EMPHATIC

A proposed hadron production experiment for improved neutrino flux predictions

Jonathan Paley
On Behalf of the
EMPHATIC Collaboration

Fermilab PAC Meeting
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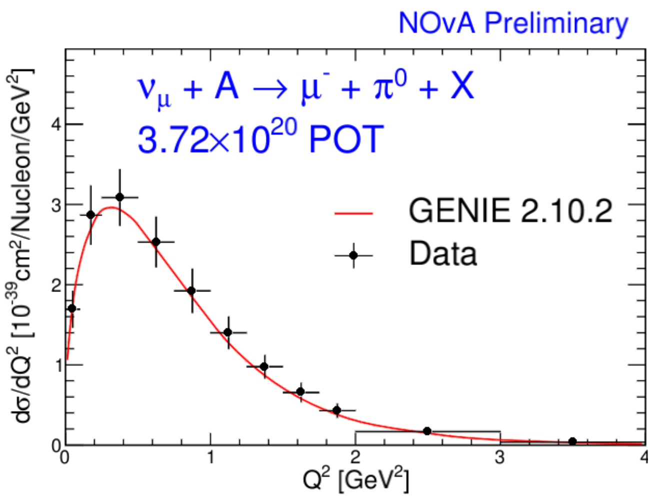
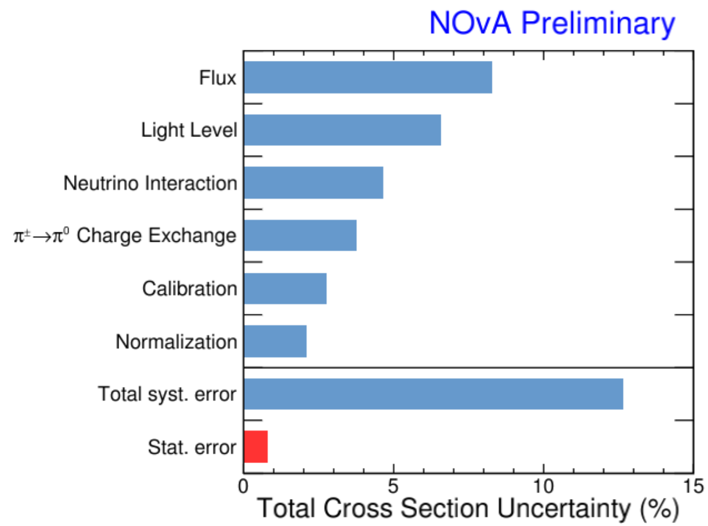
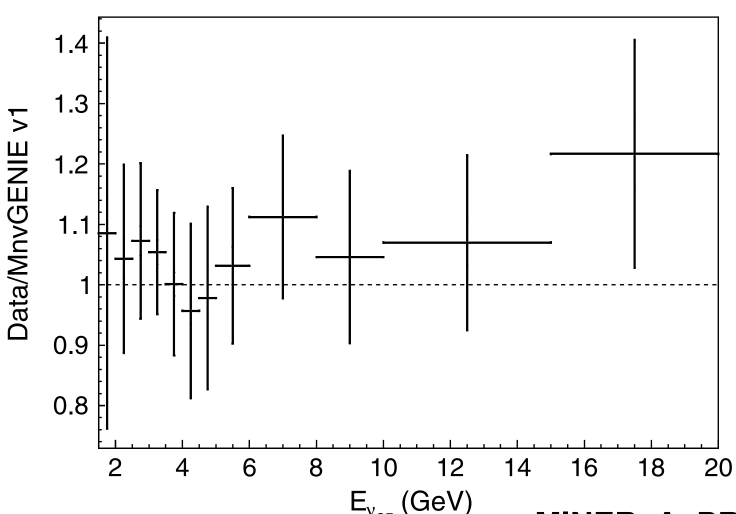
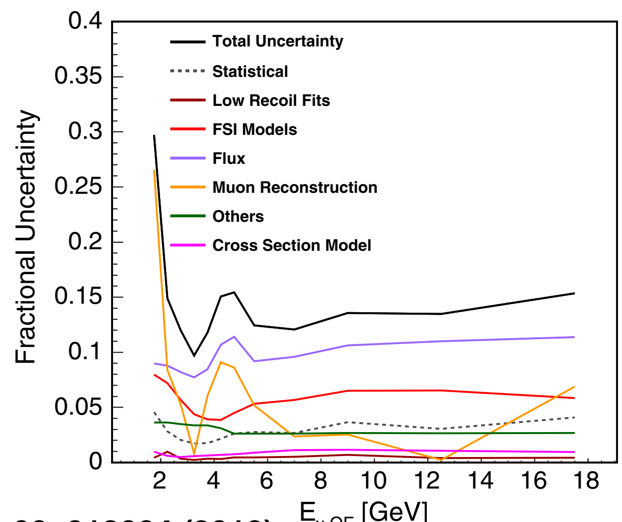
Fermilab

Flux Uncertainties - Why Should We Care?





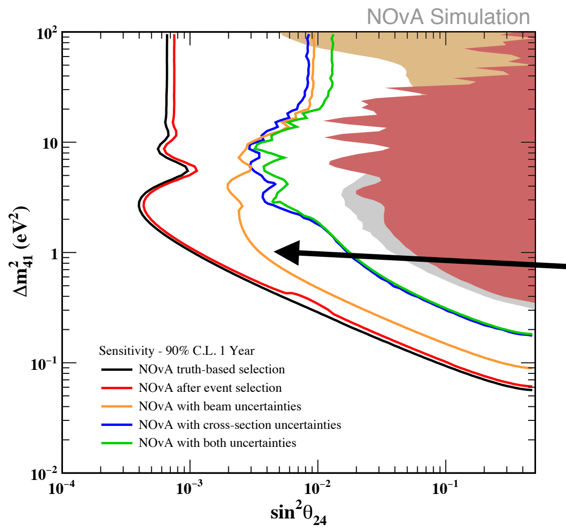


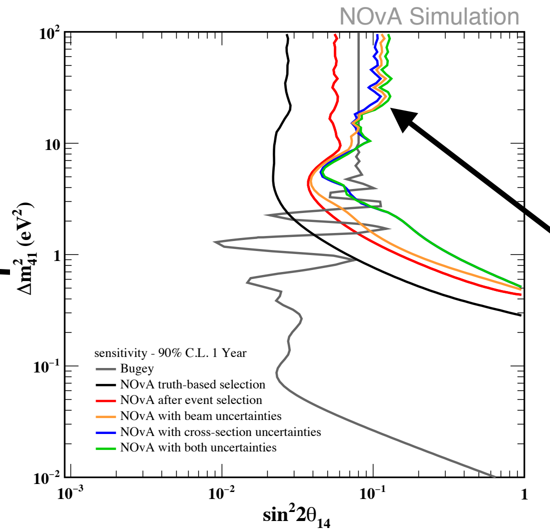


MINERvA, PRD 99, 012004 (2019)

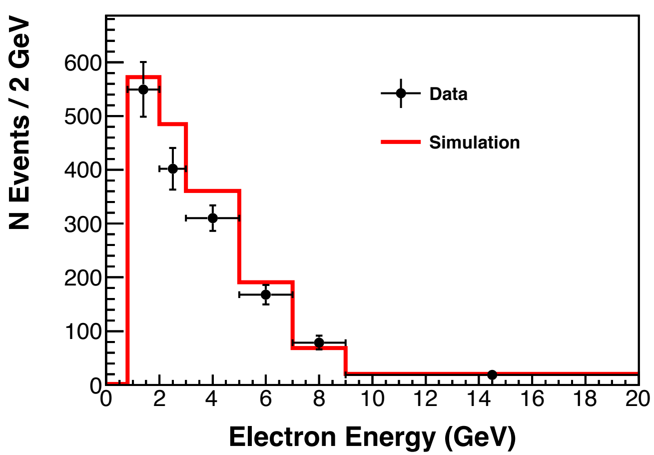
- Flux is a limiting systematic for all neutrino cross section measurements by current experiments.
- Current measurements are being used to tune neutrino scattering models.
- Uncertainties in these models impact the sensitivity of the future DUNE physics program.

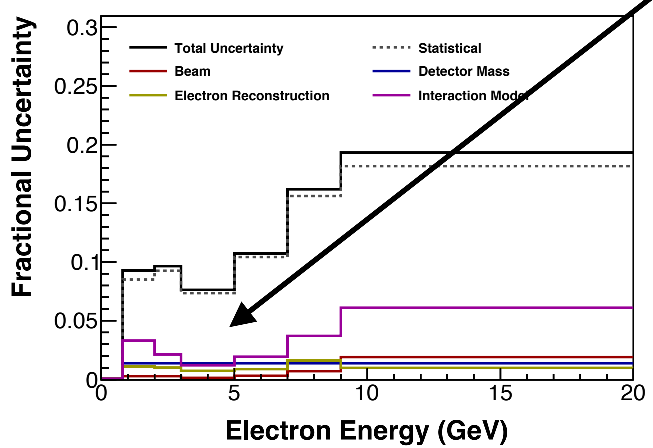
Flux Uncertainties - Why Should We Care?





- 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)

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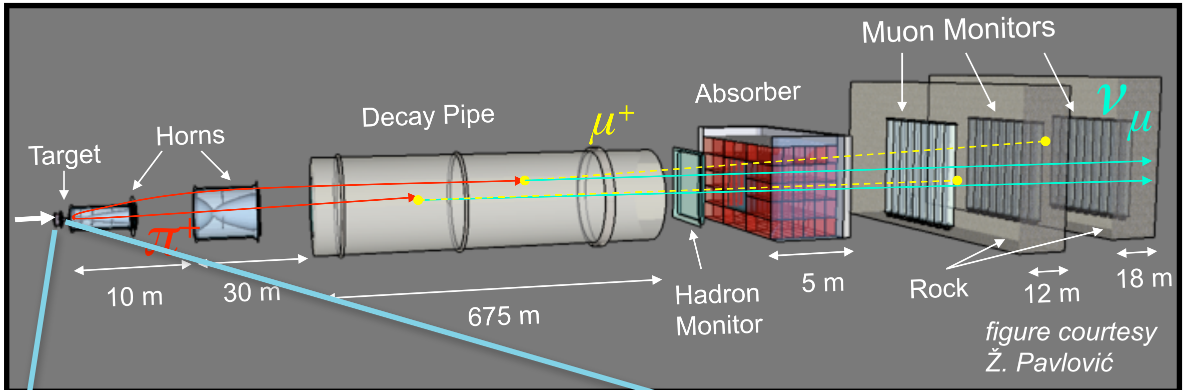
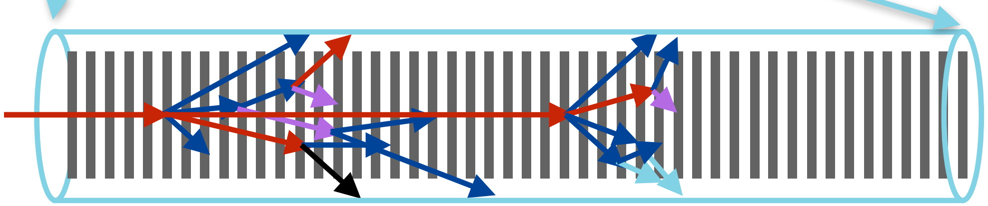
Flux Uncertainties - Where Do They Come From?



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].

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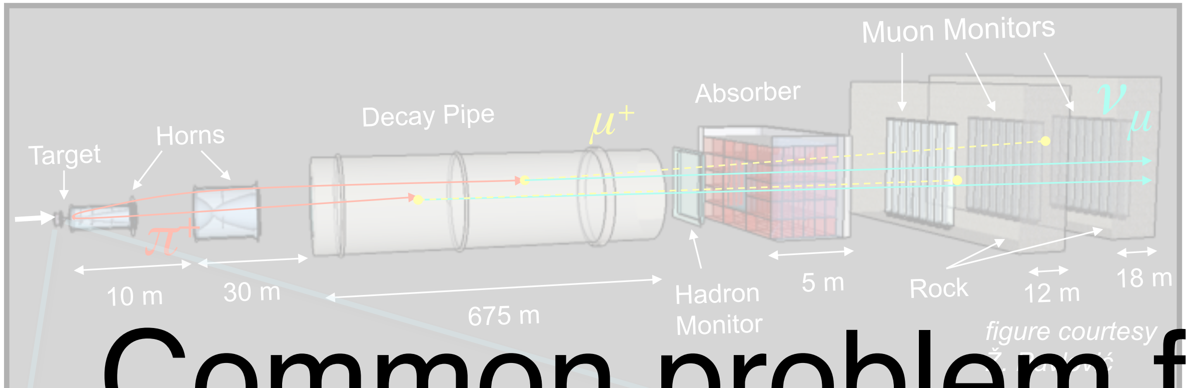

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Common problem for all accelerator and atmospheric neutrino-based experiments.

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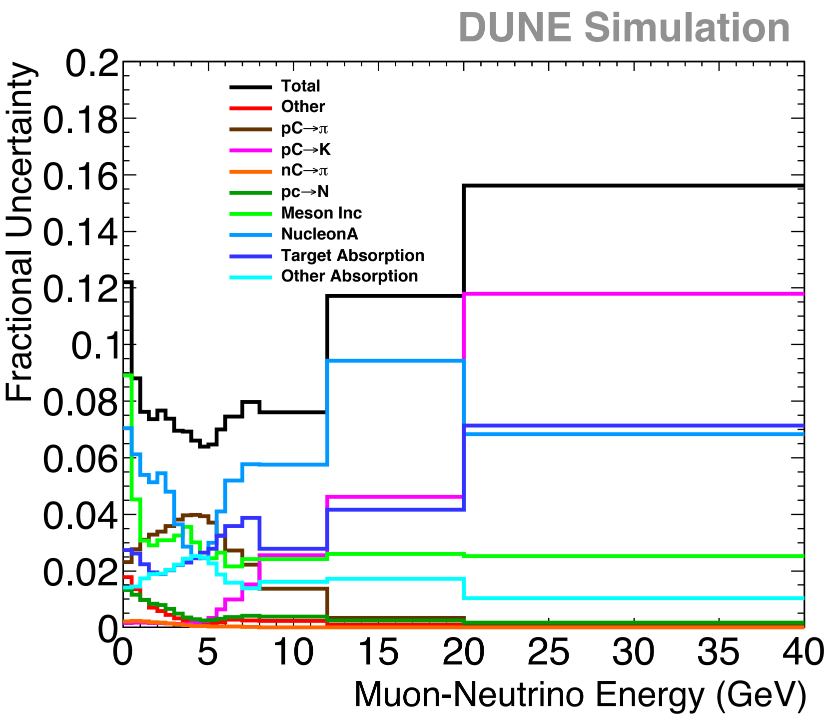
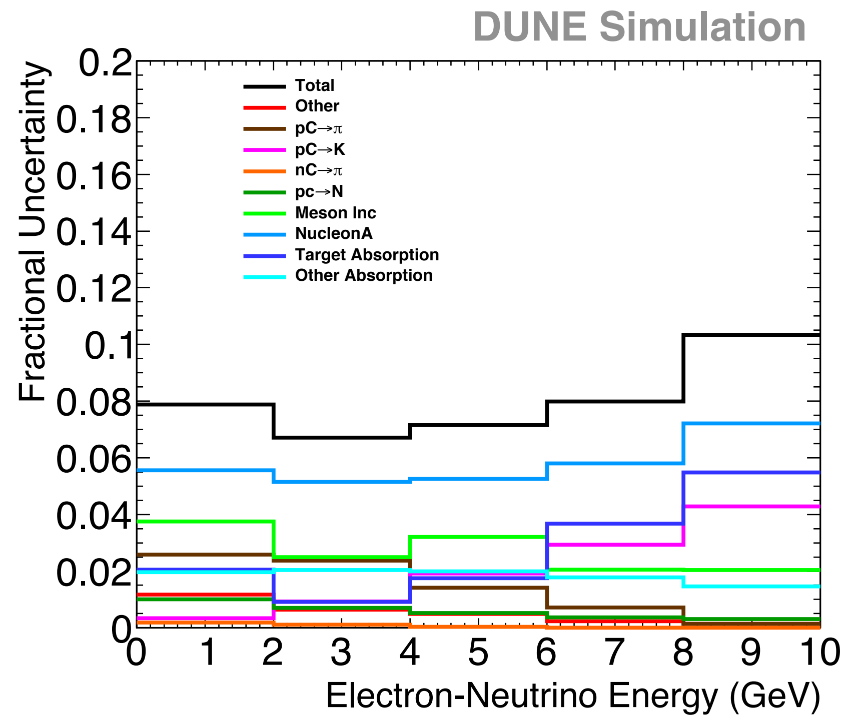
DUNE Flux Uncertainties



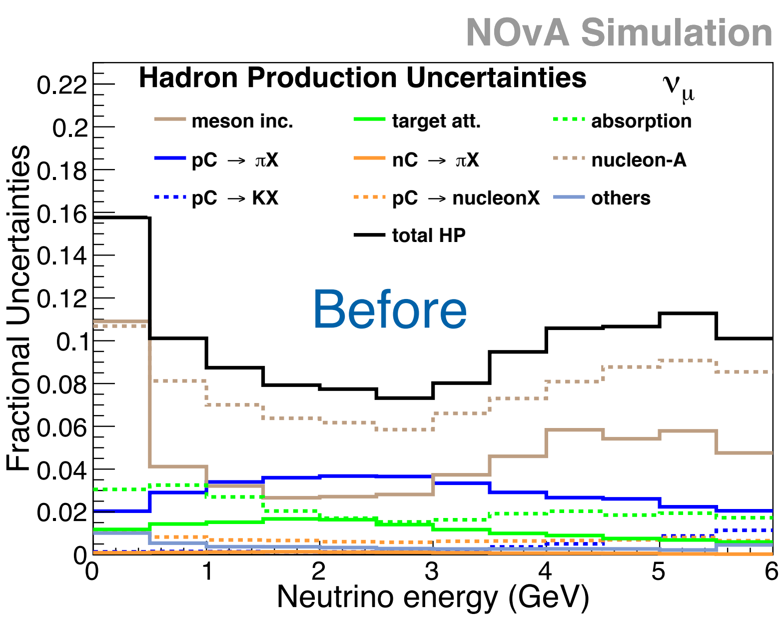


- Dominant flux uncertainties come from 40% xsec uncertainties on interactions in the target and horns that have never been measured (or have large uncertainties/spread).
- Lack of proton and pion scattering data at lower beam energies that NA61 has access to.
- **Reduction of flux uncertainties improves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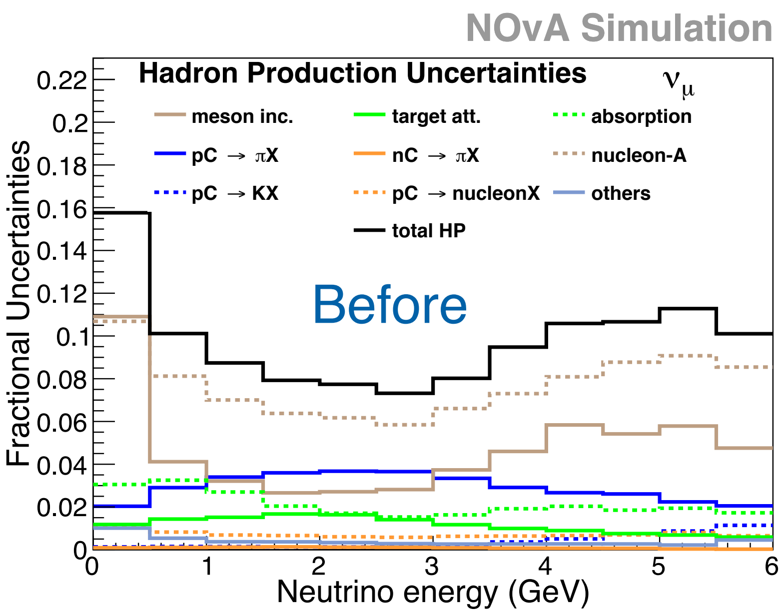
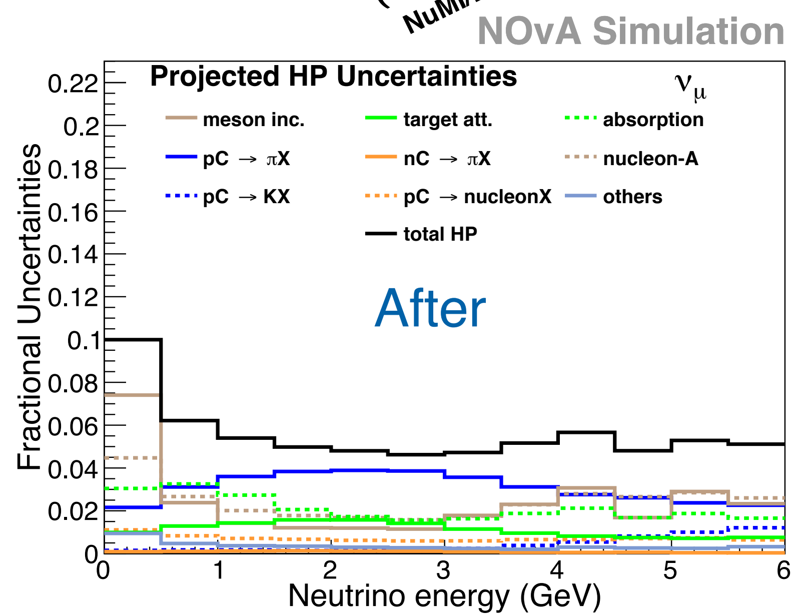
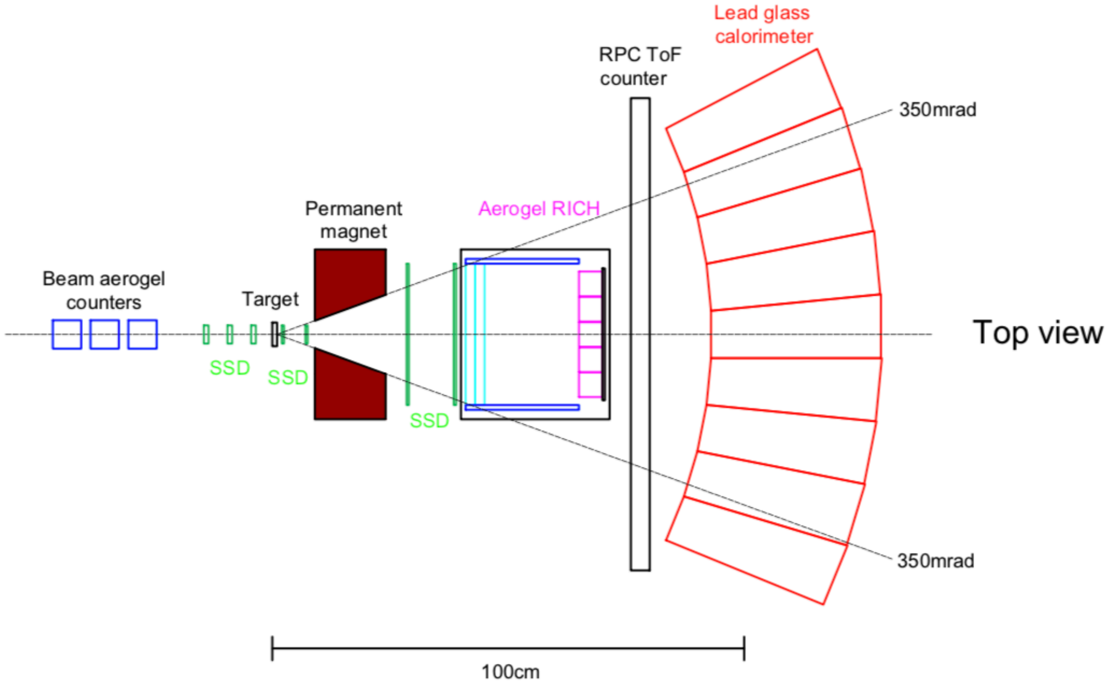




EMPHATIC

- **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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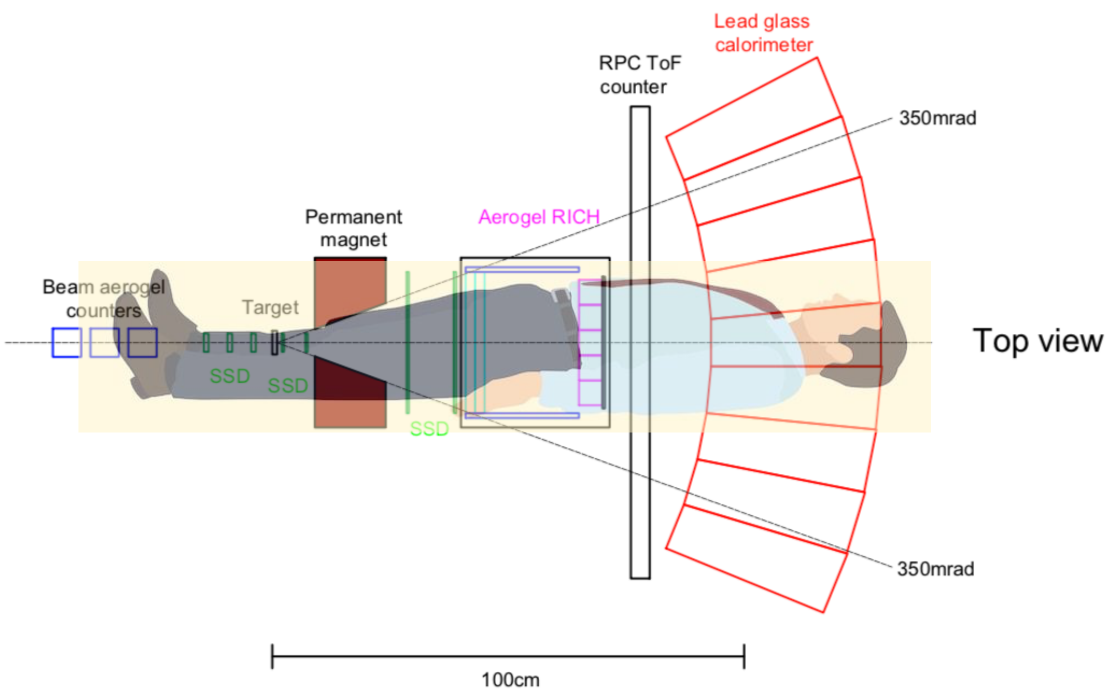

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EMPHATIC: A proposed experiment to measure hadron scattering and production cross sections for improved neutrino flux predictions

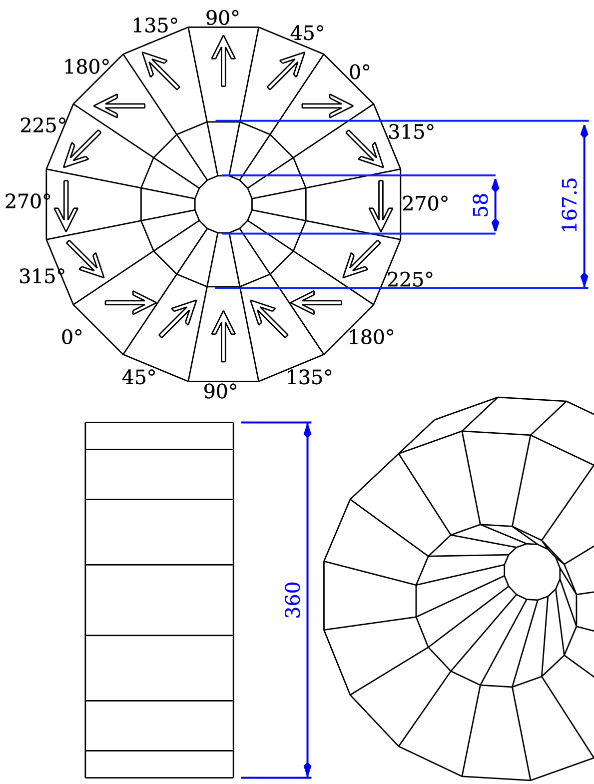
T. Akaishi,[4] L. Aliaga-Soplin,[9] H. Asano,[18] M. Barbi,[6] L. Bellantoni,[9] S. Bhadra,[21] W-C. Chang,[21] L. Fields,[9] A. Fiorentini,[21] M. Friend,[10] T. Fukuda,[15] D. Harris,[9] M. Hartz,[12,19] R. Honda,[7] T. Ishikawa,[16] B. Jamieson,[20] E. Kearns,[3] N. Kolev,[6] M. Komatsu,[15] Y. Komatsu,[10] A. Konaka,[19] M. Kordosky,[8] P. Lebrun,[9] T. Lindner,[20,19] Y. Ma,[18] M. Muether,[2] N. Naganawa,[15] M. Naruki,[14] H. Noumi,[17] K. Ozawa,[10] J. Paley,[9] M. Pavin,[19] P. de Perio,[19] F. Sakuma,[18] G. Santucci,[21] T. Sawada,[5] O. Sato,[15] T. Sekiguchi,[10] K. Shirotori,[17] A. Suzuki,[13] M. Tabata,[1] T. Takahashi,[17] N. Tomida,[17] R. Wendell,[14] and T. Yamaga[18]

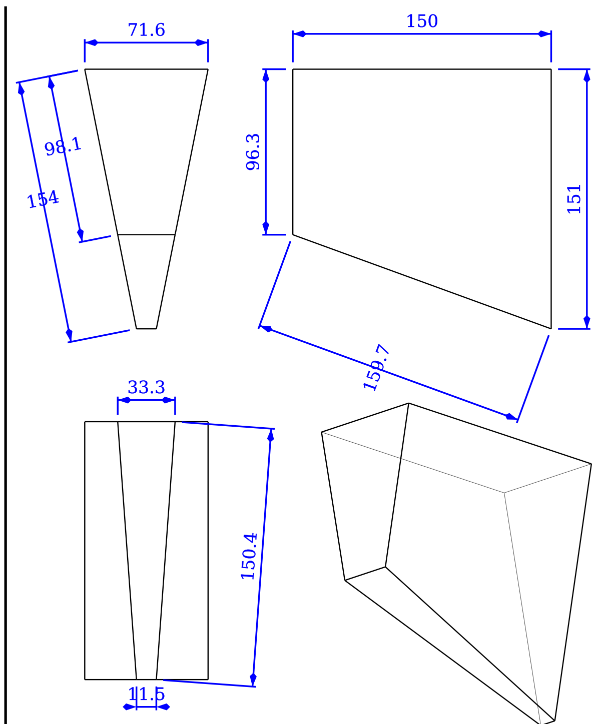
- **Highlighted authors are postdocs.**
- **Because of our smooth on-boarding process, several institutions (eg TRIUMF, Nagoya, Fermilab) have had students at various levels make significant contributions on short projects since early 2018.**
- **A handful of students are already committed to work on EMPHATIC next year. We expect more students and postdocs will join the effort with PAC/Fermilab approval of EMPHATIC.**

EMPHATIC: Permanent Magnet

Halbach Array

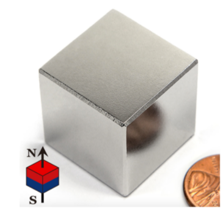
EMPHATIC Dipole Magnet
16 NdFeB (N52) segments
104 kg





all measurements are in mm

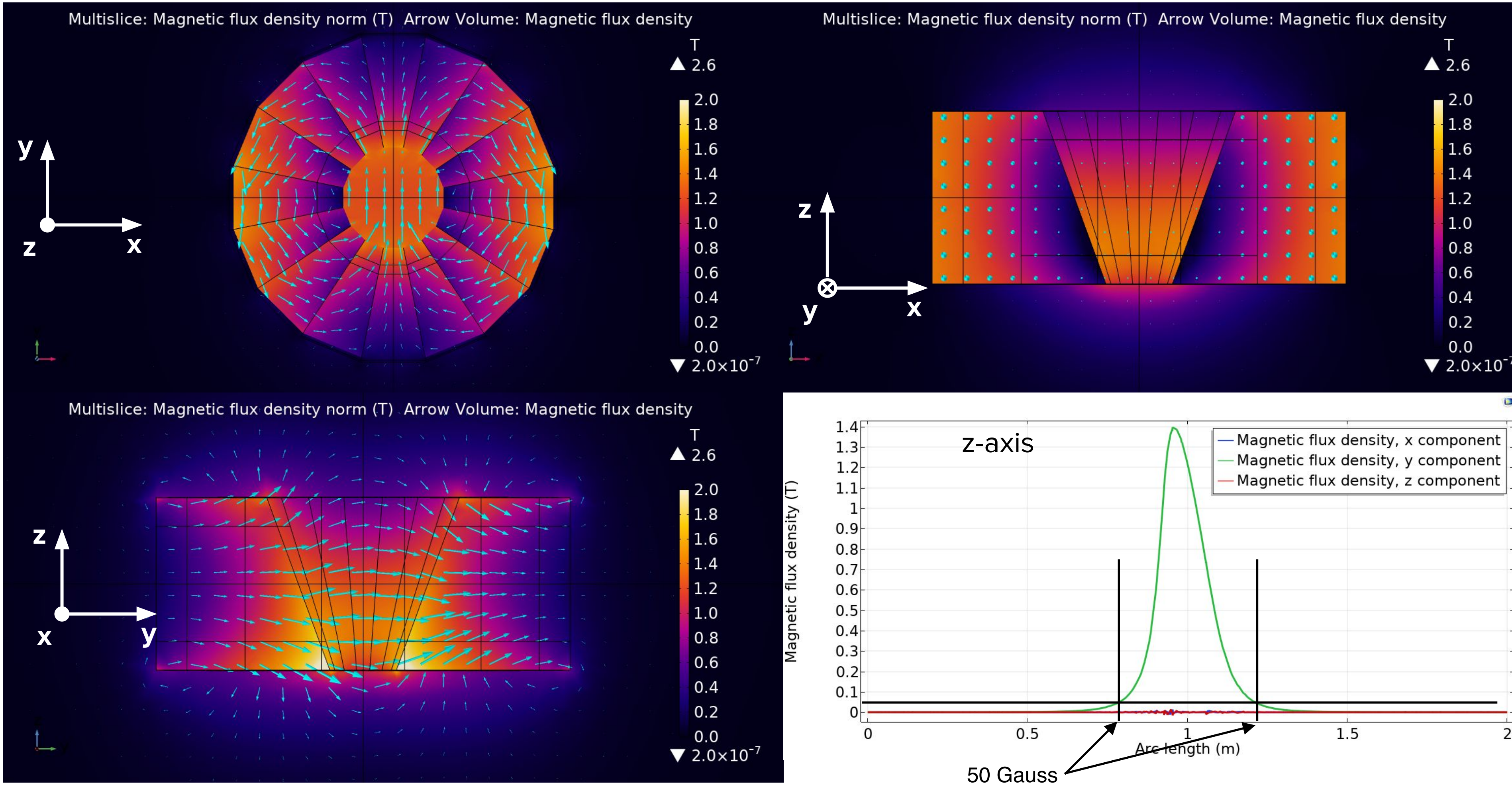
Segments made from large segments of Neodymium permanent magnets.



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

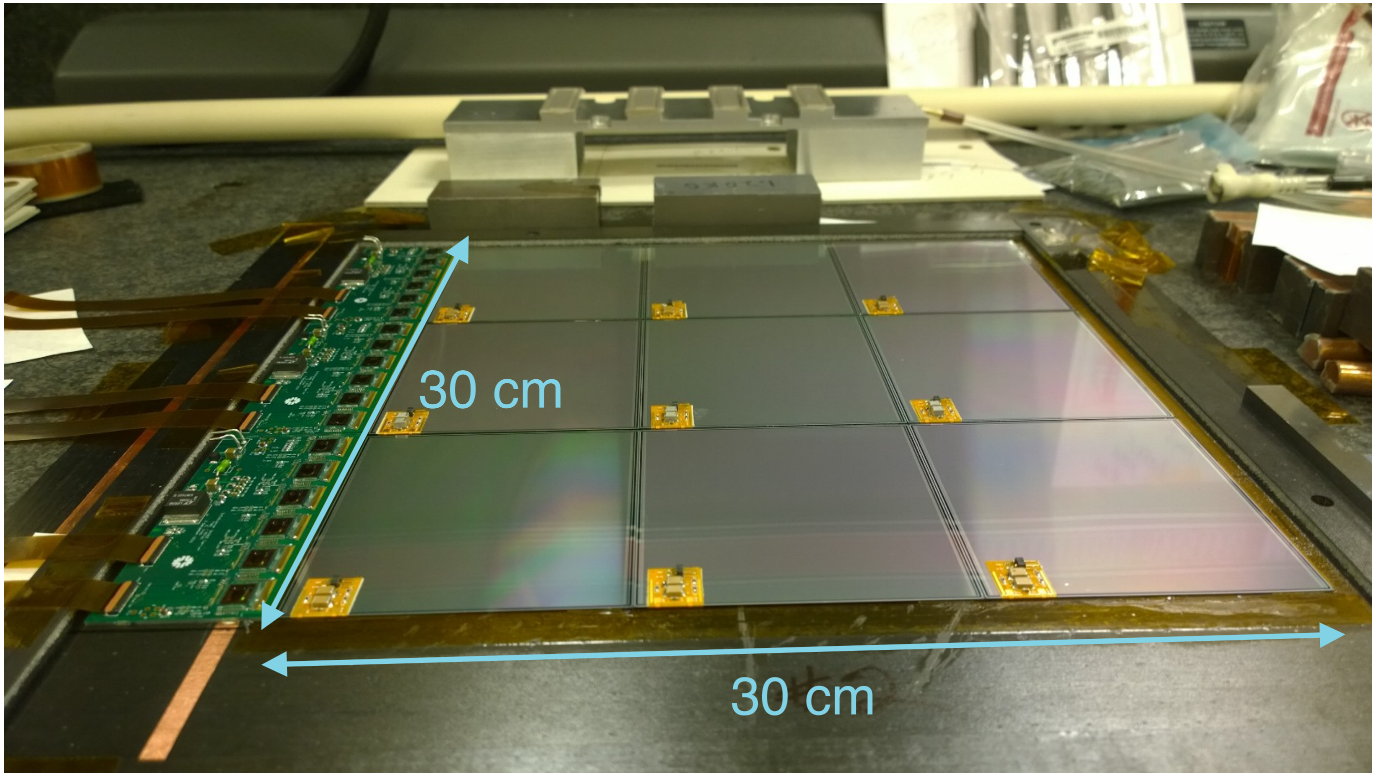
Note: we already have two quotes from companies for this design.

EMPHATIC: Magnet



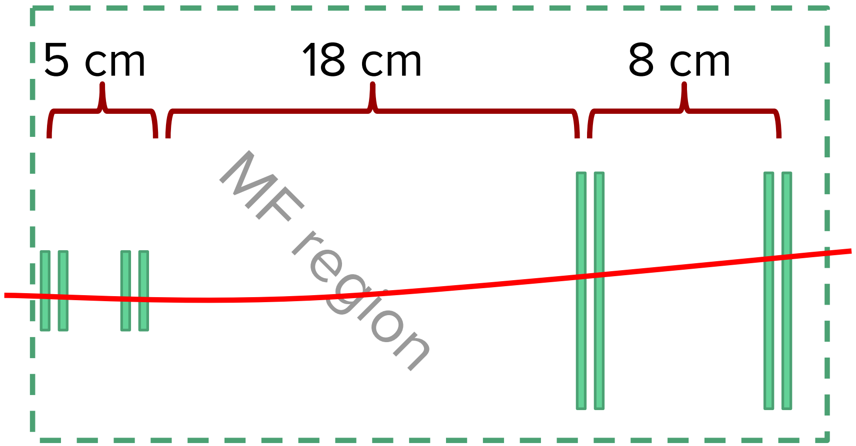
Field maps generated using COMSOL simulation.

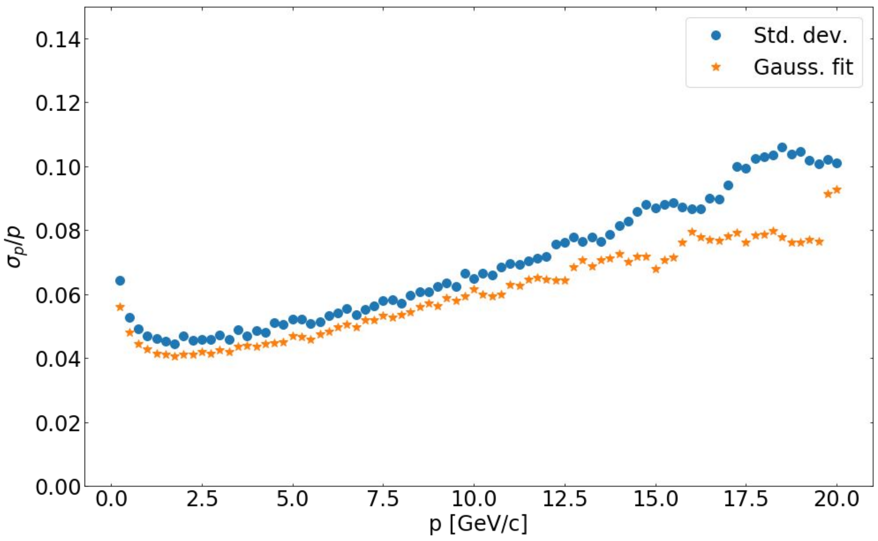
EMPHATIC: Si Strip Detectors



- Large-area SiSDs available from Fermilab SiDet. Existing DAQ system. Resolution good enough (122 μm pitch) for downstream tracking.
- Upstream tracking to be done by existing SiSDs (60 μm pitch) at the FTBF.

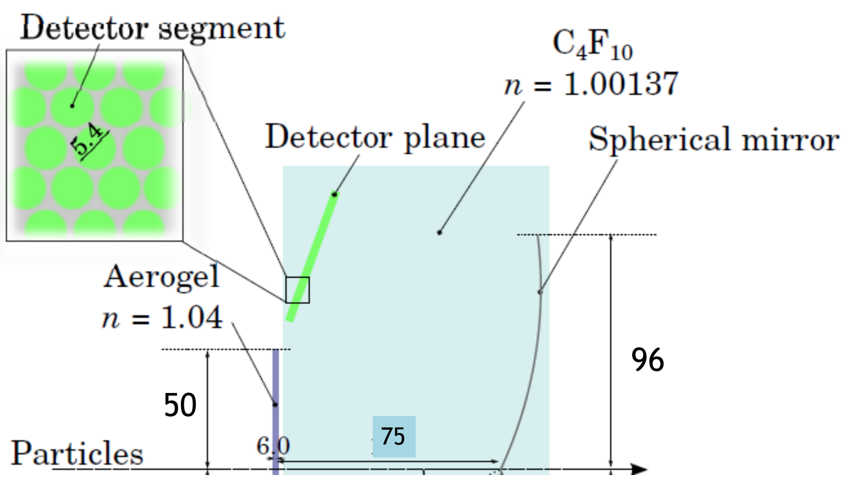
EMPHATIC: Momentum Resolution

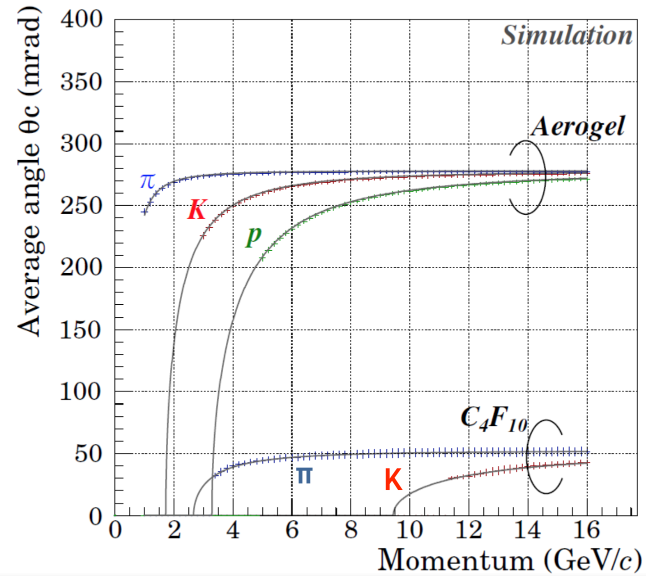




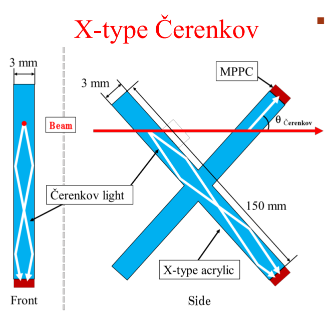
- Preliminary study based on COMSOL magnetic field maps, resolution-smeared truth, and Kalman Filter reconstruction.
- Resolution < 6% below 8 GeV/c, < 10% below 17 GeV/c.

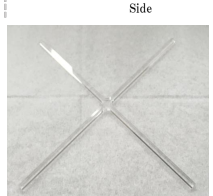
EMPHATIC: PID Detectors (from JPARC E50)





X-type Čerenkov counter

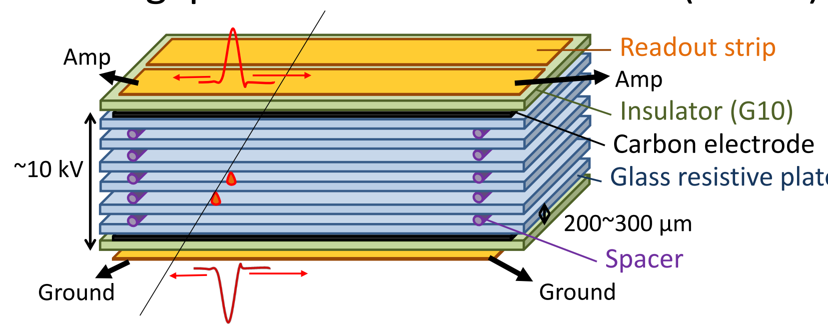




- Developing Čerenkov timing counter
  - Čerenkov lights emit in an extremely short time.
    - ✓Reduce the time spread of photons reaching to the optical sensor
    - ✓Having a fast timing response
    - ✓It has the advantage to measure the better time resolution.
  - Use "Cross shape" acrylic, called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

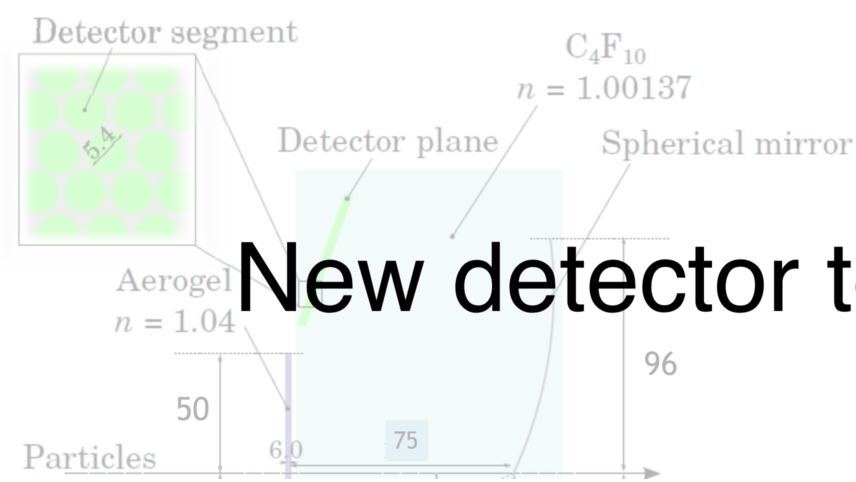


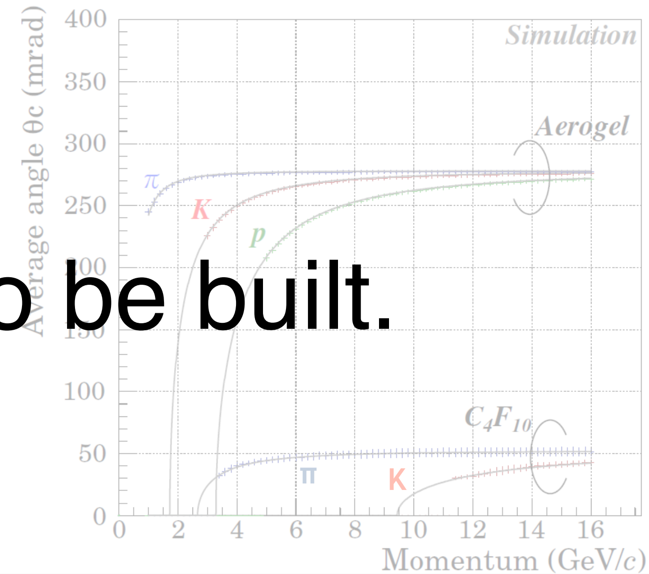
- Resistive Plate -> Avoid discharge
- Smaller gap -> Better time resolution
- Multi gap -> Higher efficiency, better time resolution

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

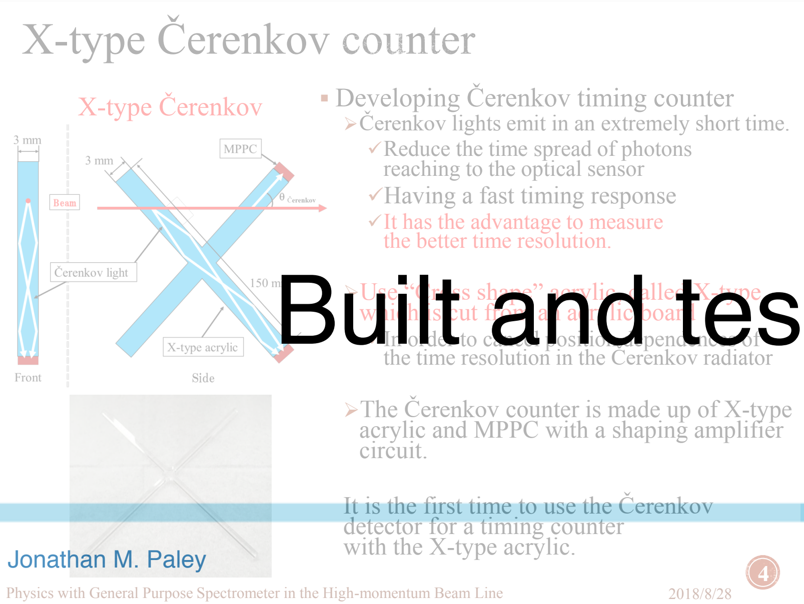
} ➡ E50 Pole face & Internal TOF detector

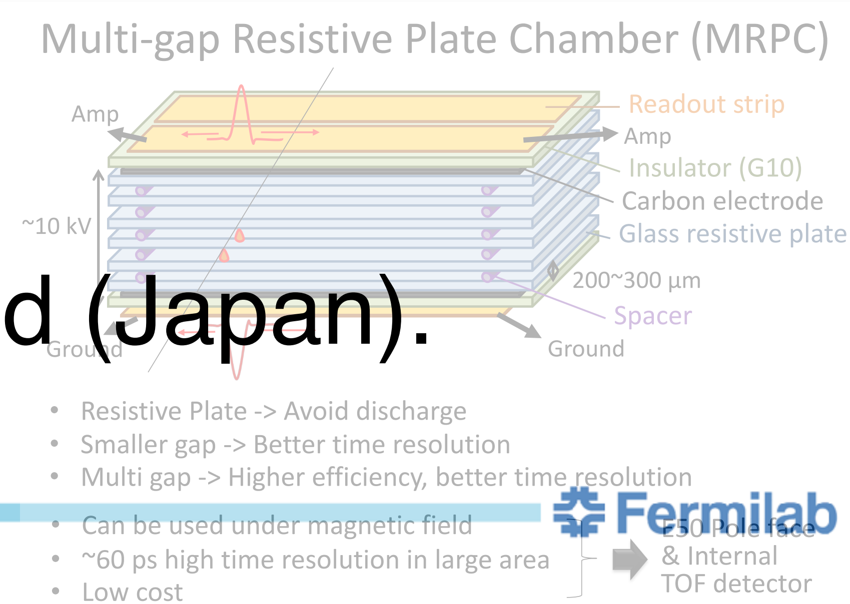
EMPHATIC: PID Detectors (from JPARC E50)





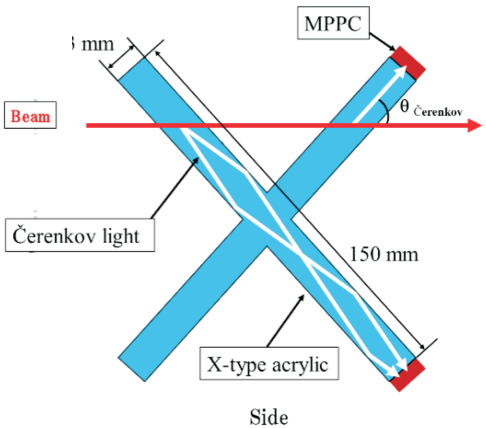
New detector to be built.

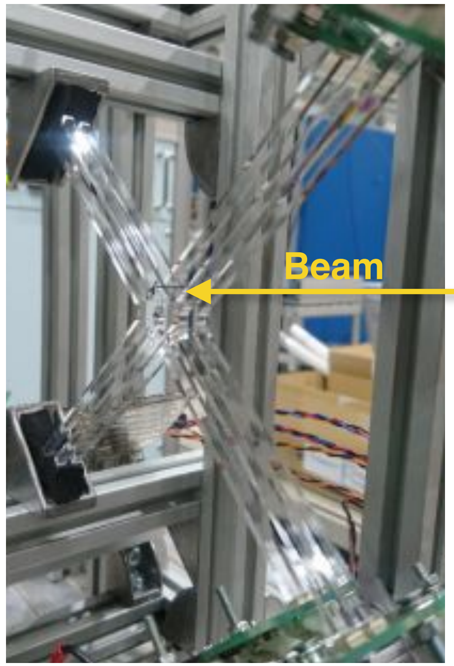


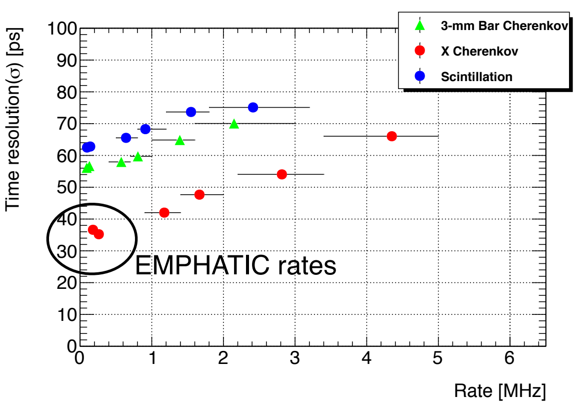


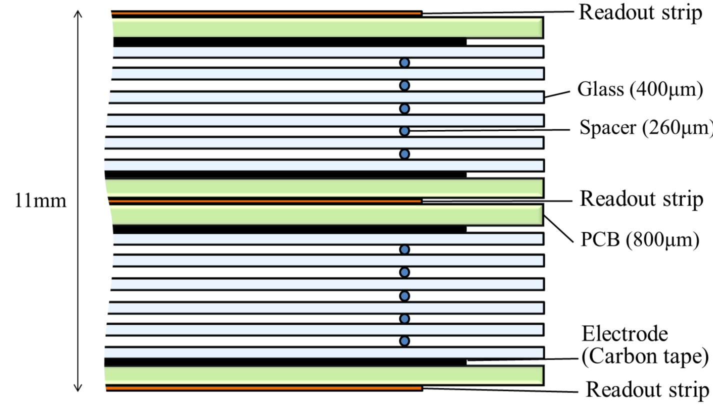
Built and tested (Japan).

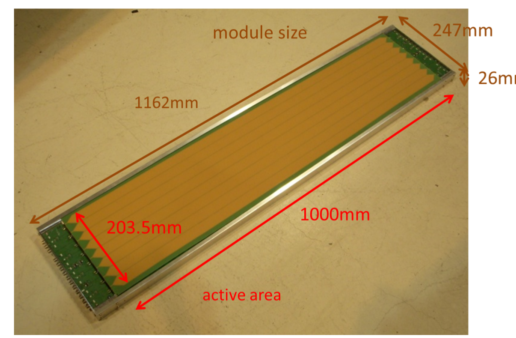
EMPHATIC: Time of Flight



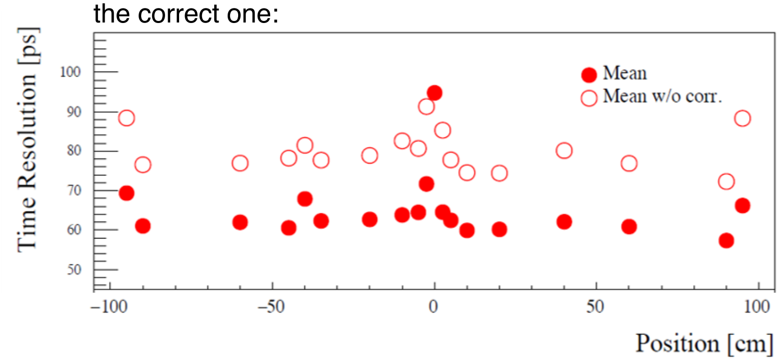




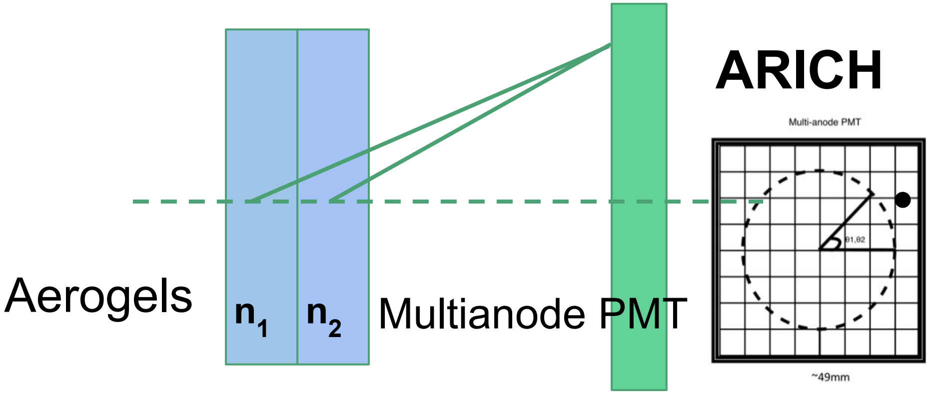


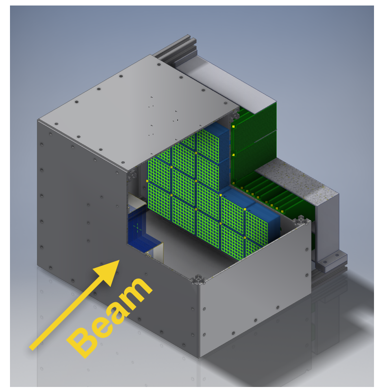


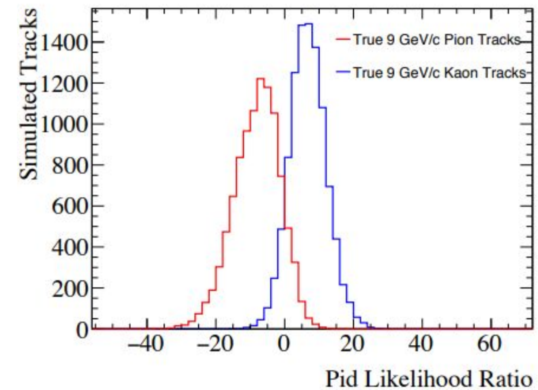
Note: Fig. 21 of the proposal has the wrong plot, this is the correct one:



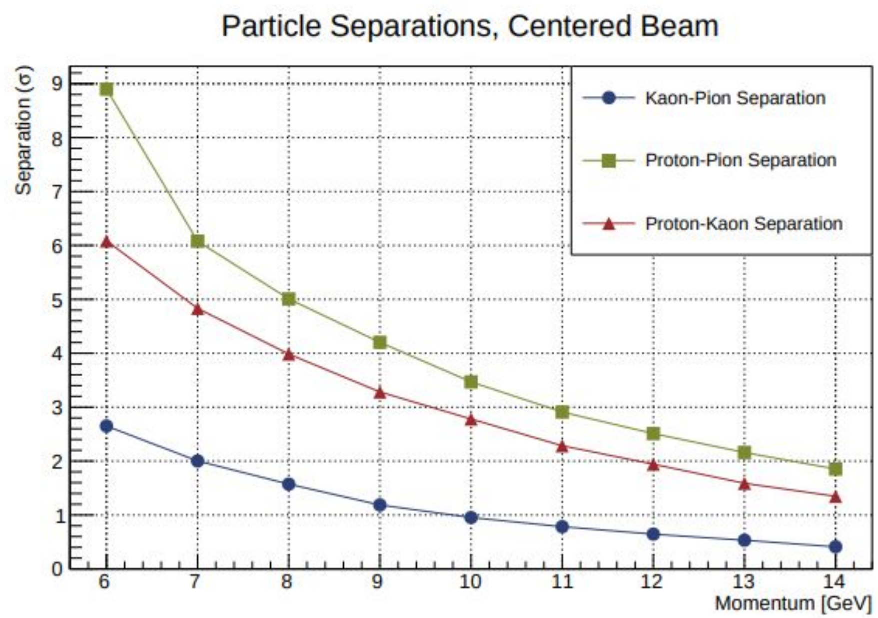
EMPHATIC: Aerogel RICH







- 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 planned for next month (August).



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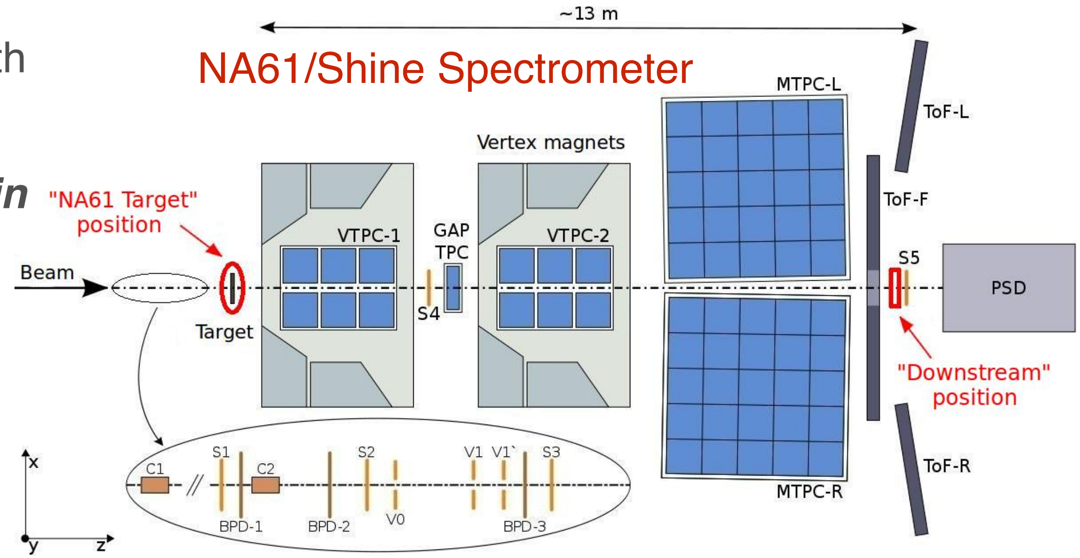
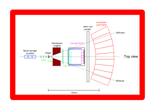
EMPHATIC: Complementarity to NA61/SHINE and MIPP

- 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

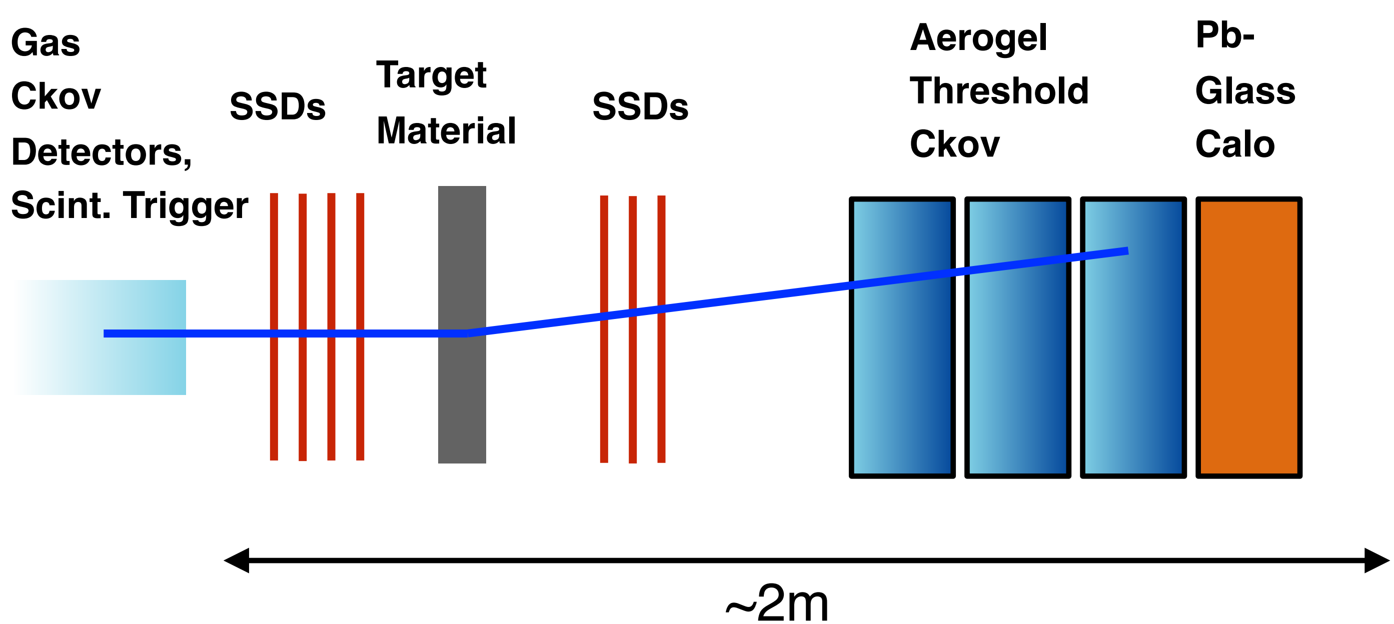
- EMPHATIC will not require an "interaction trigger" (simplifies analysis and reduces uncertainties).
- EMPHATIC needs to operate 3-4 weeks/ year over 3 years.
- ***Compact spectrometer = low cost.***

- 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.

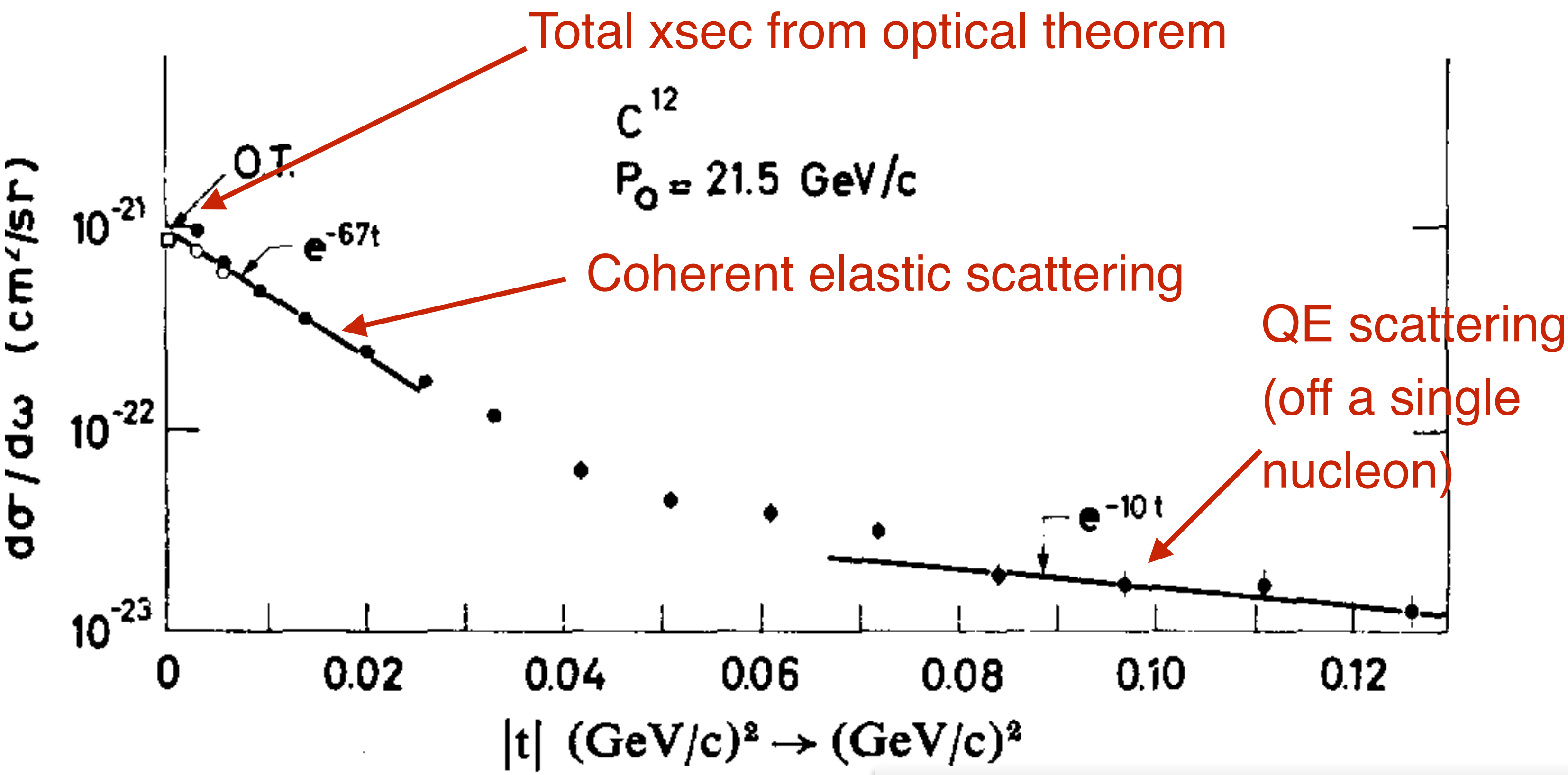
EMPHATIC: Initial beam test from Jan. 10-23, 2018

- 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)

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

EMPHATIC: Thin-target data w/ silicon tracking only

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

Systematic uncertainties

Strategy:

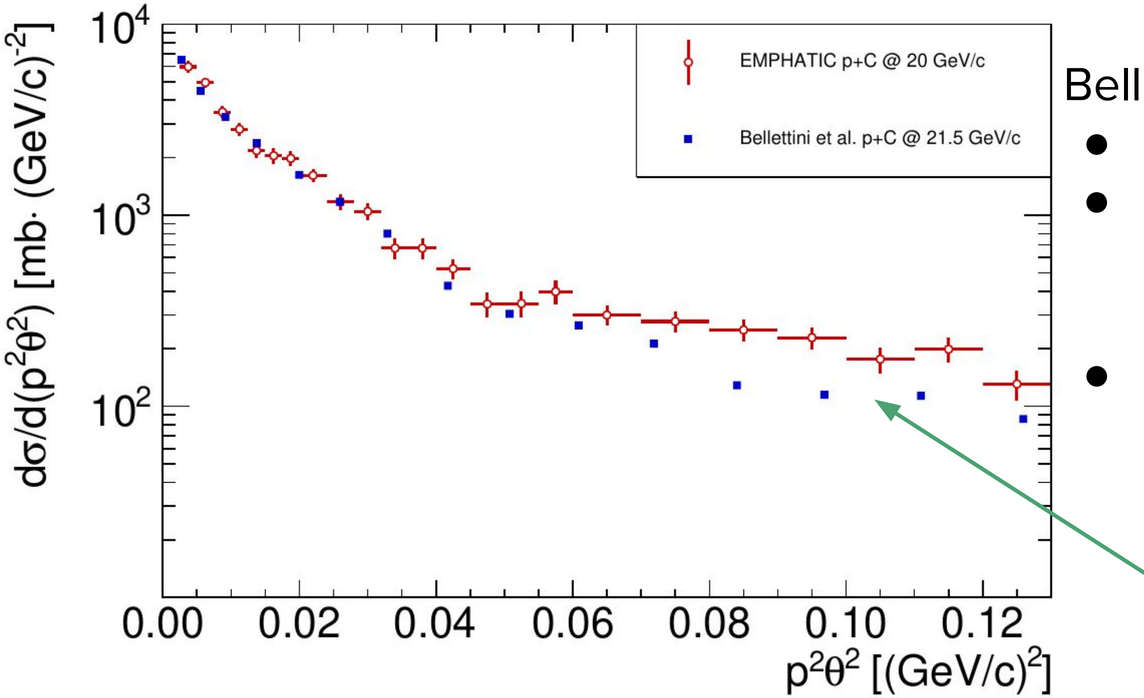
- Use data to estimate systematics
- If not possible use MC ➔ largest difference between models

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%**

Fermilab

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

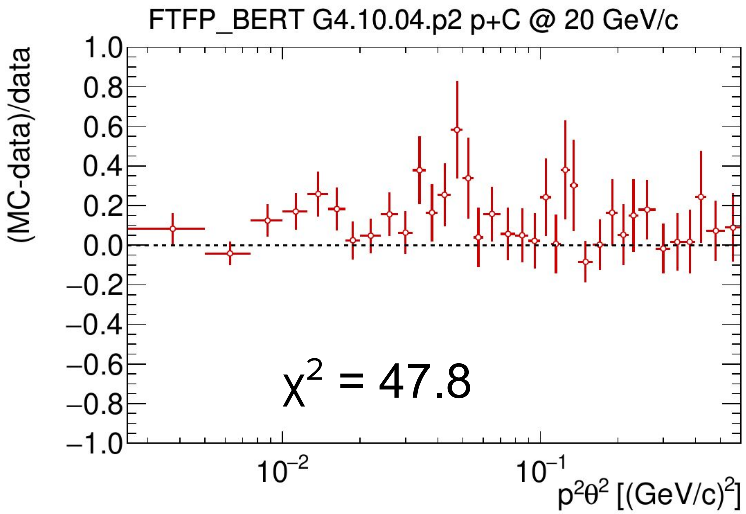
EMPHATIC and Bellettini do not measure the same thing!

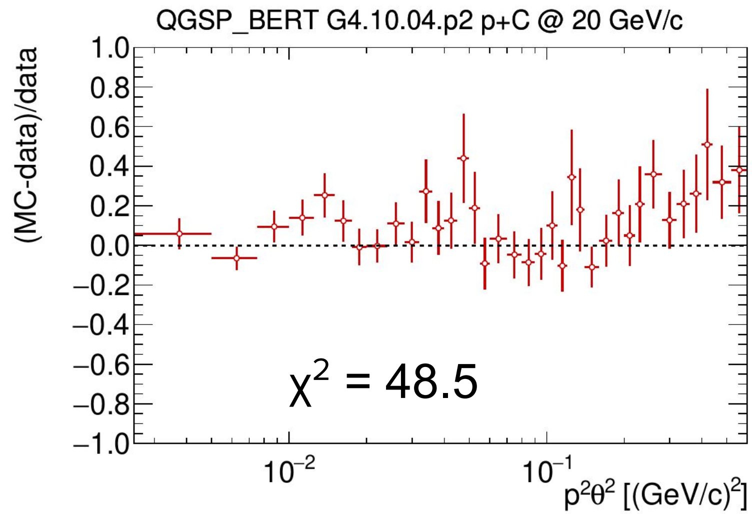
- EMPHATIC includes resonance production

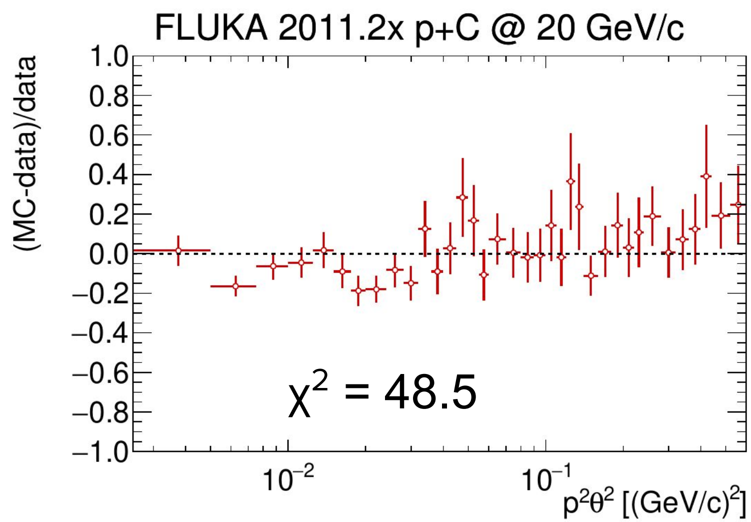
Bellettini et al., Nucl.Phys. 79 (1966) 609-624

EMPHATIC: Thin-target data w/ silicon tracking only

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



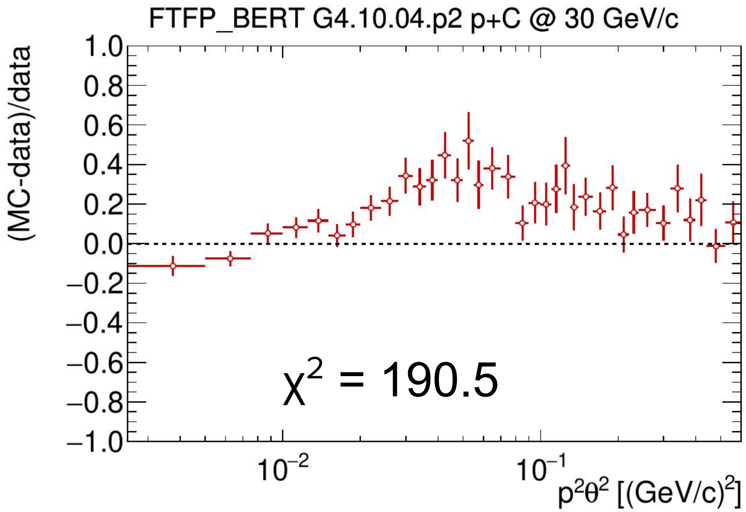


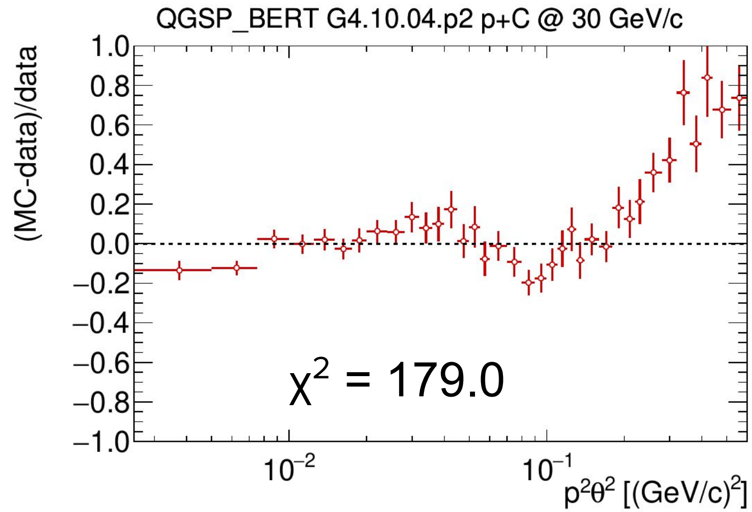


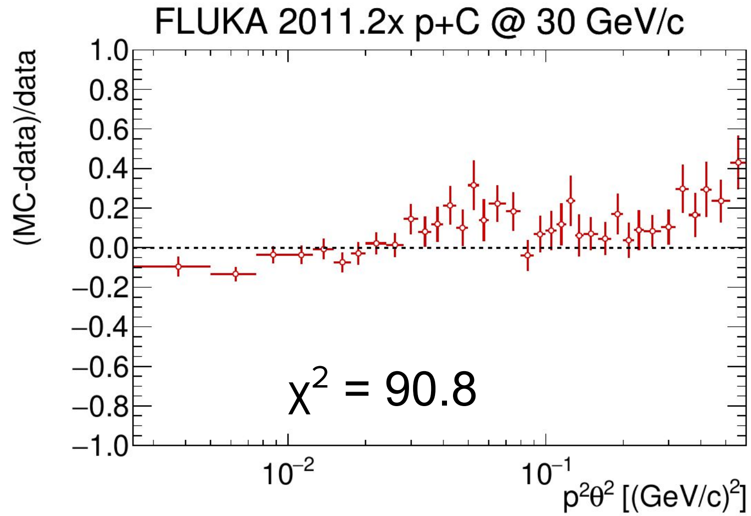
dof = 37

EMPHATIC: Thin-target data w/ silicon tracking only

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







dof = 37

EMPHATIC: Thin-target data w/ silicon tracking only

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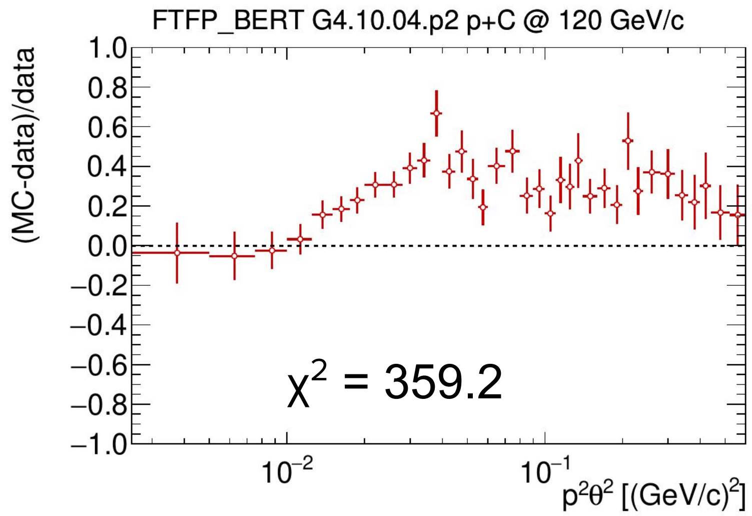

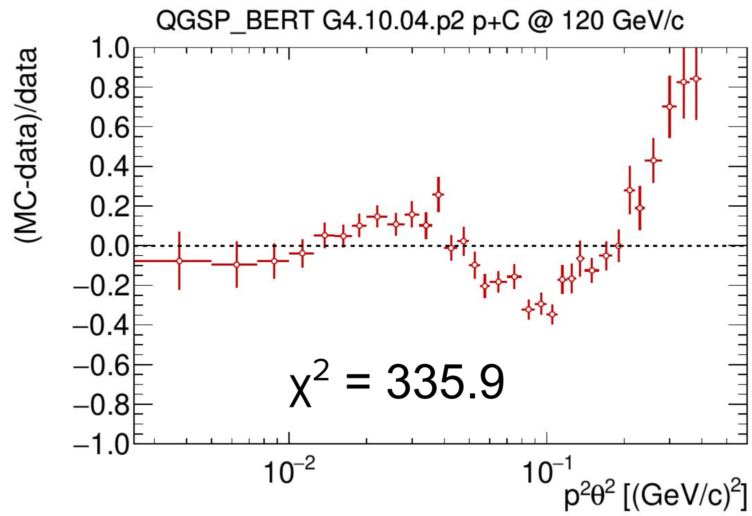

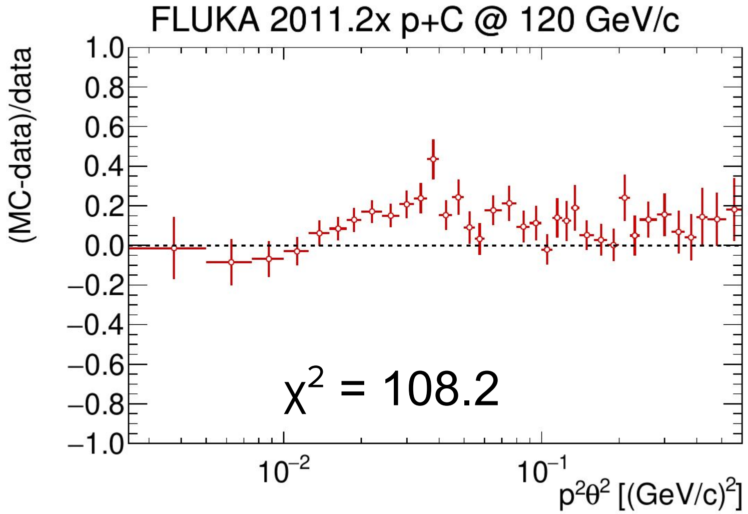

dof = 37

EMPHATIC: Thin-target data w/ silicon tracking only

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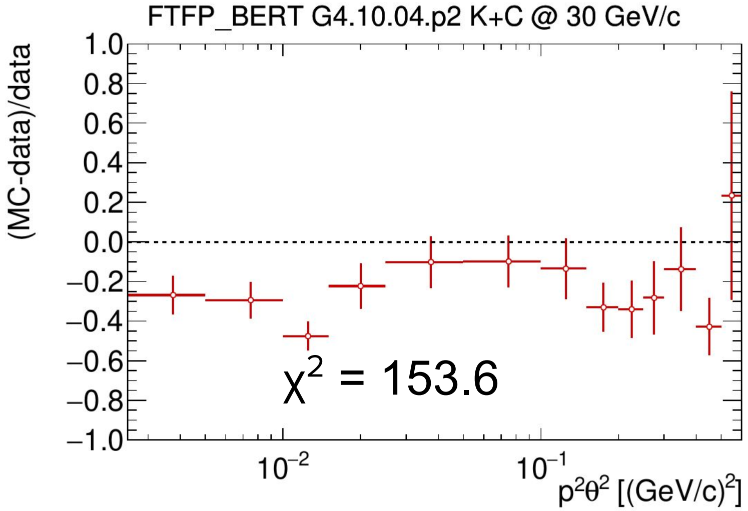
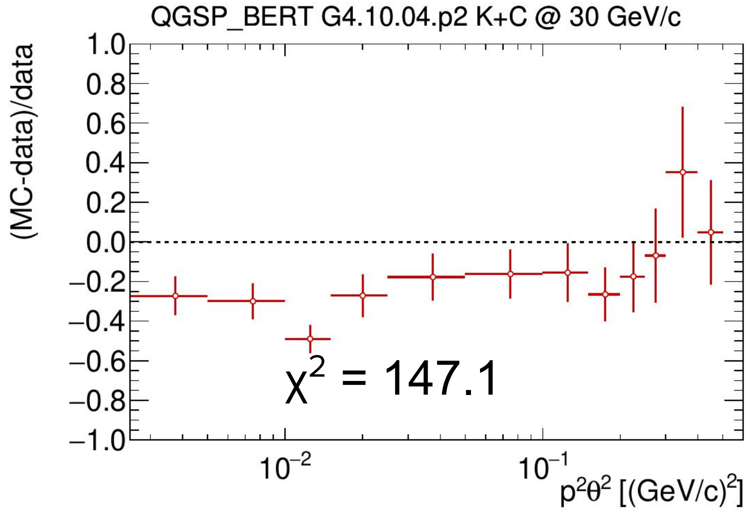




First measurement of this type for kaons!

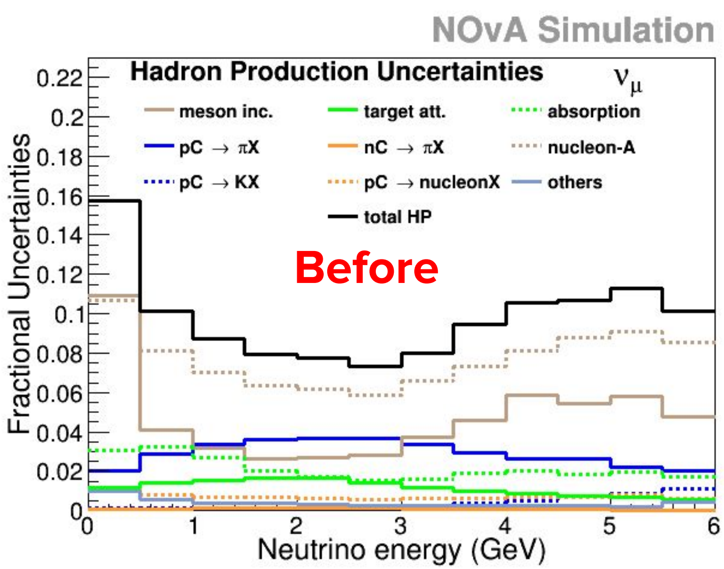
Simulations seem to underpredict by ~20%.

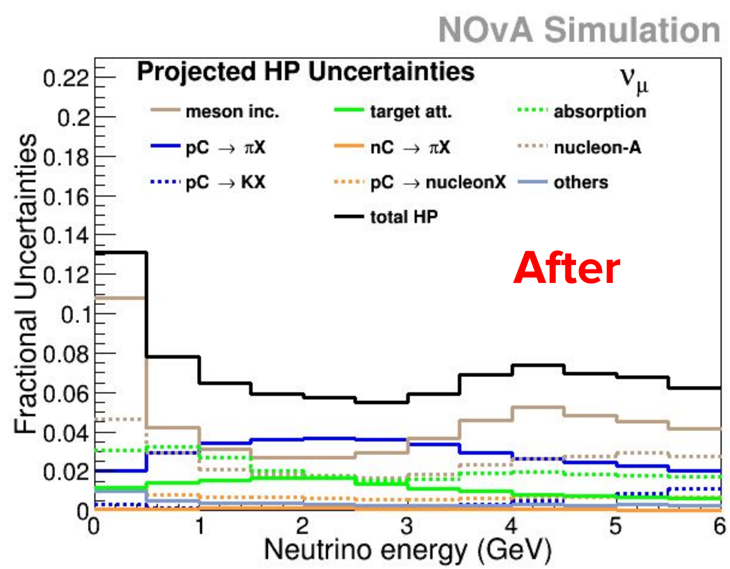
EMPHATIC: Thin-target data w/ silicon tracking only

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

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





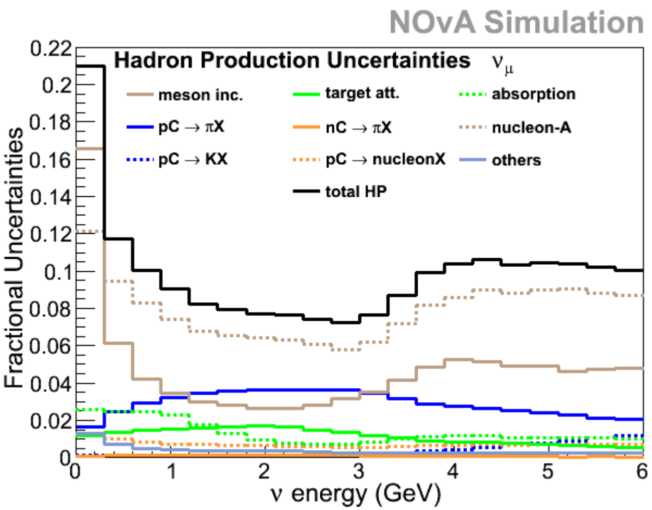
A similar reduction in flux uncertainties is expected for DUNE…

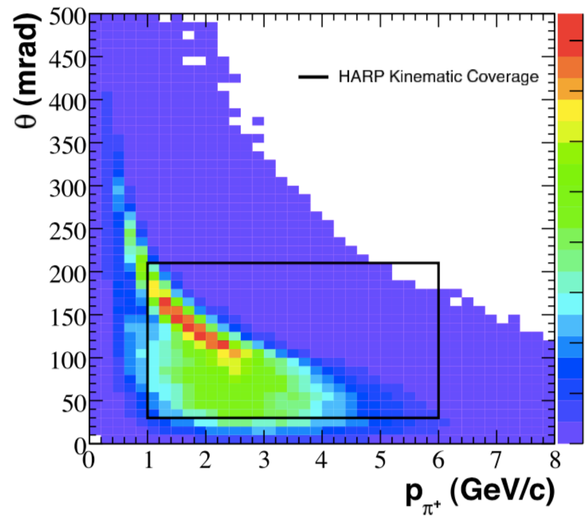
Summary

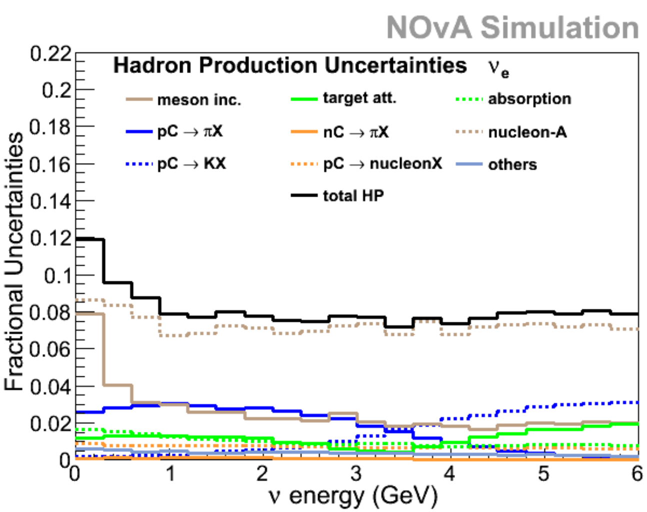
- New hadron production data are needed if we want to reduce neutrino flux uncertainties.
- EMPHATIC offers a ***cost-effective*** approach to reducing the hadron production uncertainties by at least a factor of 2.
- EMPHATIC is ***complementary*** to the existing efforts by NA61 to collect important hadron production data for improved flux predictions.
- EMPHATIC is a strong ***international collaboration*** with a mature design of the spectrometer, cost estimates and run plans for 2020-22.
- Analysis of data collected during an engineering run in January 2018 is complete, publication draft is under collaboration review. Results will have an immediate impact on flux predictions.
- Critical detectors from Canada and Japan ***are funded and will be ready for the 2020 run***. It is important to get funding for US contributions ASAP.
- We kindly request Stage 1 approval from the PAC.

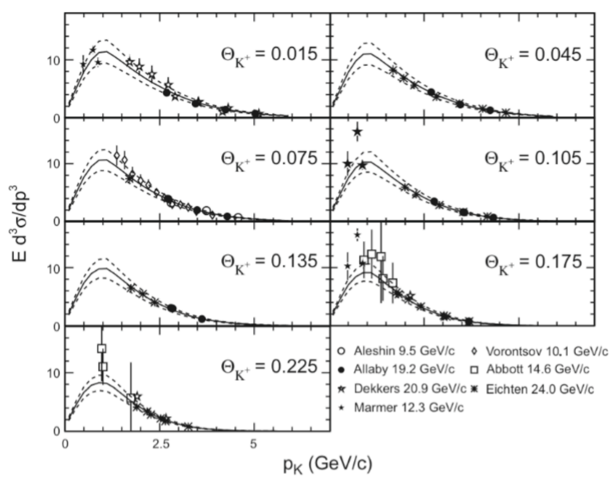
BACKUP

NuMI and Booster Flux Uncertainties







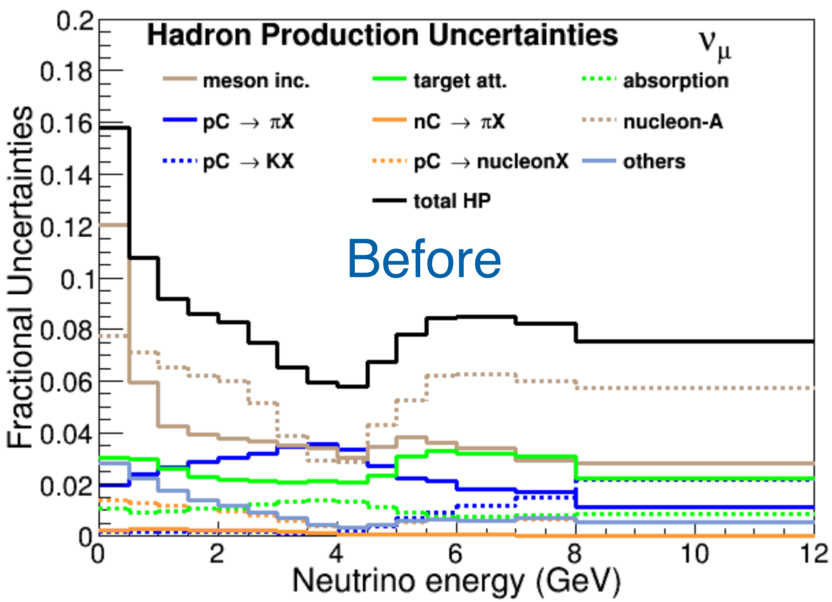


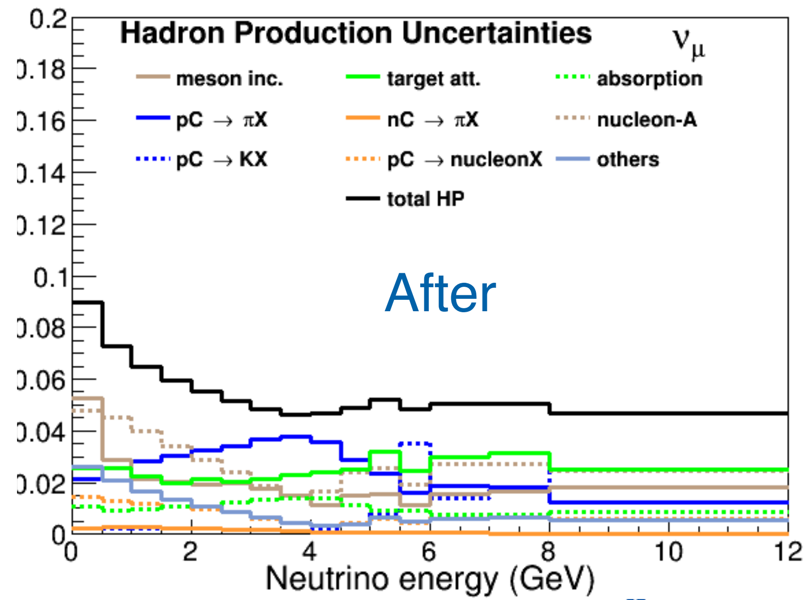
- **Reduction of flux uncertainties improves the impact that cross section measurements by NOvA, MINERvA and SBN will have on the global effort to improve ν-A models.**

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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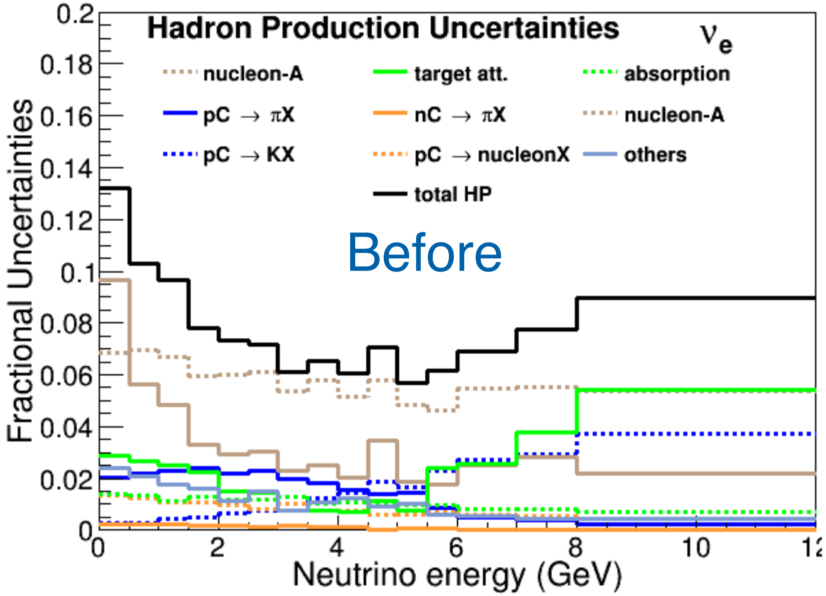
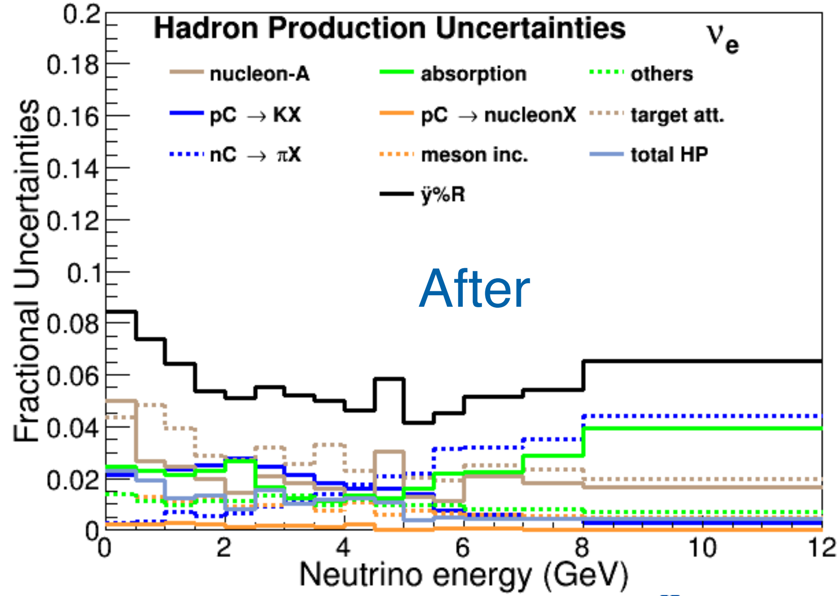
Not covered by current data

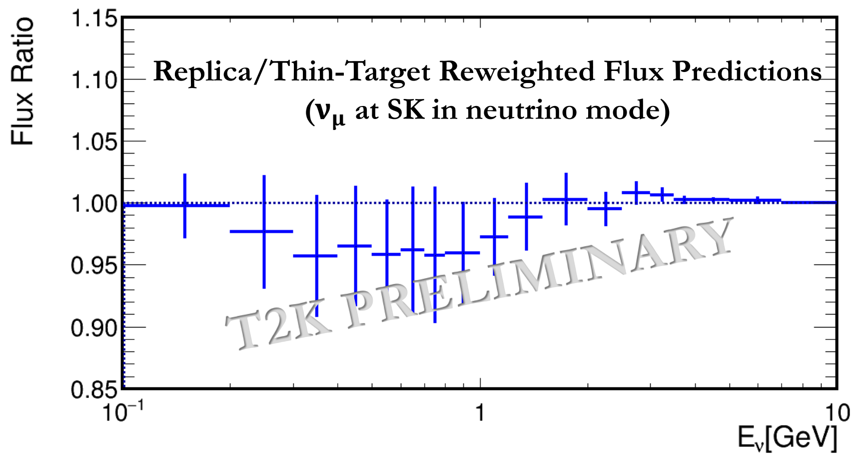


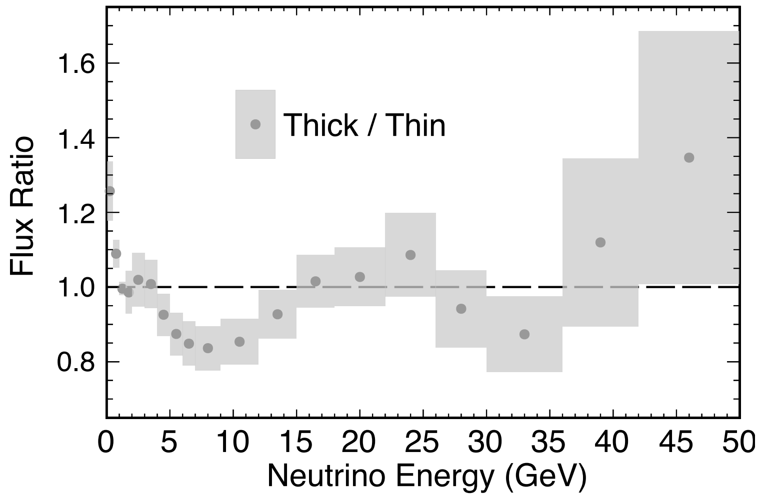


Note: flux uncertainties determined by EMPHATIC, not DUNE

DUNE Flux Uncertainties - Can we do better?

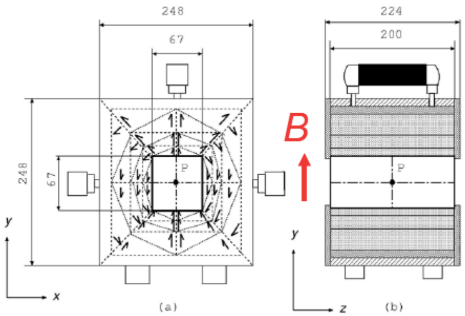
- NA61 proposes to measure the hadron yield off the LBNF target. Such a measurement should be at the ~3% level.
- However, there are many interactions outside of the target that result in neutrinos see by our detectors.
- In T2K, ~50% of all wrong-sign neutrinos come from interactions outside of the 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"…



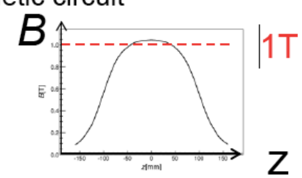


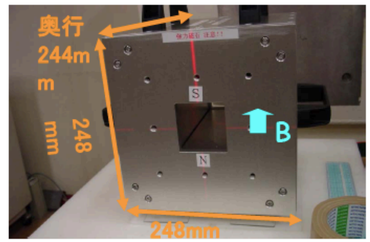
EMPHATIC: Magnet Options for 2020 Run

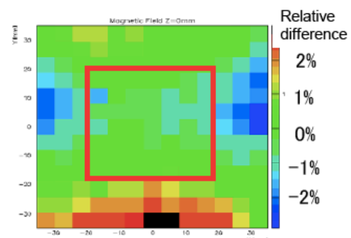
Compact permanent magnet



Halbach-type magnetic circuit







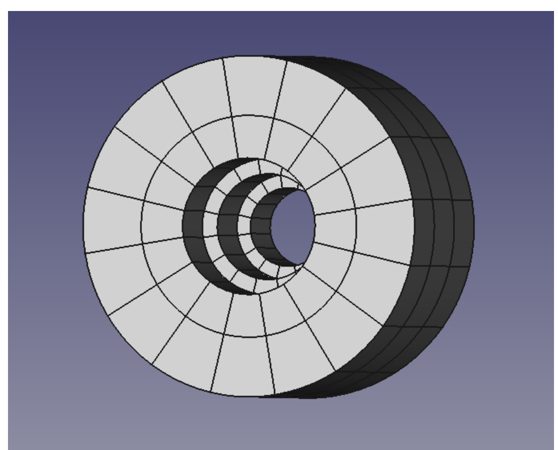
Magnetic field distribution (z=0)

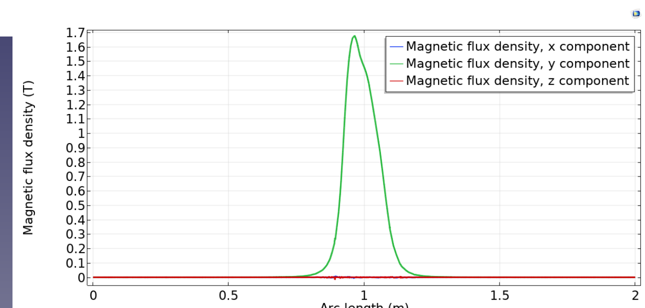
Option 1

Small aperture magnet available to borrow from Toho University, Japan.

Option 2

Small aperture magnet could be purchased. Cost under investigation.





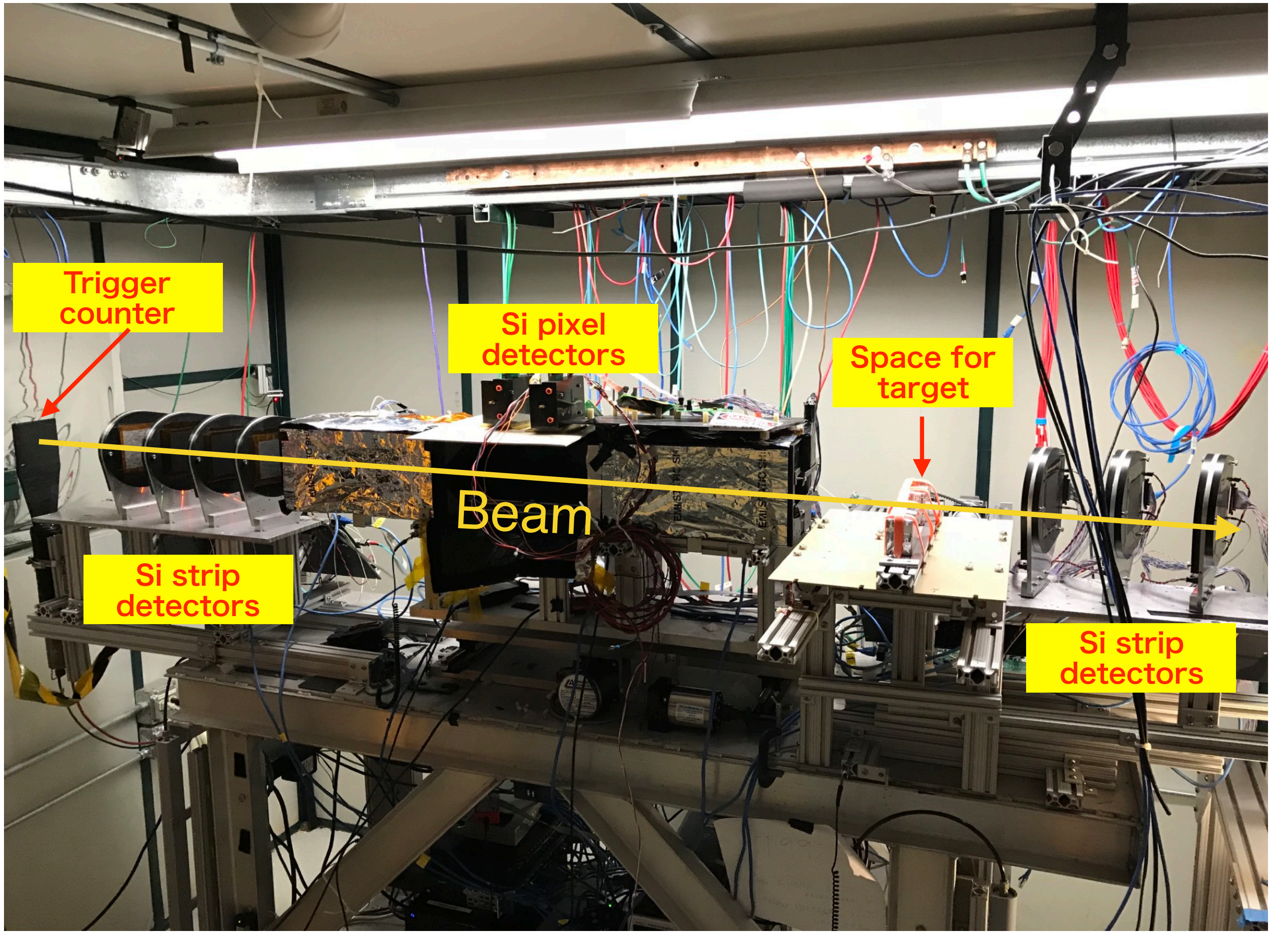
150 mrad acceptance

Fermilab

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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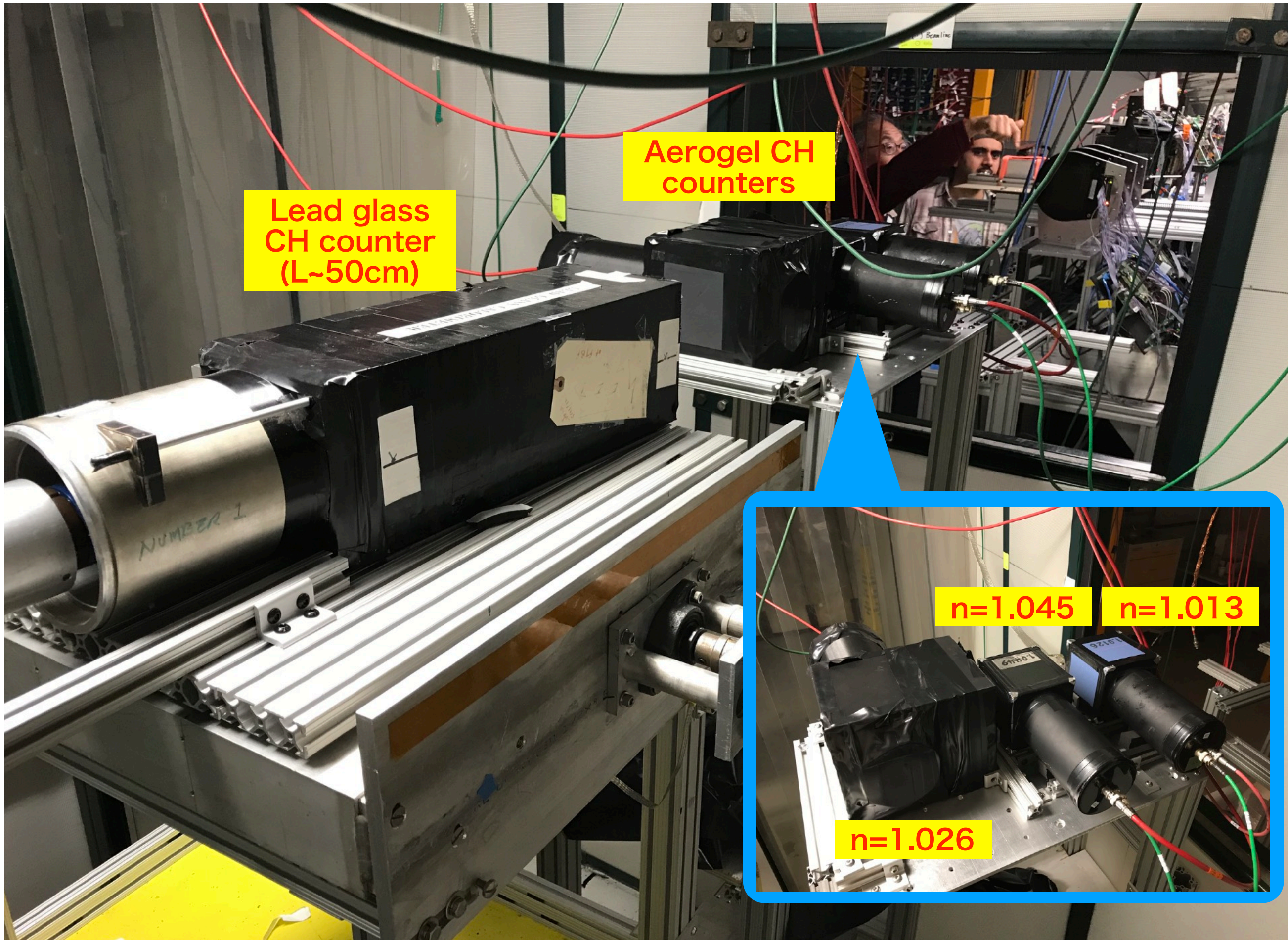
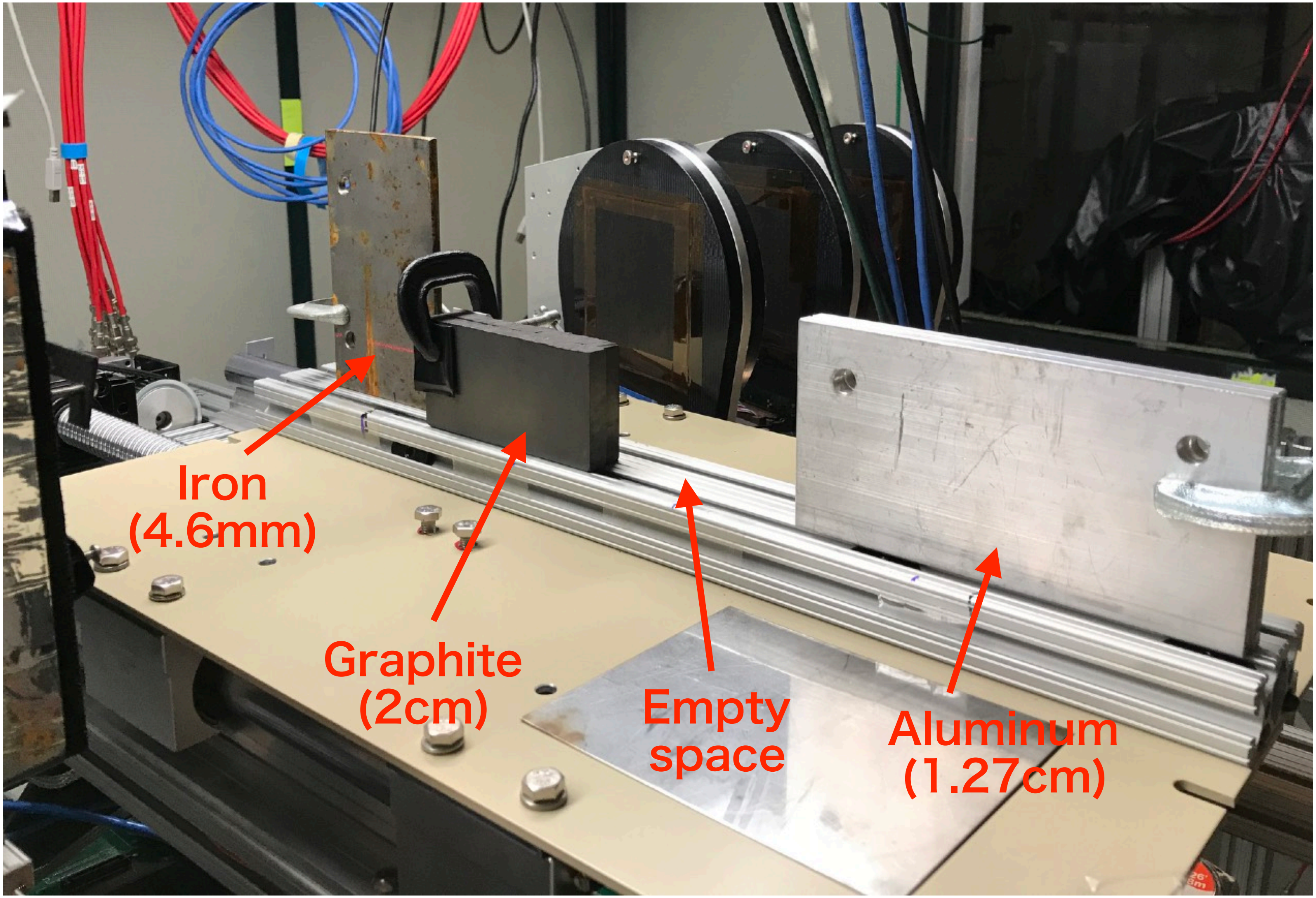
MT6.1-B



EMPHATIC: Thin-target data w/ silicon tracking only



Fermilab

EMPHATIC: Thin-target data w/ silicon tracking only

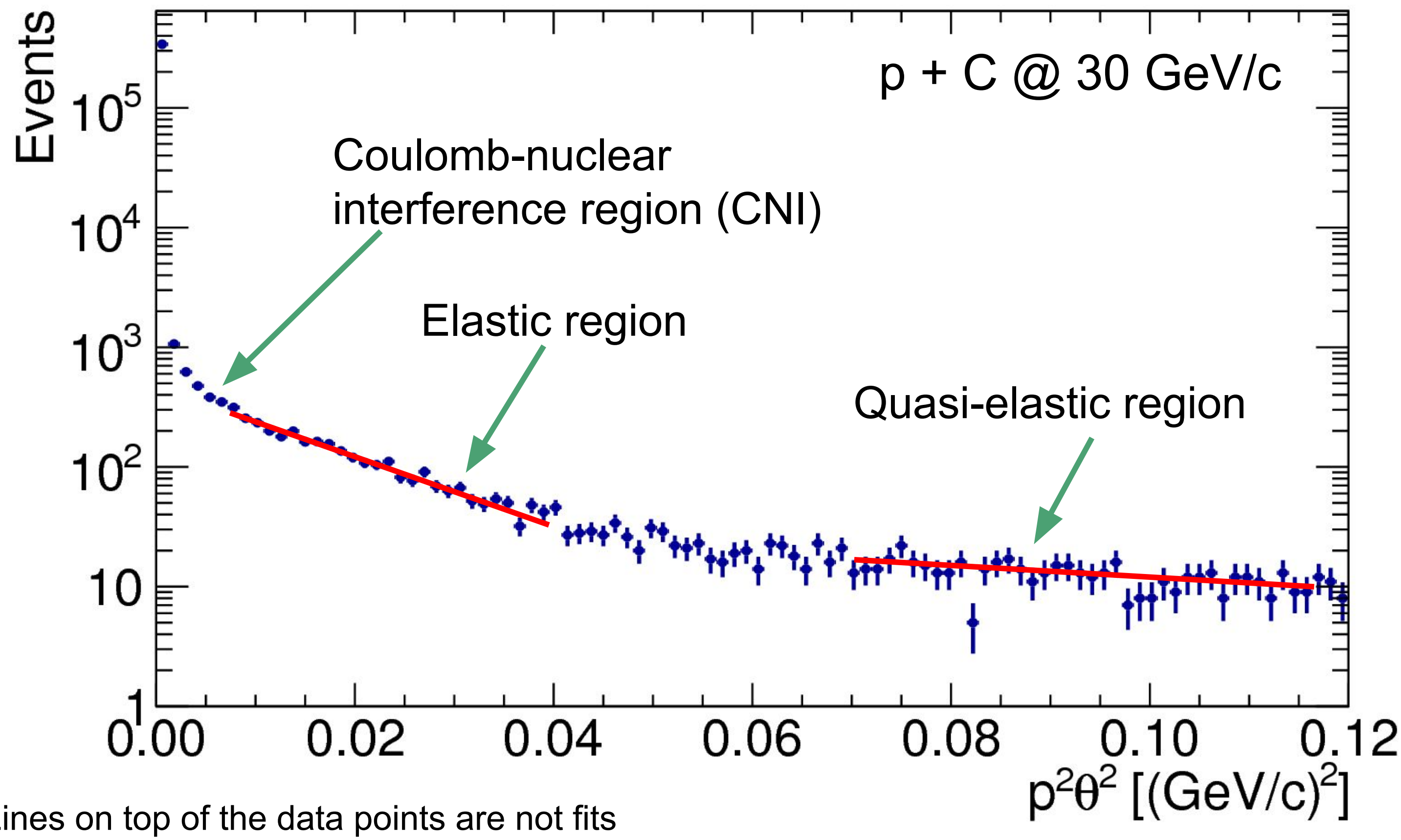
Number of min. bias triggers

	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%

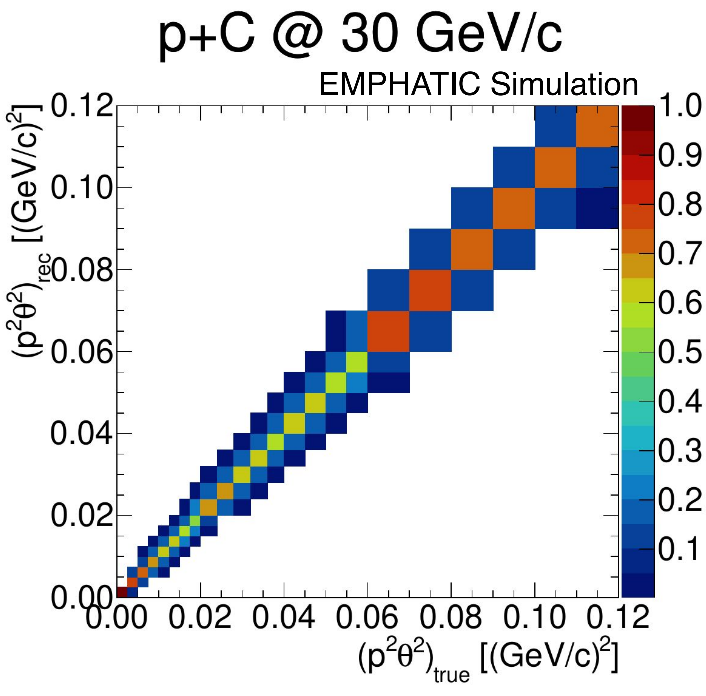
EMPHATIC: Thin-target data w/ silicon tracking only

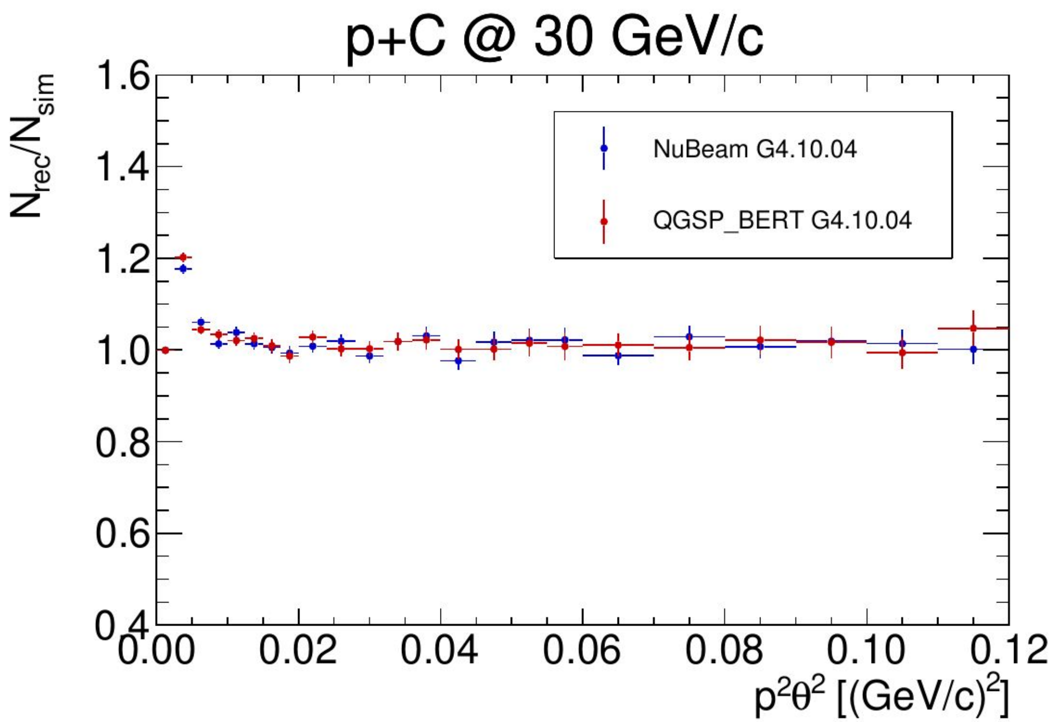
4-momentum transfer (raw data)



*Lines on top of the data points are not fits

EMPHATIC: Thin-target data w/ silicon tracking only

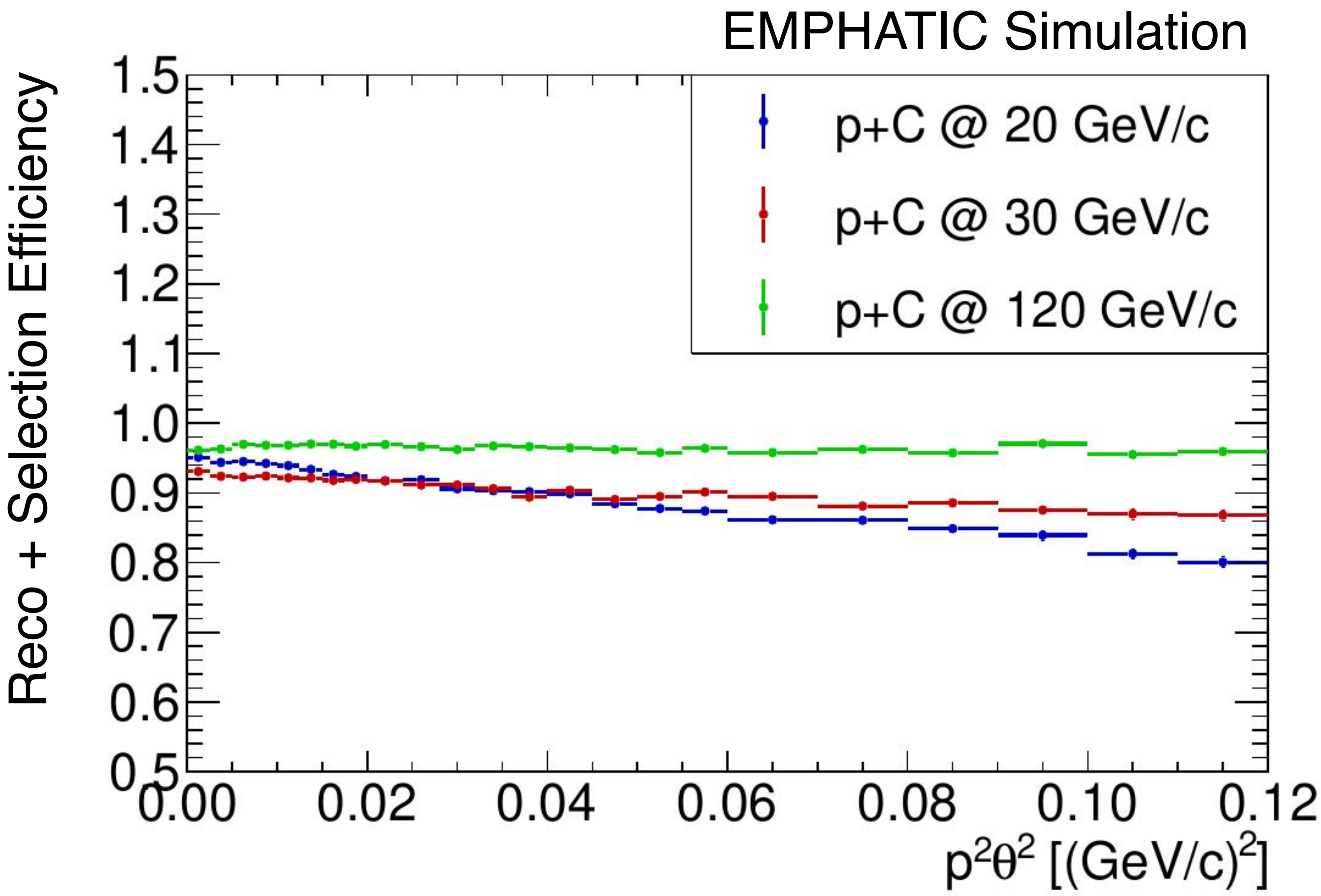




Bin migration. Plan to forego unfolding, and simply exclude first few bins from the analysis.

Fermilab

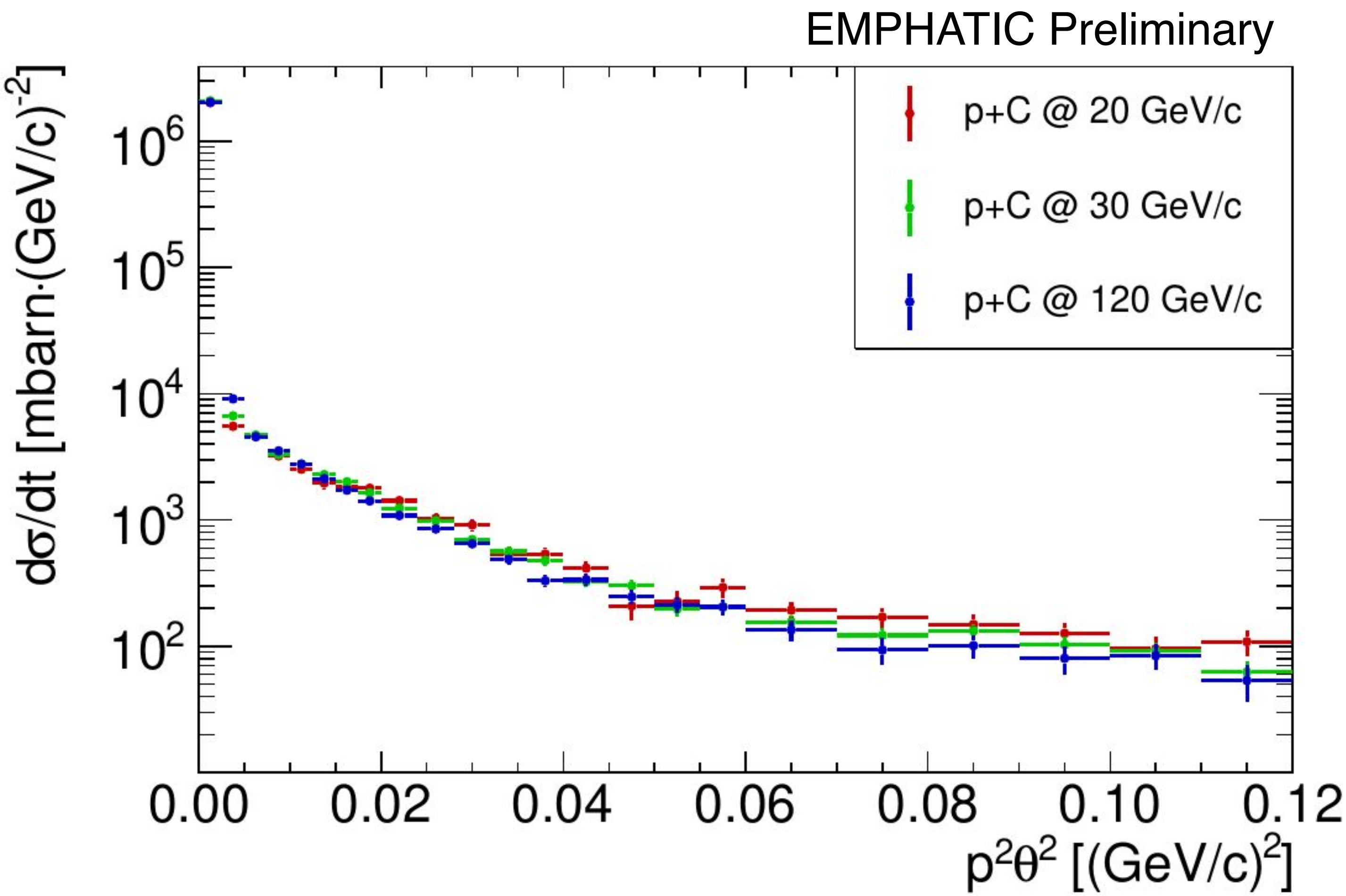
EMPHATIC: Thin-target data w/ silicon tracking only



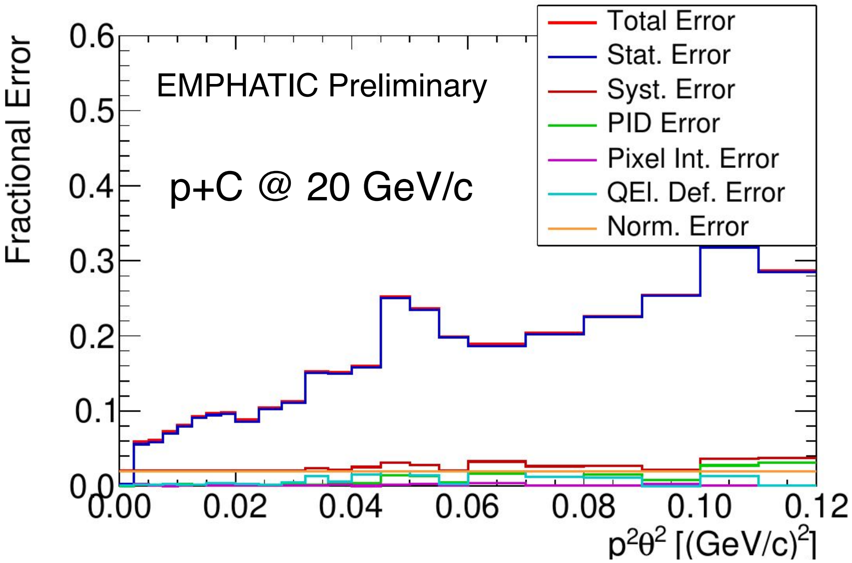
Comparisons between different simulations and models will be used to estimate an uncertainty.

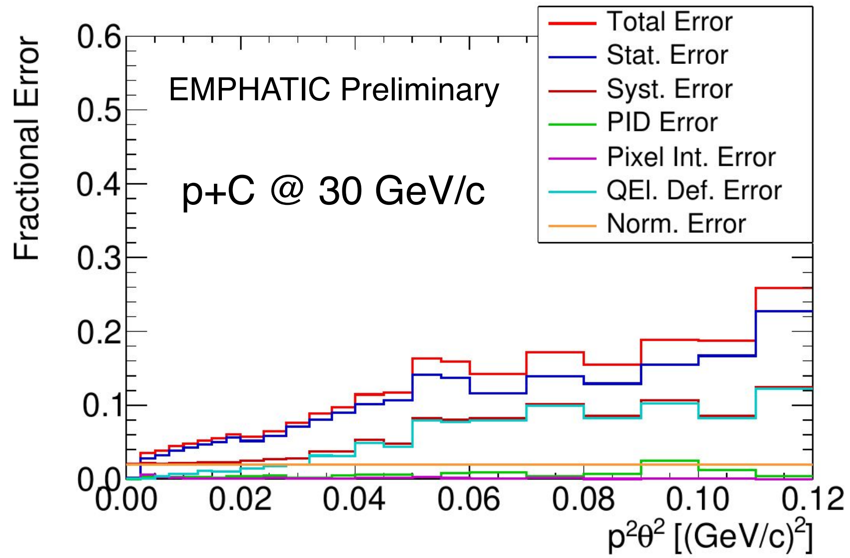
EMPHATIC: Thin-target data w/ silicon tracking only

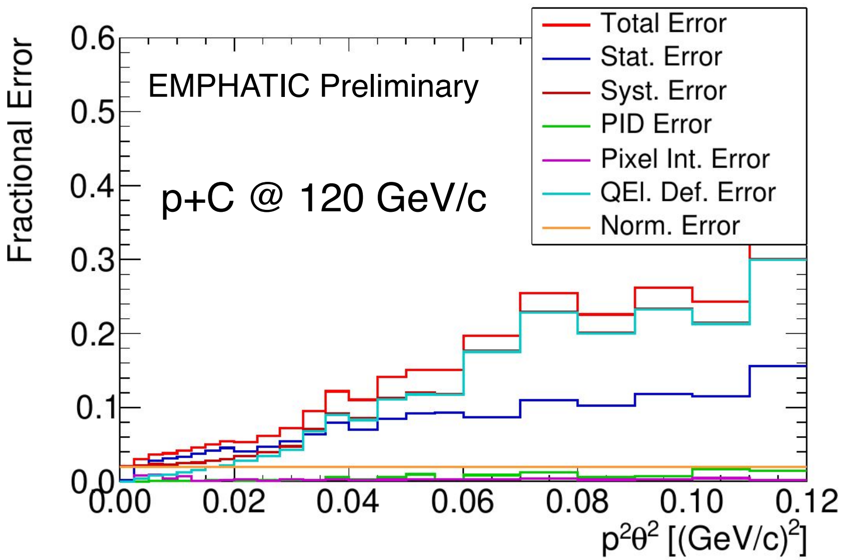
After applying efficiency correction to the data…



EMPHATIC: Thin-target data w/ silicon tracking only



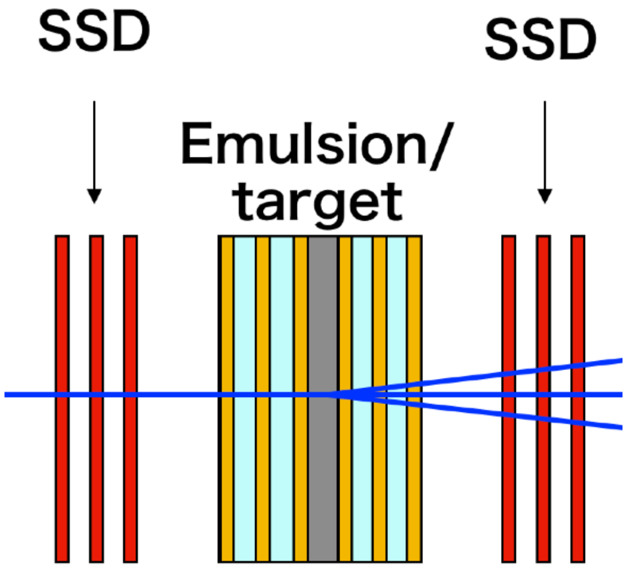




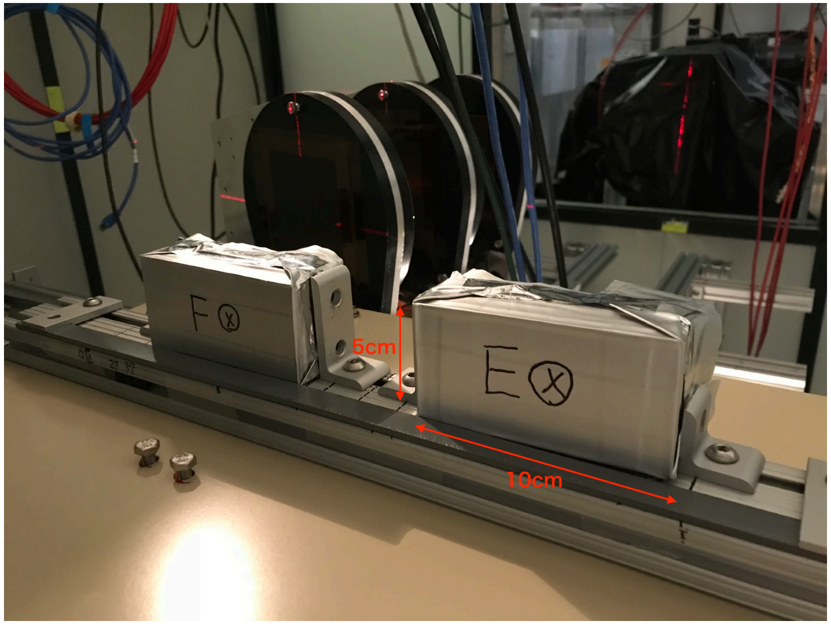
- PID Error: uncertainty on purity of beam PID.
- Pixel Int. Error: uncertainty on modeling scattering in pixel telescope.
- QEl. Def. Error: uncertainty on model-dependent correction of pion production to quasi-elastic regime. Needed only measurement of total cross section, where low "t" bins dominate.
- Norm. Error: uncertainty on density of target.

EMPHATIC: Emulsion Bricks

- 1 cm-thick graphite target
- club sandwich of 6 layers of emulsion films and 4 layers of low-density spacer material (<0.1 g/cm^3)
- expected angular resolution within emulsion brick is < 0.5 mrad
- A remotely-controlled motion table moved the emulsion bricks a few mm across the beam in-between spills.
- 3 (upstream) and 4 (downstream) SSD detectors will provide beam-track matching and timing information
- Exposed 12 bricks to O(300k) beam particles across the surface. 10 bricks were exposed to 31 GeV/c beam, 2 bricks exposed to 120 GeV/c protons.



Emulsion/Target Assembly

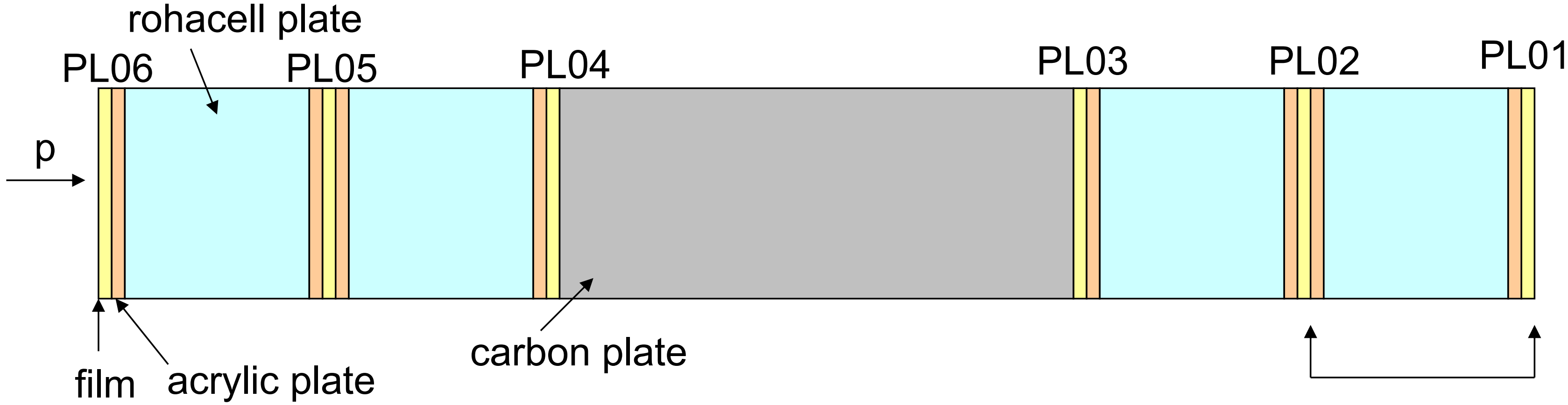


EMPHATIC: Emulsion Bricks

- An emulsion-handling facility (dark room) was set up in Lab 6 at Fermilab. Used for packaging the emulsion bricks and development of the emulsion films after beam exposure.

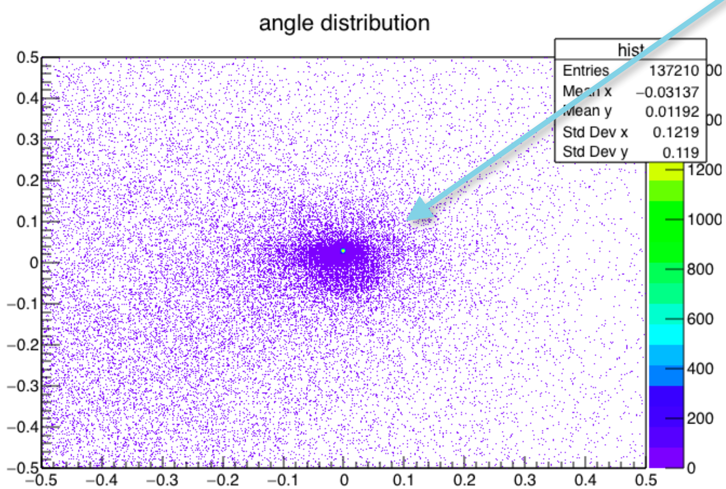
- All films were processed and have been sent back to Nagoya University to be scanned and processed (happening now).

EMPHATIC: Emulsion Brick Gap Corrections

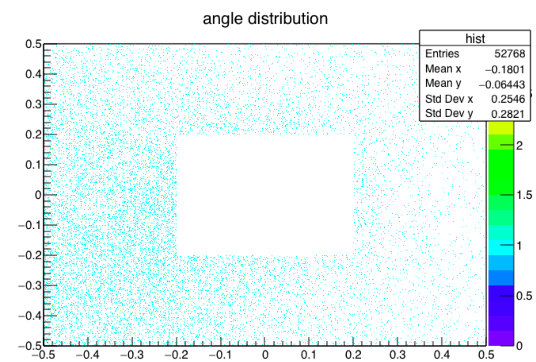


↓ PL01 & PL02 angle distribution

scanned & digitized emulsion film data



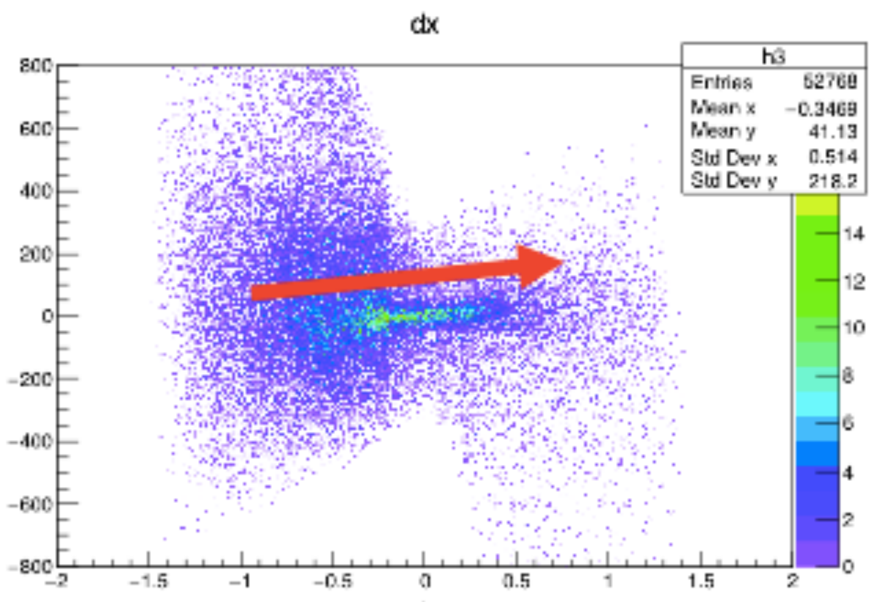
Using cosmic muon
remove beam events

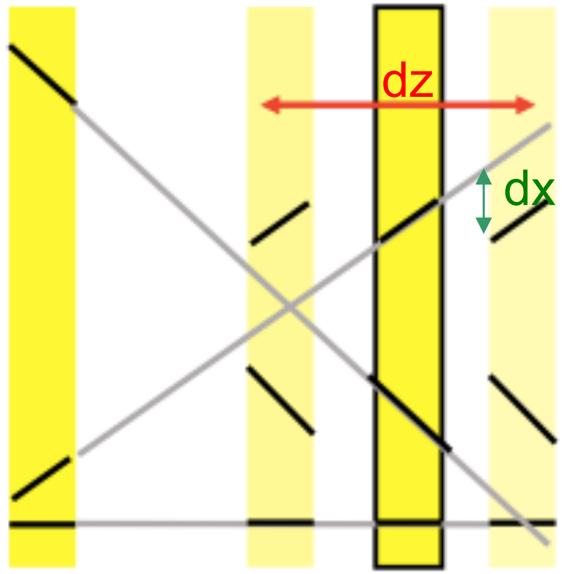


ax<-0.2 or 0.2<ax or ay<-0.2 or 0.2 <ay

Analysis by T. Sugimoto (Kobe U.), and T. Fukuda (Nagoya U.)

EMPHATIC: Emulsion Analysis

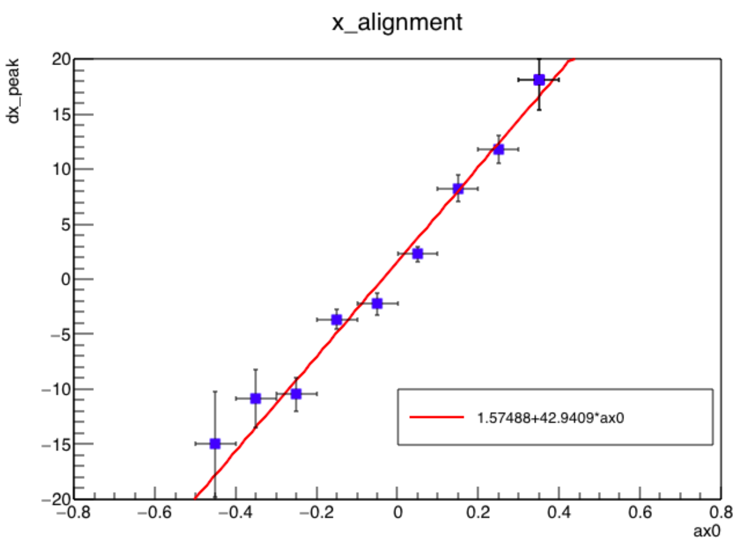


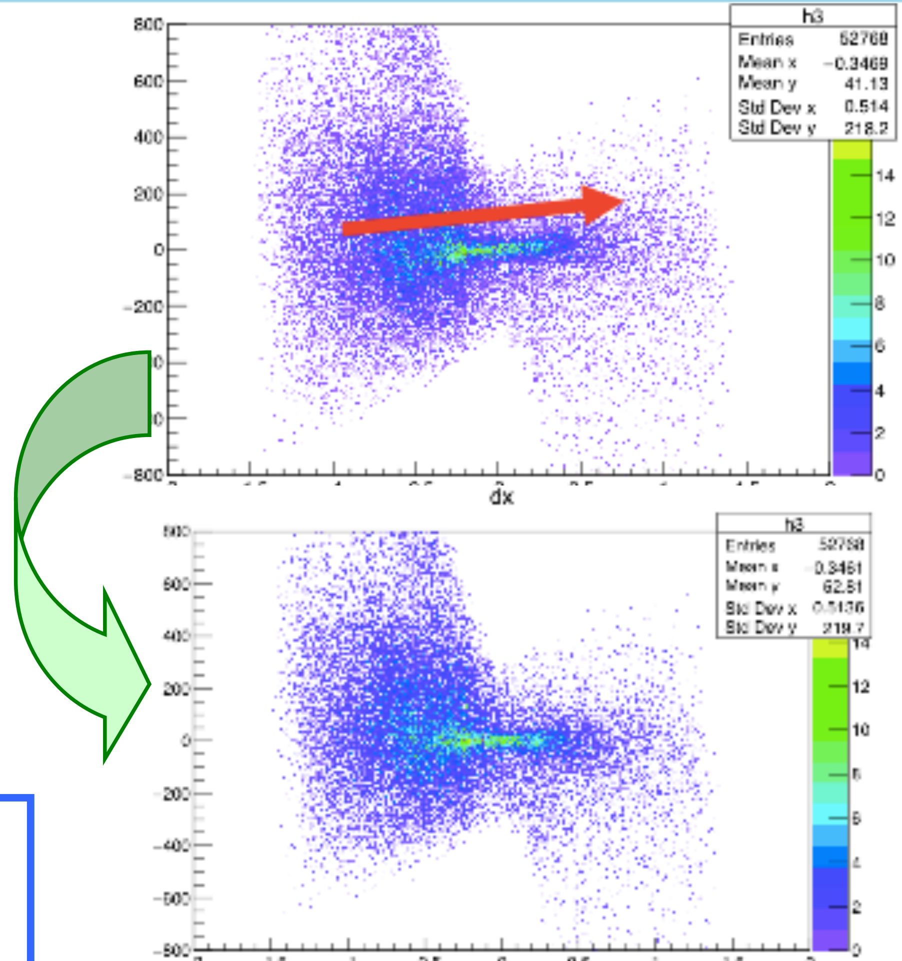


A slope of line of peaks is corresponded to dz
A segment of line of peaks is corresponded to dx

Analysis by T. Sugimoto (Kobe U.), and T. Fukuda (Nagoya U.)

EMPHATIC: Emulsion Analysis





Design :	6320 micron
After correction :	6362.9micron

~0.7% larger from designed value. But corrected.

1.57488+42.9409×ax0を反映

Analysis by T. Sugimoto (Kobe U.), and T. Fukuda (Nagoya U.)