News from PICOSEC

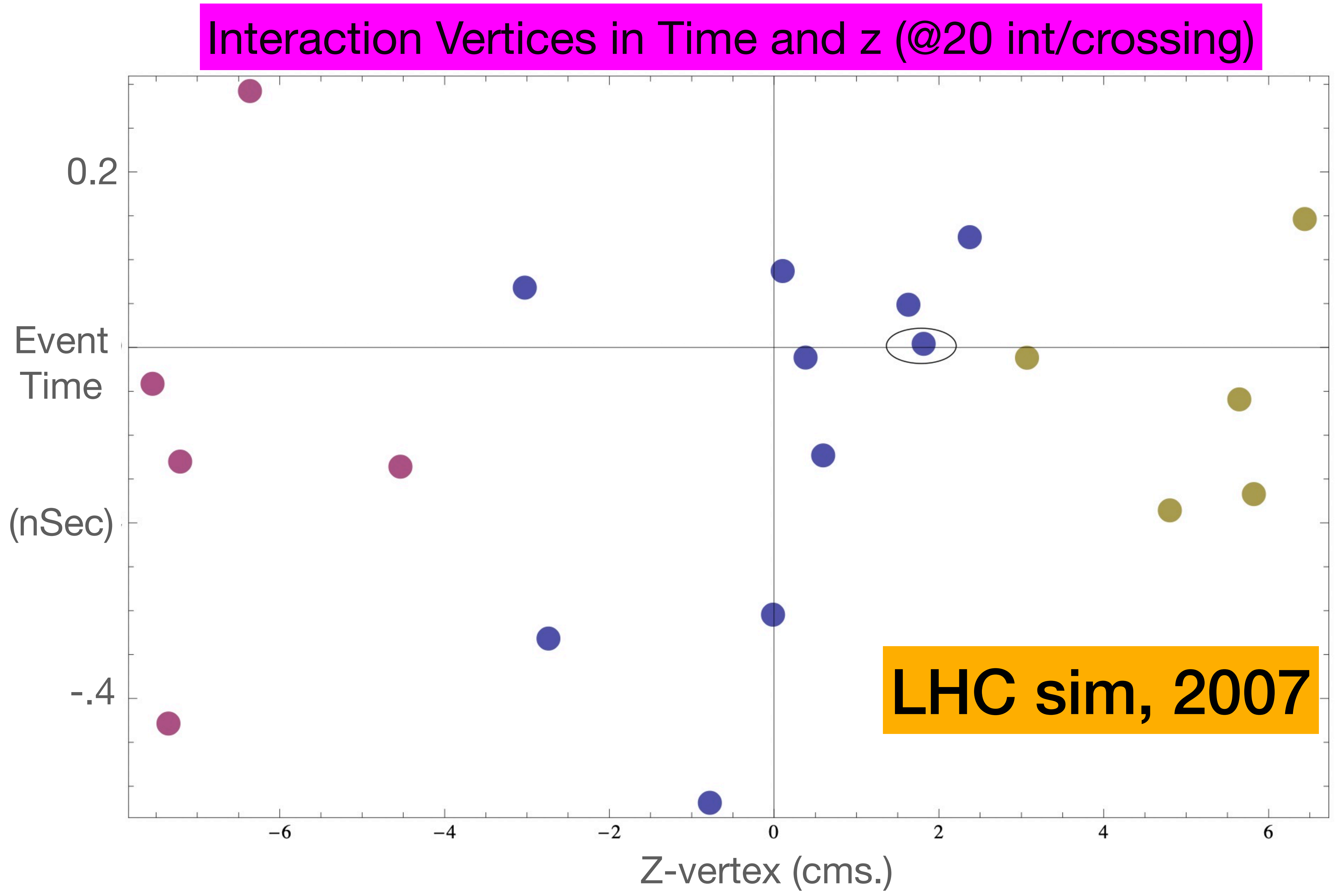
Fast Timing with micro-Pattern Gas Detector

Sebastian White

November 30, 2022

- Intro: Highlights/Driver of recent LHC Timing R&D
- FC Benchmarks (ie eIC: 10m^2,20 picosec, occupancy?)
- Relevant sensor development @ CERN
  - In SiDet-> “Deep-Depleted AD” (through 2019)-> currently LGAD
  - From “Crystal Clear”-> CMS LYSO/SiPM Barrel Timing Layer
  - In Gas Det. lab ->”PICOSEC”
- Results and Prospects in PICOSEC

Original Motivation for MIP timing in ATLAS and CMS HL-LHC upgrades



LHC simulation: SNW, 2007 - https://arxiv.org/pdf/0707.1500.pdf

Model LHC Bunch crossing:

- Bunch length (emittances)
- Crossing angles and Beta*

Gaussian Densities-> Time invariant Z-vertex shape of events

Time tagging could resolve Z overlaps.

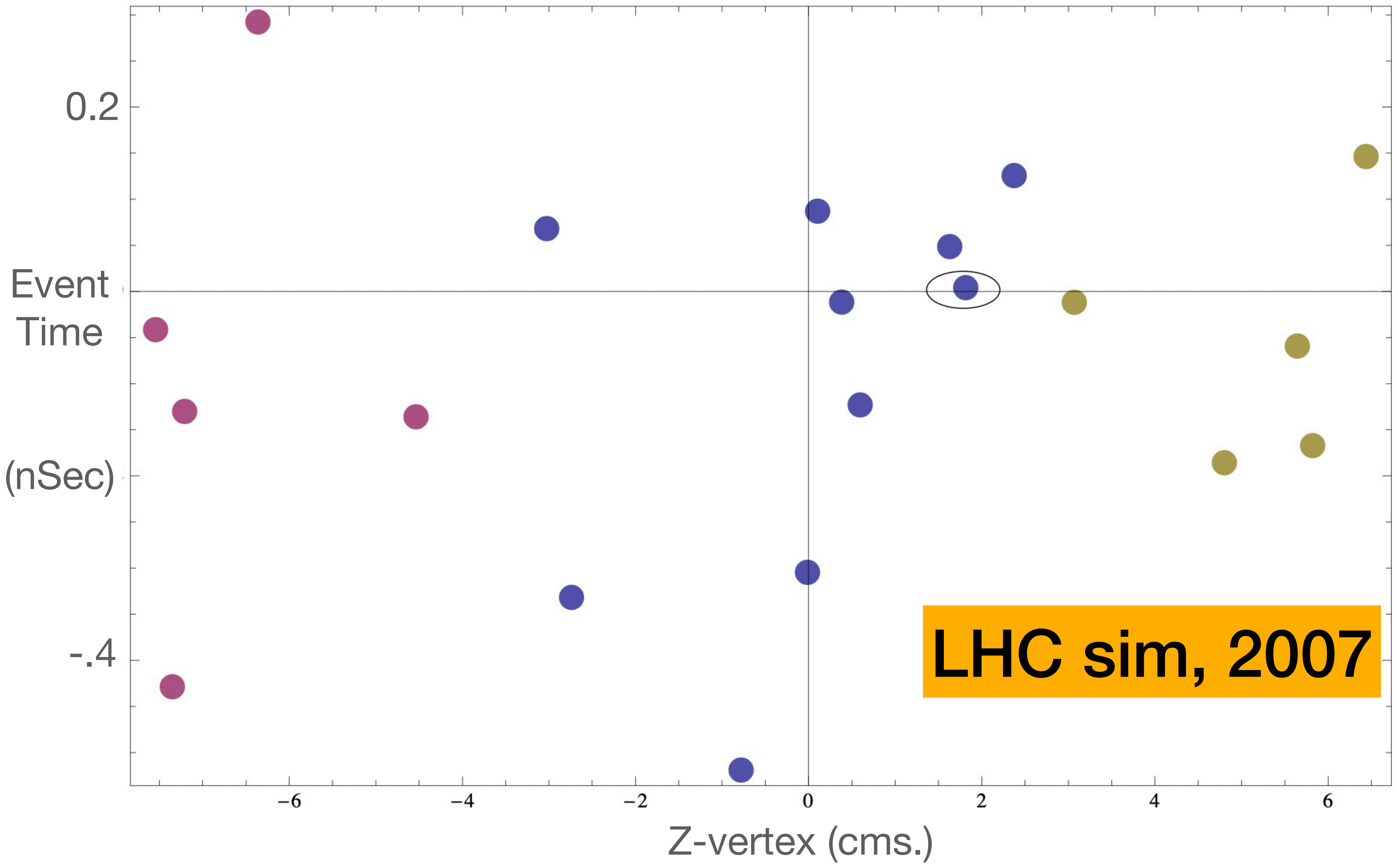
Mitigating Physics Backgrounds due to Pileup:

- Previous collider (Tevatron) reached mu~6 int./crossing—> z-vertex an adequate discriminant
- Z-vertex time to <100 picoseconds —> extends viability to higher pileup

- Since TDR, CMS exploring additional physics enabled by MTD (pid in Heavy Ions, LLPs, etc.)

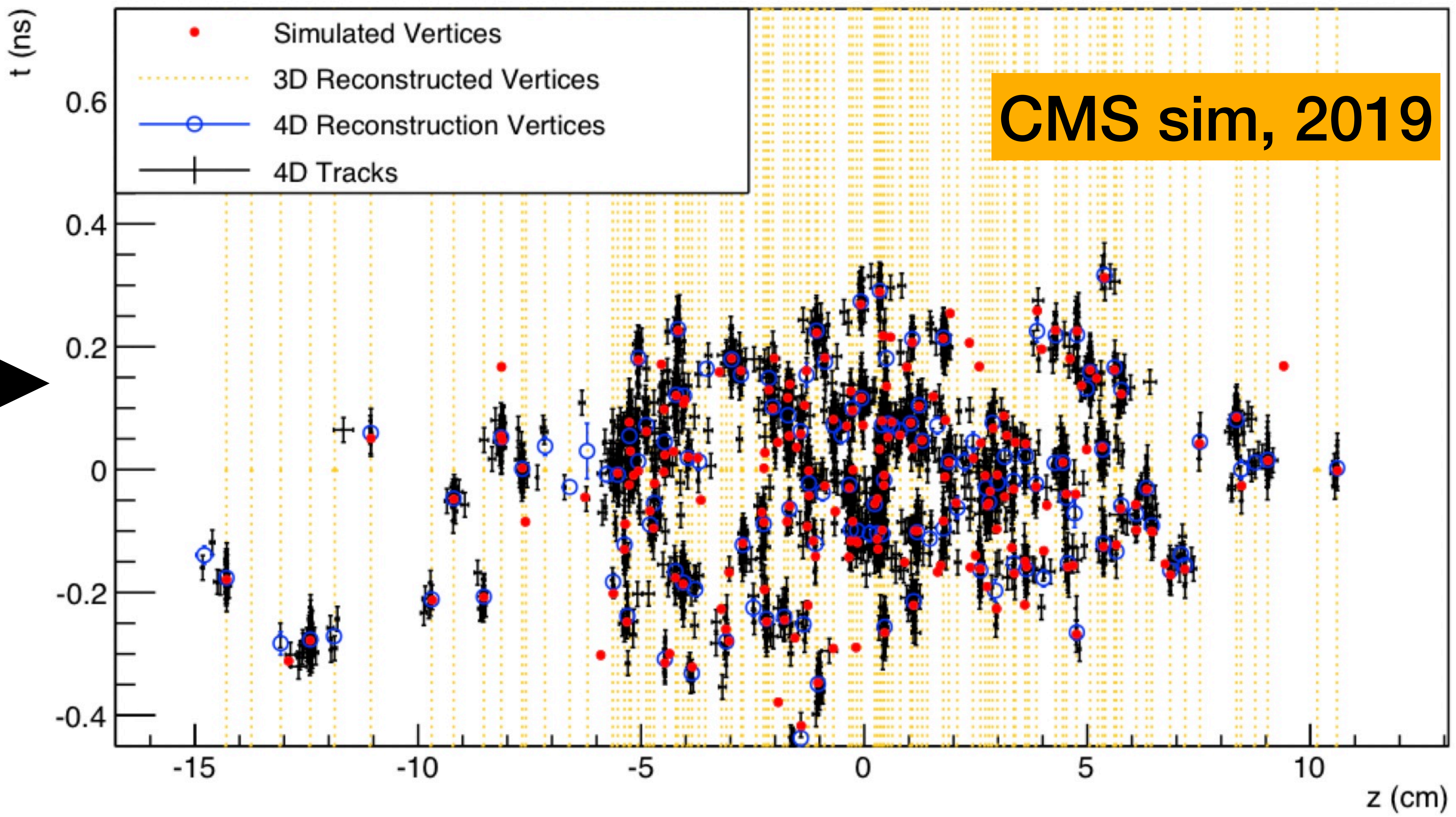
Original Motivation for MIP timing in ATLAS and CMS HL-LHC upgrades

Interaction Vertices in Time and z (@20 int/crossing)



LHC simulation: SNW, 2007 - https://arxiv.org/pdf/0707.1500.pdf

CMS Simulation (@140 int/crossing)



CMS performance simulation, 2019- CERN-LHCC-2019-003

Mitigating Physics Backgrounds due to Pileup:

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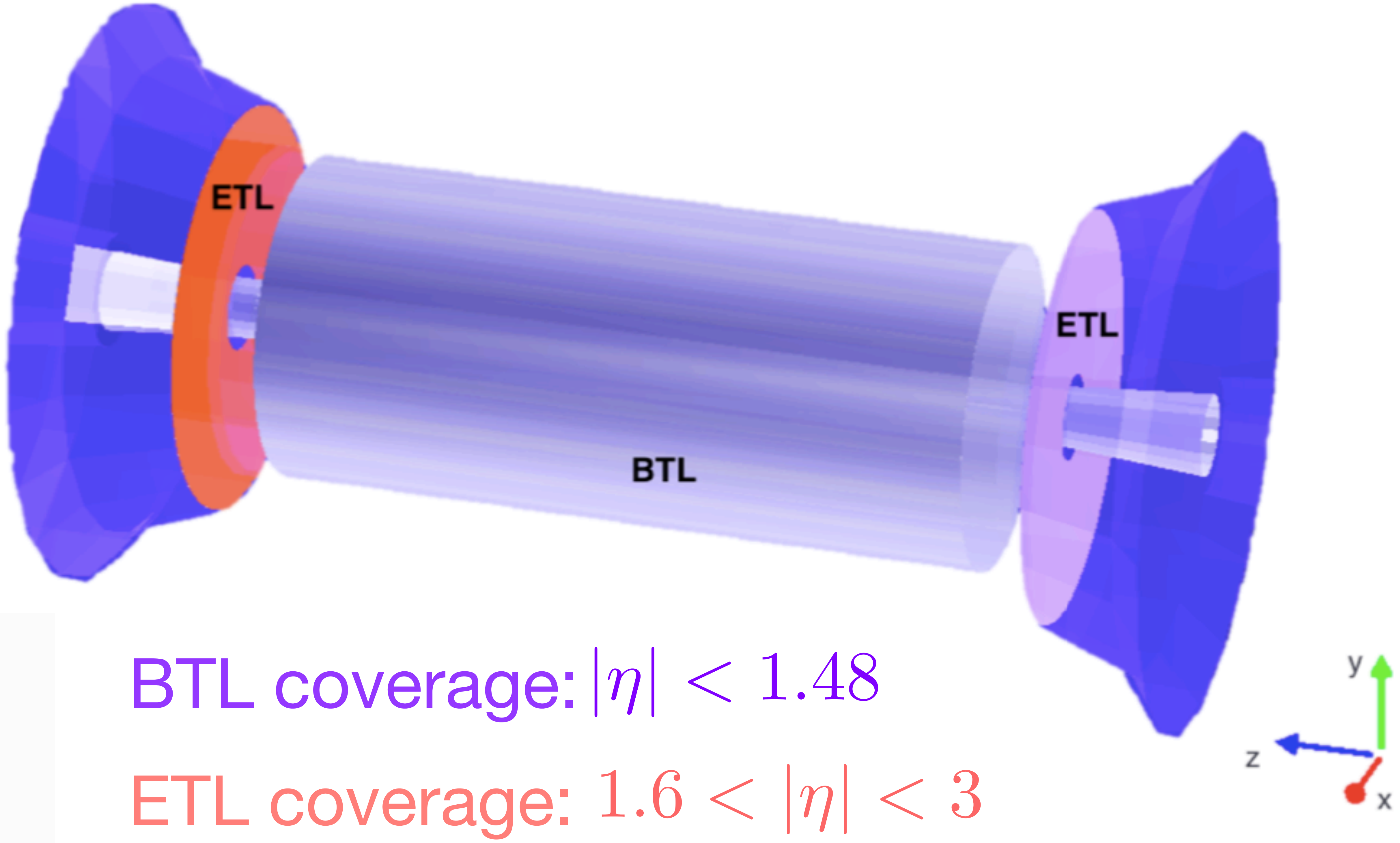
CMS approach: "Hermetic Timing"



BTL coverage: $|\eta| < 1.48$

ETL coverage: $1.6 < |\eta| < 3$

Consequences:

- Radiation dose @HL-LHC to 3000 fb^{-1}
  -> Large dose variation over timing detector
  ->Reaches ~2 e^{14} neq/cm^2 max in BTL
- Also particle density-> pixel size-> small pixel in ETL

For ETL, producers of "Low Gain Avalanche Diodes"
-> matched to ETL requirements

What Technology for Barrel Timing?

- Occupancy-> ~ 1cm^2 pixel size
- Radiation tolerance to ~2 e^{14} n_{eq}/cm^2
- Time resolution 30-> 70 picoseconds BOL->EOL at HL-LHC

Candidates for Barrel Timing:

- Several Approaches discussed in ALICE 3 LOI
  CERN-LHCC-2022-009
- See also J. Va'vra: HL-eIC timing talk
https://indico.bnl.gov/event/14504/timetable/#20220623.detailed

- Also RD51 and RD50 R&D "common projects"

https://doi.org/10.1016/j.nima.2021.165076
(1 cm^2 pixels, <25 picosecond jitter) PICOSEC

Silicon:High Gain Avalanche Diodes:
https://doi.org/10.1016/j.nima.2019.162930
(64 mm^2, ~27 psec)

Timing Requirements for future Collider Det.

FCC-ee - see A. Zabi : Particle ID (FCCee) e/π/K/p identification to cover O[1-50] GeV/c ToF Layers ~ 10ps

https://indico.cern.ch/event/877521/contributions/4745063/attachments/2524375/4341670/LHCDays_NewTech_AZabi_7Oct2022.pdf

- eIC- (2nd Detector?)- see eg J. Va'vra

https://indico.bnl.gov/event/14504/timetable/#20220623.detailed

- Muon Collider Detector- see recent CERN workshop

https://indico.cern.ch/event/1175126/contributions/5055219/attachments/2527625/4348022/MuonColliderWorkshop_13102022.pdf

- ALICE 3- recent posting on arxiv

https://arxiv.org/abs/2211.02491

Sensors for Fast Timing

Calorimetry

- SPACAL: many interesting developments in Calorimeter timing- eg demo by SPACAL that timing—>electron/hadron discrimination(never exploited)
- PHENIX EMCAL: doubled as Hadron pid by TOF
- ATLAS ZDC: achieved <100 picosecond timing on neutron showers
- Medical imaging (PET): long interest in timing low energy Gammas. Favored LYSO:Ce crystals w SiPM readout.(adopted by CMS as Barrel Timing Layer technology for MIP detection)
- LHCb Calorimeter upgrade- Schopper/Auffray , private comm.

MIP Hermetic Timing

- Whatever timing Calo provides of physics objects, the workhorse to time to vertices is charged particle timing/tracking.
- CMS (and ATLAS) MIP timing detector upgrades provide large coverage MIP timing to time tag vertices.

CMS/ATLAS technology choices have already been made.

- **Low Gain Avalanche Diodes for endcaps (hi rad doses and particle density).**
- **LYSO/SiPM for CMS Central region (Barrel).**

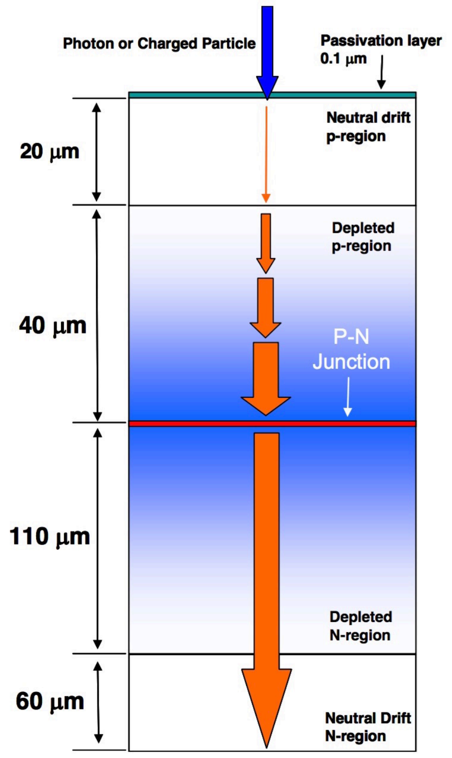
These are fully described elsewhere.

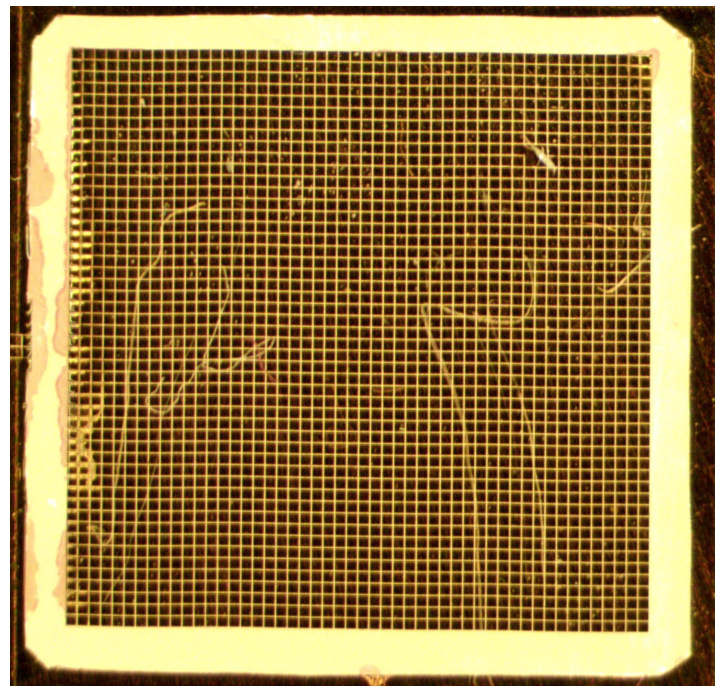
I focus on technologies not ready when the train left the station.

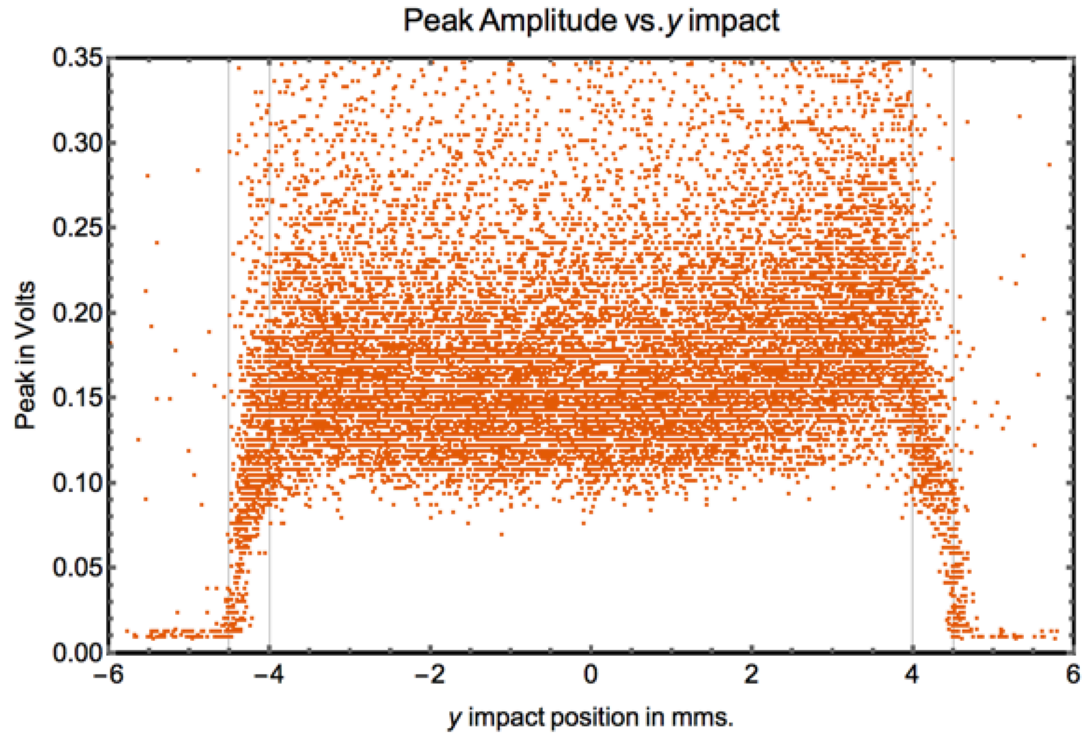
R&D@CERN: 1)Deep Depleted Avalanche Diodes

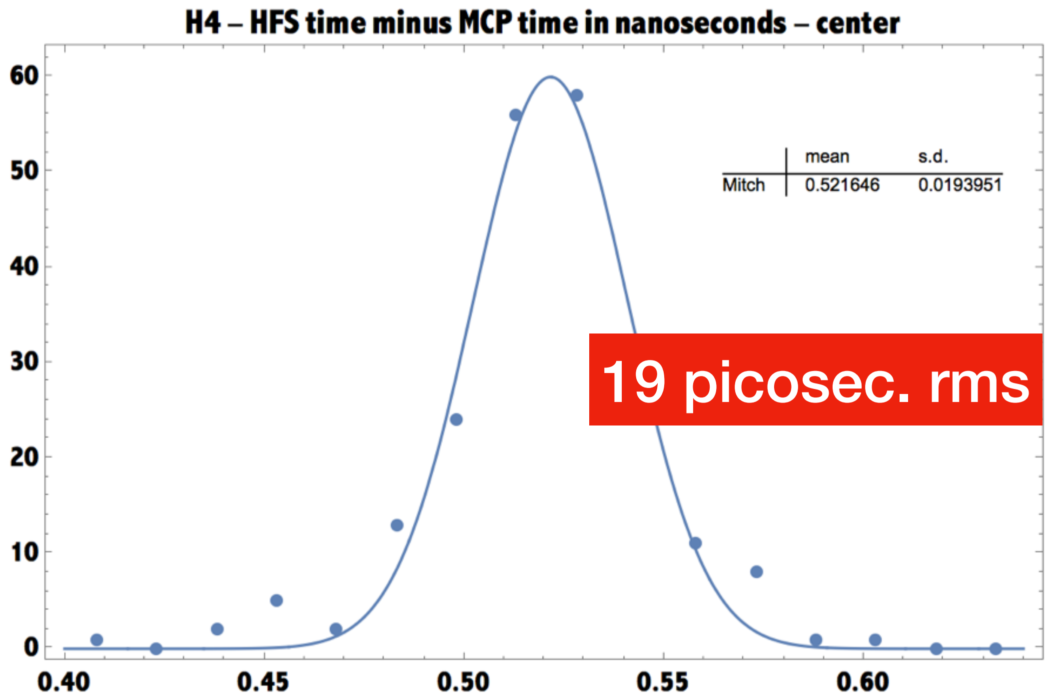
L. Gray, CMS TDR presentation

- ⦿Deep depleted APD read out through capacitatively coupled mesh
  - Silicon is biased, image charge read out
  - Gain layer and drift region overlap
  - Mesh serves to stabilize E-field shape over large area for good performance over whole device
  - Operates at high gain / high voltage
- ⦿20 ps resolution achieved on 8x8mm2 non-irradiated device
- ⦿No conclusive results yet for irradiated devices









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Lindsey Gray, FNAL

- we started DDAD development in ~2011
- Collaboration w. Rockefeller, Princeton (McDonald), BNL and "Industrial Partner"- RMD
- In 2014 expanded to include CERN, Delhi, U. Penn.
- It became a local RD50 activity: "Si w internal gain"
- Device Simulation using Silvaco at Delhi
- "HFS"(hyperfast..) name to distinguish from UFS.

- In ~2015 we overcame non-uniformity by developing "capacitive readout" using MMegas mesh from RD51.

HFS was not ready for CMS upgrades:

- In those days Dark Current impact anticipated
- but loss of gain due to rad surprised many
- Difficult to get vendors willing to invest in this tech.

see HFS NIM article : "Deep diffused APDs for charged particle timing applications: Performance after neutron irradiation", Vignali et al,NIM v 949, 162930 (Jan 2020)

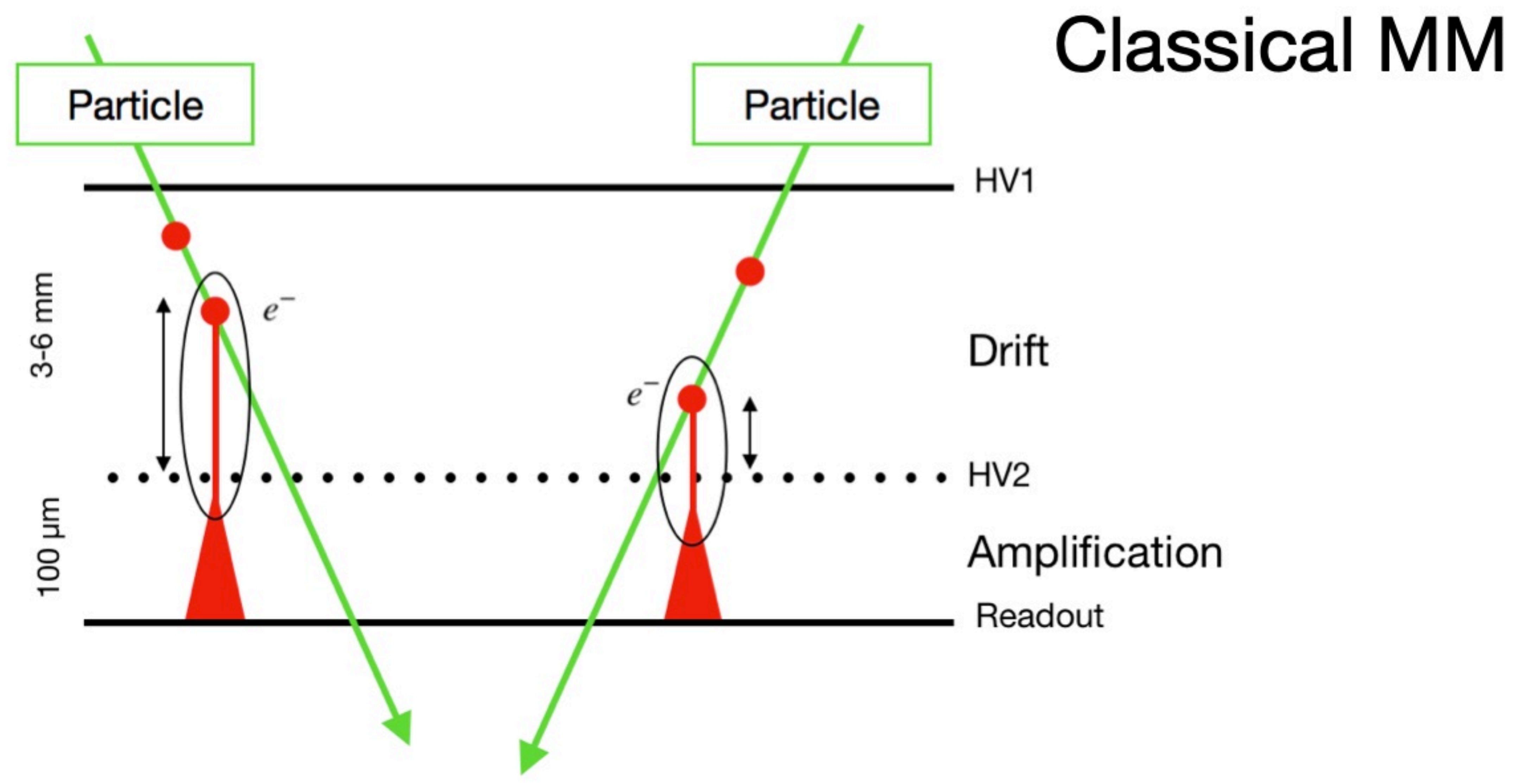
https://doi.org/10.1016/j.nima.2019.162930

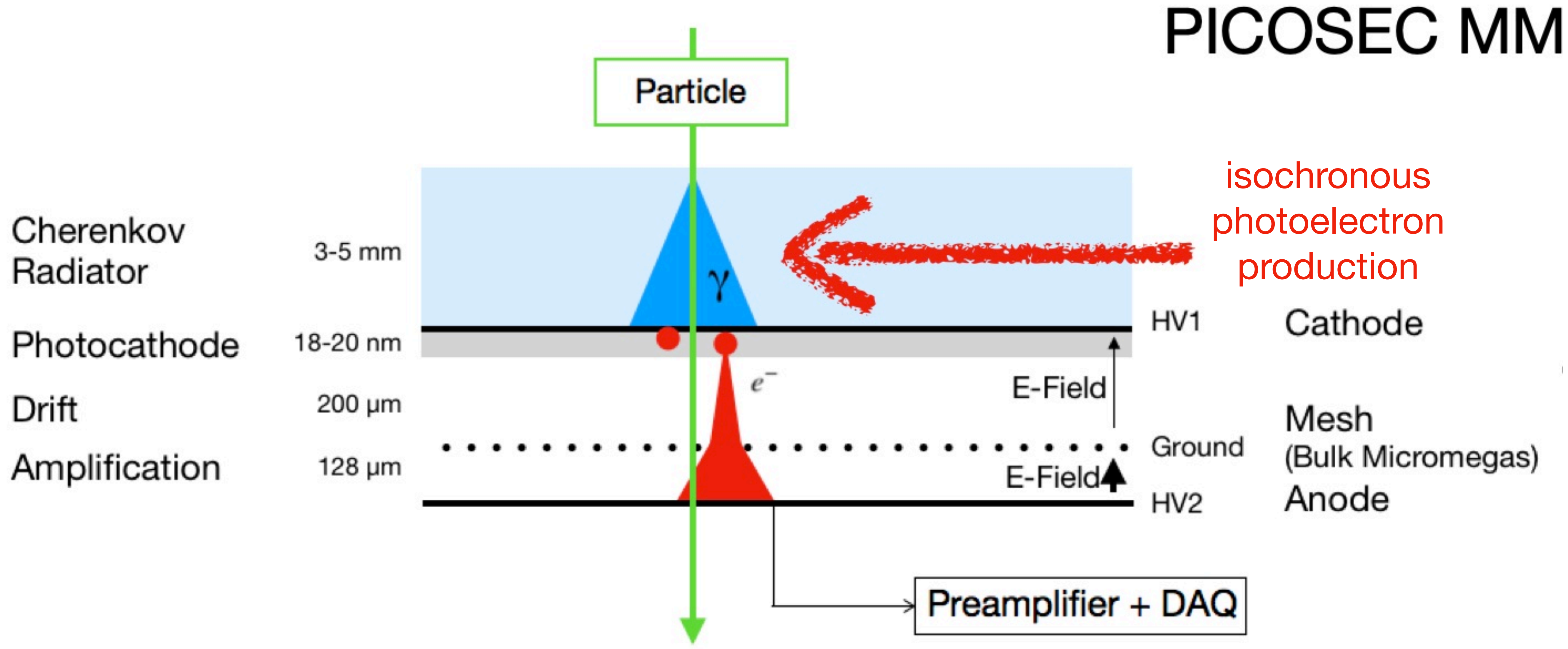
Nb: Most of DDAD Testbeam campaigns jointly with PICOSEC

R&D@CERN: 2)PICOSEC in RD51

DDAD (cont)-early use of AC coupling)

- MicroMegas mesh solved remaining time vs. position non-uniformity in the HFS sensors
- with Capacitive readout->timing on induced Q on a conducting mesh from charge motion in Si
- effective reduction also in C_D
- many interactions w Saclay/Orsay where SAMPIC developed (Delagnes, Breton)
- Giomataris and co. provided the mesh but also ideas to bring picosecond timing to gas detectors
- World record holder (Microchannel Plate PMT) many parallels w PICOSEC. see following



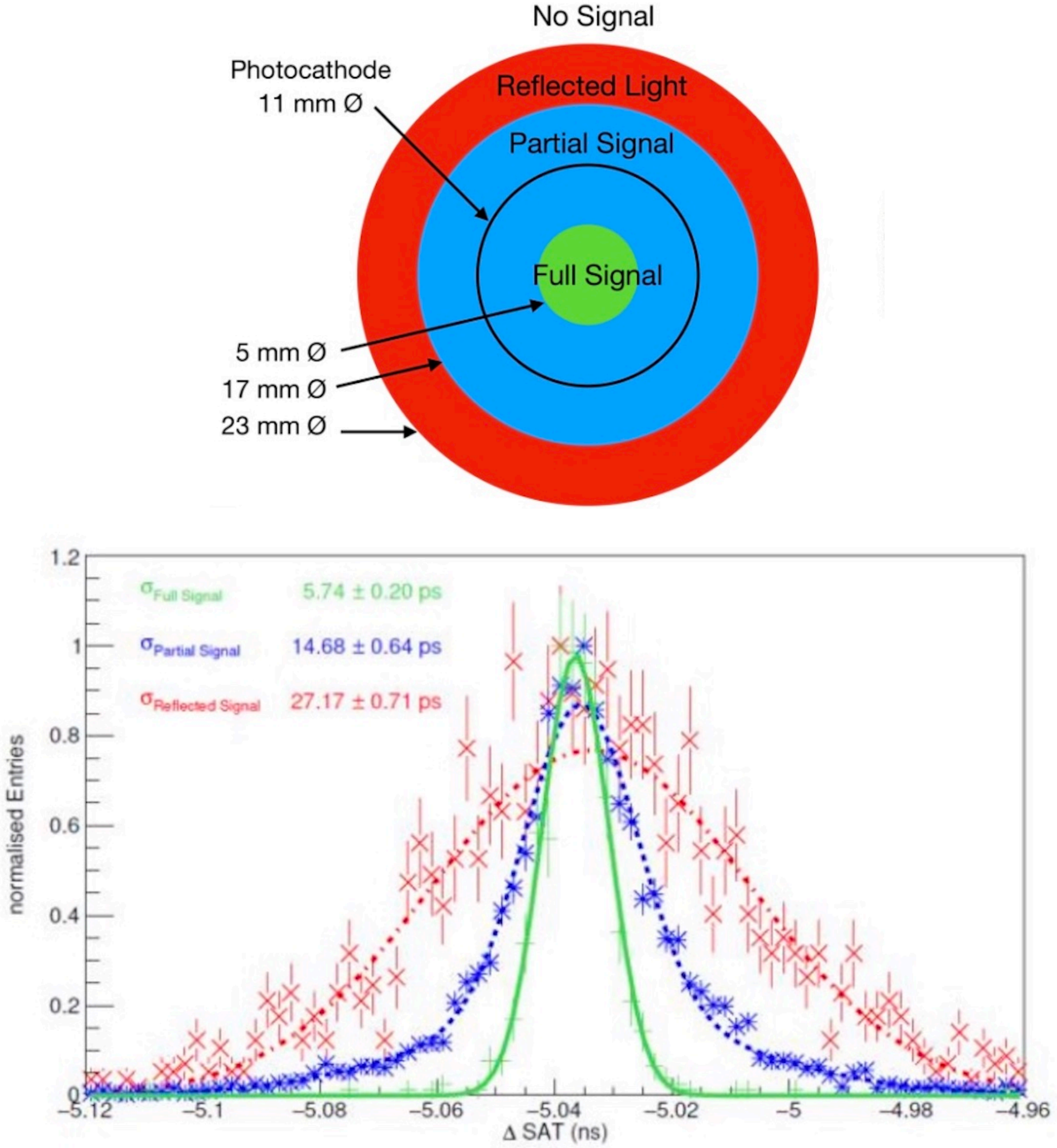


Related Technology: MCP-PMTs

used as ref. Device

1) **HPK R3809 3mm window, 11mm pc**

MCP-PMT time response



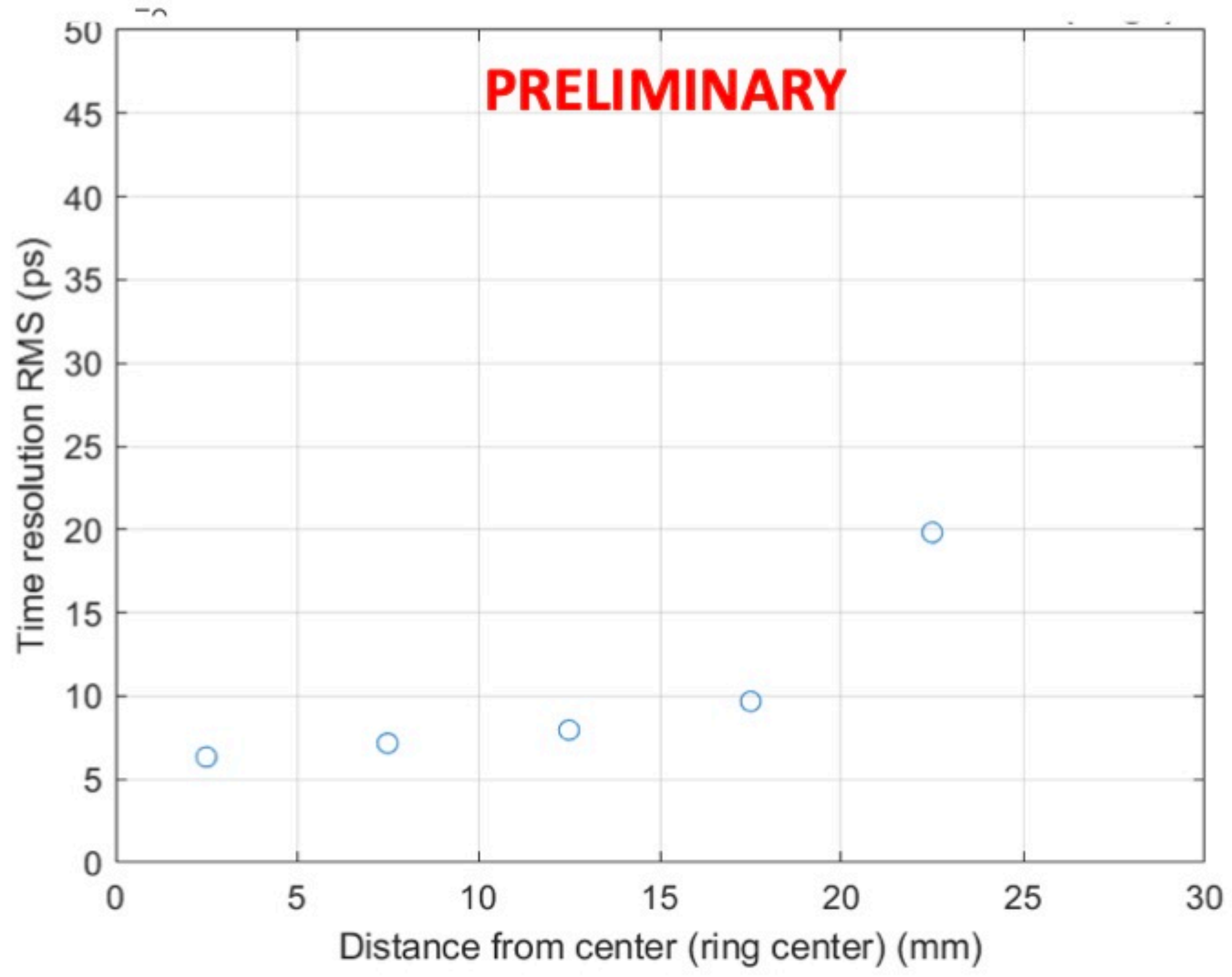
Large Area ref. Devices for 100 cm² PICOSEC

2) **Large area Photek:**

→ Uniform response up to ~30 mm dia.

→ Time resolution ~5 ps in the center

Time resolution of Photek vs Hamamatsu

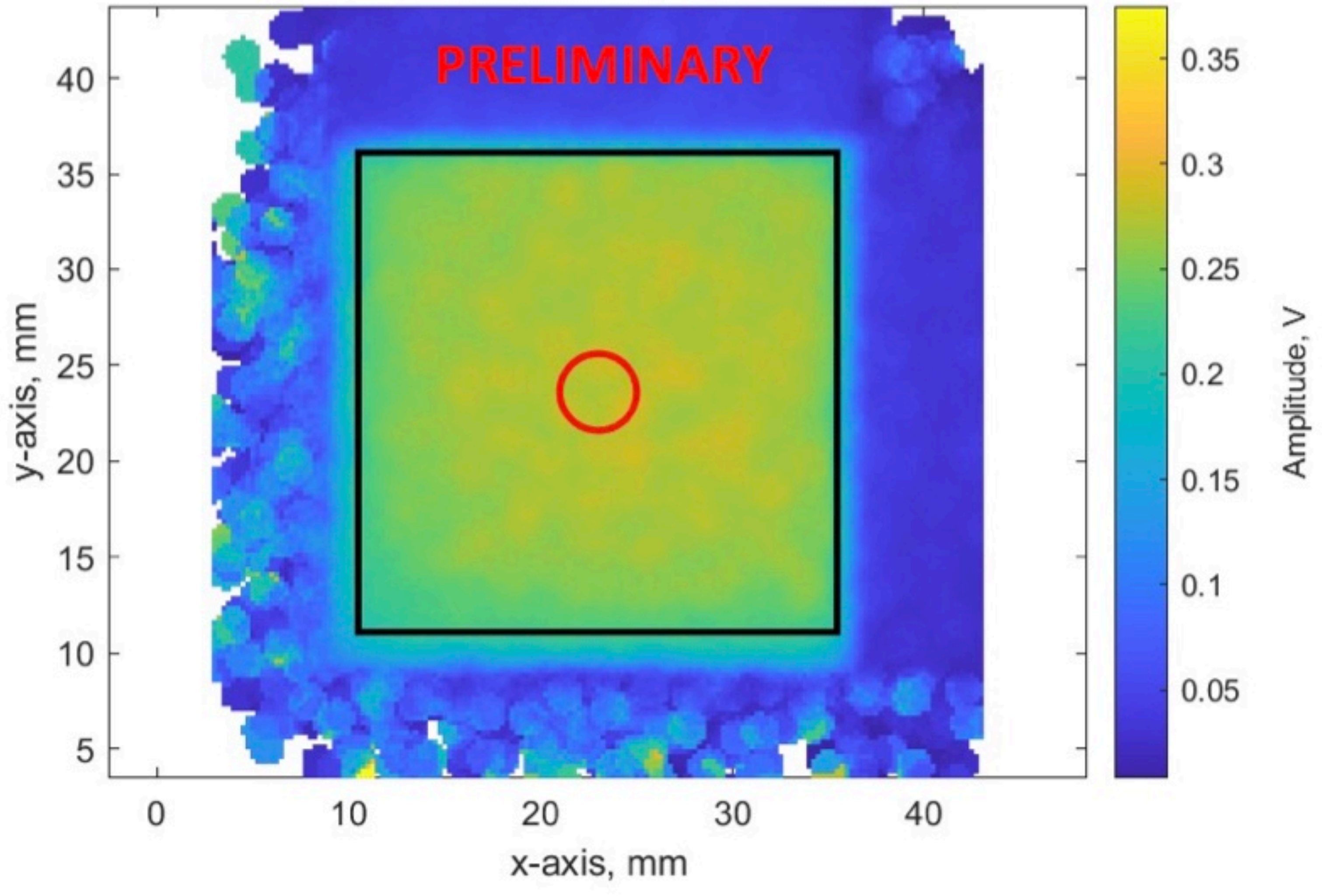


3) **Large area ALICE FIT Planacon:**

→ Remarkable flatness of each quadrant

→ Time resolution ~11 ps

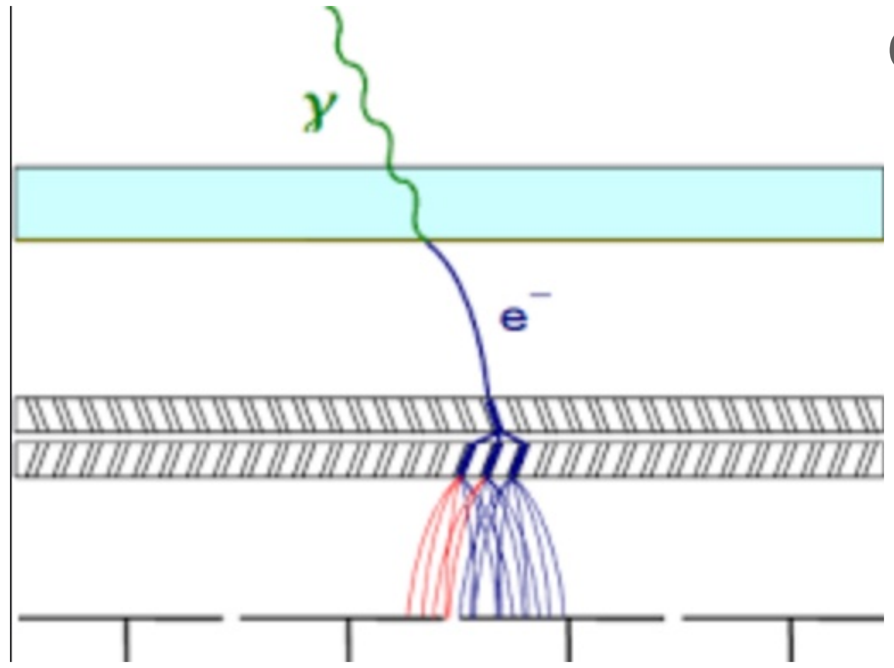
Amplitude of ALICE FIT Planacon vs Photek



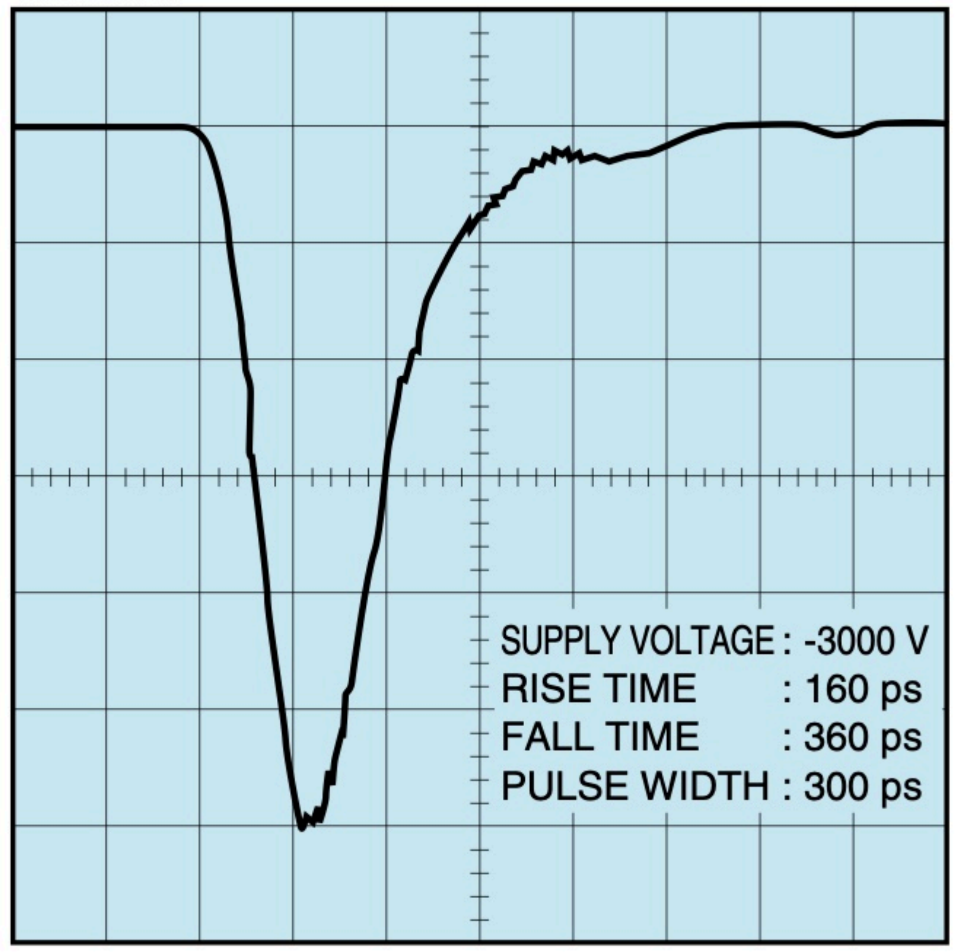
connection with Industry

- PICOSEC concept captures many benefits of MicroChannel Plate design
- small TTS arising in transition from PhotoCathode-> gain region
- we hoped to benefit from HPK's work w academic partners on "GasPMT"
- in Feb 2016, Giomataris and I visited HPK research director Suyama-San
- HPK sagacious about pc robustness
- offered engineering help if solution found
- RD51 PICOSEC &HPK compared CsI pc's - our efficiency similar

Principle of MCP
When used as MIP detector
collect Cerenkov light
from 3mm Q window



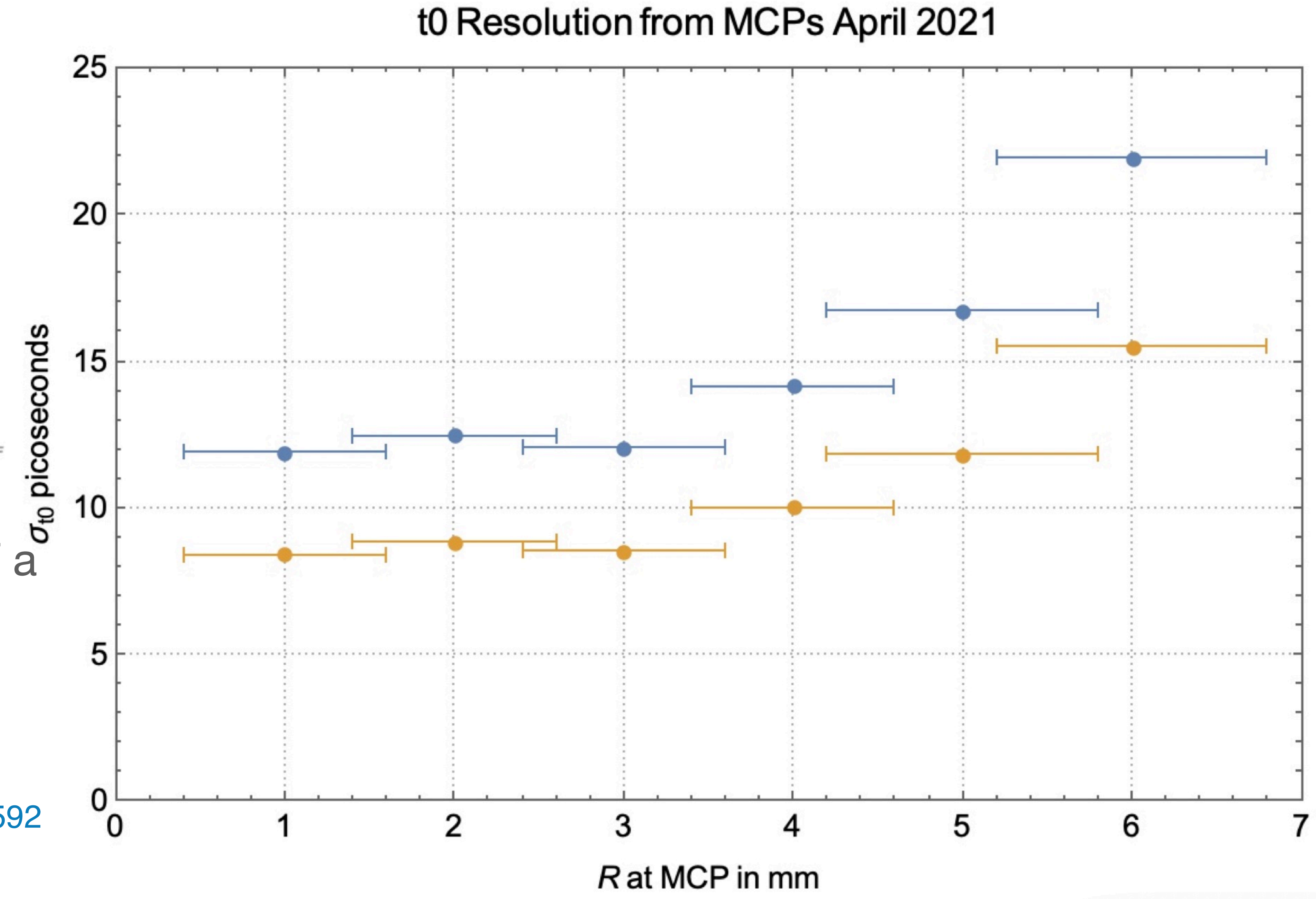
very fast!
often used
HPK R3809U
for t_0



even w. DRS @FNAL
we get ~10 picosec
t_0 resolution

somewhat better w.
20-40 GSa/s scope

see "Timing performance of a Micro-Channel-Plate Photomultiplier Tube"
J. Bortfeldt et al., NIM 960
April 2020
https://doi.org/10.1016/j.nima.2020.163592



PICOSEC: We proposed as RD51 Common Project in 2015.

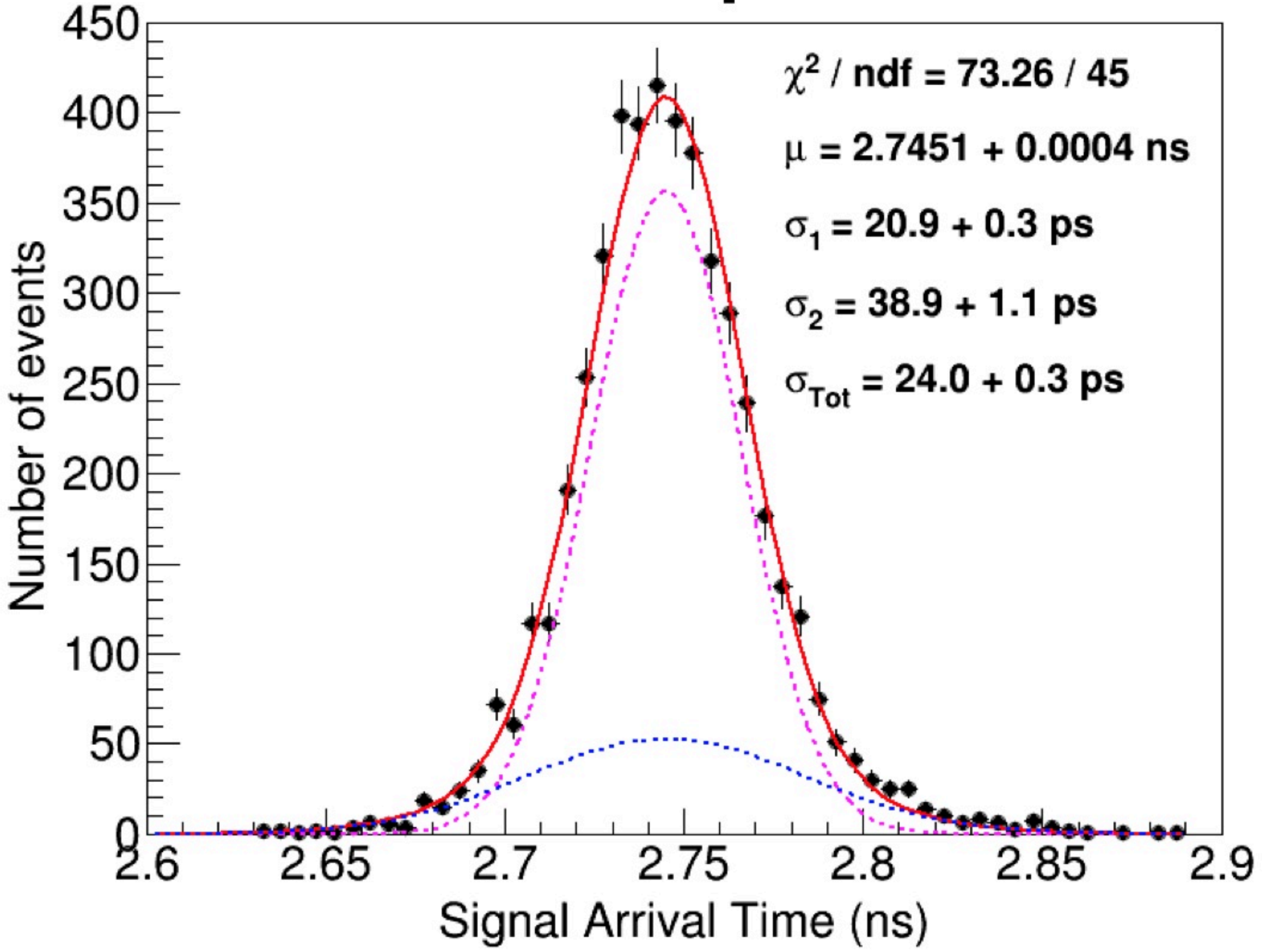
Rapid development from single ~1cm² cell test beam and laser studies.

Quest for robust photocathode:eg- “Diamond Like Carbon”

Early testbeam result using MCP as t_0

<25 picosec jitter!!

Time Resolution ~24 ps in muon beam



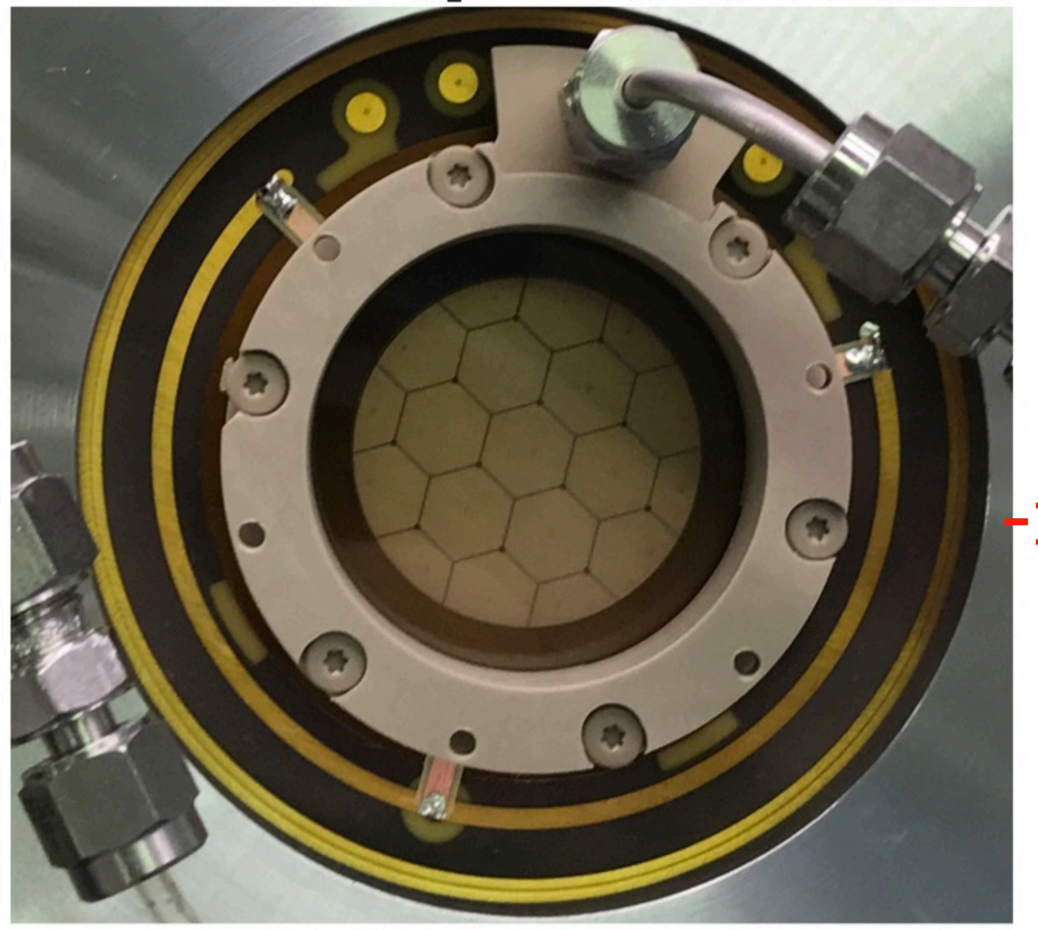
Different photocathode materials tested

Thickness of DLC film (nm)	Npe/per muon	Detection efficiency for muons
1	Bad	Bad
2.5	3.7	97%
5	3.4	94%
7.5	2.2	70%
10	1.7	68%
5 nm Cr + 18 nm CsI	7.4	100%

many papers as of 2019

- Fast Timing for High-Rate Environments with Micromegas, EPJ Web of Conferences **174**, 02002 (2018), doi: 10.1051/epjconf/201817402002
- PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector, Nucl. Instrum. Meth. **A903** (2018) 317-325. doi:10.1016/j.nima.2018.04.033.
- Charged particle timing at sub-25 picosecond precision: The PICOSEC detection concept, Nucl. Instrum. Meth. **A936** (2019) 515-518. doi:10.1016/j.nima.2018.08.070.
- Precise charged particle timing with the PICOSEC detector, AIP Conference Proceedings **2075**, 080009 (2019); doi: 10.1063/1.5091210
- PICOSEC-Micromegas: Robustness measurements and study of differentphotocathode materials, J. Phys.: Conf. Ser. **1312** (2019) 012012 ; doi: 10.1088/1742-6596/1312/1/012012

First Multipad Detector



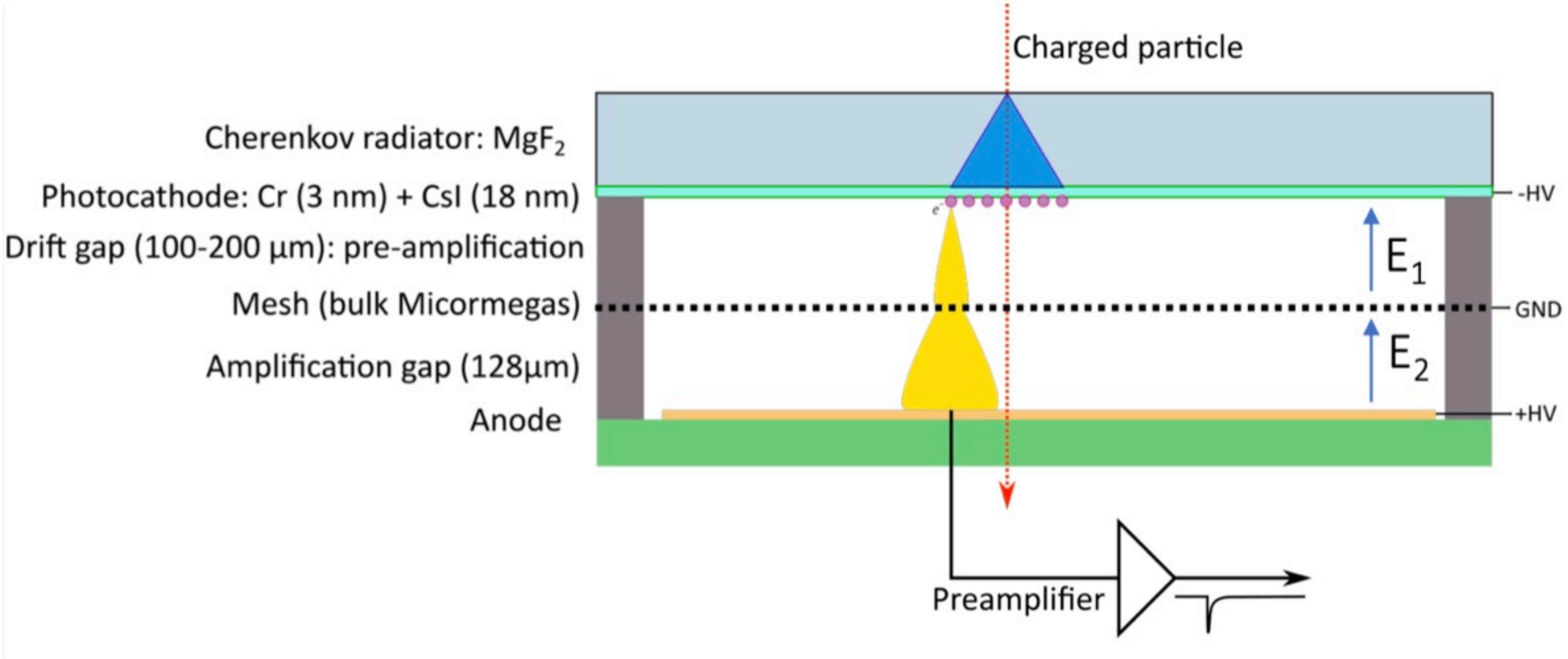
first transition from single cell -> scalable to large area

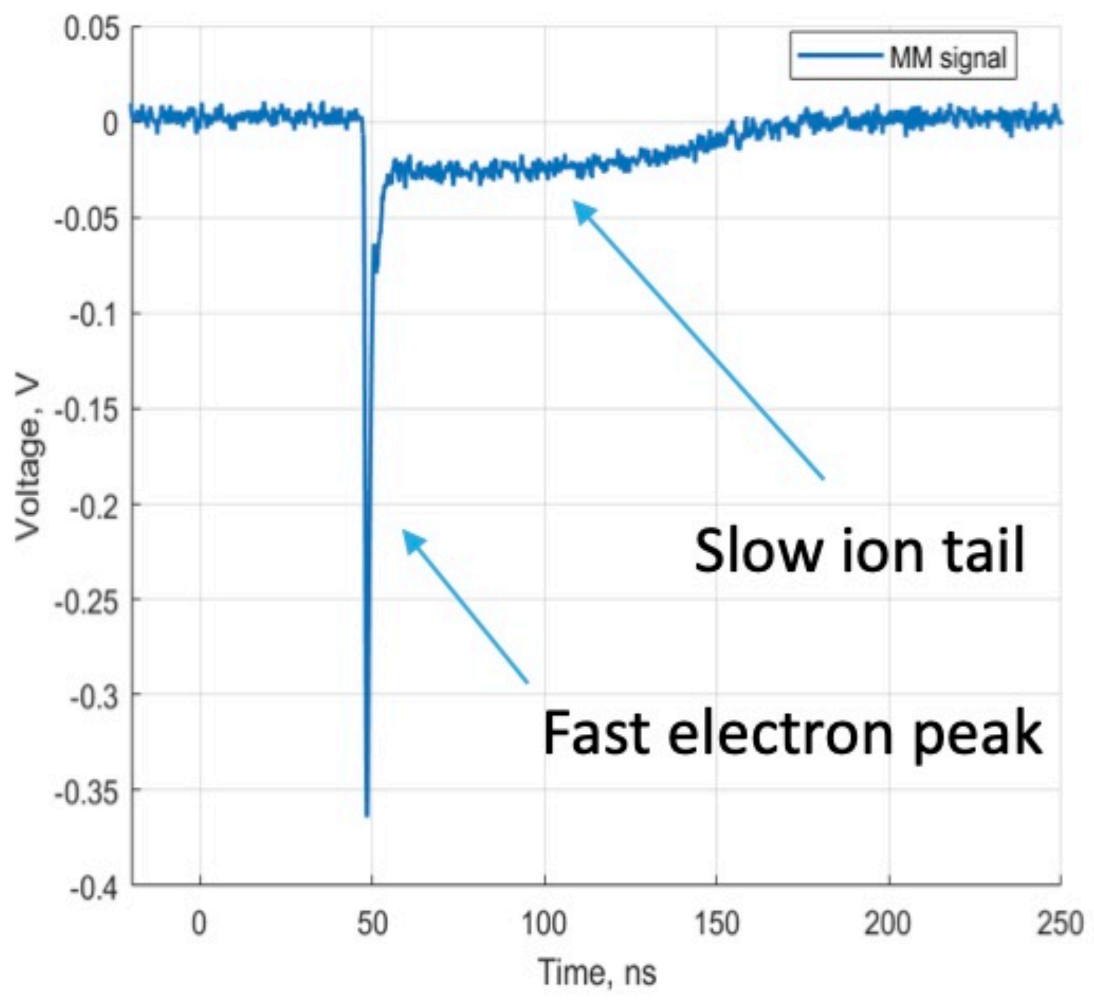
Recent Progress/Plans

- Since initial encouraging results PICOSEC focus-> scalable, robust Timing system
- Mechanics of 10cmx10cm, 100 channel device (flatness, readout, etc)-> **Solved !**
- Custom front-end amplifier for 100 channels-> **Solved !**
- Digitization of 100 channels for <25 picosecond timing-> **Solved !**
- Robust alternatives to CsI photocathode (DLC, Boron Carbide, etc)-> **in progress !**
- Secondary emission alternative-> **in progress !**
- Input guiding Practical Prototypes for future Colliders-> **Your Input Welcome !**

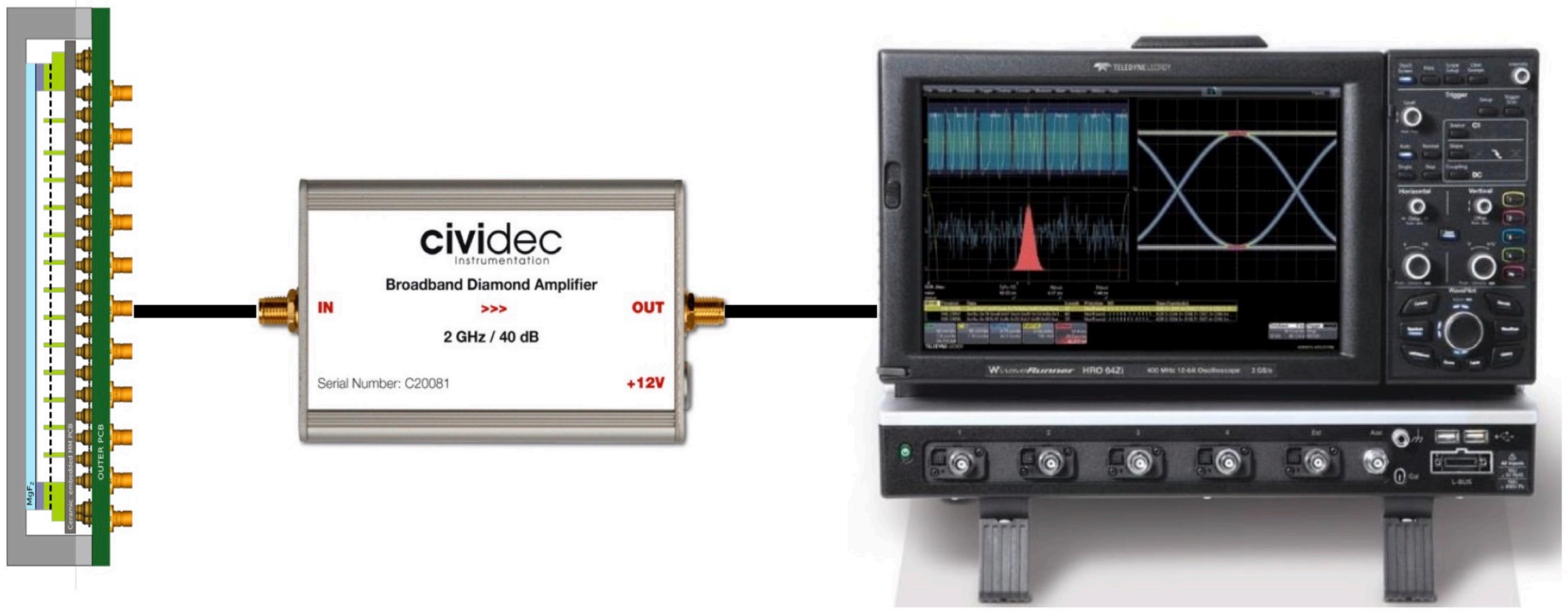
NB: excellent recent progress reports
M. Lisowska at NDIP ’22. https://indico.cern.ch/event/1188010/attachments/2489686/4275562/Marta%20Lisowska%20-%20PICOSEC%20Micromegas%20-%20NDIP.pdf
A. Utrobicic at Vienna WC Conference ’22 https://indico.cern.ch/event/911950/contributions/3912064/attachments/2064472/3464308/26June_PICOSEC.pdf

FEE/ Digitization





J. Bortfeldt et al., NIM A, 903, 317-325 (2018)



- All useful timing info in fast electron peak.
- Initially with Erich Griesmayer on fast, low noise amp
- 1 Gz digital scopes w. 20 GSa/s

- -> experience on needed sampling, BW for best timing

1st multipad PICOSEC still scopes

Initially LRS was next door in Meyrin

USTC also shipped many scopes

High Density Electronics

- Throughout project close contact w. Delagnes/Breton
- Scope data demonstrated SAMPIC-> Sufficient sampling
- (Also DRS4 @ 5GSa/s)
- This was confirmed in July ’22 testbeam

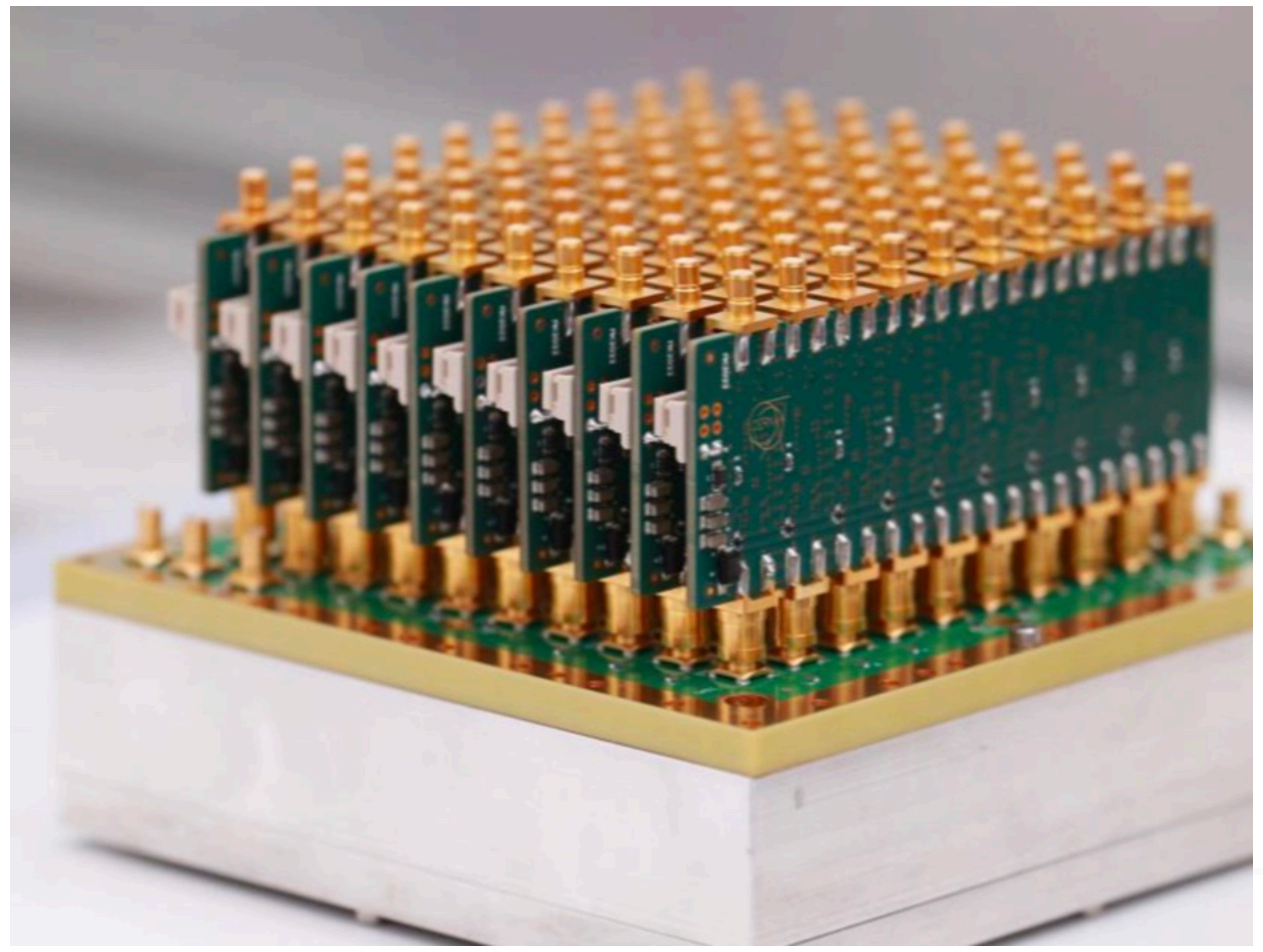
- Other, lower data volume Digitization not yet tested.

New front End electronics achieved equal/better

Results cp. commercial Diamond Amplifiers. !!!

A kitchen table husband/wife collaboration unique

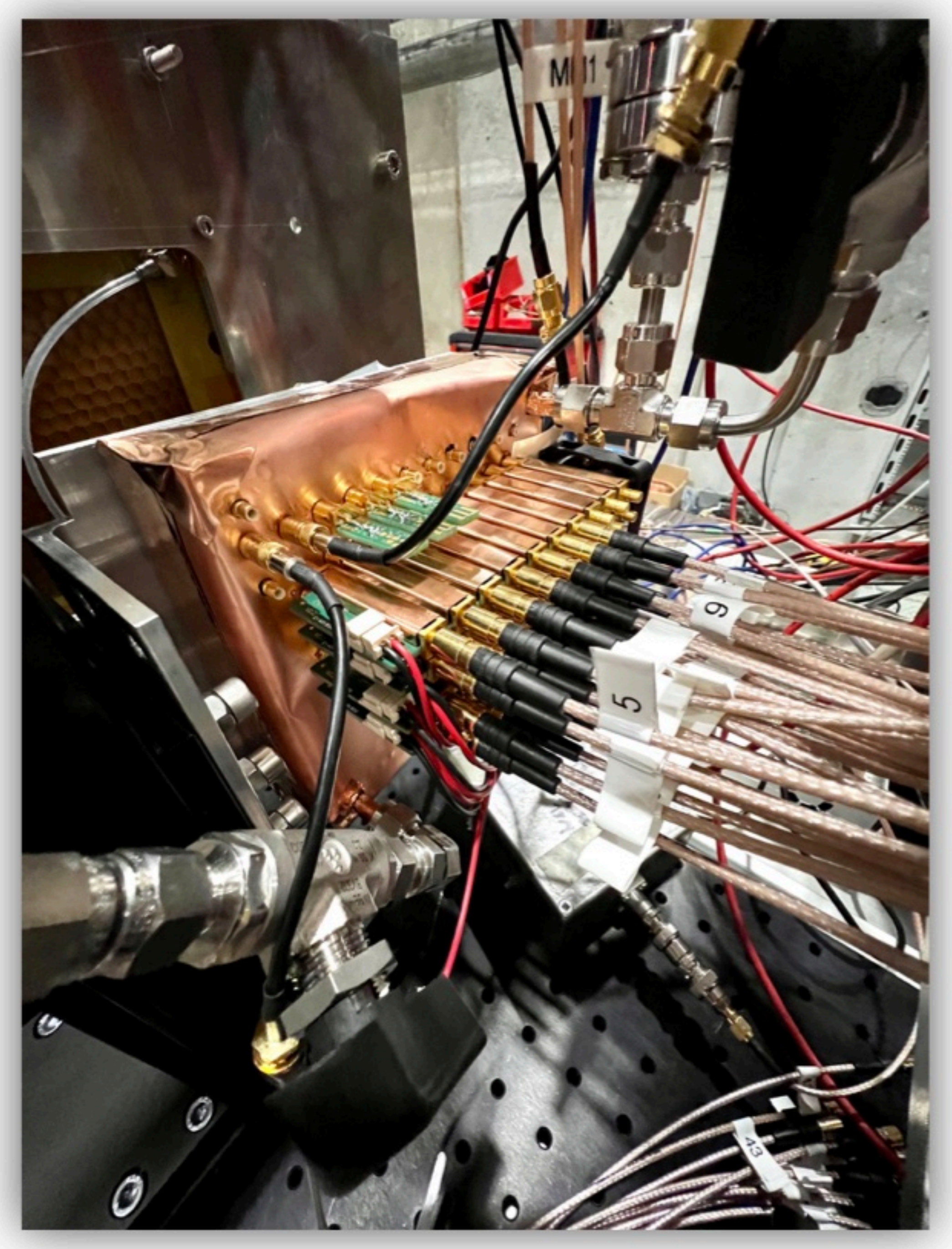
To PICOSEC!



SAMPIC digitizer:

→ 64 channel SAMPIC under test, 128 channel ready for July 2022 test beam

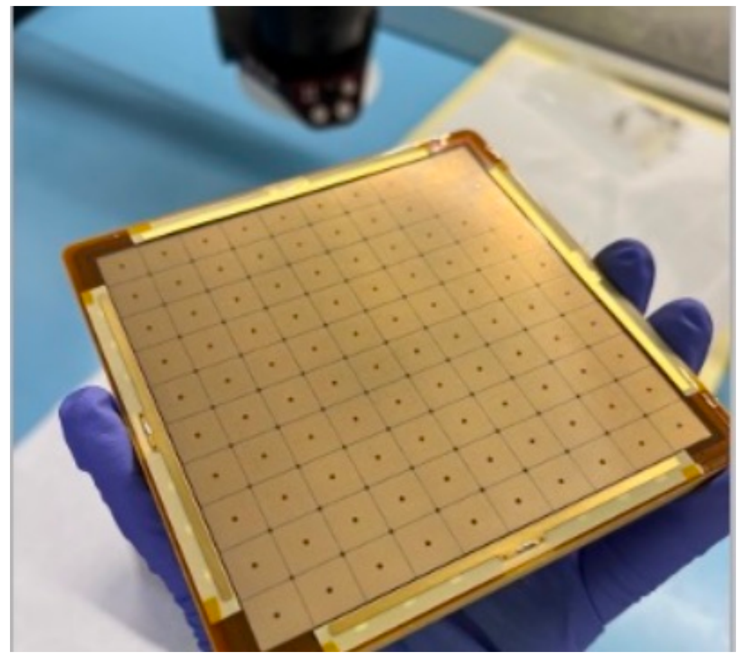
→ 6.4 vs 8.5 GS/s sampling frequency - test of achievable timing precision

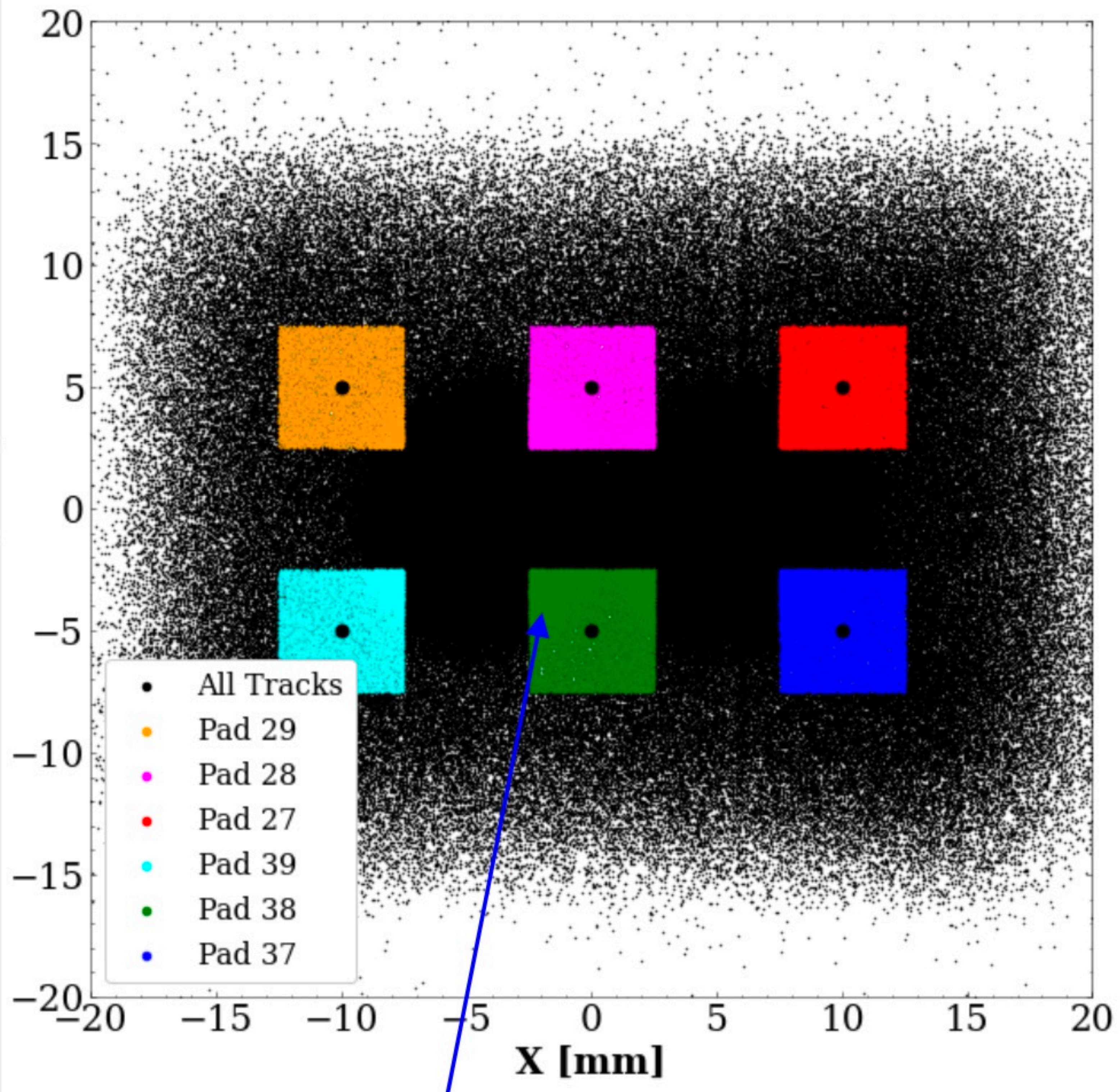


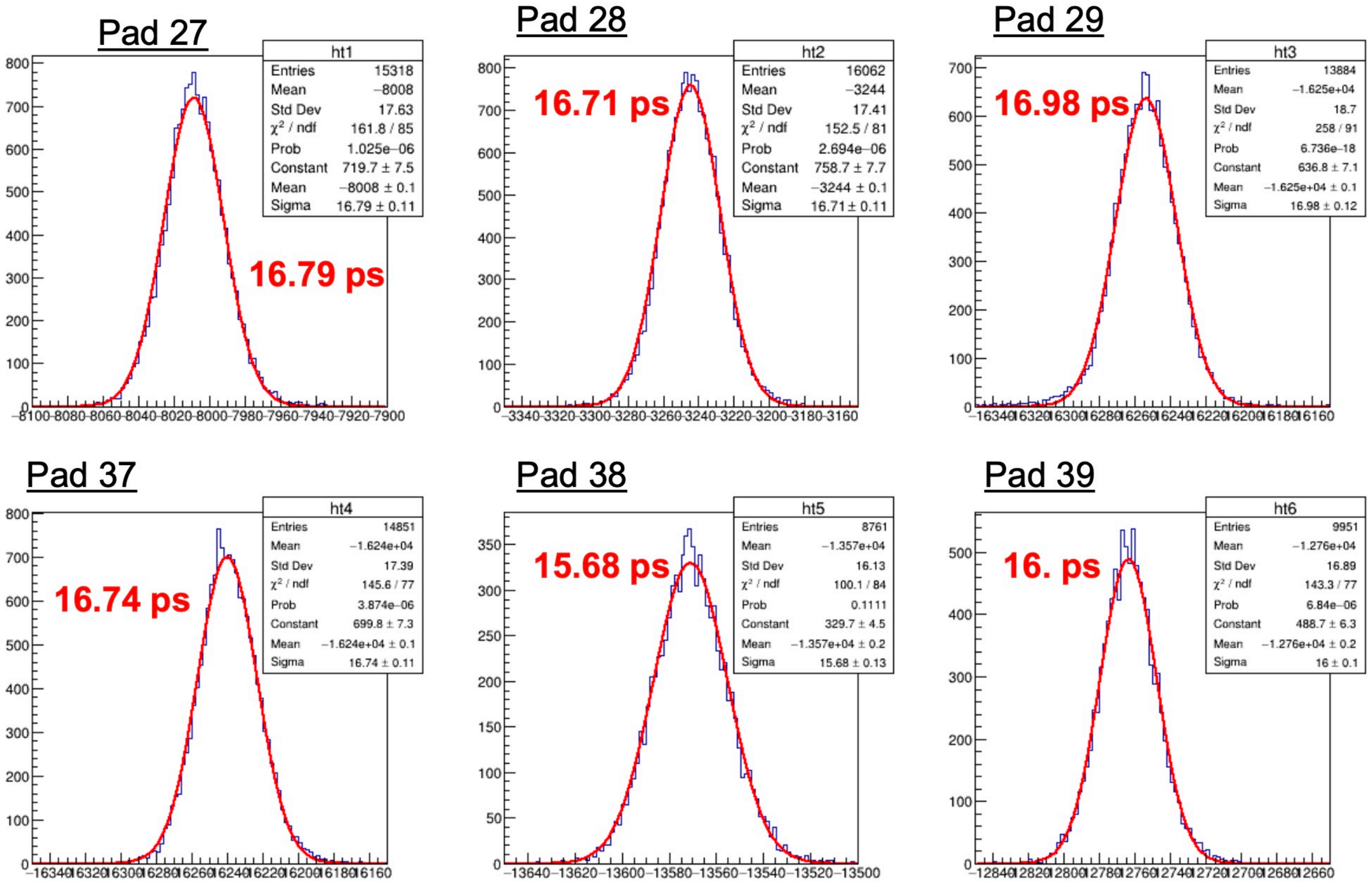
64 channel SAMPIC digitiser, J. Maalmi, D. Breton et al., CEA Saclay

The Easy Part: Near pad centers with 20 GSa/s waveforms

Below: from recent AUTH analysis. Early results with SAMPIC (~6.4GSa/s) or charge sharing ~ 20 picosecond resolution.





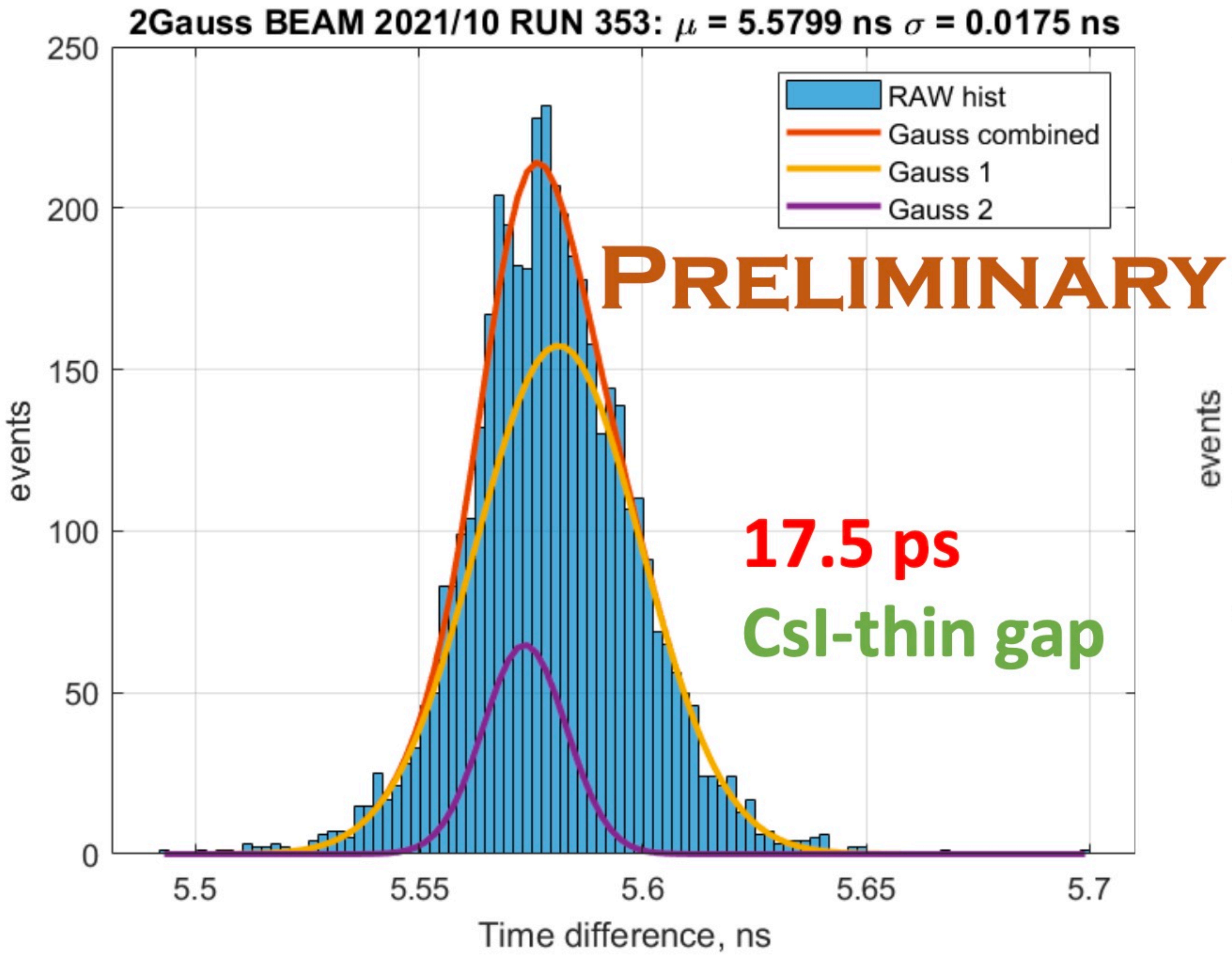


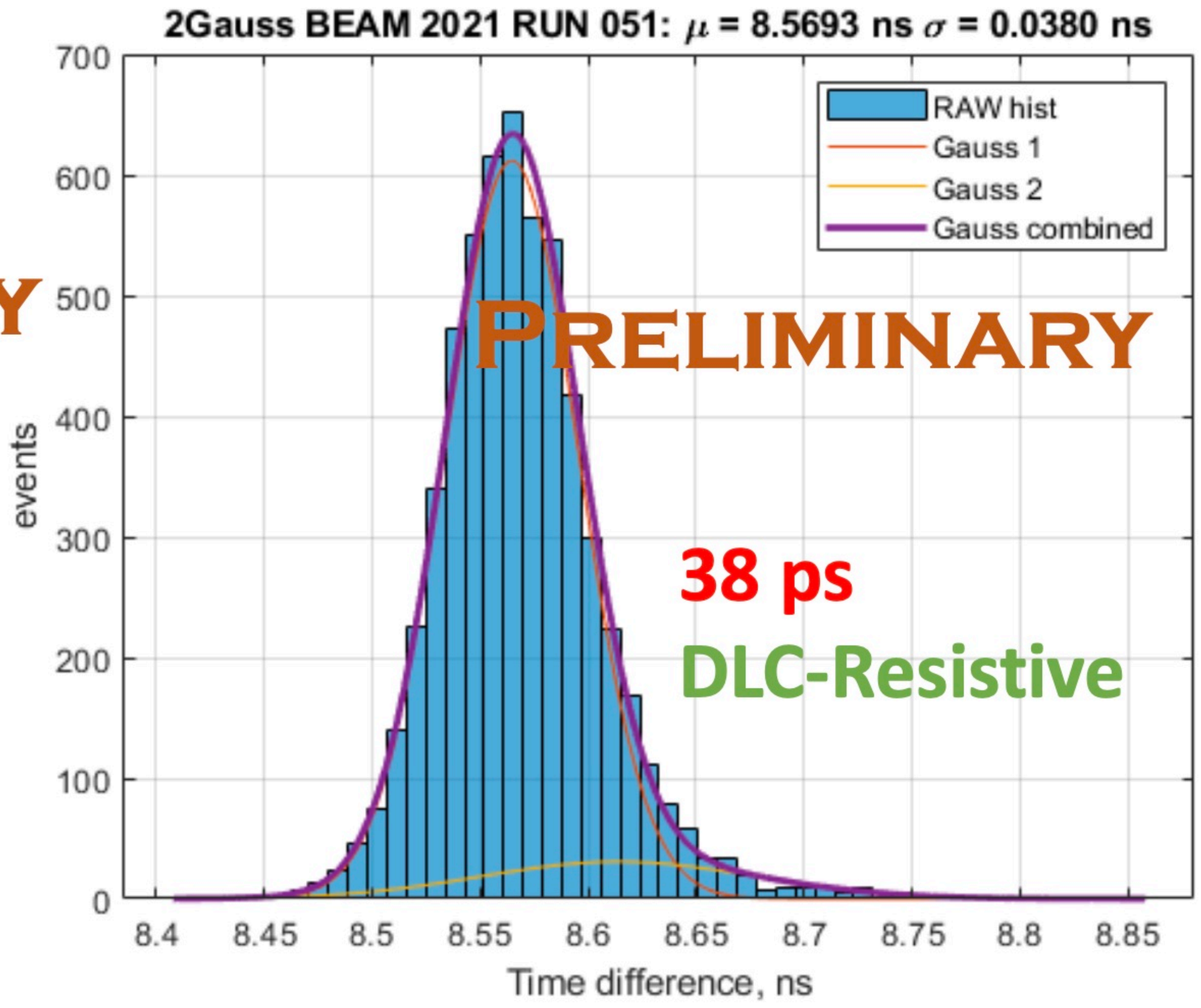
So far.. resistive multipad-> ~ 25 picosec

±2mm from each pad center

PICOSEC Future (2) Data from 2022 Testbeam runs -CERN North Area (Manuscript submitted to NDIP 2022 proceedings)

Observe **20.2 —>17 picosecond rms resolution** with preamp gap reduction (220->180 micron)
In the multipad PICOSEC, also encouraging results w DLC and resistive MM





Mechanical requirements

- <10 micron flatness for gap uniformity
- Achieved using FR4-> Ceramic PC board
- Thus achieve inherent timing uniformity

-> irreducible material budget = 3mm MgF_2 + 4mm Ceramic ++

RD51 Picosec Micromegas Collaboration

- **CEA Saclay (France):** S.Aune, D. Desforge, I. Giomataris, T. Gustavsson, F. J. Iguaz[1], M. Kebbiri, P. Legou, O. Maillard, T. Papaevangelou, M. Pomorski, L.Sohl
- **CERN (Switzerland):** J. Bortfeldt[2], F. Brunbauer, C. David, D. Janssens, M. Lisowska, M. Lupberger, H. Müller, E. Oliveri, G. Orlandini, F. Resnati, L. Ropelewski, L. Scharenberg, T. Schneider, M. van Stenis, A. Utrobicic, R. Veenhof[3], S.White[4]
- **USTC (China):** J. Liu, B. Qi, X. Wang, Z. Zhang, Y. Zhou
- **AUTH (Greece):** I Angelis, A. Kallitsopoulou , K. Kordas, C. Lampoudis, I. Maniatis, I. Manthos[5], K. Paraschou, D. Sampsonidis, A. Tsiamis, S.E. Tzamarias
- **NCSR (Greece):** G. Fanourakis
- **NTUA (Greece):** Y. Tsipolitis
- **LIP (Portugal):** M. Gallinaro
- **HIP (Finland):** F. García
- **JLAB (US):** K. Gnanvo, S. Malace
- **SBU (US):** K. Dehmelt, P. Garg

1) Now at Synchrotron Soleil, 91192 Gif-sur-Yvette, France

2) Now at University of Bonn,, Germany

3) Also MEPhI & Uludag University

4) Also University of Virginia

5) Now at University of Birmingham, UK 3

PICOSEC
Micromegas

Growing, highly motivated group w. serious commitment to Instrumentation

Concluding Remarks

- Over the past 5 years the PICOSEC Collaboration has moved from demonstrating <25 picosecond charged particle timing to addressing obvious benchmarks
- Those benchmarks could be sharpened by interaction w FCC-ee detector team
- Focus on robust photocathode development mostly based @ CERN, USTC, Saclay
- Tantalizing hints of Secondary Emission signal could have a big impact
- Other digitizing schemes could be explored as well as basic parameters of gas, etc.
- PICOSEC comprises ~45 researchers, launches beam test every few months (May,July, October….)
- Could benefit from evaluation by Future Collider Detector communities.