IOWA Caltech University of Virginia University of Notre Dame

Coe College 1851 İstanbul Üniversitesi 1453 İstanbul Teknik Üniversitesi 1773 Yıldız Teknik Üniversitesi 1911 Hofstra University

RADiCAL

a Radiation Hard Innovative EM Calorimeter

JAMES WETZEL

On behalf of the RADiCAL Collaboration

Study of time and energy resolution of an ultracompact sampling calorimeter (RADiCAL) module at EM shower maximum over the energy range 25 ≤ E ≤ 150 GeV.

JAMES WETZEL

On behalf of the RADiCAL Collaboration

RADiCAL Collaboration

COE COLLEGE — U. Akgun and J. Wetzel (also IOWA)

IOWA — D. Blend, P. Debbins, M. Herrmann, G. Karaman, O. Koseyan, A. Mestvirishvili, Y. Onel, A. Penzo

HOFSTRA UNIVERSITY — C. Pérez Lara (also Virginia)

Caltech — C. Hu, L. Zhang and R-Y. Zhu

UNIVERSITY of VIRGINIA — T. Anderson, N. Chigapurupati, B. Cox, M. Dubnowski, R. Hirosky, A. Ledovskoy and C. Perez Lara

UNIVERSITY OF NOTRE DAME — T. Barbera, C. Jessop, K. Ford, A. Heering, C. Jessop, Yu. Musienko, D. Ruggiero, R. Ruchti, D. Smith, M. Vigneault, Y. Wan and M. Wayne

B. Duran, B. Kayak, S. Hatipoglu, I. Hos, S. Ozkorucuklu, O. Potok, A. Tosun, C. Zorbilmez

S. Cerci

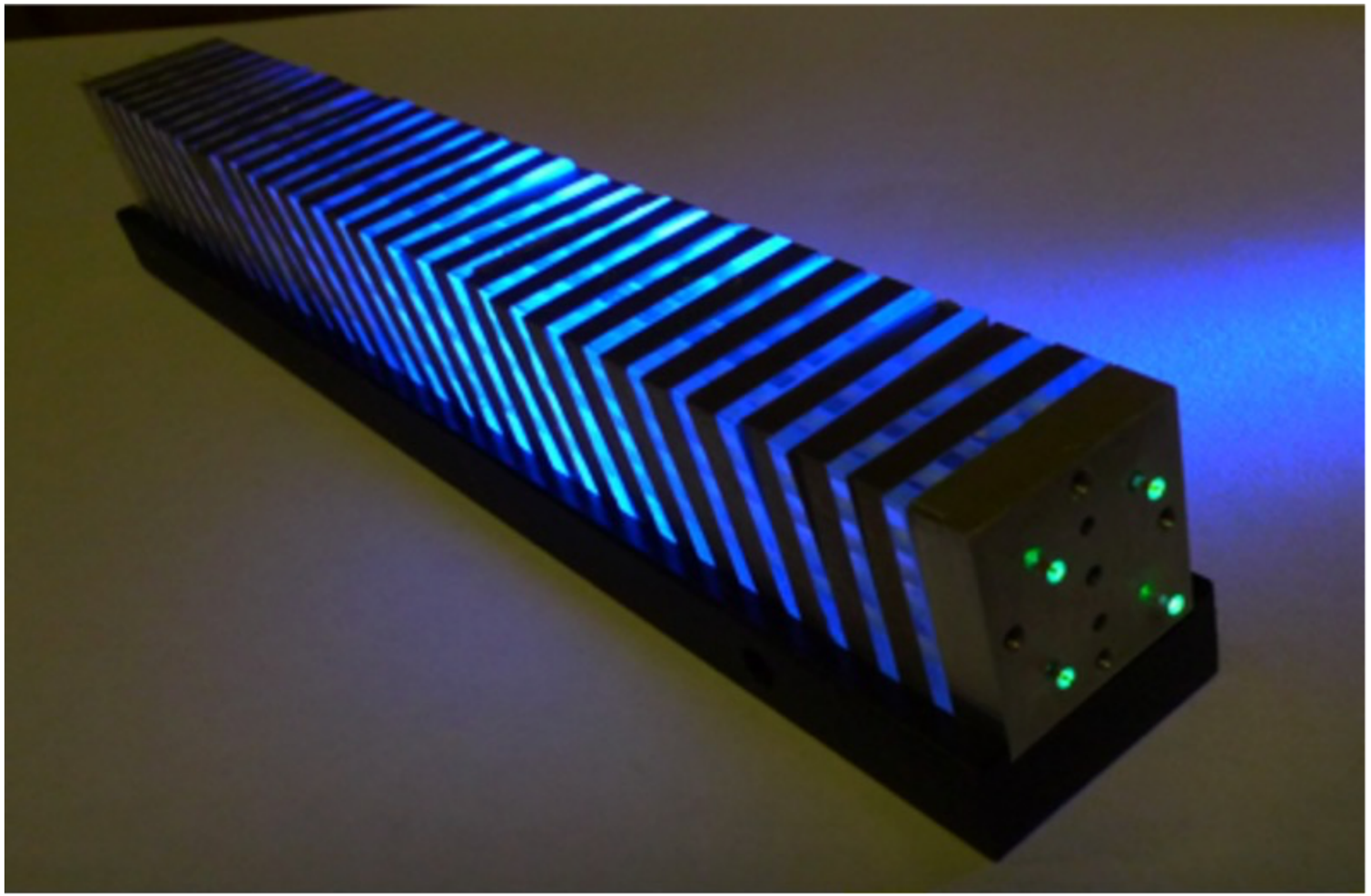
D. S. Cerci (also Adiyaman), B. Isildak, R. Kurt, A. K. Uysal, T. Yetkin

K. Cankocak, K. Dincer

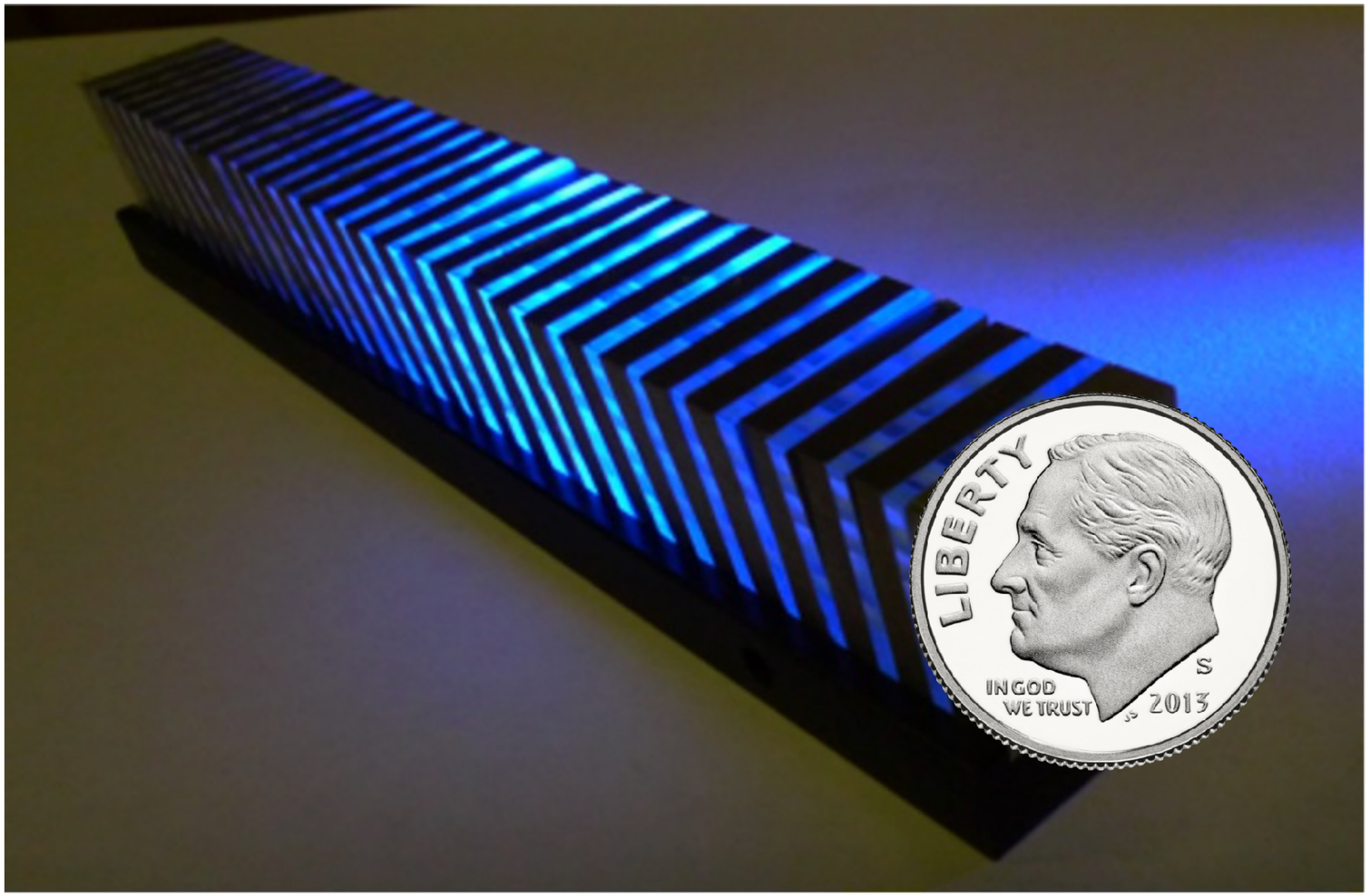
Outline

- Give an overview of the RADiCAL concept
- Briefly discuss previous results
- Present the latest results from Fermilab and CERN beam tests probing precision timing

A RADiCAL Module



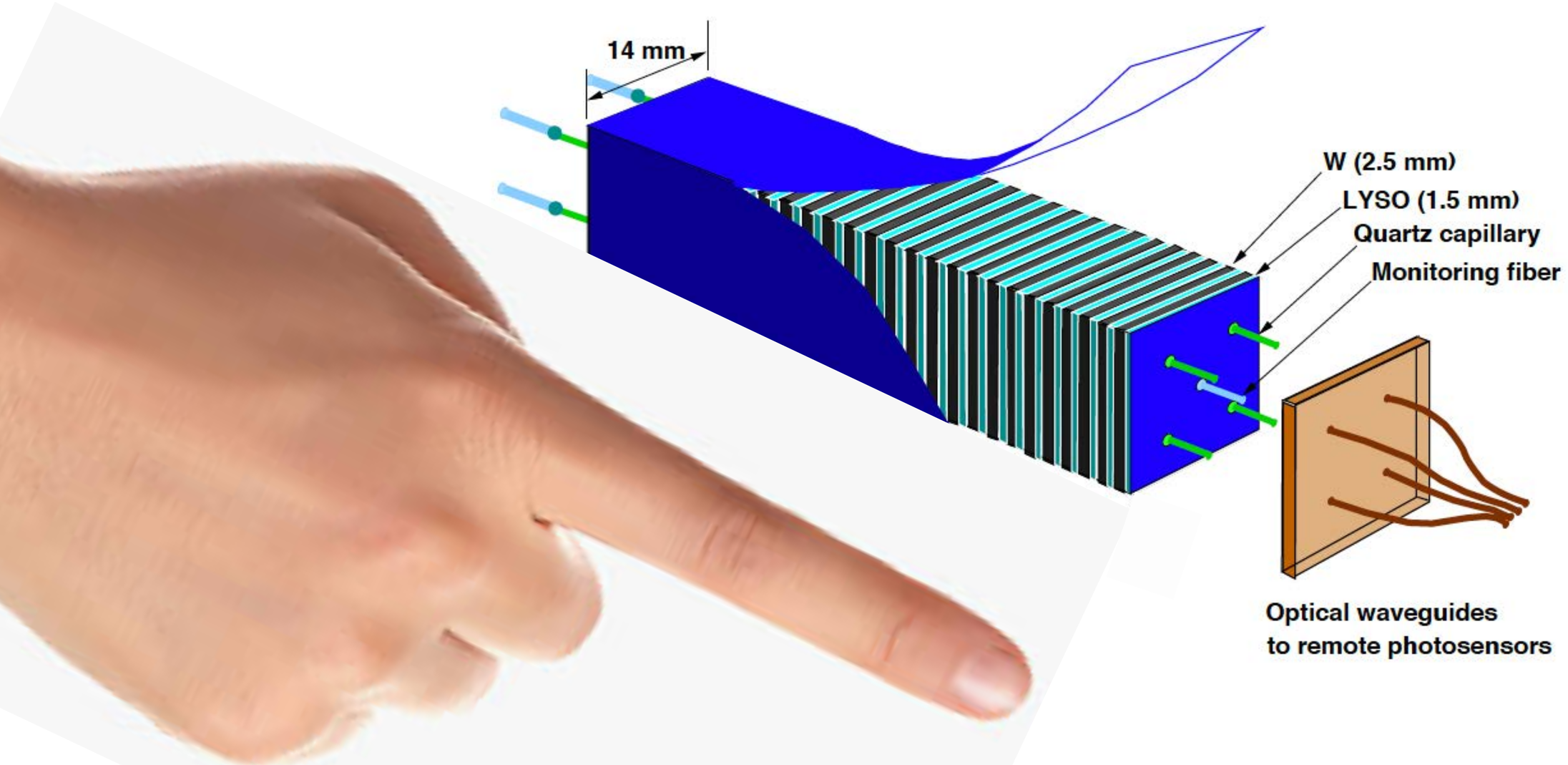
A RADiCAL Module



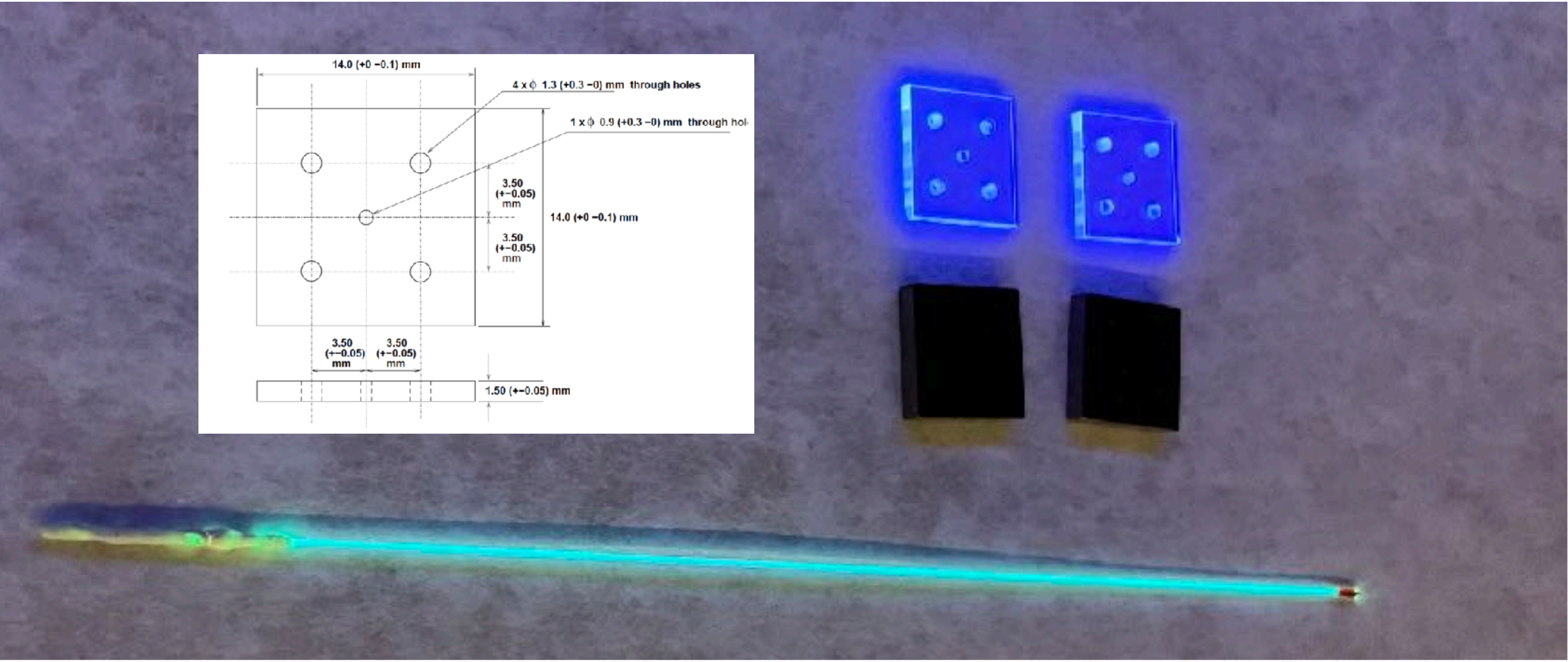
Motivation for RADiCAL

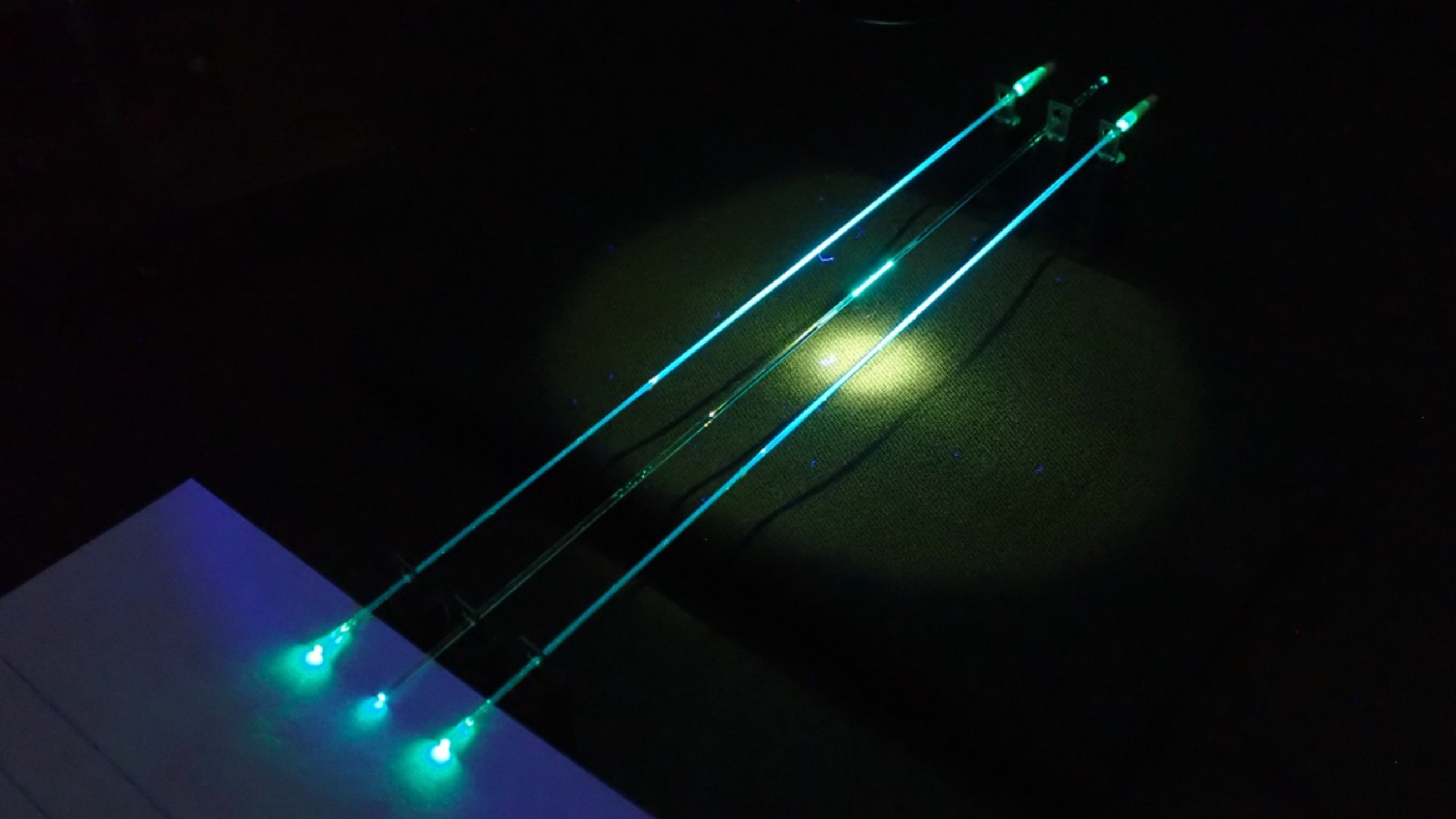
- Our goal is to develop a detector module that can:
  - Survive the unprecedented luminosity provided at a future circular collider, like the FCC-ee/hh proposed at CERN.
  - Build a compact detector which can contain EM showers, and
    1. Acquire light at shower max with a WLS infused capillary for precision timing of the event.
    2. Acquire light across the length of the module for measuring the total energy of the event.
    3. Precision shower position localization on the order of millimeters at shower max.

Overview of a RADiCAL Module



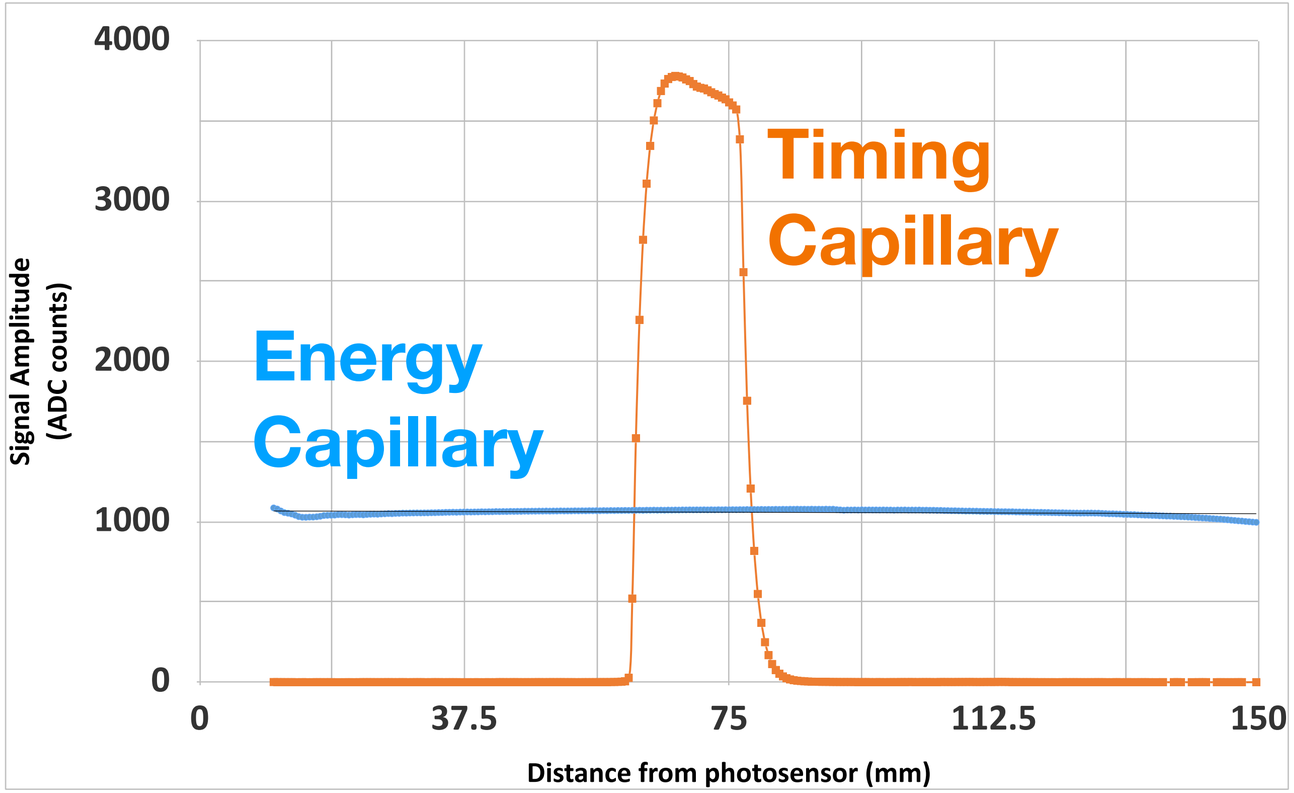
Overview of a RADiCAL Module

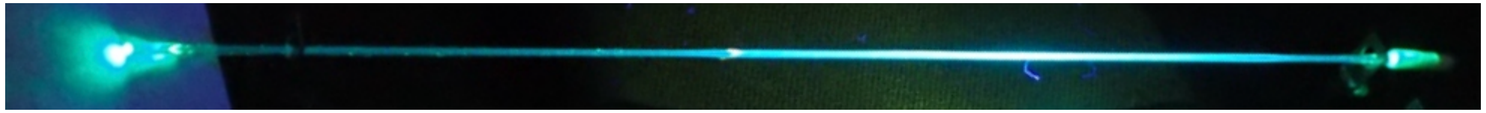




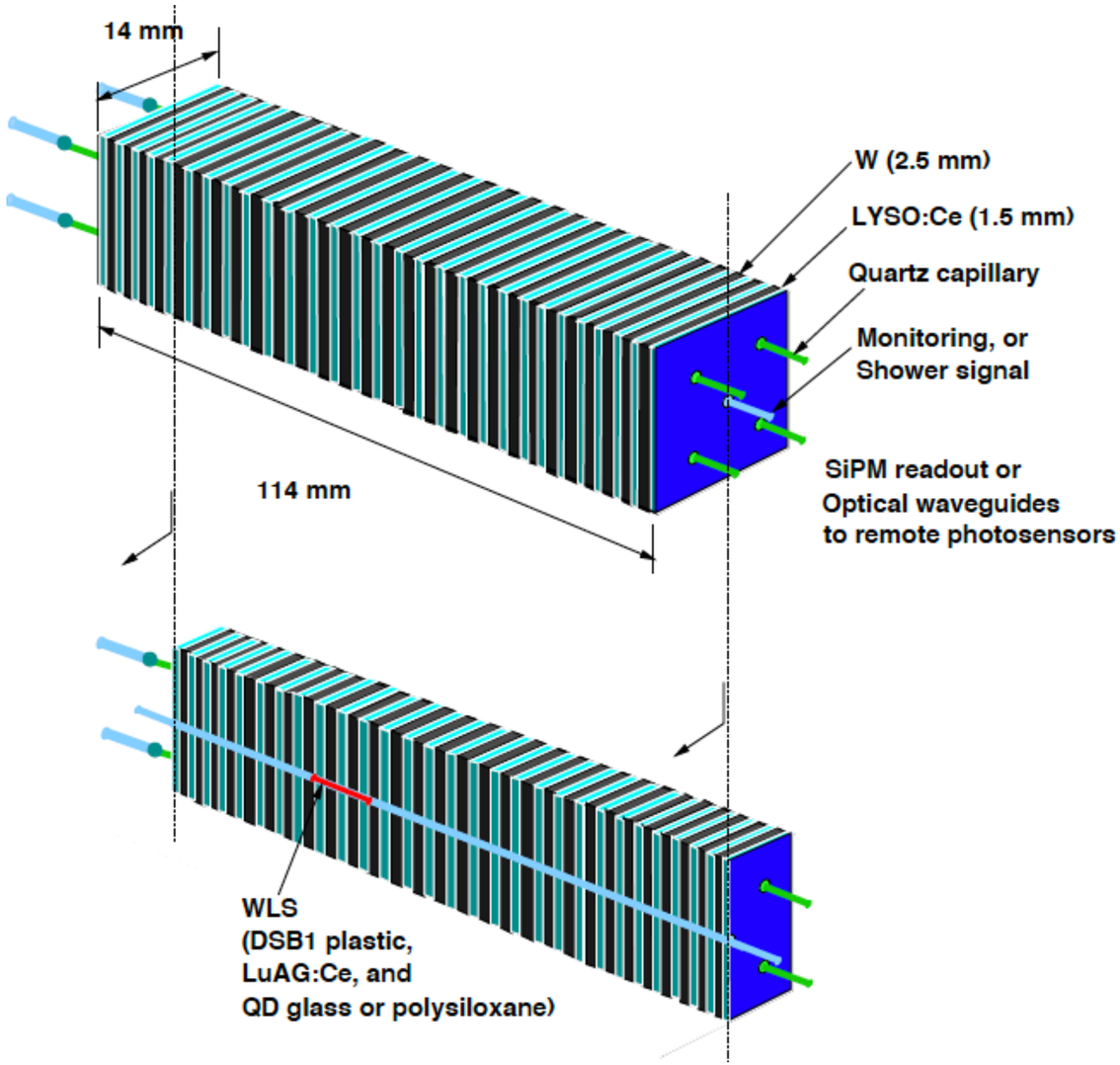
Preparing the Capillaries

K. Ford
Radiation Laboratory Glassblowing Shop
University of Notre Dame Core Facility, Radiation Laboratory, Notre Dame IN 46556





Overview of a RADiCAL Module



Fast and Ultrafast Inorganic Scintillators

	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	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	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 <0.6	600 <0.6	<1	1.5	4	148 6	40	820 50	191 25	800 80	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

Scintillator and Wavelength Shifters

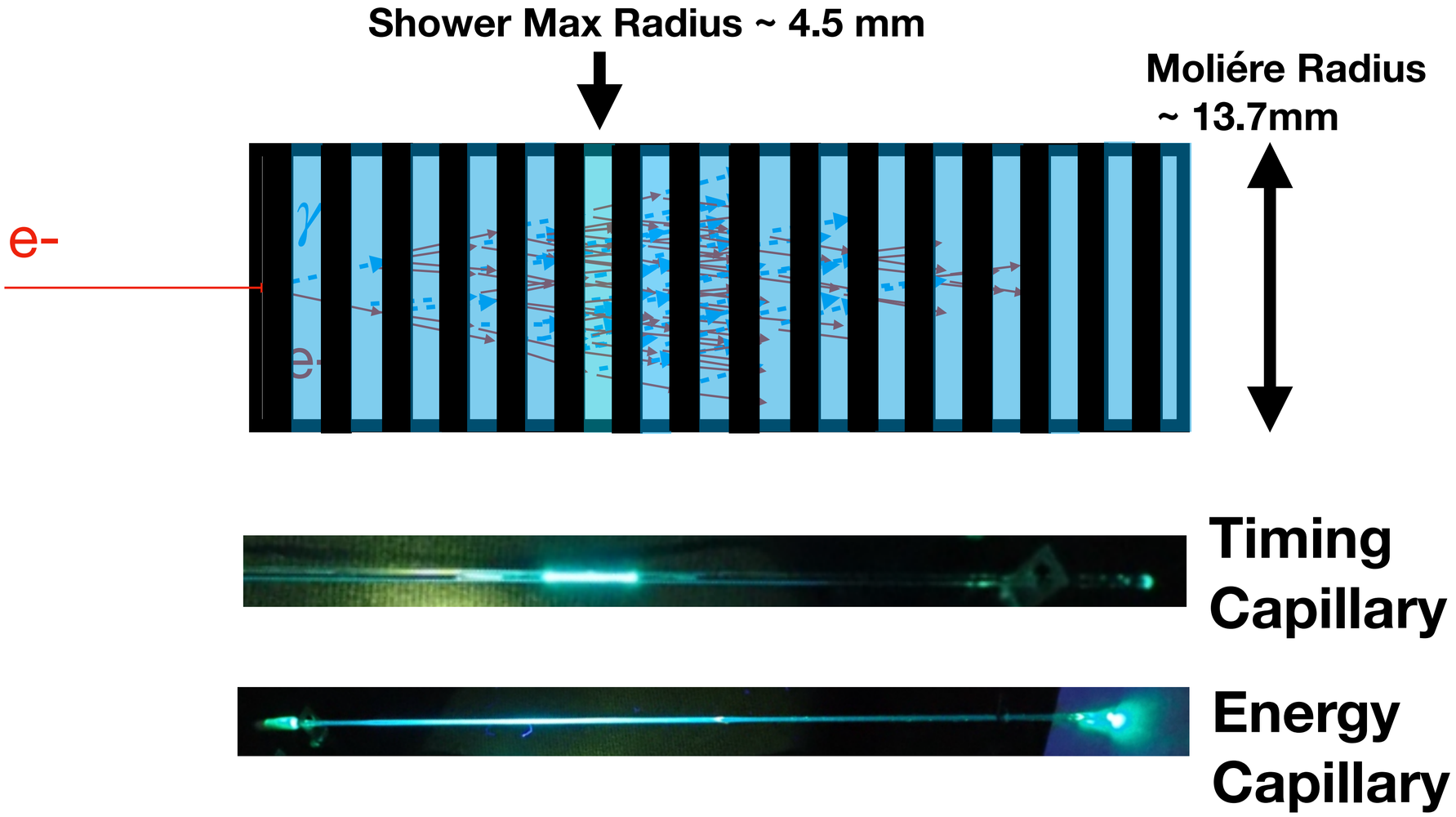
Optimizing timing, position and energy

Caltech, Coe College, Hofstra U., U Iowa, Istanbul U., Istanbul-Cerrahpasa U., U. Notre Dame, U. Virginia, Yildiz Technical U.

Some examples for study through a variety of methods including RADiCAL modular structure and other methods

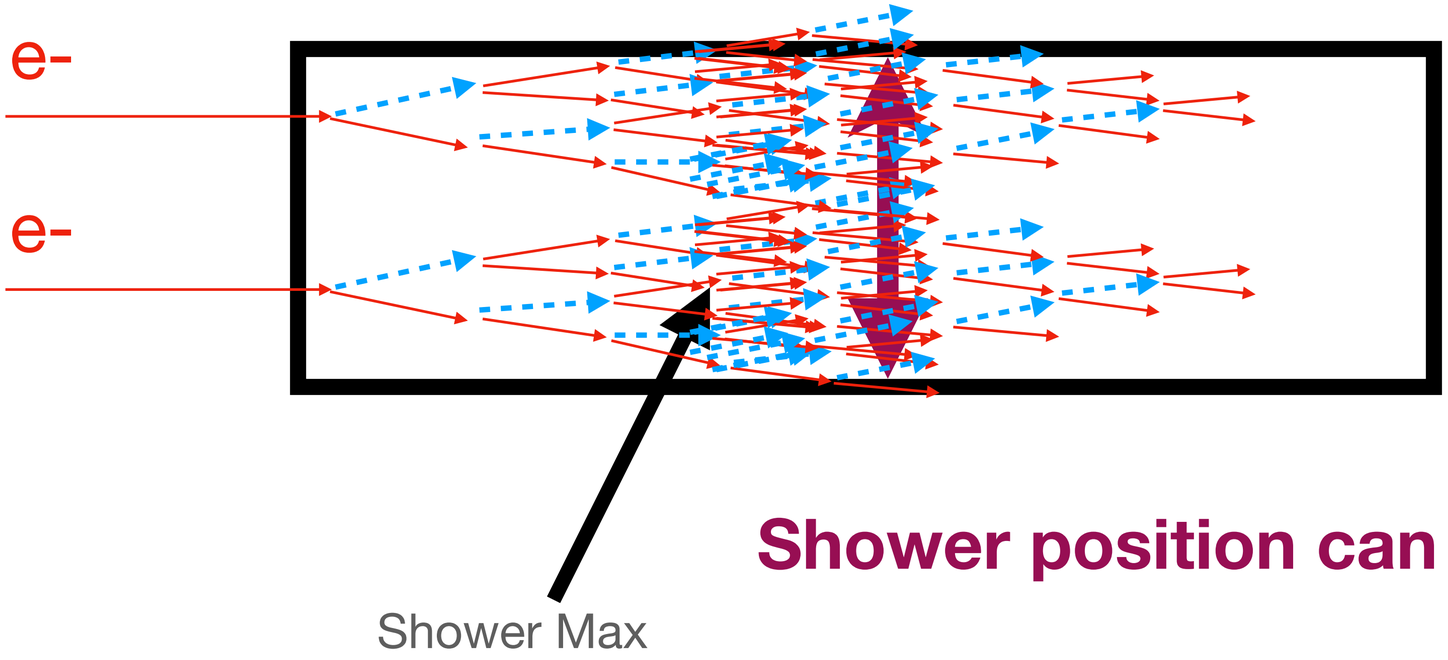
Example Scintillator Material	Candidate Matched Wavelength Shifter
LYSO:Ce (420nm) inorganic crystal	DSB1 (495nm) organic filament
LYSO:Ce (420nm) inorganic crystal	LuAG:Ce (510nm) ceramic filament
LuAG: Ce (510 nm) crystal, ceramic	Quantum Dots (580nm) glass or ceramic
LuAG:Pr (310 nm) crystal, ceramic	pTP (350nm) organic filament
CeF_3 (330nm) crystal	pTP (350nm) organic filament
CeF_3 (330nm) crystal	Flavonols (530-560nm) organic filament
Lu_2O_3:Yb (370nm) ceramic	Flavonols (530-560nm) organic filament
BaF_2:Y (220nm, fast component) crystal	TBD

RADiCAL Calorimetry in a Nutshell



Calorimetry in a Nutshell

But at shower max, shower cross section is ~Radiation Length (4.5mm)

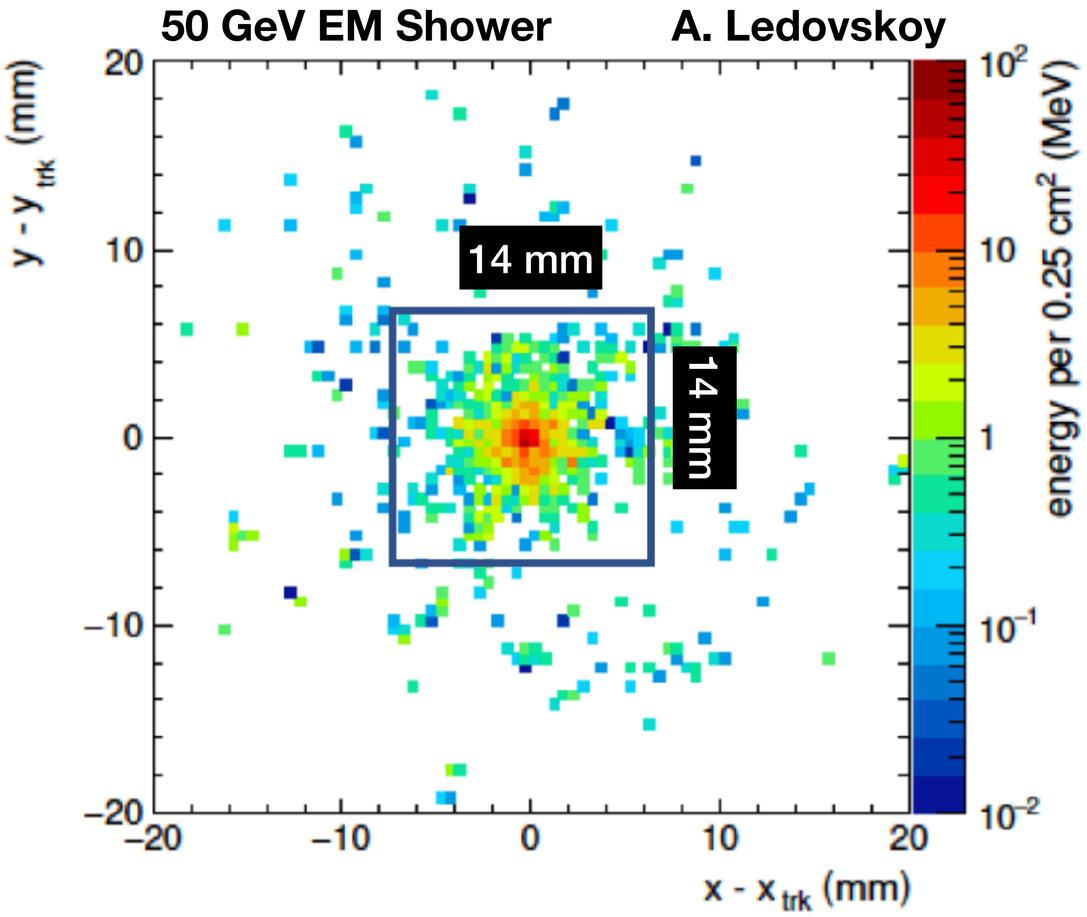


Shower position can be determined

Motivation for RADiCAL

GEANT4 Simulations predict Molière radius of 13.7 mm

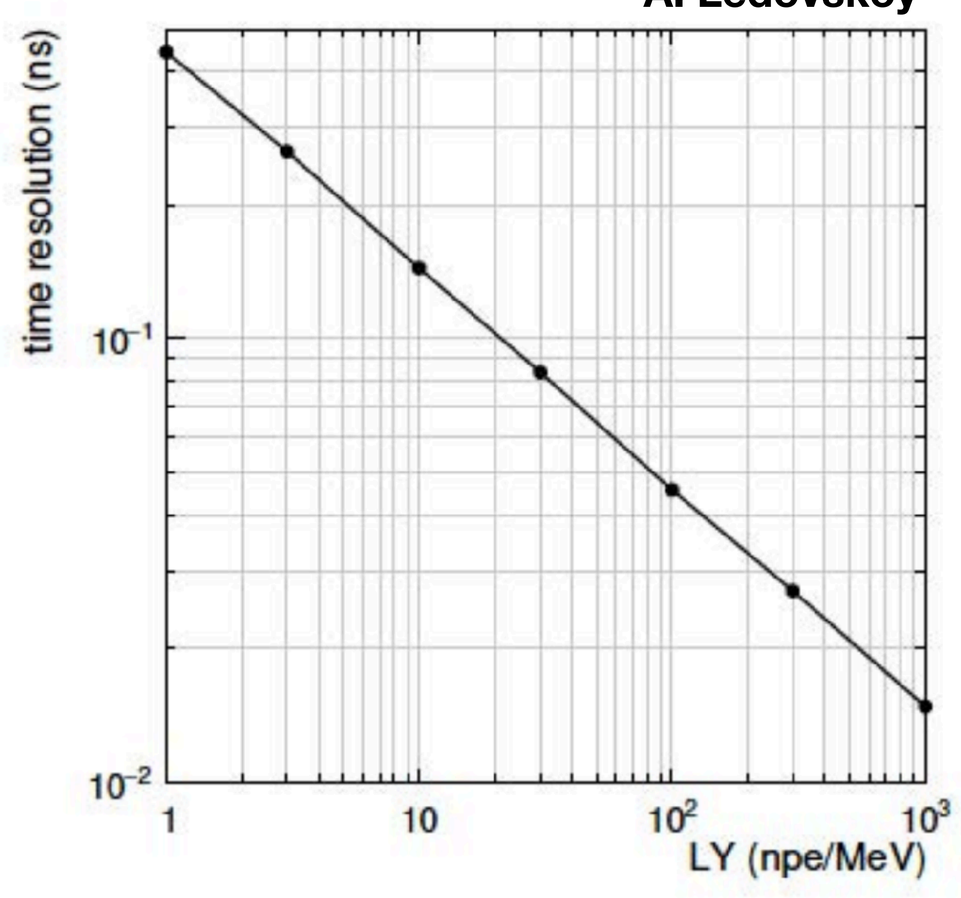
By contrast: at shower max radius is 4.5 mm



Motivation for RADiCAL

GEANT4 Simulations predict time resolution of ~10 ps

A. Ledovskoy



Motivation for RADiCAL

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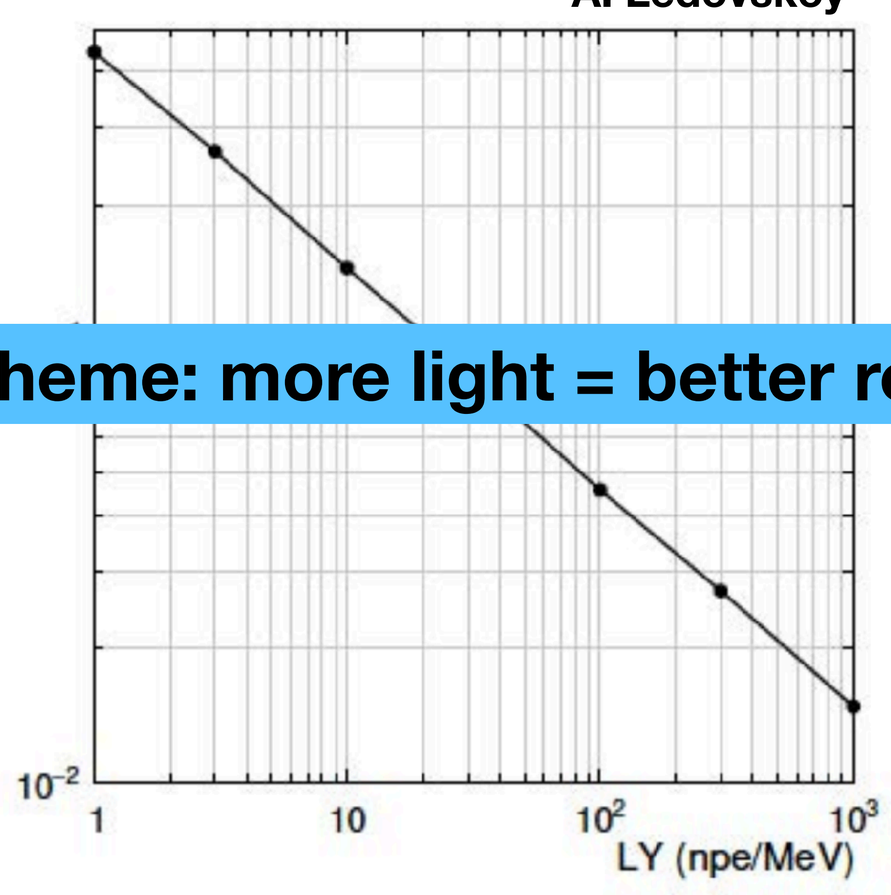


A common theme: more light = better resolution

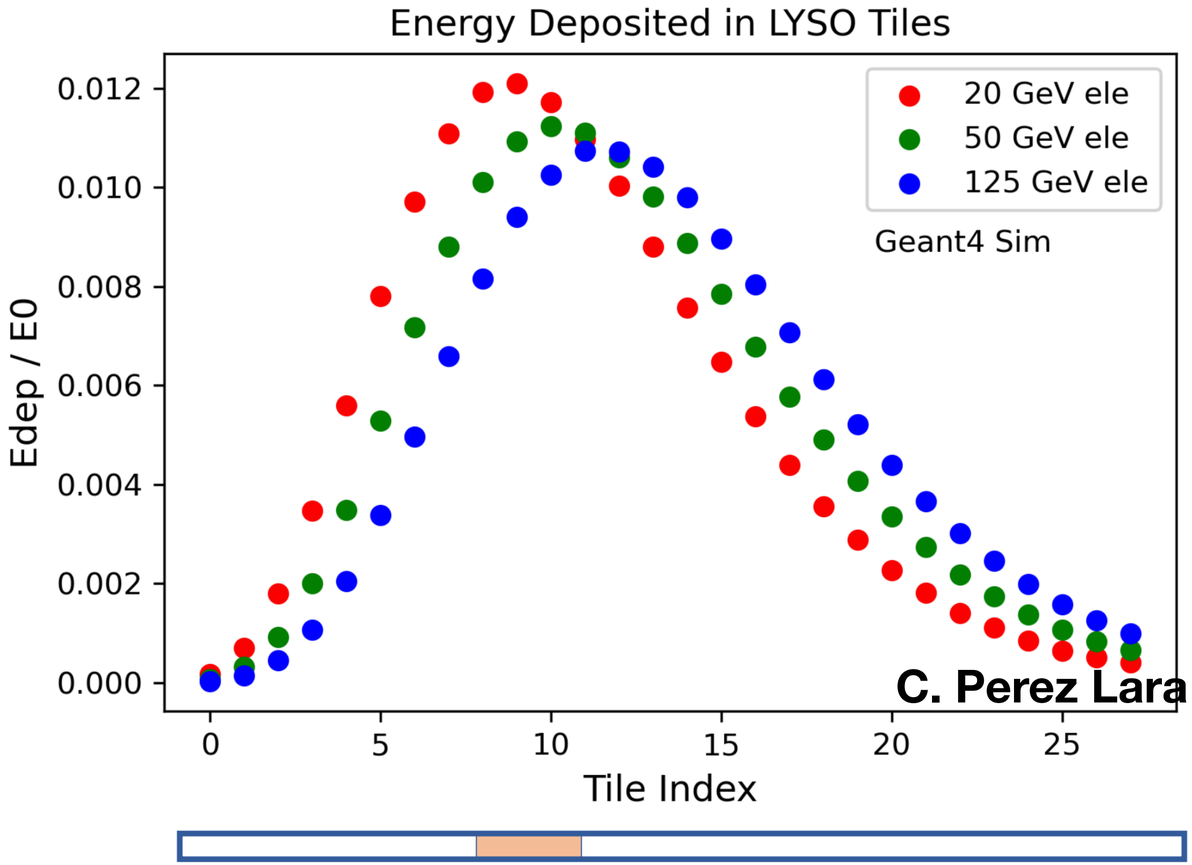
Depth of shower max is slightly energy dependent

Geometry used:
- Number of Layers: 28
  - Absorber Thickness: 2.5 mm
  - Detector Thickness: 1.5 mm

Materials used:
- Tungsten: "G4_W"
- LYSO:
  - Prelude: 99.81%
    - NISTManager::Lu 71%
    - NISTManager::Si 7%
    - NISTManager::O 18%
    - NISTManager::Y 4%
  - NISTManager::Ce 0.19%

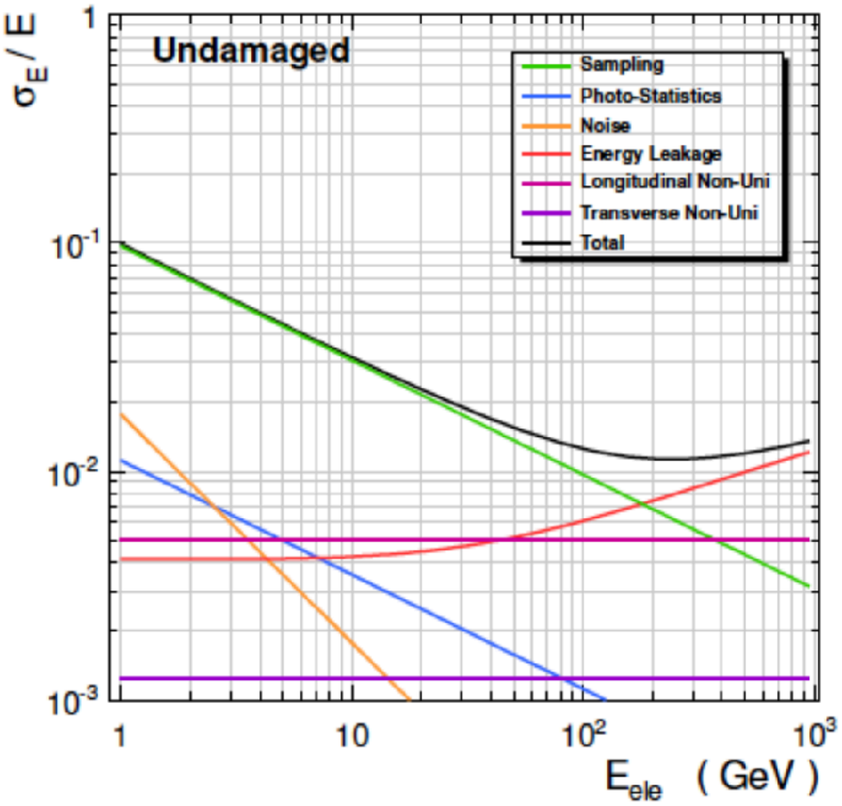
Physics Process List:
- FTFP_BERT

Tracking:
- Total Edep in Detector Layers



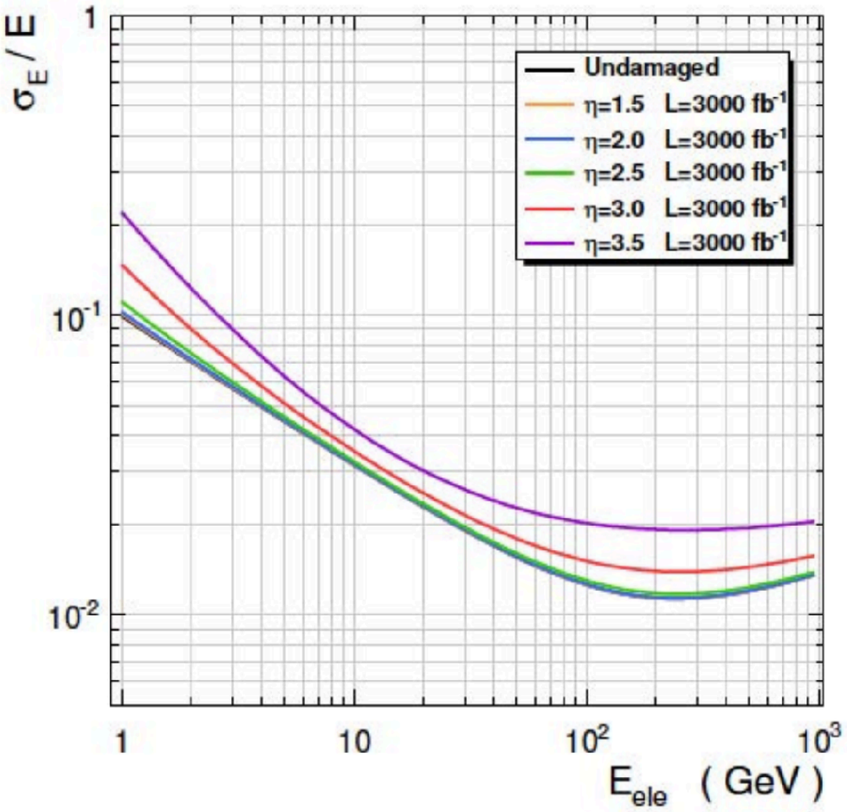
Motivation for RADiCAL

GEANT4 Simulations predict energy resolution



10%/√E experimental target

CERN H4 Beam Test measured resolution vs radiation (FCC-hh)



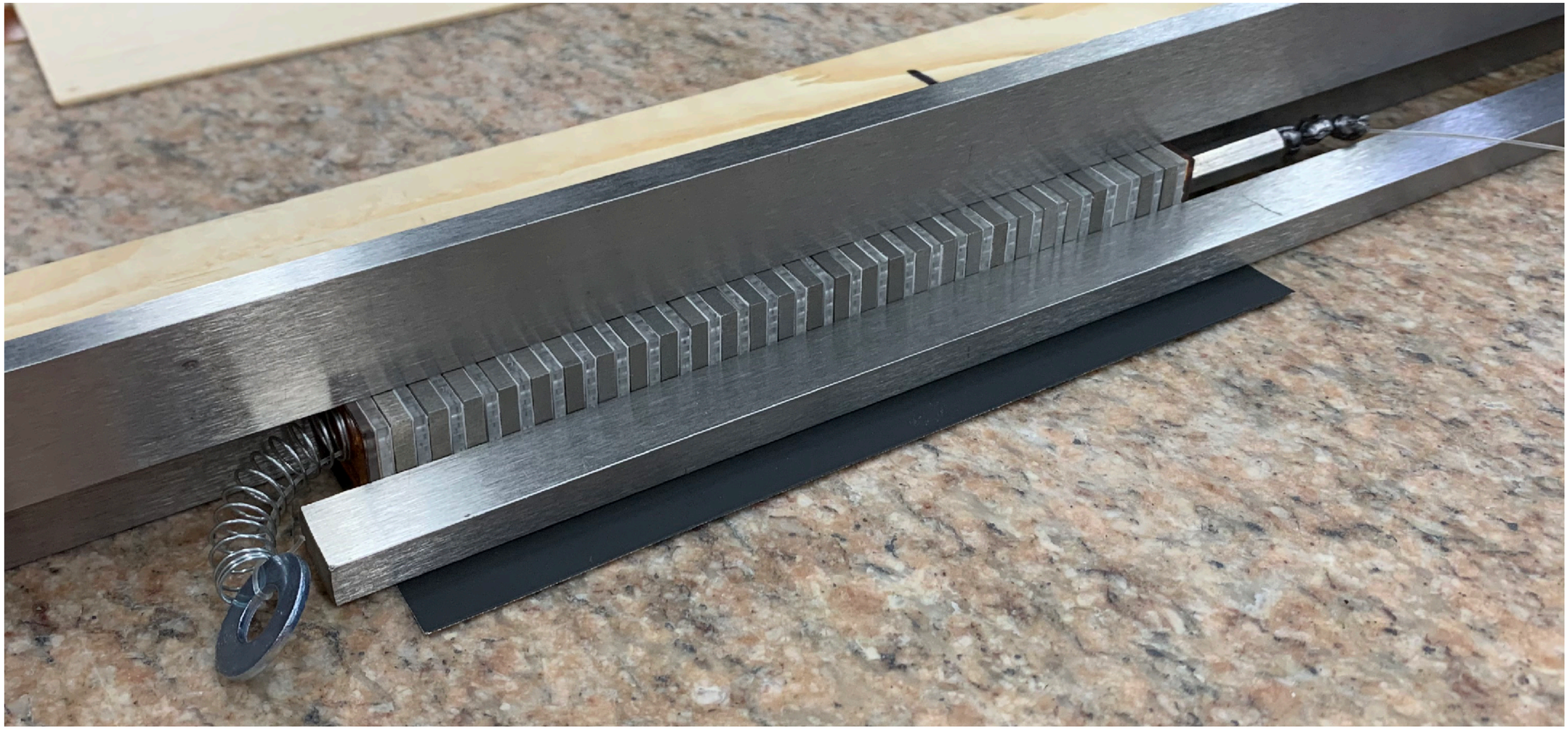
EXPERIMENTS

At Fermilab and at CERN

- Fermilab -
  - Limited to 28 GeV mixed beam e- and pions
  - Capillary was designed and placed at shower max for a 28 GeV Beam
- CERN -
  - 25 - 150 GeV pure electron beam available, can better investigate timing resolution

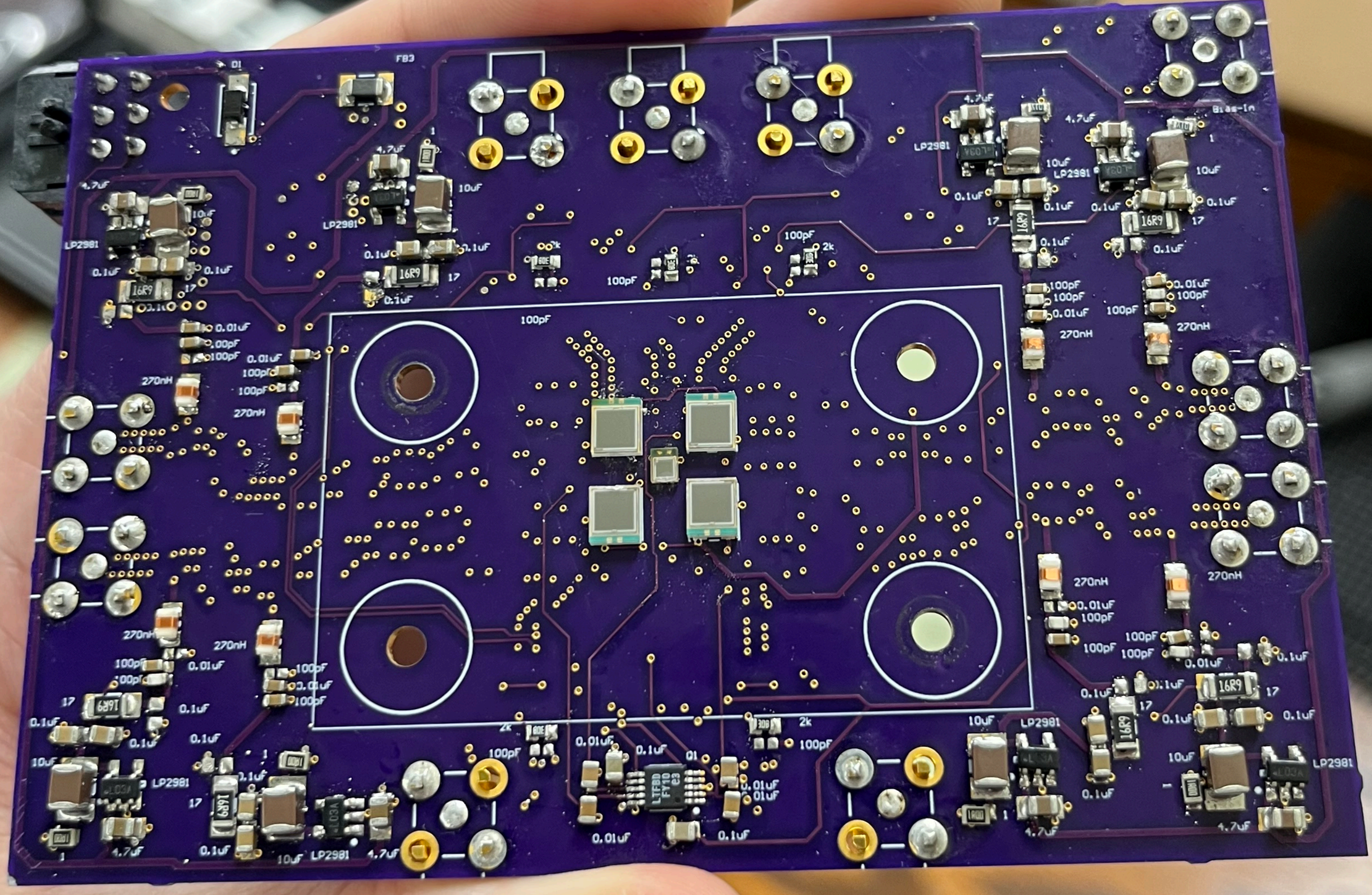
Assembling the Module

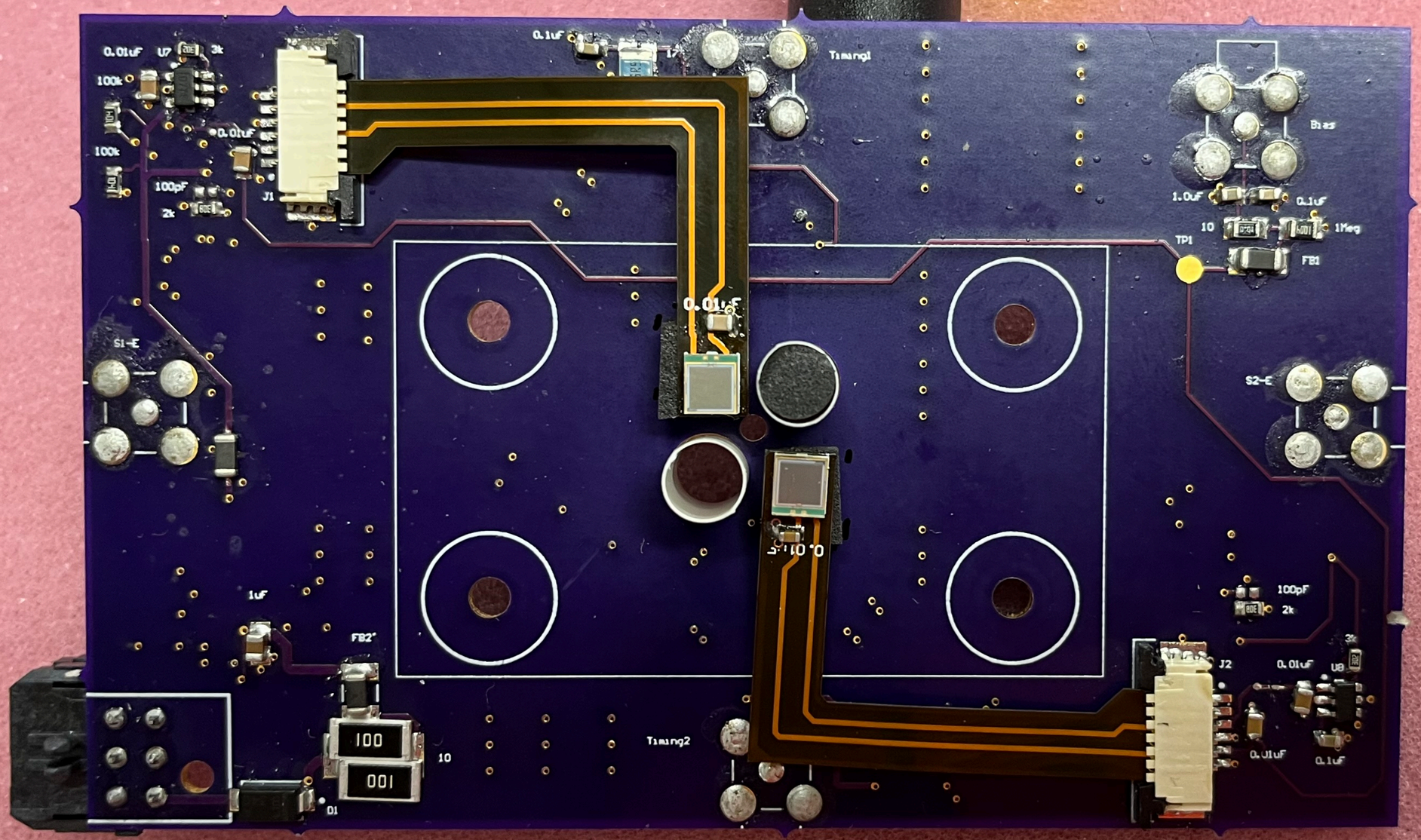
P. Debbins (IOWA)



Assembling the Module

Mechanics: P. Debbins (IOWA) Electronics: T. Anderson (Virginia)


D1
FB3
4.7uF
10uF
LP2981
0.1uF
16R9
17
100pF
2k
0.01uF
270nH
Bias-In
LTFBD
FY1D
e3
Q1

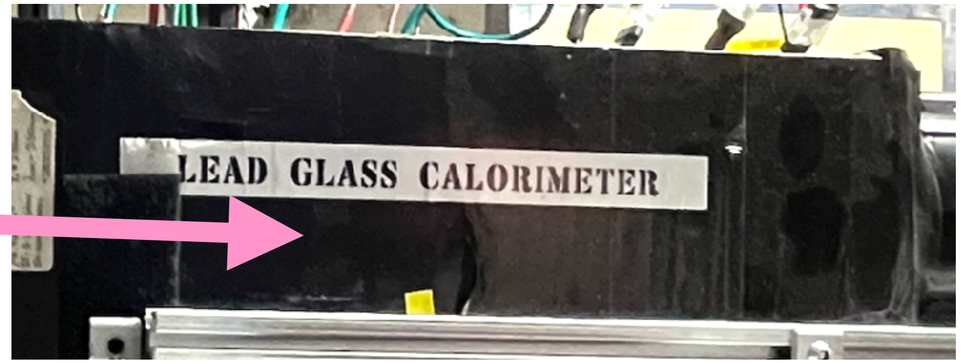

0.01uF
U7
3k
100k
100k
0.01uF
100pF
2k
J1
0.1uF
Timing1
Bias
1.0uF
0.1uF
10
1Meg
TP1
FB1
0.01uF
S1-E
S2-E
0.01uF
1uF
FB2
100
001
10
Timing2
D1
100pF
2k
J2
0.01uF
U8
3k
0.01uF
0.1uF

RADiCAL at Fermilab

MCP

RADiCAL

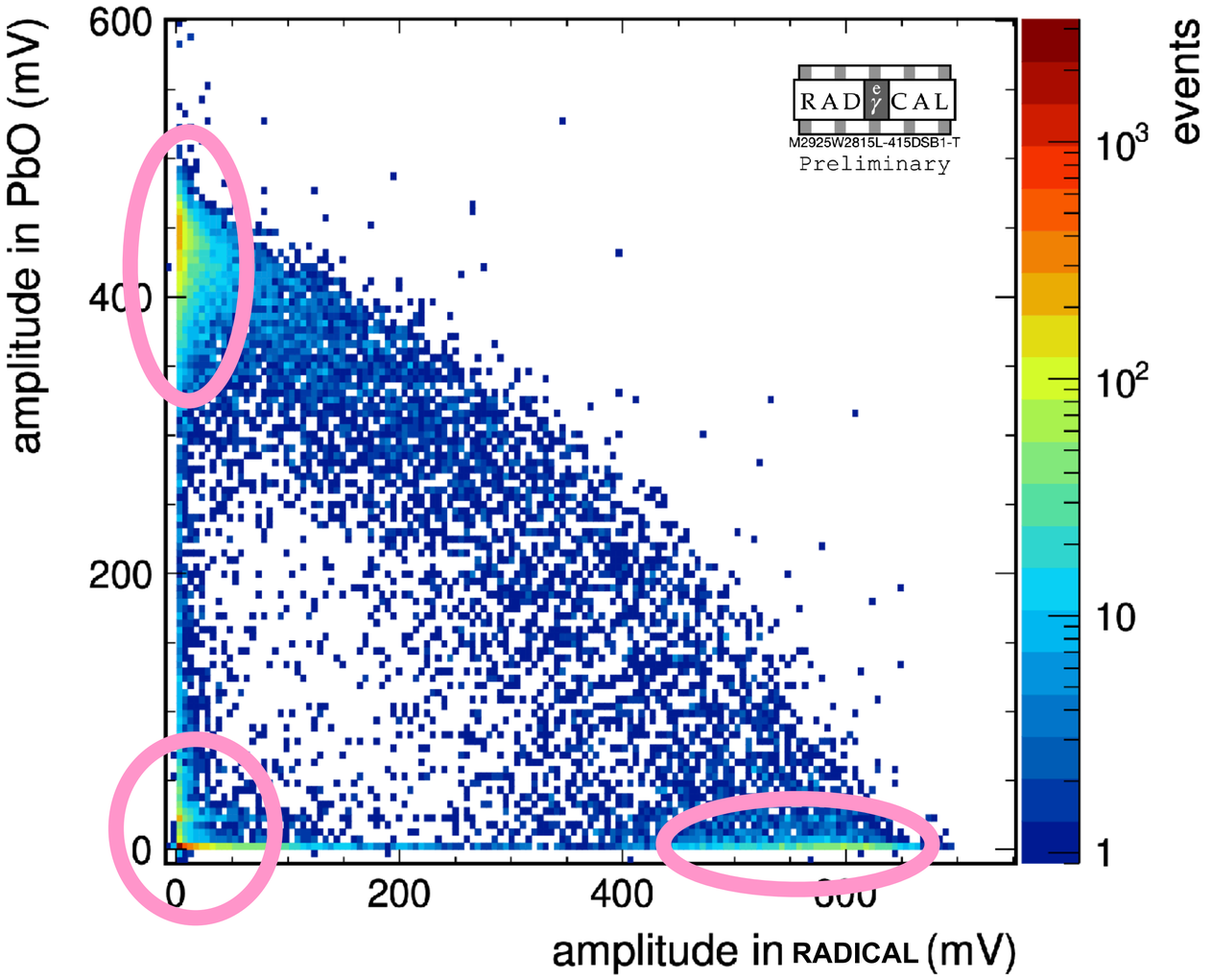
Pb Glass



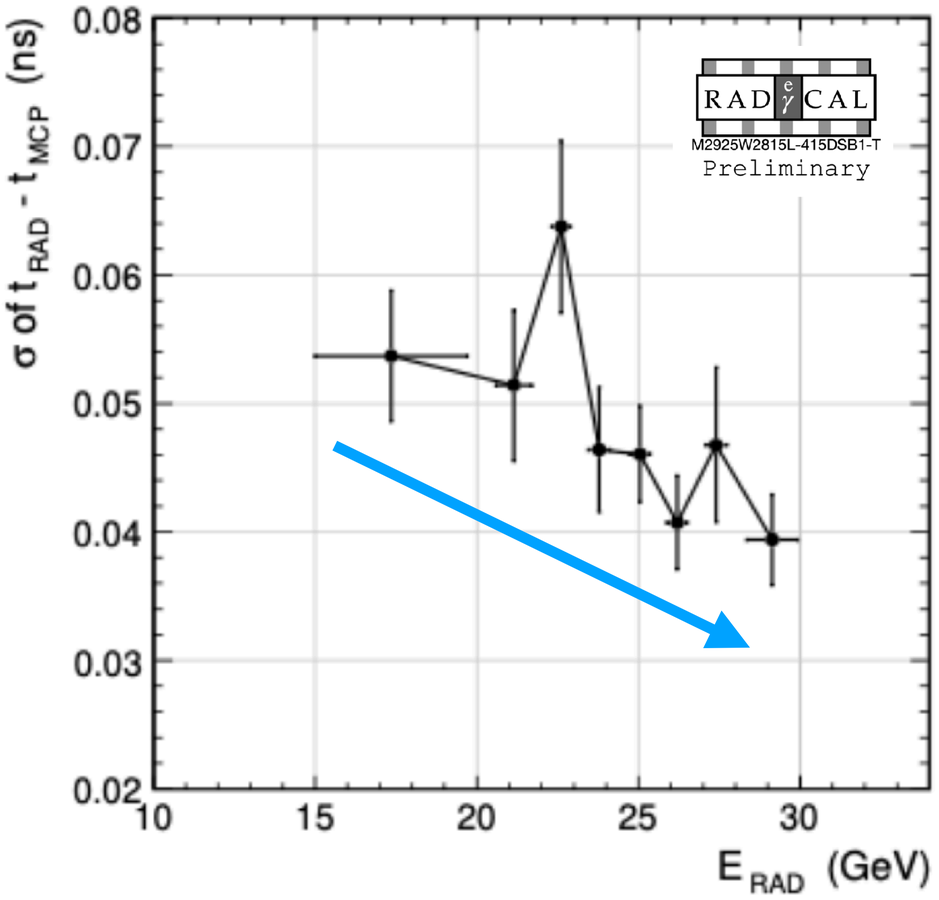
28 GeV e- MIXED beam, we need Pb glass to separate particles


WARNING
Class 3B Laser
Controlled Area
FRIDGE
I got my COVID – 19 Vaccine
I got my COVID – 19 Vac

RADiCAL at Fermilab 28 GeV

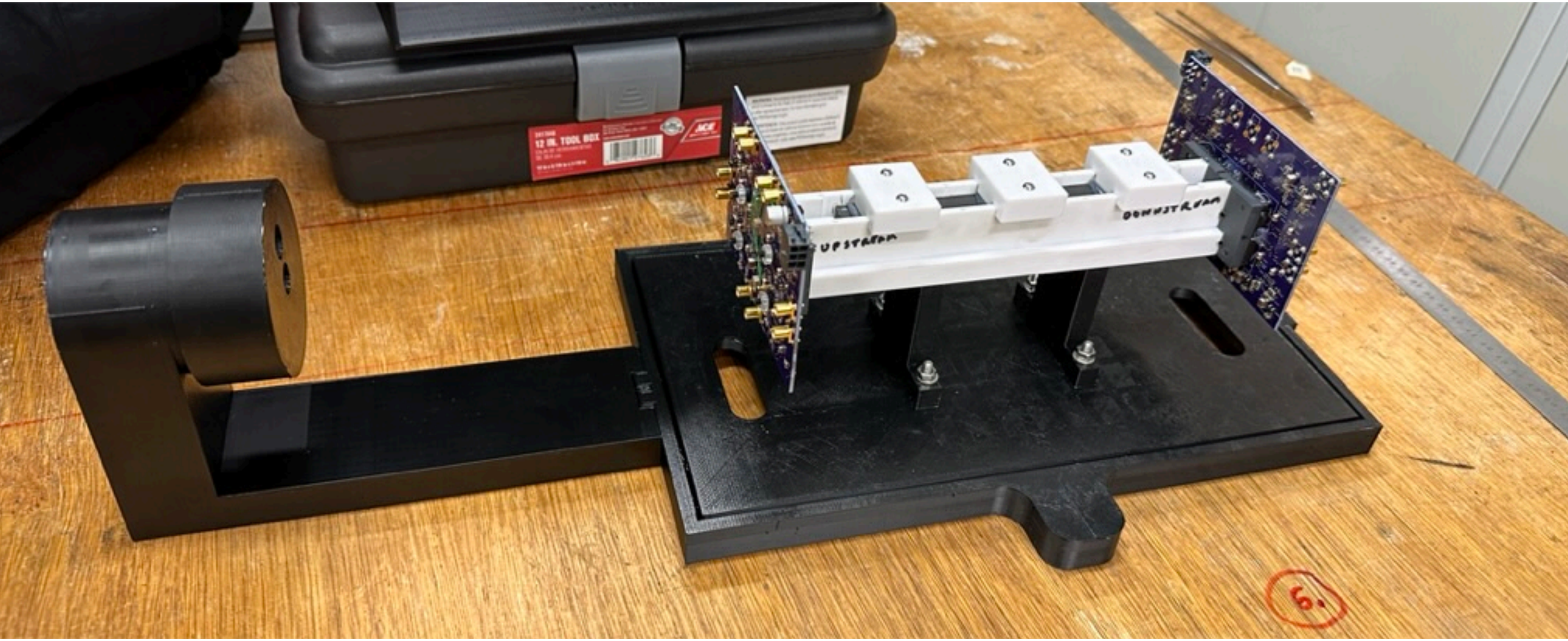


RADiCAL at Fermilab 28 GeV

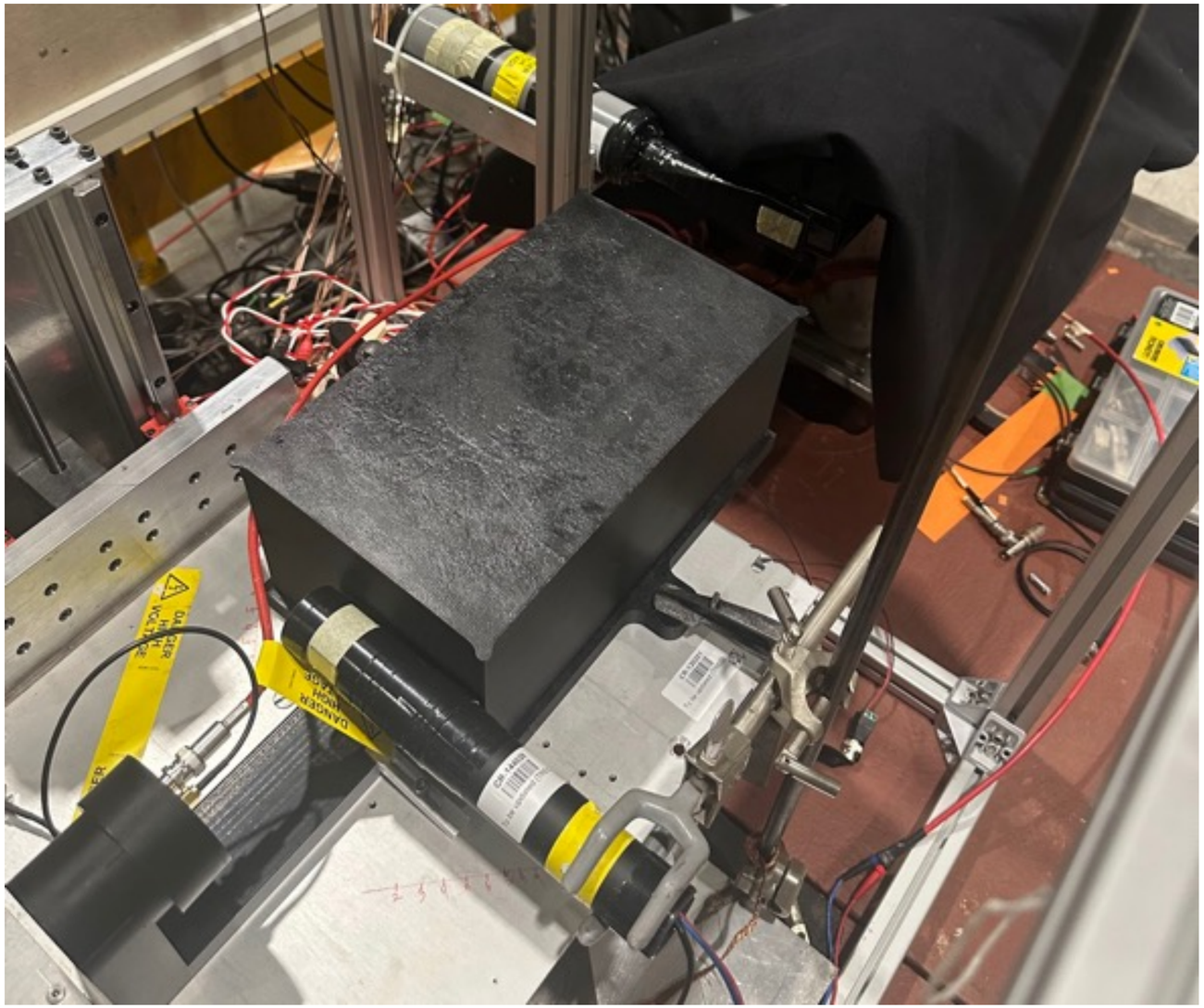


J. Wetzel et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 7, JULY 2023

RADiCAL at CERN 25 - 150 GeV

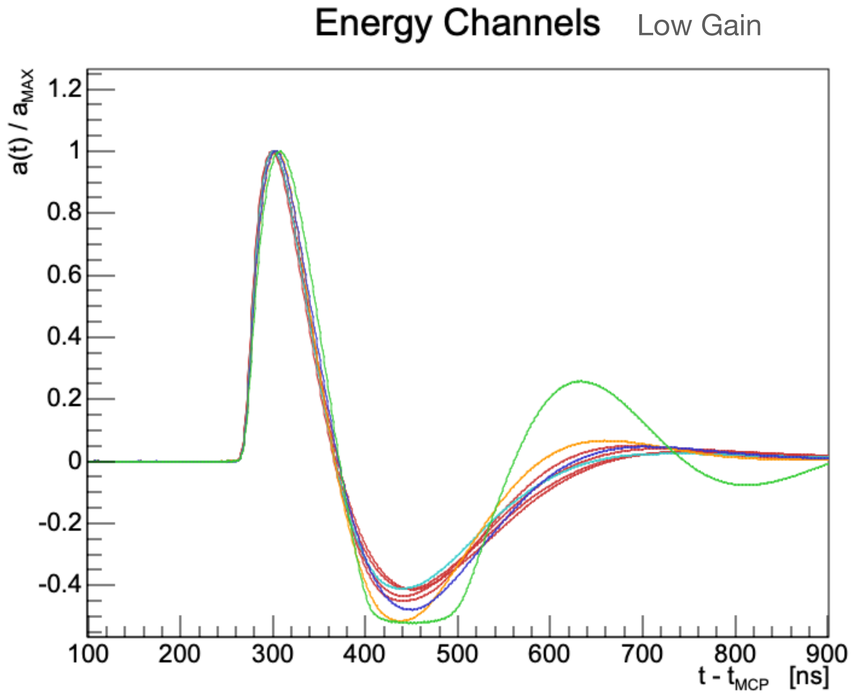


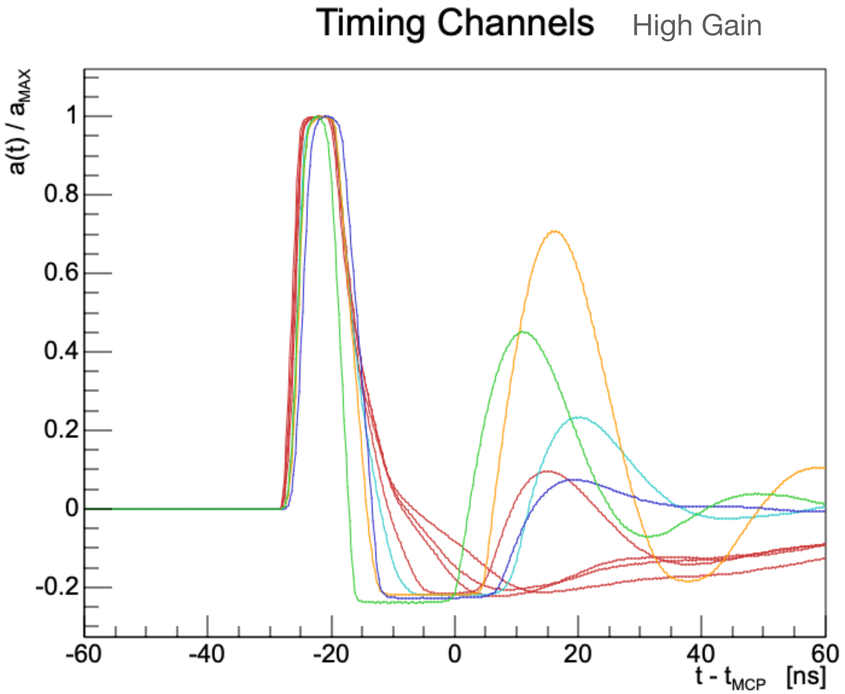
RADiCAL at CERN 25 - 150 GeV



RADiCAL at CERN 25 - 150 GeV

Signals





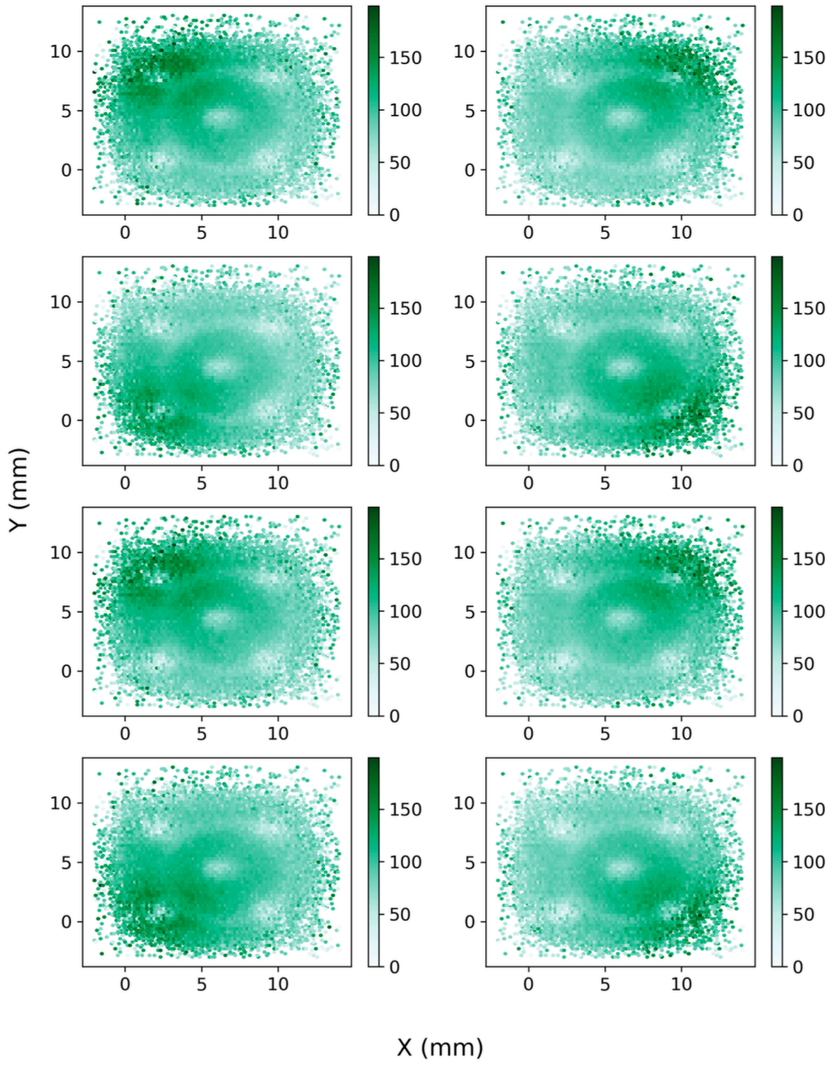
RADiCAL

M2925W2815L-415DSB1-T

Preliminary

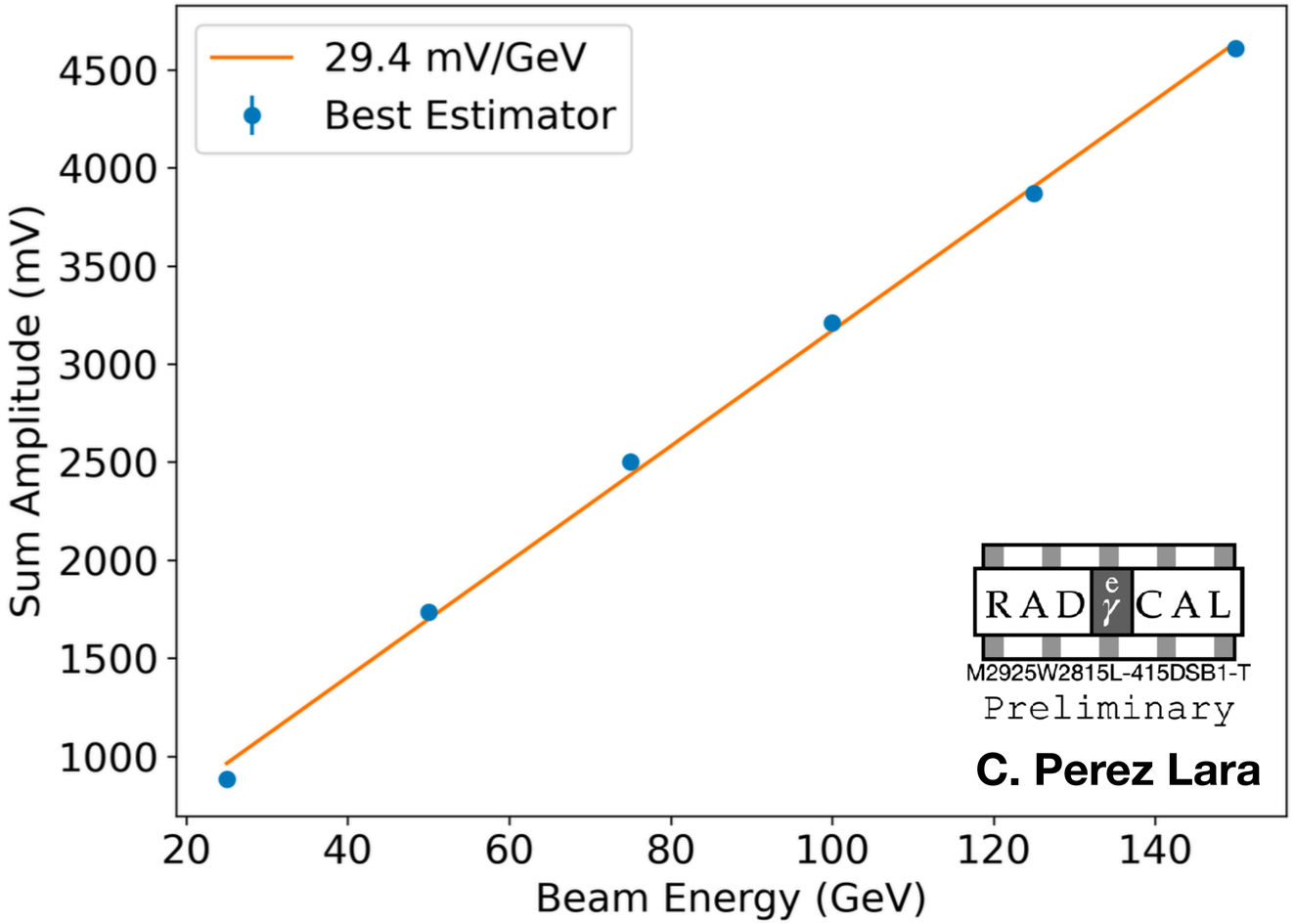
C. Perez Lara

Signals seen in each SiPM

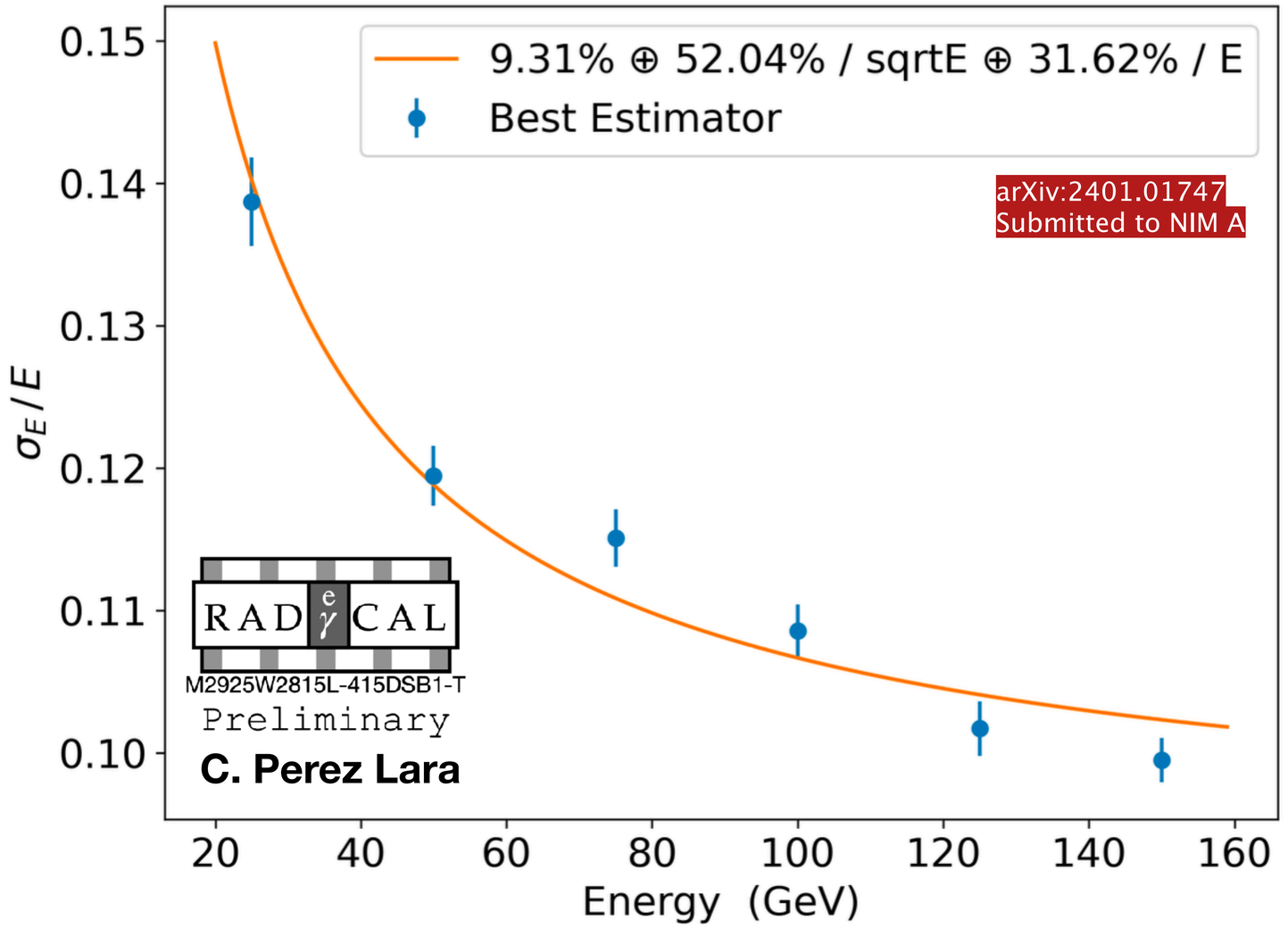


RADiCAL at CERN 25 - 150 GeV

Average signal increases linearly with increasing beam energy at shower max



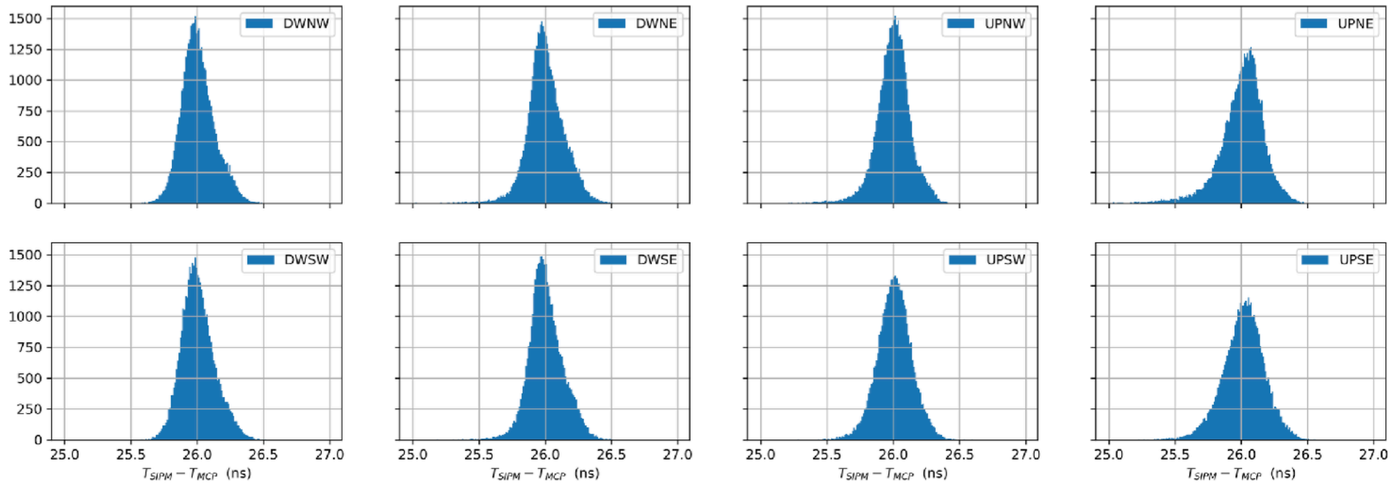
RADiCAL at CERN 25 - 150 GeV



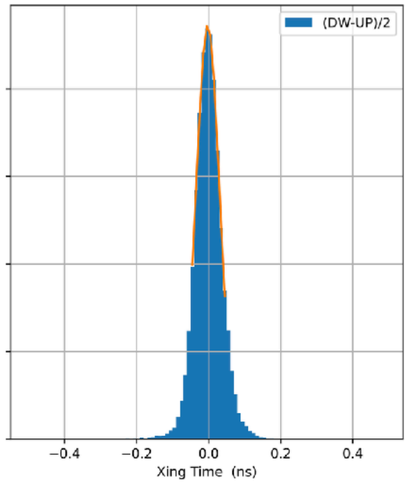
RADiCAL at CERN 25 - 150 GeV

Timing Analysis

Timing Signal collected at each end of the capillaries



Full Timing Signal

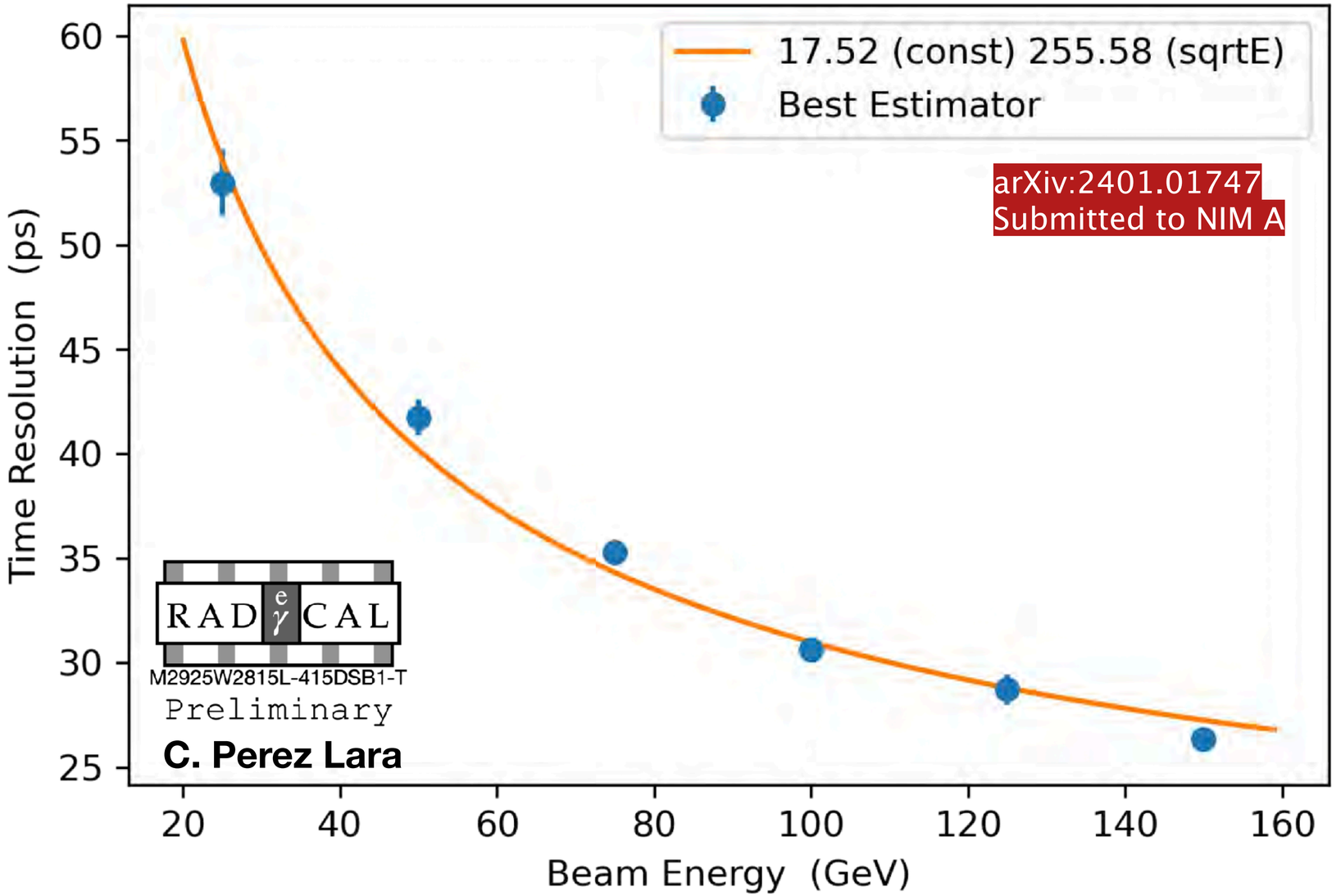


M2925W2815L-415DSB1-T

Preliminary

C. Perez Lara

RADiCAL at CERN 25 - 150 GeV



EXPERIMENTS

Summary of Fermilab and CERN Test Results

- Fermilab -
  - June 2022
  - Measured timing resolution of 45 ps @ 28 GeV
- CERN -
  - May 2023
  - Moved to higher energy: 25 - 150 GeV e- beam
  - Measured timing resolution of 25 ps @ 150 GeV, with limiting resolution of ~18 ps
- Future CERN - Up to 200 GeV e- hopefully this summer

Results thus far demonstrate:

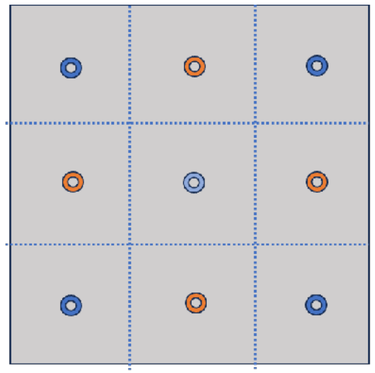
- The RADiCAL module is radiation hard.
- The RADiCAL concept is an effective calorimeter.
- The RADiCAL can achieve < 30 ps for 150 GeV electrons - meets needs of FCC EndCap
- The RADiCAL has potential to reach < 10ps timing resolution at >150 GeV

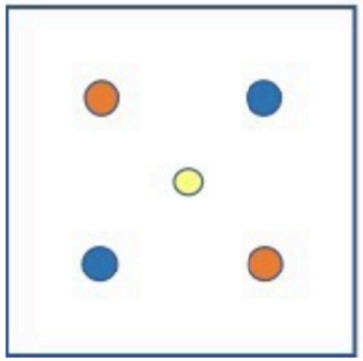
Results thus far demonstrate:

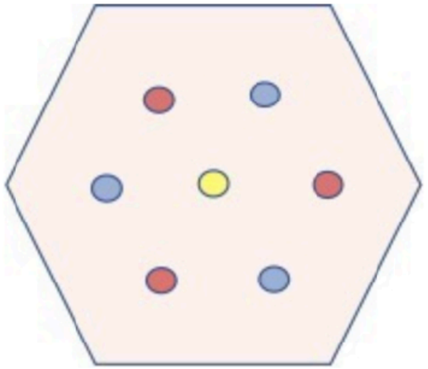
- Can act as an application test structure for new scintillation and wave shifting materials
- The module is potentially capable of measuring shower **energy**, shower **time**, and shower **position** with high precision.
- Suitable for EM applications at future colliders

Future Work

- Optimize module for highest achievable time resolution:
  - Adjustable capillary position
  - Higher sampling fraction near shower max
- Simulate and build different geometries:







In Conclusion

- The RADiCAL concept has been demonstrated to meet the needs of high radiation and high luminosity environments at current or future collider experiments.
- Special thanks to FTBF Staff at Fermilab and SPS Coordination at CERN, DOE, and NSF for Financial Support

- **Work Supported by in part by:**
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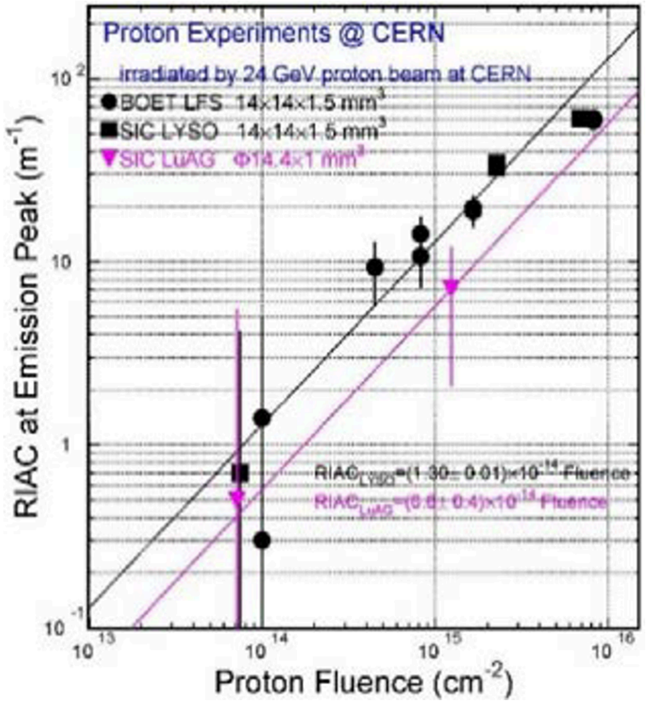
U. S. National Science Foundation: NSF-PHY-1914059
University of Notre Dame: Resilience and Recovery Grant Program

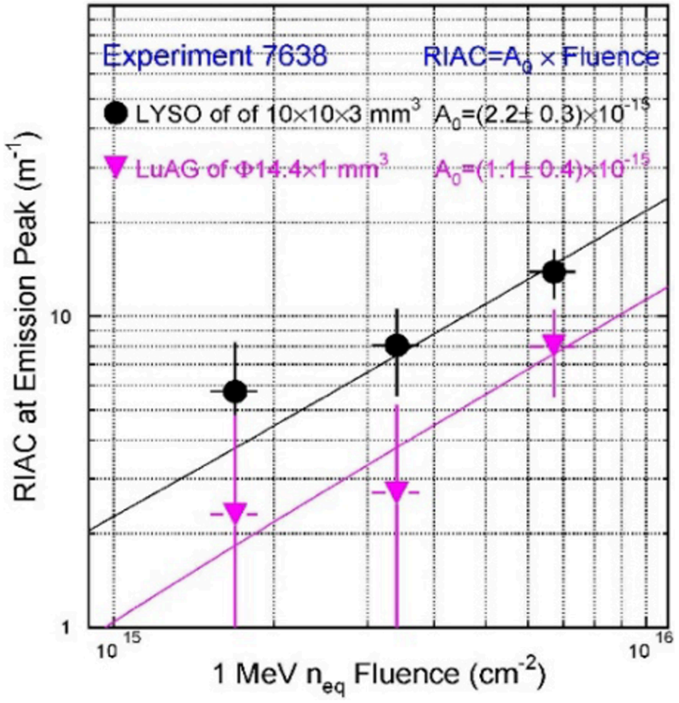

Thank You!
CAUTION
ATTENTION
WET
FLOOR
PISO
MOJADO

Backup

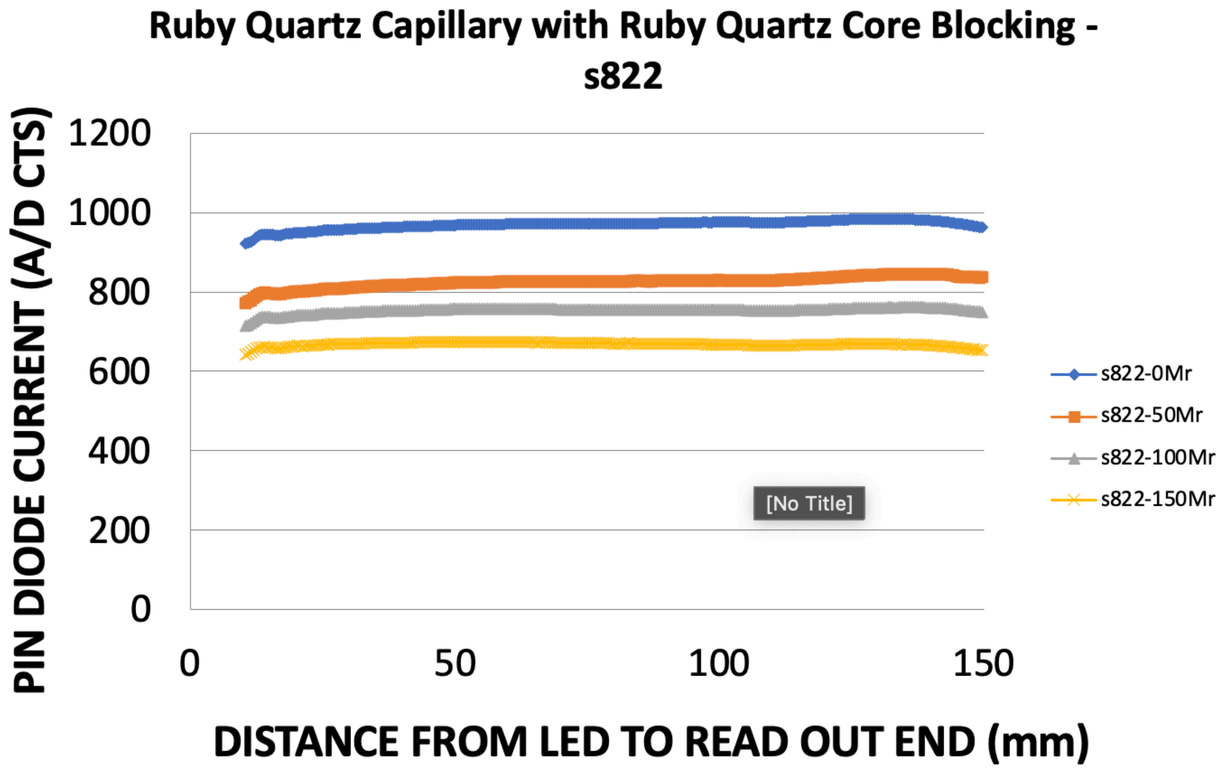
LYSO:Ce and LuAG:Ce Comparison under Irradiation by protons and neutrons

Caltech Measurements

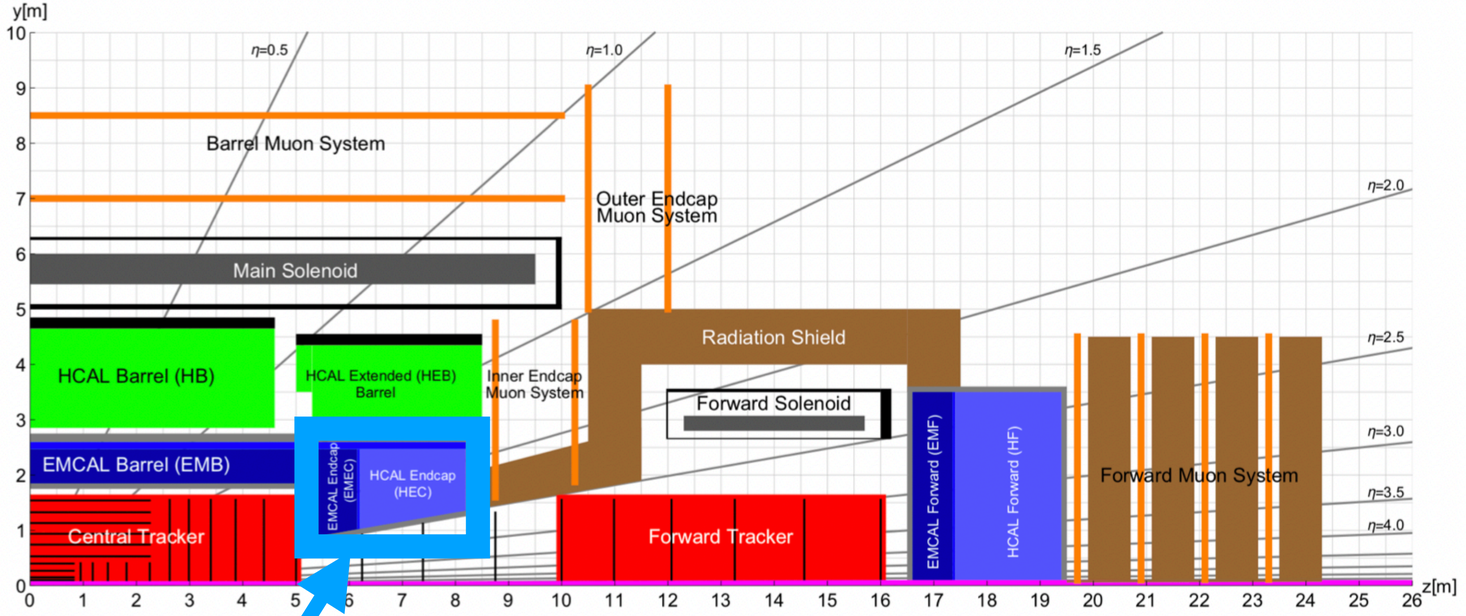




Co-60 Irradiation Study – Capillaries with DSB1 WLS and Ruby Quartz Inserts at the Readout End

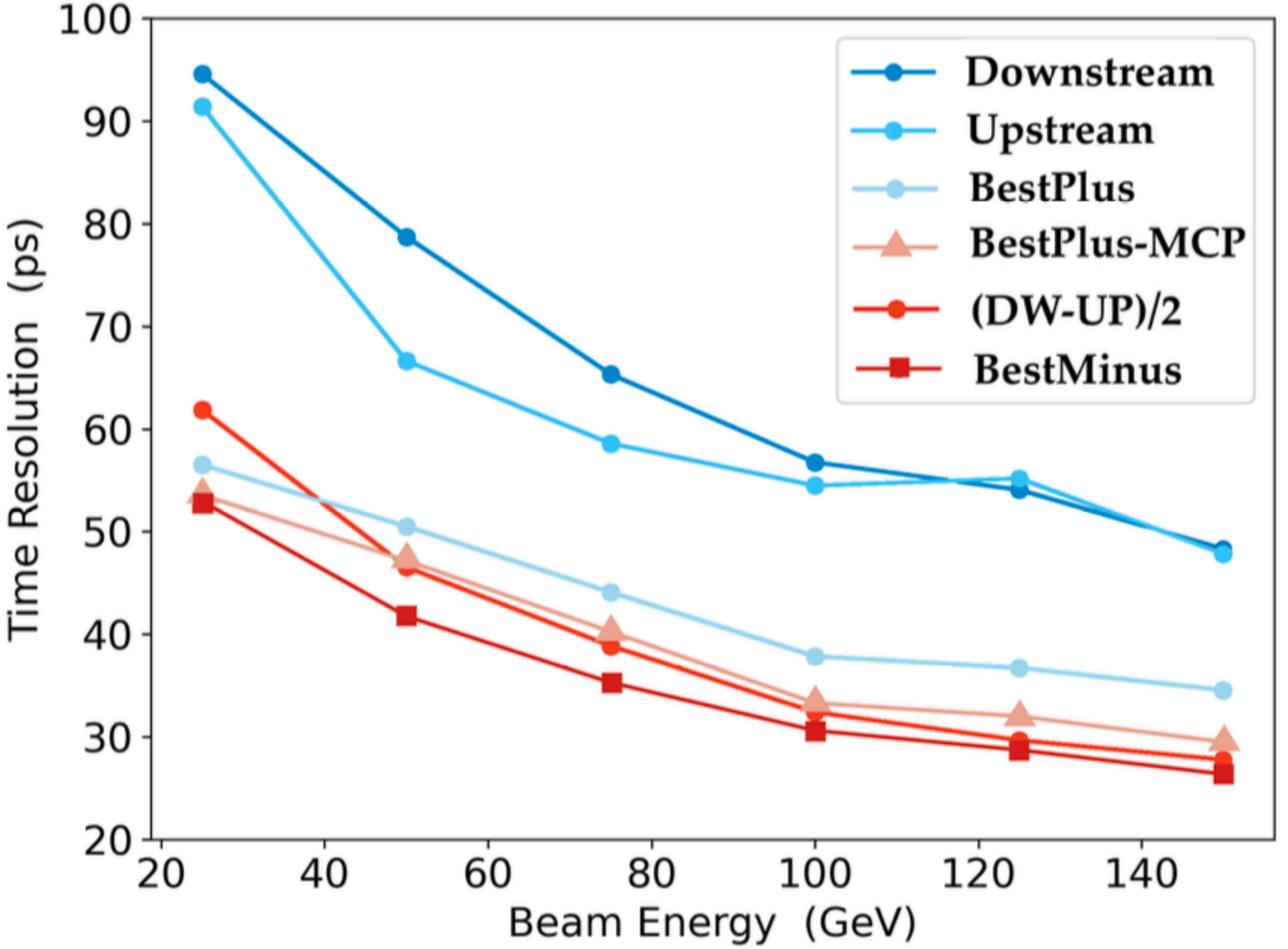


An example FCC-hh Detector



	R_{min}	R_{max}	z coverage	η coverage	Dose	1 MeV n_{eq} fluence
Unit	m	m	m		MGy	$\times 10^{15}$ cm^{-2}
EMB	1.75	2.75	$\lvert z\rvert < 5$	$\lvert\eta\rvert < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \lvert z\rvert < 6.05$	$1.48 < \lvert\eta\rvert < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \lvert z\rvert < 17.15$	$2.26 < \lvert\eta\rvert < 6.0$	5000	5000
HB	2.85	4.89	$\lvert z\rvert < 4.6$	$\lvert\eta\rvert < 1.26$	0.006	0.3
HEB	2.85	4.59	$4.5 < \lvert z\rvert < 8.3$	$0.94 < \lvert\eta\rvert < 1.81$	0.008	0.3
HEC	0.96-1.32	2.7	$6.05 < \lvert z\rvert < 8.3$	$1.59 < \lvert\eta\rvert < 2.50$	1	20
HF	0.065–0.077	3.6	$17.15 < \lvert z\rvert < 19.5$	$2.29 < \lvert\eta\rvert < 6.0$	5000	5000

Calorimeters for the FCC-hh, M. Aleksa et al. CERN-FCC-PHYS- 2019-0003, 23 December 2019


Time Resolution (ps)
Beam Energy (GeV)
Downstream
Upstream
BestPlus
BestPlus-MCP
(DW-UP)/2
BestMinus
100
90
80
70
60
50
40
30
20
20
40
60
80
100
120
140