Fermilab

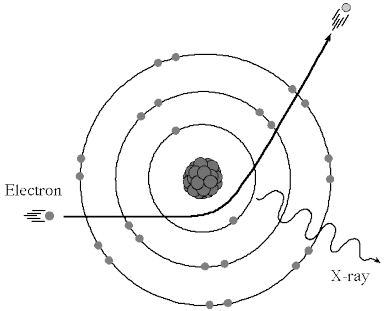
Challenges for calorimeter design at the muon collider

Grace E. Cummings

US Muon Collider Meeting, 08 August 2024

Calorimetry is challenging as it is

Electromagnetic Calorimetry



Electrons like to interact.

Whatever layer is first is your ECAL.

Hadron Calorimetry

electromagnetic and hadronic fractions fluctuate event-to-event, and have different responses

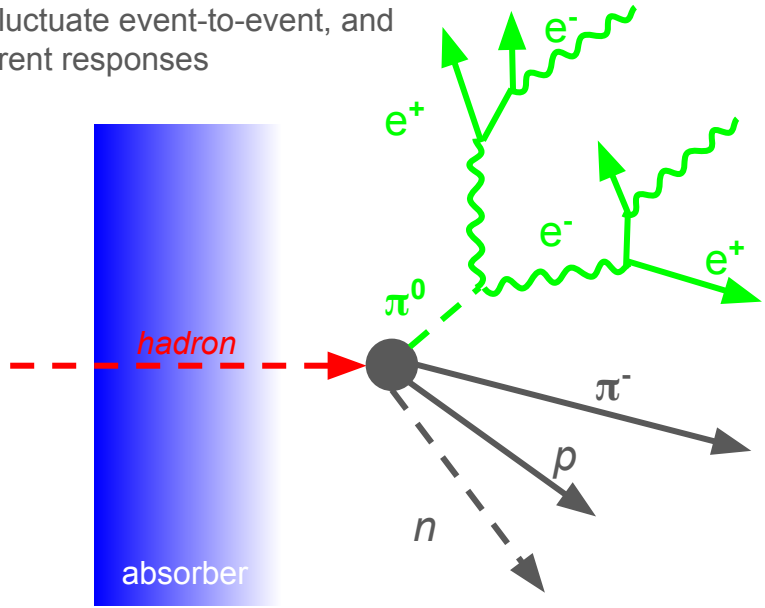
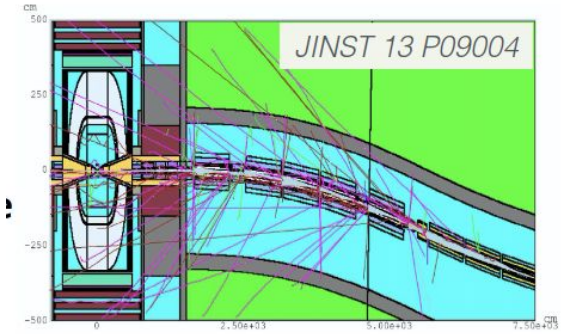


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

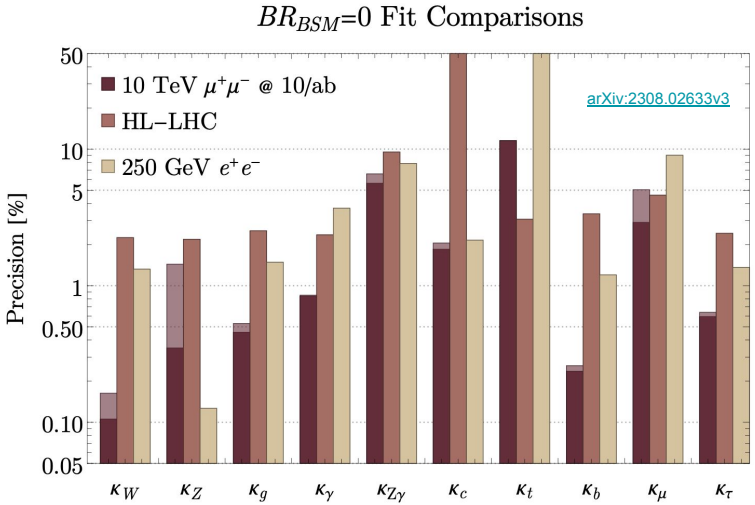
Additional challenges of a Muon Collider

Beam Induced Background (BIB)



1. occupancy
2. radiation tolerance
3. BIB rejection

Physics



dynamic range and precision

Additional challenges of a Muon Collider

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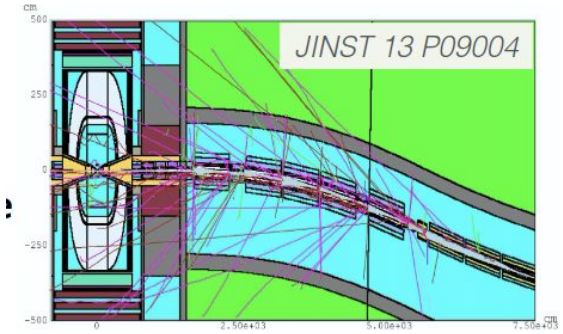

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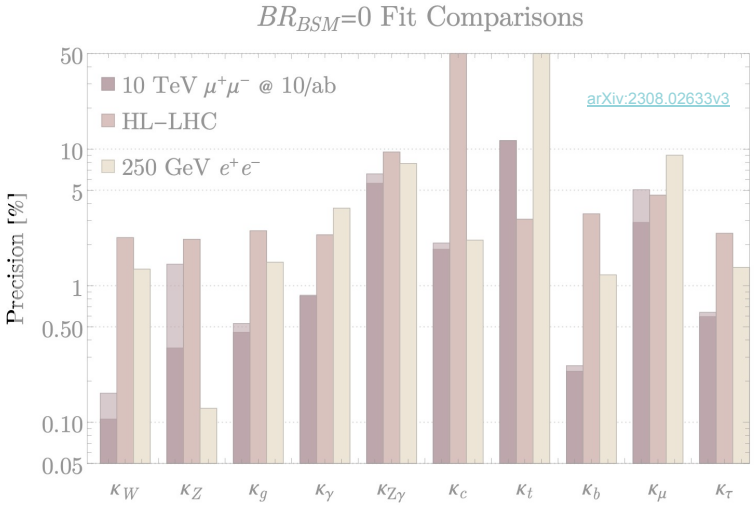
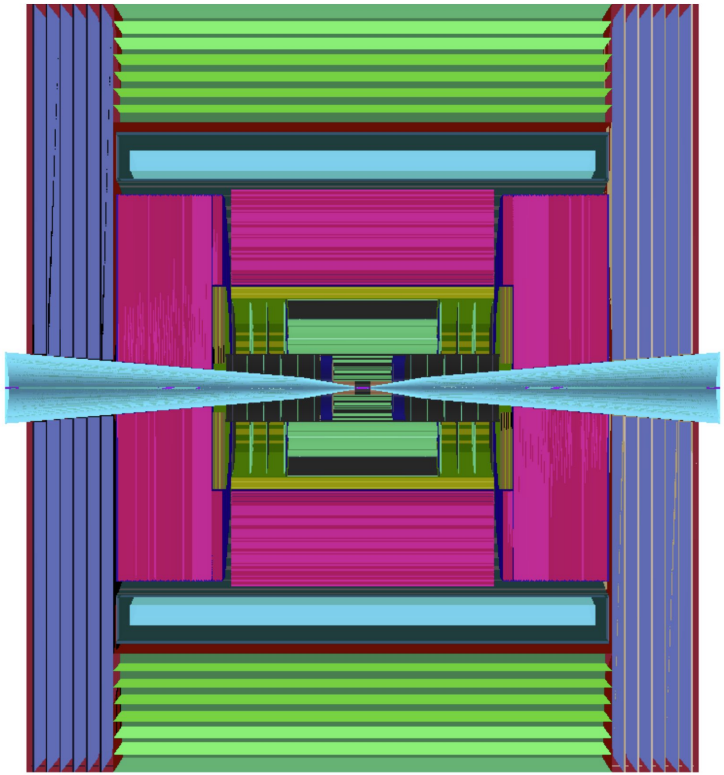


dynamic range and precision

To orient ourselves

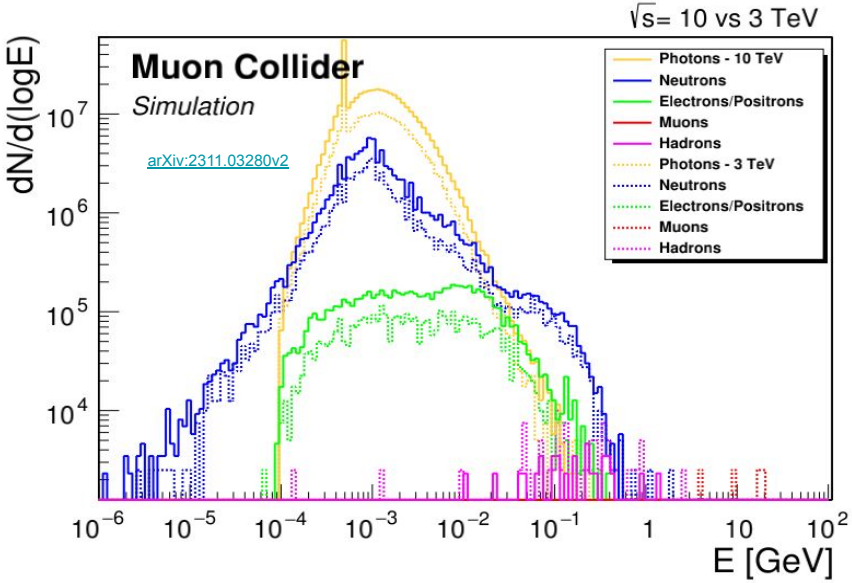
BIB photons and neutrons coming from electrons showering in the nozzles



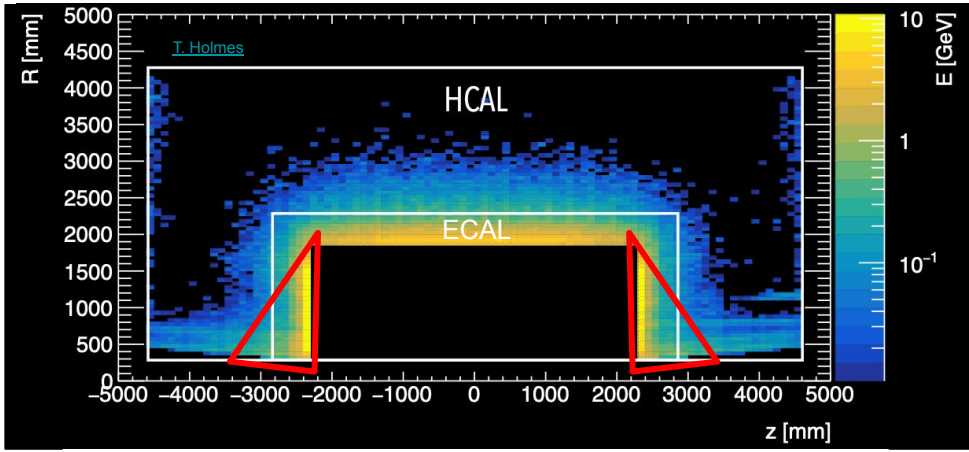
arXiv:2311.03280v2

BIB Concern - energy deposition and occupancy

Good news - Low energy!



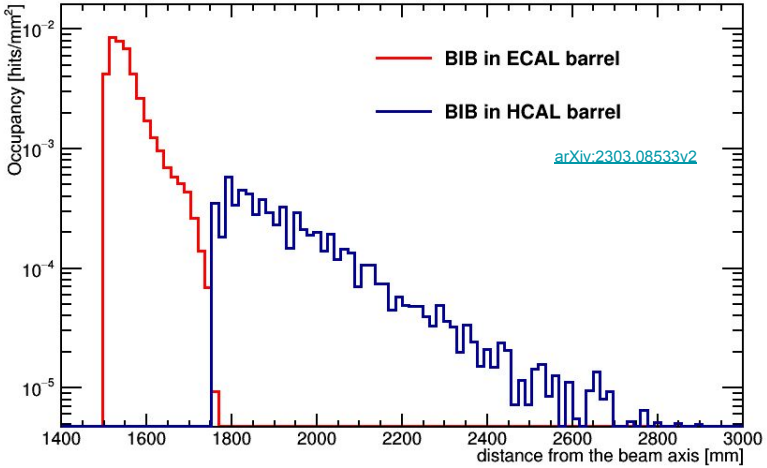
bad (ok?) news - occupancy in ECAL can be high



FORWARD REGIONS PARTICULARLY CHALLENGING

BIB Solution - energy deposition and occupancy

depth segmentation +
transverse granularity



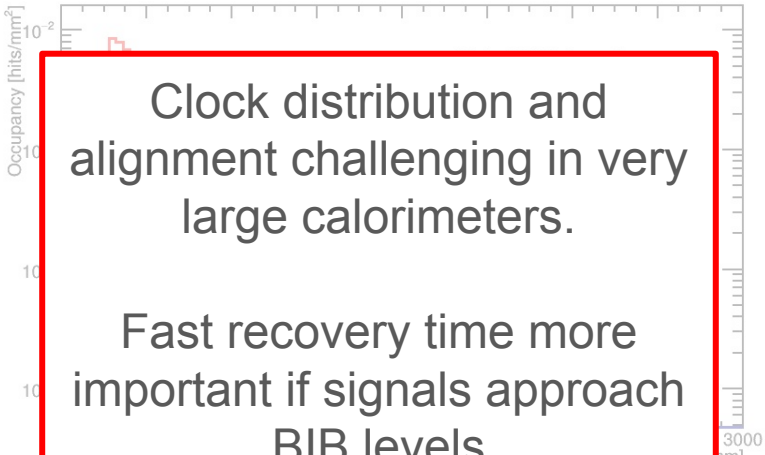
most BIB in first few layers!

BIB Solution - *time* for some good news!

depth segmentation + transverse granularity

SEE ARTUR'S TALK

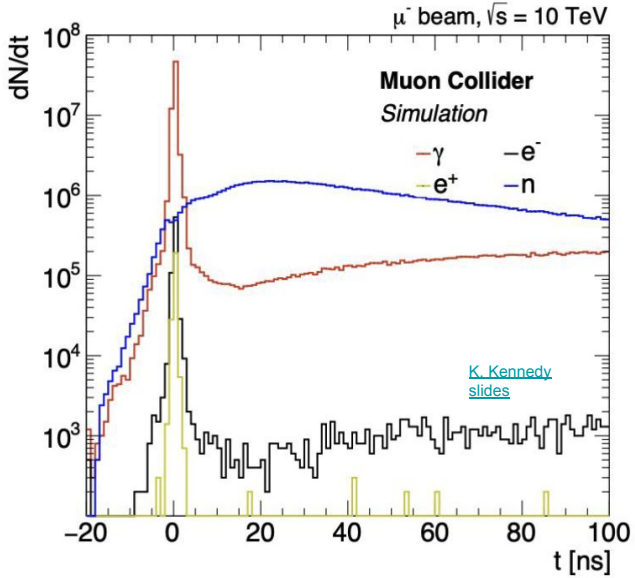
timing + fast materials + fast readout



Clock distribution and alignment challenging in very large calorimeters.

Fast recovery time more important if signals approach BIB levels

most BIB in first few layers!

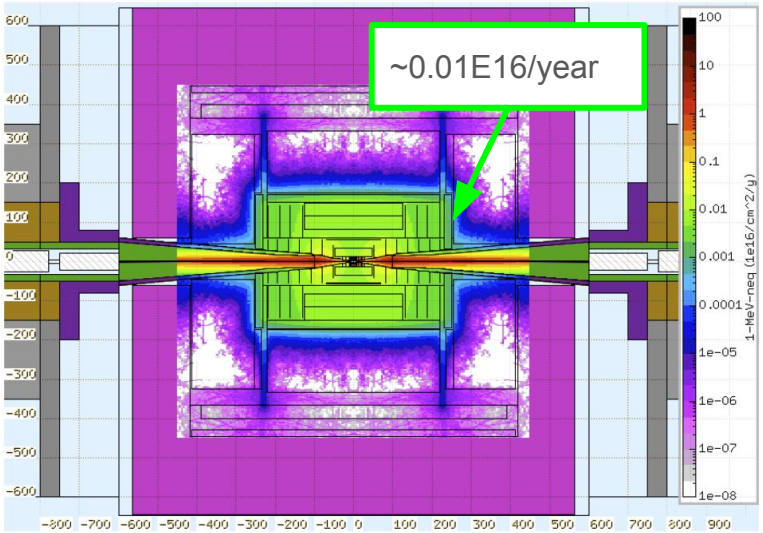


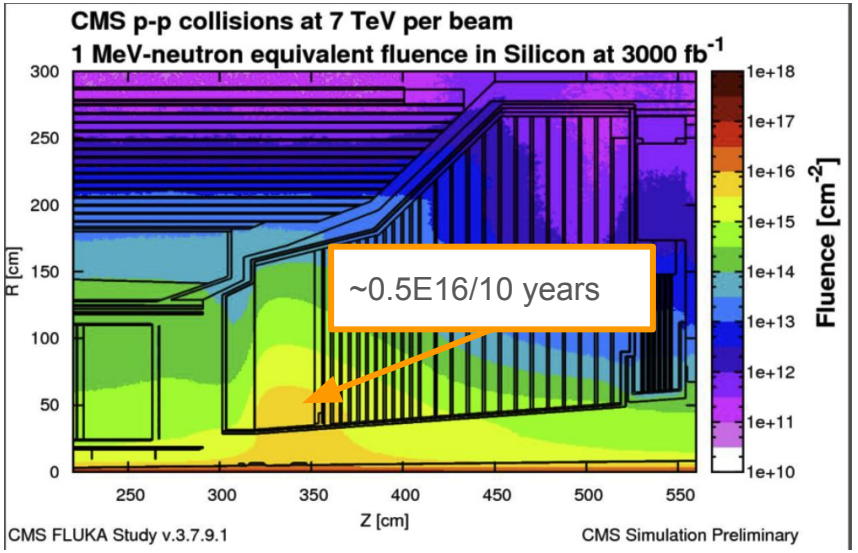
~100 ps resolution

BIB Concern - Radiation Tolerance

- "Like" HL-LHC,... but how much like really matters
  - will learn a lot from HL-LHC calorimeter upgrades
- The LHC has taught us a lot already

In my opinion, this is the largest challenge





arXiv:2303.08533v2

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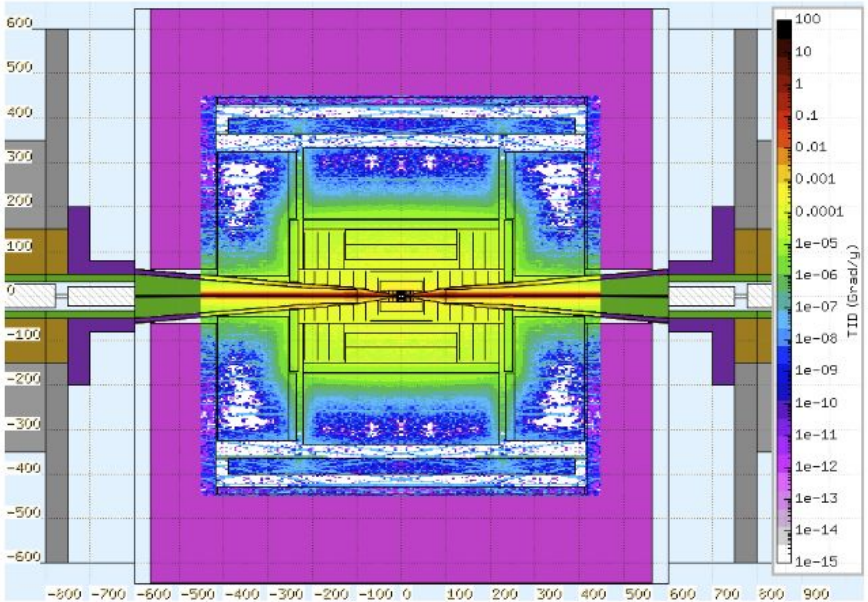


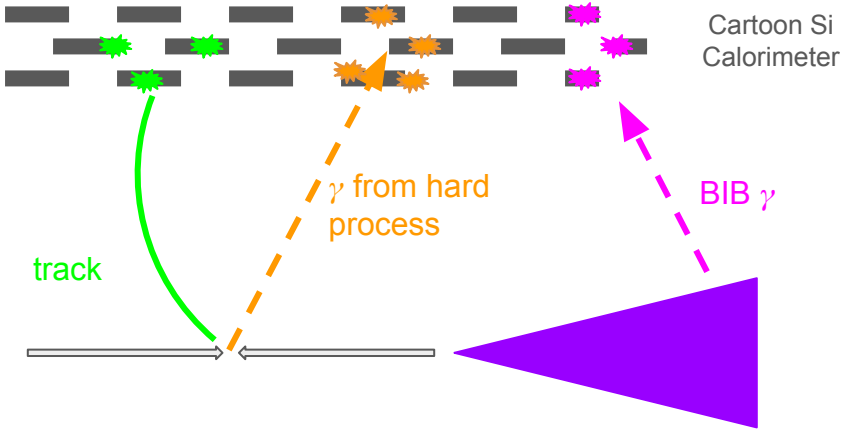
Total Ionizing Dose not terrible in comparison

~% MRad/ year in forward region… order of magnitude of so more @ HL-LHC

arXiv:2303.08533v2

BIB Solution - reconstruction for rejection

- Intimately related to Particle Flow
- But BIB probably too soft



Need enough info to know if photon is coming from vertex.

Also want to know it isn't matched to a track

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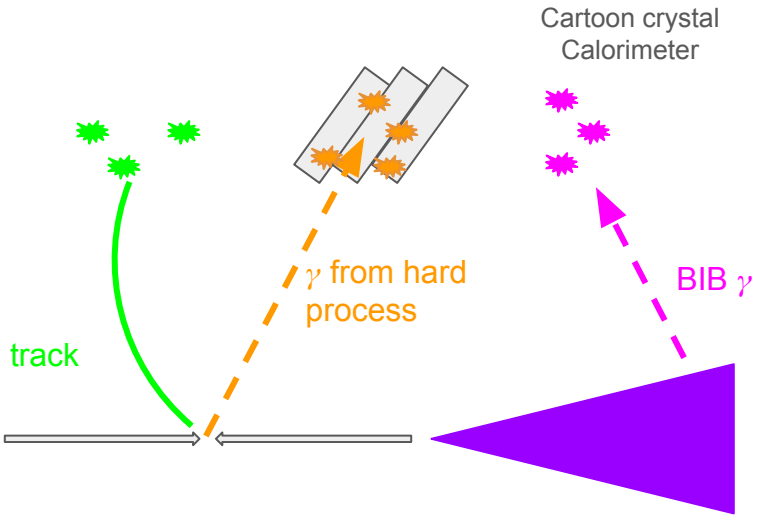

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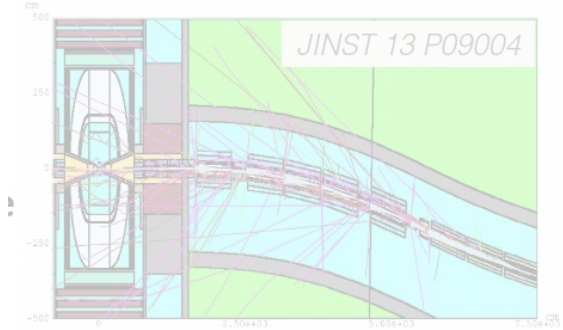

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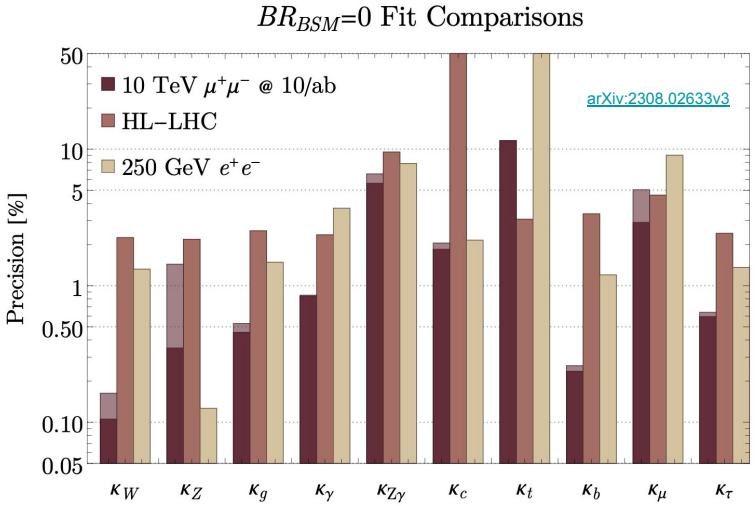
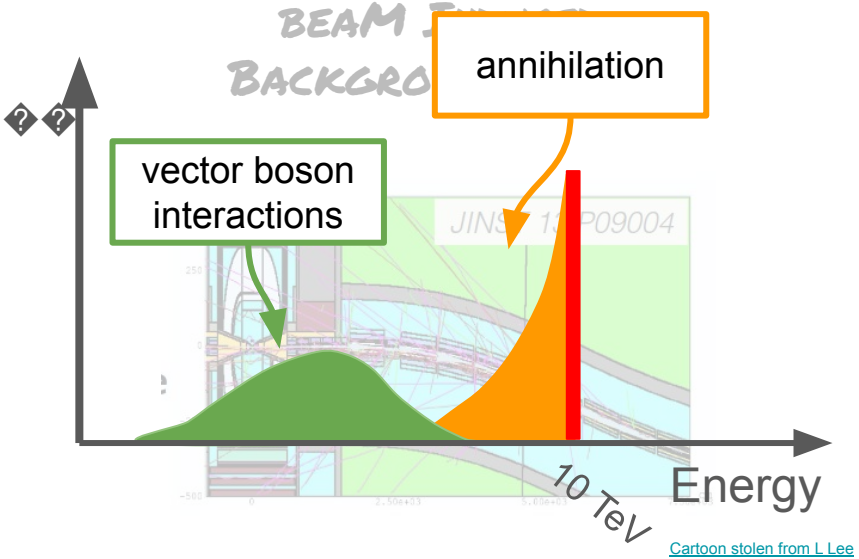


dynamic range and precision

Additional challenges of a Muon Collider

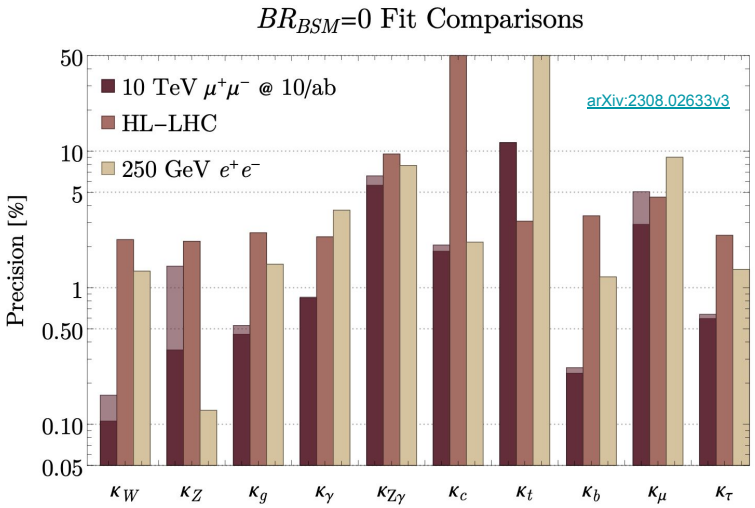


Cartoon stolen from L Lee

Huge dynamic range required!

Readout + sensors have to accommodate

Physics



dynamic range and precision

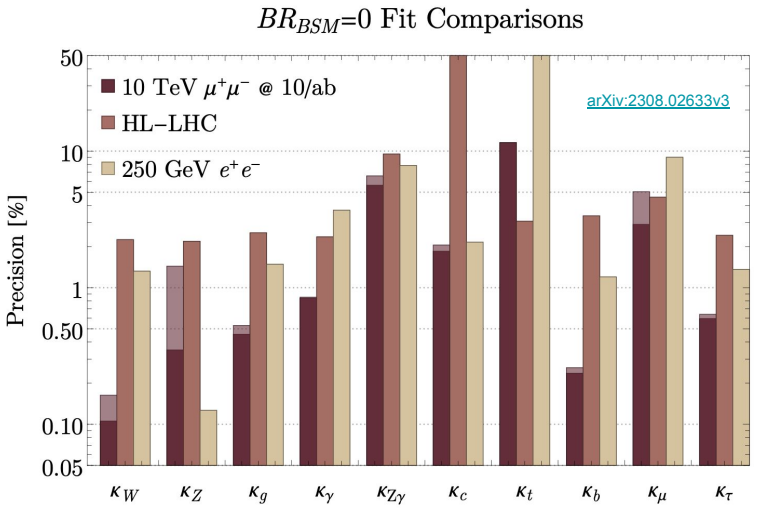
Additional challenges of a Muon Collider

Beam Induced Background (BIB)

This is a Higgs Factory. Let's talk about like it is one. We have time.

1. radiation tolerance
2. occupancy
3. BIB rejection

Physics



dynamic range and **precision**

Beyond surviving, let's thrive!

Electromagnetic Calorimeter Examples

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
CsI(Tl) (BES III)	$15X_0$	2.5% for $E_\gamma = 1$ GeV	2010
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
$PbWO_4$ (PWO) (ALICE)	$19X_0$	$3.6\%/\sqrt{E} \oplus 1.2\%$	2008
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

SAMPLING!

https://pdg.lbl.gov/2022/web/viewer.html?file=../reviews/rpp2022-rev-particle-detectors-accel.pdf

Homogenous calorimeters win at resolution

What type of calorimeter meets physics goals?

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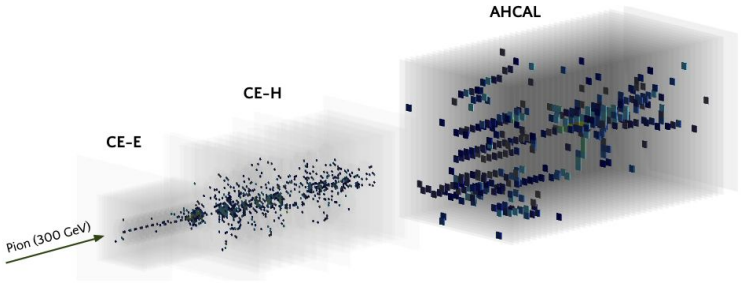
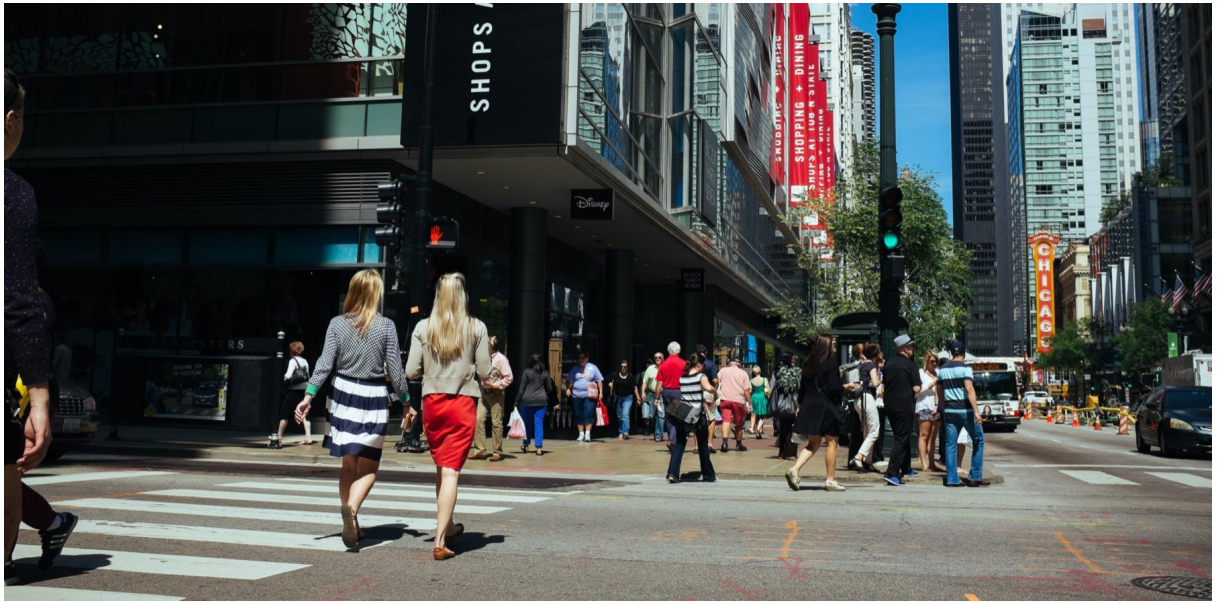


arXiv:2211.04740v2

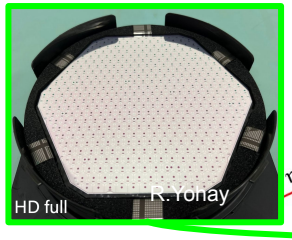
But sampling offers direct access to shower structure, straight forward LLP searches

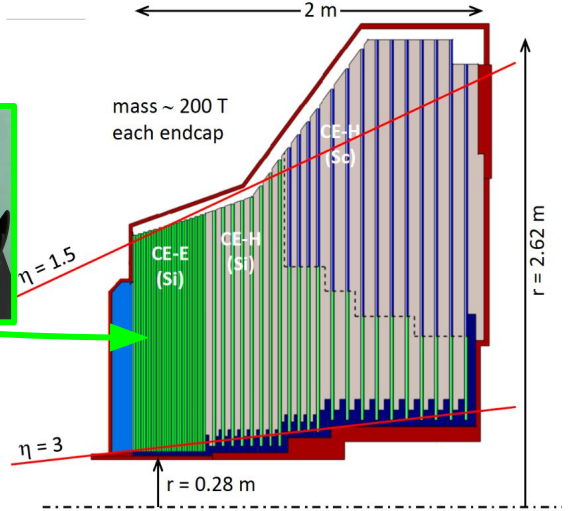


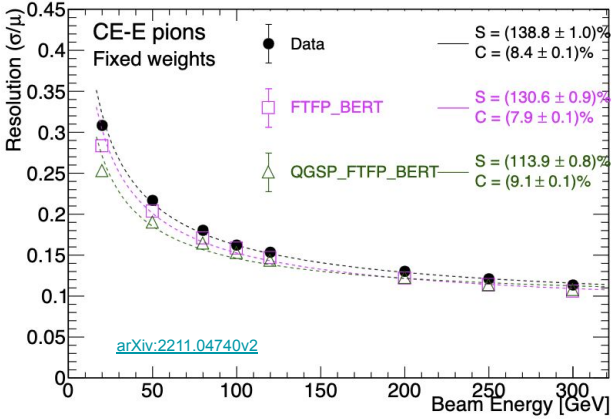
Let’s go shopping

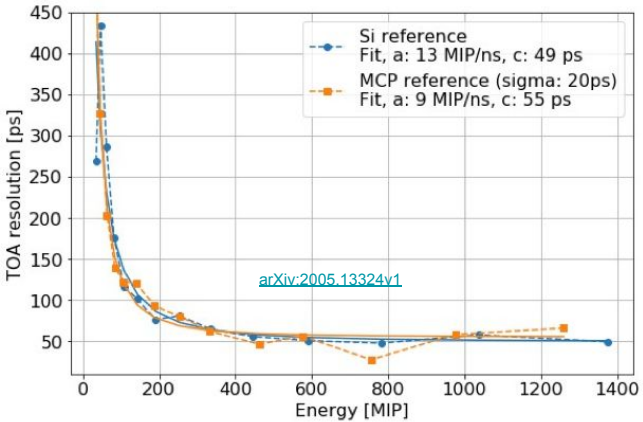
Silicon-based sandwich calorimeters

- CMS HGCAL
  - low and high density regions
  - plastic scintillator HCAL w/ SiPMs
- 50 ps timing and 10% energy resolution







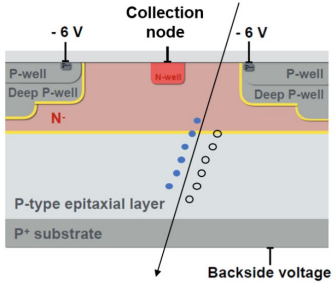


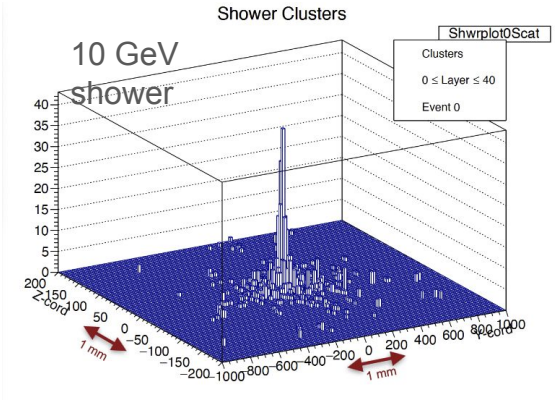
HL-LHC ultimate test of performance!

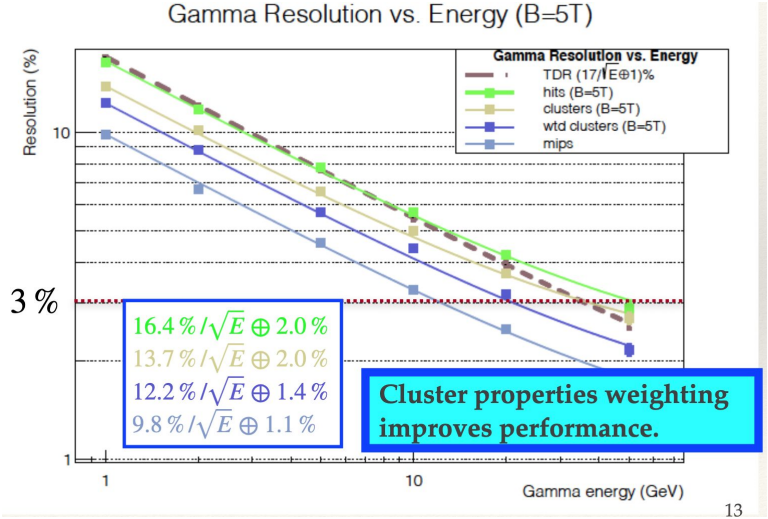
Digital MAPs Calorimeters

- CMOS → less expensive silicon sandwich calos
  - 10 cm x 10 cm2 chip
  - 25 x 100 um2 pixel
- Strictly counting

TIMING?





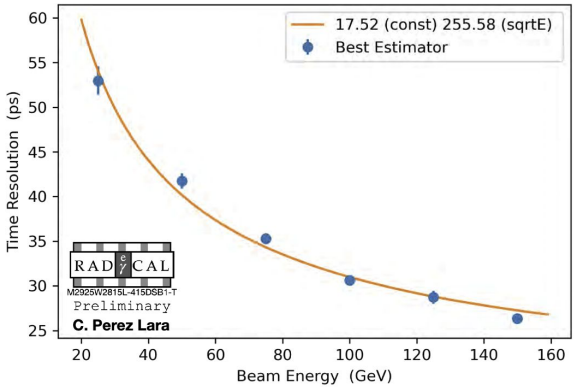


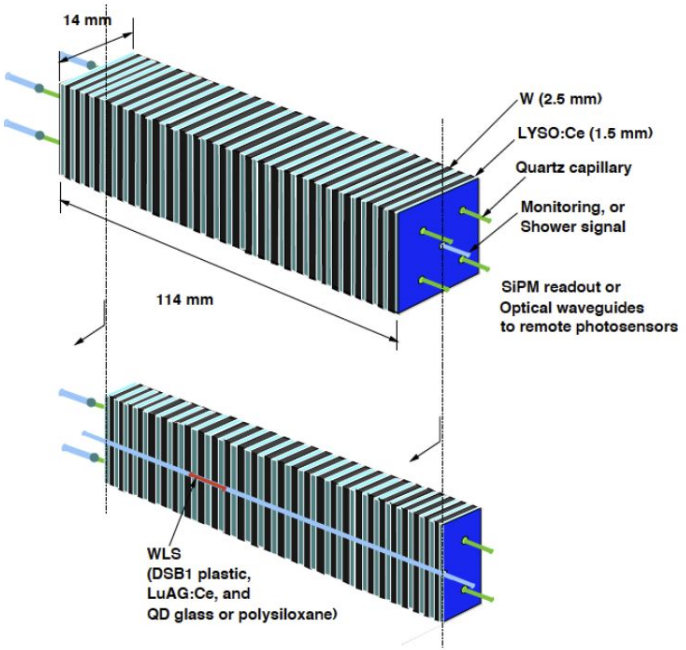
SID design (ILC) w/ fully digital calorimetry - High Granularity at the extreme. PF at its extreme

content from C.Vernieri, J. Brau

RadiCAL - **Rad**iation Hard **I**nnovative EM **Cal**orimeter

- LYSO and tungsten sampling calorimeter
  - ½ cm radiation length
- Highly granular
- sub-50 ps time resolution
- Radiation tolerance goal → FCChh
  - SiPM readout limiting

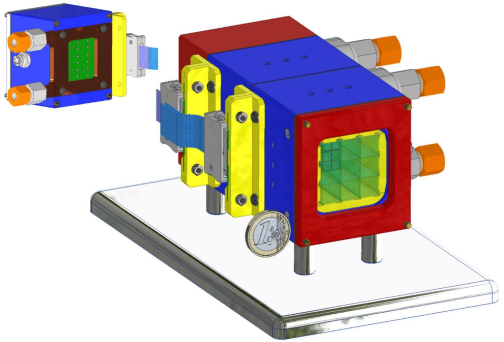




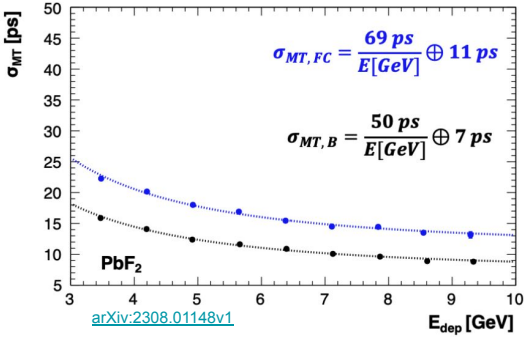
taken from J. Wetzel's CPAD talk

Crilin: **Cr**ystal Calor**i**meter with **L**ongitudinal **In**formation

- PbF_2 Cherenkov Calorimeter
  - radiation hard
  - 20 ps @ test beam!
- high granularity crystal!
  - 1 cm x 1 cm x 40 cm crystals
  - 3 mm x 3 mm UV-extended SiPMs



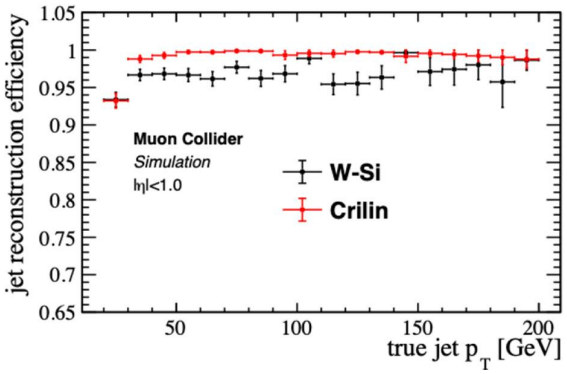
https://doi.org/10.1016/j.nima.2022.167817

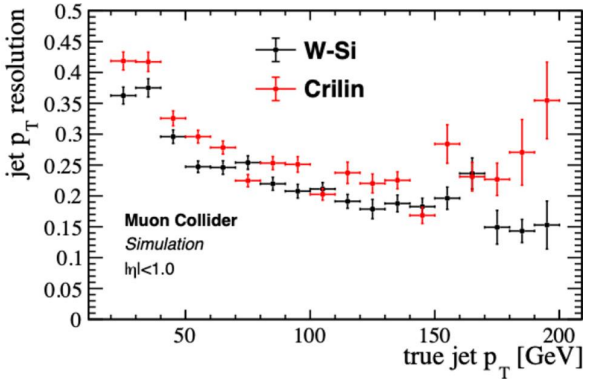


arXiv:2308.01148v1

CRILIN

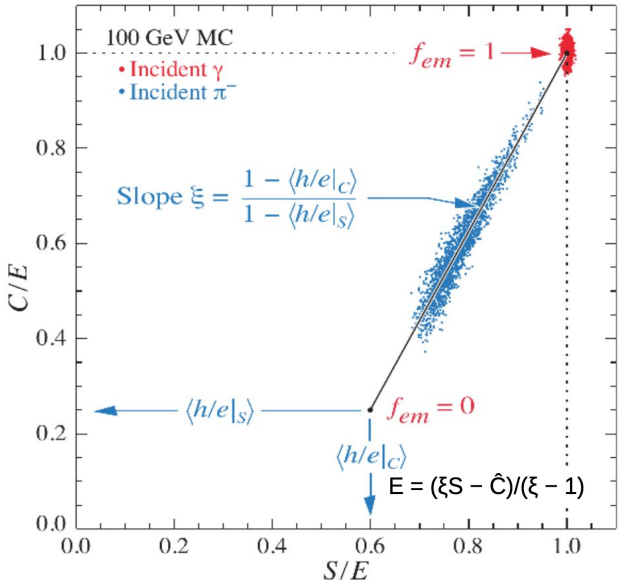
arXiv:2206.05838





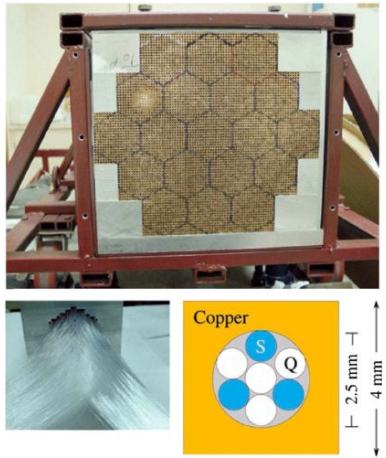
What is Dual Readout (DR)?

- EM/had ratio can be inferred from ratio of Cerenkov to scintillation light
  - *Event-by-event correction* to account for EM/had deposition fluctuations



S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002

2 methods



Dedicated Cerenkov radiators and scintillators (like DREAM/RD52)

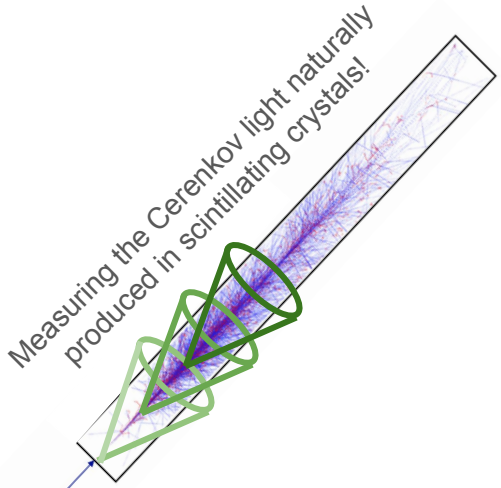


image credit, PWO w/ electron https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

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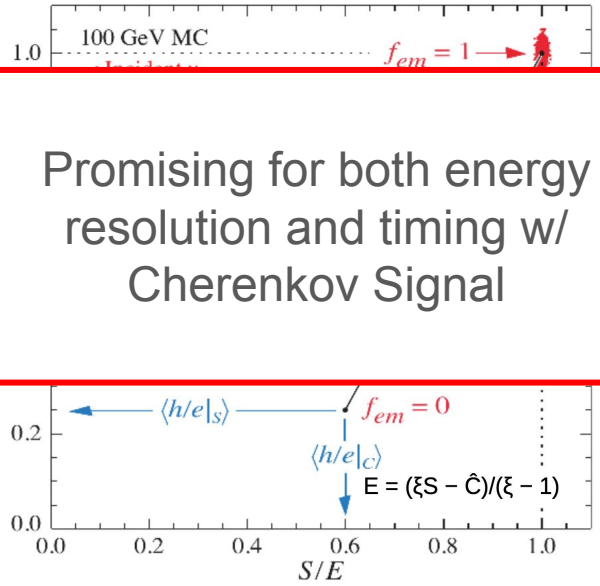
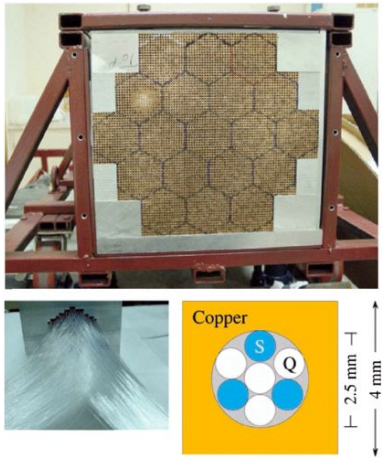
  - *Event-by-event correction* to account for EM/had deposition fluctuations



Promising for both energy resolution and timing w/ Cherenkov Signal

S. Lee, M. Livan, and R. Wigmans, Rev. Mod. Phys. 90, 025002

2 methods



Dedicated Cerenkov radiators and scintillators (like DREAM/RD52)

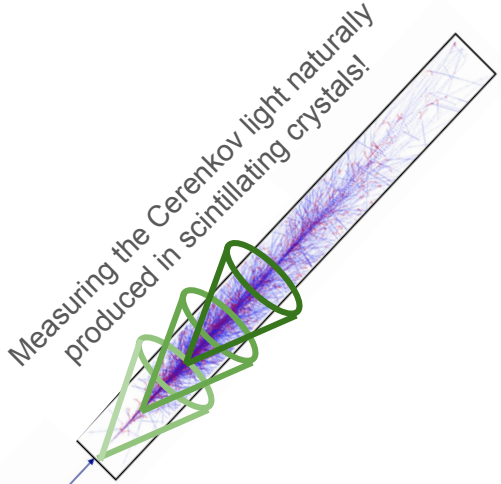


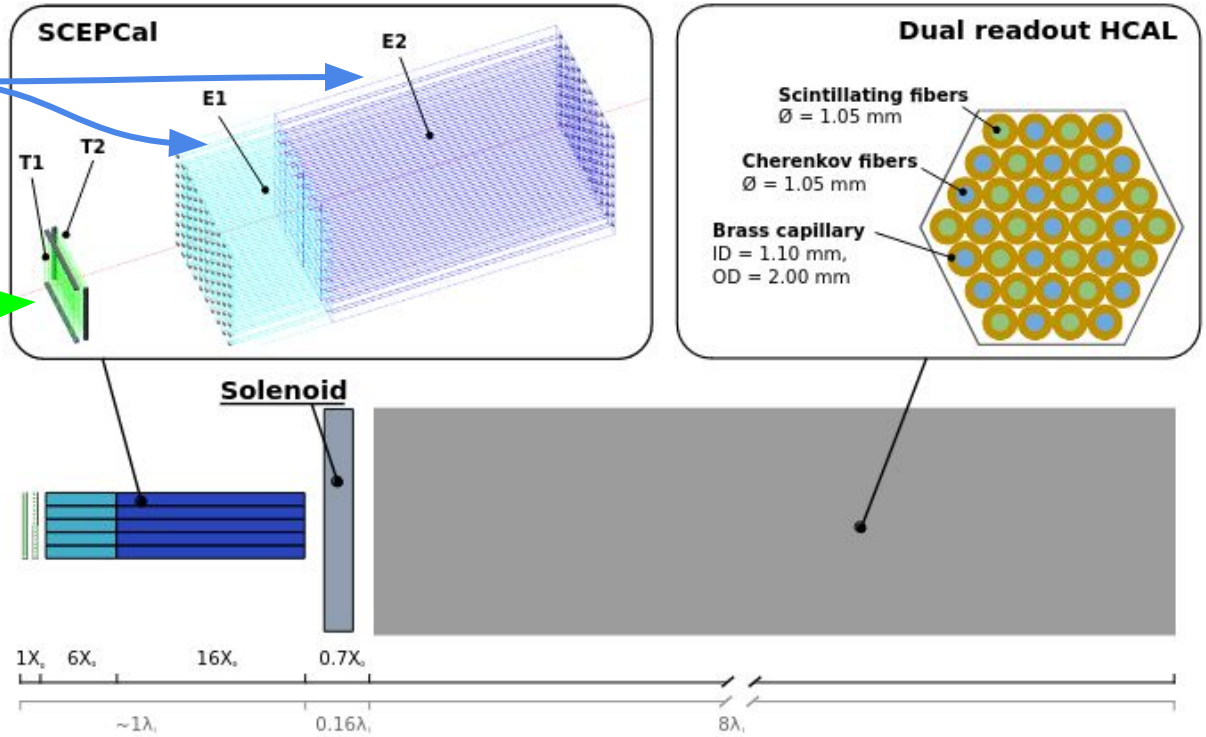
image credit, PWO w/ electron https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

Dual Readout SCEPCAL+ Fiber HCAl

arXiv:2008.00338

Two crystal segments*

Timing layer

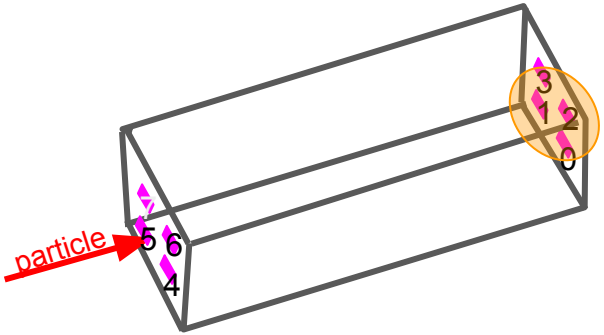


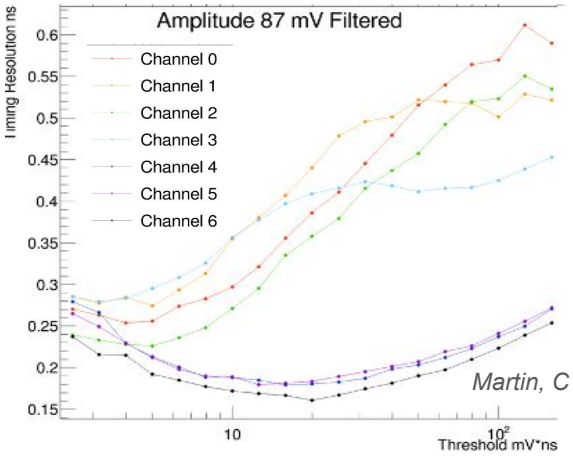
Segmented
Crystal
Electromagnetic
Precision
CALorimeter

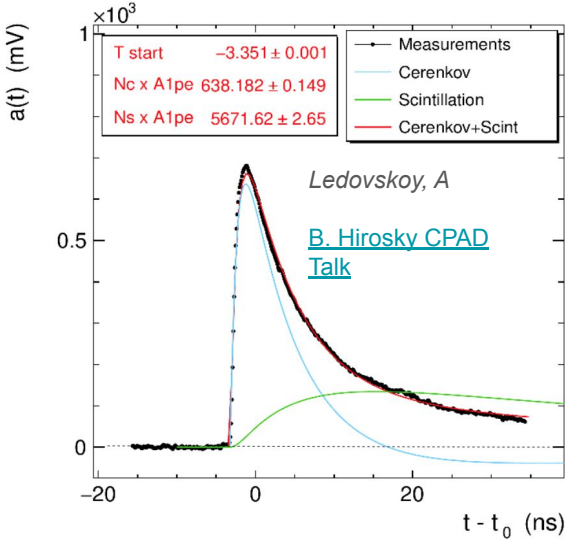
*more on next slide

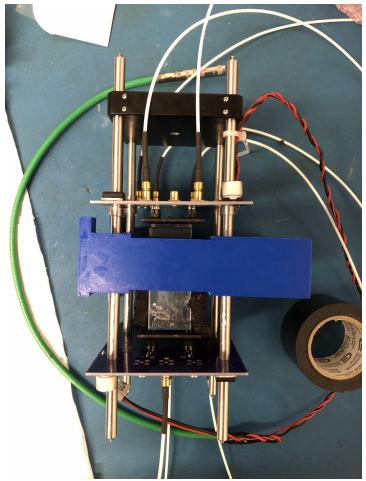
Dual Readout in Crystals for ECAL

- ~MIP Timing resolution < 150 ps / channel
  - 6 cm long PWO
  - will improve with longer crystals → more light
  - better leverage Cherenkov light
- Extract Cherenkov component w/ waveform analysis
  - BGO







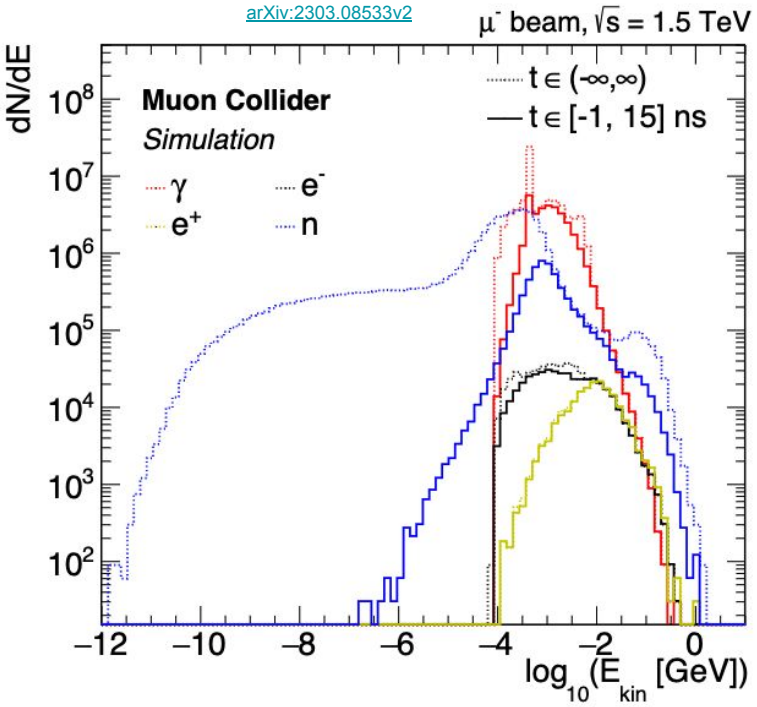


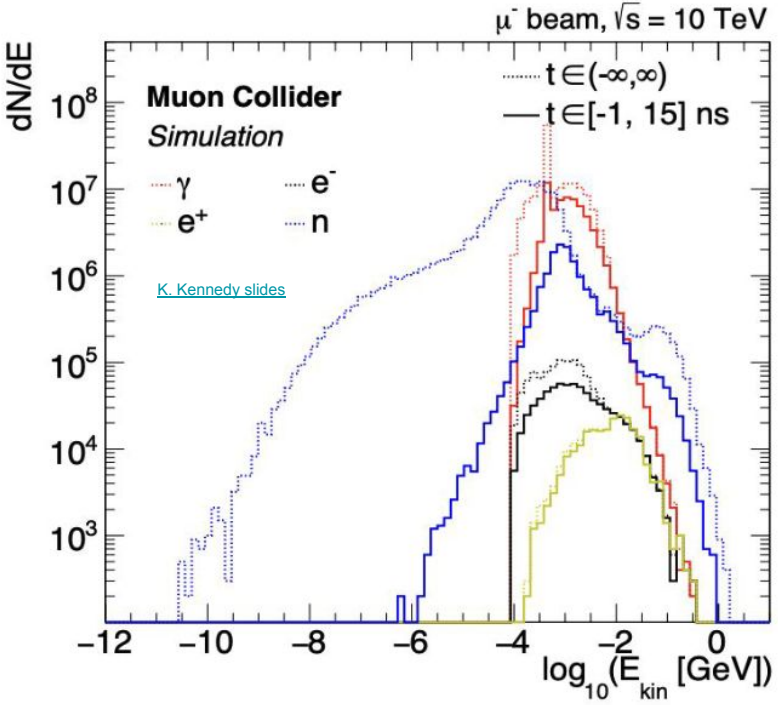
Summary

- Beam induced background is a challenge, but one we know how to solve
  - many technologies exist w/ sufficient timing
  - HL-LHC will give a lot of experience w/ high granularity
- Do not shy away from asking more of the detector
  - many technologies offer high granularity + work with PF
  - Precision calorimetry may be possible, if it is pursued
  - Most “new” ideas are currently targeting FCCee w/ the energy resolution challenge
- Large uncertainties on calorimeter environment
  - unclear if requirements vary a lot with energy/how much the MDI re-optimization will help
- There is no “optimal calorimeter”
  - it is taste what you prioritize
  - cost is a large component

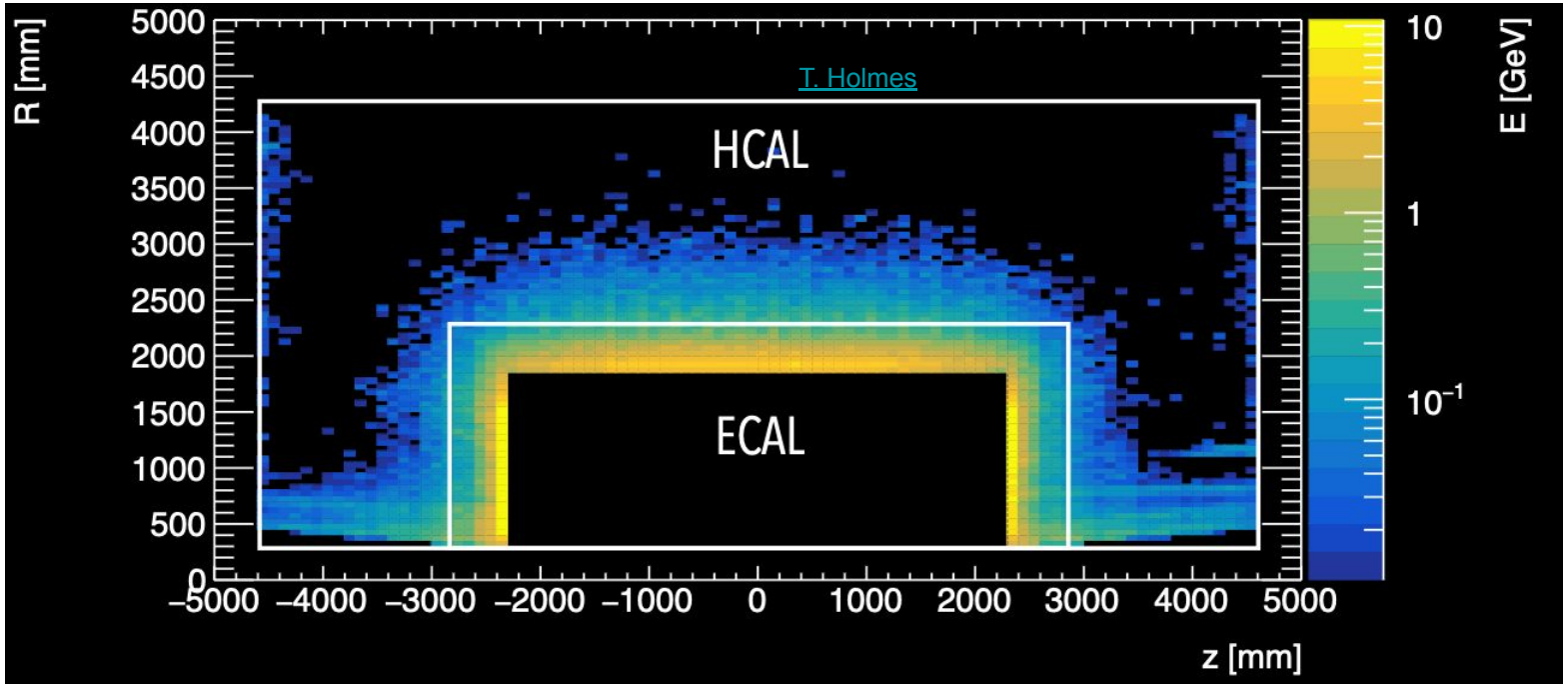
back-up

How the numbers scale





BIB Energy deposition original color



TID for muon collider