EMPHATIC

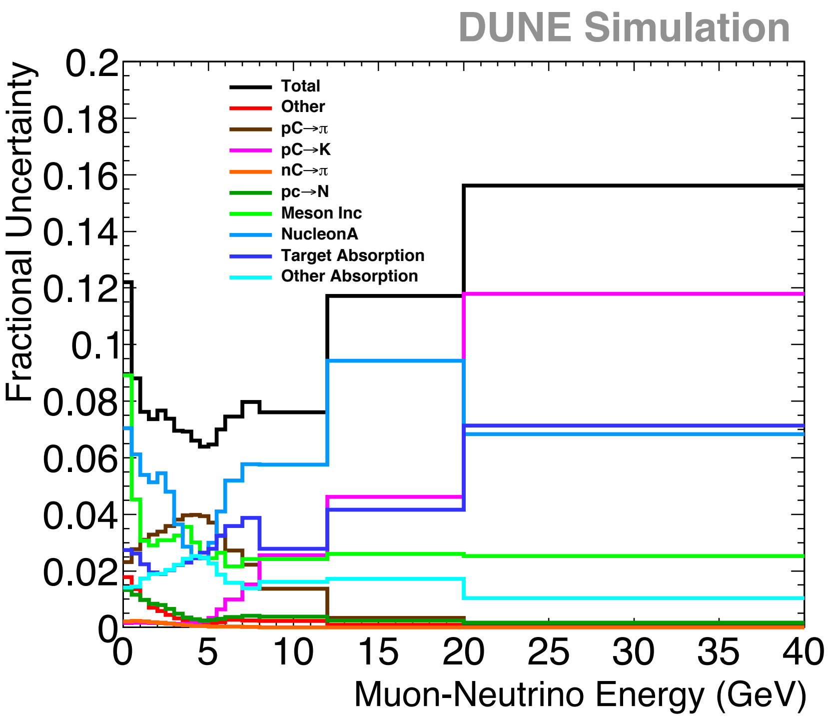
A Fermilab PAC-approved

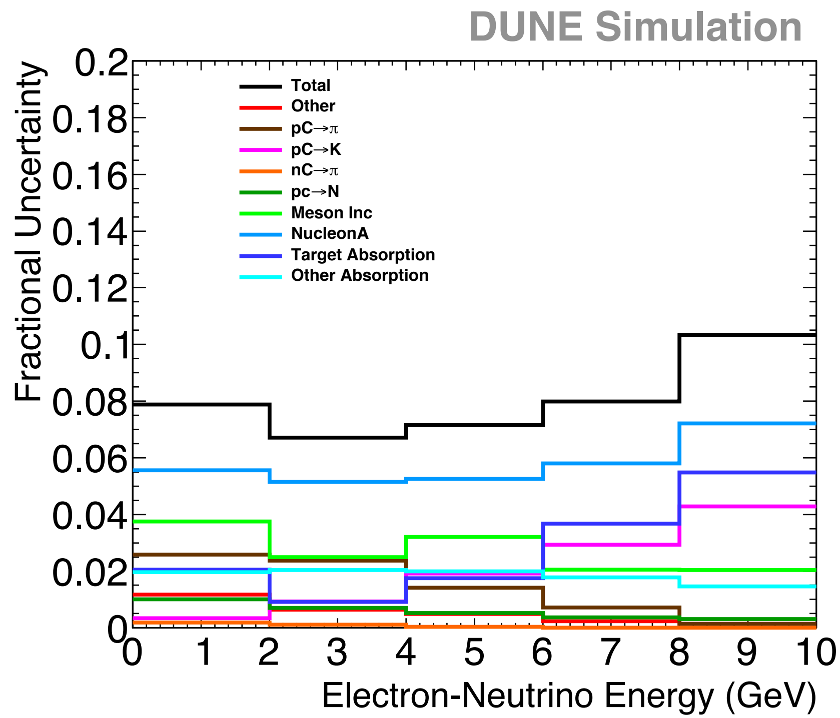
~~A proposed~~ hadron production experiment for improved neutrino flux predictions

Jonathan Paley
On Behalf of the
EMPHATIC Collaboration

NBI Workshop
Tuesday, October 22, 2019

DUNE Flux Uncertainties





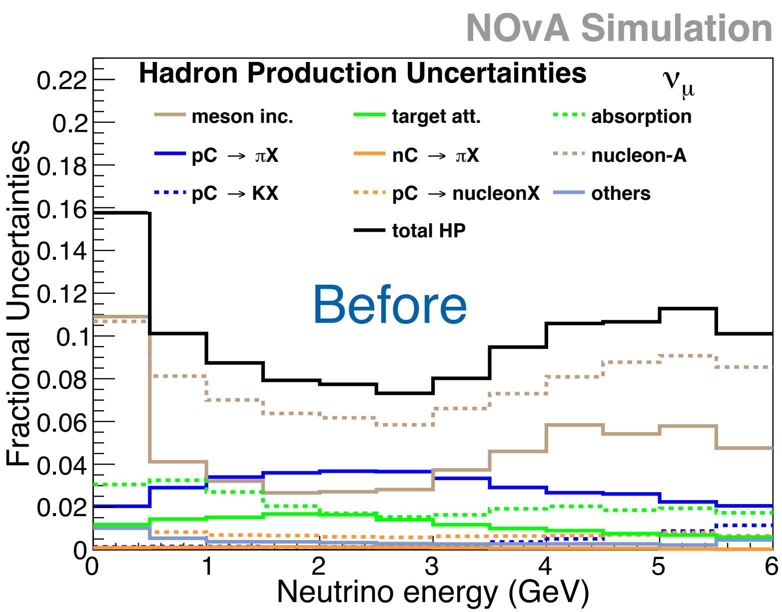
- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread).
- Lack of proton and pion scattering data at lower beam energies that NA61 has access to.
- **Reduction of flux uncertainties improves 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 predictions 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

(40% of all interactions relevant for NuMI/LBNF's ν_μ flux, 4% for T2K)



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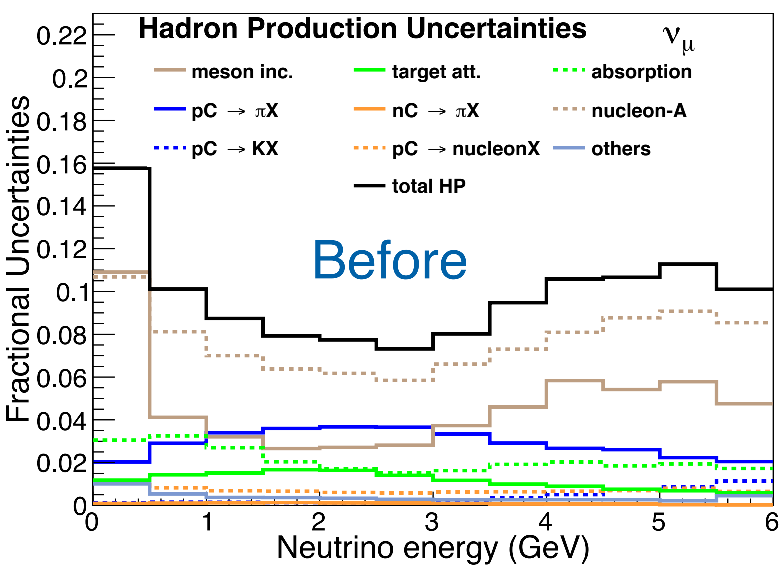
NOvA Simulation



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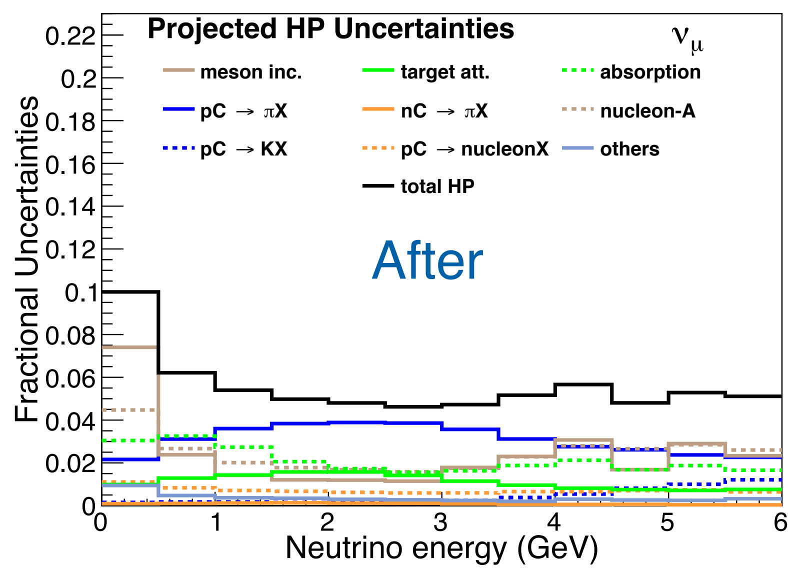

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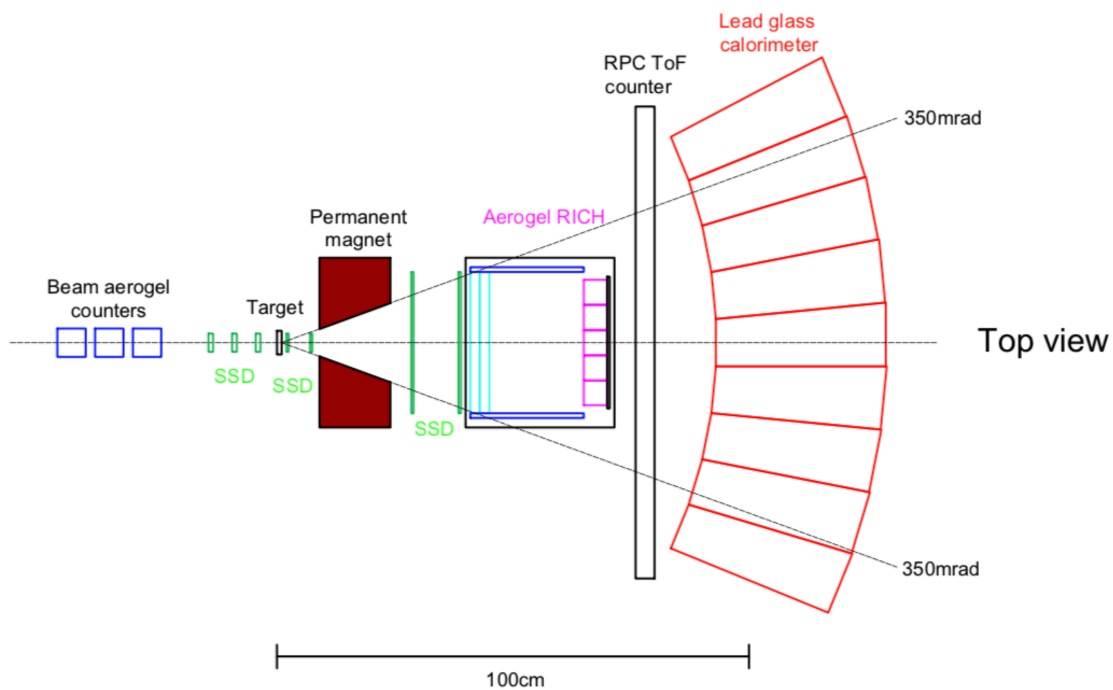
EMPHATIC

- **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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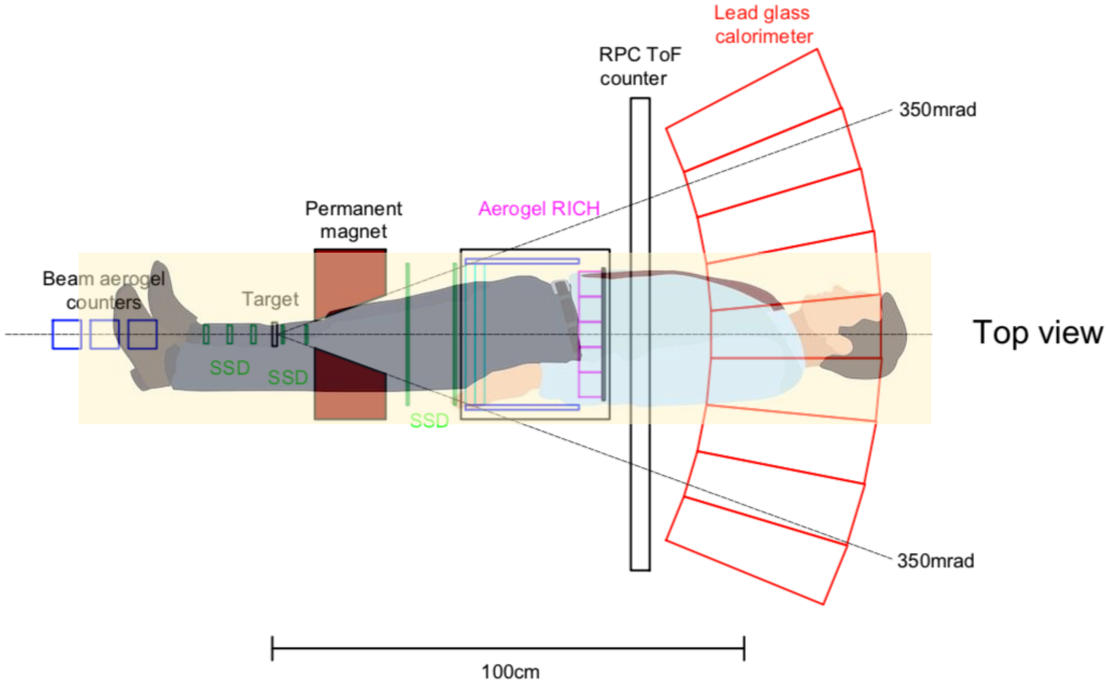
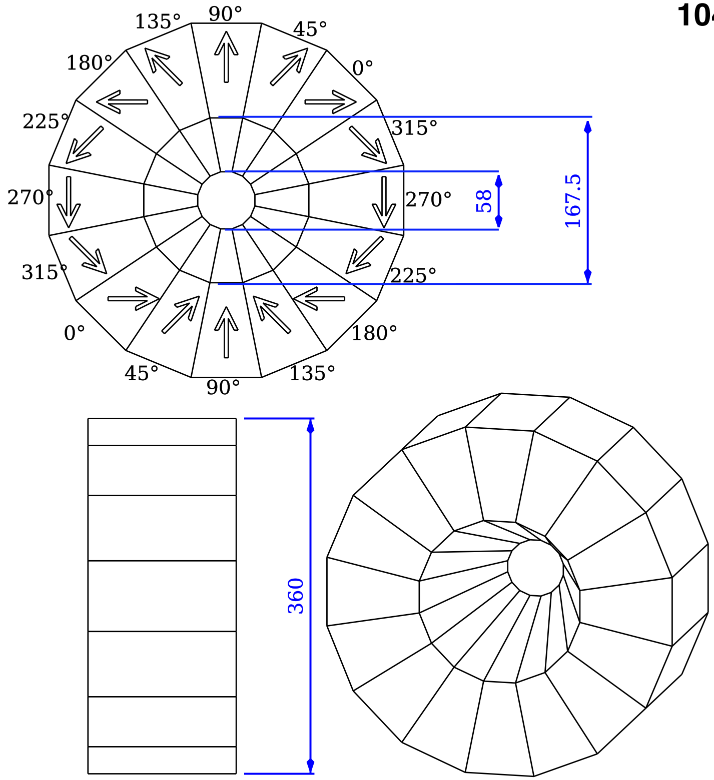
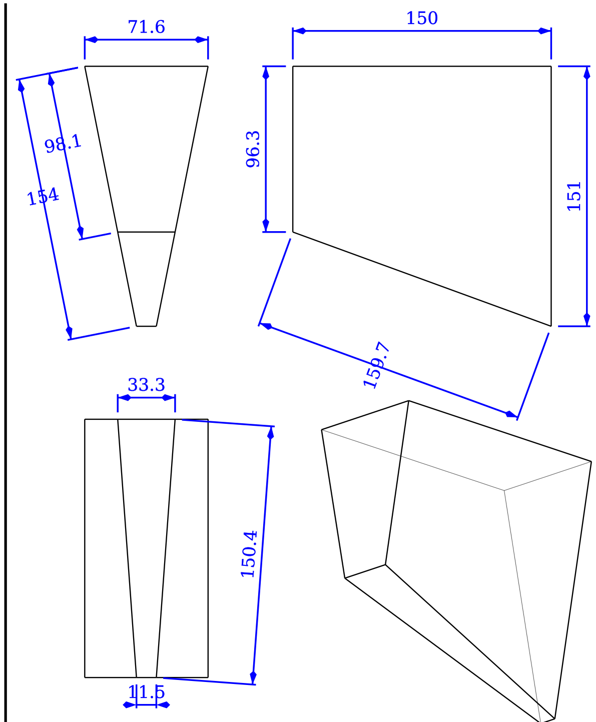


EMPHATIC: Permanent Magnet

Halbach Array

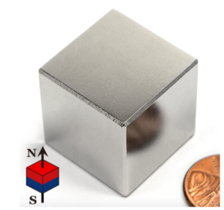
EMPHATIC Dipole Magnet
16 NdFeB (N52) segments
104 kg





all measurements are in mm

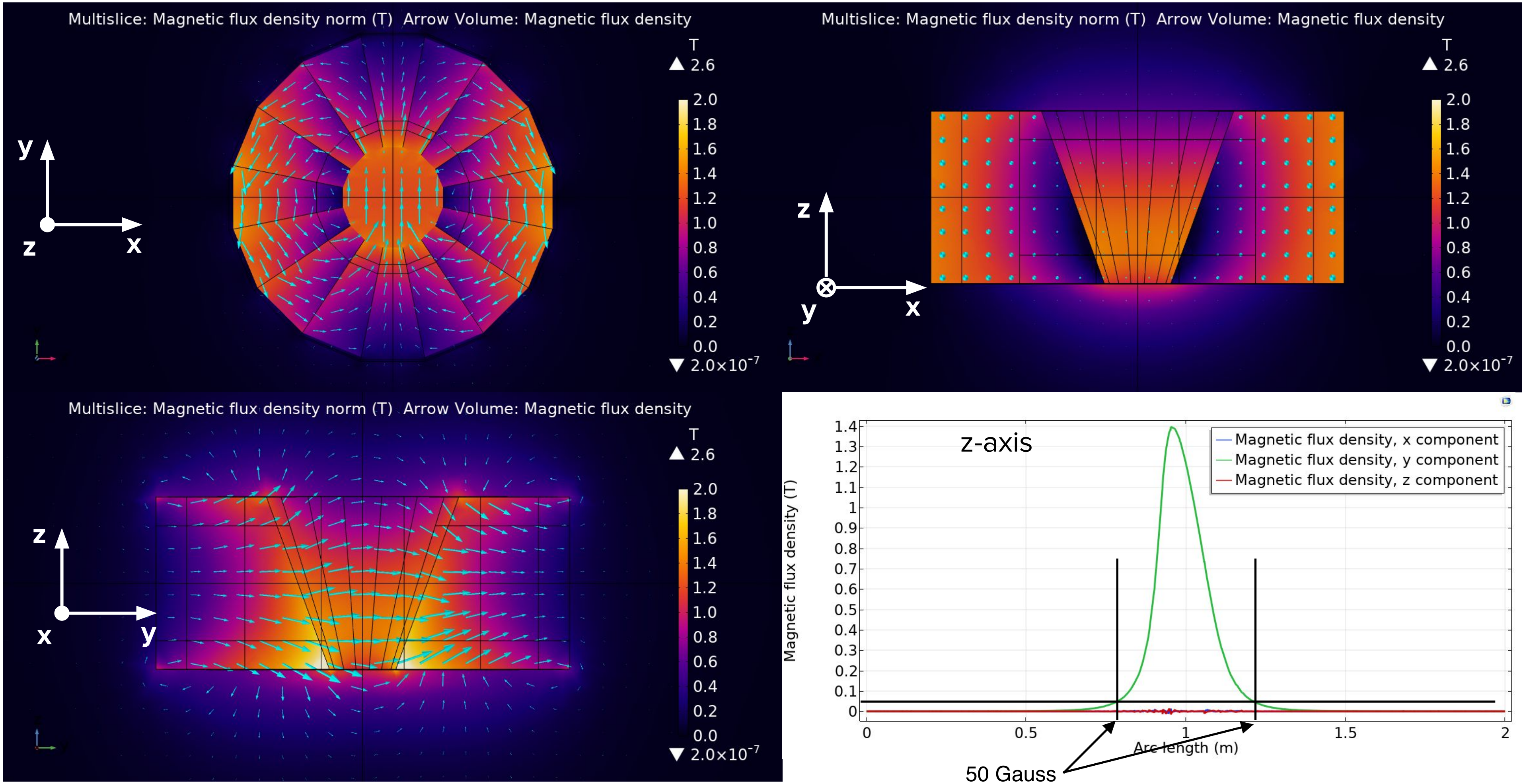
Segments made from large segments of Neodymium permanent magnets.



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

Note: we already have two quotes from companies for this design.

EMPHATIC: Magnet



Field maps generated using COMSOL simulation.

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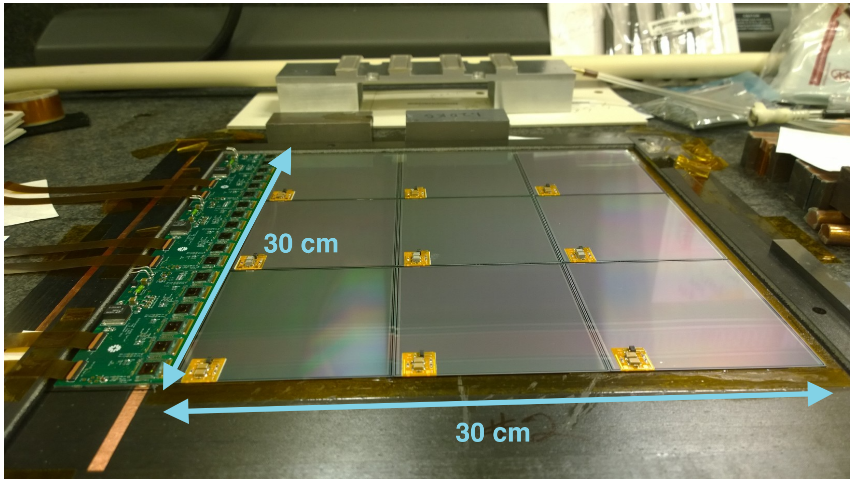
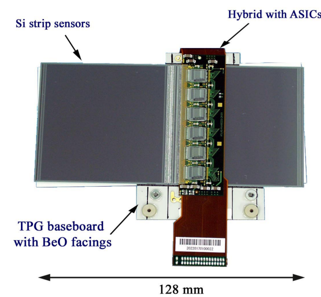
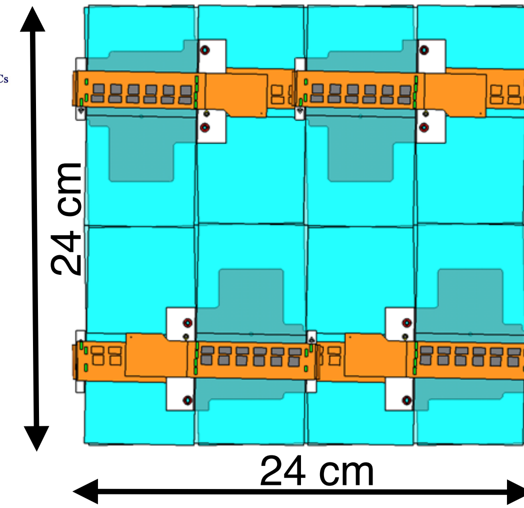
EMPHATIC: Si Strip Detectors

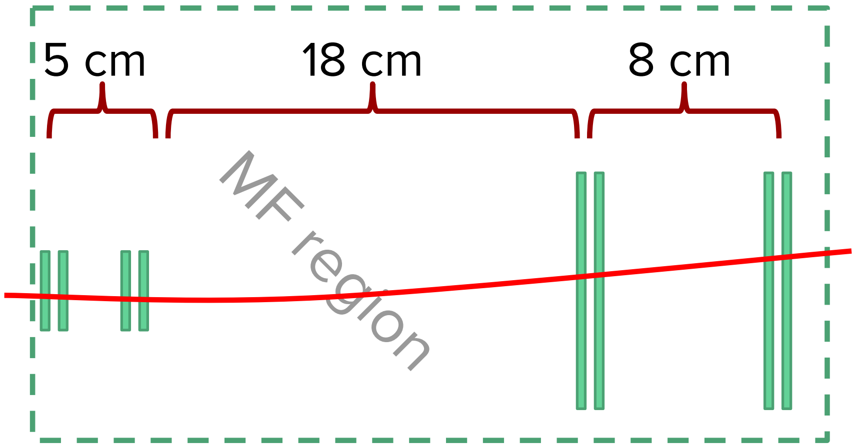


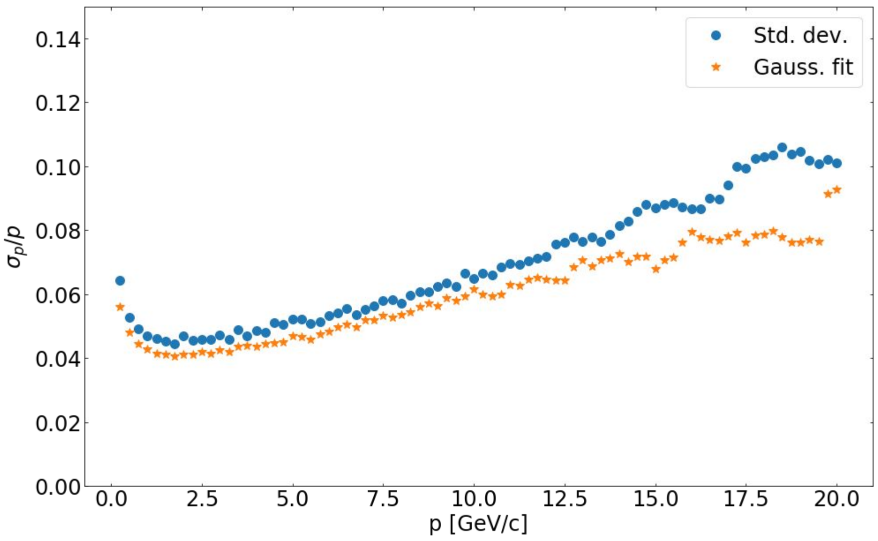




- Left: Large-area SiSDs with 122 µm pitch available from Fermilab SiDet. New chips and some DAQ development needed. Or…
- Right: Large-area SiSDs with 80 µm pitch available from ATLAS SCT group, using FASER design and DAQ.
- Upstream tracking to be done by existing SiSDs (60 µm pitch) at the FTBF.

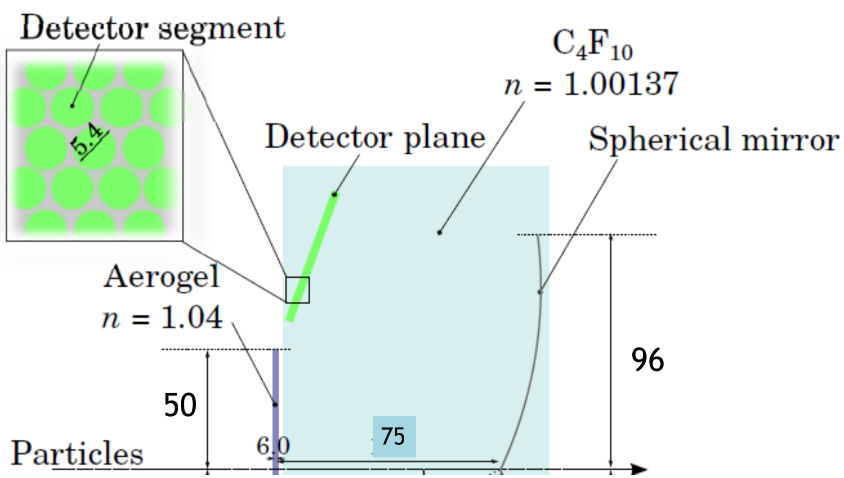
EMPHATIC: Momentum Resolution

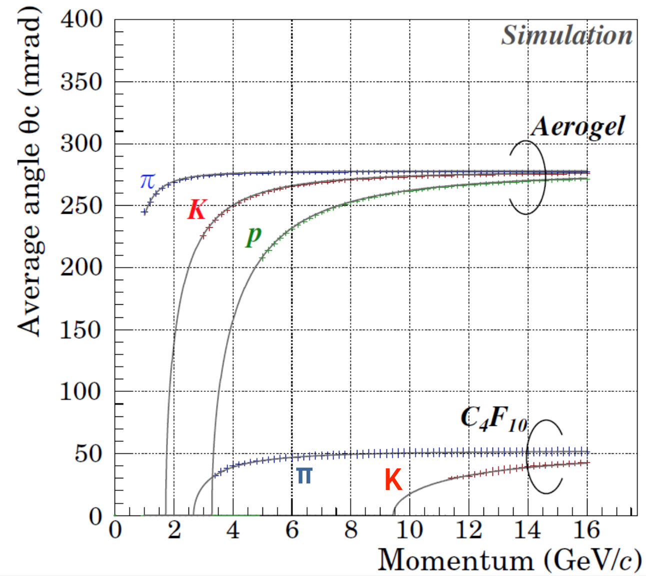




- Preliminary study based on COMSOL magnetic field maps, resolution-smeared truth (122 μm pitch), and Kalman Filter reconstruction.
- Resolution < 6% below 8 GeV/c, < 10% below 17 GeV/c.

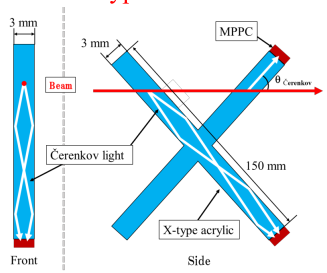
EMPHATIC: PID Detectors (from JPARC E50)

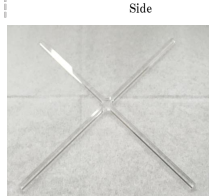




X-type Čerenkov counter

X-type Čerenkov



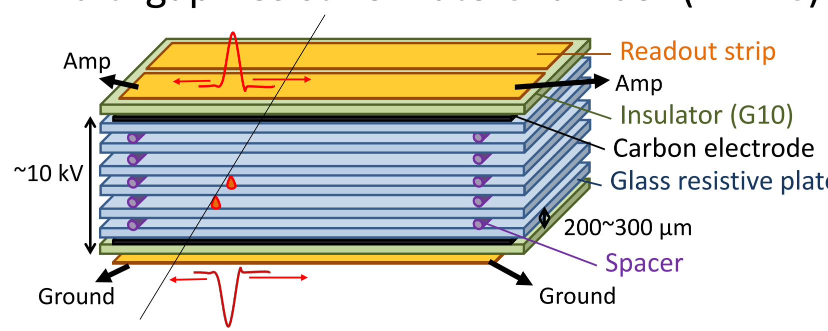


- Developing Čerenkov timing counter
  - ➢Čerenkov lights emit in an extremely short time.
    - ✓Reduce the time spread of photons reaching to the optical sensor
    - ✓Having a fast timing response
    - ✓It has the advantage to measure the better time resolution.
  - ➢Use "Cross shape" acrylic, called 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.

Physics with General Purpose Spectrometer in the High-momentum Beam Line 2018/8/28 4

Multi-gap Resistive Plate Chamber (MRPC)

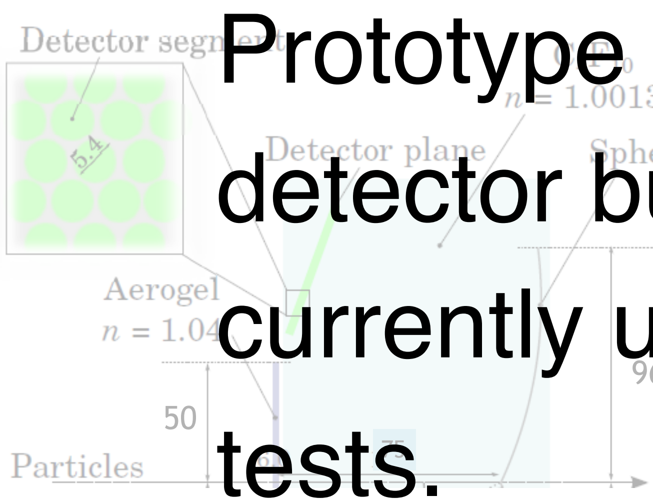


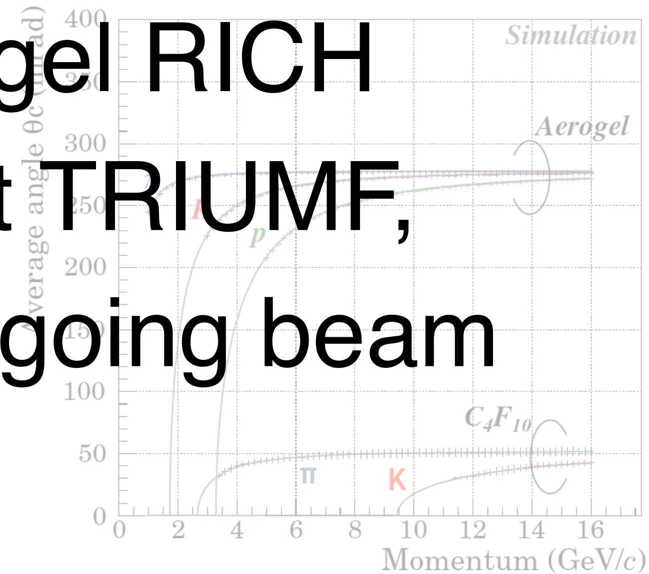
- Resistive Plate -> Avoid discharge
- Smaller gap -> Better time resolution
- Multi gap -> Higher efficiency, better time resolution

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

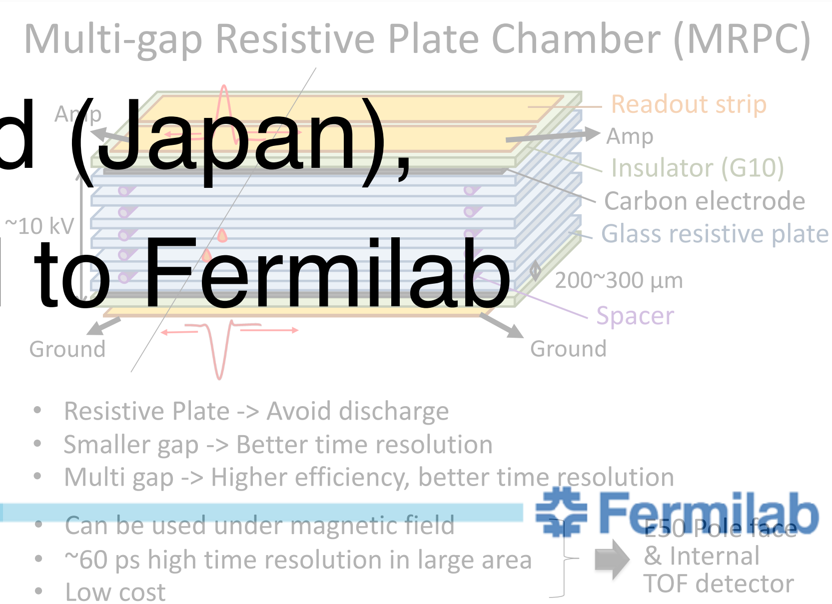
→ E50 Pole face & Internal TOF detector

EMPHATIC: PID Detectors (from JPARC E50)





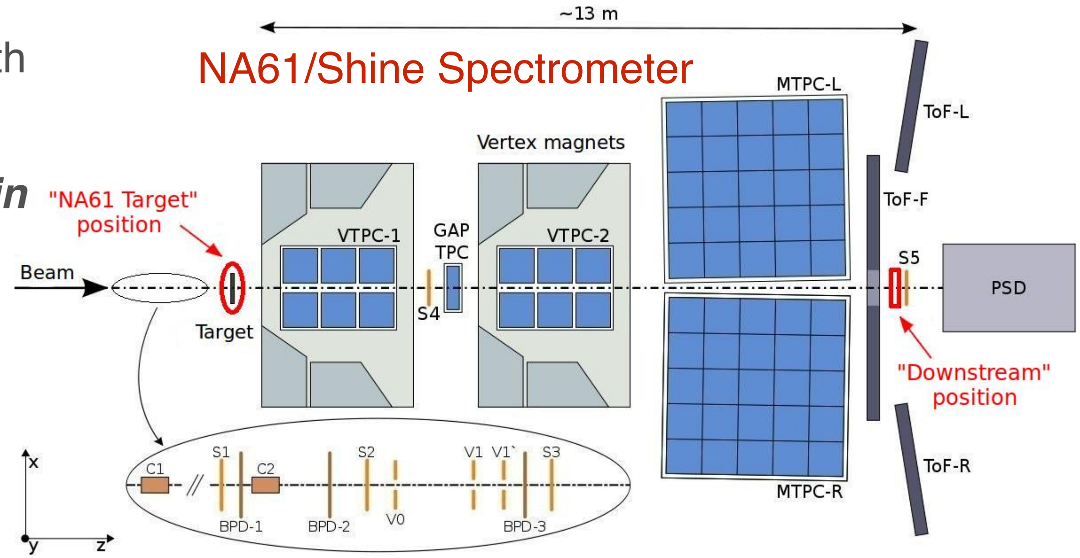
Prototype aerogel RICH detector built at TRIUMF, currently undergoing beam tests.

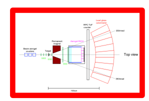


Built and tested (Japan), will be shipped to Fermilab this winter.

EMPHATIC: Complementarity to NA61/SHINE and MIPP

- EMPHATIC will make measurements with ***beam energies below 15 GeV***.
- EMPHATIC has ***excellent acceptance in the forward region***, enabling precision quasi-elastic scattering measurements.
- EMPHATIC's run plan is ***singularly focused*** on the issue of neutrino flux modeling.
- EMPHATIC will ***not*** make measurements using the ***neutrino production target***.





EMPHATIC Spectrometer

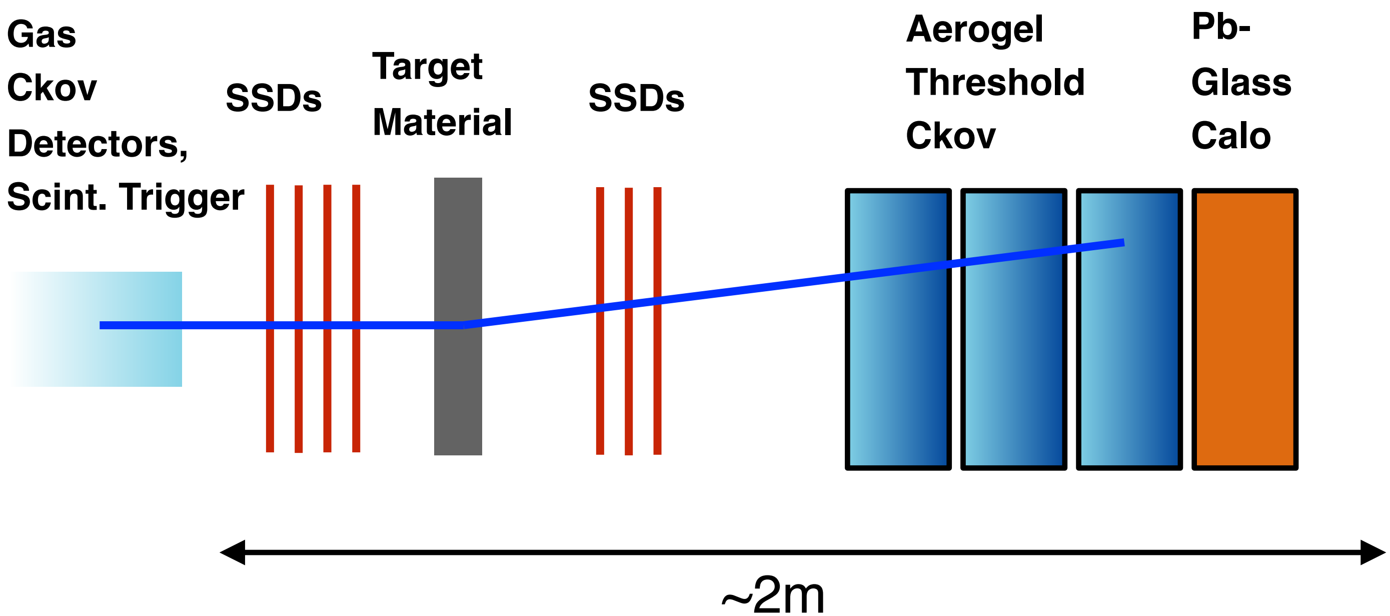
- EMPHATIC will not require an "interaction trigger" (simplifies analysis and reduces uncertainties).
- EMPHATIC needs to operate 3-4 weeks/ year over 3 years.
- ***Compact spectrometer = low cost.***

- EMPHATIC establishes a hadron production program at Fermilab focused on meeting the needs of the Fermilab program.
- EMPHATIC could be a first step to a future LBNF spectrometer.

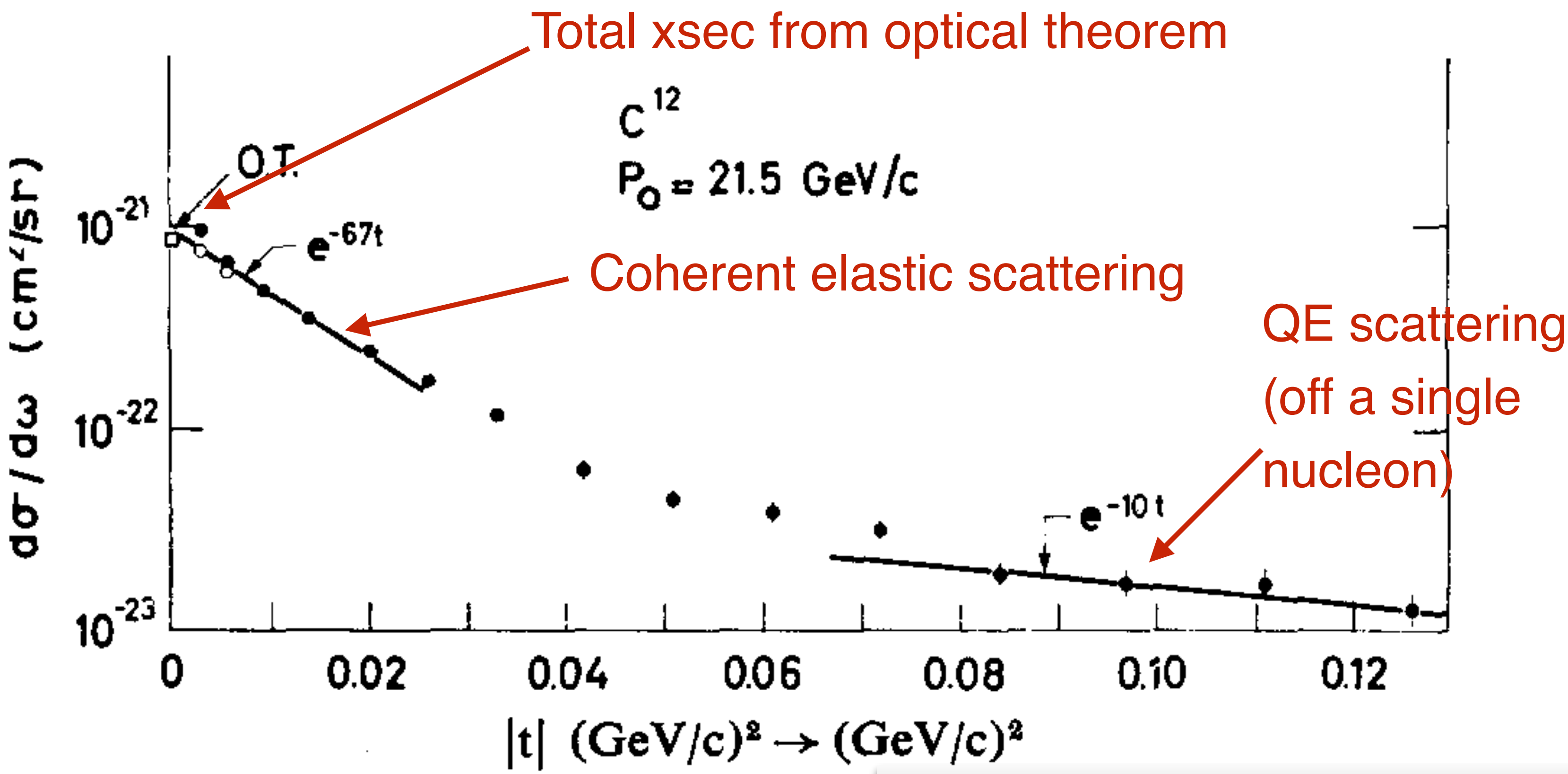
EMPHATIC: Initial beam test from Jan. 10-23, 2018

- 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



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

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

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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

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Systematic uncertainties

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

p + C → A + X±

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

Systematics are being re-evaluated.

Strategy:

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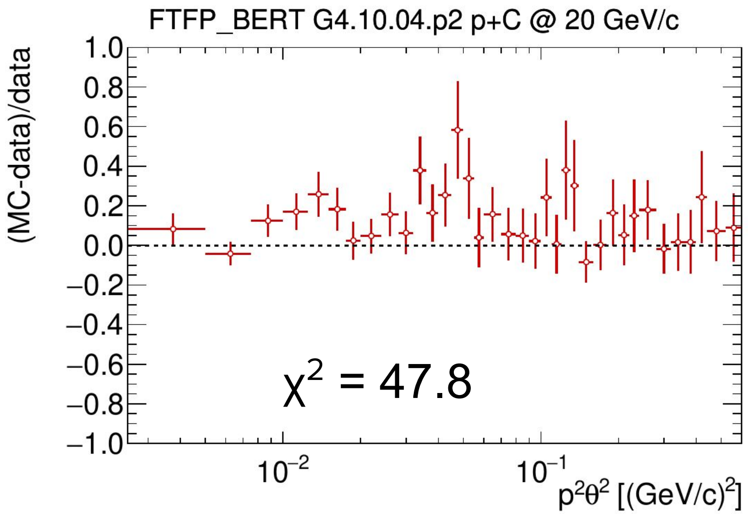

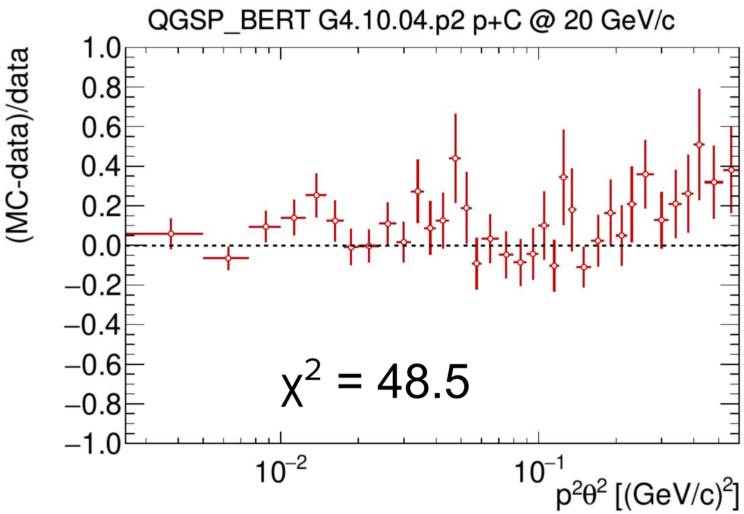

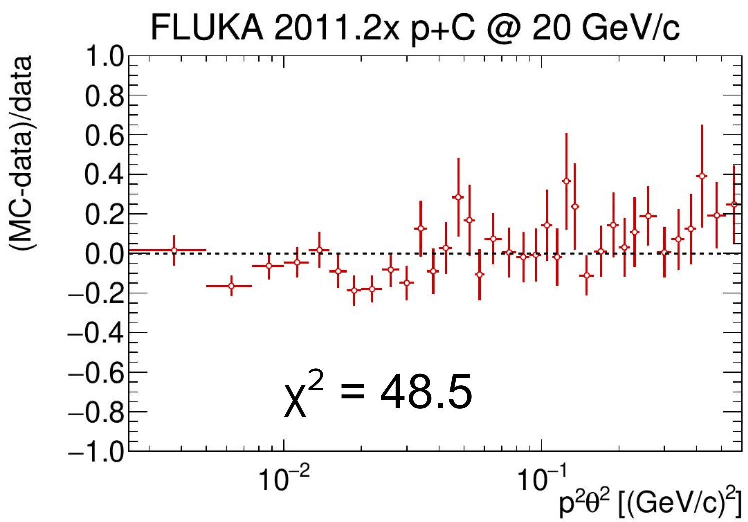

dof = 37

EMPHATIC: Thin-target data w/ silicon tracking only

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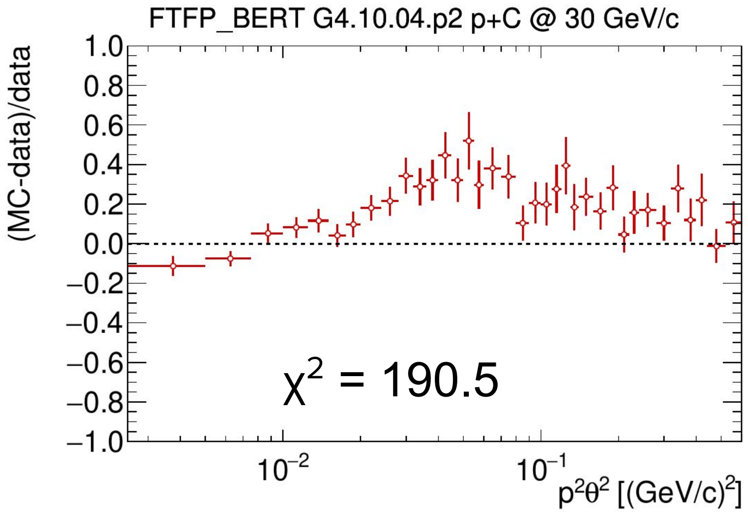

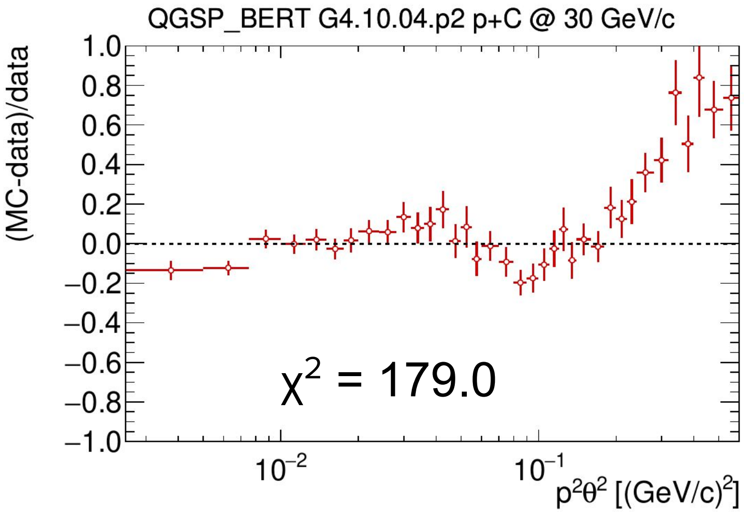

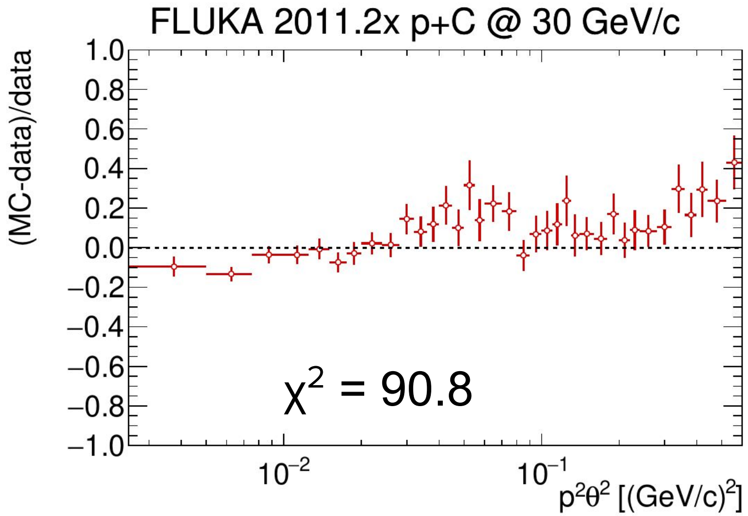

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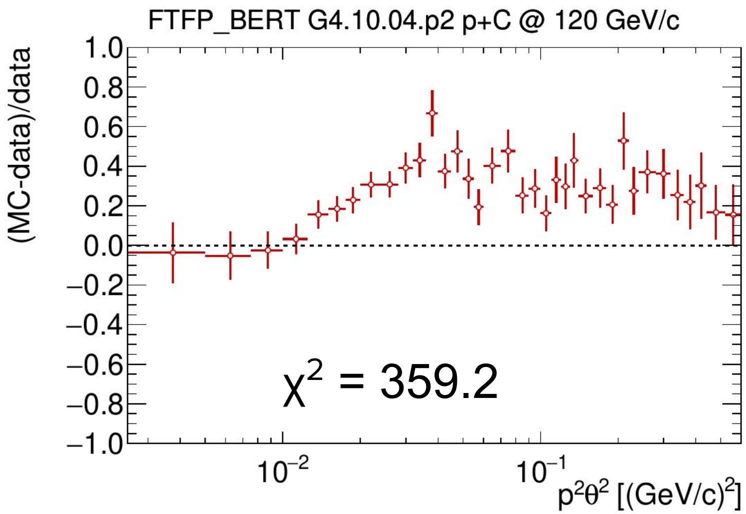

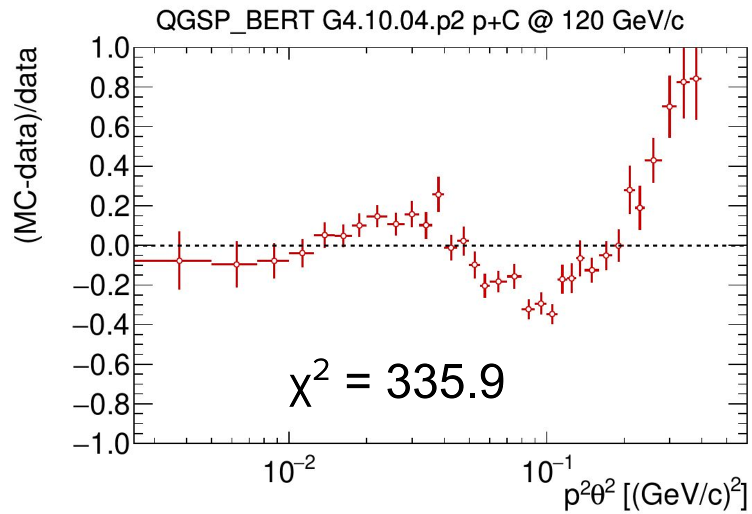

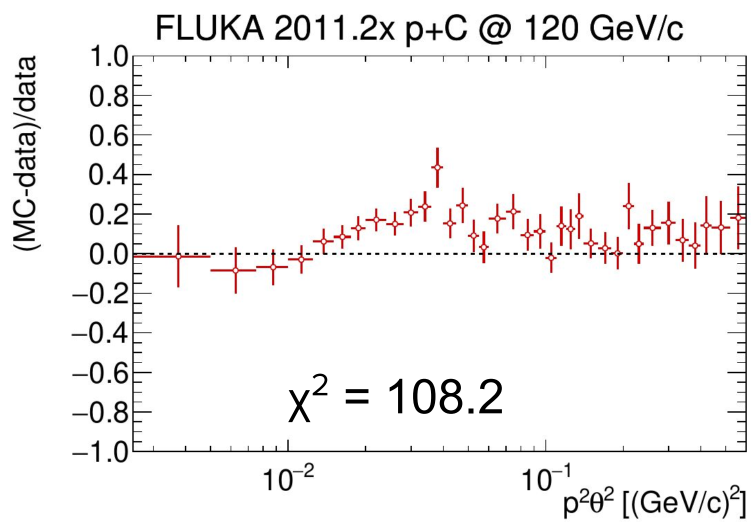

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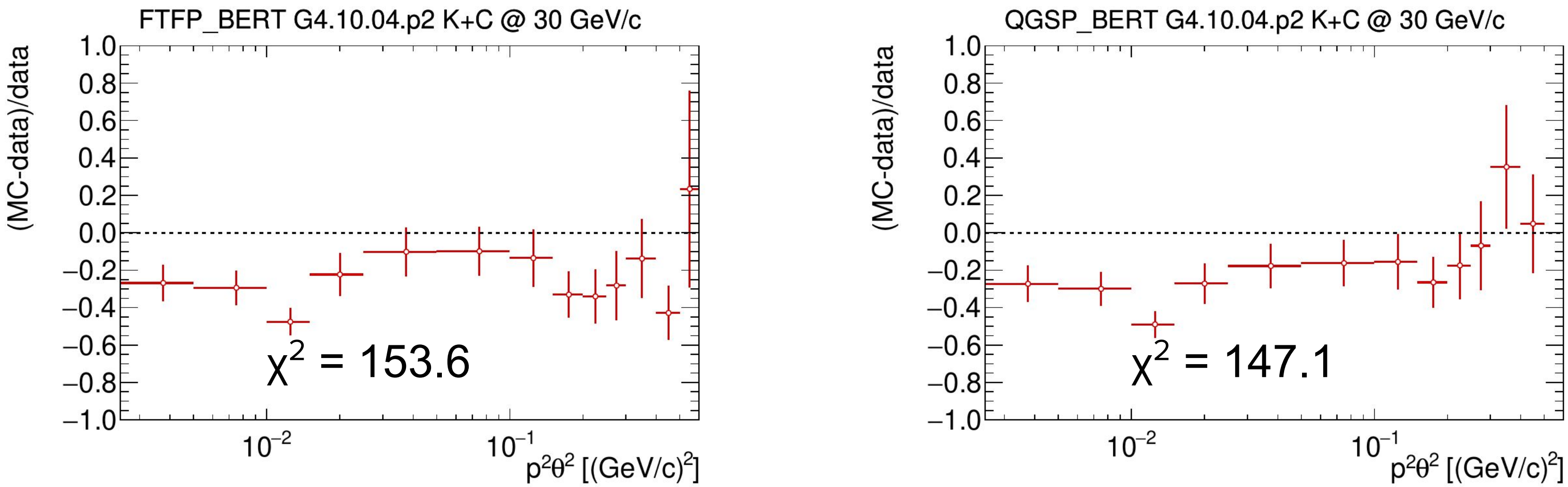

First measurement of this type for kaons!

Simulations seem to underpredict by ~20%.

EMPHATIC: Thin-target data w/ silicon tracking only

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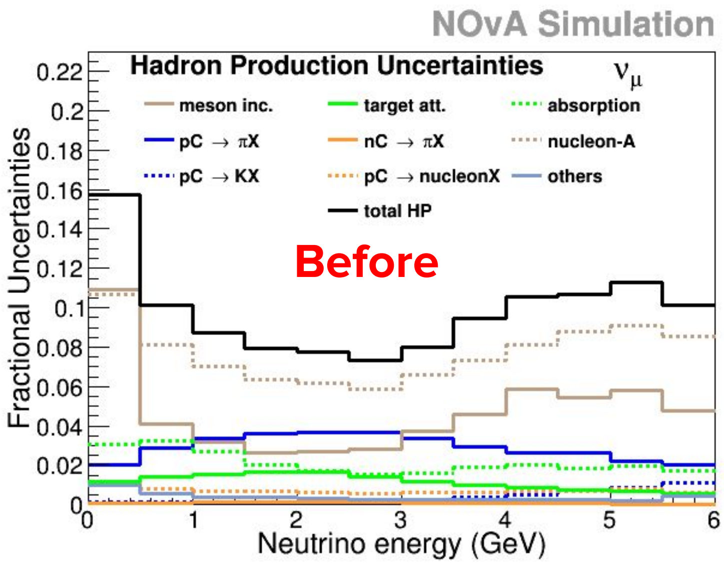
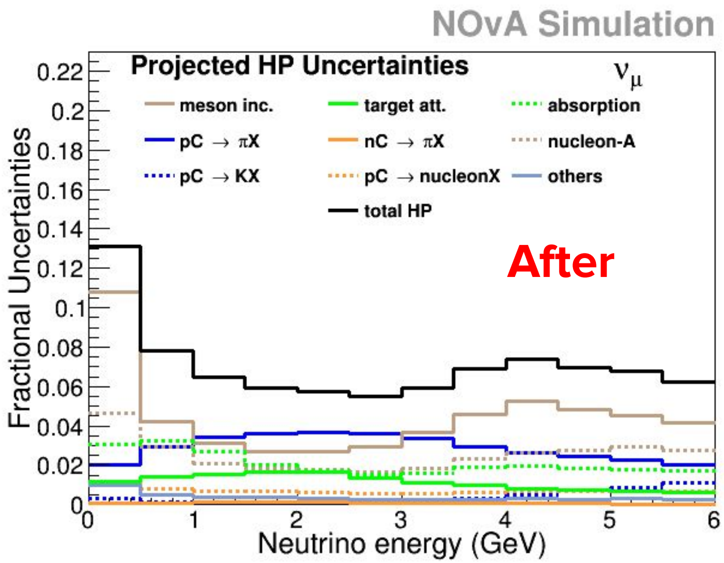
Impact of the current results (I)

- Quasi-elastic cross-section measurements can significantly impact the flux uncertainty in NOvA
- Assuming 10% uncertainty on proton-nucleus quasi-elastic interactions





A similar reduction in flux uncertainties is expected for DUNE…

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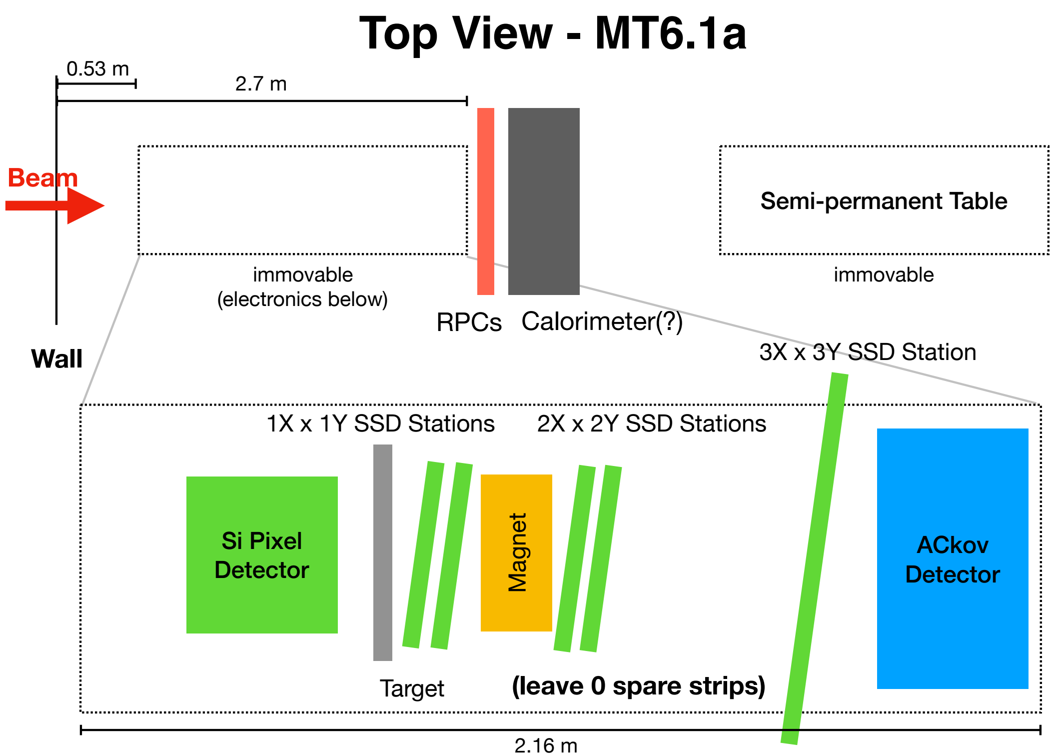
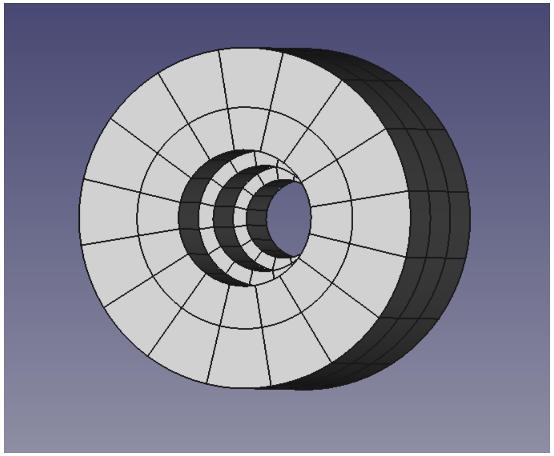
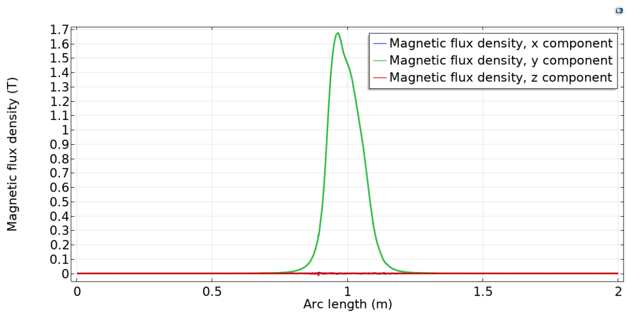
EMPHATIC: Proposed Future Runs

Phase	Date	Subsystems	Momenta	Targets	Goals
1	Spring 2020	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + Small-acceptance magnet (borrowed) + Downstream ACkov Time-of-flight	4, 8, 12, 20, 31, 60, 120	C, Al, Fe	Improved elastic and quasi-elastic scattering measurements, low-acceptance hadron production measurements
2	Spring 2021	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + New Large-area SiStrip Detectors + Full-acceptance magnet + Downstream ACkov + Time-of-flight	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	Spring 2022	Same as Phase 2 + Extended RICH	20, 31, 60, 80, 120	Same as Phase 2 + Ca, Hg, Ti	Full-acceptance hadron production with PID up to 15 GeV/c

EMPHATIC: Planned 2020 Run







- **Dates of run are set: April 1 - April 21, 2020**
- Small-aperture magnet purchased by TRIUMF
- Will reconfigure existing SSDs at FTBF for larger acceptance than they currently provide.

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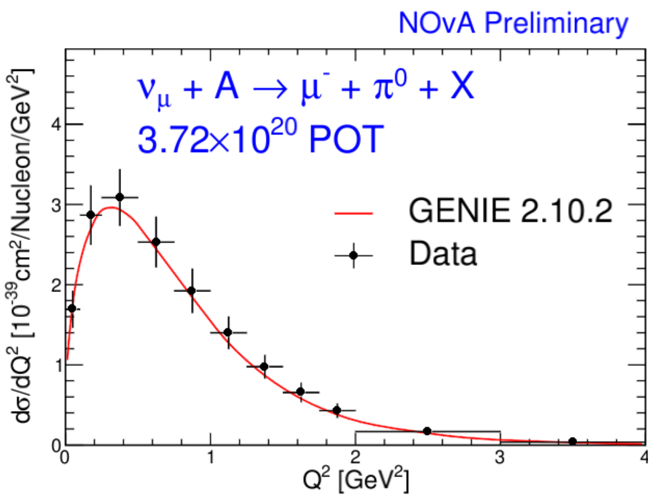
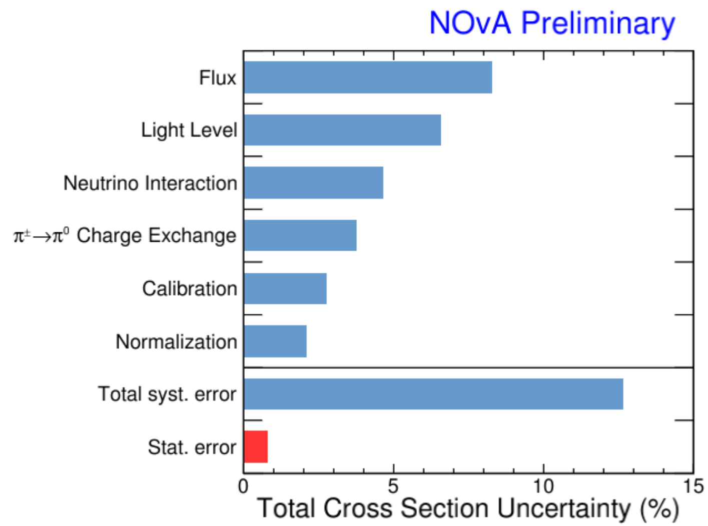
Summary

- 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 ***complementary*** to the existing efforts by NA61 to collect important hadron production data for improved flux predictions.
- EMPHATIC is a strong ***international collaboration*** with a mature design of the spectrometer and run plans for 2020-22.
- Analysis of data collected during an engineering run in January 2018 is complete and under collaboration review. Publication expected very soon.
- Critical detectors from Canada and Japan ***are funded and will be ready for the 2020 run***.
- We have requested and **received Stage 1 approval** from the Fermilab PAC.
- **New collaborators are welcome!**

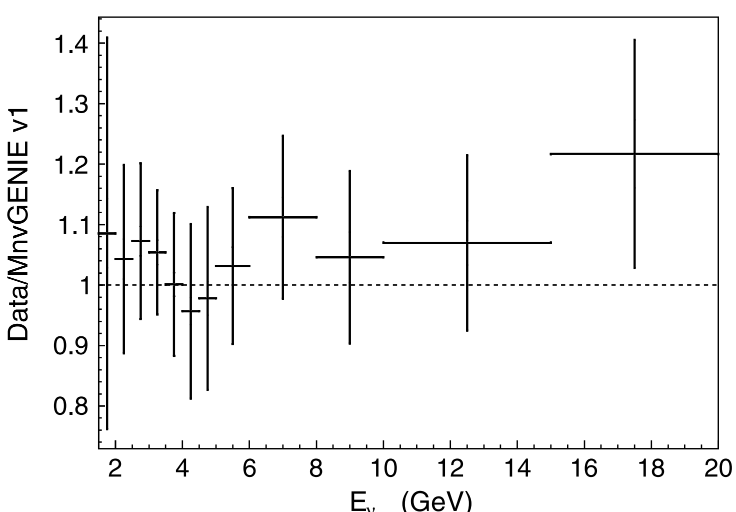
BACKUP

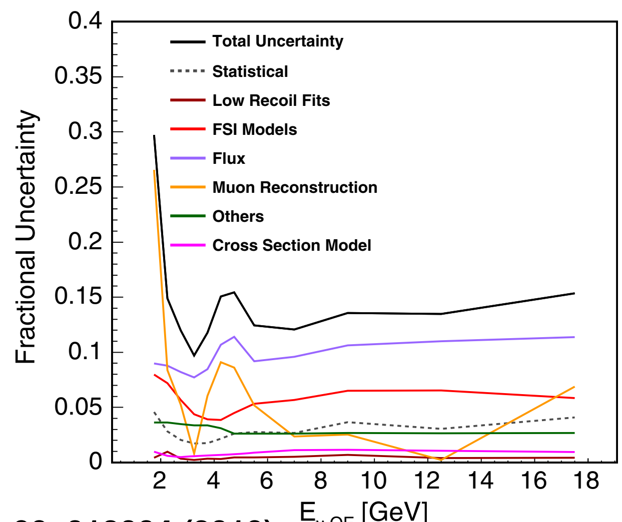
Flux Uncertainties - Why Should We Care?





- Flux is a limiting systematic for all neutrino cross section measurements by current experiments.
- Current measurements are being used to tune neutrino scattering models.
- Uncertainties in these models impact the sensitivity of the future DUNE physics program.

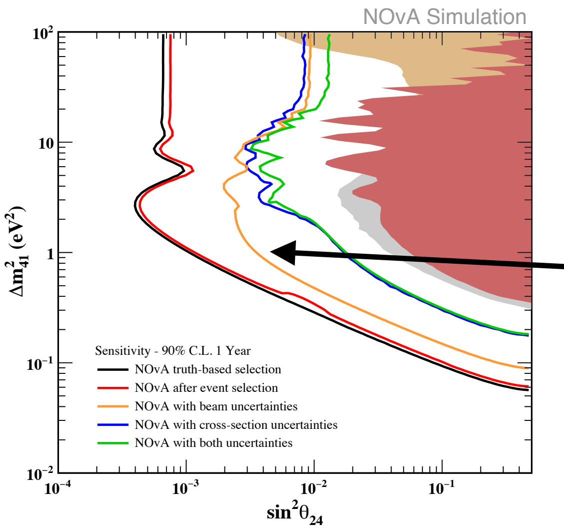


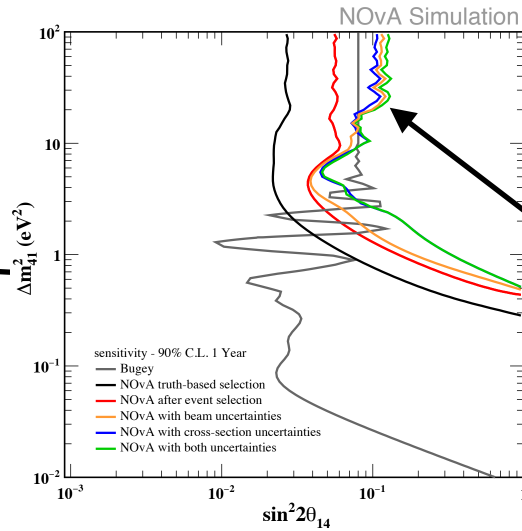


MINERvA, PRD 99, 012004 (2019)

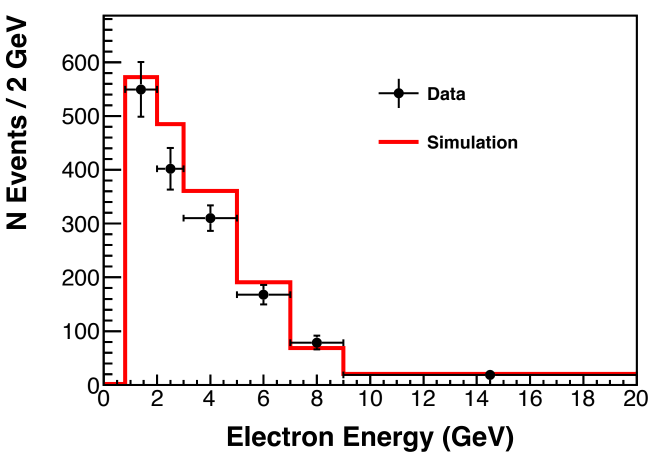
Fermilab

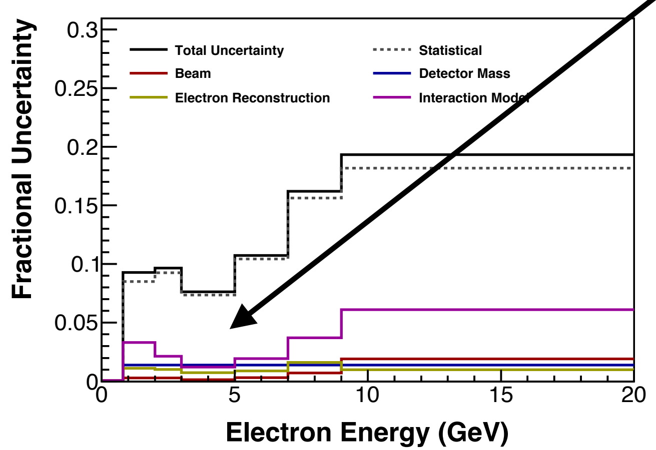
Flux Uncertainties - Why Should We Care?





- Flux is a limiting systematic for nearly all single-detector measurement.
- Single-detector searches for sterile neutrinos are severely limited by flux uncertainties.
- Percent-level ν-e scattering measurements can also be used to constrain "new ν" physics, eg NSI, ν magnetic moments, etc. But again these constraints will be limited by flux uncertainties.





MINERvA, arXiv:1906.00111v1 (2019)

Flux Uncertainties - Where Do They Come From?

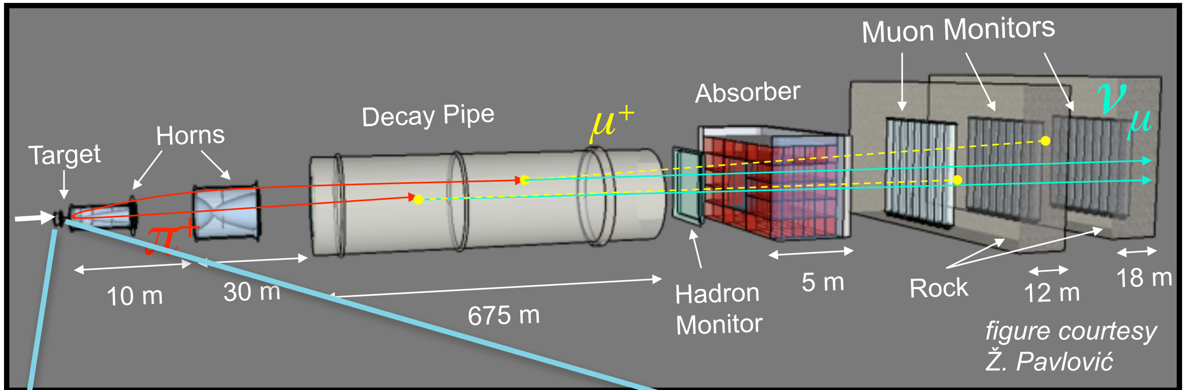
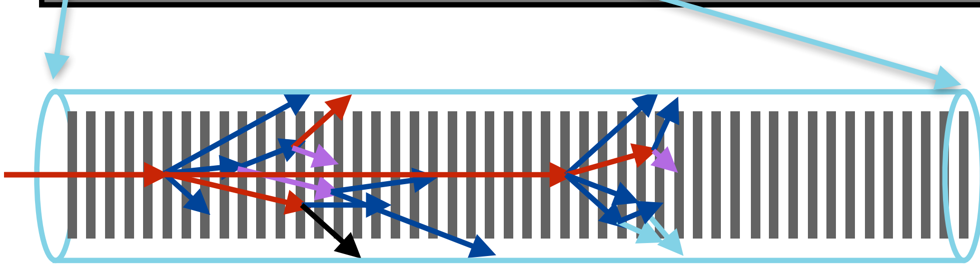


figure courtesy Ž. Pavlović

Production target = Series of thin graphite [or Be] slabs

Horns = Aluminum

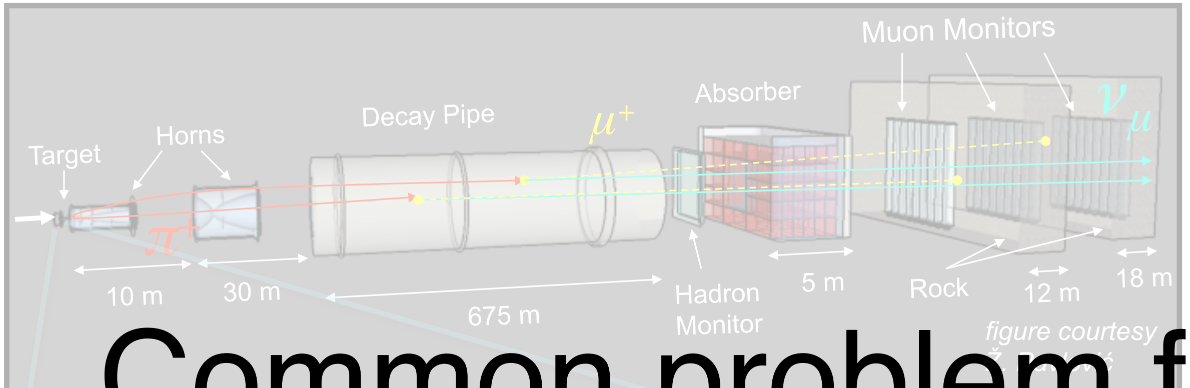
Lots of other materials for particles to interact with



- We measure flux*xsec in our detectors.
- Very difficult to measure the flux by itself.
- We rely on simulation to predict the flux.
- Simulations need the production cross sections for p,π,K hitting a broad range of nuclear targets across a broad range of energies.

- Uncertainty on the flux is obtained by varying the cross sections of all processes within their uncertainties, and varying the beam focusing parameters within their tolerances, in the simulation.
- Hadron production cross section uncertainties are the dominant contribution to the neutrino flux uncertainty.
- Hadron production uncertainties are significantly smaller for interactions that have been measured.
- There are a lot of relevant interactions that have not been measured [well].

Flux Uncertainties - Where Do They Come From?



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Common problem for all accelerator and atmospheric neutrino-based experiments.

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- Very difficult to measure the flux by itself.
- We rely on simulation to predict the flux.
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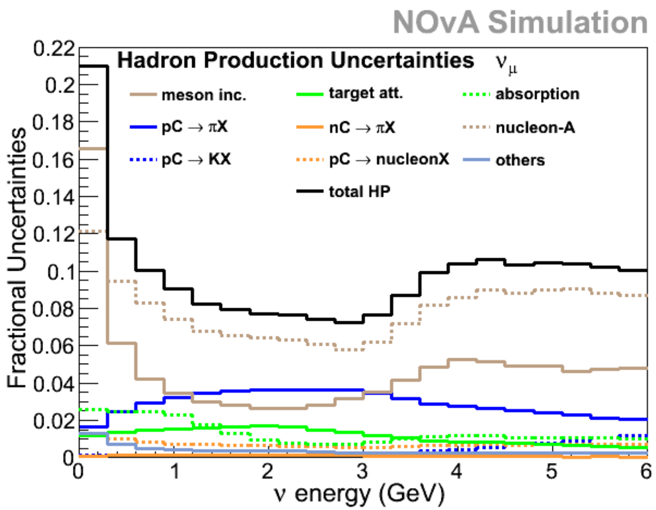
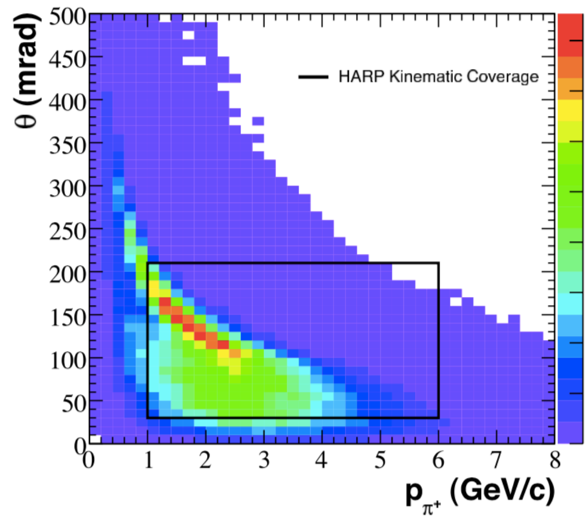
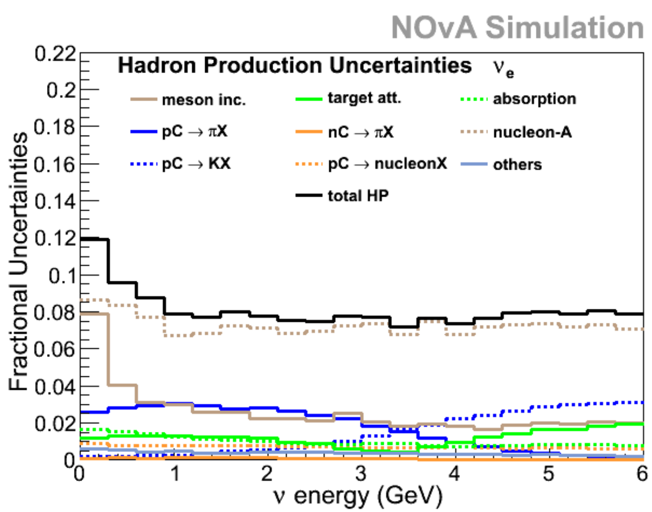
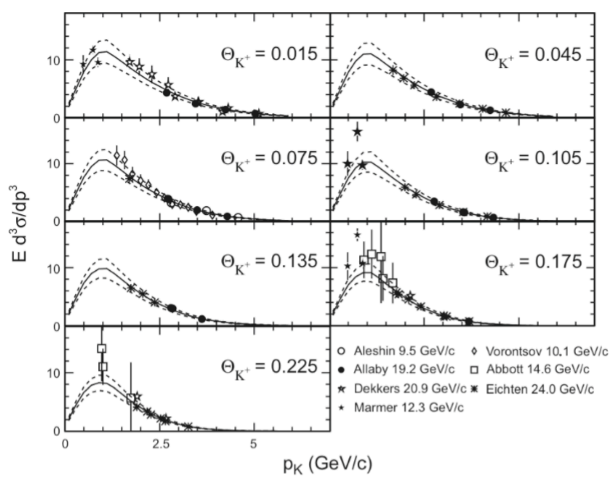
NuMI and Booster Flux Uncertainties







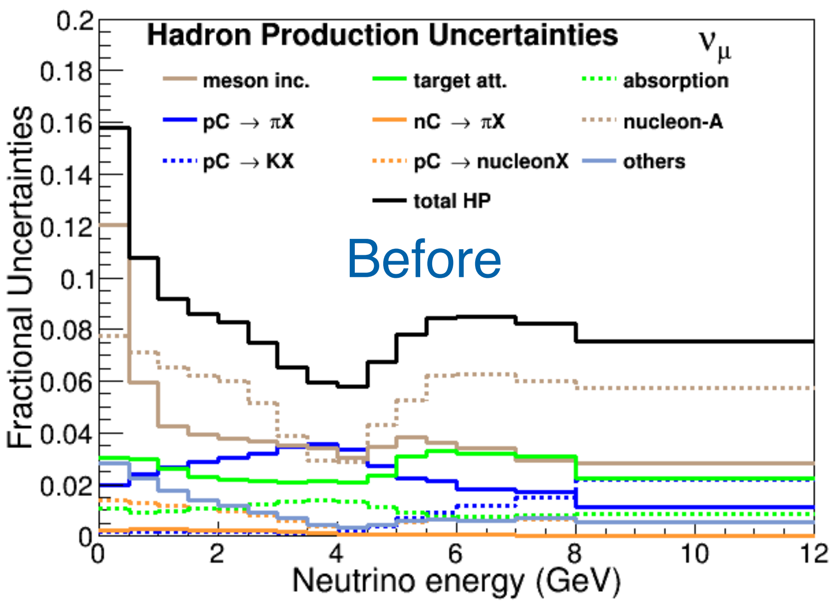


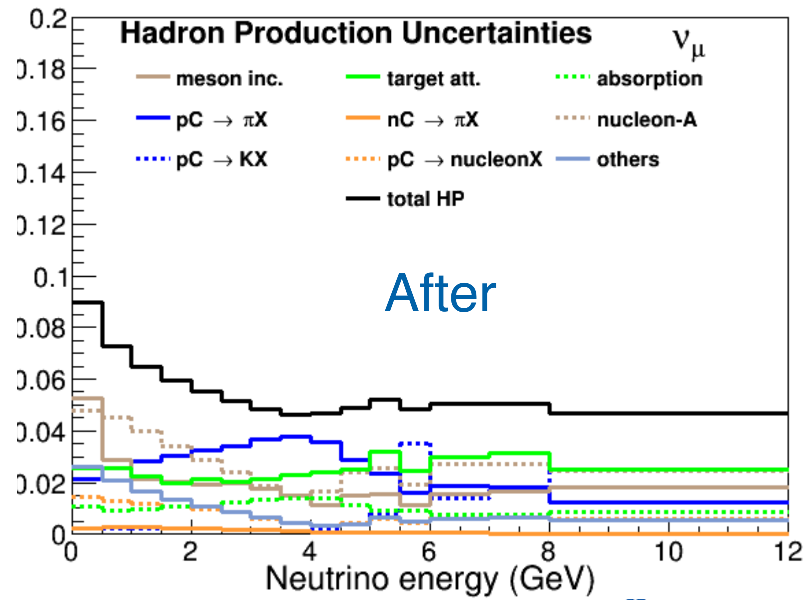
- **Reduction of flux uncertainties improves the impact that cross section measurements by NOvA, MINERvA and SBN will have on the global effort to improve ν-A models.**

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] —> $K^{\pm}$ + X (down from 40%)

Not covered by current data





Note: flux uncertainties determined by EMPHATIC, not DUNE

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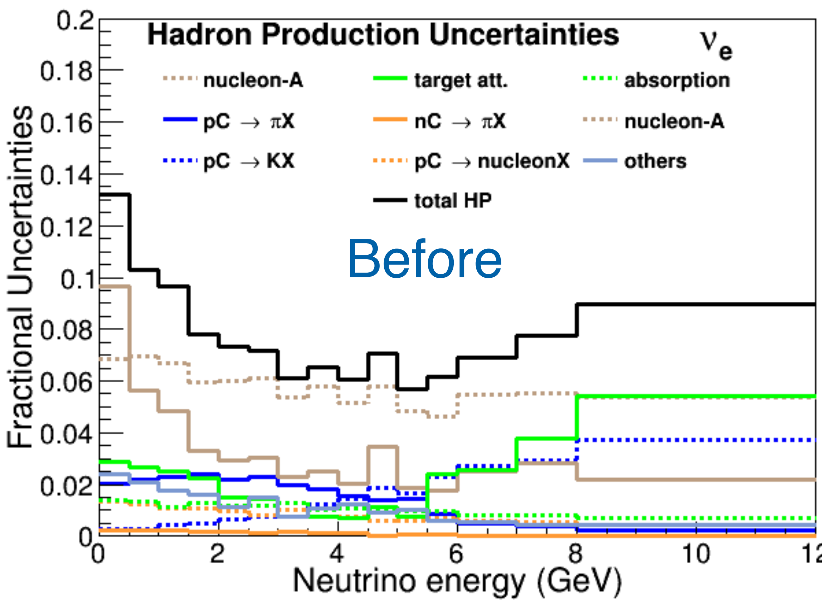
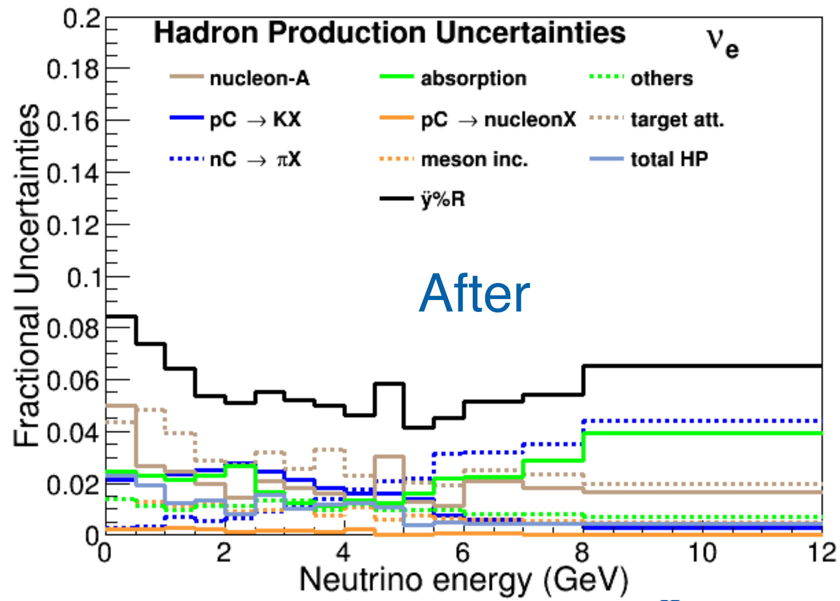
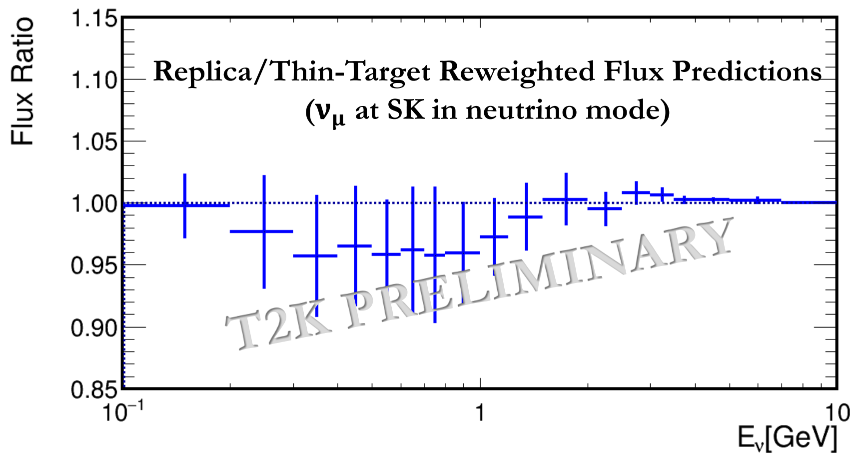


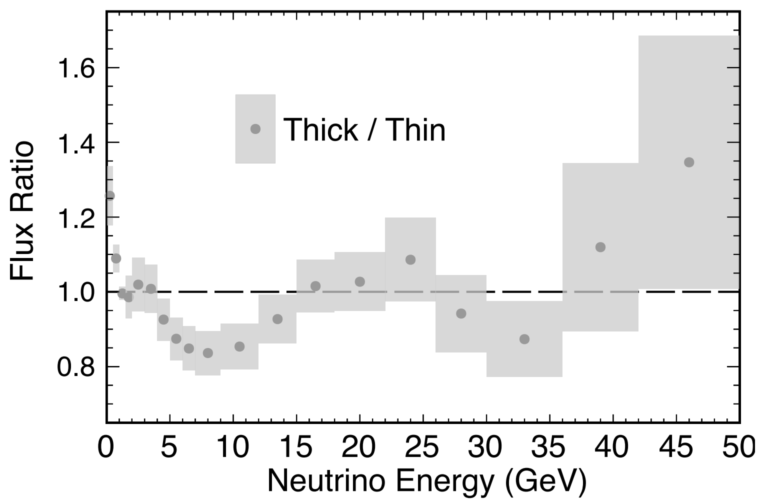


Note: flux uncertainties determined by EMPHATIC, not DUNE

DUNE Flux Uncertainties - Can we do better?

- NA61 proposes to measure the hadron yield off the LBNF target. Such a measurement should be at the ~3% level.
- However, there are many interactions outside of the target that result in neutrinos see by our detectors.
- In T2K, ~50% of all wrong-sign neutrinos come from interactions outside of the target. Studies are underway to determine this fraction for DUNE, but it should be similar.
- Improved thin-target measurements are needed if we want to get the final hadron-production flux uncertainty to be < few percent.
- And then of course there is the thin vs. thick target “anomaly”…





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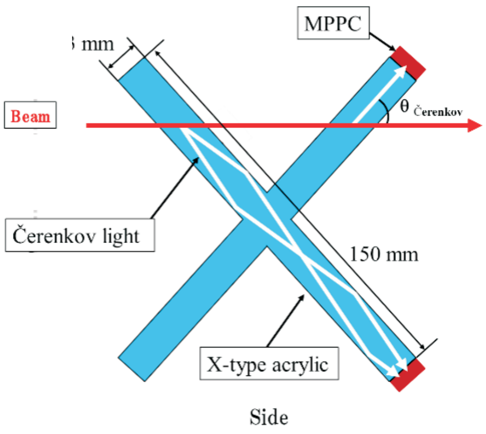
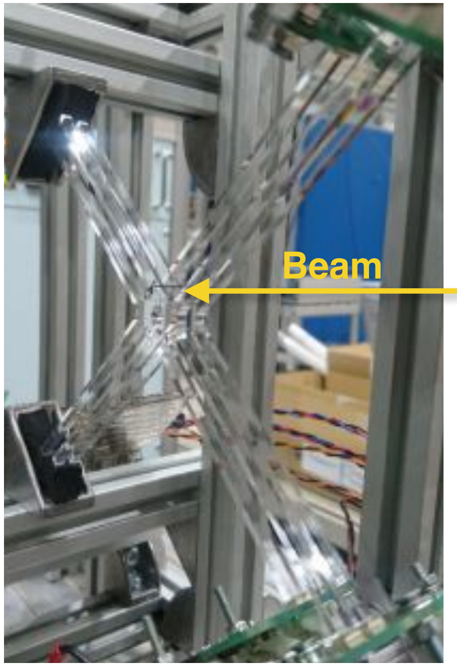
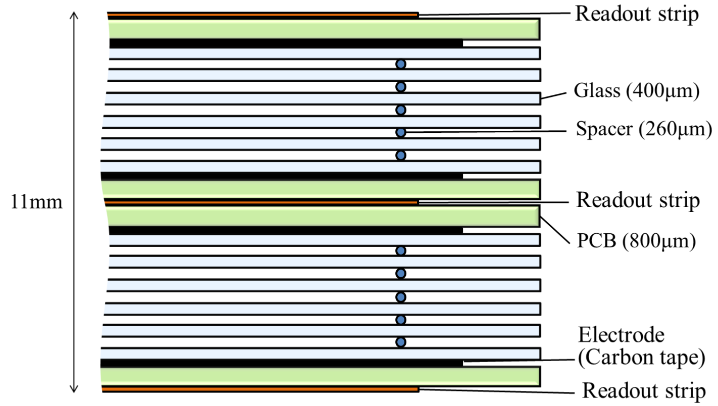
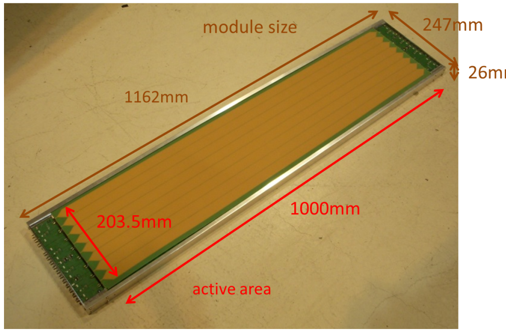
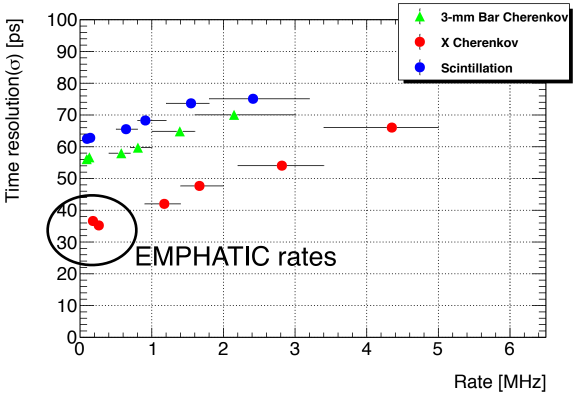
EMPHATIC: Time of Flight



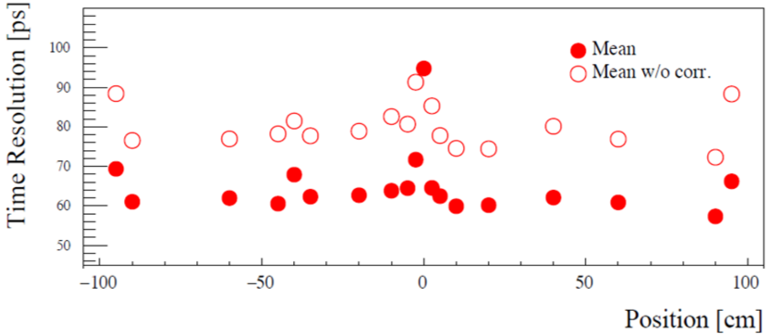




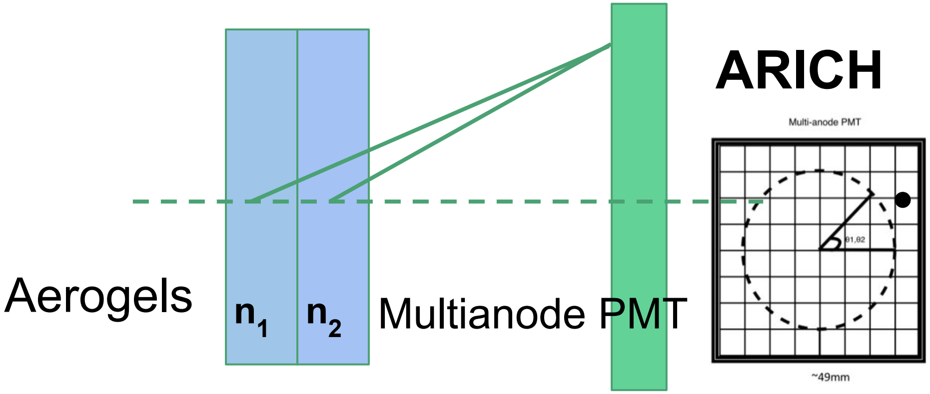


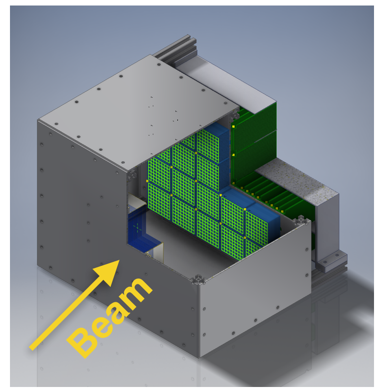


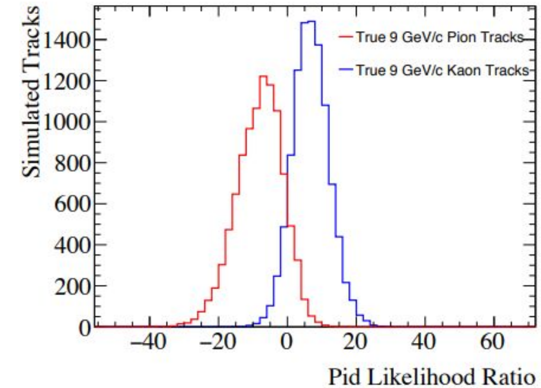
Note: Fig. 21 of the proposal has the wrong plot, this is the correct one:

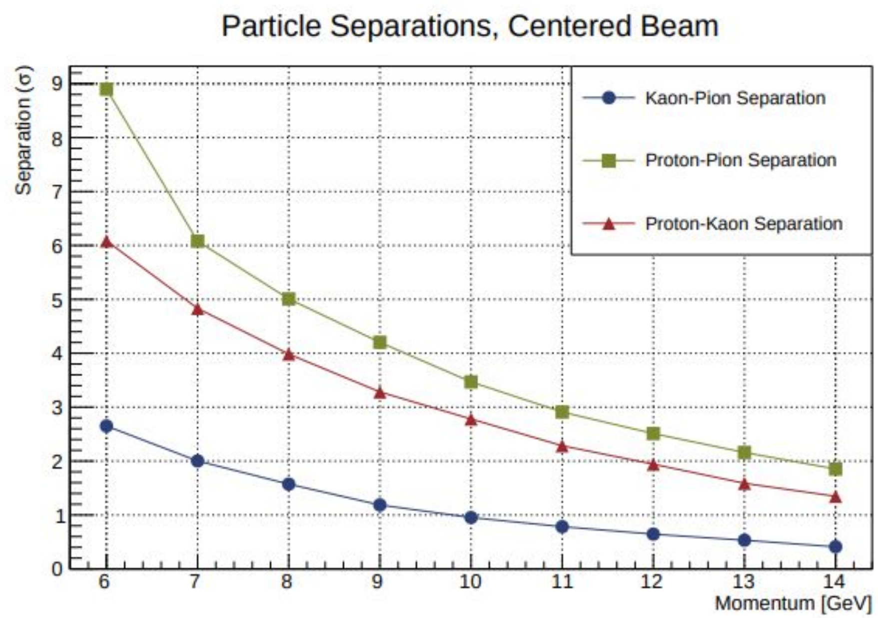


EMPHATIC: Aerogel RICH







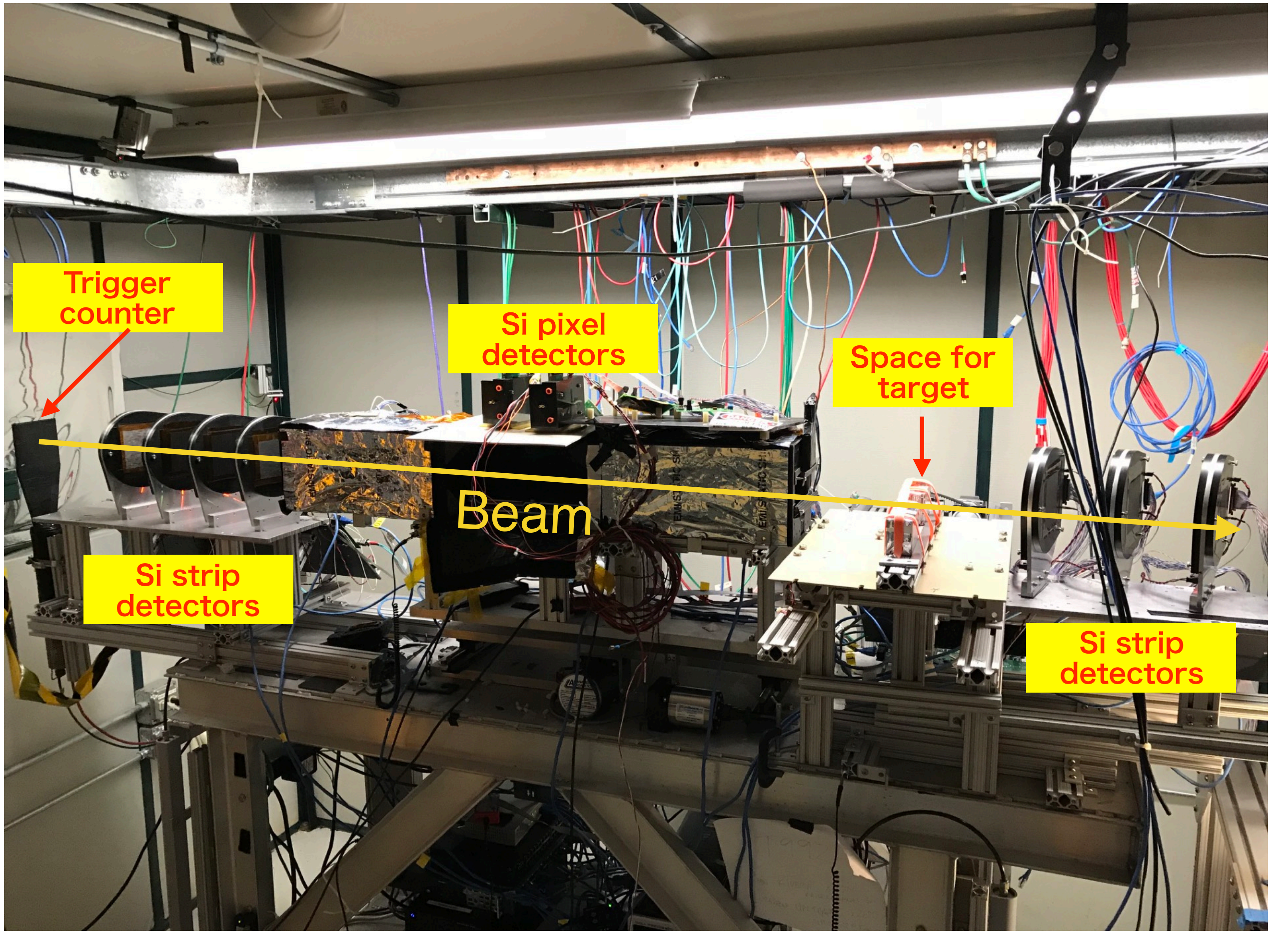


- Based on the Belle II RICH detector
- Aerogels with lower indices of refraction (n=1.02-1.03) and good transmittance available thanks to advances in aerogel production at Chiba U.
- 2σ π-K separation for p<8 GeV/c.
- Beam test at TRIUMF happening now.

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



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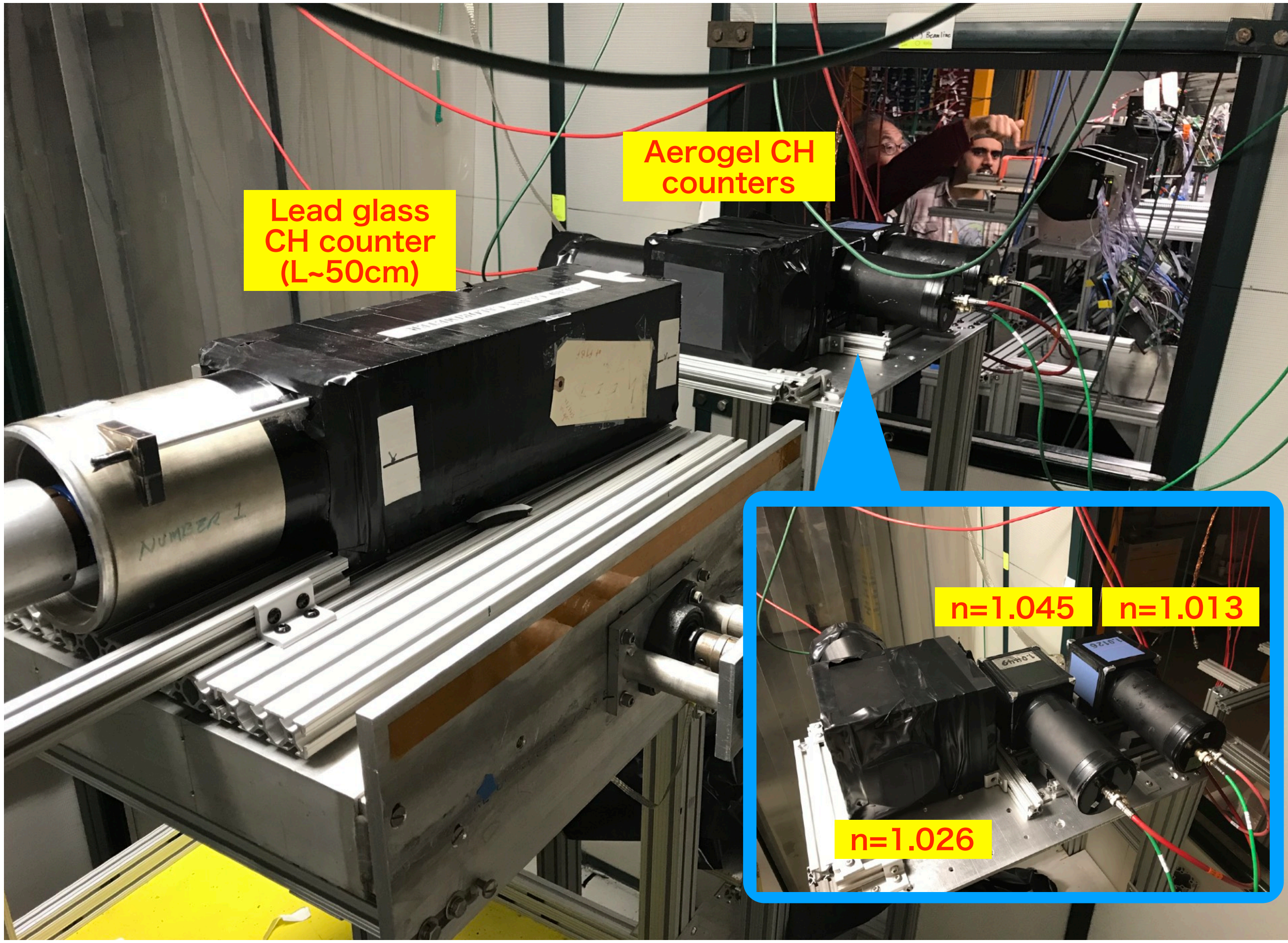
MT6.1-B



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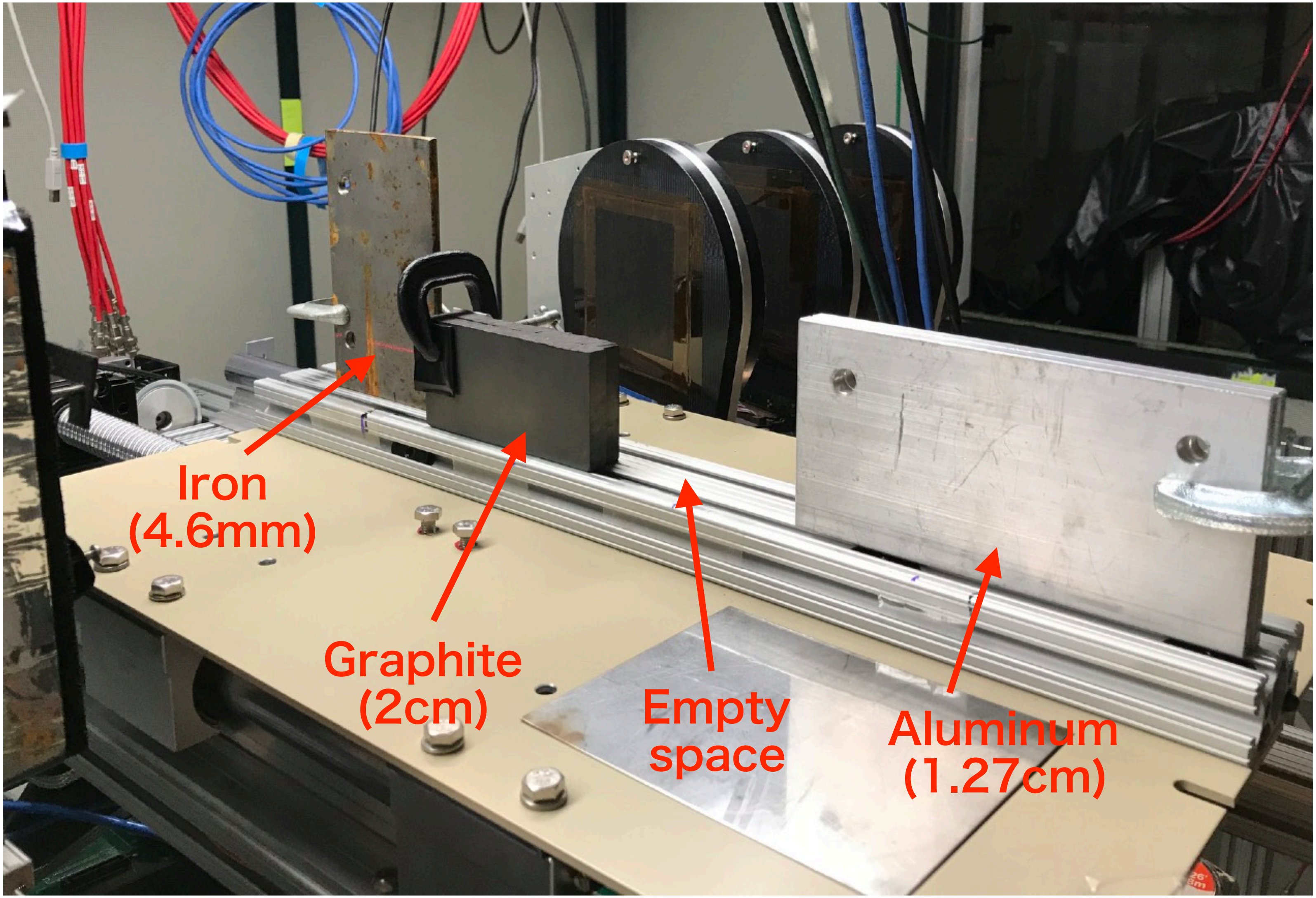
EMPHATIC: Thin-target data w/ silicon tracking only



Fermilab

EMPHATIC: Thin-target data w/ silicon tracking only

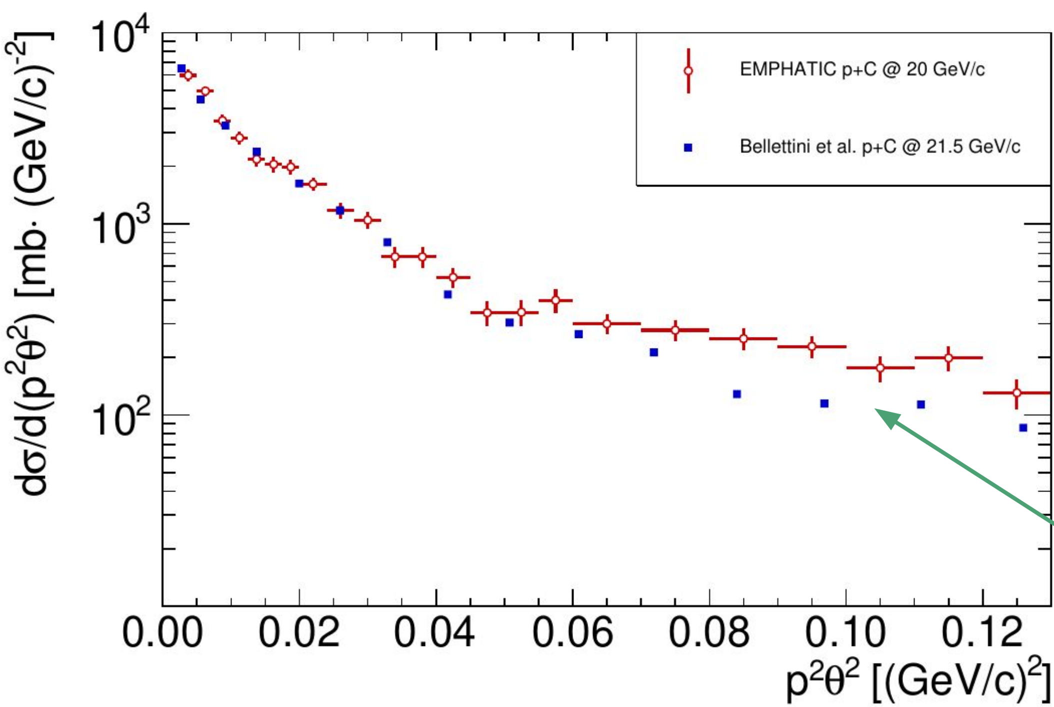
Number of min. bias triggers

	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

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