Dual Readout Calorimetry

Grace E. Cummings, somewhat on behalf of CalVision/MaxiCC

US Higgs Factory Planning, 19 December 2024

Challenges of Hadron Calorimetry

- quarks hadronize
  - Jets have
    - “electromagnetic” (EM) fraction
      - really a charged, relativistic fraction (mostly π^0)
    - “hadronic” (had) fraction
      - slower stuff
      - lots of protons and neutrons
- EM to hadronic ratio fluctuates event-to-event
- Detector response to EM energy deposition differs from hadronic energy deposition

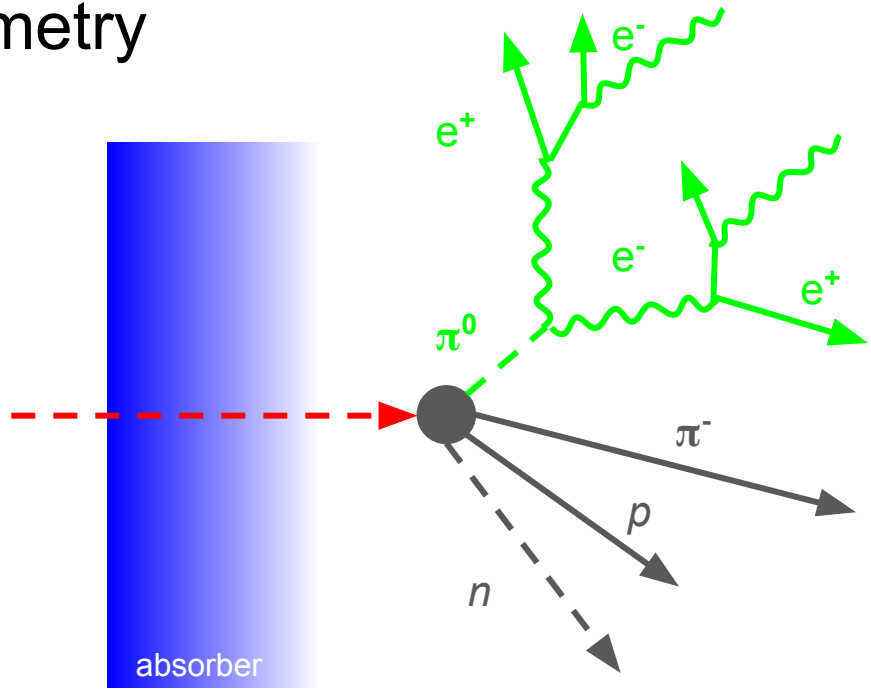
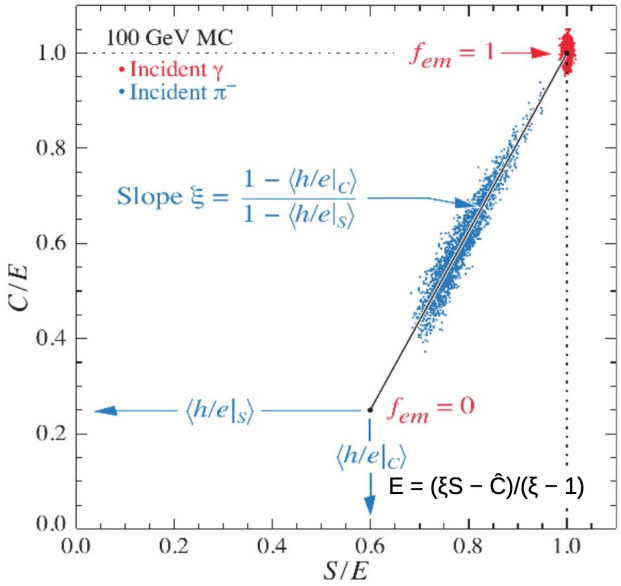


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

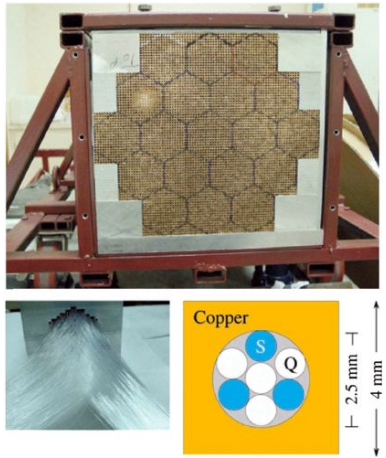
What is Dual Readout (DR)?

- 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/IDEA)

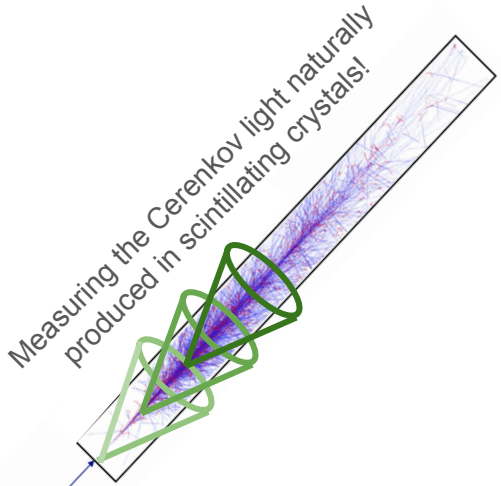


image credit, PWO w/ electron https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

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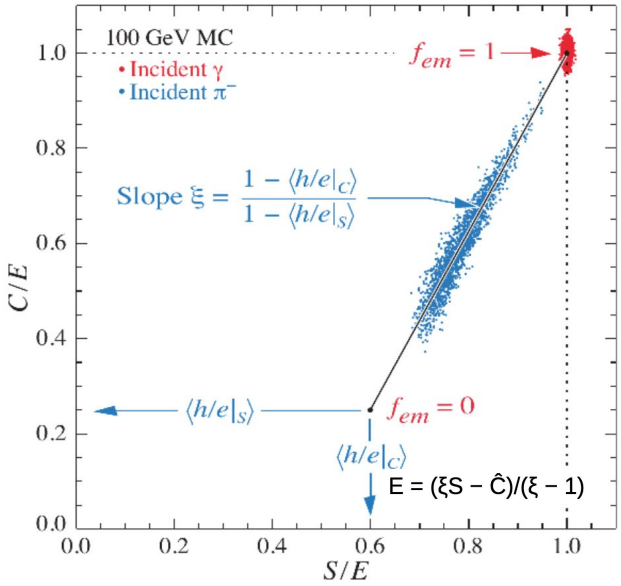

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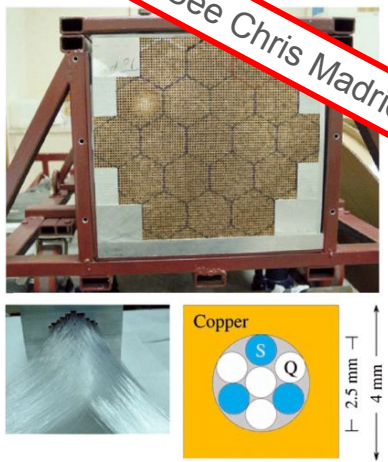
See Chris Madrid's talk!



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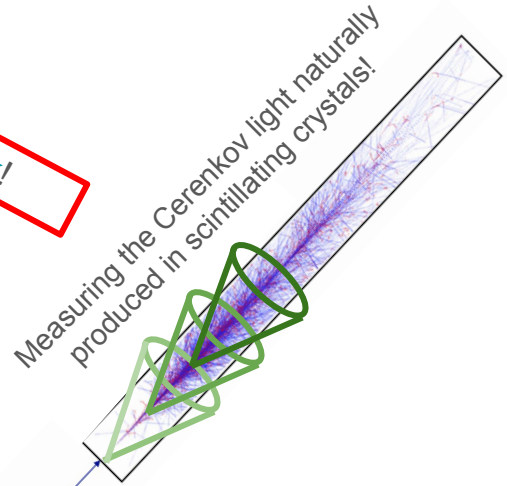

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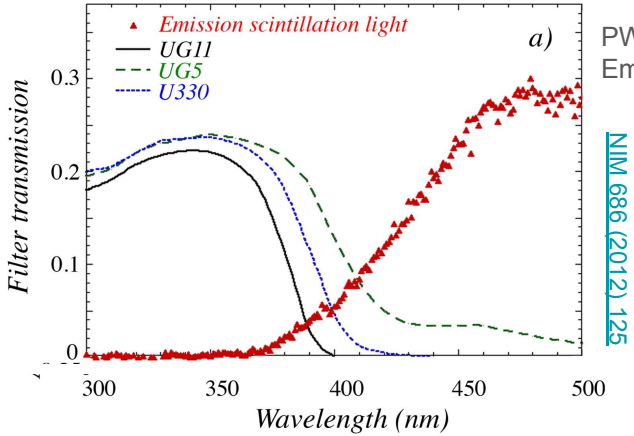
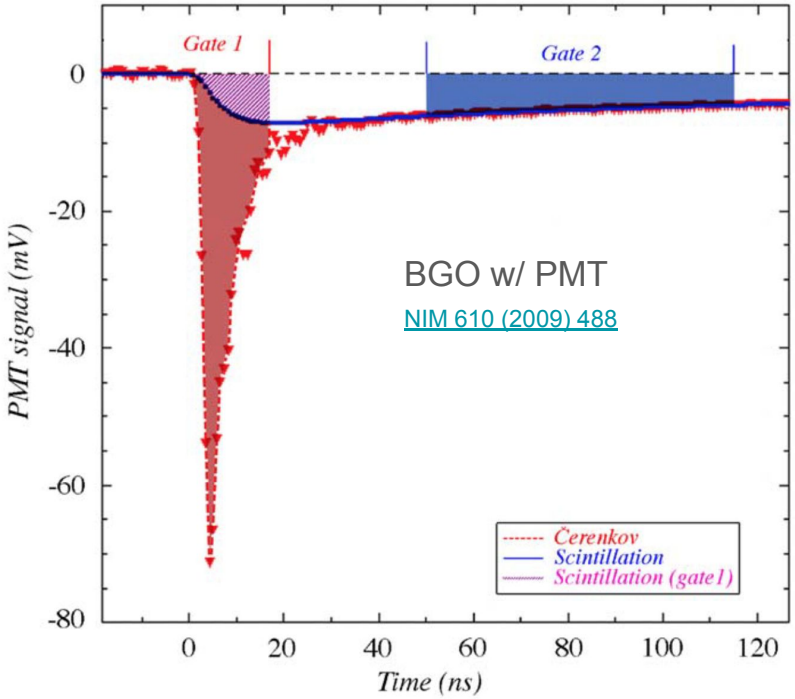
Previous homogenous DR attempts

- Successfully separated Cherenov and Scintillation light!
  - wavelength
  - timing



PWO Scint Emission

NIM 686 (2012) 125

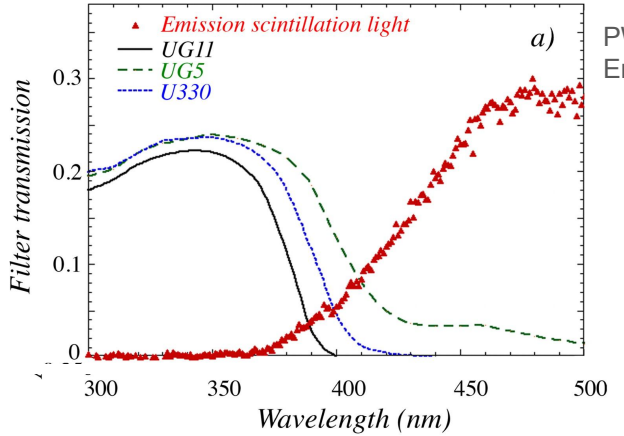


BGO w/ PMT

NIM 610 (2009) 488

Previous homogenous DR attempts

- BGO and PWO matrices
  - instrumented w/ PMTs
  - targeted UV spectrum
- Not enough light for good resolution
  - scint spectrum killed w/ filters
  - not accepting enough cherenkov



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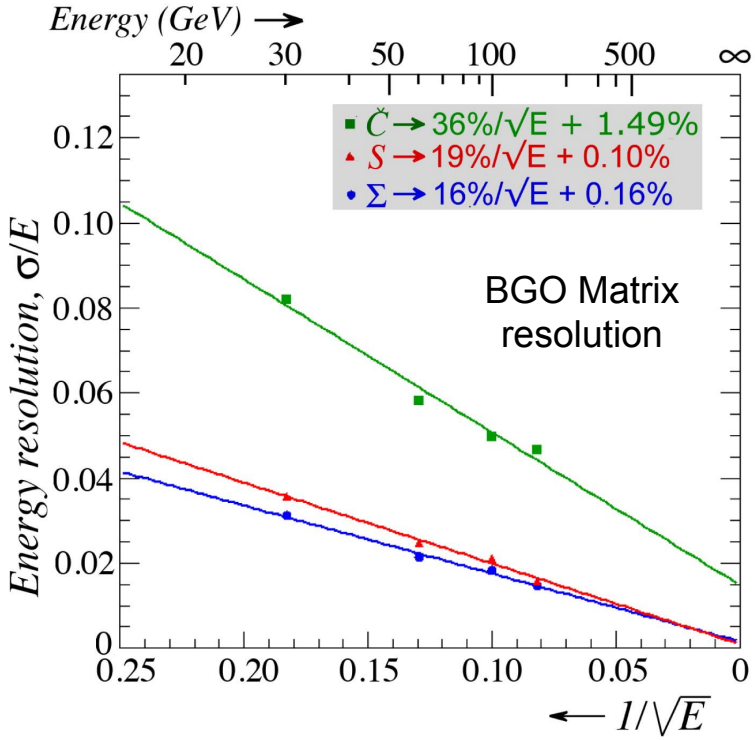

N. Akchurin et al. (2012) Nucl. Instr. and Meth. **A 686** (125)

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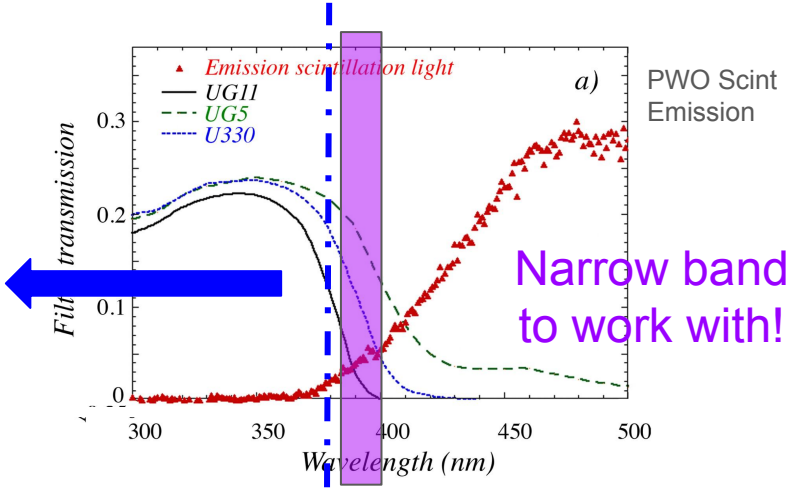
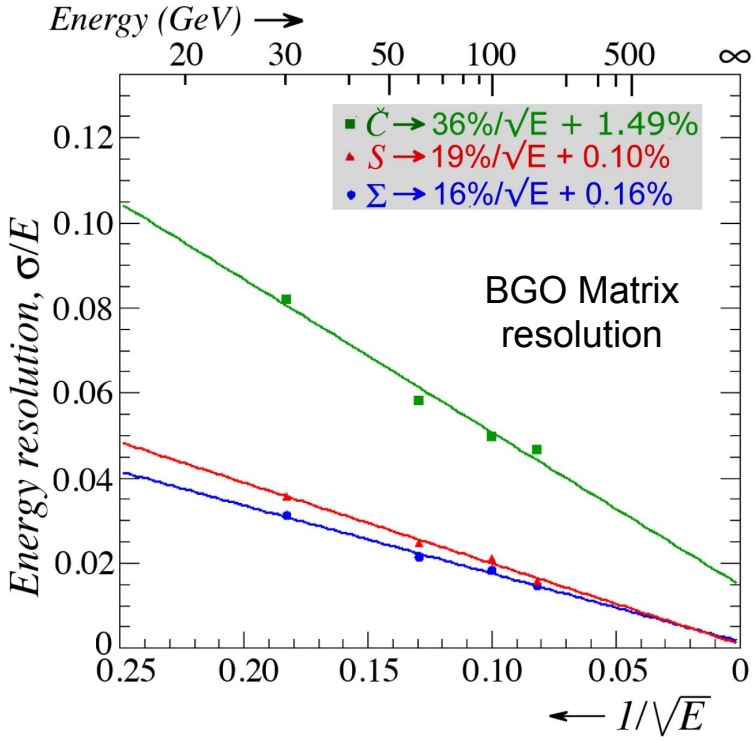
Re-absorbed into crystal!



PWO Scint Emission

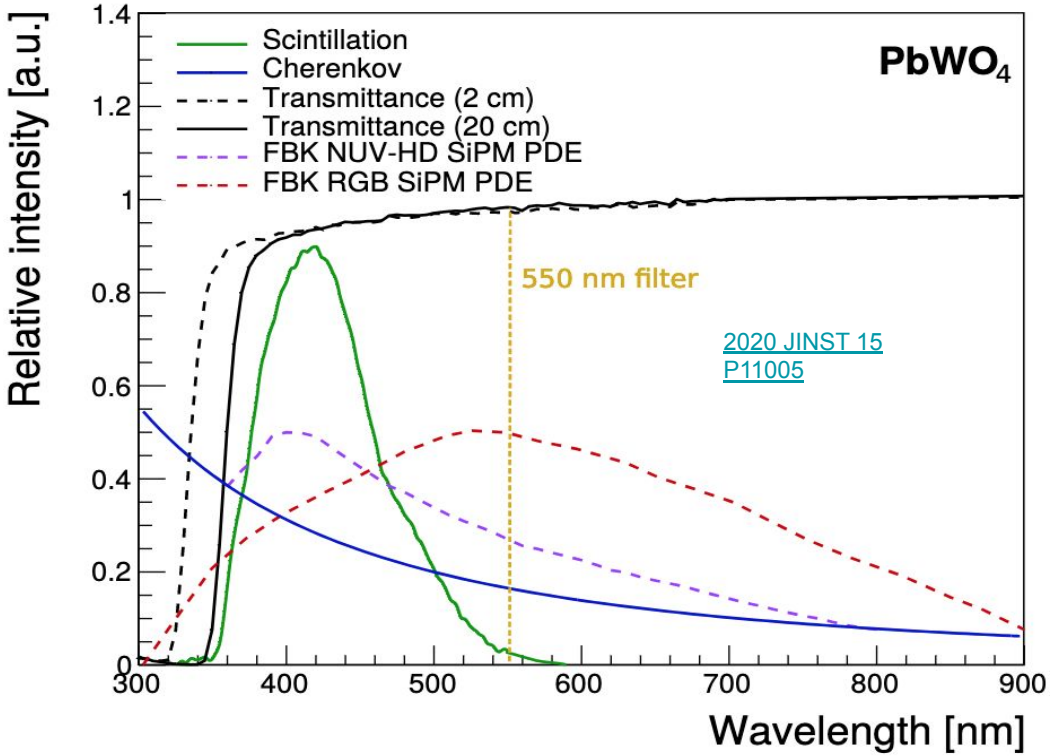
Narrow band to work with!



N. Akchurin et al. (2012) Nucl. Instr. and Meth. **A 686** (125)

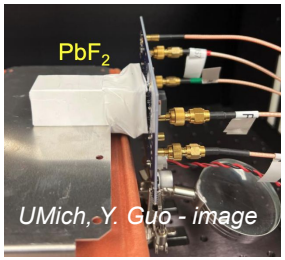
SiPMs bring new opportunities

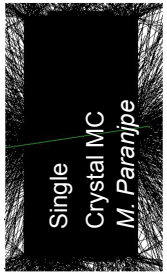
- target the **infrared**
  - avoid self-absorption
  - In peak of SiPM acceptance
- Goal: ~ 100 Cherenkov photons / GeV

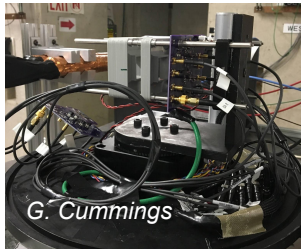


CalVision - DR for e+e- colliders

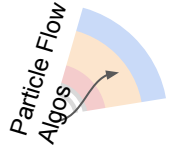
Single crystal + matrix studies







Full detector sim



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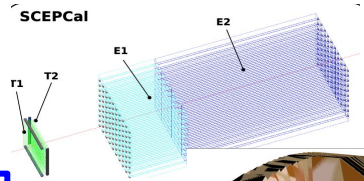
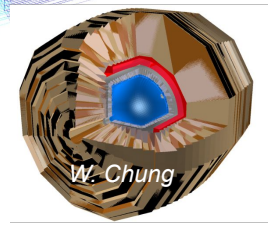
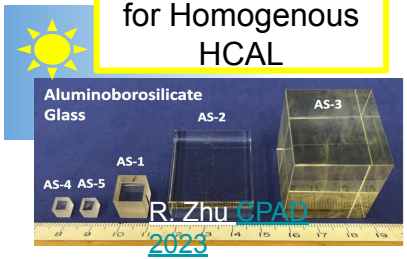
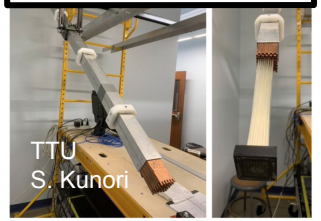




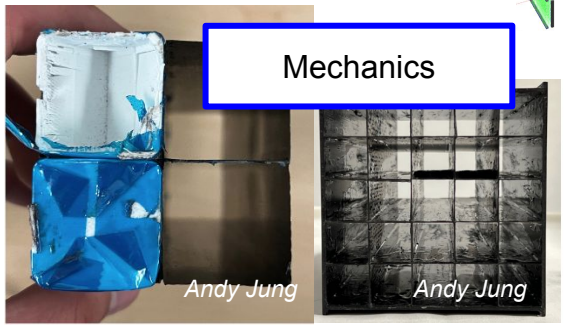
Heavy Glasses for Homogenous HCAL



DR Fiber HCAL



Mechanics



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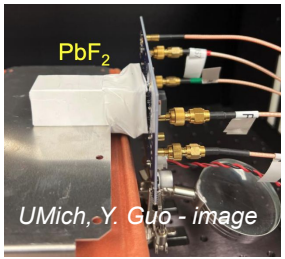

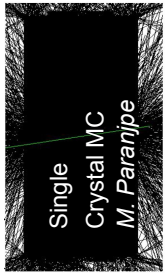

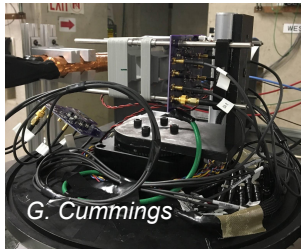

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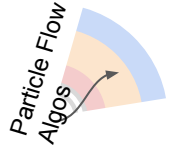

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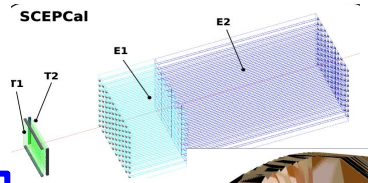

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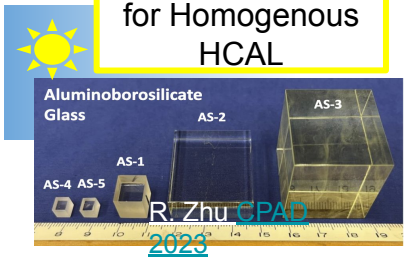
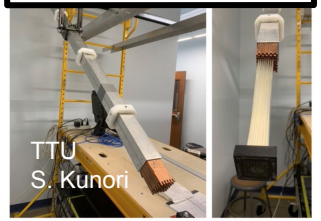


R. Zhu CPAD 2023

DR Fiber HCAL



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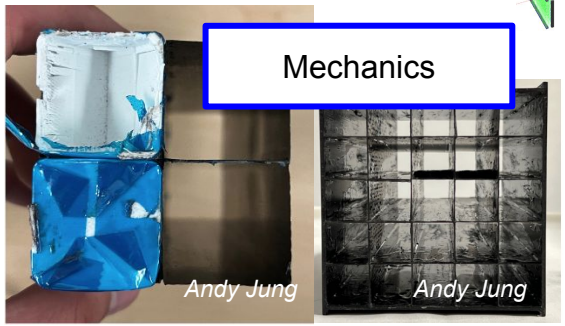
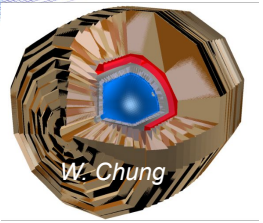


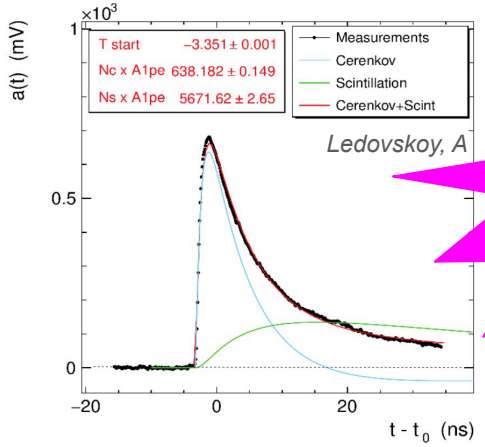


Fermilab Caltech Argonne NATIONAL LABORATORY UNIVERSITY OF MARYLAND Brandeis

Stony Brook University · Rutgers · Università degli Studi di Milano Bicocca · MIT · Oak Ridge National Laboratory · Purdue · University of Virginia · Baylor

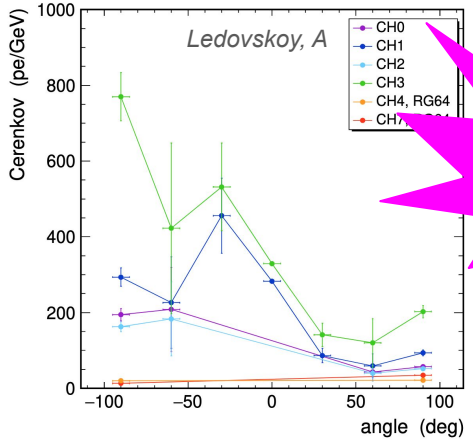
New Era for homogenous DR

- > 100 Cherenkov photoelections / GeV acceptance measured!
- Waveform analysis for Cherenkov and Scint Separation
  - BGO
  - Heavy glasses
- First tests of novel heavy glasses for homogenous HCAL
  - Aluminoboroscilicate (ABS)
  - Barium Disilicate (DSB



Single-event BGO Shower (partial)

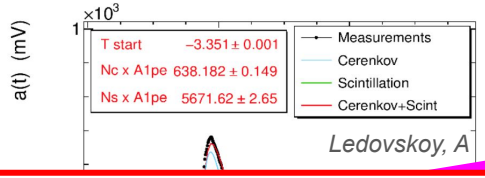
B. Hirosky CPAD 2023 Talk First separation!



DSB Cherenkov yield!

G. Cummings CPAD 2024 Talk - Most recent test beam results!

New Era for homogenous DR

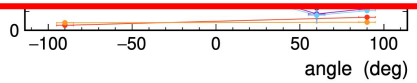


Single-event Shower

This is just a taste of what has been done in CalVision! **There are other DR projects in the US, but not as e+e- targeted**

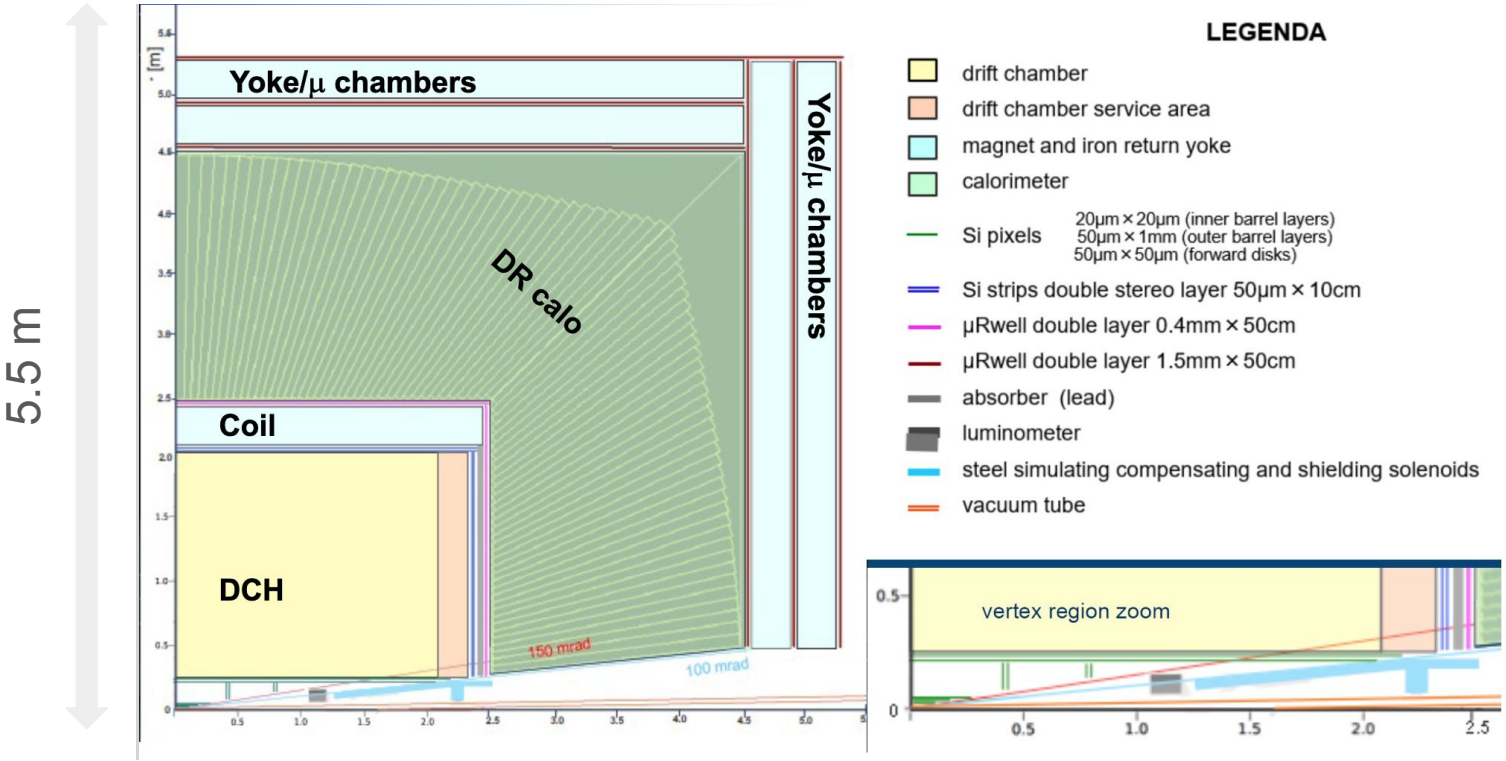
More CalVision Reading:

- PbF2 test beam paper: https://doi.org/10.1016/j.nima.2024.170109
- Fiber DR CALOR 2024 Talk and Proceedings
- Crystal DR hCALOR 2024 Talk and Proceedings
- Crystal DR +Timing USFCC 2024 Talk
- PbF2 USFCC 2024 Talk
- CPAD 2023 Talk
- CPAD 2024 Talk



G. Cummings CPAD 2024 Talk - Most recent test beam results!

IDEA Detector Concept

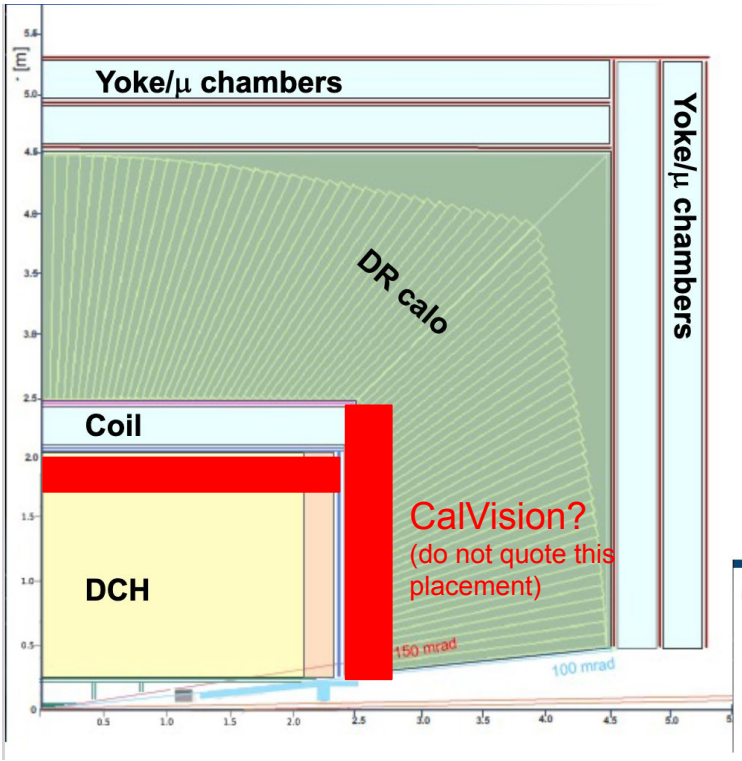


N. De Fillippis: https://indico.cern.ch/event/1077114/attachments/2318206/3994245/DeFilippis_IDEA.pdf

Ideas for IDEA Detector Concept

Crystal DR Layer

5.5 m



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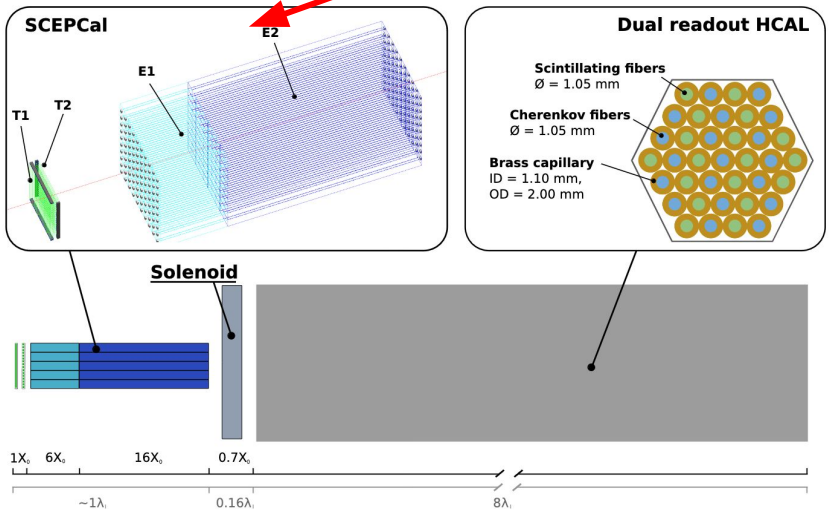

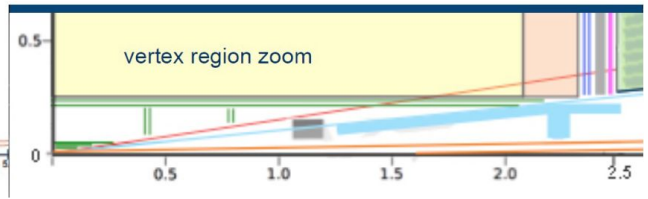

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Summary

- DR is a promising method for improving hadron calorimetry
  - SiPMs are enable technology
- First meeting of the DR Subgroup
  - Oct 29, 2024: https://indico.cern.ch/event/1473473/
  - DR projects outside of what I introduced today!
- CalVision is exploring DR in calorimeters for future colliders
  - DR in crystals + fiber HCAL
  - Scintillating glasses for homogenous HCALs
  - Detector simulation
  - Algorithms
  - Front end electronics and readout → not covered today
  - Test beam results are promising!
- **Other DR R&D programs in the US exist, but not as targeted to a collider concept → we should not forget them as the technology evolves**

back-up

Why DR in *Crystal* Electromagnetic Calorimeters?

- Why crystals?
  - Homogenous calorimeters
  - Scintillating? → more light, better energy
  - Good for electromagnetic sections
    - dense
    - large EM/had ratios
- Why use DR technique in crystals?
  - **Combine few % EM energy resolution with good hadron energy resolution!**
  - precision of a crystal ECAL
  - less hadron energy degradation!

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

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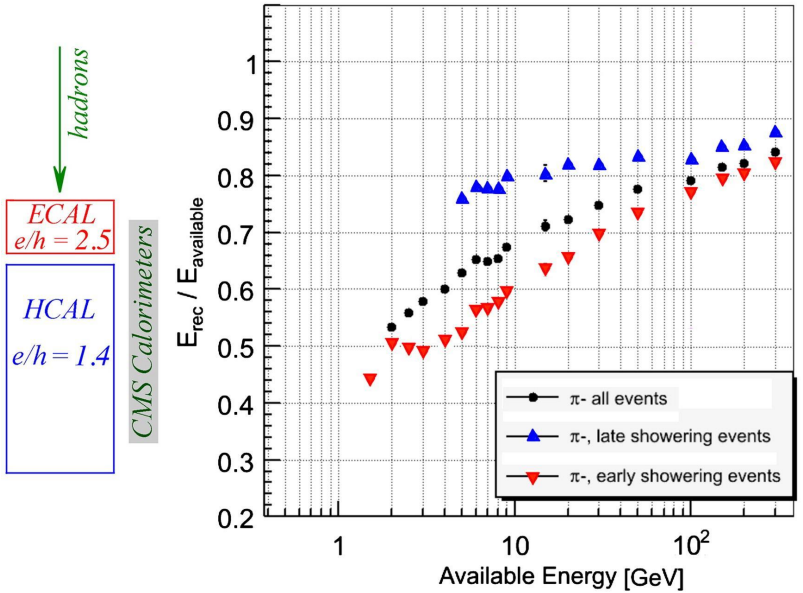
Great ECALs can degrade good HCALs



N. Akchurin, R. Wigmans, (2012) Nucl. Instr. and Meth. **A666** (80)