Calorimeters for Muon Collider

Discussion leader : Jim Hirschauer

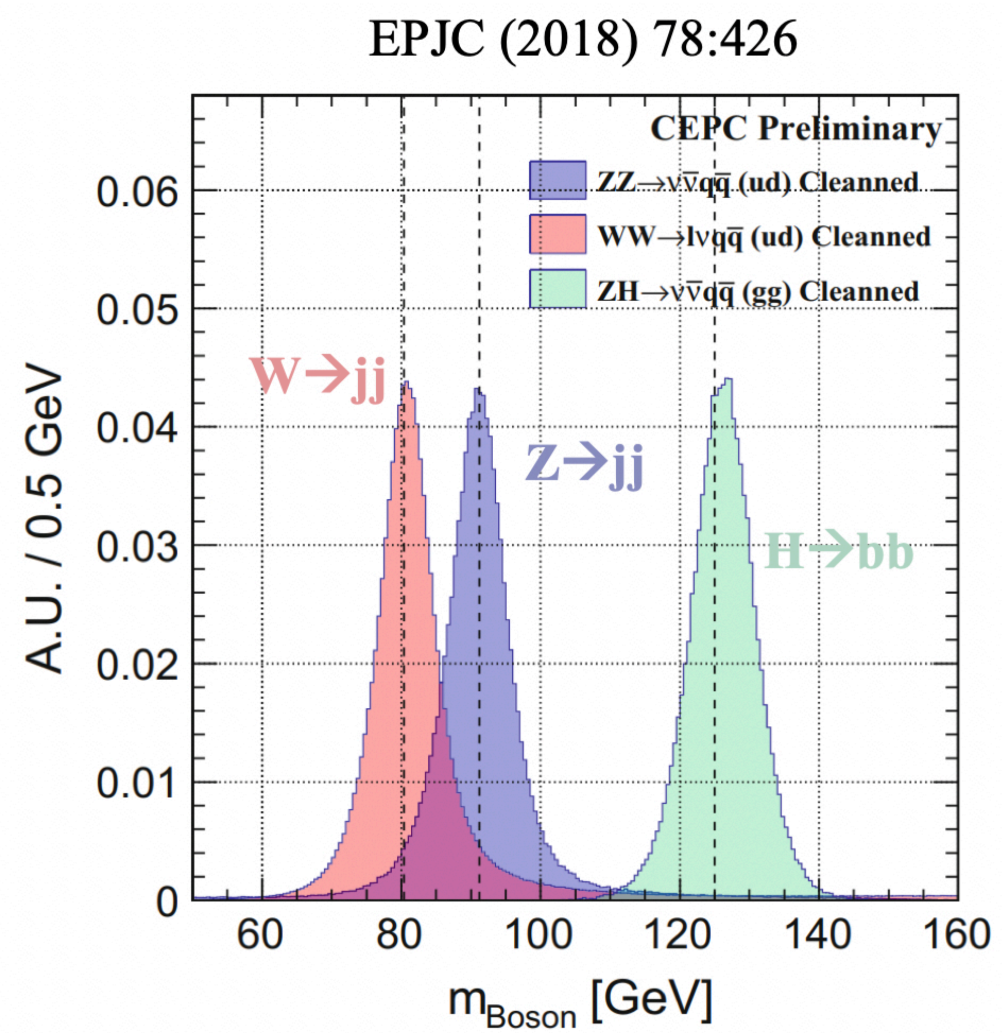
Fermilab

LPC Colliders of Tomorrow
12 Oct 2023

(NB : HGCAL-like calorimeter covered in previous LPC CoT talk; not much today)

General requirements for future calorimeters

- Documented in DOE BRN for HEP Detector R&D from 2020.
- **Energy Resolution** : 4% resolution for PF jets allows discrimination between hadronic decays of W and Z bosons
  - Essential for e+e- colliders where ZH is required for Higgs total width measurement
- **Timing resolution** :
  - 5 ps per shower to match HL-LHC pile-up rejection at 100 TeV pp collider
  - 10 ps per shower to provide particle ID for SM and new particles at any collider
- **High longitudinal and transverse granularity** for pile-up rejection, particle flow, and jet substructure.



TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps
TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) n$_{eq}$/cm^2 in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps

Particle ID from time-of-flight

- In addition to identification of out-of-time backgrounds, good **timing resolution provides particle identification** for SM and BSM particles.

- ~1 ps timing precision allows K/π separation up ~20 GeV momentum!

- Momentum reach for heavy BSM particles extends further, obviously.

https://psec.uchicago.edu/Simulation/tim_credo_Rome_paper.pdf

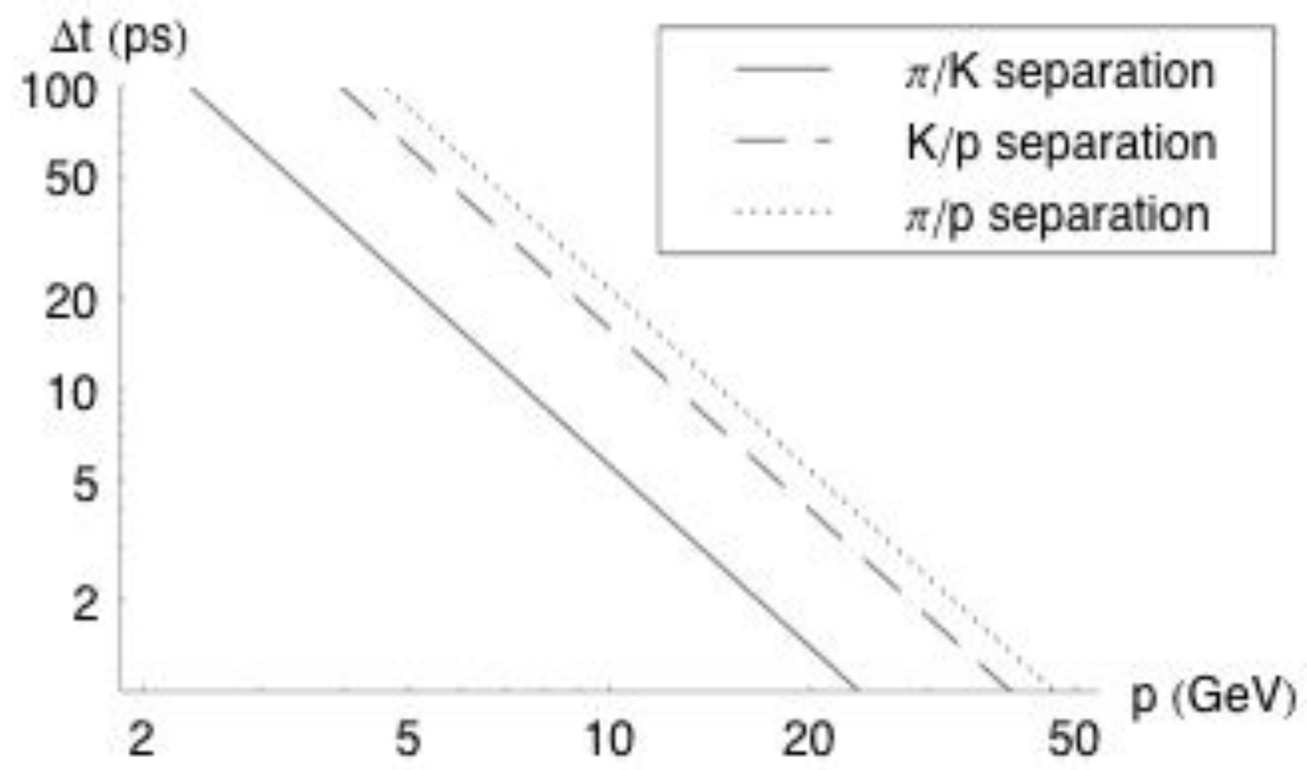


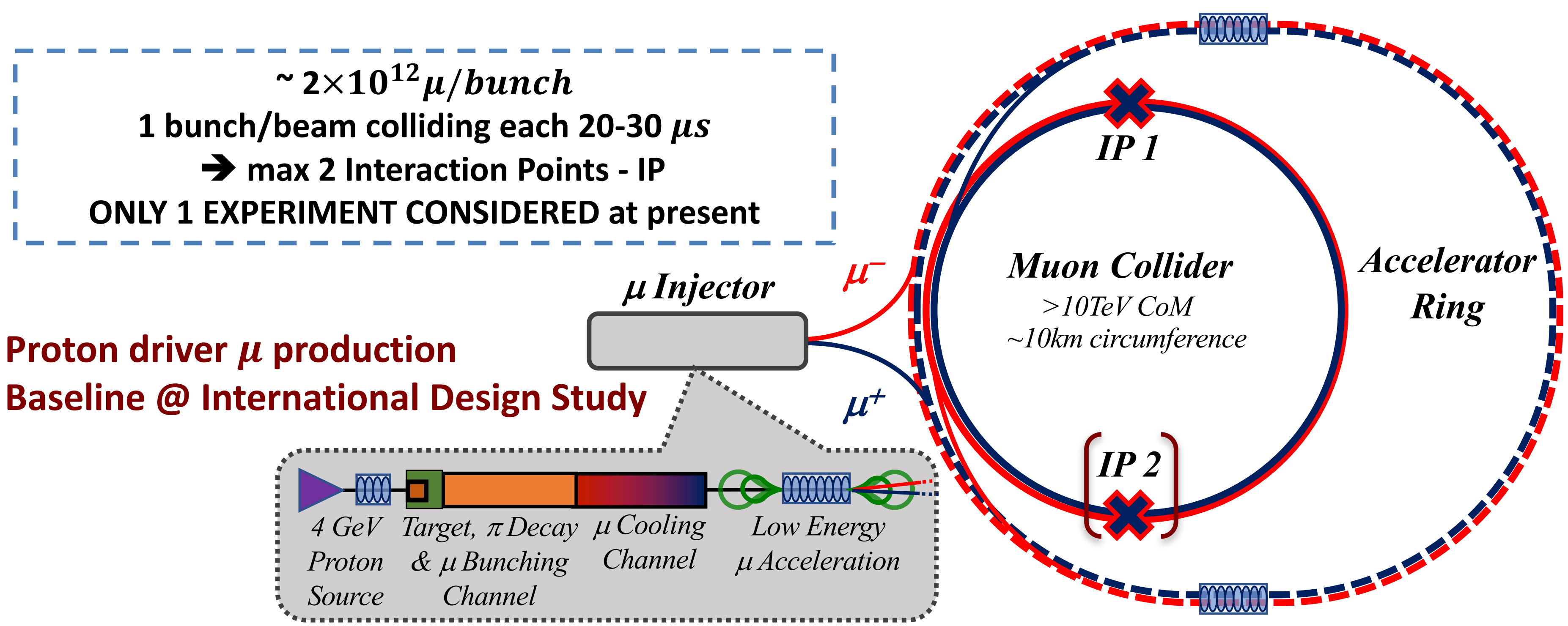
Fig. 1. The separations of pions, kaons, and protons, the difference in the time it takes two different particles with the same momentum to travel 1.5 m, as a function of momentum. Large time-of-flight detector systems have a time resolution on the order of 100 ps [2]-[4].

Muon Collider

Why use Muon Collider to probe higher mass scales?

- Muons are heavy
  - Small synchrotron radiation.
  - Compact accelerator+storage rings.
- Muons are fundamental
  - All particle energy available for each collision.
  - Momentum of initial state is known.
- Good efficiency (power/luminosity)

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	$ab^{-}1$/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300
Muons per bunch	10^{12}	4	2.2	1.8
Average field in ring	T	4.4	7	10.5



Muon Collider Detector

https://muoncollider.web.cern.ch/design/muon-collider-detector

hadronic calorimeter

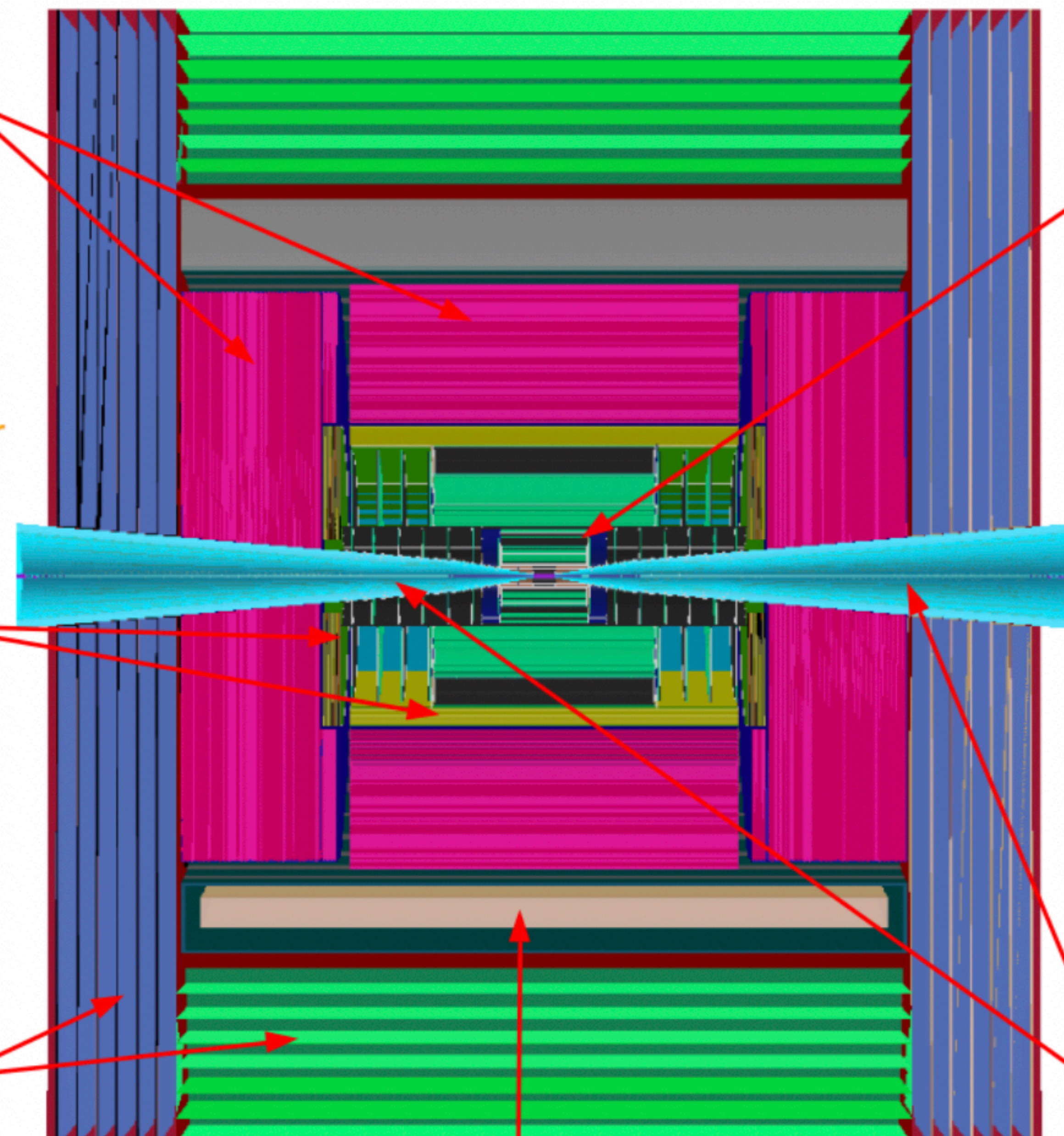
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

Calorimeter radiation requirements

- Radiation levels for Muon Collider calorimeter are generally lower than for HL-LHC
  - Not an issue for readout electronics, silicon detectors, silicon photomultipliers

- Radiation tolerance will impact **choice of scintillators**

	NIEL [1 MeV-neq/cm^2]	TID [Mrad]
FCC-hh Endcap Calo*	3E+16	400
HGCAL Si	1E+16	200
HGCAL Scint+SiPM	5E+13	—
MuCol ECAL**	1E+14	1

*FCC-hh CDR

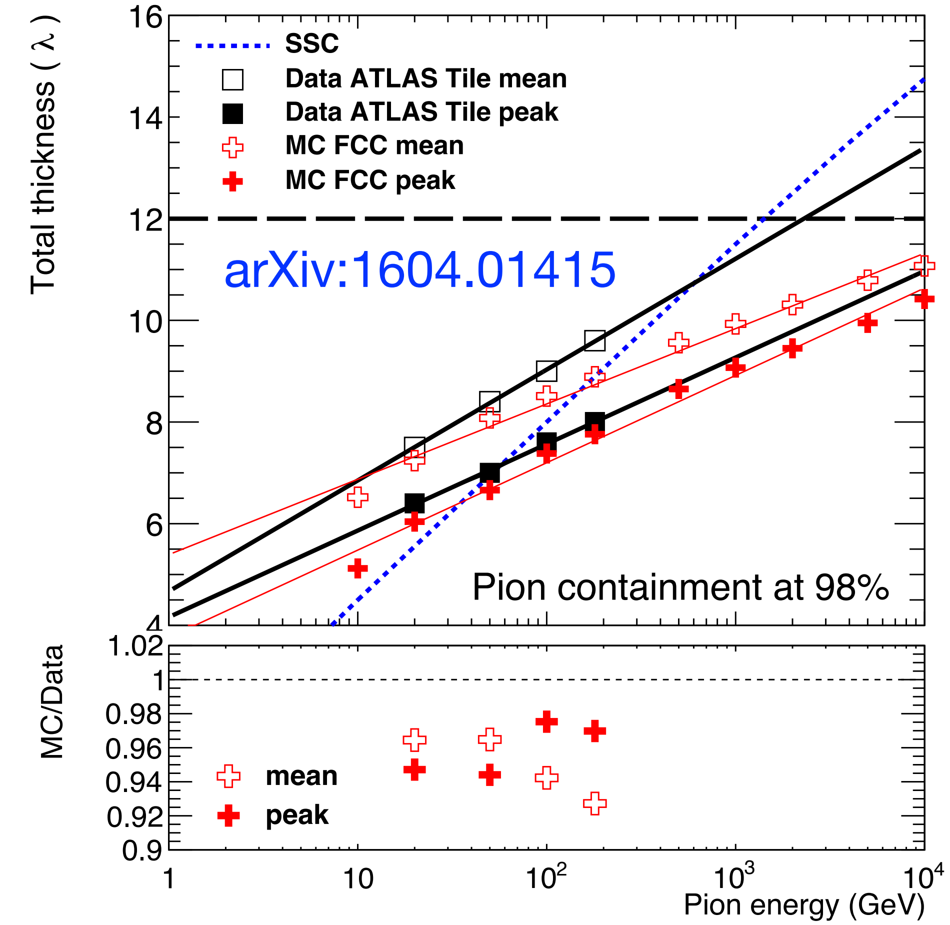
** Crilin paper (https://doi.org/10.1016/j.nima.2022.167817)

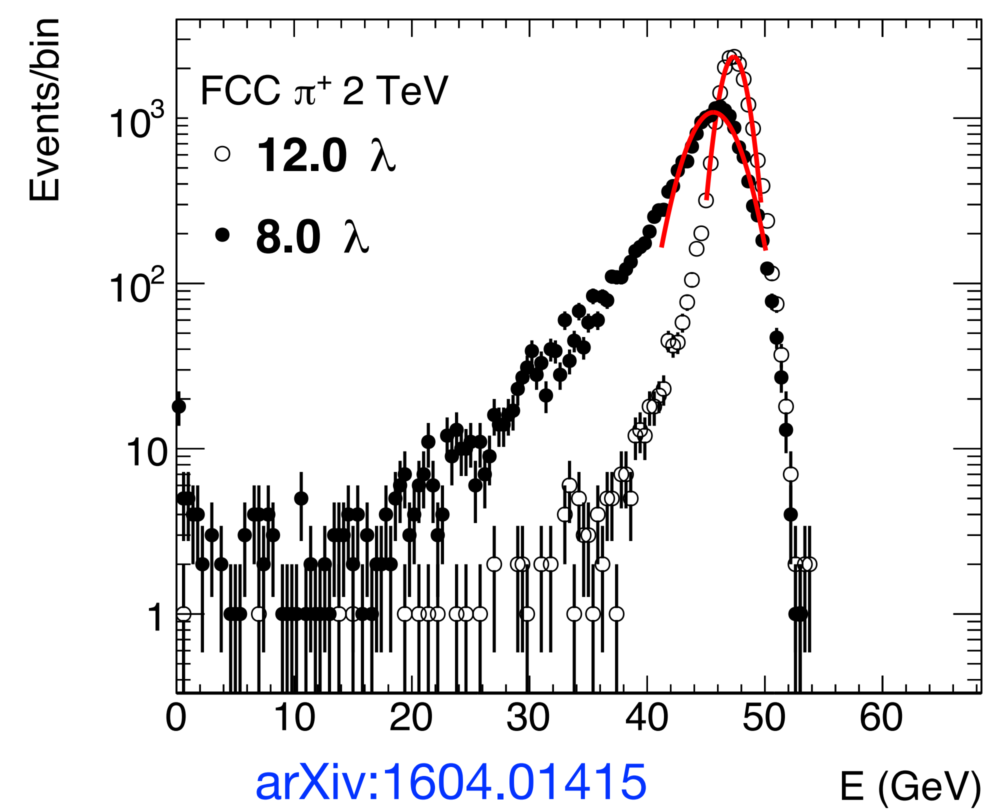
Hadronic shower containment at high CM energy

- Calorimeter thickness required for constant shower containment has ~**logarithmic dependence** on particle energy.

- **Shower containment not a significant challenge** even for 10 TeV muon collider.

	Thickness [nuclear interaction lengths]
ATLAS	10-12
CMS	7-10
Muon collider detector	8.5 (barrel?)
FCC-hh	12

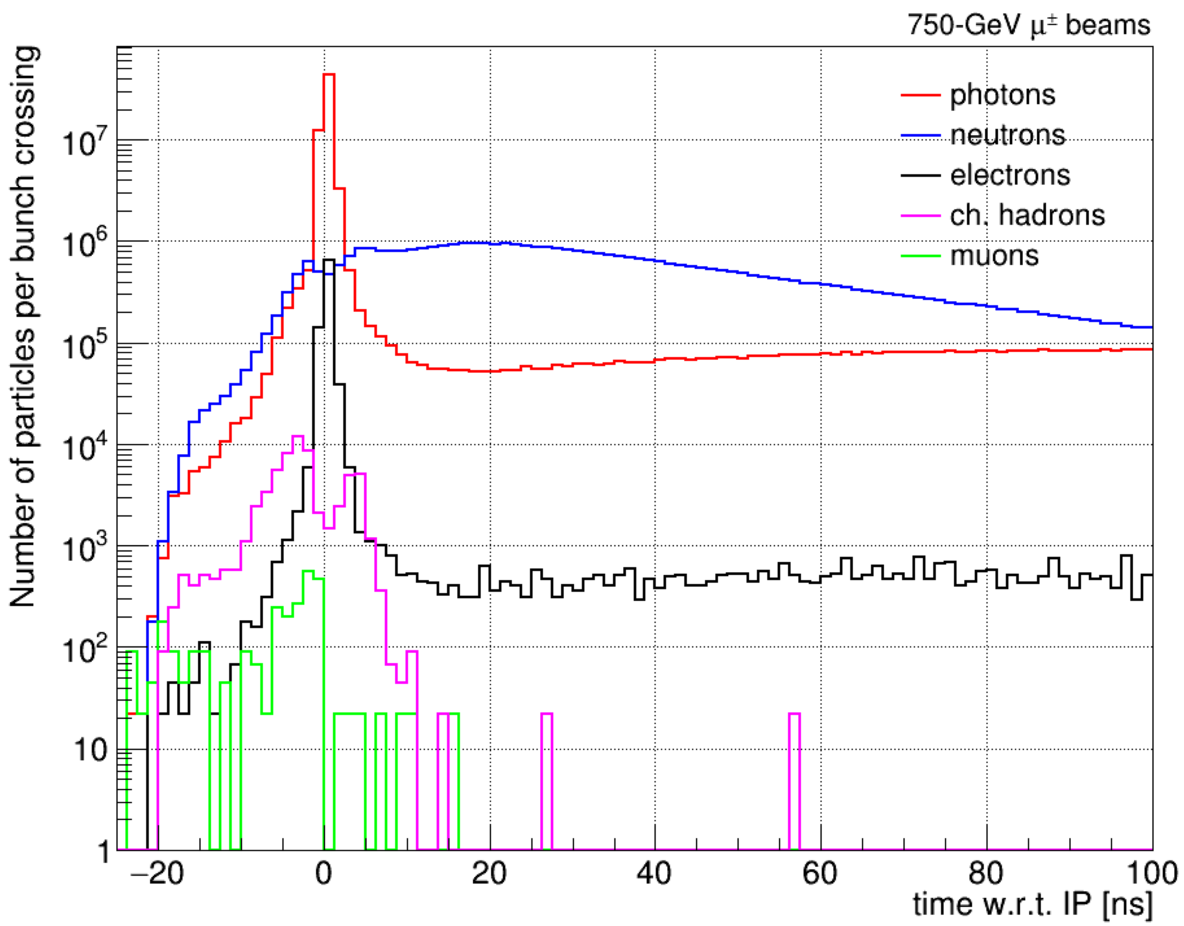


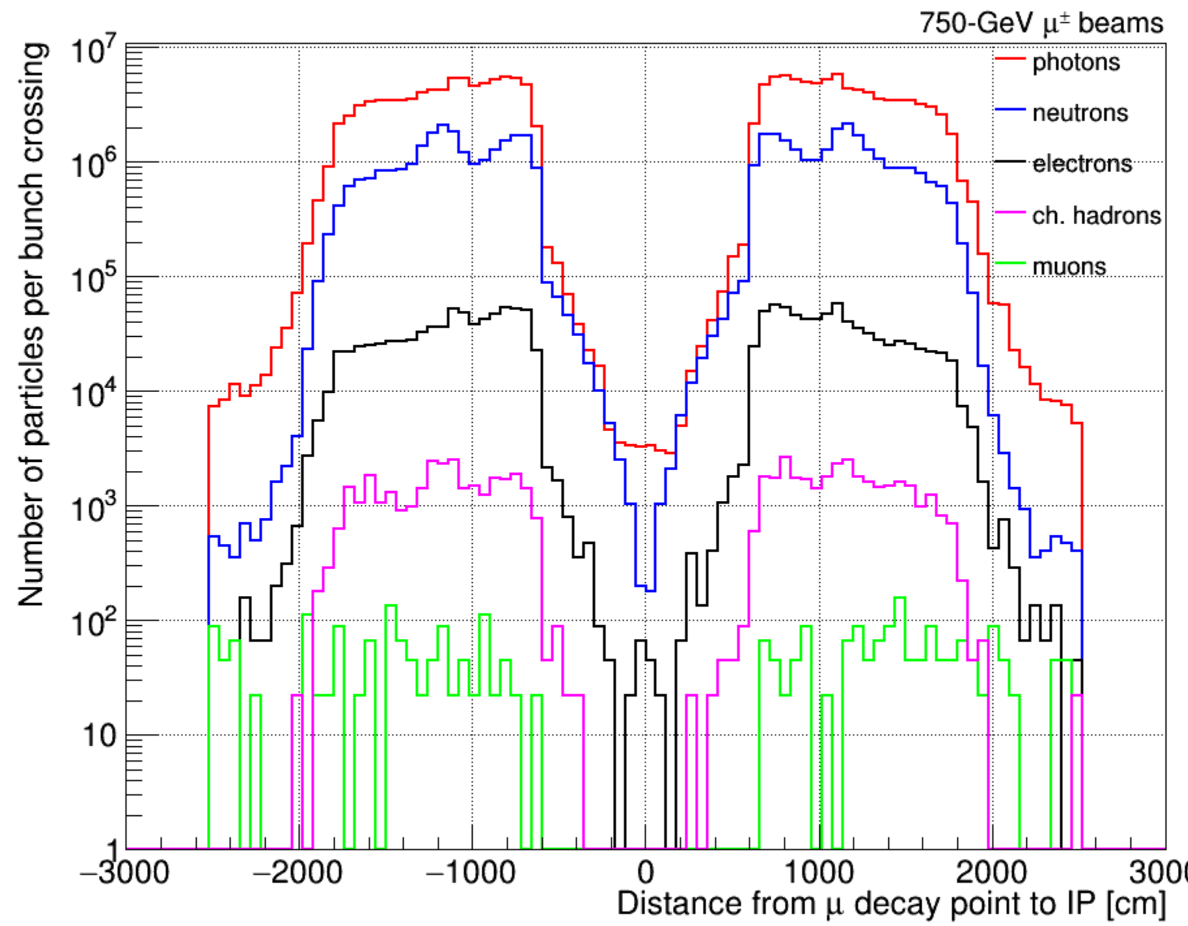


Beam Induced Background (BIB)

- Beam muon daughters interact with machine components producing ~continuous flux of particles interacting in detectors.
    - 2e12 muons/bunch
    - Collision spacing : 1-15 us

beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	4.7×10^6
μ decays/m per beam	5.1×10^6	4.3×10^5
photons ($E_{\text{ph.}}^{kin} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E_{\text{n}}^{kin} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E_{\text{el.}}^{kin} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons ($E_{\text{ch.had.}}^{kin} > 1$ MeV)	2.2×10^4	6.2×10^4
muons ($E_{\text{mu.}}^{kin} > 1$ MeV)	2.5×10^3	2.7×10^3



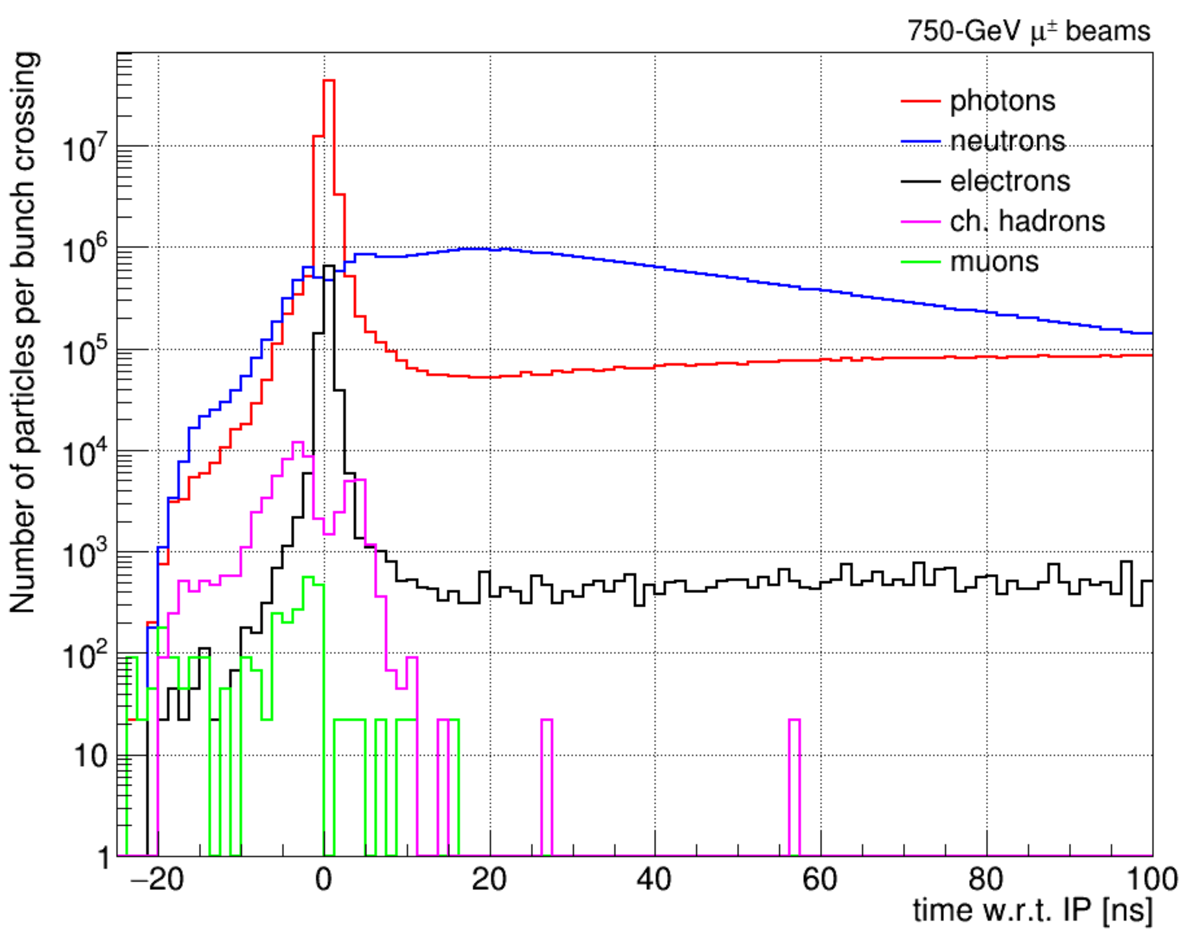


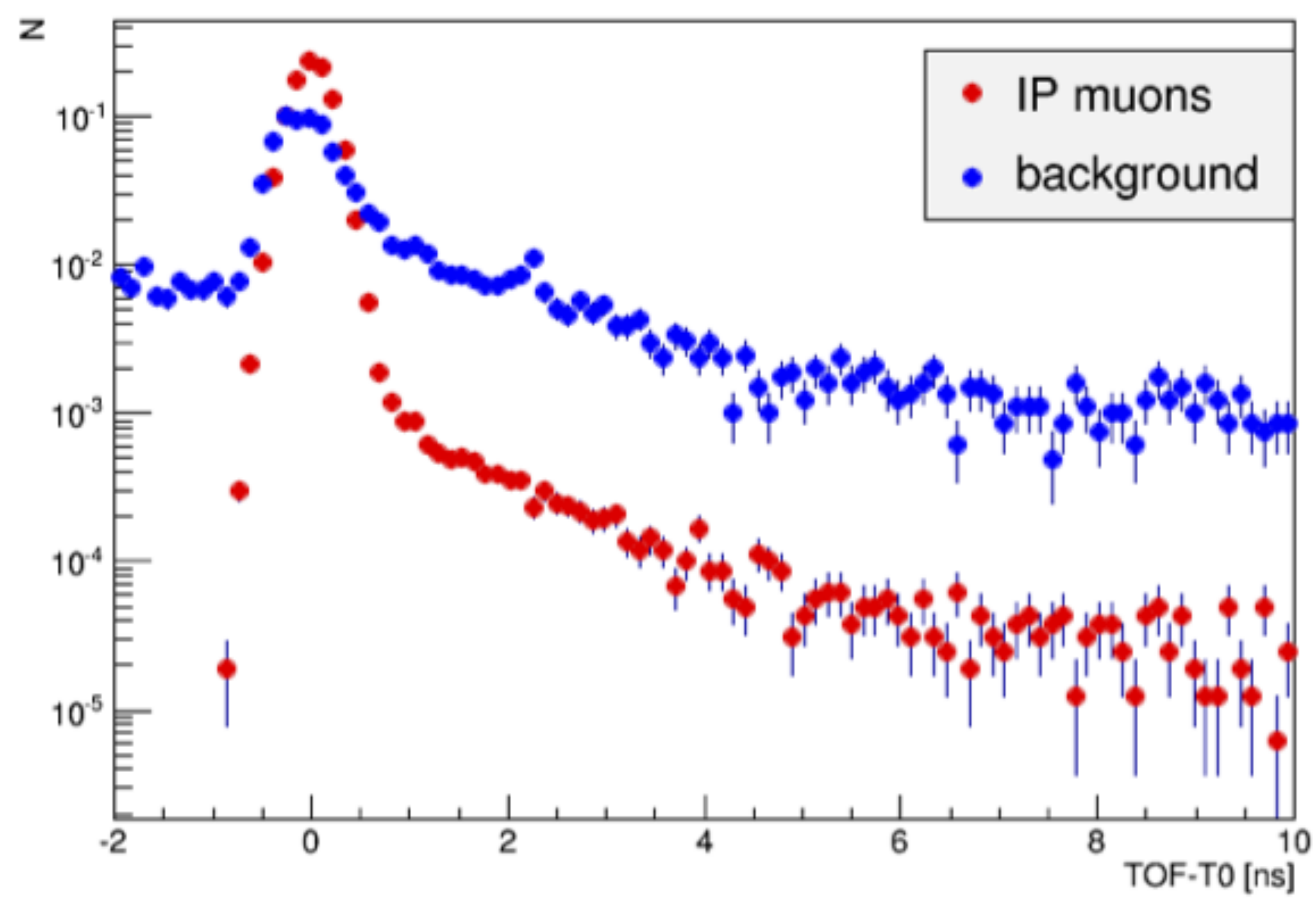
arXiv:1905.03725

Beam Induced Background (BIB)

- Beam muon daughters interact with machine components producing ~continuous flux of particles interacting in detectors.
    - 2e12 muons/bunch
    - Collision spacing : 1-15 us

beam energy [GeV]	62.5	750
μ decay length [m]	3.9×10^5	4.7×10^6
μ decays/m per beam	5.1×10^6	4.3×10^5
photons ($E_{\text{ph.}}^{kin} > 0.2$ MeV)	3.4×10^8	1.6×10^8
neutrons ($E_{\text{n}}^{kin} > 0.1$ MeV)	4.6×10^7	4.8×10^7
electrons ($E_{\text{el.}}^{kin} > 0.2$ MeV)	2.6×10^6	1.5×10^6
charged hadrons ($E_{\text{ch.had.}}^{kin} > 1$ MeV)	2.2×10^4	6.2×10^4
muons ($E_{\text{mu.}}^{kin} > 1$ MeV)	2.5×10^3	2.7×10^3

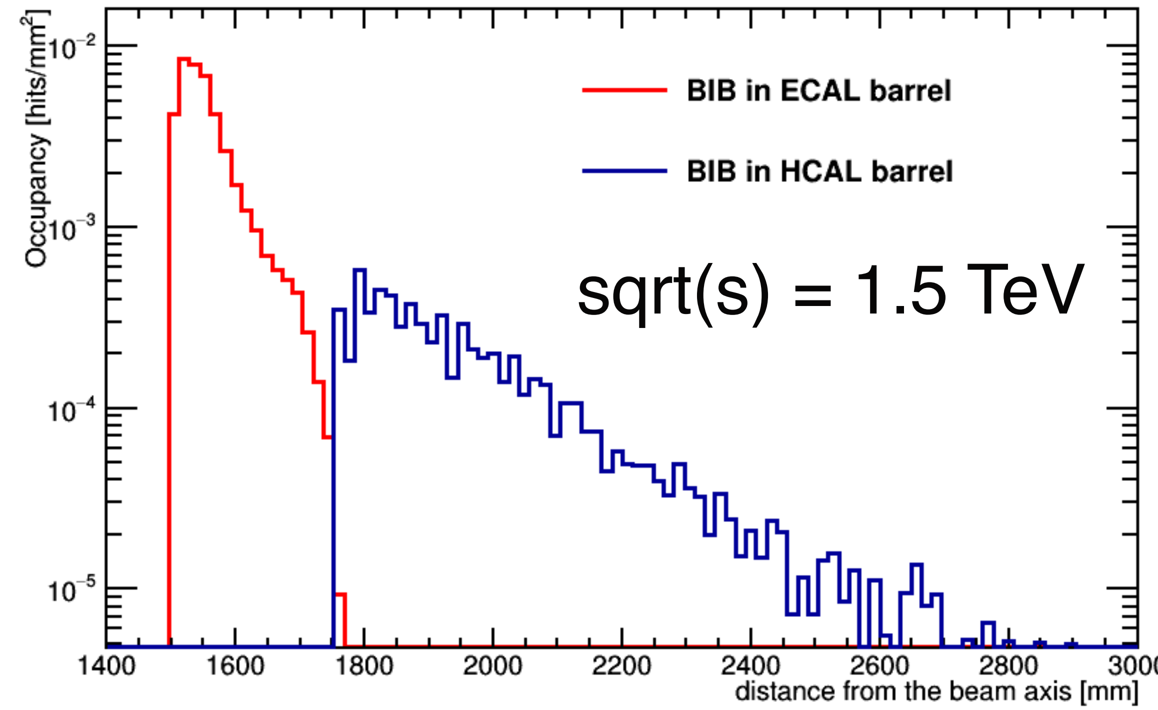




arXiv:1905.03725

BIB calorimeter occupancy

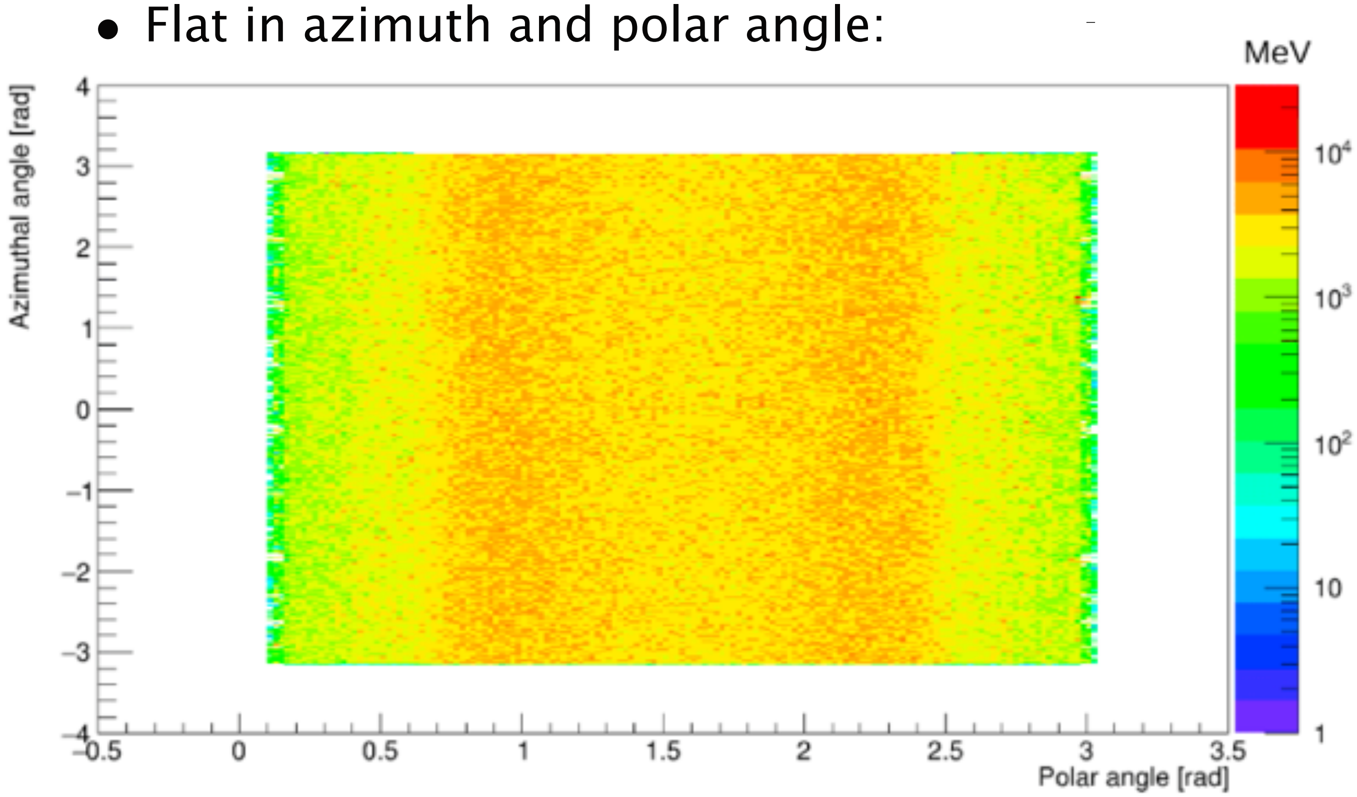
https://muoncollider.web.cern.ch/calorimeters

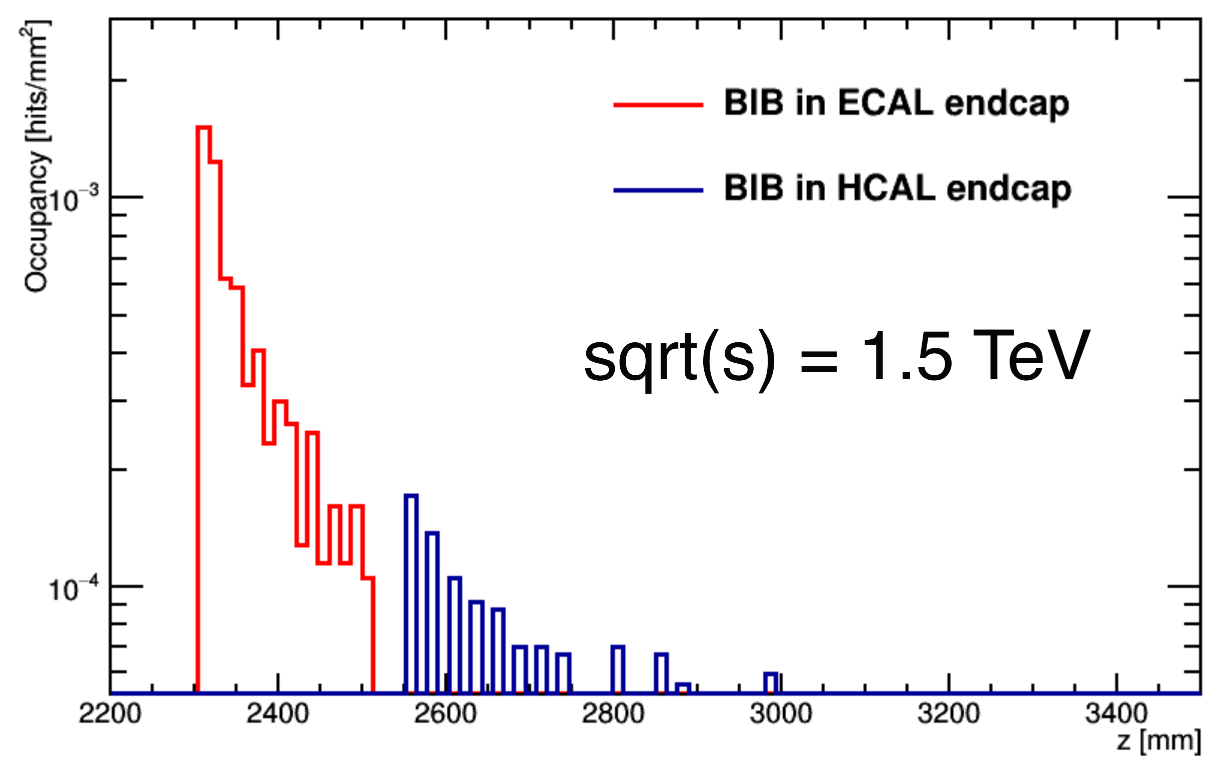


Occupancy per BX for E>0.2 MeV (no timing) at calorimeter surface:

- ECAL Barrel: 0.9 hits/cm^2
- ECAL Endcap: 0.2 hits/cm^2
- HCAL Barrel: 0.06 hits/cm^2
- HCAL Endcap: 0.02 hits/cm^2

- Flat in azimuth and polar angle:

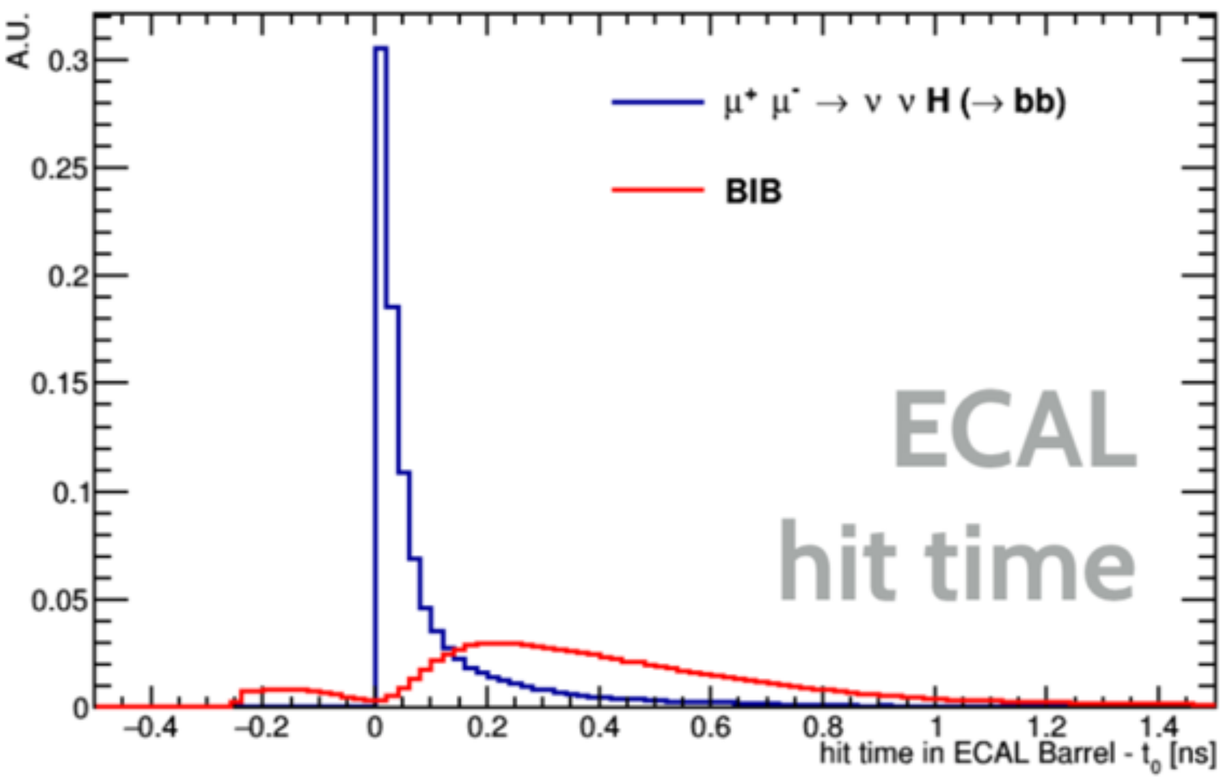




BIB identification in calorimeters

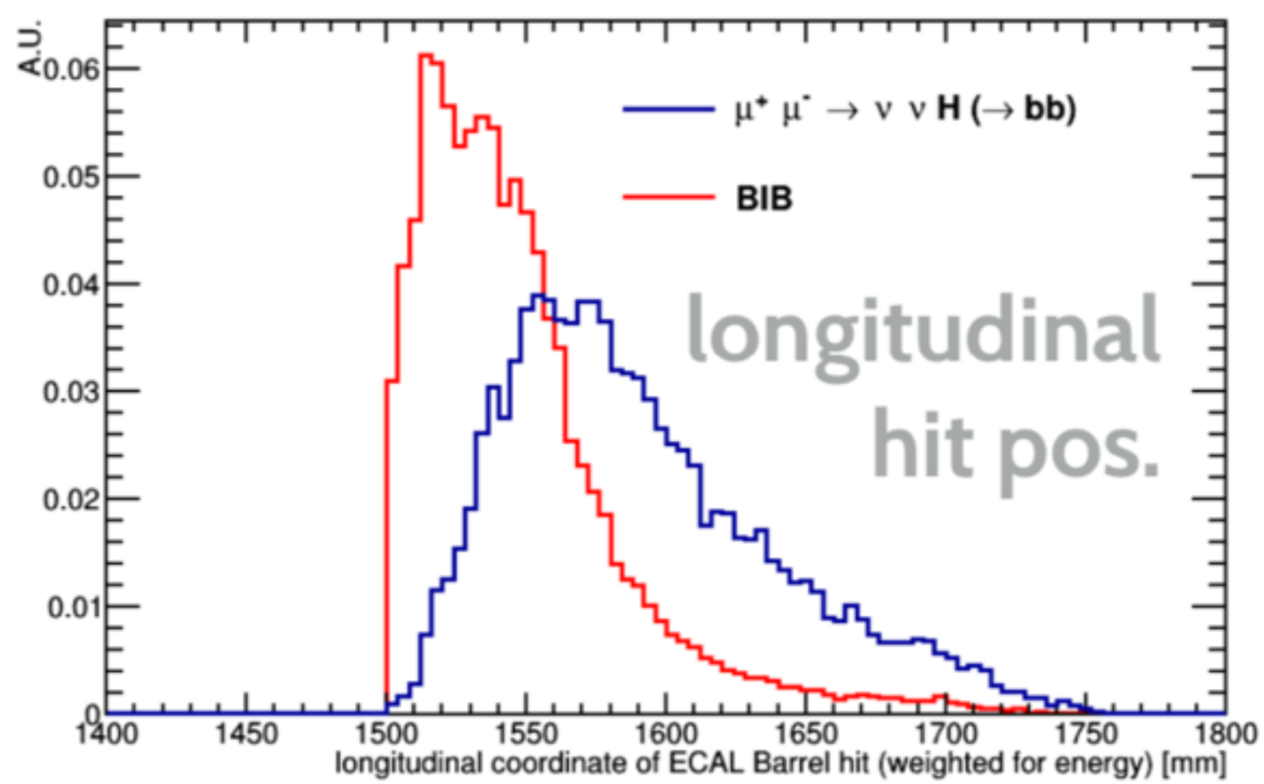
Timing information is essential for removal of BIB.

- Precision order of 100-250 ps is useful.
- Time measurements in hadronic showers complicated



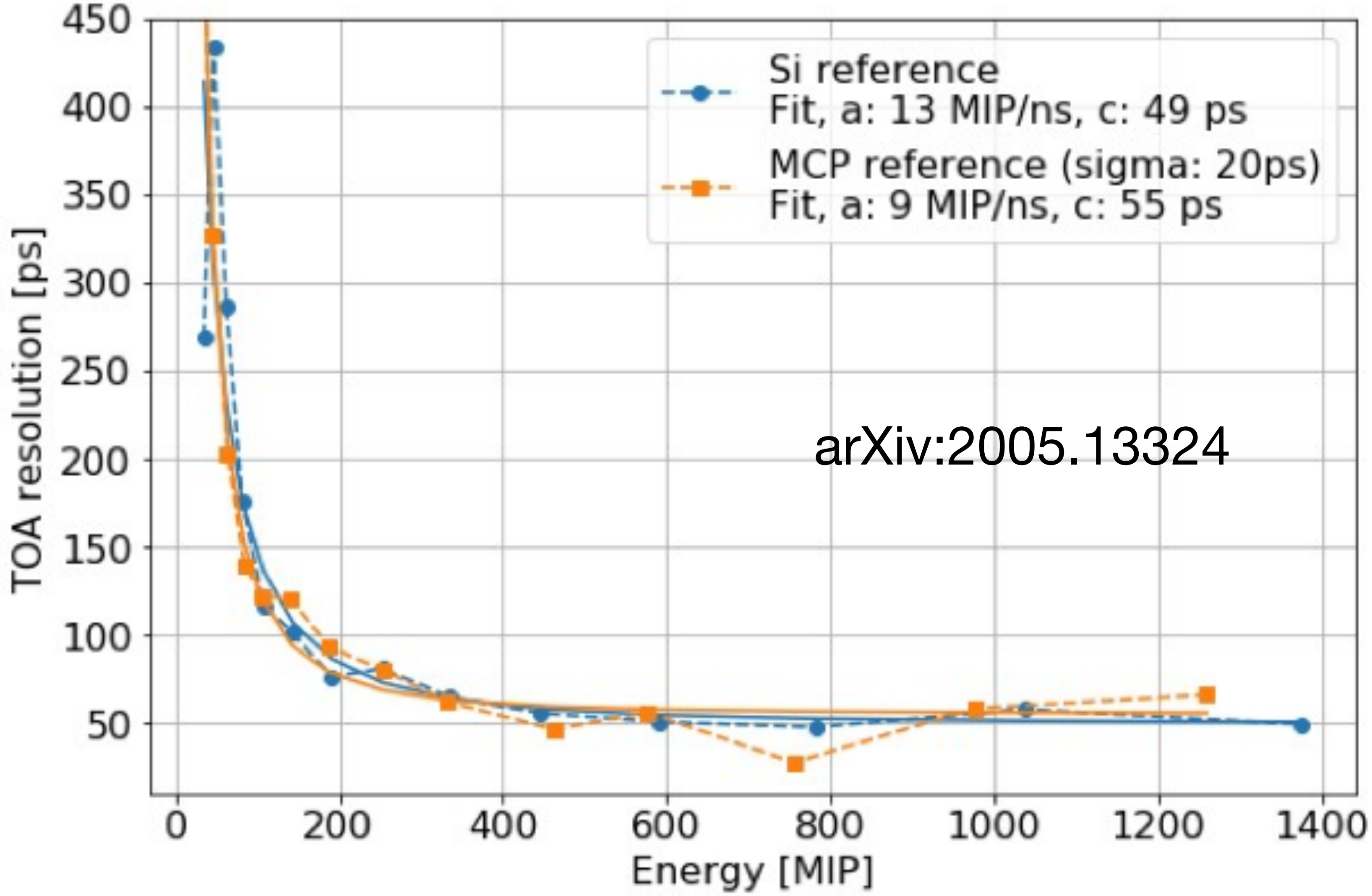
Good granularity also essential for BIB removal

- Both longitudinal and transverse granularity
- Clustering and particle flow performance will be important to simultaneously remove BIB, identify sub-structure, and obtain excellent energy resolution.



Current single cell timing resolution

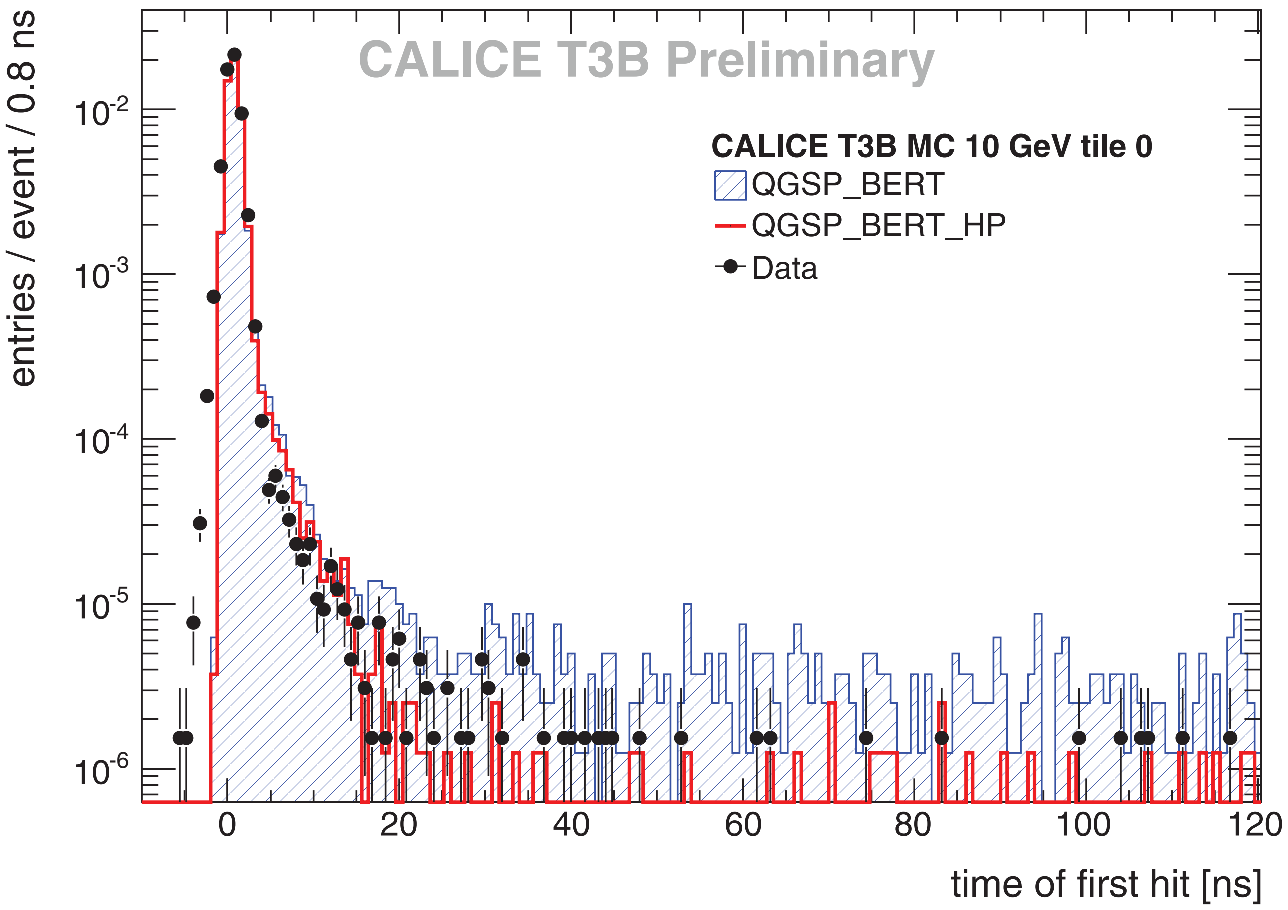
- CMS HGCAL (Si sampling calorimeter) obtains ~100 ps resolution for single cells with energy > ~150 MIP.
    - 150 MIP ~ 150 MeV (order of magnitude) for electrons

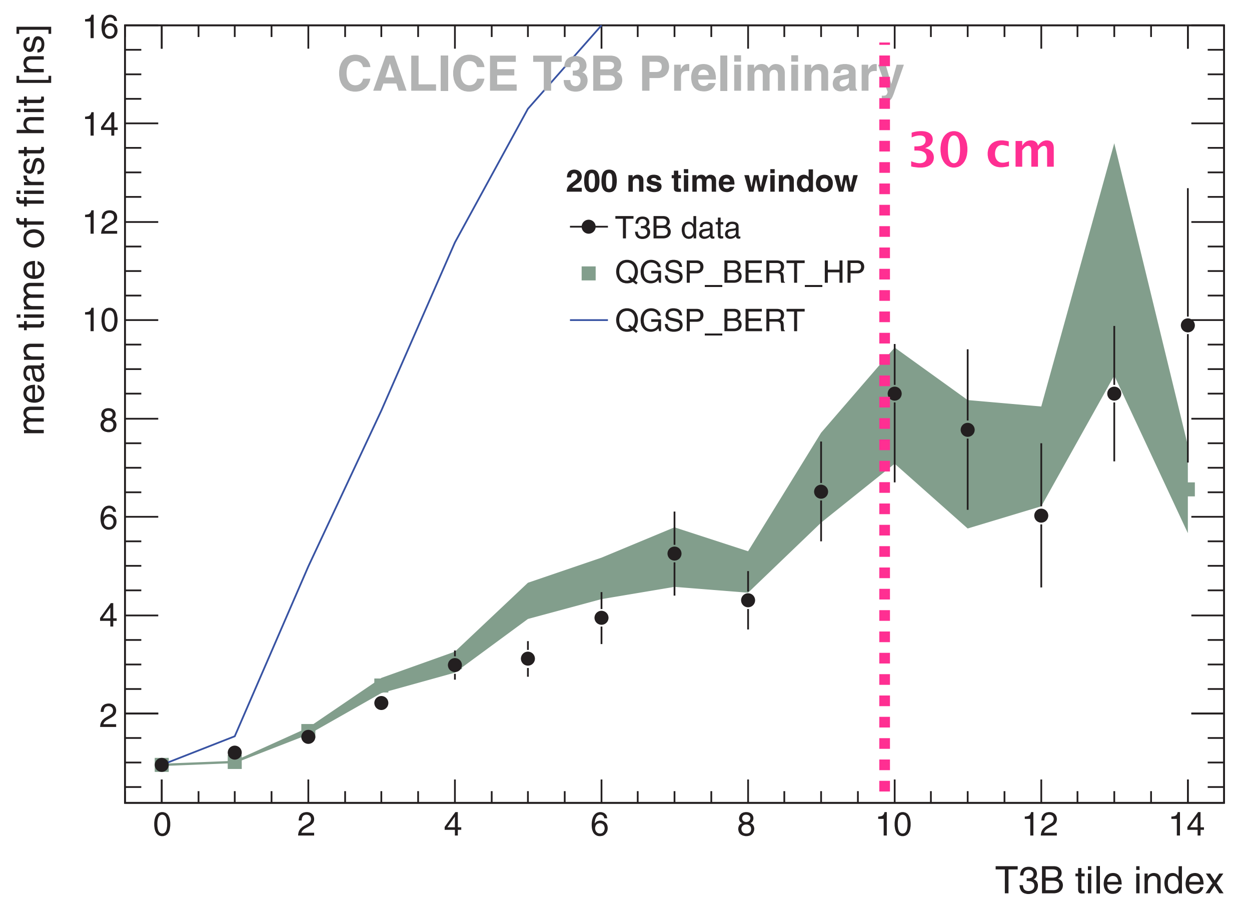


Time structure of hadronic showers

- Inherently slower evolution of hadronic showers makes time measurements less useful.
    - Detailed study of front HCAL layers required.

- Data from CALICE WHCAL 30-layer SiW sampling calorimeter with 10 GeV pi-.





https://doi.org/10.1016/j.phpro.2012.02.371

Calorimeter optimization

- **Cost →** as low as possible

- EM energy resolution → **total absorption** to address sampling fluctuations → monolithic crystals (CMS $PbWO_4$ ECAL)

- Hadronic energy resolution → **dual readout** (scintillation + Cherenkov) to address fluctuations in EM fraction (DREAM or IDEA)

- EM timing resolution
  - **Segmentation** to minimize variation of light paths
  - Bright, fast, rad-hard scintillators → **higher cost**

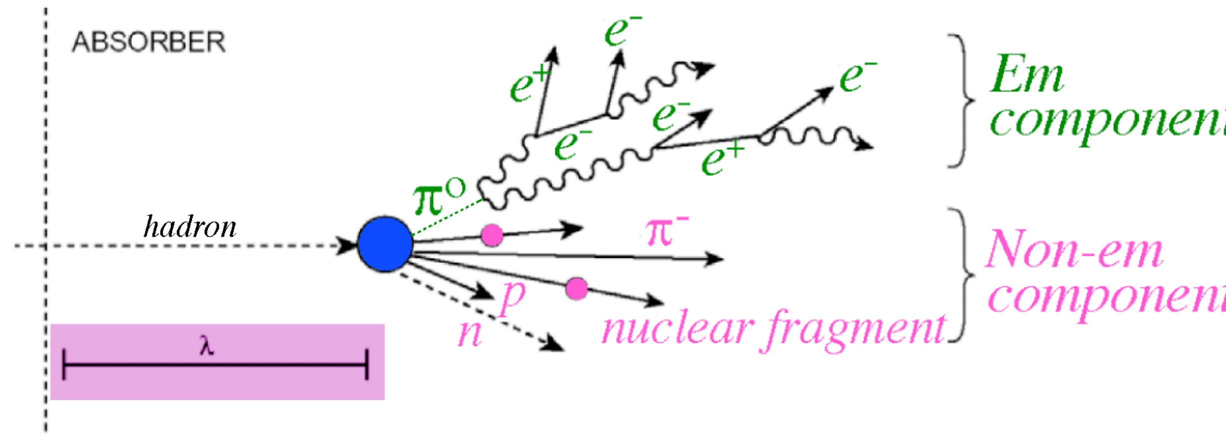
- Transverse granularity → **higher cost**
  - No introduction of dead material → minimal impact on energy resolution

- Longitudinal granularity → **higher cost**
  - dead material → **harms energy resolution**

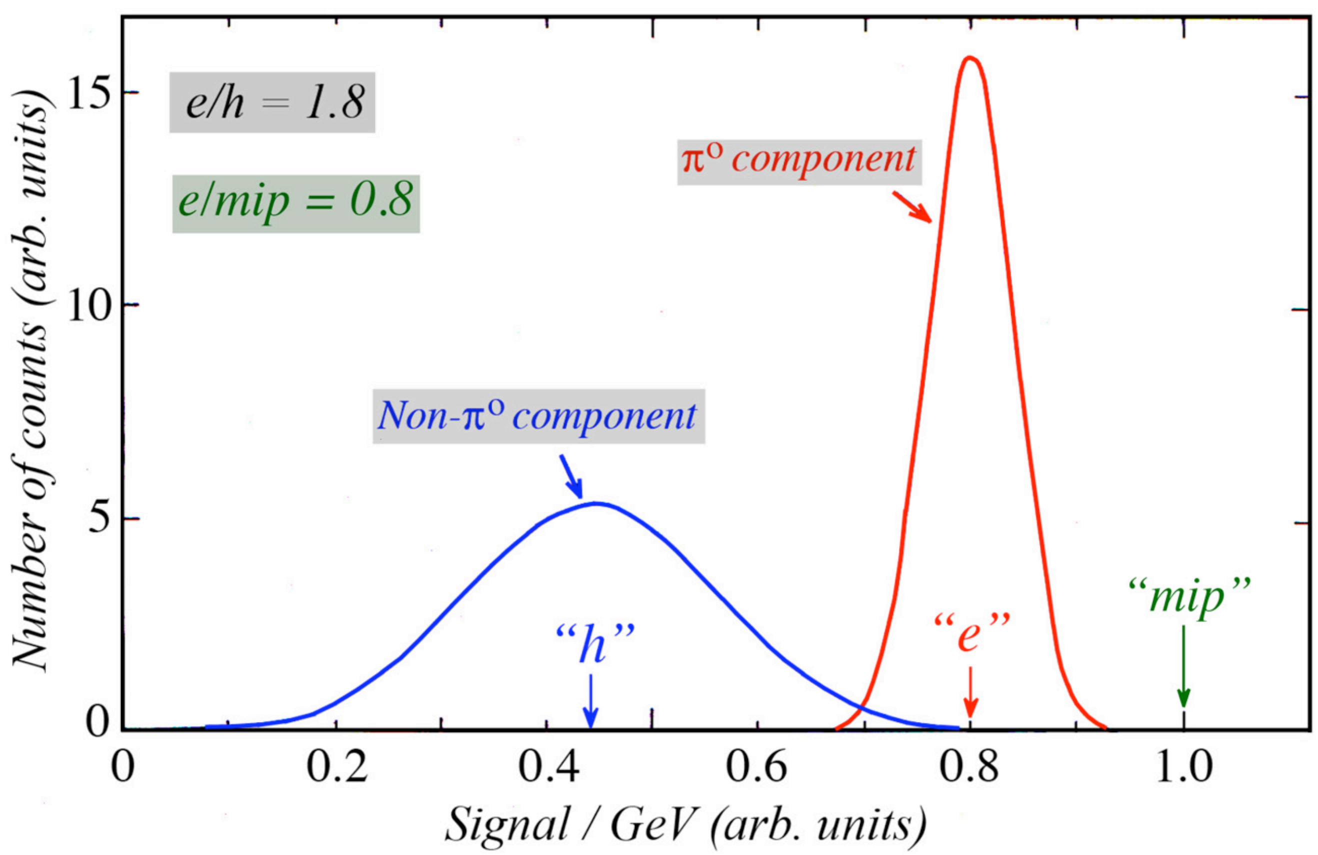
Dual Readout (DRO) for hadronic energy resolution

arXiv:1712.05494

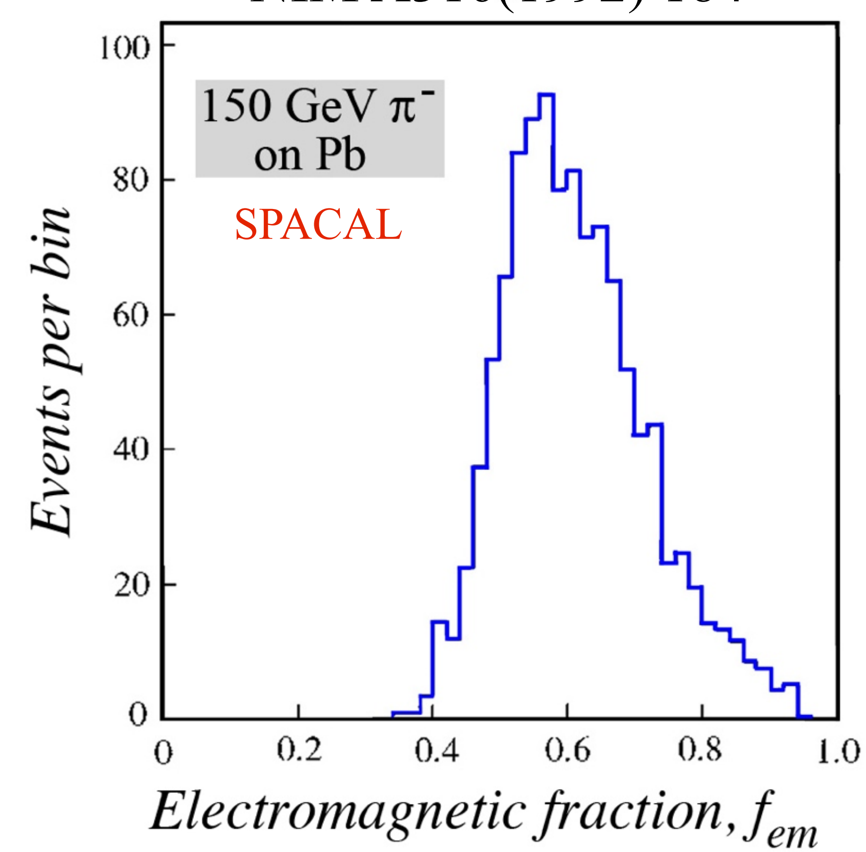
- Hadronic showers are composed of both EM (π^0) and hadronic (non-π^0) components.
- Detector response to EM and hadronic components is usually very different.



- Event-by-event fluctuations in EM fraction (f_{EM}) dominates hadronic energy resolution



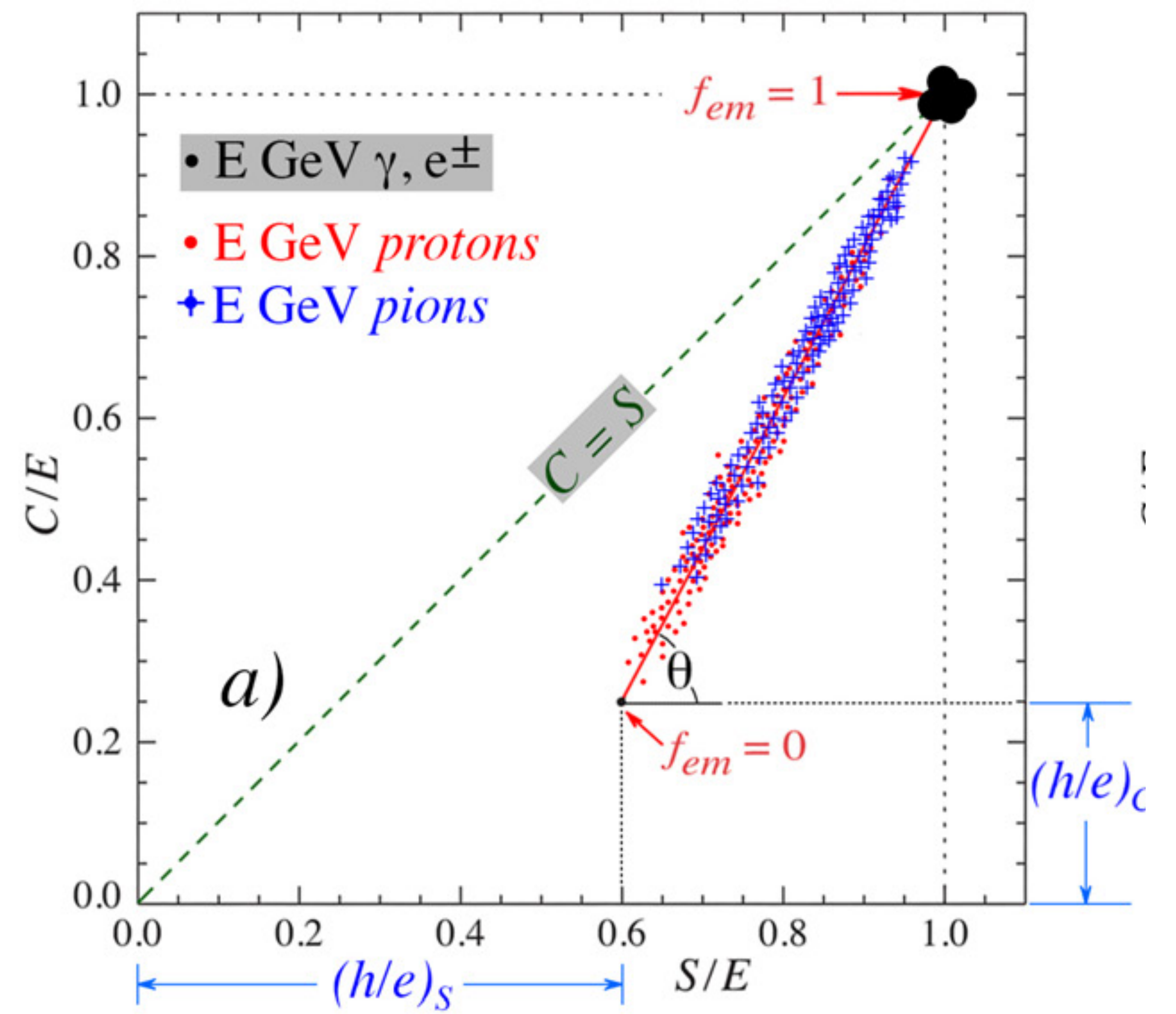
NIM A316(1992) 184



Dual Readout (DRO) for hadronic energy resolution

arXiv:1712.05494

- **Solution to f_{EM} fluctuations** : measure f_{EM} event-by-event through separate measurements of Scintillation (S) and Cherenkov (C) signals.
  - C signal dominated by EM component since i is produced only by relativistic particles
- Measure (h/e) for S and C with test beam to determine χ factor.
- Measure S and C separately event-by-event in situ and use χ to determine E.



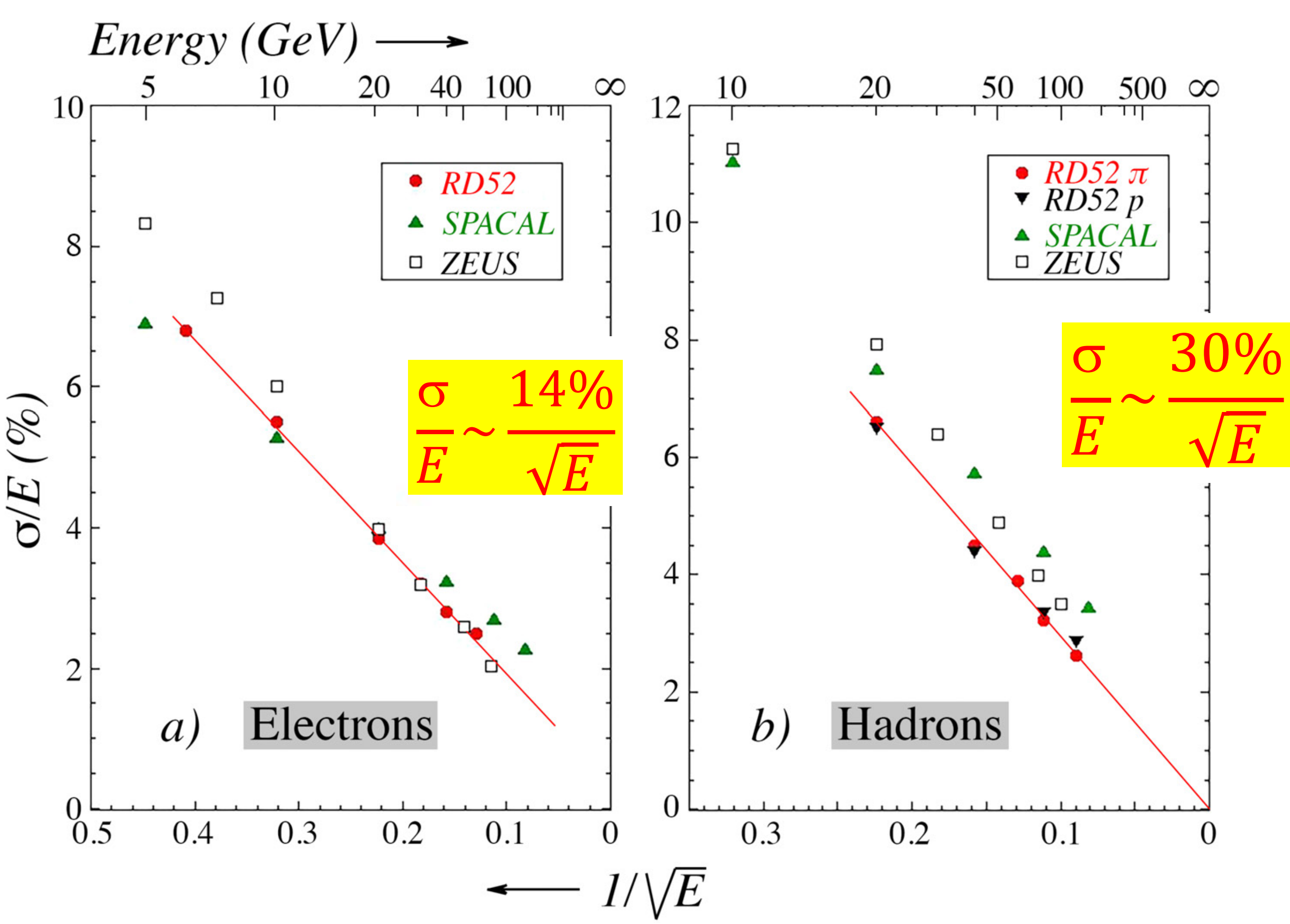
$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S-\chi C}{1-\chi}$$

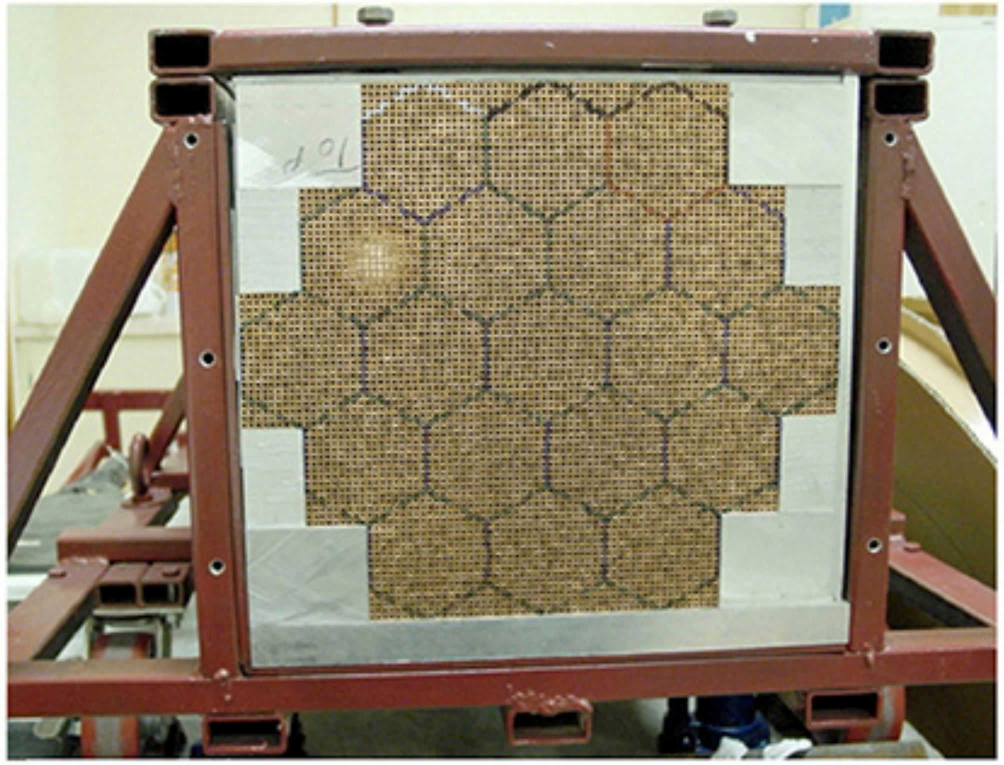
Dual Readout (DRO) for hadronic energy resolution

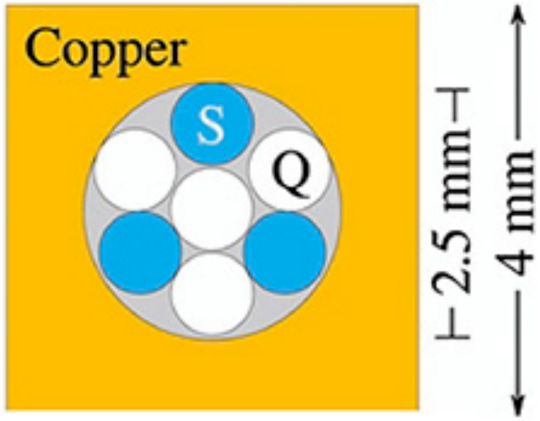
arXiv:1712.05494

- Extensive R&D with DREAM/IDEA/RD52 detectors
- Excellent hadronic energy resolution of 30% / sqrt(E)!!
- Insufficient EM energy resolution of 14% / sqrt(E)



- DREAM detector





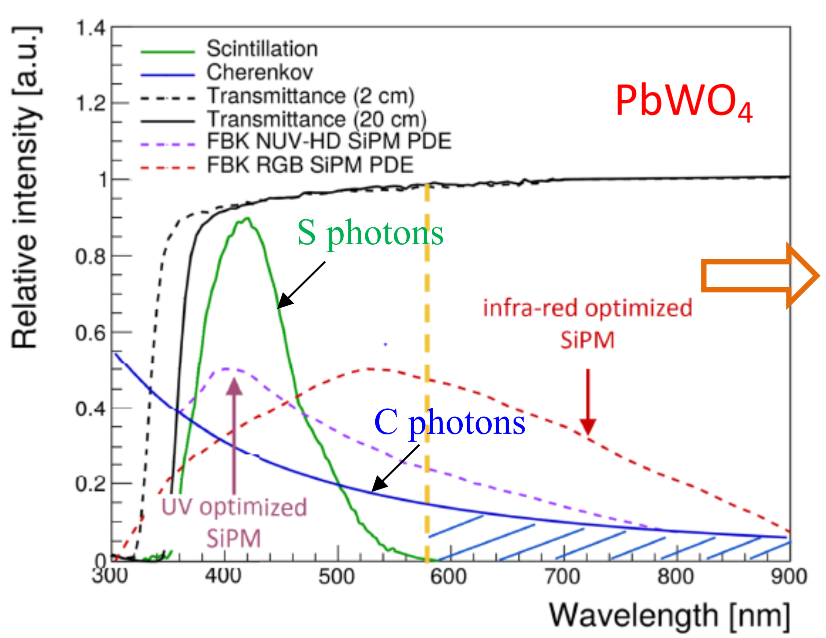
CalVision : Crystal ECAL + DRO

https://detectors.fnal.gov/projects/calvision/

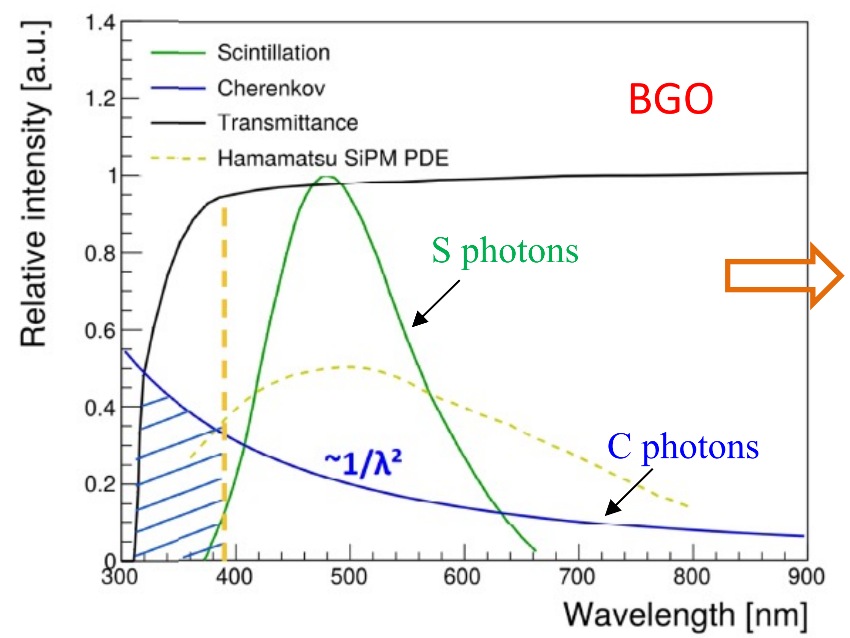
- Homogenous, total absorption crystal ECALs provide optimal resolution of 3% / sqrt(E)
- Apply DRO to crystal for ultimate ECAL + HCAL system.
- How to separate S and C in homogenous crystal?
    - Wavelength and pulse shape (time)
    - Angular distribution, polarization
- **Wavelength separation** using SiPMs with crystal-specific wavelength optimization and/or filtering.

Lucchini, Eno, Tully, et al JINST 15 (2020) P11005

Annotation from Y. Lai (UMD) CALOR 2022



Cherenkov photons above the scintillation peak are much less affected by self-absorption



Larger detection window for Cherenkov photons below the scintillation peak

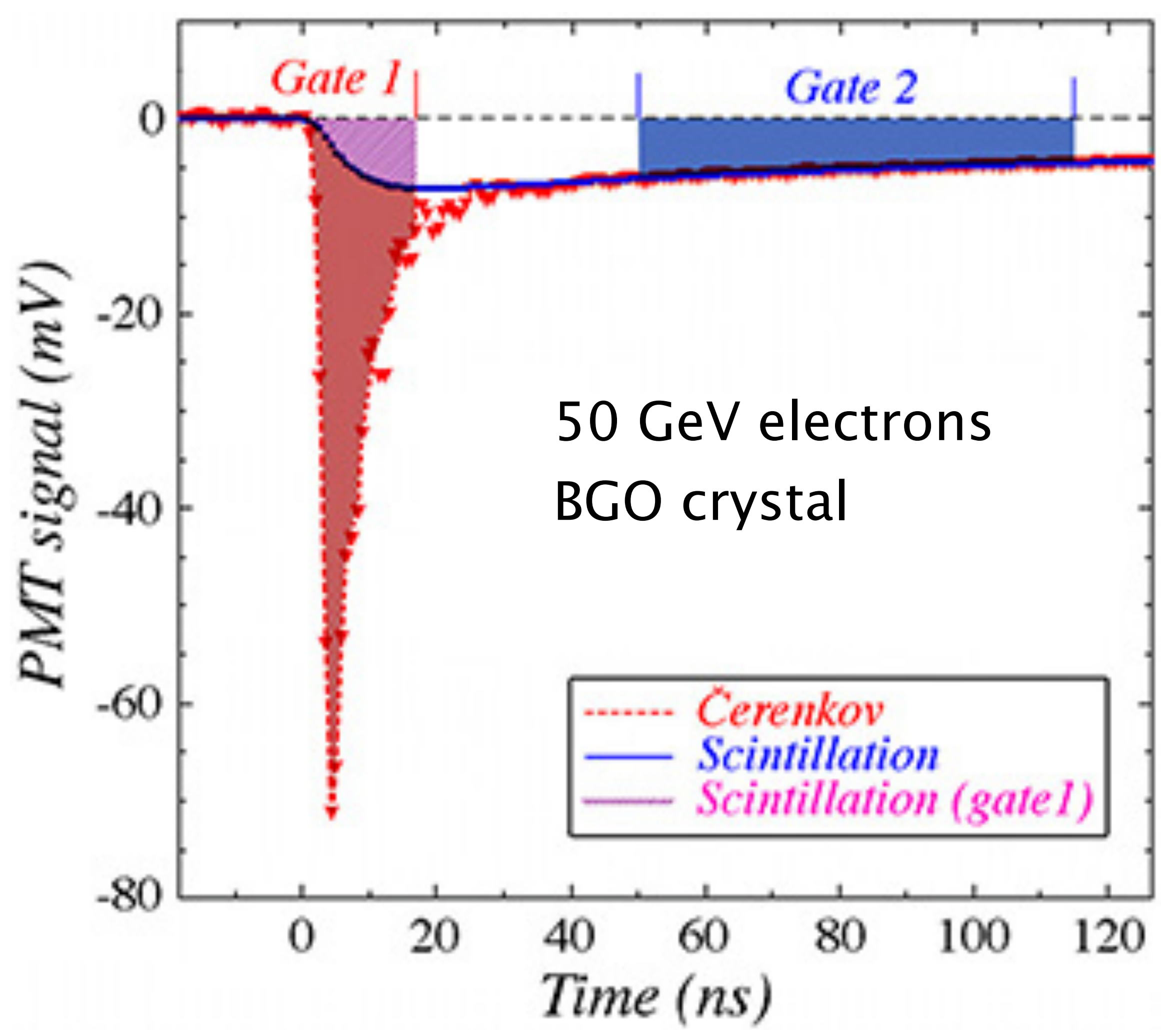
11

CalVision : Crystal ECAL + DRO

- Homogenous, total absorption crystal ECALs provide optimal resolution of 3% / sqrt(E)
- Apply DRO to crystal for ultimate ECAL + HCAL system.
- How to separate S and C in homogenous crystal?
  - Wavelength and pulse shape (time)
  - Angular distribution, polarization

- **Timing separation** based on prompt C signal and slower S signal.
- Smart front-end electronics essential for prompt S/C separation based on timing.

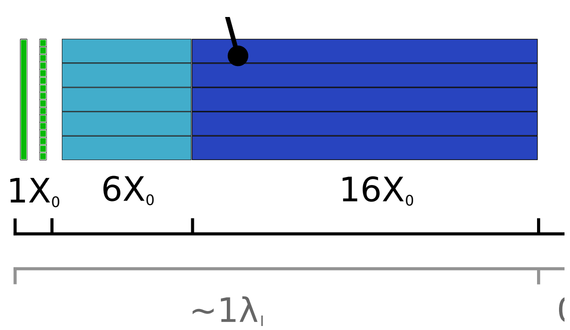
arXiv:1712.05494

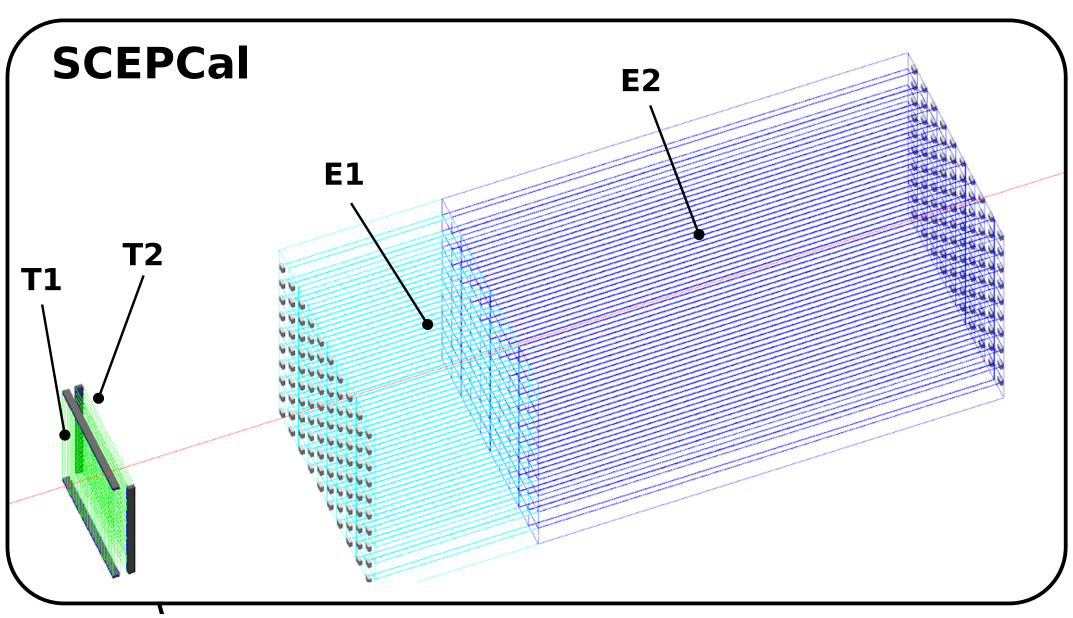


Segmented Crystal ECAL

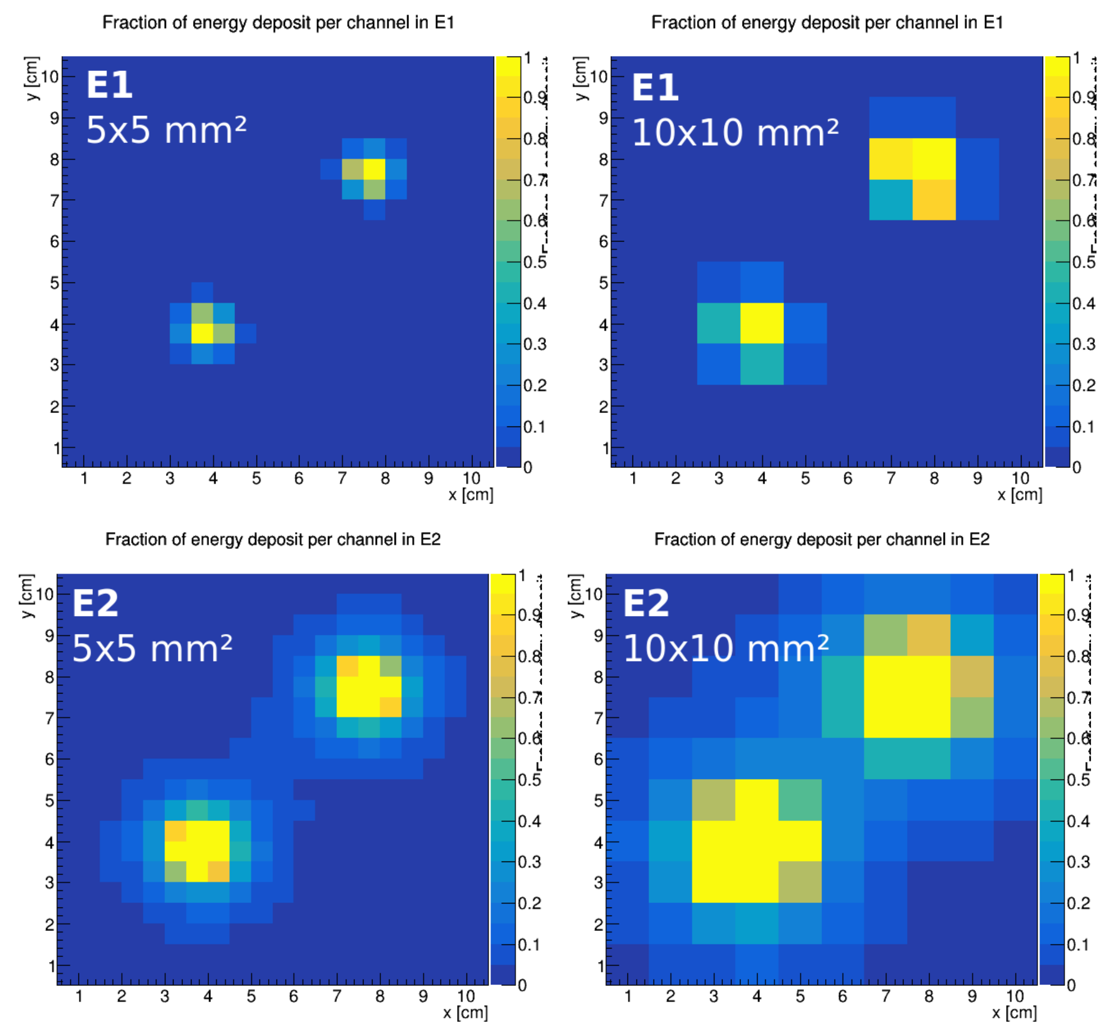
- Segmented Crystal EM Precision Calorimeter (SCEPCal) concept.
- 2 timing layers (T1, T2)
  - Fast, bright crystals (LYSO:Ce)
  - 3mm thick (1 X0)
  - Provides 20 ps timing precision for MIPs
- 2 EM calorimetric segments using DRO-capable crystals (PbWO4, BGO, BSO)
  - No dead material between segments (read out from front and back)
  - 2 segments improve photon separation in general
  - 2 segments provide segmentation for BIB

Lucchini, Eno, Tully, et al JINST 15 (2020) P11005





PbWO4 separation of 2 photons with 3° opening angle



SCEPCAL materials

Lucchini, Eno, Tully, et al JINST 15 (2020) P11005

Table 1. Comparison of some of the key crystal properties for HEP applications. From left to right: crystal name, density, interaction length, radiation length, Molière radius, light yield relative to that of $PbWO_4$, scintillation decay time, photon time density and estimated cost for mass production.

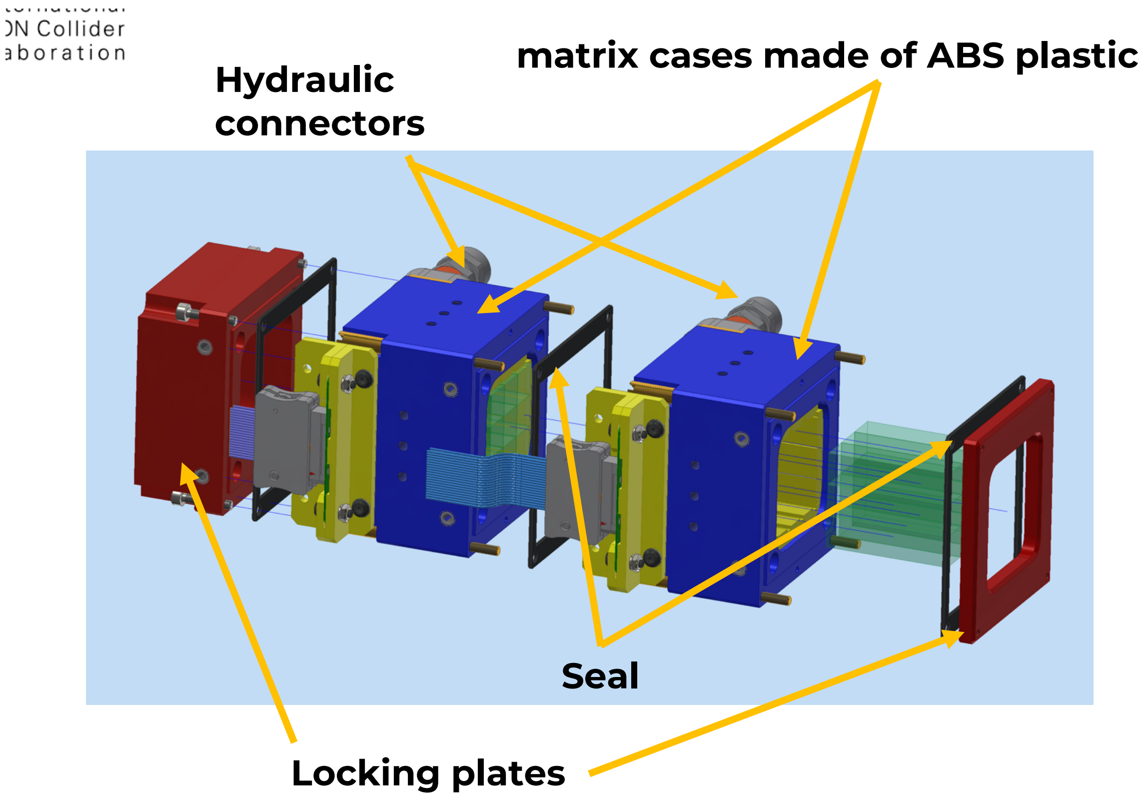
Crystal	ρ [g/cm^3]	λ_I [cm]	X_0 [cm]	R_M [cm]	LY/LY$_0$ [a.u.]	τ_D [ns]	Photon density [photons/ns]	Est. cost [\$/cm^2/X_0]
$PbWO_4$	8.3	20.9	0.89	2.00	1	10	0.10	7.1
BGO	7.1	22.7	1.12	2.23	70	300	0.23	7.8
BSO	6.8	23.4	1.15	2.33	14	100	0.14	7.8
CsI	4.5	39.3	1.86	3.57	550	1220	0.45	8.0

Table 2. Photon yield for both Cherenkov and scintillation light in response to a 45 GeV electron shower in the rear SCEPCal segment assuming a $PbWO_4$ crystal and the SiPM spectral sensitivity shown in figure 24 (left).

	Scintillation [photons/GeV]	f_S [%]	Cherenkov [photons/GeV]	f_C [%]
Generated	200000	100	56000	100
Collected	10000	5.0	2130	3.8
Detected by NUV SiPM #1 ($\lambda < 550$ nm)	2000	1.0	140	0.25
Detected by RGB SiPM #2 ($\lambda > 550$ nm)	< 20	< 0.01	160	0.3

50 C photons/GeV sufficient that photostatistics do not impact energy resolution

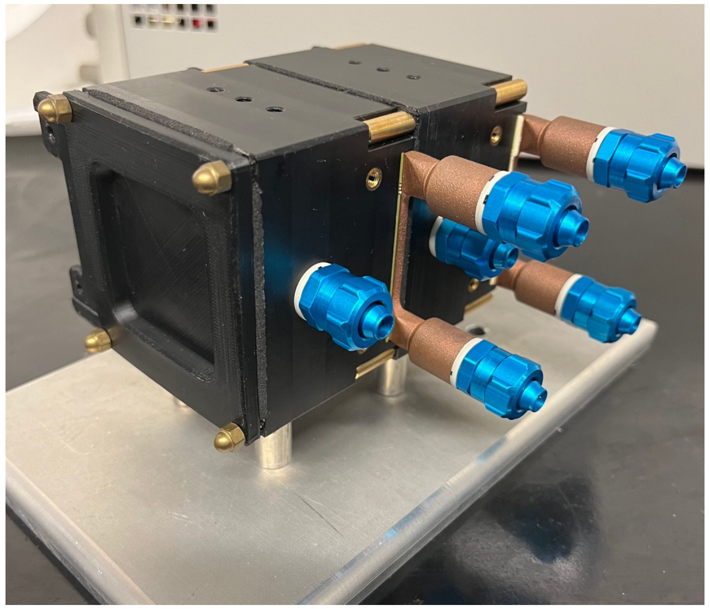
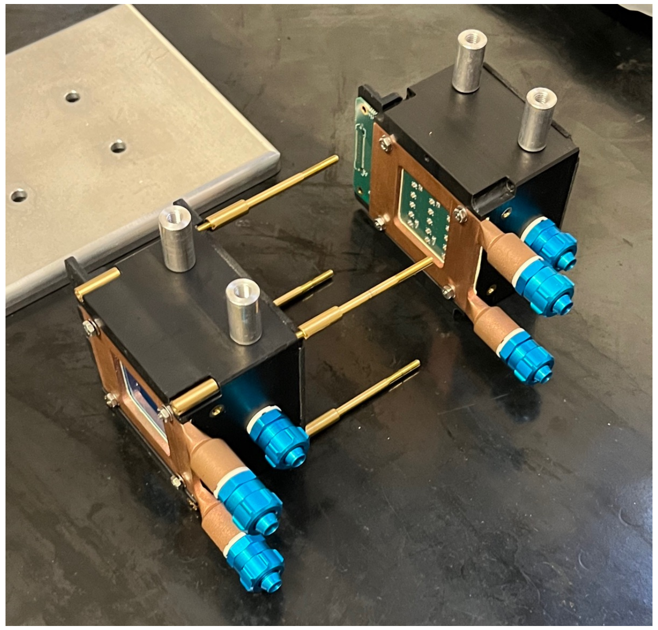
Crilin : CRystal calorImeter with Longitudinal INformation



- Muon collider specific EM calorimeter focusing on timing and longitudinal segmentation for minimizing BIB.

Key properties:

- Fine granularity : 5 layers of 10x10x40 mm^3
- Timing resolution ~100 ps @ 1 GeV
- Good energy resolution ~ 10% / sqrt(E)
- 1/10th cost reference Si-W reference (!!)
- Highly modular

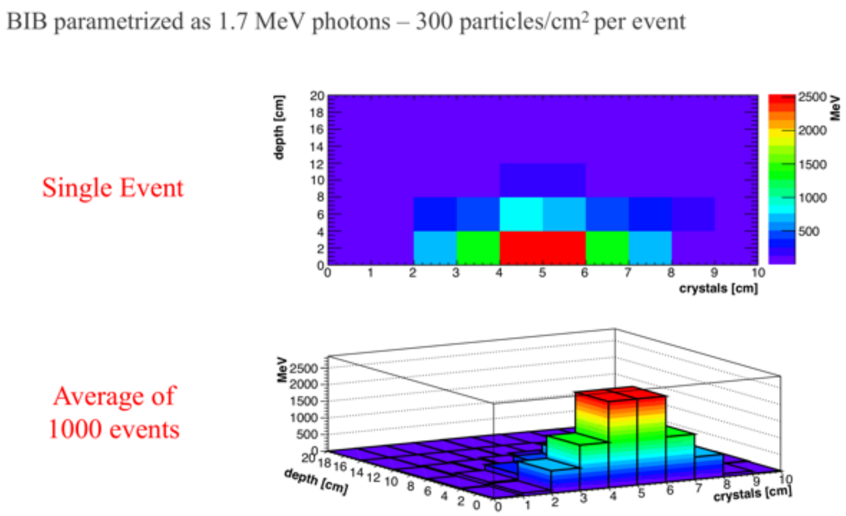




https://www.sciencedirect.com/science/article/abs/pii/S0168900222011093
E. Diociaiuti, IMC Collaboration Mtg, Sep 2023

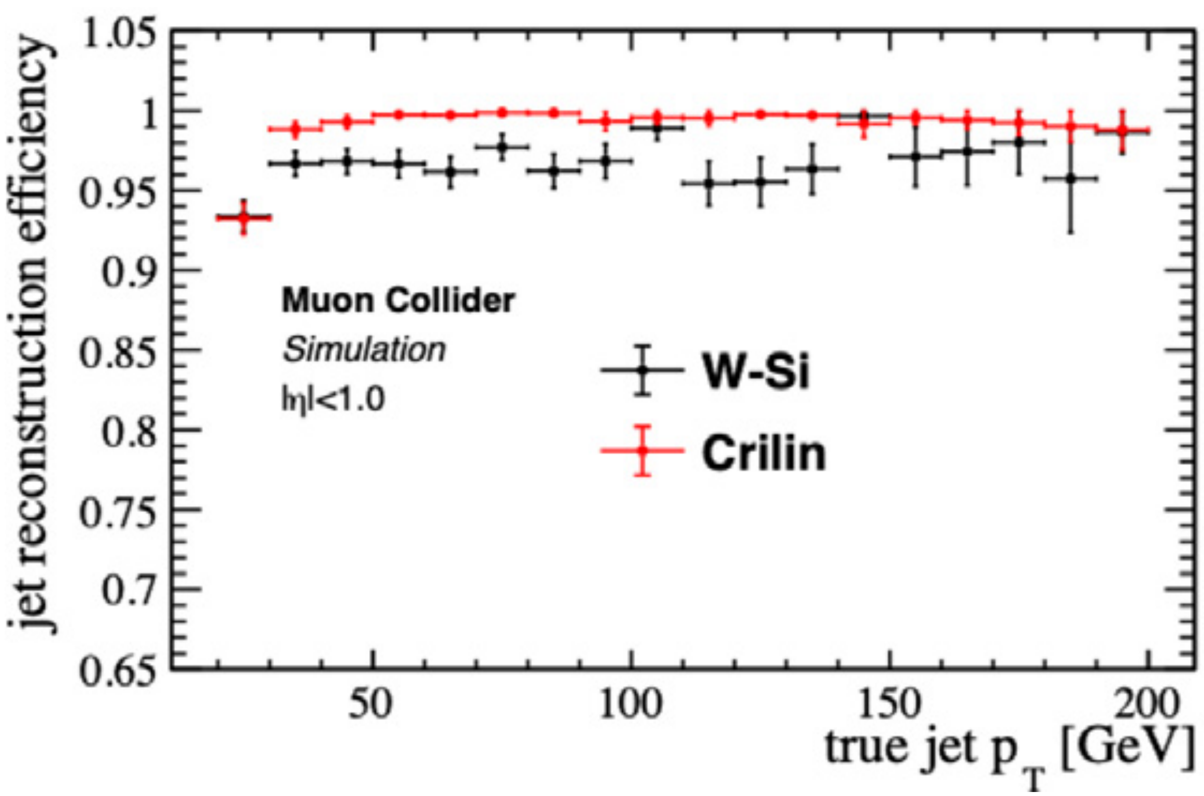
Crilin performance

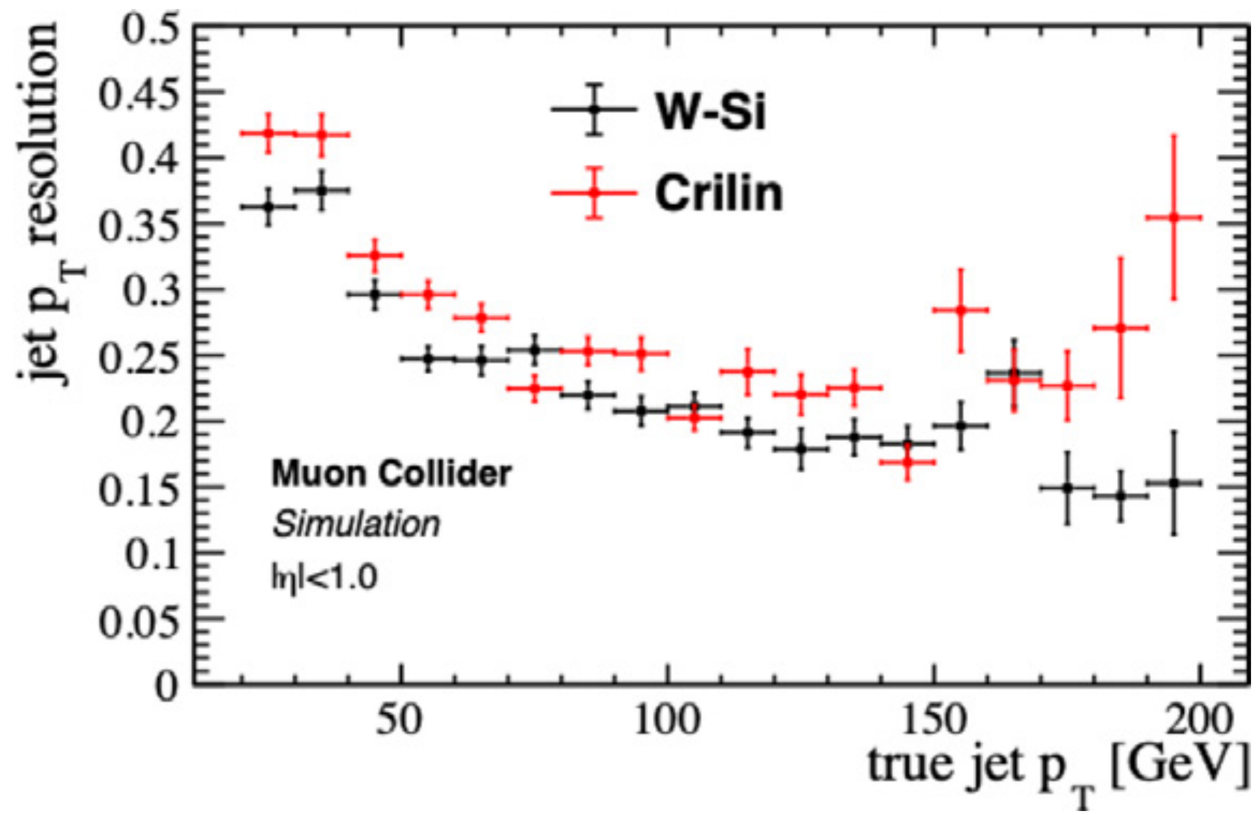
- Simulate H->bb at sqrt(s) = 1.5 TeV
- BIB = 300 photon/cm2/BX
- Use particle flow with tracker and HCAL
- Compare jet reconstruction efficiency and jet pT resolution for Si-W and Crilin ECALs
  - Jet fake rate comparable between two configurations

Most of BIB photons are absorbed in the first layer



:





https://www.sciencedirect.com/science/article/abs/pii/S0168900222011093
E. Diociaiuti, IMC Collaboration Mtg, Sep 2023

Crilin 2023 Beam Test

arXiv:2308.01148

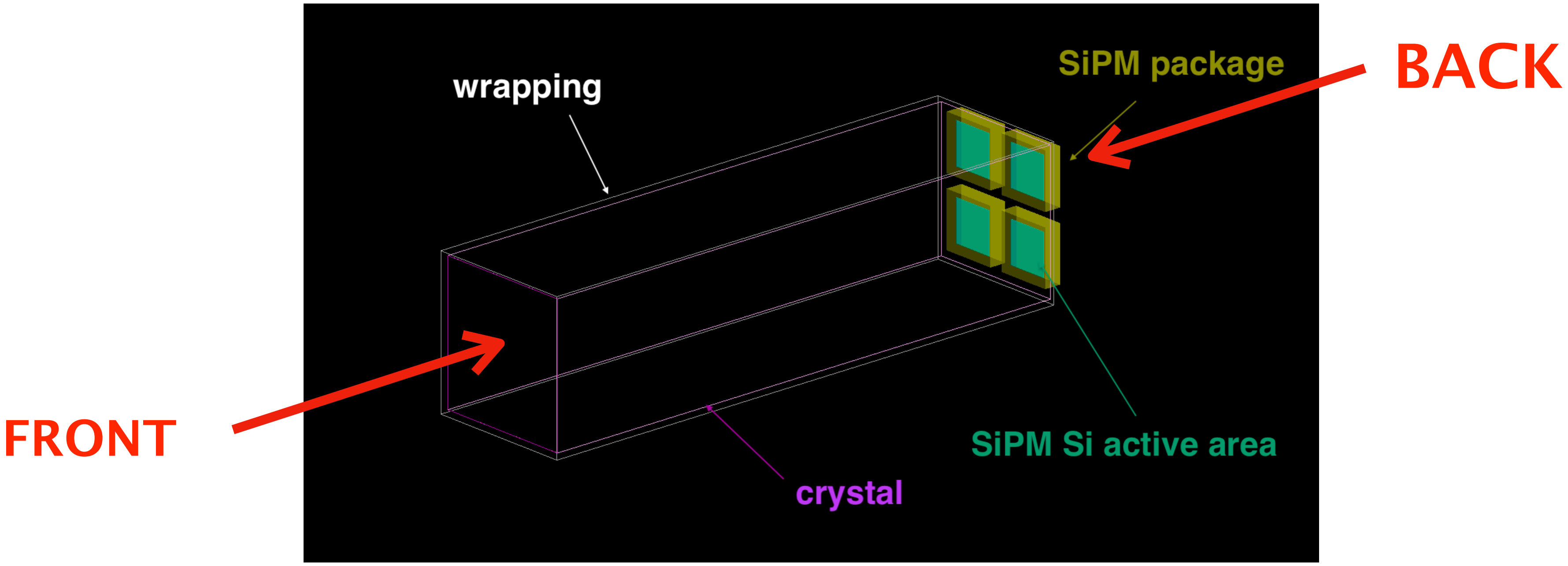
Evaluated single crystals of

- PbF2 with UV-extended SiPMs
- $PbWO_4$-UF crystals.

Crystal	PbF_2	PWO-UF
Density [g/cm^3]	7.77	8.27
Radiation length [cm]	0.93	0.89
Molière radius [cm]	2.2	2.0
Decay constant [ns]	-	0.64
Refractive index at 450 nm	1.8	2.2
Manufacturer	SICCAS	Crytur

Evaluated two crystal+SiPM orientations relative to beam

- Beam from FRONT
- Beam from BACK

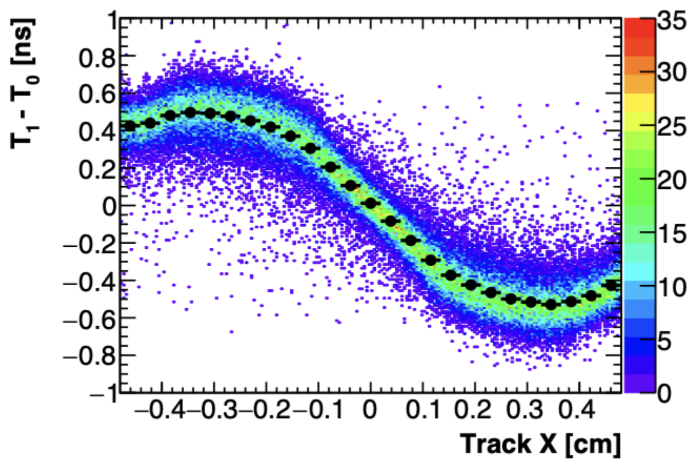


Crilin 2023 Beam Test Results

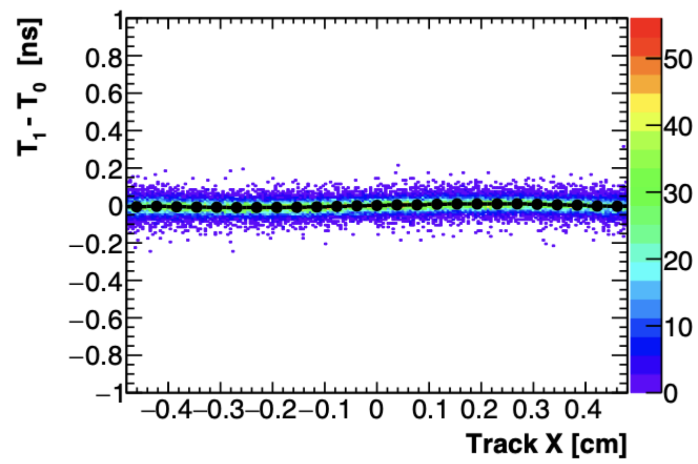
arXiv:2308.01148

- PbF2 outperforms PbWO4 b/c all light is Cherenkov, Cherenkov is "faster" than UF scintillator
- Back illumination outperforms Front because Front suffers from strong timing dependence on particle location on face of crystal.

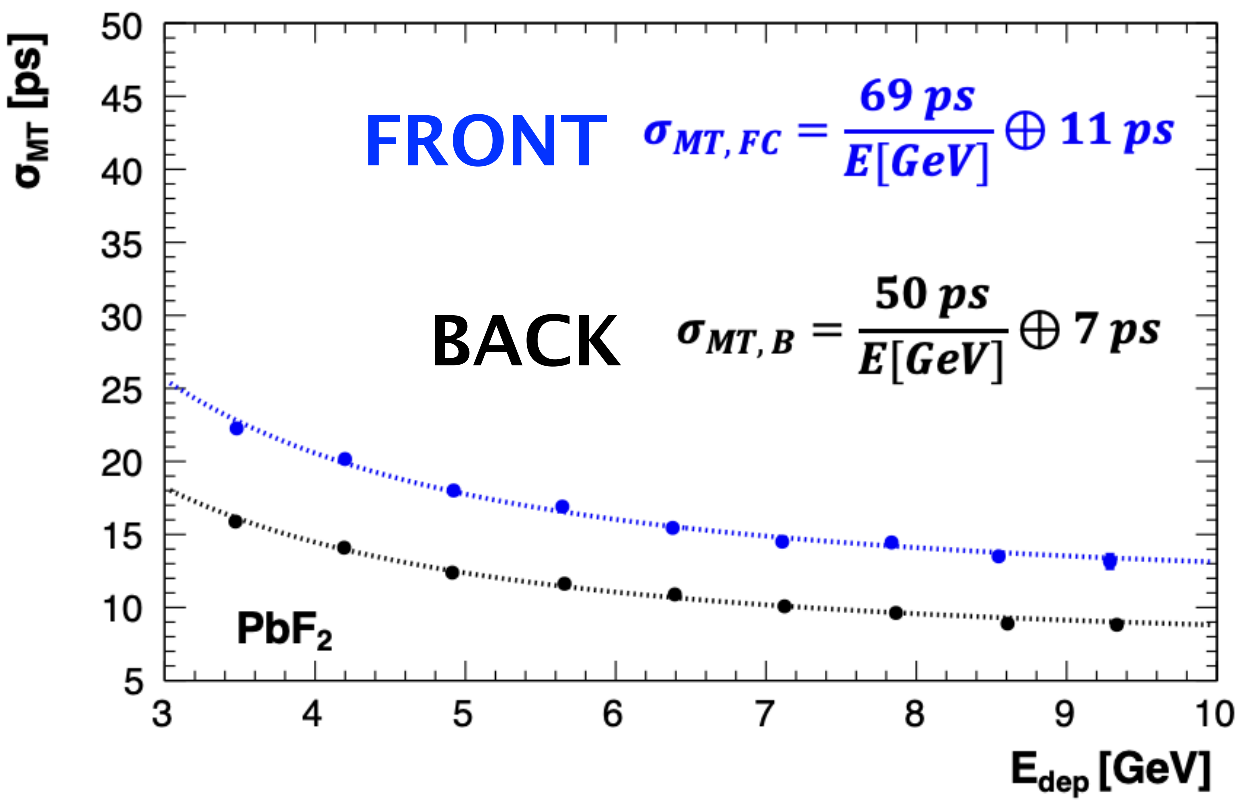
FRONT



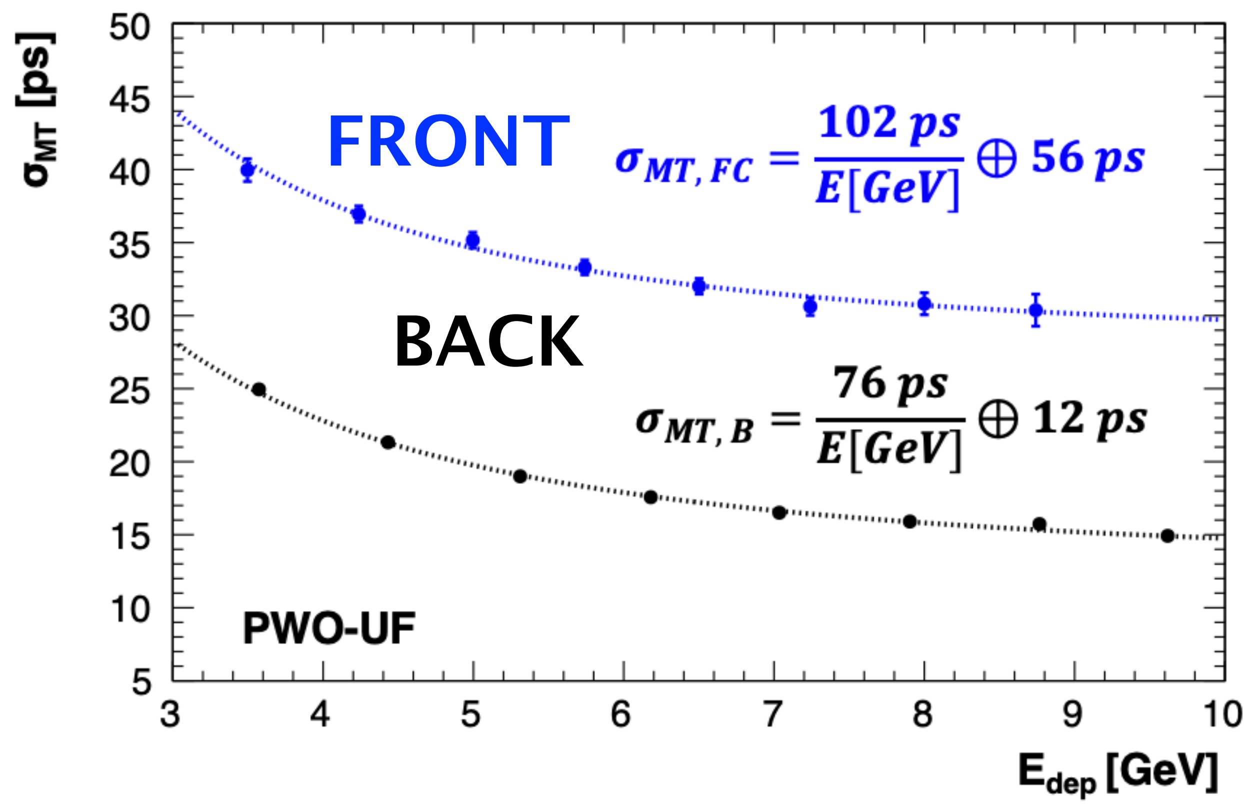
BACK



PbF_2



$PbWO_4$–UF



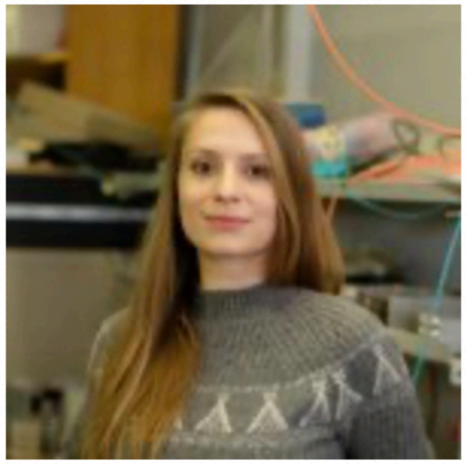
Join us for Calo R&D at LPC!

- The CalVision collaboration is active here at the LPC working on a couple fronts:

Using wavelength, timing, polarization in homogeneous calorimetry to improve hadronic resolution while maintaining state-of-the-art EM resolution and developing novel particle-flow and machine-learning algorithms for application in DRO calorimetry.

- While CalVision nominally targets an e+e- Higgs factories, the same principles can be applied at a Muon Collider.
- Most recent work targeting characterization and optimization of timing properties : How does optimal timing for DRO crystal calorimeters depend on segmentation, orientation/arrangement of photosensors, material properties, wavelength sensitivity, etc.?

- New Initiatives 2023 Awardee — https://detectors.fnal.gov/seeding-new-ideas/



PI: Grace Cummings

Co-PI: Jim Hirschauer, Jim Freeman, Hans Wenzel (all Fermilab)

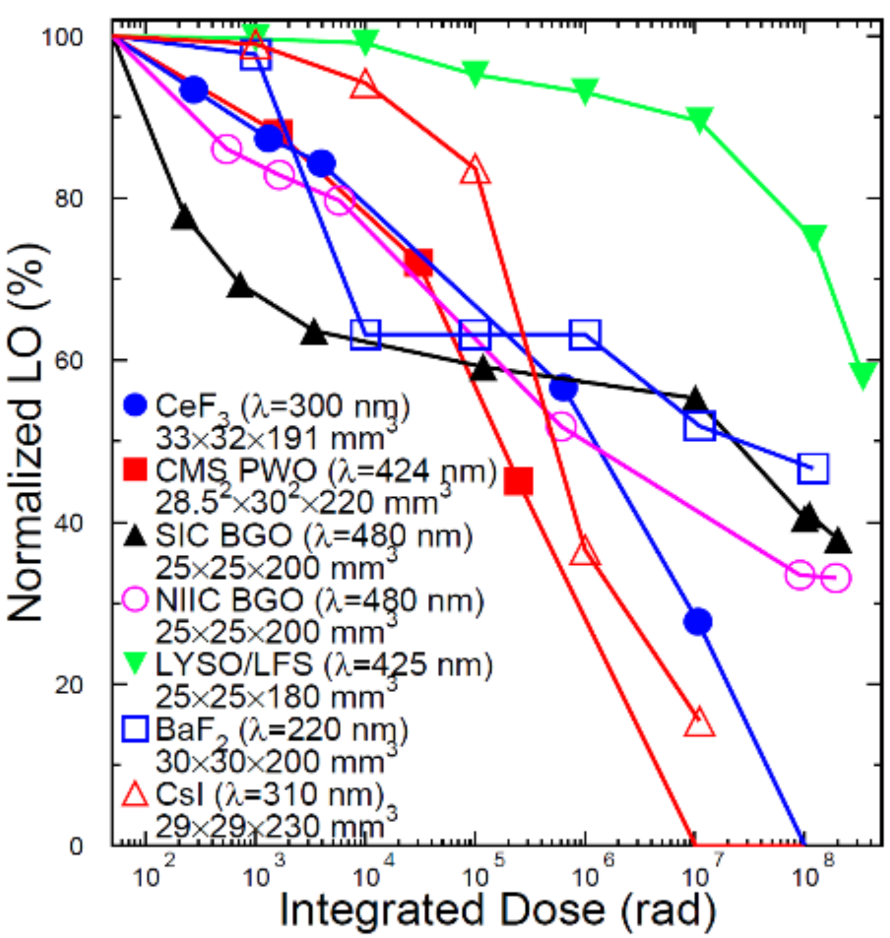
Maximal Information Calorimetry – characterizing picosecond timing capabilities of total absorption dual-readout calorimeters
This proposal aims to understand the picosecond timing capabilities of dual-readout (DR) crystal calorimeters. The DR method is the separate measurement of the electromagnetic and hadronic components of a hadronic shower through the independent readout of scintillation and Cerenkov light. This optimizes energy resolution through separate calibration of each component. We propose to study the timing resolution achievable with such a DR calorimeter using the separate time measurements of scintillation (S) and Cerenkov (C) light pulses. This proposal brings the new thrust of picosecond timing to the CalVision consortium, which performs R&D for DR calorimetry for the FCC-ee.

Additional Material

Scintillator radiation tolerance

- Extensive R&D by RY Zhu (Caltech) and others.
- Recently:
  - doi:10.1088/1742-6596/1162/1/012022
  - arXiv:2203.06788

	BGO	BSO	PWO	PbF_2	PbFCl
Density (g/cm³)	7.13	6.8	8.3	7.77	7.11
Melting point (°C)	1050	1030	1123	824	608
X_0 (cm)	1.12	1.15	0.89	0.94	1.05
R_M (cm)	2.23	2.33	2.00	2.18	2.33
λ_I (cm)	22.7	23.4	20.7	22.4	24.3
Z_{eff} value	71.5	73.8	73.6	76.7	74.7
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68
Emission Peak[a] (nm)	480	470	425 420	\	420
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15
LY (ph/MeV)[c]	7,500	1,500	130	\	150
Decay Time[a] (ns)	300	100	30 10	\	3
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?
Cost ($/cc)	6.0	7.0	7.5	6.0	?



	CsI	LYSO:Ce	BaF_2	BaF_2:Y
Density (g/cm³)	4.51	7.4	4.89	4.89
Melting points (°C)	621	2050	1280	1280
X_0 (cm)	1.86	1.14	2.03	2.03
R_M (cm)	3.57	2.07	3.10	3.10
λ_I (cm)	39.3	20.9	30.7	30.7
Z_{eff}	54.0	64.8	51.6	51.6
dE/dX (MeV/cm)	5.56	9.55	6.52	6.52
λ_{peak}[a] (nm)	420 310	420	300 220	300 220
Refractive Index[b]	1.95	1.82	1.50	1.50
Normalized Light Yield[a,c]	4.2 1.3	100	42 4.8	1.7 4.8
Total Light yield (ph/MeV)	1,650	30,000	13,000	2,000
Decay time[a] (ns)	30 6	40	600 0.5	600 0.5
LY in 1st ns (photons/MeV)	100	740	1,200	1,200
1st ns LY/Total LY (%)	6.1%	2.5%	9.2%	60%

Collider Calorimeters

- ALICE FoCal-E (Si-W sampling) + FoCal-H (Cu + Scintillator fiber)
- https://indico.cern.ch/event/847884/contributions/4833007/attachments/2444499/4188638/RS_Calor-2022-RS.pdf

- CEPC high granularity, crystal ECAL
- https://indico.cern.ch/event/847884/contributions/4833028/attachments/2444738/4189238/20220516_R&D of a novel high granularity crystal ECAL.pdf

- SiD digital ECAL with large area MAPS
- https://indico.cern.ch/event/847884/contributions/4833035/attachments/2444859/4189669/calor2022-brau.pdf

- RADiCAL - Compact, rad-hard, ECAL
- https://indico.cern.ch/event/847884/contributions/4833038/attachments/2444198/4188065/RADiCAL-Ultracompact Radiation-hard Fast-timing EM Calorimetry.pdf

- ADRIANO2 - High granularity, Dual readout (lead-glass + plastic scintillator tiles)
- https://indico.cern.ch/event/847884/contributions/4833201/attachments/2445108/4189657/CALOR2022_20220517.pdf

- Crilin
- https://indico.cern.ch/event/847884/contributions/4833216/attachments/2444171/4191530/Crilin-Calor_v3.pdf

- CalVision Dual Readout
- https://indico.cern.ch/event/847884/contributions/4833223/attachments/2446287/4193575/CALOR_Lai.pdf

- IDEA and DREAM — dual readout

Reference Calorimeter Details

https://muoncollider.web.cern.ch/calorimeters

ECAL

- Barrel: 40 layers of Tungsten absorber (1.9 mm) + Silicon Pad sensor; cell size: 5x5 mm2; r_min = 1500 mm; r_max = 1702 mm; half_length = 2210 mm; symmetry = dodecahedron
- Endcap: 40 layers of Tungsten absorber (1.9 mm) + Silicon Pad sensor; cell size: 5x5 mm2; r_max = 1700 mm; z_min = 2307; z_max = 2509; symmetry = dodecahedron

HCAL

- Barrel: 60 layers of Steel absorber (19 mm) + plastic scintillating tiles; cell size: 30x30 mm2; r_min = 1740 mm; r_max = 3330 mm; half_length = 2210 mm; symmetry = dodecahedron
- Endcap: 60 layers of Steel absorber (19 mm) + plastic scintillating tiles; cell size: 30x30 mm2; r_max = 3246 mm; z_min = 2539; z_max = 4129; symmetry = dodecahedron