Overview

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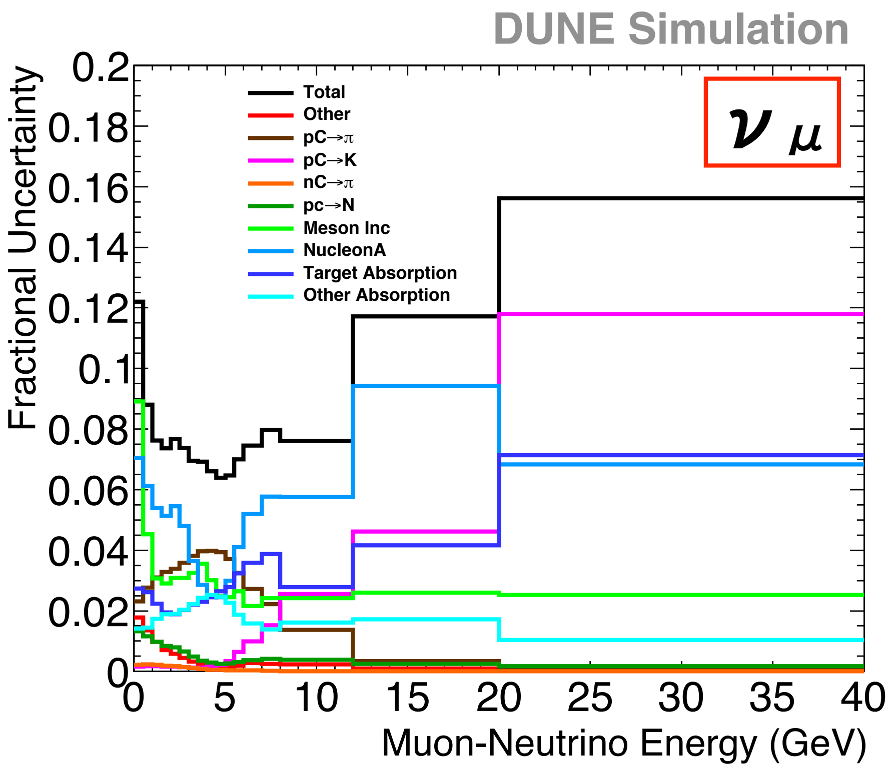
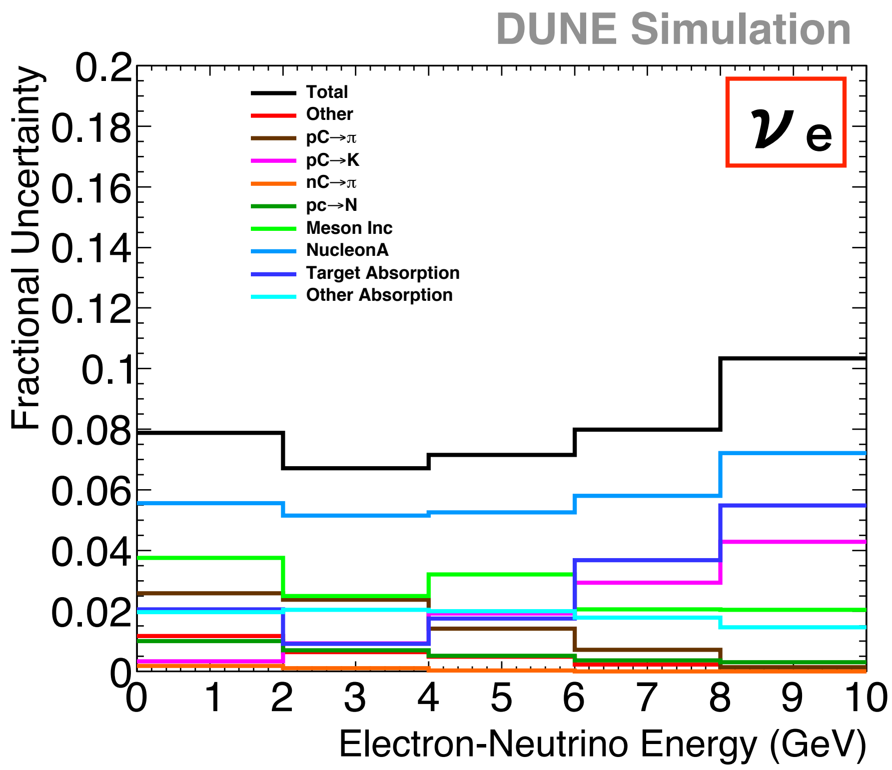
On behalf of the EMPHATIC Collaboration

January 22, 2021

DUNE Flux Uncertainties



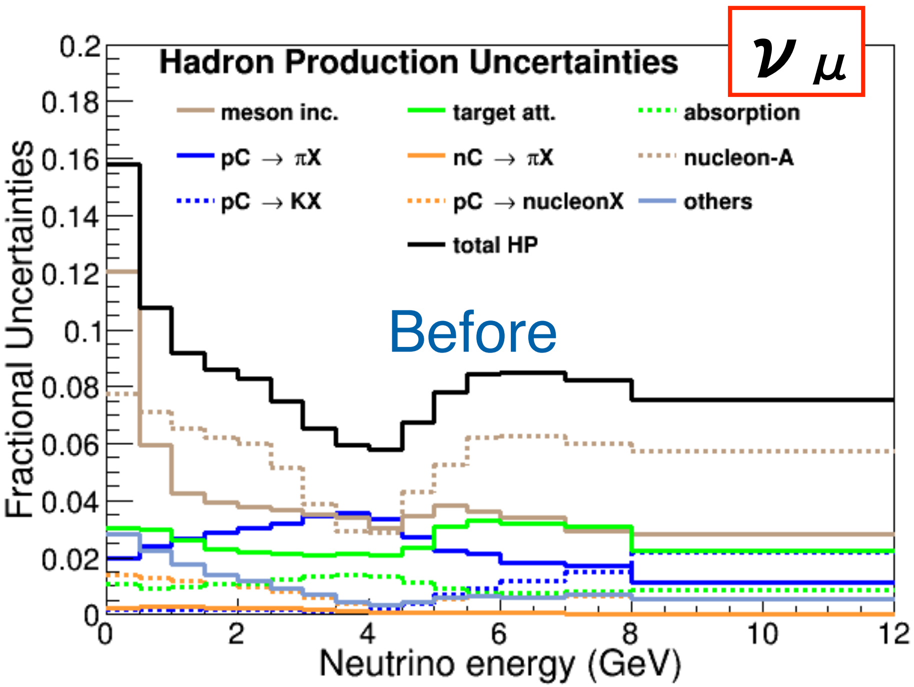


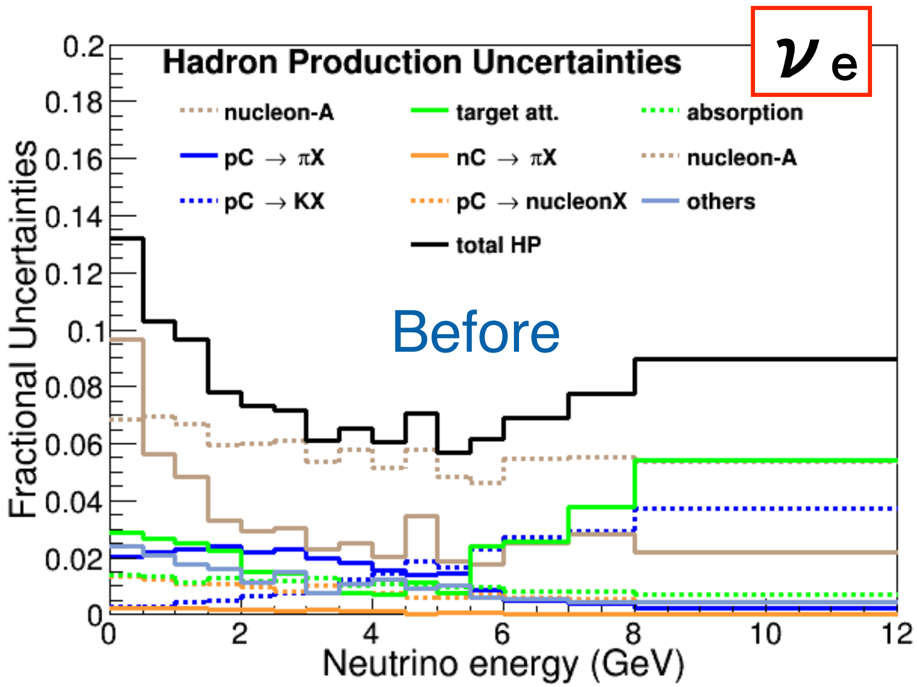
- Dominant flux uncertainties come from 40% cross-section uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread)
- Lack of proton and pion scattering data at lower beam energies (e.g. <10 GeV/c) that NA61 has access to
- Reduction of flux uncertainties improves physics reach of most DUNE near detector analyses. New hadron production measurements support the DUNE oscillation program by increasing confidence in the a-priori flux and ND measurements

Flux Uncertainties - Can we do better?

- Reasonable assumptions:
  - 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

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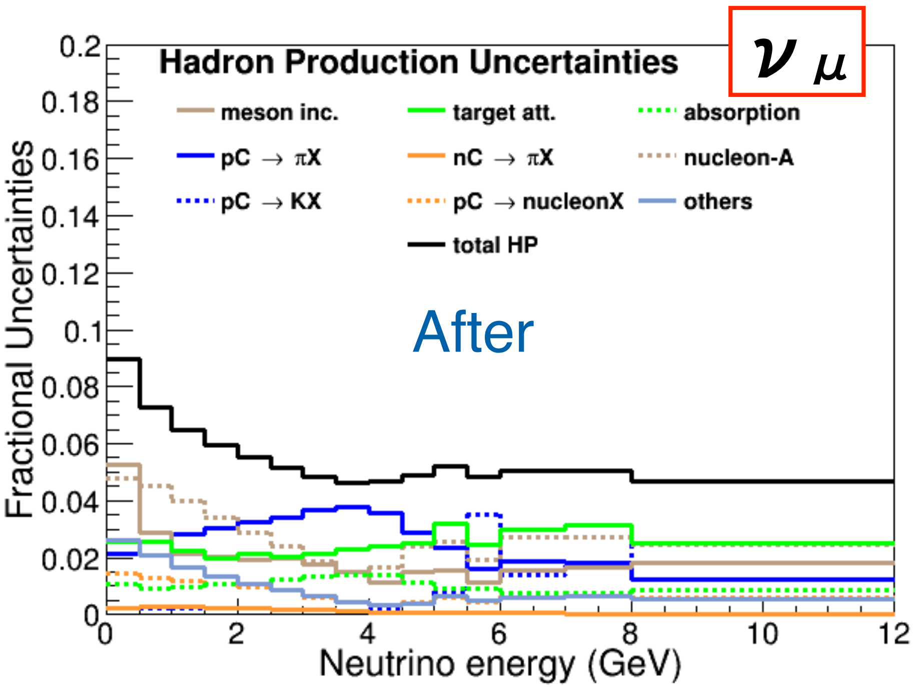

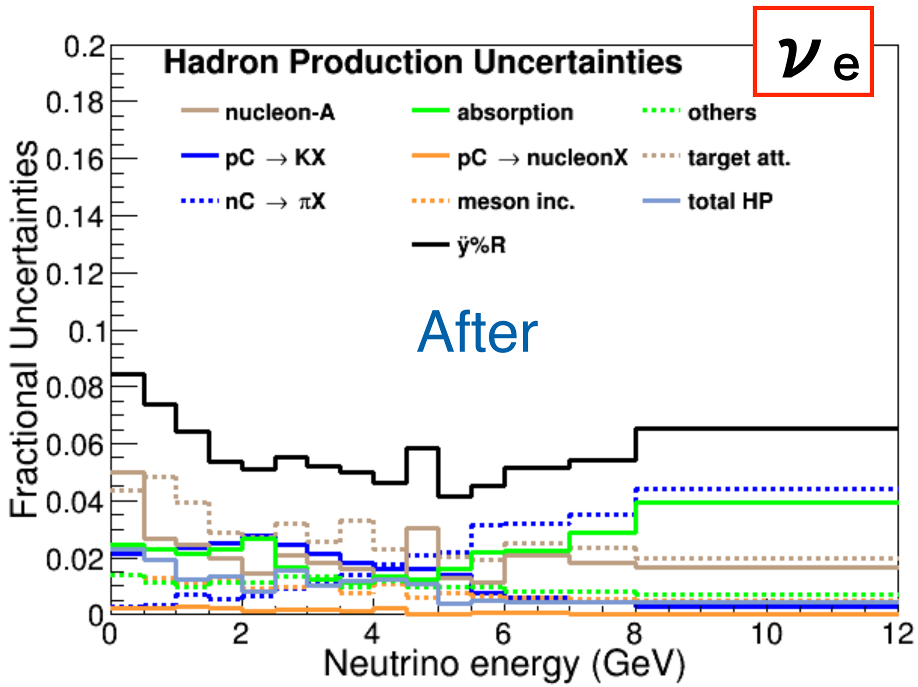

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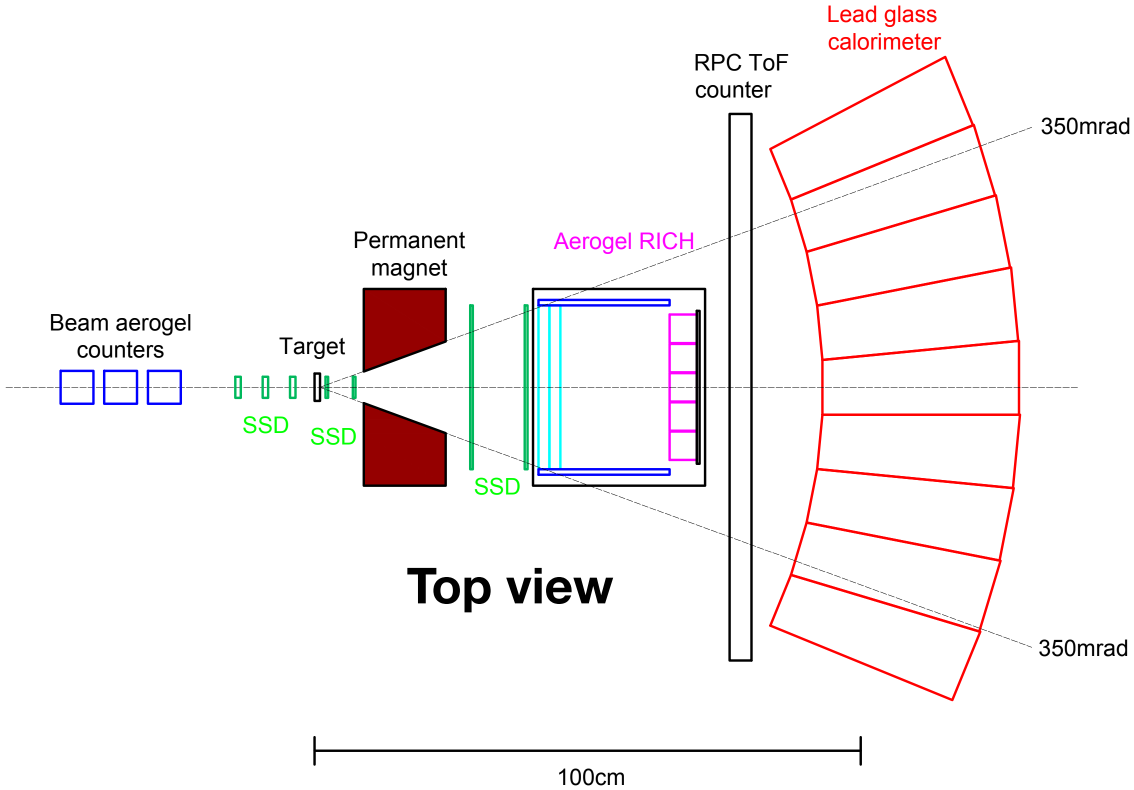
EMPHATIC

- **Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland**
  - Uses the Fermilab Test Beam Facility (FTBF)
  - 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.
  - We are aiming to reduce the hadron production uncertainties by a factor of two
- **Design concept:**
  - High-rate DAQ, precision tracking and timing
  - Compact size reduces overall cost
- **International collaboration from US, Japan, and Canada**
  - Involvement of experts from NOvA/DUNE and T2K/Hyper-K
  - Critical detectors from Canada and Japan are funded and ready for Phase-1 run



EMPHATIC Measurement Plan

Phase	Date	Sub-system	Momenta	Targets	Goals
1 (Engineering run)	Fall 2021	Beam Aerogel counter FTBF SSDs Small aperture magnet Small aperture A-RICH ToF counters Lead glass calorimeter	4, 8, 12, 20, 31, 60, 120 GeV/c	C, Al, Fe	• Low-acceptance (150mrad) hadron production with PID up to 8 GeV
2	Spring/Fall 2022	Beam Aerogel counter FTBF SSDs Large-area SSDs Full aperture magnet Full aperture A-RICH ToF counters Lead glass calorimeter	4, 8, 12, 20, 31, 60, 120 GeV/c	C, Al, Fe, H_2O, Be, B, BN, B_2O_3	• Full-acceptance (350mrad) hadron production with PID up to 8 GeV
3	2023	Same as Phase 2 + Extended RICH	20, 31, 60, 80, 120 GeV/c	Same as Phase 2 + Ca, Hg, Ti	• Full-acceptance (350mrad) hadron production with PID up to 15 GeV
4	2024	350 mrad acceptance spectrometer	120 GeV/c	Spare NuMI target and horn	Charged-particle spectrum downstream of horns

EMPHATIC Measurement Plan

Was supposed to be Spring 2020, but then COVID-19 happened…

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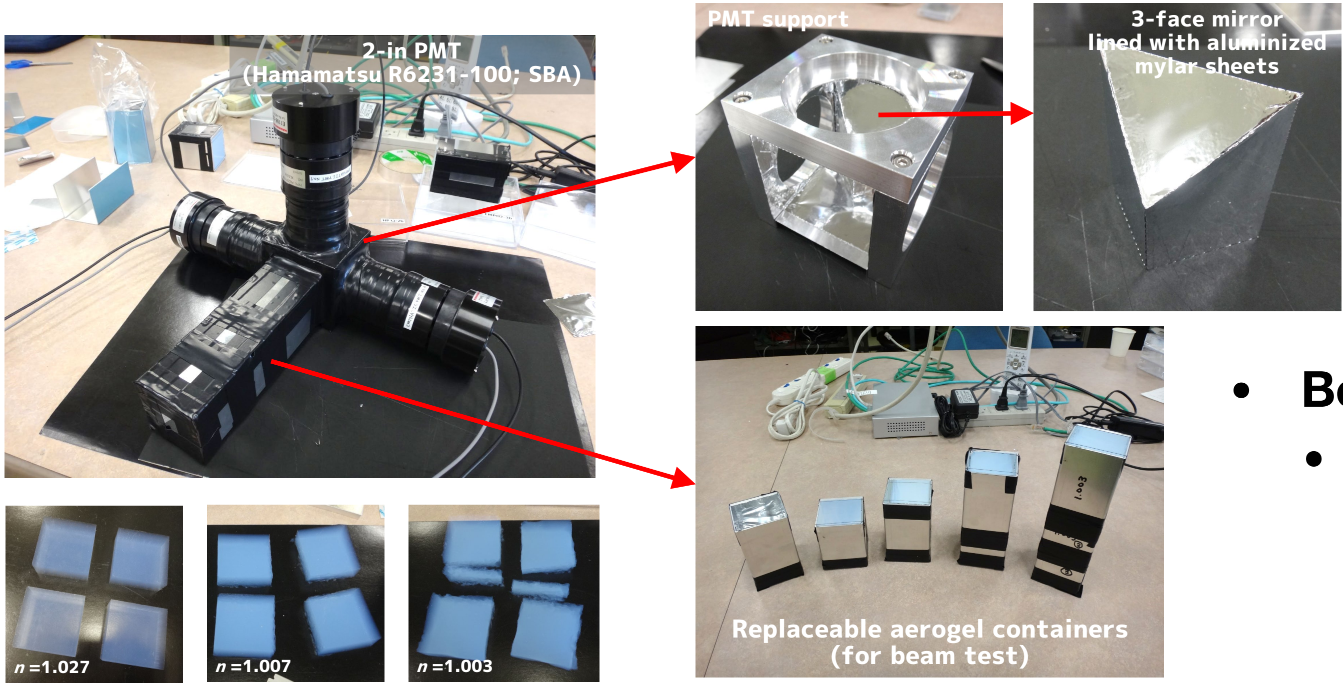
Beam Particle ID

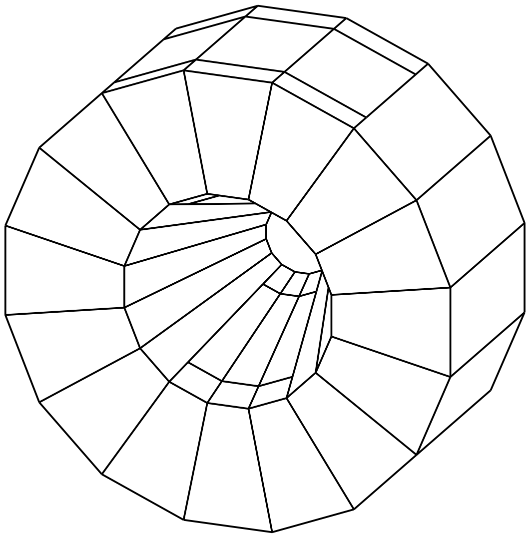


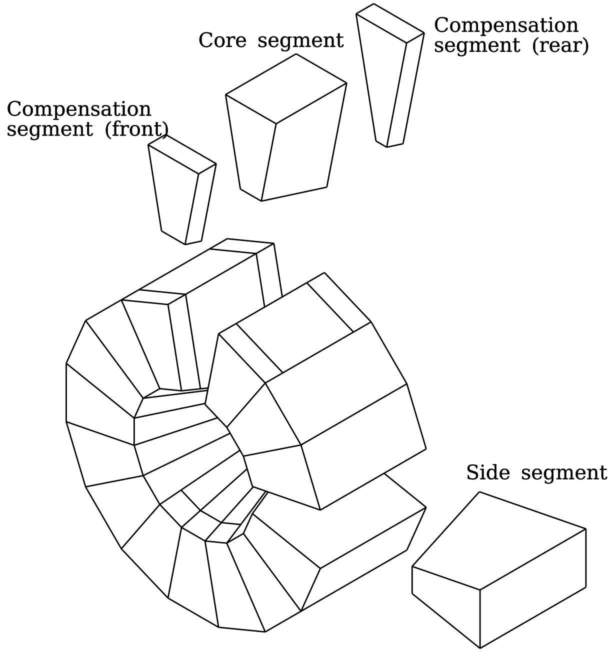
Aerogel	Particle (Equivalent)	Threshold			$N_{p.e.}$ (Average)
		0.5 p.e.	1 p.e.	1.5 p.e.	
1.027 (60 mm thick)	*K* (4 GeV/*c*)	99.3	99.2	99.1	30.7–34.4
1.007 (65 mm thick)	*K* (8 GeV/*c*)	98.7	98.3	97.9	7.6–8.3
	π (4 GeV/*c*)	98.9	98.5	98.1	9.6–10.6
1.003 (160 mm thick)	*K* (12 GeV/*c*)	98.7	97.7	96.1	4.9–5.2

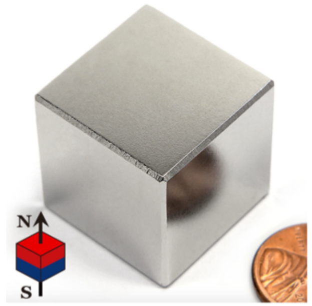
- **Beam PID**
  - Gas Cherenkov detectors can be used for p>6 GeV/c
    - No p/K separation for p<18GeV/c
- **Beam aerogel counter**
  - Developed by Chiba Univ. (aerogel expert)
  - Very low index (n=1.004) aerogel newly developed for EMPHATIC
    - Can cover up to 12 GeV/c

Permanent Magnet

Dipole magnet made from segments of Neodymium permanent magnets

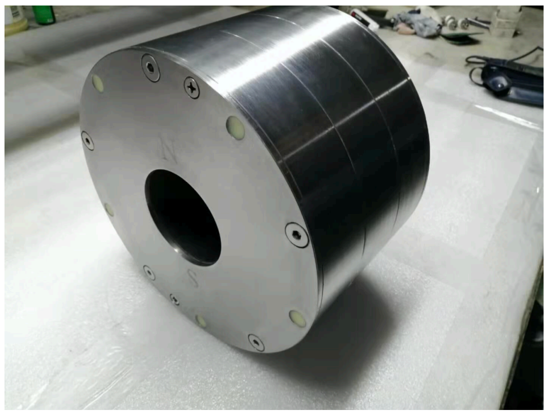


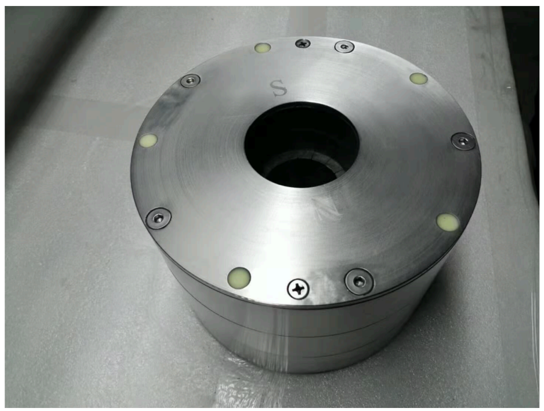


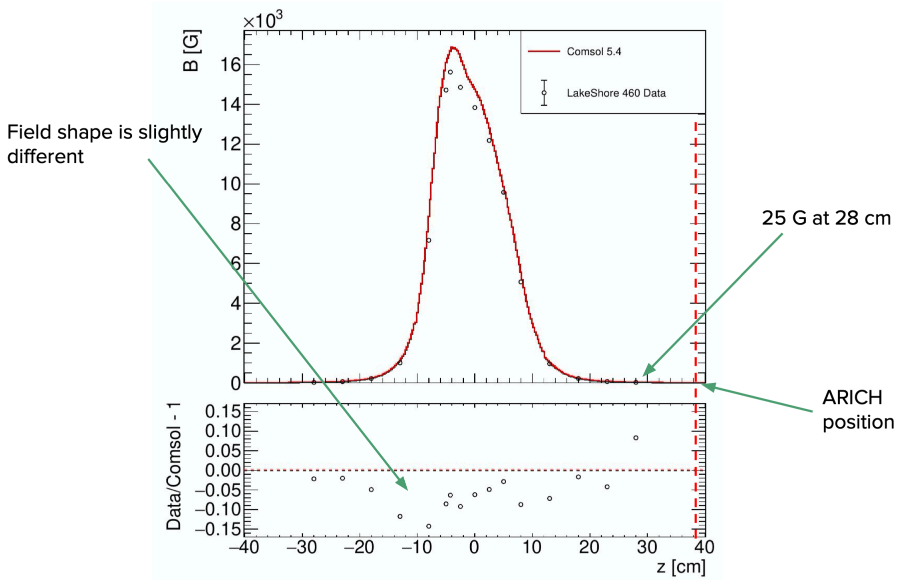


Magnet type	dipole
Material	NdFeB (N52)
Total number of segments	28
Mass	~104 kg

Small aperture magnet purchased by TRIUMF for 2020 run (150mrad coverage)

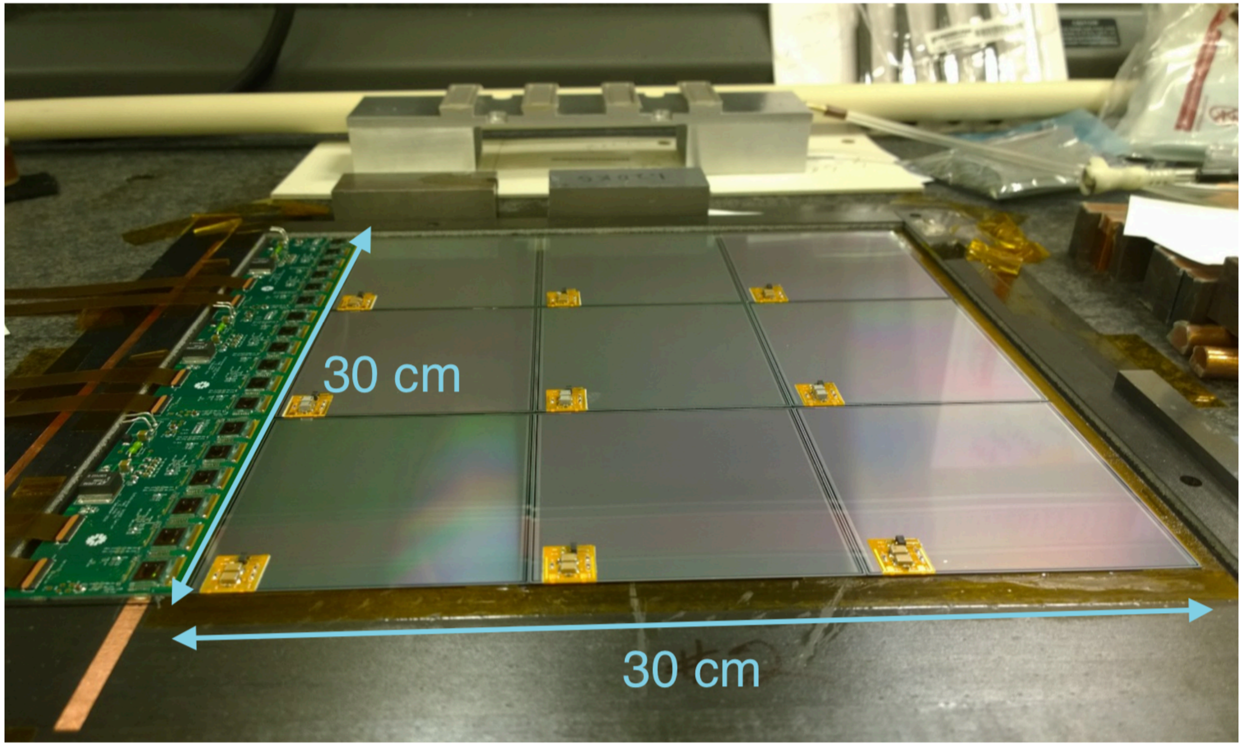




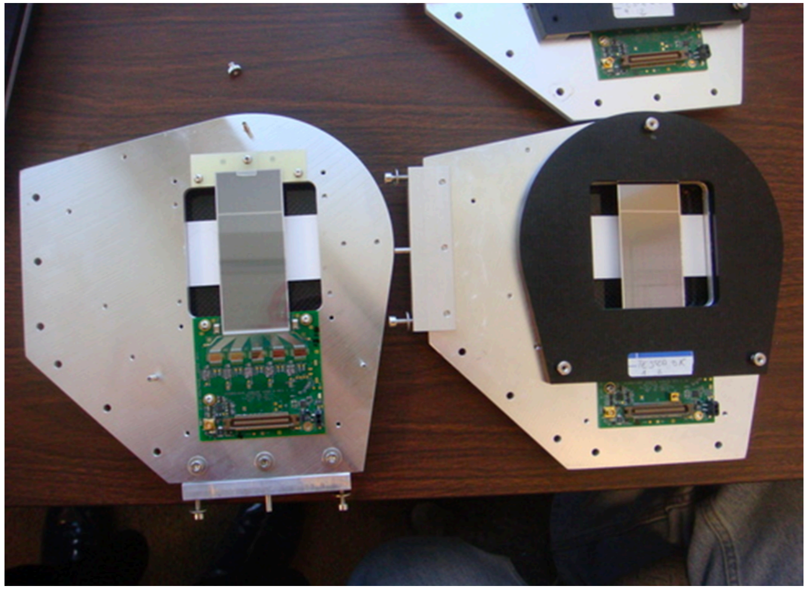


Silicon Strip Detectors

Downstream of magnet

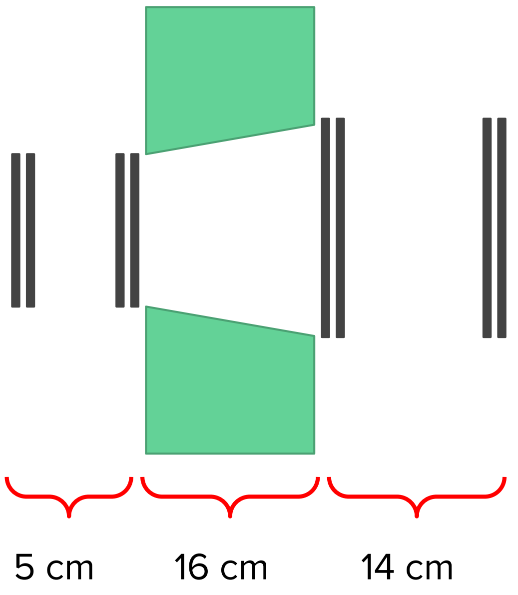


Upstream of magnet
Existing FTBF SSDs
(4cm x 4cm active area)



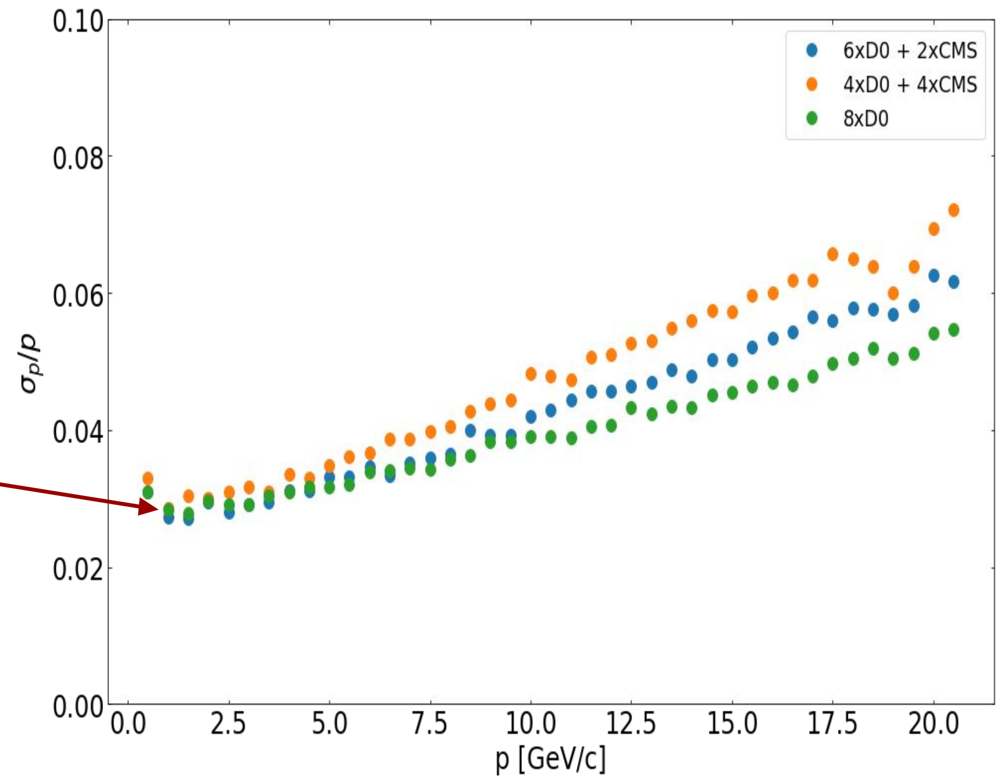
- Phase-1: upstream tracking can be done with existing FTBF SSDs
  - If we move to other location, other SSDs will be needed
- Phase-2: **Large-area SSDs** are needed
  - CMS ($10x10cm^2$) / D0 ($10x5cm^2$) sensors available from Fermilab SiDet facility.
  - Resolution good enough (122μm) for downstream tracking

Momentum Resolution



DO = 60 µm pitch, 300 µm Si + 300 µm carbon fiber
CMS = 122 µm pitch, 500 µm Si + 300 µm carbon fiber

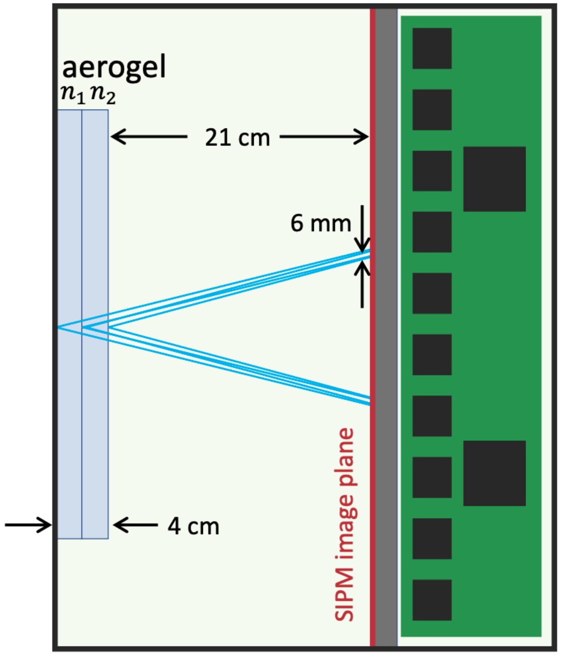
Back of the envelope calculation confirms 2.5% resolution at 1 GeV due to multiple scattering

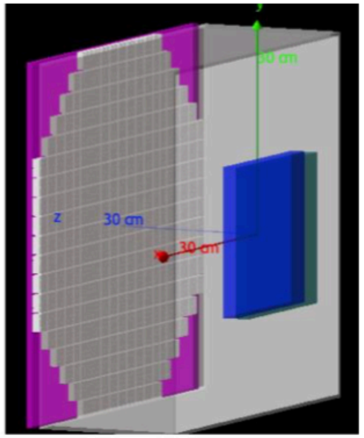


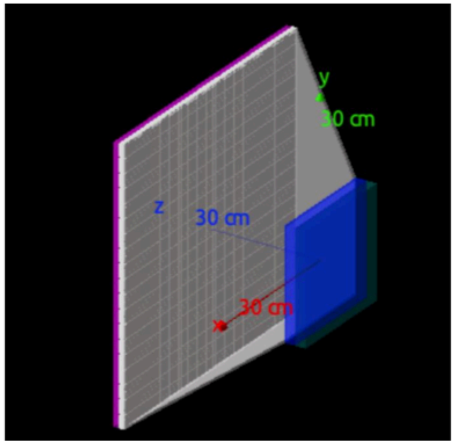
- Tracking simulation using GEANT4
  - Preliminary study based on COMSOL magnetic field maps.
  - SSD resolution taken into account
- Momentum resolution < 6% below 15 GeV/c
  - Resolution dominated by multiple scattering at low momentum

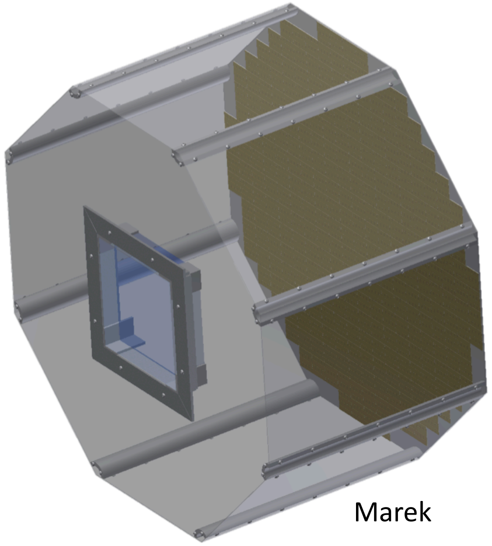
PID Detectors : Aerogel RICH

Large Acceptance Aerogel RICH





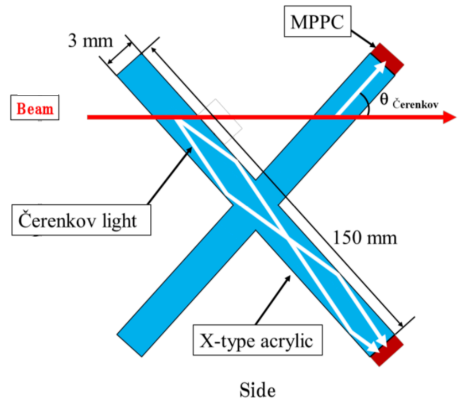


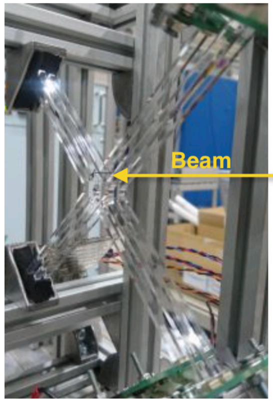


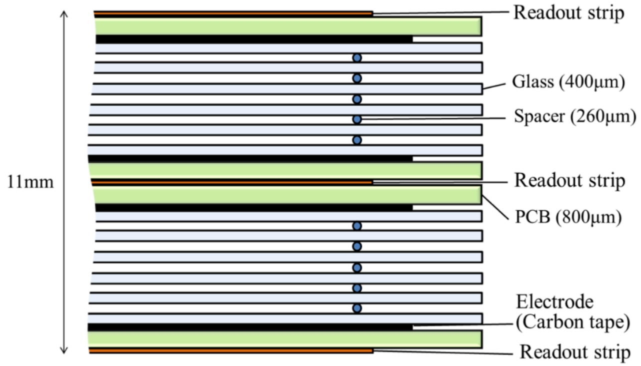
Marek

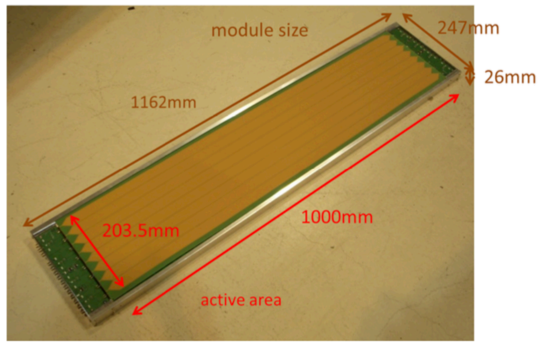
- Proximity-focusing RICH based on Belle II ARICH detector
- Aerogels with lower indices of refraction (n=1.03-1.04) and good transmittance
- Light detected by SiPMs (6mm-pitch)
- 3σ π-K separation for p<7 GeV/c.
- A prototype developed by Canada group for Phase-1 run
- Hybrid aerogel + gas RICH by adding gas for Phase-3 to extend up to 15 GeV/c

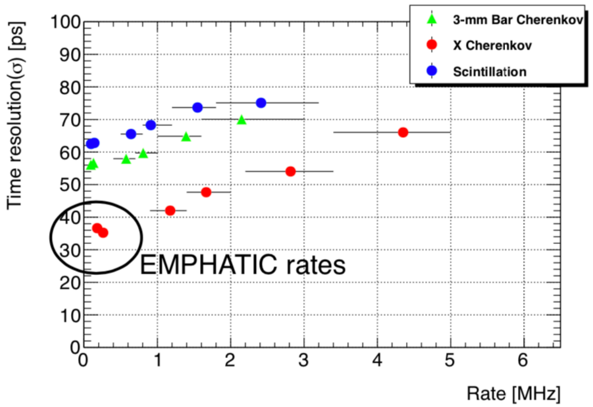
PID Detectors : ToF Counters

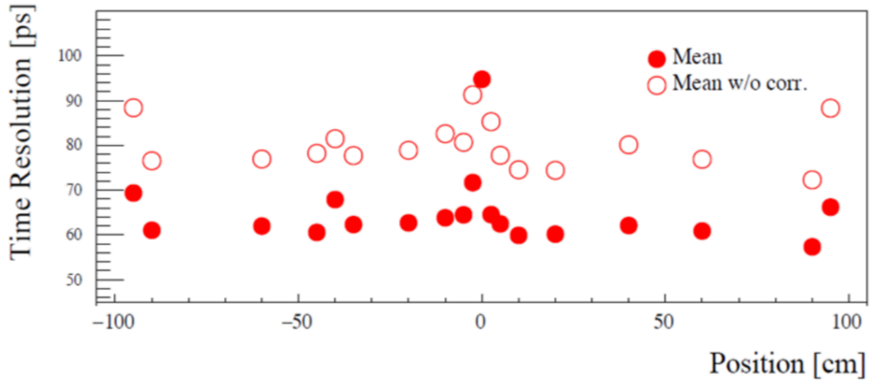




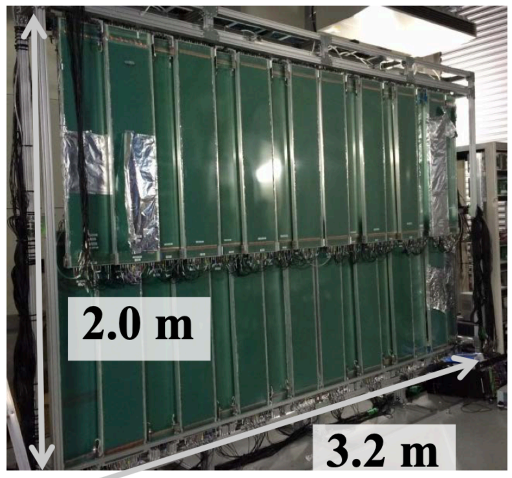








BGOegg RPC @ Spring-8



- PID by ToF counters for low momentum particles (~1 GeV/c)
- Start counter : X-shaped Cherenkov detector (Acrylic + MPPC)
  - < 40 ps timing resolution
- Stop counter : Multi-gap Resistive Plate Chamber (RPC)
  - ~60 ps timing resolution
- Developed by J-PARC E50 group
  - Joined EMPHATIC for BG measurements

Some Important Points

- **EMPHATIC is an international experiment,**
  - with very significant contributions from international partners,
  - much of which is already in hand, and the rest will be ready before the end of this summer.
- **We have a significant number of early career scientists in the collaboration**
  - Including 9 postdocs and 5-6 graduate students in Phase-1 and -2 runs
  - EMPHATIC is an excellent training ground for these scientists, a rare opportunity to participate in the full life cycle of an experiment, from design through publication of results
- **We have lost at least 1.5 years in our original run plan due to the pandemic**
  - Canadian and Japanese participation is limited in time, and we expect all non-US groups to have to cease participation by the end of 2023, but some may need to cease earlier.
  - **It is therefore imperative that we move as quick as possible to collect data, starting at the end of 2021.**