EMPHATIC

Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland

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on behalf of

EMPHATIC Collaboration

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21st International Workshop on Neutrinos from Accelerators (NuFact2019)

Outline

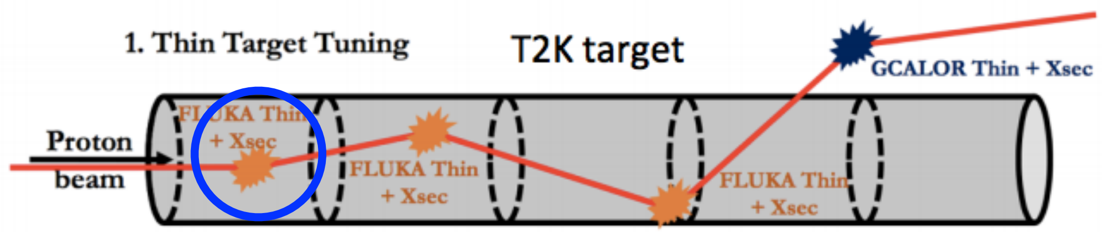
- Introduction
- EMPHATIC
- 2018 test run
- Summary

Neutrino Flux Prediction

- **It is difficult to measure neutrino flux itself in our detectors**
  - We just measure **flux** × **cross-section**
  - ν-e scattering → low statistics
  - In-situ direct measurement of secondary hadrons is very challenging (high radiation area)
- **Need Monte Carlo simulations to predict neutrino flux**
  - ~30% differences between models → large systematic uncertainty
  - **Hadron production data is used to tune the models**

Hadron Production Measurements

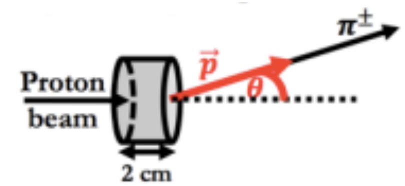
Hadron interactions in target



Primary int.
(p+C)
~60%

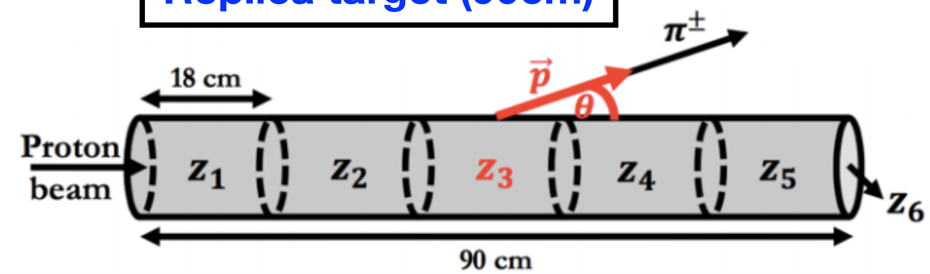
Secondary/tertiary int.
(π,K+C)
~30%

Thin target (2cm)



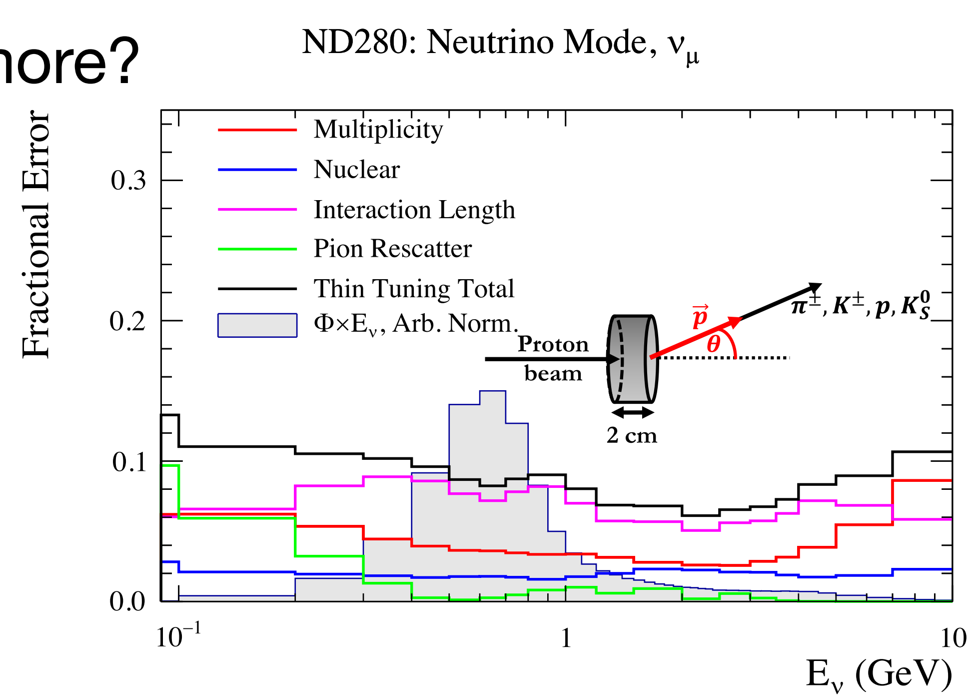
~60% of all interactions

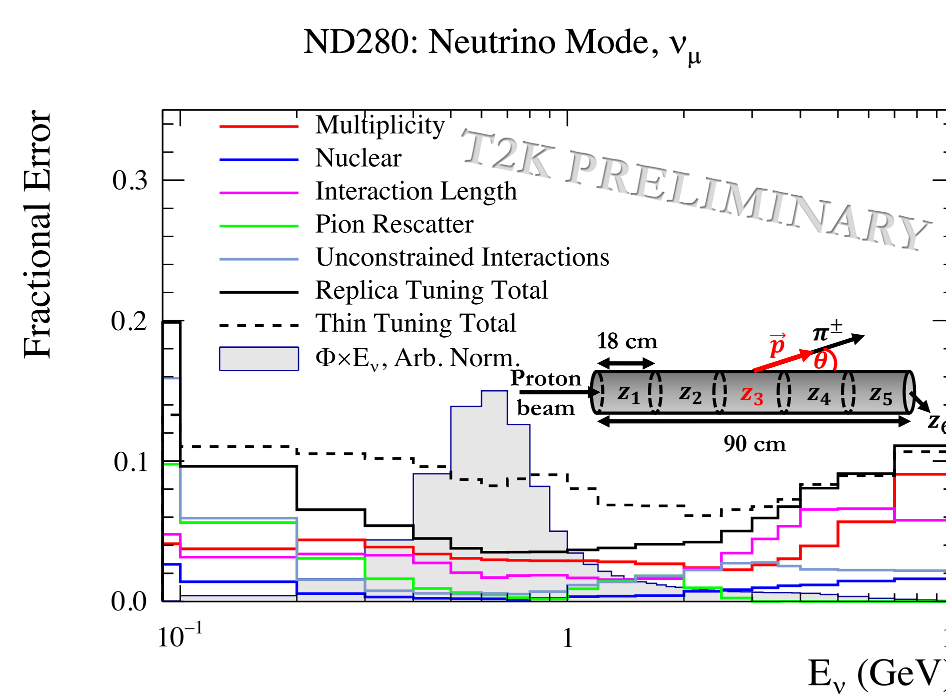
Replica target (90cm)



Measure all interactions inside target ~90%

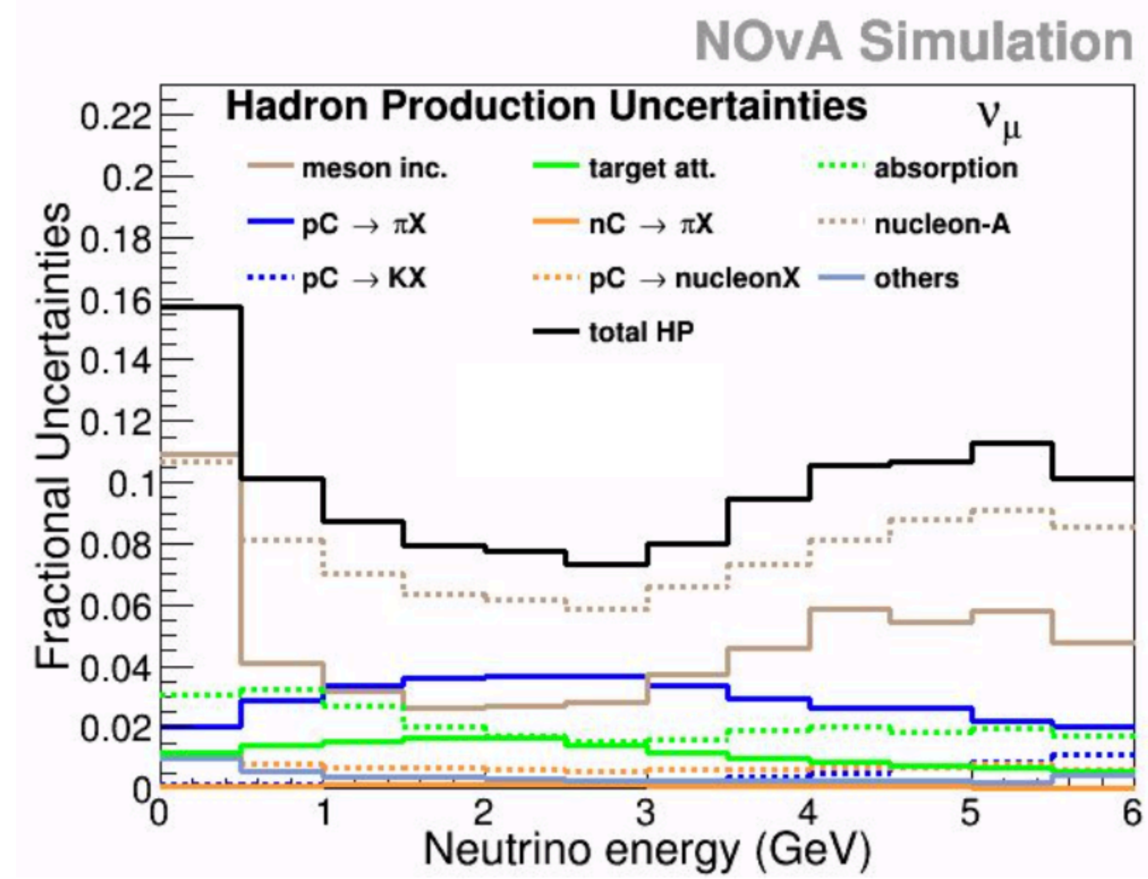
- Hadron production experiments
  - NA49, HARP, MIPP, NA61/SHINE, etc
    - T2K uses mainly NA61 data (both thin and replica)
    - NOvA uses NA49, MIPP, (NA61) data
- Flux uncertainties successfully reduced to 10% level (5% in near future)
  - Can we improve more?

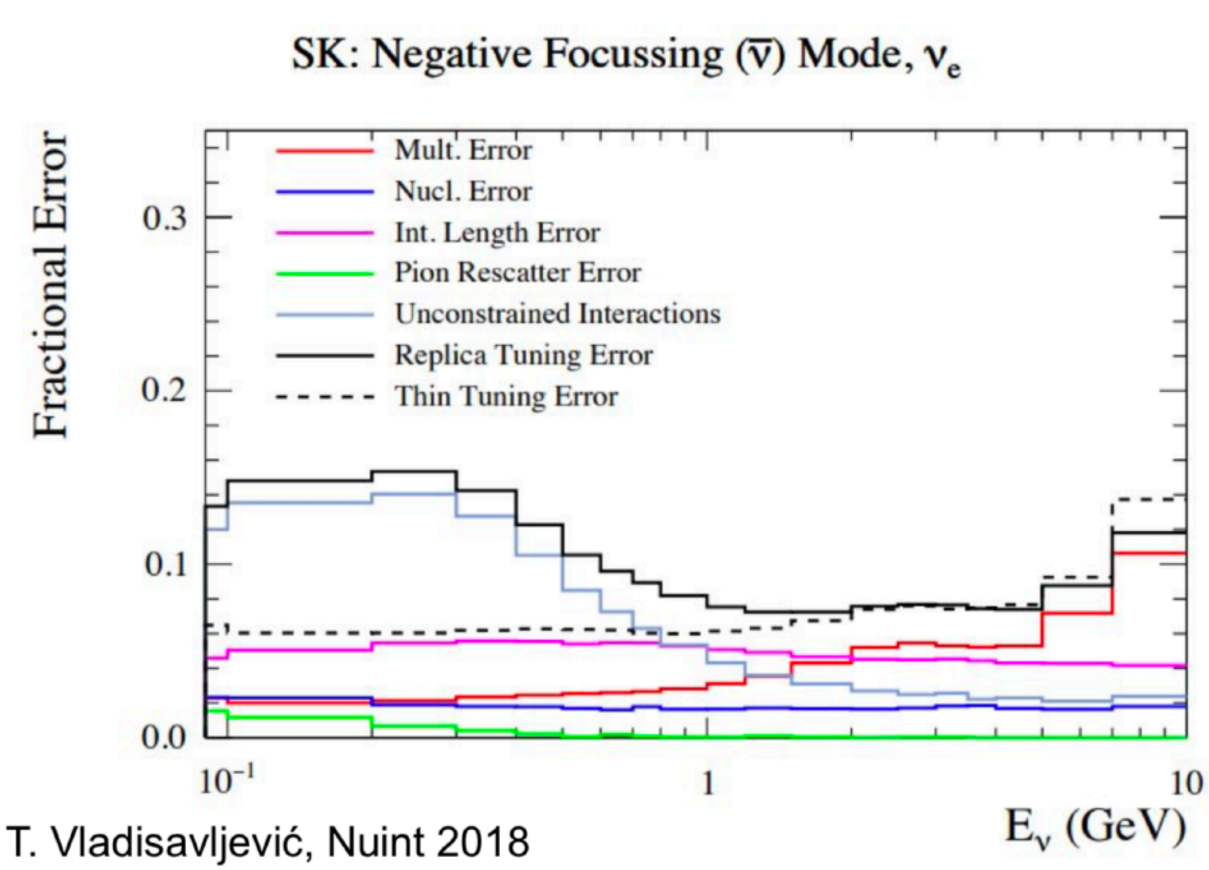




What Do We Need?

- Dominant flux uncertainty in NOvA comes from 40% XSEC uncertainty on interactions in target or horns that were not measured (well)
    - Lack of proton and pion scattering data at low energies
- T2K flux uncertainty at low energies is limited by untuned interactions out of target
    - $\pi^{\pm}$ + Al (Fe)→ $\pi^{\pm}$ + X (Fe)
    - $K^{\pm}$ + Al (Fe) → $K^{\pm}$ + X (Fe)
- Nearly 50% of wrong-sign neutrinos come from interactions out of target
- Measurement of π, K interactions at low energies (<10 GeV/c) is quite important for future experiments
    - Existing data are very limited

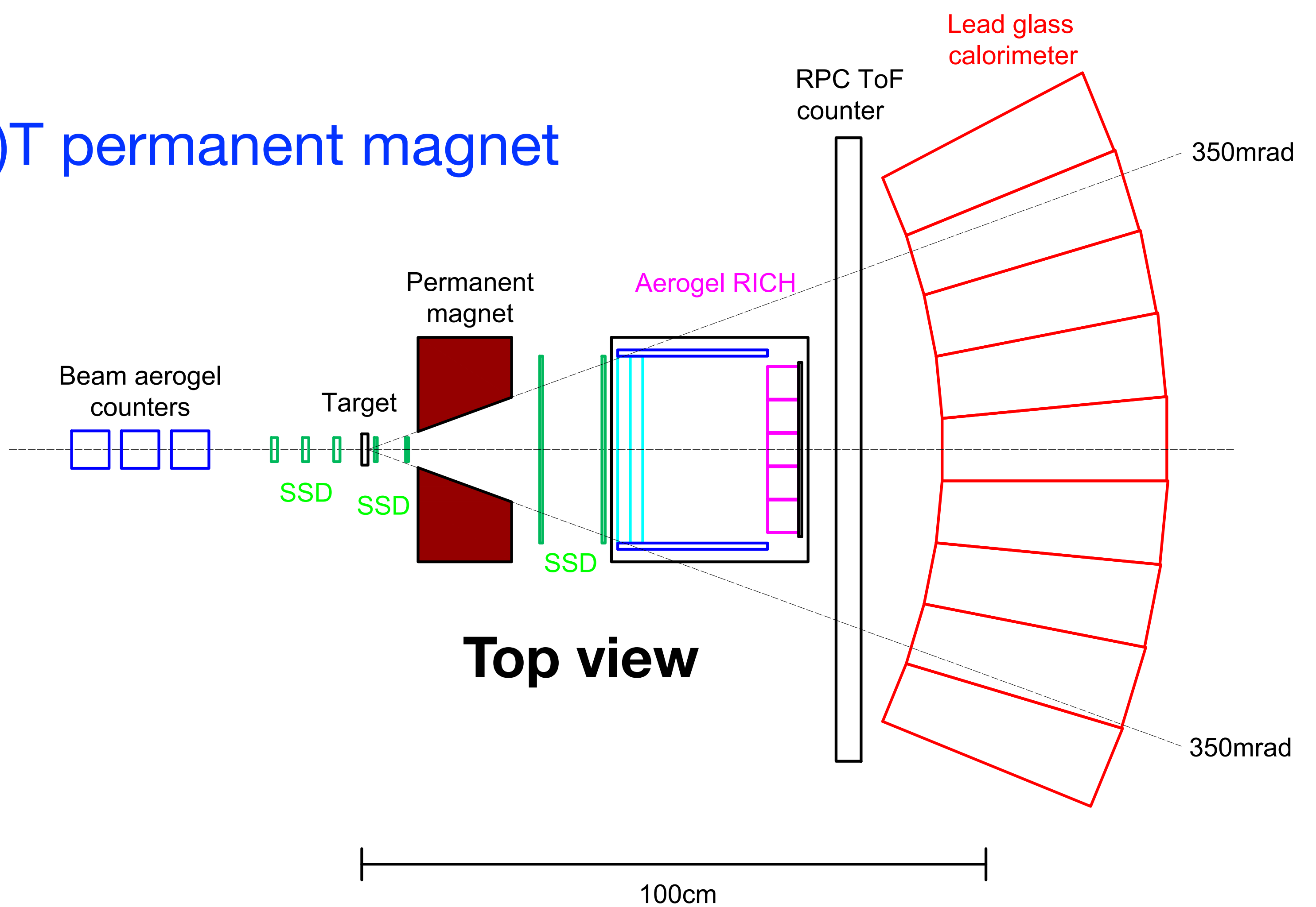




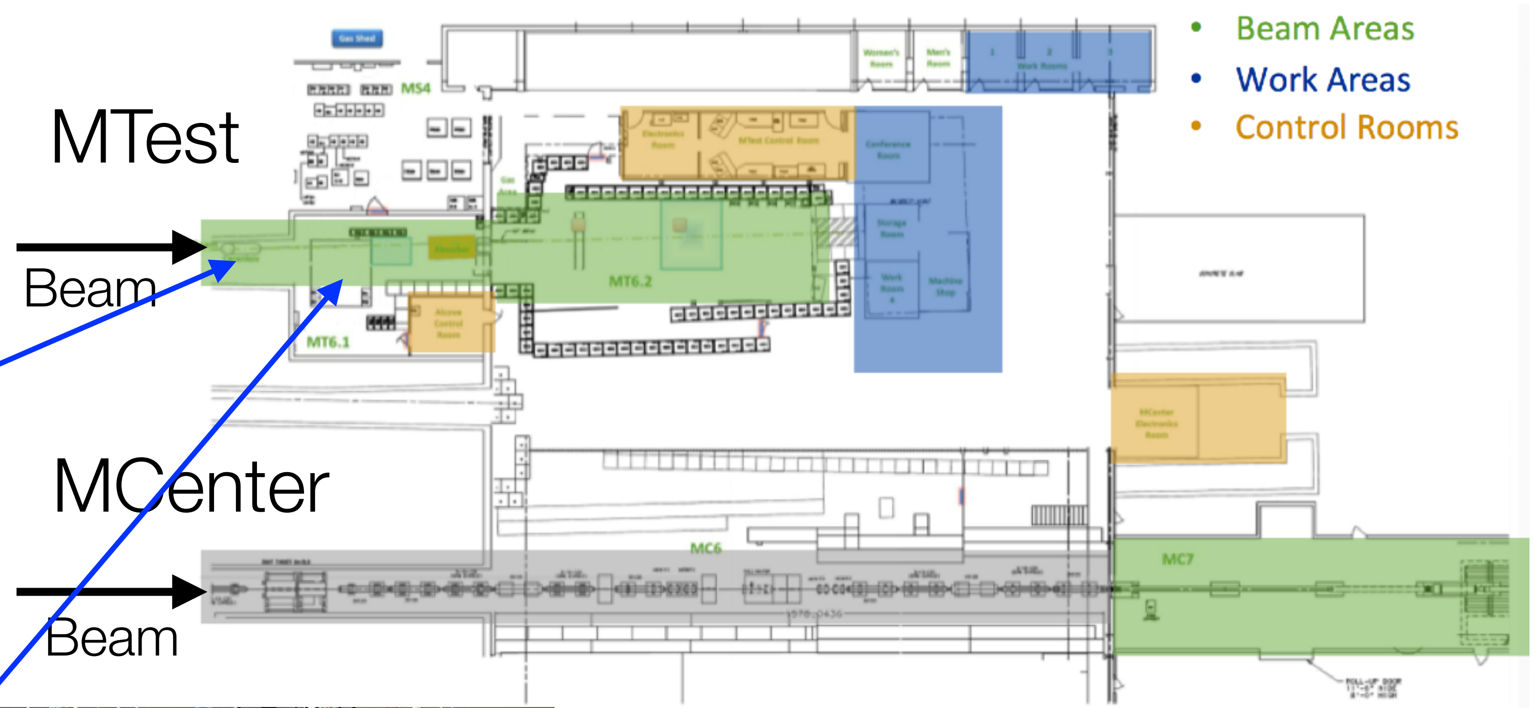
T. Vladisavljević, Nuint 2018

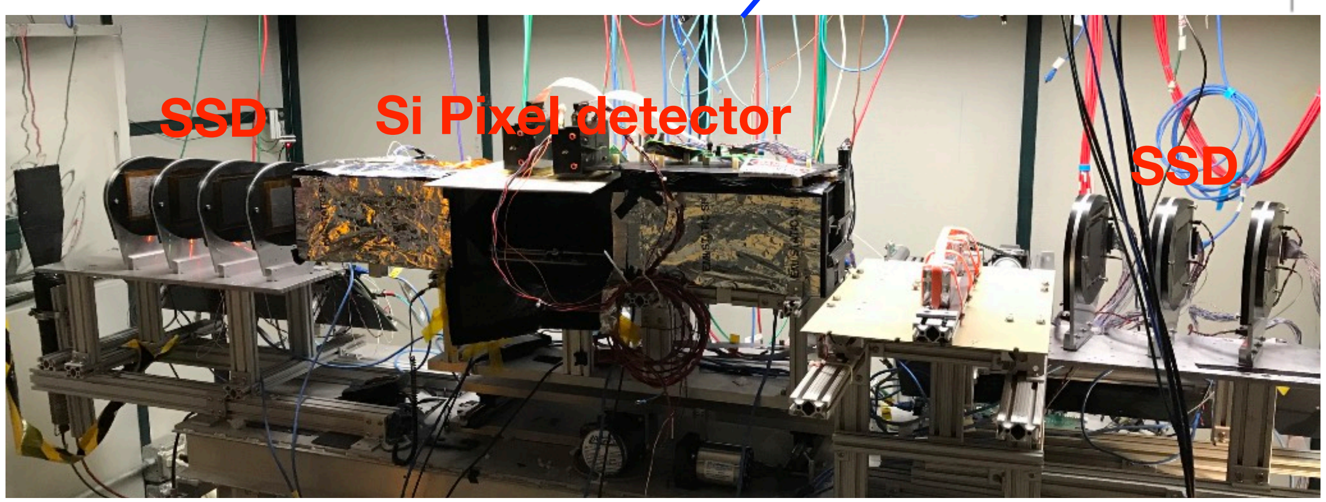
EMPHATIC

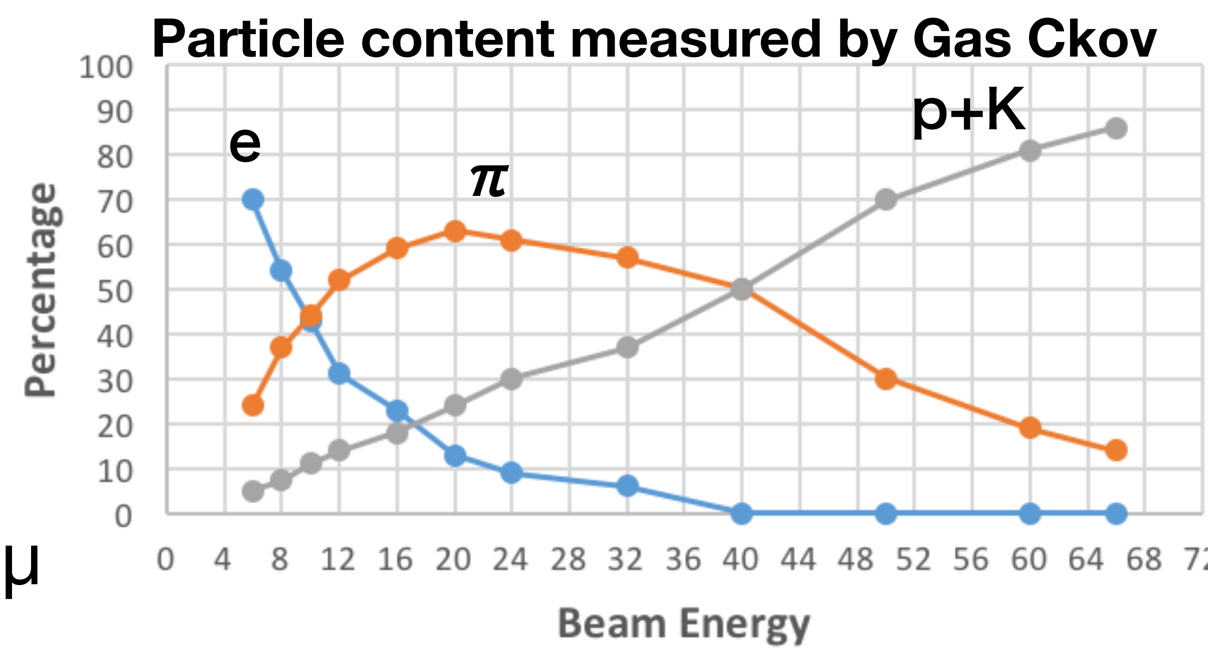
- Experiment to Measure the Production of Hadrons At a Test beam In Chicagoland
  - Uses the Fermilab Test Beam Facility (FTBF)
  - Table-top size experiment focused on hadron production measurements with p_{beam} < 15 GeV/c, but will also make measurements with beam from 20-120 GeV/c.
  - International collaboration from US, Japan, and Canada : 20~30 researchers
- Ultimate design:
  - Thin target (~5% int. length)
  - Precision tracking with SSDs
  - Momentum measurement with *O*(1)T permanent magnet
  - PID for secondary particles
    - Aerogel RICH and ToF counters
  - Large phase space coverage (~350mrad)
  - Compact size
    - Low overall cost
    - Simple systematics



Fermilab Test Beam Facility (FTBF)





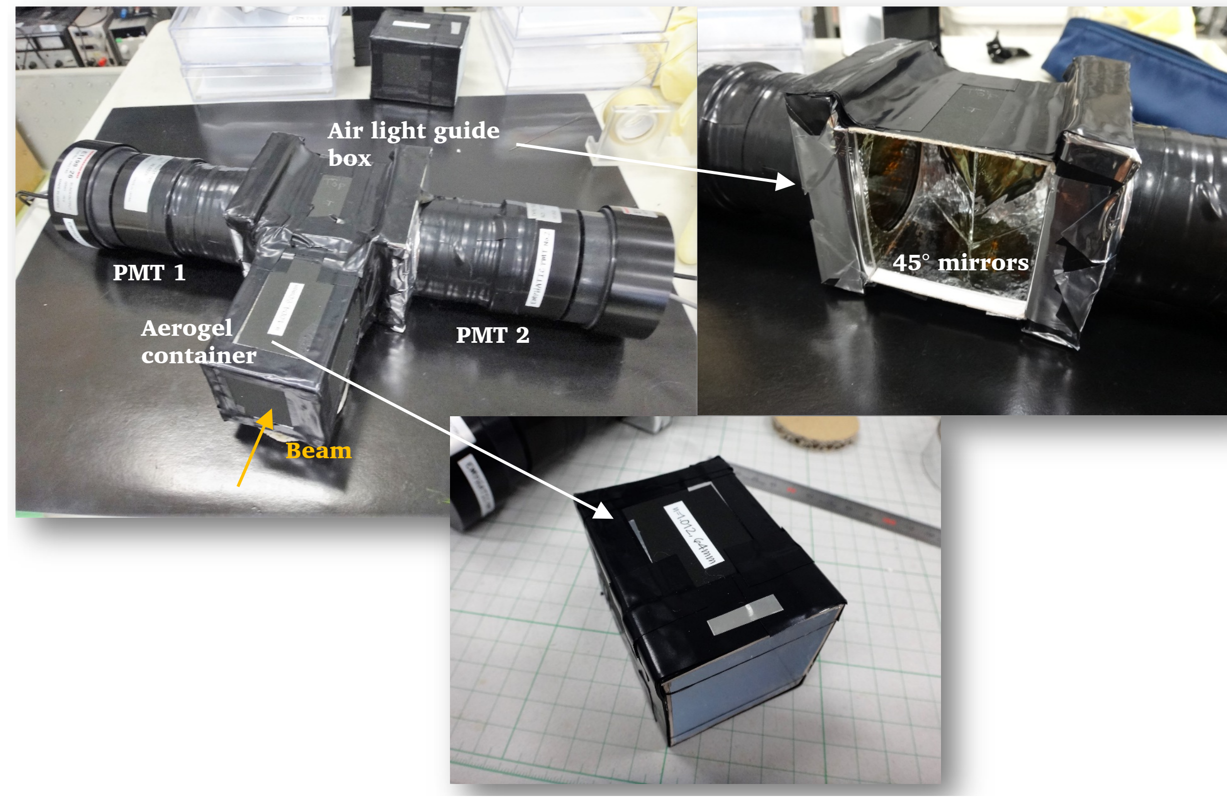


- 2-120 GeV/c beam including p, π, K, e, μ
- Beam intensity up to ~100 kHz
- 4-sec-long spill once a minute
- Many beam instrumentation available (SSD, gas Ckov, MPPC, etc)

Beam Particle ID

- Beam PID
  - Gas Cherenkov detectors : can be used for p>6 GeV/c
    - No p/K separation for p<18GeV/c
  - PID for low momentum beam

  ⇒ Threshold aerogel Cherenkov counters

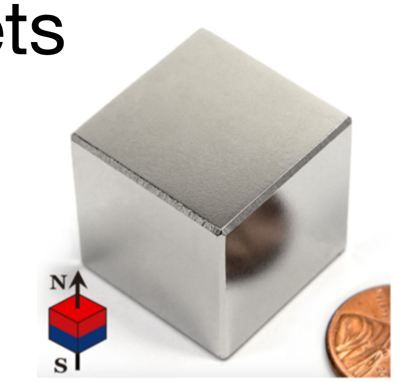


- Beam aerogel counter
  - Developed by Chiba Univ. (aerogel expert)
  - Very low index (n=1.004) aerogel newly developed for EMPHATIC
    - Can cover 5-10 GeV/c region
    - Very high transparency, but low light yield
  - Prototype being tested with electron beam at Tohoku Univ.
    - n=1.004 → N_{PE} = 5.7 (detection eff. >99%)
    - n=1.012 → N_{PE} = 16.8
    - n=1.045 → N_{PE} = 41.0

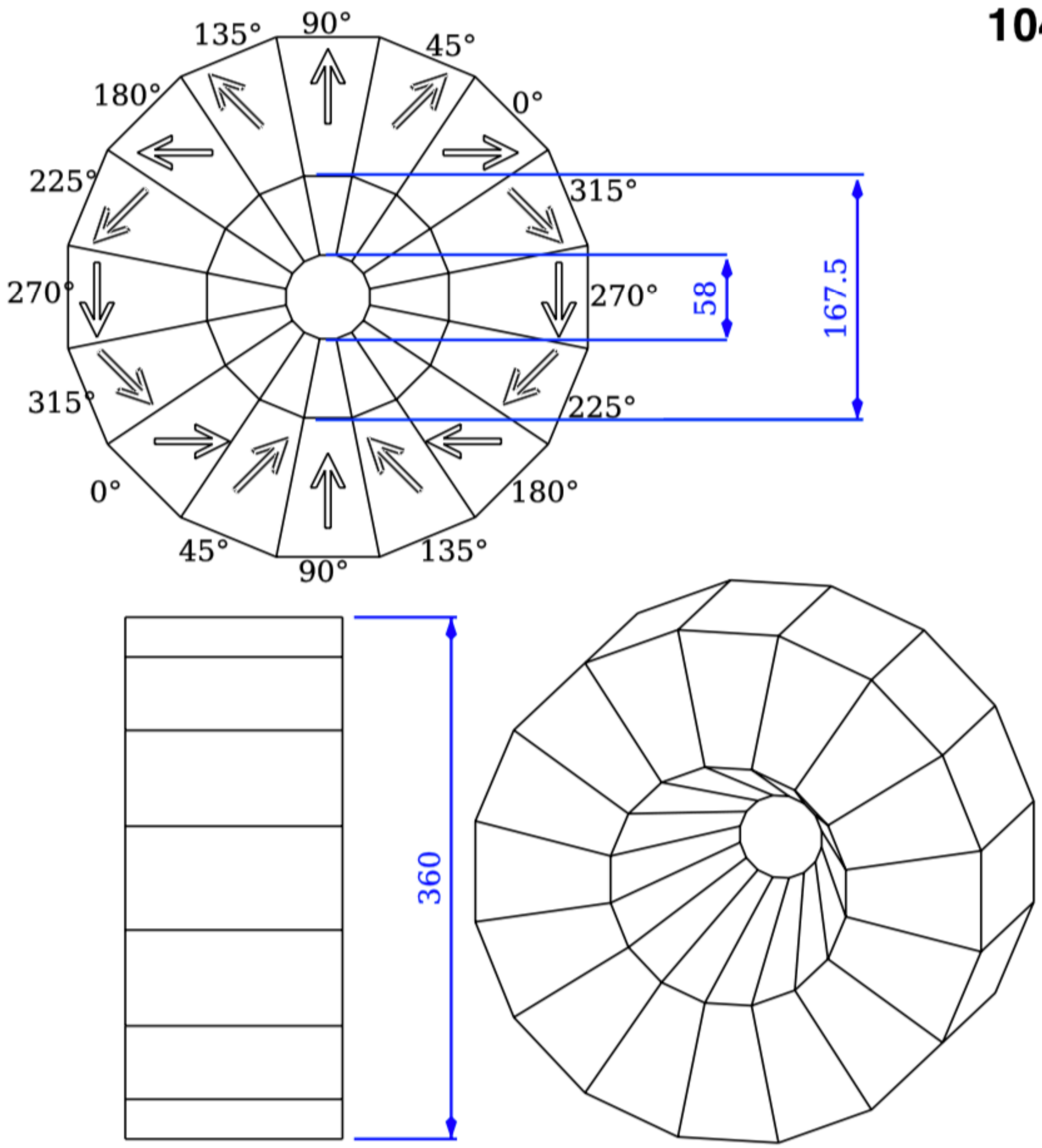
n	Threshold momentum (GeV/c)		
	π	K	p
1.004	1.6	5.5	10.5
1.012	0.9	3.2	6.0

Magnet

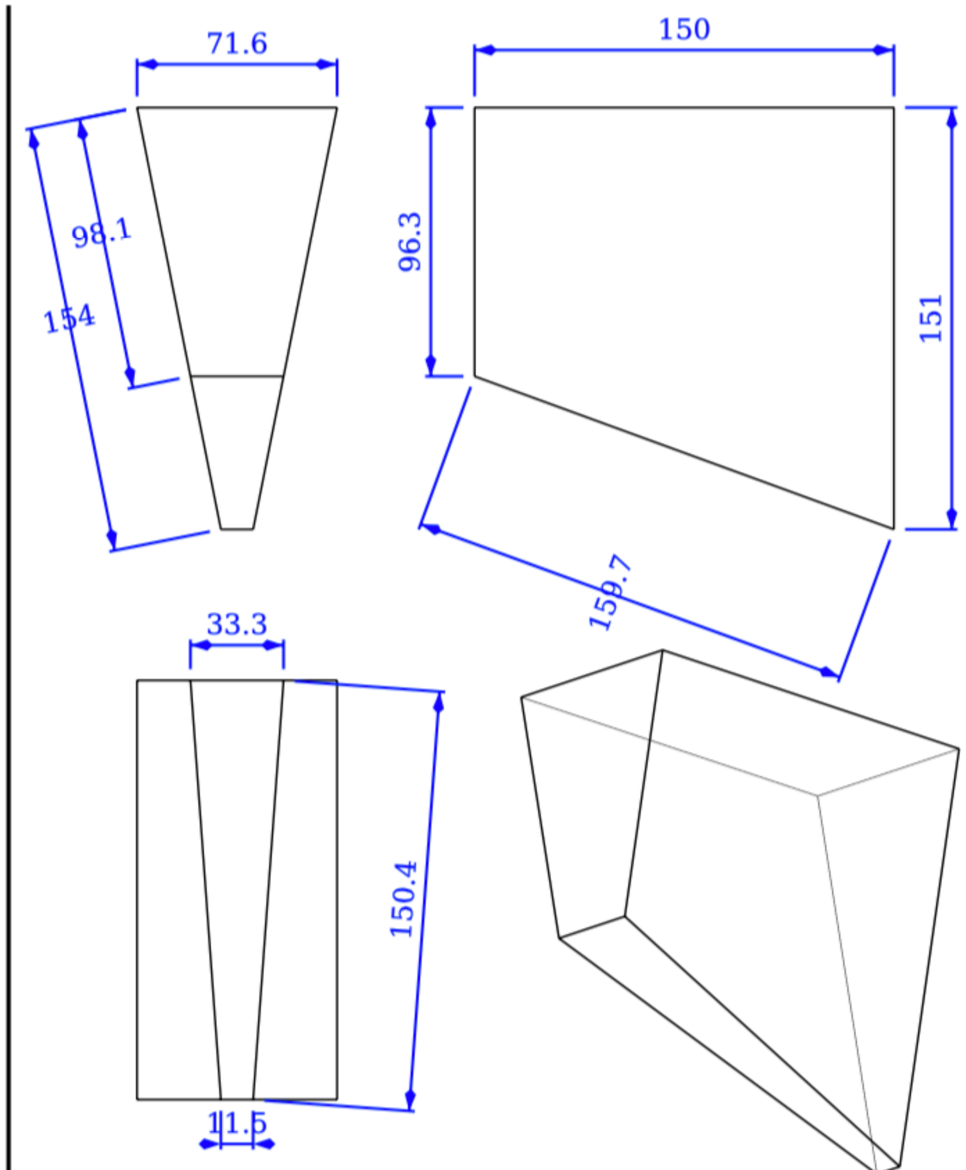
Made from segments of Neodymium permanent magnets



Halbach Array

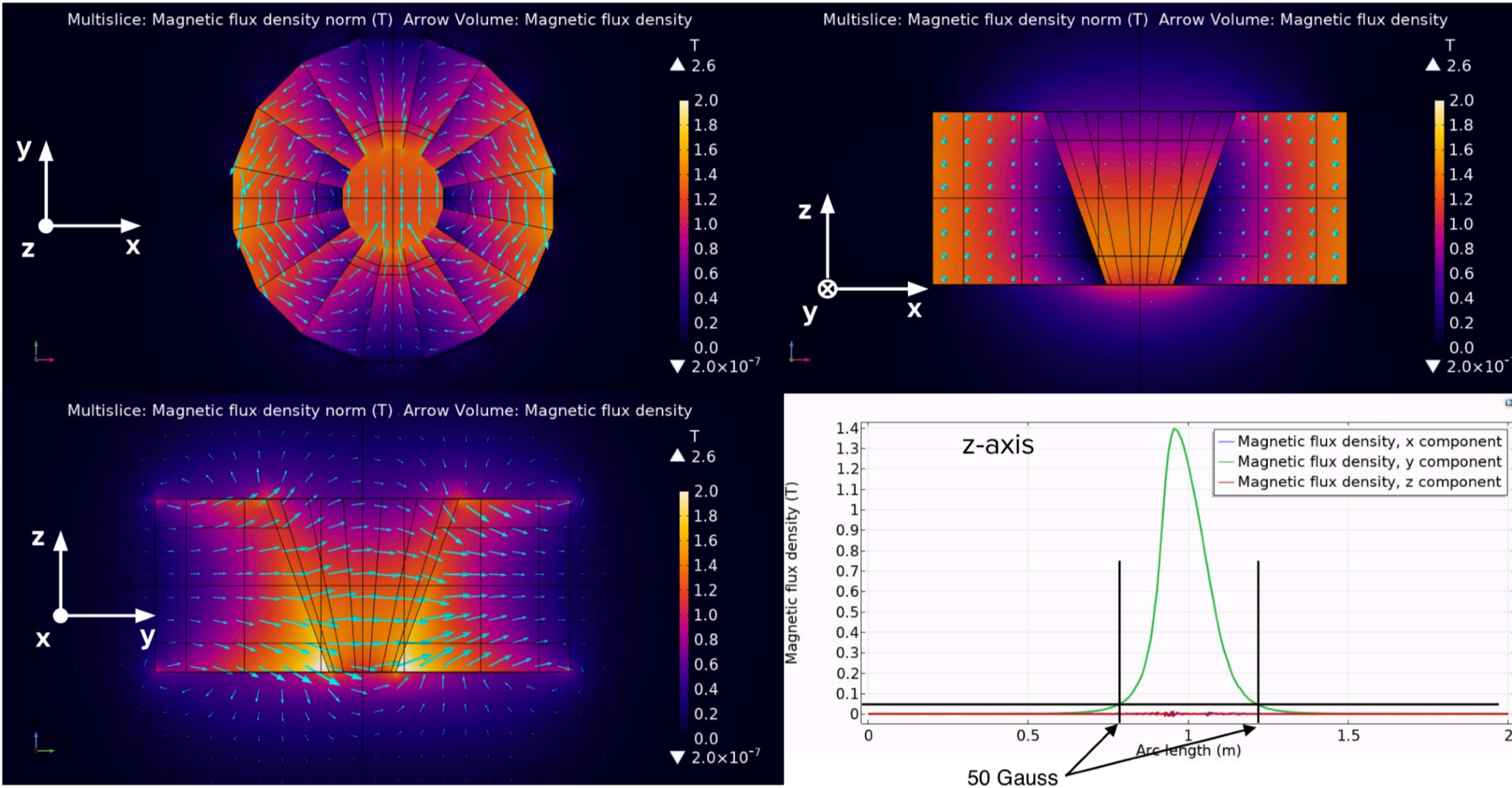


EMPHATIC Dipole Magnet
16 NdFeB (N52) segments
104 kg



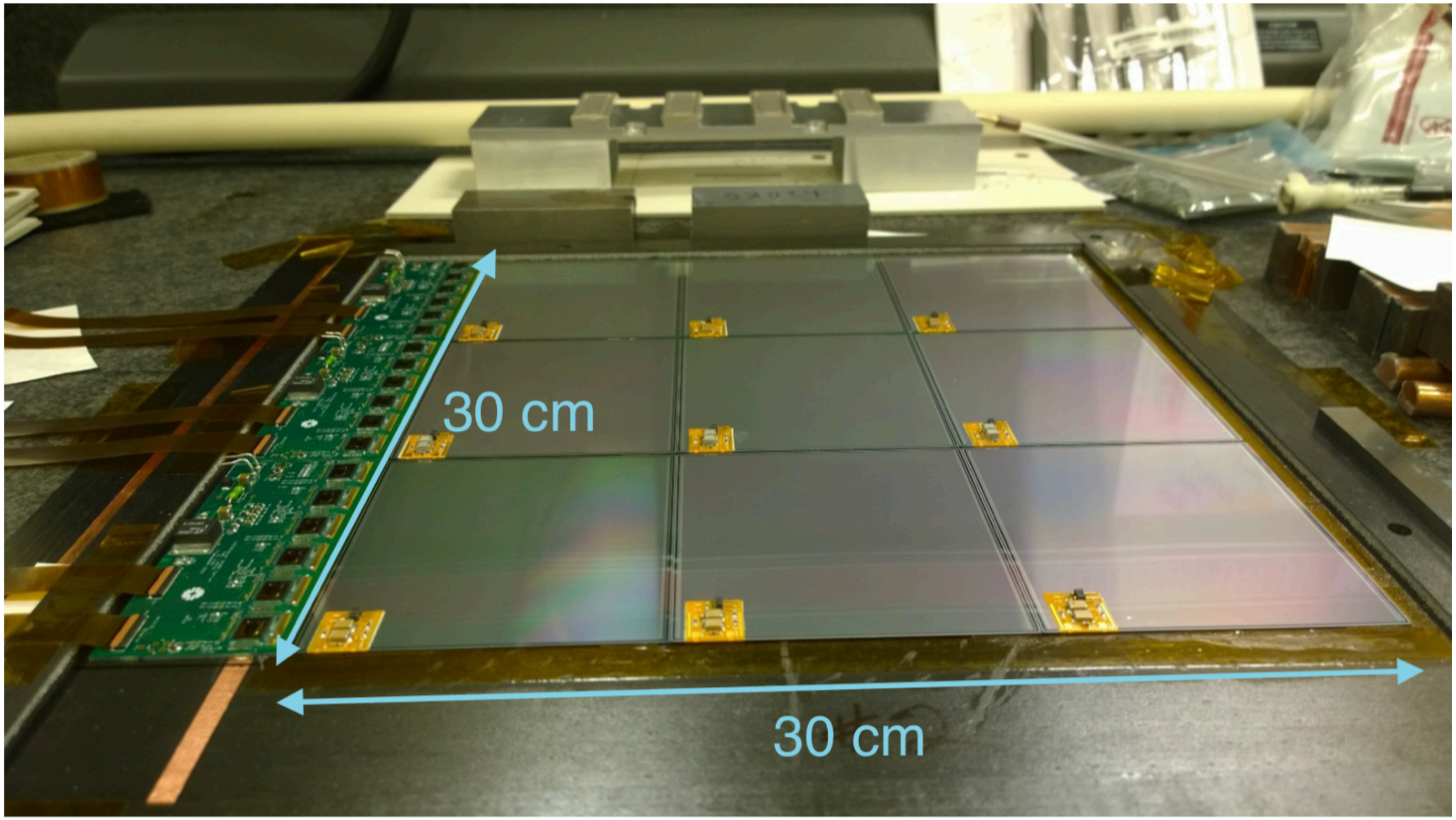
all measurements are in mm

Magnetic Field Simulation



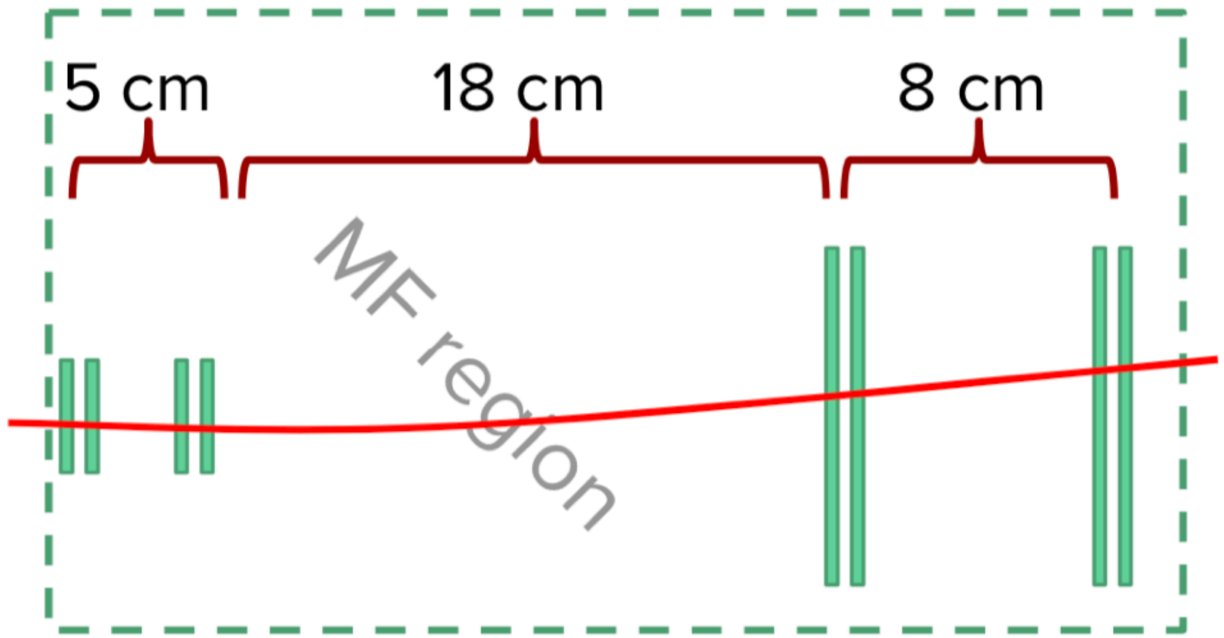
Field maps generated using COMSOL simulation ⇒ 1.4 T max.

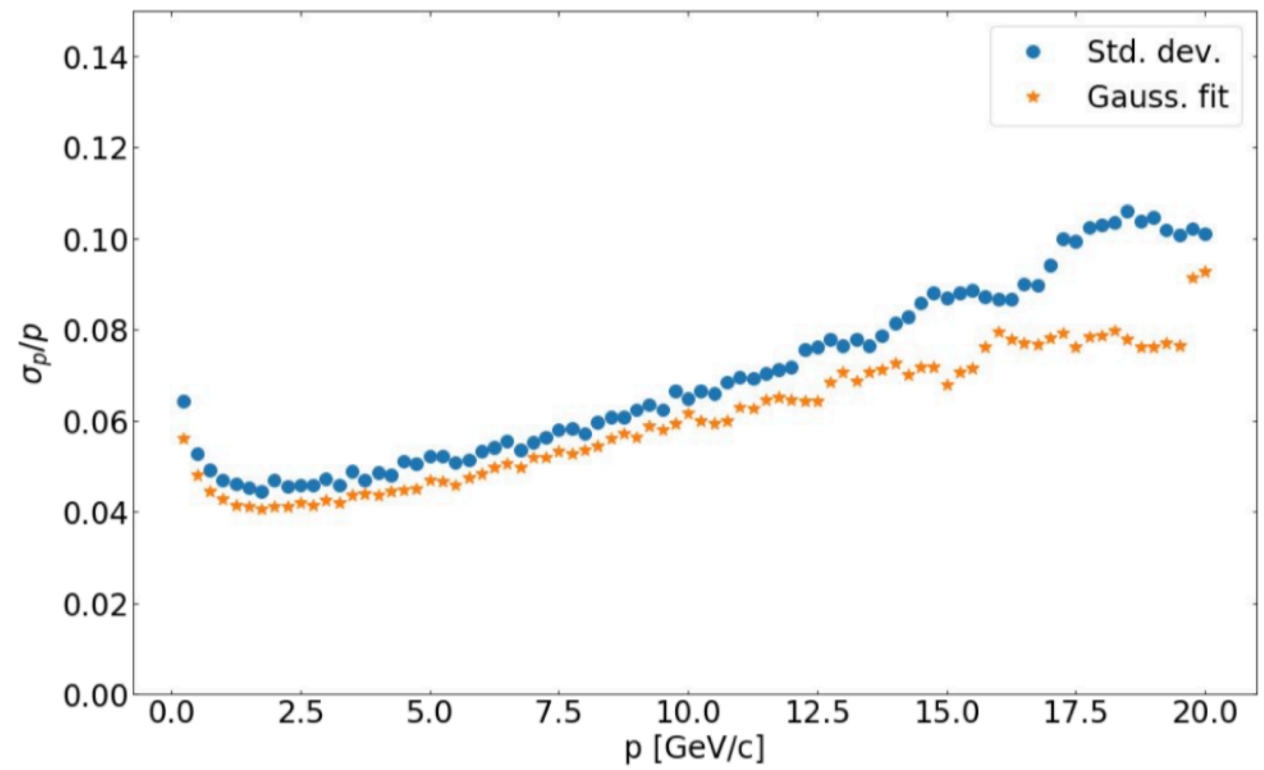
Silicon Strip Detectors



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

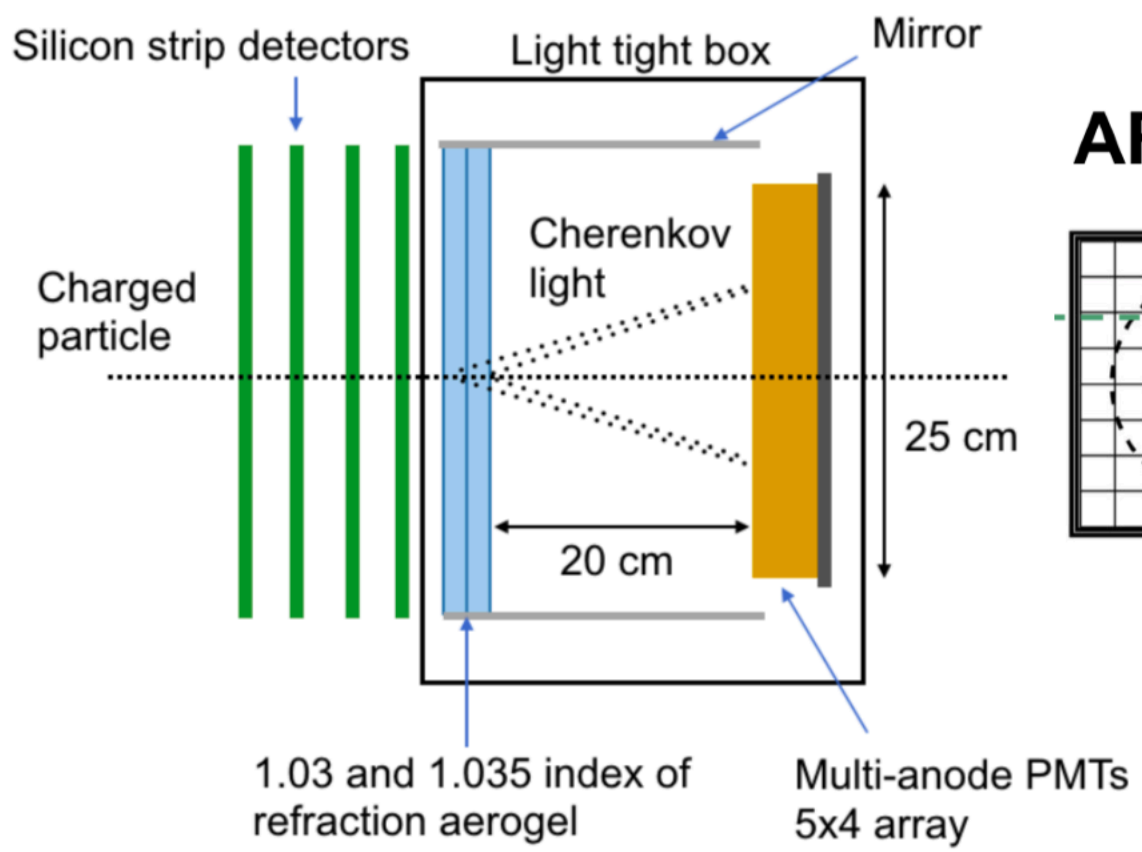
Momentum Resolution

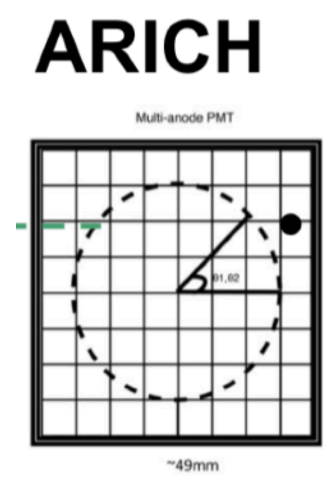


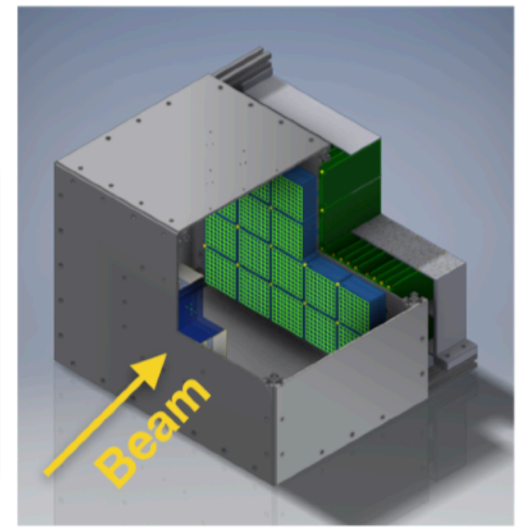


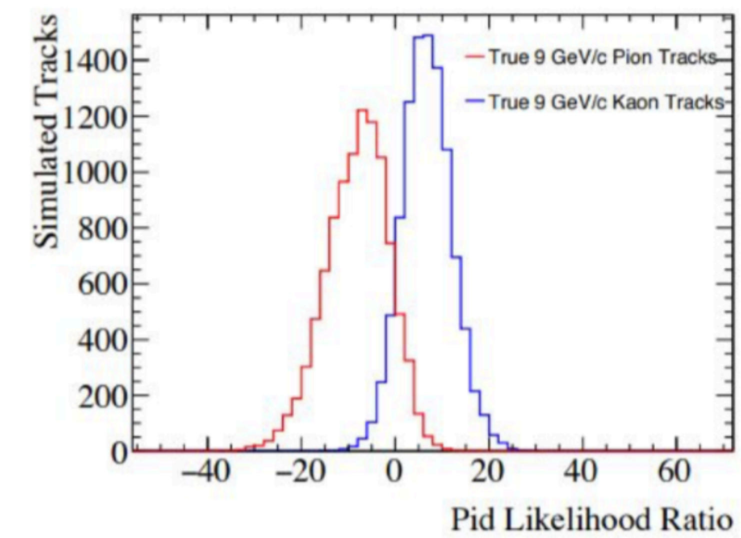
- Tracking simulation using GEANT4
- Preliminary study based on COMSOL magnetic field maps.
- SSD resolution taken into account
- Momentum resolution < 6% below 8 GeV/c, <10% below 17 GeV/c
  - Resolution dominated by multiple scattering at low momentum

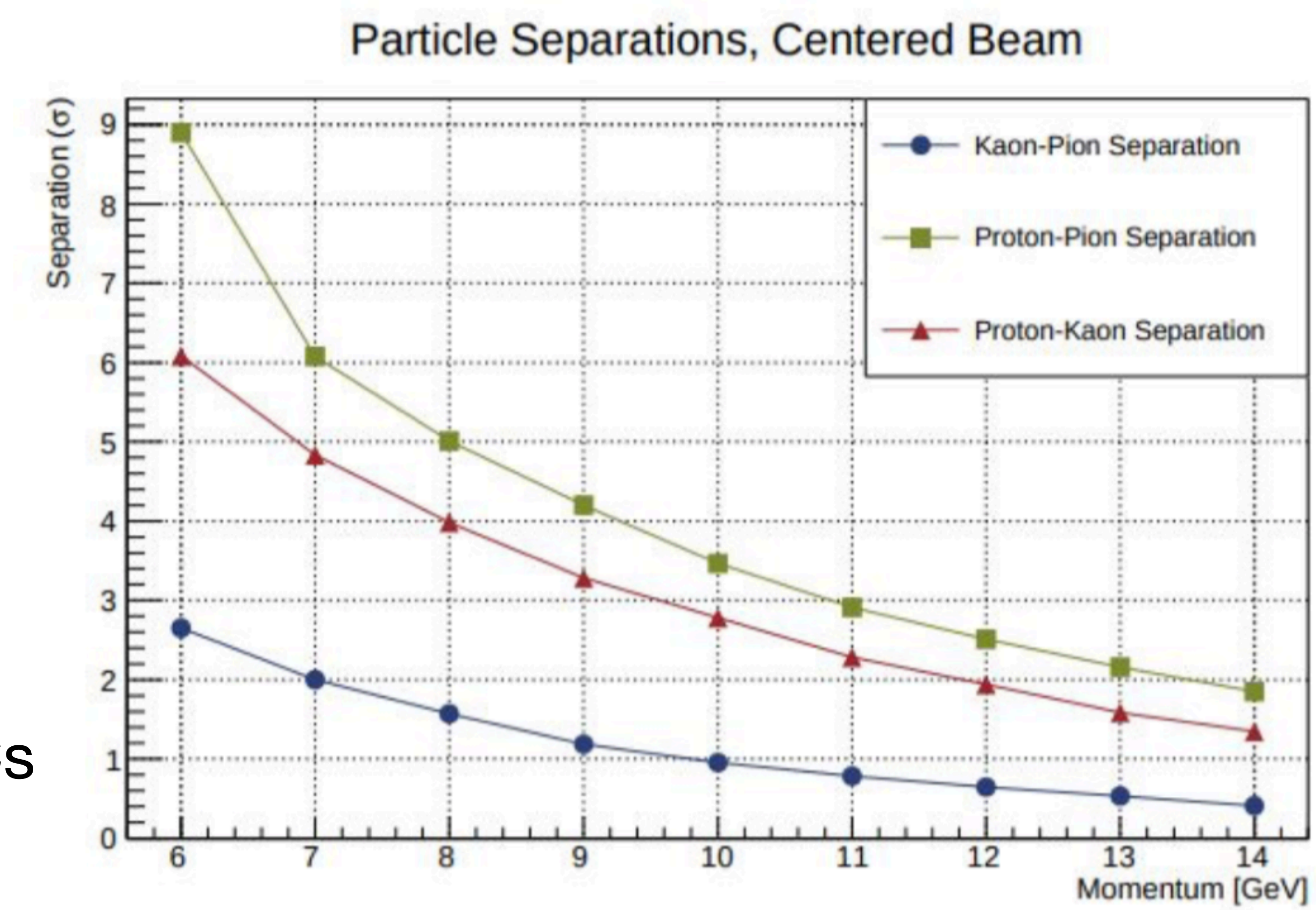
Aerogel RICH





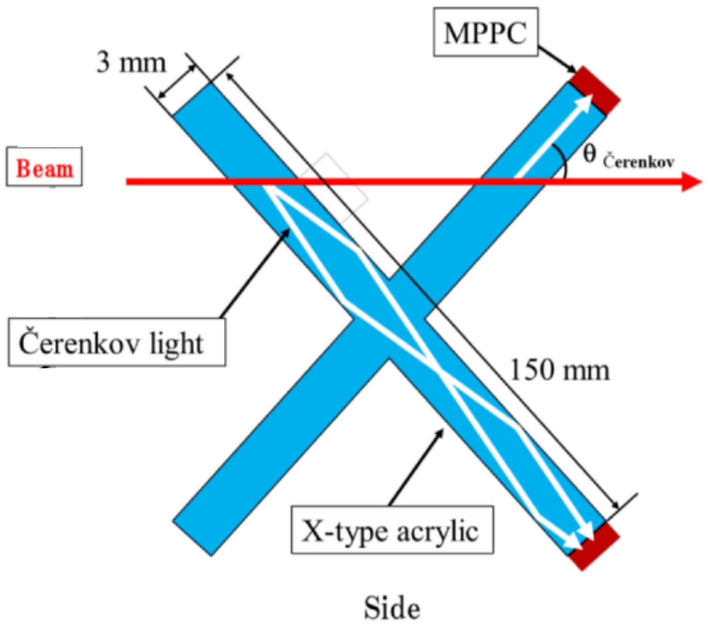


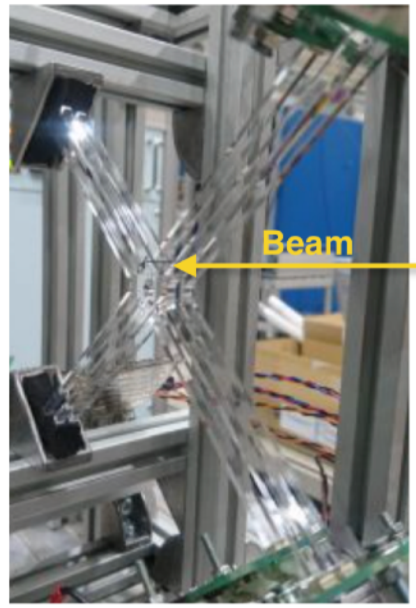


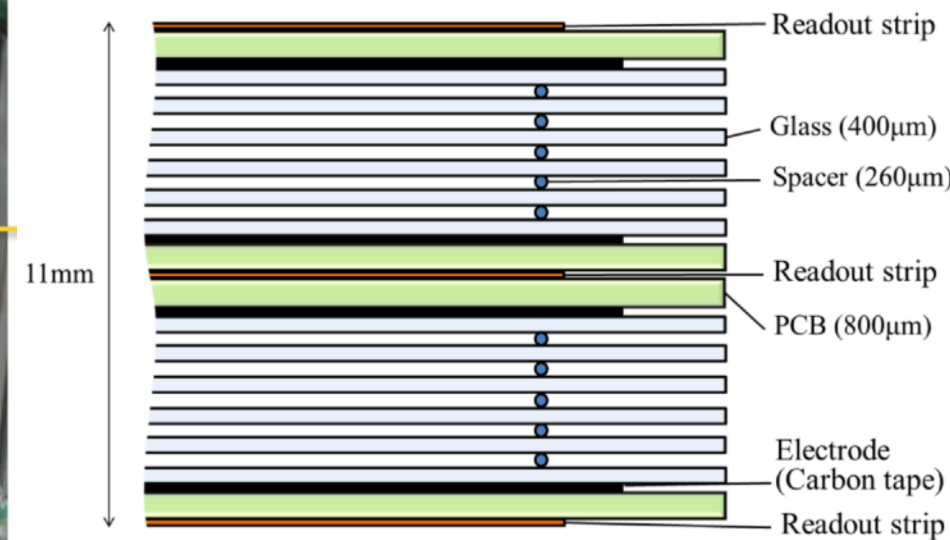


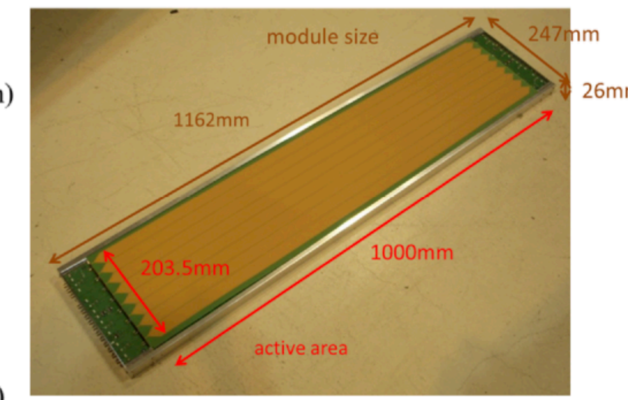
- Proximity-focusing RICH based on Belle II ARICH detector
- Aerogels with lower indices of refraction (n=1.03-1.04) and good transmittance
- Light detected by multi-anode PMTs (6mm-pitch) or possibly MPPC (3mm-pitch)
  - 20ps-timing resolution by GSI TRB3 TDCs
- 2σ π-K separation for p<7 GeV/c.
- Beam test at TRIUMF ongoing in this summer

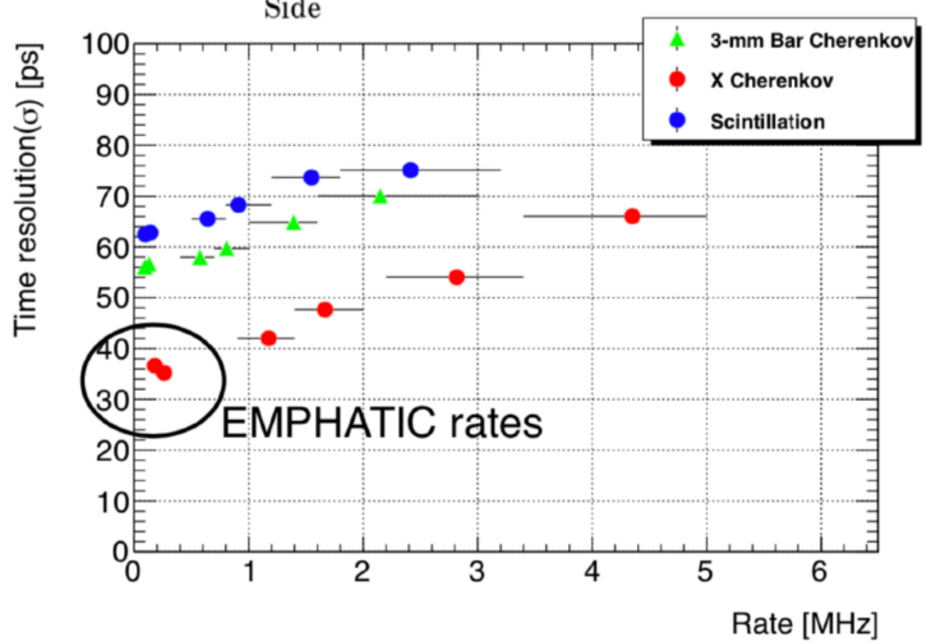
ToF Counters

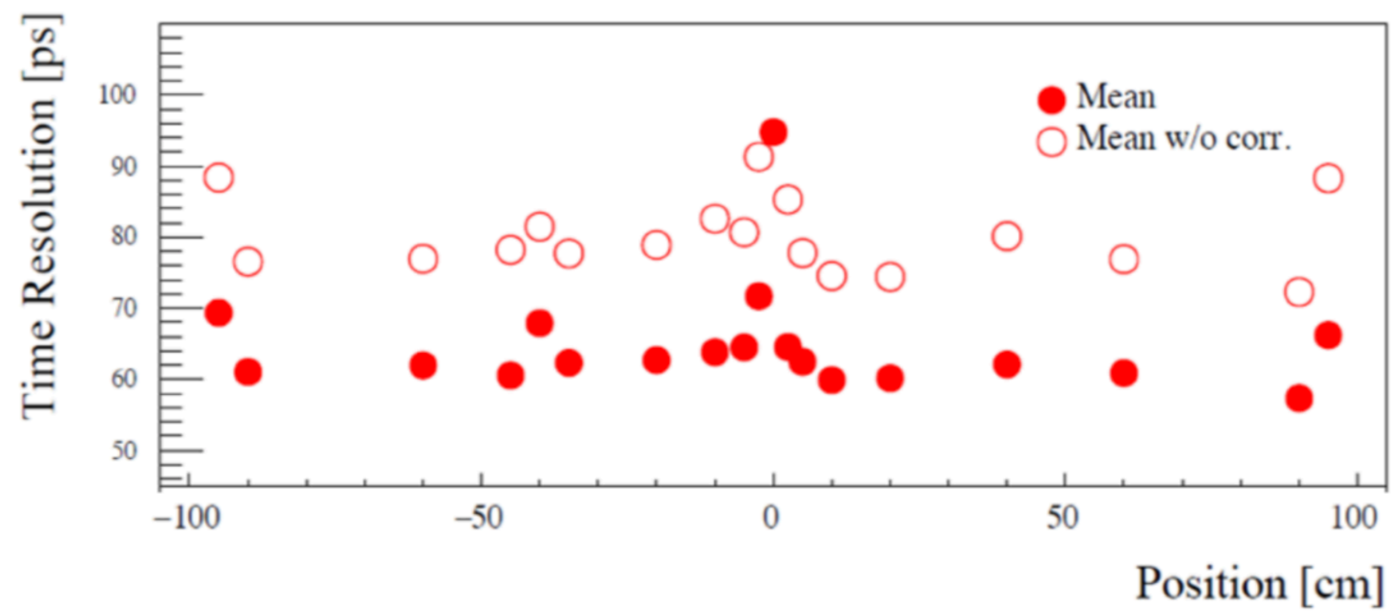












- PID for low momentum particles below Cherenkov threshold
- Start counter : X-shaped Cherenkov counter (Acrylic + MPPC)
- Stop counter : Multi-gap Resistive Plate Chamber (RPC)
- Developed by J-PARC E50 group
- Timing resolution as good as 70 ps

EMPHATIC Measurement Plan

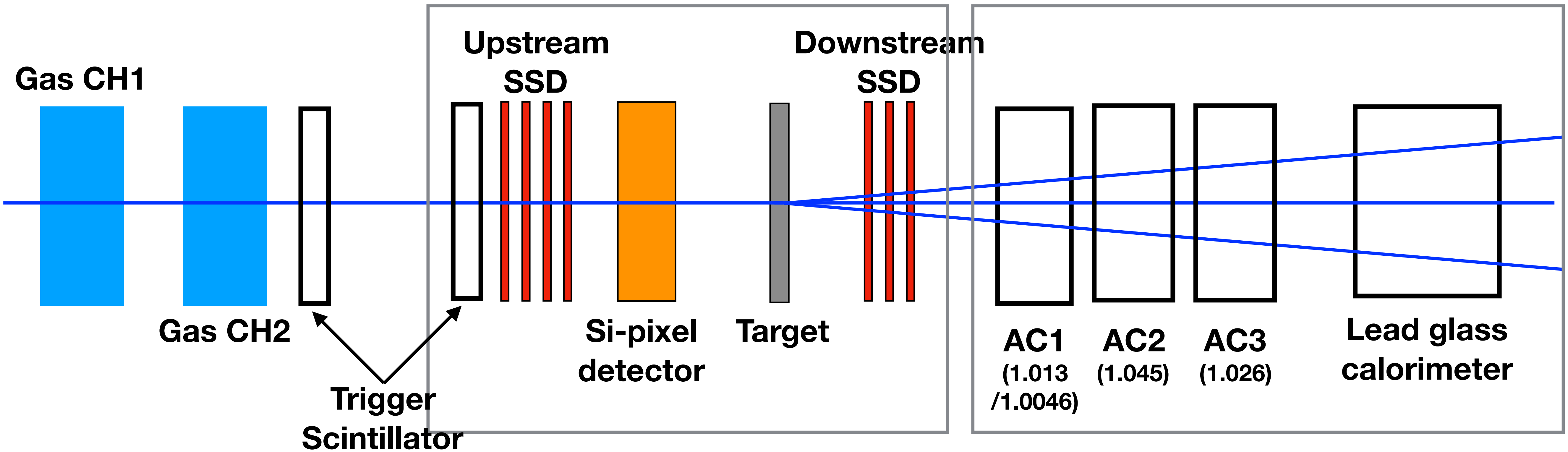
Phase	Date	Sub-system	Momenta	Targets	Goals
1	Spring 2020	Beam Aerogel counter FTBF SSDs Small aperture magnet Aerogel RICH ToF counters Lead glass calorimeter	4, 8, 12, 20, 31, 60, 120 GeV/c	C, Al, Fe	• Improved elastic and quasi-elastic scattering measurements • Low-acceptance (150mrad) hadron production measurements
2	Spring 2021	Beam Aerogel counter FTBF SSDs Large-area SSDs Full aperture magnet Aerogel RICH ToF counters Lead glass calorimeter	4, 8, 12, 20, 31, 60, 120 GeV/c	C, Al, Fe, H_2O, Be, B, BN, B_2O_3	• Full-acceptance (350mrad) hadron production with PID up to 8 GeV
3	Spring 2022	Same as Phase 2 + Extended RICH	20, 31, 60, 80, 120 GeV/c	Same as Phase 2 + Ca, Hg, Ti	• Full-acceptance (350mrad) hadron production with PID up to 15 GeV

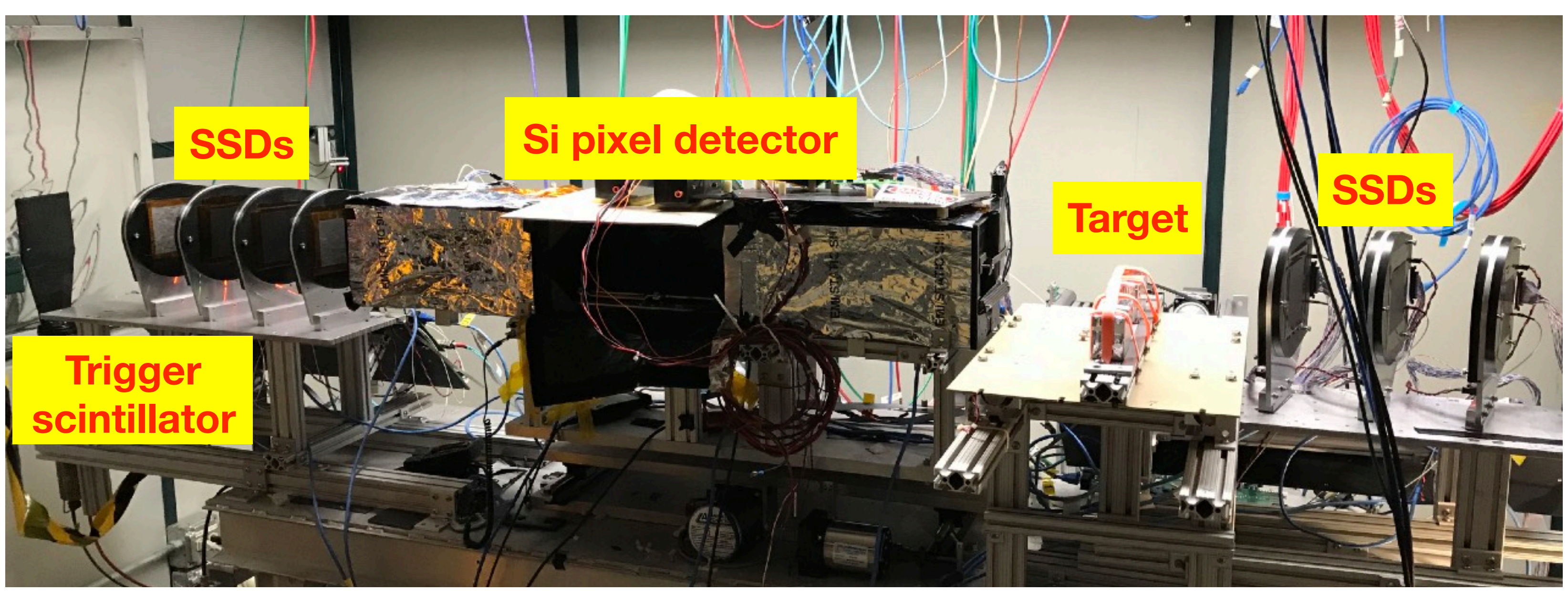
Proof-of-Principle Test

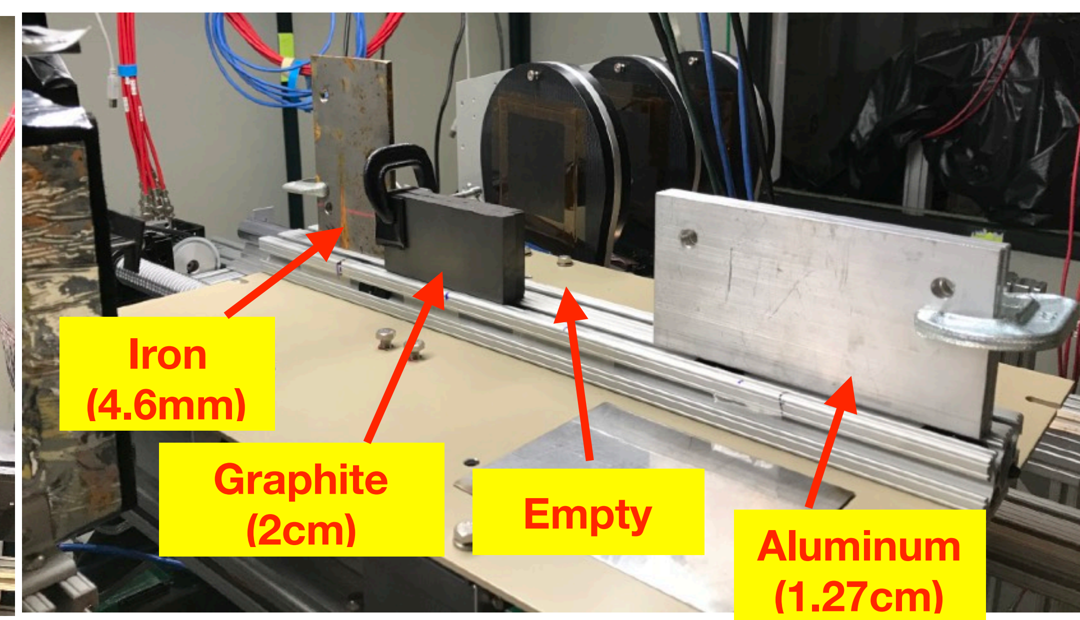
- EMPHATIC performed beam test in January 2018 for proof-of-principle
  - Detector development (Aerogel counters and emulsion detector)
  - Precise scattering measurements with high resolution trackers (SSD, emulsion)
- Initial beam test
  - January 10-24, 2018 for three weeks
  - 20M triggers collected in 7 days of running
  - 2, 10, 20, 30, 120 GeV/c beam on C, Al, Fe (and empty) targets

Beam momentum	Graphite	Aluminum	Iron	Empty
120 GeV/c	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

Beam Test Setup

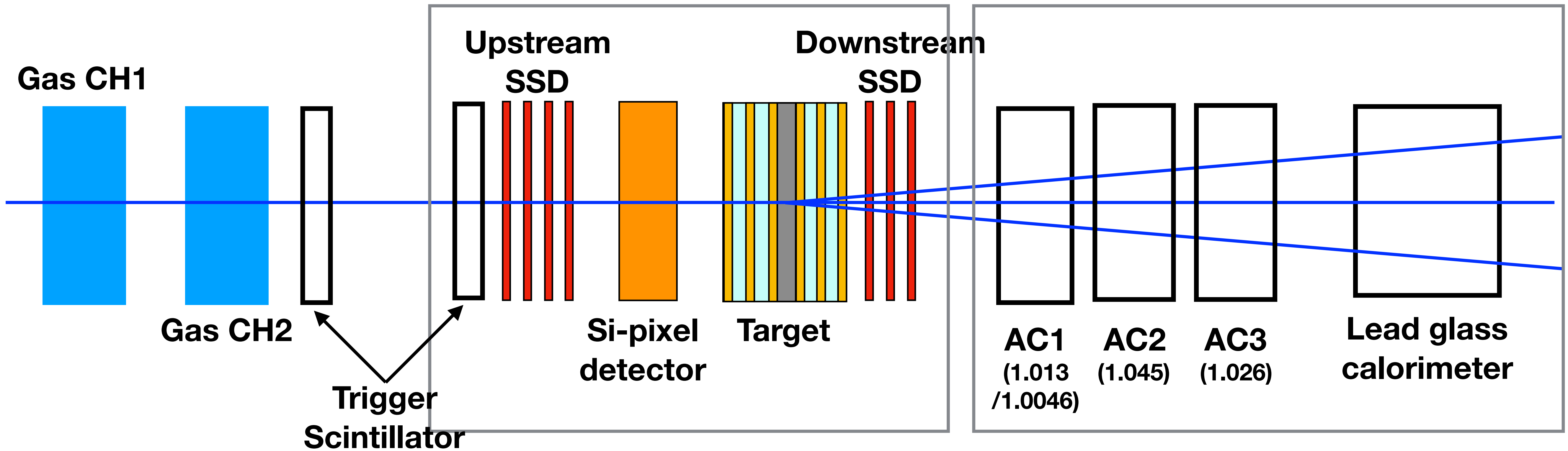


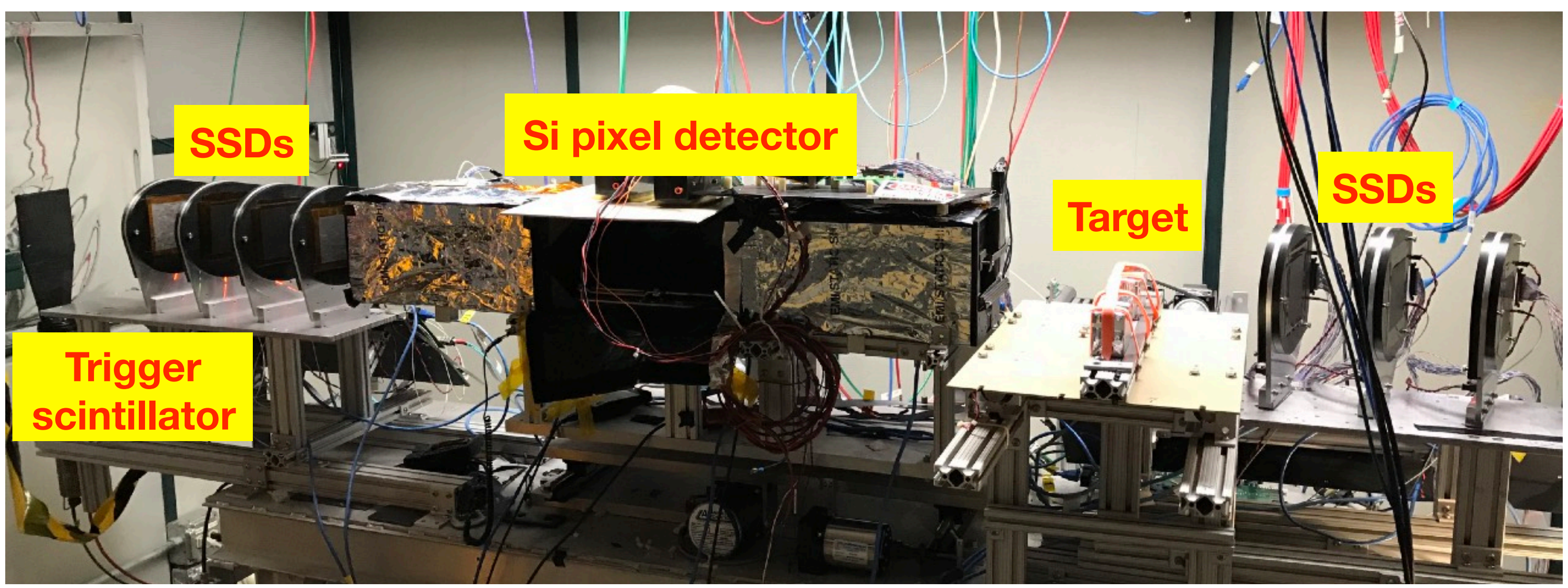


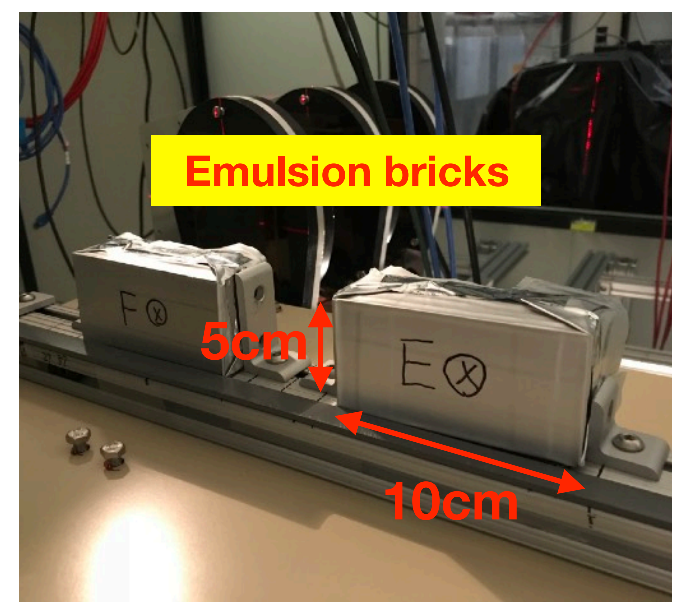


- Targets with 2% interaction length
- Target can be changed remotely using motion table

Beam Test Setup



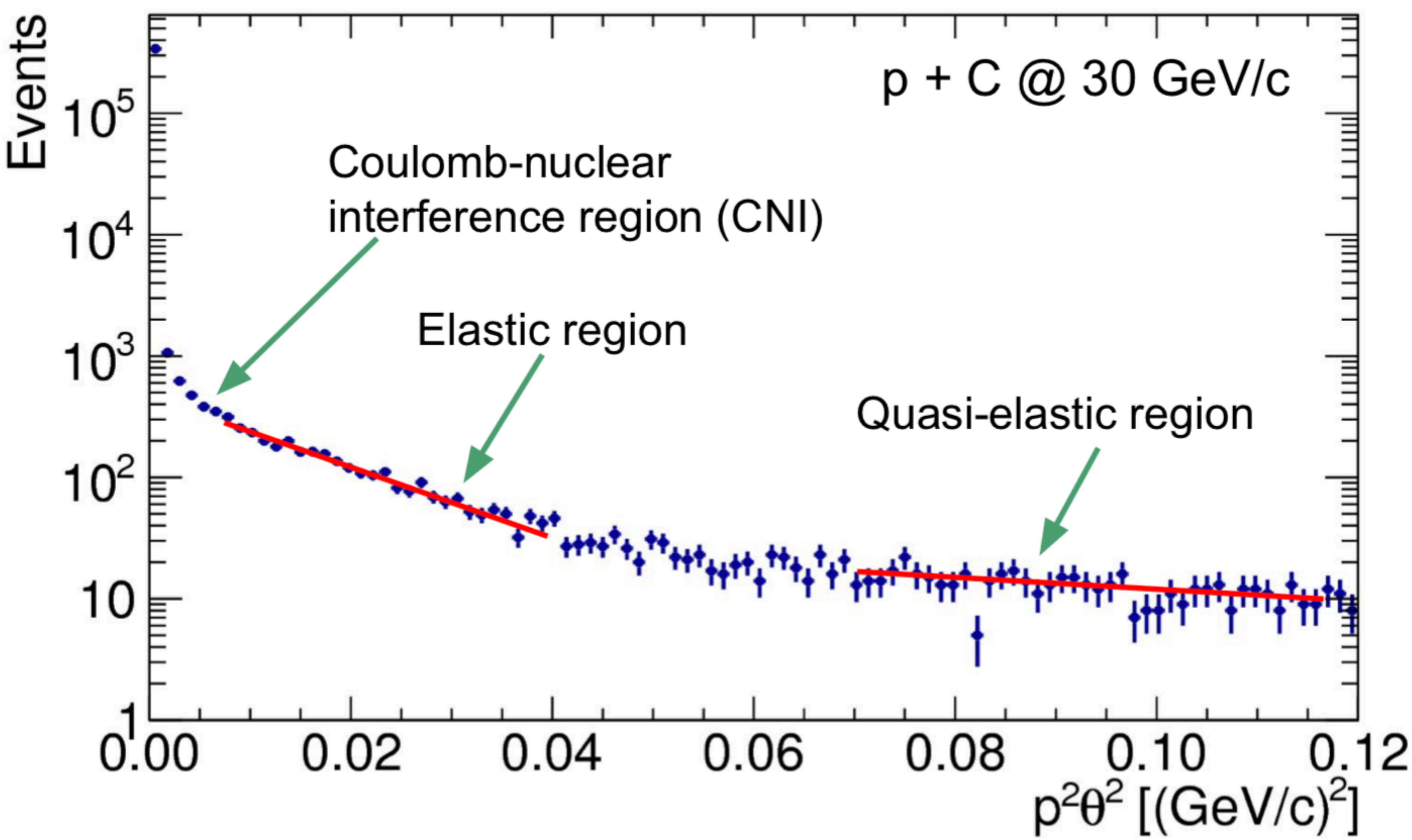




- Emulsion bricks include target and emulsion films
- Talk by Fukuda-san on Thursday

Forward Scattering Measurements

- Elastic and quasi-elastic scattering cross-sections can be determined by forward scattering data
- 20, 30, 120 GeV/c p + C data have been analyzed
- ~0.3mrad resolution was achieved with FTBF SSDs (60μm pitch)

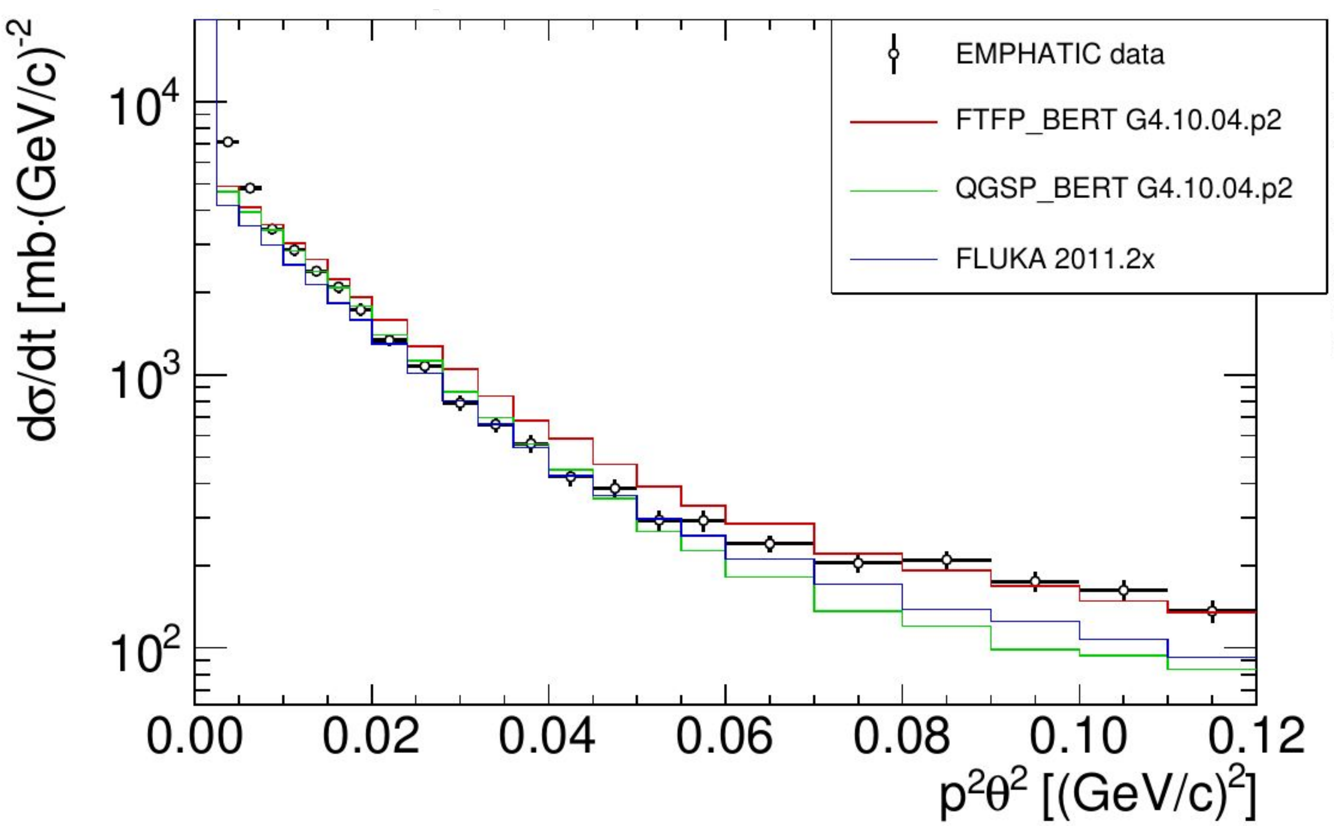


Momentum transfer $t \approx p^2\theta^2$ (p : incident momentum, θ: scattering angle)

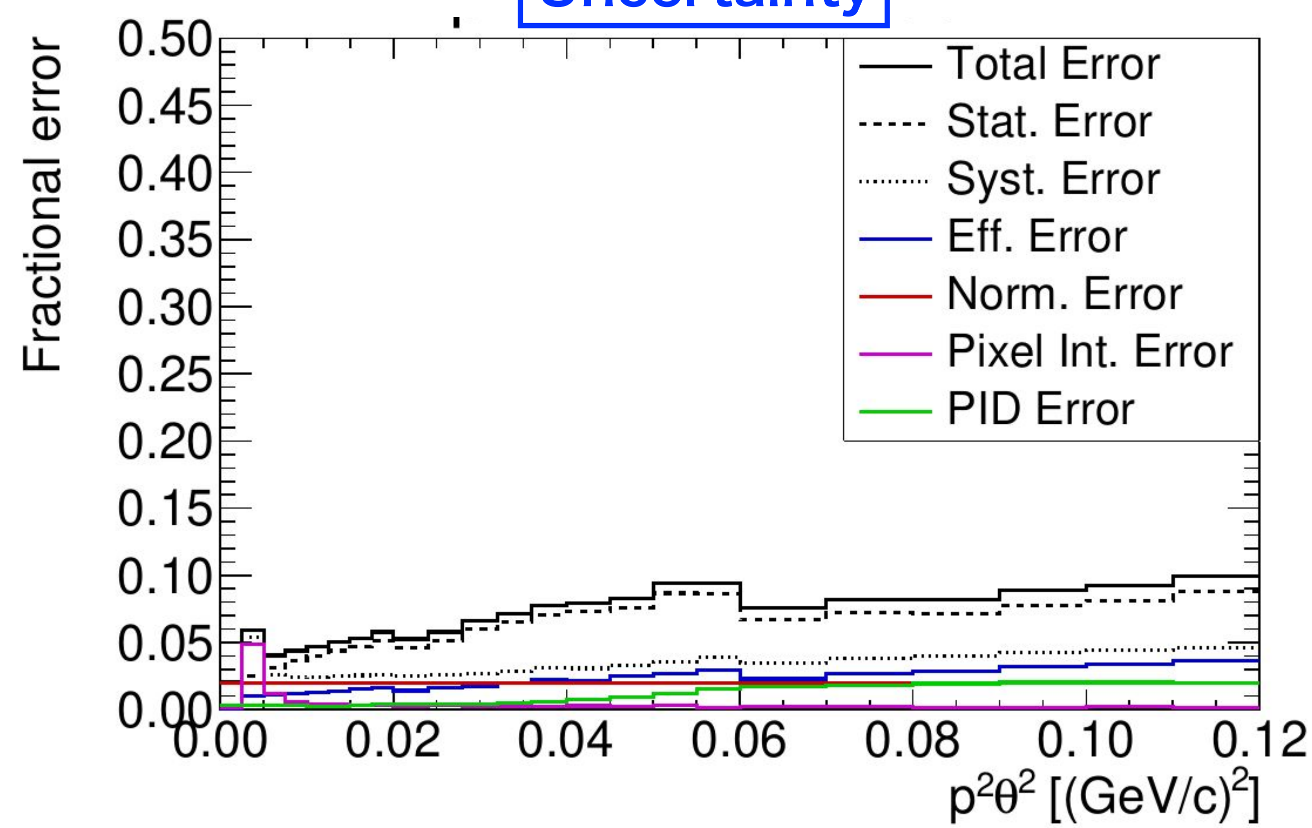
Forward Scattering Results

- Differential cross section for 30 GeV/c p + C data
- Measurement uncertainties <10%
  - Dominated by statistical uncertainty
  - Systematic uncertainties estimated with both data and MC ⇒ <5%
    - Dominant error is due to efficiency estimation by MC (model dependence) ~4%

Differential cross section



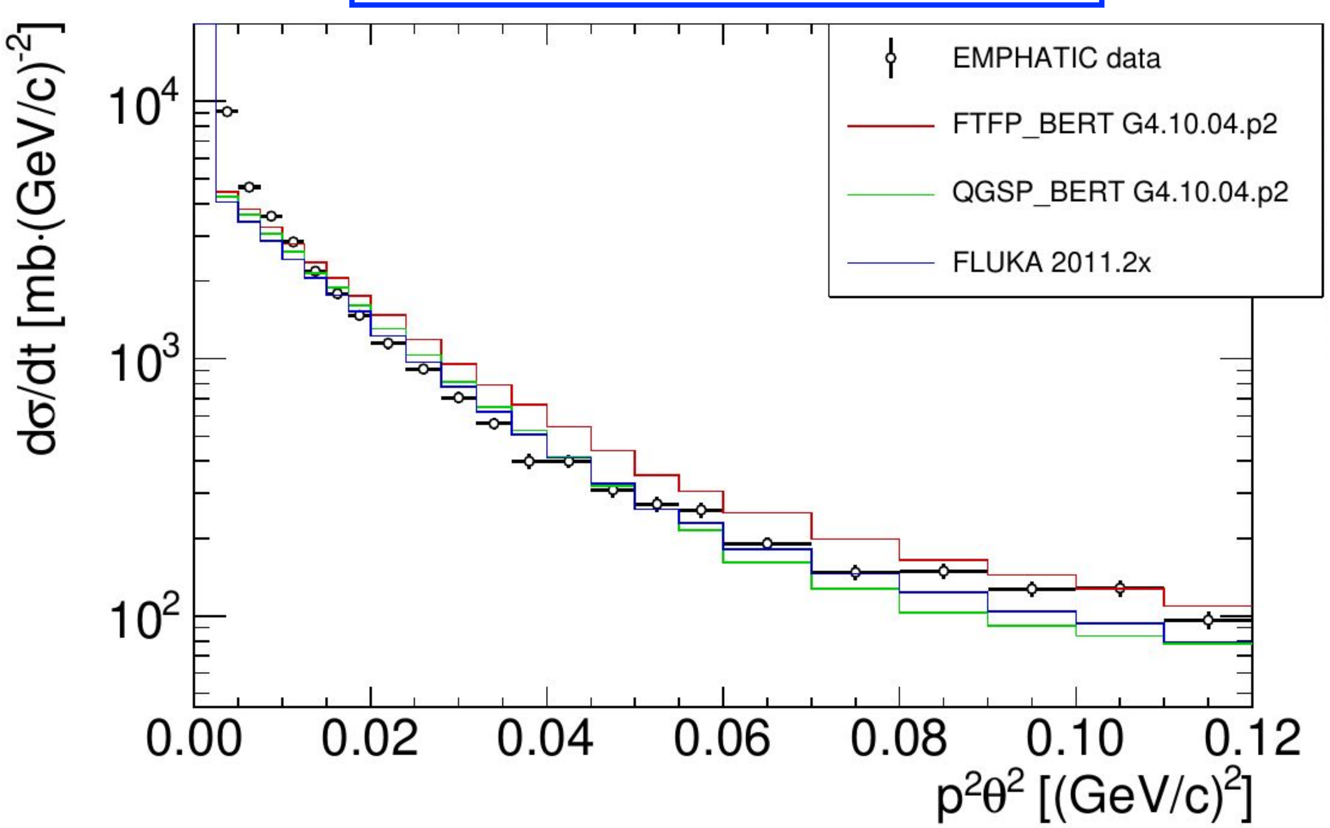
Uncertainty



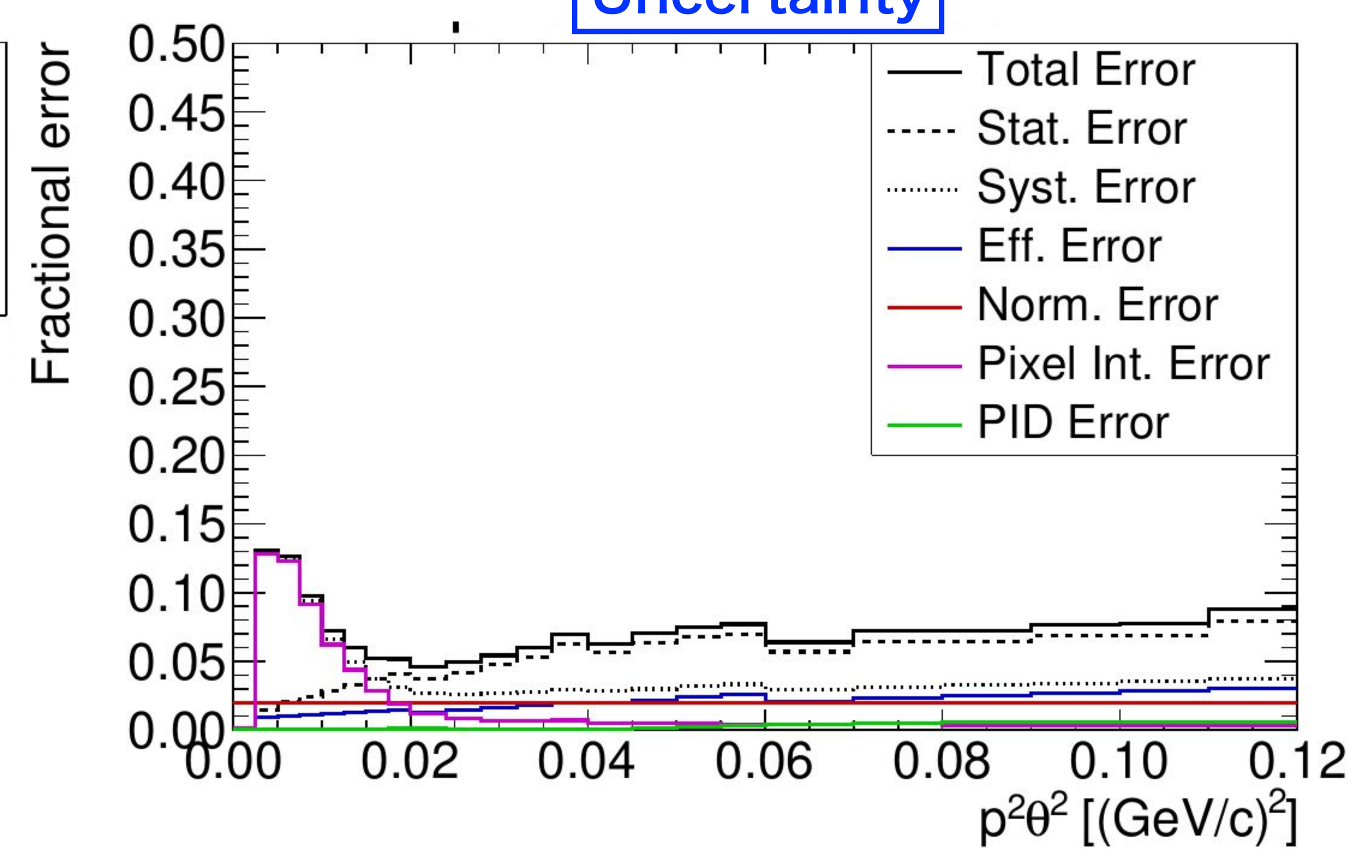
Forward Scattering Results

- Differential cross section for 120 GeV/c p + C data
- Measurement uncertainties <10%
  - Dominated by statistical uncertainty
  - Systematic uncertainties estimated with both data and MC ⇒ <4%
    - Dominant error is due to efficiency estimation by MC (model dependence) ~3%
    - Large pixel interaction error in lower bins

Differential cross section

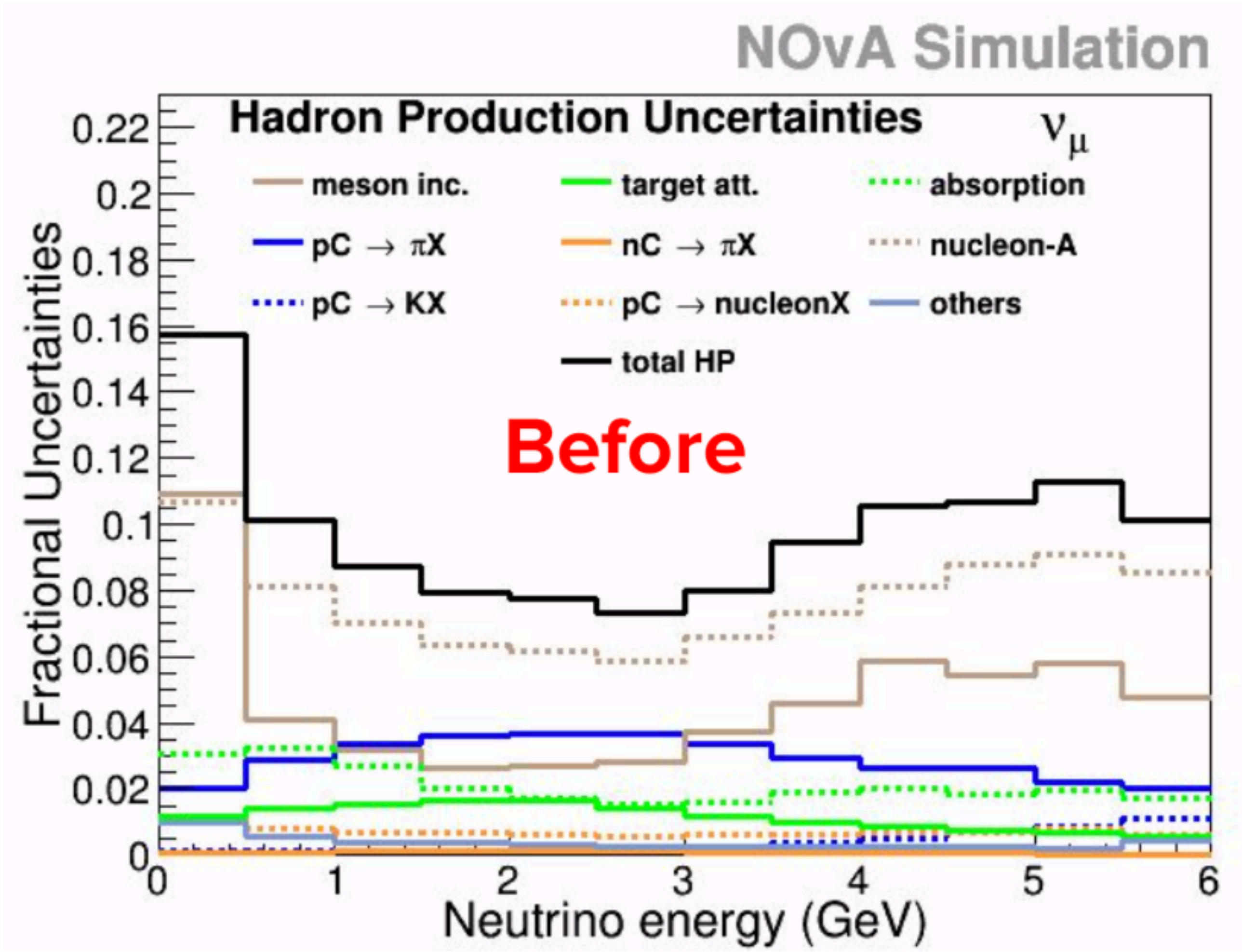


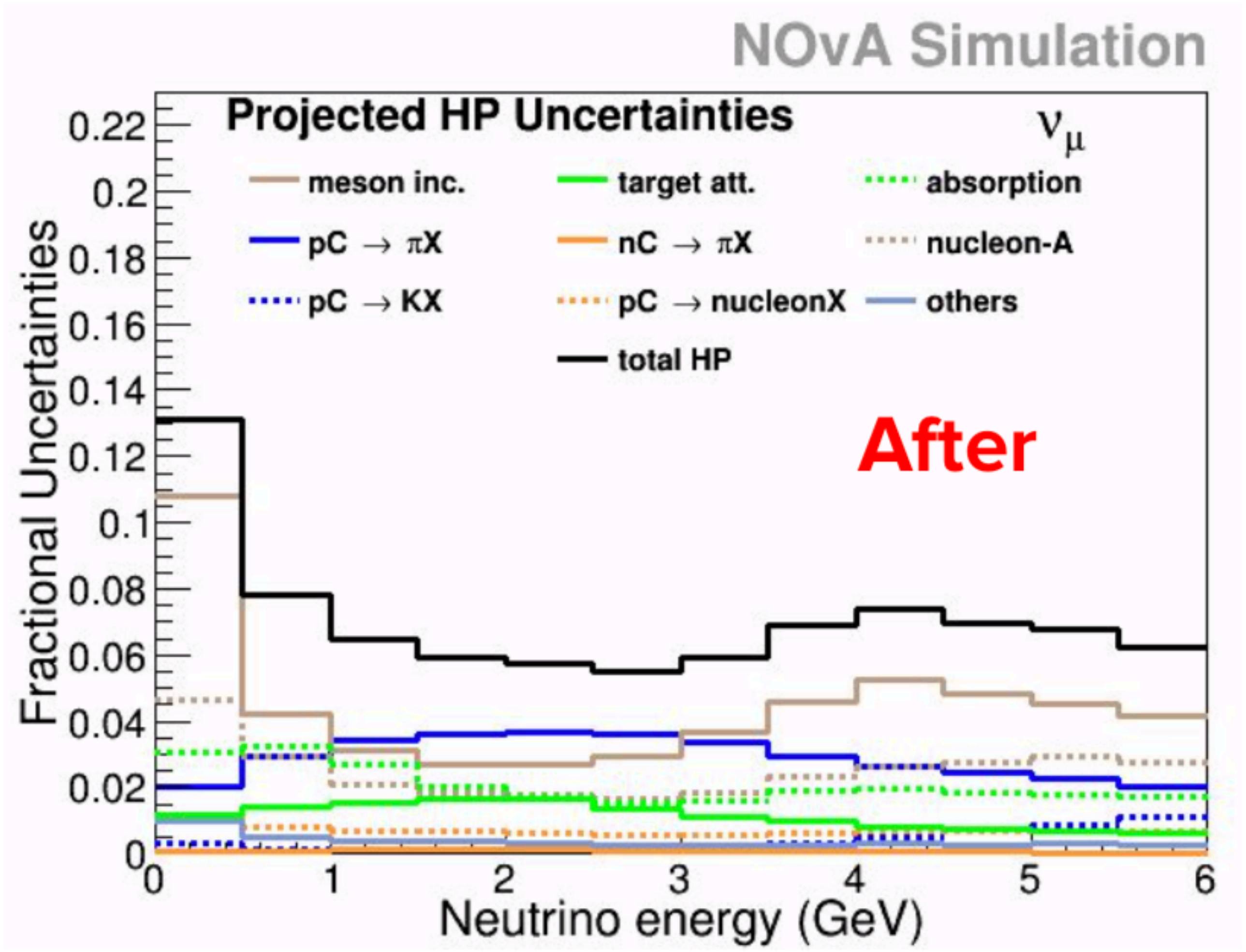
Uncertainty



Impact of 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





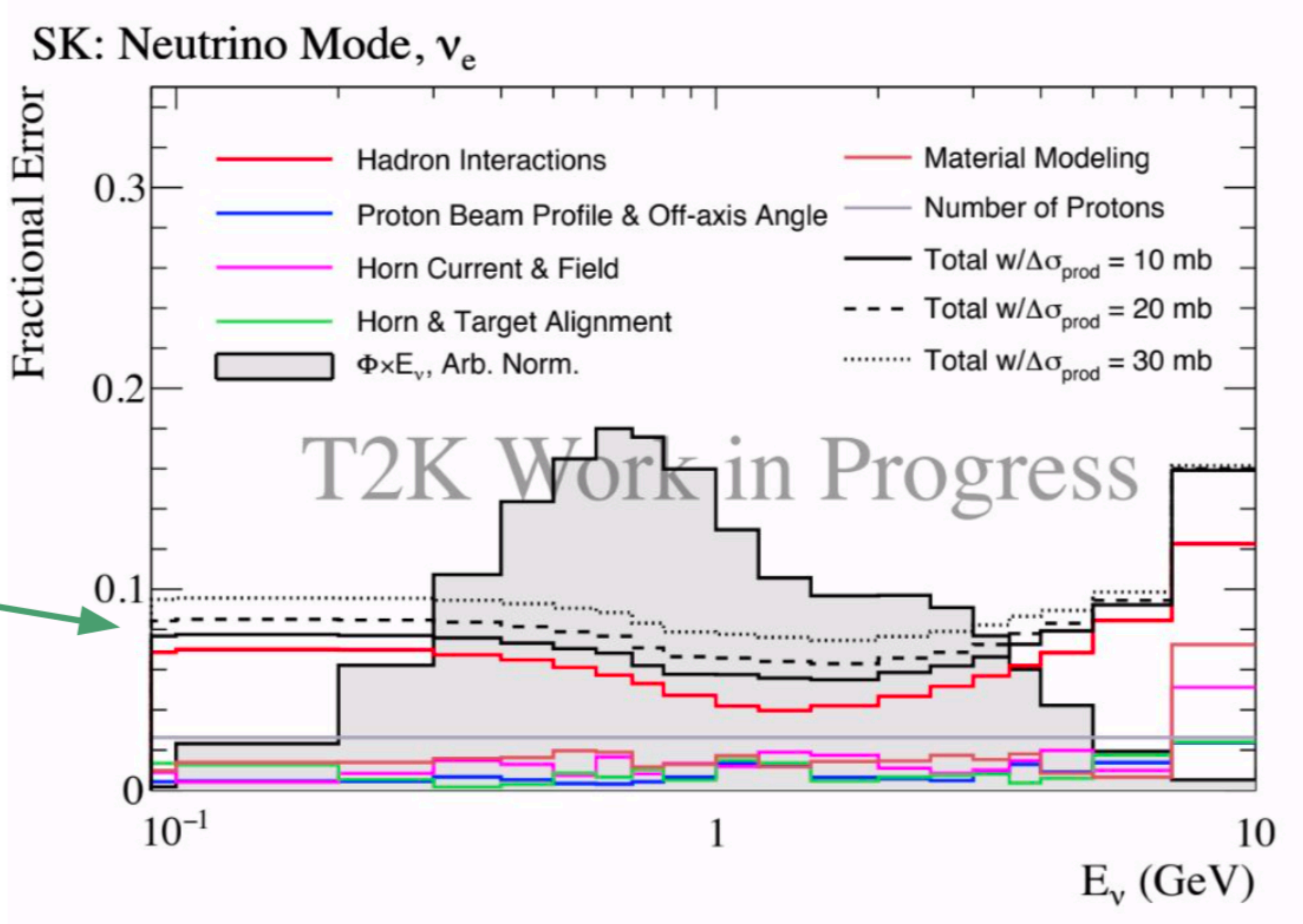
Impact of Current Results (II)

- EMPHATIC results can reduce thin target reweighting uncertainty in T2K
- Thin vs. replica differences (under investigation)

$$\sigma_{pro} = \sigma_{inel} - \sigma_{qe}$$

Dominant uncertainty on σ_{pro} comes from uncertainty on σ_{qe}

Different lines show uncertainties after reducing production cross-section uncertainty to 30, 20, and 10 mb



Current Status

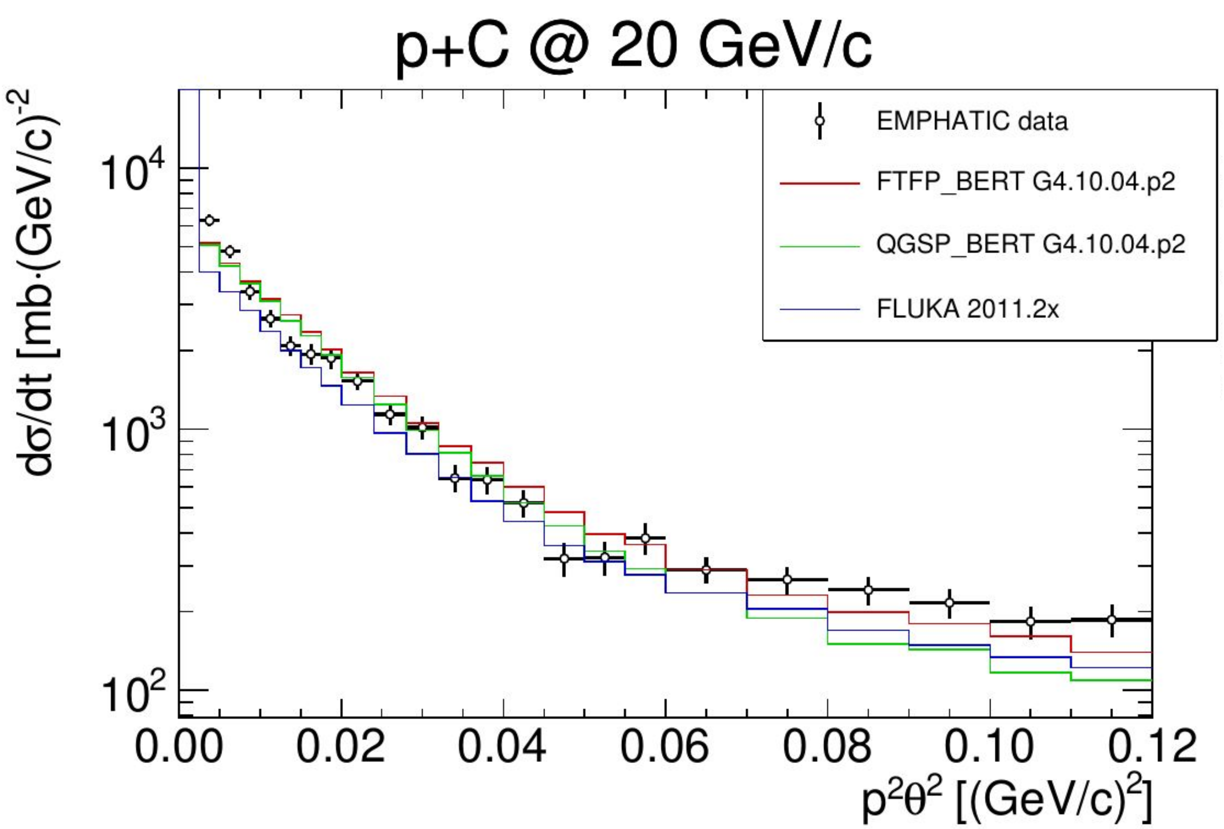
- Preparing a paper for 2018 results → to be submitted soon
- Budget situation
  - Funding for detector construction approved in Japan and Canada
  - Severe situation in US
- Proposal submitted to Fermilab PAC in July 2019
- Detector development ongoing toward 2020 run
  - Beam aerogel counter
  - Magnet
  - Aerogel RICH
  - ToF
  - Lead glass calorimeter
- New collaborators are really welcome !!

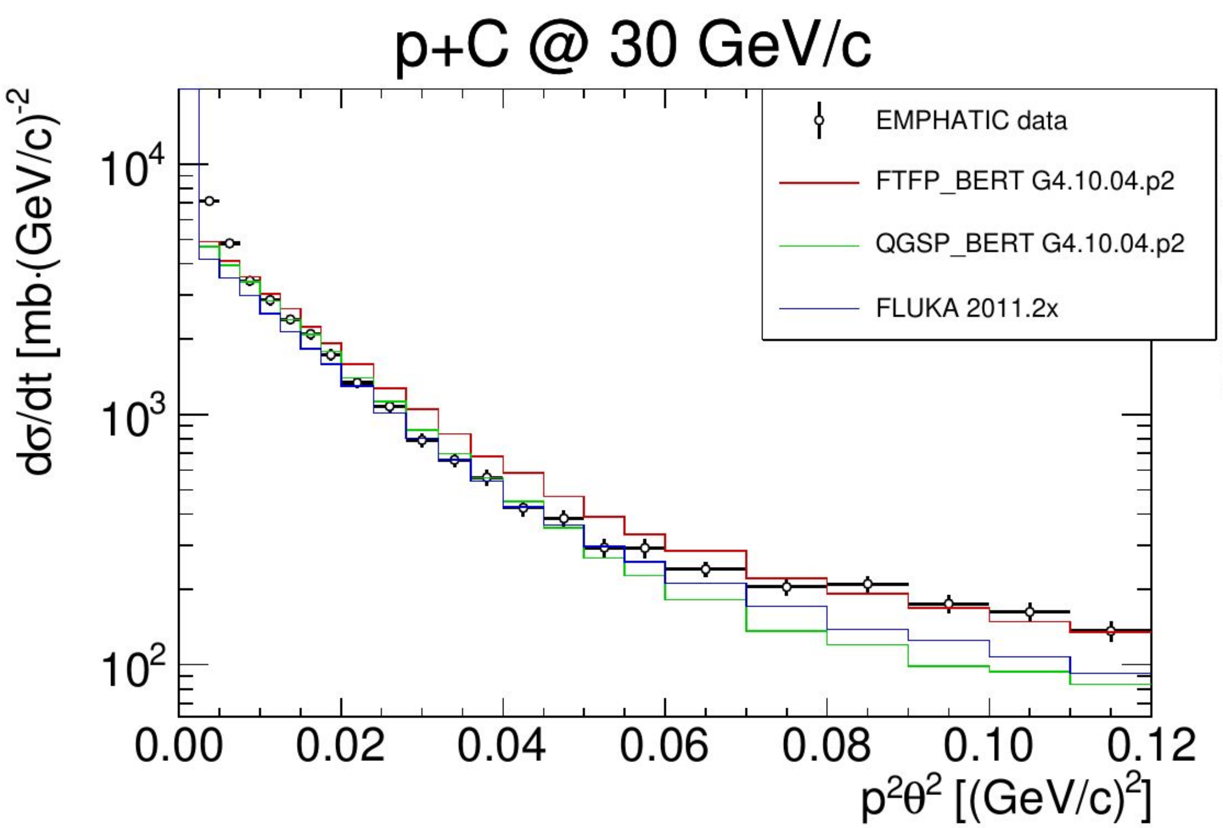
Summary

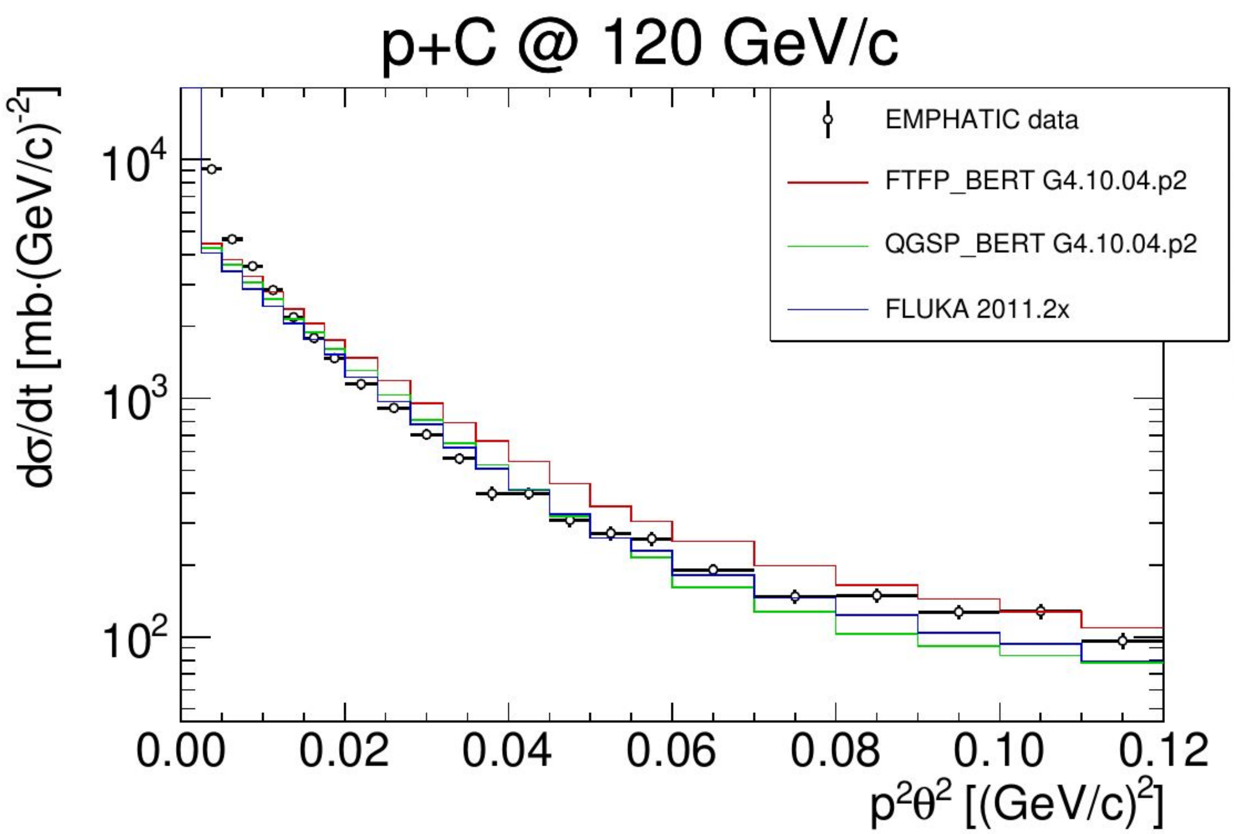
- Hadron production measurements played significant role in reducing neutrino flux uncertainties to 5-10% level
- Measurements of π and K at low energies important for future neutrino experiments, but current data are very limited
- EMPHATIC aims to perform precise hadron production measurements using high resolution trackers and compact spectrometer
- Measurements with various targets across various momenta planed in 2020-2022
- Detector development ongoing for 2020 run
- Performed a pilot run in January 2018 and forward scattering results with 10% uncertainties which can improve flux uncertainties

Backup

Forward Scattering Results







Systematic Error Estimation