FJPPN-D_RD_33
AC-LGAD Detector with Continuous Readout for 4-Dimensional High-Resolution Measurement at EIC ePIC

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TYL/FJPPN and FKPPN Joint Workshop

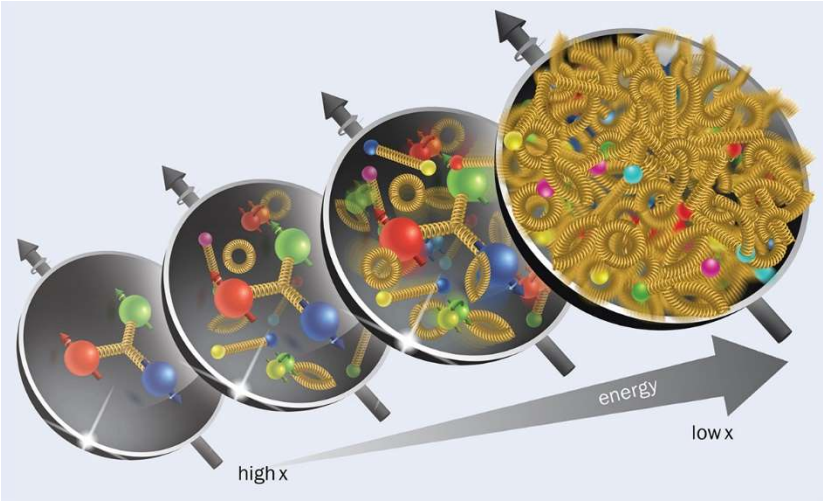
14–16 May 2025, Nantes, France

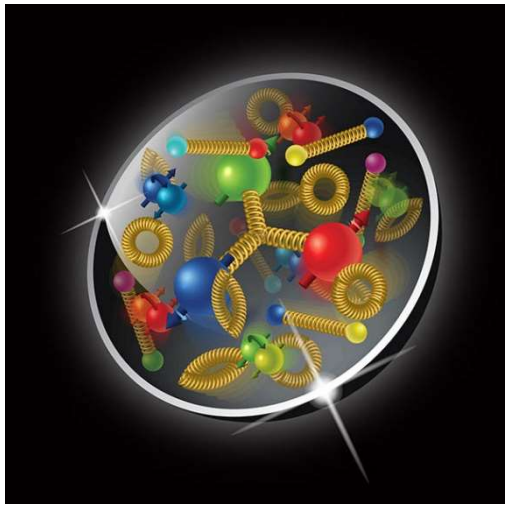
Presentation Outline

- ePIC experiment at electron ion collider
- barrel time of flight detector with strip AC-LGAD
  - perfect combination of Japan - France (- US)
- 2024 highlights (and thanks)
- 2025 plans (and thanks in advance)
- collaborators
  - France/Japan institutes, members, roles
  - PhD students
- summary and concluding remarks

ePIC at Electron Ion Collider at BNL

- electron beam as world premier microscope
- emergent properties of proton/nucleus
  - especially hadronic mass and spin



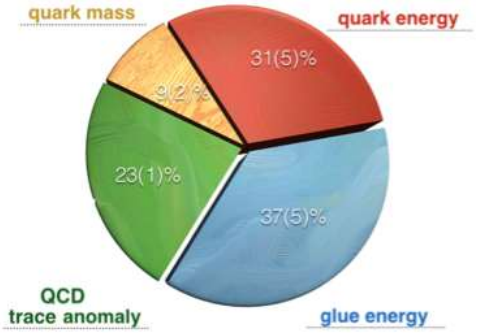


- launched and shooting for start in ~2032
- both particle and nuclear physicists involved

(*Personally Biased*) Physics Interests

- origin of hadronic mass
  - trace anomaly ~ gluon condensation
    - various hadrons' generalized parton distribution function
    - near-threshold quarkonia

Y.-B. Yang *et al.*,
EPJ Web Conf. 175, 14002 (2018)

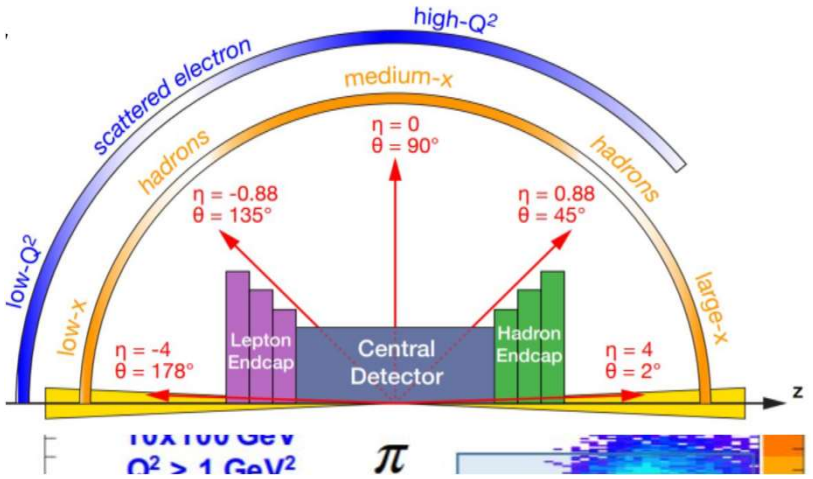


cf. chiral symmetry breaking ~ quark pair condensation
  - low mass vector meson spectra
  - chiral mass degeneracy (via chiral V-A mixing)

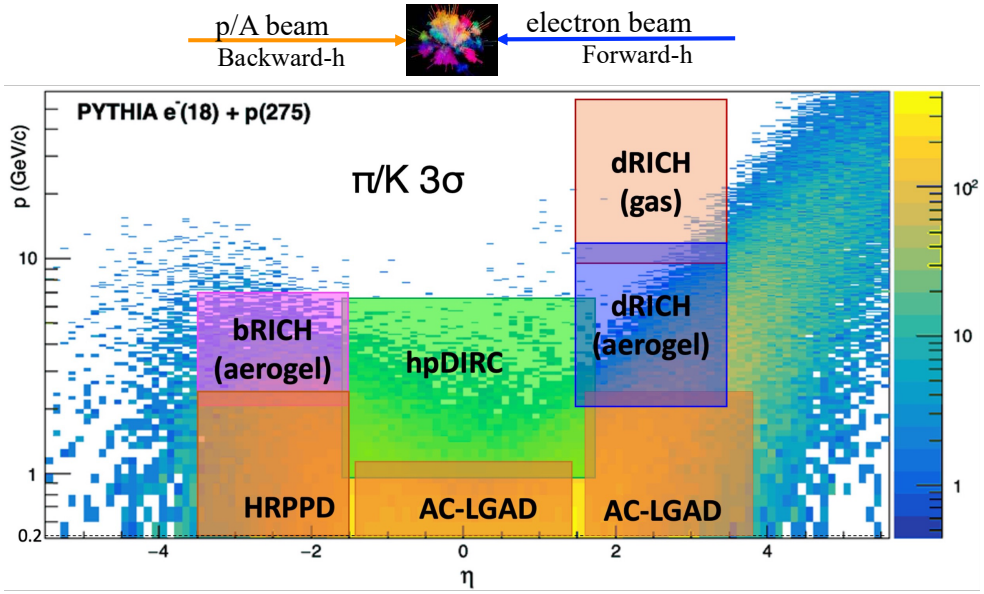
- ..., origin of hadronic spin, gluon saturation,
  3-d imaging inside hadron, confinement, ...

Particle Identification Essential

- multiple physics channels
  - electron/pion/kaon/proton identification
    - > 3 σ separation
- multiple technologies demanded
  - wide rapidity coverage
    - |η| < ~1.5 (barrel)
    - ~1.6 < |η| < ~4.0 (endcaps)
  - wide momentum coverage
    - < 50 GeV/c in hadron endcap
    - < 8 GeV/c in barrel
    - < 10 GeV/c in electron endcap



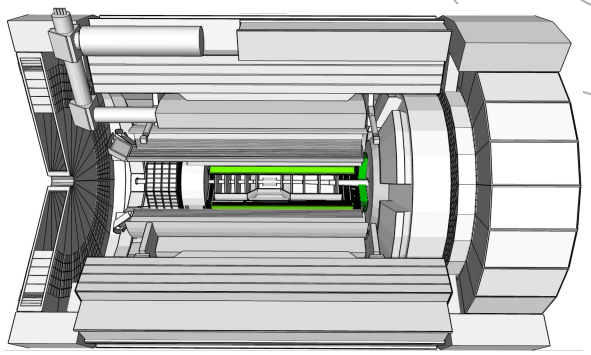
PID Technology Choice



- ToF (Time of Flight)
  - key in low- to mid- transverse momentum regions
  - in barrel and hadron endcap
- RICH (Ring Imaging Cherenkov)
- DIRC (Detection of Internally Reflected Cherenkov)

ToF Detector Requirements

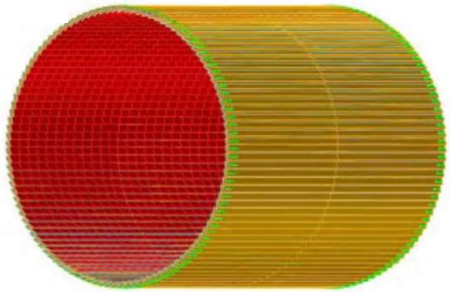
- main PID device at low- to mid- p_T region
  - $|\eta| < 1.4$ (barrel)
  - $1.8 < \eta < 3.9$ (hadron endcap)
  - e/π/K/p separation
    - π/K up to 1.3/2.4 GeV/*c* in barrel/endcap



- excellent time resolution required
  - short path length due to compact ePIC design
    - 35/25 ps in barrel/endcap
- position resolution also demanded
  - to help tracking and momentum measurement
    - 30/30 μm in barrel/endcap

ePIC Barrel Time of Flight Detector

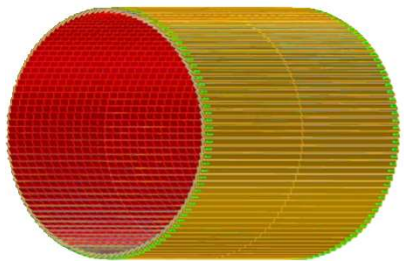
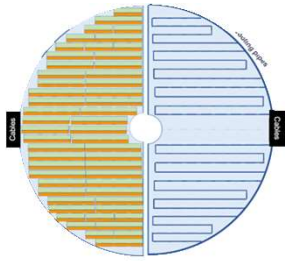
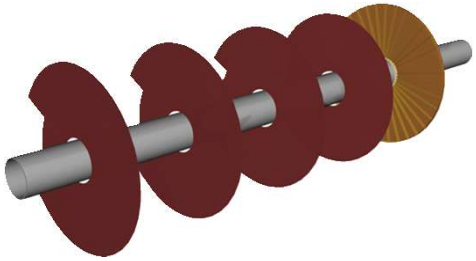
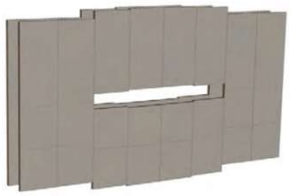
- requirements for barrel ToF at < 0.7 m radius:
  - ~35 ps time resolution
  - ~30 μm position resolution to help tracking
    - despite with low multiplicity and spatial density
  - a few % X_0 thinness for angle resolution of DIRC behind
  - ~10^{10} n_{eq} cm^{-2} radiation tolerance
    - integrated at top luminosity L ~ 10^{34} $cm^{-2}s^{-1}$
    - *cf.* HL LHC 10^{15-16} n_{eq} cm^{-2} at L ~ 10^{35} $cm^{-2}s^{-1}$
  - ~12 m^2 area
  - insensitivity to magnetic field
- AC-LGAD chosen along with endcap ToF



Unique Strip AC-LGAD in ePIC

- **AC-LGAD popularity**

Barrel TOF (strips) | Forward TOF (pixel) | B0 tracker (pixel) | Roman/OMD (pixel)

	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	35 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.4	0.5*0.5	5.6M	25 ps	30 μm in x and y	0.05 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.05 X_0
RPs/OMD	0.14/0.08	0.5*0.5	0.56M/0.32M	30 ps	140 μm in x and y	no strict req.

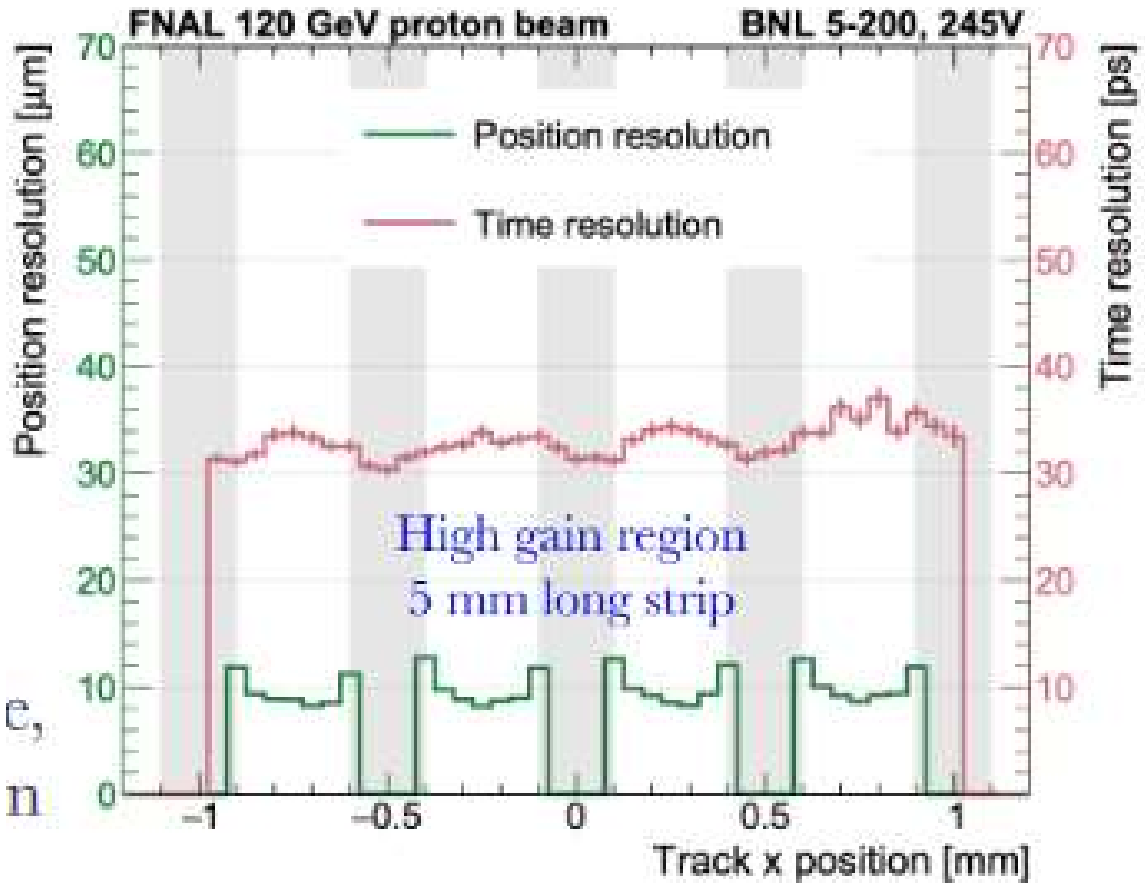
- **only barrel TOF adopting strip-type AC-LGAD**
  - large area ~ 12 m^2
  - need of own readout ASIC development

Strip AC-LGAD Sensors

- HAMAMATSU PHOTON IS OUR BUSINESS (Japan)
  - multiple meetings in 2024–2025
- first prototypes in fall 2025
  - sensor electrode geometry
    - timing resolution, position resolution
  - active layer thickness
    - timing resolution, signal strength
  - readout geometry
    - impact on overall detector design
- first results coming soon

AC LGAD performance [FNAL]

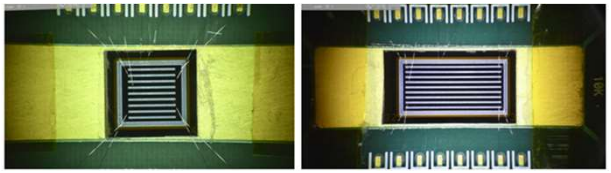
- Strips 500 µm x 5 mm
  - 30-35 ps timing res.
  - 10 µm position res.
- New and promising detector

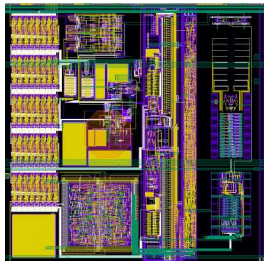


From S. Nanda : https://indico.cern.ch/event/1232761/contributions/5321425/

Readout ASICs as R&D Focal Point

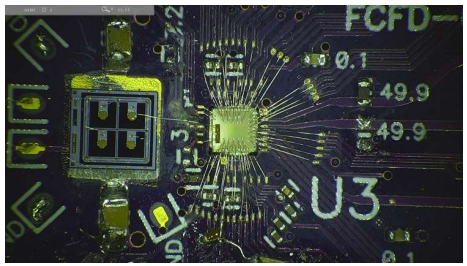
- FCFD by FNAL (US)
  - "official" first candidate under development
- CALOROC by Omega (France)





EICROC

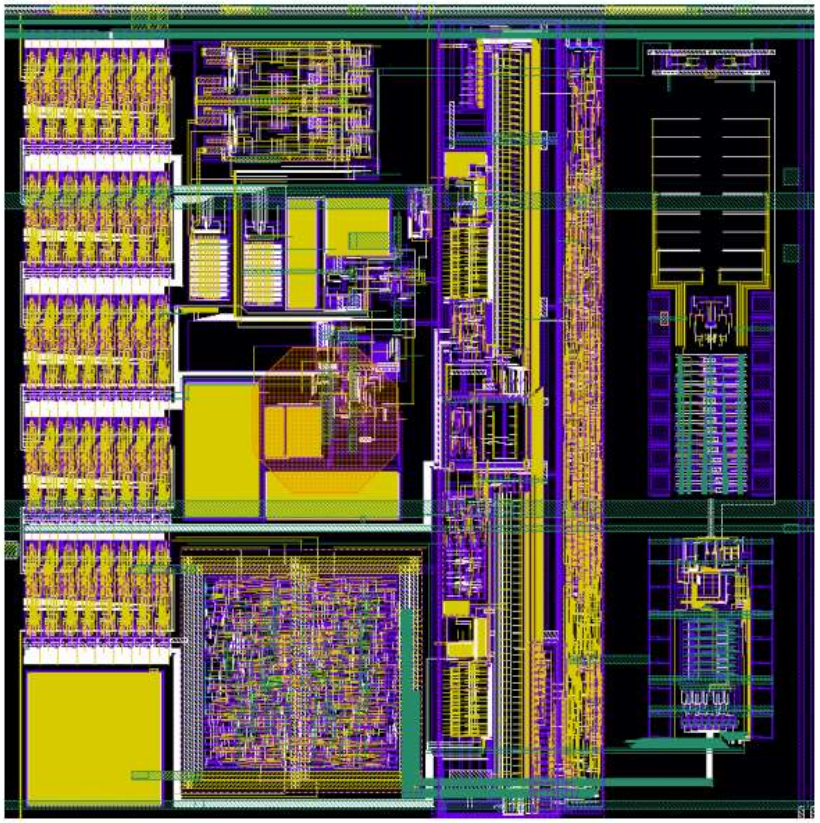
FCFD

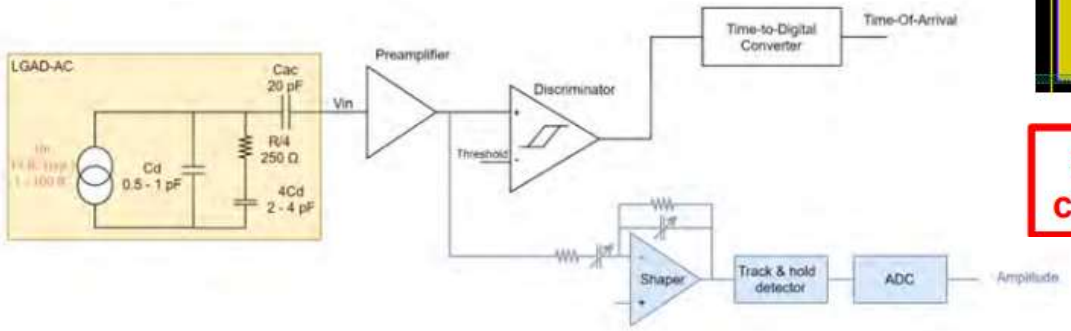


- *cf.* EICROC by Omega (France) for pixel AC-LGAD
  - based on ALTIROC (ATLAS) and HGCROC (CMS)
  - under development for ePIC roman pods (500 µm pixel)
    - 2-dimensional layout
    - input capacitance range < 5 pF

EICROC

- (500 µm)² pixel readout
  - Derived from ATLAS HGTD
  - ToT replaced by ADC [AGH]
  - TDC from CMS HGCAL [IRFU]





Slow control | PA +discri | TOA TDC | 8b 40M ADC

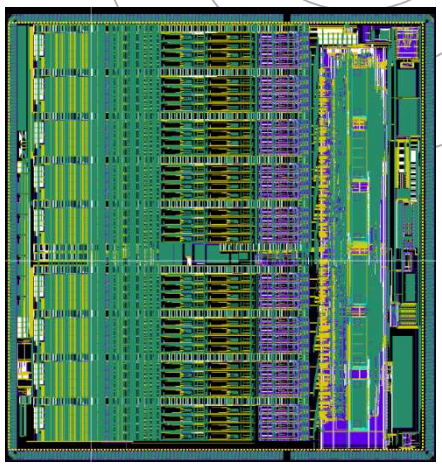
OMEGA Microelectronics

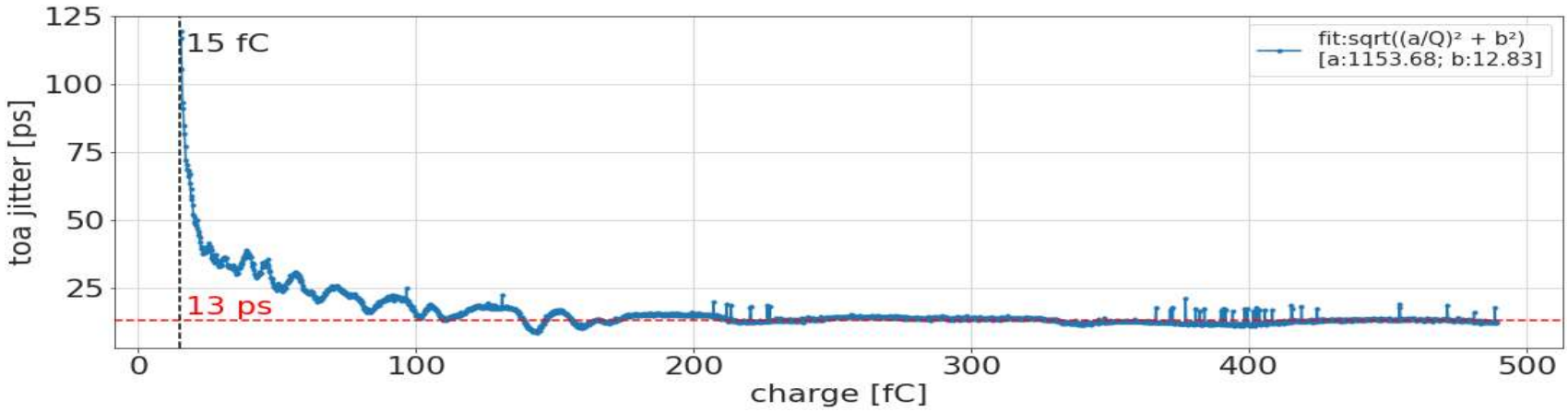
Irfu

AGH

CALOROC

- **Adaptation of CMS HGCAL HGCROC**
  - HGCROC analog front-end
  - Streaming readout
  - 36 channels 10mW/ch
  - Cd < 50 pF Qmax = 10 pC ENC=0.3 fC





TYL/FJPPN 2024 Highlights

- enhanced collaboration for ePIC barrel TOF
  - Japan taking major responsibilities
    - overall design, AC-LGAD sensor, structures
    - S. Yano (Hiroshima) as deputy detector subsystem lead
  - France perfectly covering “Achilles' heel”
    - readout ASIC

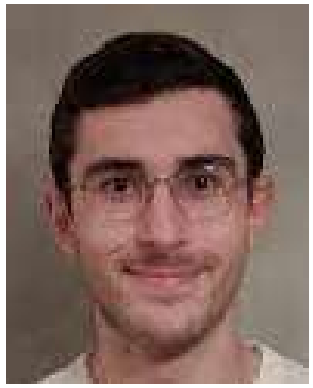
- “in person” readout ASIC meetings
  - 5 people from Japan (incl. KS) on this budget
    - 27–28 January 2025 at Omega and IJCLab
- 3 (!) new PhD candidates at Hiroshima U.
  - external supports (á la FJPPN) greatly appreciated

TYL/FJPPN 2025 Plans

- from R&D to Preliminary Engineering Design
  - final technology choices on overall barrel TOF
- full chain test of module assemblies
  - AC-LGAD with various geometries and parameters
    - HPK and BNL prototypes at Hiroshima U
  - multiple readout ASICs with analog + digital parts
    - FCFD ver.2 by FNAL
    - CALOROC1C by Omega
- performance tests
    - e.g. temperature dependence
  - lab tests with β particles, IR laser
  - beam tests with protons (FNAL), electrons (ELPH)

TYL/FJPPN France Side

- **Ecole Polytechnique, Omega/IN2P3**
  - **leading roles in readout ASIC development**

- **CALOROC, EICROC, HGCROC (de La Taille)**

TYL/FJPPN Japan Side

- Hiroshima U, Shinshu U, Nara Women's U, RIKEN
  - leading roles in many aspects of barrel ToF project

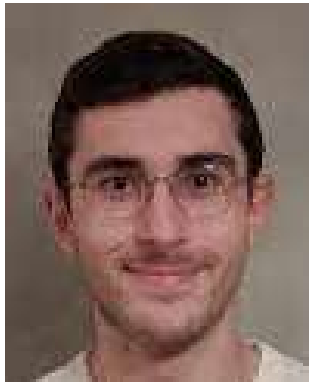




- test/production facility (Shigaki)
- project coordination, sensor (Yano)
- database, simulation, software, calibration (Kawade)
- system test and validation (Hachiya)

Promoting Young Generation

- joint PhD student supervision
  - A. Verplancke (PhD student, Ecole Polytechnique)
  - S. Muraoka (PhD student, Hiroshima U)
  - K. Matsutani (PhD student from 2026, Hiroshima U)



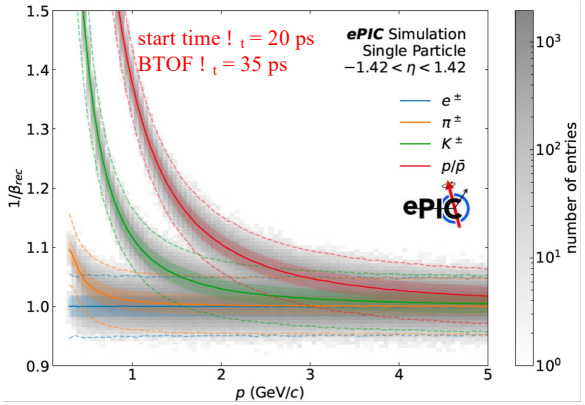
Summary and Concluding Remarks

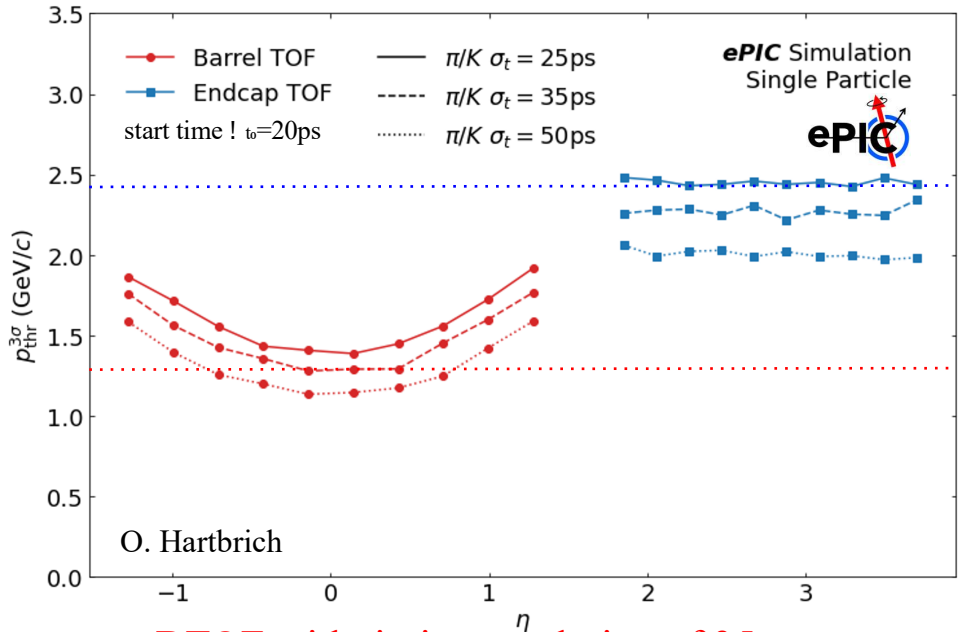
- ePIC ToF with AC-LGAD for PID in low- to mid- p_T
  - excellent timing resolution (~30 ps)
  - high granularity and high fill factor
- 2024–2027 vitally important for ePIC barrel ToF
  - full detector chain design due in 2025
    - e.g. strip AC-LGAD and readout ASIC compatibility issue
  - R&D and prototyping due in 2026
- France–Japan(–US) collaboration essential
- TYL/FJPPN support very effective for us
  - tight collab. including PhD students and post docs
  - face-to-face meetings/workshops in France and Japan

Backup Slides Hereafter

ToF Performance Simulation

- detector geometry, digitization, tracking



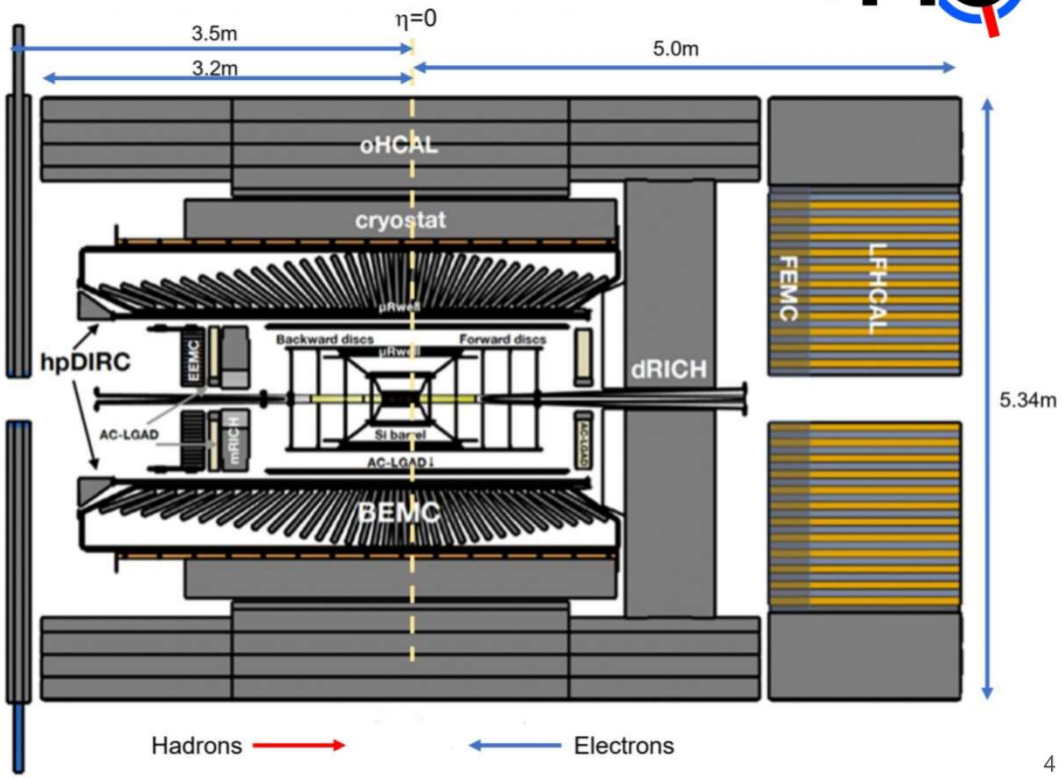


- 35/25 ps resolution assumed in barrel/endcap

Tue 09:00
R Milner

The ePIC barrel detector

- **tracking**
  - new 1.7 T magnet
  - Si-MAPS + MPGDs
- **calorimetry**
  - e-side: $PbWO_4$ EMCal
  - barrel: SciGlass / imaging
  - h-side: finely segmented
  - outer barrel HCal
- **particle ID**
  - AC-LGAD TOF
  - mRICH / pfRICH
  - hpDIRC
  - dRICH



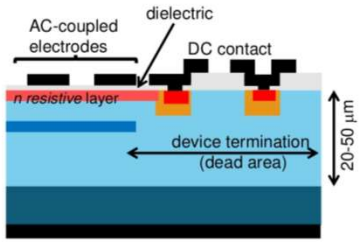
4

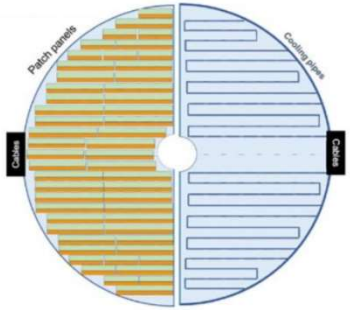
AC-LGAD Based ToF

TOF – Time of Flight

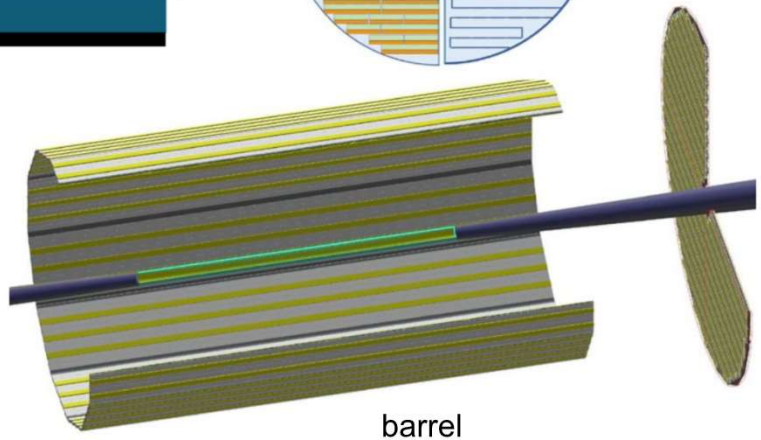
based on AC-LGAD technology, also used in far forward ePIC instrumentation

- **two AC-LGAD layers**
  - barrel, $|\eta| < 1.4$
  - forward, $1.5 < \eta < 3.5$
- **barrel**
  - 500 µm x 1 cm strips
  - 1% X_0
- **forward**
  - 500 µm x 500 µm pixels
  - 8% X_0
- **performance**
  - space resolution: 30 µm
  - time resolution: σ ~ 25 ps





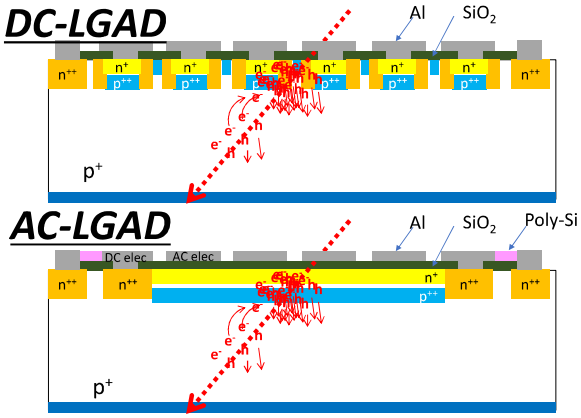
forward



barrel

Low Gain Avalanche Diode (LGAD)

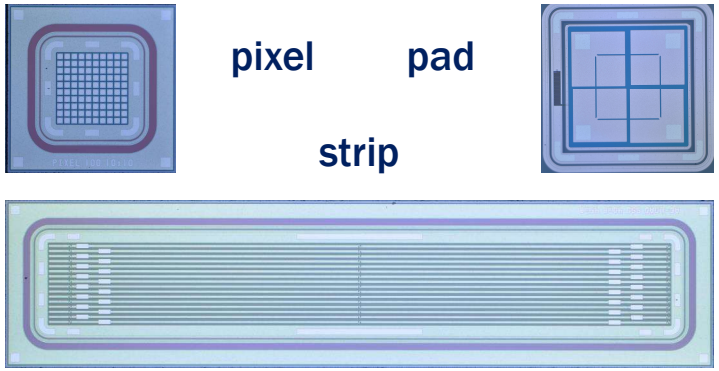
- DC (*i.e.* standard) -LGAD
  - n^{++}-in-p type sensor w/ p^{+} gain layer
  - individual p^{+} gain layer per electrode
    - inactive gaps between granules
- AC-LGAD
  - n^{+}- in-p type sensor w/ p^{+} gain layer
    - lower dope for low sideward conductivity
  - spanning p^{+} gain layer w/ multiple electrodes
    - AC coupling w/ oxide layer between n^{+} layer and electrodes
    - ~100% fill factor w/ fine pitch
    - good position resolution with charge sharing
- high hope for relatively new AC-LGAD technology

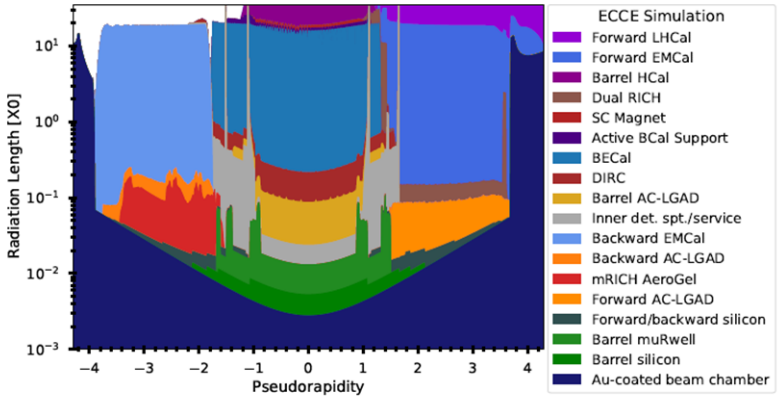


K. Nakamura *et al.*,
JPS Conf. Proc. 34, 010016 (2021)

AC-LGAD ToF R&D Guidelines

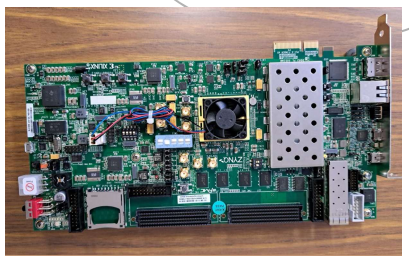
- basics: resolution, stability, radiation tolerance
- large area sensor with uniformity
  - simple construction and operation
  - cost reduction
- material budget
  - ~1% radiation length in barrel
  - tracking/EM performance





Test bench at Hiroshima

- Test of the AC-LGAD and EICROC (readout board for EIC)
  - Work closely with HPK for effective development

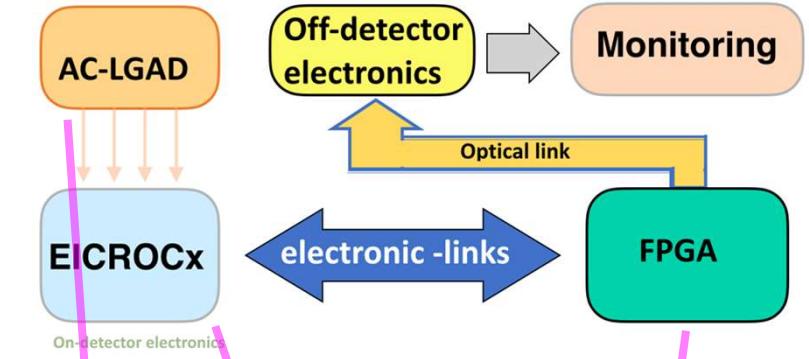


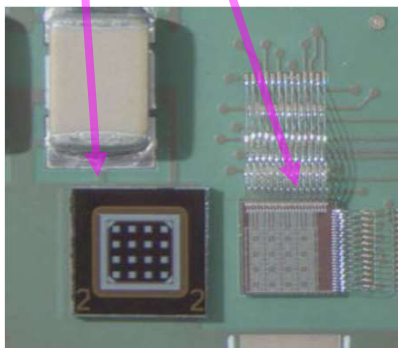
- Equipment based on the suggestion from BNL/KEK/Tsukuba teams
  - Focusing on timing resolution and cross-talk (charge measurement

- FPGA, digitizer (flash ADC), oscilloscope, and PM
  - FPGA: ZC706
  - Oscilloscope: WaveRunner 8208HD (10GS/s, 8ch)
  - Digitizer: CAEN DT5742 (5GS/s, 16ch)
  - PMT: PHOTEK PMT240 (60 ps rising time)
  - Looking forward to receiving AC-LGAD and EICRO

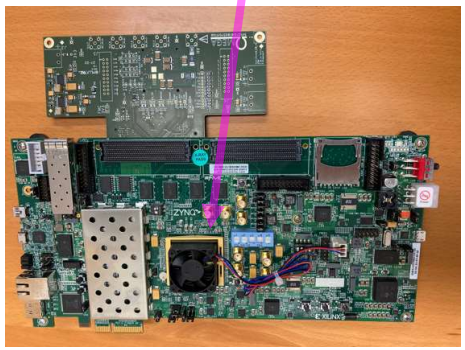
Full Chain Test Bench at Hiroshima U

- second facility following only BNL
  - in collaboration with IJC Lab (France)

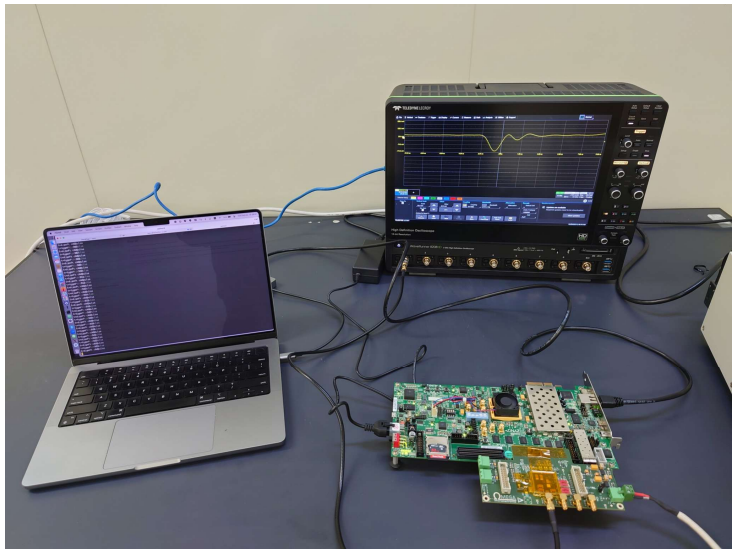




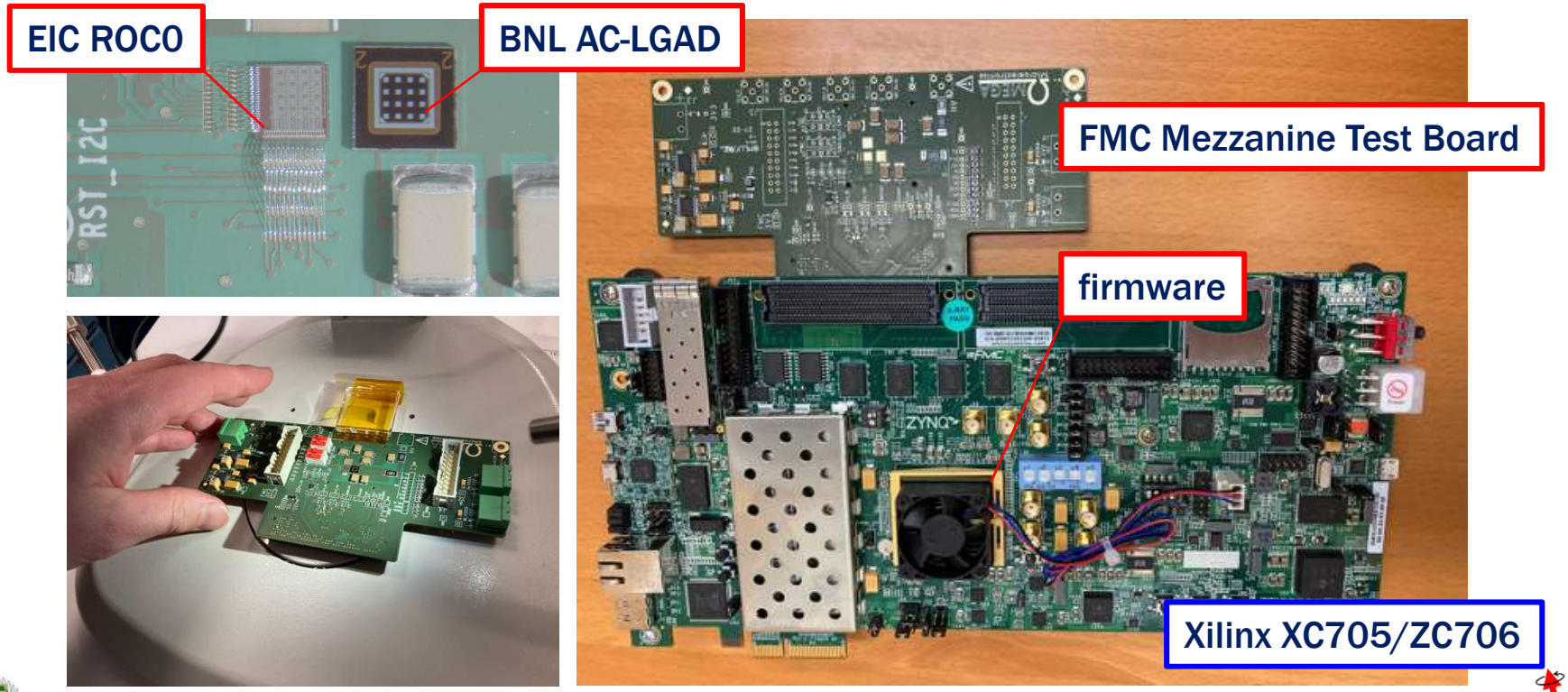
AC-LGAD and EICROC0 on mezzanine board



prototype RDO (Xilinx development kit = FPGA + ZYNQ processor)

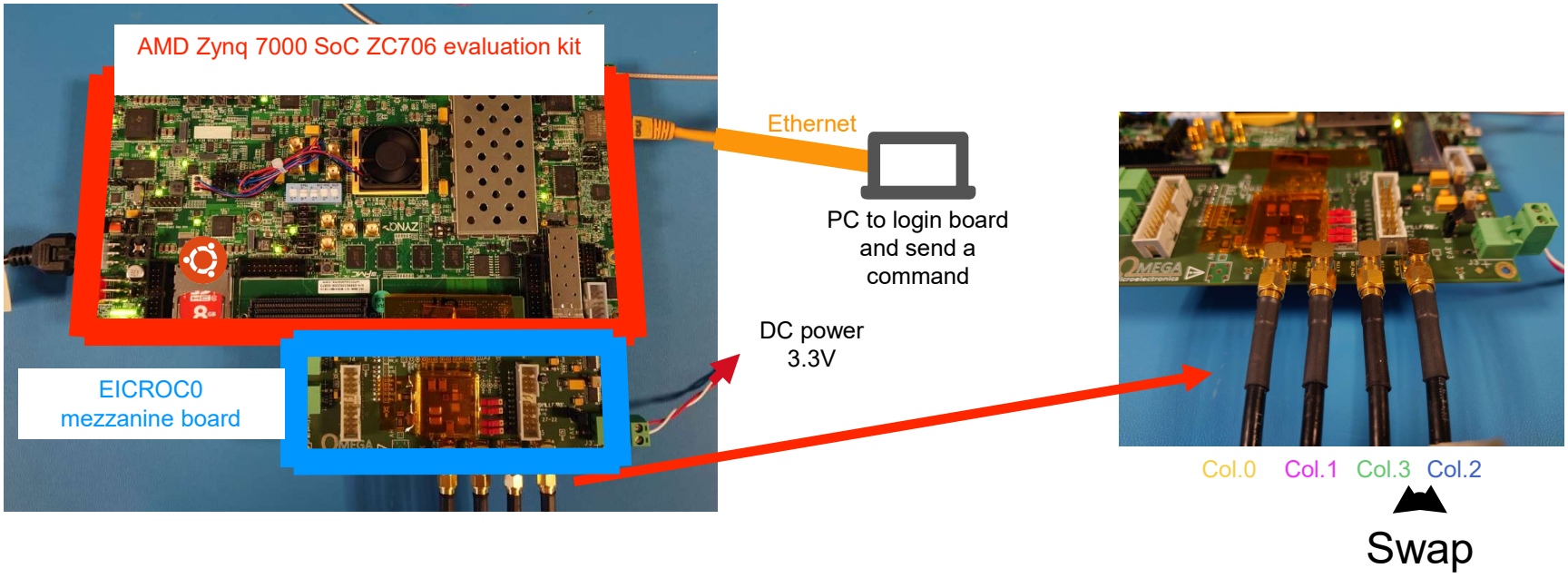


Hiroshima test bench (only partially shown)


EIC ROC0
BNL AC-LGAD
FMC Mezzanine Test Board
firmware
Xilinx XC705/ZC706

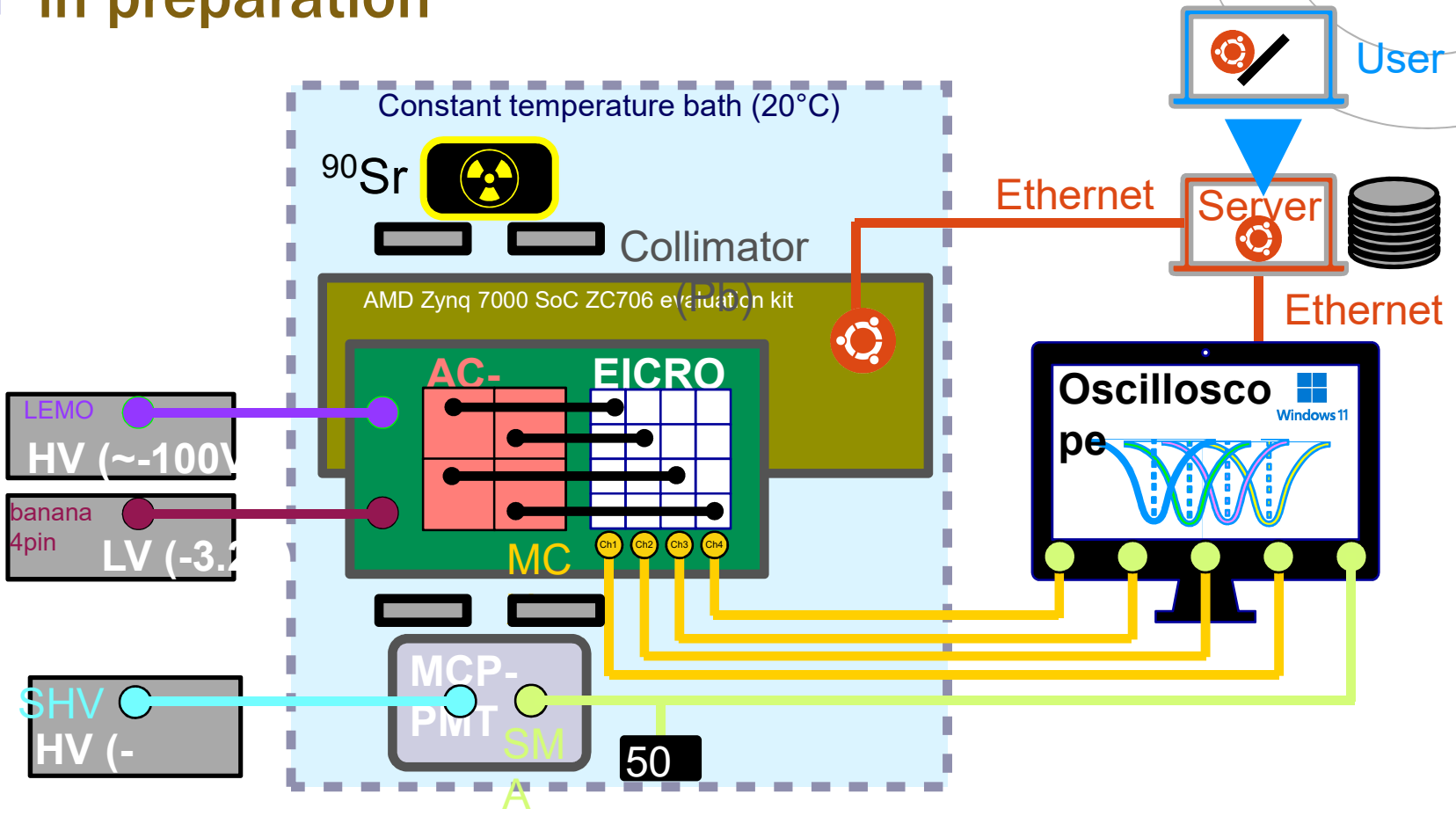
Activity for EICROC R&D @ BNL

- charges

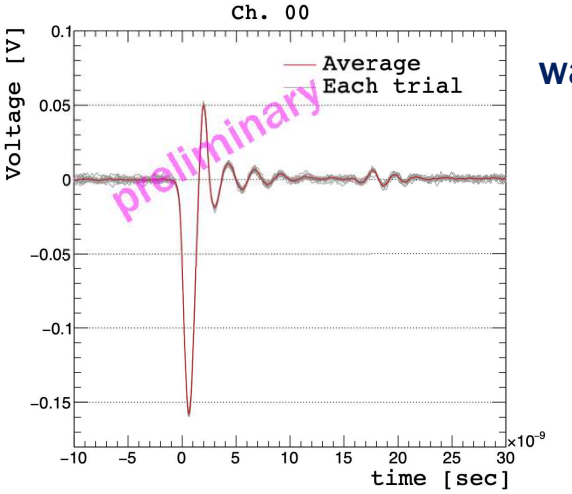


Hiroshima Test Bench Overview

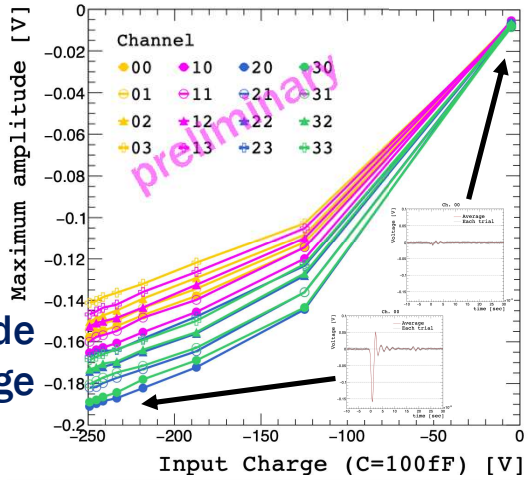
- in preparation



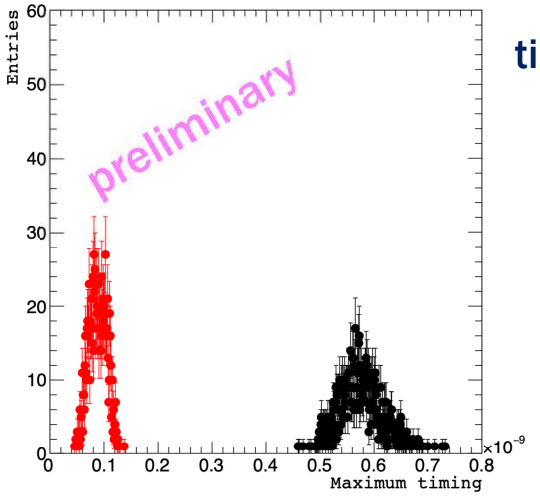
Quick Look at First Measurements



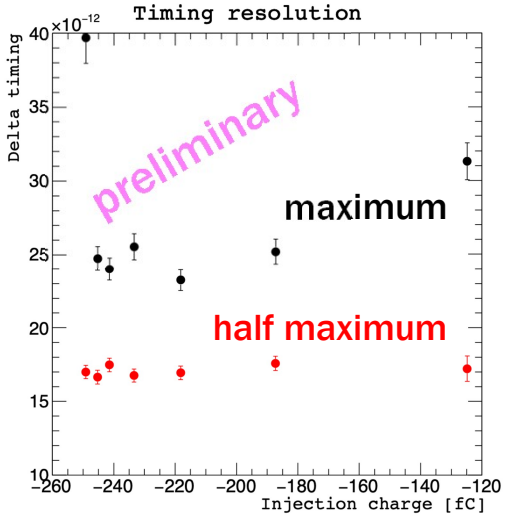
waveform



signal amplitude
v.s. injected charge



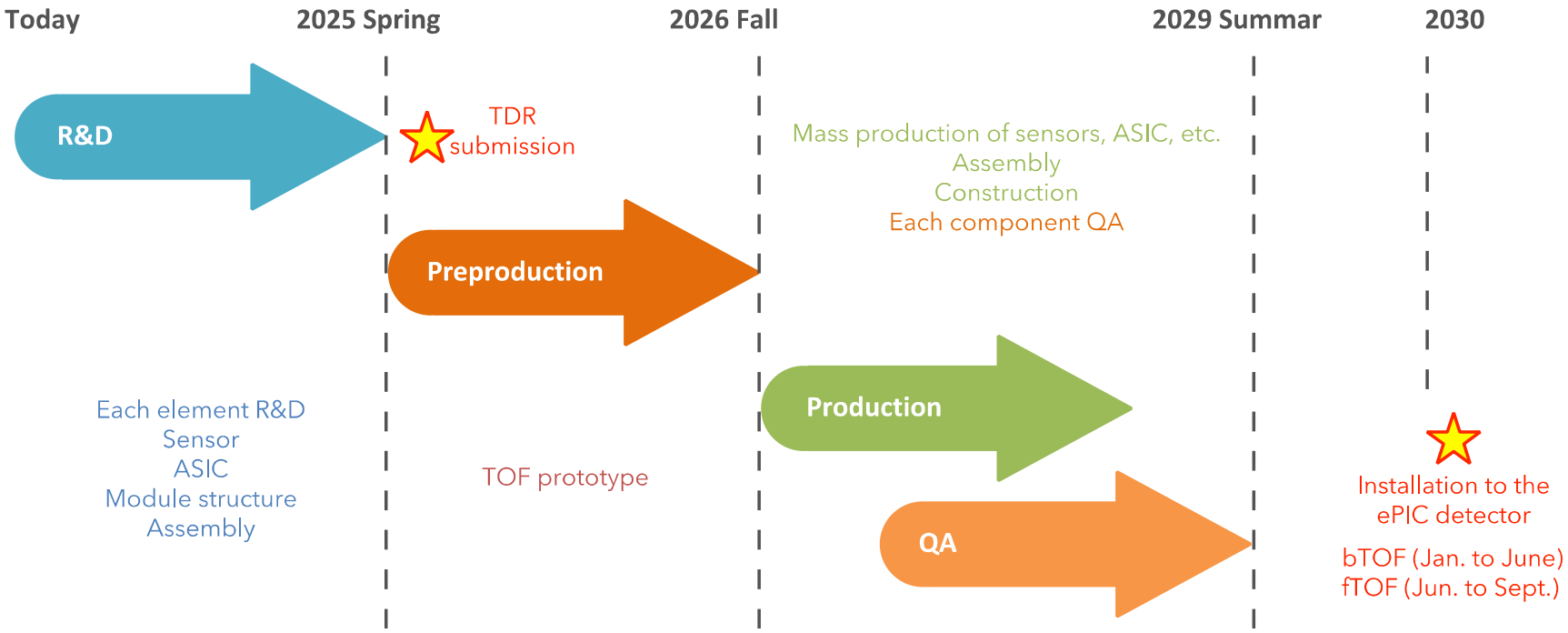
timing fluctuation



timing fluctuation
v.s. injected charge

Longer Term Scope (up to 4 Years)

- 2.5 more years for R&D and prototyping



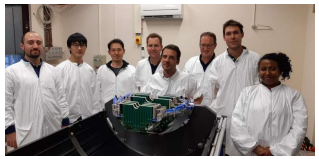
Team Japan Background

- Riken w/ sPHENIX INTT experience
  - w/ Japanese technologies
  - R&D, mass production, QA environments available
- Hiroshima w/ ALICE forward μ tracker experience

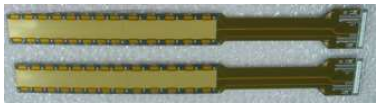
sPHENIX INTT Japan (led by Riken) (spin)
+ Hiroshima Univ. (heavy ion)
+ Shinshu Univ. (high energy)

Bas extender

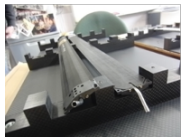
MFT assembling @ CERN



FPC



Staves



Silicon sensor

France–Japan Collaboration

- vital and pressing for ePIC barrel ToF
  - full detector chain design due in 2025
- Japan–US link on AC-LGAD
- France–US link on readout ASIC
- direct France–Japan link only since 2023
  - biweekly EICROC meetings hosted by Omega
  - feedback from Hiroshima test bench (as well as BNL)
- also fostering strip AC-LGAD expertise in Japan
  - design, fabrication, simulation, integration, analysis