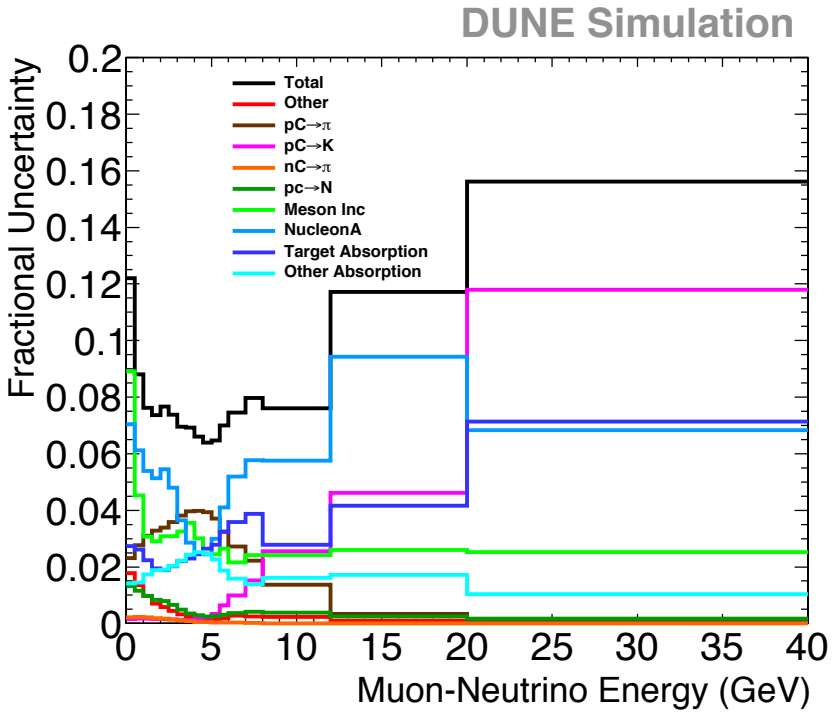
EMPHATIC

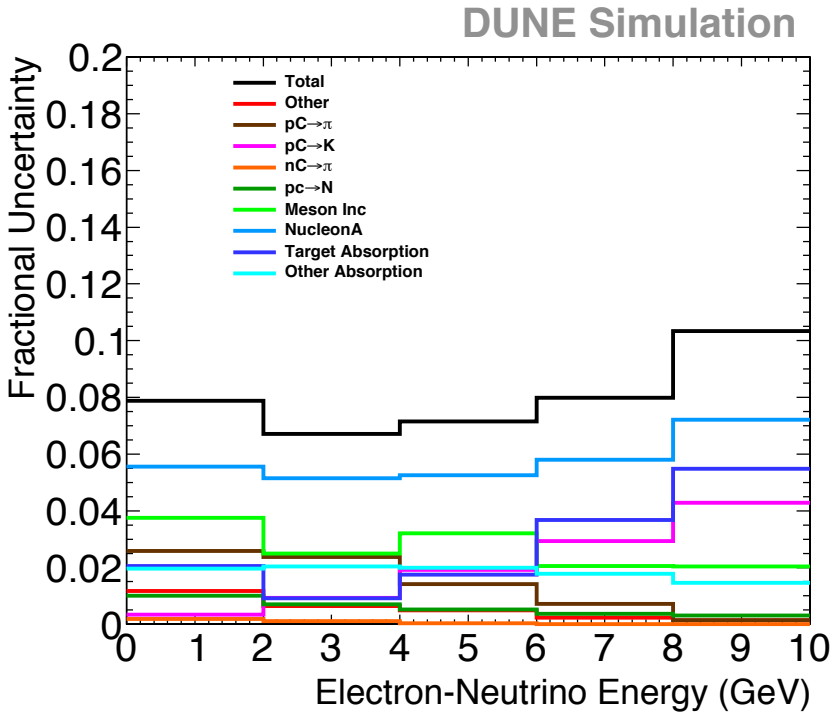
A new table-top hadron production experiment for improved neutrino flux predictions

Jonathan Paley
On Behalf of the EMPHATIC Collaboration

Aug. 2, 2022
NuFact
Snowbird, UT

Neutrino Flux Uncertainties





- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread).
- Lack of proton and pion scattering data at lower beam energies.
- **Reduction of flux uncertainties improves physics reach of most near detector analyses, and any non-3-flavor (PMNS) oscillation analysis.**
- **New hadron production measurements support the oscillation program by increasing confidence in the a-priori flux predictions and ND measurements.**

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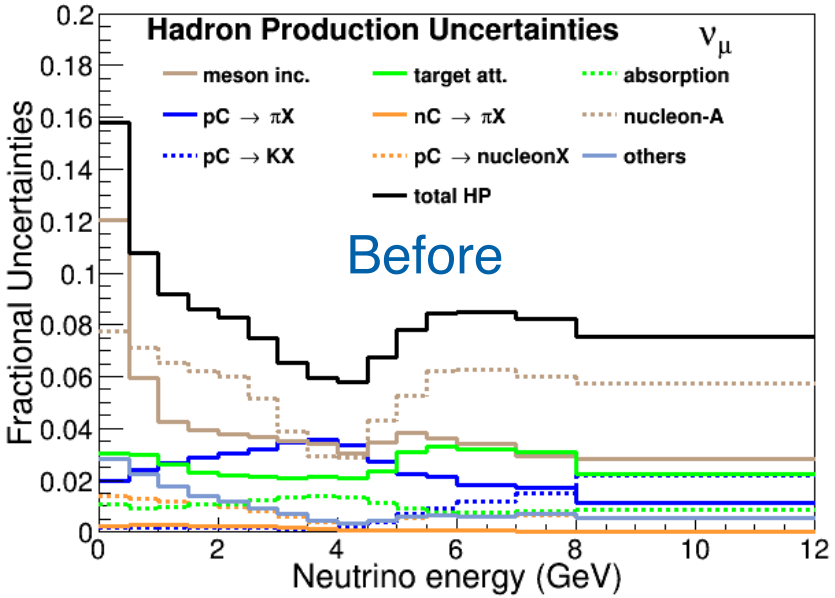
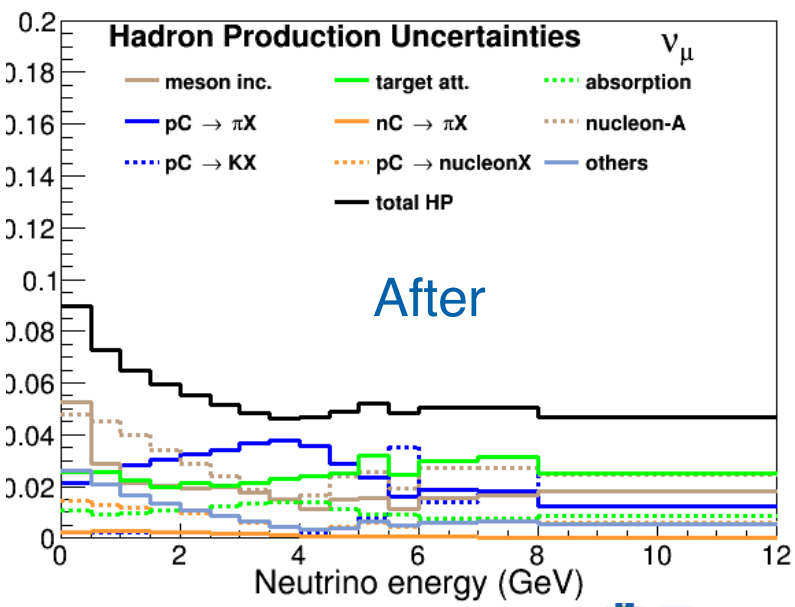
Neutrino Flux Uncertainties - Can we do better?

- Reasonably achievable uncertainty reduction:
  - No improvement for π production where ≲ 5% measurements already exist
  - 10% uncertainty for K absorption (currently 60-90% for p<4 GeV/c, 12% for p>4 GeV/c)
  - 10% on quasi-elastic interactions (down from 40%)
  - 10% on p,π,K + C[Fe,Al] —> p + X (down from 40%)
  - 20% on p,π,K + C[Fe,Al] —> $K^{\pm}$ + X (down from 40%)

Not covered by current data

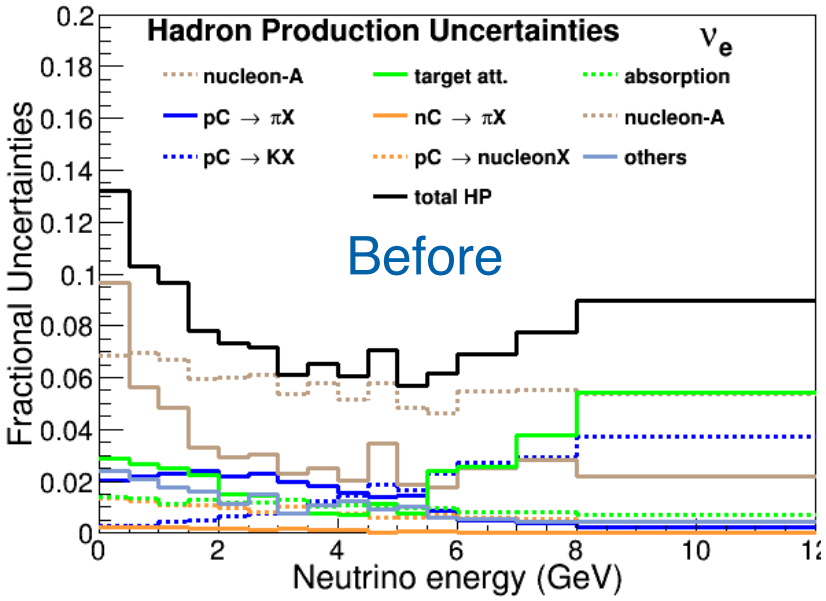


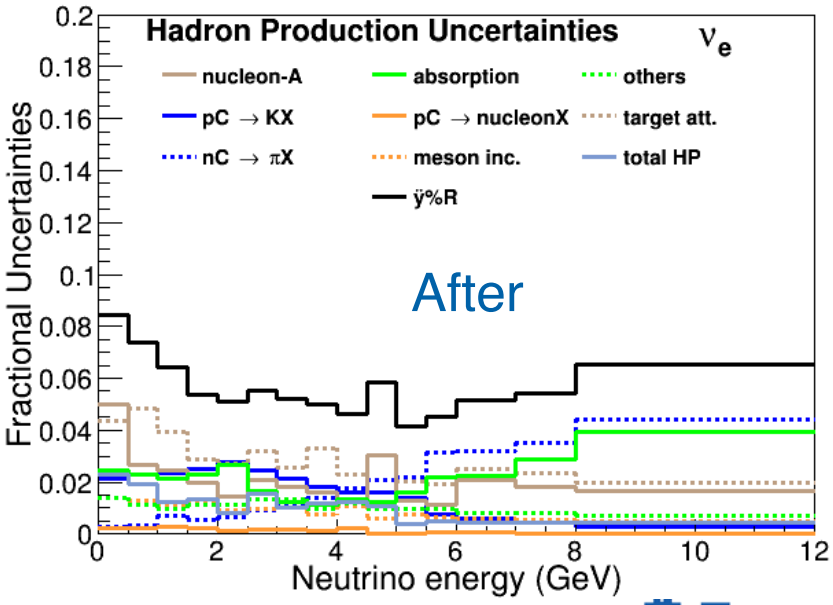


Note: flux uncertainties determined by EMPHATIC, not DUNE

Neutrino Flux Uncertainties - Can we do better?

- Similar observations for the electron-neutrino flux.





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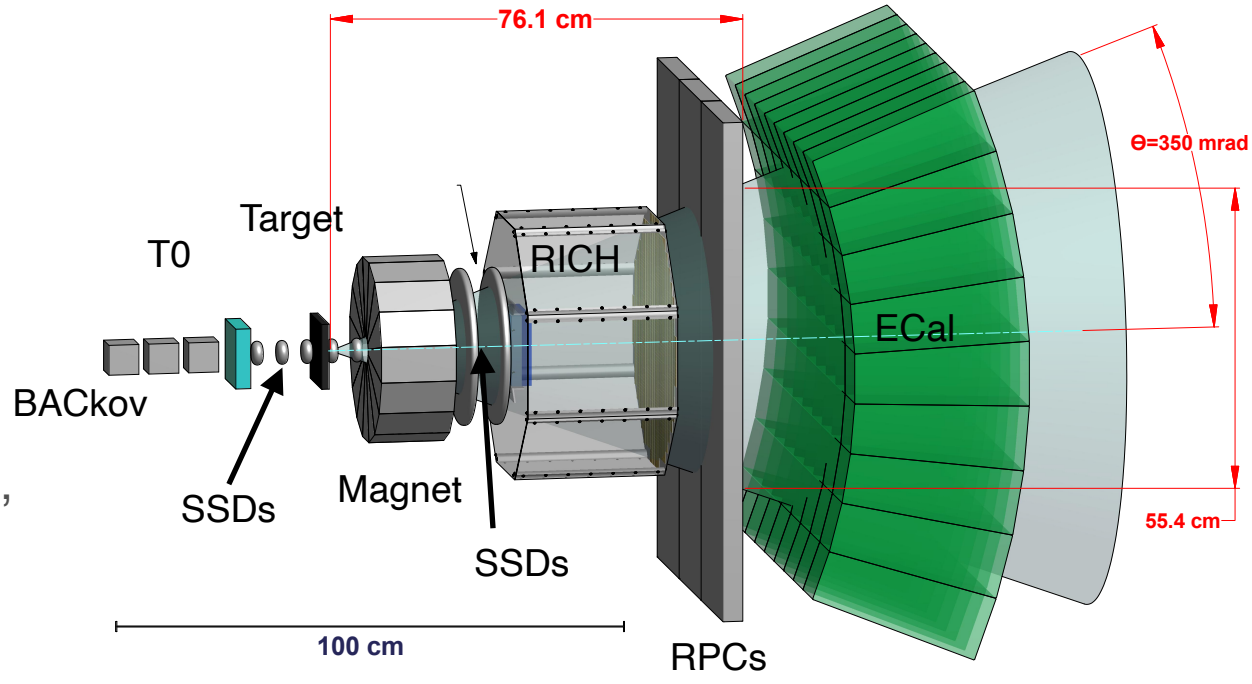
EMPHATIC

- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**est beam **I**n **C**hicagoland
  - Uses the FNAL Test Beam Facility (FTBF) (eg, MTest)
  - Table-top size experiment, focused on hadron production measurements with $p_{beam} < 15$ GeV/c, but will also make measurements with beam from 20-120 GeV/c.
- Ultimate design:
  - 350 mrad acceptance, compact size reduces overall cost
  - high-rate DAQ, precision tracking and timing
- International collaboration, with involvement of experts from NOvA/ DUNE/SBN and SK/T2K/ HK.



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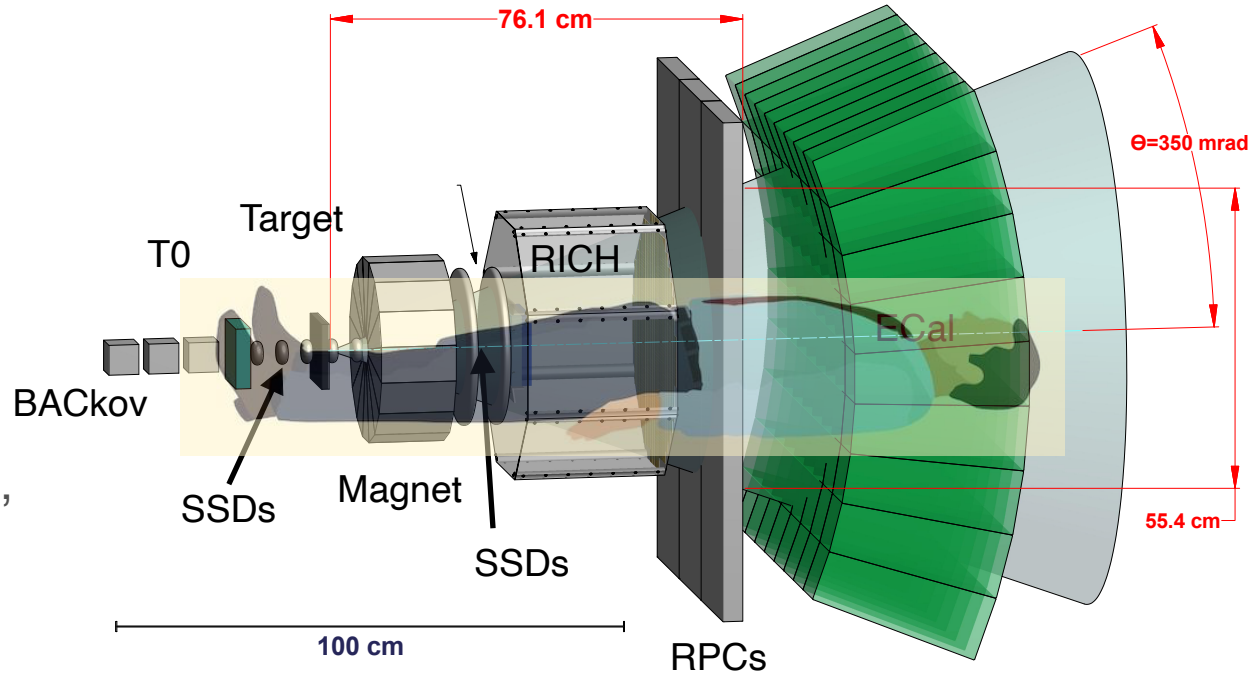

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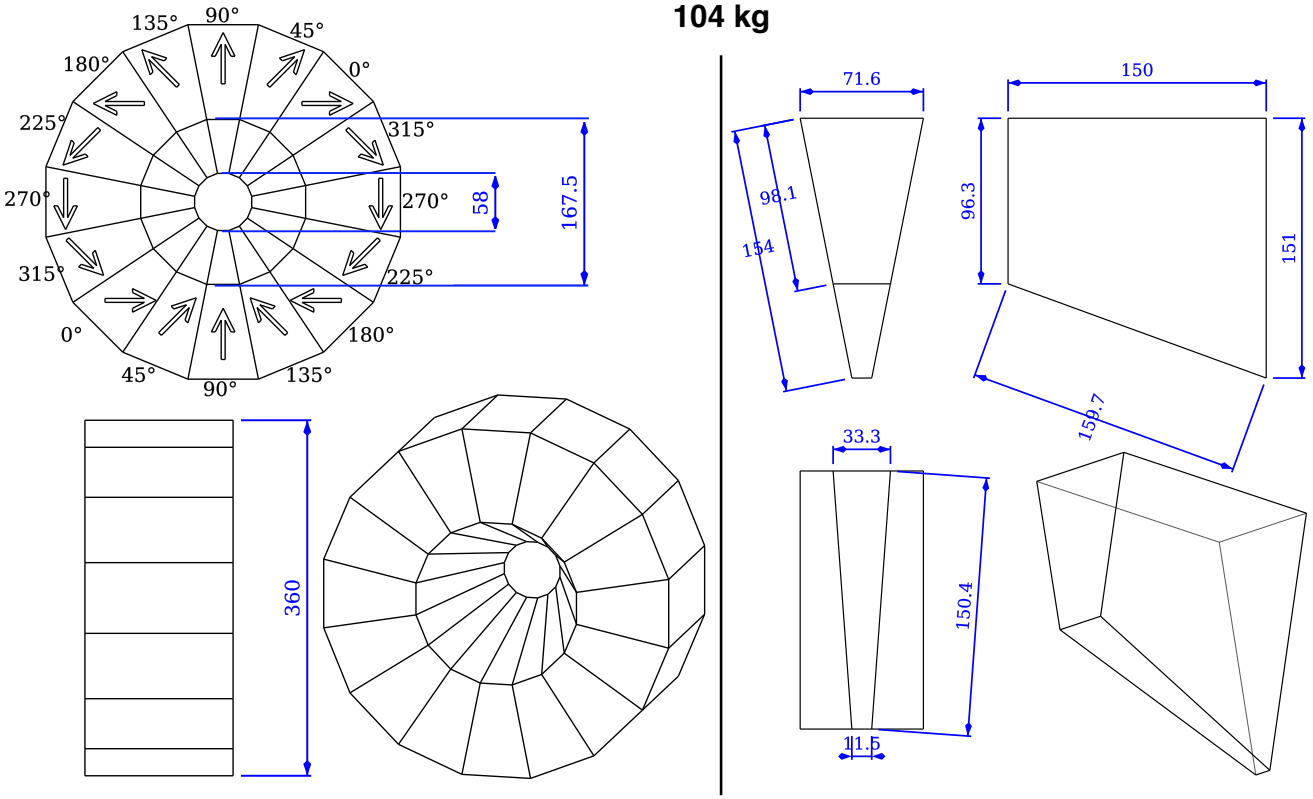
Goals:

- fill in the gaps of missing hadron-scattering and hadron-production cross sections with better than 10% measurements.
- First-ever measurement of the hadron spectrum downstream of a target and horn.

EMPHATIC: Permanent Magnet

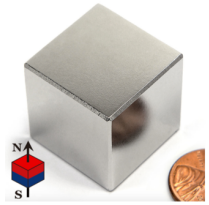
Halbach Array

EMPHATIC Dipole Magnet
16 NdFeB (N52) segments
104 kg



all measurements are in mm

Segments made from large segments of Neodymium permanent magnets.



Many companies with expertise dealing with these magnets for the **windmill industry**.

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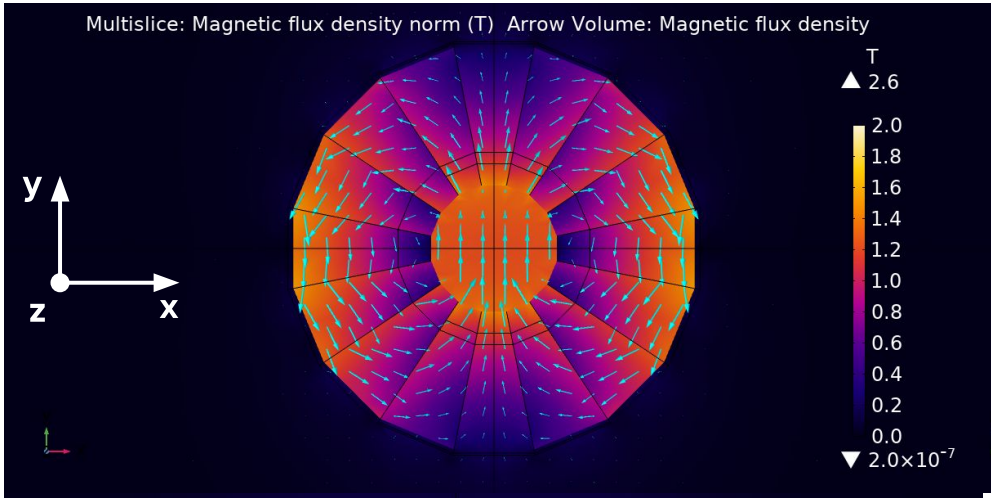
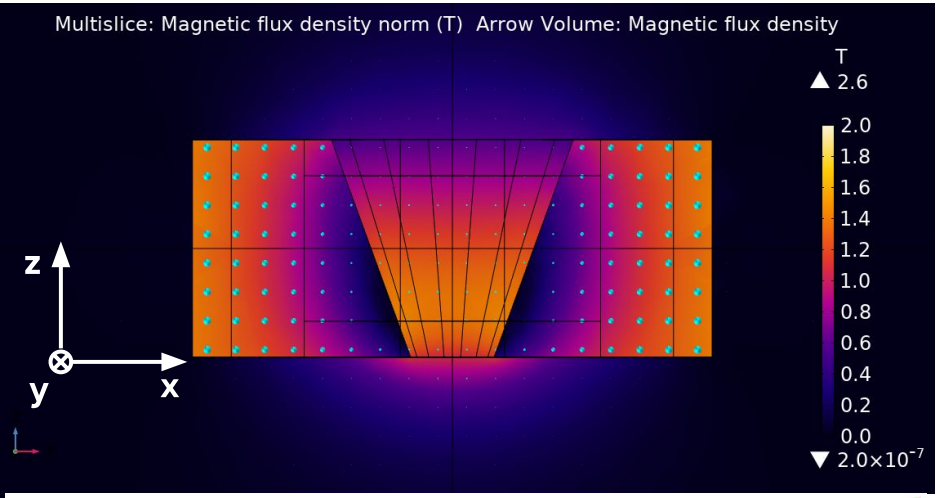
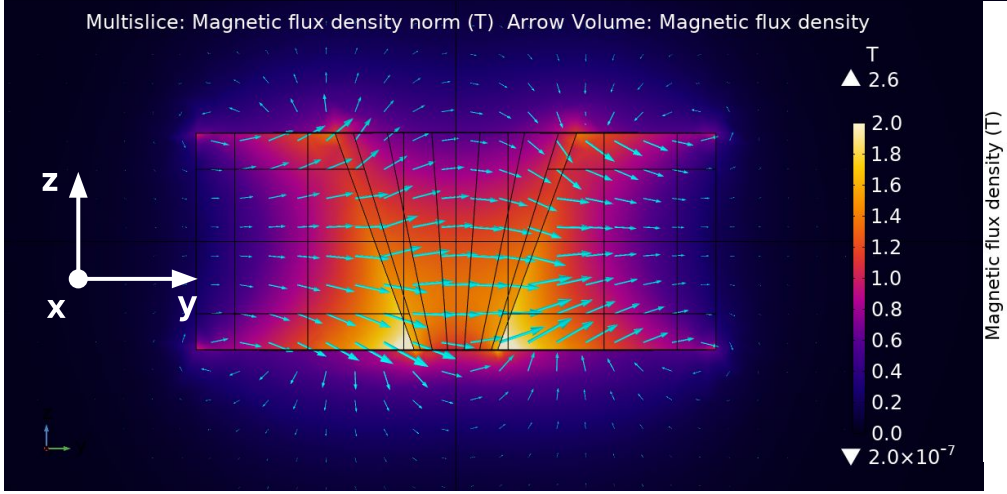
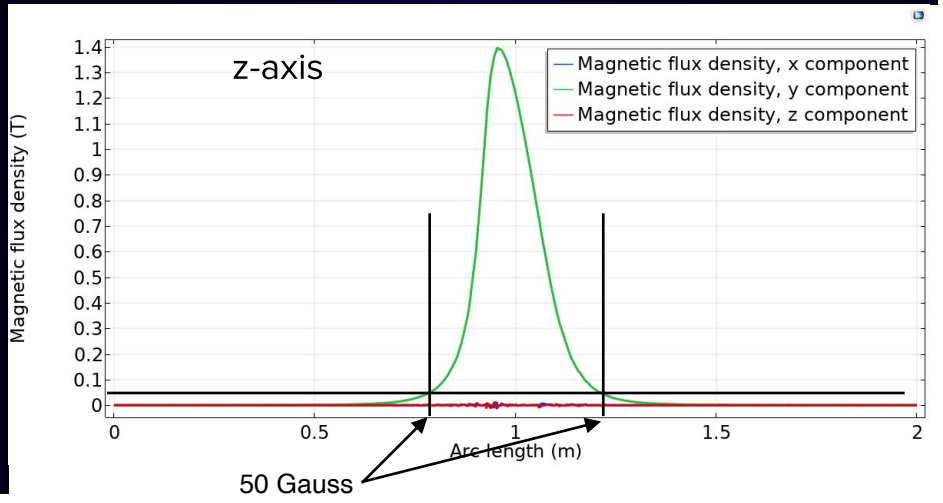
EMPHATIC: Magnet









Field maps generated using COMSOL simulation.

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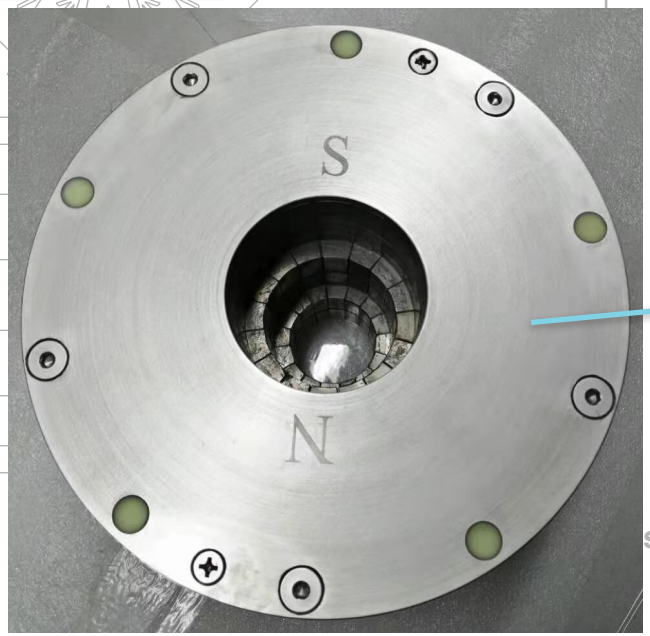
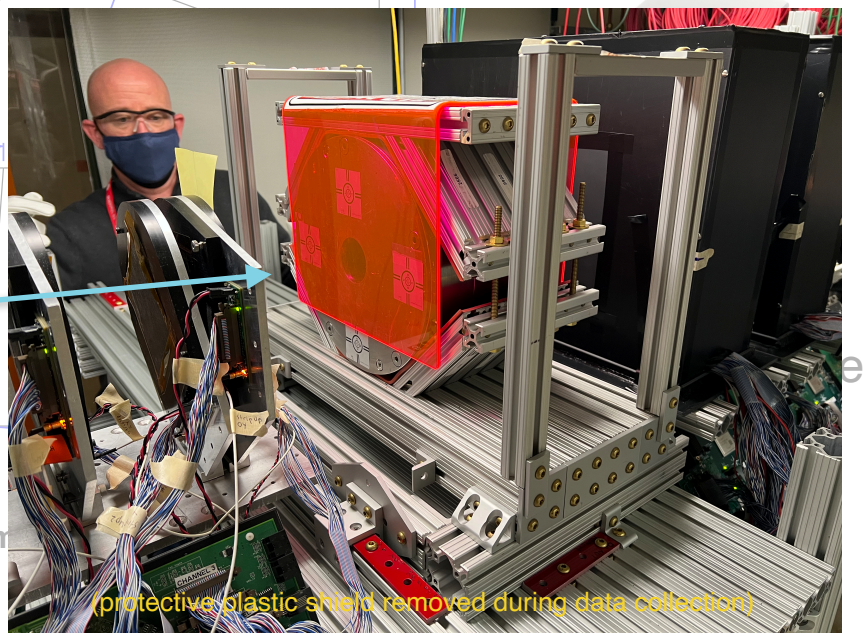
EMPHATIC: Permanent Magnet

Prototype small-aperture magnet purchased by TRIUMF, used in January and June/July 2022 runs at Fermilab.





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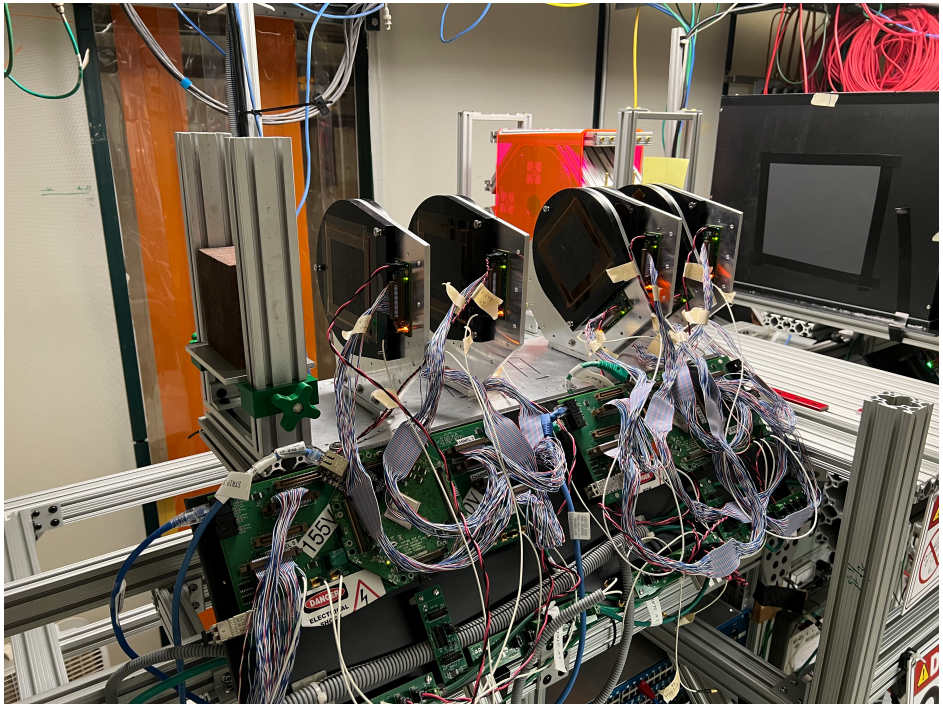
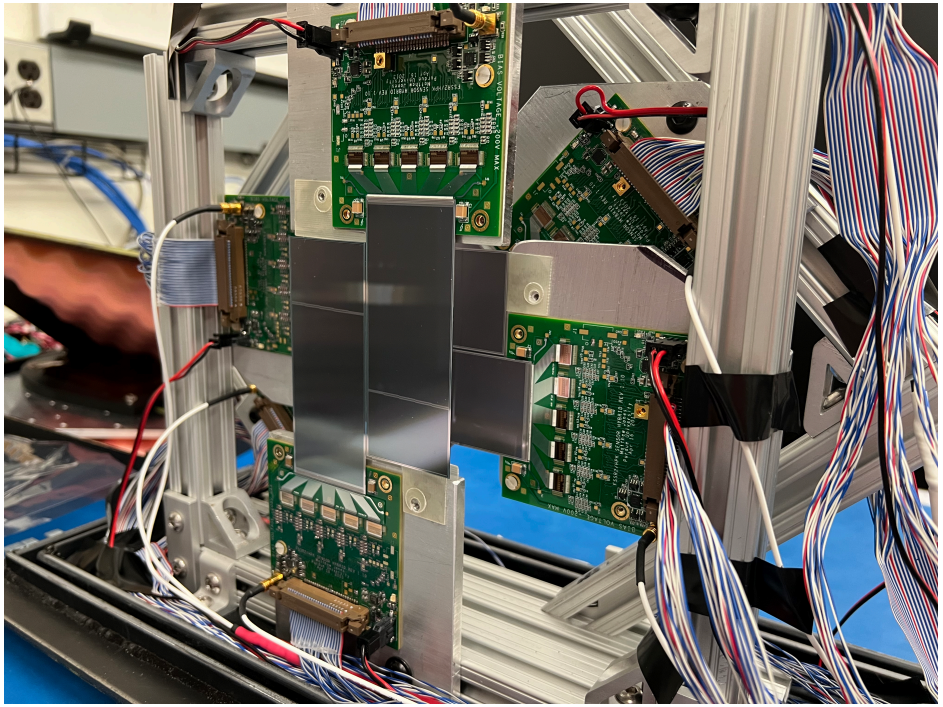
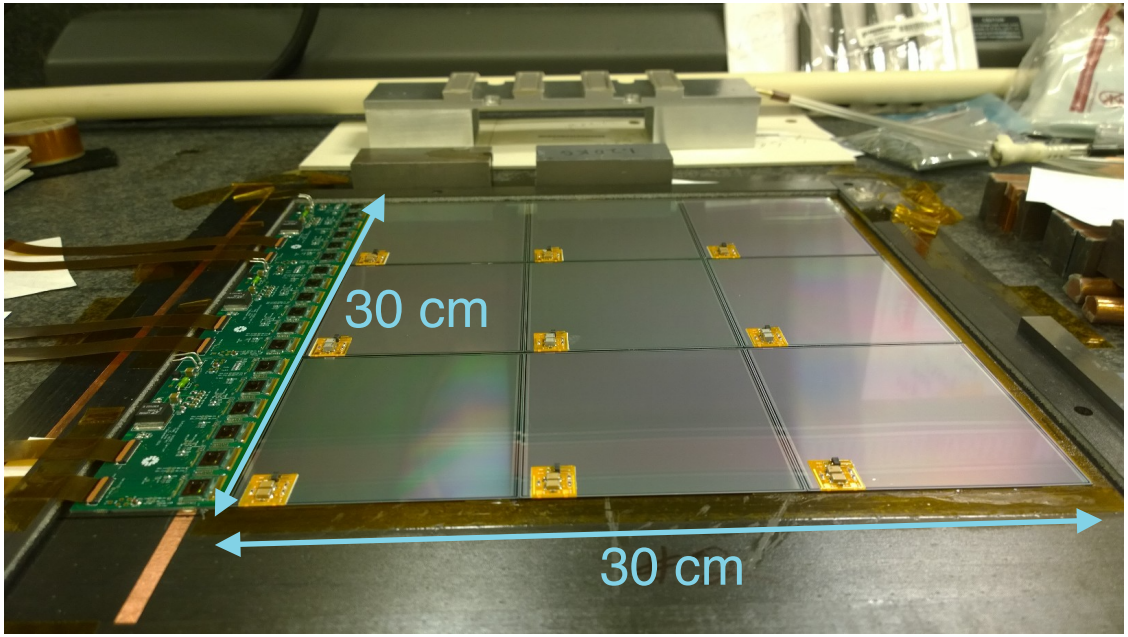
EMPHATIC: Si Strip Detectors (SSDs)

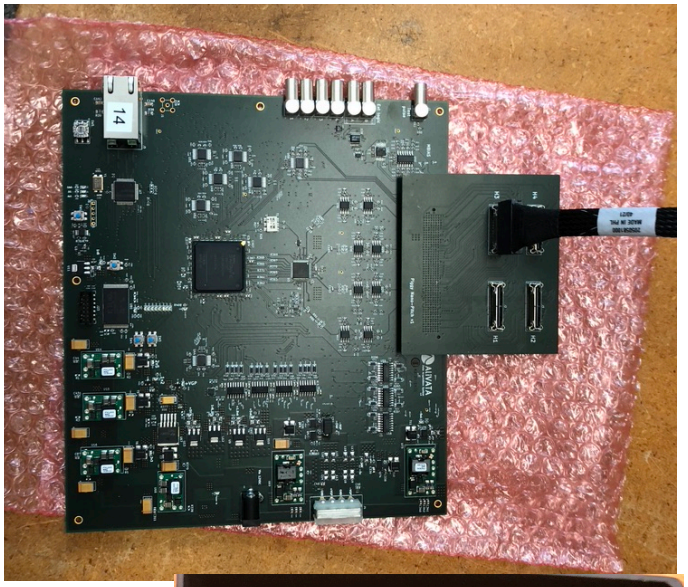




- Upstream tracking to be done by existing SSDs at the FTBF.
  - 60 μm pitch, ~10 μm resolution
  - Mature DAQ, lots of experience using these detectors at FTBF
  - Used in the 2018 and 2022 runs for a ~100 mrad acceptance spectrometer

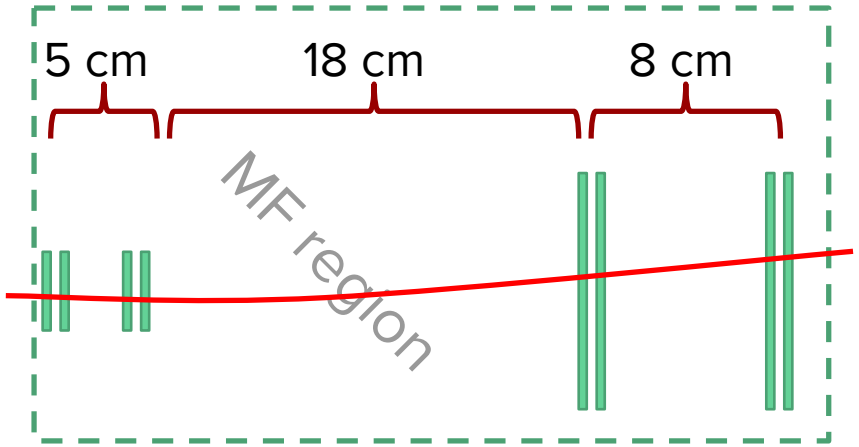
EMPHATIC: Si Strip Detectors (SSDs) - Upgrade

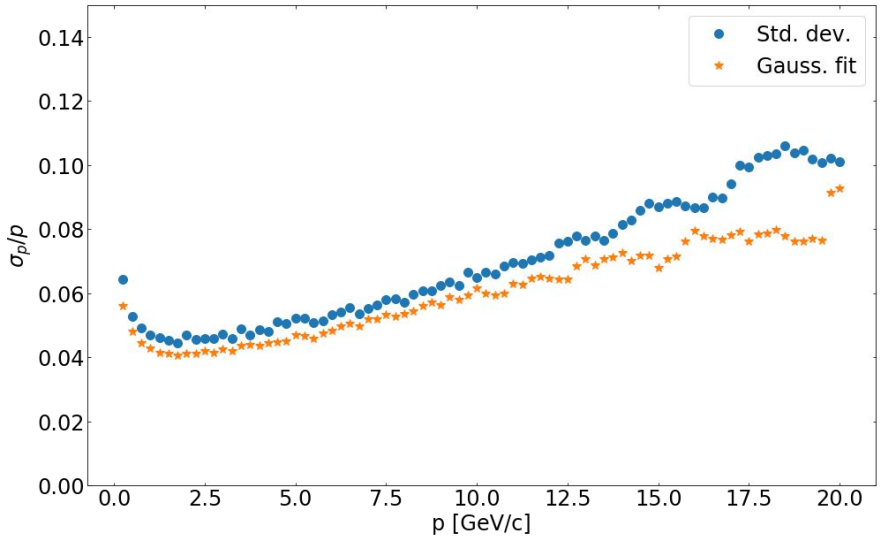




- To achieve 350 mrad acceptance, need to cover up to ~30 x 30 cm^2 area
- Large-area SSDs available from Fermilab SiDet. Resolution good enough (122 µm pitch) for downstream tracking.
- New ASICs and off-the-shelf front-end electronics reduce overall cost.
- Prototype ready to test this summer and fall.

EMPHATIC: Momentum Resolution

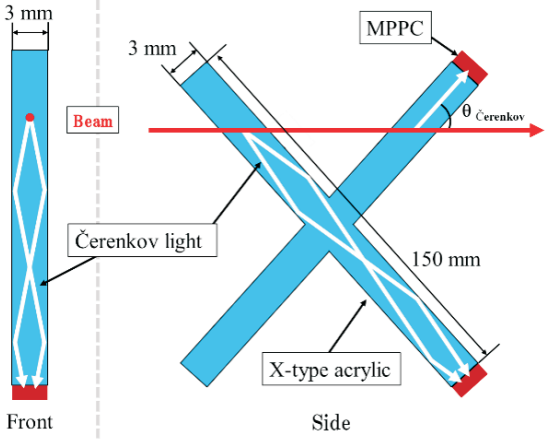


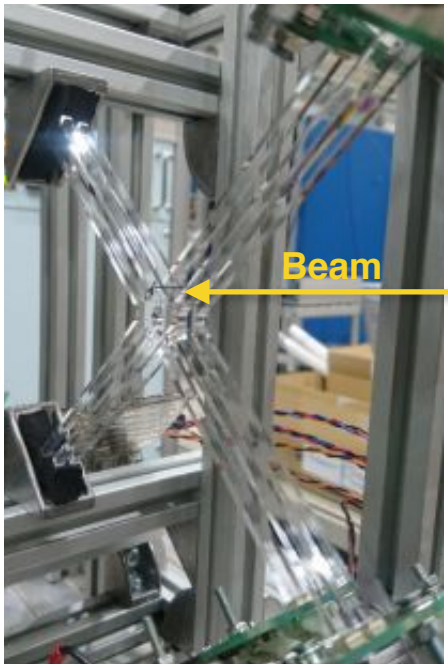


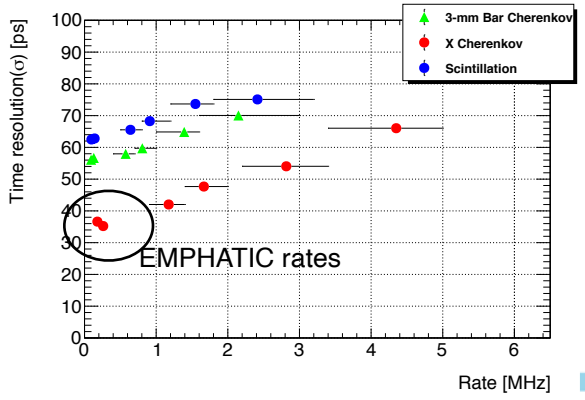
- Preliminary study based on COMSOL magnetic field maps, resolution-smeared truth, and Kalman Filter reconstruction.
- Resolution < 6% below 8 GeV/c, < 10% below 17 GeV/c.

EMPHATIC: Time of Flight

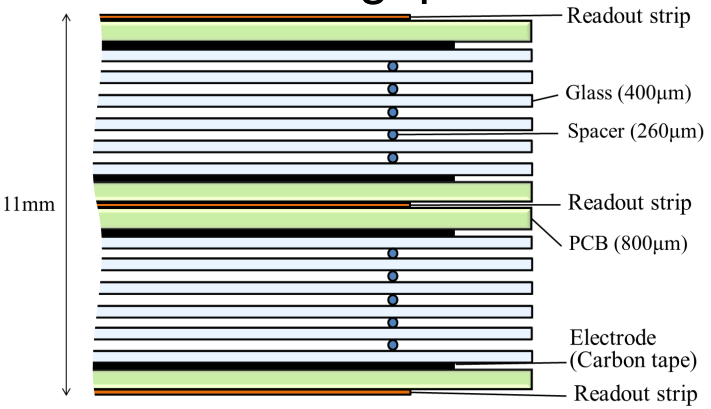
X-shaped Acrylic Ckov Counter

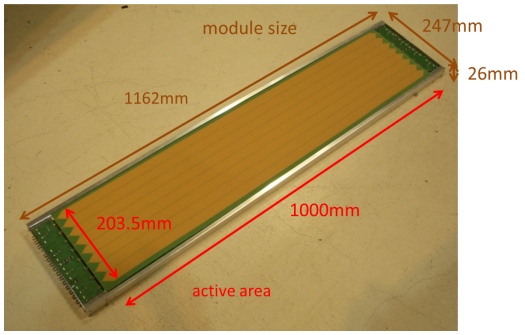




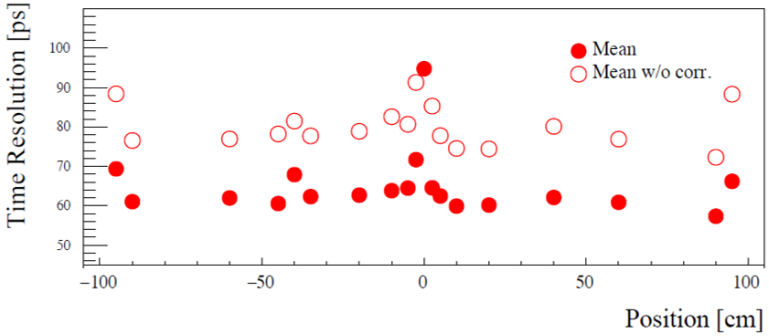


Multi-gap RPC





Note: Fig. 21 of the proposal has the wrong plot, this is the correct one:



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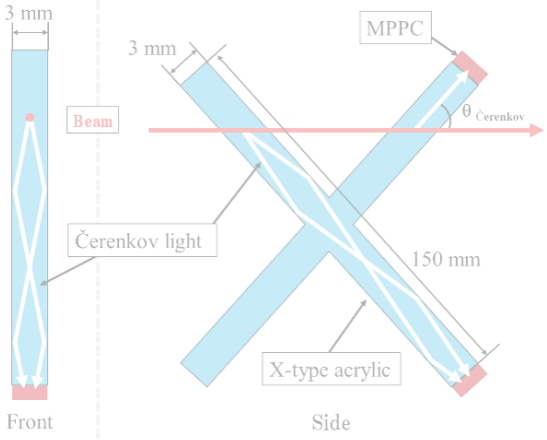

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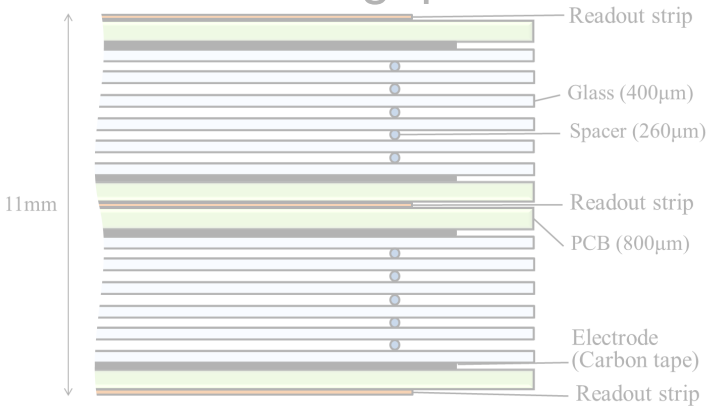
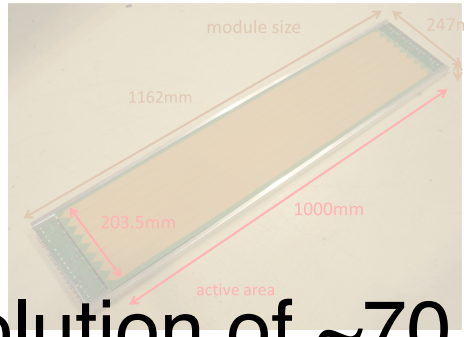
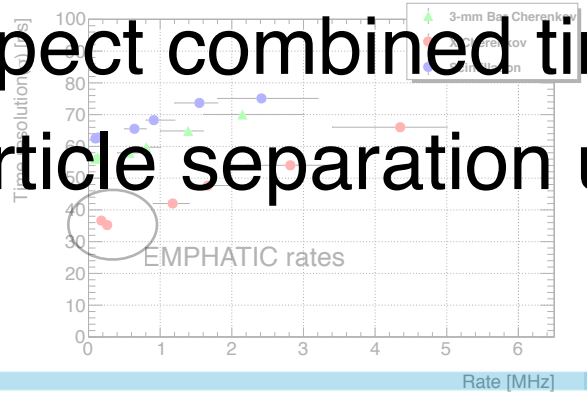




Expect combined timing resolution of ~70 ps, particle separation up to ~1.5 GeV/c.



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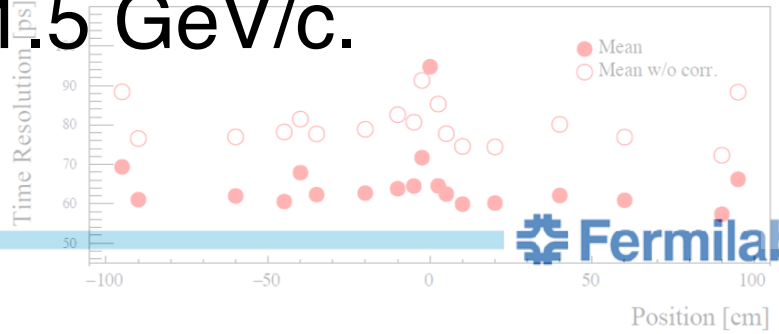

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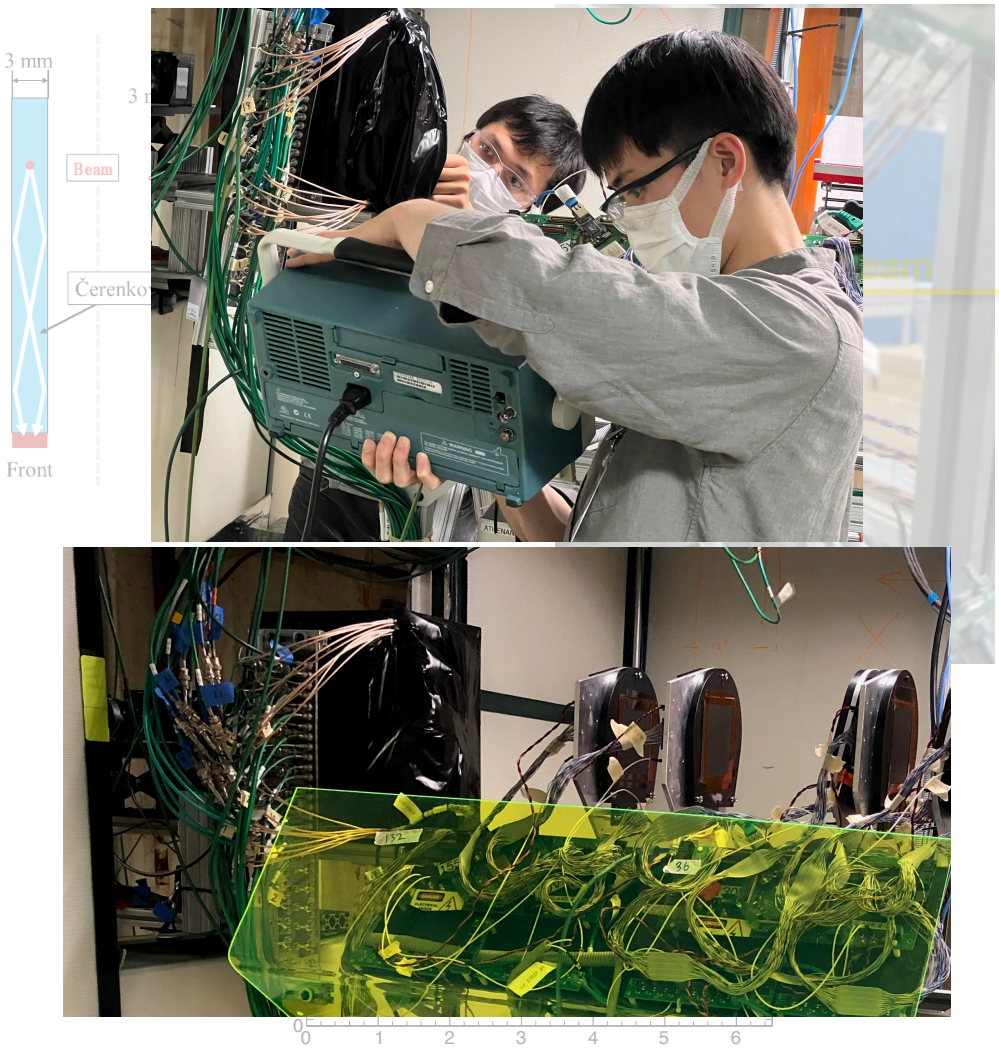

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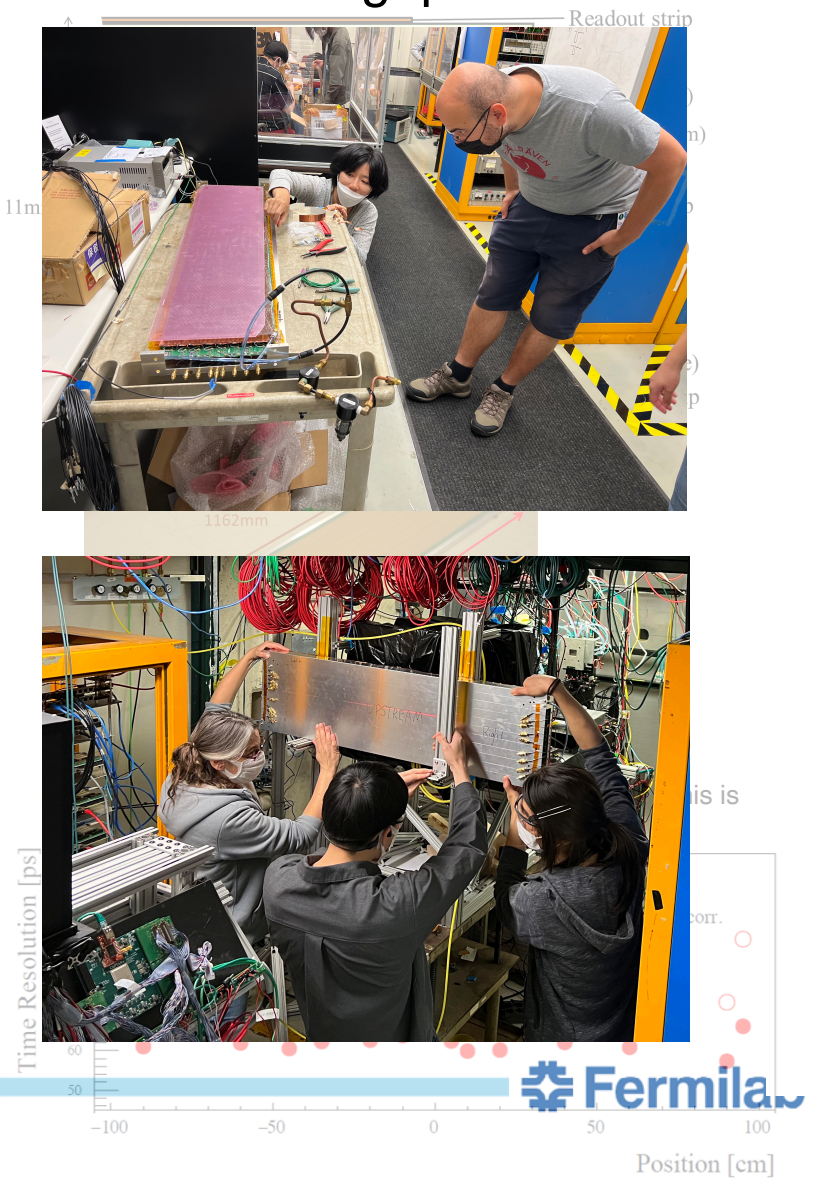
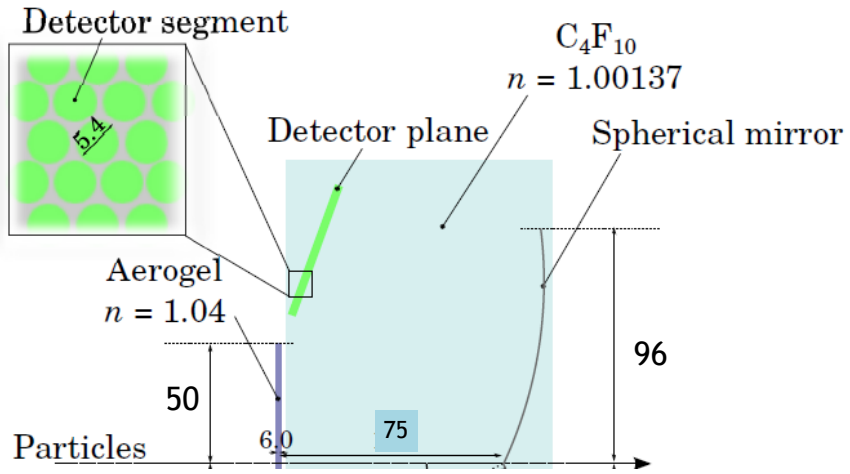
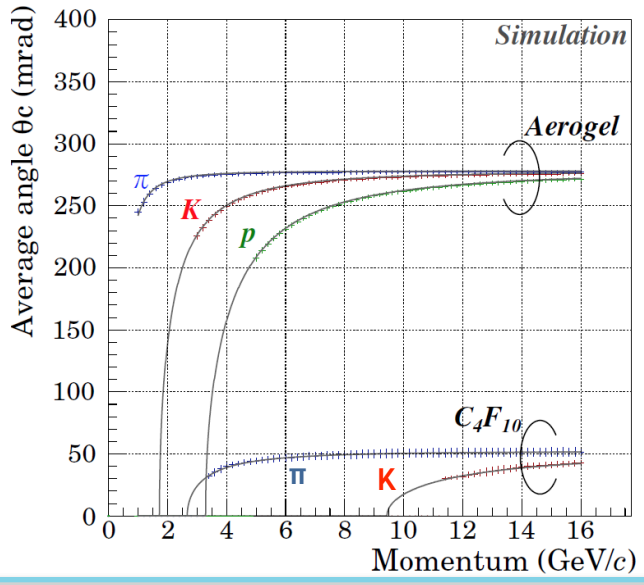
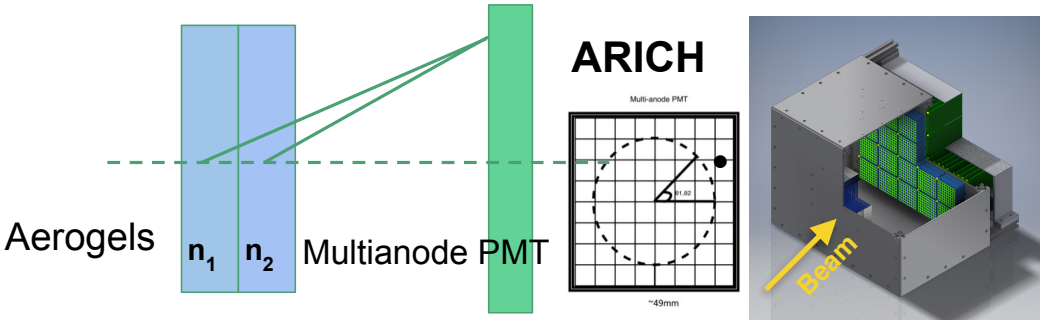


EMPHATIC: RICH Detector



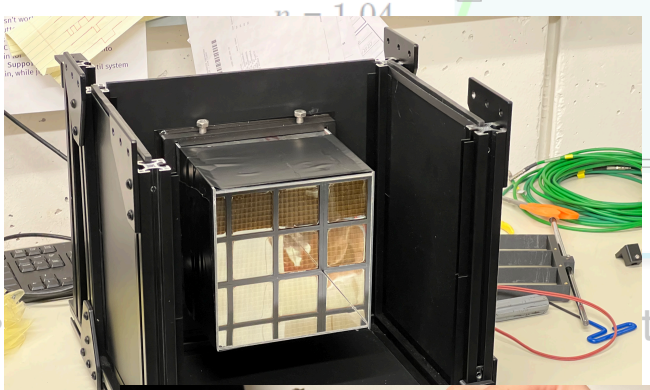


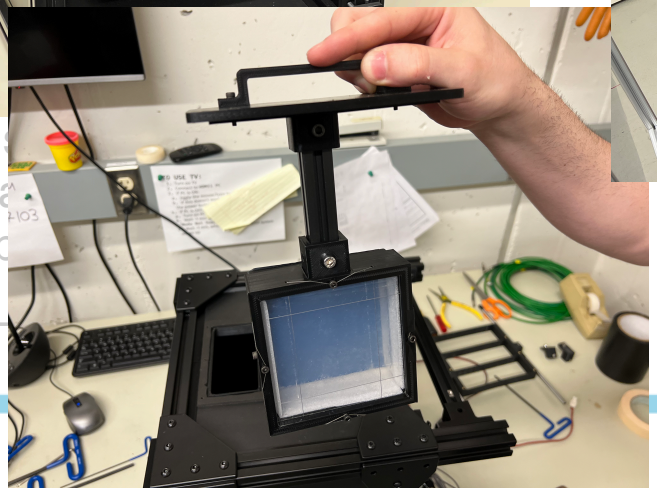
- Based on the Belle II RICH detector
- Aerogels with lower indices of refraction (n=1.02-1.03) and good transmittance available thanks to advances in aerogel production at Chiba U.
- 2σ π-K separation for p<8 GeV/c.

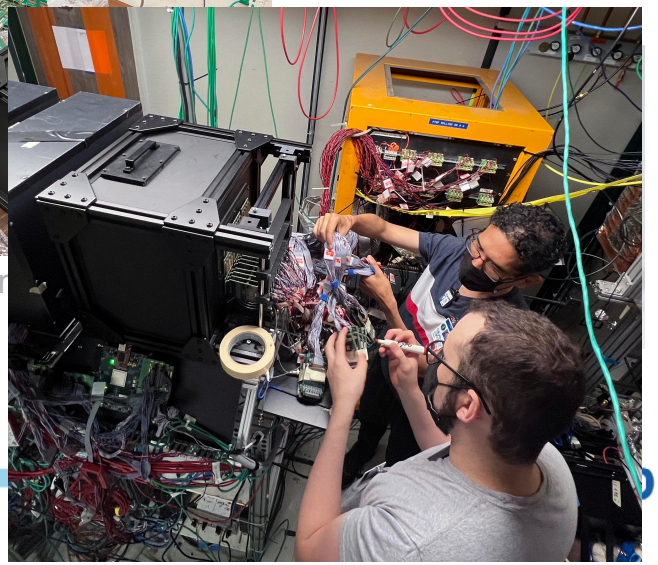


EMPHATIC: RICH Detector

Aerogel-only RICH based on PMTs built at TRIUMF with 150 mrad acceptance. Used in most recent run (ended a few weeks ago).







EMPHATIC: Run Plan

Phase	Date	Subsystems	Momenta (GeV/c)	Targets	Goals	Status
0	2018	Beam Gas Ckov + FTBF SiStrip Detectors + Emulsion Bricks	20, 31, 60, 120	C, Al, Fe	Proof-of-concept Forward-scattering measurement w/ 20 mrad acceptance	Complete - Paper submitted to PRD
1	2022-23	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + Small-acceptance magnet + Prototype ARICH + ToF + Small-acceptance Calorimeter	4, 8, 12, 20, 31, 60, 120	C, CH2, Al, Fe, Be, Ti, Ca, H20	Improved elastic and quasi-elastic scattering measurements, 100 mrad-acceptance hadron production measurements	In-progress
2	2023-24	Phase 1 on Motion Table	4, 8, 12, 20, 31, 60, 120	Spare NuMI Target and [unpowered horn] + various thin-targets	Charged-particle spectrum downstream of horn + thin-target measurements at larger angle	Proposed - Under Discussion
3	2024-25	Upgrade spectrometer to 350 mrad acceptance + Hybrid RICH	4, 8, 12, 20, 31, 60, 120	Same as Phase 2	Full-acceptance hadron production with PID up to 15 GeV/c	Concept
4	2025-26	Upgraded spectrometer + Hybrid RICH + Powered Horn	120	Spare NuMI Horn and Target	Charged-particle spectrum downstream of horns	Concept

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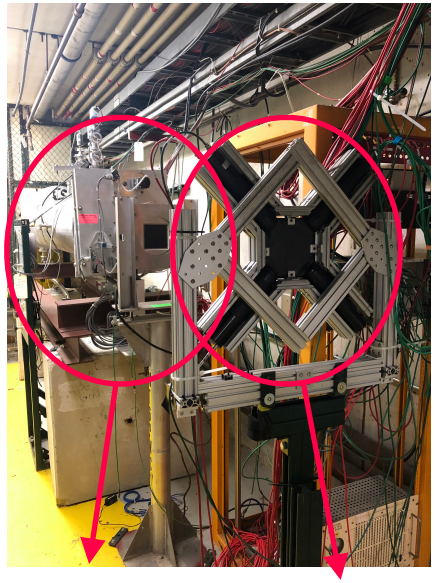
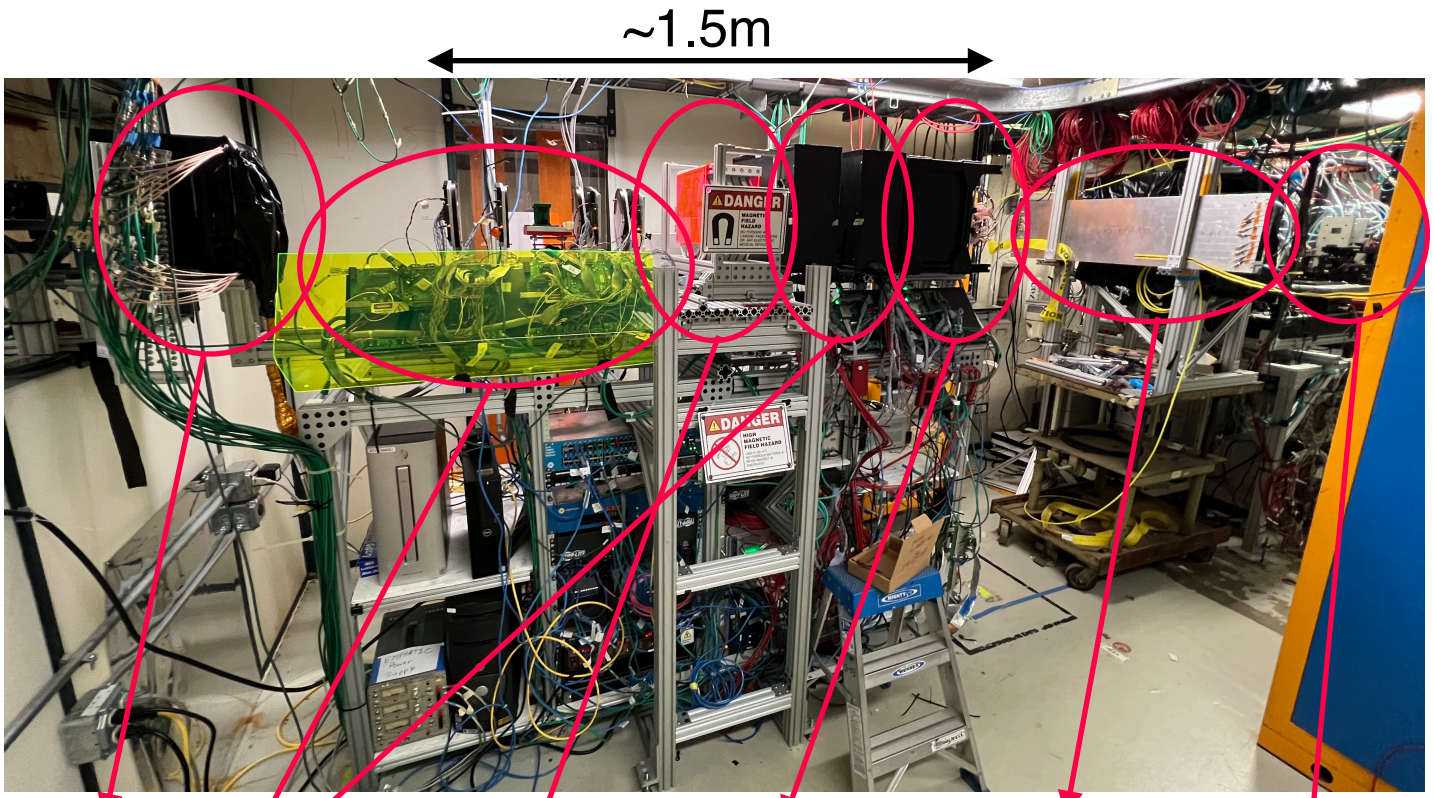
EMPHATIC Phase 1



Gas Ckov + Trigger

Beam aerogel Ckov



- > 100M triggers collected over 4 weeks of data collection so far.
- All systems installed in < 2 days during our last run (just a few weeks ago)

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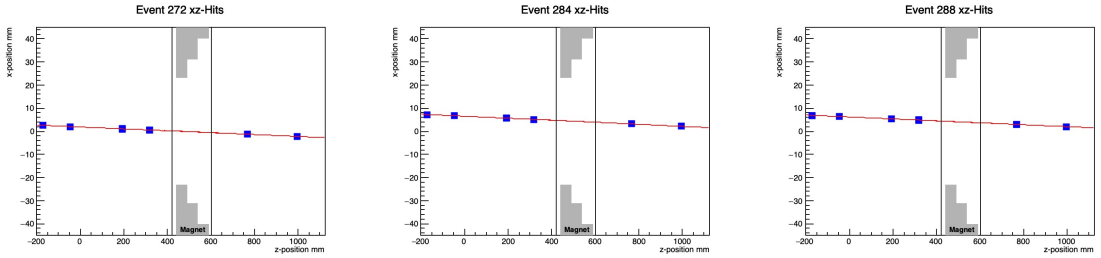
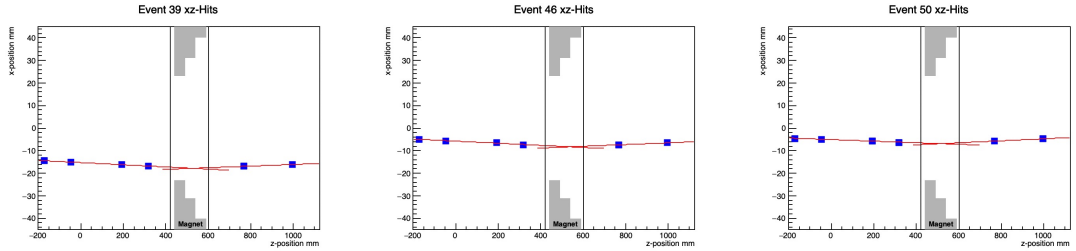
EMPHATIC Phase 1 - First Look at the Data

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

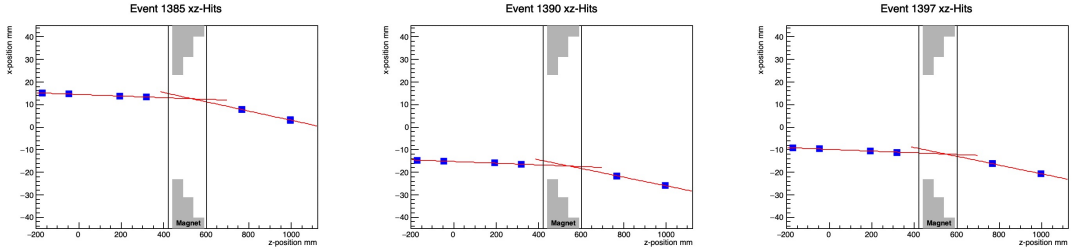


- We see tracks!
- We see them bend!

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

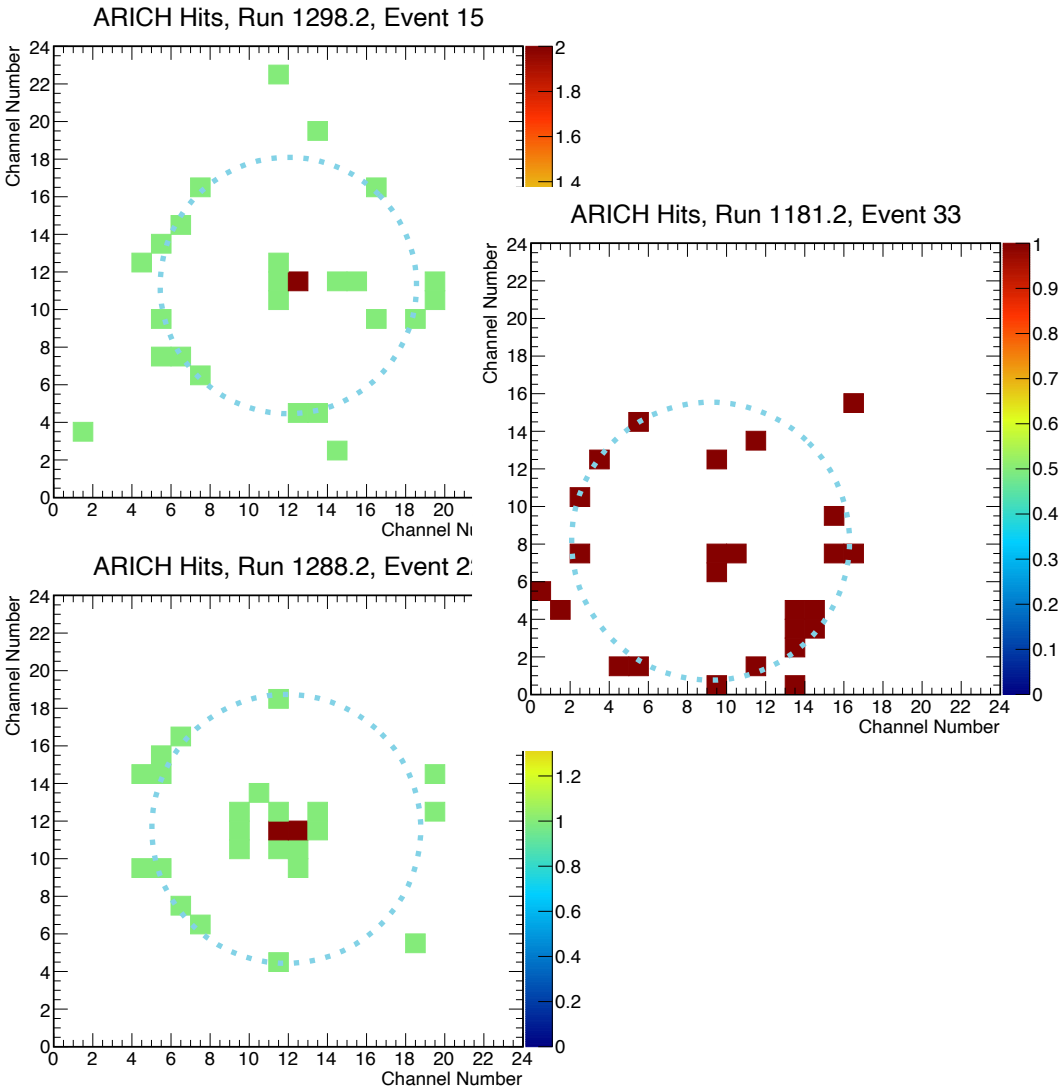


+4 GeV/c Pion: XZ-Plane, Expected Bending



Fermilab

EMPHATIC Phase 1 - First Look at the Data

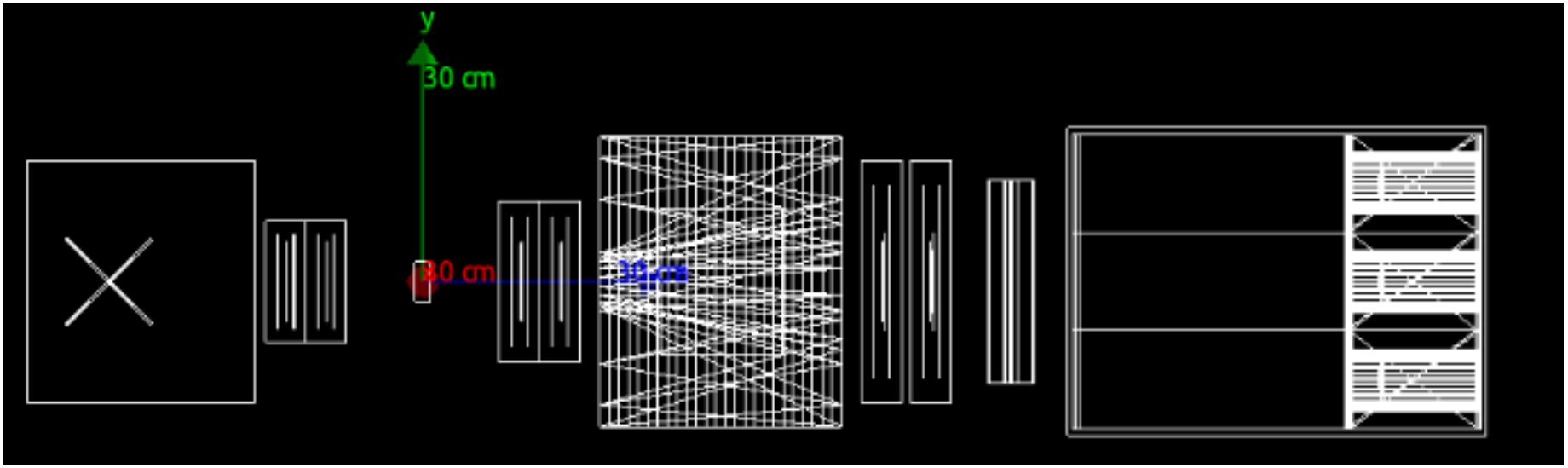


- We see tracks!
- We see them bend!
- We see Ckov rings!

Fermilab

EMPHATIC Phase 1 - Next Steps

- We have data in hand and will collect more early next year (2023).
- The collaboration is working hard on the reconstruction and analysis of the data.
- Simulation will play an important role and is under development.

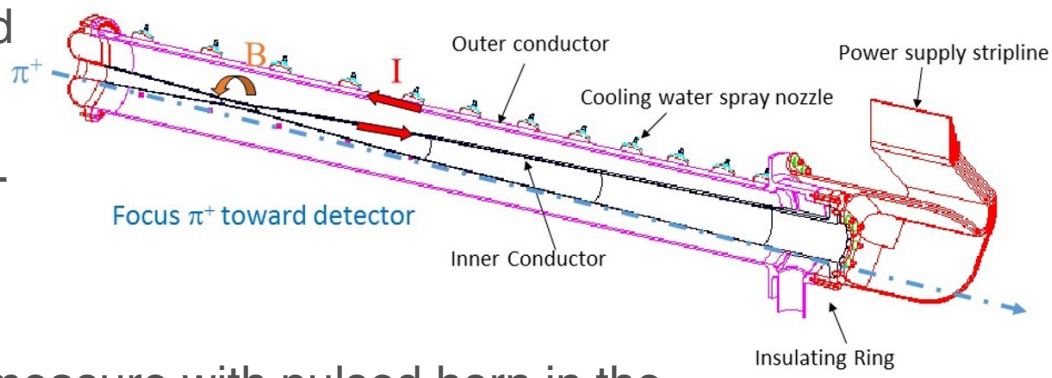


EMPHATIC: Run Plan

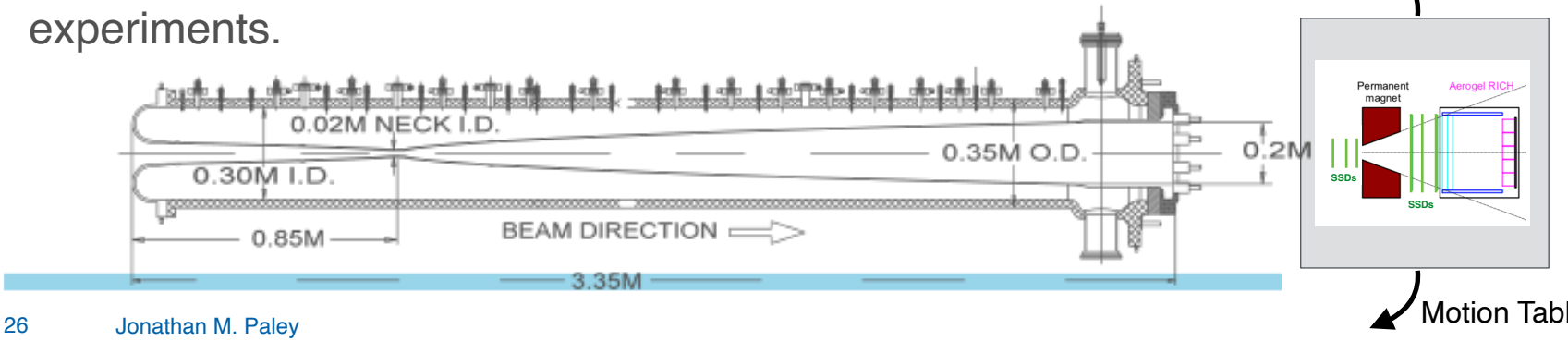
Phase	Date	Subsystems	Momenta (GeV/c)	Targets	Goals	Status
0	2018	Beam Gas Ckov + FTBF SiStrip Detectors + Emulsion Bricks	20, 31, 60, 120	C, Al, Fe	Proof-of-concept Forward-scattering measurement w/ 20 mrad acceptance	Complete - Paper submitted to PRD
1	2022-23	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + Small-acceptance magnet + Prototype ARICH + ToF + Small-acceptance Calorimeter	4, 8, 12, 20, 31, 60, 120	C, CH2, Al, Fe, Be, Ti, Ca, H20	Improved elastic and quasi-elastic scattering measurements, 100 mrad-acceptance hadron production measurements	In-progress
2	2023-24	Phase 1 on Motion Table	4, 8, 12, 20, 31, 60, 120	Spare NuMI Target and [unpowered horn] + various thin-targets	Charged-particle spectrum downstream of horn + thin-target measurements at larger angle	Proposed - Under Discussion
3	2024-25	Upgrade spectrometer to 350 mrad acceptance + Hybrid RICH	4, 8, 12, 20, 31, 60, 120	Same as Phase 2	Full-acceptance hadron production with PID up to 15 GeV/c	Concept
4	2025-26	Upgraded spectrometer + Hybrid RICH + Powered Horn	120	Spare NuMI Horn and Target	Charged-particle spectrum downstream of horns	Concept

EMPHATIC Phase 2 - Beyond Target HP Uncertainties

- Put EMPHATIC on a motion table downstream of spare NuMI horn and target.
- Minimal goal is to measure charged-particle spectrum downstream of target+horn.



- Power supply also available; aim to measure with pulsed horn in the future.
- Establishes program to address questions re: HP in horns and modeling of horn geometry and magnetic field.
- With %-level flux uncertainties, we significantly improve the sensitivity of BSM physics in current and future neutrino experiments.



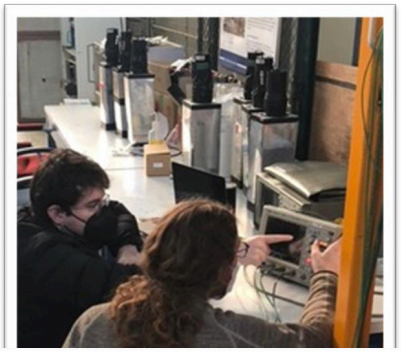
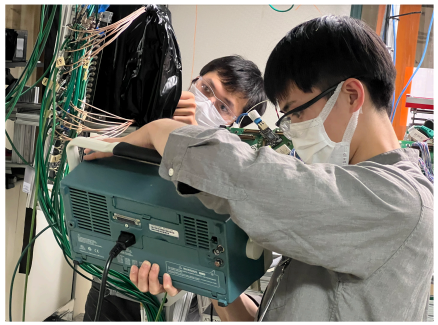
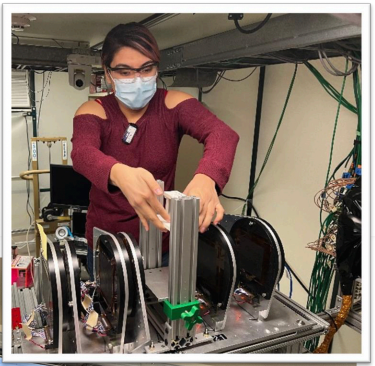
Summary

- New hadron production data are needed to reduce neutrino flux uncertainties.
- EMPHATIC offers a ***novel, table-top*** approach to reducing the hadron production uncertainties by at least a factor of 2 with measurements of both thin and thick targets.
- EMPHATIC is ***complementary*** to the existing efforts (eg, NA61/SHINE) to collect important hadron production data for improved flux predictions.
- First results from EMPHATIC using data from a 2018 proof-of-principle run are now available. Let us know if you would like access to the data and covariance matrices.
- We have begun to collect high-statistics data using a small-acceptance spectrometer, more runs are planned.
- **Funding and community support for the upgrades for Phases 2-4 are needed.**

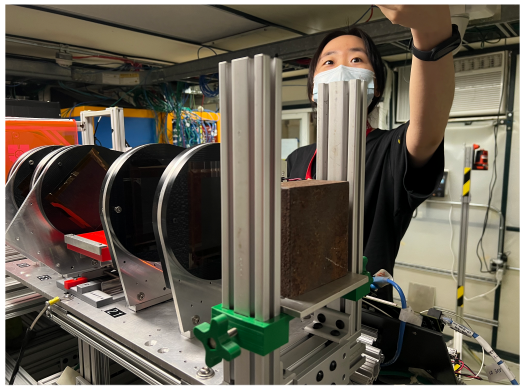
Summary

- We're young, we're fun, and we continue to grow.
- Several new institutions have joined this year.
- Plenty of hardware, software and analysis opportunities over the next few years. New collaborators are welcome!

Great Training Ground for Early Career Scientists!

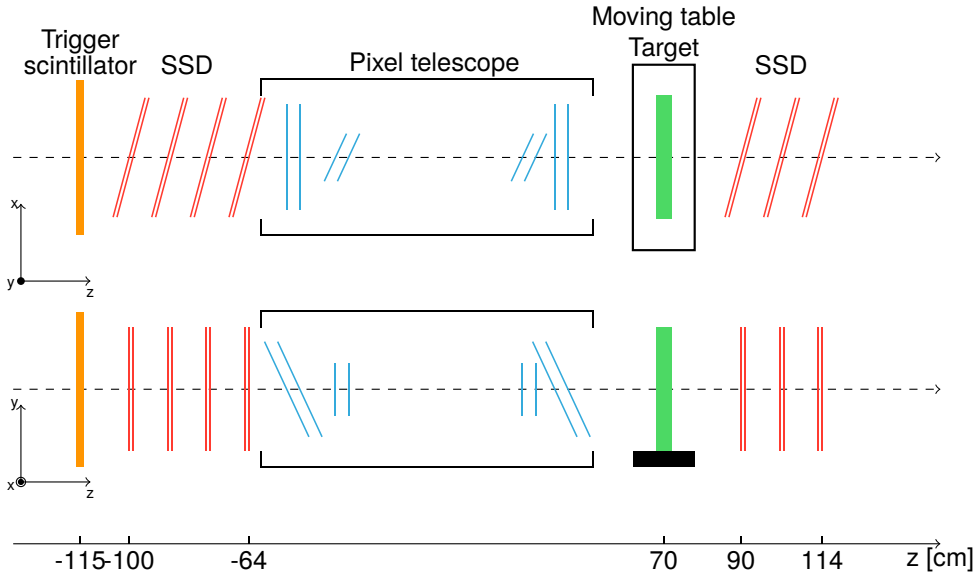






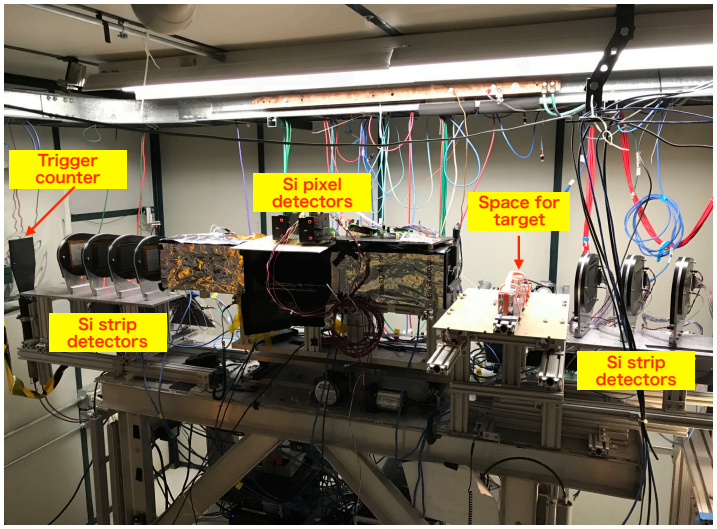



Backup

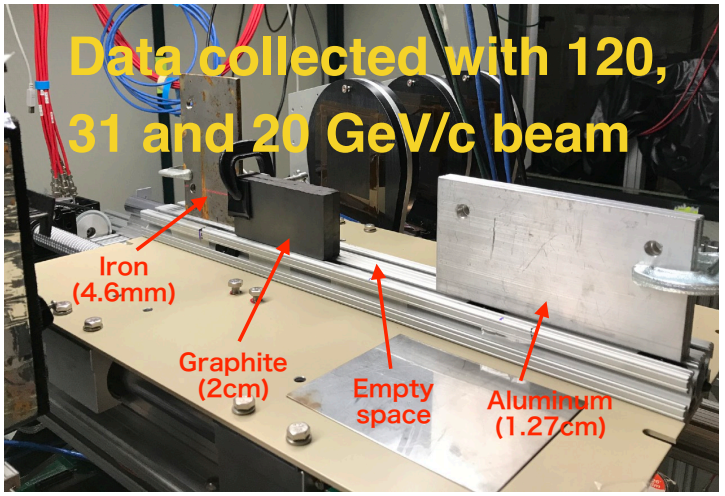
EMPHATIC: Proof-of-principle run from Jan. 10-23, 2018



MT6.1-A



- Proof-of-principle/engineering run: just SSDs, beam gas Ckov
  - No magnet
  - No secondary PID
  - 20 mrad acceptance
  - Pixel detector in place but not used (extra dead material)



Fermilab

EMPHATIC: Proof-of-principle run from Jan. 10-23, 2018

Results submitted to PRD, collaboration has responded to referee comments.

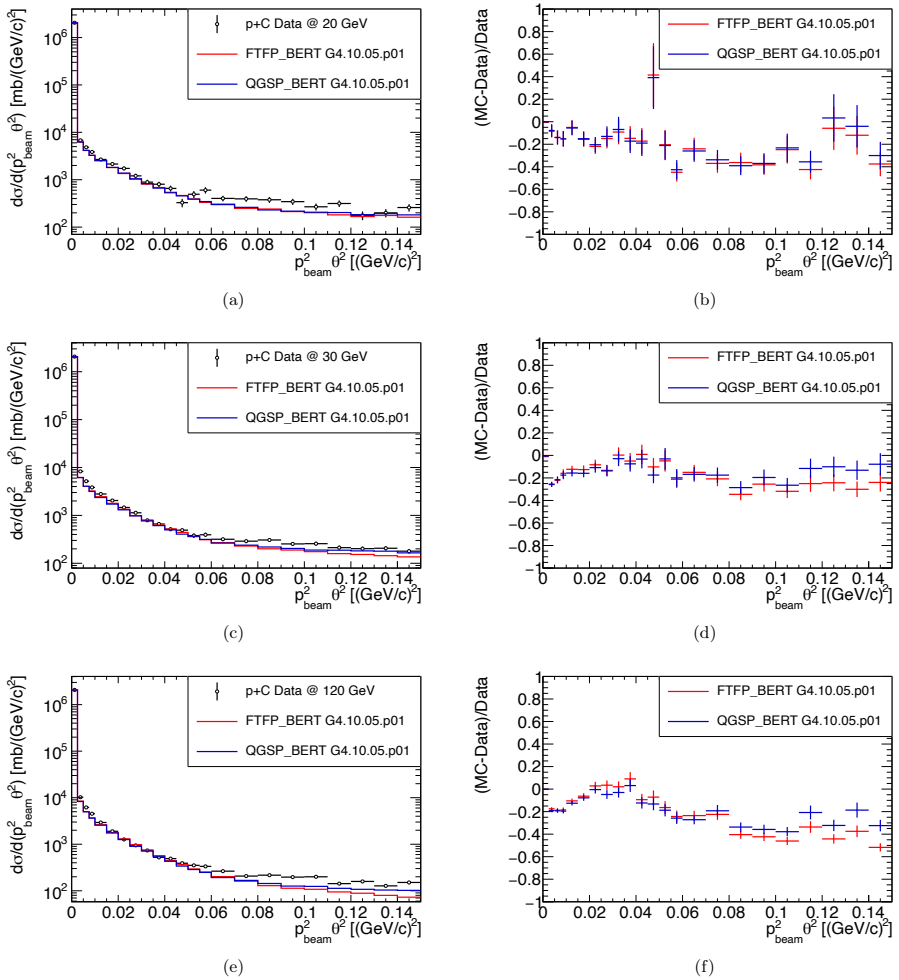


FIG. 7: The p+C differential cross-section at 20 GeV/c (a), 30 GeV/c (c), and 120 GeV/c (e), and their corresponding comparisons to the FTFP_BERT and QGSP_BERT models from Geant 4.10.05.p01 (b), (d), and (f).

arXiv:2106.15723

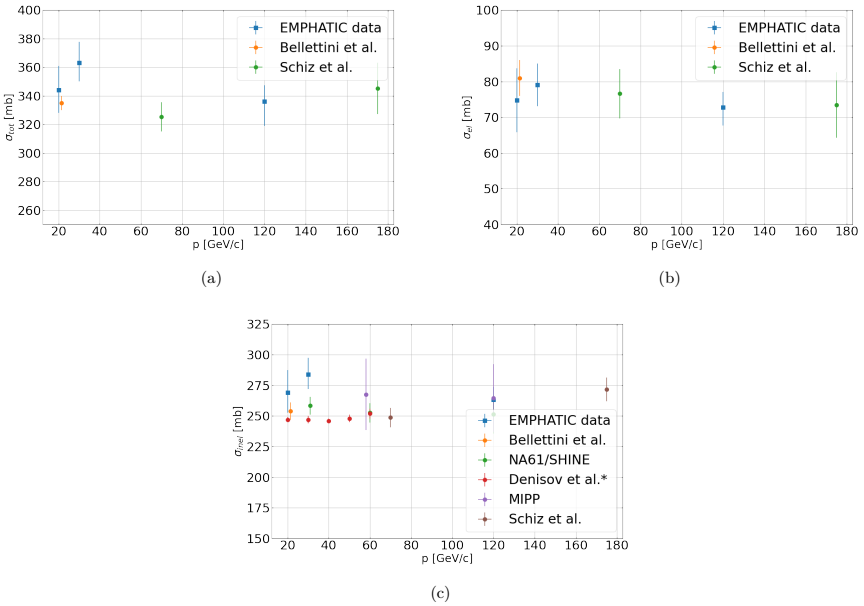
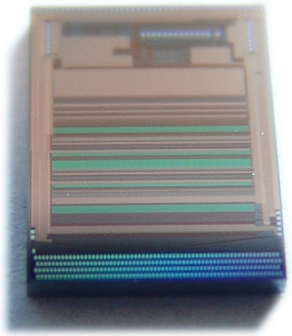


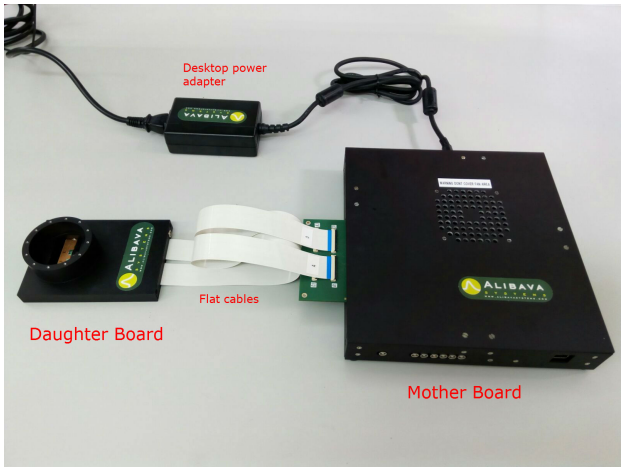
FIG. 16: Comparisons of the total (a), elastic (b), and inelastic cross-section (c) obtained from the fits with older data. The total cross-section is compared to the data from Bellettini et al. [17]. The elastic cross-section is compared to values obtained from Bellettini et al. [17] and Schiz et al. [22]. The inelastic cross-section is compared to the results from Bellettini et al. [17], NA61/SHINE collaboration [4, 6], Denisov et al. [23], and MIPP collaboration [24].

EMPHATIC: Si Strip Detectors (SSDs)

- IDEAS VATA GP7.1 chips:
  - 128 channels, designed for counting and imagine applications
  - Off-the-shelf solution, test kits available.
- AliVATA system from Alibava (company) for front-end electronics. Each board is guaranteed to read out 4 streams of 8 chips. Designed to work with VATA GP7.1 chips. Boards have been purchased, awaiting delivery.



First AliVATA for Microdosimeters

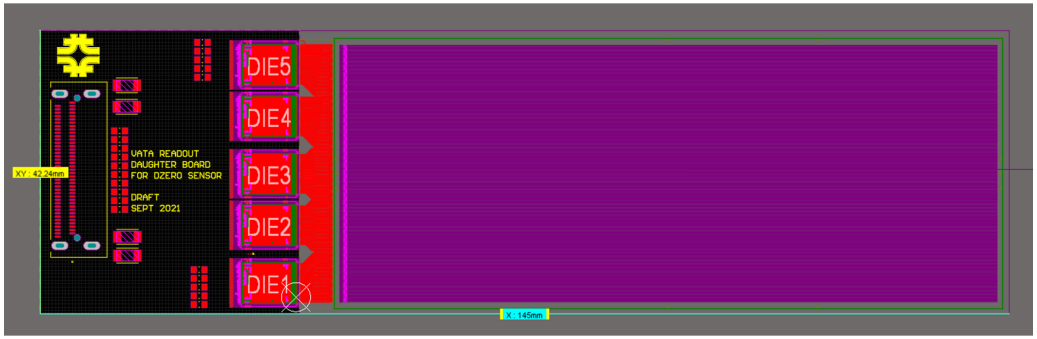


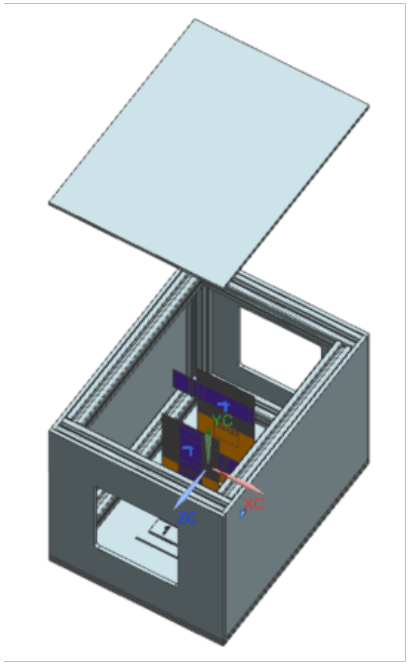
Summary

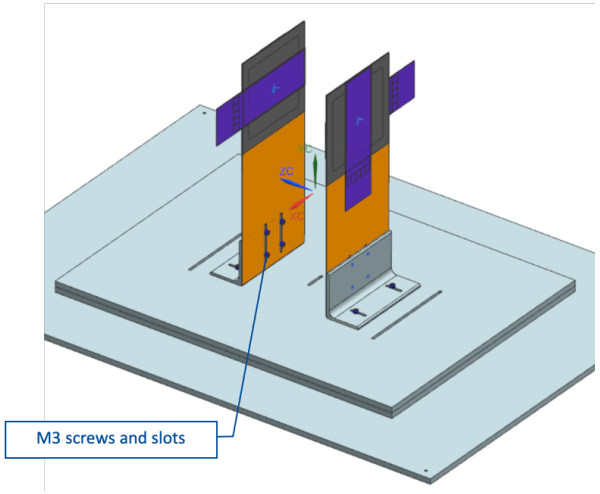
✔ ALIVATA readout system for spectroscopy
- ➔ Several detector types (Silicon strips, pads or pixels, SiPM, etc.)
- ➔ Self-trigger
- ➔ Time stamping
- ➔ Really scalable (with the IDEAS GP7 chip, up to 8192 channels per motherboard)

EMPHATIC: SSD Prototype

- Pitch adapter (connects the sensor strips to a series of daisy-chained GP7s) design complete, and will be produced on silicon by U. Chicago.
- Sensor (daughter) board design is nearly complete. Will be able to test readout of 1, 2, or 5 daisy-chained chips. Expect final design to be sent to vendor by end of September.
- Housing and mounting of sensors is being designed for use on an optical table.
- The prototype could be ready for testing before end of October. Options exist to test on a cosmic-ray stand, or with beam at FTBF.







Phase II: 350-mrad ARICH based on SiPM Array

Prototype studies underway in parallel with full system design

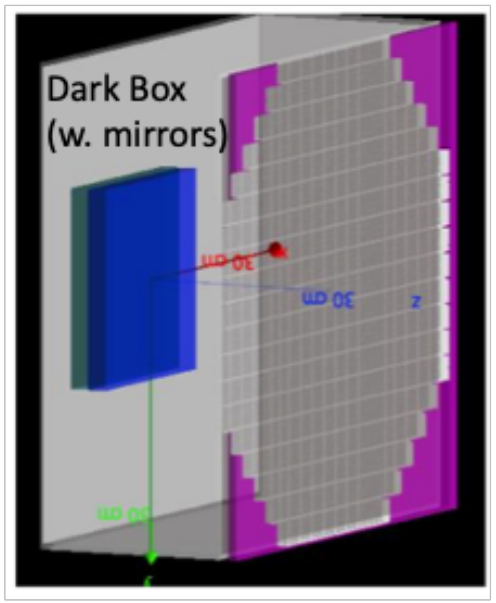
Dark box	– rectangular shape chosen, conceptual design details under discussion
	– hope to accommodate gas tight for Phase III
Aerogel	– Chiba U. will provide tiles cut to our shape request
Mirrors	– Regina studied efficacy, suggested materials, will incorporate in prototype
Cooling plate	– calculations underway, somewhat challenging to design for < 10°C
	– cooling to reduce dark rate may be traded off against readout time window achieved
Image plane	– final design of (9x9) x (2x2) 64-channel SiPM arrays chosen
	– lab tests of single 2x2 64-channel PCB underway (with custom breakout PCB)
Backplane	– prototype PCB being assembled (1/9 of full detector).
Readout Boards	– prototype PCBs being assembled (2x CAEN CITIROC, capable of reading out 64 channels)
	– each Readout Board requires 6 FPGAs, pre-purchased final design quantity to overcome supply chain issues
Readout Firmware	– prototype design in progress

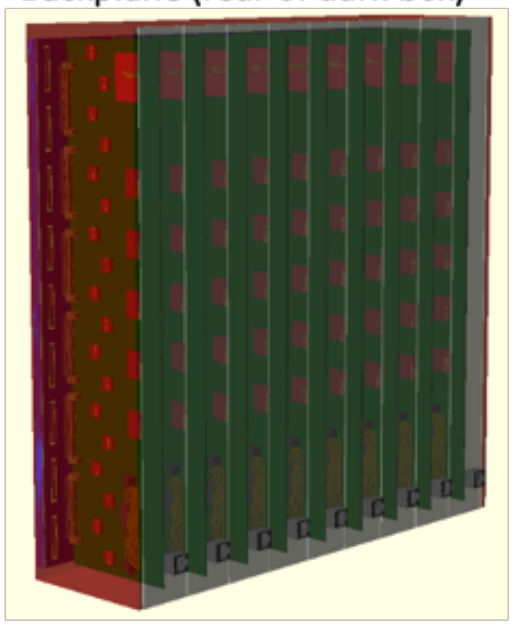
Progress and Schedule for ARICH Prototype

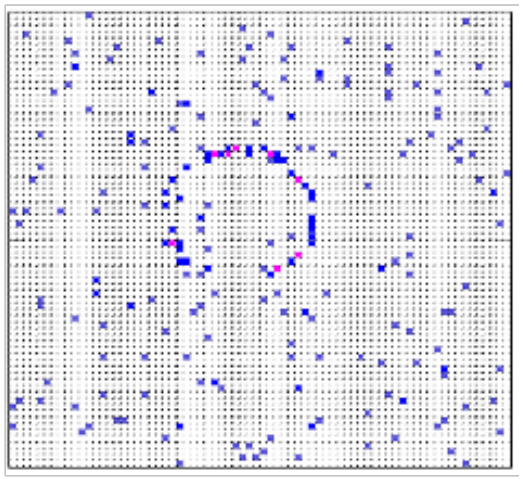
Phase II: 350-mrad ARICH based on SiPM array

SiPM Image Plane

Backplane (rear of dark box)





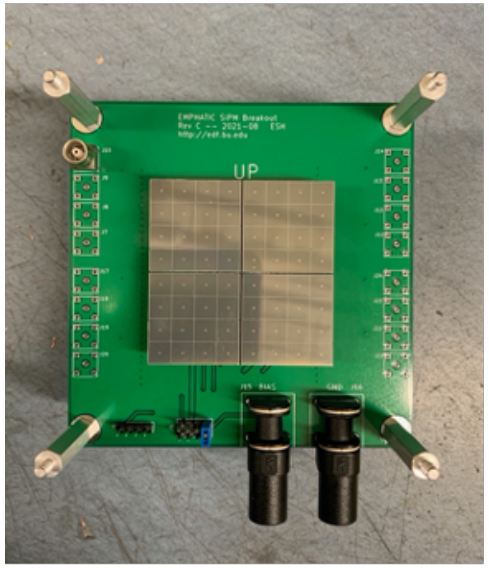


324 Hamamatsu S14160-6050 SiPM
16 channels each: 6 mm x 6 mm

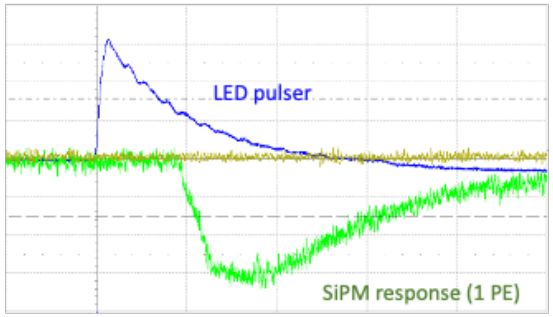
9 Readout Modules
18 CITIROC / module
6 FPGA / module

Fermilab

ARICH Prototype Work and PCBs



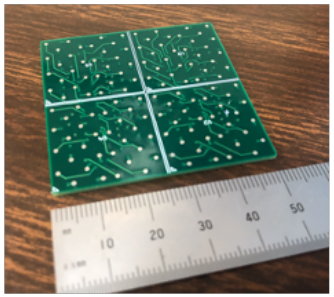
2 x 2 SiPM PCB
mounted on breakout PCB

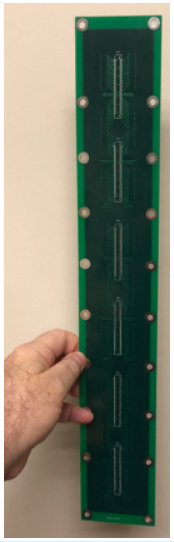


(inside walk-in Faraday cage)

FPGAs are mounted on eval boards

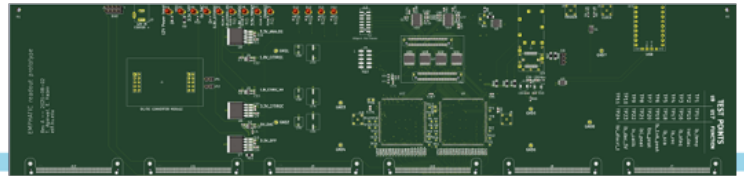
SiPM Carrier PCB





Prototype backplane PCB
(full height, 1/9 width)

Prototype readout PCB (full size, but only 64 channels instrumented)



Fermilab

ARICH Sensitivity Studies

π-K separation at 8 GeV/c:

At 5°C, 5 ns trigger window, separation = 2.5 σ

At 20°C, 5 ns trigger window, or 5°C, 20 ns trigger window, separation = 2.0 σ

At 20°C, 20 ns trigger window, separation = 1.8 σ