2D Pixelated LAPPDs for Ring Imaging Cherenkov Detectors in High Energy and Nuclear Physics Experiments

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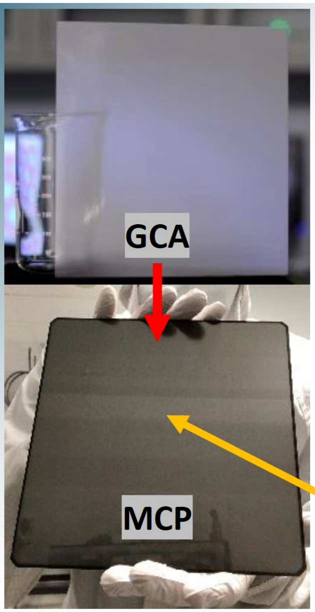
Topics

- Lab measurements
- Beam tests at Fermilab

- DC-coupled HRPPD interface

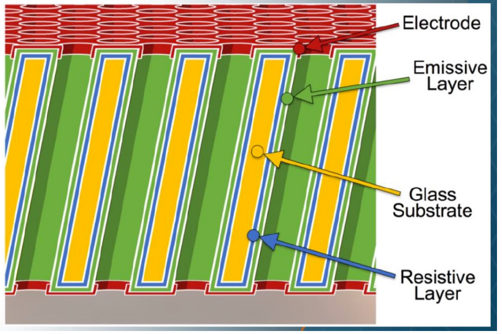
- HRPPD application in a TOF PET setup
- Proximity focusing RICH with HRPPD photosensors for EIC

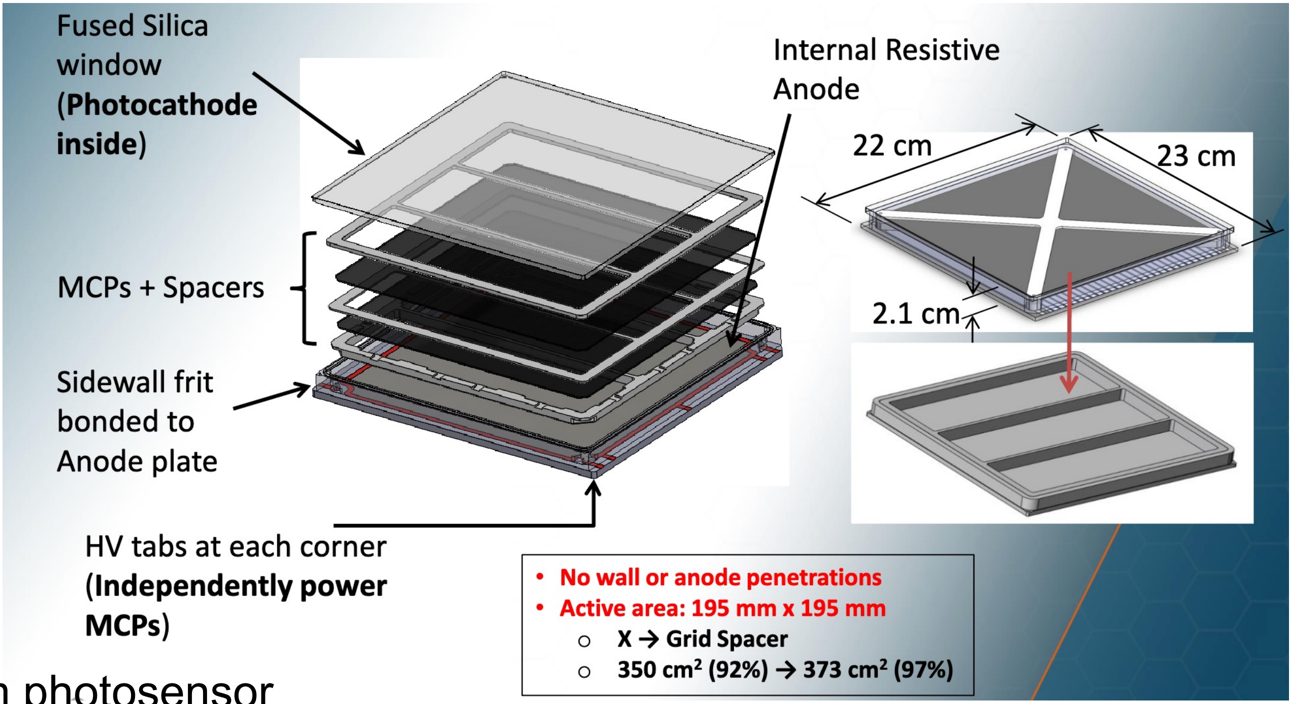
LAPPDs / HRPPDs by Incom Inc.



- *Hollow core* **Glass Capillary Array** (GCA) substrate
  - Borosilicate glass (AKA Pyrex)
    - Little radioactive ^{40}K
  - *No etching necessary! Already hollow*
- **Atomic Layer Deposition** (ALD) is a thin-film deposition technique used to functionalize GCAs
  - **GCA + ALD = MCP**
- Flexible adjustment of film composition and resistivity

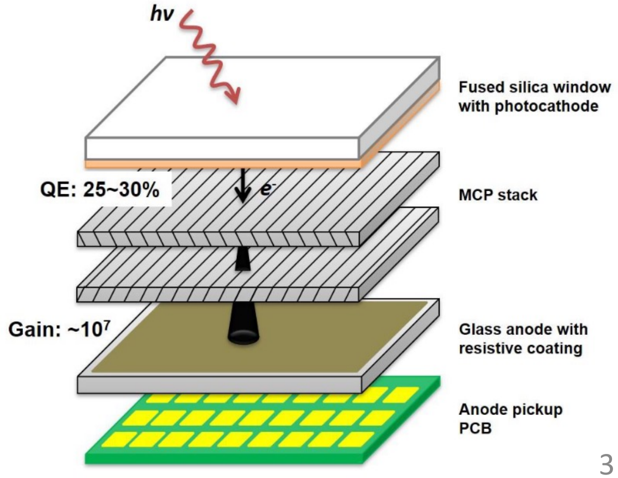
Open Area Ratio (OAR) **up to 74%**





- An affordable large area (finely pixelated) vacuum photosensor
- 10x10 cm^2 or 20x20 cm^2 active area
- DC- (Gen I) or capacitively (Gen II) coupled species
- DC-coupled 1D strips or 2D pixellation
- Expected to be (very) cost efficient in mass production
- Quantum efficiency above 30% and uniform high gain up to $\sim 10^7$
- Sub-mm spatial resolution for finely pixelated tiles
- Single-photon timing resolution on a ~50ps level or higher

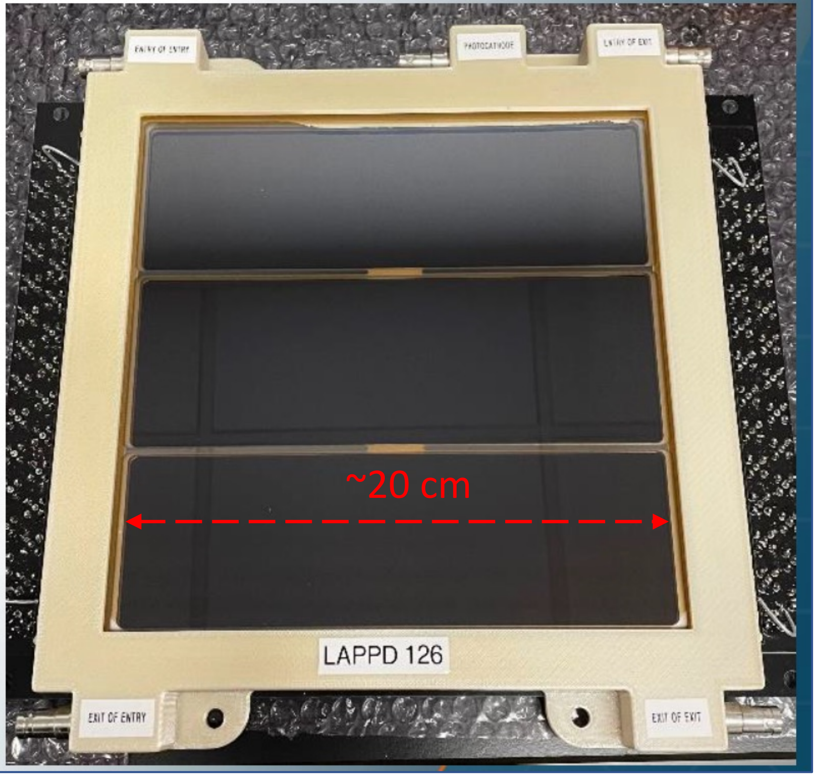
Gen II variety



History & notation

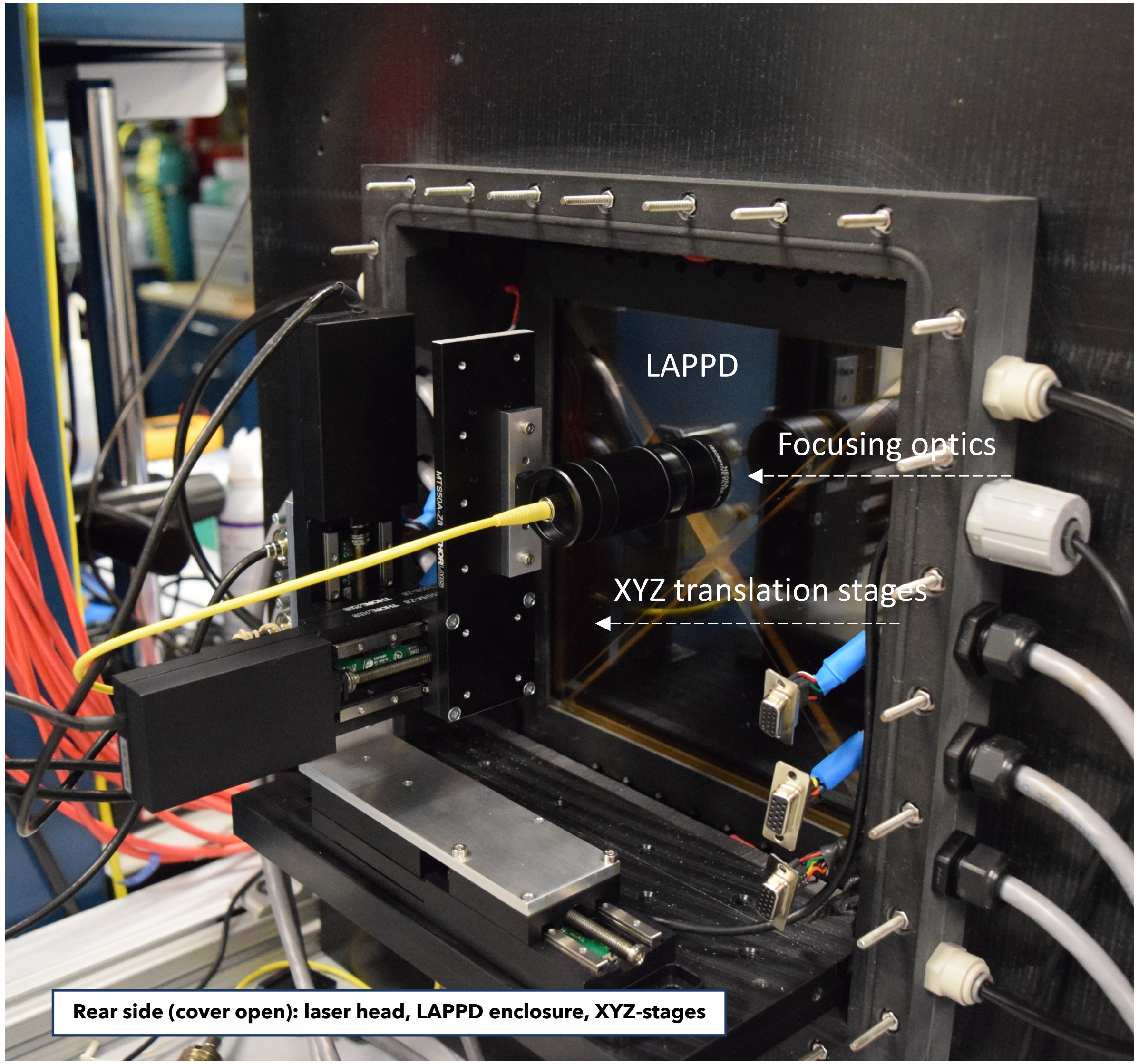
LAPPD (20cm): Large Area Picosecond Photon Detector
HRPPD (10cm): High Rate Picosecond Photon Detector

- **2009**: LAPPD Collaboration founded by Prof. Henry Frisch (U Chicago)
  - Motivation: Low cost, large detection coverage with picosecond timing
- **2015**: Early commissioning trials at Incom, Inc.
- **2018**: Demonstrated pilot production of LAPPDs
- **2022**:
  - 141 LAPPDs starts all time
  - 6 HRPPDs starts in 2022
  - Current capability of 36 LAPPDs / year
  - Current max capacity of 96 LAPPDs / year
- **Future**:
  - Improved performance
  - Commercial production



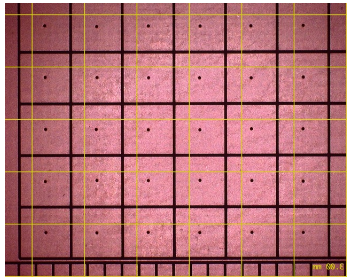
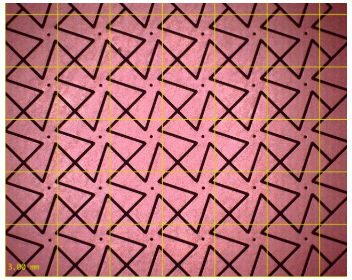
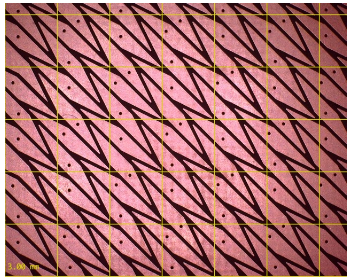
Lab measurements at Brookhaven

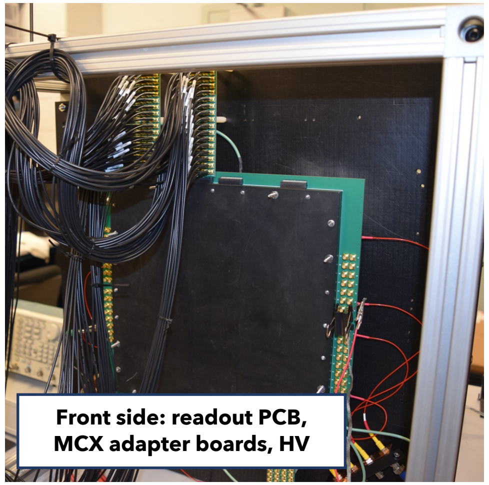
Equipment

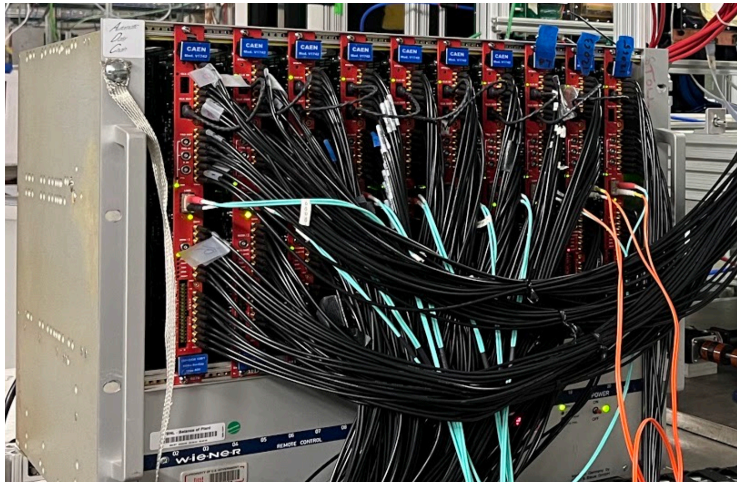


Rear side (cover open): laser head, LAPPD enclosure, XYZ-stages

- Picosecond PiLas laser
- Compact light-tight enclosure
- 320 (soon 512) DRS4 channels (V1742 digitizers)
- MCX to high-density Samtec adapter cards
- A variety of finely pixelated readout boards

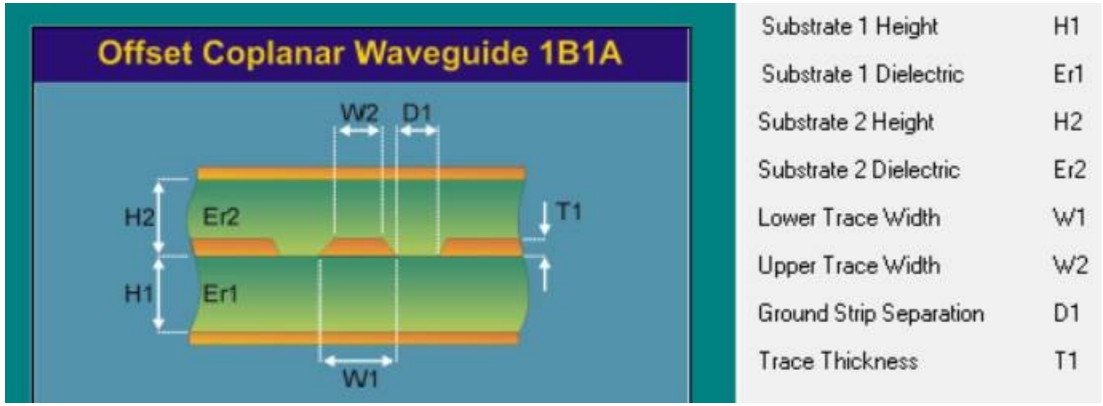




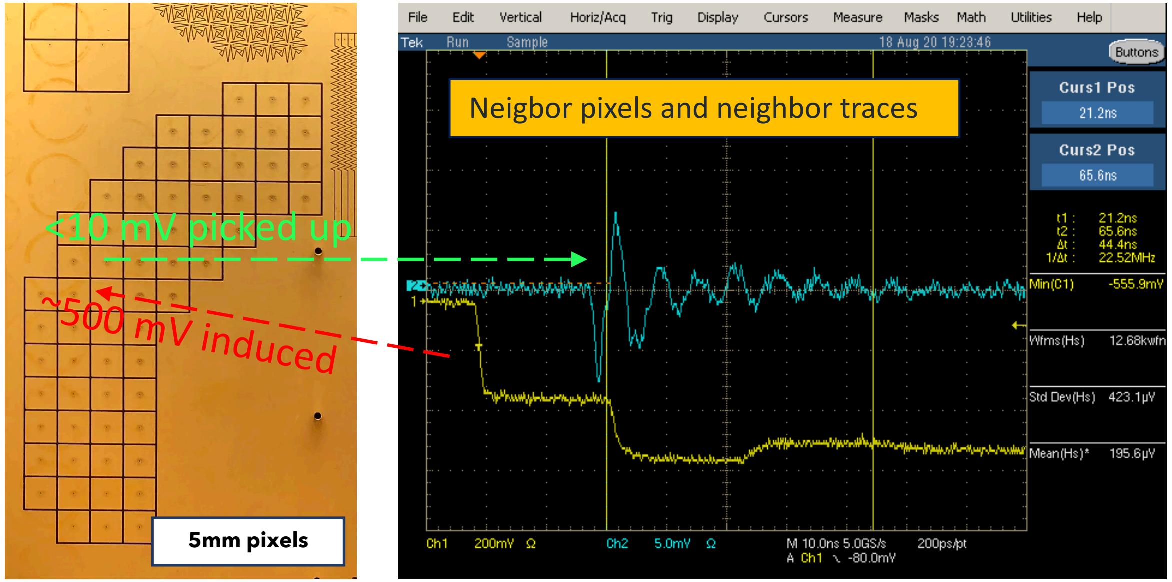

Front side: readout PCB, MCX adapter boards, HV



Modular setup: it takes one only half an hour to exchange (or rotate) the readout board

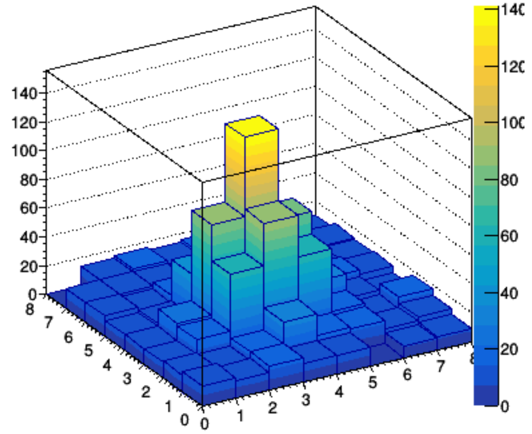
PCB design, cross-talk, single photon cluster size



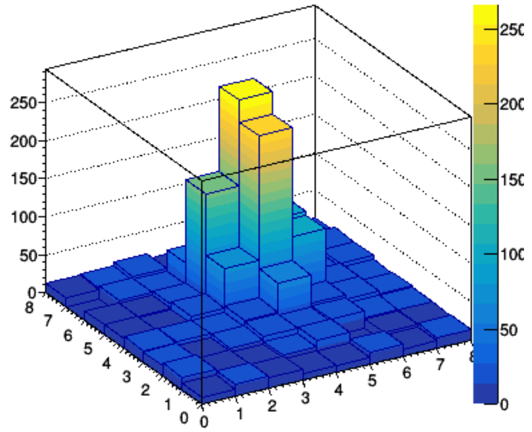


- Multi-layer stack-up; through vias; isolated traces
- Worst case X-talk ~few % level

3mm pixels

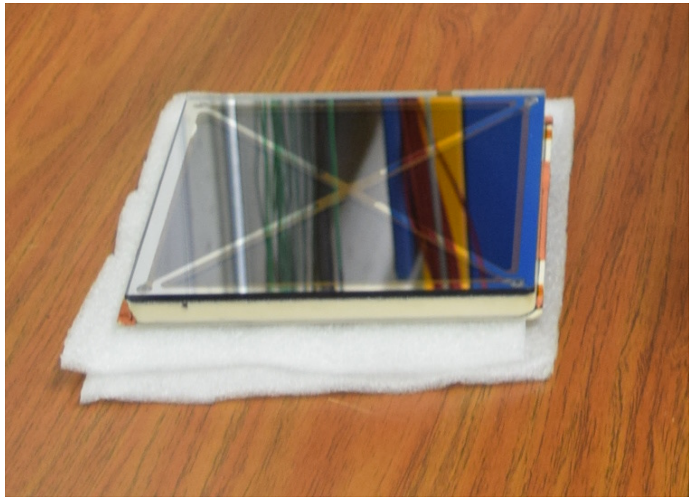


6mm pixels

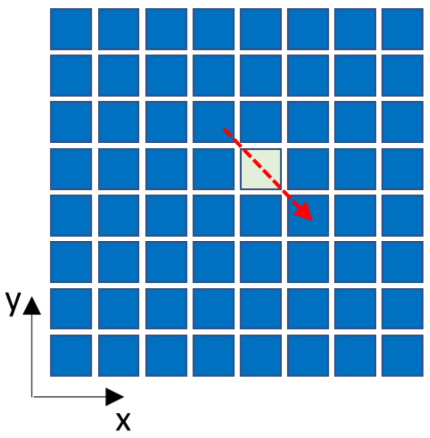


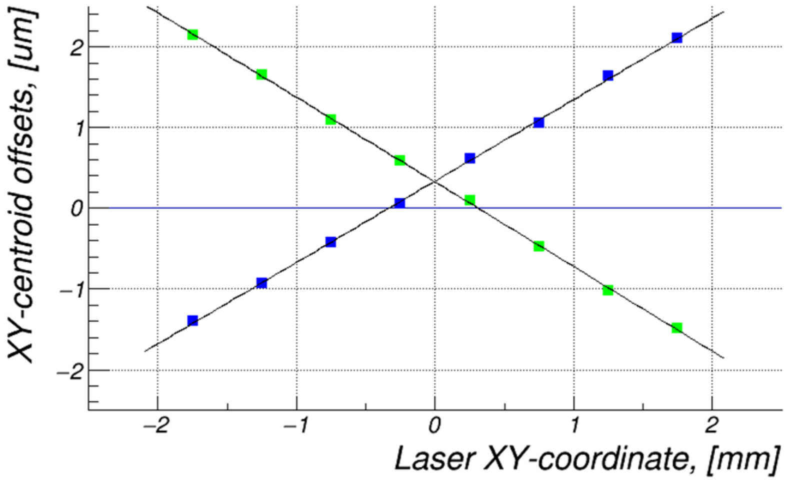
- For a capacitively coupled LAPPD with a "standard" stack and 2mm thick anode base cluster size RMS ~3.5mm
- Will be certainly smaller in a "short" stack configuration
- No data for DC-coupled tiles yet

Spatial resolution with 3mm square pixels



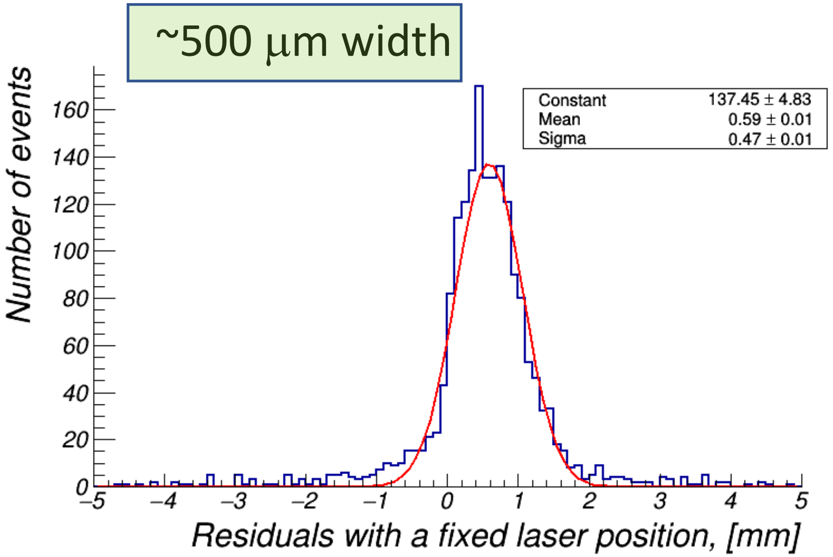
- Gen II LAPPD tile #97 provided by Incom
  - 2mm thick ceramic base





- 8x8 field with 3mm pixels, connected to a pair of V1742s
- Linearity scan along the diagonal direction shown

Photo cathode	2375 V
MCP#1 top	2300 V
MCP#1 bottom	1375 V
MCP#2 top	1175 V
MCP#2 bottom	250 V



- “Single-photon” mode

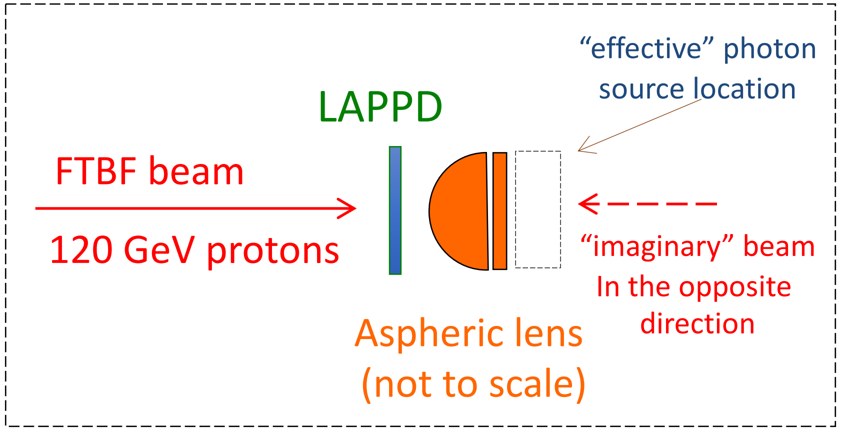
$$X \sim \frac{\sum_i^n q_i x_i}{\sum_i^n q_i}$$

Beam tests at Fermilab

(BNL, Incom Inc., Argonne, GSU, Stony Brook, MSU, INFN Trieste & other groups)

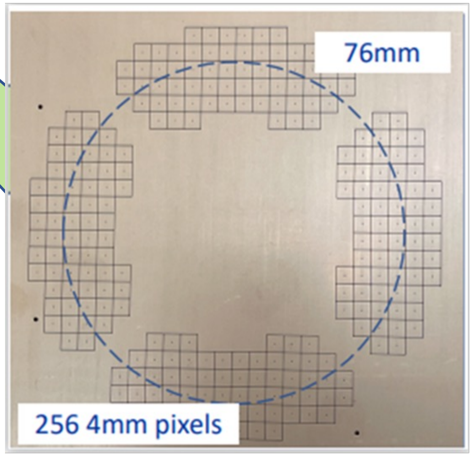
2021 setup and Cherenkov ring radius resolution

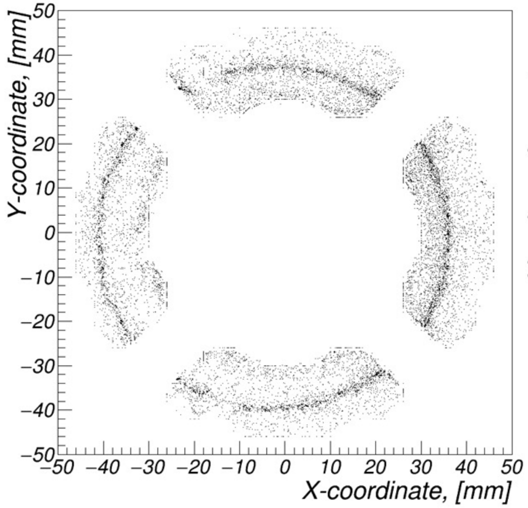
- The same setup as in the lab, but instead of a laser use *a thick aspheric lens* as a well controlled Cherenkov light source

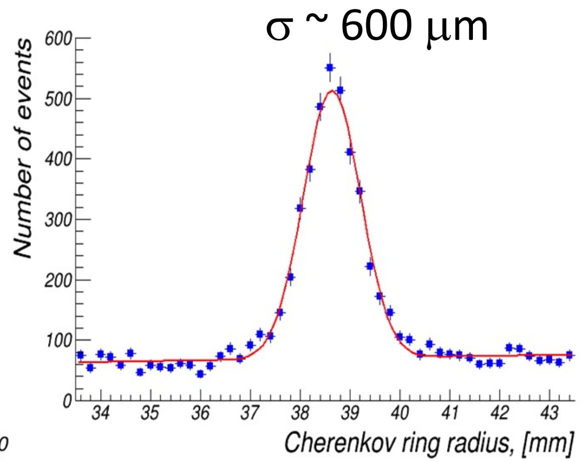


- Off-the-shelf component
- (Almost) no stray photons
- To first order no need in tracking
- The used model (Edmund Optics #67-265, EFL 20.0mm) produces a crisp ~76mm diameter ring at the focal plane

Pixel pattern & accumulated single photon XY-coordinates

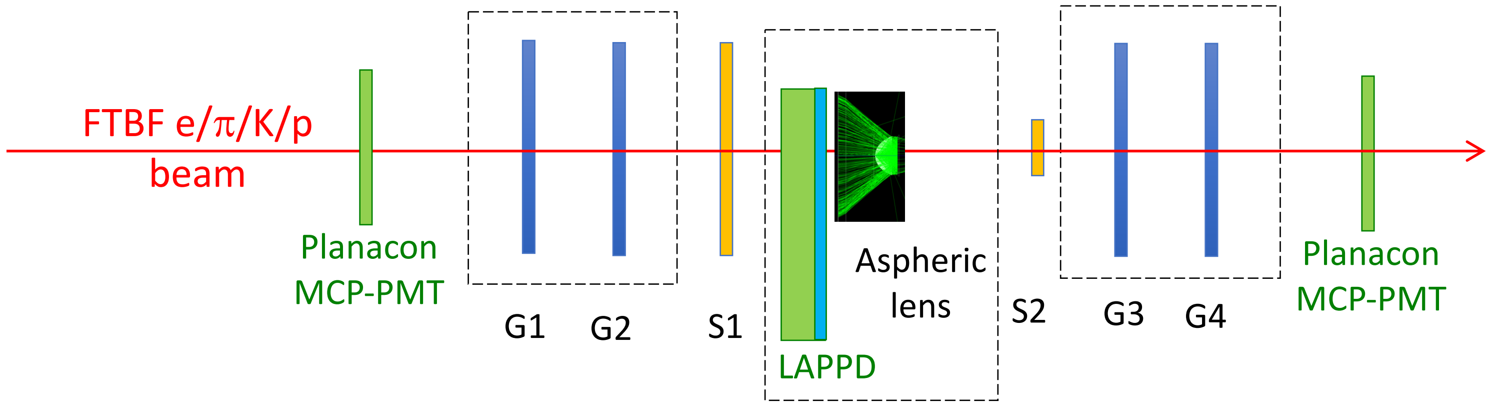


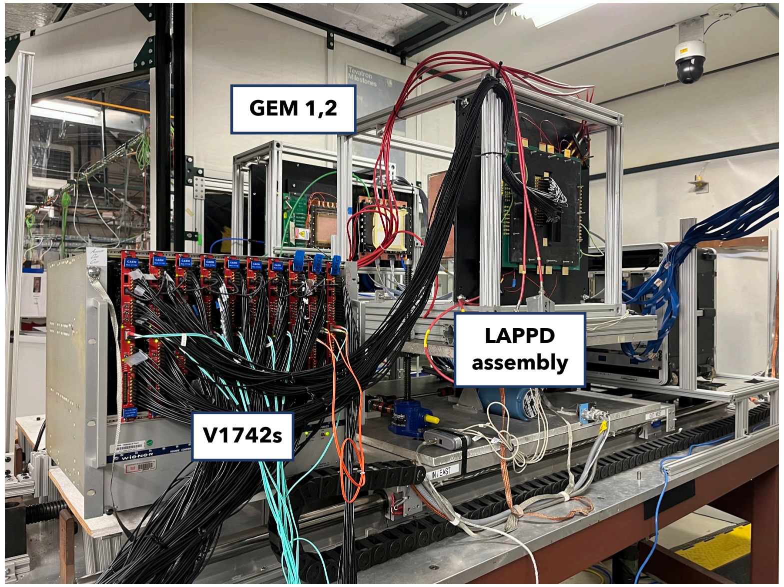




2022 setup

- G1 .. G4 – COMPASS GEM reference tracker
- S1 .. S2 – trigger scintillator counters

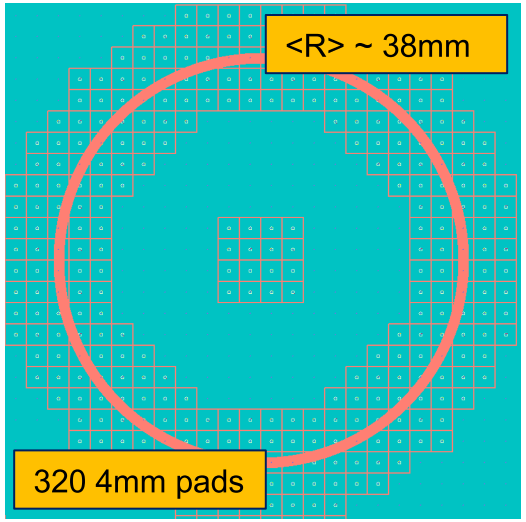


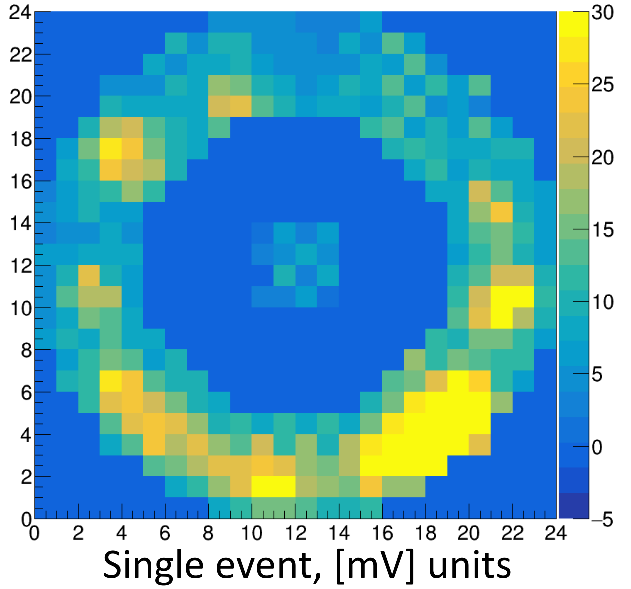


- A new 20 cm Gen II LAPPD tile 136
  - 10 μm pore MCPs
  - Full glass body (implies 5 mm thick anode base plate)
  - Window material -> UV grade quartz
- GEM reference tracker
- New set of the pixelated readout boards
- A pair of Planacon MCP-PMTs as a timing reference

Enough data on tape to quantify **single-photon** timing resolution

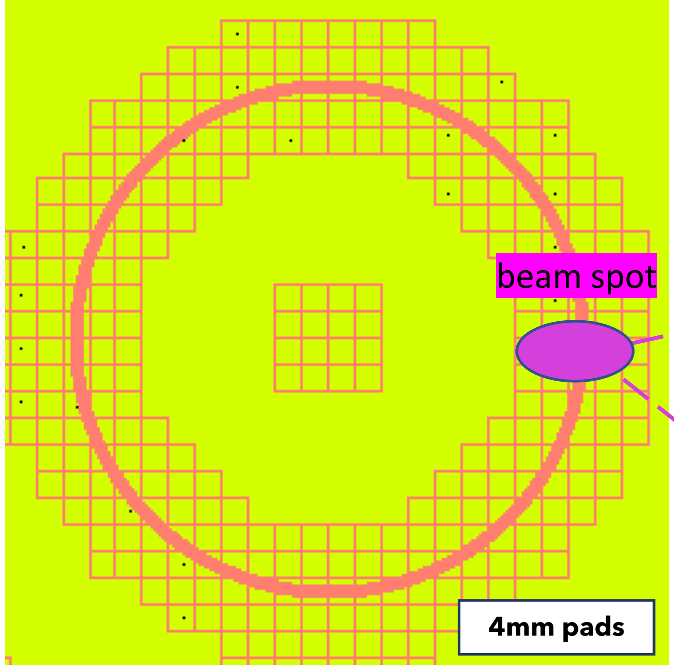
Aspheric lens as a source of coherent Cherenkov photons



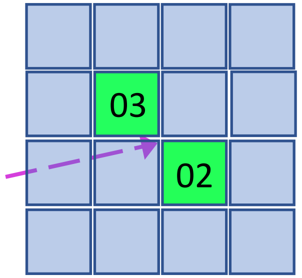


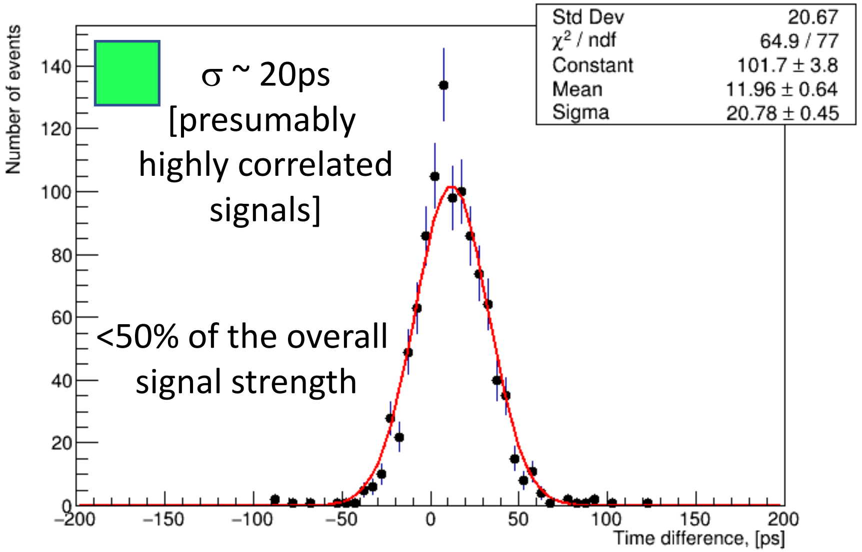
Timing resolution for Time-of-Flight applications

LAPPD quartz window as a Cherenkov radiator



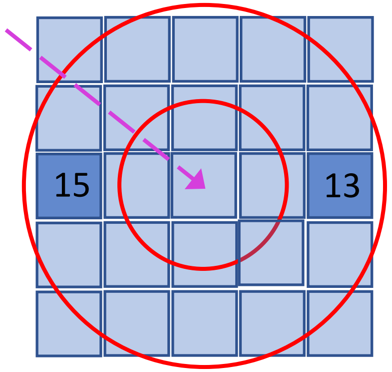
Event selection (A)

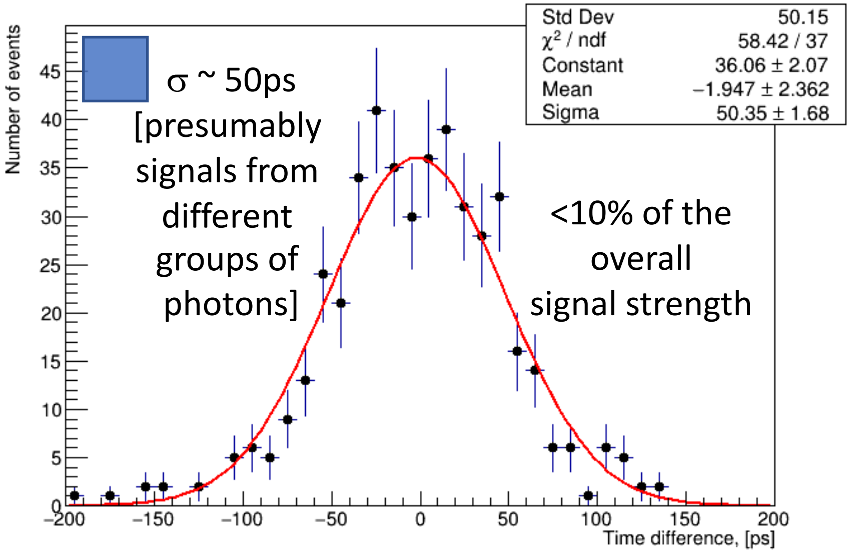




DRS4 chip#0: time(ch#03) – time(ch#02)

Event selection (B)





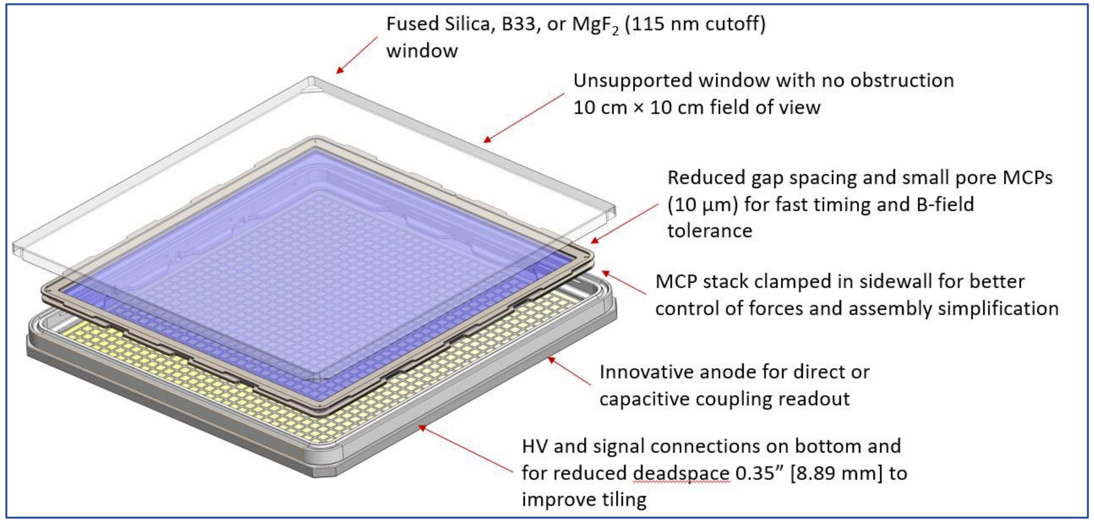
DRS4 chip#1: time(ch#15) – time(ch#13)

- *Single* photon TTS <50 ps
- 5mm thick UV grade quartz window: a 120 GeV proton produces a **blob of ~100 p.e.'s**

Due to the TIR, photons only hit the PC in a radial band ~[5.5 .. 12.0] mm

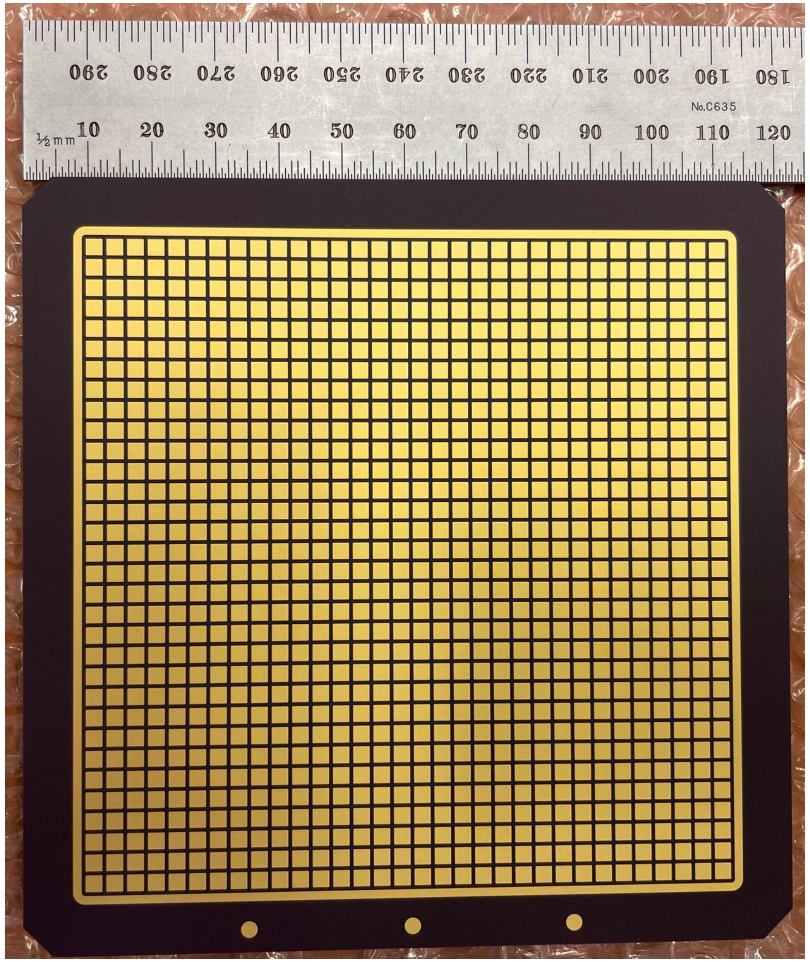
DRS4 and trace delay calibrations are still "in progress"

DC-coupled HRPPD interface



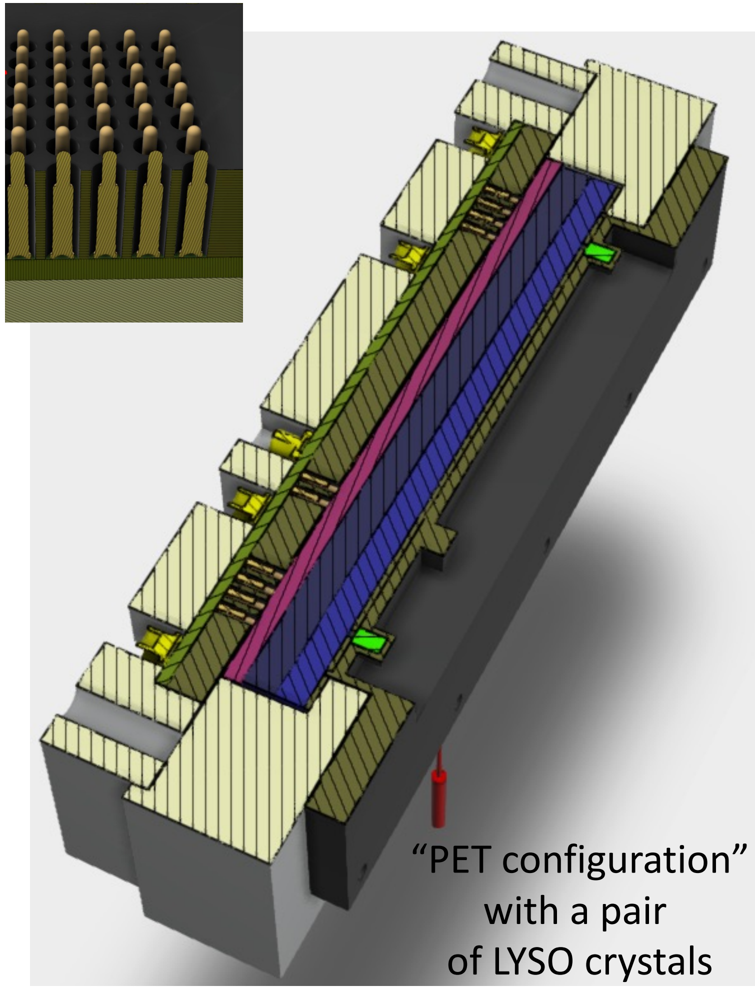
HRPPD photosensor

Tile #4 delivered to BNL beginning of October

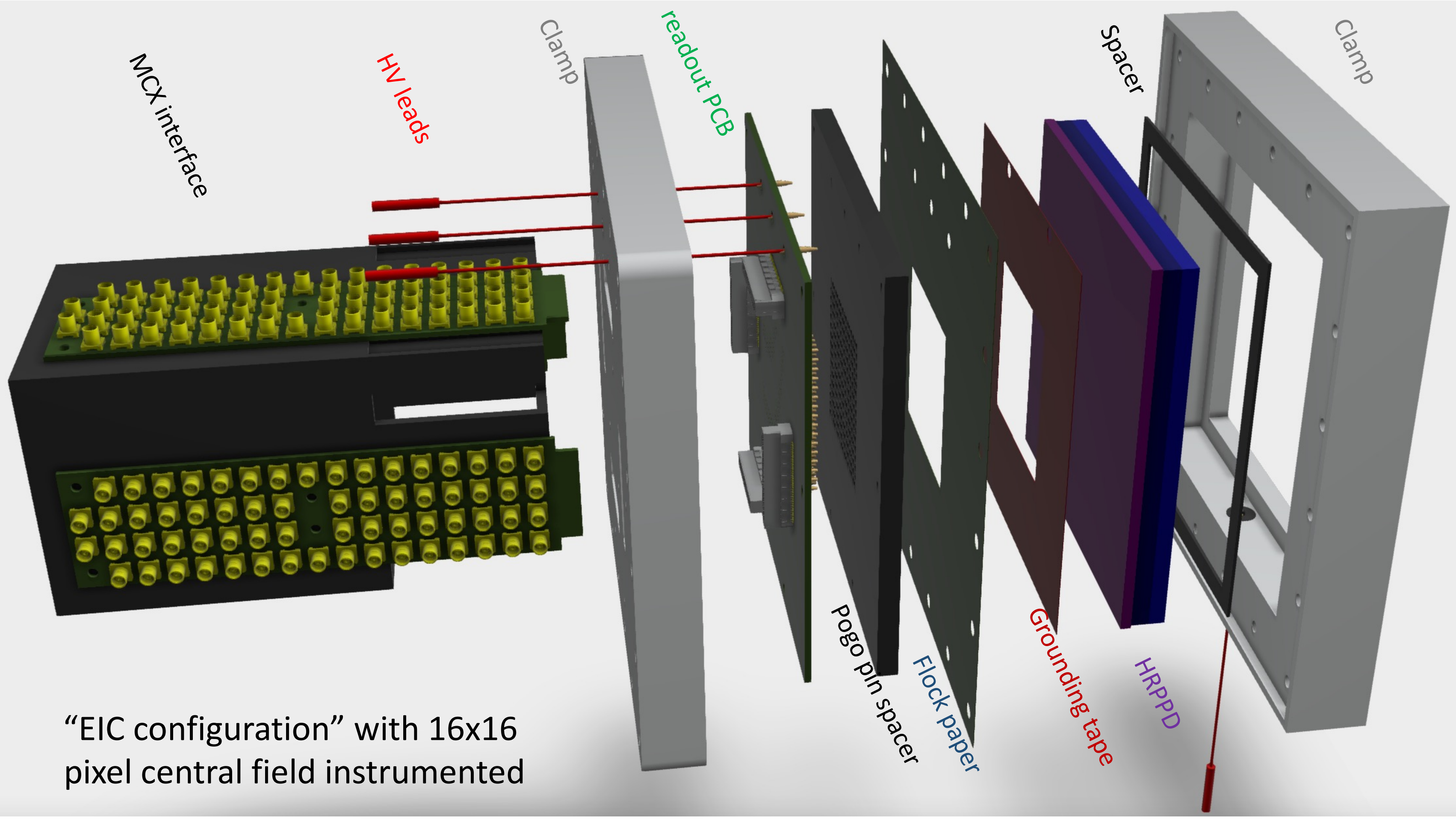


- ~120 x 120 mm² footprint; ~100x100 mm² unobscured active area
- 1024 pads, hermetic through vias, 1/8" (~3.2 mm) pitch
- Short MCP stack with 5 mm thick quartz window and 3.3 mm thick ceramic base plate

Electrical interface and 3D integration model



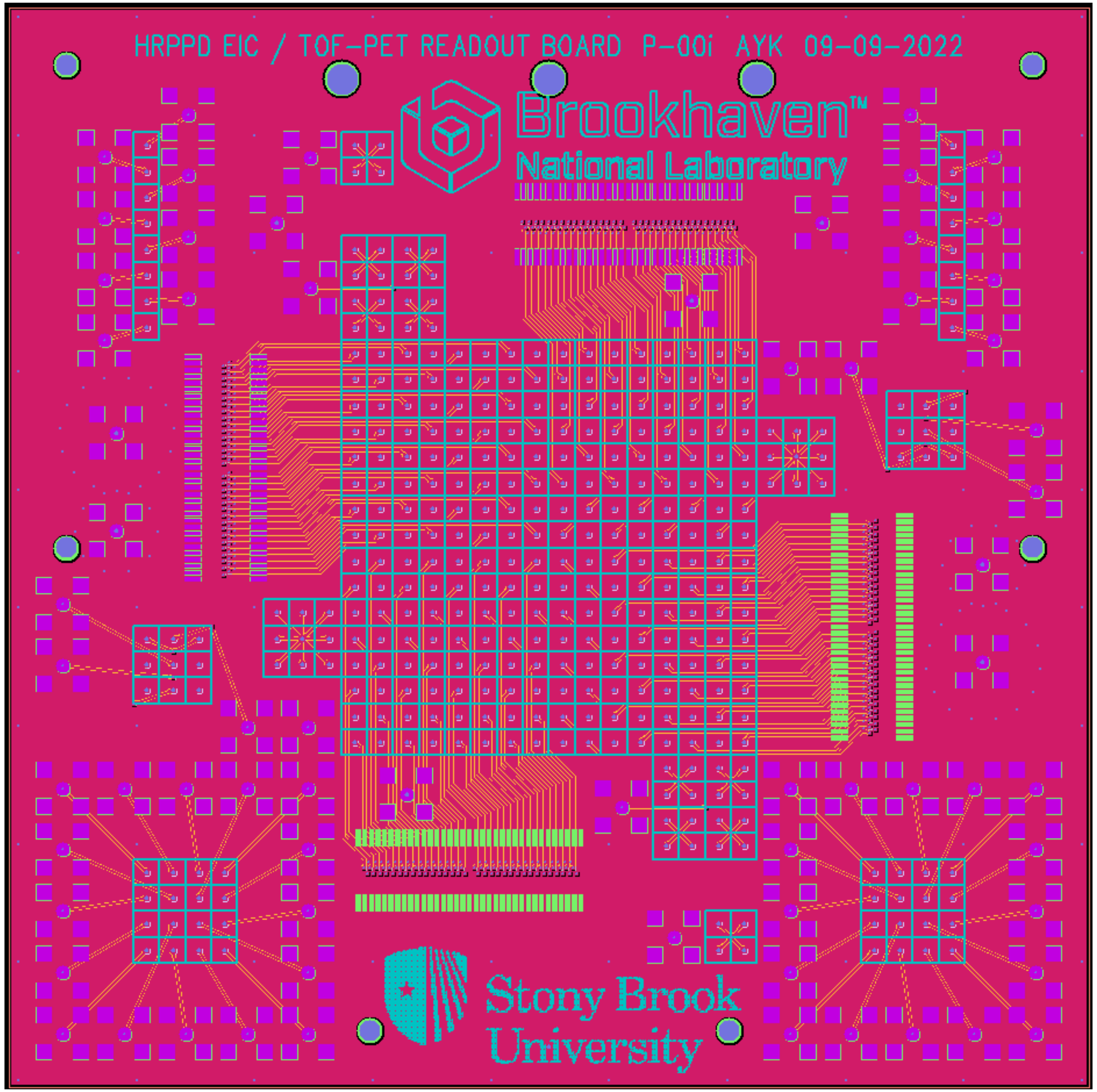
“PET configuration” with a pair of LYSO crystals



“EIC configuration” with 16x16 pixel central field instrumented

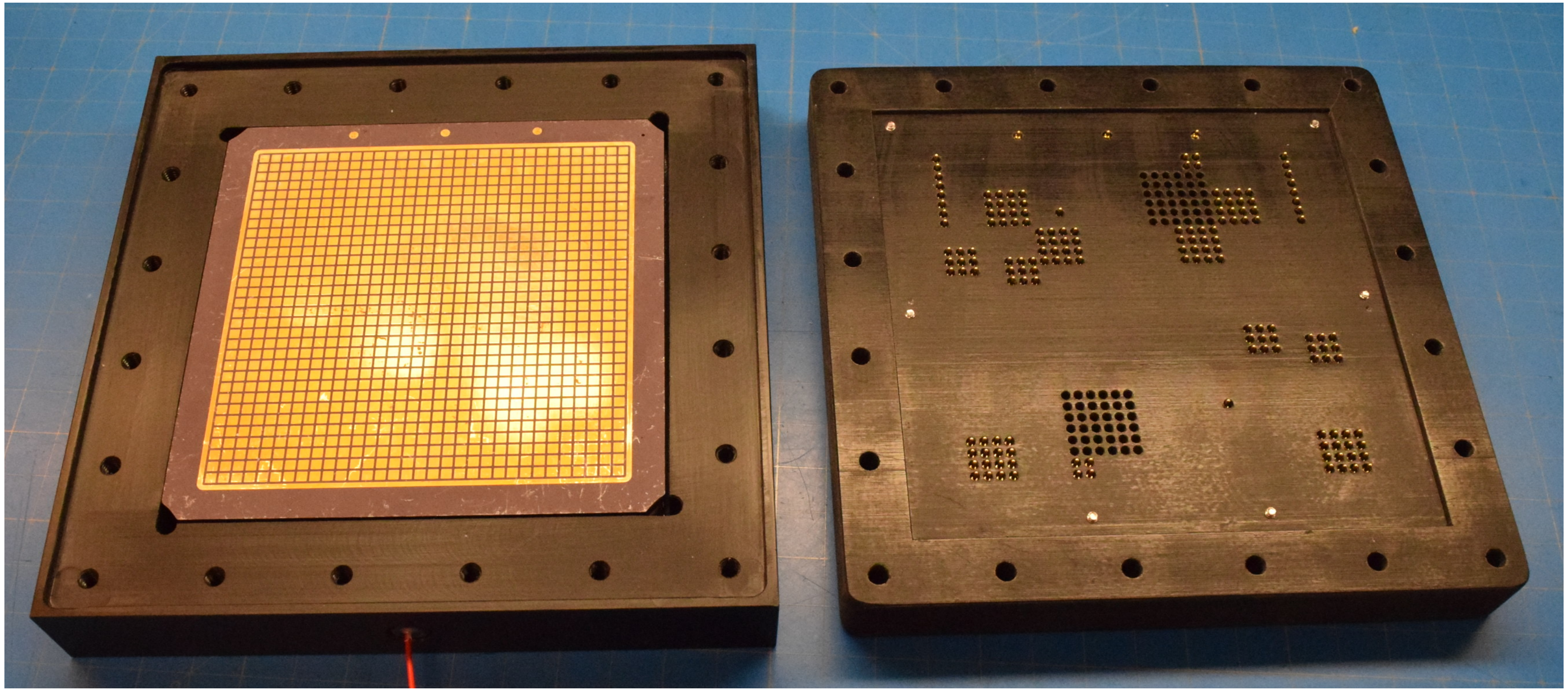
- Signal connection: a simple pogo pin interface
  - Should suffice for a basic performance evaluation (and for the TOF PET project application)
  - Further options: custom LGA or ZIF sockets, BGA+PCB, *ceramic unibody concept*, ..?

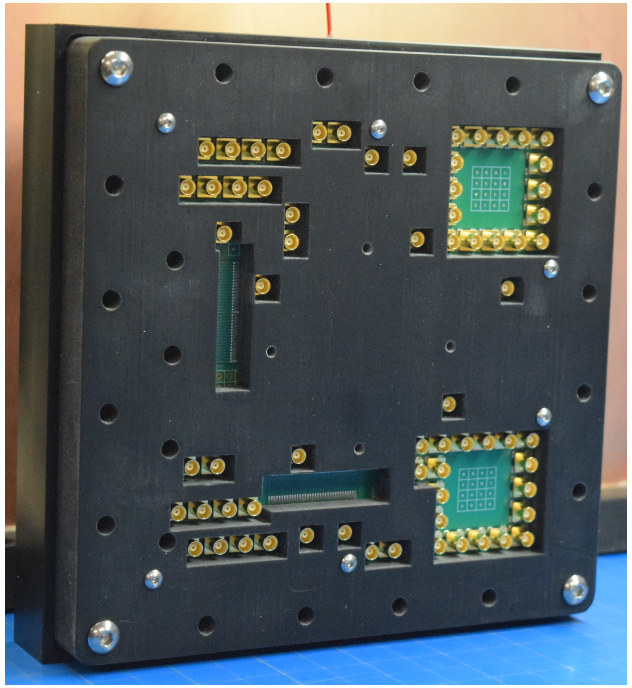
Dual purpose readout PCB

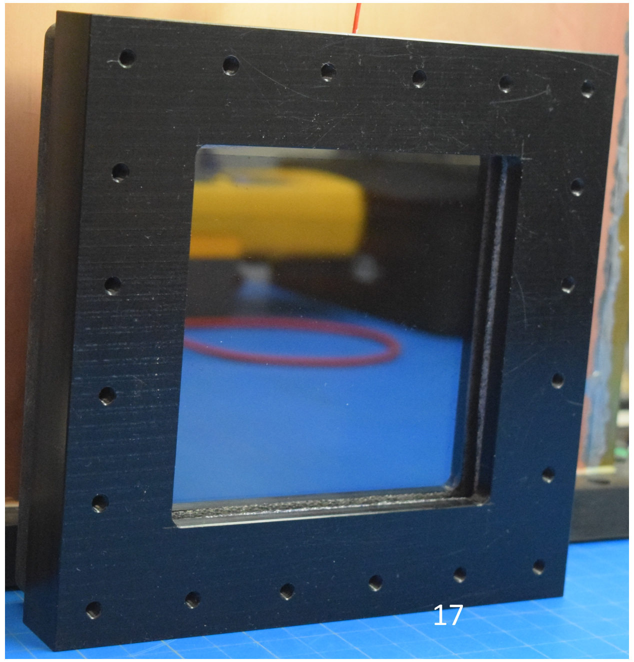


- A compact universal 132 x 132 mm^2 board
- Pixellation follows ~3.2mm HRPPD pad pitch
- Two “main” instrumentation options:
  - A 16x16 pad field in the center
  - Pairs of individual pad fields for systematic studies
- Connectivity via either MCX->MCX cables or Samtec->MCX adapters
- Can be used for the DC-coupled HRPPDs (assembly with the pogo pins), as well as for the capacitively coupled HRPPDs / LAPPDs (assembly without the pogo pins)
- Can also be used in a coincidence setup with a picosecond laser

HRPPD evaluation prospects







- All the ingredients are in place
- Assembly process started
- First lab tests will happen by the end of December

Proximity focusing RICH for EIC

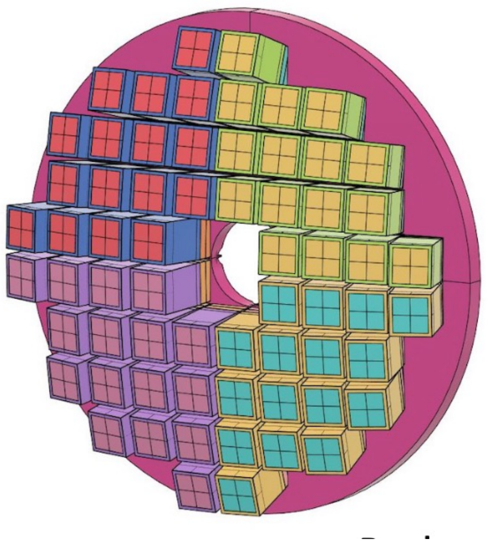
(BNL, Duke, INFN Trieste, MSU, SBU, IJS)

Possible HRPPD applications for the ePIC detector

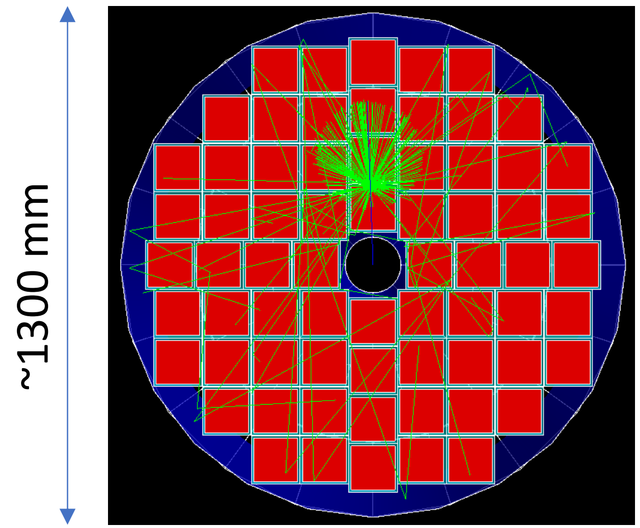
- mRICH / pfRICH: low dark noise, Time of Flight capability (vs SiPMs)
- DIRC: expected to be more cost-efficient (vs other MCP-PMTs)
- dRICH: problematic, because of the magnetic field orientation
- Preferred variety:

mRICH	either DC-coupled or Gen II
pfRICH	either DC-coupled or Gen II
DIRC	DC-coupled

electron-going endcap

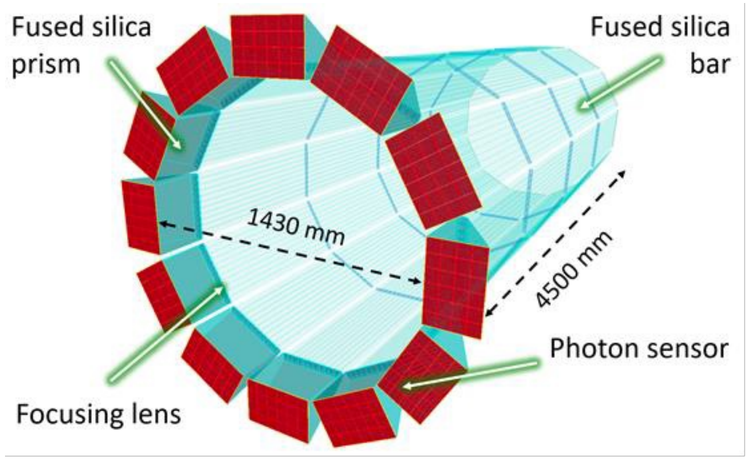


mRICH: 64 modules



pfRICH sensor plane: 68 tiles

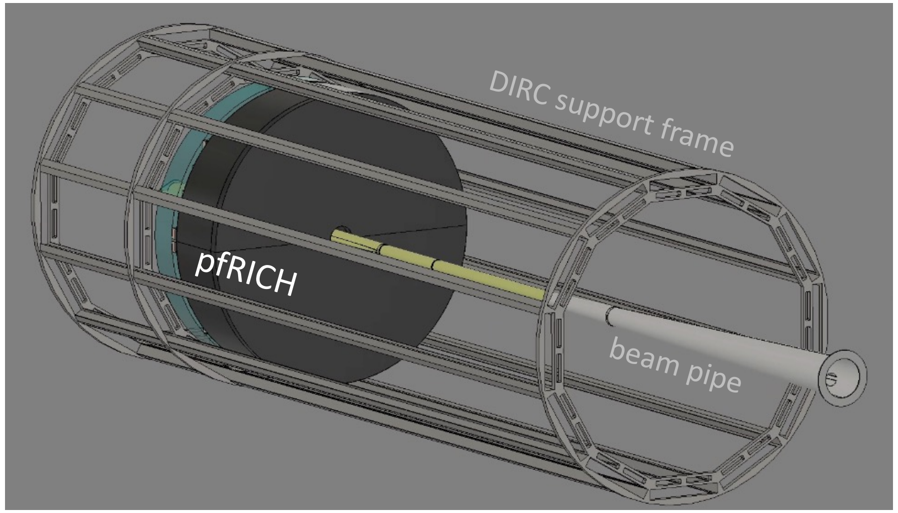
barrel



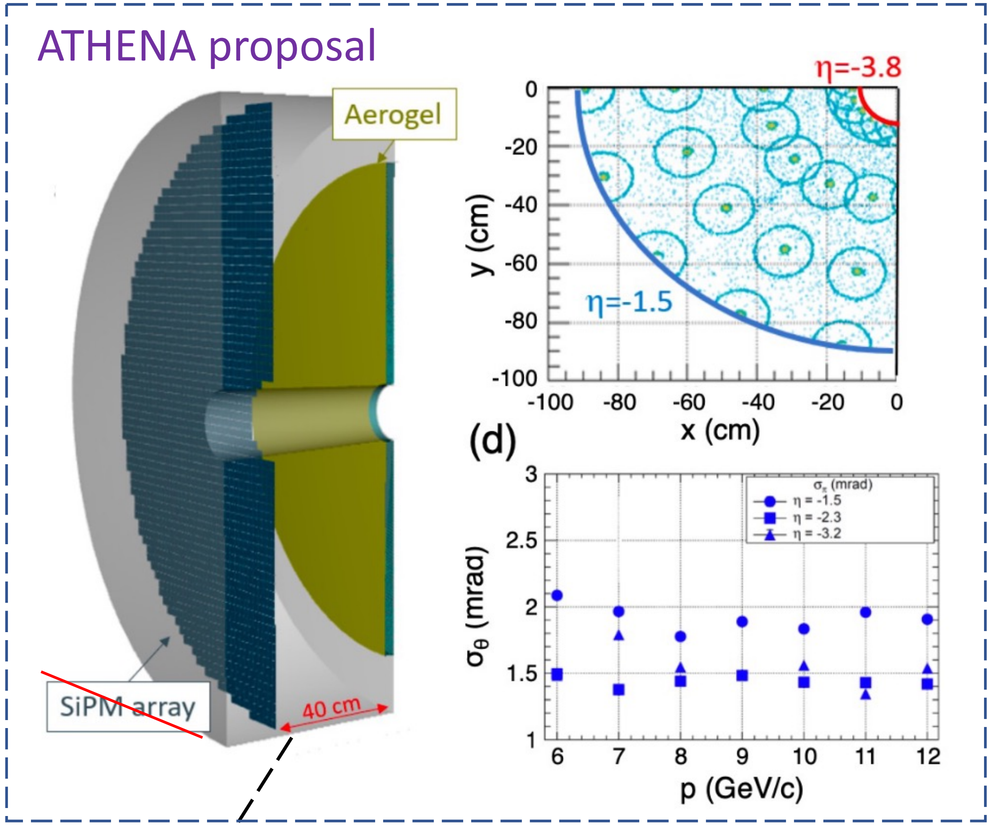
DIRC: 12*3*2 = 72 tiles

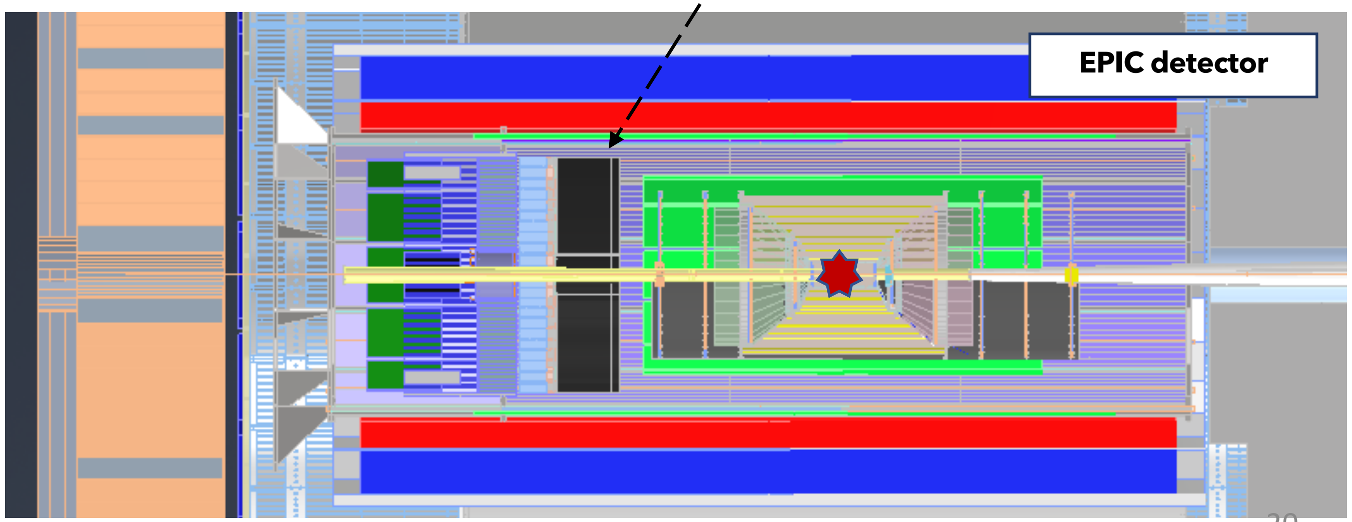
pfRICH detector concept

- A “simple” proximity focusing RICH inspired by the ATHENA EIC detector proposal, with the SiPMs replaced by HRPPDs as a photosensor solution



Inner radius	~60 mm
Outer radius	~650 mm
Total length	~540 mm

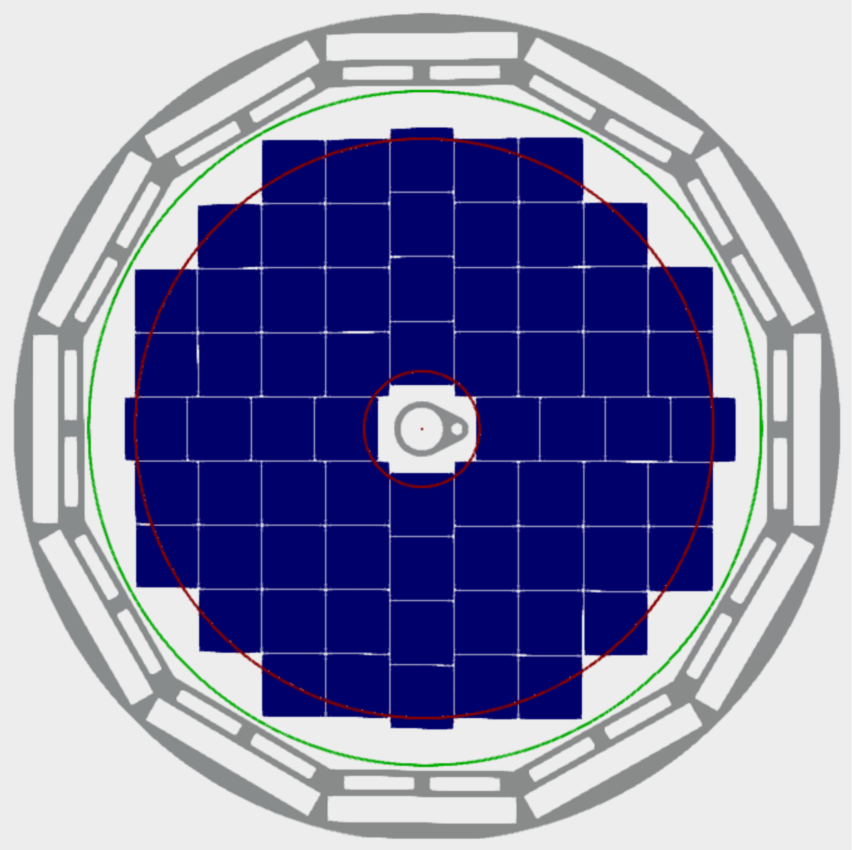




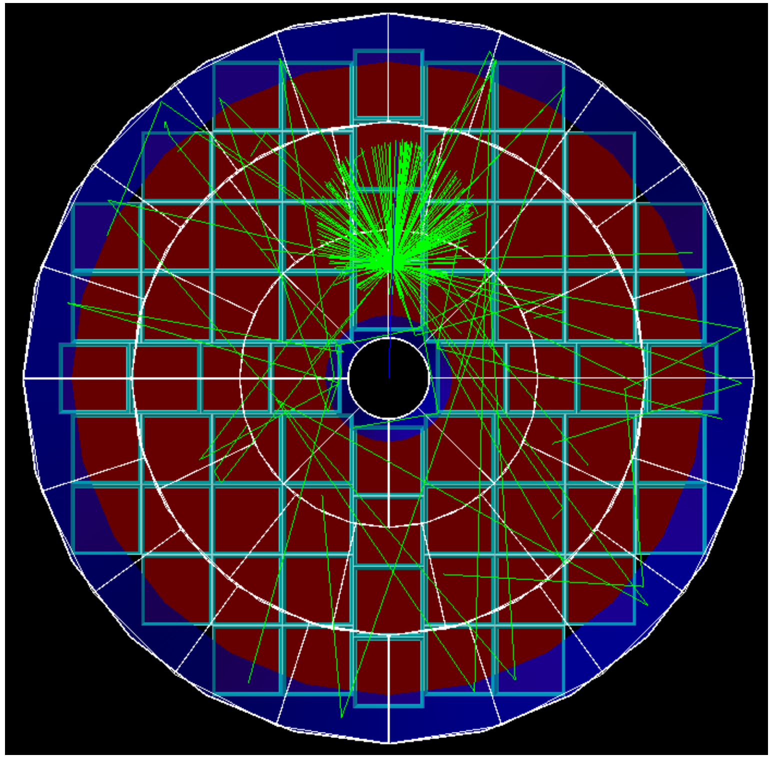
~9.5m along the beam line

Implementation details

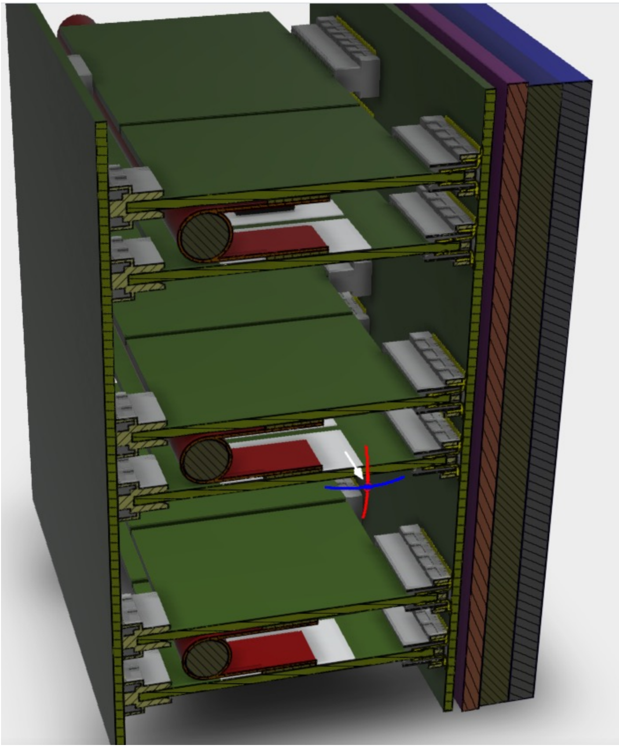
CAD model



GEANT model



Electronics integration



- Continuous flat sensor plane coverage with minimal gaps (~120 mm HRPPDs)
- Conical mirrors at the inner and outer vessel boundaries
- Optional mirror “pyramids” around HRPPD boundaries (to achieve ~100% geometric efficiency)

TOF PET Seed Grant project

(SBU & BNL)

Application requirements in HEP/NP & TOF PET

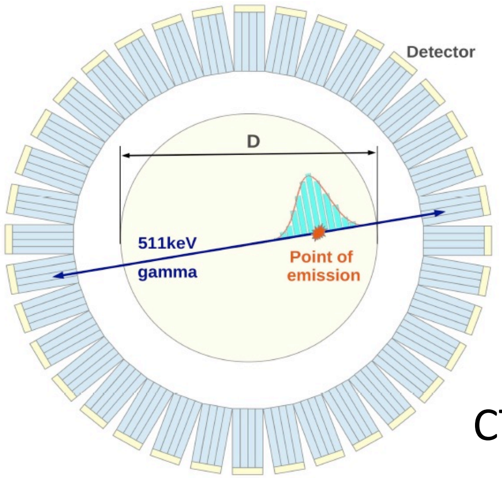
"Conventional" HEP/NP Cherenkov light detectors

But for TOF applications: $\sigma_t < 20$ ps

	Single photon time resolution	MCP-PMT anode plane segmentation
CERN: LHCb TORCH	~70 ps	1mm wide "strips"
FAIR: PANDA endcap DIRC	<100 ps	<0.5 mm wide "strips"
(e)RHIC: EIC barrel DIRC	<100 ps	3x3 mm^2 pixels

Time of Flight Positron Emission Tomography (TOF PET)

<1 mm spatial resolution required in transverse direction



Time difference between the two 511 keV gammas in opposing crystals can be used to localize the decay *along the line of response*

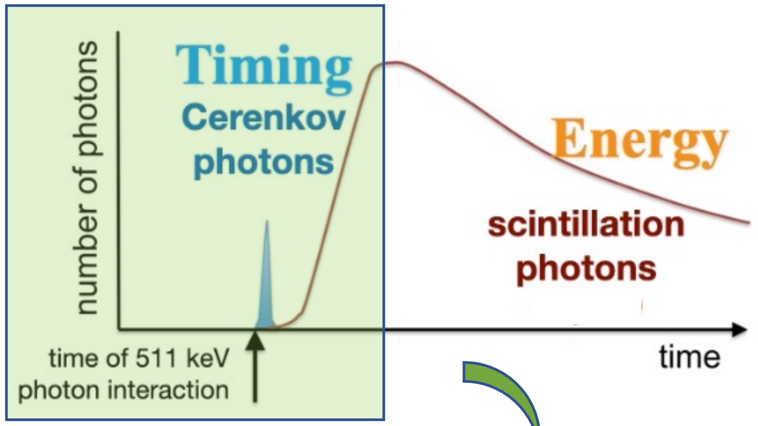
S/N Gain with TOF

$$G = \frac{SNR_{TOF}}{SNR_{non\,TOF}} = \sqrt{\frac{2*D}{c*CTR}}$$

CTR	G
100	5.2
50	7.3
10	16.3

CTR (Coincidence Time Resolution) = 100 ps $\Rightarrow \Delta x$ = 1.5 cm

When a 511 keV gamma photon interacts in a scintillator, a number of Cerenkov photons are produced promptly by energetic electrons.

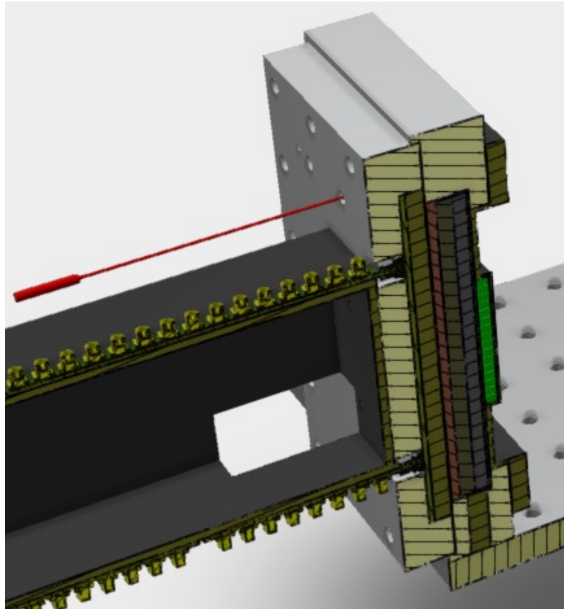


Reducing CTR to dozens of ps opens a possibility to use *direct imaging* instead of multi-event reconstruction

SBU / BNL Seed Grant proposal

- *"LAPPDs for TOF PET: a breakthrough in ultra-high sensitivity Positron Emission Tomography using fast affordable Micro-Channel Plate photomultipliers"* was approved and started in July 2022
  - Quite some synergy with the HEP / NP LAPPD R&D activities

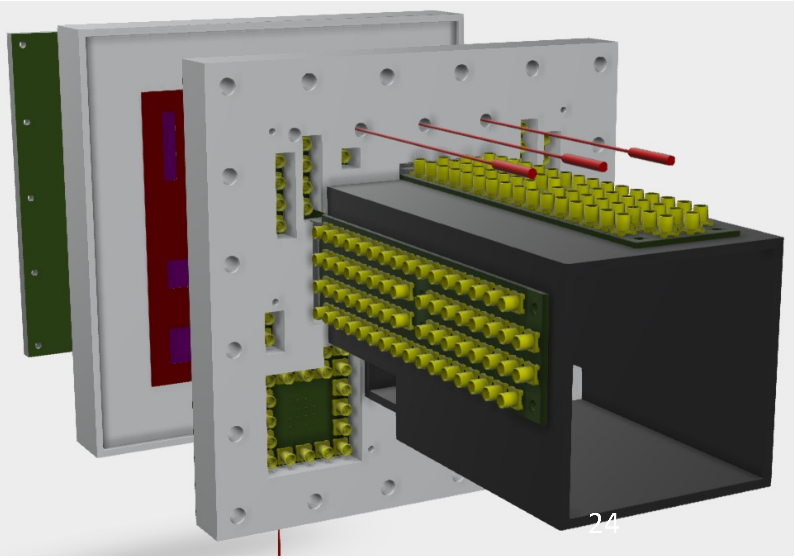
Combine expertise and equipment gained via the earlier and ongoing NIH- & DOE-funded projects with a brand new Incom HRPPD as a photosensor

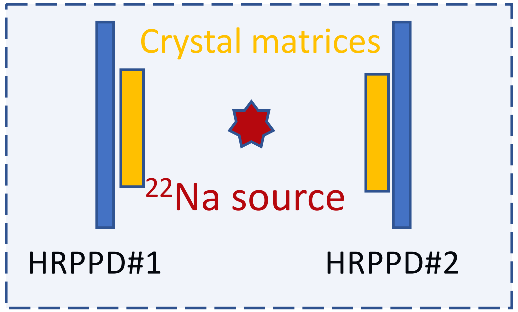


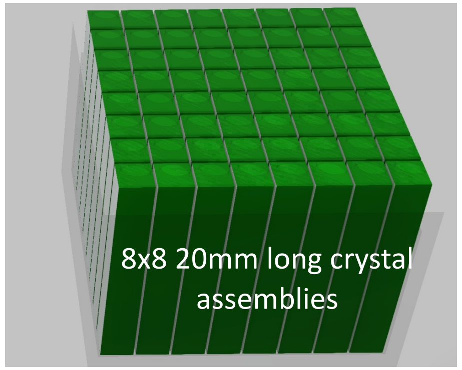
Assembly variant with
a 16x16 5mm long crystal matrix

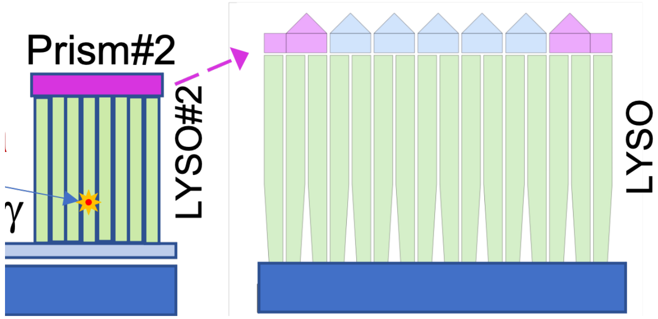
- Same readout board as to be used for EIC-related HRPPD evaluation
- 16x16 LYSO crystal matrices matching HRPPD pixellation
- Prism-PET for Depth-of-Interaction compensation
- 512 DRS4 electronics channels

Assembly variant for systematic studies







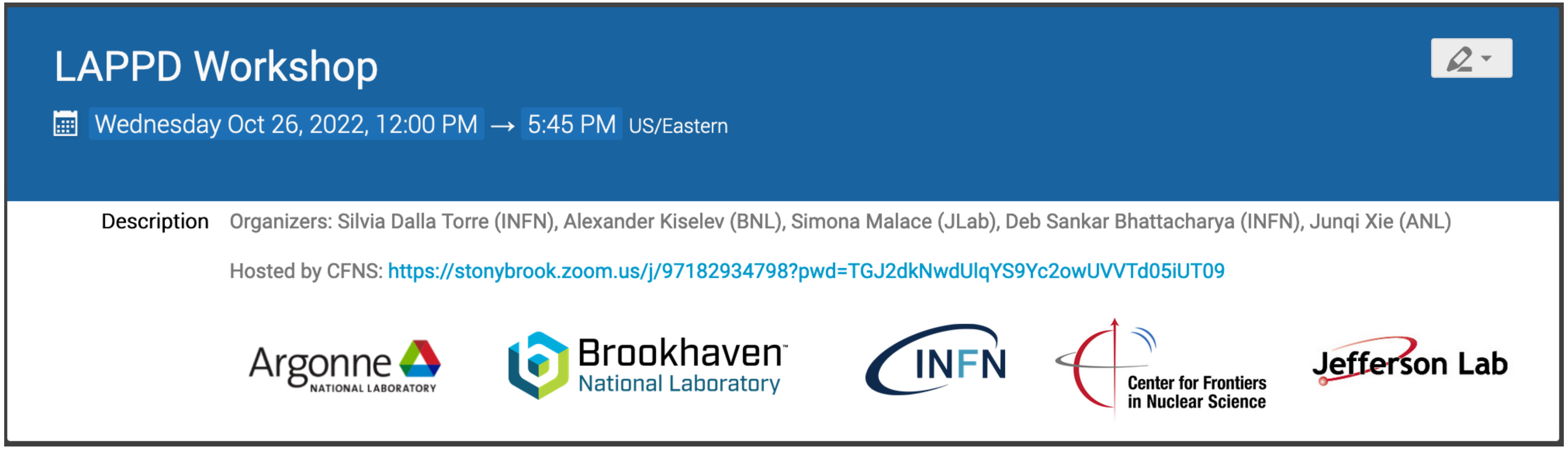


Other resources

LAPPD workshops

Workshop #1 (March 2022) : https://indico.bnl.gov/event/15059/

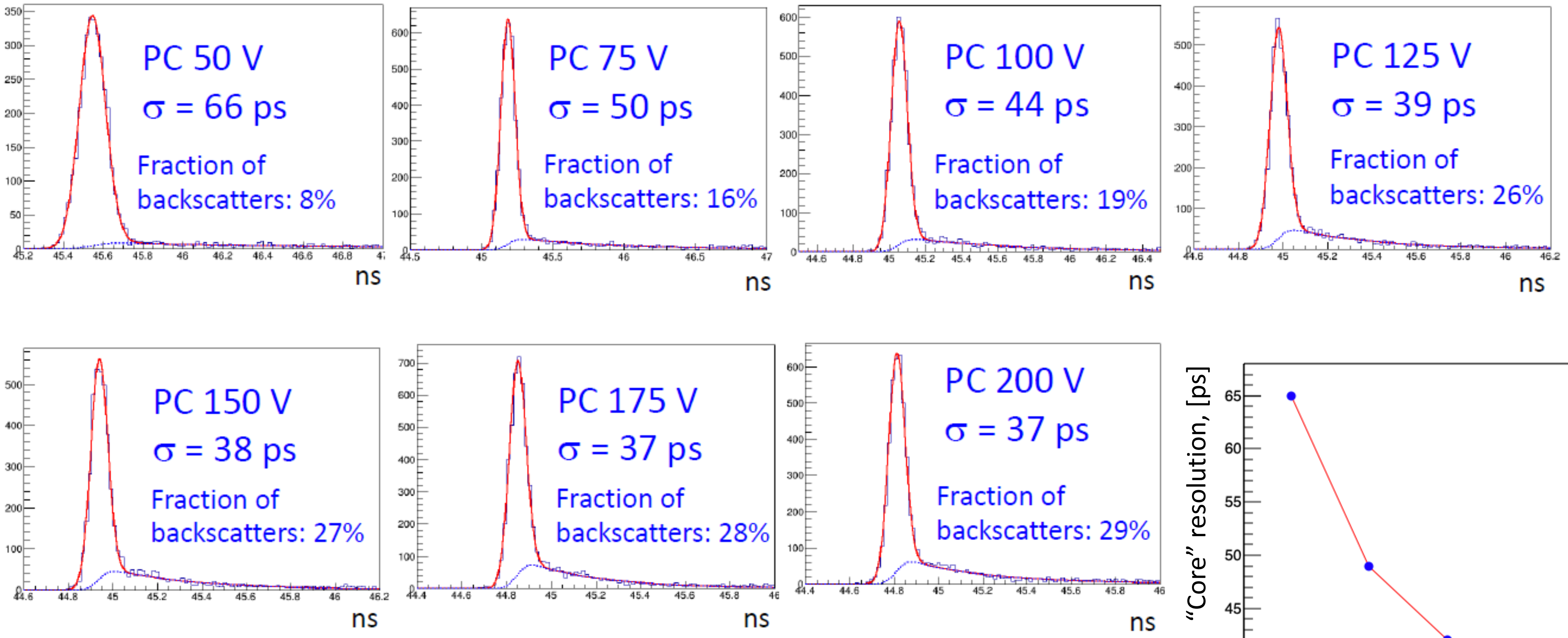
Workshop #2 (October 2022): https://indico.bnl.gov/event/17475/



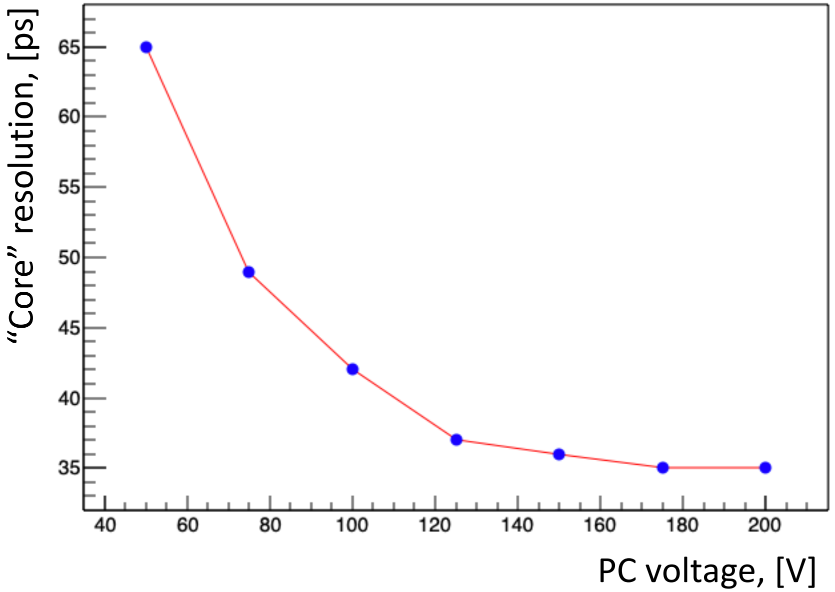
LAPPD mailing list: https://lists.bnl.gov/mailman/listinfo/lappd-l

Backup

Single photon timing resolution



Data: V. Vagnoni (INFN Bologna)



- Remember: EIC requirement is "<100 ps"
- Tail is of course a concern for the DIRC
- We are collecting our own beam data on this (INFN, BNL)

Data: V. Vagnoni (INFN Bologna)