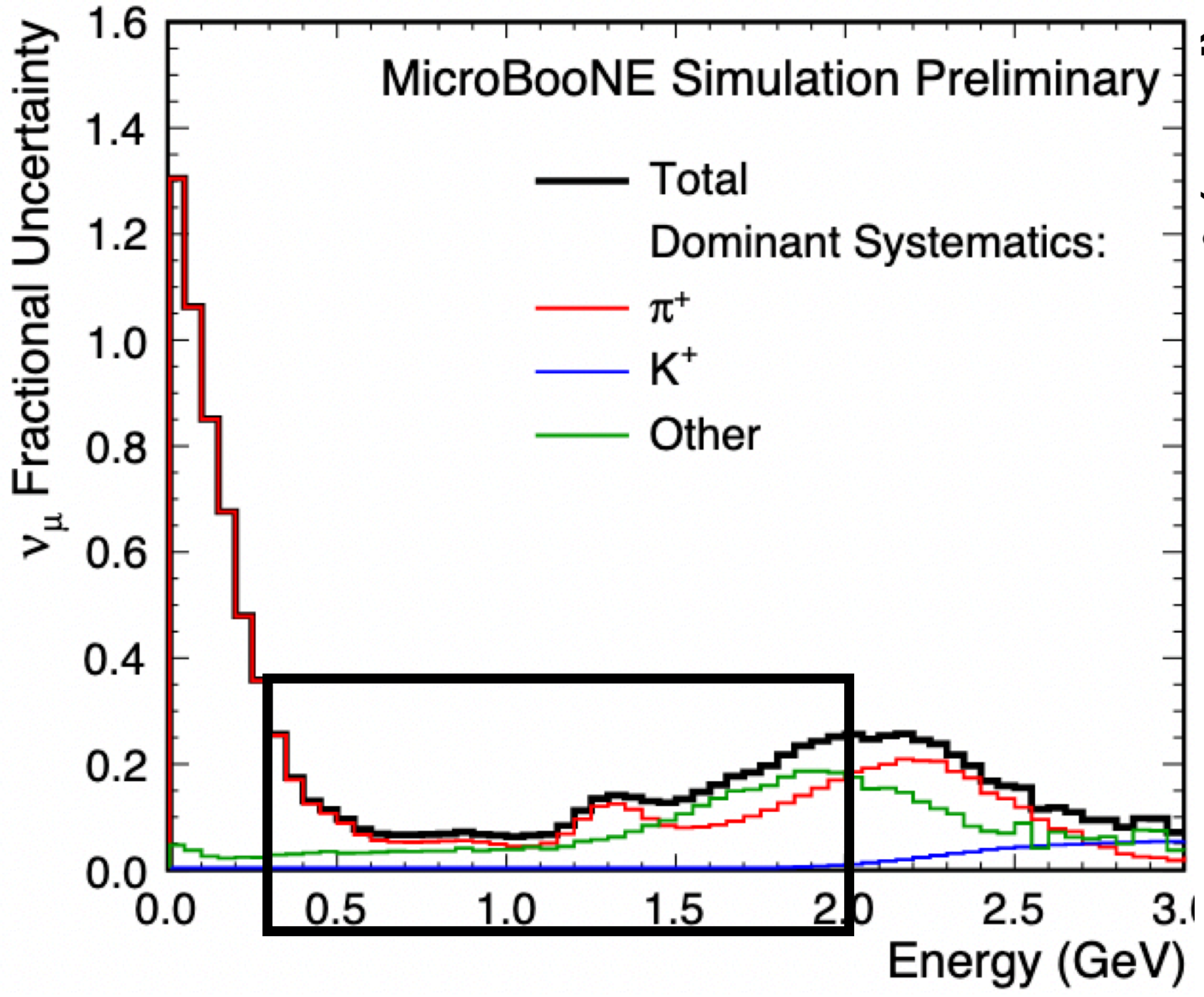
- *Impacts baseline predictions for near and far detectors, single-detector measururements and neutrino background in BSM searches*
- *Dominant uncertainties come from interactions in materials (target, horn, etc) or energies or phase spaces that have never been measured.*

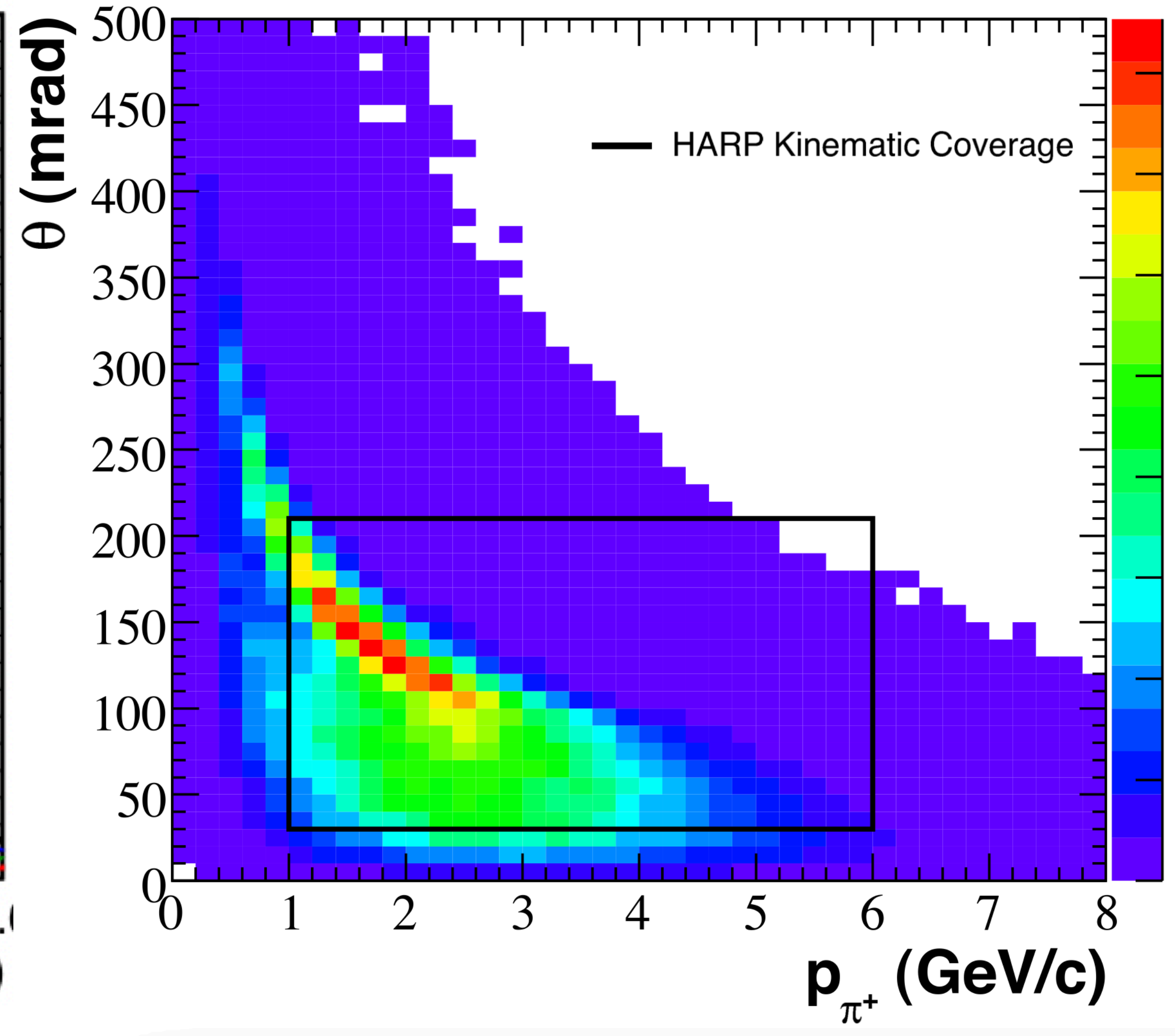
The flux prediction for BNB is based on:

- HARP and E910 p-Be data for pions
- xF-scaling based on fit world for pBe for kaons



Phys. Rev. D 79, 072002





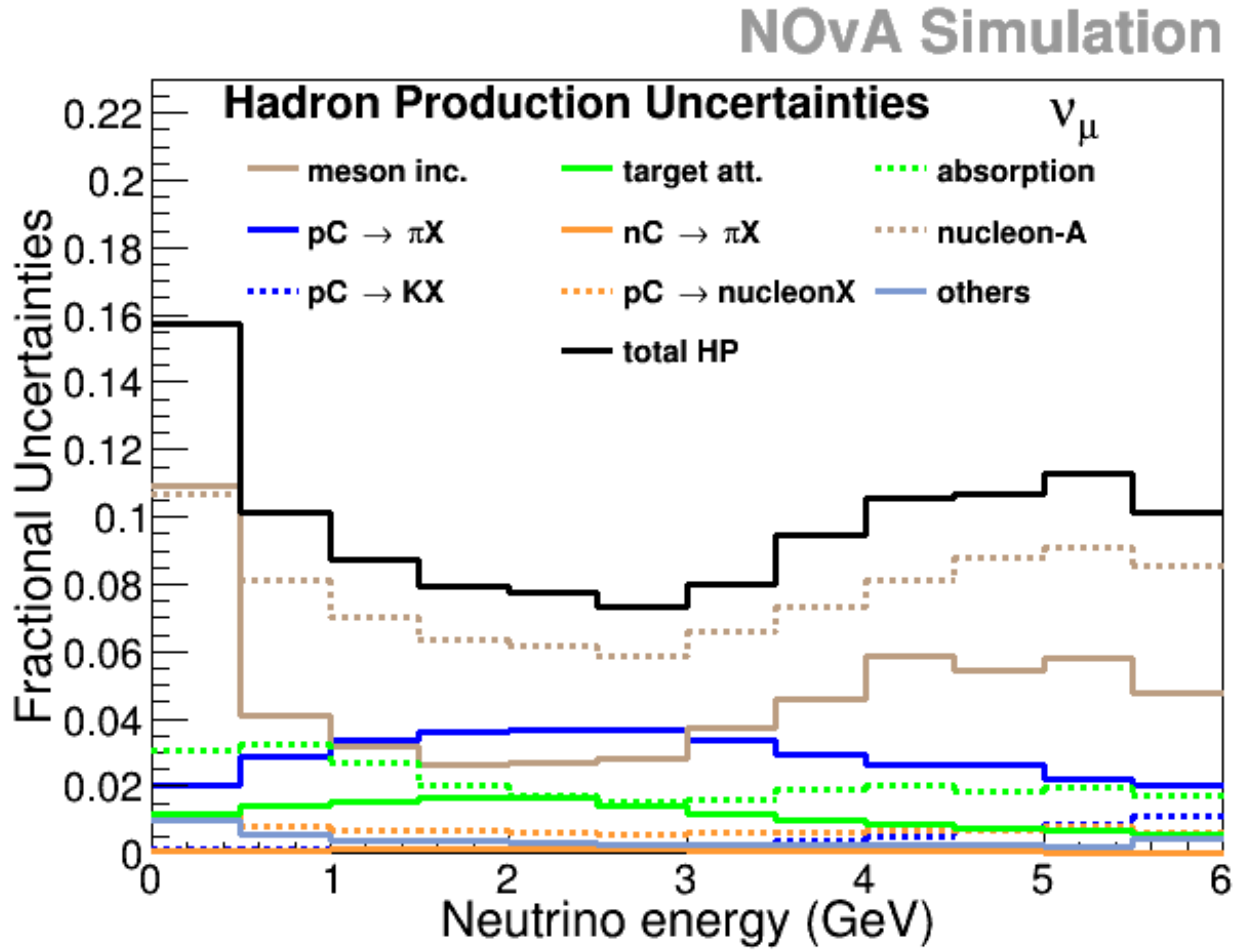
Large uncertainties in the BNB come from regions not covered by HARP

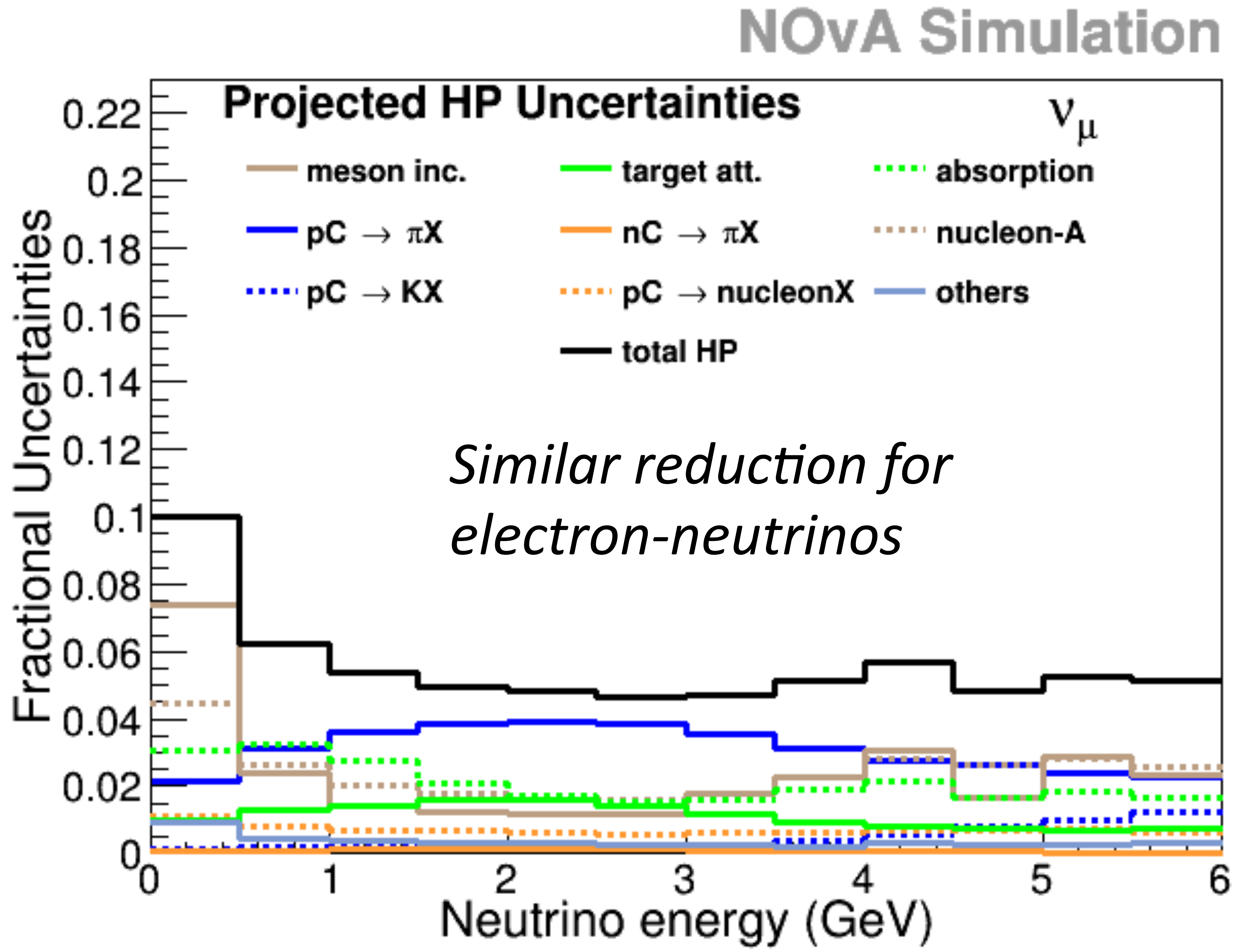
We need more data to improve our knowledge of the hadron production and improve the flux prediction

Reasonably achievable gain from new data

With some conservative assumptions, we can expect a significant reduction in the uncertainty

- ***K absorption**: 60-90% -> 10%*
- ***QE interations**: 40 -> 10%*
- ***p,π,K + C[Fe,Al] -> p X**: 40 -> 10%*
- ***p,π,K + C[Fe,Al] -> K^{+-} X**: 40 -> 20%*

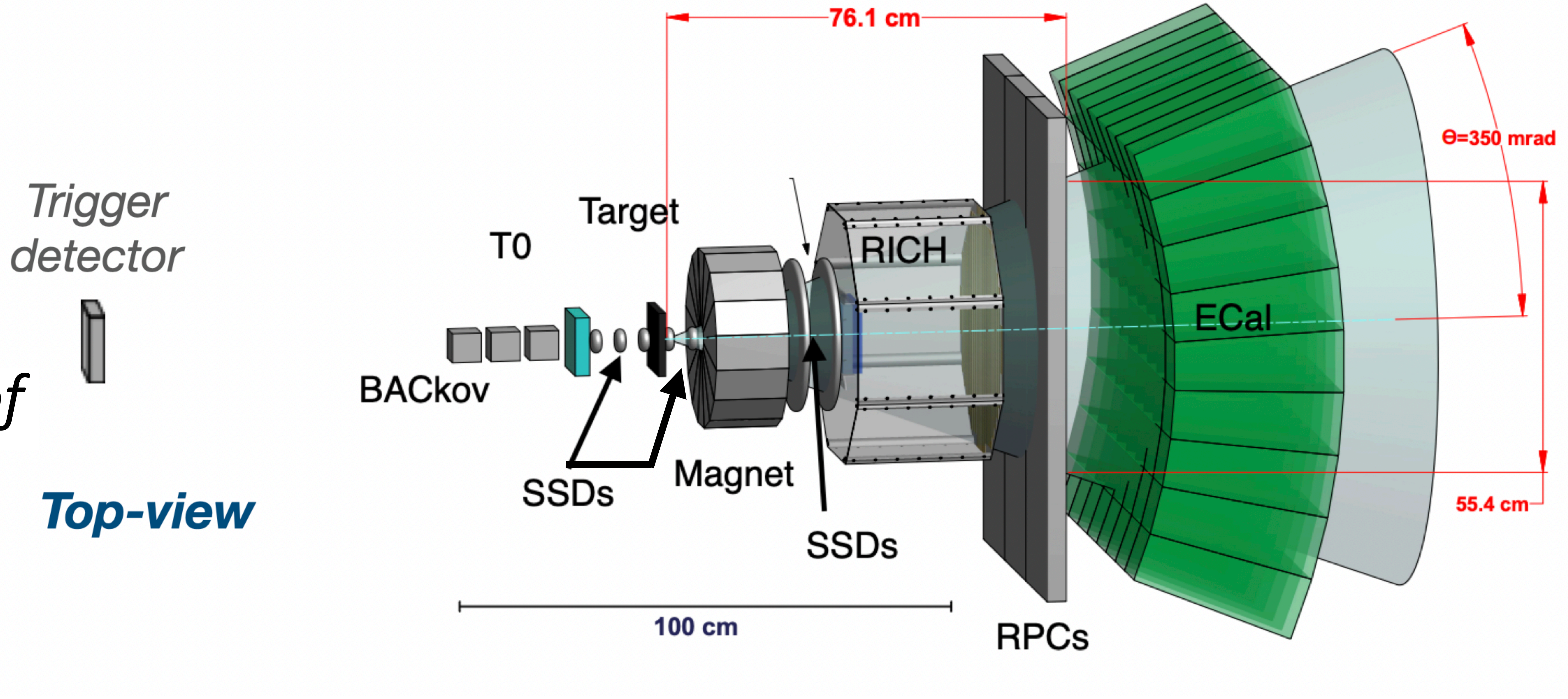




New data not only will reduce the uncertainty but will also enhance the robustness of our flux prediction

EMPHATIC

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



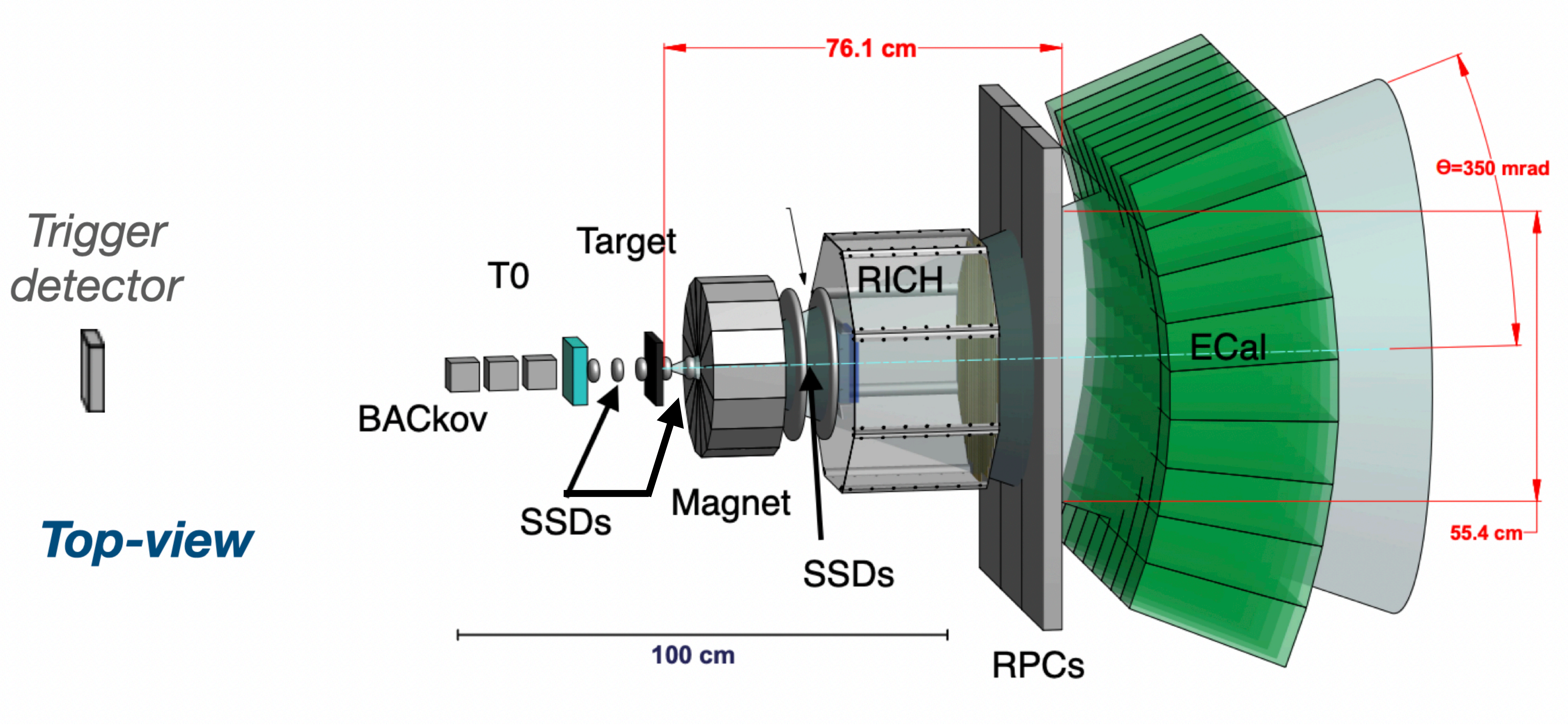
Goals:

- *Fill in the gaps of missing hadron-scattering and hadron-production cross sections with measurements of better than 10%*
- *Make the first-ever measurement of the hadron spectrum downstream of a target and horn*

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

EMPHATIC

Small-scale experiment (detectors fit within 4 meters) at the M(eson)Test beamline in the Fermilab Test Beam Facility.

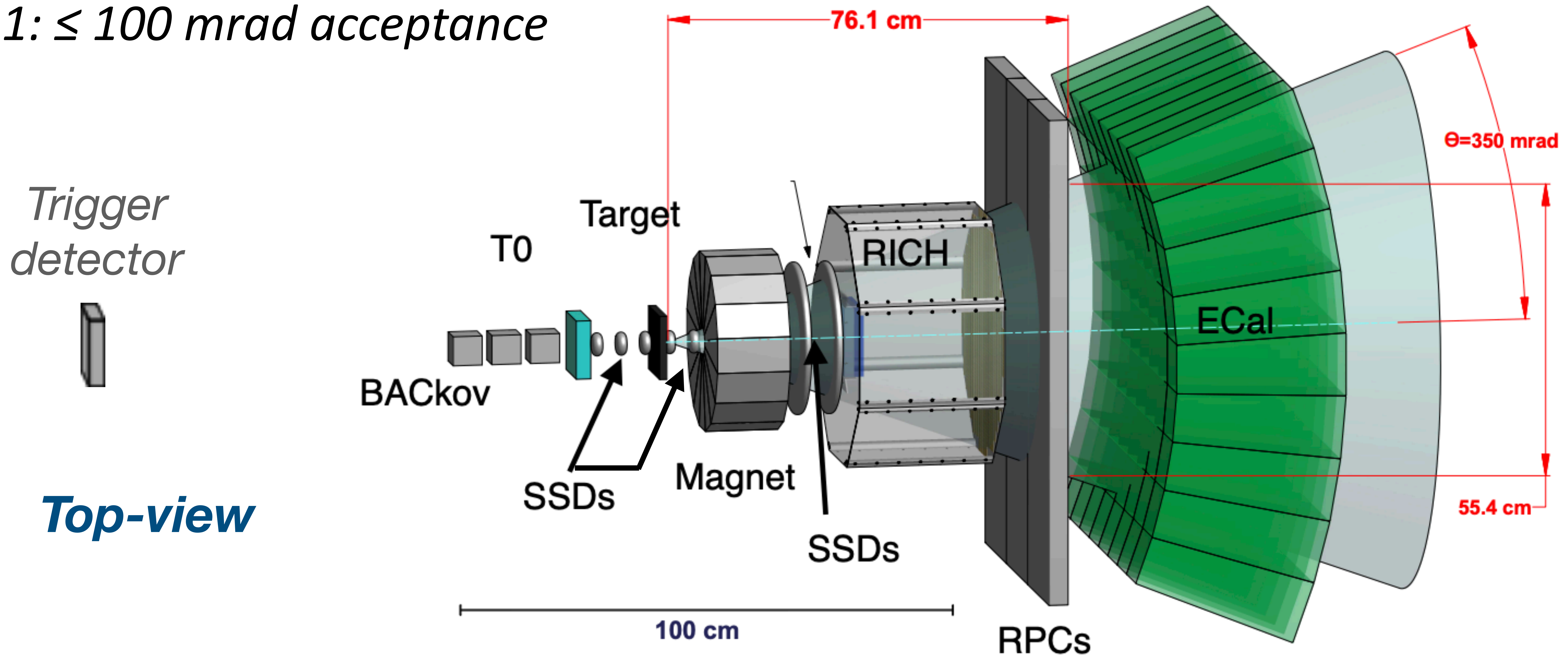


- Focus on low-momentum beam: pbeam < 15 GeV/c, but will also make measurements with beam from 20-120 GeV/c. **Ultimate design: 350 mrad acceptance**

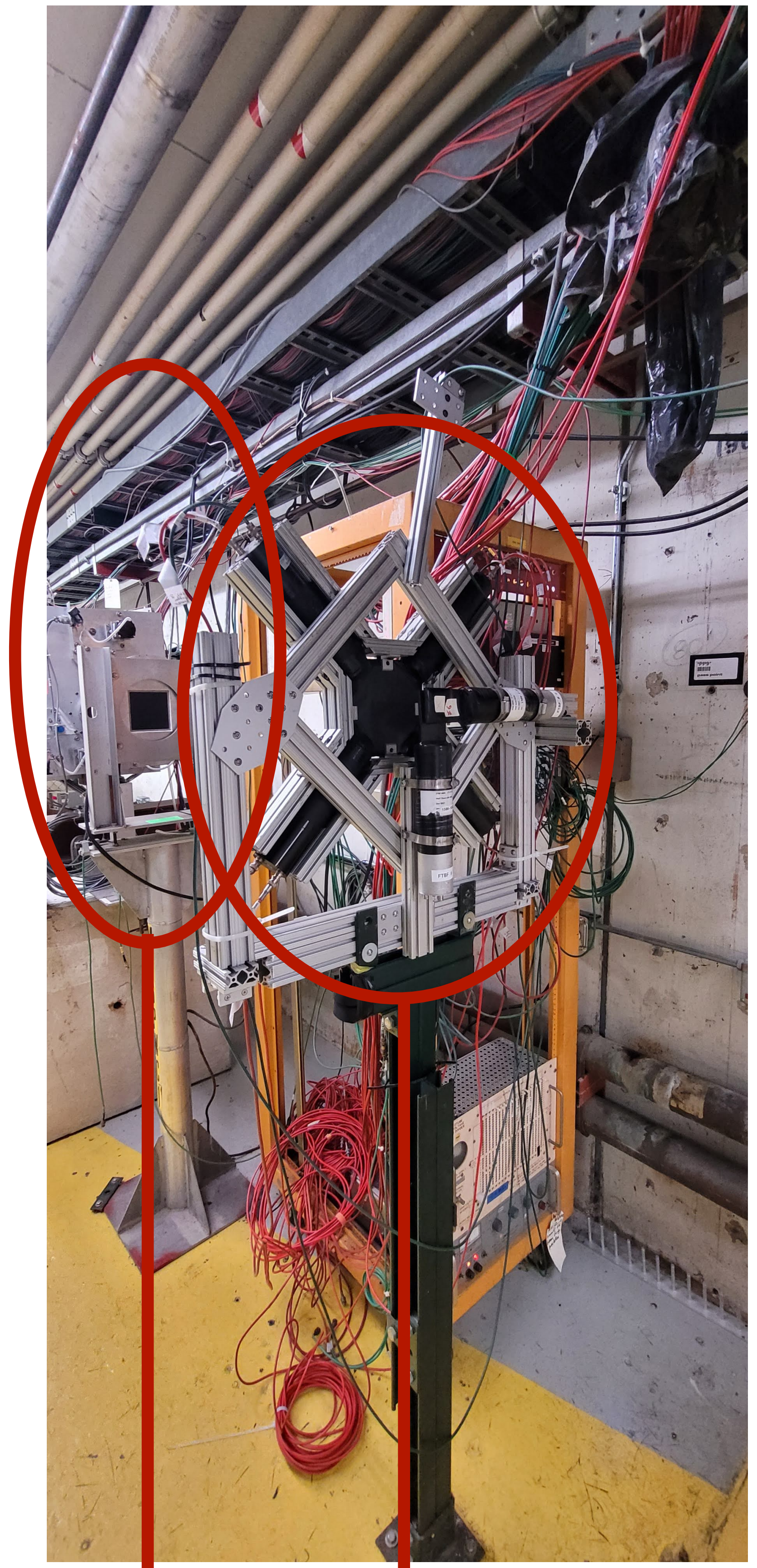
- Collection of small detectors to track particles with high precision before and after a target, perform particle identification, and measure calorimetric energy.

Detector layout

Smaller versions of the Magnet, RICH and ECal used in Phase 1: ≤ 100 mrad acceptance



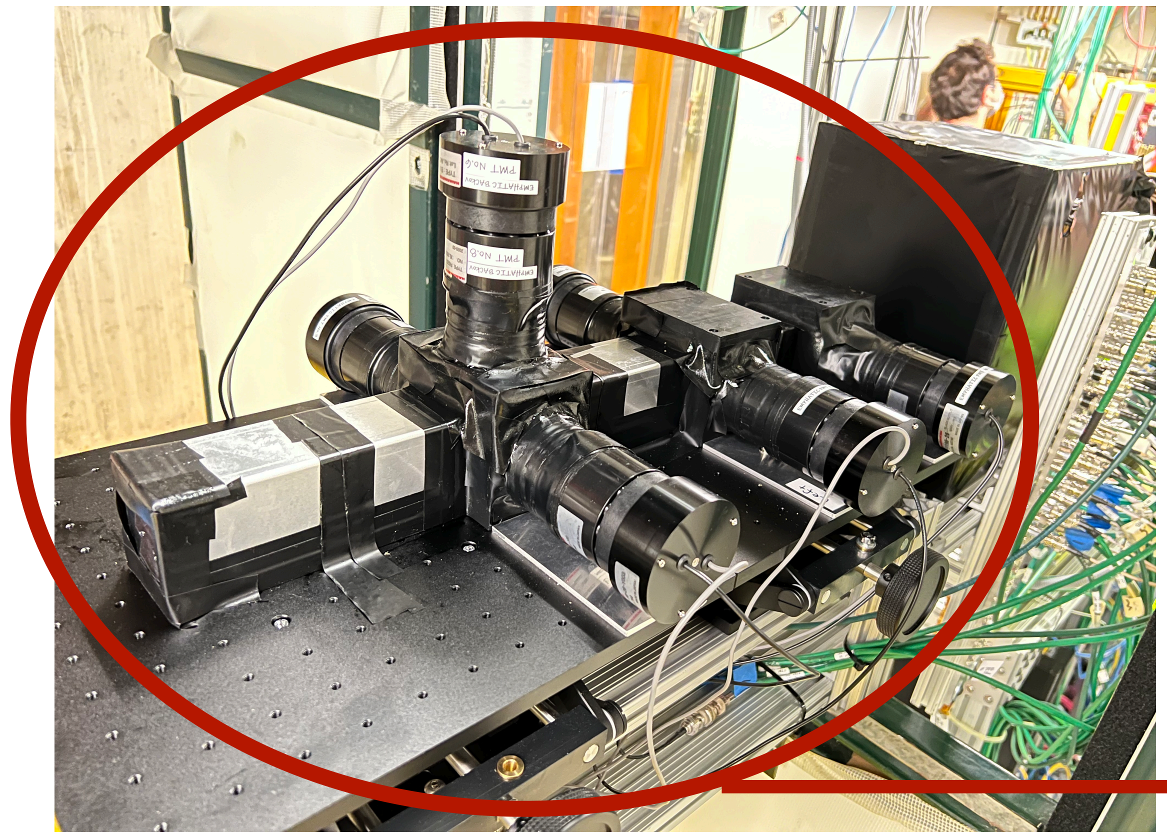
EMPHATIC Phase 1: ≤100 mrad acceptance



T0 SSDs Magnet ARICH RPC Lead-glass Calorimeter

Gas Ckov

Trigger

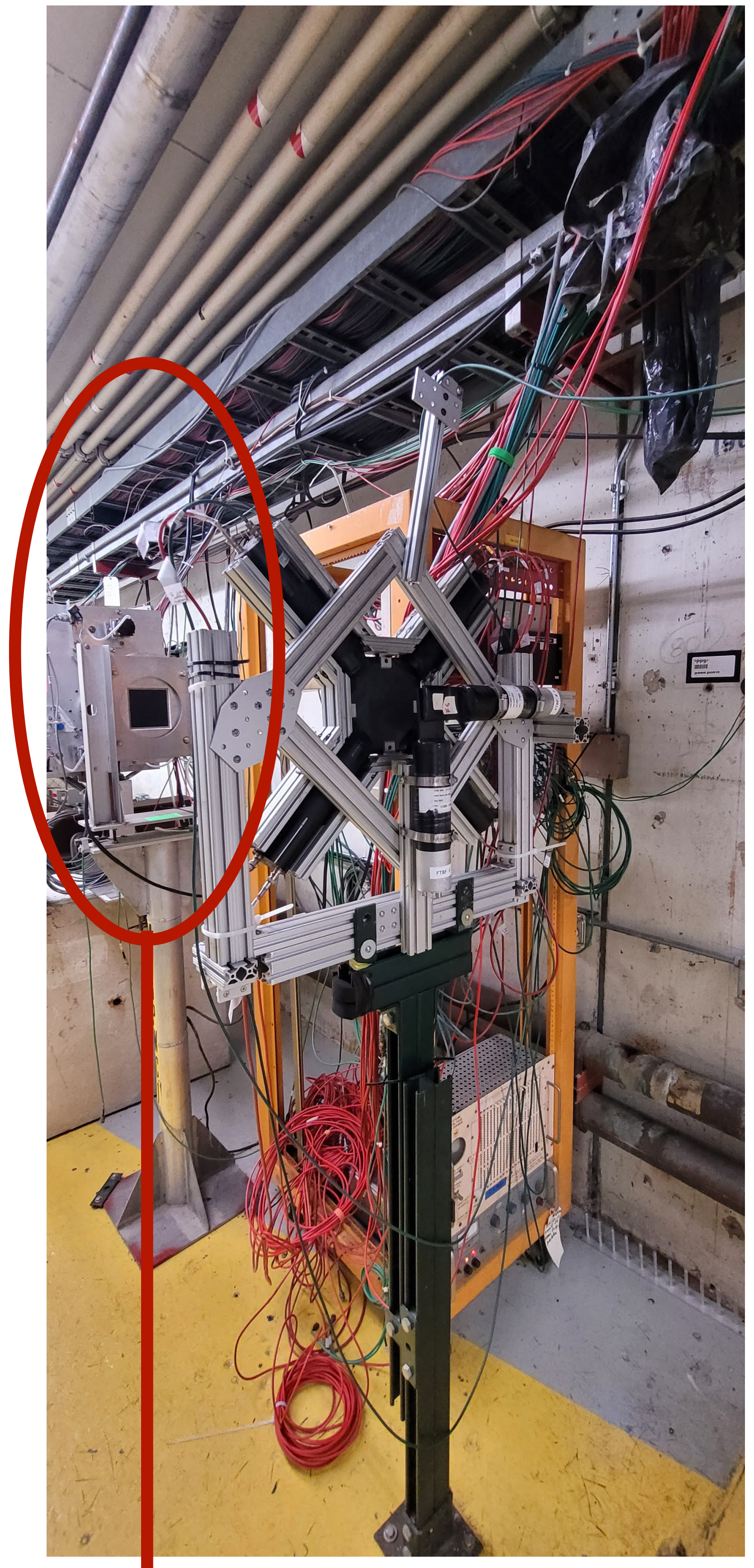


Beam aerogel Ckov

During the 6-week data collection period, we collected over 250 million triggers.

All installations completed within 2-3 days as part of our Phase 1 operations.

Beam characterization



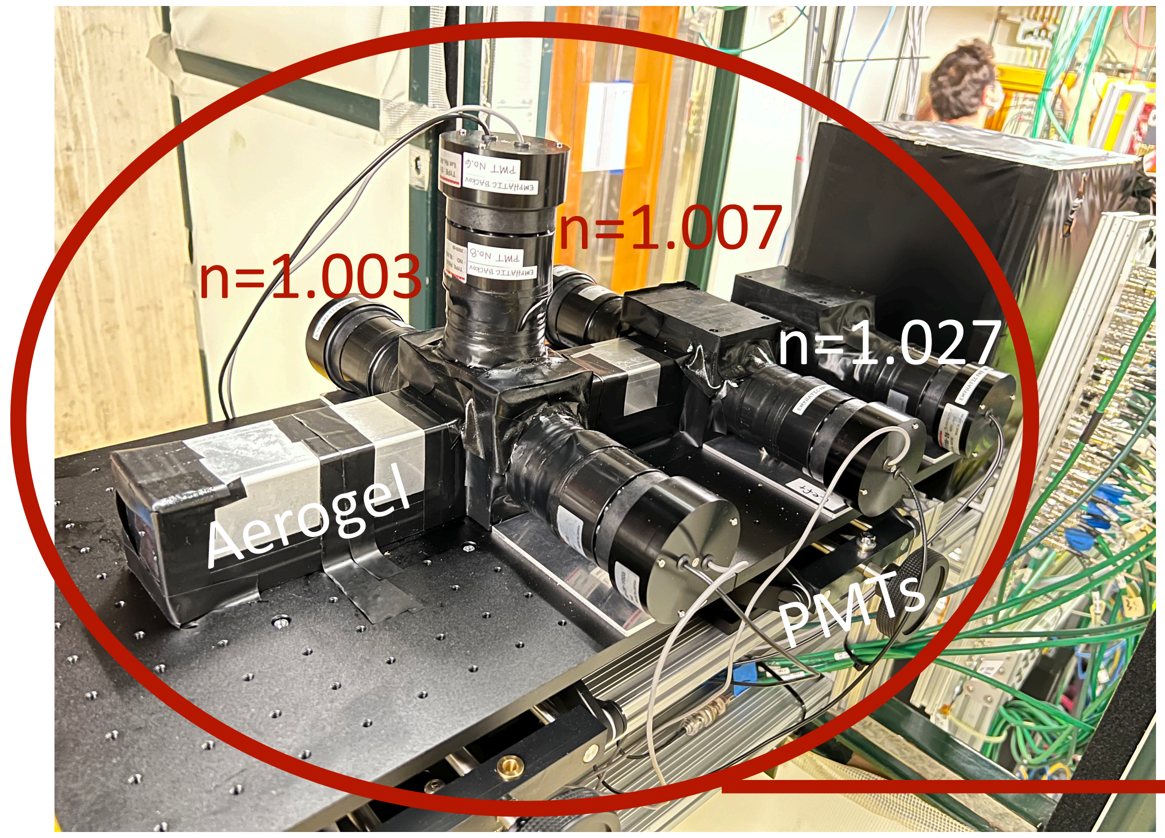
Gas Ckov

Gas Cherenkov:

- *Facility Cherenkov detector with inner and outer mirrors*
- *Filled with CO_2, pressure varied depending on the beam momentum.*

Beam Aerogel Cherenkov (BACkov):

- *Used for beam particle identification*



Beam aerogel Ckov

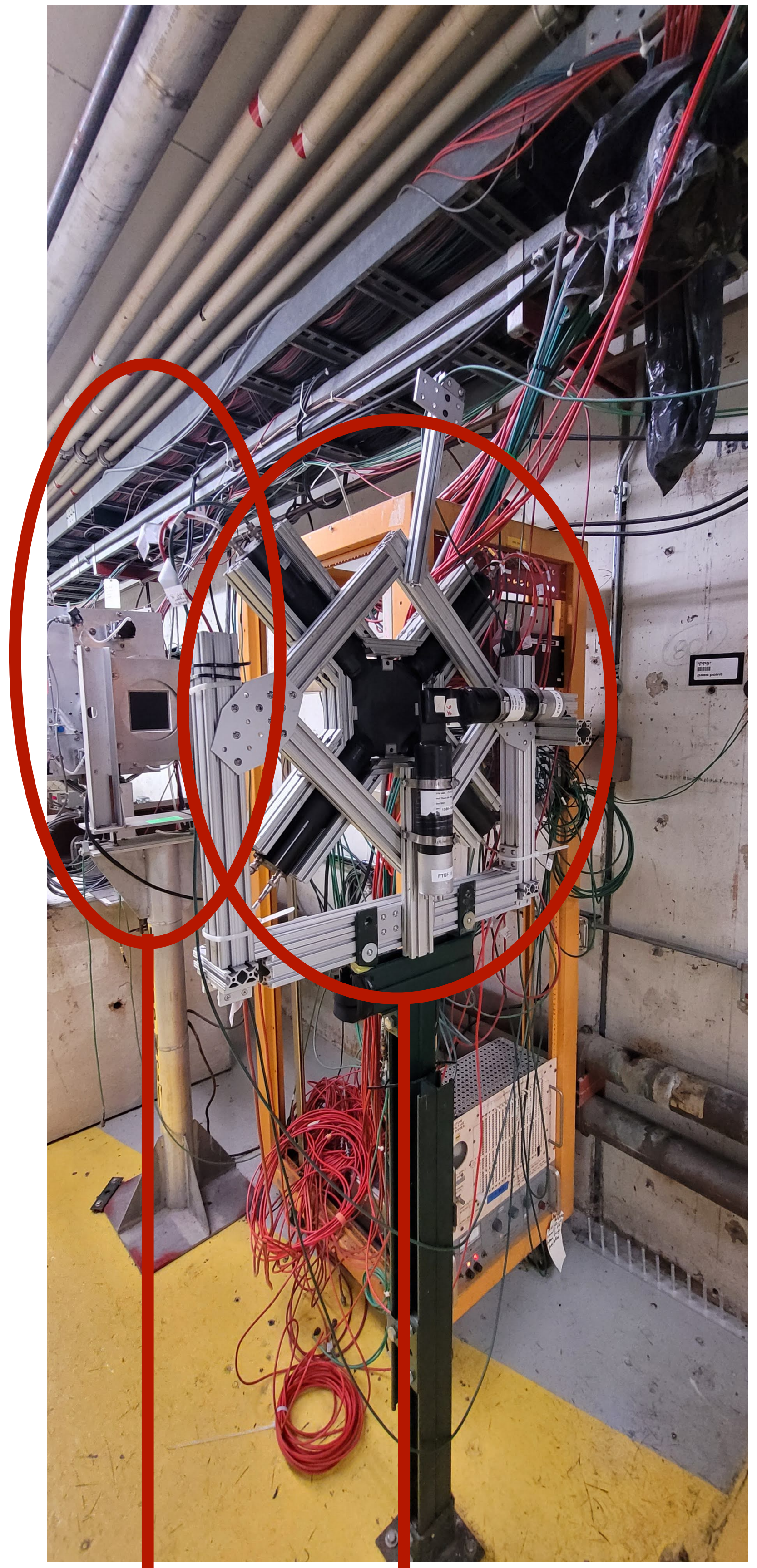
BACkov performace

- *Detect* (✓) or *no detect* (–) diagram

Beam	Particle	High-index n=1.027	Middle-index n=1.007	Low-index n=1.003
4 GeV/c	π	✔	✔	✔
	K	✔	–	–
	p	–	–	–
8 GeV/c	π or K	✔	✔	✔
	p	✔	–	–
12 GeV/c	π or K	✔	✔	✔
	p	✔	✔	–
120 GeV/c	(p)	✔	✔	✔

K/p separation (high-index, 4 GeV/c); π/K separation (middle-index, 4 GeV/c); Act as trigger counter (high-index, 8 and 12 GeV/c); K/p separation (middle-index, 8 GeV/c); K/p separation (low-index, 12 GeV/c); Calibration (120 GeV/c)

Beam characterization



Gas Ckov

Trigger

Gas Cherenkov:

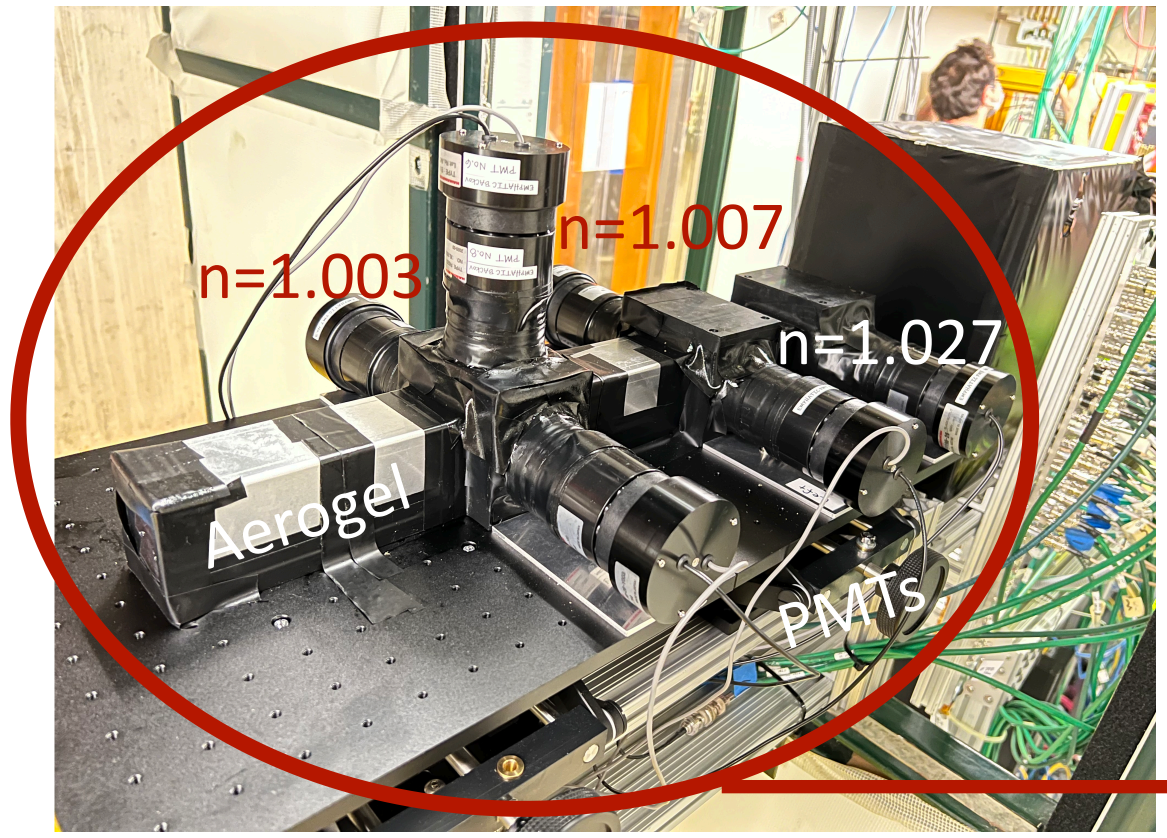
- *Facility Cherenkov detector with inner and outer mirrors*
- *Filled with CO_2, pressure varied depending on the beam momentum.*

Trigger detector:

- *Scintillator paddle with 4 PMTs, required 3-of-4 coincidence*

Beam Aerogel Cherenkov (BACkov):

- *Used for beam particle identification*



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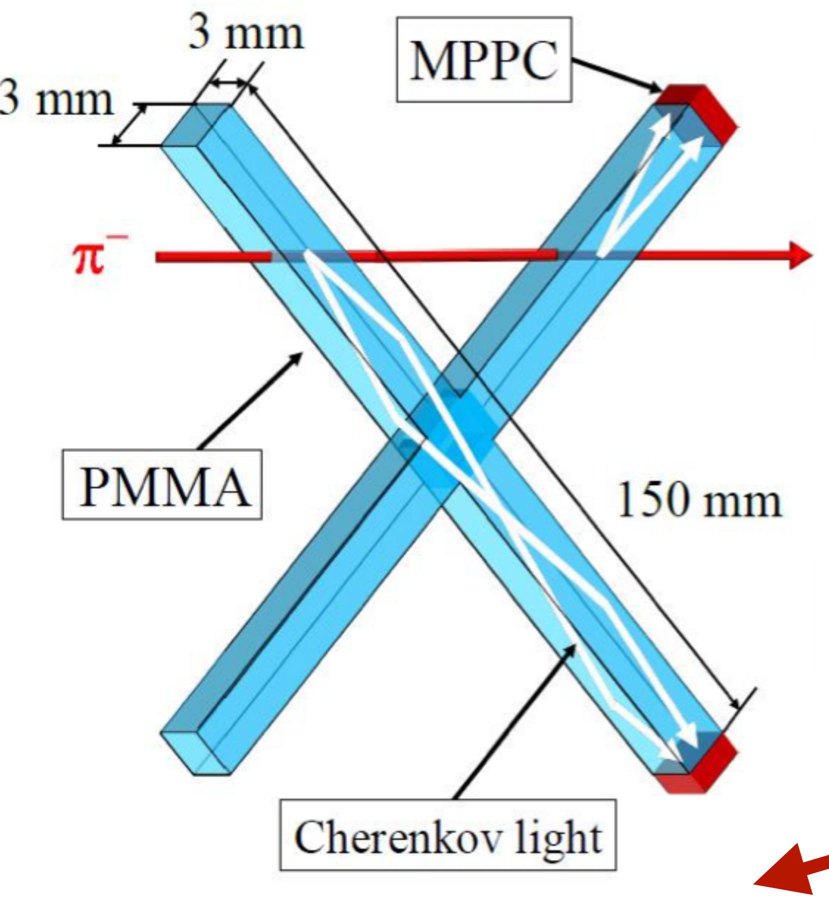
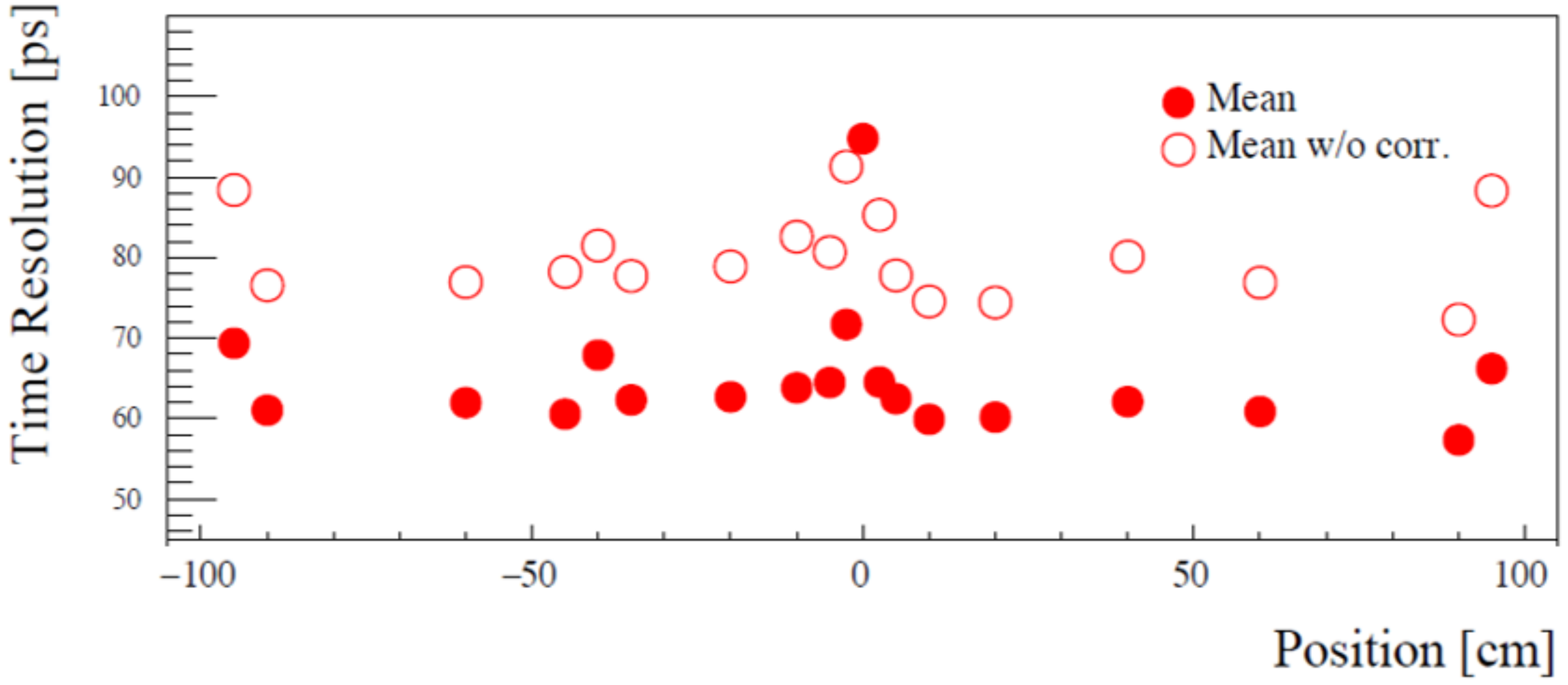
Beam	Particle	High-index n=1.027		Middle-index n=1.007		Low-index n=1.003	
4 GeV/c	π	✔		✔	π/K separation	✔	
	K	✔	K/p separation	–		–	
	p	–		–		–	
8 GeV/c	π or K	✔	Act as trigger counter	✔	K/p separation	✔	
	p	✔		–		–	
12 GeV/c	π or K	✔		✔		✔	K/p separation
	p	✔		✔		–	
120 GeV/c	(p)	✔		✔		✔	Calibration

Time of flight system



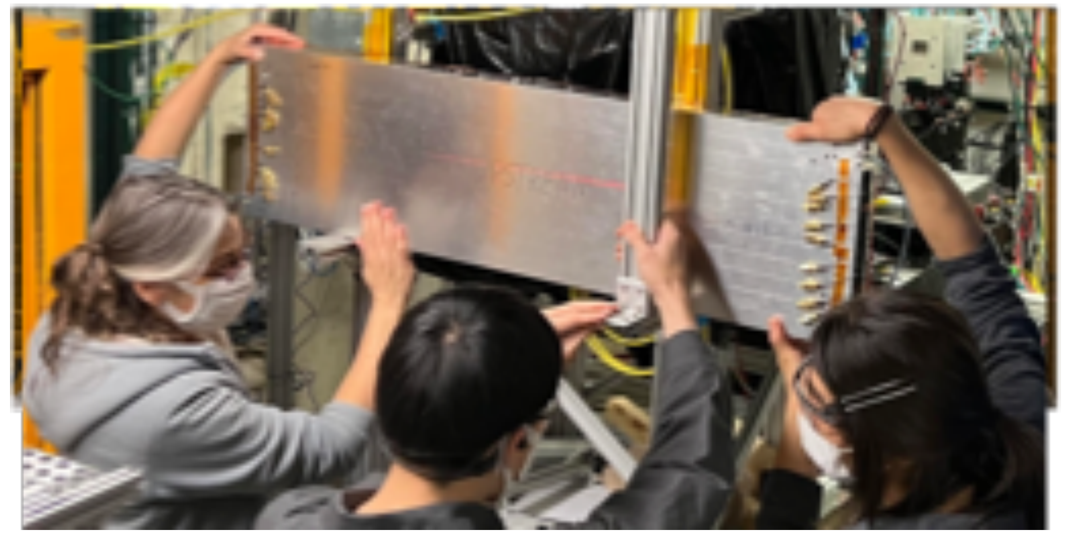
T0 ○ *x-shaped acrylic Cherenkov layered detector*

Expect combined timing resolution of ~70ps, particle separation up to ~1.5 GeV/c

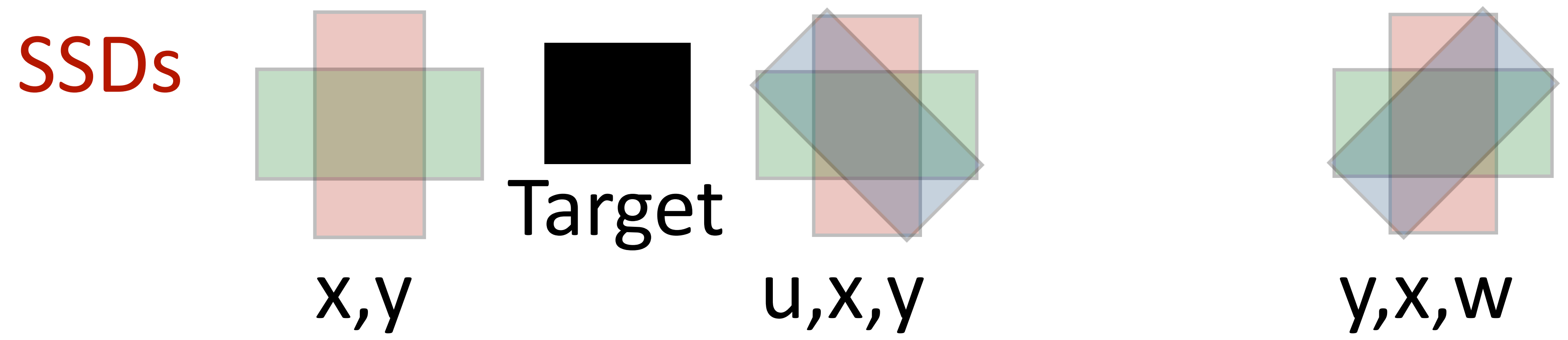


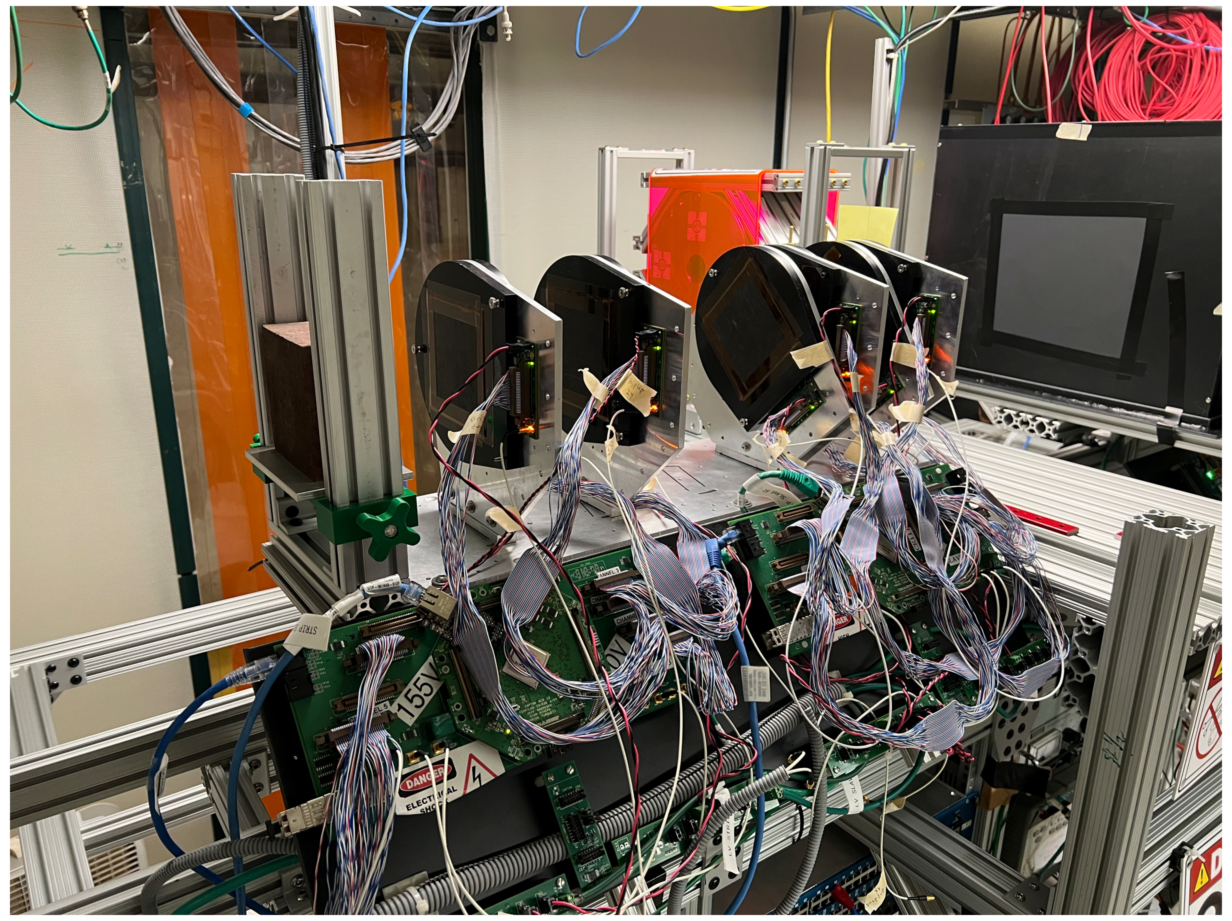
RPC

○ *Glass plates in acrylic boxes filled with gas*

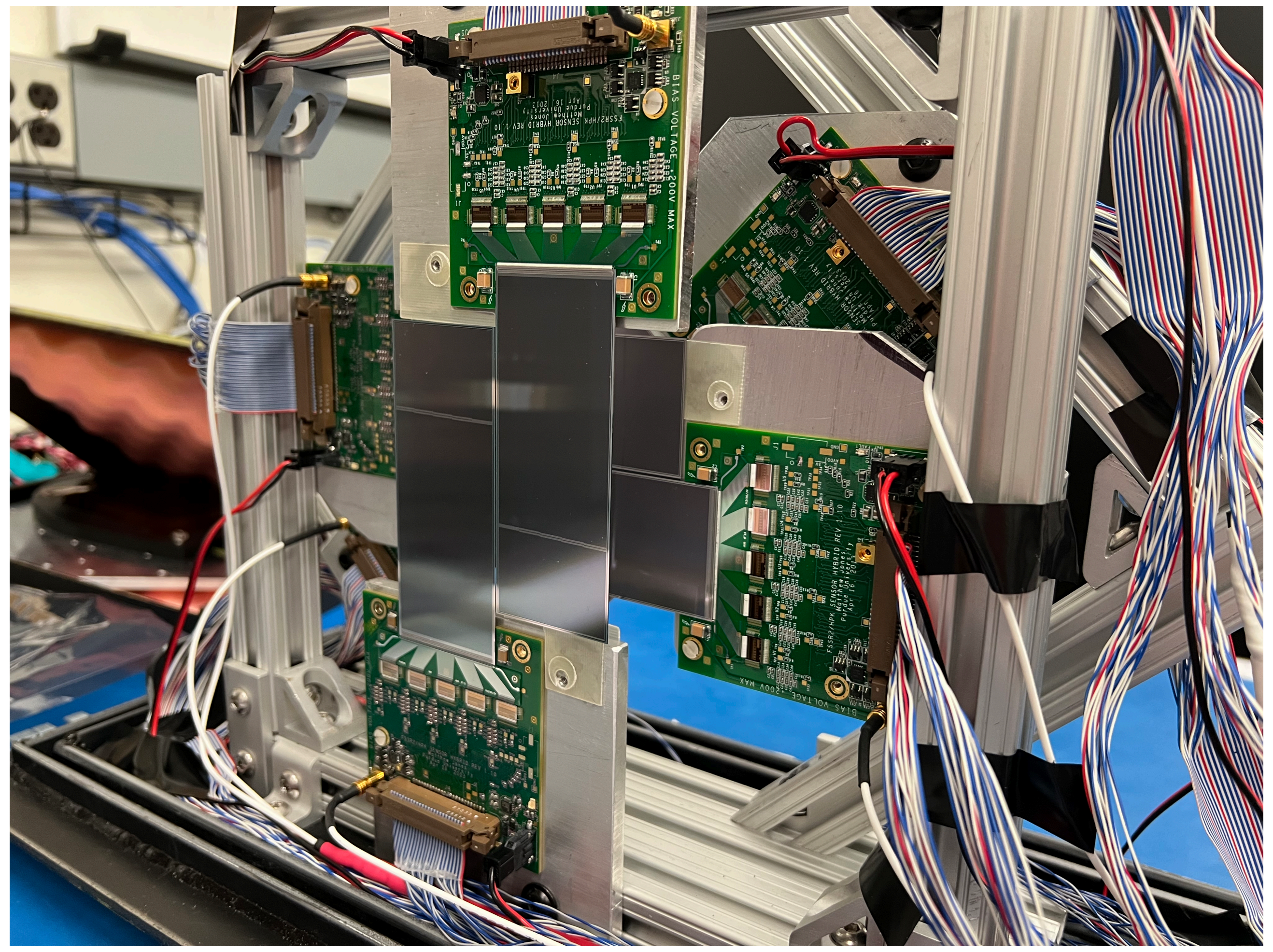


Silicon Strip Detectors (SSDs)



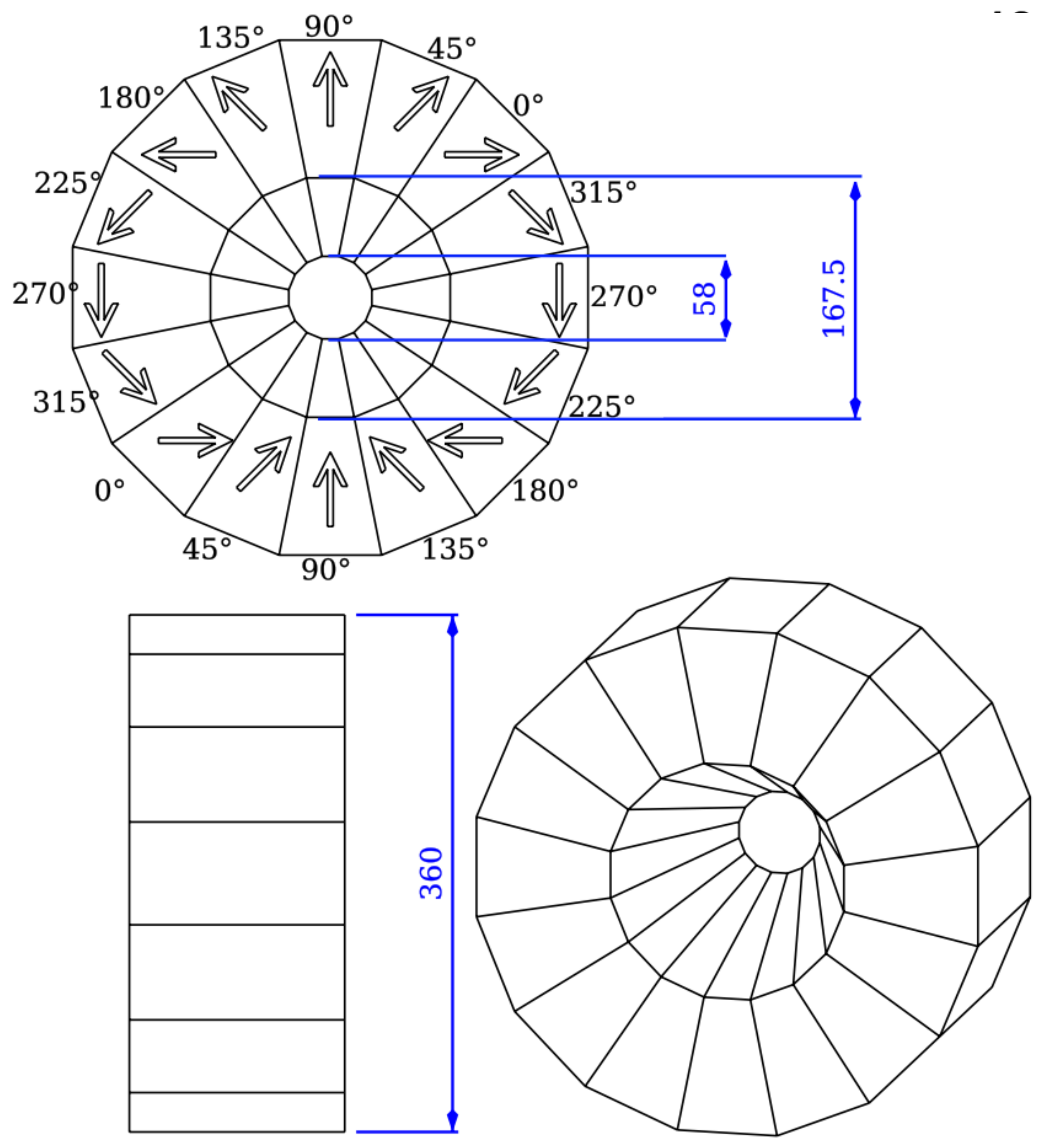


- *60 µm pitch and ~17.3 µm spatial resolution*
- *Used in the Phase1 runs for a ~100 mrad acceptance spectrometer*



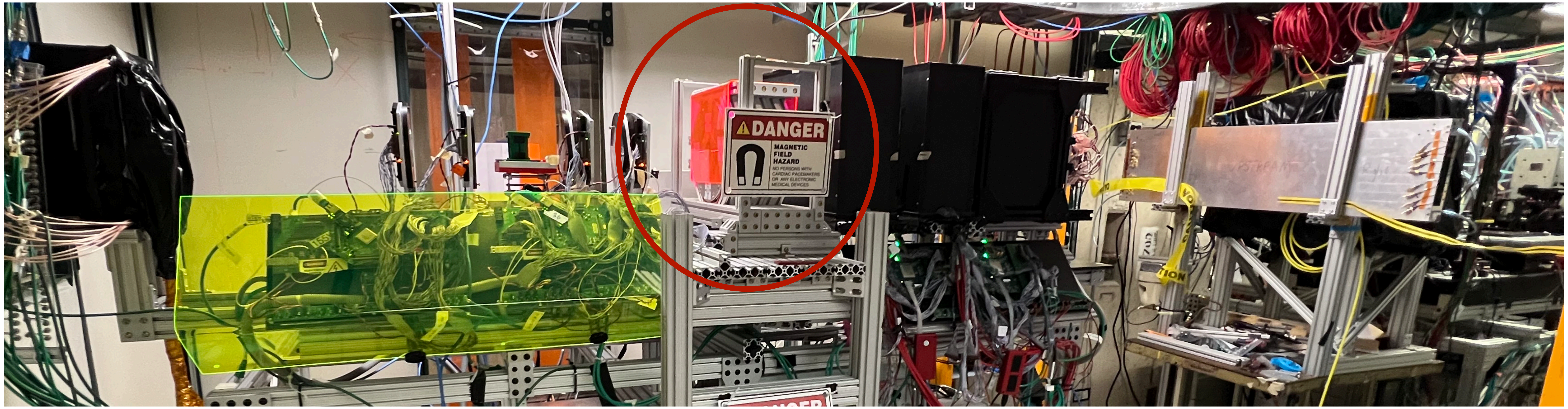
Permanent Magnet

Halbach Array



all measurements are in mm

$$\oint B \cdot dl = 1.2 \text{ Tm}$$

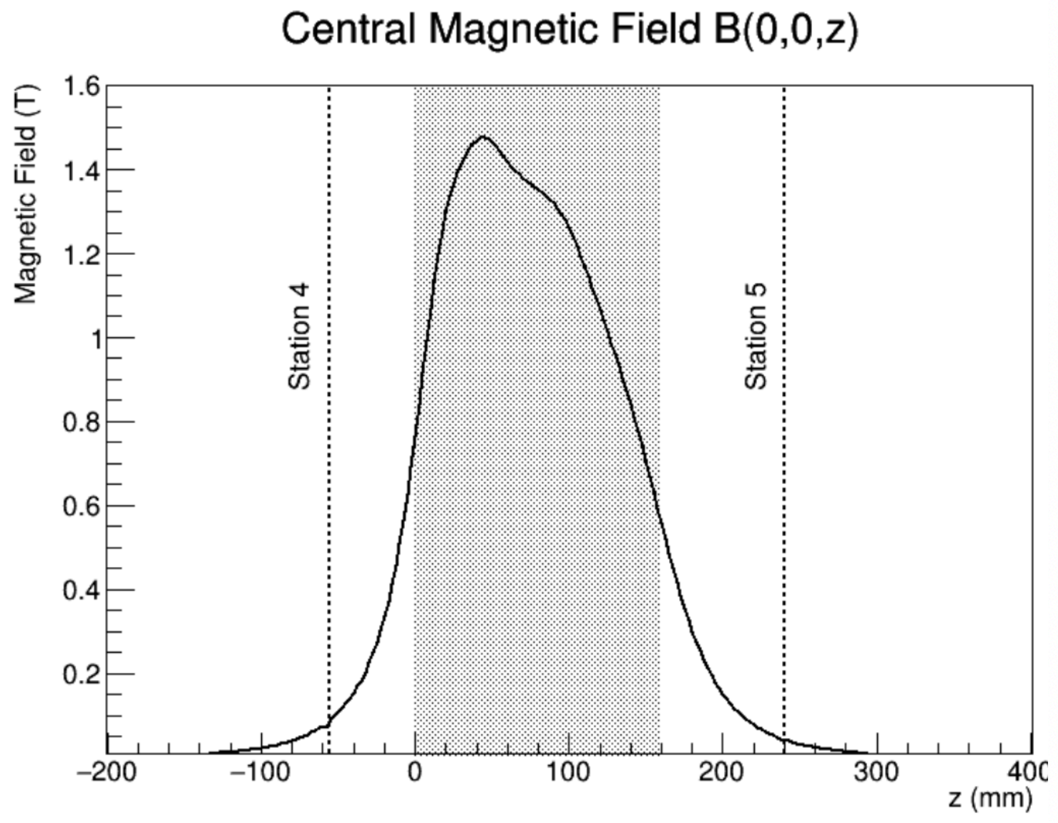


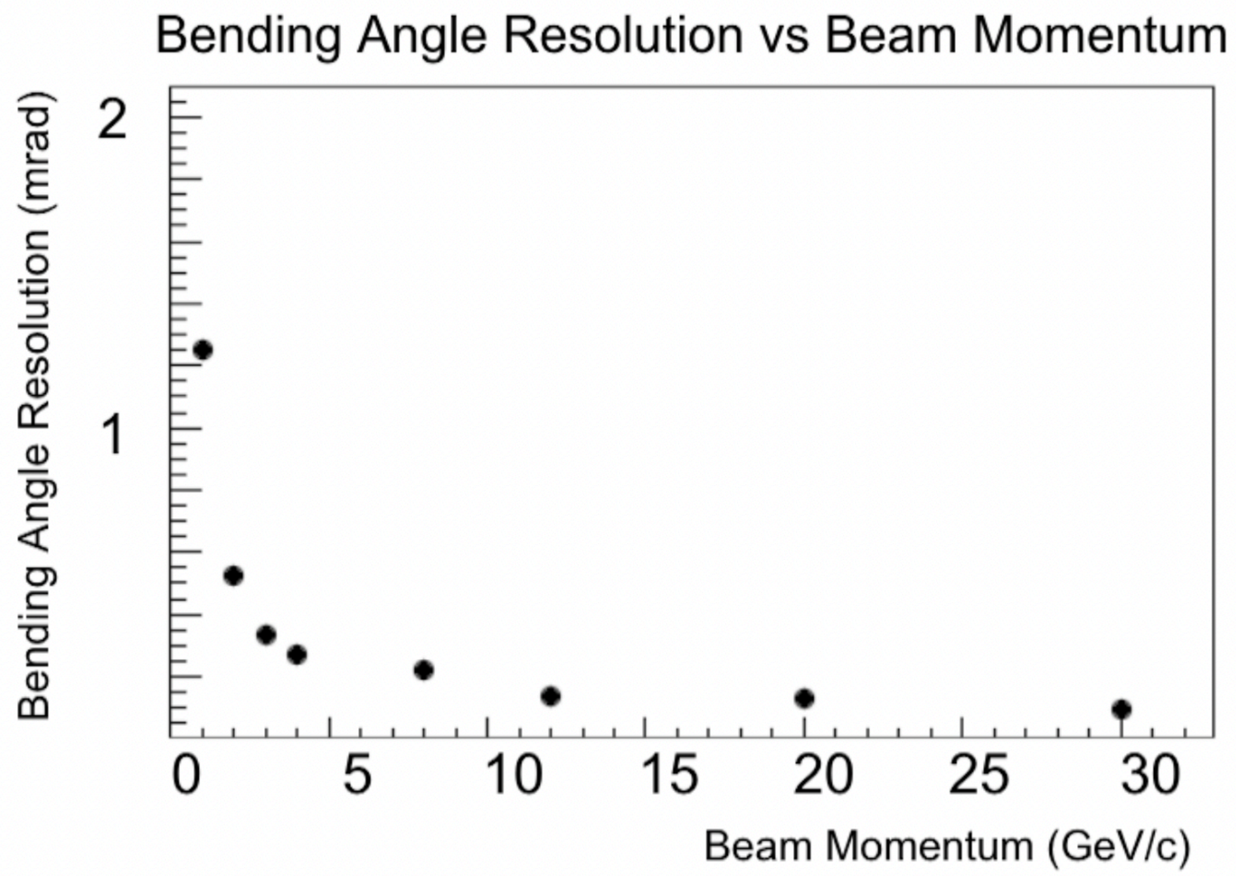
Segments made from large segments of Neodymium permanent magnets.

- *Prototype small-aperture magnet used in Phase-1*

Ongoing efforts on single-track and momentum reconstruction

- *Reconstruct:*
  - *scattering angle*
  - *bending angle*





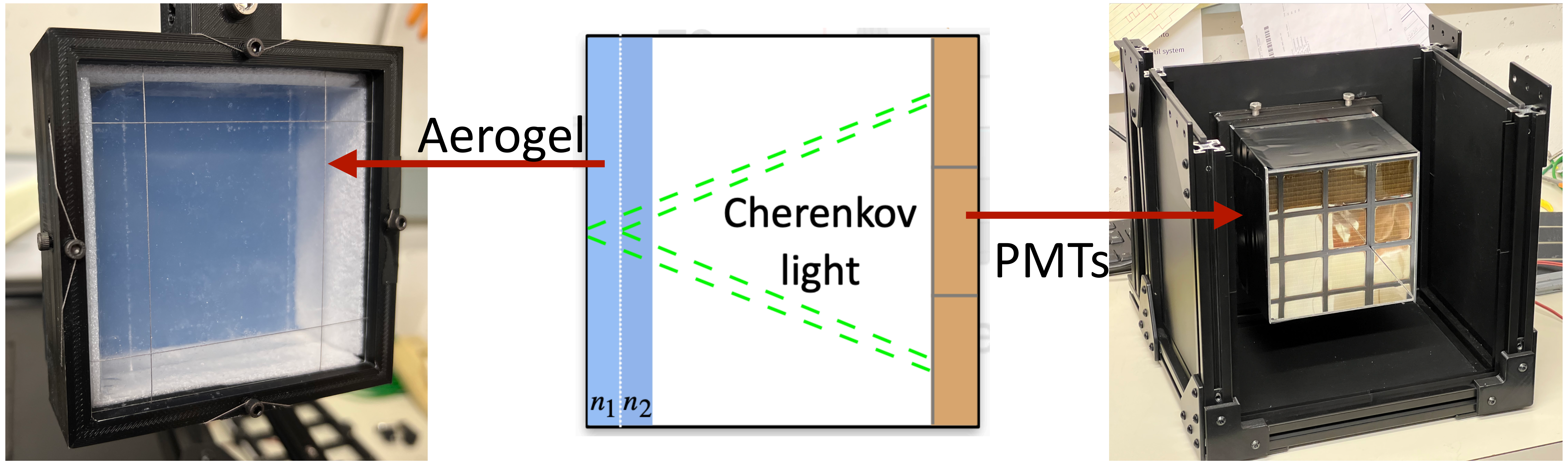
Visit Robert Chirco's poster for more details

Aerogel Ring Imaging CHerenkov (ARICH)

Prototype ARICH in Phase-1:

150 mrad acceptance

- 2 layers of aerogel, developed for Belle II by Chiba
- Aerogels with lower indices of refraction (n=1.02-1.03) and good transmittance
- Expect to achieve 2σ π-K separation for p<8 GeV/c.



Phase-1 data runs

Target	Beam Mom (GeV/c)	# Triggers	Target	Beam Mom (GeV/c)	# Triggers
Graphite	120	2.5M	**Berylium**	-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

An additional 20% of data was collected across all settings specifically targeting alignment and background studies

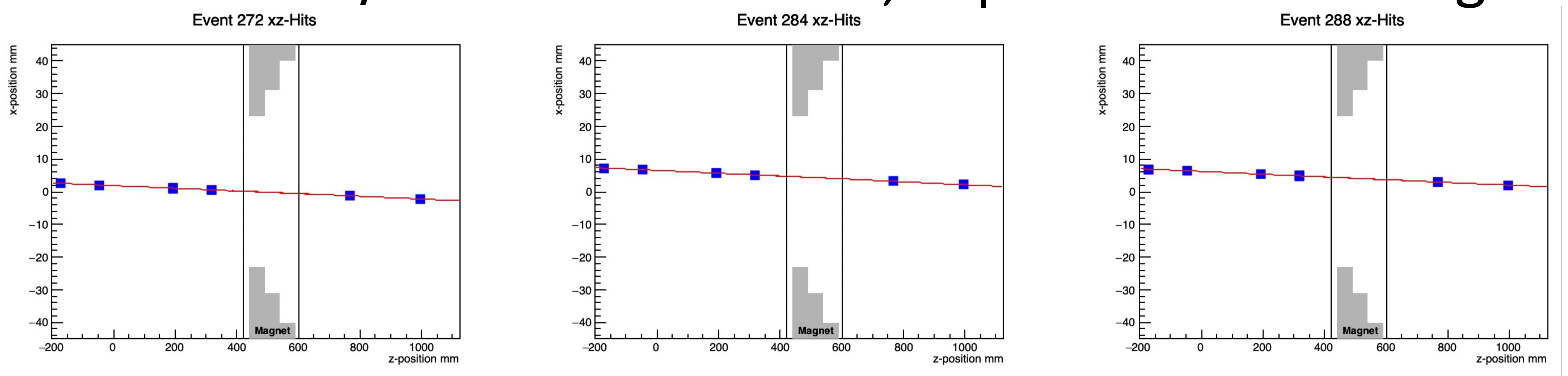
- configurations: both target-out and magnet-out.

Collected over 2 runs (3 weeks each run. This includes installation and removal : ~20 days of data collection

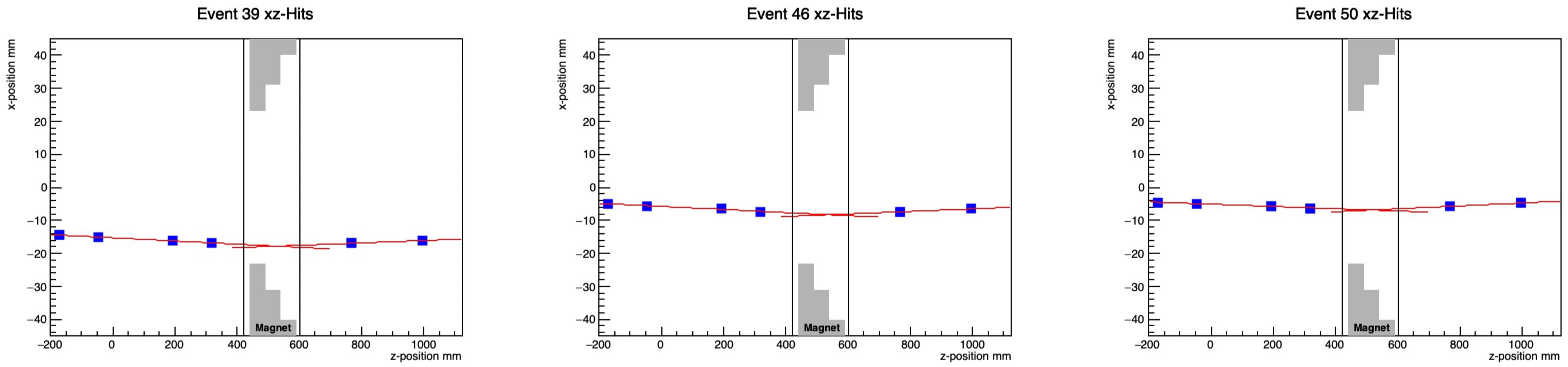
Data rates at $p < 20$GeV/c are very low, takes time to collect statistics

Phase-1: first look at the data

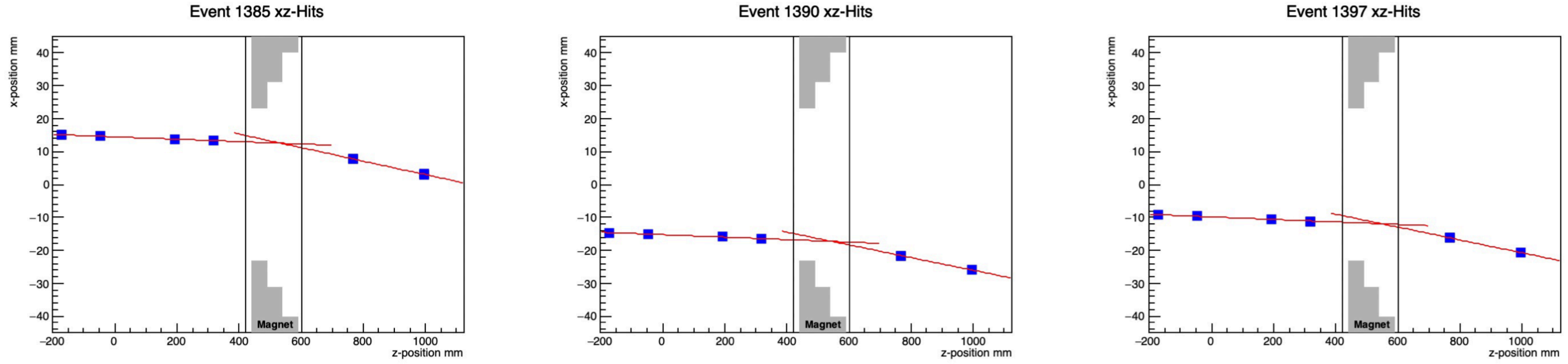
120 GeV/c Proton: XZ-Plane, Expected no Bending



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



We see bending tracks.



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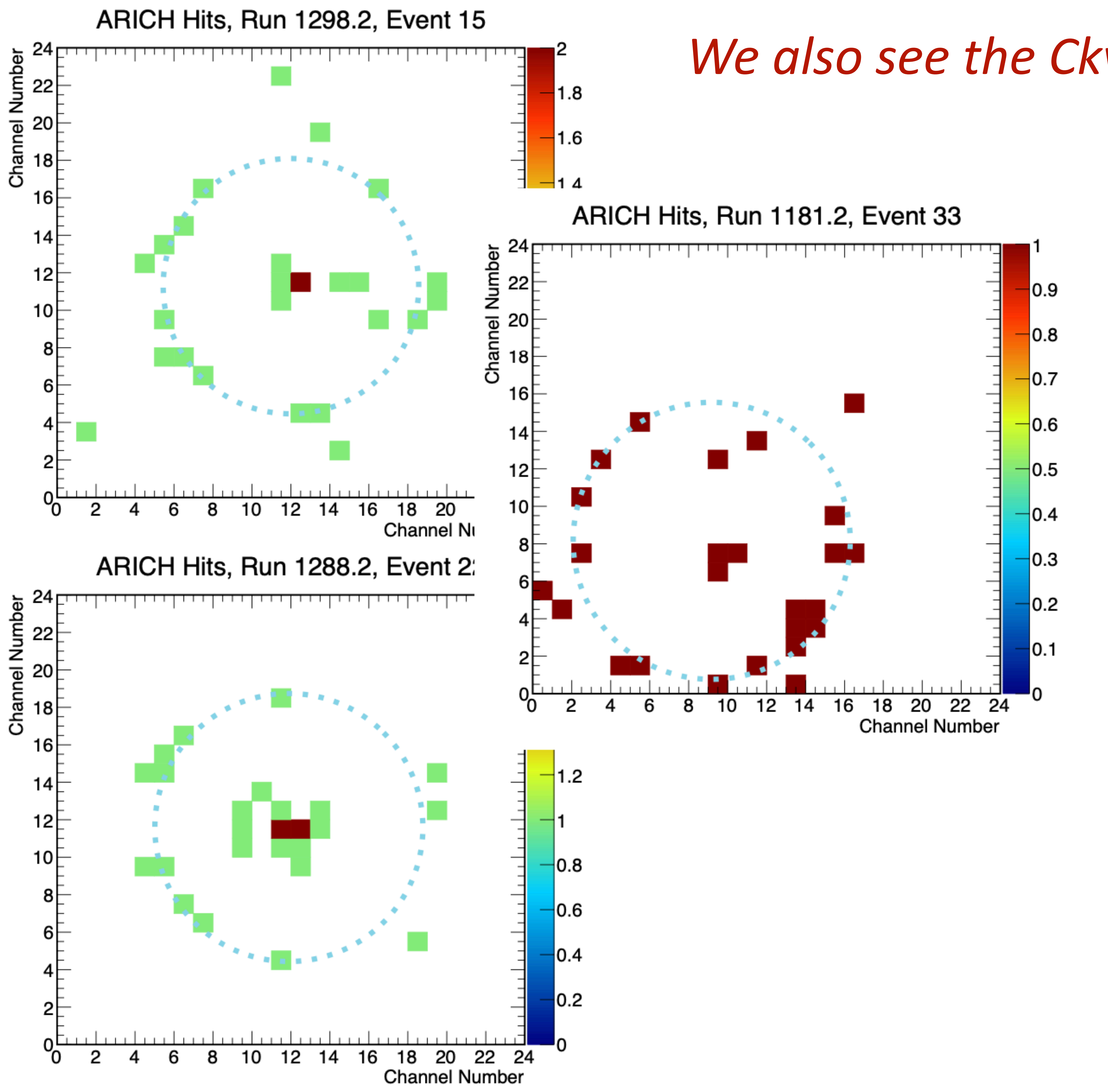


We also see the Ckv rings

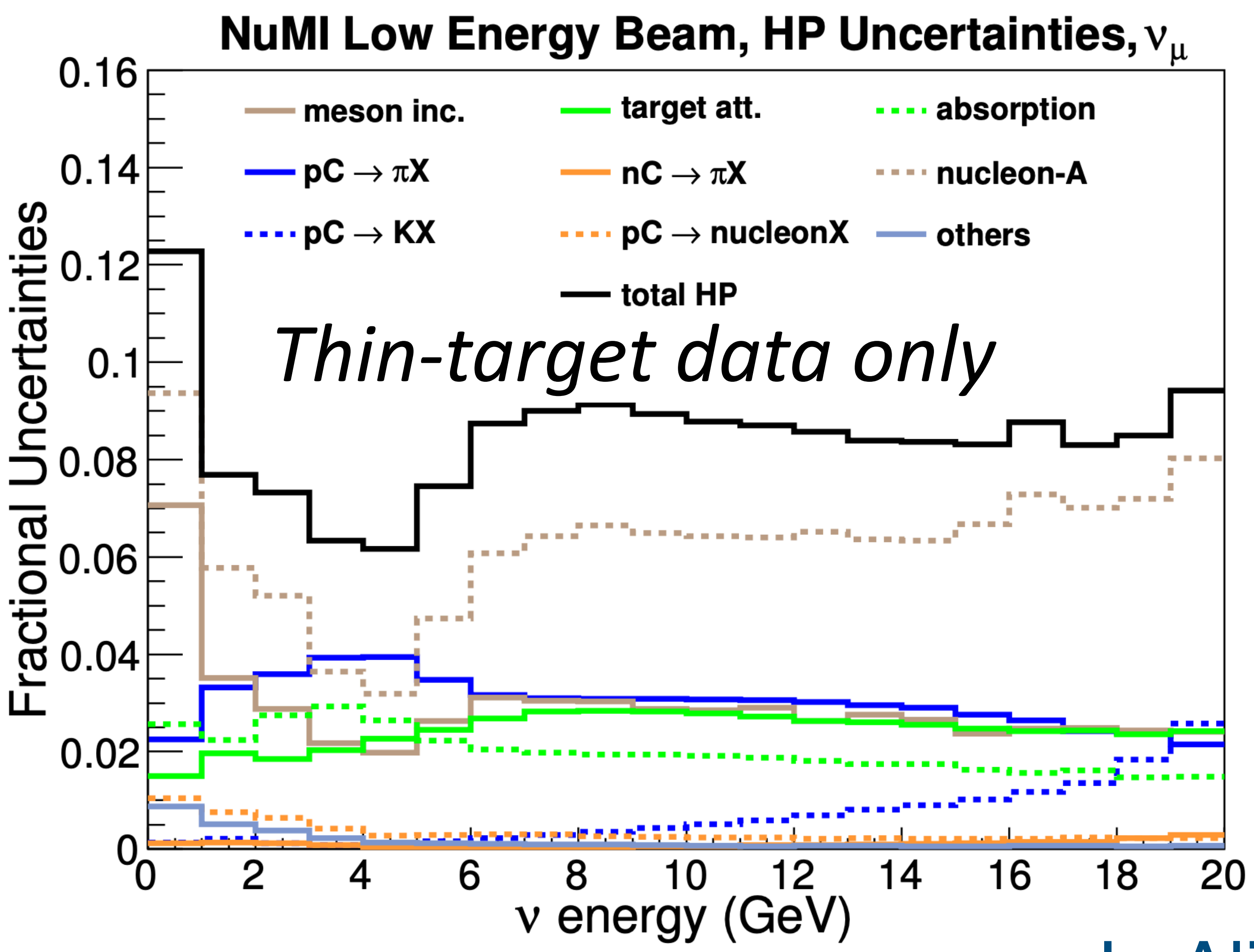
The collaboration is focused on

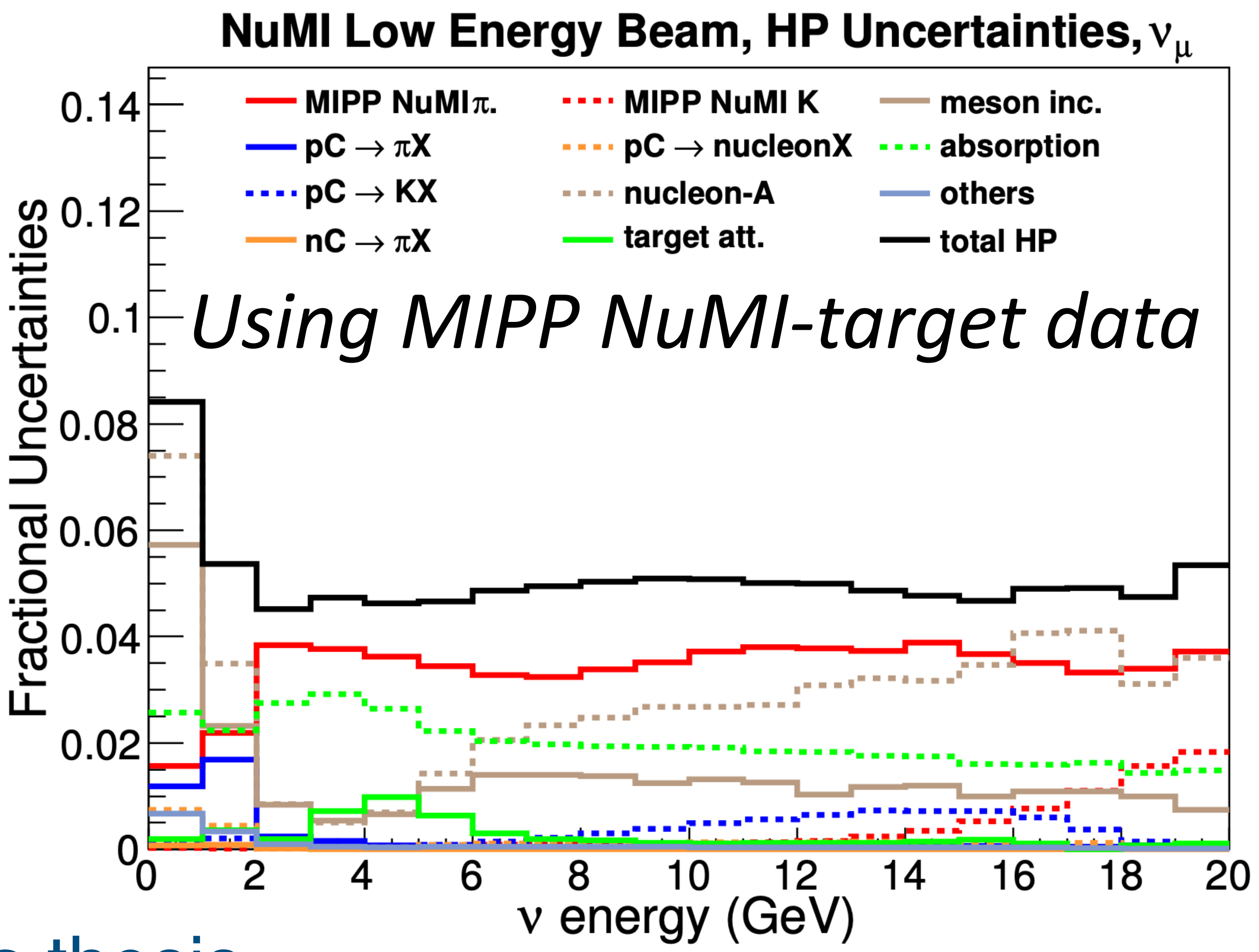
- alignment and calibration
- implementing more precise magnetic field
- improving track reconstruction and PID
- developing the analsys infraestruture (CAFs)

Phase 2: neutrino production target

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

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





L. Aliaga thesis

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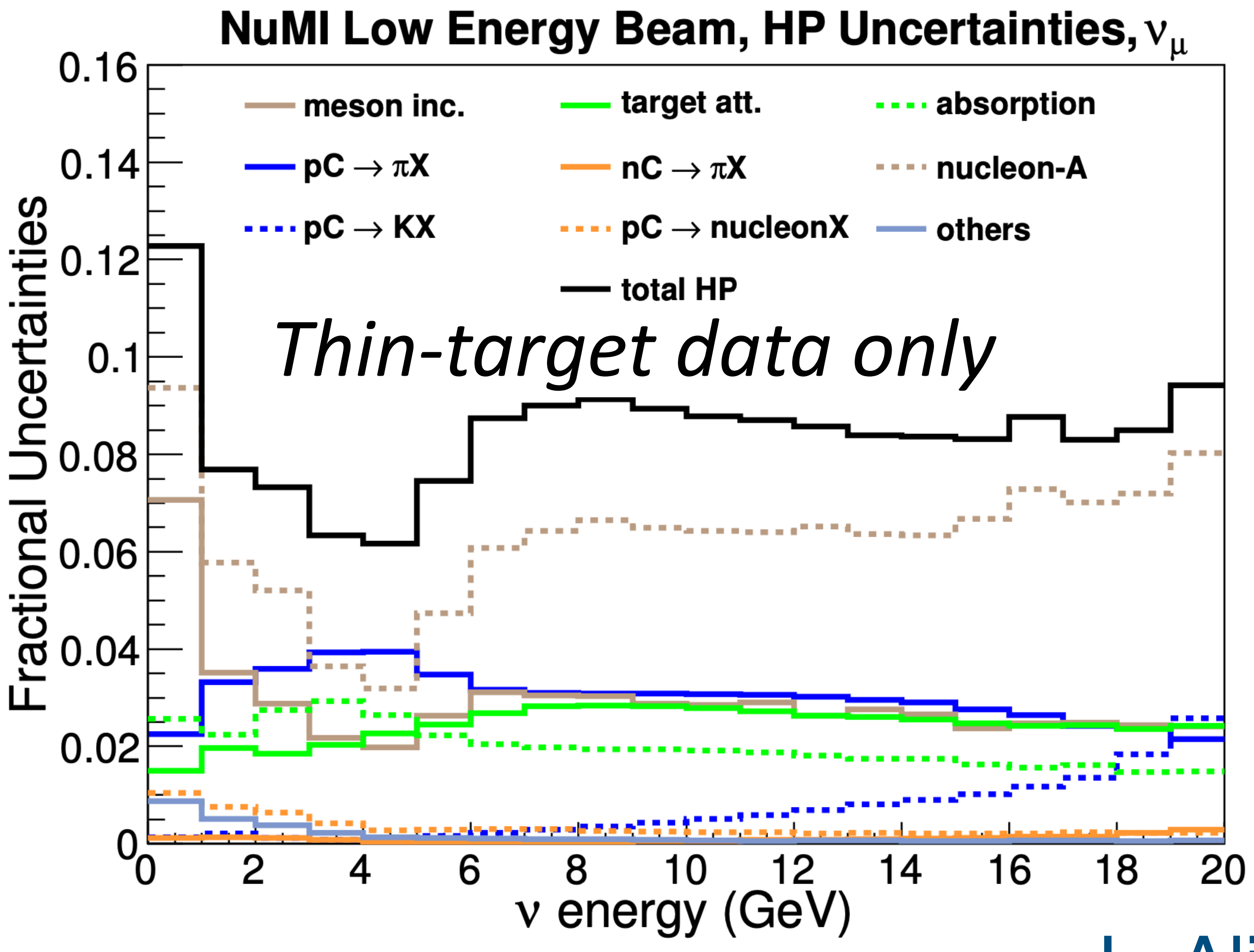
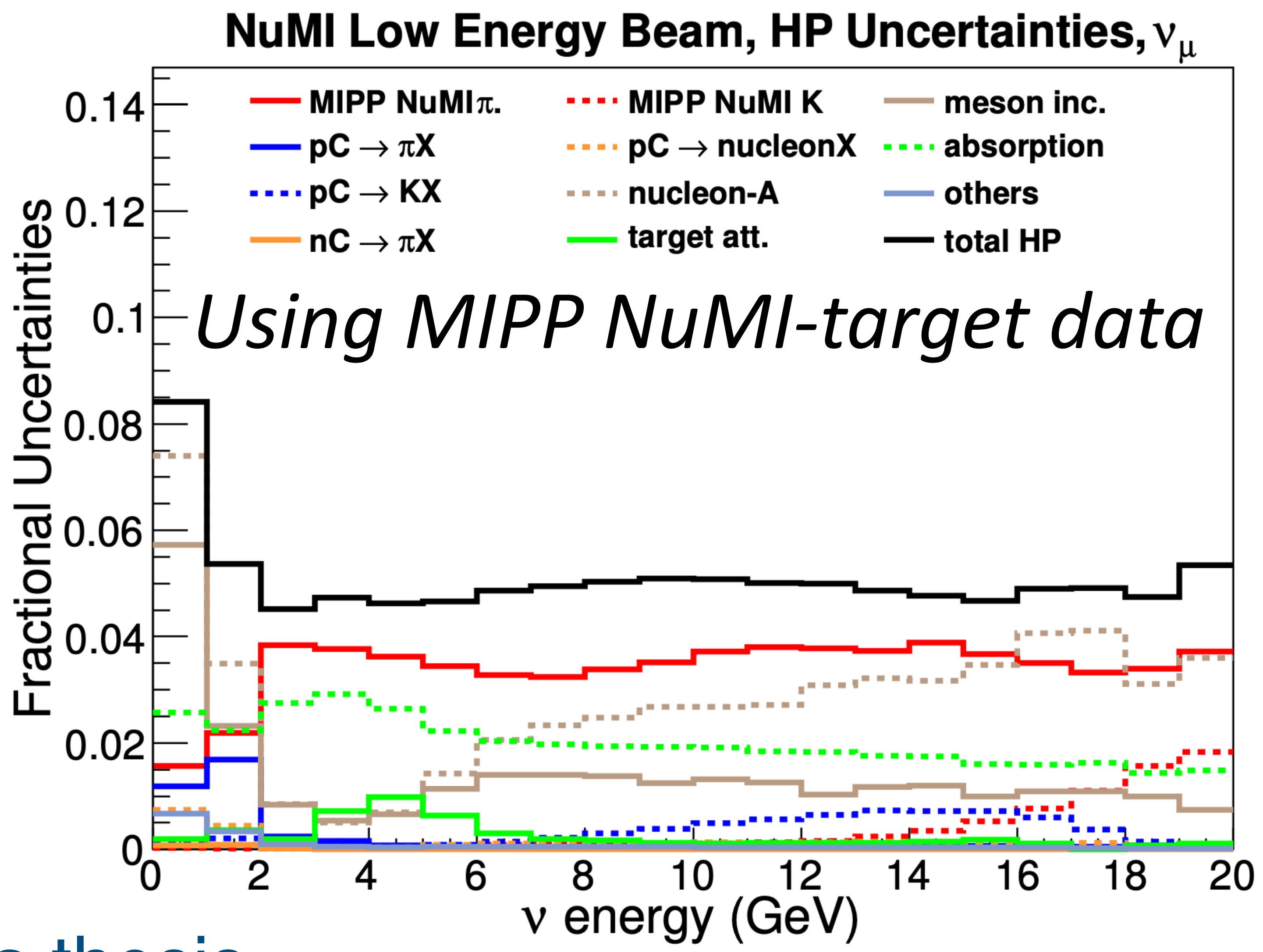
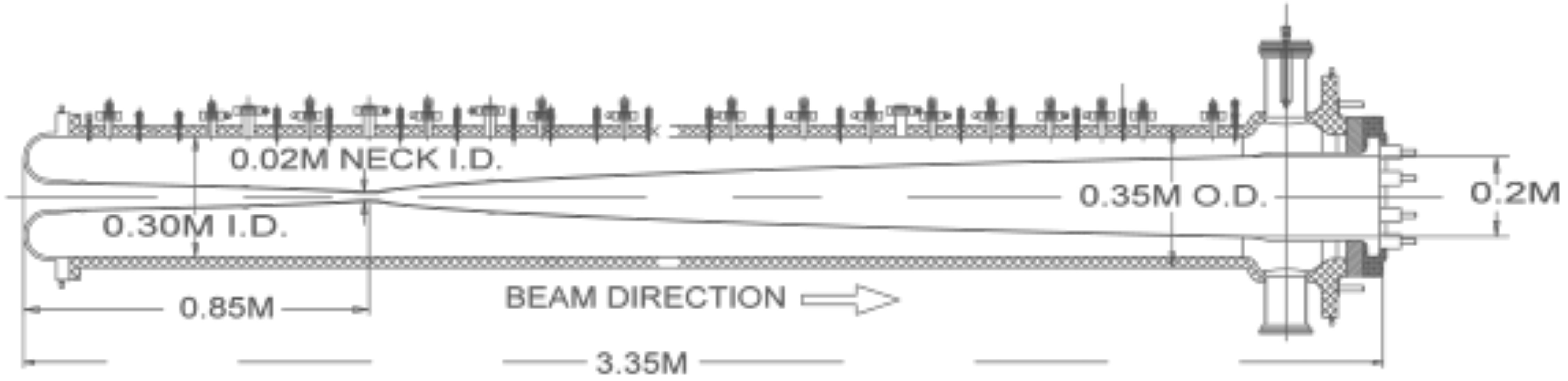




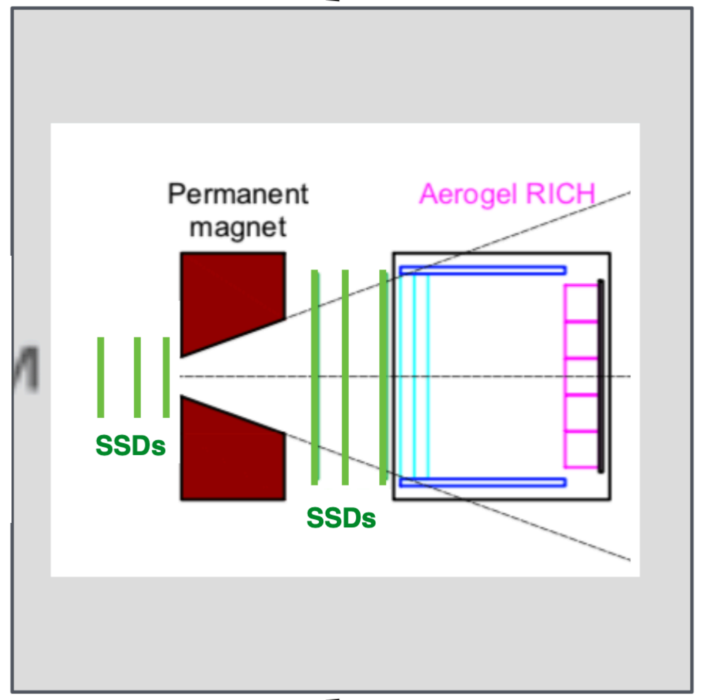
L. Aliaga thesis

We are going to put the EMPHATIC Phase1 spectrometer on a motion table downstream of spare NuMI horn and target.

- *Minimal goal: to measure charged-particle spectrum downstream of target+horn.*
- *Power supply also available; hope to measure with pulsed horn in the future.*



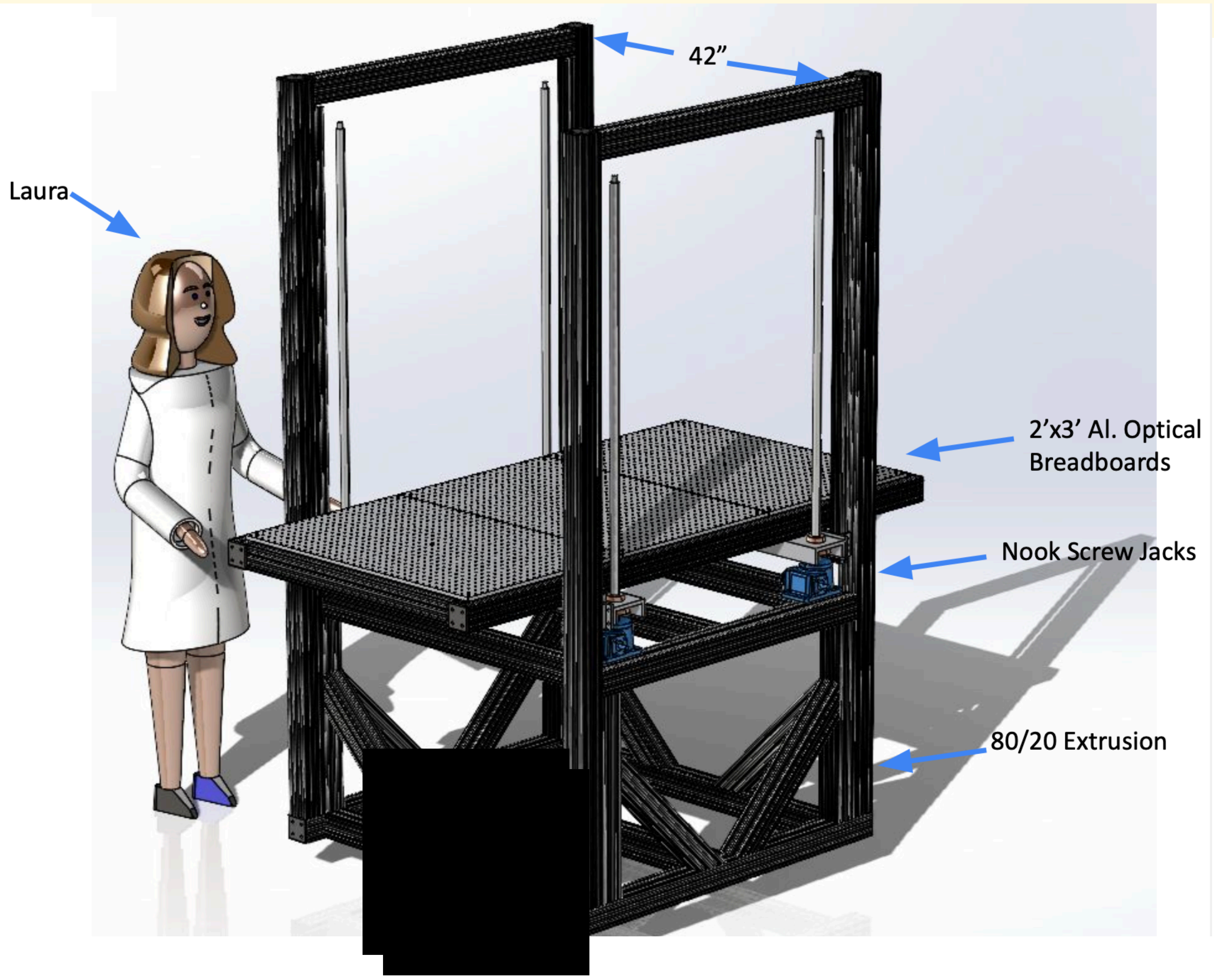
NuMI target + Horn 1

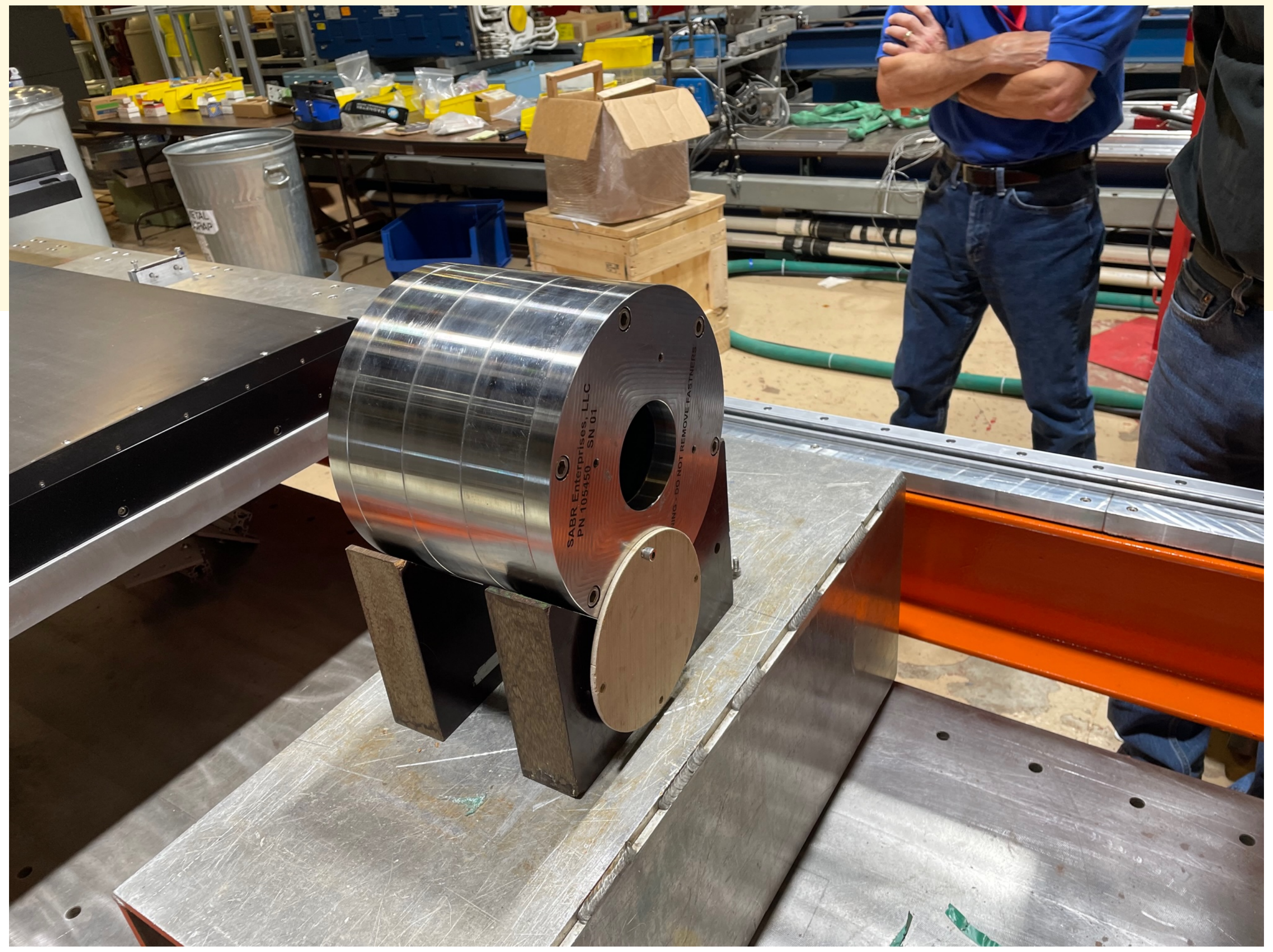


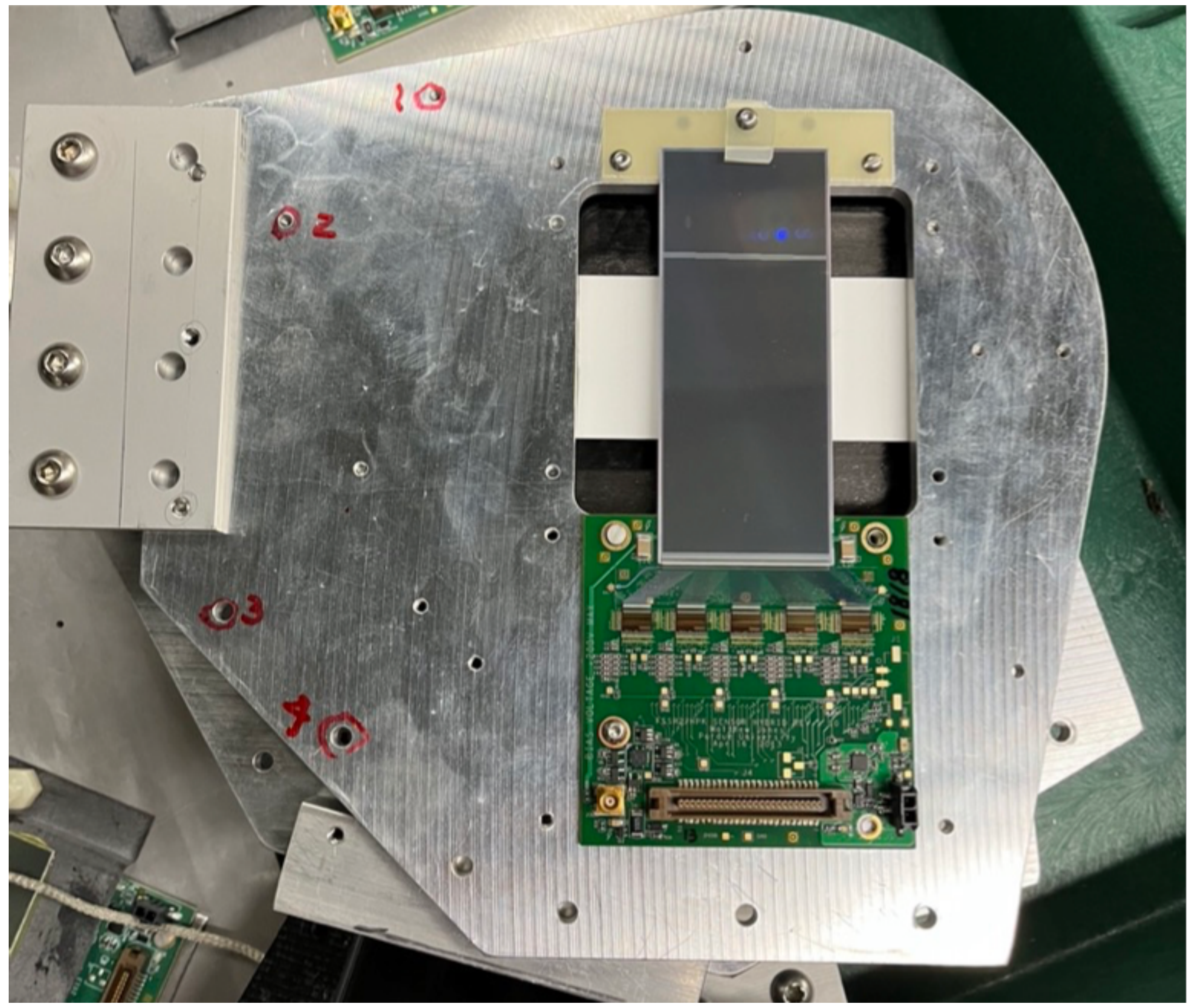
Motion Table

Phase 2: preparation

- New magnet purchased
- Motion table and SSD mounts
- NuMI Target and Horn + mounting
- New SSDs (more old-style, some w/ new front-end electronics)







Move into MCenter this summer: more space and collect data for a long time

We will be ready for Phase-2 when beam returns in late 2024.

Summary

- Predicting the neutrino flux at both detectors in oscillation experiments, several single-detector measurements, and in the exploration of Beyond Standard Model (BSM) physics requires new HP data
- EMPHATIC is addressing this need for more data to improve our knowledge of hadron production, improve flux prediction, and reduce flux uncertainties.
- EMPHATIC initial results, obtained during a proof-of-principle run in 2018, have been published (Phys. Rev. D 106, 112008).
- We currently analyzing data from Phase-1 thin-target data.
- Our team is currently in preparations for Phase 2, which include additional thin-target data and measurements using the NuMI target and horn with a small-acceptance spectrometer, promising further advancements in the improvements of the flux prediction.

Thank you!

RCNP
University of Regina
THE UNIVERSITY OF WINNIPEG
NAGOYA UNIVERSITY
KOBE UNIVERSITY
OSAKA CITY UNIVERSITY
大阪大学 OSAKA UNIVERSITY
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
ACADEMIA SINICA
TOHOKU UNIVERSITY
CHIBA UNIVERSITY
RIKEN
Fermilab
KYOTO UNIVERSITY
KEK-JAPAN
UNIVERSITY OF HOUSTON
THE UNIVERSITY of MISSISSIPPI
KENNESAW STATE UNIVERSITY
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