Particle Physics Technologies for Medical Applications

Capabilities from the Physical Sciences

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Advancing Medical Care through Discovery in the Physical Sciences
Radiation Detection

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Introduction

- Many of the technologies being developed for particle physics are the same or similar to many of the technologies that are used for medical applications.
  - Photon detection
  - Fast timing
  - Charged particle tracking
  - Readout electronics & DAQ
  - Patter Recognition/Image Reconstruction (AI/ML)

  Detector Technologies

- This talk will focus mainly on detector technologies for the first two bullets, although these technologies are intimately connected with all the others.

Detector Technologies Used in NP/HEP and Medical Applications

Technology	NP/HEP Applications	Medical Applications
Photon detector materials Inorganic Scintillators: NaI, CsI, BGO, LSO/LYSO, PWO,… Semiconductors: HPGe, CZT,…	Gamma Ray Detection (few hundred keV $\rightarrow$ 1 TeV)	PET, SPECT, Compton & Gamma Ray Imaging, X-Ray Imaging (10's keV $\rightarrow$ ~ MeV)
Photosensors PMTs, SiPMs, MCPs, LAPPDs	Calorimetry, Tracking, PID, RICH	PET, SPECT, Isotope Therapy
Fast Timing ($\rightarrow$ 10 ps)	Particle ID, Event timing (TOF, RICH, Pileup separation at high luminosity)	TOF-PET
Charged Particle Tracking	Tracking detectors (MPGDs, Si Strips/Pixels, LGADs, RPCs…)	Proton/Ion Beam Therapy, Dosimetry

Fast Inorganic Scintillators

Courtesy of R-Y Zhu, Caltech

Fastest (BaF2, BaF2:Y) — PET (LYSO:Ce)

	BaF_2	BaF_2:Y	Lu_2O_3:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	0.81	2.59	3.53	2.51	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R_M (cm)	3.1	3.1	1.72	2.45	2.76	2.28	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	18.1	23.1	25.2	22.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z_{eff}	51.0	51.0	67.3	32.8	29.3	27.7	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	11.6	7.91	7.01	8.34	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	370	350	350	380	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.0	1.96	1.87	2.1	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	0.95	0.19[d]	0.36[d]	2.6[d] 4.0[d]	6.5 0.5	100	35[e] 48[e]	9 32	190	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	280	57[d]	110[d]	2,000[d]	2,100	30,000	25,000[e]	12,000	58,000	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	1.1[d]	1.1[d]	1.8[d]	3.0[d] 1.0[d]	110 5.3	40	820 50	191 25	570 130	1485 36	75
LY in 1[st] ns (photons/MeV)	1200	1200	170	34[d]	46[d]	980[d]	43	740	240	391	400	125	318
LY in 1[st] ns /Total LY (%)	9.0	64	60	60	43	49	2.0	2.5	1.2	3.3	0.7	1.4	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.127	0.314	0.439	0.407	0.394	0.185	0.251	0.314	0.319	0.214	0.334

Sub-ns Fast Component

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by Alpha particles; [e] 0.3 Mg at% co-doping; [f] $Lu_{0.7}Y_{0.3}AlO_3$:Ce.

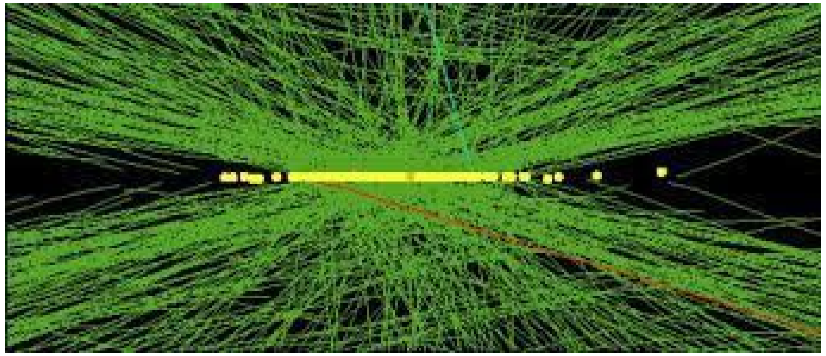
We are still searching for the "Perfect Scintillator"

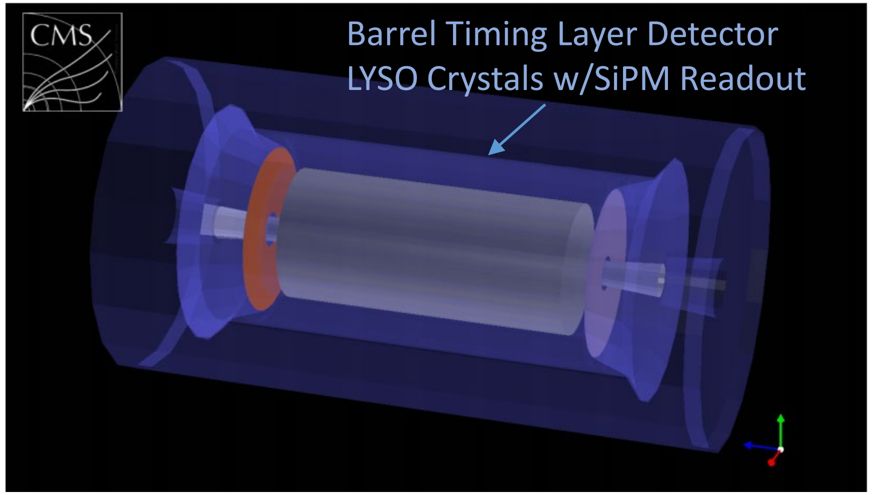
- Dense (> 7 g/cm^3)
- High light output in the visible (30K-40K γ/MeV)
- Fast (< 100 ps rise time with no slow component)
- Rad hard (> 10 Mrad)
- Non-hygroscopic
- Cheap !

Use of LYSO in HEP – CMS Barrel Timing Layer

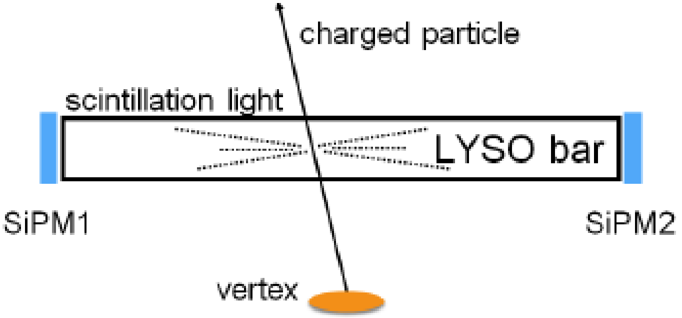
Precision timing layer surrounding the CMS Central Tracker used to distinguish multiple interaction vertices (“pileup”) at very high luminosity at the HL-LHC

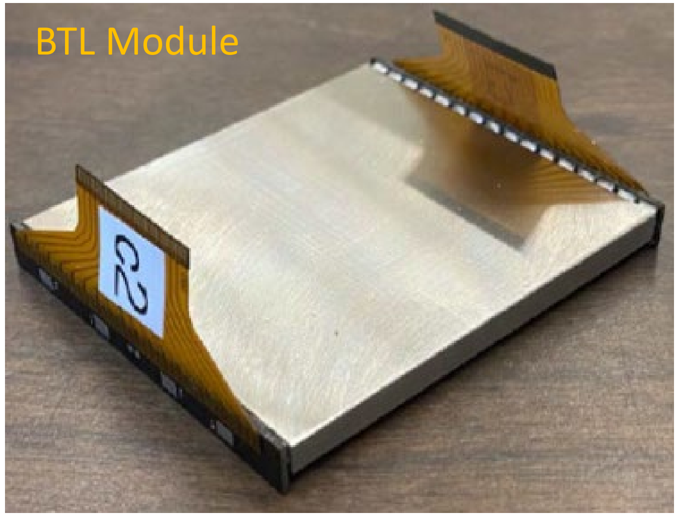
140 interactions per bunch crossing





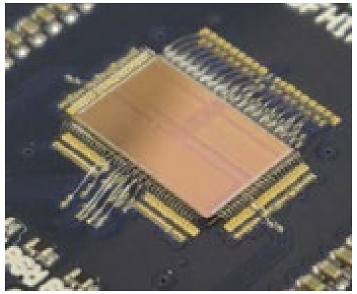
Courtesy of A. Bornheim, Caltech





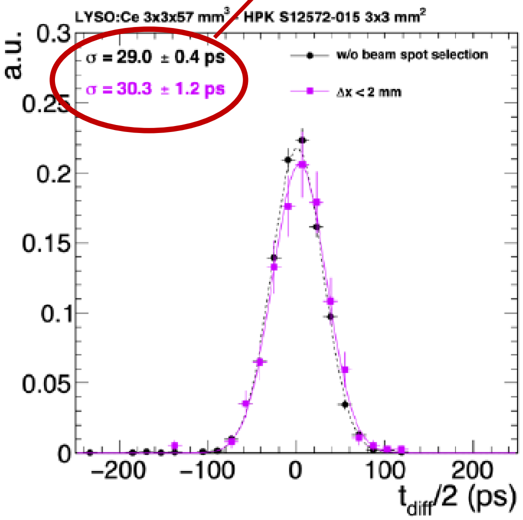
16 LYSO bars read out by 32 SiPMs
LYSO is rad hard (~ 3 Mrad). SiPMs are sensitive to neutrons (> 10^{14} n/cm^2) and must be cooled to -30 °C

ASIC used for readout (TOFHIR) was derived from TOFPET ASIC for PET applications



Will be used to suppress noise due to radiation damage of SiPMs

Time Resolution
σ ~ 30 ps

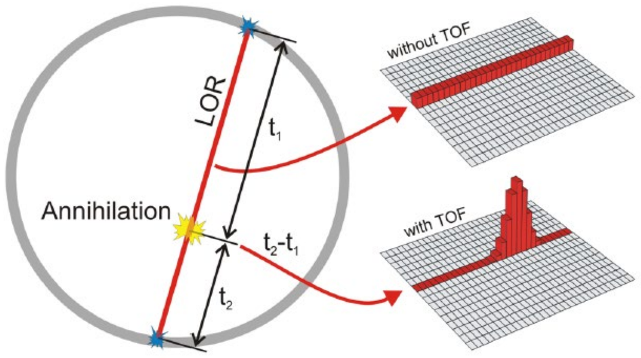


The 10 ps Challenge

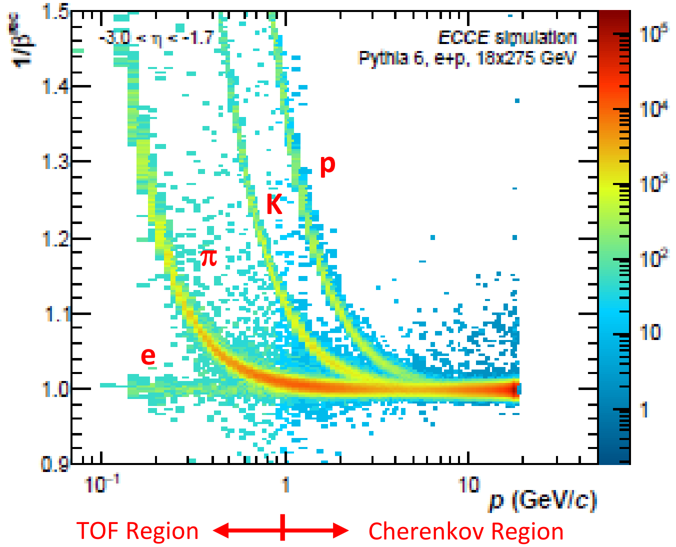
Proposed by Paul Lecoq in 2019 to push the limits of TOF-PET to achieve a CTR of 10 ps

Benefits: This would be a transformational change in PET imaging

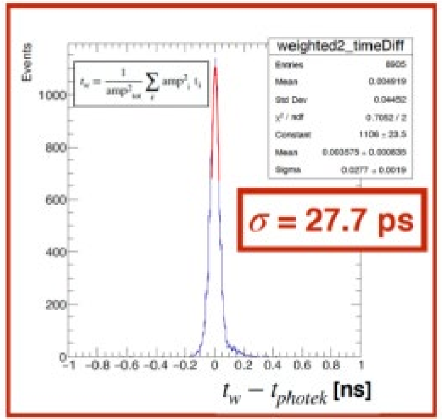
- Providing a CTR of 10 ps would allow localizing the decay vertex to ~ 1.5 mm and allow direct 3D volumetric determination of the source distribution, eliminating the need for tomographic image reconstruction
- It would improve the S/N ratio by ~ x16 compared to non TOF-PET
- The increase in sensitivity would allow reduced patient dose, shorter scan times and permit more studies with short lived radiotracers (e.g.,^{11}C)



Similar requirements are needed for particle id in HEP and NP



AC-LGAD Time Resolution



Similar or better timing performance can be achieved with fast photosensors

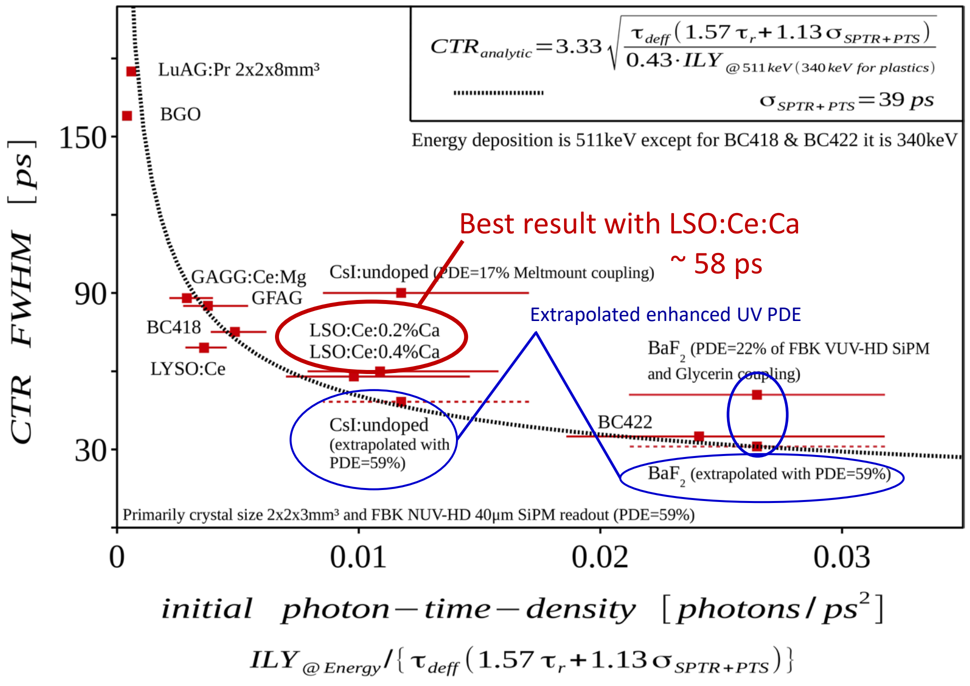
Both HEP/NP and TOF-PET would benefit from a photon detector-photosensor combination that could achieve ~ 10 ps time resolution

How to achieve 10 ps Time Resolution ?

"Roadmap toward the 10 ps Time-of-Flight PET challenge"
P. Lecoq et.al., 2020 *Phys. Med. Biol.* 65 21RM01

"Experimental time resolution limits of modern SiPMs and TOF-PET detectors exploring different scintillators and Cherenkov emission"
S. Gundacker et al 2020 Phys. Med. Biol. 65 025001

"Ideal Measurement" Results



Coincidence Time Resolution of various scintillators coupled to a UV sensitive SiPM with fast readout electronics

- Best timing resolution achieved today under "ideal" laboratory conditions with small (~ 2x2x3 mm^3) samples of materials that would be suitable for PET (LYSO:Ce:Ca) is ~ 60 ps.
- Need DOI resolution ~ few mm to achieve this in larger (e.g., 20-30 mm) crystals for PET.

Reaching the 10 ps goal will require new improvements in high density scintillator materials, fast photosensors and fast readout electronics

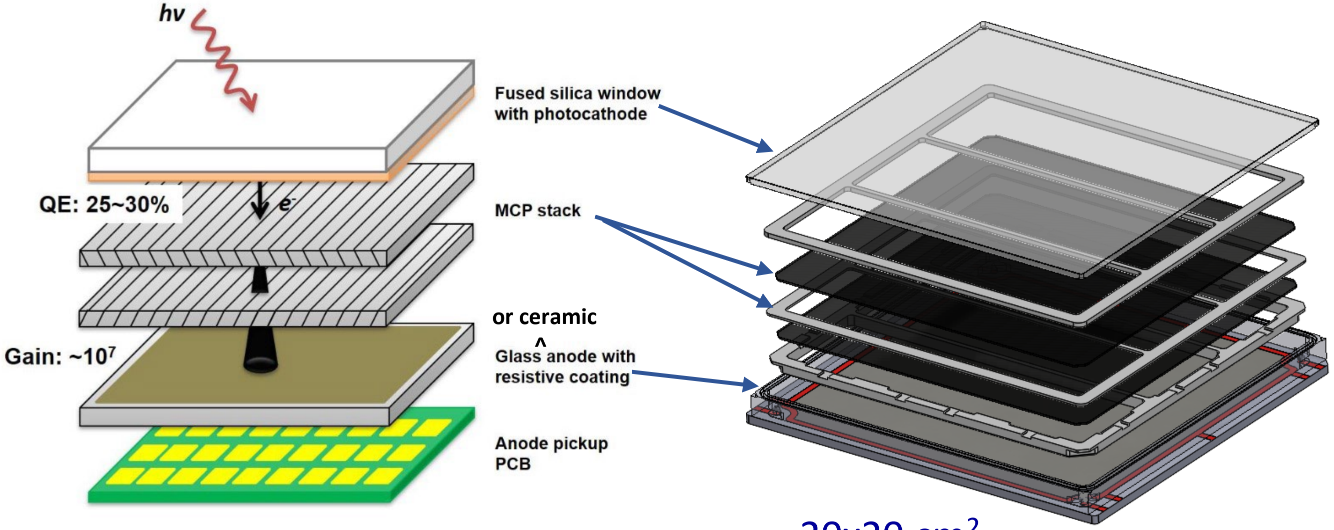
LAPPDs/HRPPDs

Originally developed at Argonne for use in HEP

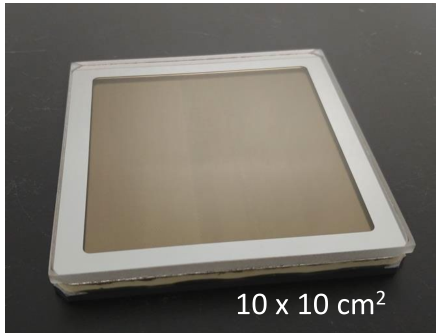
Principle of Operation

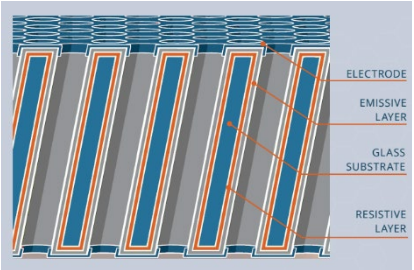
Large Area Picosecond Photo Detector

High Resolution Picosecond Photo Detector



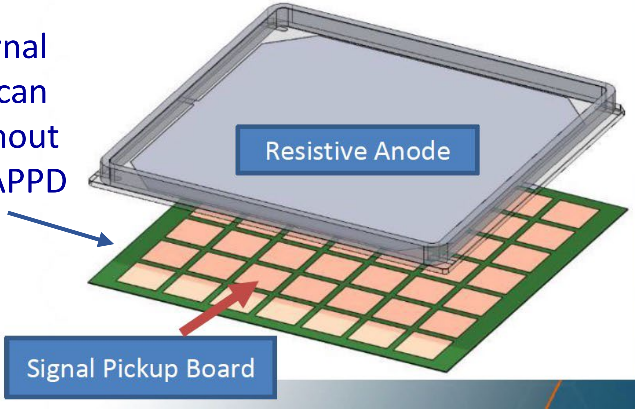
20x20 cm^2





MCP stack consists of a pair of chevron shaped 10 μm or 20 μm glass capillaries with emissive ALD coating

Pixellated external readout board can be changed without modifying the LAPPD detector



- 10 μm pore diameter
- Gain ~ 10^7 ($\Rightarrow$ single photon sensitivity)
- Bialkalai Photocathode (QE ~ 30% @ 365 nm)
- Active photocathode area ~ 70%
- Capacitive Coupled or DC readout
- Magnetic field compatible (w/limitations)
- Single Photon Timing Resolution ~ 23 ps
- Position Resolution < 0.6 mm

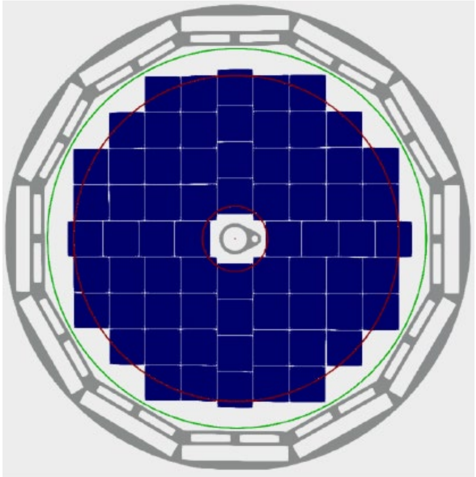
Produced by Incom, Charlton, MA

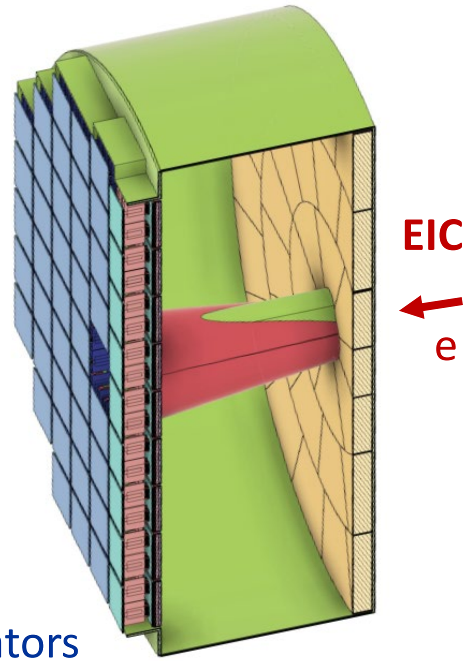
Combined Cherenkov-TOF Detector Using LAPPD/HRPPDs

Ring Imaging Cherenkov Detector for the ePIC Experiment at EIC

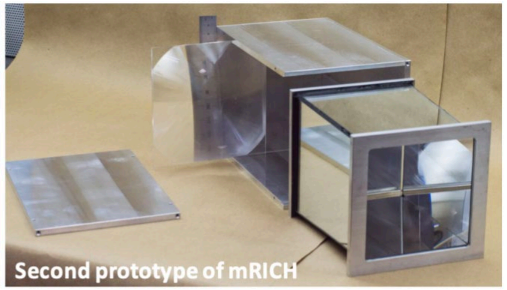
Proximity Focused RICH

A. Kiselev (BNL)



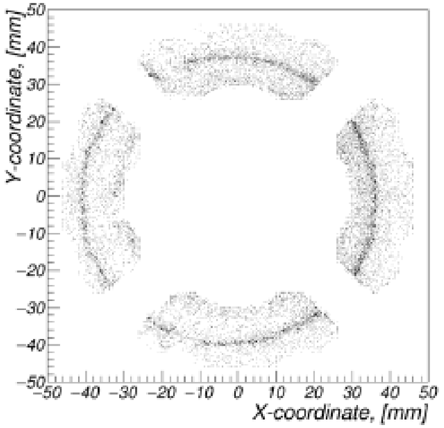


Array of modules with HRPPDs with Aerogel Radiators

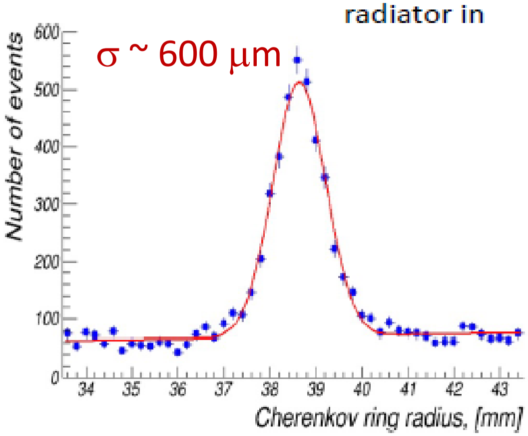


Modular RICH with Focusing Lens

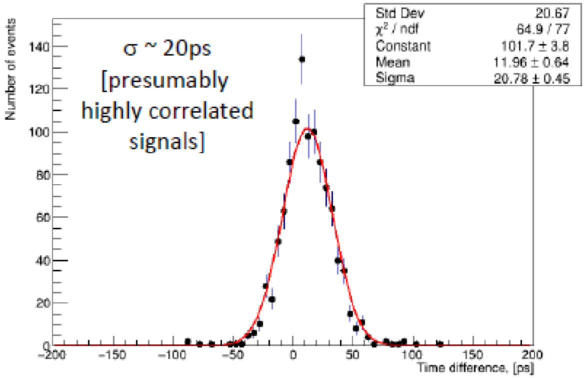
Beam Test Results (Fermilab 2022)



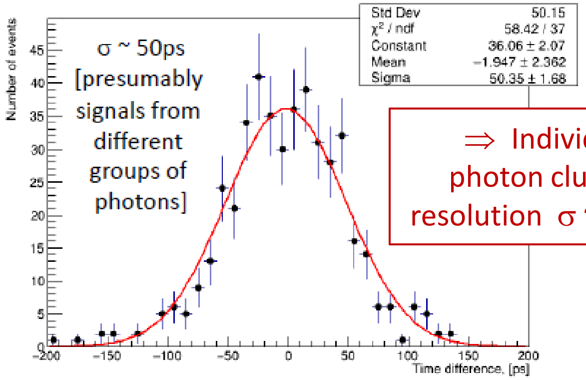
Cherenkov ring imaged by the LAPPD for multiple beam events



Spatial resolution for the radius of the Cherenkov ring for multiple events



Time resolution for correlated single photon hits on the Cherenkov ring



⇒ Individual photon cluster resolution σ ~ 35 ps

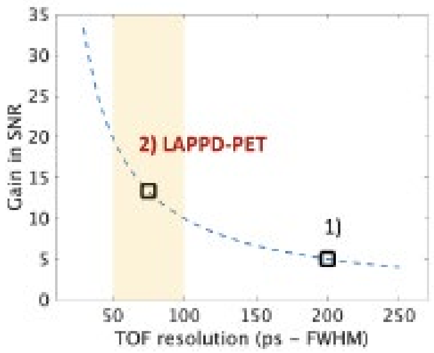
Time resolution for photon hits from different groups on the ring

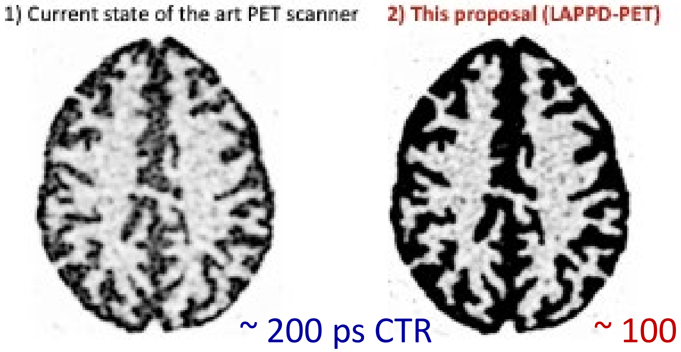
Use of MPCs/LAPPDs for TOF-PET

First proposed by H. Frisch & W. Moses in 2010 (H. Kim et.al. Nucl. Inst. Meth. A622 (2010) 628-636)

First results with LAPPDs for PET achieved ~ 300 ps CTR (S.Kwon et.al, 2020 ISSS NSS/MIC Conf. Rec.)

LAPPD-PET combines the PrismPET concept with LAPPDs to achieve ~ 100 ps CTR,
~ 500-800 μm position resolution, ~ 2-3 mm DOI resolution and ~ 12-15% energy resolution

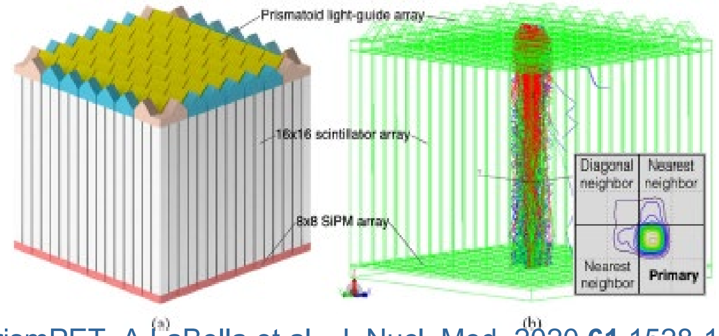




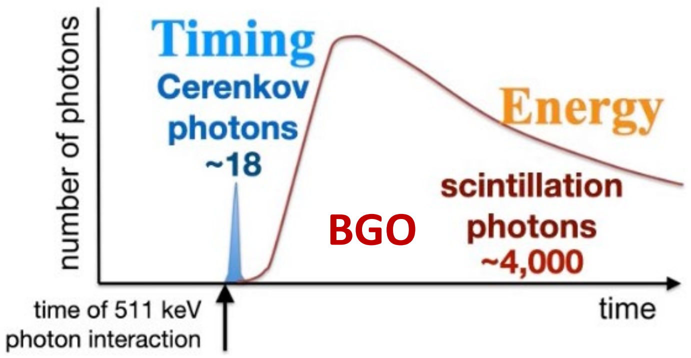
~ 200 ps CTR

~ 100 ps CTR

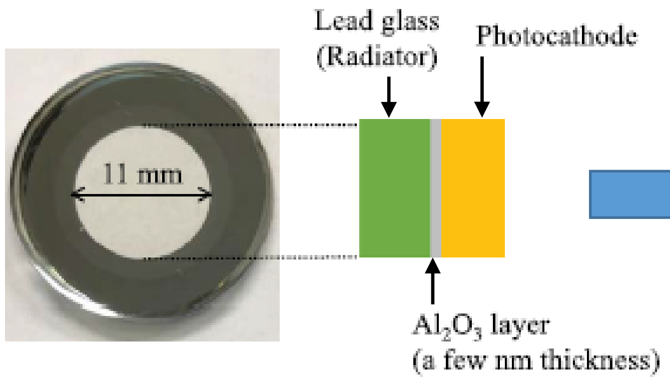
A.Goldan (Cornell)



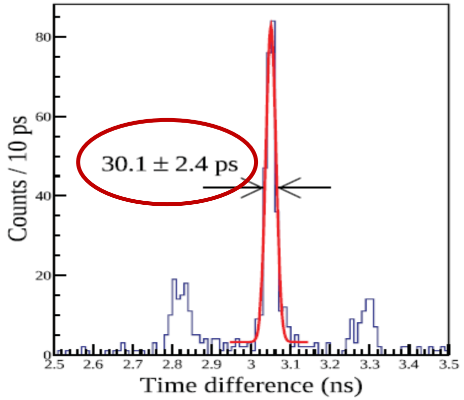
PrismPET, A.LaBella et.al., J. Nucl. Med. 2020 **61** 1528-1533



Cherenkov photons can also be used for fast timing in addition to early arrival scintillation photons



MCP with integrated lead glass window to produce and detect Cherenkov photons



CTR ~ 30 ps but with low gamma ray detection efficiency

Ota et.al., Phys. Med. Bio. 2019 **64** 07LT10

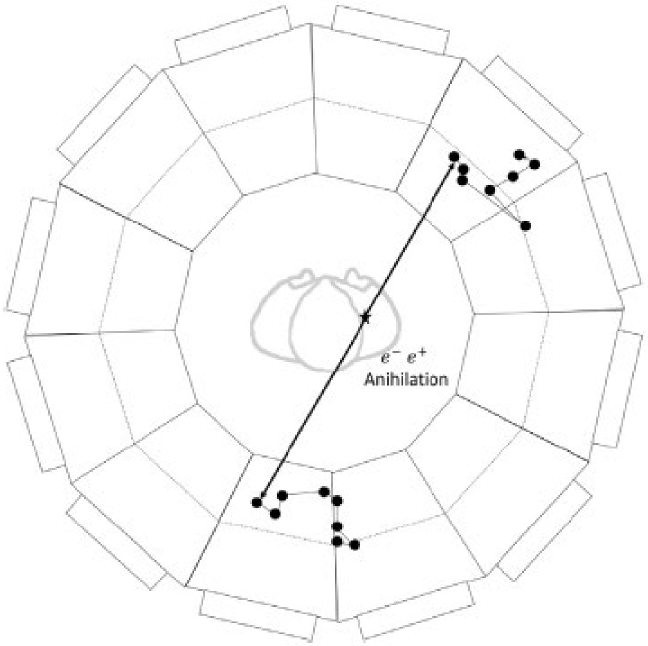
TOF-PET Using Fully Reconstructed Compton Events

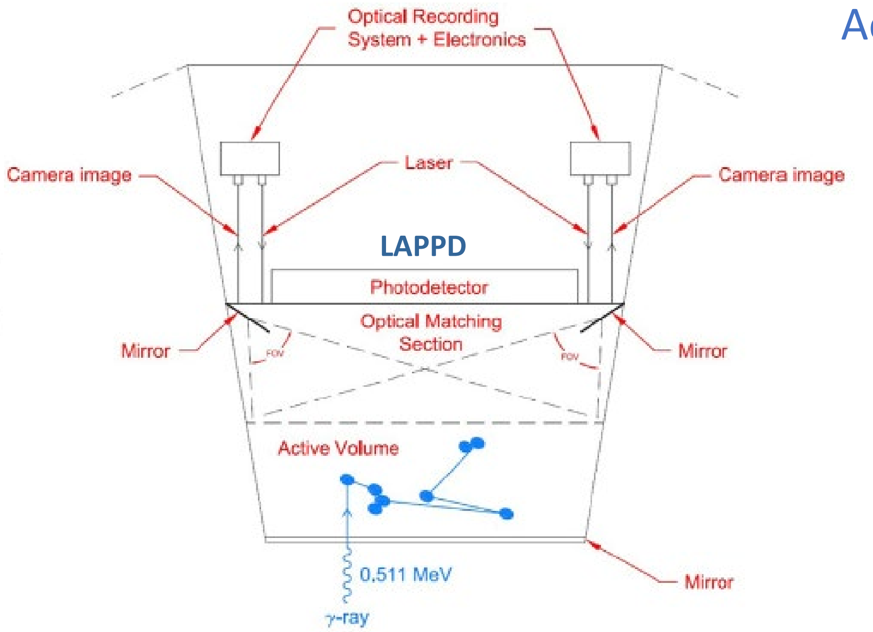
Concept: Fully reconstruct Compton processes in the active volume of the detector to measure the direction and energy of the gamma ray.

→ Measure the energy, position and time of every Compton scatter event.

Low Dose High Resolution TOF-PET Using Ionization Activated Multi-State Low-Z Detector Media

J.F.Shida et.al., Nucl. Instr. Meth. A 1017 (2021) 165801





"Optical Time Projection Chamber"

Active medium consists of a liquid scintillator with a photoswitchable organic dye

- Compton electron deposits ionization in the liquid scintillator
- Scintillation photons excite the fluorescent dye
- A laser is used to further excite the dye resulting in optical an emission
- The number of fluorescent photons are then "counted" which gives a measure of the deposited energy.
- The LAPPD provides a time stamp for each step of the decay process.

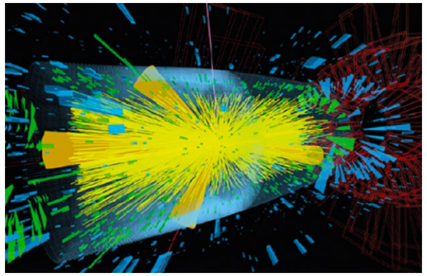
"5D" Imaging Calorimetry

Particle Flow Calorimetry

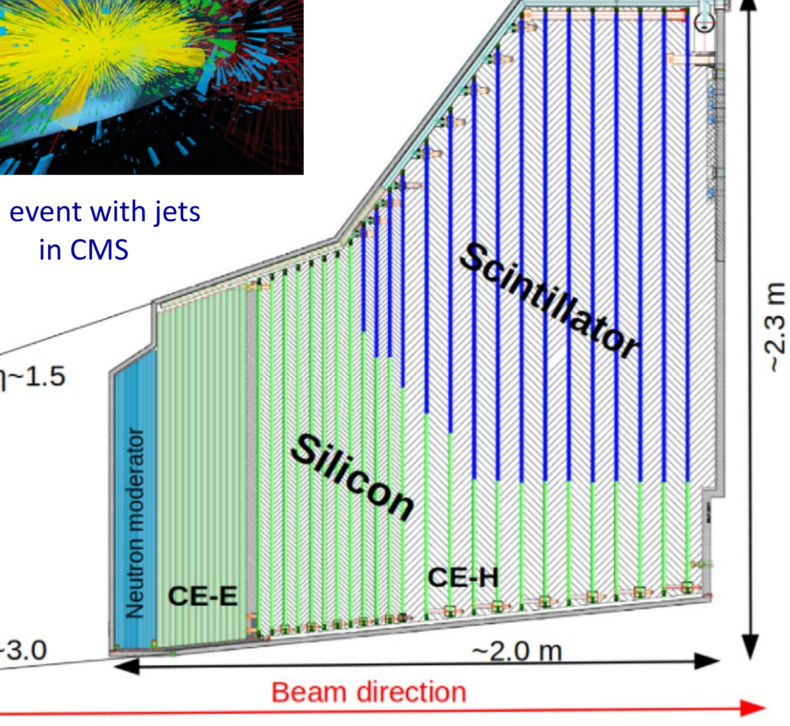
Concept: Measure the energy, position and timing information of all particles in the calorimeter and combine this with position and momentum information from the tracking system to measure all particles in an event collision using AI/ML algorithms

The CMS High Granularity Calorimeter

Designed for the High Luminosity Upgrade at the CERN LHC (HL-LHC) L = 5x10^{34} cm^{-2}s^{-1}



An event with jets in CMS



Used to measure jets in HL pp collisions at 14 TeV E_{cm} with up to 200 pileup events per bunch crossing

The calorimeter is divided into many small voxels which measure the energy (1D), position (3D) and time (1D) of each voxel (similar to the information provided by GEANT4 MC simulations)

- W/Cu, Pb and SS absorbers
- 620 m^2 of silicon sensors (6M channels 0.5 cm^2 $\rightarrow$ 1.1 cm^2)
- 27,000 Si modules cooled to – 30 C° (140 kW per Endcap)
- 400 m^2 scintillator read out with SiPMs
- Radiation levels up to ~ 10^{16} n/cm2 and 2 MGy
- Custom designed ASIC readout (HGCROC - 10 bit ADC, 10/12 bit TDC)
- 20–150 ps time resolution

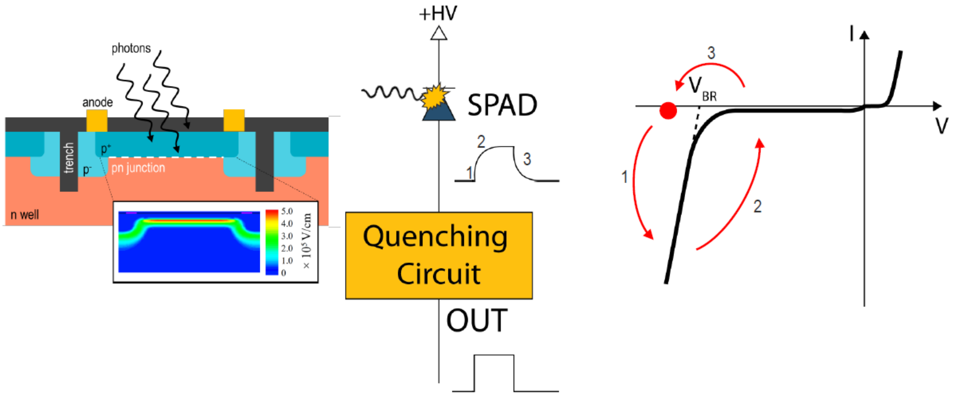
Summary and Conclusions

- There are many synergies between technologies used in particle physics and medical applications that can share mutual benefits from developments in both of these fields.
- Advances in detector materials, photosensors, ASIC development and readout electronics, DAQ systems, computing, simulations, pattern recognition algorithms, artificial intelligence and machine learning will all contribute to these benefits.
- Of particular interest is the goal of achieving ultra fast timing resolution (~ 10 ps) for many of the detector systems used in both particle physics and medical imaging.
- However, it is not possible to achieve a time resolution of 10 ps in a practical large scale system today. This will require new advances in detector materials, photosensors and fast readout electronics to achieve this goal.

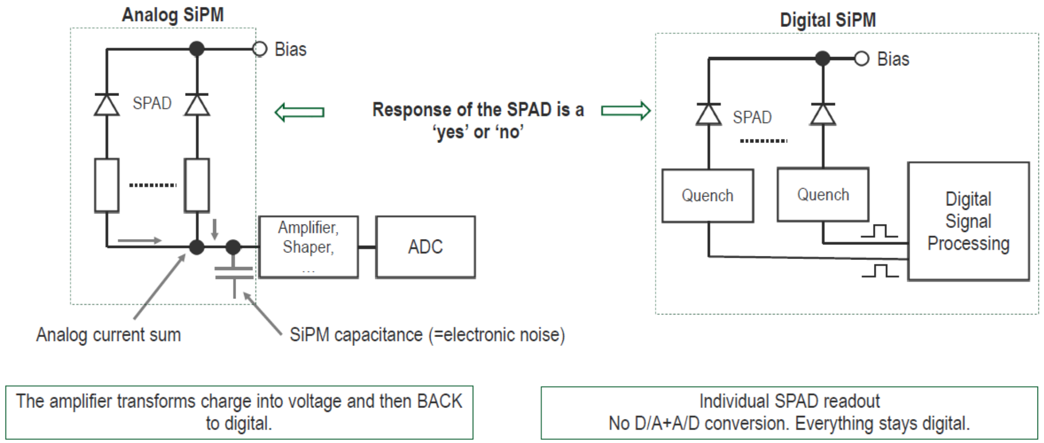
Backup

SiPMs/dSiPMs

SiPMs are based on Single Photon Avalanche Diodes (SPADs)

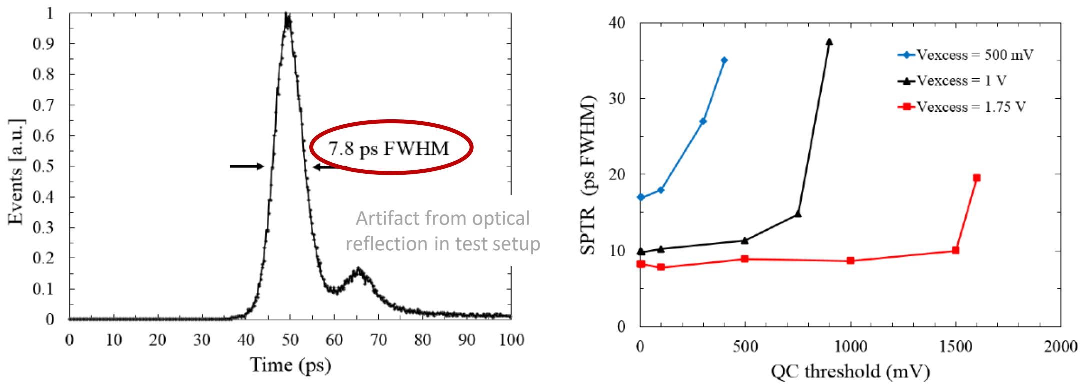


SPAD : Single-Photon Avalanche Diode



From J-F Pratte's presentation at the 2022 IEEE NSS/MIC Conference (Nov 7, 2022, Milan, Italy)

These are inherently digital devices that detect an avalanche discharge in a single pixel with an intrinsically fast time response.



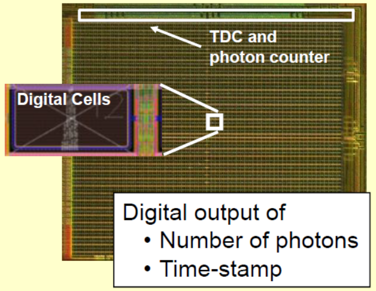
Single Photon Time Resolution of a single 20 µm SPAD and Quenching Circuit (F.Nolet et.al, *Instruments* 2,19 2018)

- Analog SiPMs sum the analog current from each pixel discharge to provide a measure of the number of pixels firing.
- Digital SiPMs simply count the number of pixels firing above some threshold. They can therefore also be integrated with subsequent digital signal processing.

dSiPMs and 3D Integration

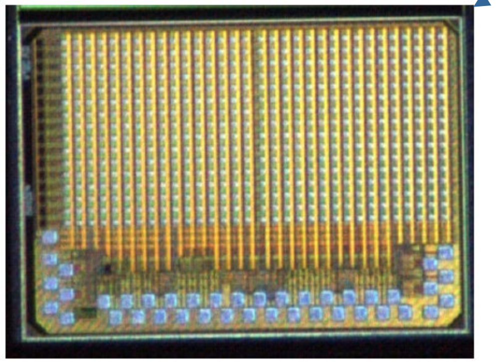
Digital SiPMs were originally introduced by Phillips ~ 2010 with the intention that they would be used for TOF PET. However, they proved to be very costly and were never developed for commercial use.

digital SiPM (dSiPM)



Integrated readout electronics is the key element to superior detector performance

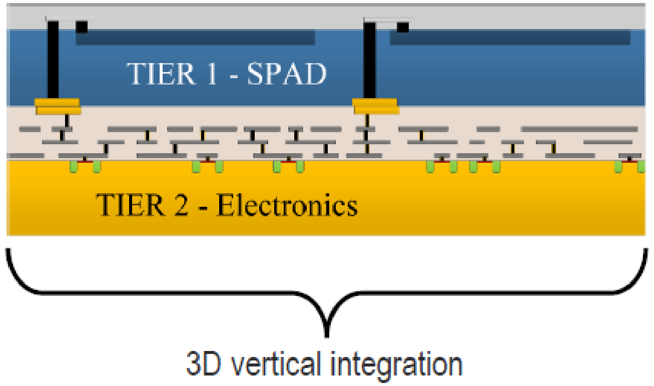
Y. Hamisch, CERN, Feb 2011



N. Nicolet et.al., NIMA, 949 (2020): 162891

Technological advancements over the past 10 years has made the concept of integrating SPAD photosensors with digital processing electronics much more feasible. This would provide significantly superior performance over analog SiPMs with separate readout electronics for both particle physics as well as medical imaging applications.

TSMC 65 nm CMOS
- 16 × 16 pixels in 1.1 × 1.1 mm^2
- Jitter: 18 ps RMS for 256 pixels

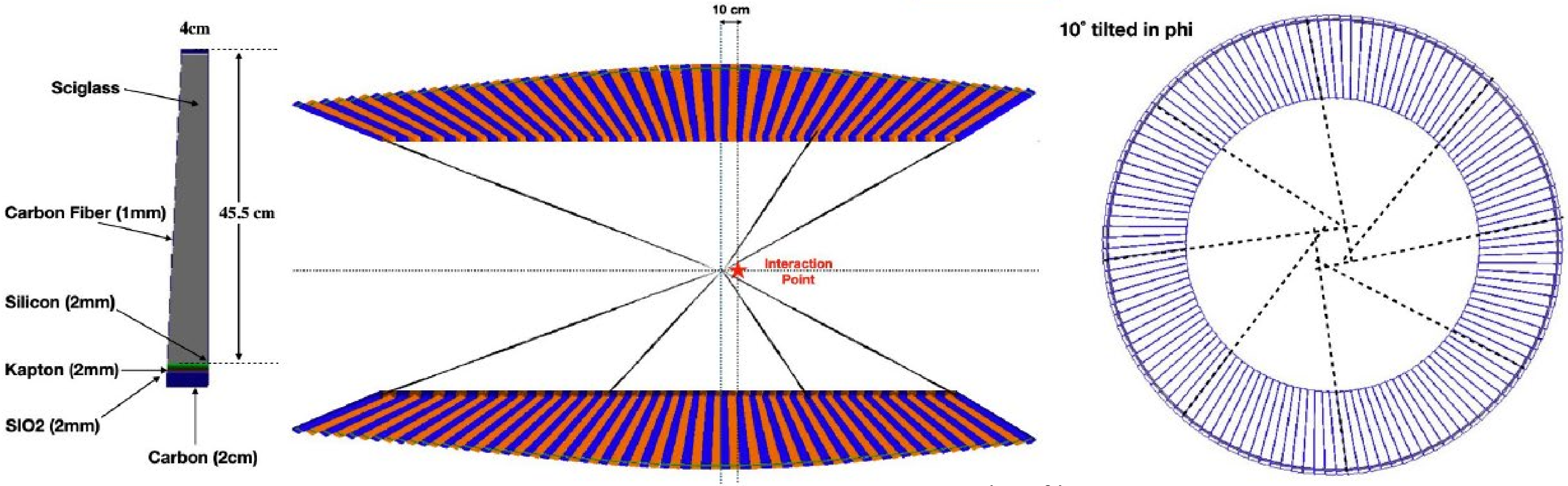


Sherbrooke University
(J-F Pratte's, 2022 IEEE NSS/MIC Conference)

- Improved S/N
  - Small SPAD capacitance
  - Can turn off noisy pixels

    (important for minimizing the effects of radiation damage !)
- Improved PDE (better fill factor)
- Improved timing resolution (reduced timing jitter and overall system timing performance)
  - TOF-PET
  - TOF Particle ID
  - Single photon detection applications (e.g., RICH)
- Fast particle tracking using direct ionization
- Neutrino & Dark Matter experiments (cryogenic operation)
- Neutron imaging

ePIC Scintillating Glass Barrel EMCAL



Carbon fiber support

- Coverage: $(-1.7 < \eta < 1.3)$
- Consists of ~ 8000 blocks of *new* Scintillating Glass (SciGlass)
- 2 x 2 cm^2 inner area, 5 x 5 cm^2 $\rightarrow$ 6 x 6 cm^2 outer, 45.5 cm long (17 X0)
- Projective in η and ϕ (but not pointing to the vertex)
- Read out with SiPMs (3x3 mm^2) (4 or 16 per crystal)
- Expected energy Resolution : $2.5\%/\sqrt{E} \oplus 1.6\%$ (similar to PWO)

Status of Scintillating Glass

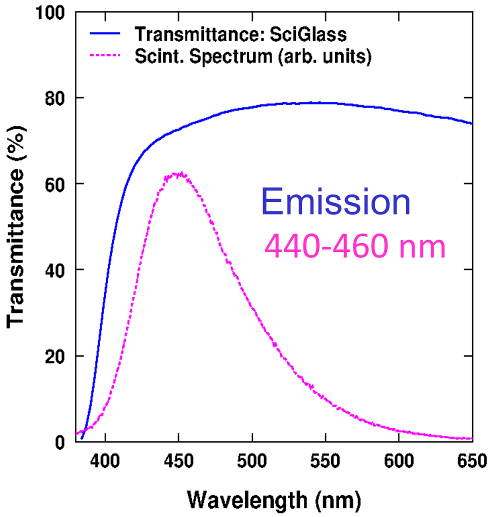
A new type of Scintillating Glass is being developed at Catholic University and the Vitreous State Laboratory

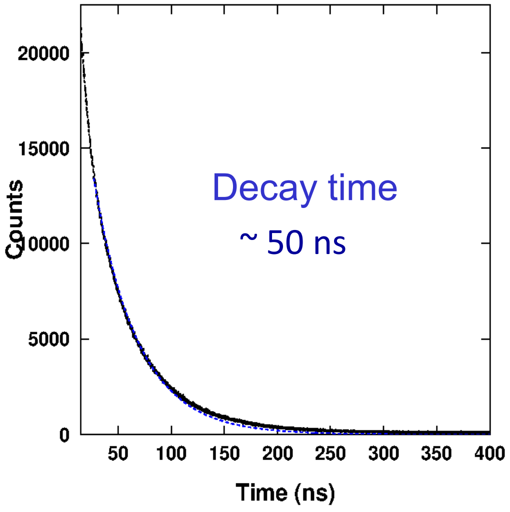
Info provided by T. Horn CUA/JLAB

Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
$(BaO*2SiO_2)$:Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
$(BaO*2SiO_2)$:Ce glass loaded with Gd	4.7-5.4 **4.22**	2.2 **2.8**	**4.5**	~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

GEANT 4

Also: $(BaO*2SiO_2)$:Ce shows no temperature dependence

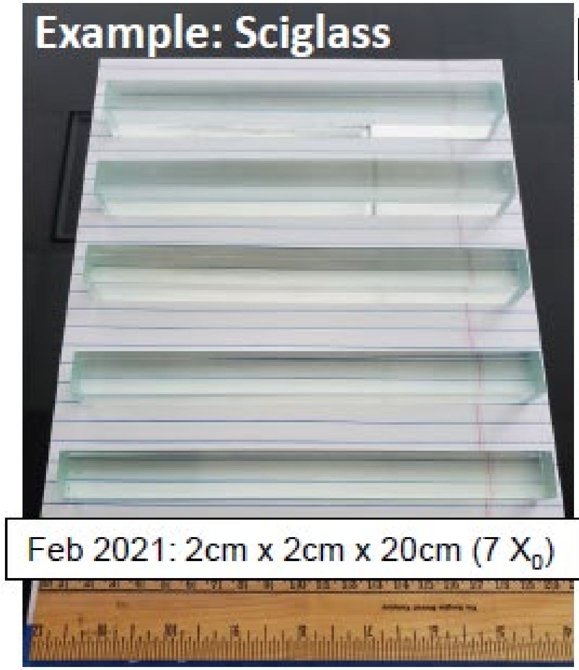




- Light Yield comparable to PWO (> 100 γ/MeV)
- Lower density than PWO ⇒ longer blocks (17 X0 > 45 cm)

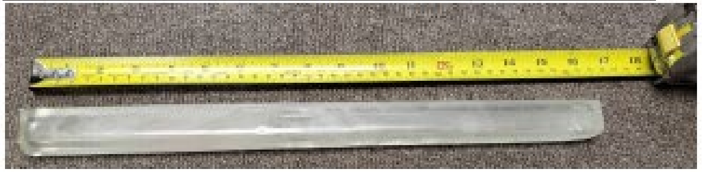
Scaling up to Produce 45 cm Blocks for EIC

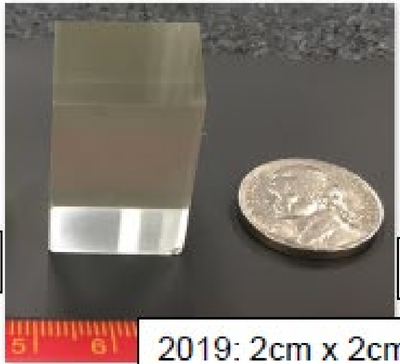
A Joint Collaboration was formed between Catholic University/Vitreous State Laboratory and a new startup company SCINTILEX



Feb 2021: 2cm x 2cm x 20cm (7 X_0)

Dec 2021: 2cm x 2cm x 40cm





2019: 2cm x 2cm x 4cm

2018: 1cm x 1cm x 1cm

Spring 2023: SciGlass 40cm can now be produced routinely

Summer 2022: 2cm x 2cm x 40cm first detector prototypes