EMPHATIC

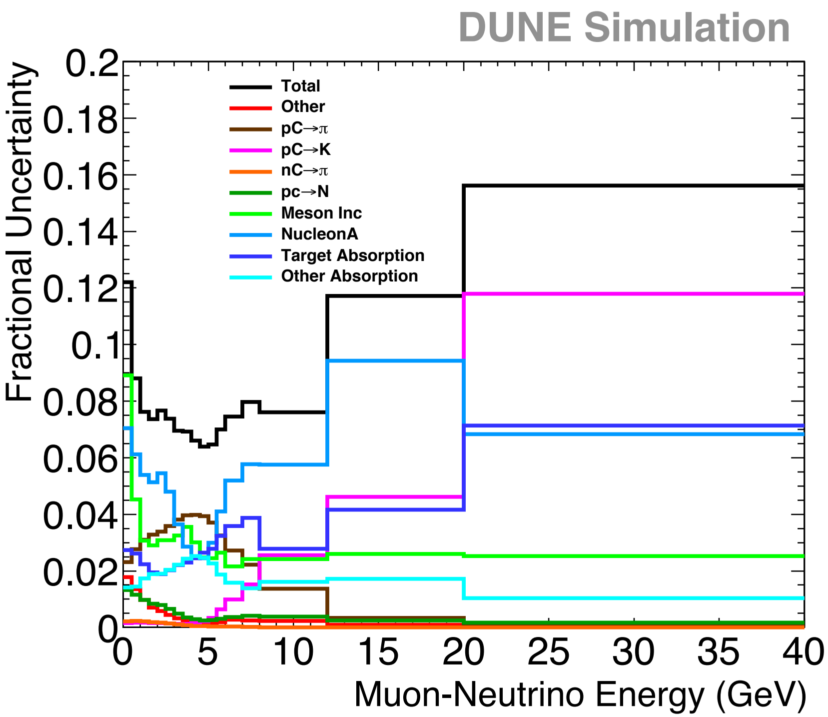
A new hadron production experiment for improved neutrino flux predictions

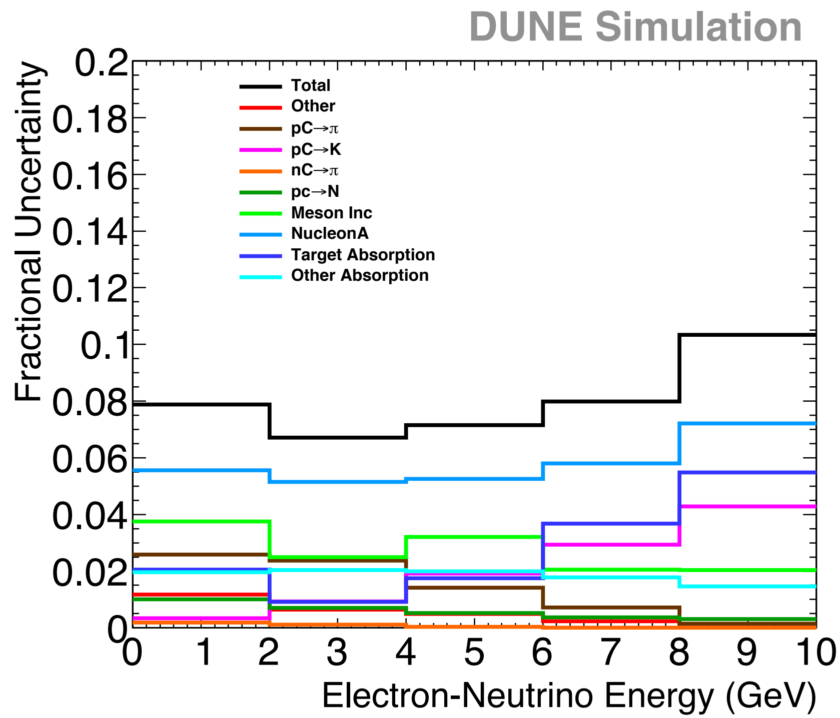
Jonathan Paley
On Behalf of the
EMPHATIC Collaboration

NA61 Low Energy Workshop

December 9, 2020

DUNE Flux Uncertainties



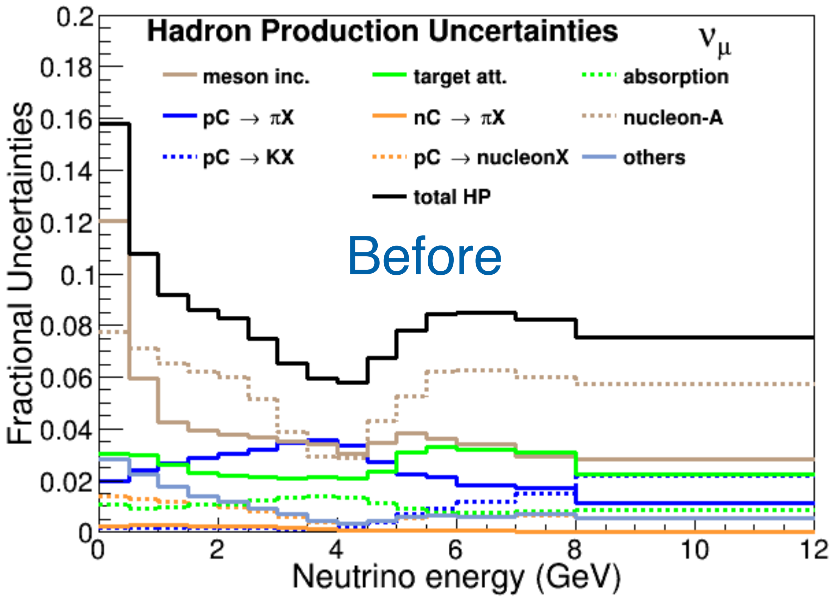


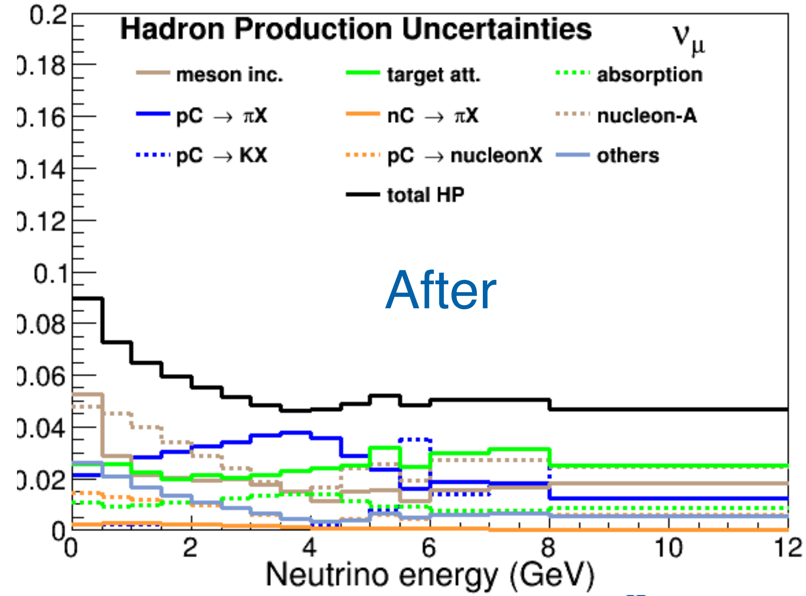
- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread).
- Lack of proton and pion scattering data at lower beam energies.
- **Reduction of flux uncertainties improves physics reach of most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

DUNE 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± + X (down from 40%)

Not covered by current data





Note: flux uncertainties determined by EMPHATIC, not DUNE

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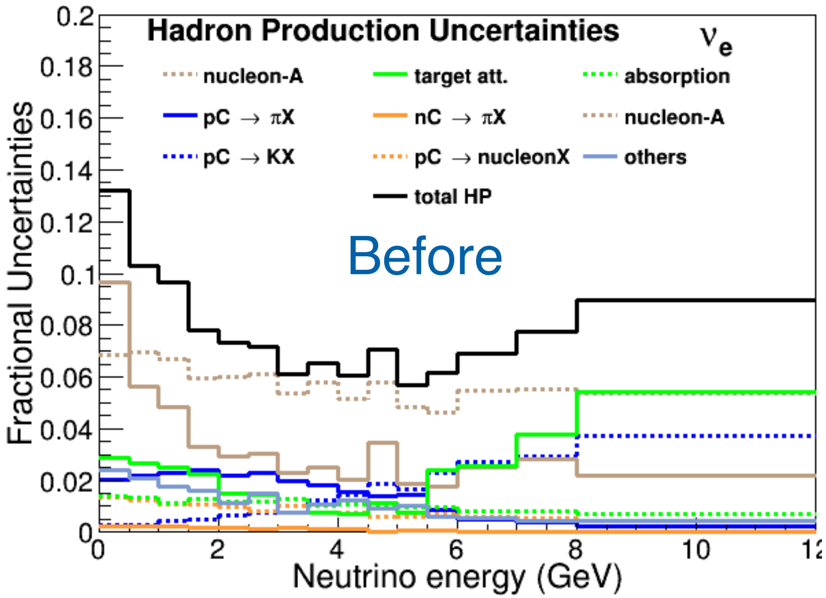

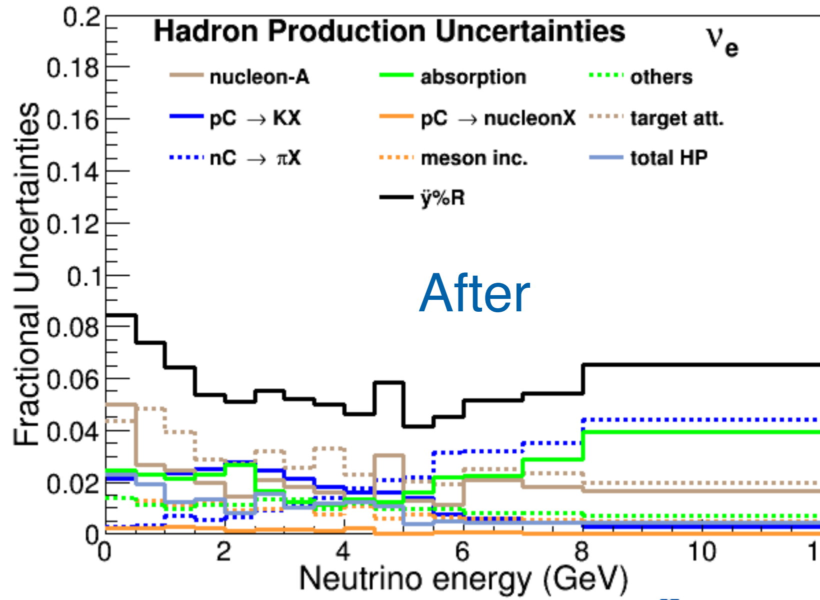

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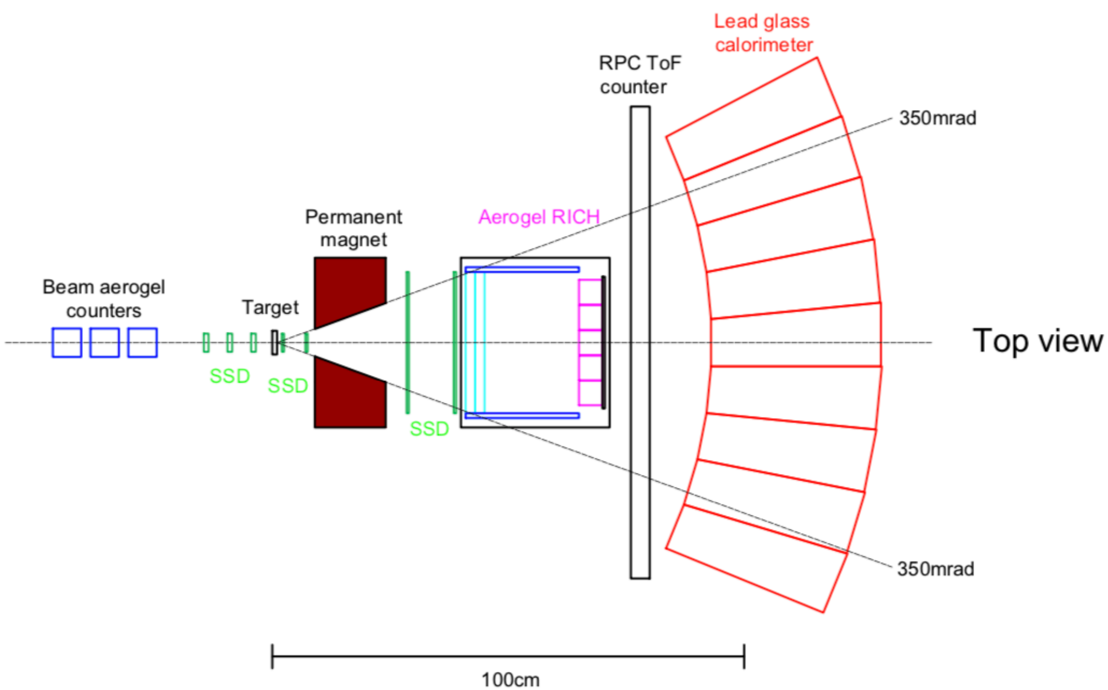
EMPHATIC

- **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:
  - compact size reduces overall cost
  - high-rate DAQ, precision tracking and timing
- International collaboration, with involvement of experts from NOvA/DUNE and T2K/HK.



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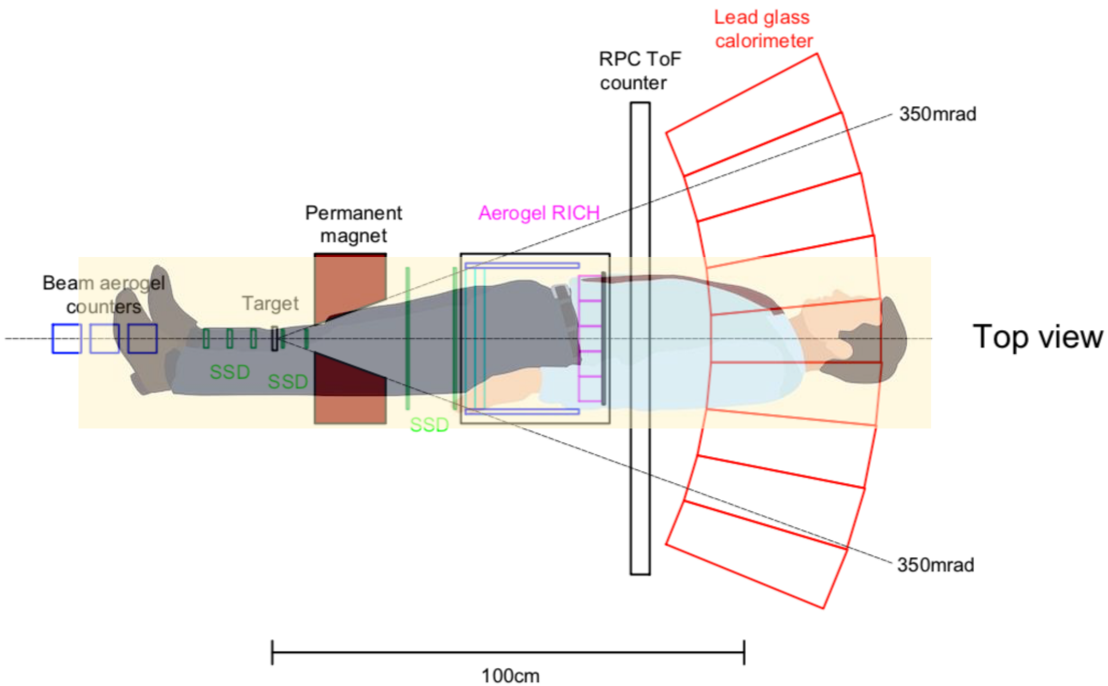
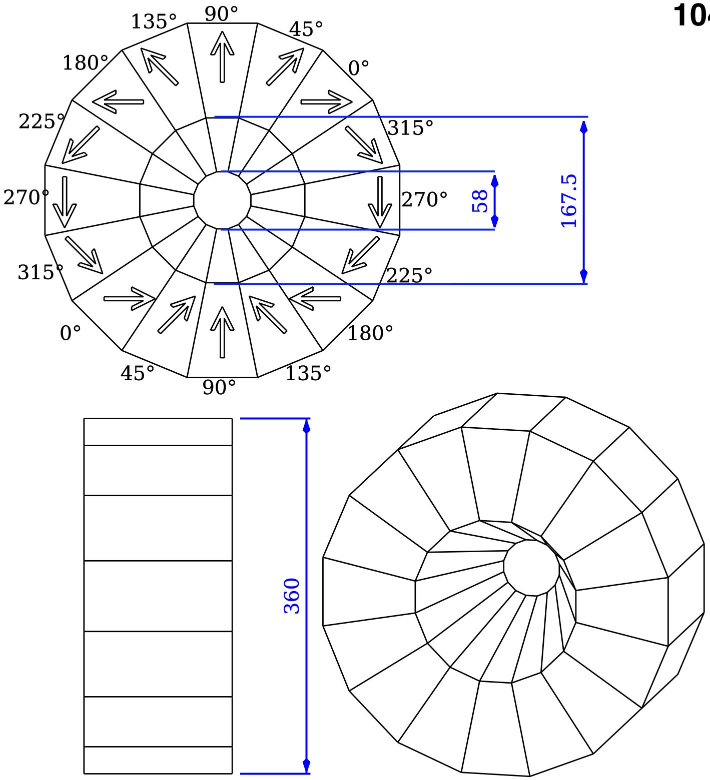
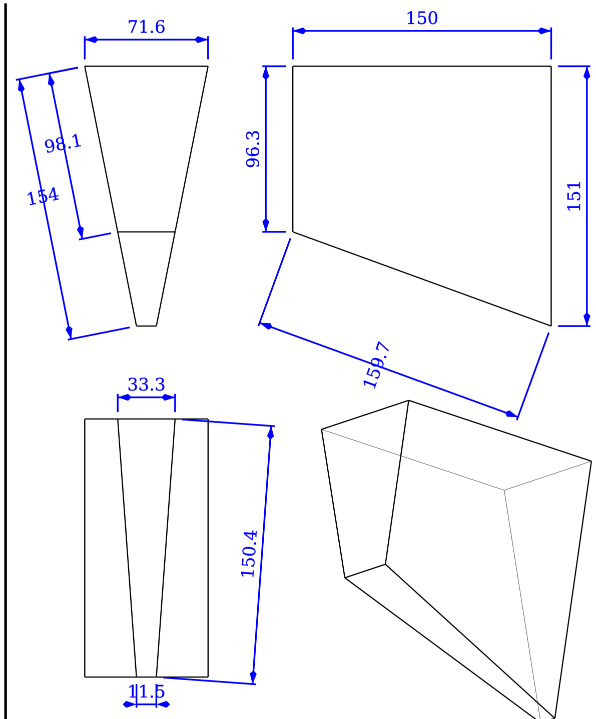


EMPHATIC: Permanent Magnet

Halbach Array

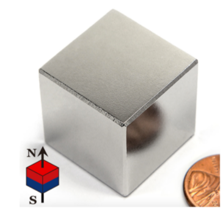
EMPHATIC Dipole Magnet
16 NdFeB (N52) segments
104 kg





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**.

Fermilab

EMPHATIC: Permanent Magnet

Prototype small-aperture magnet purchased by TRIUMF, now at Fermilab waiting for precise mapping.

Halbach Array

EMPHATIC Dipole Magnet
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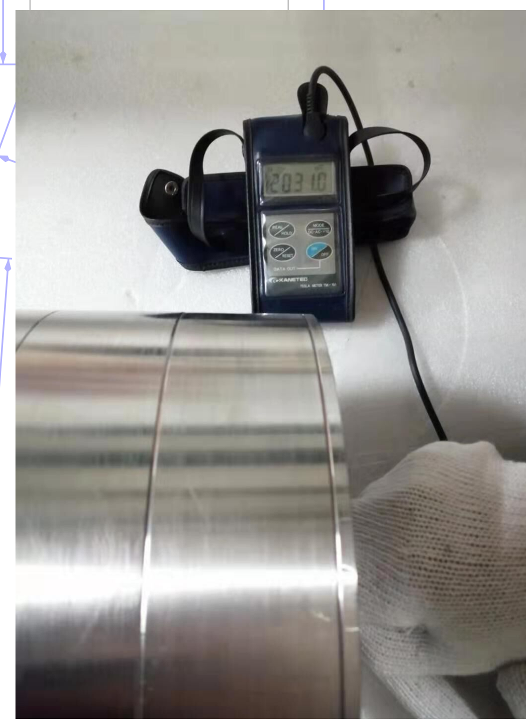

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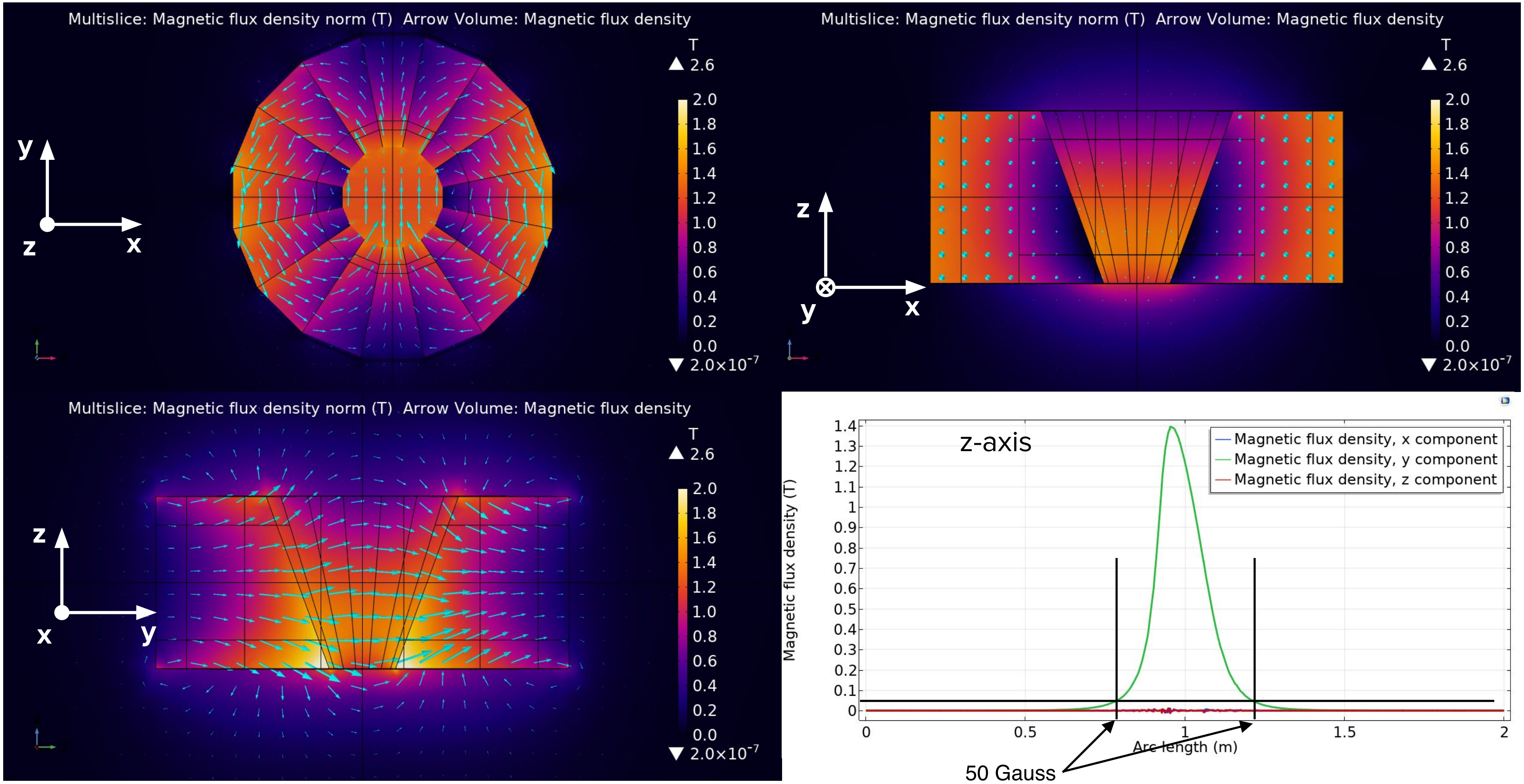
Fermilab

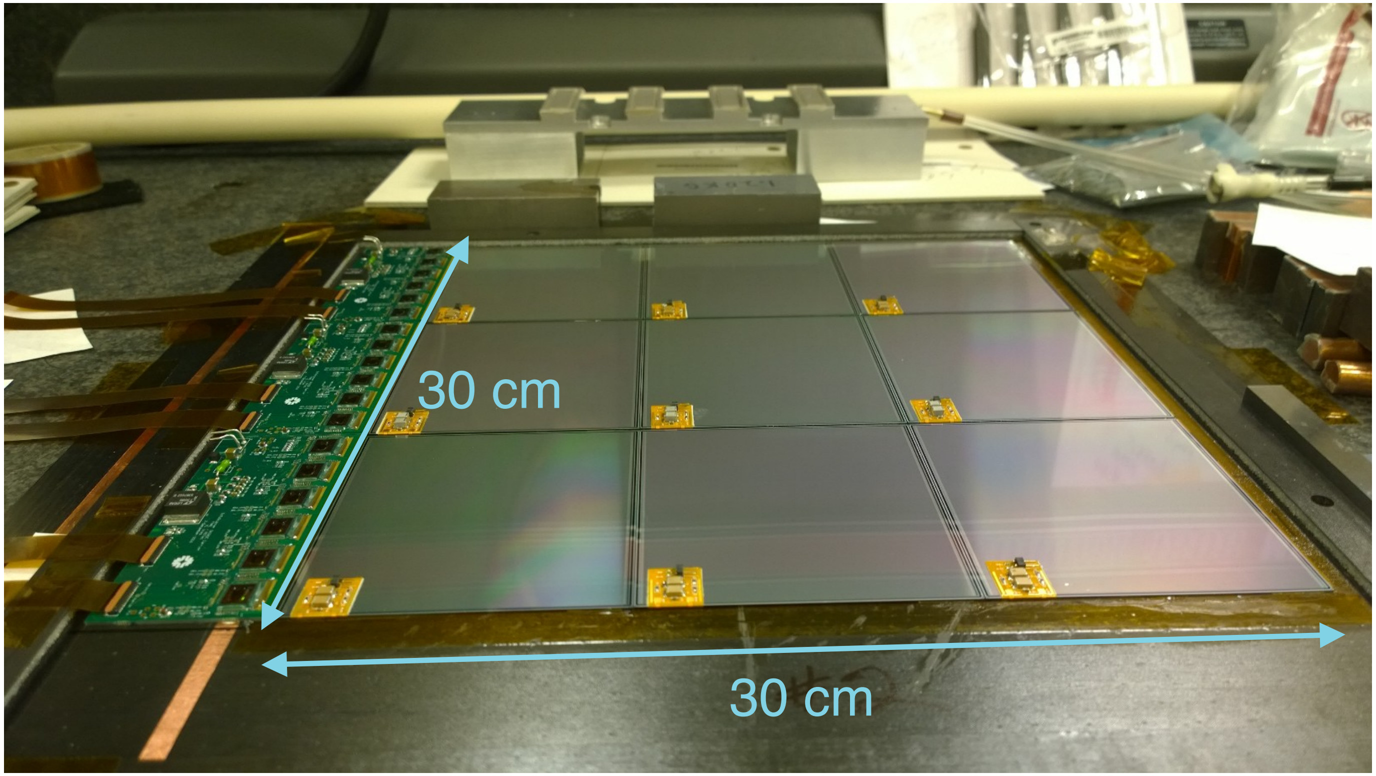
EMPHATIC: Magnet



Field maps generated using COMSOL simulation.

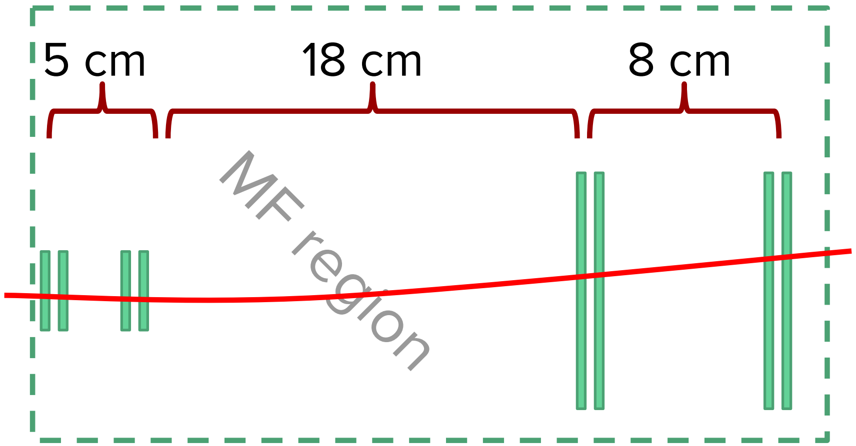
Fermilab

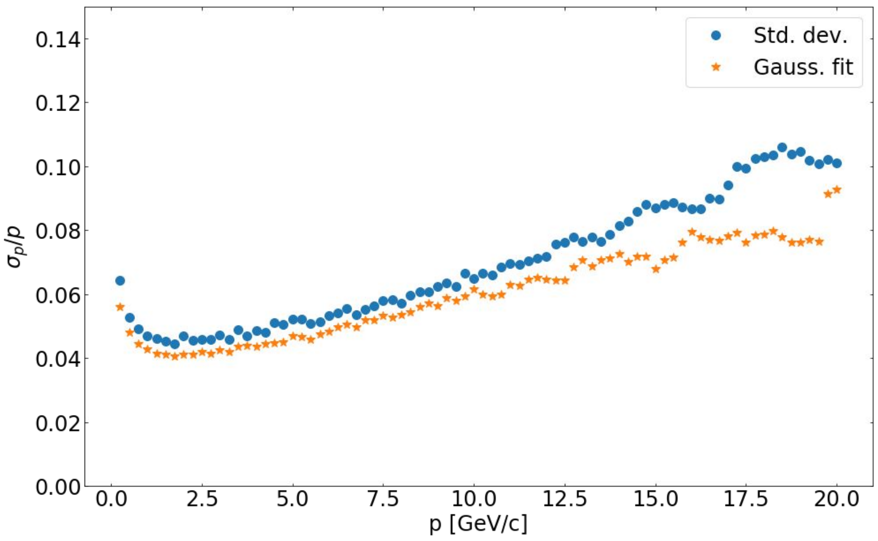
EMPHATIC: Si Strip Detectors



- Upstream tracking to be done by existing SSDs (60 µm pitch) at the FTBF.
- Large-area SSDs available from Fermilab SiDet. Resolution good enough (122 µm pitch) for downstream tracking.
- Will likely upgrade readout electronics and DAQ.
- Could be built and ready in 4-6 months.

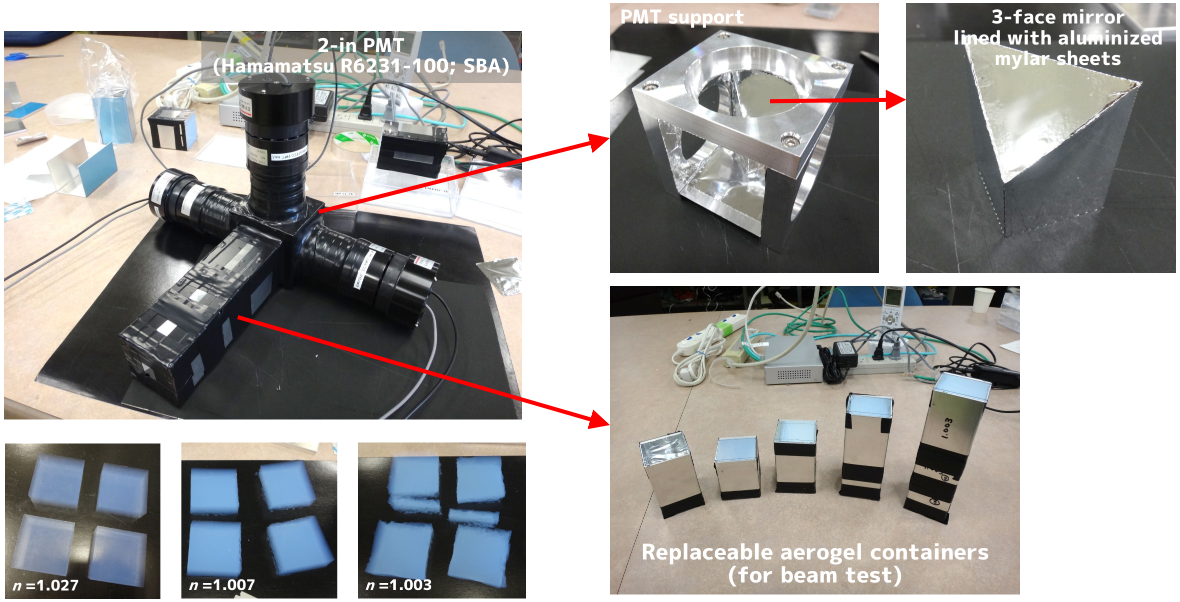
EMPHATIC: Momentum Resolution





- 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.

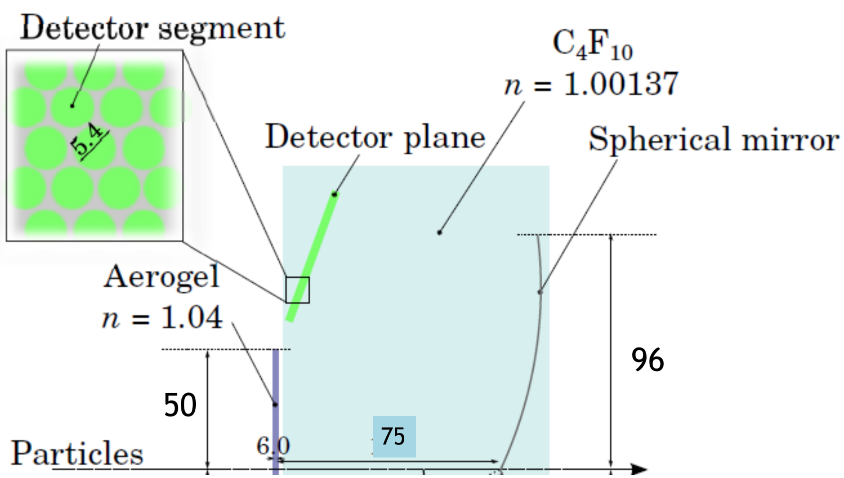
EMPHATIC: Beam PID

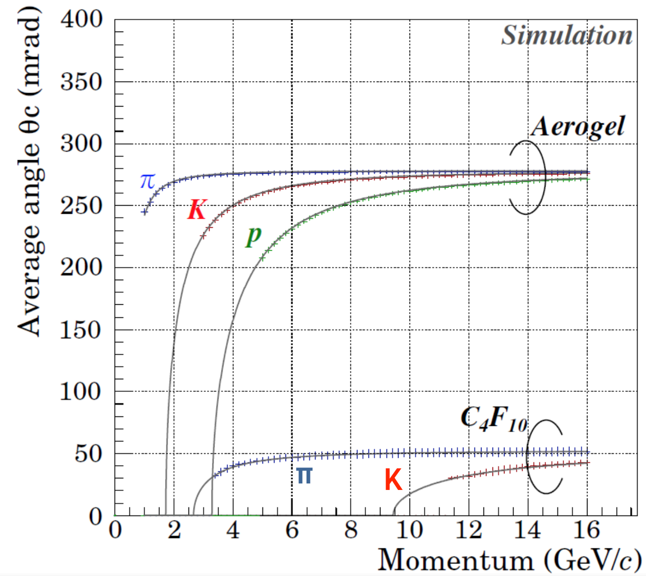


Aerogel	Particle (Equivalent)	Threshold			$N_{p.e.}$ (Average)
		0.5 p.e.	1 p.e.	1.5 p.e.	
1.027 (60 mm thick)	*K* (4 GeV/*c*)	99.3	99.2	99.1	30.7–34.4
1.007 (65 mm thick)	*K* (8 GeV/*c*)	98.7	98.3	97.9	7.6–8.3
	π (4 GeV/*c*)	98.9	98.5	98.1	9.6–10.6
1.003 (160 mm thick)	*K* (12 GeV/*c*)	98.7	97.7	96.1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

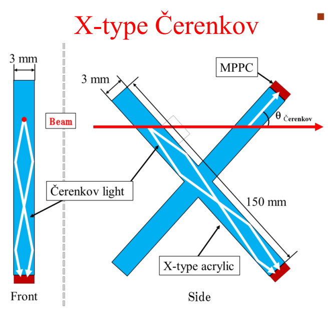
- Existing gas threshold Ckov detectors at FTBF can be used for electron veto and/or hadron beam PID above ~10 GeV/c.
- Will use new aerogel Ckov detector for PID < 12 GeV/c.
- Detector built and tested by M. Tabata at Chiba U., will be shipped to Fermilab in the coming weeks.

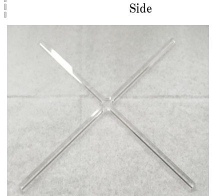
EMPHATIC: PID Detectors (from JPARC E50)





X-type Čerenkov counter

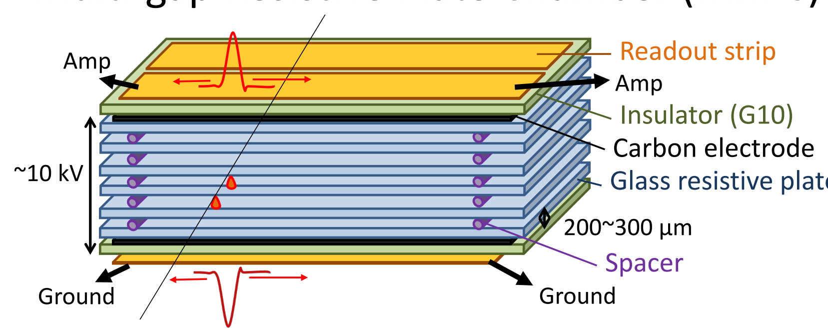




- Developing Čerenkov timing counter
  - Čerenkov lights emit in an extremely short time.
    - ✓Reduce the time spread of photons reaching to the optical sensor
    - ✓Having a fast timing response
    - ✓It has the advantage to measure the better time resolution.
  - Use "Cross shape" acrylic, called X-type, which is cut from an acrylic board
    - ✓In order to cancel position dependences of the time resolution in the Čerenkov radiator
  - The Čerenkov counter is made up of X-type acrylic and MPPC with a shaping amplifier circuit.

It is the first time to use the Čerenkov detector for a timing counter with the X-type acrylic.

Multi-gap Resistive Plate Chamber (MRPC)

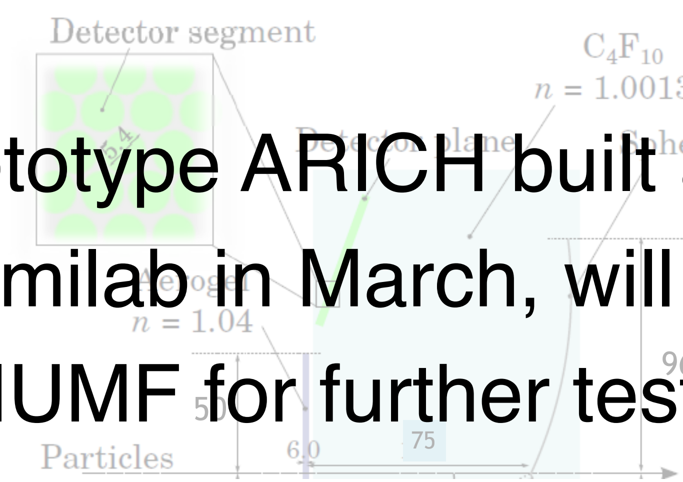


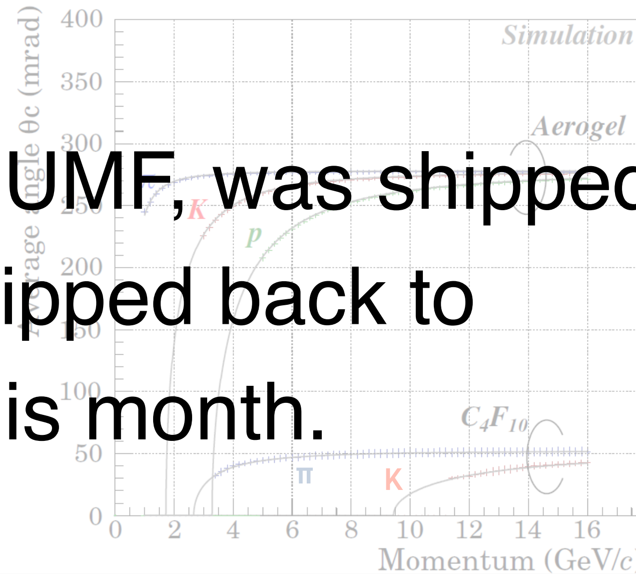
- Resistive Plate -> Avoid discharge
- Smaller gap -> Better time resolution
- Multi gap -> Higher efficiency, better time resolution

- Can be used under magnetic field
- ~60 ps high time resolution in large area
- Low cost

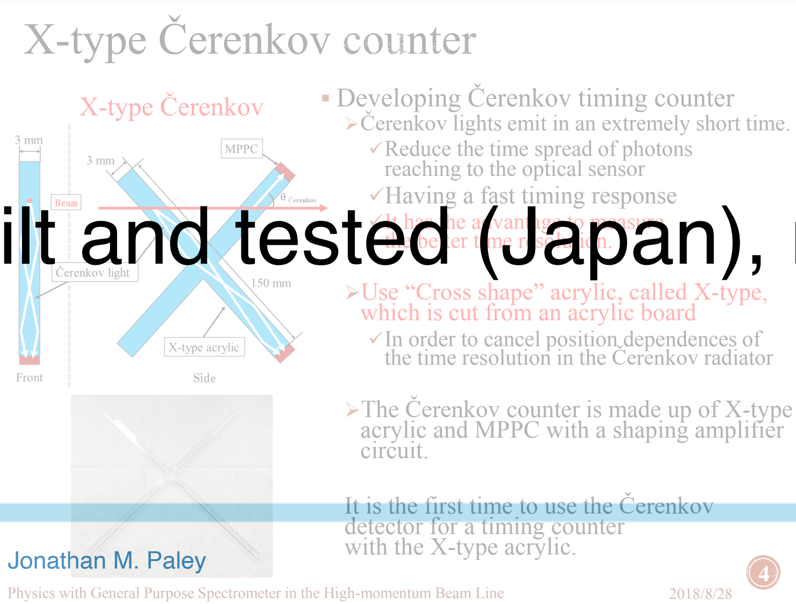
} ➡ E50 Pole face & Internal TOF detector

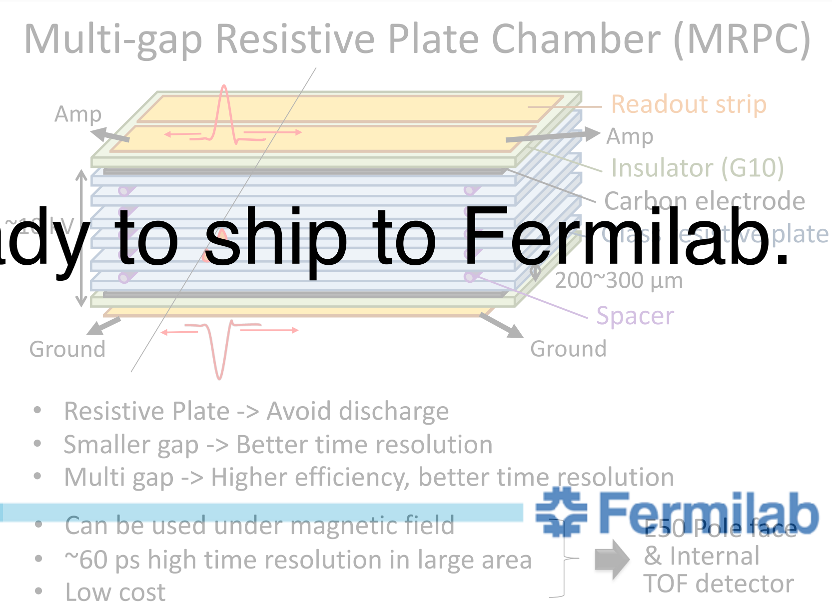
EMPHATIC: PID Detectors (from JPARC E50)





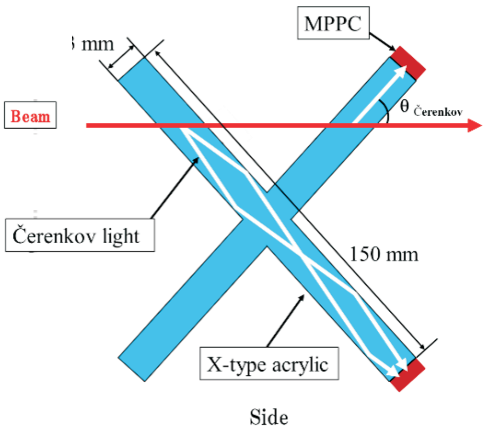
Prototype ARICH built at TRIUMF, was shipped to Fermilab in March, will be shipped back to TRIUMF for further testing this month.

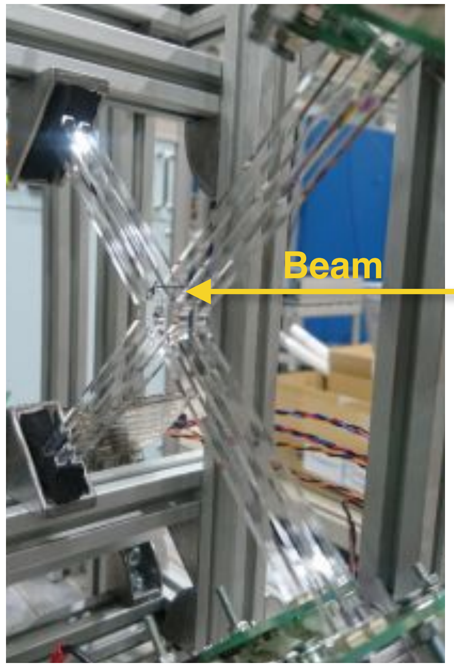


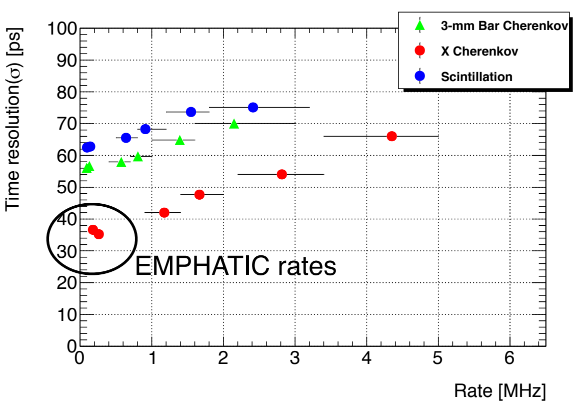


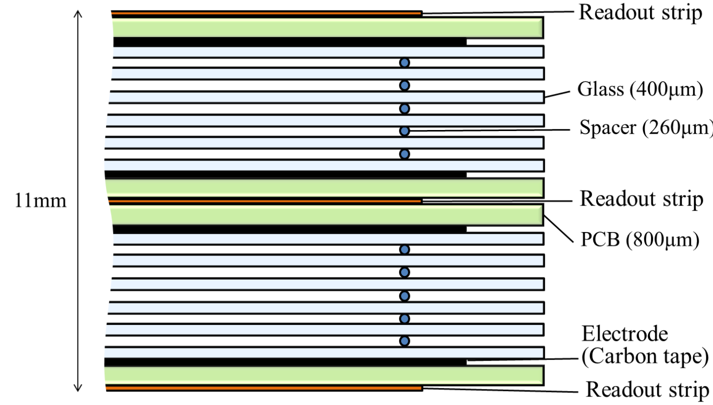
Built and tested (Japan), ready to ship to Fermilab.

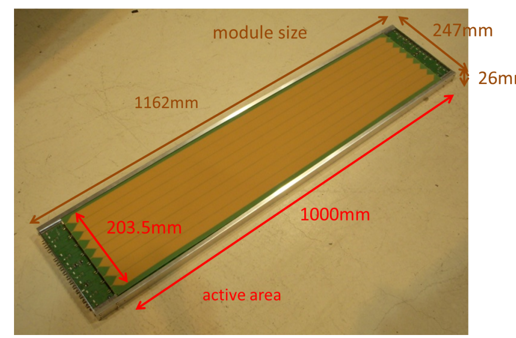
EMPHATIC: Time of Flight



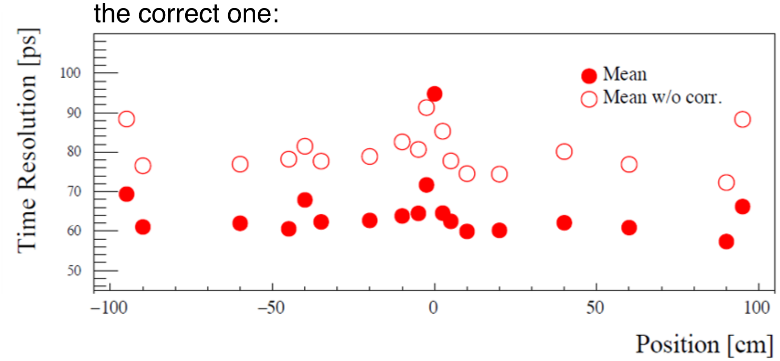




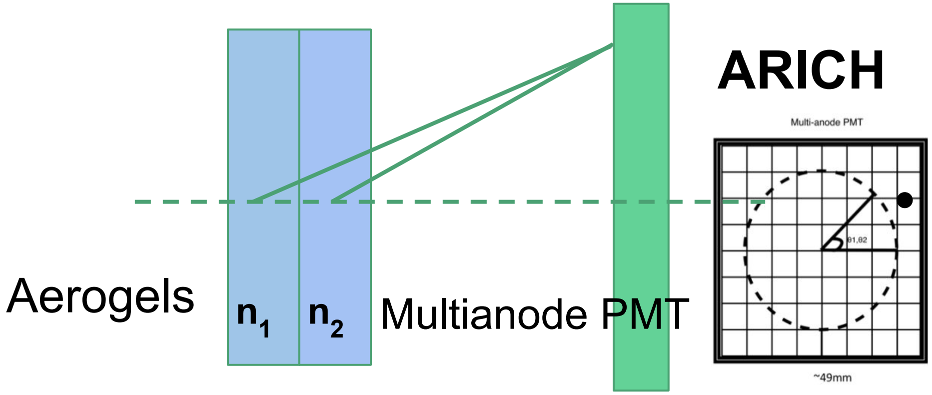


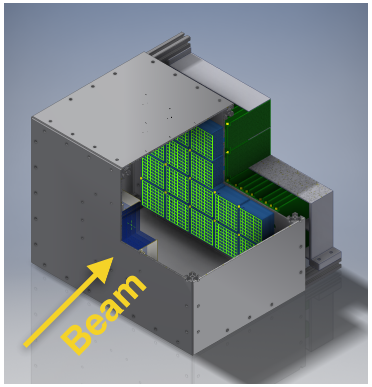


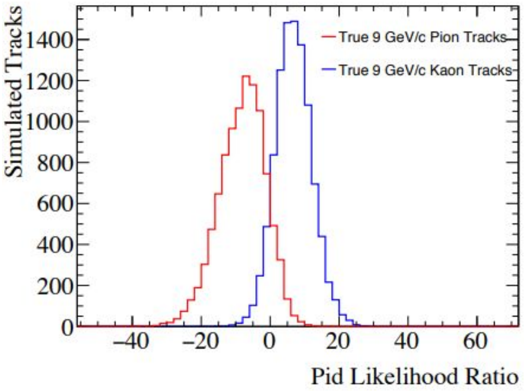
Note: Fig. 21 of the proposal has the wrong plot, this is the correct one:



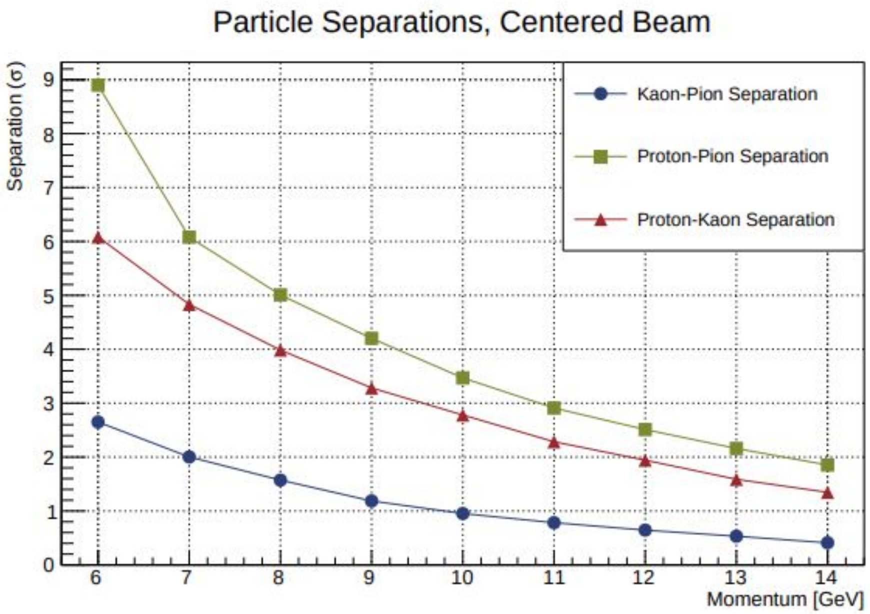
EMPHATIC: Aerogel RICH







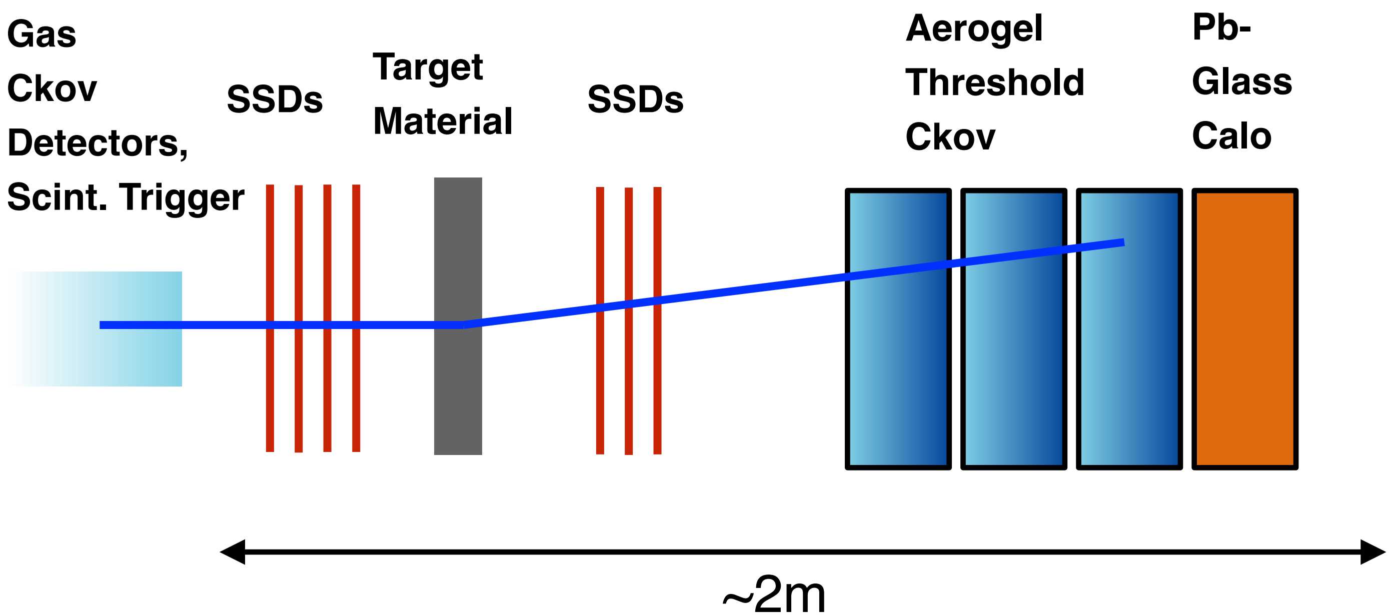
- Based on the Belle II RICH detector
- Aerogels with lower indices of refraction (n=1.02-1.03) and good transmittance available thanks to advances in aerogel production at Chiba U.
- 2σ π-K separation for p<8 GeV/c.



EMPHATIC: Initial beam test from Jan. 10-23, 2018

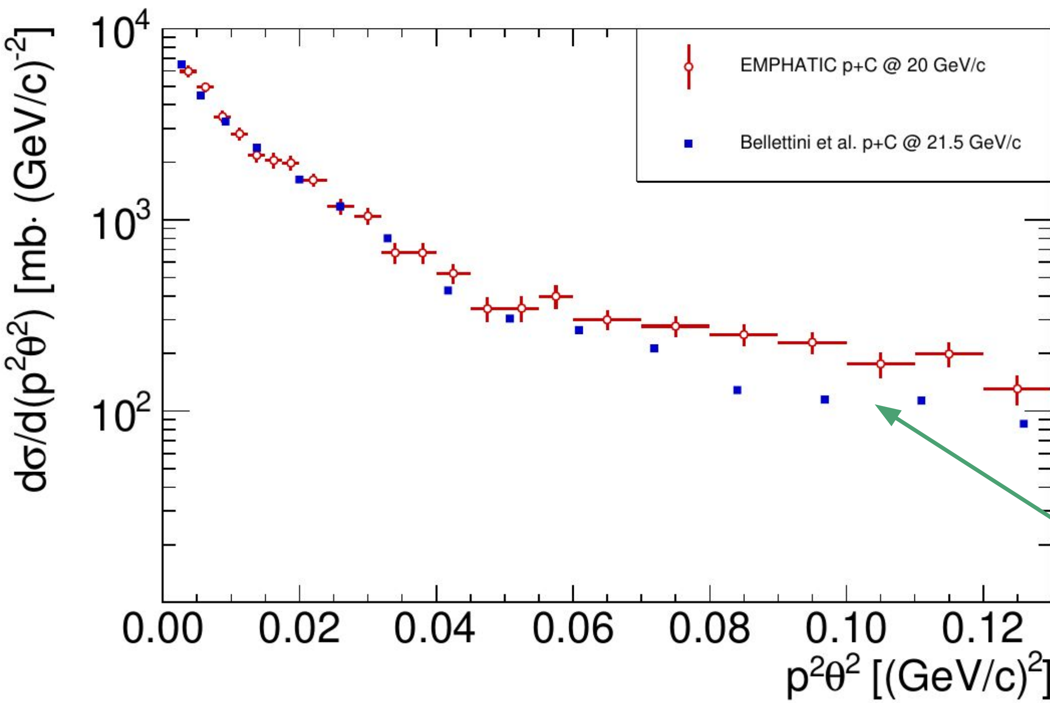
- Proof-of-principle/engineering run enabled primarily by 2017 US-Japan funds
  - Japan: aerogel detectors, emulsion films and associated equipment, travel
  - US: emulsion handling facility at Fermilab
  - Critical DAQ, motion table and manpower contributions from TRIUMF

- ~20M beam triggers collected in ~7 days of running
- Beams of p,π at 20,31,120 GeV
- Targets: C, Al and Fe (+ MT)



EMPHATIC: Thin-target data w/ silicon tracking only

results presented by M. Pavin, Fermilab JETP Seminar, May 10, 2019



Bellettini et al.

- Angular coverage 1.5 - 20 mrad
- Momentum measurement ➜ contamination of inelastic events 1%
- Uncertainties are not known

EMPHATIC and Bellettini do not measure the same thing!

- EMPHATIC includes resonance production

Bellettini et al., Nucl.Phys. 79 (1966) 609-624

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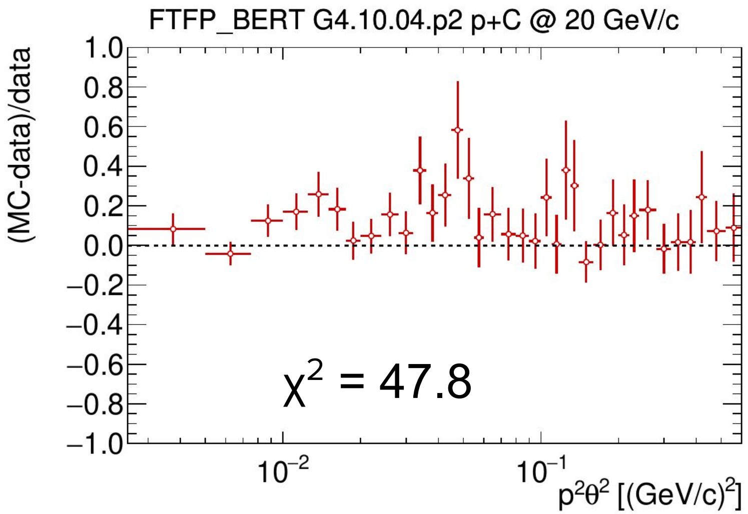

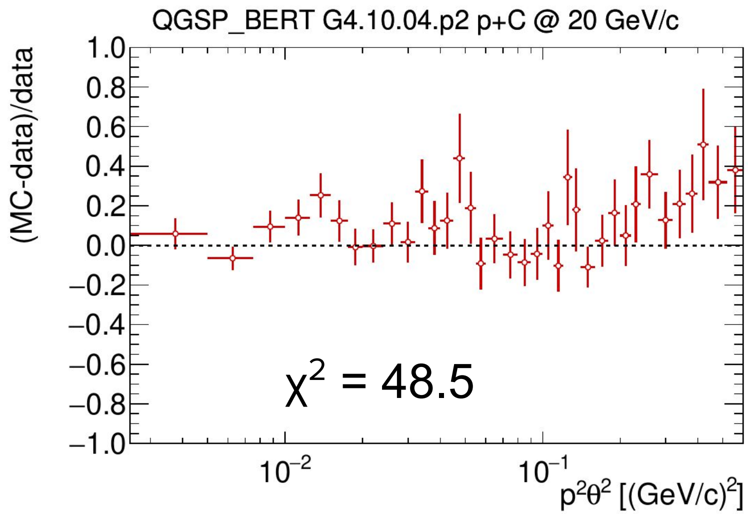

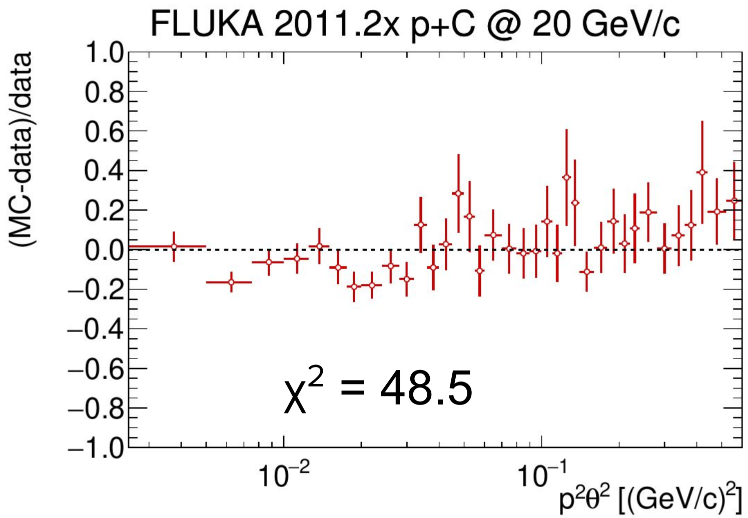

dof = 37

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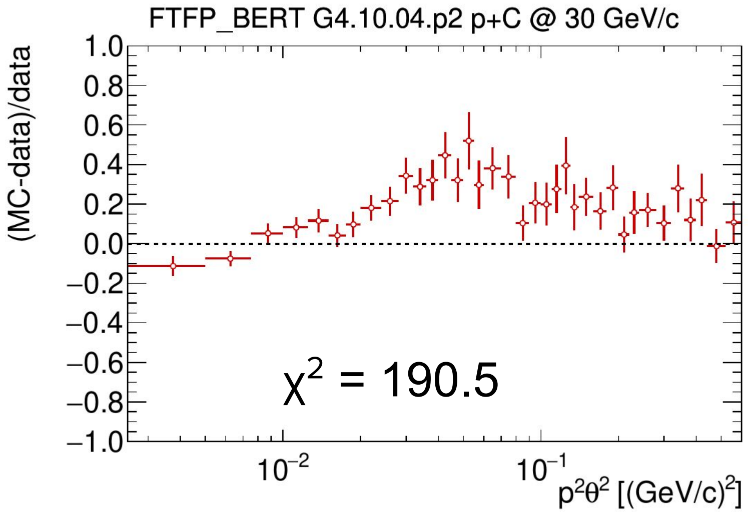

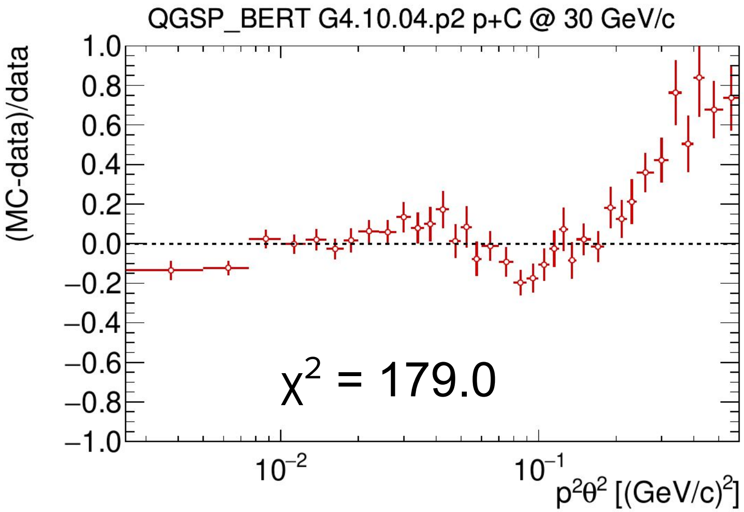

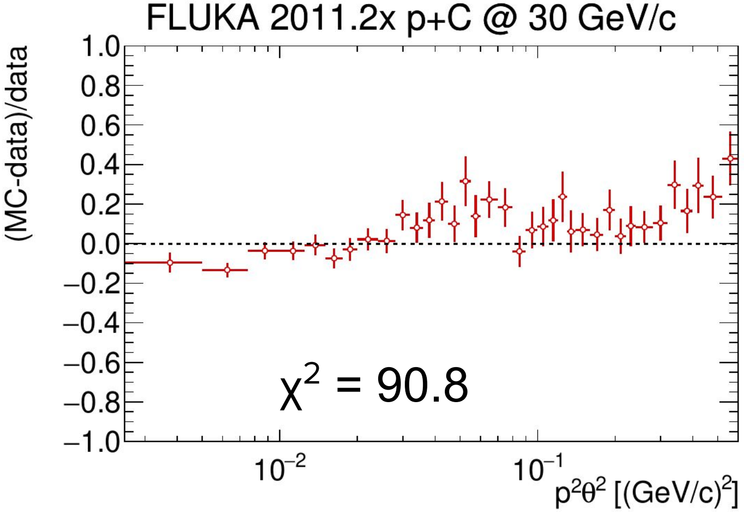

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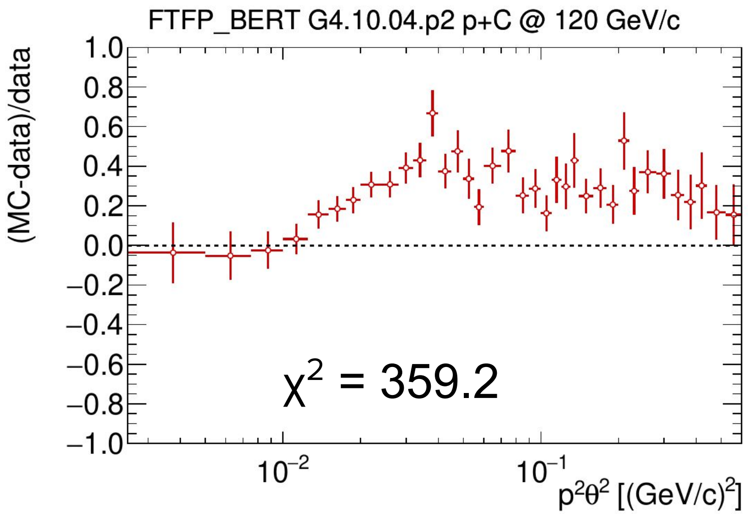

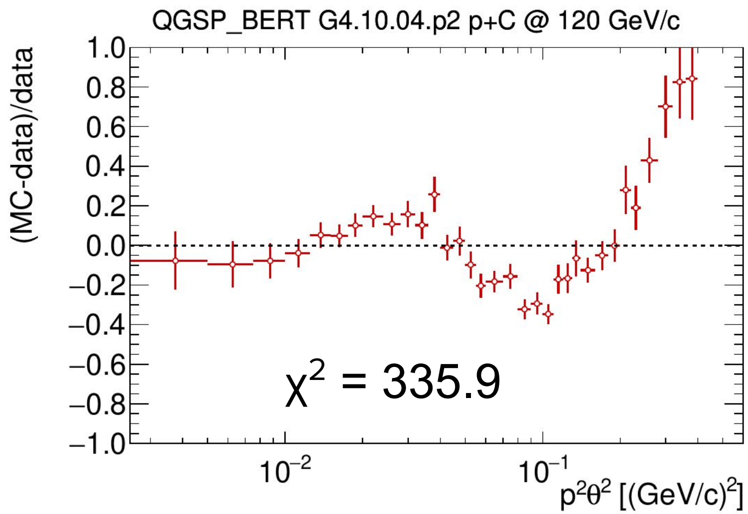

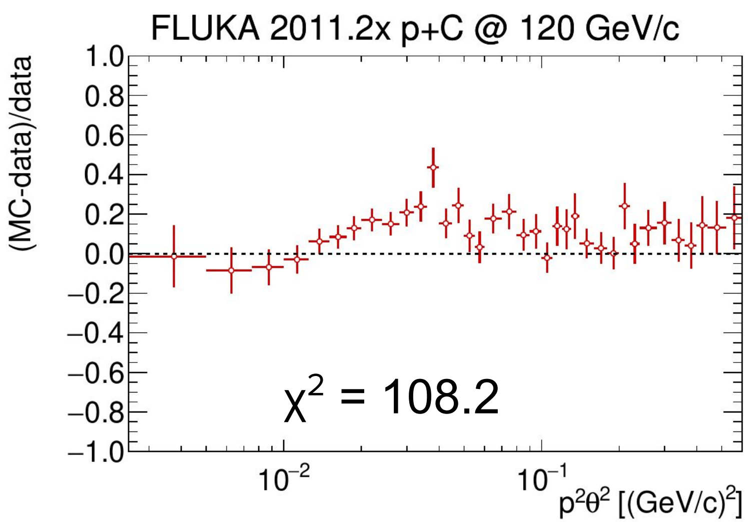

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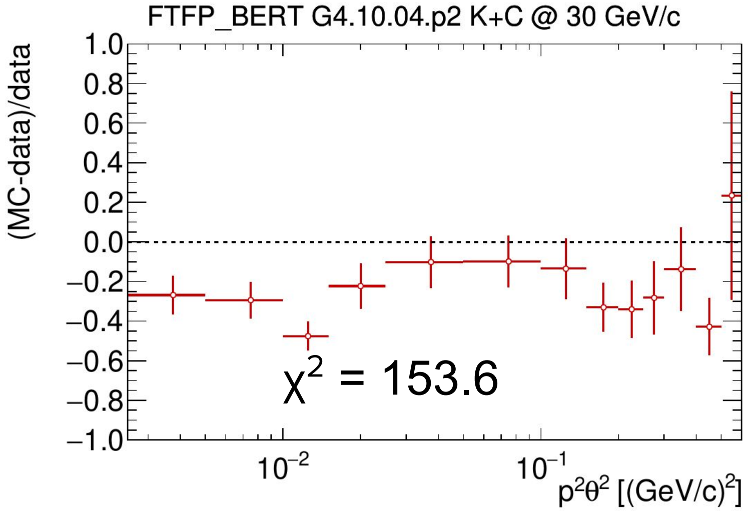

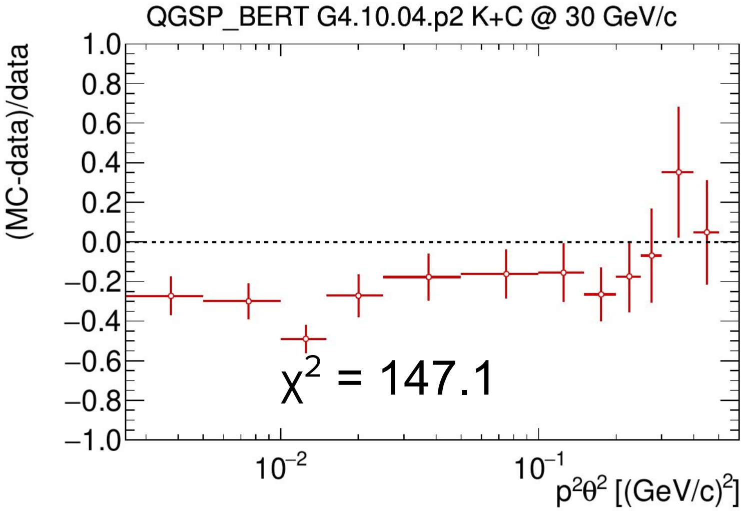

First measurement of this type for kaons!

Simulations seem to underpredict by ~20%.

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EMPHATIC: Proposed Future Runs

Phase	Date	Subsystems	Momenta (GeV/c)	Targets	Goals
1	Spring or Fall 2021	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, Al, Fe	Improved elastic and quasi-elastic scattering measurements, low-acceptance hadron production measurements
2	Spring or Fall 2022	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + New Large-area SiStrip Detectors + 350 mrad acceptance (magnet + ARICH+calorimeter) + ToF	4, 8, 12, 20, 31, 60, 120	C, Al, Fe, H2O, Be, B, BN, B2O3	Full-acceptance hadron production with PID up to 8 GeV/c
3	2023	Same as Phase 2 + Extended Hybrid RICH	20, 31, 60, 80, 120	Same as Phase 2 + Ca, Hg, Ti	Full-acceptance hadron production with PID up to 15 GeV/c
4	2024	350 mrad acceptance spectrometer	120	Spare NuMI Horn and Target	Charged-particle spectrum downstream of horns

EMPHATIC: Proposed Future Runs

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

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2	Spring or Fall 2022	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + New Large-area SiStrip Detectors + 350 mrad acceptance (magnet + ARICH+calorimeter) + ToF	4, 8, 12, 20, 31, 60, 120	C, Al, Fe, H_2O, Be, B, BN, B_2O_3	Full-acceptance hadron production with PID up to 8 GeV/c
3	2023	Same as Phase 2 + Extended Hybrid RICH	20, 31, 60, 80, 120	Same as Phase 2 + Ca, Hg, Ti	Full-acceptance hadron production with PID up to 15 GeV/c
4	2024	350 mrad acceptance spectrometer	120	Spare NuMI Horn and Target	Charged-particle spectrum downstream of horns

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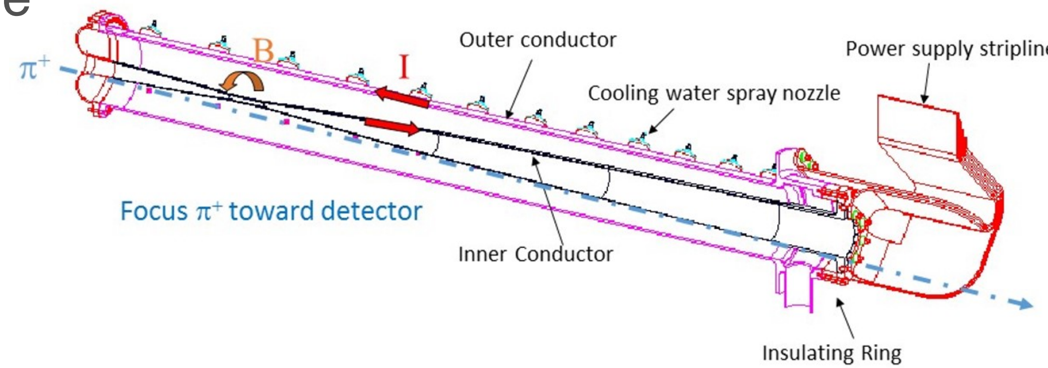
EMPHATIC: Proposed Future Runs

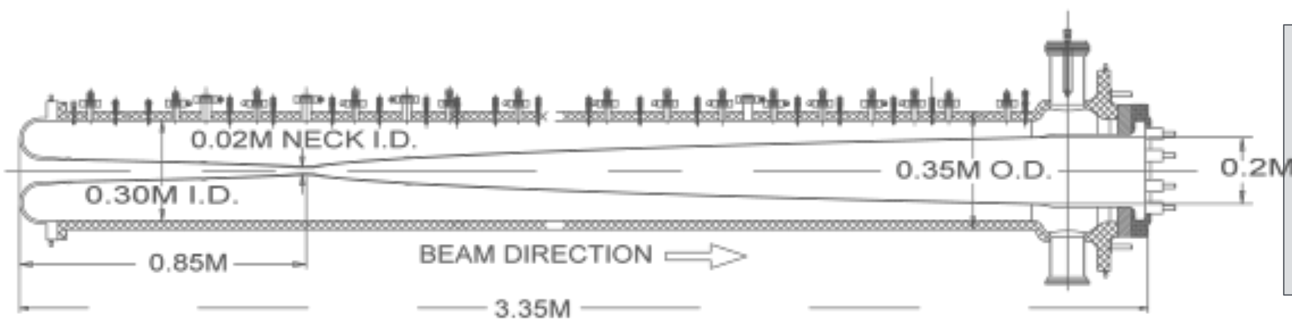
Phase	*Date*	*Subsystems*	*Momenta (GeV/c)*	*Targets*	*Goals*
1	*Spring or Fall 2021*	*Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + Small-acceptance magnet + Prototype ARICH + ToF + Small-acceptance Calorimeter*	*4, 8, 12, 20, 31, 60, 120*	*C, Al, Fe*	*Improved elastic and quasi-elastic scattering measurements, low-acceptance hadron production measurements*
2	*Spring or Fall 2022*	*Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + New Large-area SiStrip Detectors + 350 mrad acceptance (magnet + ARICH+calorimeter) + ToF*	*4, 8, 12, 20, 31, 60, 120*	*C, Al, Fe, H2O, Be, B, BN, B2O3*	*Full-acceptance hadron production with PID up to 8 GeV/c*
3	*2023*	*Same as Phase 2 + Extended Hybrid RICH*	*20, 31, 60, 80, 120*	*Same as Phase 2 + Ca, Hg, Ti*	*Full-acceptance hadron production with PID up to 15 GeV/c*
4	*2024*	*350 mrad acceptance spectrometer*	*120*	*Spare NuMI Horn and Target*	*Charged-particle spectrum downstream of horns*

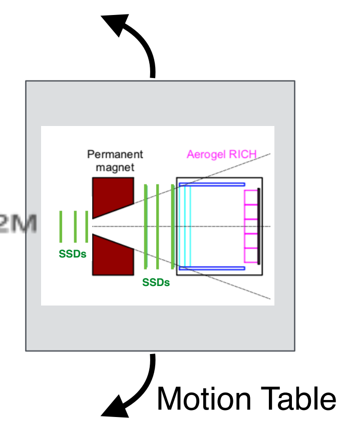
EMPHATIC Phase 4 - Beyond Target HP Uncertainties

- 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 and without current.
- Establishes program to address questions re: HP in horns and modeling of horn geometry and magnetic field.





Summary

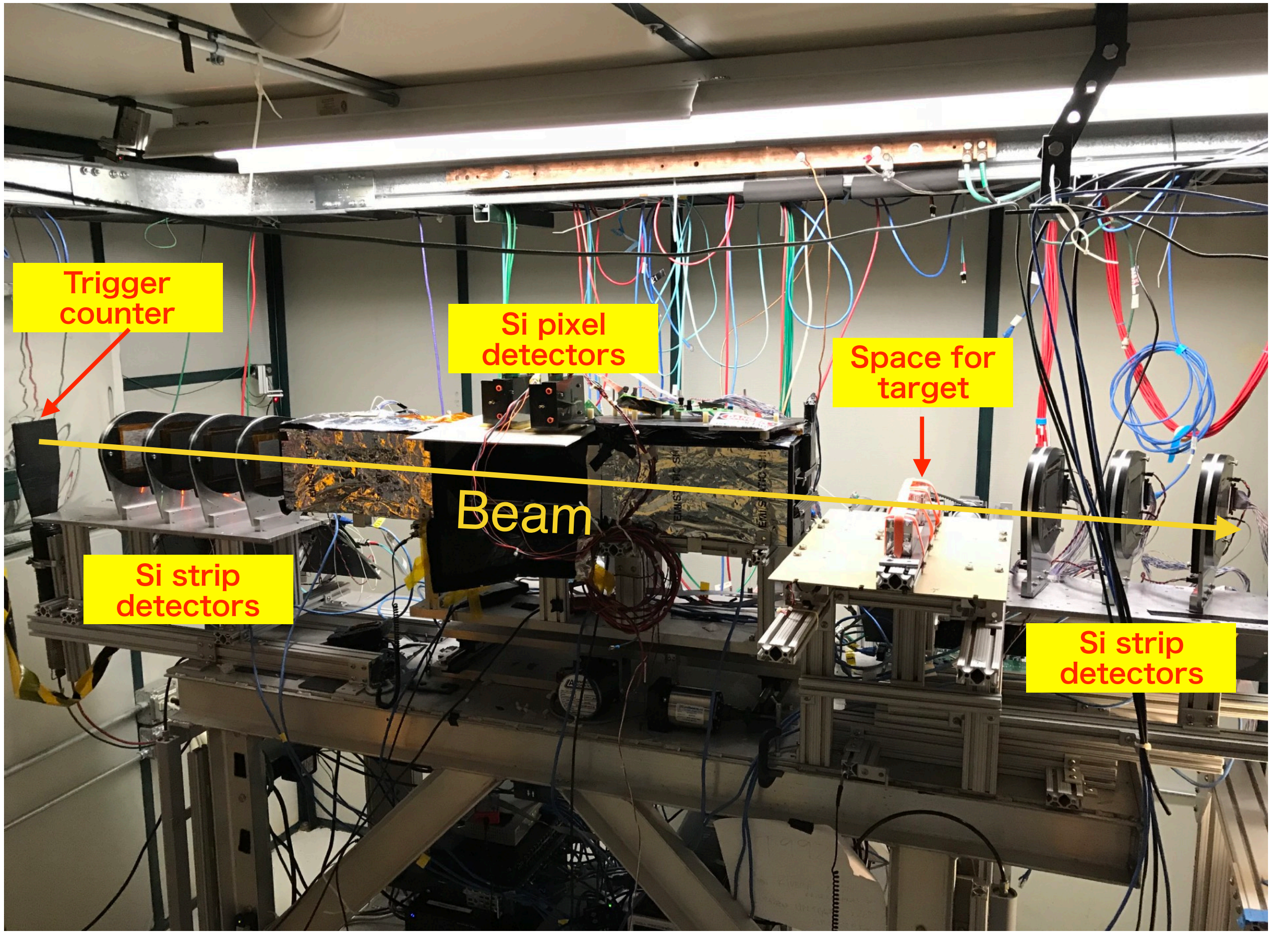
- New hadron production data are needed if we want to reduce neutrino flux uncertainties.
- EMPHATIC offers a ***cost-effective*** approach to reducing the hadron production uncertainties by at least a factor of 2.
- EMPHATIC is a strong ***international collaboration*** with a mature design of the spectrometer and run plans for 2021-24. Details in arXiv:1912.08841.
- Critical detectors from Canada and Japan ***are funded and ready for the 2021 run.***
- We have requested and **received Stage 1 approval** from the Fermilab PAC. Funding request submitted to DOE for full-acceptance magnet, SSDs and RICH. Cost-and-schedule review in early January.
- EMPHATIC is ***complementary*** to the existing efforts by NA61 to collect important hadron production data for improved flux predictions.

BACKUP

EMPHATIC: Initial beam test from Jan. 10-23, 2018

- Two setups in this run: one with emulsion bricks, another with thin targets
- In each case, we used the existing:
  - SSDs for tracking upstream and downstream of the targets
  - Aerogel Ckovs and Pb-glass calorimeter downstream
  - Two differential gas Ckov detectors upstream to tag the beam (1 w/ two mirrors)

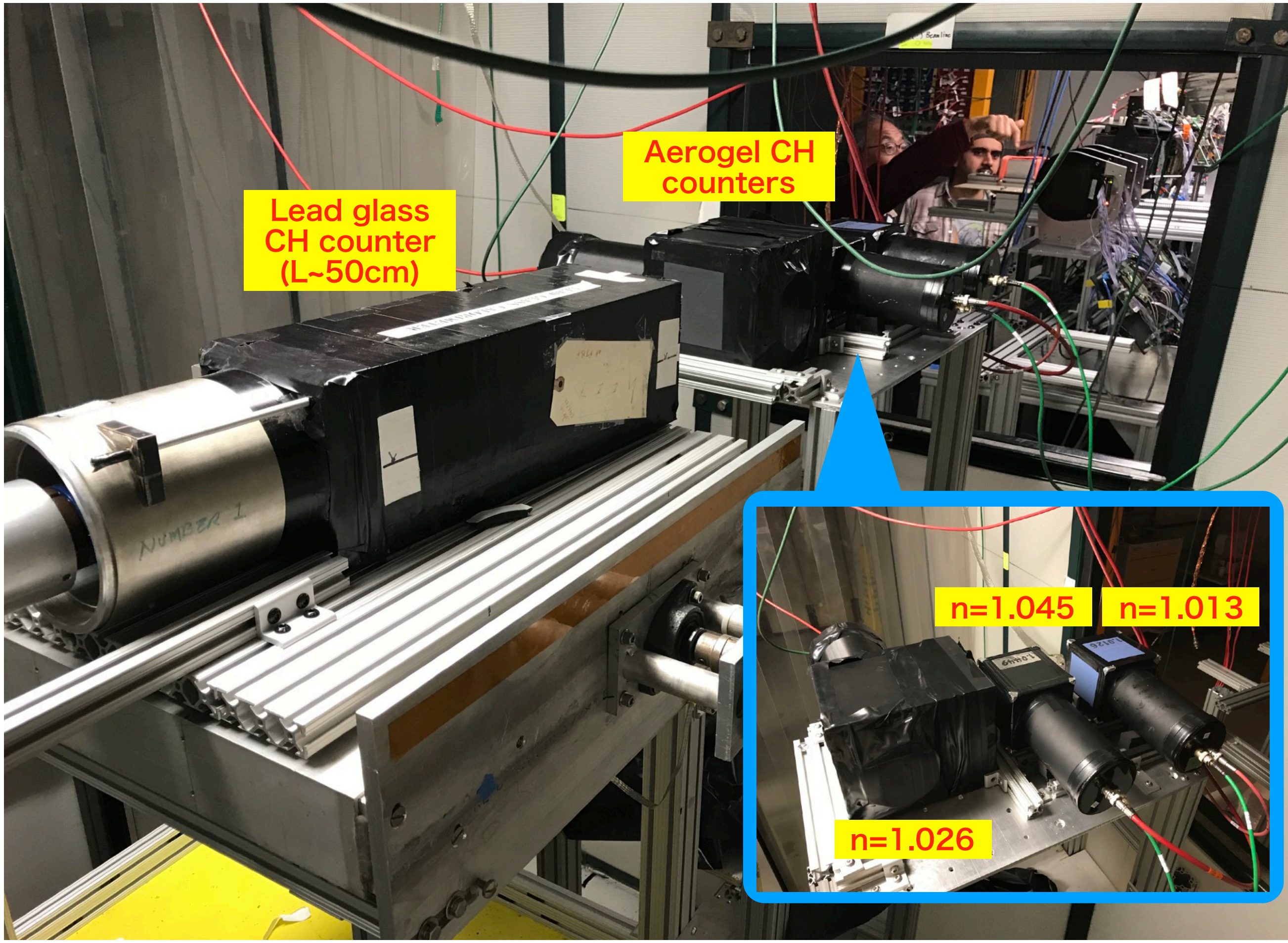
MT6.1-A



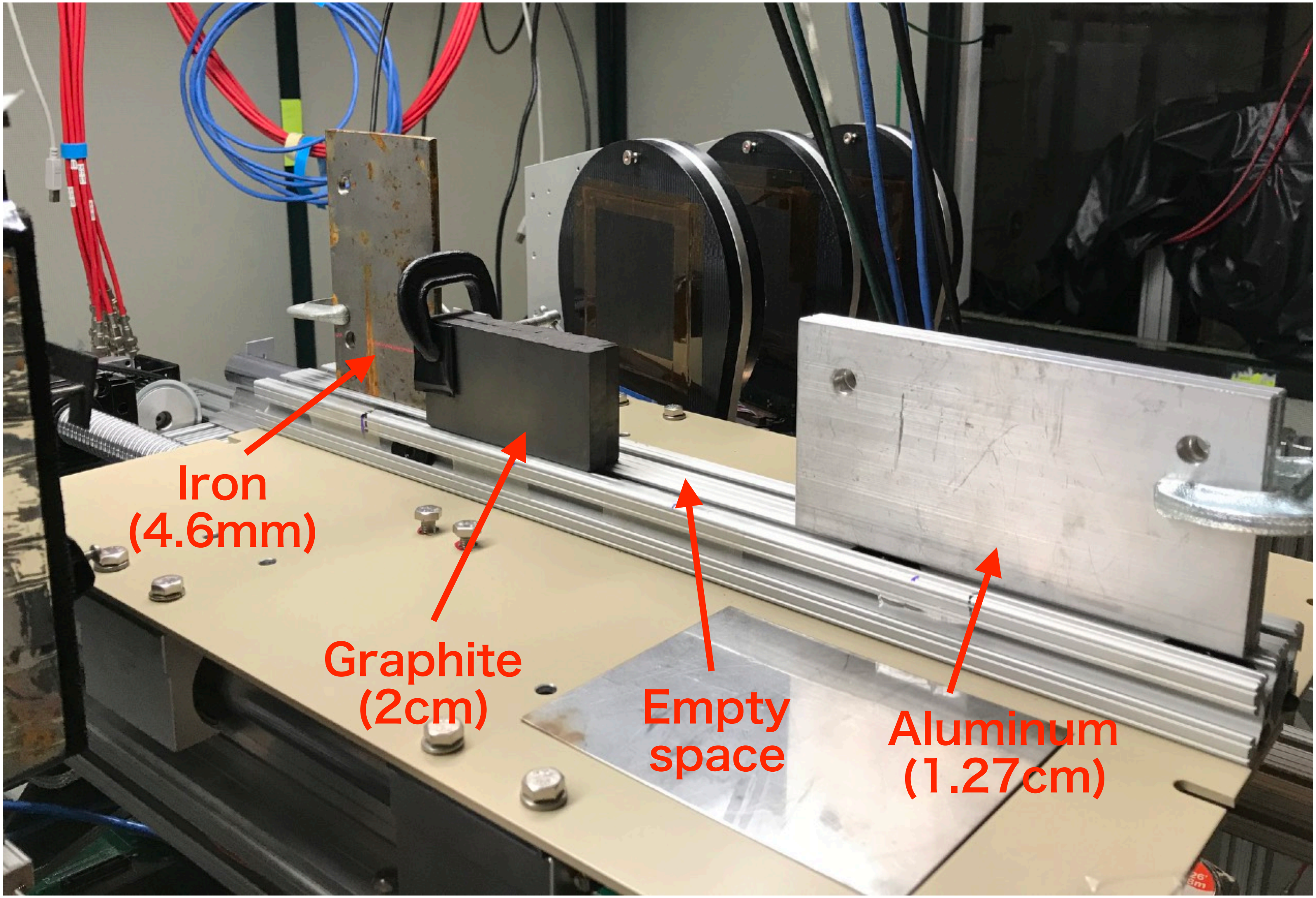
EMPHATIC: Initial beam test from Jan. 10-23, 2018

- Two setups in this run: one with emulsion bricks, another with thin targets
- In each case, we used the existing:
  - SSDs for tracking upstream and downstream of the targets
  - Aerogel Ckovs and Pb-glass calorimeter downstream
  - Two differential gas Ckov detectors upstream to tag the beam (1 w/ two mirrors)

MT6.1-B



EMPHATIC: Thin-target data w/ silicon tracking only



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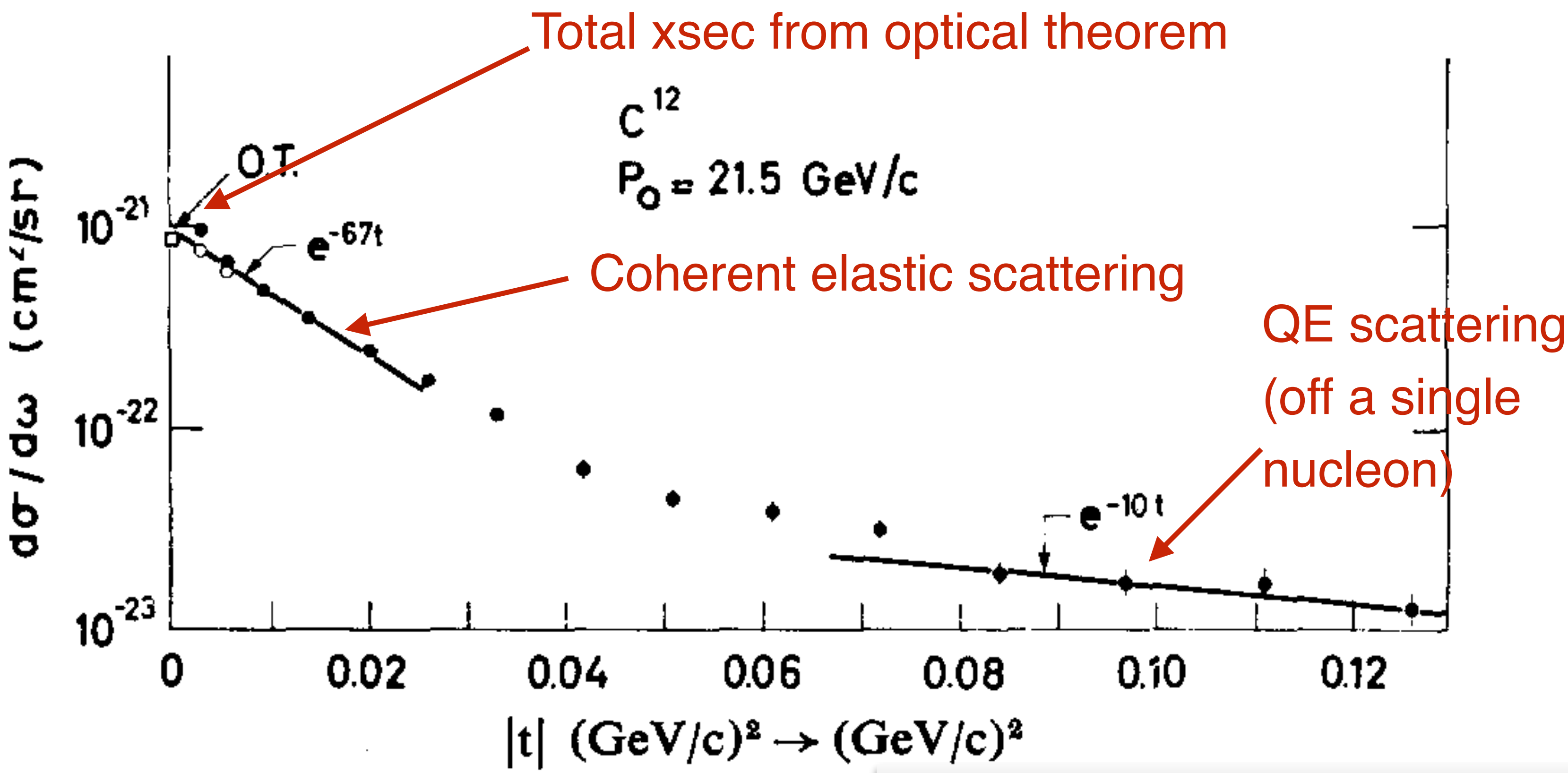
EMPHATIC: Thin-target data w/ silicon tracking only

Number of min. bias triggers

	Graphite	Aluminum	Iron	Empty
120 GeV	1.63M	0	0	1.21M
30 GeV/c	3.42M	976k	1.01M	2.56M
-30 GeV/c	313k	308k	128k	312k
20 GeV/c	1.76M	1.76M	1.72M	1.61M
10 GeV/c	1.18M	1.11M	967k	1.17M
2 GeV	105k	105k	183k	108k

Note: min. bias trigger efficiency is 100%

EMPHATIC: Thin-target data w/ silicon tracking only

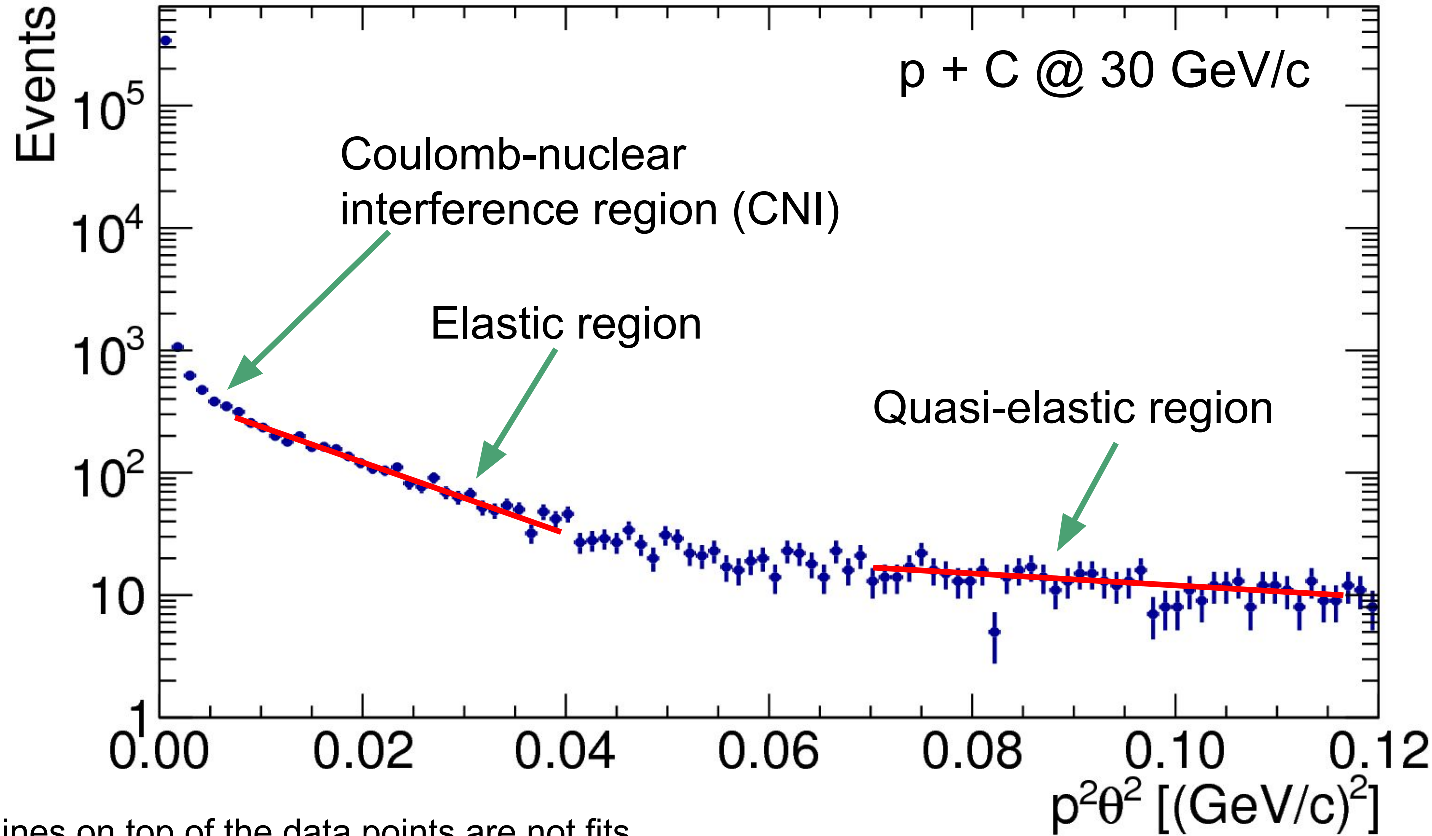


G. Bellettini et al., Nucl. Phys. 79, 609 (1966)

$$|t| \simeq p_{beam}^2 \theta_{scatt}^2$$

EMPHATIC: Thin-target data w/ silicon tracking only

4-momentum transfer (raw data)



*Lines on top of the data points are not fits

EMPHATIC: Thin-target data w/ silicon tracking only

results presented by M. Pavin, Fermilab JETP Seminar, May 10, 2019

Systematic uncertainties

Strategy:

- Use data to estimate systematics
- If not possible use MC → largest difference between models

1. Beam contamination (kaons in proton beam) ➜ **negligible << 1% contamination**
2. Upstream interactions in the trigger scintillator or SSDs ➜ **negligible < 0.5%**
3. Interactions between upstream SSDs and target (shape) ➜ **negligible for t > 0.01 GeV^2**
4. Secondary particles (not leading protons or kaons) **< 6%**
5. Efficiency uncertainty (model dependence) **< 3%**
6. Normalization (target thickness and density) ➜ **2%**
7. POT correction for upstream losses ➜ **0.5%**

EMPHATIC: Thin-target data w/ silicon tracking only

results presented by M. Pavin, Fermilab JETP Seminar, May 10, 2019

Systematic uncertainties

Strategy:

- Use data to estimate systematics
- If not possible use MC → largest difference between models

Note: Since this presentation, we have redefined our signal (deliverable) to be the model independent measurement of

$p + C \rightarrow A + X^{\pm}$

where A is the final-state nucleus and X is a charged particle with a scattering angle < 20 mrad.

Systematics are now at the few % level.

1. Beam contamination (kaons in proton beam) → **negligible << 1% contamination**
2. Upstream interactions in the trigger scintillator or SSDs → **negligible < 0.5%**
3. Intera[illegible] (shape) → [illegible] GeV²
4. Secon[illegible]s) < 6%
5. Efficiency uncertainty (model dependence) < 3%
6. Normalization (target thickness and density) → 2%
7. POT correction for upstream losses → 0.5%