



A Novel Modular Ring Imaging Cherenkov (mRICH) Detector for the Experiments in the Electron-Ion Collider

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Georgia State University

For the EIC RD14 Collaboration



Outline

1. Motivation
2. Modular RICH prototype detector and beam test
3. Ongoing Study

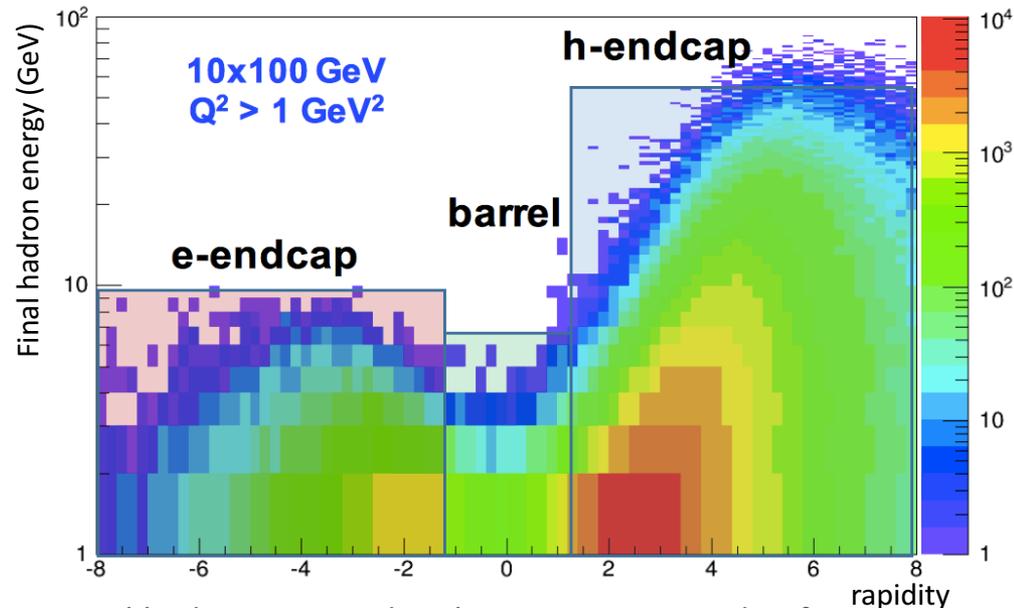
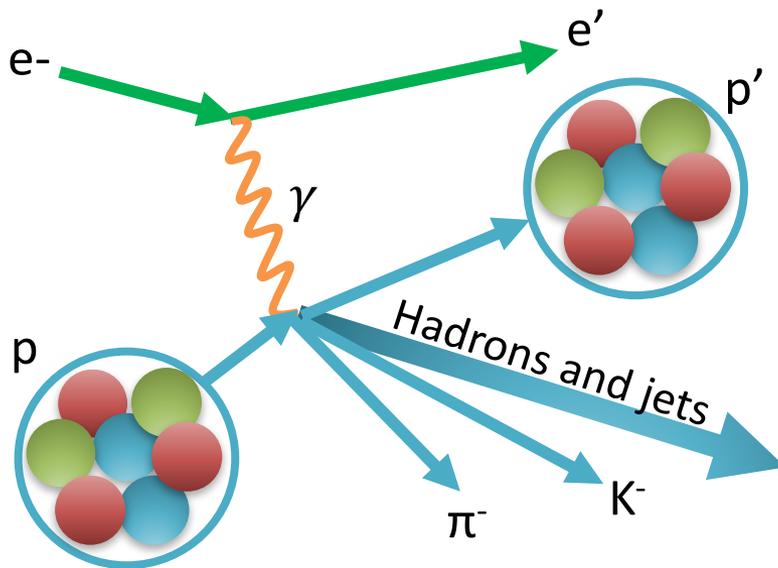


Motivation



Charged Hadron Identification in EIC

Tagging the flavor of the struck quark in semi-inclusive deep inelastic scattering

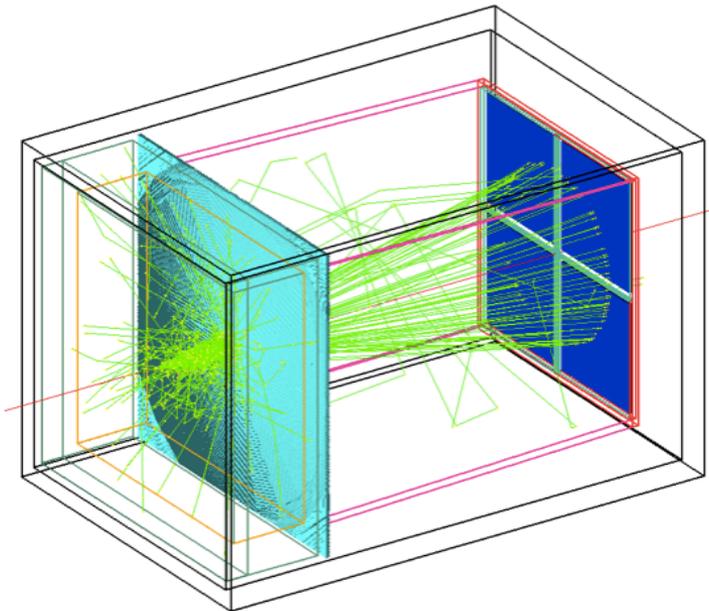


Final hadron energy distribution versus rapidity from proton (10 GeV/c) electron (100 GeV/c) collision Pythia simulation

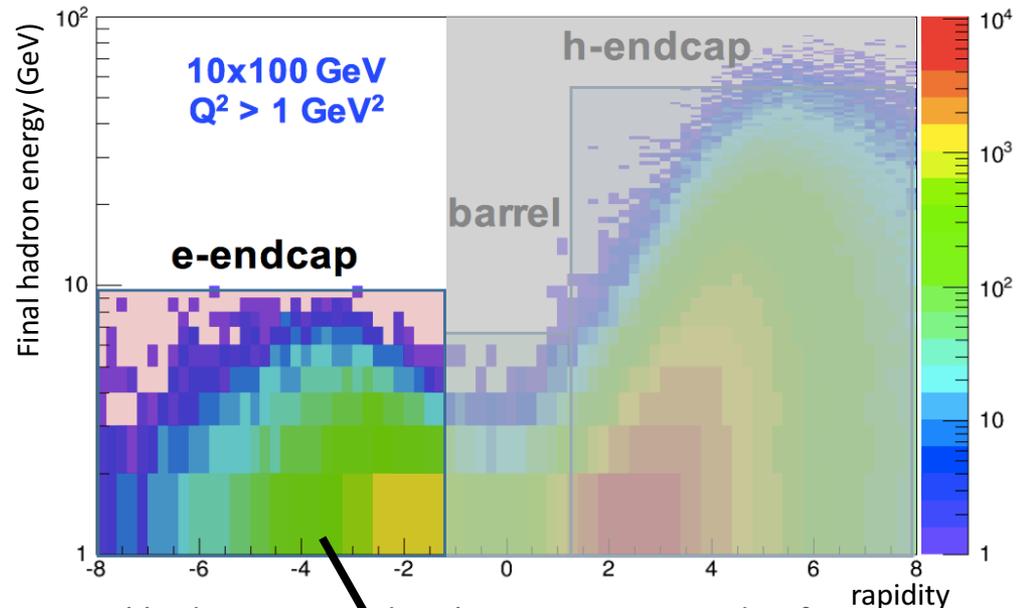
- Obtain gluon and quark distributions in spatial, momentum and spin space from transverse momentum of final hadrons (kaons and pions)
- $K^- (s\bar{u})$ from final $\phi(s\bar{s})$ decay \rightarrow strange sea quarks distribution inside nucleon



Charged Hadron PID in EIC Experiment



Modular RICH (mRICH) Detector

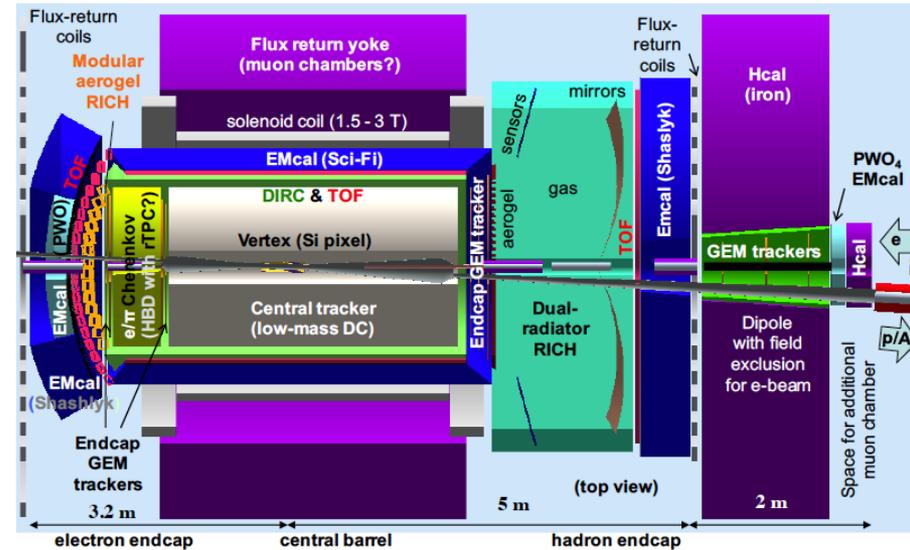
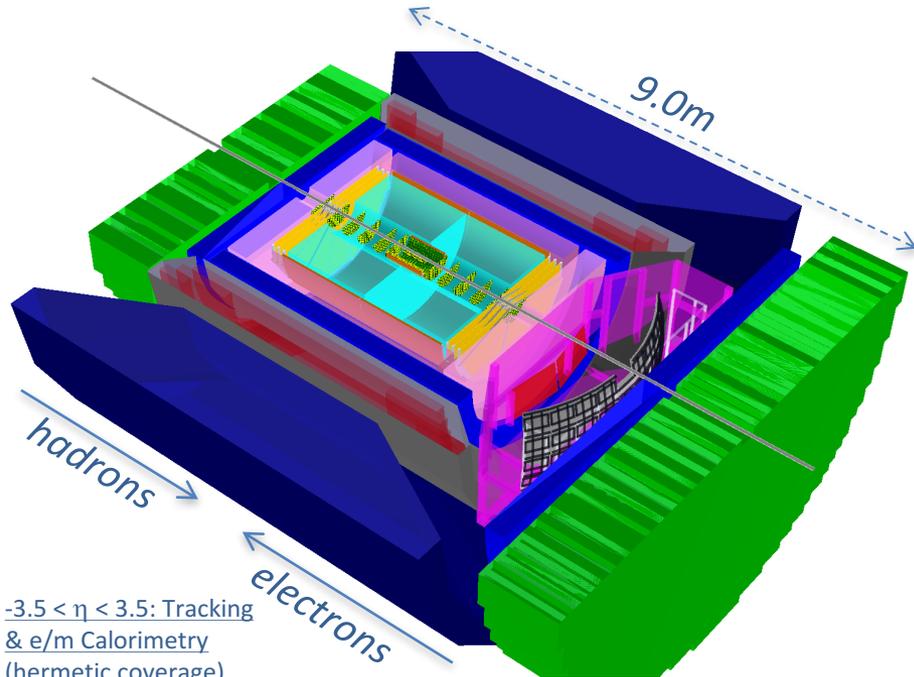


Final hadron energy distribution versus rapidity from proton (10 GeV/c) electron (100 GeV/c) collision Pythia simulation

k/pi separation up to 10 GeV/c

EIC Detector Designs

e/m calorimeters hadronic calorimeters silicon trackers RICH detectors



JLEIC Detector

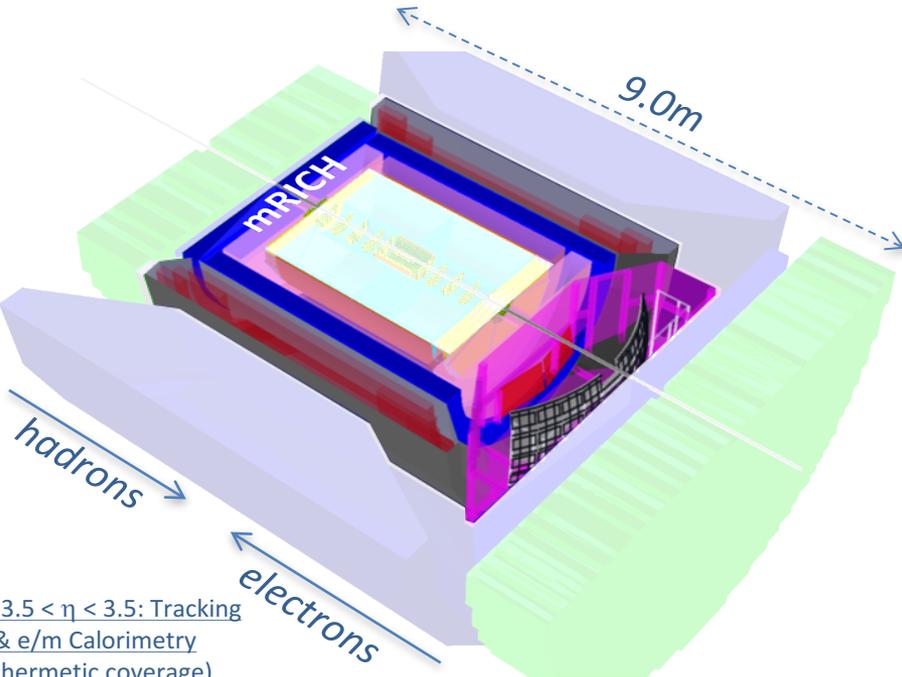
GEM trackers Micromegas barrels 3T solenoid cryostat TPC magnet yoke

BeAST Detector

Alexander Kiselev, The Electron Ion Collider User Group Meeting, July 2016

EIC Detector Designs

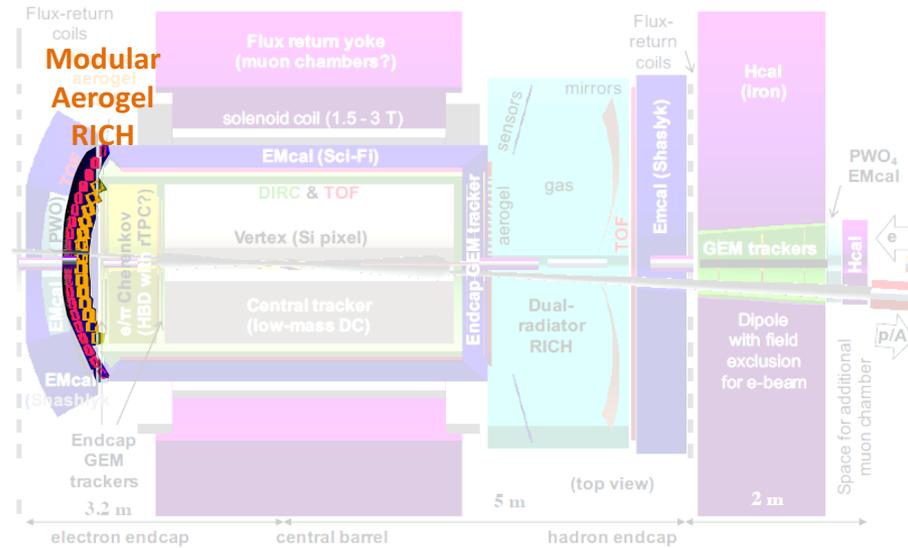
e/m calorimeters hadronic calorimeters silicon trackers RICH detectors



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BeAST Detector

Alexander Kiselev, The Electron Ion Collider User Group Meeting, July 2016

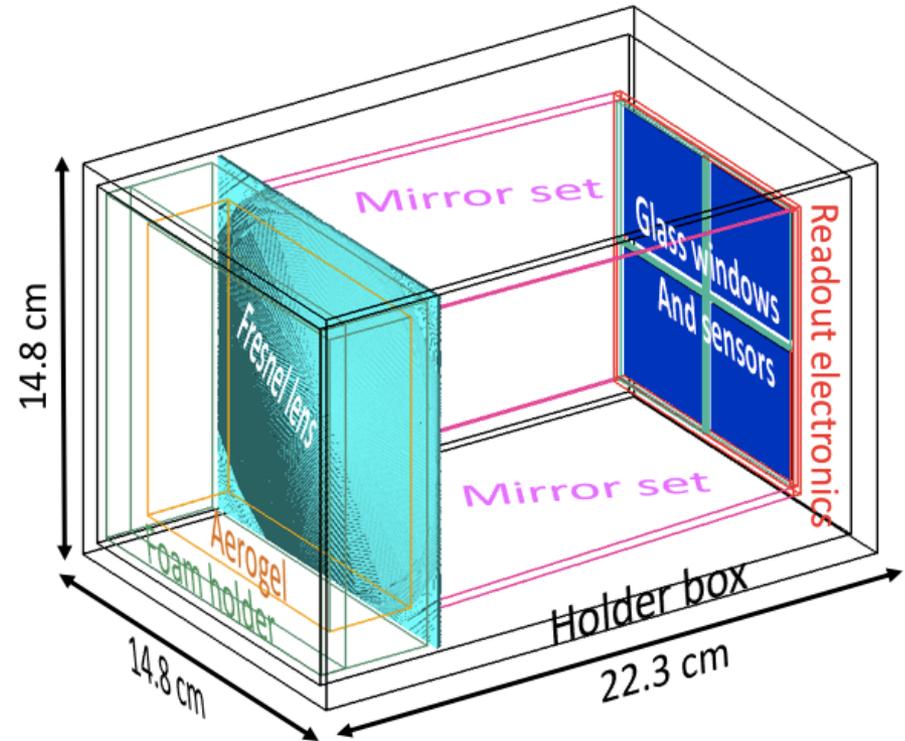
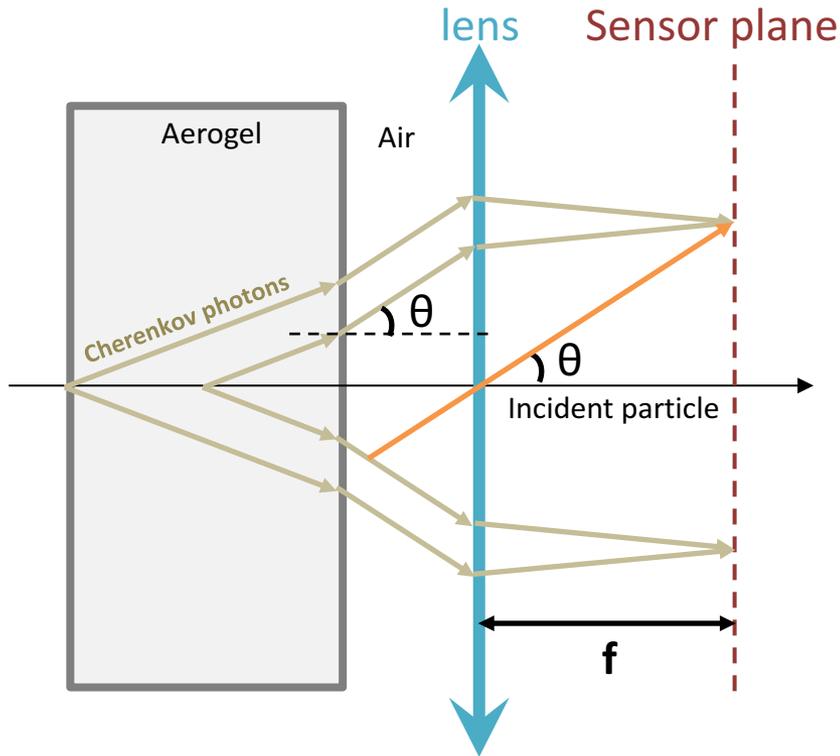


JLEIC Detector



Modular RICH (mRICH) Prototype and Beam Test

Design of mRICH Prototype

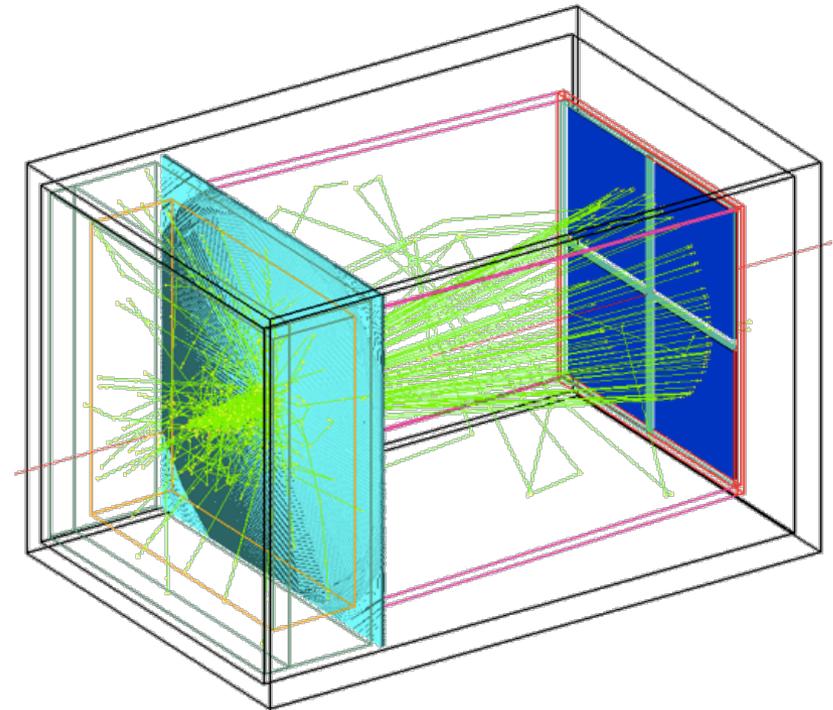
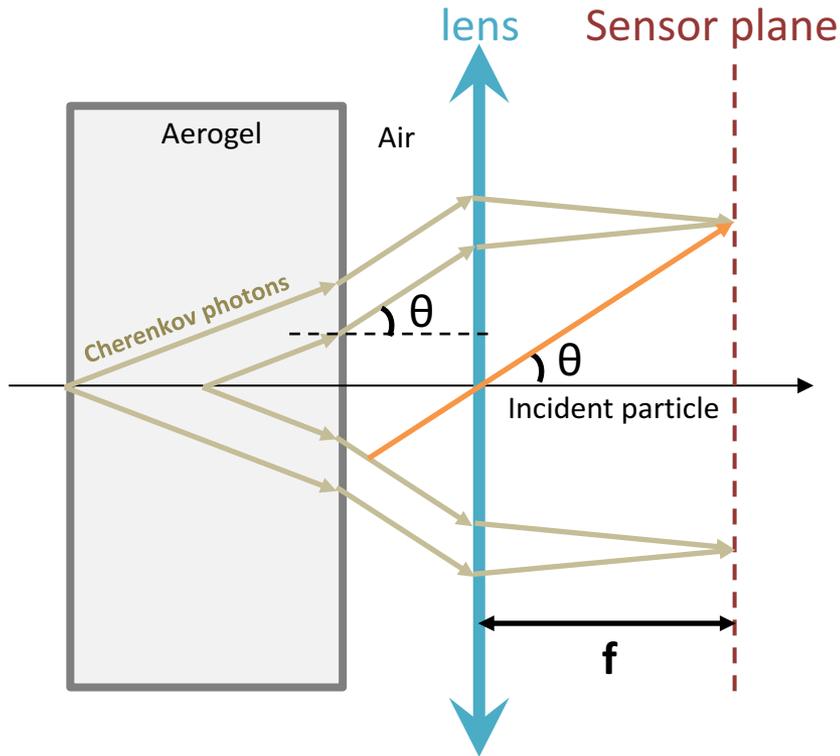


Since parallel rays are focused at the same point, emission point uncertainty which is raised by thickness of aerogel is minimized

Detector layout shown in Geant4 simulation



Lens Based Design of mRICH Prototype

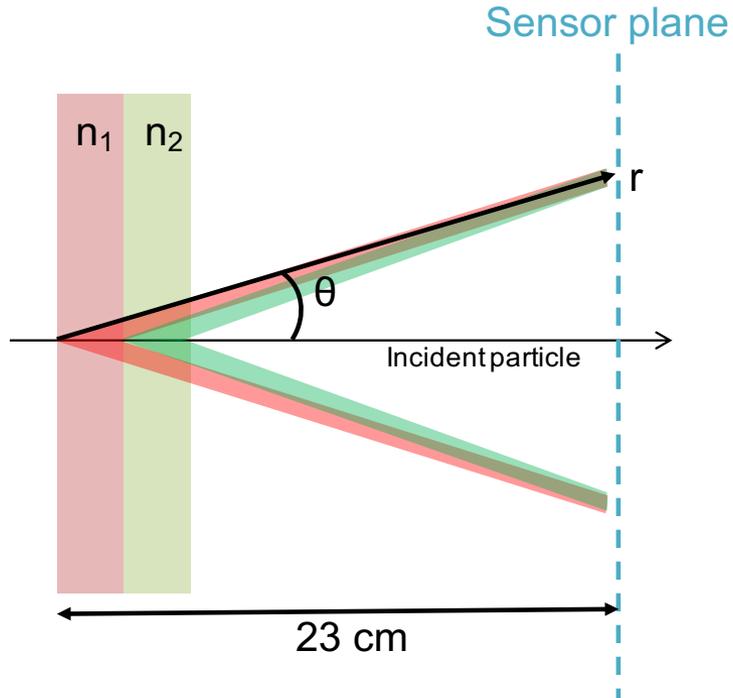


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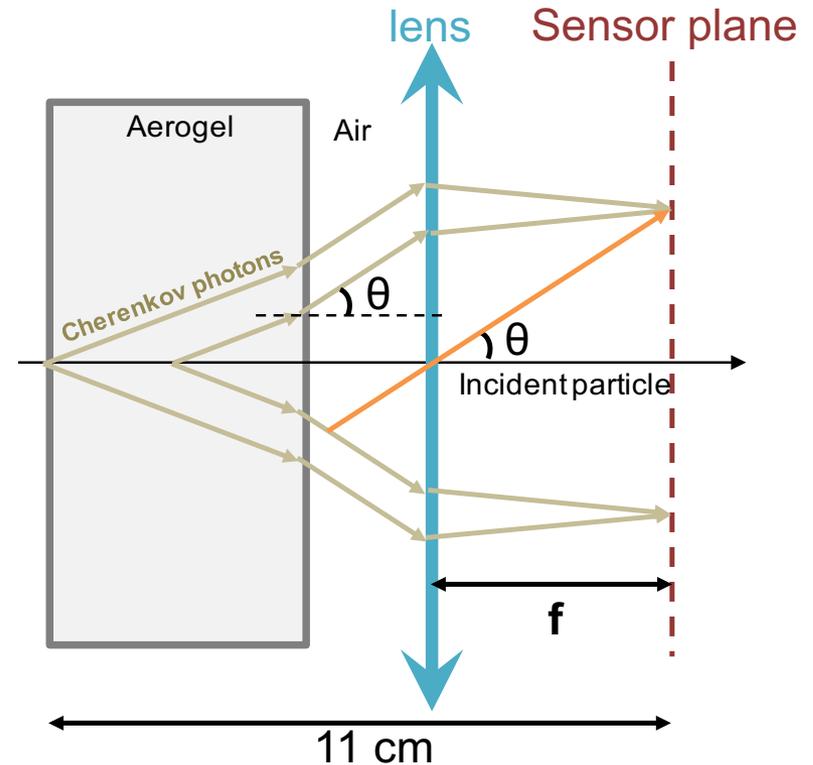
Event display of single pion at 10 GeV/c

Lens Based Design -- Focusing

Proximity Focusing Design

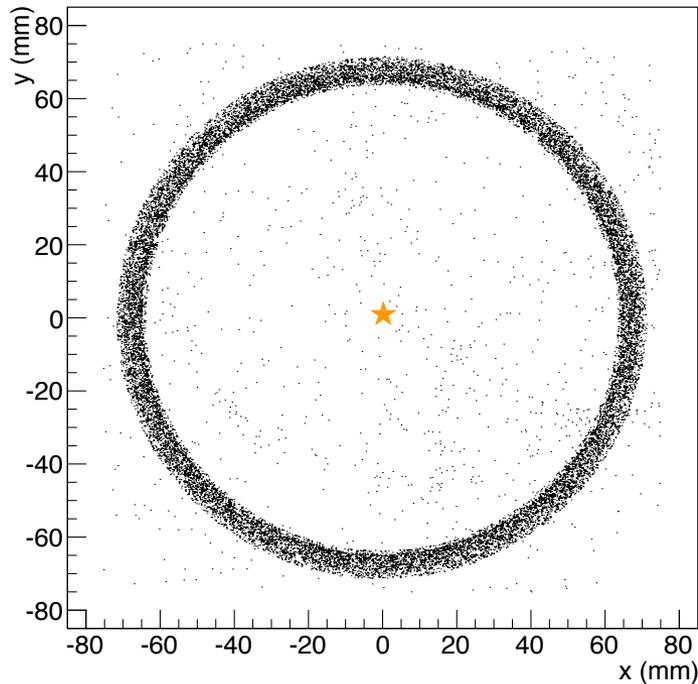


mRICH Design



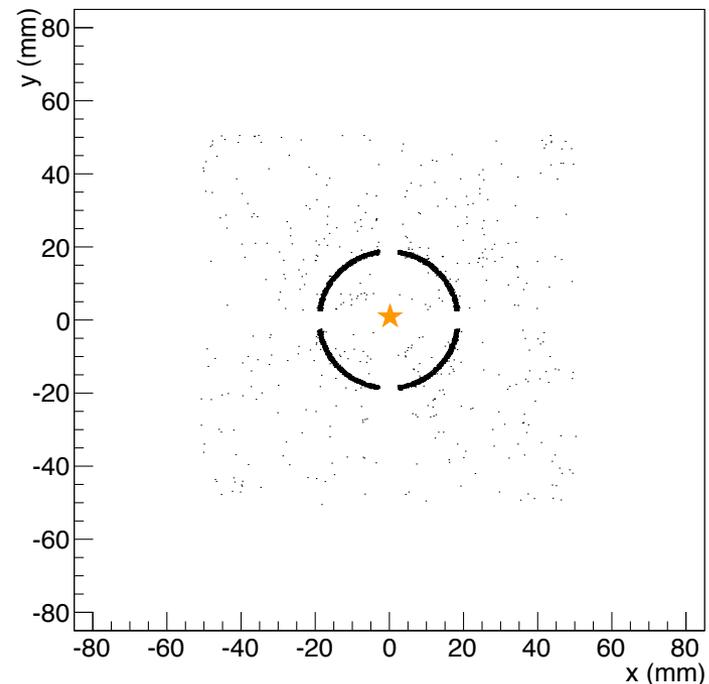
Lens Based Design -- Focusing

Proximity Focusing Design



Larger and smeared ring

mRICH Design

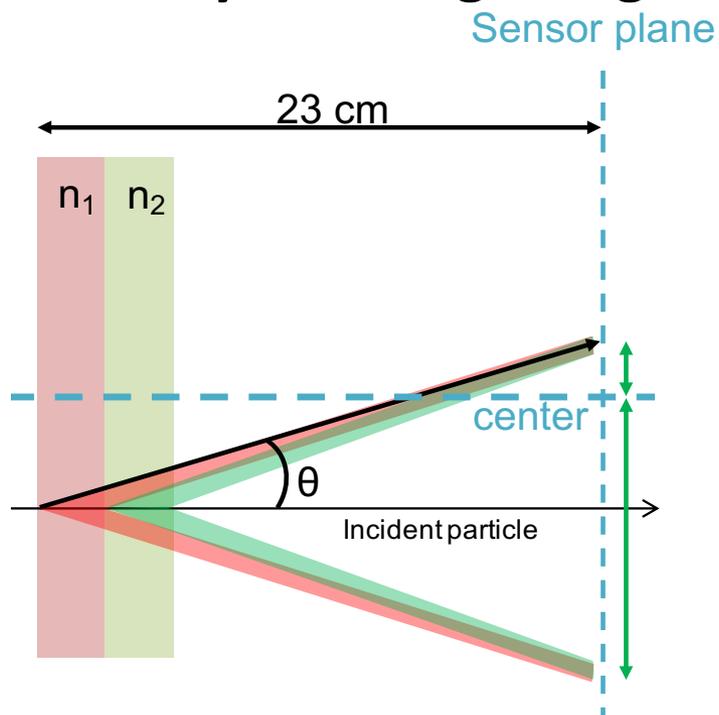


smaller and thinner ring

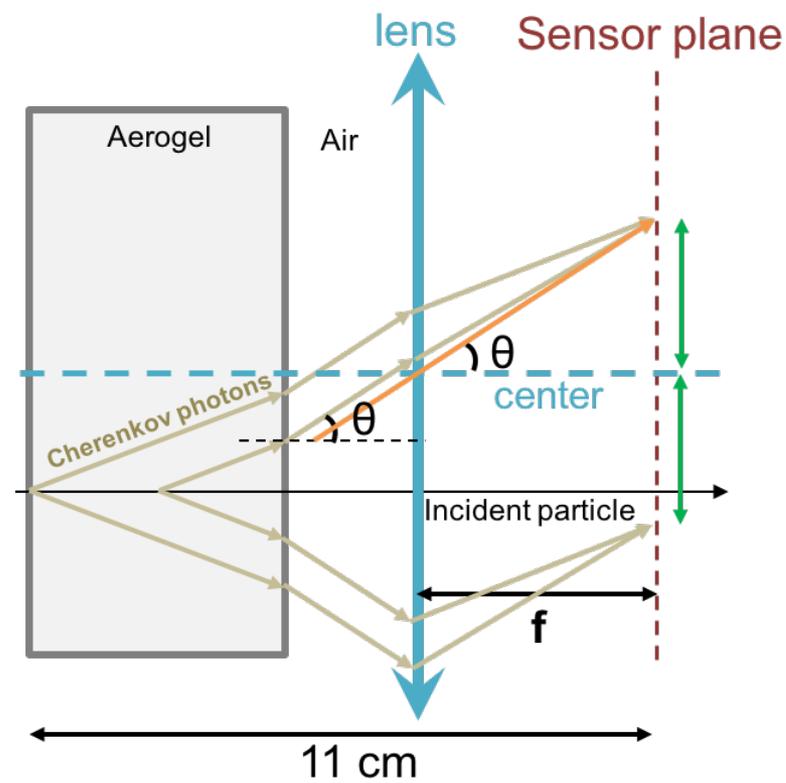


Additional mRICH Design Feature

Proximity Focusing Design



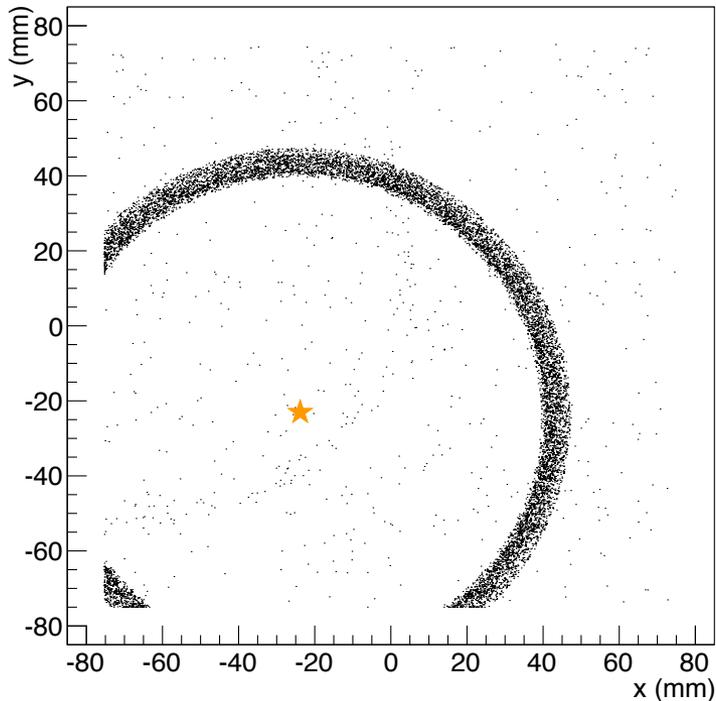
mRICH Design



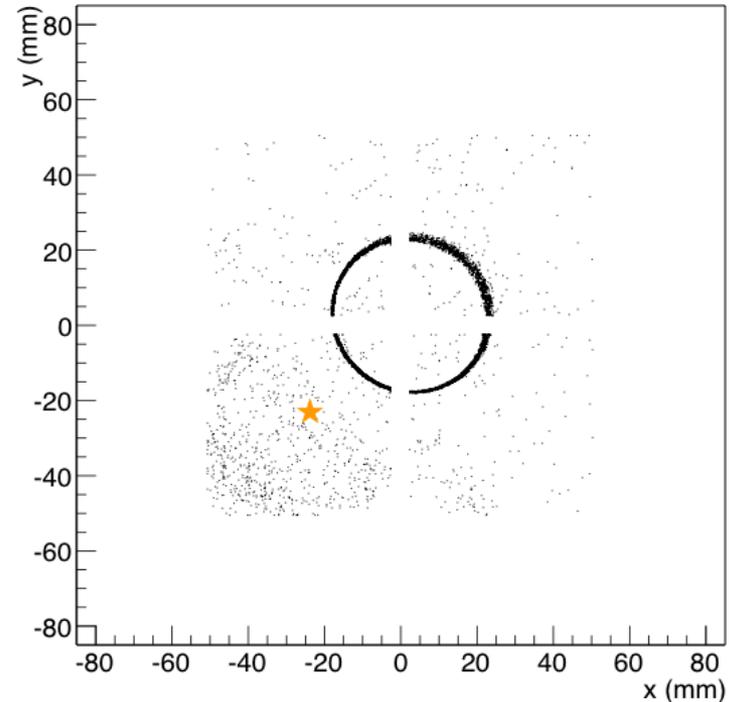


Additional mRICH Design Feature

Proximity Focusing Design

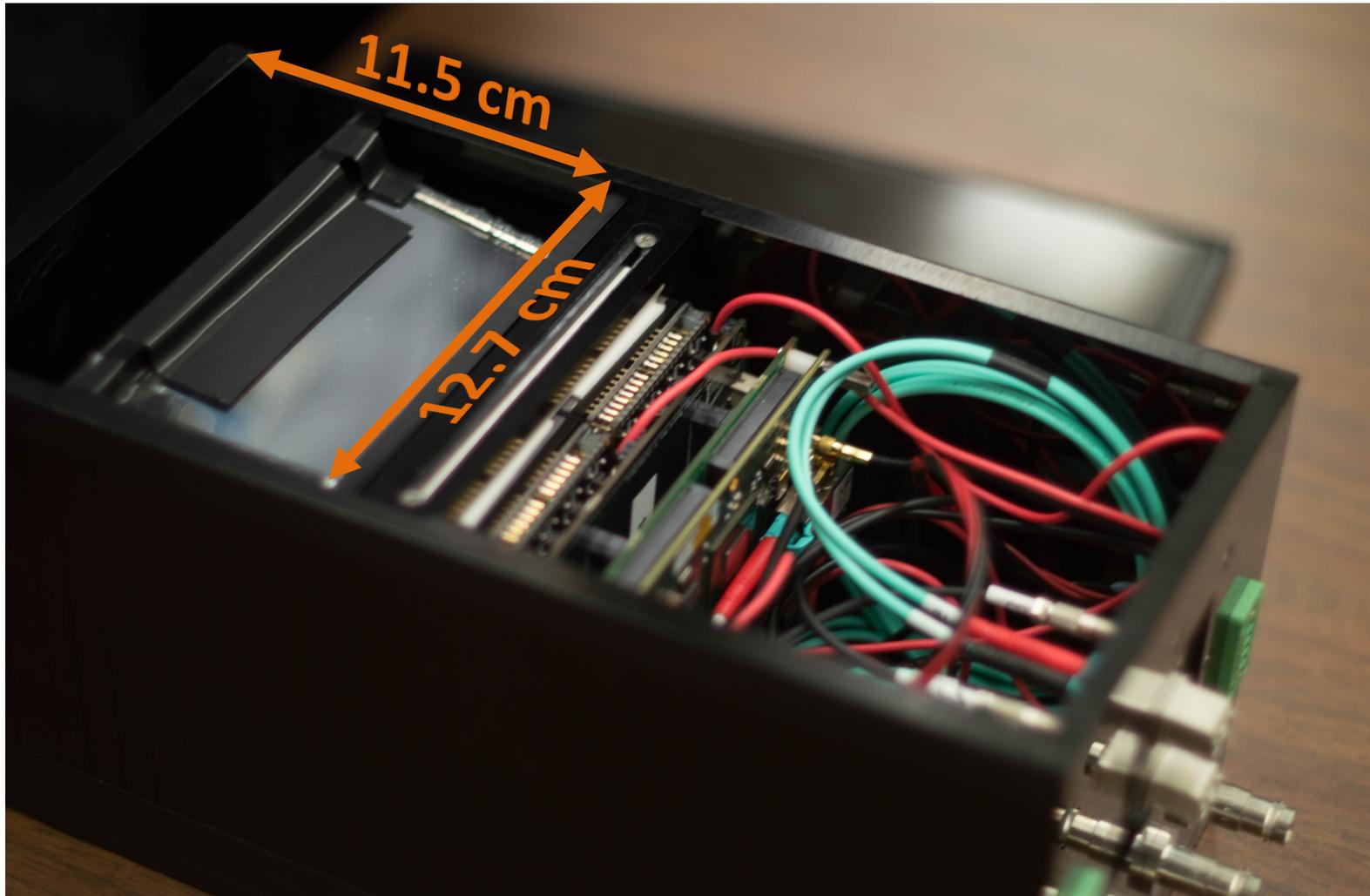


mRICH design

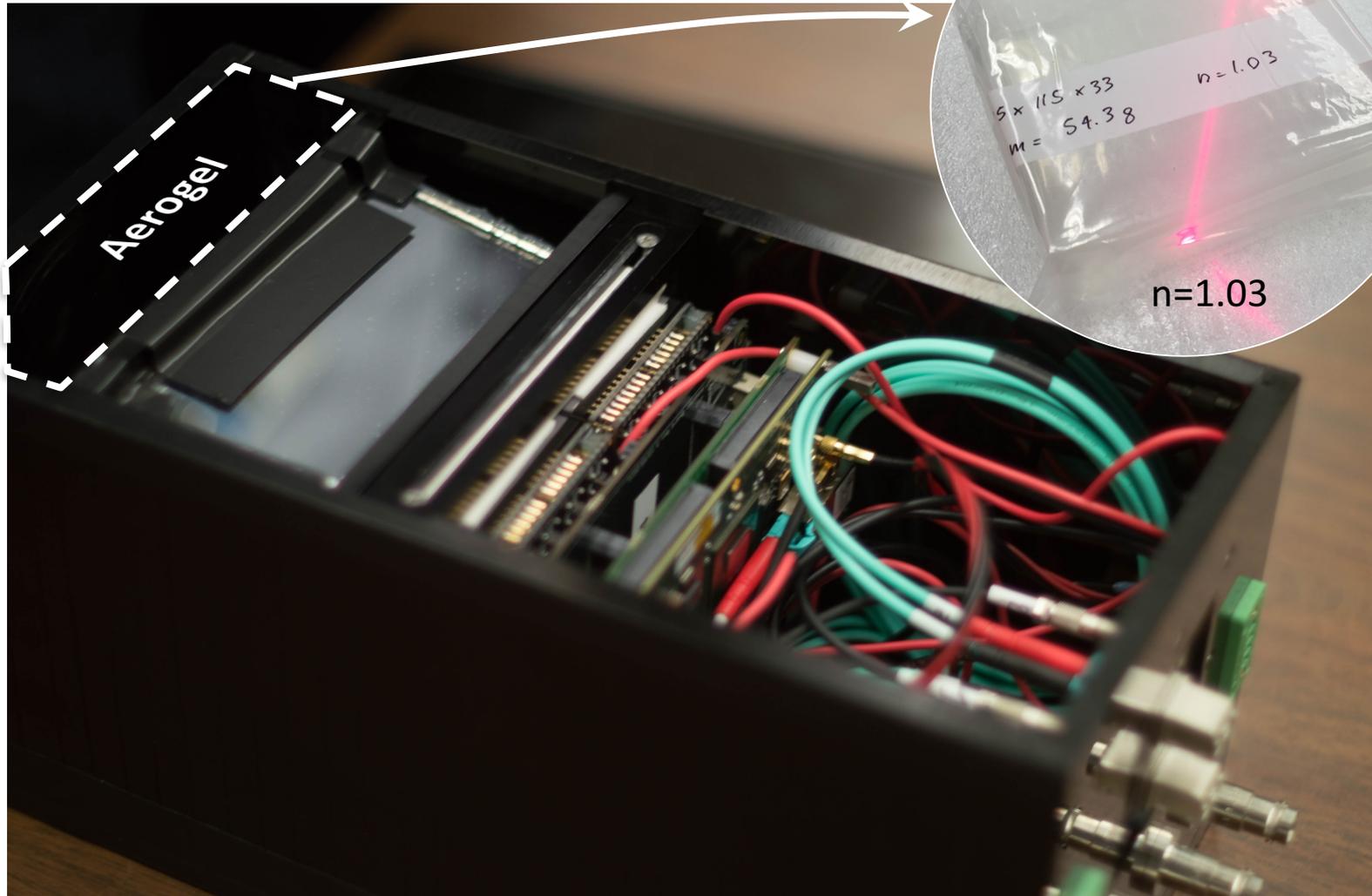


Ring image remain in the central area of the sensor plane

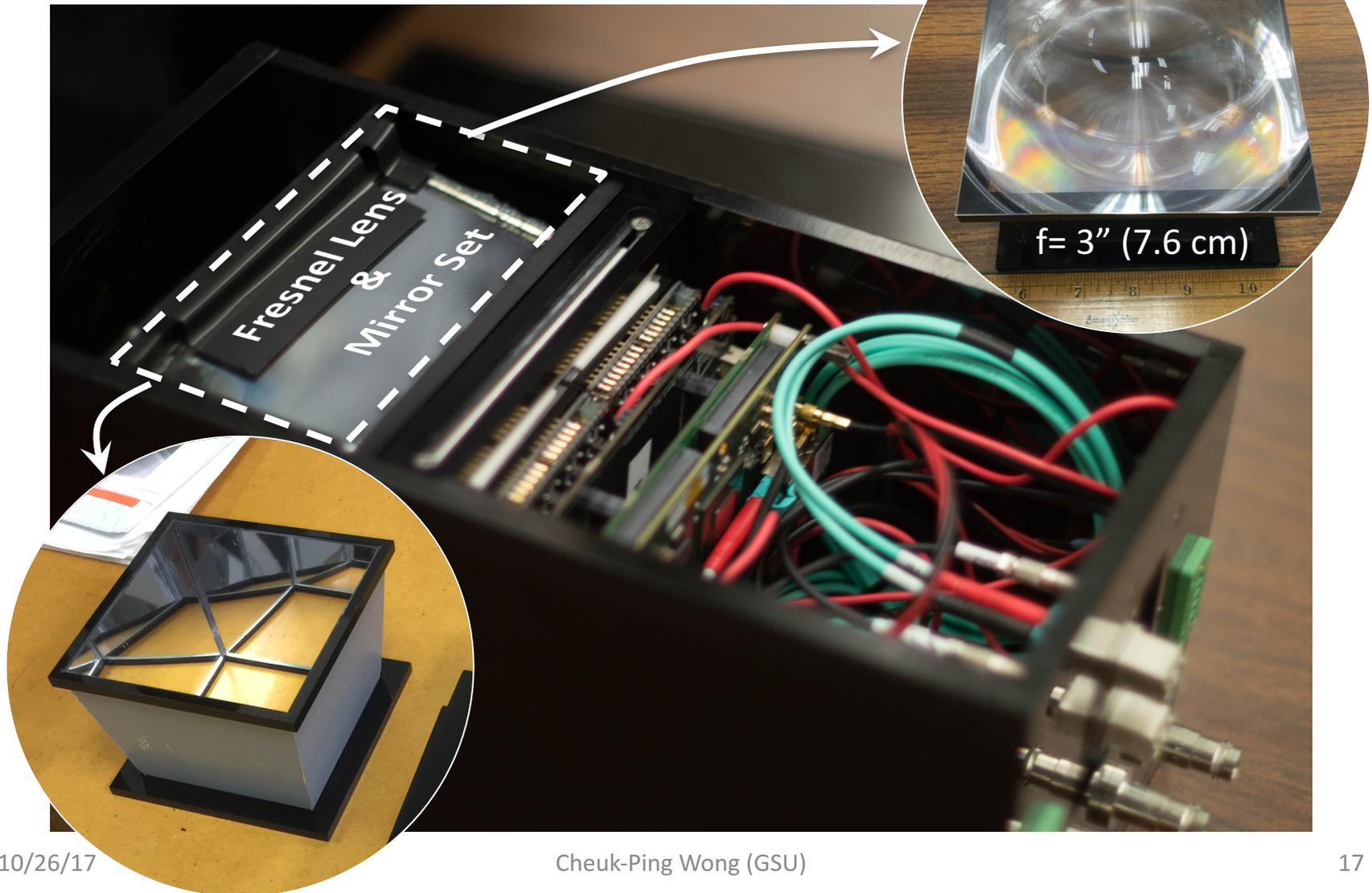
1st Prototype



1st Prototype



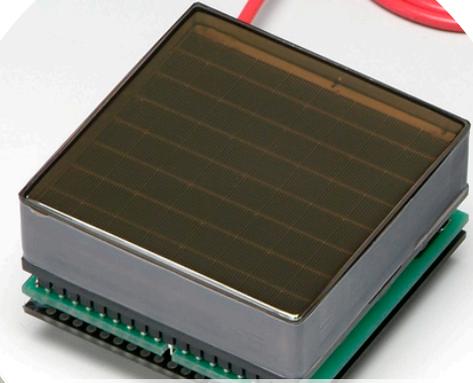
1st Prototype



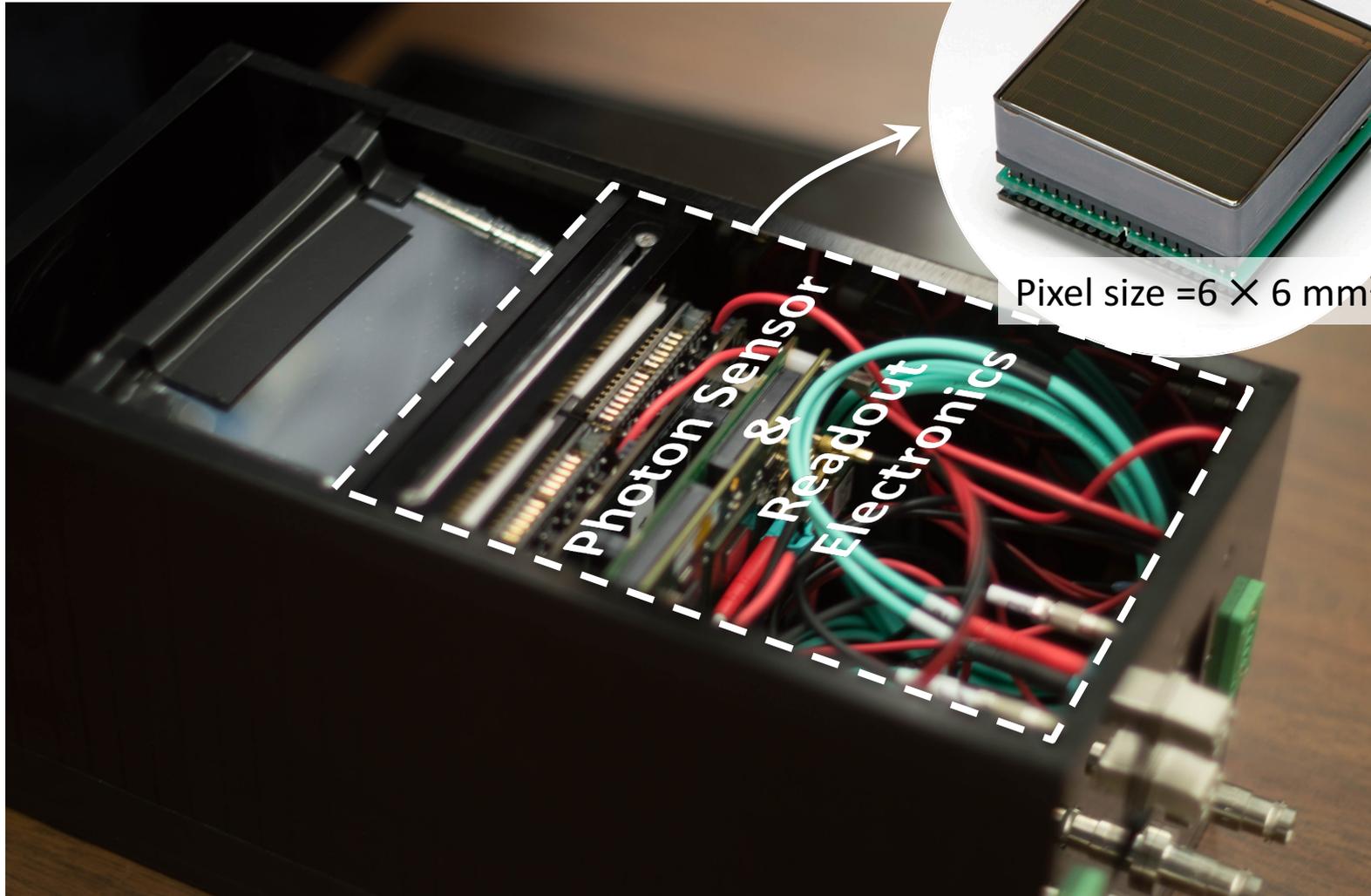


1st Prototype

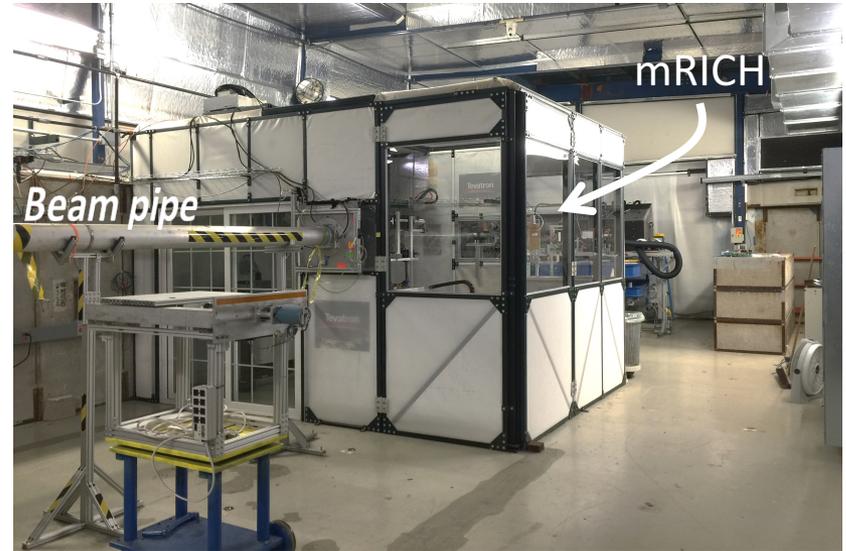
Hamamatsu H8500



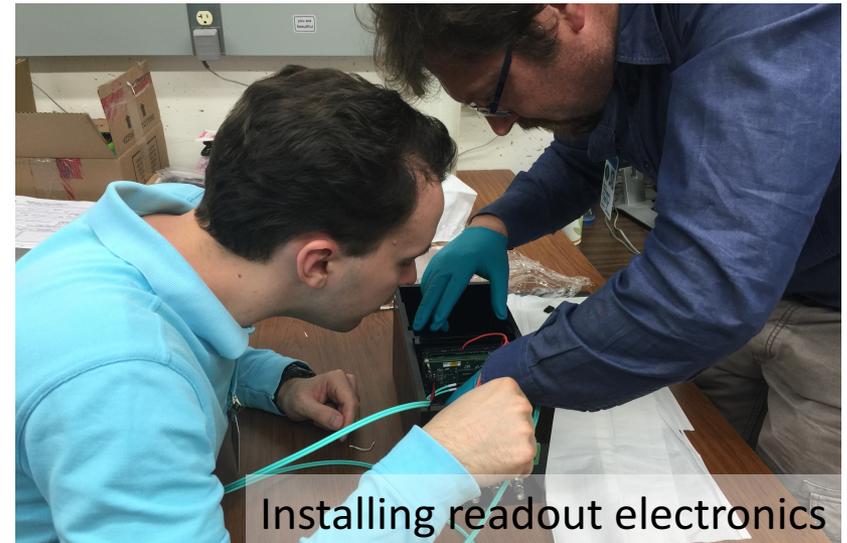
Pixel size = $6 \times 6 \text{ mm}^2$



Beam Test at Fermilab

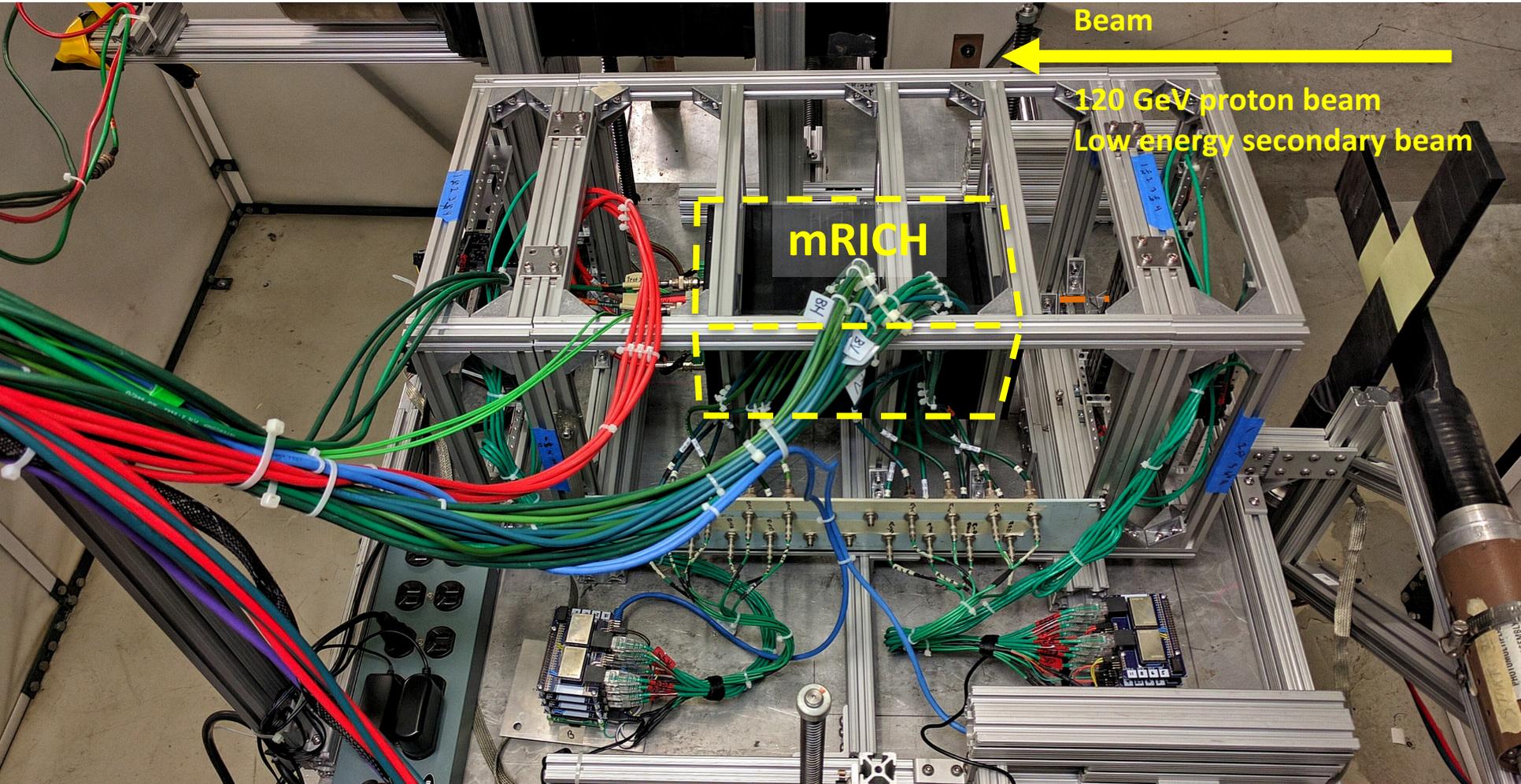


- April 17th to 29th 2016
- At Fermilab Mtest facility
- Goal of beam test : Testing mRICH working principle



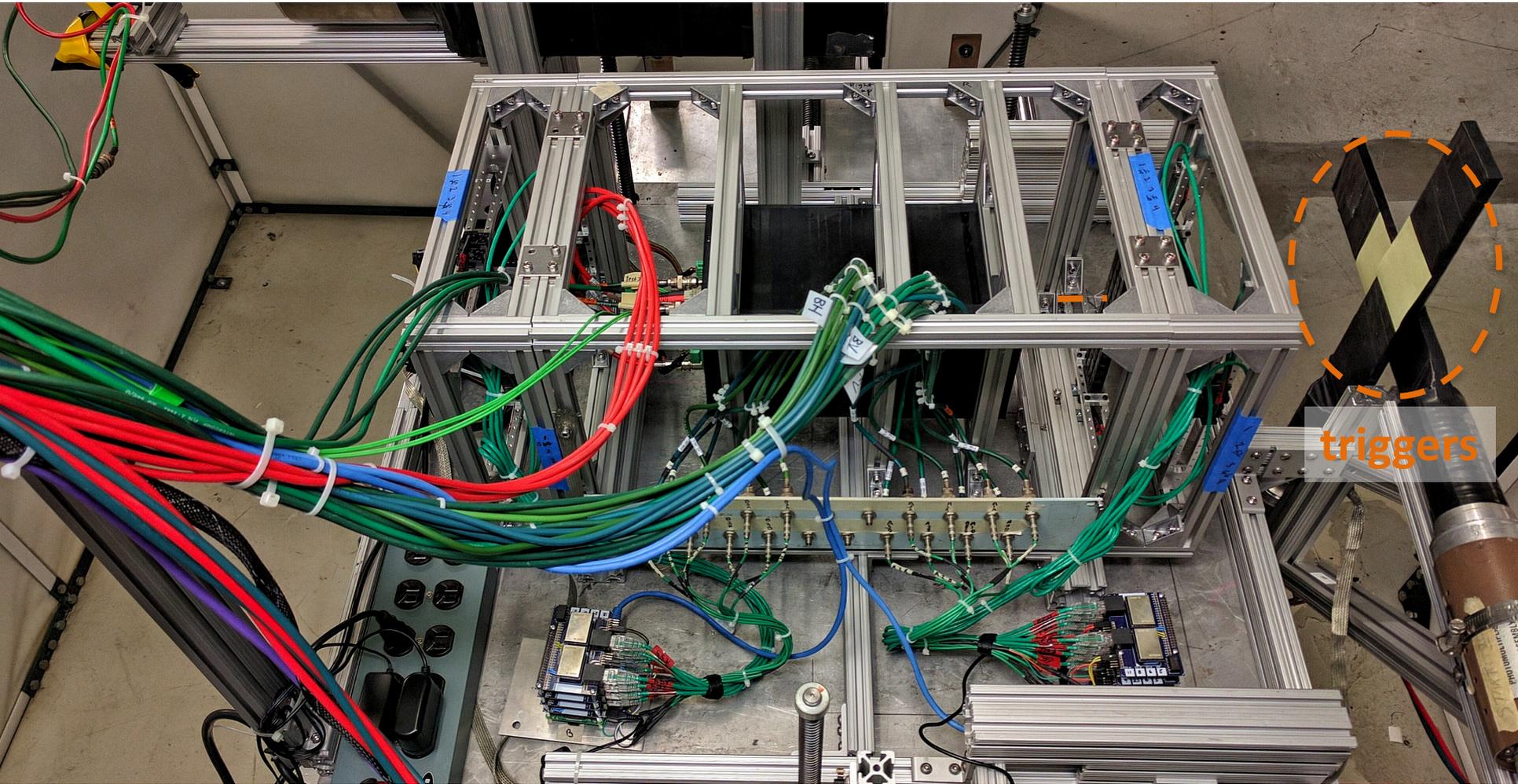


Beam Test Setup



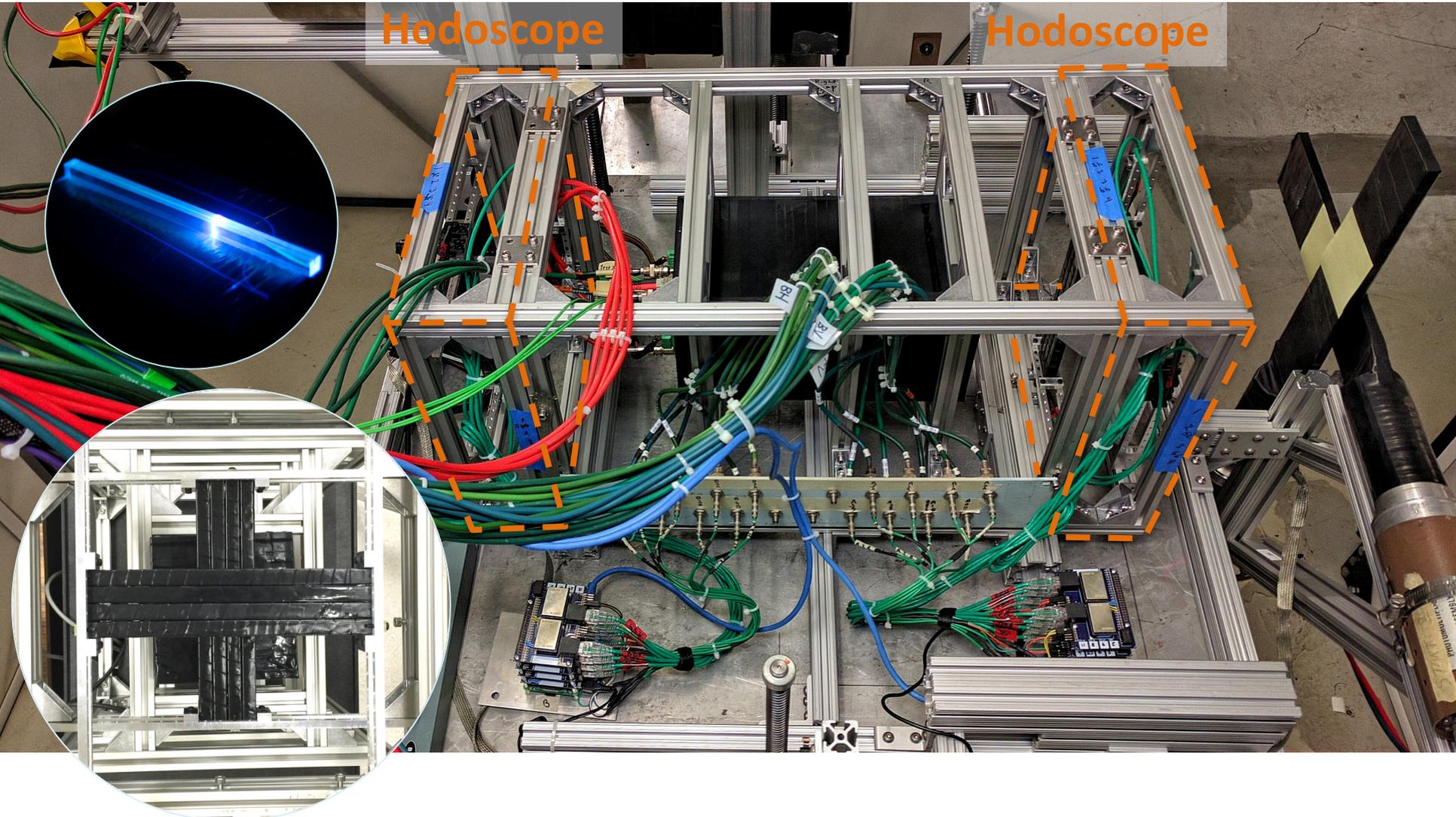


Beam Test Setup





Beam Test Setup



Hodoscope

Hodoscope



Beam Test Configurations

	120 GeV Proton	8 GeV pion	4 GeV pion
Full Setup with n=1.03 Aerogel	✓	✓	✓
Full Setup with n=1.02 Aerogel	✓		
Without Mirror	✓		

- 
- Primary beam
 - Small beam size → quick tool for detector alignment
 - High momentum → saturated ring image, i.e. clearer ring image



Beam Test Configurations

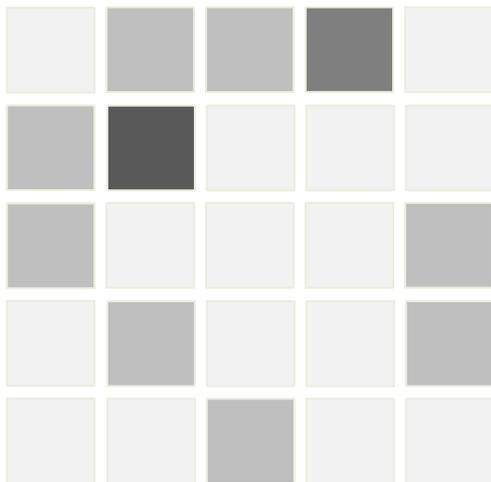
	120 GeV Proton	8 GeV pion	4 GeV pion
Full Setup with n=1.03 Aerogel	✓	✓	✓
Full Setup with n=1.02 Aerogel	✓		
Without Mirror	✓		

- Primary beam
- Small beam size → quick tool for detector alignment
- High momentum → saturated ring image, i.e. clearer ring image



Ring Finder Algorithm

Hough Transform Algorithm

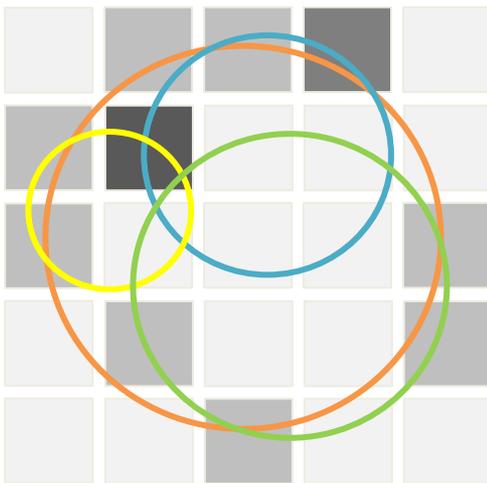




Ring Finder Algorithm

Hough Transform Algorithm

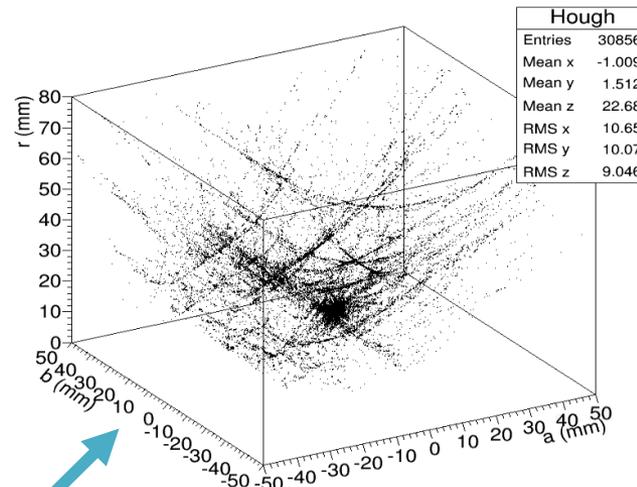
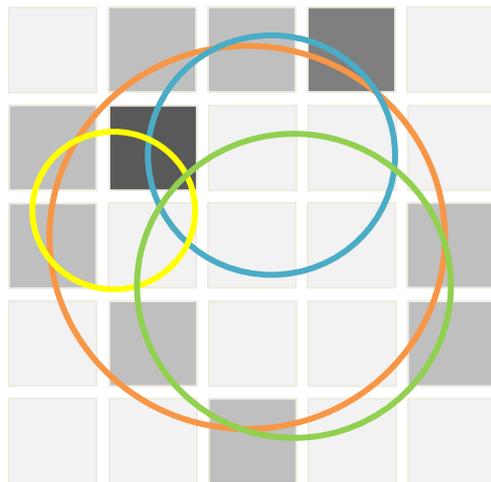
Find all possible rings
in an event



Ring Finder Algorithm

Hough Transform Algorithm

Find all possible rings
in an event

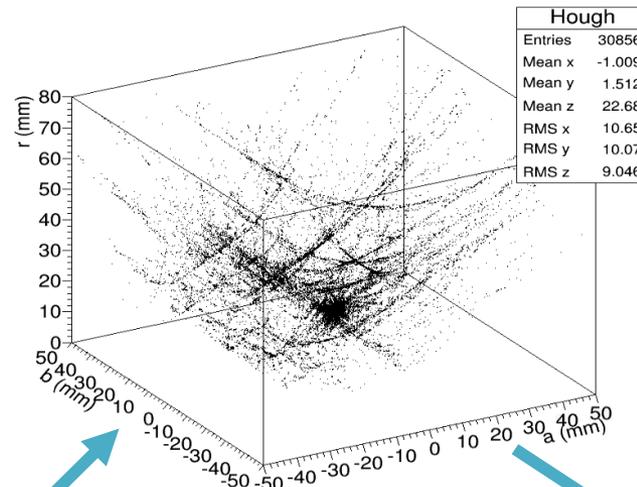
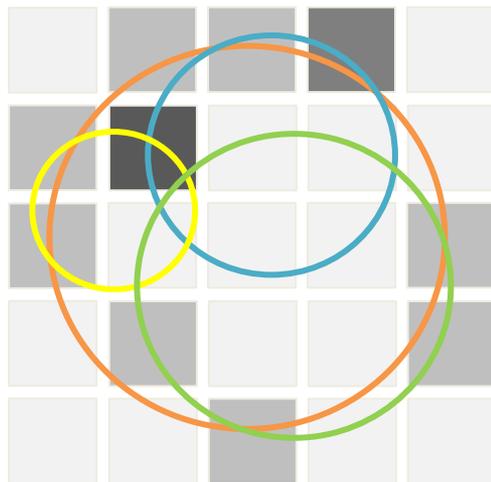


Fill (a,b) and r of possible
rings in a probability density
histogram

Ring Finder Algorithm

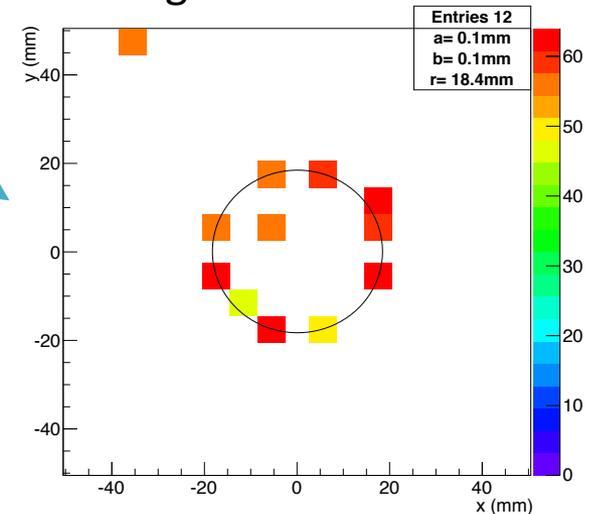
Hough Transform Algorithm

Find all possible rings in an event



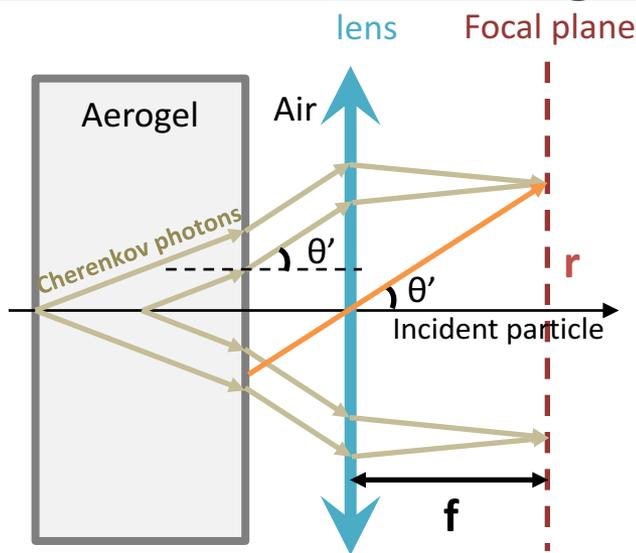
Fill (a,b) and r of possible rings in a probability density histogram

The most possible ring is the densest bin in the probability density histogram



Cherenkov Ring Radius

Estimated value of Cherenkov ring radius in modular RICH detector:



Proportional to focal length

$$r = f \cdot \tan \theta'$$

$$= f \cdot \sqrt{\frac{(n^2-1)p^2 - m_0^2}{(2-n^2)p^2 + m_0^2}}$$

$$= 76.2 \cdot \sqrt{\frac{(1.03^2-1)p^2 - m_0^2}{(2-1.03^2)p^2 + m_0^2}}$$

$$r_{120 \text{ GeV proton}} = 19.4 \text{ mm}$$

Estimated number of Cherenkov photons in modular RICH detector:

Fresnel lens transmission

Sensor quantum efficiency

$$N = 2\pi\alpha d \left(1 - \frac{1}{\beta^2 n^2}\right) \cdot 0.92 \cdot 0.92 \int_{\lambda_1}^{\lambda_2} 0.34 e^{-\frac{(\lambda - 345 \times 10^{-7})^2}{2 \times (119 \times 10^{-7})^2}} \cdot 0.83 e^{-\frac{d \times 56.29 \times 10^{-20}}{\lambda^4}} \frac{d\lambda}{\lambda^2}$$

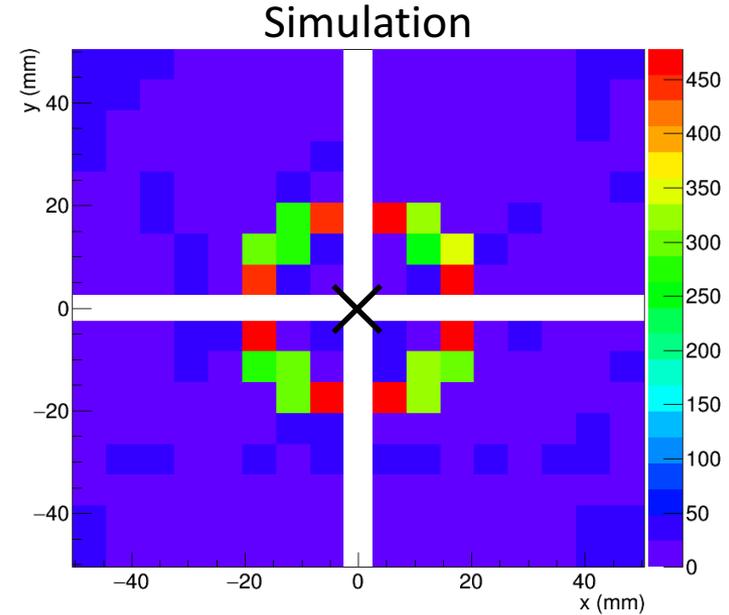
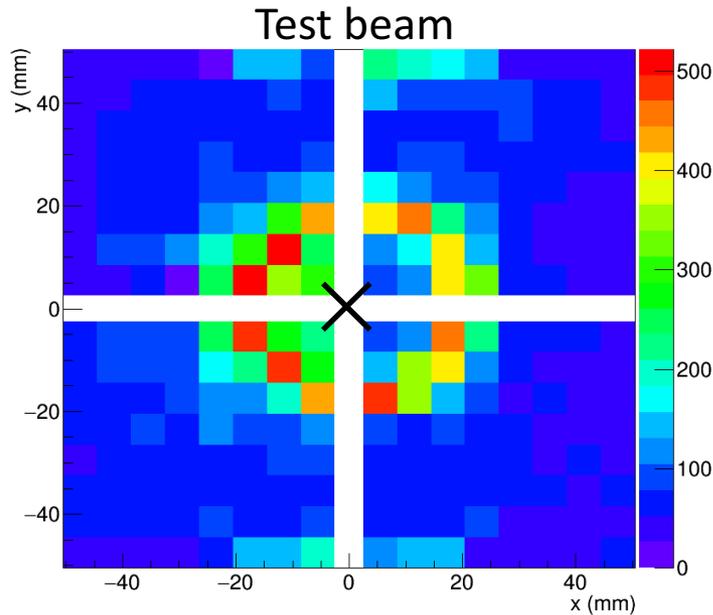
$$N = 10.4 \text{ (with } n=1.03)$$

Glass window transmission

Aerogel transmission

1st Test Beam Results

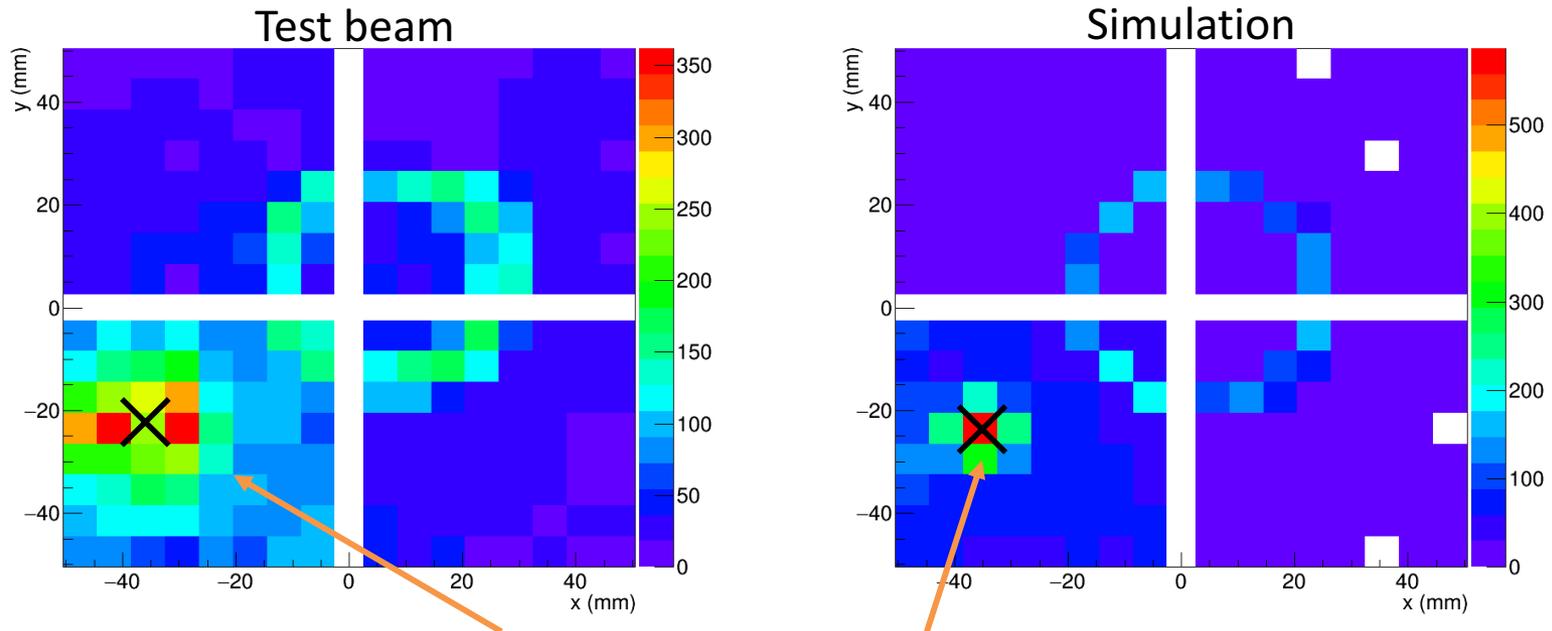
from 120 GeV/c Proton Beam



	Analytical Calculation	Test Beam Data	Simulation
Radius (mm)	19.4	19.0 ± 1.3	18.9 ± 1.0
Number of detected photons per event	10.4	11.0 ± 2.9	11.1 ± 2.9

1st Test Beam Results

from 120 GeV/c Proton Beam



Noise around the beam spot :
Cherenkov photons generated inside the
glass window under internal reflection

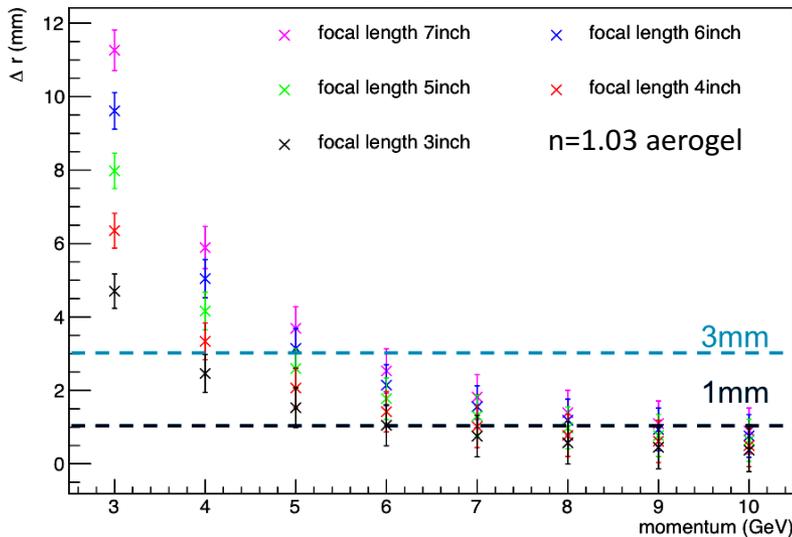
- The 1st test beam result **verified mRICH working principle** and **validated simulation**
- Paper has been published: **NIM A 871 (2017) 13 – 19.**



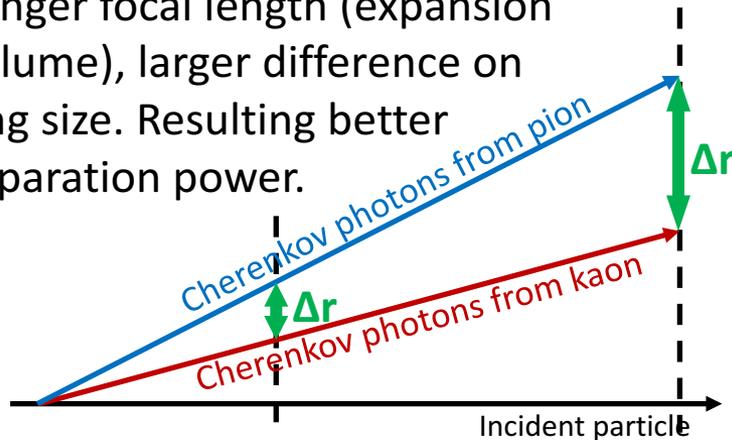
Next Prototype and Beam Test

Detector Optimization

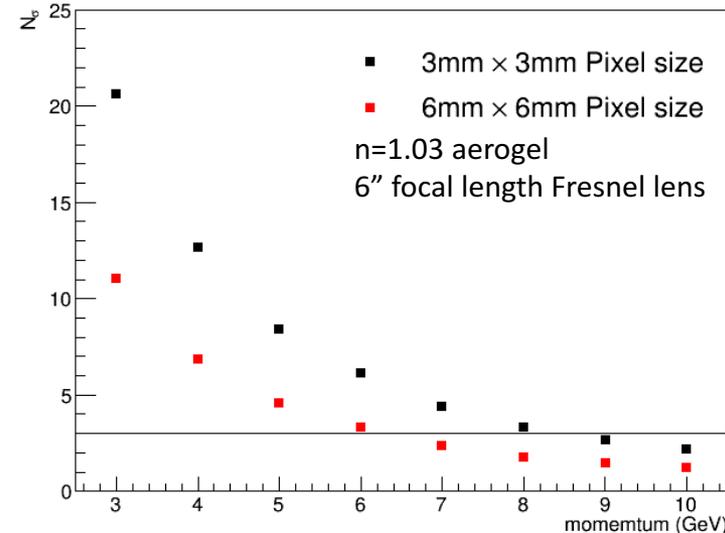
1. Longer focal length Fresnel lens



Longer focal length (expansion volume), larger difference on ring size. Resulting better separation power.

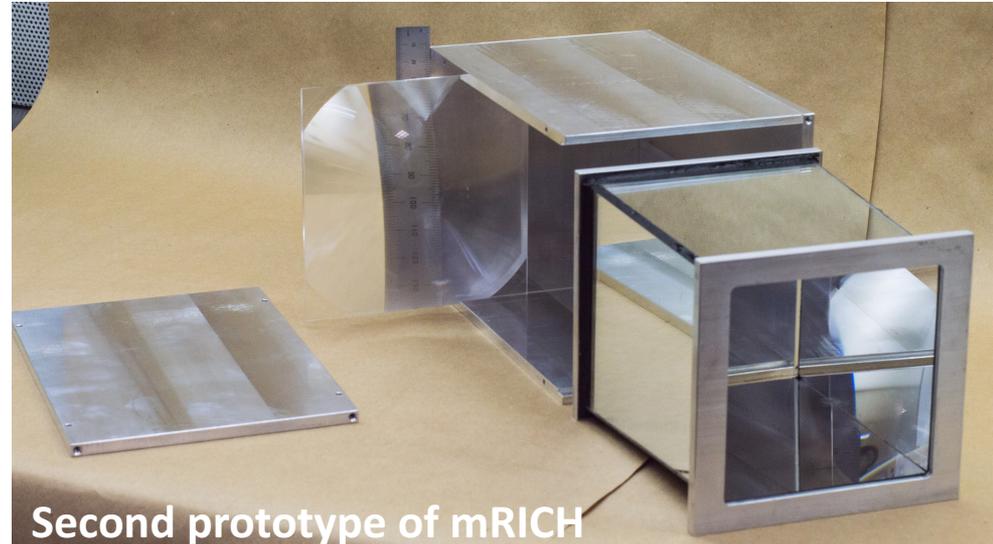
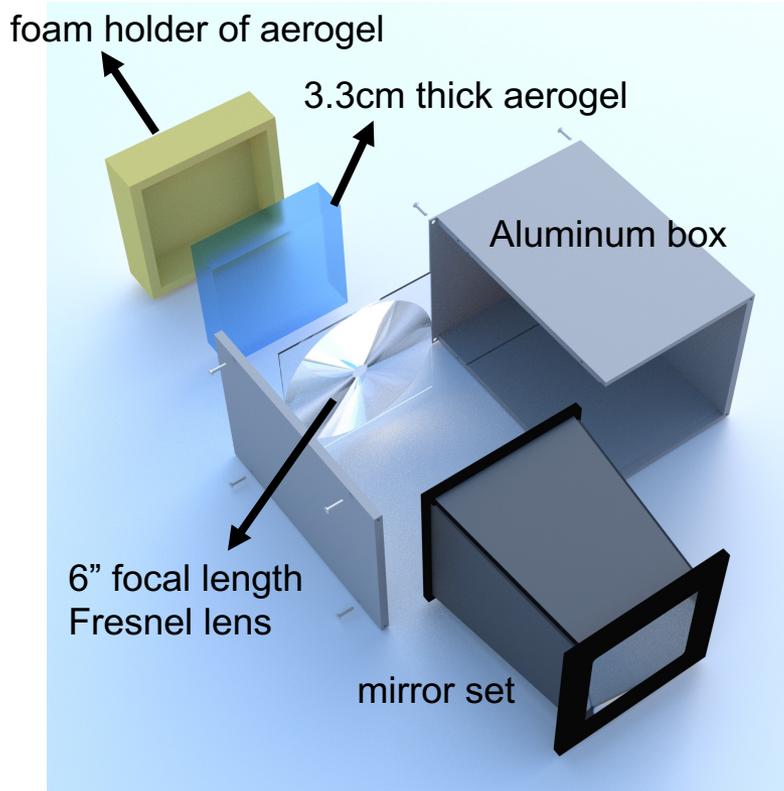


2. Smaller pixel size sensors



- Considering ring size from different focal lengths, 6" focal length Fresnel lens (gives $r \approx 38\text{mm}$ at $10\text{GeV}/c$) is suggested for 2nd mRICH prototype design
- $3 \times 3\text{mm}^2$ pixel size sensor is also suggested to increase PID performance in high momentum region

Next Prototype



Second prototype of mRICH

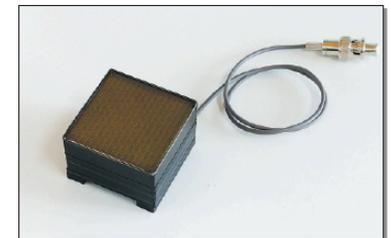
TECHNICAL INFORMATION

OCT. 2016

FLAT PANEL TYPE MULTIANODE PMT ASSEMBLY H13700 SERIES

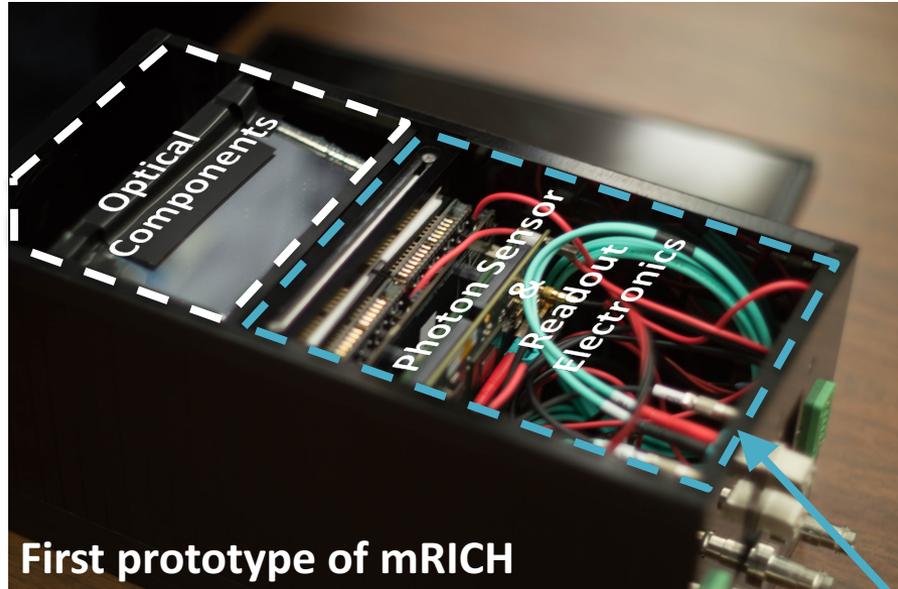
FEATURES

- High quantum efficiency: 33 % typ.
- High collection efficiency: 80 % typ.
- Single photon peaks detectable at every anode (pixel)
- Wide effective area: 48.5 mm × 48.5 mm
- **16 × 16 multianode, pixel size: 3 mm × 3 mm / anode**

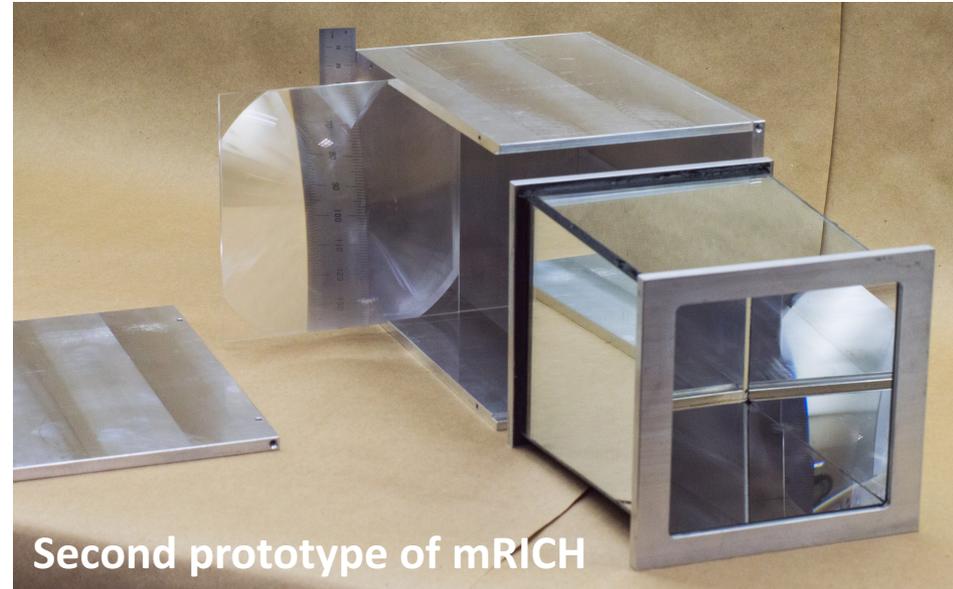


1. Longer focal length Fresnel lens
2. smaller pixel size sensors

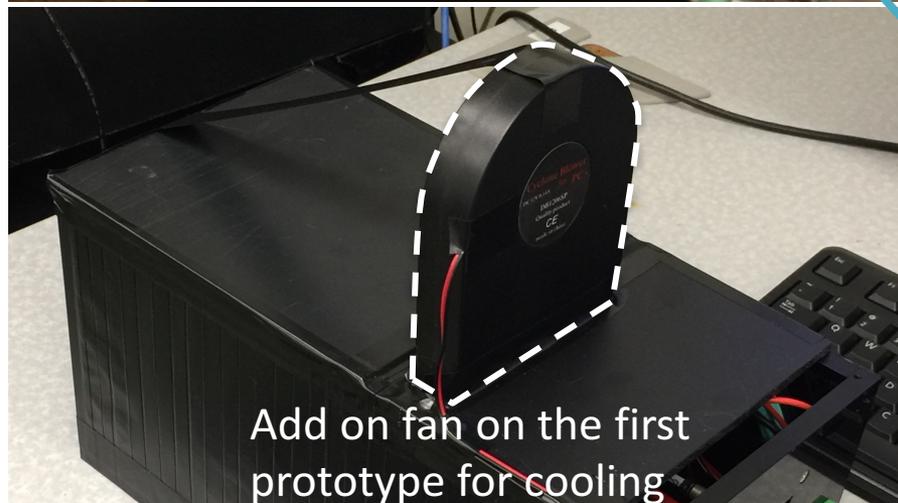
Next Prototype



First prototype of mRICH



Second prototype of mRICH



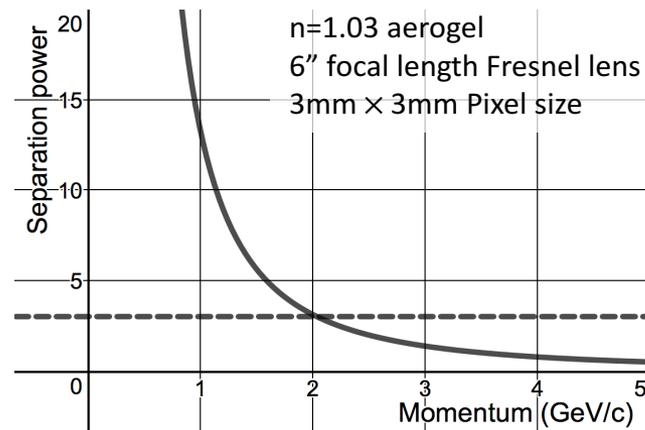
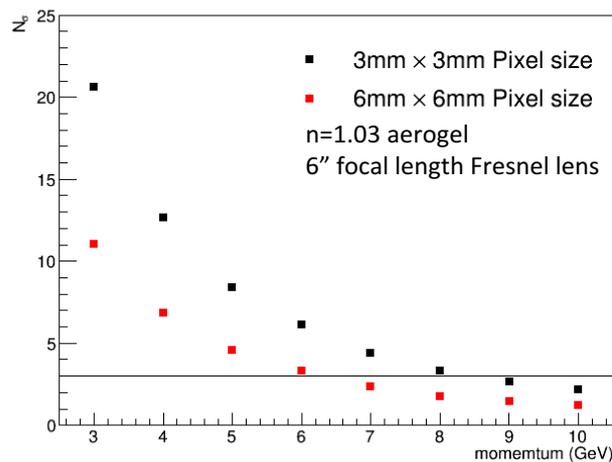
Add on fan on the first prototype for cooling

3. Readout electronics will be separated from the optical components to avoid overheating



Next Beam Test

- In Spring 2018
- Measure K/pi separation power up to 8 GeV/c
- Measure e/pi separation power up to 2 GeV/c



- Projected K/pi separation of next mRICH prototype detector (**black dots**)
- 2nd prototype detector can achieve 3-sigma K/pi separation up to 8 GeV/c
- Projected e/pi separation of next mRICH prototype detector
- 2nd prototype detector can achieve 3-sigma e/pi separation up to 2 GeV/c



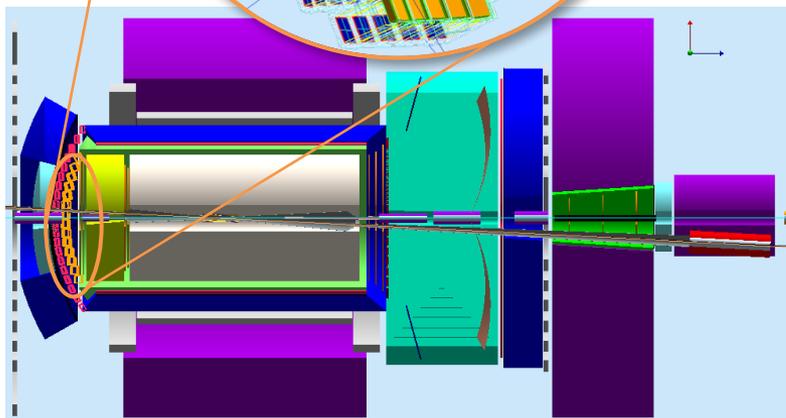
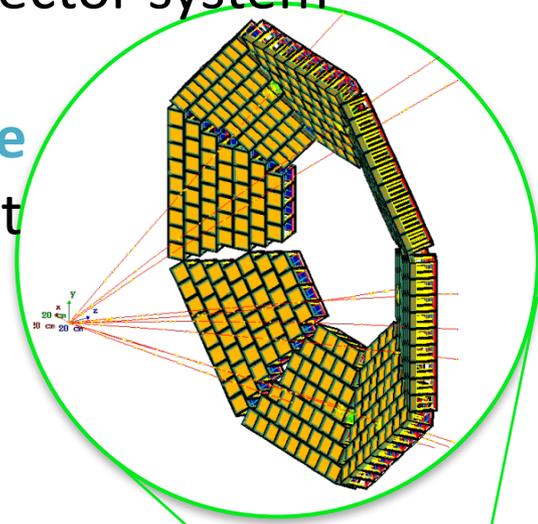
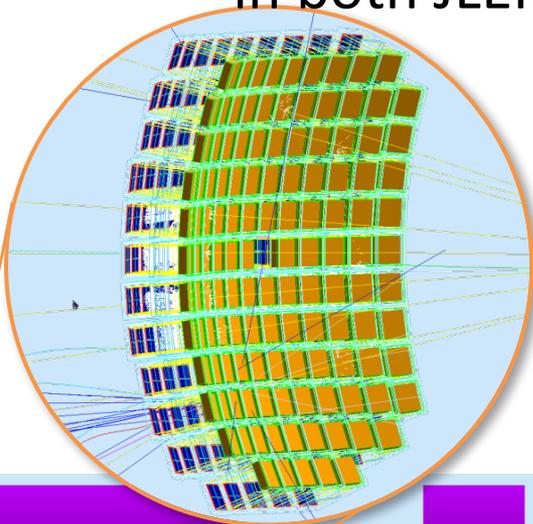
Simulation of mRICH Detector System in EIC detector Designs

Simulation of mRICH Detector System (mRICH wall)

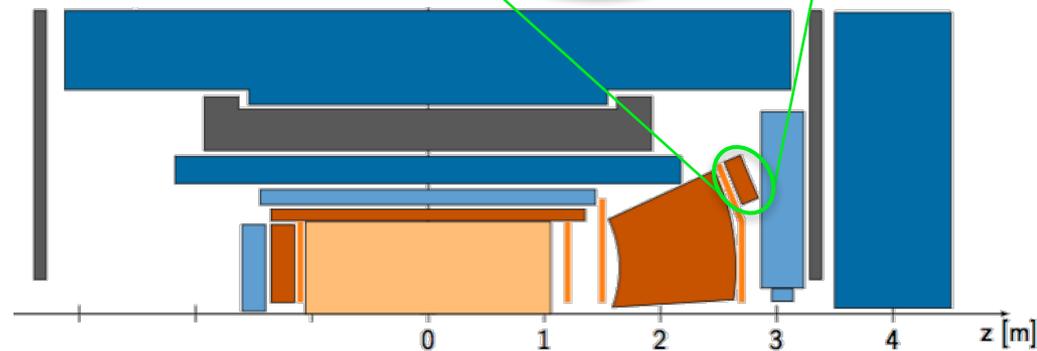
mRICH detector system has been implemented
in both JLEIC and sPHENIX detector system

Easy maintenance

You can plug in/out
individual module



mRICH detectors in JLEIC detector design



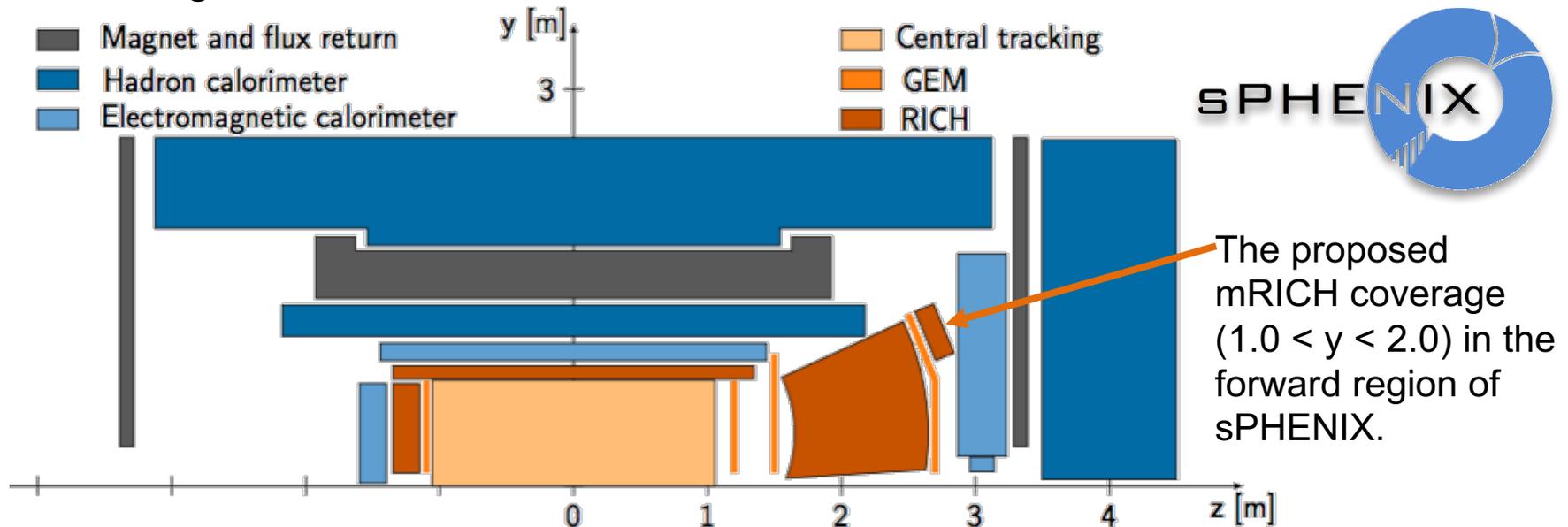
Design of sPHENIX with mRICH detectors



mRICH Wall in Forward Region of sPHENIX

An implementation of the mRICH detector concept in the Forward sPHENIX has been proposed in a Letter of Intent to BNL.

- Enhance of the **physics capabilities** of the sPHENIX experiment.
- Make the sPHENIX detector system an **available eRHIC detector** for the future EIC experiments.
- **Validate the mRICH detector PID performance** in real experiments before EIC coming online.



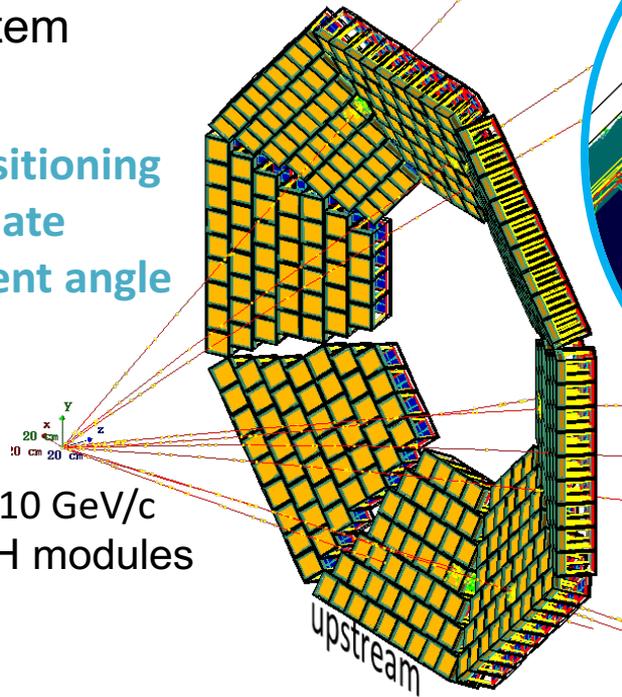
Conceptual design of the sPHENIX



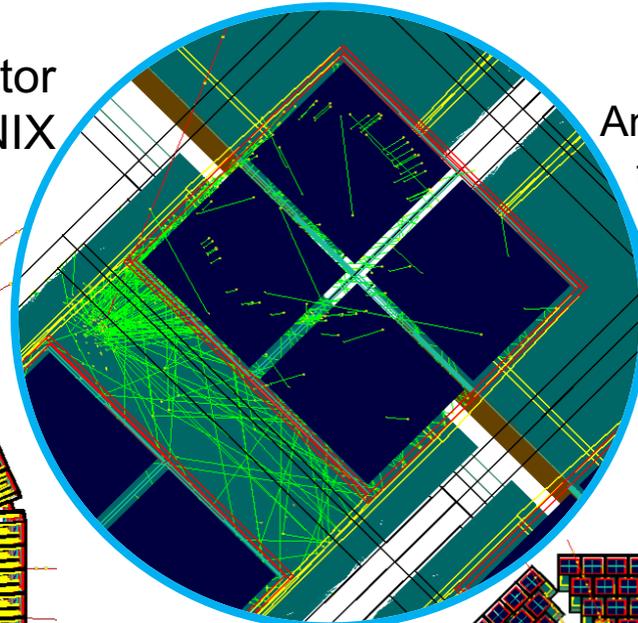
Simulation of mRICH wall in sPHENIX

Implementation of the mRICH detector modules in the Forward sPHENIX detector system

Individual positioning to accommodate particle incident angle



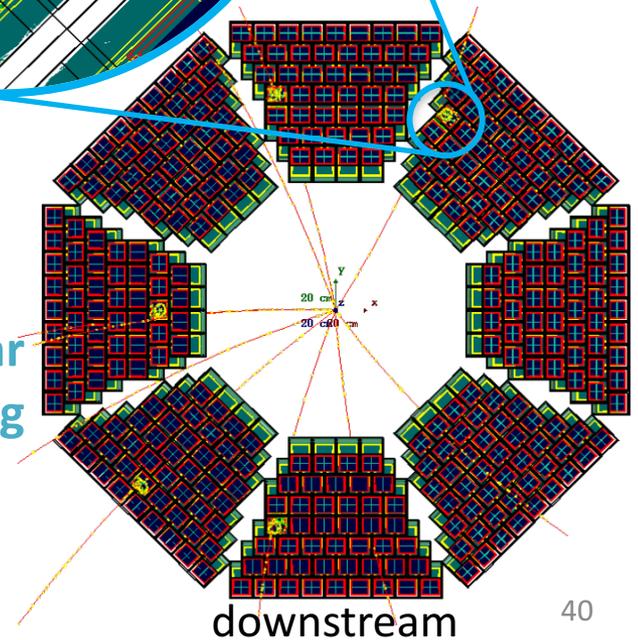
10 pions at 10 GeV/c
360 mRICH modules



An expanded view of the Cherenkov rings generated from a pion track

To do list

- Implement **PYTHIA simulation** to obtain **angular distribution** of final charged hadron for **positioning** each detector module
- mRICH detector system implementation **in BeAST**





Summary

- **Lens-based mRICH design and its advantages**
 - Smaller and thinner ring
 - Centering ring image
 - Compact and modularized design
- **Recap of mRICH prototype and beam test**
 - Detector working principle and simulation are verified
- **Ongoing work**
 - New prototype with optimized detector design
 - Implementation of mRICH in sPHENIX
 - mRICH subsystem simulation



eRD14 Collaborators

An integrated program for particle identification (PID) for a future Electron-Ion Collider

Abilene Christian University
Argonne National Lab
Brookhaven National Lab
Catholic University of America
City College of New York
College of William & Mary
Duke University
Georgia State University
GSI Helmholtzzentrum für
Schwerionenforschung GmbH
Howard University
Institute for High Energy Physics,
Protvino, Russia

INFN, Sezione di Ferrara
INFN, Sezione di Roma
Istituto Superiore di Sanità
Jefferson Lab
Los Alamos National Lab
North Carolina A&T State University
Old Dominion University
Stony Brook University, Stony Brook
Universidad Técnica Federico Santa María
University of Hawaii
University of Illinois
University of New Mexico
University of South Carolina
Yale University



Back Up



Uncertainty of Measured Cherenkov Angle σ_θ

- Sources of error

- Emission position $\sigma_{EP} = \frac{t}{D\sqrt{12}} \sin \theta \cos \theta$

- D : Expansion volume
- t : thickness of radiator

- Chromatic Dispersion σ_{chro} . Refractive index n is a function of wavelength. Thus, there is fluctuation on Cherenkov angle.

- Sensor pixel size $\sigma_{pix} = \frac{a}{D\sqrt{12}} \cos^2 \theta$

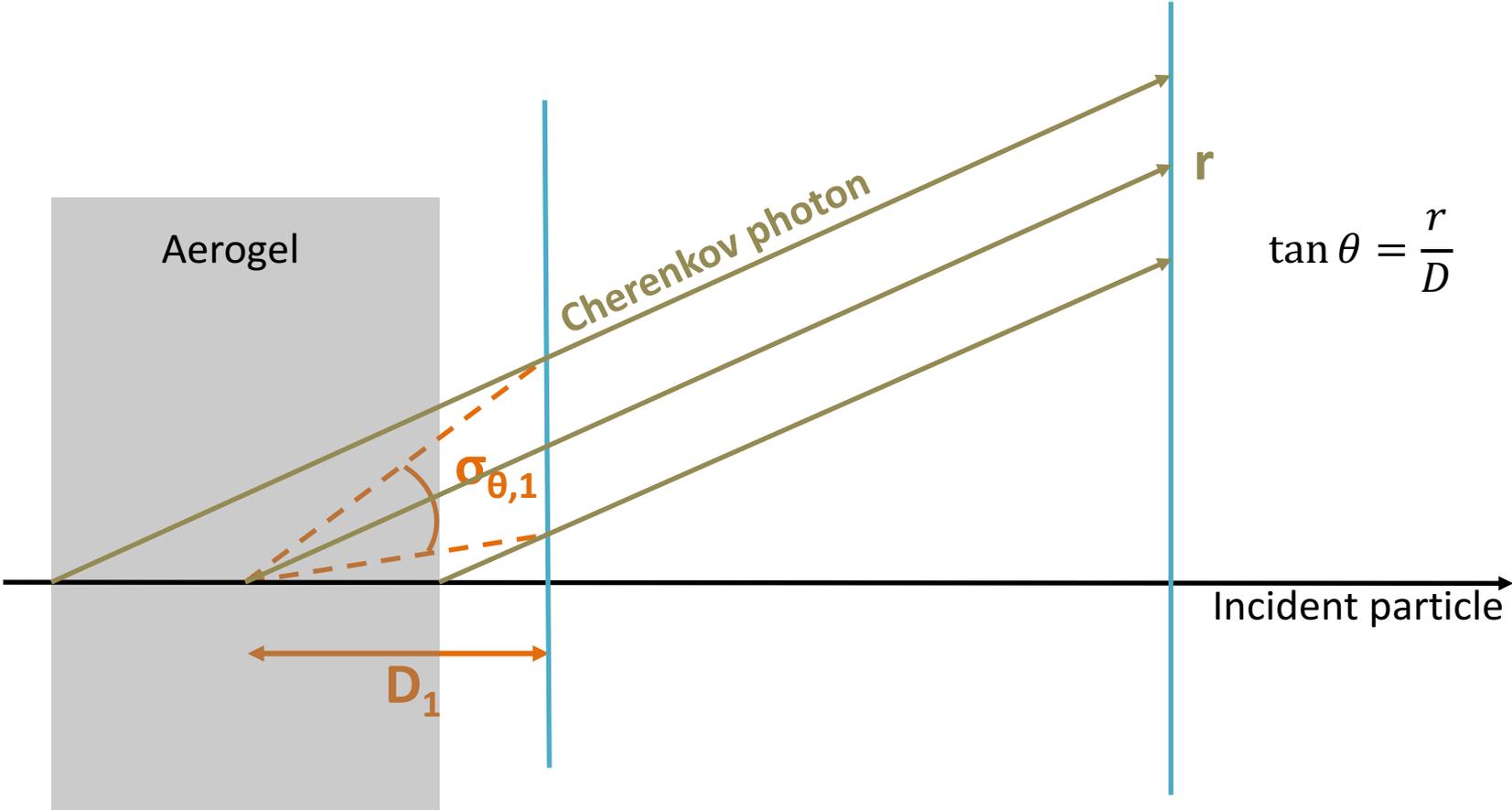
- a : pixel dimension

Larger expansion volume D, smaller uncertainty on Cherenkov Angle. (See next slide)

- Resulting uncertainty $\sigma_\theta = \sqrt{\sigma_{EP}^2 + \sigma_{chro}^2 + \sigma_{pix}^2}$

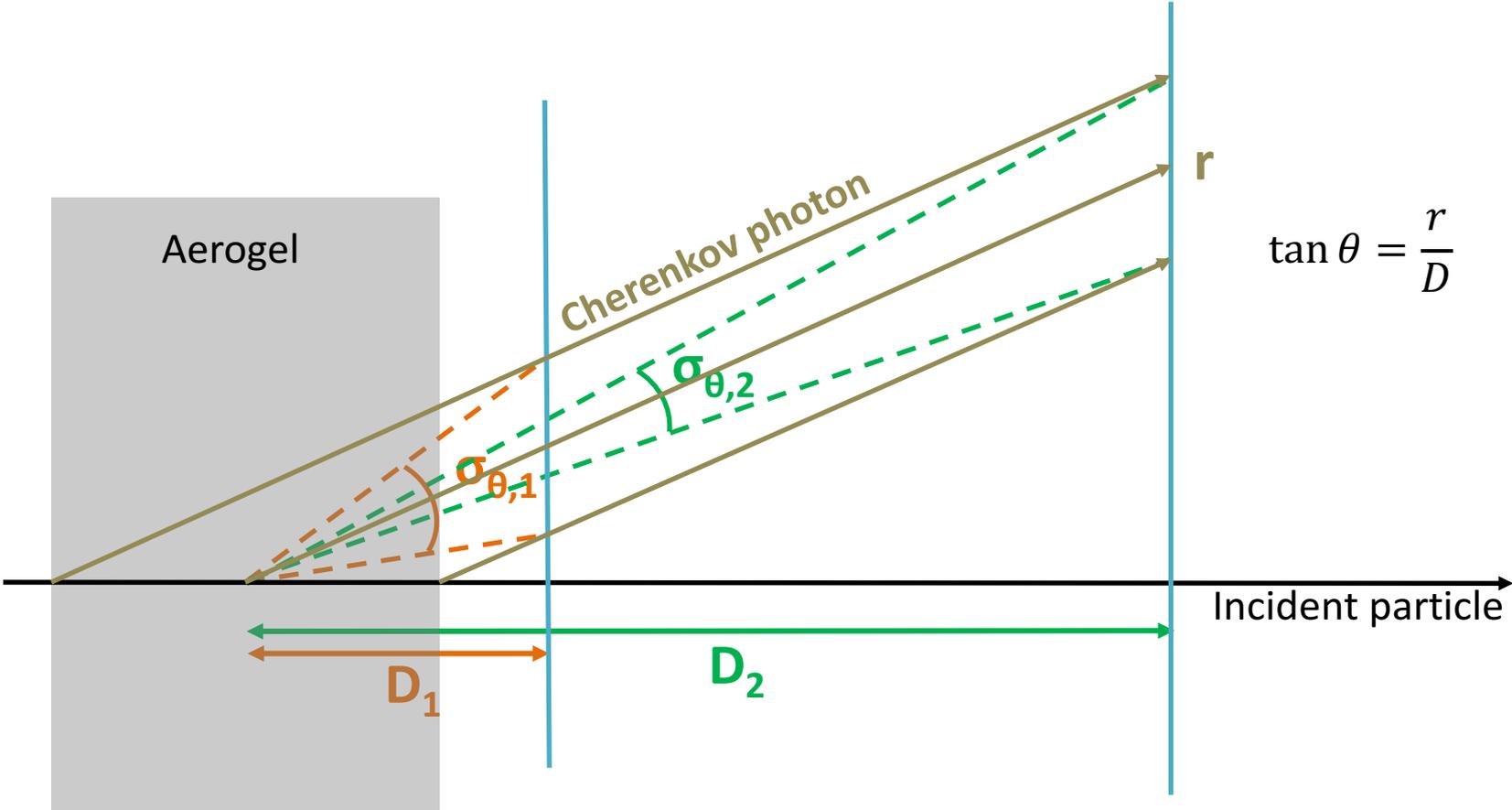
Mitja Predikaka, *Hybrid Avalanche Photo detector for Belle II ARICH Detector*, December 27, 2014

Emission Position Uncertainty σ_{EP} of a Simple RICH Detector



Larger expansion volume D , smaller uncertainty on Cherenkov Angle.

Emission Position Uncertainty σ_{EP} of a Simple RICH Detector

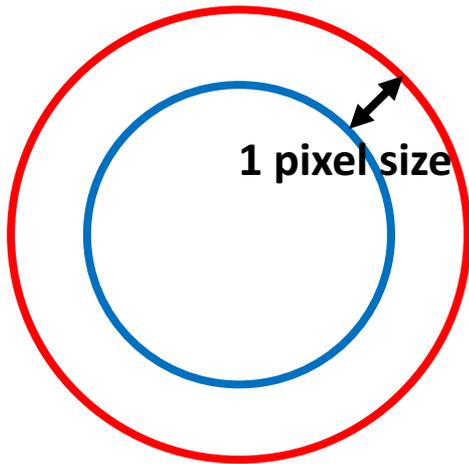


Larger expansion volume D , smaller uncertainty on Cherenkov Angle.



Desired Pixel Size

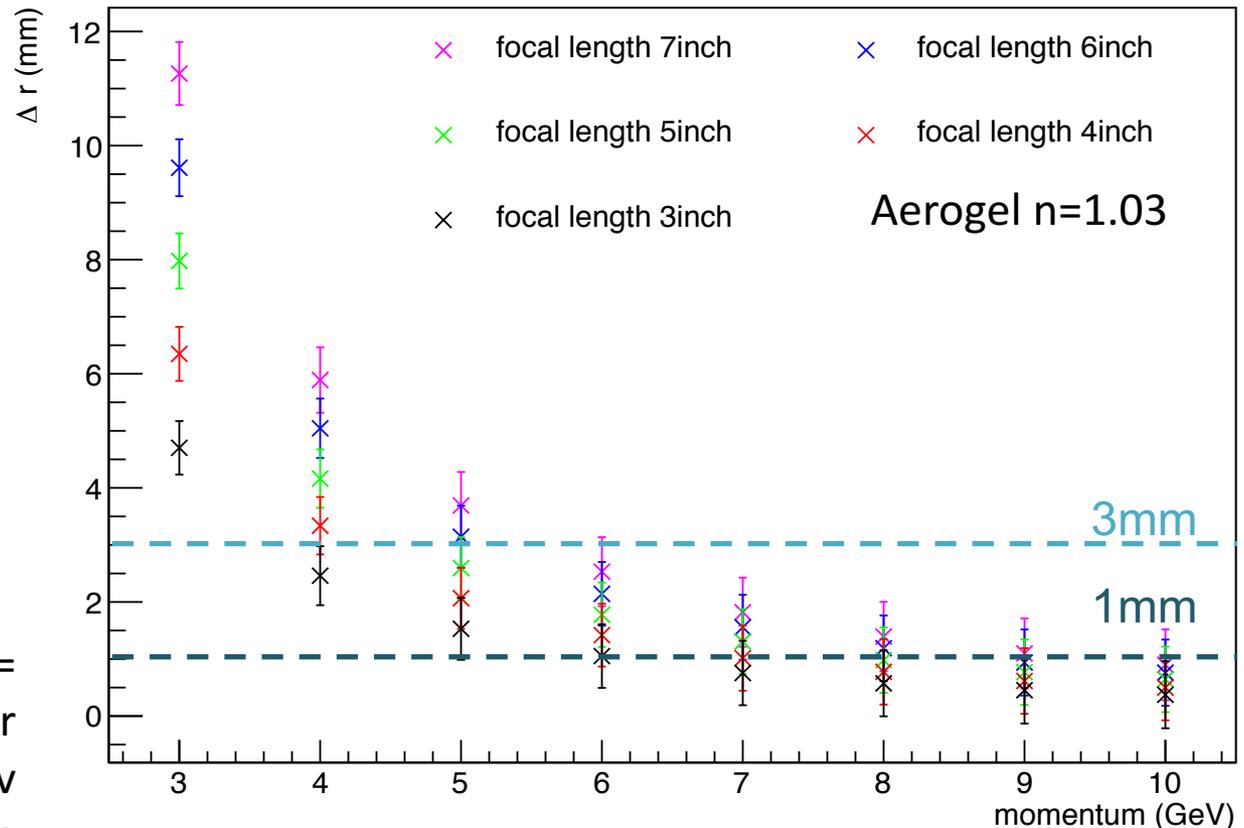
Ring from pion



Ring from kaon

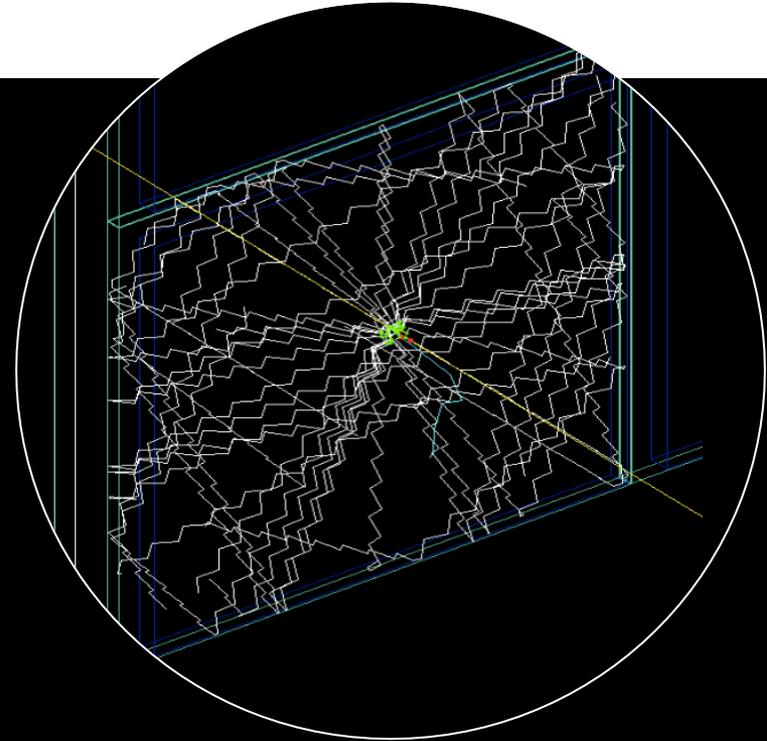
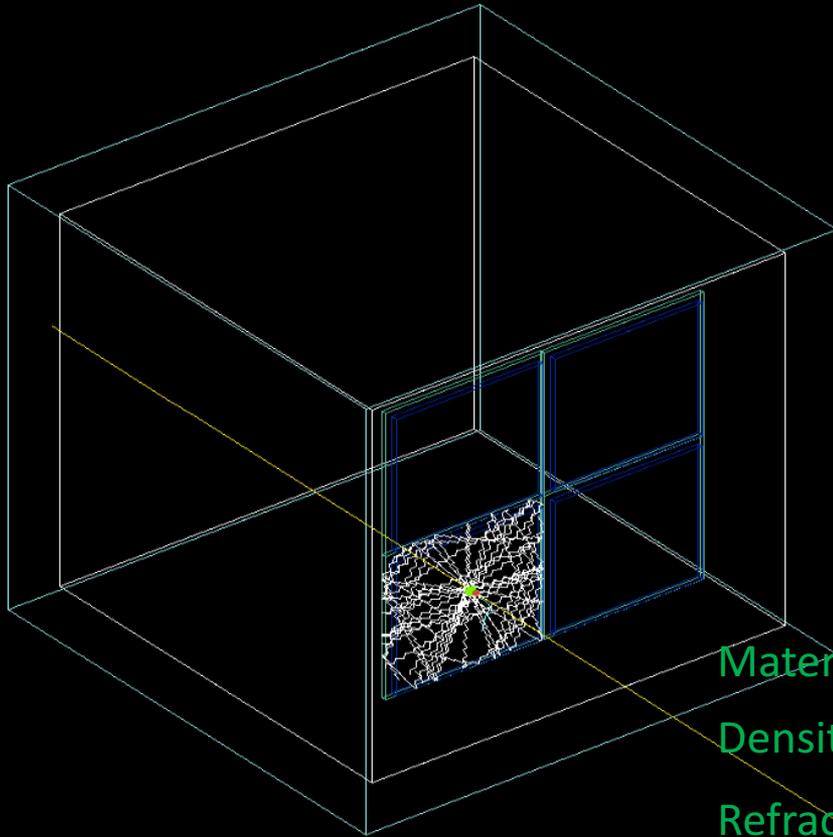
Naive case :
required pixel size =
Difference in diameter
between Cherenkov
rings emitted by pion
and kaon

Difference in Radius vs Momentum





Internal Reflection inside Glass Window



Material

Pyrex glass (Borosilicate glass)

Density

2.23 g/cm³

Refractive index

1.47

transmittance

92% in 400-700nm wavelength region



Number of Cherenkov Photons per Event

Maximum number of Cherenkov photons:

$$N = 2\pi\alpha d \left(1 - \frac{1}{\beta^2 n^2}\right) \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2}$$

Fine structure const. \leftarrow $2\pi\alpha$
 Thickness of radiator \leftarrow d
 $\beta=v/c$ \leftarrow β
 Refractive index of radiator \leftarrow n

Estimated number of Cherenkov photons in modular RICH detector:

$$N = 2\pi\alpha d \left(1 - \frac{1}{\beta^2 n^2}\right) \cdot \boxed{0.92} \cdot \boxed{0.92} \int_{\lambda_1}^{\lambda_2} \boxed{0.34 e^{-\frac{(\lambda - 345 \times 10^{-7})^2}{2 \times (119 \times 10^{-7})^2}}} \cdot \boxed{0.83 e^{-\frac{d \times 56.29 \times 10^{-20}}{\lambda^4}}} \frac{d\lambda}{\lambda^2}$$

Fresnel lens transmission \leftarrow 0.92
 Sensor quantum efficiency \leftarrow $0.34 e^{-\frac{(\lambda - 345 \times 10^{-7})^2}{2 \times (119 \times 10^{-7})^2}}$
 Glass window transmission \leftarrow 0.92
 Aerogel transmission \leftarrow $0.83 e^{-\frac{d \times 56.29 \times 10^{-20}}{\lambda^4}}$

$N = 10.3$ (with $n=1.03$)



Requirements of Readout Electronics

readout electronics that can be commonly used between all three RICH detectors

- “Universal”

MaPMT, MCP-PMT, and SiPM

- Large number of channels

For a single H13700 MaPMT: 16x16 array of 3 mm pixel size

- Good timing

<100 ps for DIRC

- Mass production technology
- Photon counting
- Excellent time resolution
- Compatible with magnetic field
- High dark rate
- Low radiation tolerance

TECHNICAL INFORMATION

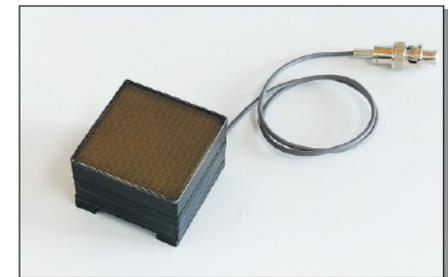
OCT. 2016

FLAT PANEL TYPE MULTIANODE PMT ASSEMBLY H13700 SERIES

**256 channels within
4.85 × 4.85 cm² area!**

FEATURES

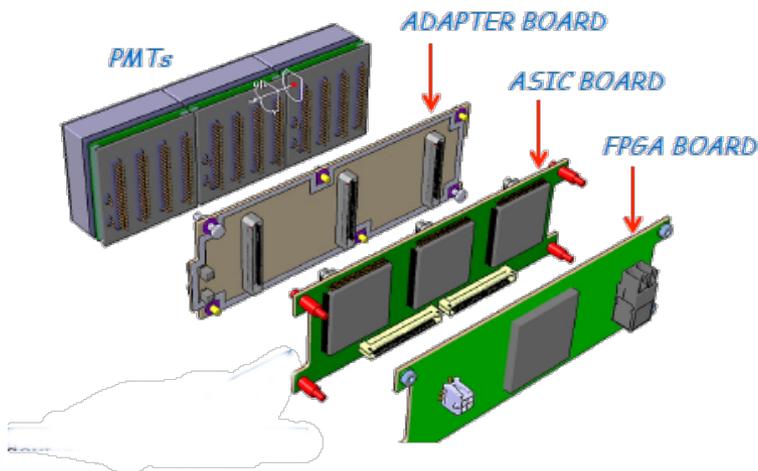
- High quantum efficiency: 33 % typ.
- High collection efficiency: 80 % typ.
- Single photon peaks detectable at every anode (pixel)
- Wide effective area: 48.5 mm × 48.5 mm
- 16 × 16 multianode,
pixel size: 3 mm × 3 mm / anode



Development of Readout Electronics in EIC R&D14 Consortium

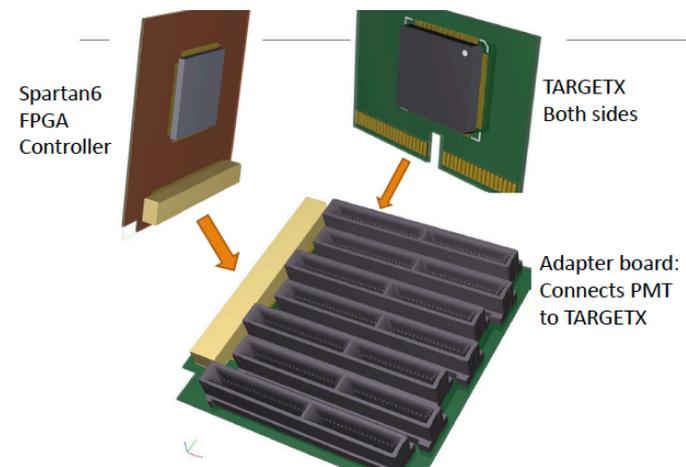
INFN (Ferrara)

Maroc-based electronics
used in CLAS12



University of Hawaii

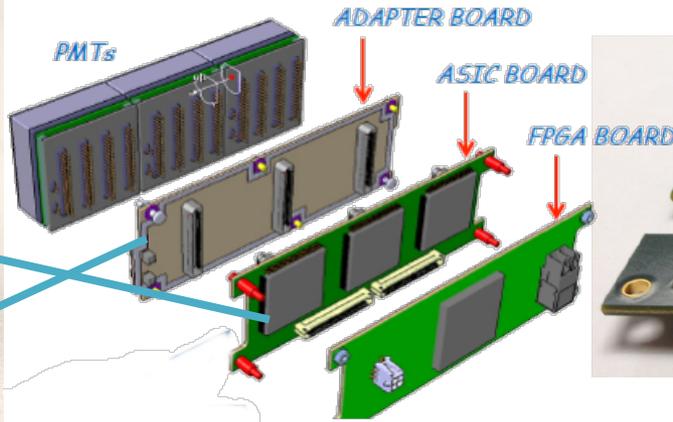
TARGETX used in BELLE-2
Good timing (100 ps) for DIRC



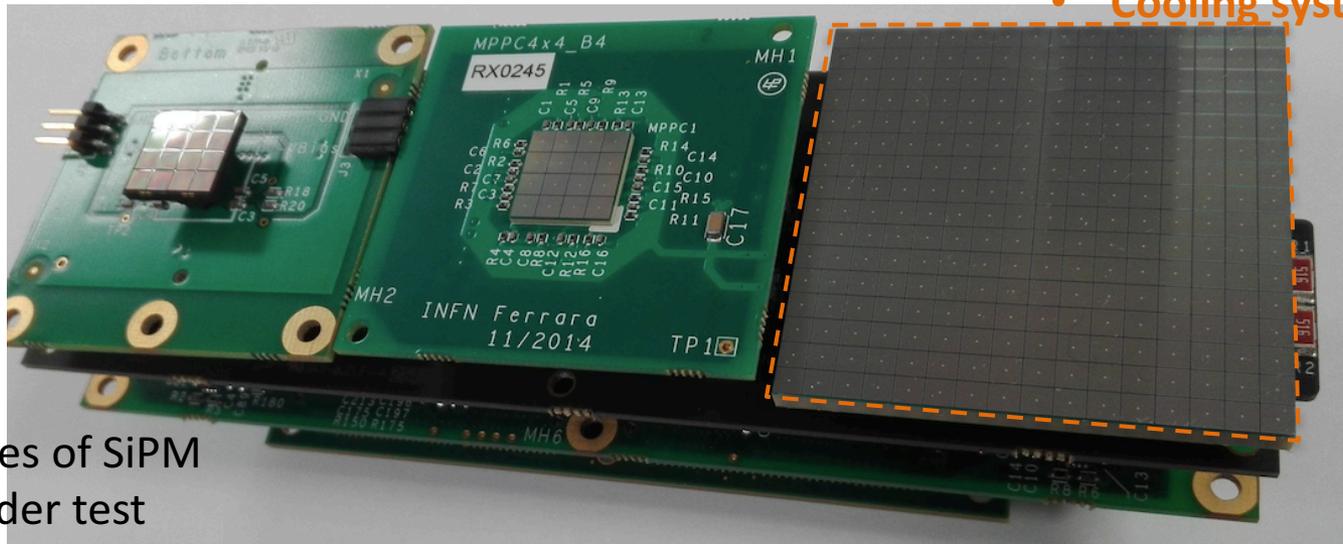
Next stage of development:

- Larger pixel ($6 \times 6 \text{mm}^2$) \rightarrow smaller pixel ($3 \times 3 \text{mm}^2$)
- MaPMT and MCP-PMT \rightarrow SiPM

Maroc from INFN (Ferrara)

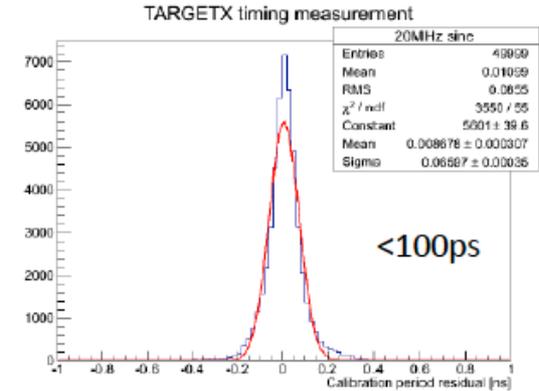
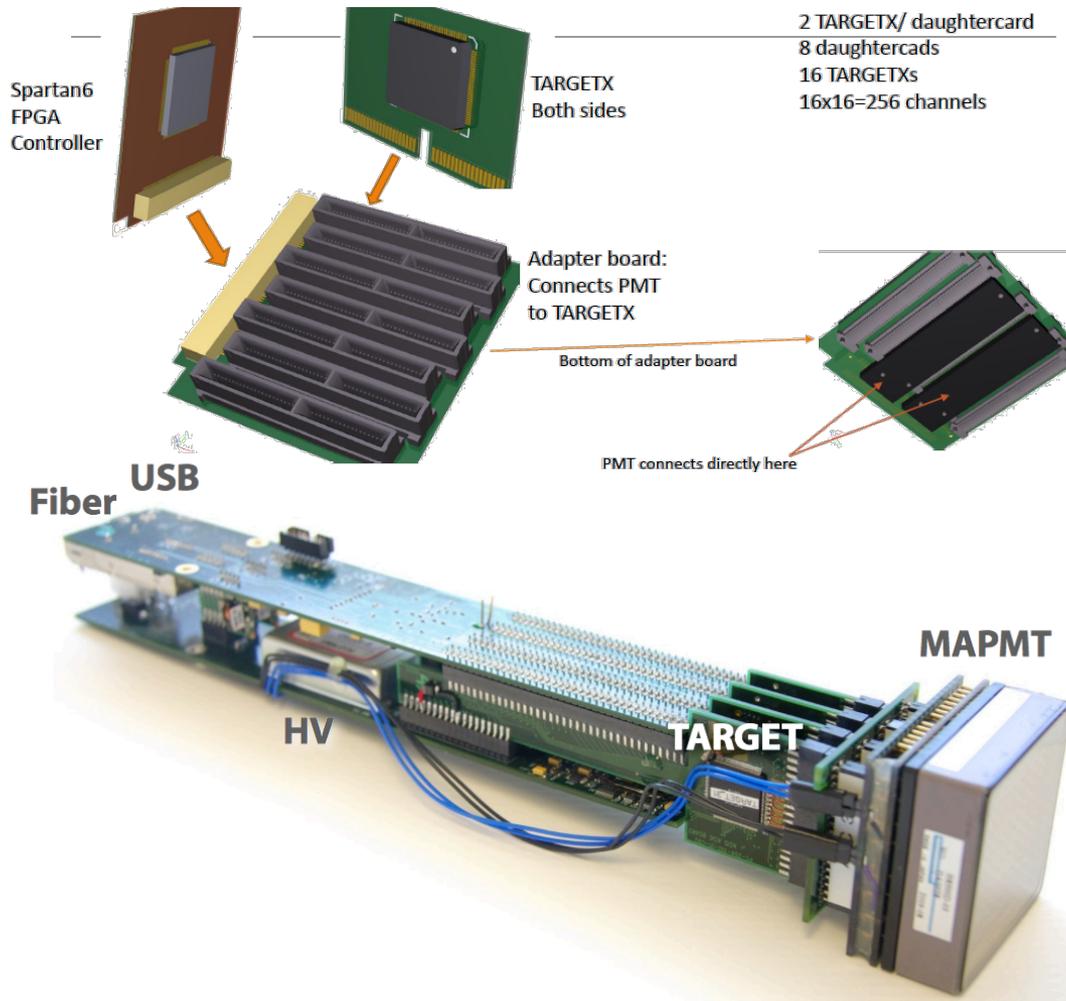


- BGA mounting
- Cooling system on PCB

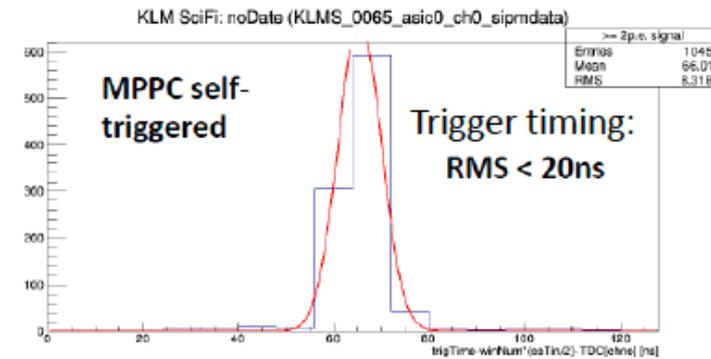


Different sizes of SiPM matrices under test

Target-X from University of Hawaii



Sine scan data (zero crossing)



TARGETX ASIC upgrade to SiREAD ASIC

- Reduced power
- Further compactness : 64 channels