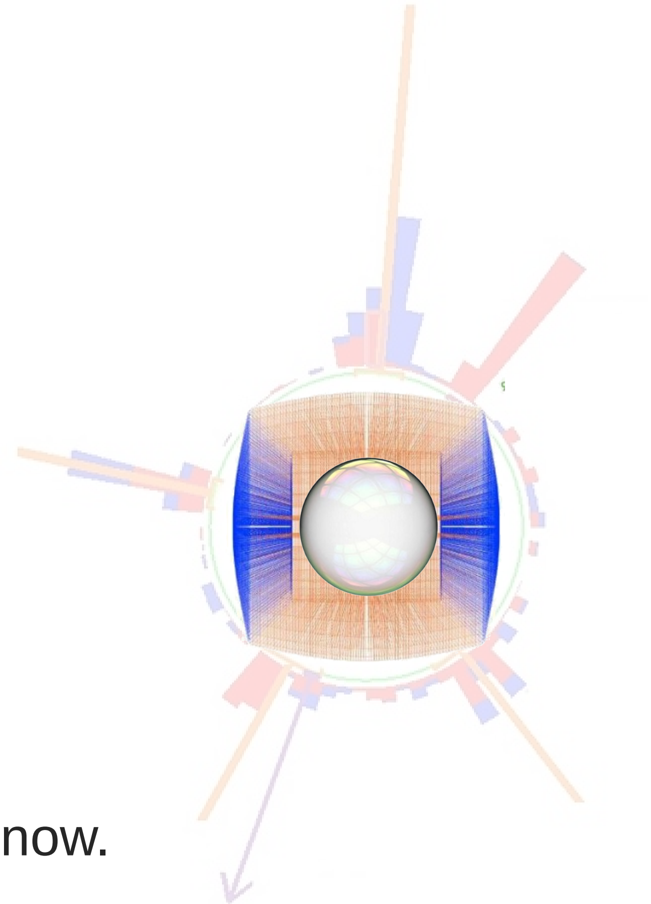
Dual Readout Calorimetry

Bob Hirosky
The University of Virginia

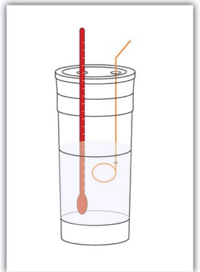


This talk will mostly focus on aspects of DR calorimetry

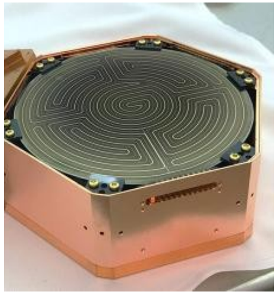
- Some background on DR
- Including a review of DREAM/RD52 work
- Summary of R&D plans by the CALVISION team
- Impossible to do justice to all prior art and ideas!
- Early days, looking to ramp efforts among US groups now.

This talk greatly benefits from presentions by Sarah Eno, Marco Lucchini, and the CALVISION team

A short introduction to Calorimetry

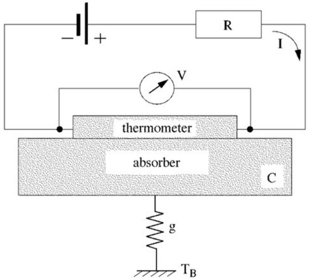


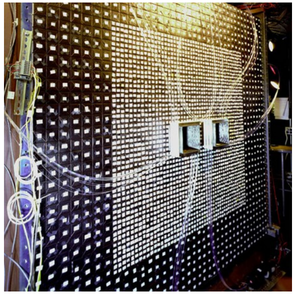
Calorimeters are ubiquitous tools in the physical sciences

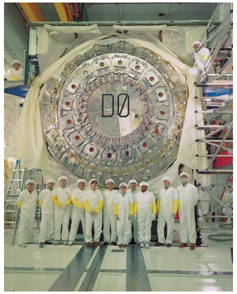


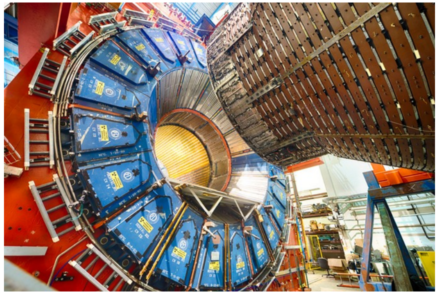
The basic concept is to measure energy via some convenient proxy:

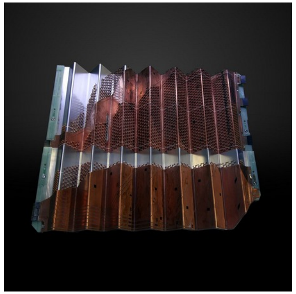
- Temperature
- Light
- Charge

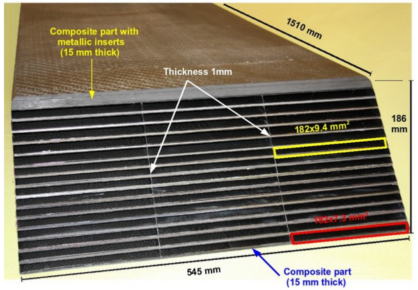








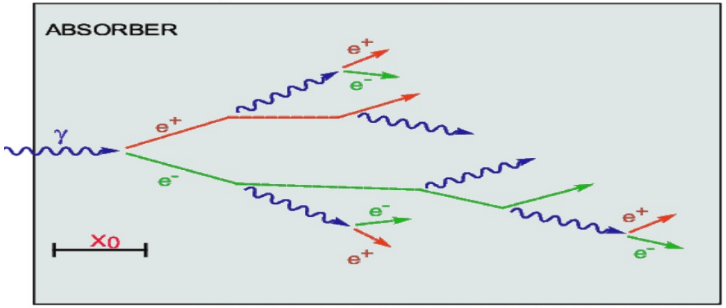


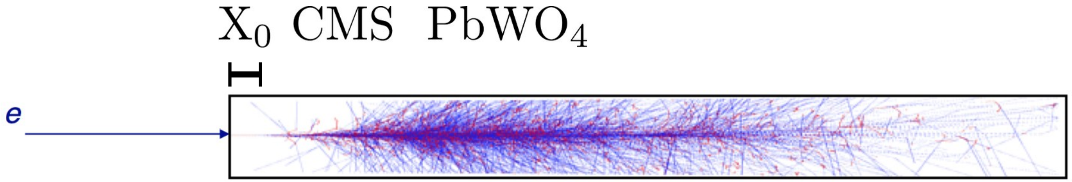


Typical applications in HEP cover KeV to TeV range

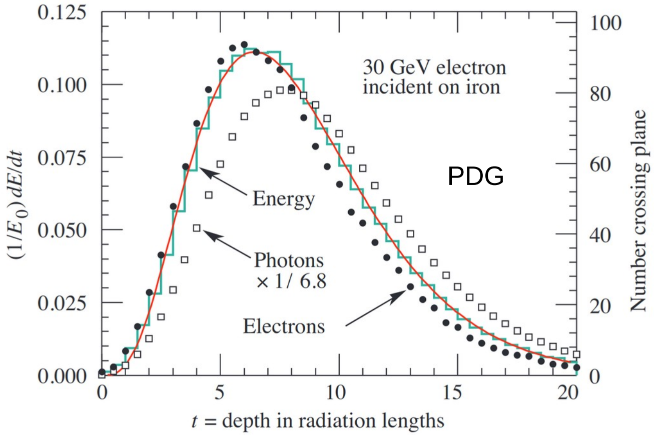
EM calorimetry

Showers relatively* uniform. Good energy resolution has been realized in numerous EM calorimeters over the past few decades.





$$X_0\ [\mathrm{cm}] = \frac{716.4\ [\mathrm{g\,cm^{-2}}]}{\rho\ [\mathrm{g\,cm^{2}}]}\ \frac{\mathrm{A}}{\mathrm{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}}$$



Shower max ~6-9 X_0 in interesting E range for HEP

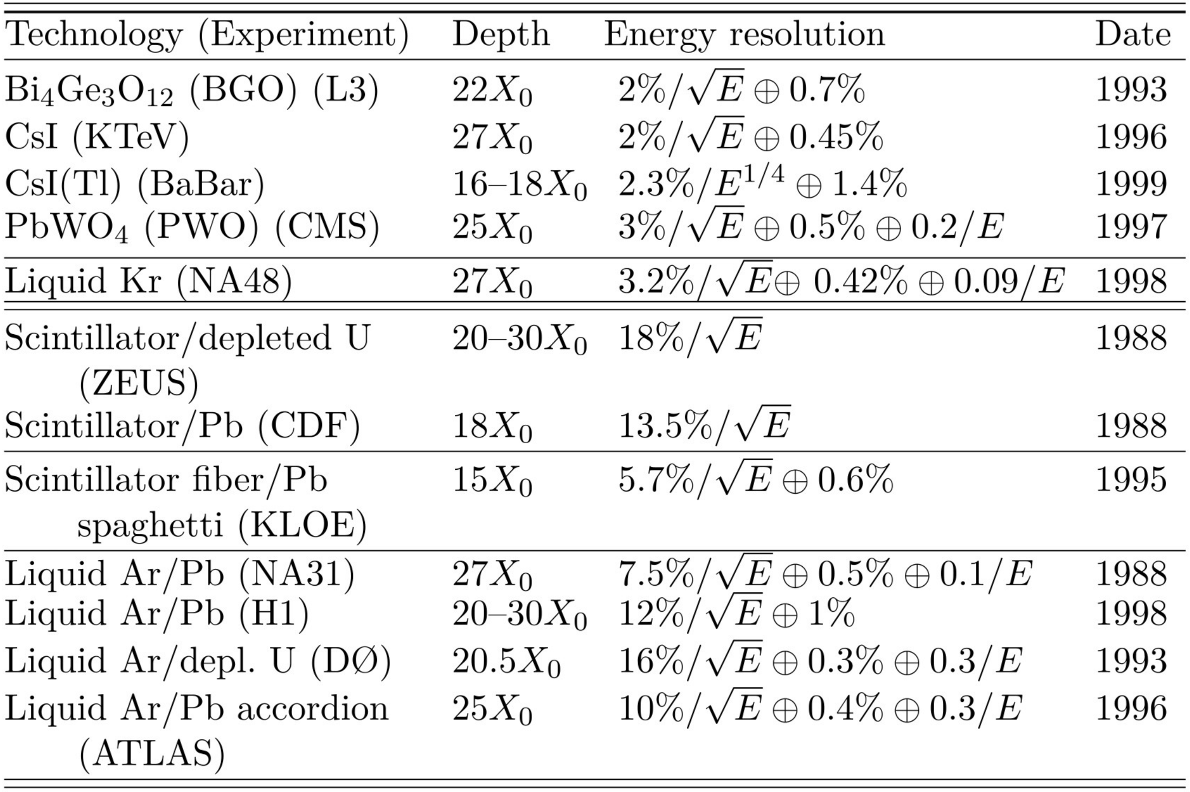
*RMS fluctuations of E profile ~1.5x mean vs depth

- Correlated in depth
- Early/late shower development ("Landau flucts.")
- Make ECAL sufficiently deep to minimize leakage
- Other systematics also drive ultimate performance

Examples of EM resolutions in major detectors

homogeneous

sampling



Technology (Experiment)	Depth	Energy resolution	Date
$Bi_4Ge_3O_{12}$ (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
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
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 (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

PDG

Achieved resolutions in the range:

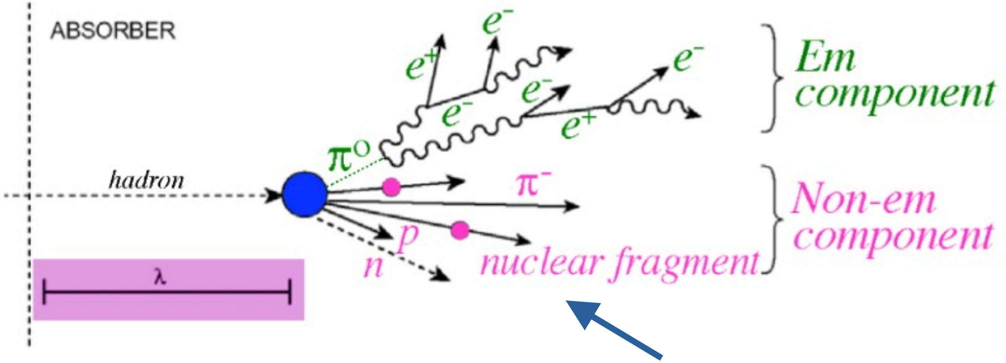
Homogeneous:
~ few %/sqrt(E) $\oplus$ .5%

Sampling
~10-15%/sqrt(E) $\oplus$.5%

Hadron calorimetry

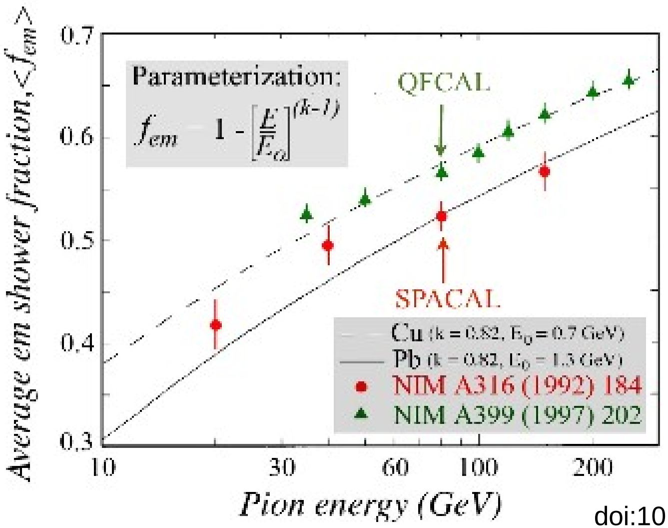
Much more interesting/challenging to precisely measure energy deposition by hadrons

$$\lambda_I\ [\mathrm{cm}] \simeq \frac{35.00\ [\mathrm{g\,cm}^{-2}]\sqrt[3]{A}}{\rho\ [\mathrm{g\,cm}^3]}$$



Purely hadronic component can result in significant amount of missing energy (eg ~8 MeV/nucleon release, neutrons interacting late wrt integration times, ...

(1) Showers include a pure EM component with <u>large</u> E dependence and fluctuations
=> different response,e/h>1, degrades resolution



doi:10.1088/1742-6596/1162/1/012043

Also dependence on materials

Hadron calorimetry

Much more interesting/challenging to precisely measure energy deposition by hadrons

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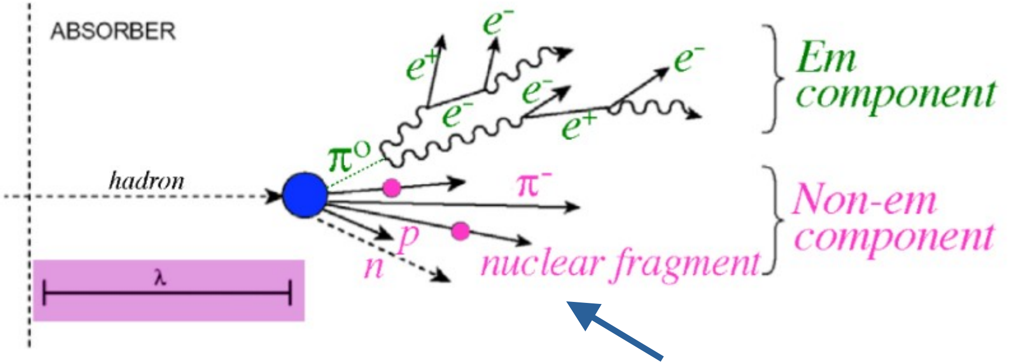

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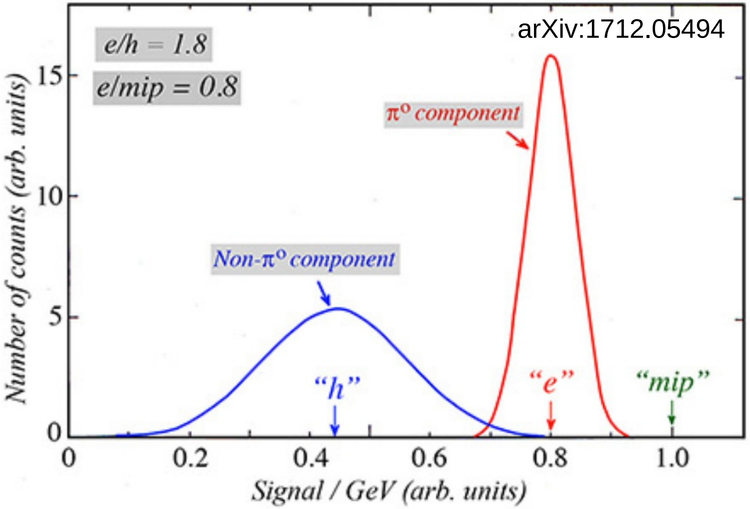


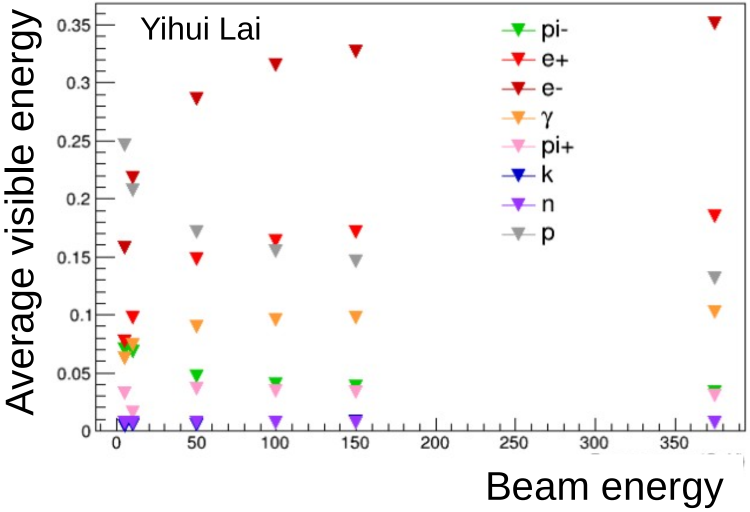
arXiv:1712.05494

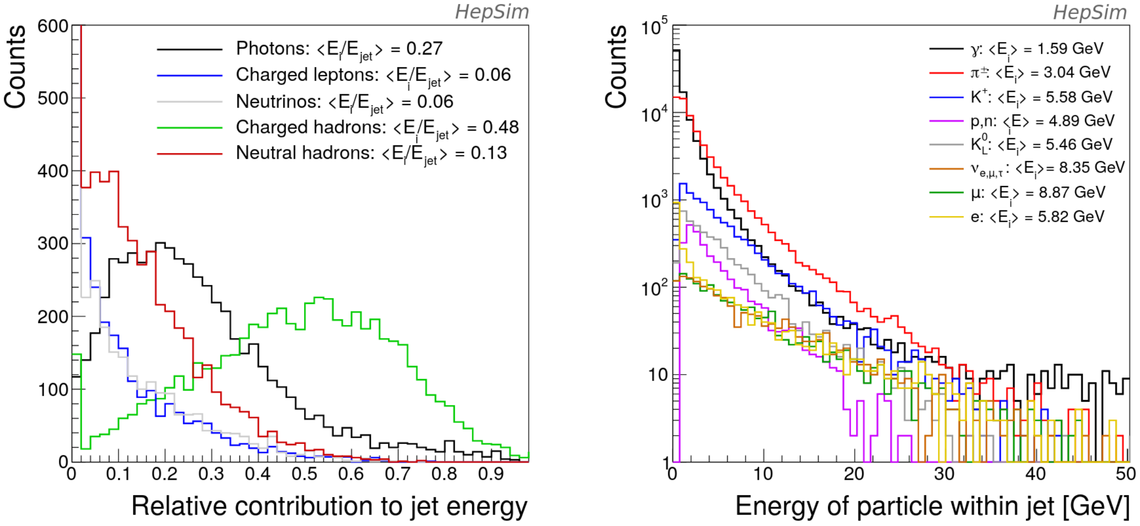
Examples of e/h
CMS: 2.4 (1.3) ECAL(HCAL)
ATLAS 1.37

Hadron calorimetry

Much more interesting/challenging to precisely measure energy deposition by hadrons

(2) Large variety of particle species, possibly w/ different nominal responses




$Z \rightarrow b\bar{b}$ events from e^+e^- collisions at 250 GeV

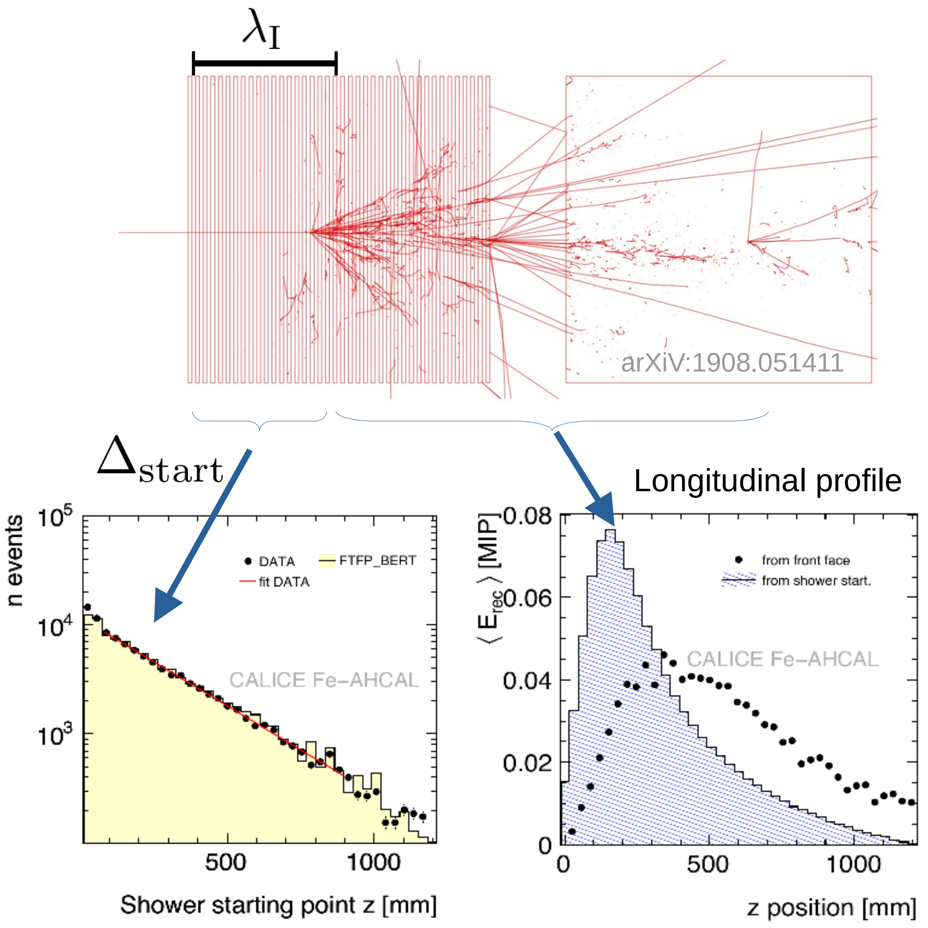
Jet composition: notice energy range of incident hadrons overlaps with largest energy dependence of left plot...

Hadron calorimetry

Much more interesting/challenging to precisely measure energy deposition by hadrons

(3) Extended longitudinal profile

- Significant fluctuations in starting location
- Depending on technology, may cross detector regions, eg different sampling fractions, e/h,...



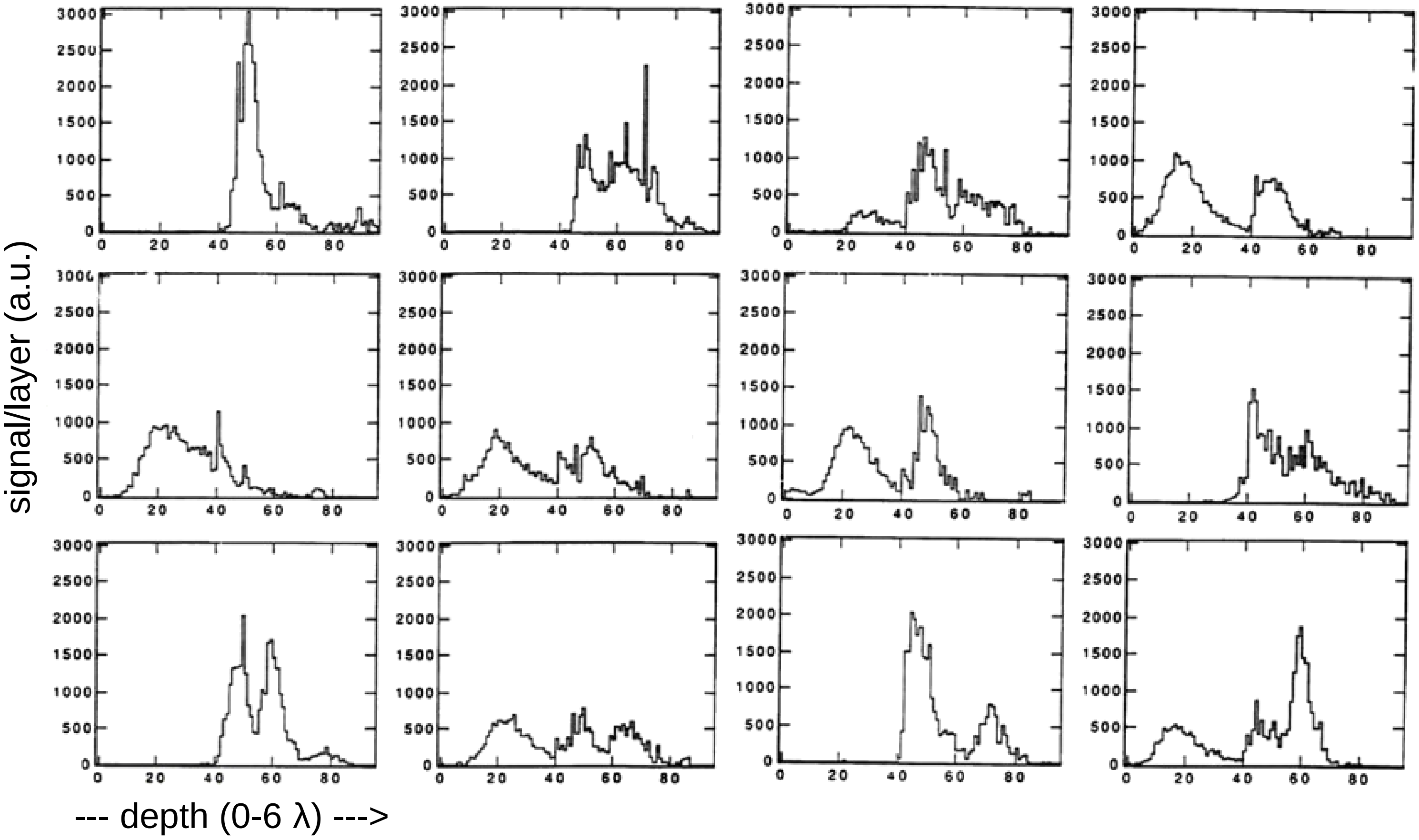
Longitudinal profile

arXiV:1908.051411

PDG

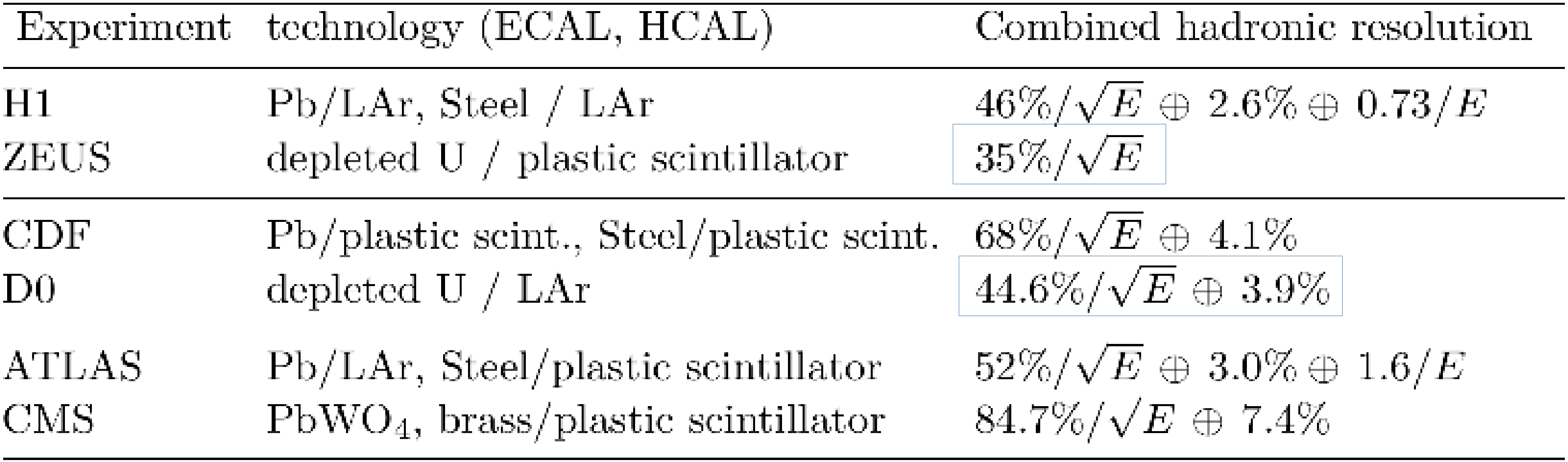
Hadron shower (longitudinal) fluctuations

Longitudinal energy deposit profiles for different 270 GeV pion showers in a lead/iron/plastic-scintillator calorimeter



Akchurin & Wigmans, NIM A666 (2012) 80

Examples of hadron resolutions in major detectors

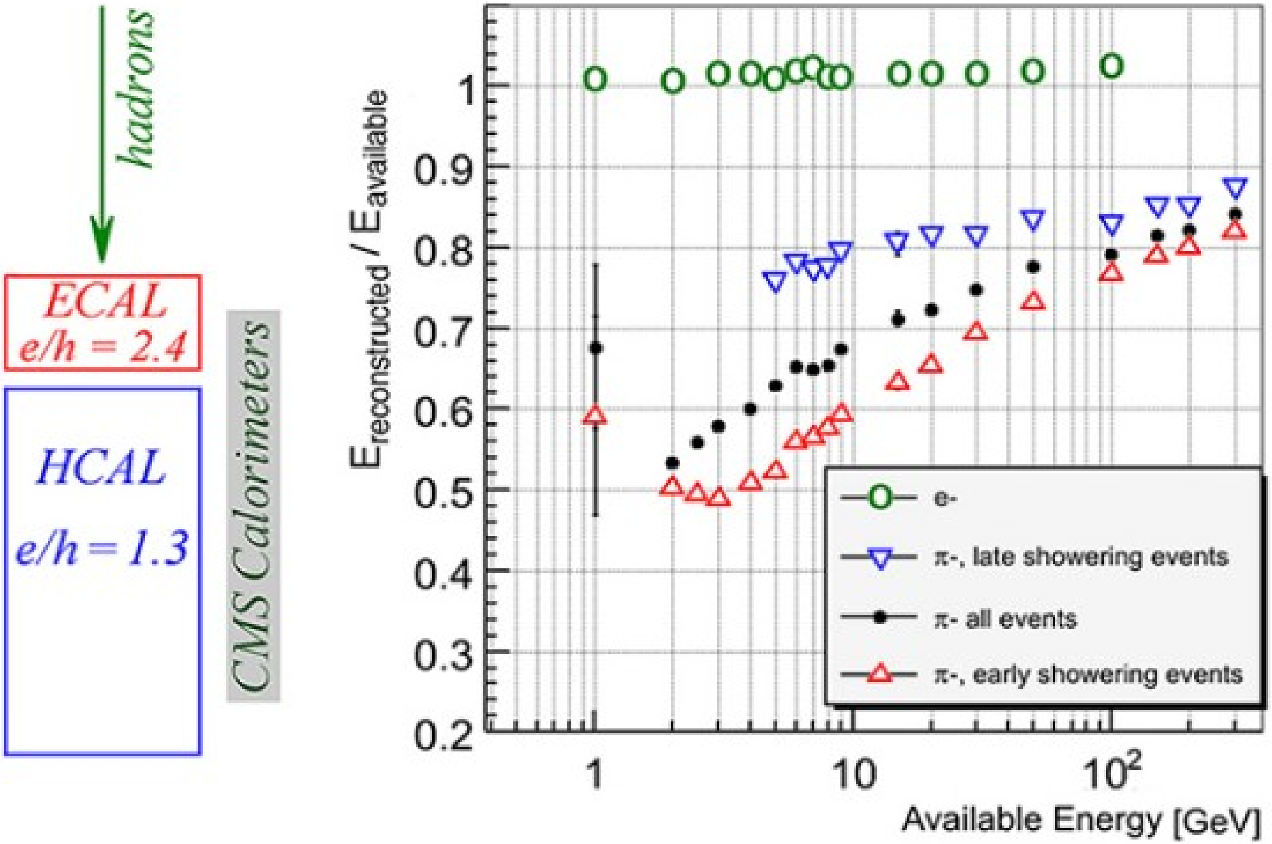


Experiment	technology (ECAL, HCAL)	Combined hadronic resolution
H1	Pb/LAr, Steel / LAr	$46\%/\sqrt{E} \oplus 2.6\% \oplus 0.73/E$
ZEUS	depleted U / plastic scintillator	$35\%/\sqrt{E}$
CDF	Pb/plastic scint., Steel/plastic scint.	$68\%/\sqrt{E} \oplus 4.1\%$
D0	depleted U / LAr	$44.6\%/\sqrt{E} \oplus 3.9\%$
ATLAS	Pb/LAr, Steel/plastic scintillator	$52\%/\sqrt{E} \oplus 3.0\% \oplus 1.6/E$
CMS	$PbWO_4$, brass/plastic scintillator	$84.7\%/\sqrt{E} \oplus 7.4\%$

PDG

Near compensating calorimeter systems (e/h~1) AND more uniform construction of EM/Hadronic sections $(e/h)_{ECAL}$~$(e/h)_{HCAL}$

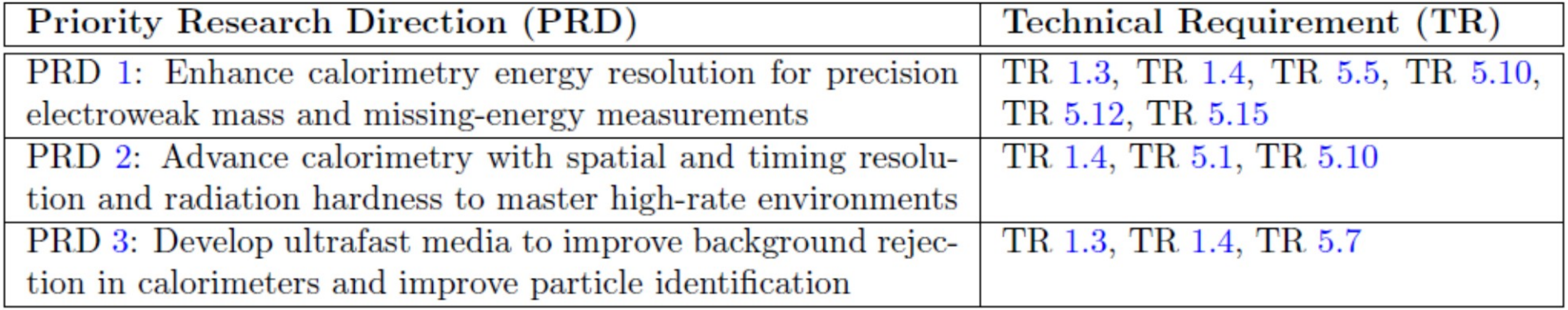
Effect of adding an optimized EM section



Large dispersions and non-linearity for hadrons!

10.1088/1748-0221/15/11/P11005

Some goals for future calorimetry



Priority Research Direction (PRD)	Technical Requirement (TR)
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	TR 1.3, TR 1.4, TR 5.5, TR 5.10, TR 5.12, TR 5.15
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	TR 1.4, TR 5.1, TR 5.10
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification	TR 1.3, TR 1.4, TR 5.7

Basic Research Needs for High Energy Physics Detector Research & Development doi:10.2172/1659761

Eg:

State of the art EM resolution => Higgs from recoil in Z→ll + H→X (even invisible)
State of the art jet resolution => Separate hadronic W,Z,H decays ($\sigma_E/E \sim 4\%$ @80-90 GeV)
Spatial resolution and timing for PFA, particle ID
…

Improving resolutions

Taking state of the art EM calorimeter energy resolution as sufficient for future physics needs, the focus is (simultaneously) improving hadron performance

Two general approaches

- **Particle-flow** approach using tracker information to measure charged jet fragments and calorimeter data mainly for the measurement of neutral particles.
  - Requires fine (transverse) granularity to separate showers
  - “Confusion term” for co-linear particles/showers important at high energy
- **Dual-readout** approach uses a proxy for invisible energy component of hadron showers
  - Effectively use an evt-by-evt measure of EM fraction of hadronic showers
  - Complimentary to (also compatible with) PF methods
  - More moderate requirements on granularity

What to we mean by Dual Readout Calorimetry?

DR calorimetry relies on two different signals to give information on showers

Typically ionization/scintillation signal plus Cherenkov light

Cherenkov light (Ĉ) ~only results from EM component of showers

- e+,e- radiate Ĉ down to around 200 keV
- While the majority of the purely hadronic component comes from nonrelativistic hadrons from nuclear collisions, eg scintillation (S), but no Ĉ in an optical calorimeter

Measurements of S and Ĉ are related to the EM shower fraction.

Total shower energy is then determined using e/h values of the calorimeter.

A bit of trivia

The 1st reference to the technique goes back to the ‘83 SLAC Summer School

A REVIEW OF THE PHYSICS AND TECHNOLOGY OF HIGH-ENERGY CALORIMETER DEVICES #25

P.M. Mockett (Washington U., Seattle) (Jul, 1983)

Published in: *Conf.Proc.C* 830727 (1983) 335-393 • Contribution to: 11th SLAC TOPICAL Conference on Particle Physics: Dynamics and Spectroscopy at High Energy (Follows SLAC Summer Inst.), 11th SLAC Summer Institute on Particle Physics: Dynamics and Spectroscopy at High Energy (Followed by 3-day Topical Conference) (SSI 83)

SLAC-267, 335 (1983)

https://www.slac.stanford.edu/vault/pubvault/bln19801989/bln1983sep.pdf

How DR works

1) Ĉ, S signals normalized to electron response can be written as:

$$\hat{C} = [f_{em} + (h/e)_{\hat{C}}\,(1 - f_{em})]\,E$$
$$S = [f_{em} + (h/e)_{S}\,(1 - f_{em})]\,E$$

eg, f_{em}=1 for electrons,
$\hat{C},S = 1,1$

2) Solve for E in terms of detector properties

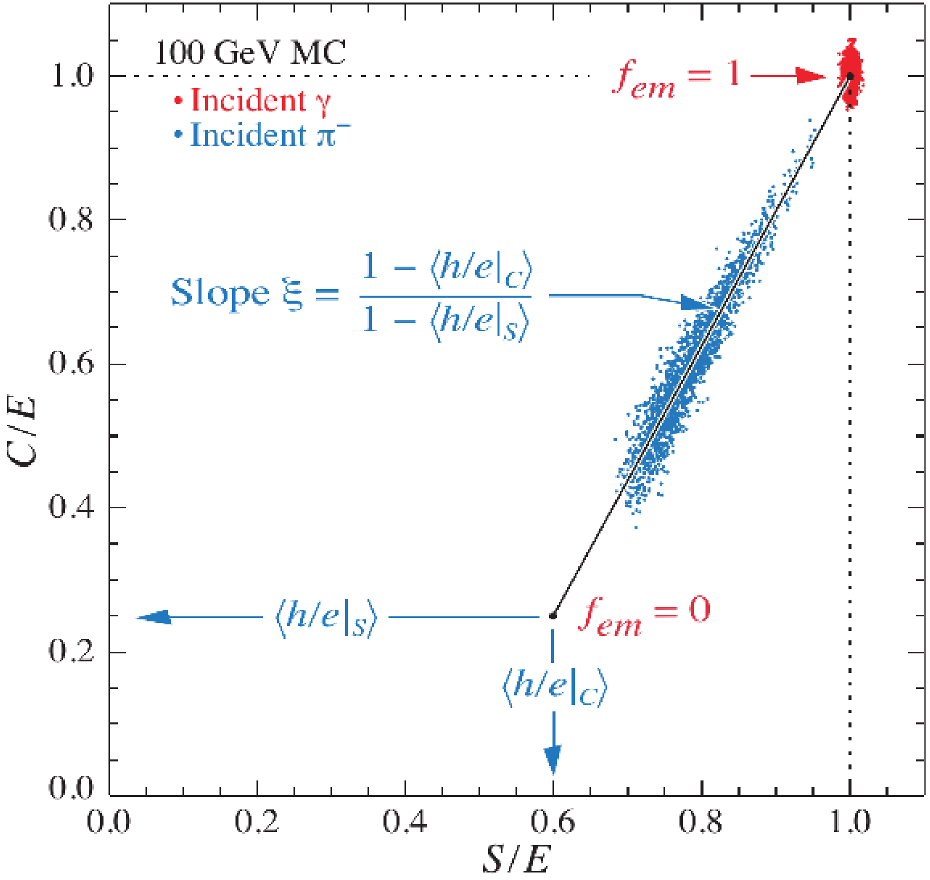
$$E = (\xi S - \hat{C})/(\xi - 1),$$
$$\xi = [1 - (h/e)_{\hat{C}}\,]/[1 - (h/e)_{S}\,]$$

3) Need to determine ξ which describes the average h/e response for each component.

Note that e/h (≣h/e) describes the ratio of light produced by EM to non-EM components of a hadronic shower, not e/π which is E dependent!

NIM A308 (1991) 481, NIM A 259 (1987) 389

How/why DR works



PDG

$$E = (\xi S - \hat{C})/(\xi - 1)$$

Hadronic event (π^- here) can be seen to scatter about the fixed slope

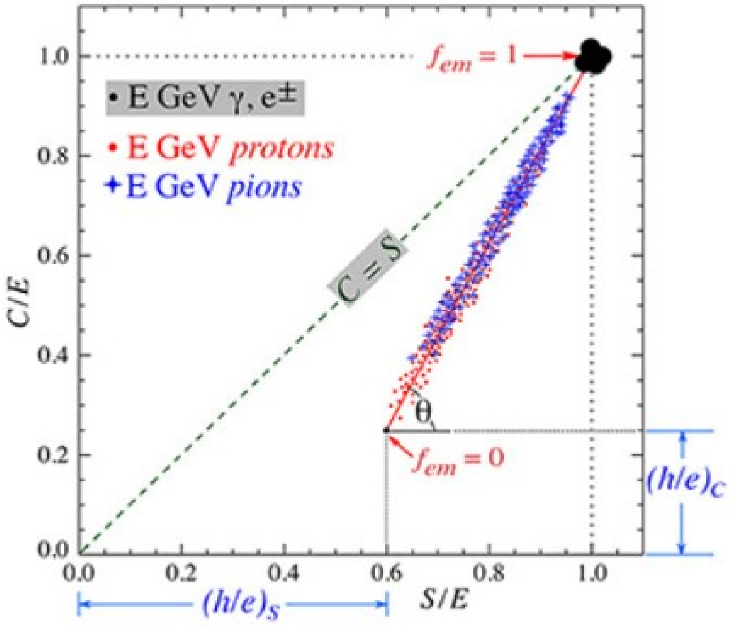
Slope depends only on e/h values and is therefore energy independent

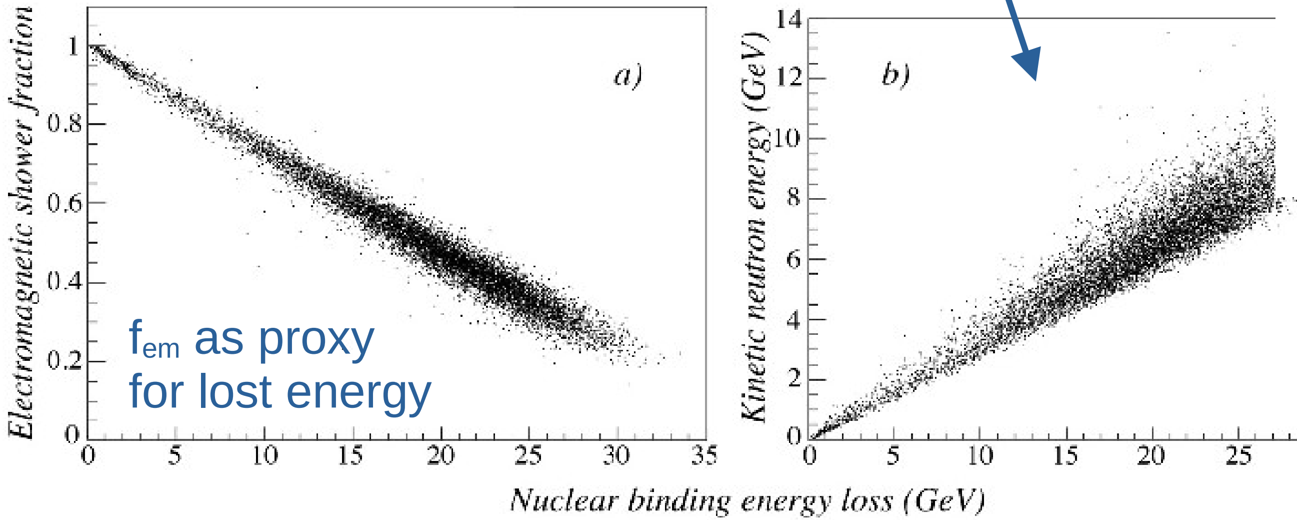
$\hat{C}$,S measurements effectively determine f_{em} and allow a shower-by-shower correction

How/why DR works

Slope is independent of hadron species, even though <f_{em}> varies by hadron

Bonus? Additional correlation of neutron KE with binding energy loss suggests additional information may be found in later signal windows

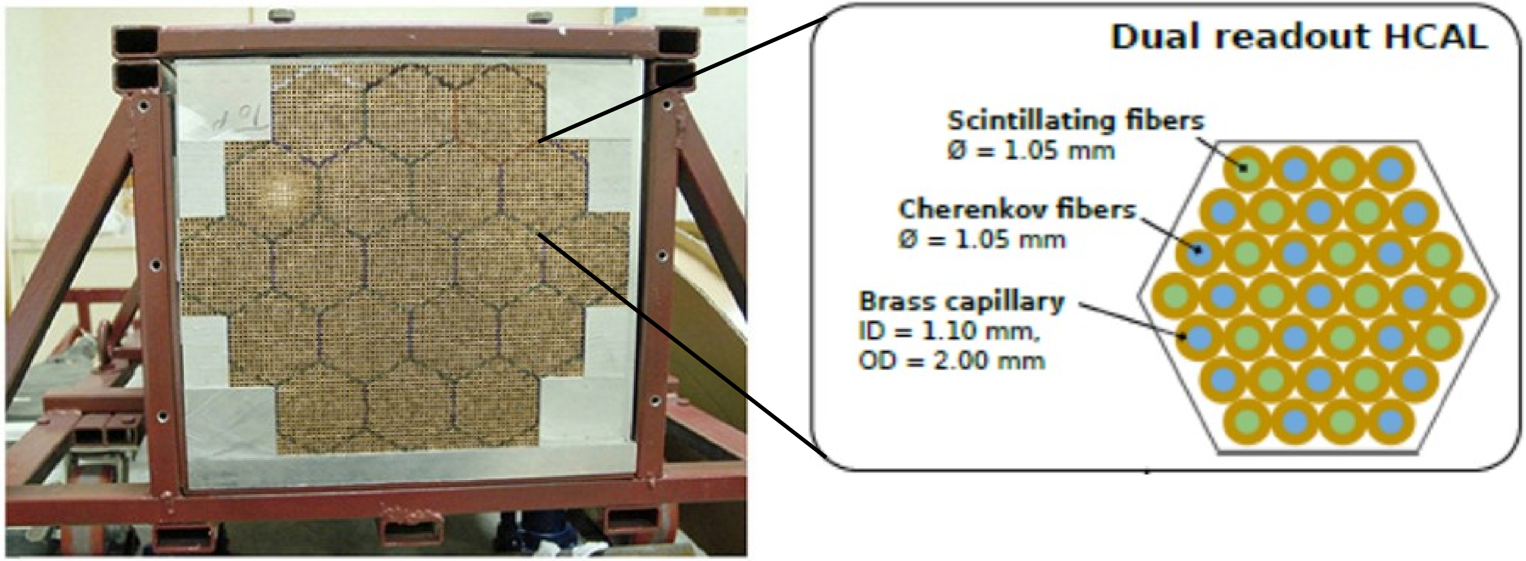


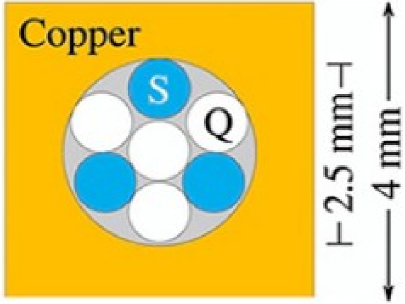


f_{em} as proxy for lost energy

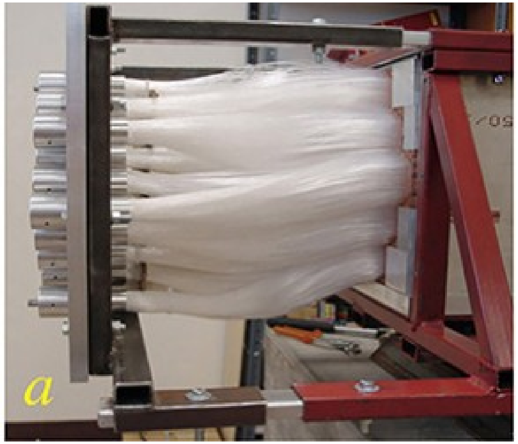
NIM.A 882 (2018) 148-157

Prior art: DREAM calorimeter





- Quartz fiber for Ĉ
- 10 λ_I copper structure
- Ĉ,S fibers grouped in each tower, readout by PMTs



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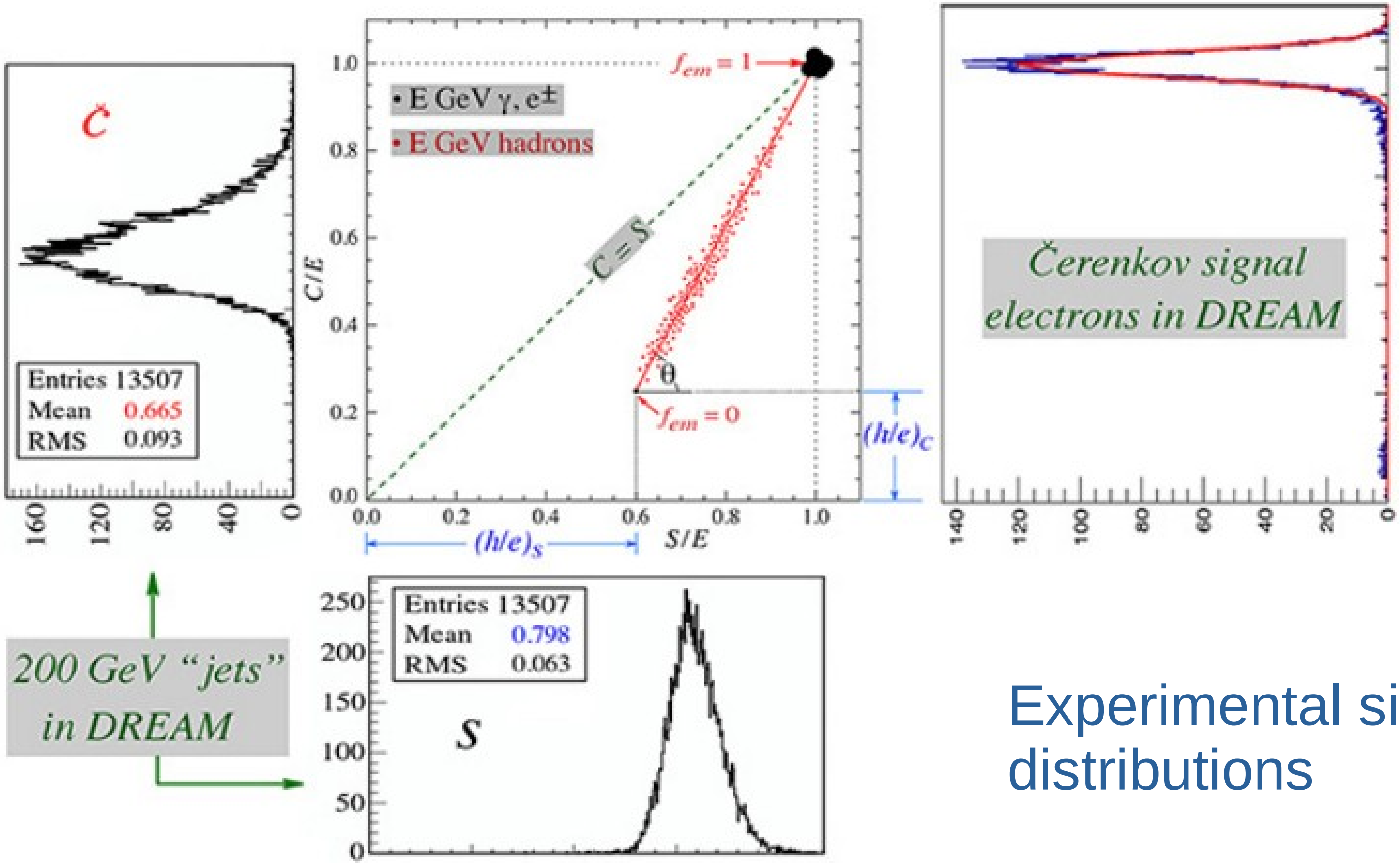
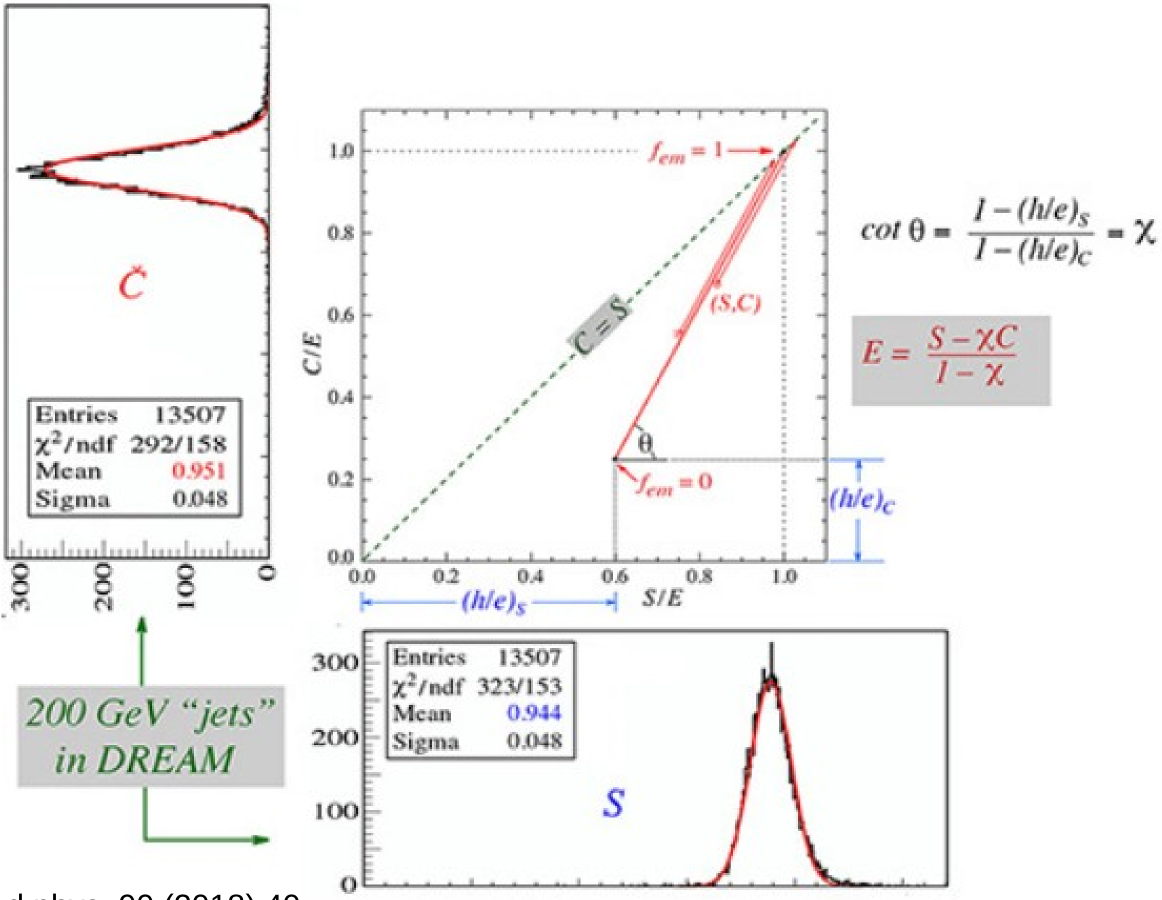


Experimental signal distributions

Rev. Mod phys. 90

Prior art: DREAM calorimeter



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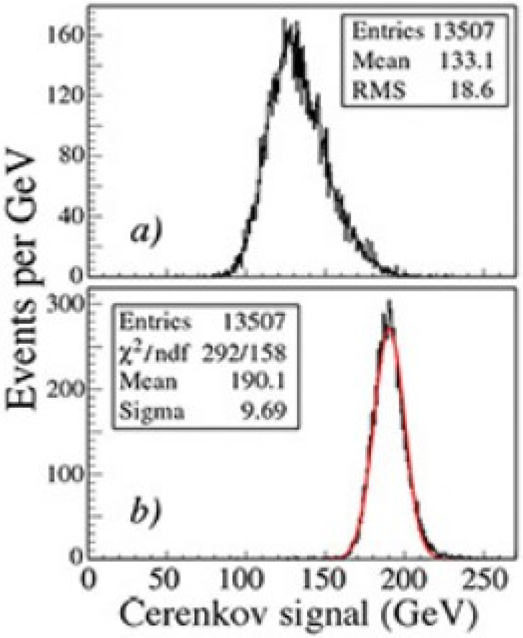
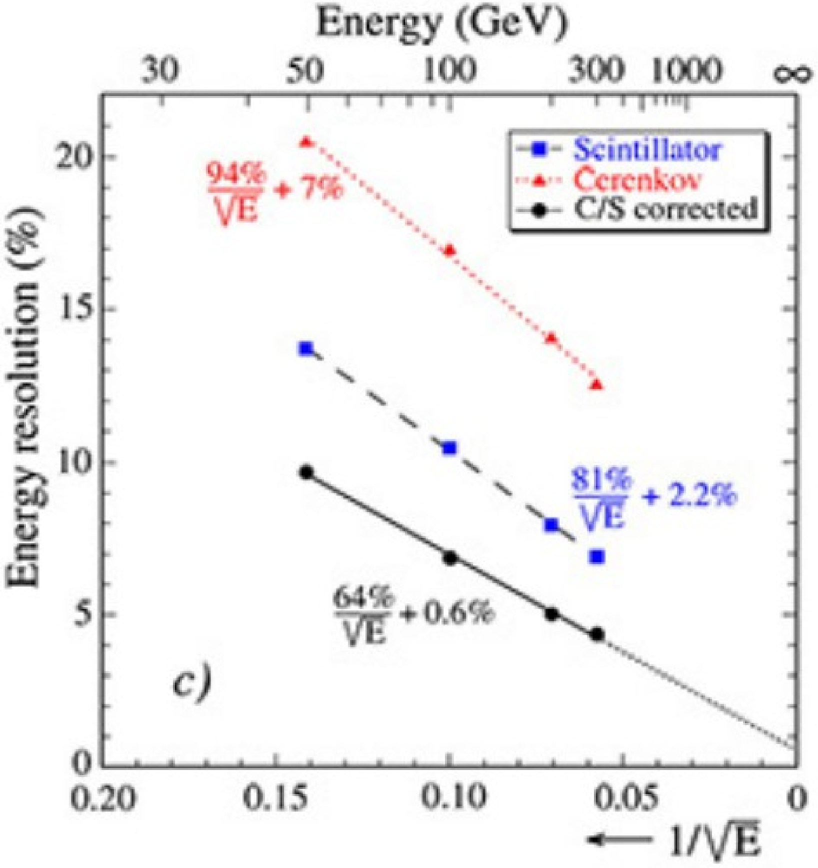
Relative response after applying DR correction

Note: non-closure at the few % level is attributed to transverse shower leakage from small prototype

Prior art: DREAM calorimeter



After correction ==>



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Proof of principle

Clear improvement in resolution, but performance limited in this detector by:

- Transverse shower leakage
- Cherenkov light yield only ~8 photons/GeV

Prior art: RD52

The RD52 Collaboration completed a number of studies at the CERN H8 test beam.

- Applying the DR technique to homogeneous crystal elements
- Performed a combined test with a crystal ECAL + the DREAM fiber calorimeter
- Constructed a larger hadronic straw-type calorimeter for further demonstrate the method

A brief summary of their results follows for more details see:
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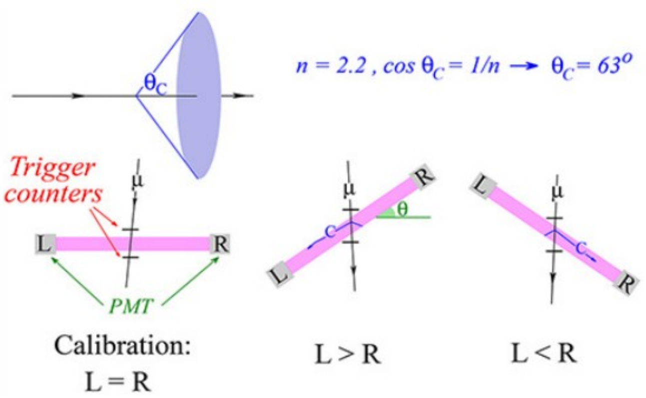
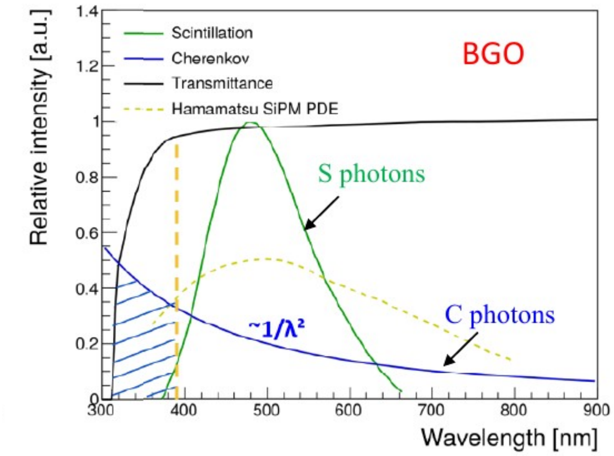
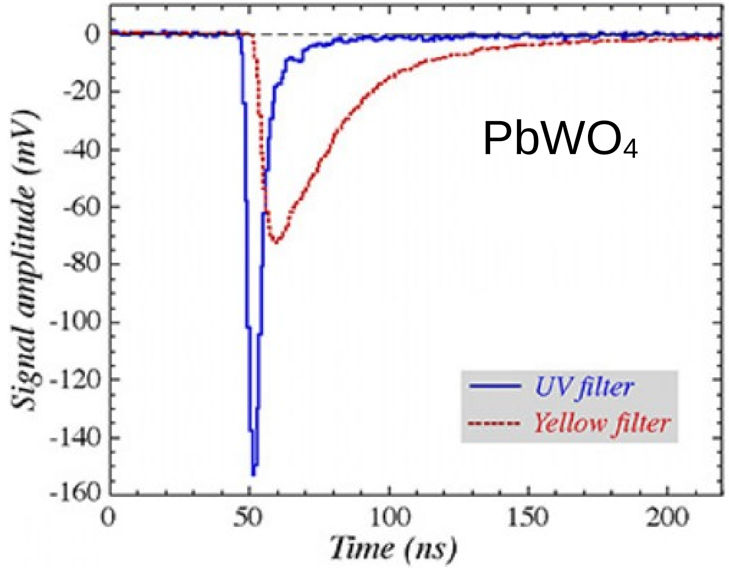
Prior art: RD52

Tests of single crystal ($PbWO_4$, BG[S]O) w/ PMT readout, wavelength filters to separate
Ĉ vs S light, also pulse shapes studied

=> proof of principle of Ĉ/S separation in xtals







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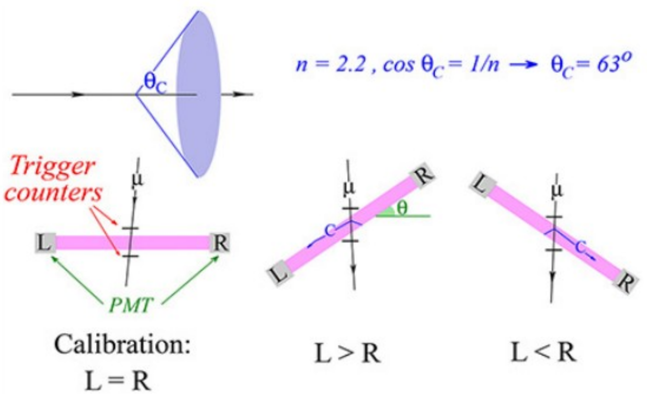

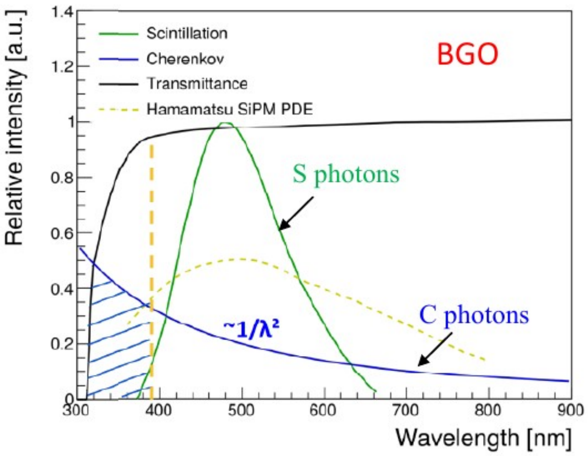

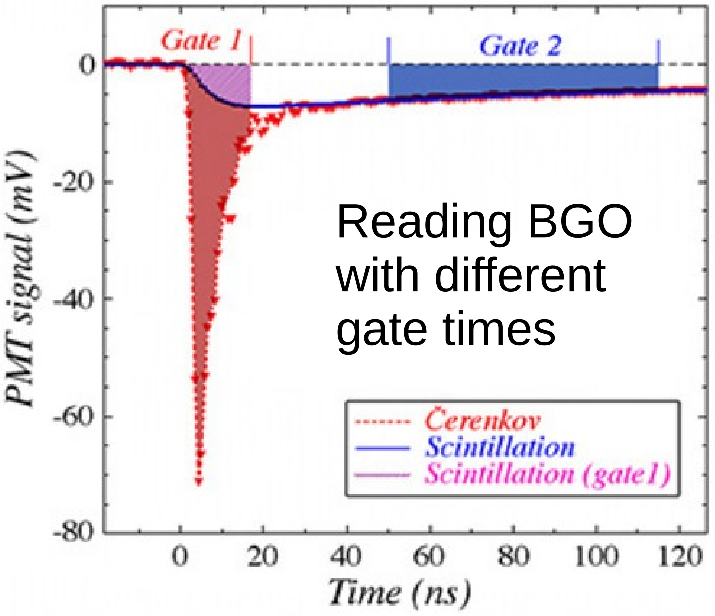

Reading BGO with different gate times

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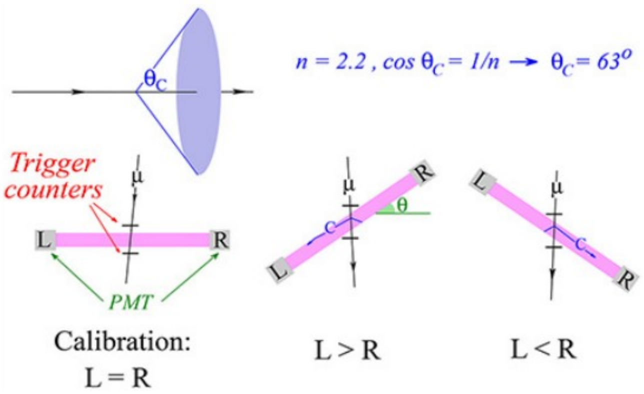
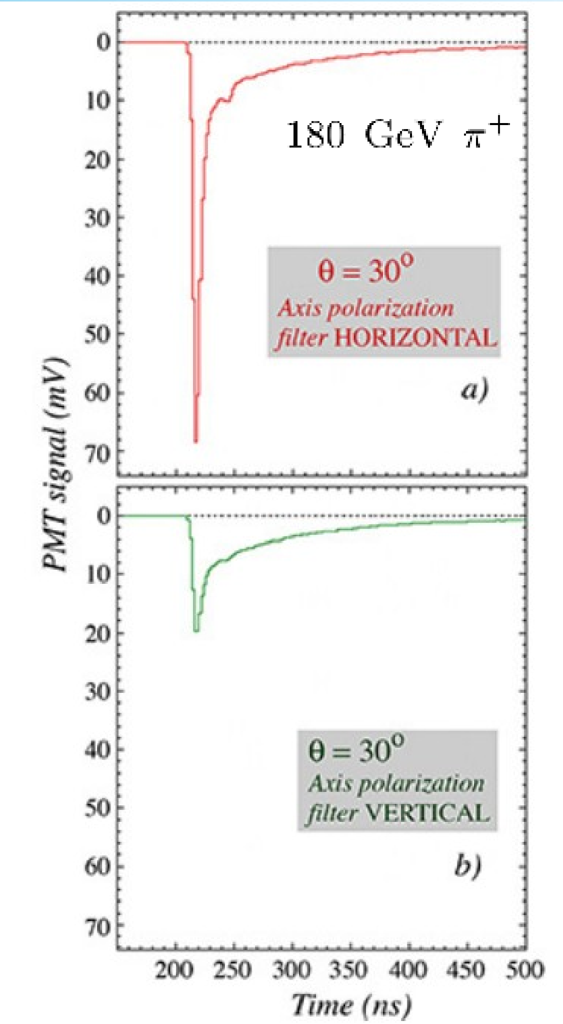
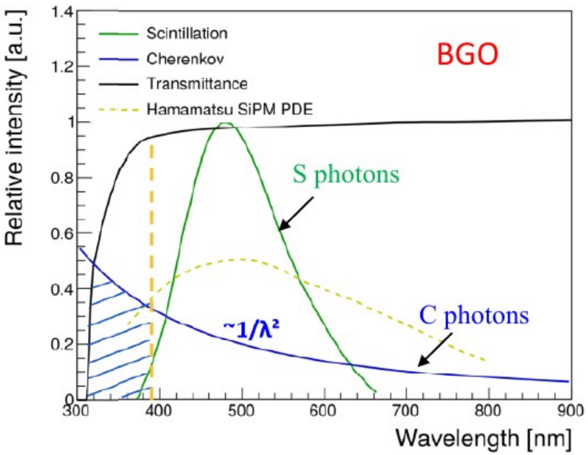
Prior art: RD52



Also polarization effects observed, consistent w/ Ĉ light. Tests here in BSO w/ filter+polarizer





Multiple options exist for identifying Ĉ light!

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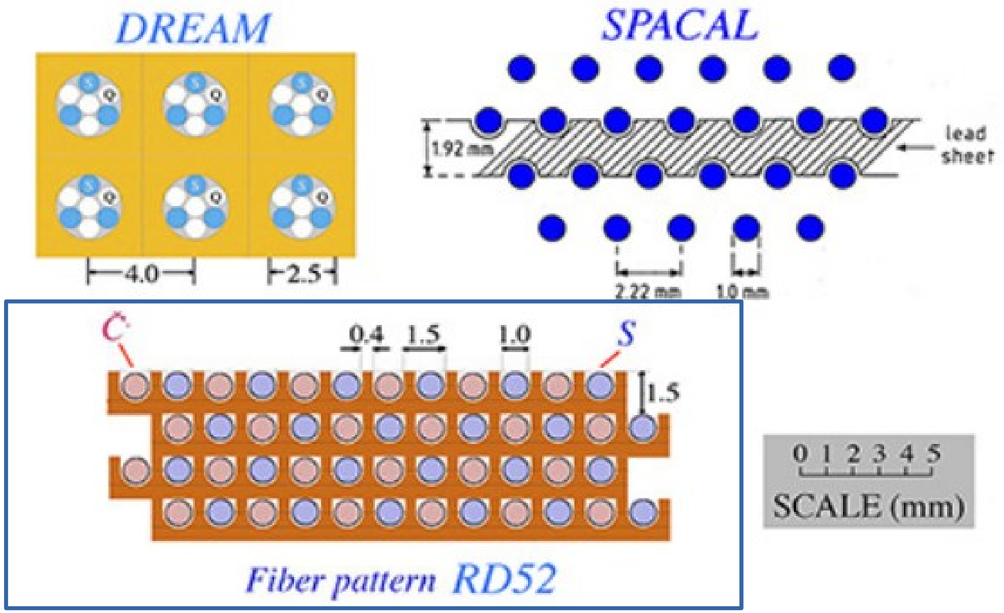
Improving on proof of DR

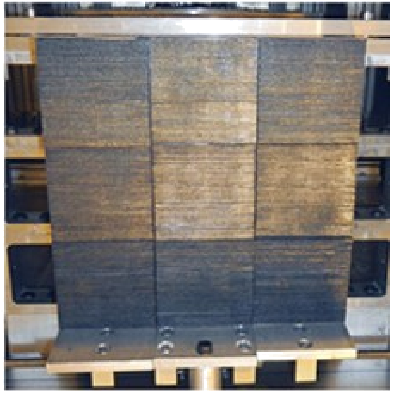
Another proof of principle showed that the DR method was applicable to a combined detector of crystals + DREAM as a backing calorimeter, but pointed out a number of difficulties w/ the crystal readout, namely attenuation lengths, photon statistics, temperature dependence, ...

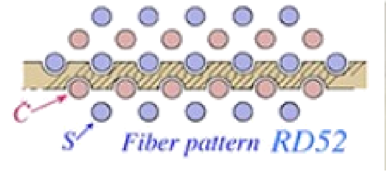
The collaboration focused on improving the HCAL in the next phase.

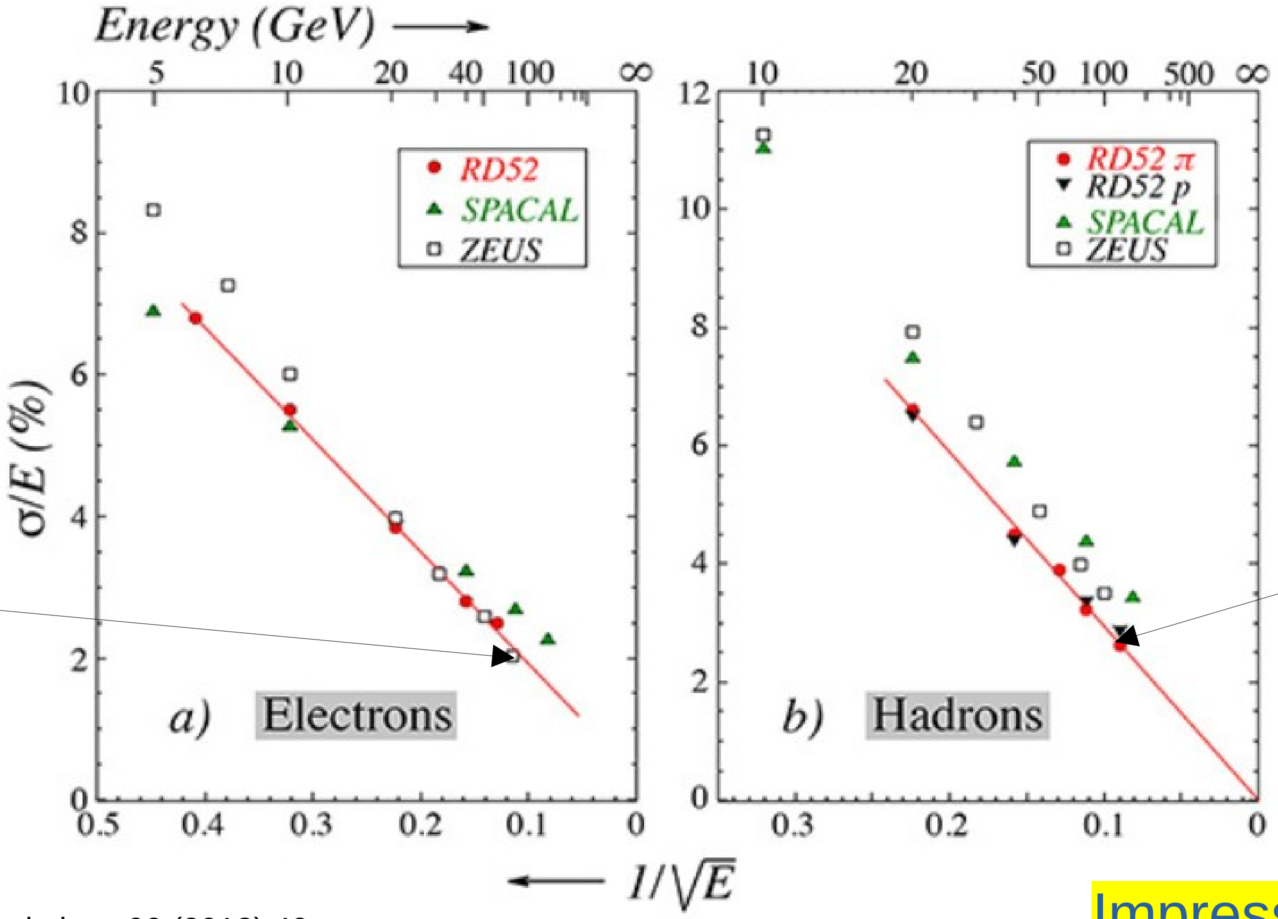


Most importantly:
- Improving Ĉ light collection
  - Larger NA for fibers
  - Larger sampling fraction
  - Higher efficiency PMTs
- Improving transverse containment

Skip to the summary plots from RD52cal







$\simeq 20\%/\sqrt{E}$

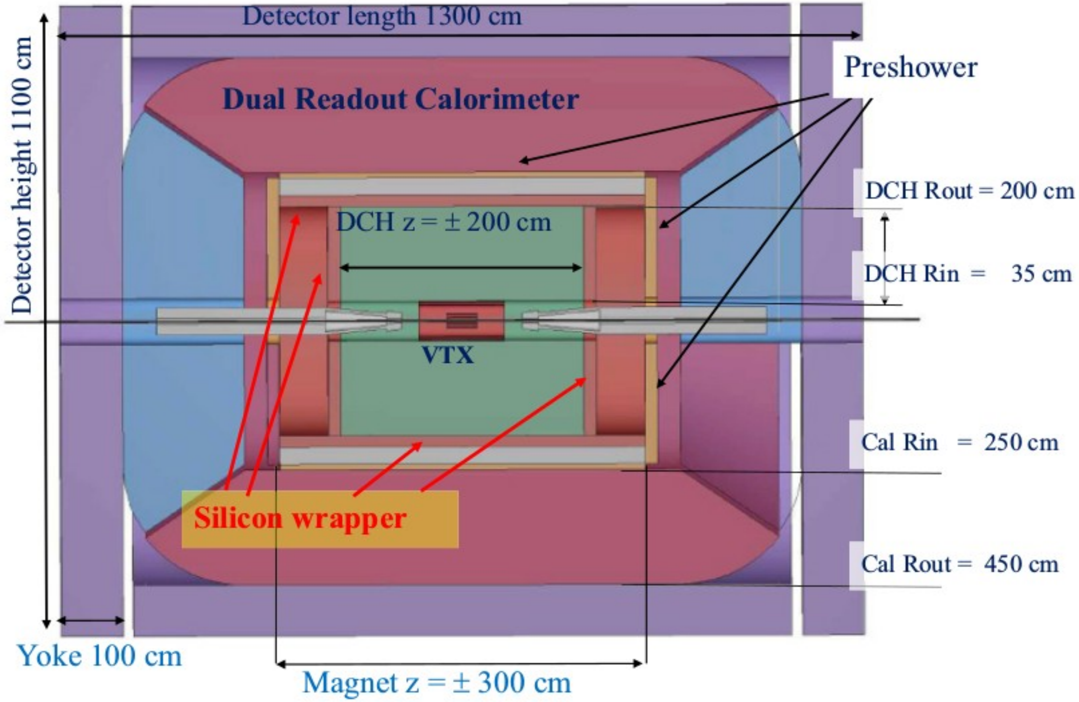
$\simeq 30\%/\sqrt{E}$

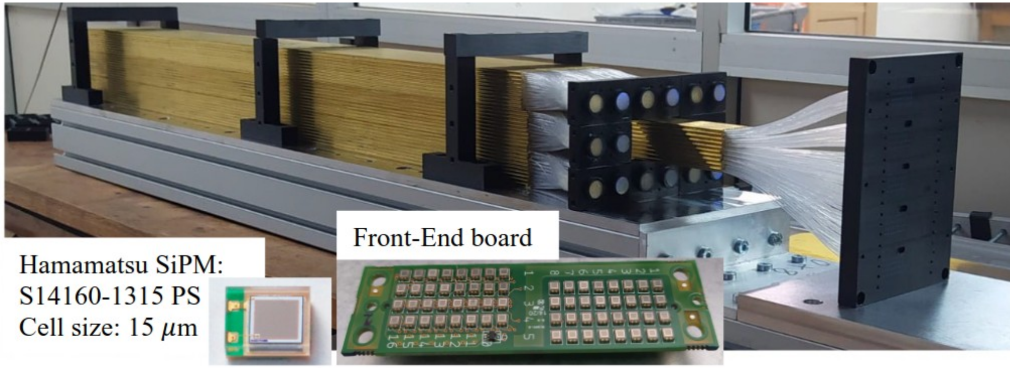
Rev. Mod phys. 90 (2018) 40

Impressive results!

Continuing work

Strong efforts (mainly centered in Europe, Korea, P.R.C.) have started on next generation DR fiber calorimeter prototypes as part of the IDEA Collaboration (Innovative Detector for Electron-positron Accelerators)





IDEA DR fiber calorimeter concept
w/ SiPM readout

https://www.mdpi.com/2410-390X/6/4/59

CALVISION

R&D consortium dedicated to detector R&D future colliders, emphasis on detector to meet physics requirements for next lepton collider.

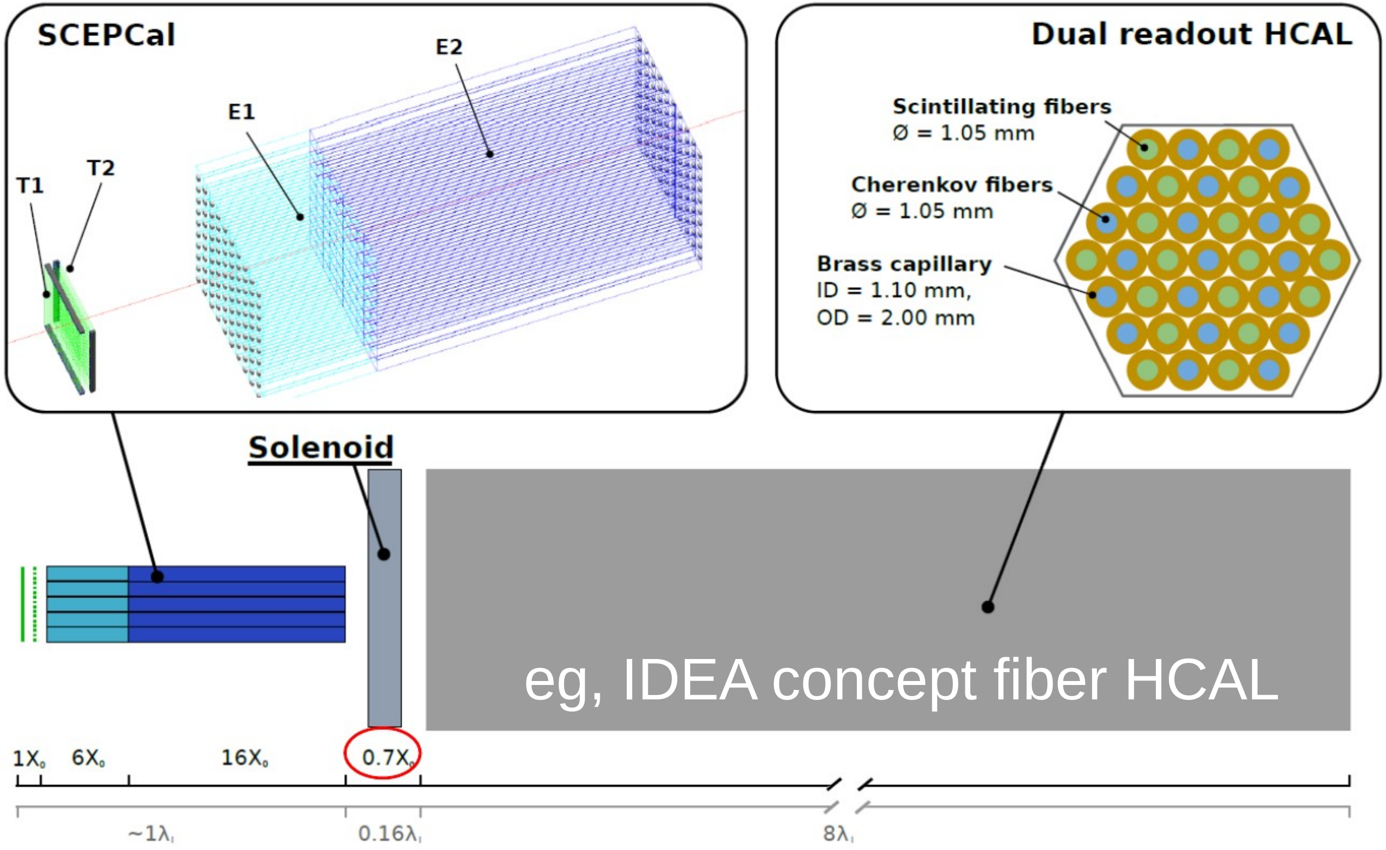
- Precise measurements of the Higgs boson properties, and
  - W and Z bosons physics as critical tests of Standard Model,
  - and their use in exploration of new physics beyond the SM
- Develop complimentary technologies to typical PFA approaches
- Explore (moderately) high granularity calorimetry with:
  - Intrinsic dual readout capabilities
  - State of art EM resolution (homogeneous crystal)
  - Hadron performance comparable to fiber-based DR
- Bluesky R&D on materials, readout, techniques
- Collaborate in international efforts on best detector solutions

A Segmented DRO Crystal ECAL + DRO Fiber HCAL

Concept:

- (Optional) timing layer
- Segmented ECAL
- Thin solenoid
- DREAM/RD52 style HCAL

SCEPCal:
Segmented
Crystal
Electromagnetic
Precision
Calorimeter

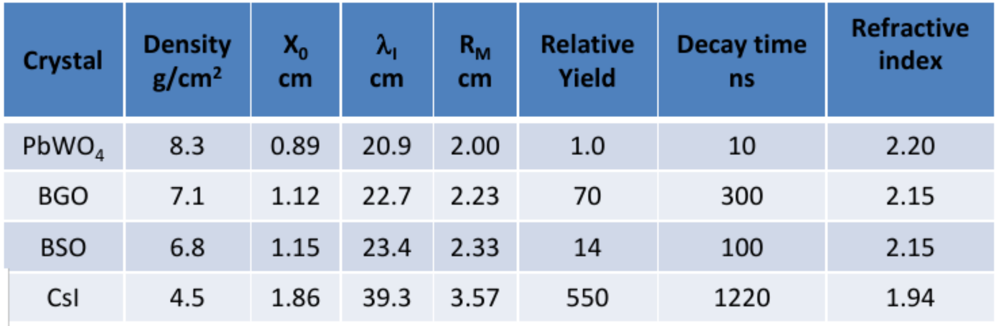


Concept highlights advantages for physics program with precision ECAL

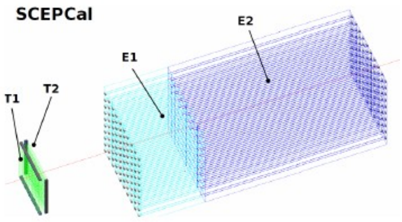
Segmented ECAL

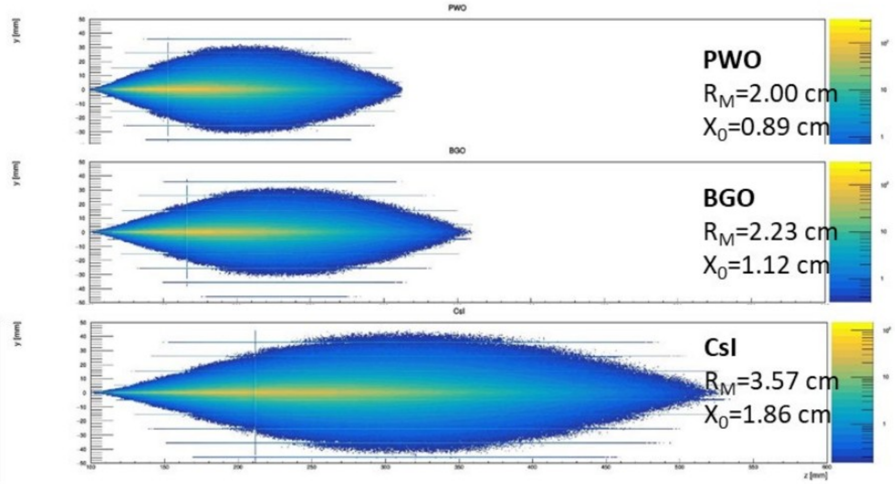
Two layers w/ high density (short X_0, small R_M)

- Fast signal, reasonable Ĉ/S ratio, cost effective
- **$PbWO_4$**, BGO and BSO are good candidates

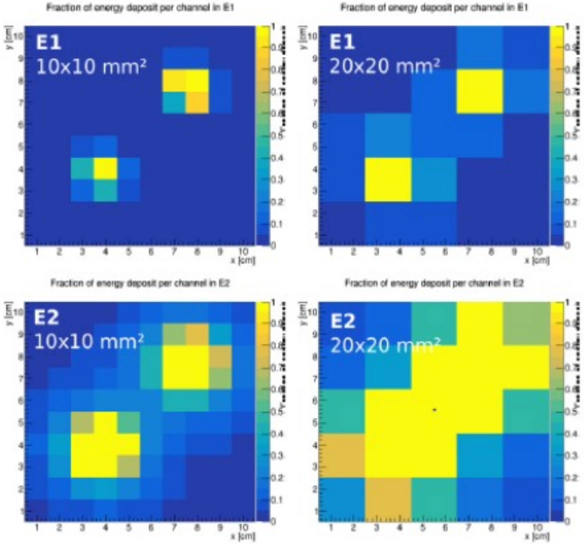


Crystal	Density g/cm²	X_0 cm	λ_I cm	R_M cm	Relative Yield	Decay time ns	Refractive index
$PbWO_4$	8.3	0.89	20.9	2.00	1.0	10	2.20
BGO	7.1	1.12	22.7	2.23	70	300	2.15
BSO	6.8	1.15	23.4	2.33	14	100	2.15
CsI	4.5	1.86	39.3	3.57	550	1220	1.94





Longitudinal profiles

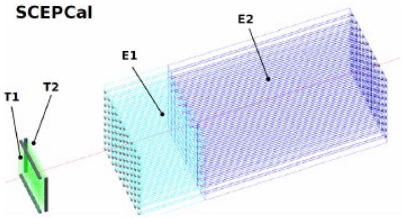


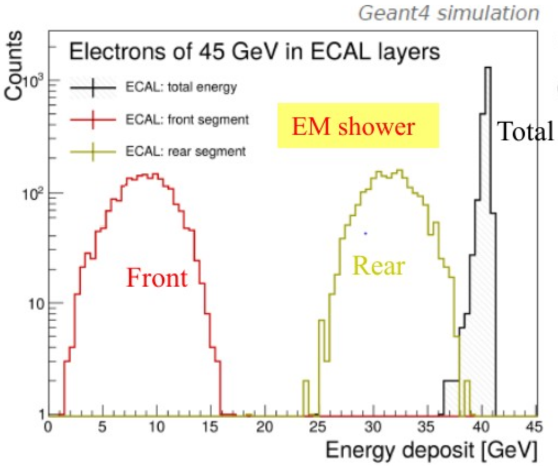
Separation of photons w/ 3° opening angle

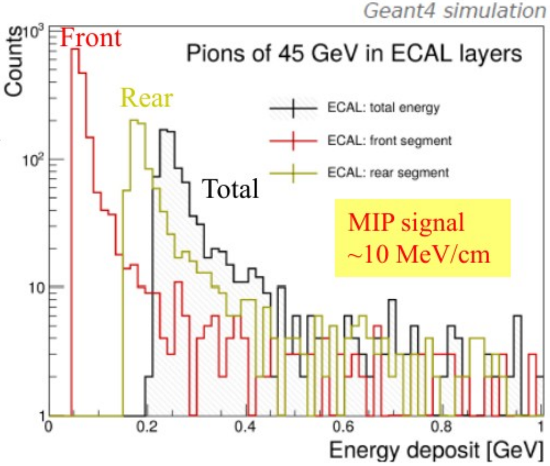
Segmented ECAL

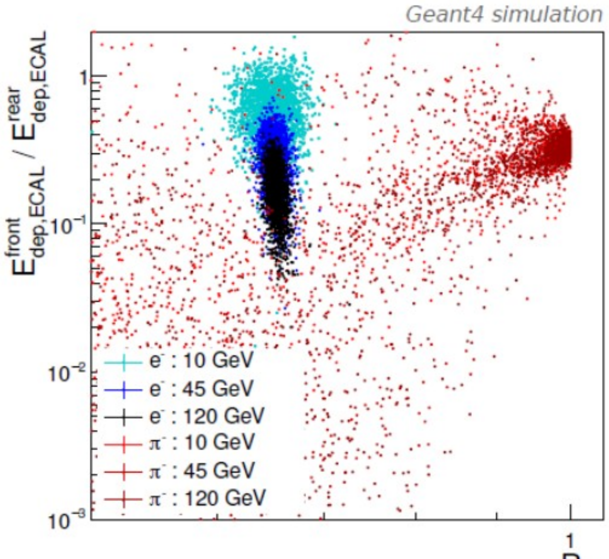
Two segmentation layers

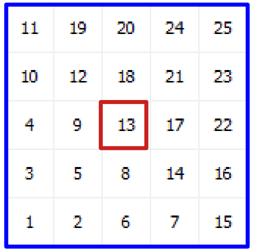
- Front segment (~6 X_0, ~50 mm)
- Rear segment (~16 X_0, ~140 mm)
- Longitudinal segmentation useful for the separation of electrons and pions (can also be included in e/γ/$\pi^\pm$, separation methods)











11	19	20	24	25
10	12	18	21	23
4	9	13	17	22
3	5	8	14	16
1	2	6	7	15

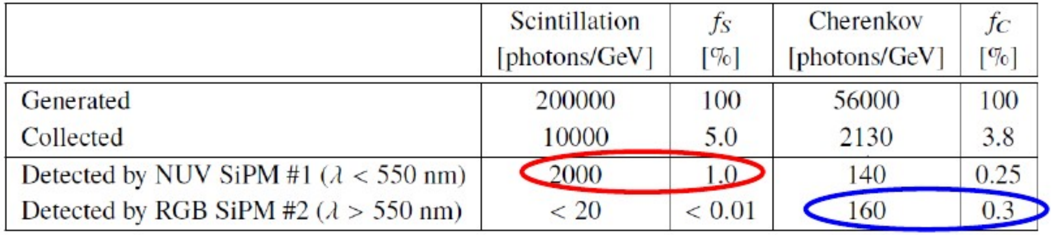
$$R_{25} = \frac{\boxed{\text{cell } 13}}{\boxed{5\text{x}5}}$$

Front to rear energy vs transverse distribution

Segmented ECAL: E2 DR segment

Light collection study (rear segment)

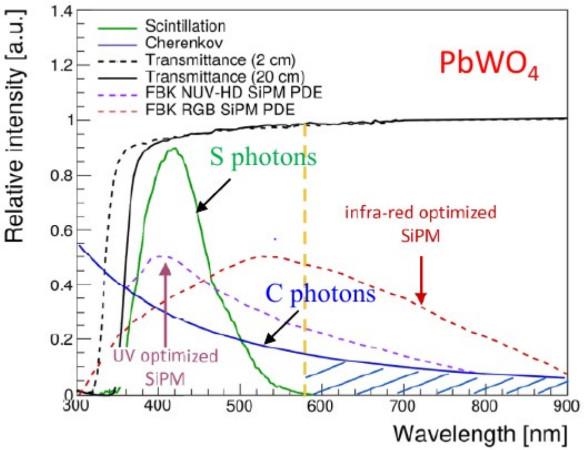
- 5×5 mm^2 SiPM (10-15 µm cell size)
  - Optical filters to separate S and Ĉ
  - **Unlike previous studies also focus on long wavelength Ĉ signal**
- 3 SiPMs (one on entrance, two on exit)
  - Front: optimized for scintillation light
  - Rear: two SiPMs optimized for scintillation and Cerenkov light

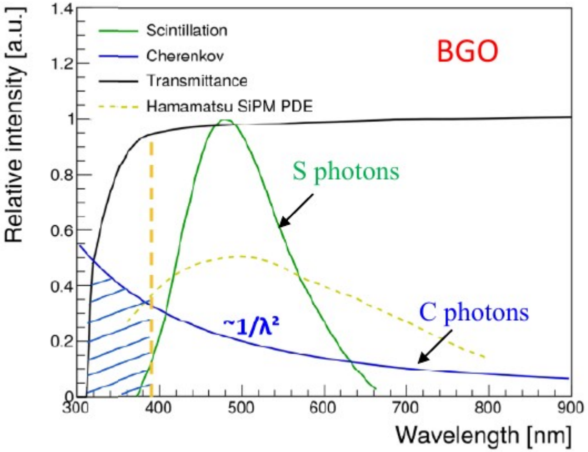


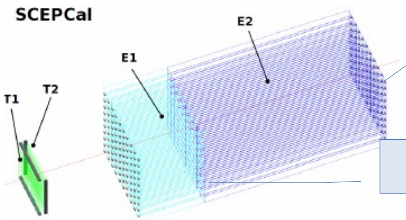
	Scintillation [photons/GeV]	f_S [%]	Cherenkov [photons/GeV]	f_C [%]
Generated	200000	100	56000	100
Collected	10000	5.0	2130	3.8
Detected by NUV SiPM #1 ($\lambda < 550$ nm)	2000	1.0	140	0.25
Detected by RGB SiPM #2 ($\lambda > 550$ nm)	< 20	< 0.01	160	0.3

Light yield (PbWO$_4$): ~2000 S and ~56 C photons/GeV

- Local collection eff: ~5% assumed
- PDE: ~20% assumed





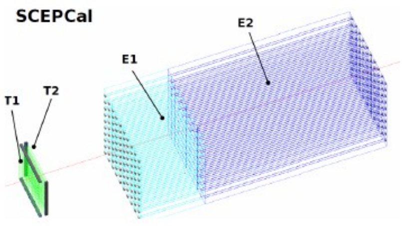


C+S readout

S readout

S readout

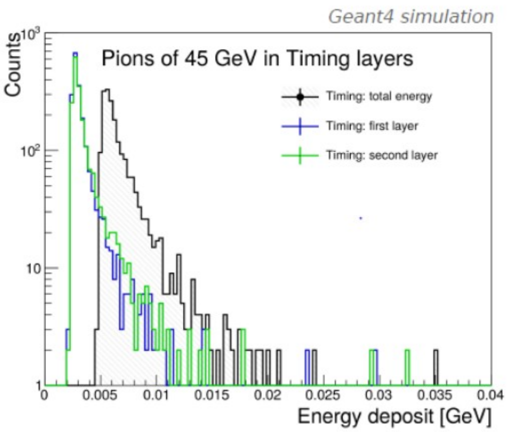
Timing layer concept

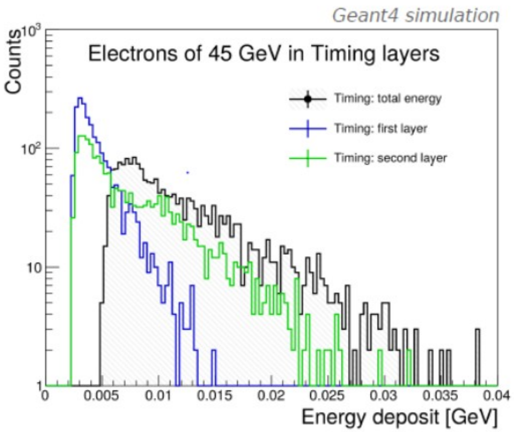


Two timing layers (σ_t~20 ps)

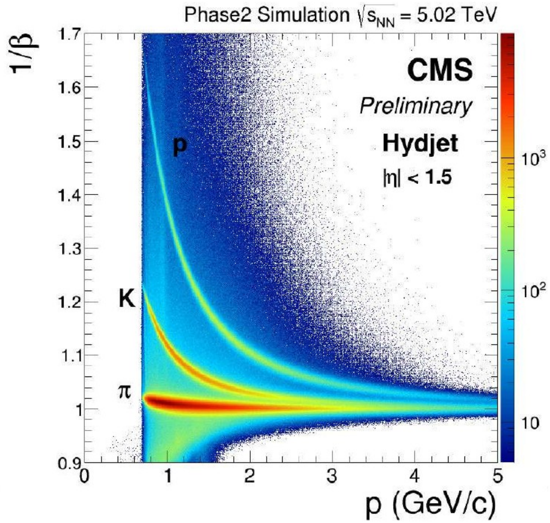
- Similar timing performance as the CMS barrel MIP Timing detector
- LYSO:Ce scintillating crystals (~0.8 X_0), O(10^4) photons/MeV
- 3×3×100 mm^3 thin crystal bar
- 3×3 mm^2 SiPM (15-20 μm cell size)
- Orthogonal layers => position resolution ~ 1 mm in x-y directions
- Excellent timing resolution will be useful for searches of long-lived particles, and for providing new possibilities for identification of charged hadrons through TOF

e/π separation





Flavor physics



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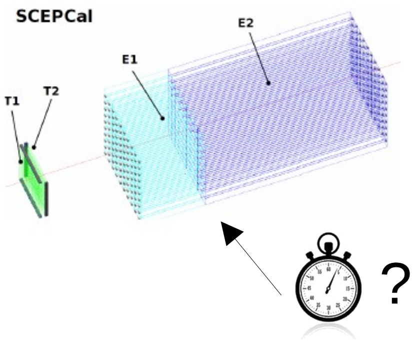
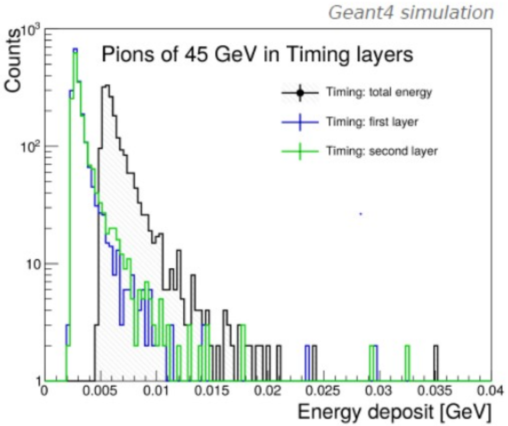
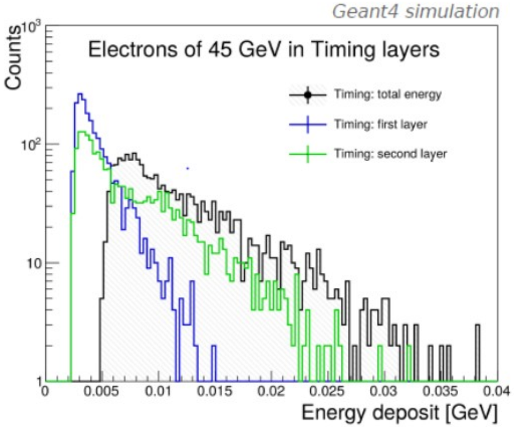
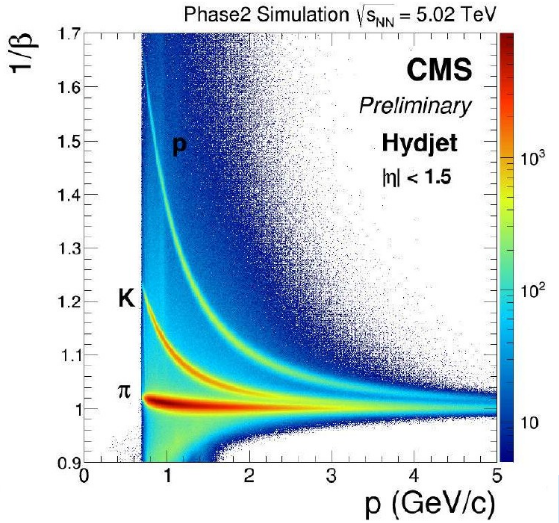


e/π separation



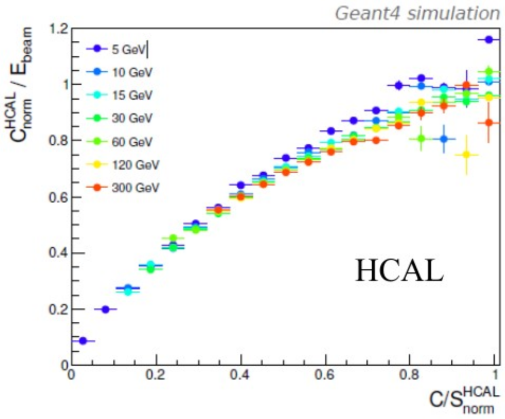


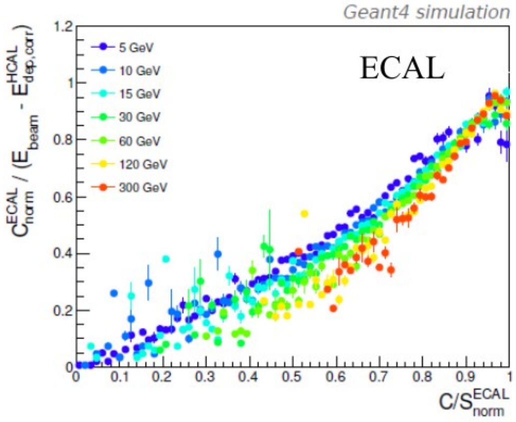
Flavor physics



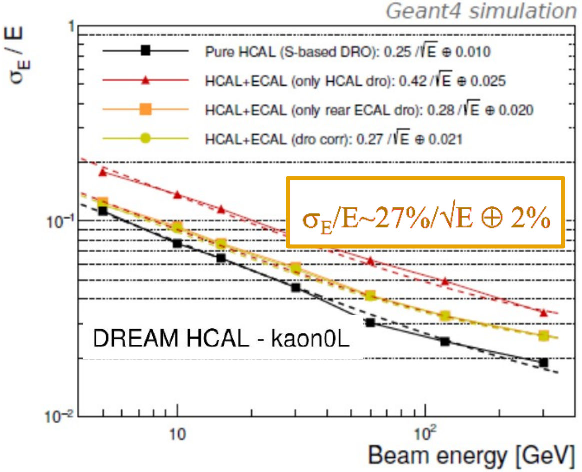
SCEPCal +DRO HCAL performance studies

DRO corrections





Neutral hadron E resolution



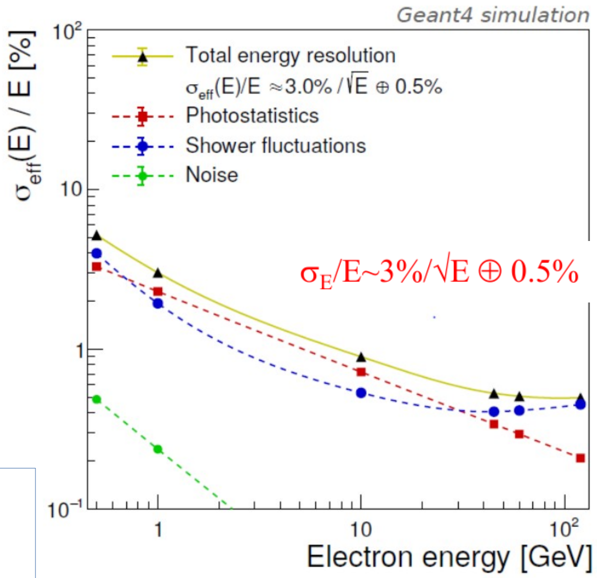
Similar sampling term as that of a pure DRO HCAL

- DR in EM + hadron sections

Slightly larger constant term:

- intrinsic limitation in system combining segments with different e/h ratios
- material budget from the ECAL services and the solenoid

Electron E resolution



Electron energy resolution maintained at level of best crystal calorimeters

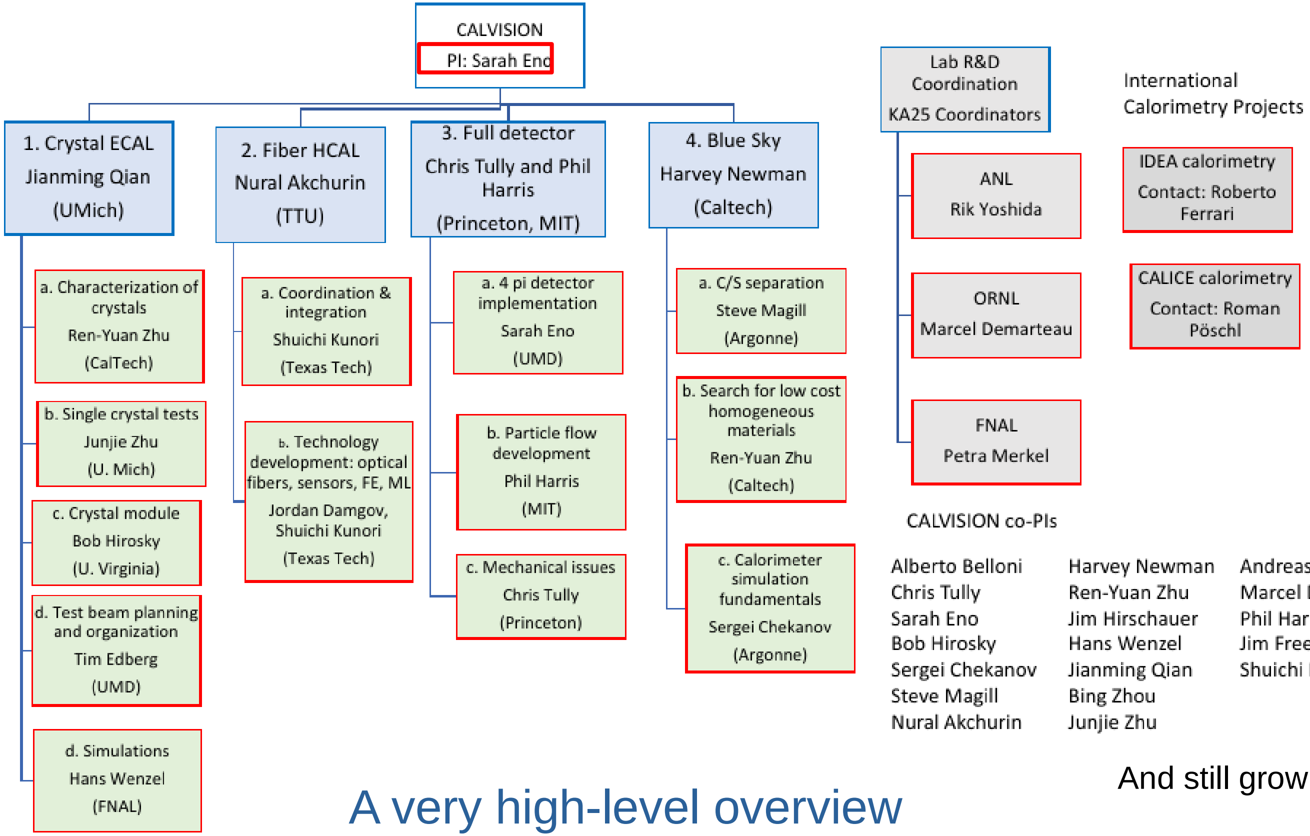
Organization of effort

CALVISION formed to pursue calorimetry efforts on multiple fronts:

- Crystal DRO Ecal
- Fiber DRO HCAL
- Full Detector studies
- BlueSky R&D

Multi-year efforts proposed in each area.

1st phase is ~summer '22 – '25
- Lower level R&D
- Single modules, small arrays
- Materials/technology evaluations
- Scale up modules in next phase



CALVISION
PI: Sarah Eno

1. Crystal ECAL
Jianming Qian
(UMich)

a. Characterization of crystals
Ren-Yuan Zhu
(CalTech)

b. Single crystal tests
Junjie Zhu
(U. Mich)

c. Crystal module
Bob Hirosky
(U. Virginia)

d. Test beam planning and organization
Tim Edberg
(UMD)

d. Simulations
Hans Wenzel
(FNAL)

2. Fiber HCAL
Nural Akchurin
(TTU)

a. Coordination & integration
Shuichi Kunori
(Texas Tech)

b. Technology development: optical fibers, sensors, FE, ML
Jordan Damgov, Shuichi Kunori
(Texas Tech)

3. Full detector
Chris Tully and Phil Harris
(Princeton, MIT)

a. 4 pi detector implementation
Sarah Eno
(UMD)

b. Particle flow development
Phil Harris
(MIT)

c. Mechanical issues
Chris Tully
(Princeton)

4. Blue Sky
Harvey Newman
(Caltech)

a. C/S separation
Steve Magill
(Argonne)

b. Search for low cost homogeneous materials
Ren-Yuan Zhu
(Caltech)

c. Calorimeter simulation fundamentals
Sergei Chekanov
(Argonne)

Lab R&D Coordination
KA25 Coordinators

ANL
Rik Yoshida

ORNL
Marcel Demarteau

FNAL
Petra Merkel

International Calorimetry Projects

IDEA calorimetry
Contact: Roberto Ferrari

CALICE calorimetry
Contact: Roman Pöschl

CALVISION co-PIs

Alberto Belloni
Chris Tully
Sarah Eno
Bob Hirosky
Sergei Chekanov
Steve Magill
Nural Akchurin

Harvey Newman
Ren-Yuan Zhu
Jim Hirschauer
Hans Wenzel
Jianming Qian
Bing Zhou
Junjie Zhu

Andreas Jung
Marcel Demarteau
Phil Harris
Jim Freeman
Shuichi Kunori

And still growing!

A very high-level overview of planned activities follows

Initial test beams overview: ECAL

Initial bench and beam tests for xtal ECAL will focus on understanding photon collection in various bars of similar size to those needed for a real detector
(smaller bars will require large corrections from simulation)

and various materials(PWO, BGO, PbF, BSO?)
Different advantages/challenges for performance criteria

A focus of this year is to
- acquire data for tuning simulation
- to guide choices for a 'phase 2' ECAL module sufficient in size to contain an electron shower
- Gain experience with FE electronics, readout and beam interfaces to run efficient beam tests

'Phase 3' is planned to develop a larger ECAL, sufficient to use with single hadrons in ECAL+HCAL resolution studies in collaboration with IDEA

Performance/feasibility of concept strongly depends on:

- Adequate sampling statistics of Č light (ideally >~50 photons/GeV)
- Sufficient separation of Č from S signal to avoid washing it out
- For state of art ECAL resolution, reasonably large S is desirable. But may require some care to address saturation effects in SiPMS/readout

Initial test beams overview: HCAL (TTU)

Texas Tech group is developing an R&D program based on DREAM modules.

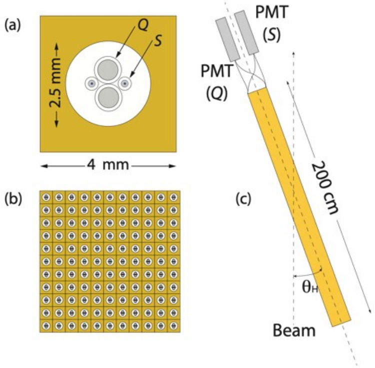
Conceptual design for fast SiPM readout system for "Longitudinal Segmentation with Timing".

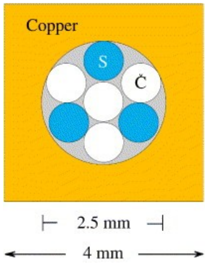
[1] 2023 Test

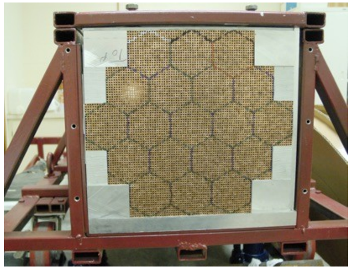
[2] 2024 Test

GOAL 1 (2023)

- Longitudinal segmentation with timing
- R&D of fast SiPM and readout
- Electron beam in North Area

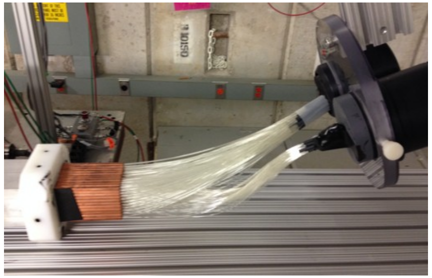






GOAL 2 (2024)

- Verify Cherenkov calorimetry with Neural Network
- Hadron and electron beams in North Area



36 x 32 x 200 cm^3
1000 kg

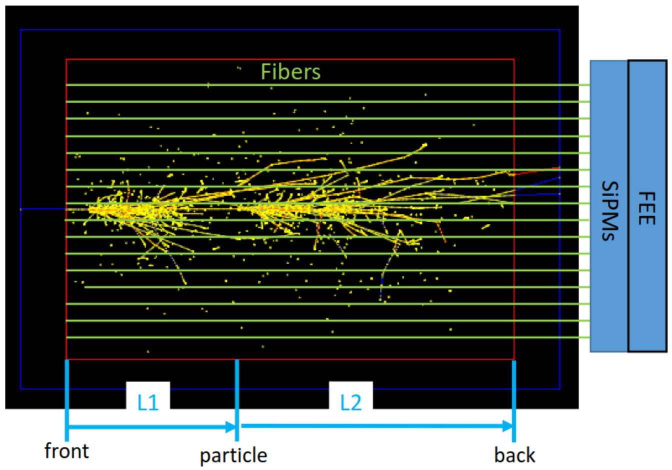
5130 rods (total)

3x3 rods/tower
➔ 324 ch
(in 21.6 x 21.6 cm^2)

[1] https://iopscience.iop.org/article/10.1088/1748-0221/13/04/P04010
[2] https://www.sciencedirect.com/science/article/pii/S0168900204018091

TTU TEST BEAM PLANS 2023 & 2024

Cherenkov Fiber Calorimeter: Longitudinal Segmentation with Timing



Signal Time = L1/c + L2/kc,
c = velocity of particle
kc = velocity of light in fiber (k~0.6)

- ❖ 2D readout: Fewer readout channels
- ❖ SiPM, readout electronics on backside: Lower radiation environment
- ❖ Easier calibration, no need to calibrate in depth
- ❖ Longitudinal Segmentation:

Δt=150 ps, corresponding to Δz =7 cm along fibers. (~1/3 λ)

Timing Resolution	σ/E @ 100 GeV
0 ps	3.6 %
100 ps	3.9 %
150 ps	4.0 %
200 ps	4.2 %

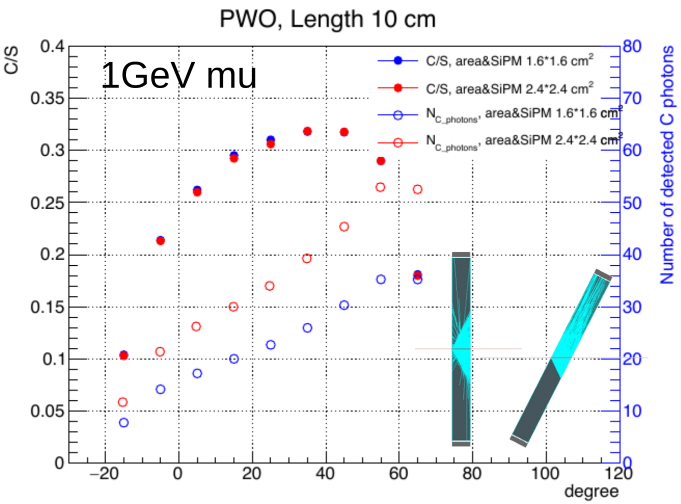
- (Goal1) Constructing a 2-meter long (4.4 cm x 4.4 cm) copper absorber structure with embedded quartz fibers for ”bench-top” pulse shape and timing studies.
- (Goal2) Encouraging studies in simulation performance of DREAM module with modified readout scheme for high granularity / long. segmentation.

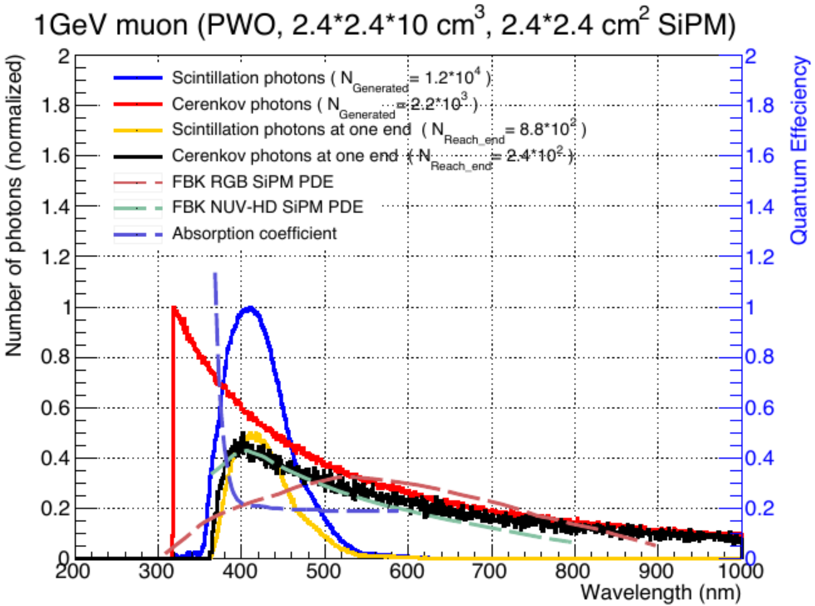
S. Kunori

ECAL performance/modeling

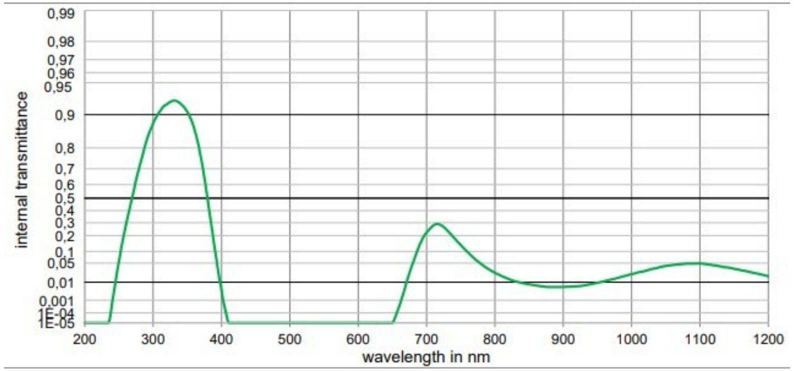
Initial ECAL studies will focus on muon data

- Clean beam
- Good Č yield, S light saturation less likely
- Acquire data aimed at tuning light collection model and signal shape for different detector configurations
- Data on other particles can be used as cross check of low level tuning





Example spectra and SiPM QE



Example of band pass filter

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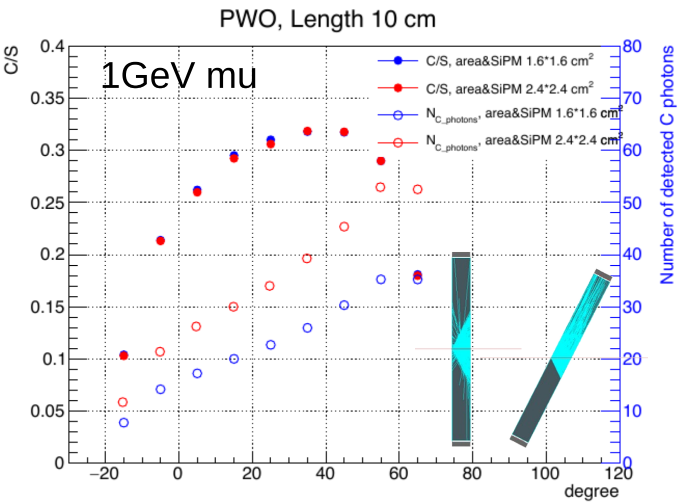
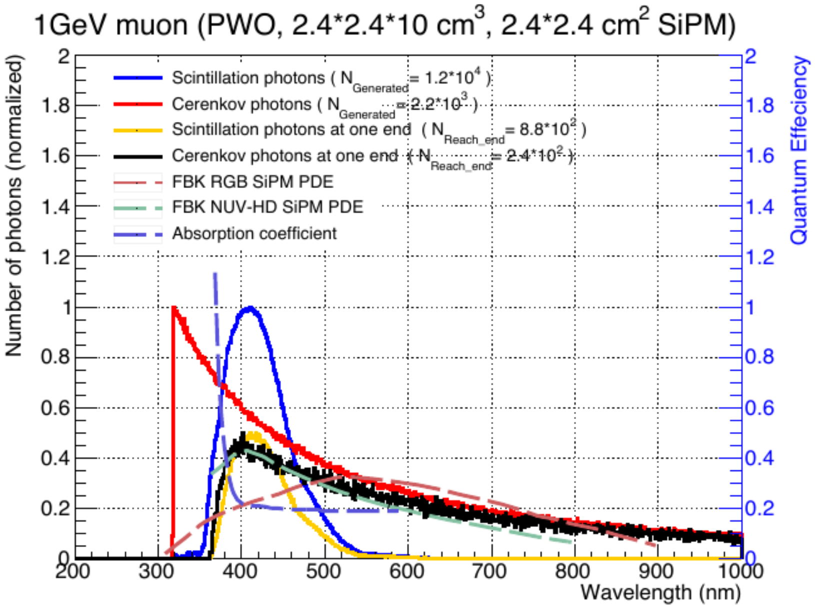
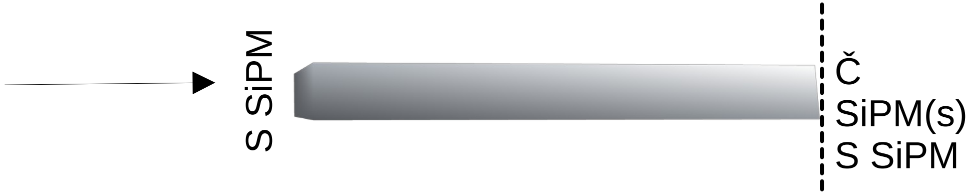




Example spectra and SiPM QE

Baseline bar configuration



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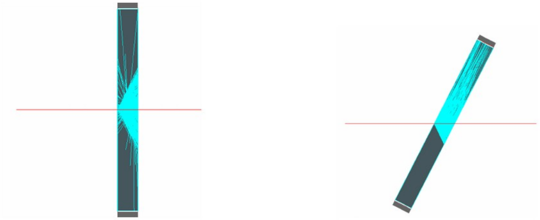
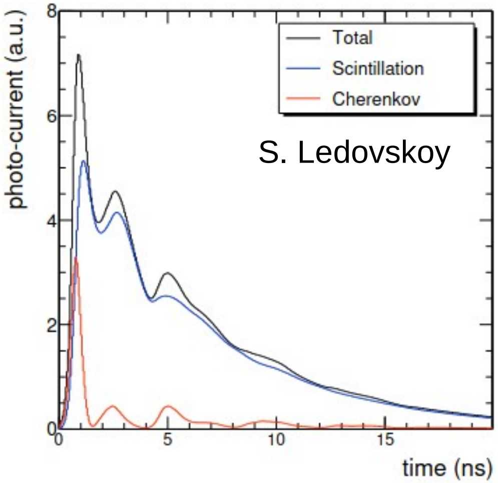


For illustration only:
simulations for CMS ECAL



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Details to verify

For each configuration (crystal, SiPMs*, amplitude, beam, etc)

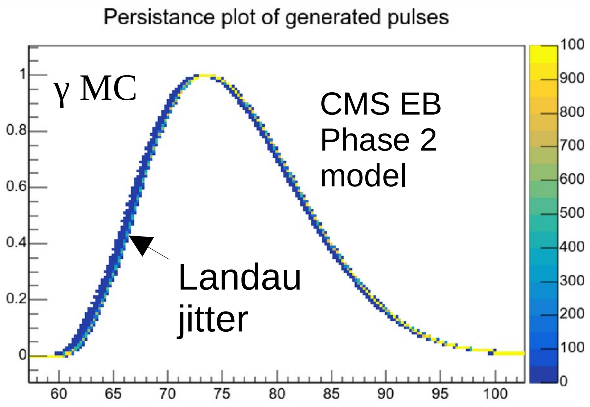
- Average photo-current pulse in each and SiPM response
- Separate contributions from Ĉ and S
- Time structure
- Light Output

* We currently have an assortment from Hamamatsu and Broadcom

ECAL performance/modeling

Initial ECAL studies will focus on muon data

- Clean beam
- Good Č yield, S light saturation much less of an issue
- **Acquire data aimed at tuning light collection model and signal shape for different detector configurations**
- Data on other particles can be used as cross check of low level tuning

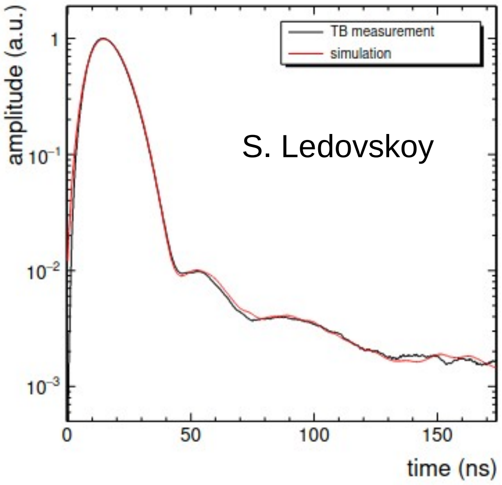

Persistance plot of generated pulses

γ MC

CMS EB
Phase 2
model

Landau
jitter

For illustration only:
simulations vs measurements
for CMS ECAL


S. Ledovskoy

- Simulated photo-current is shaped by SiPM + Amplifier (convolution with SPR function)
  - At sim level can be parametrized in for example in E, depth, time
- Compare measured average waveform with simulations for each SiPM.
- Validate our understanding of detector response.
- Compare measurements and simulations for correlations between the SiPMs.
- Validate simulations to be used to optimize dual-readout technique.
- Note: this extends similar studies in CMS which only focused on scintillation

ECAL performance/modeling

Goals for 2022 test beam instrumentation and data

- Initial pass at optimizing xtal/SiPM/filter combinations to start
- Fast digitizer readout (16 channel DRS) to measure signal shapes (timing and amplitude)
  - May use feed through channels of Citiroc for simplicity or prepare two readouts if time permits
- Local tracker eg,
  - a small scintillator telescope made from LYSO plates
  - and/or mini drift tube setup from UM if feasible
- Angle scan data with muons to compare relative Č/S yields with simulation
- Measure at least PWO + PbF + BGO samples (ideally BSO as well)
- Some samples of other particle species for comparison w/ tuned MC (TBD)

Develop ~turnkey test beam setup for xtals/small arrays

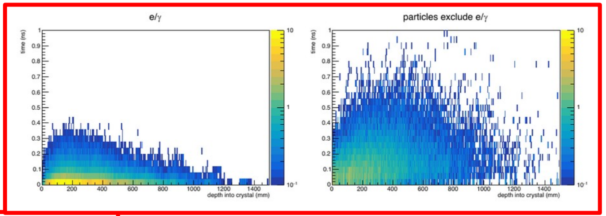
General R&D plans

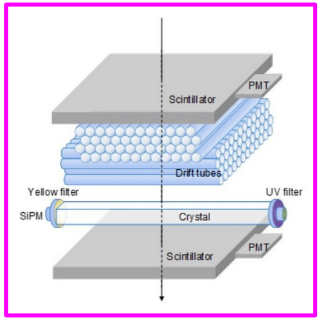
- Crystal properties measurements, light collection studies (fast lasers, sources, cosmics)
- Development of fast optical simulation frmwk(s)
- Mechanical and readout design of modules for 1st test beams
- Portable tracker design for integral DAQ

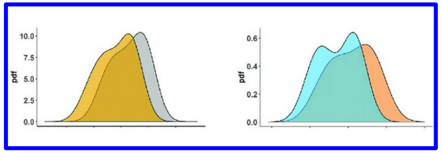
- Test beam w/ single module prototypes
- Measure C and S yields vs particle species
- Continue simulation development, characterize components/materials
- Development of ~8x8 matrix: mechanical, electrical, laser calibration systems

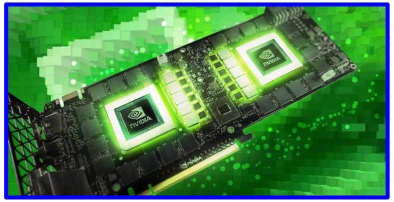
Target:

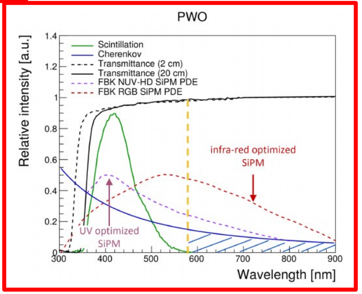
- **Beam tests of ~8x8 assembly**
- **Validate, tune simulation**
- **Prepare new matrix/DAQ for joint tests with fiber HCAL (IDEA collaboration) in next funding cycle**

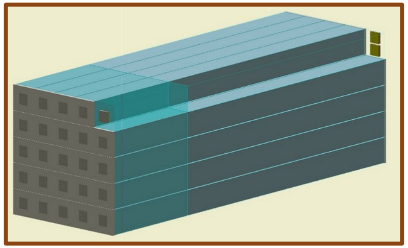


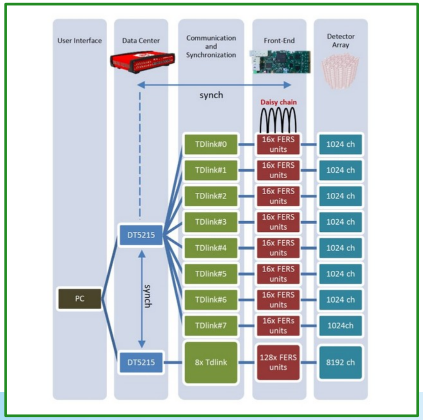






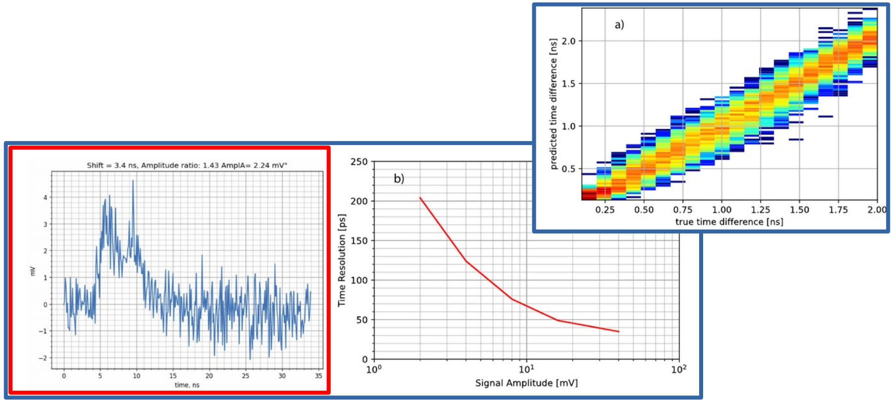


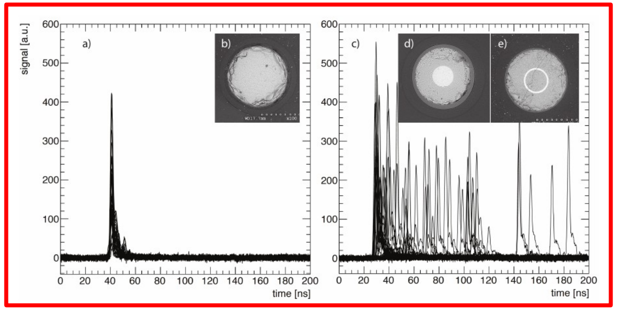


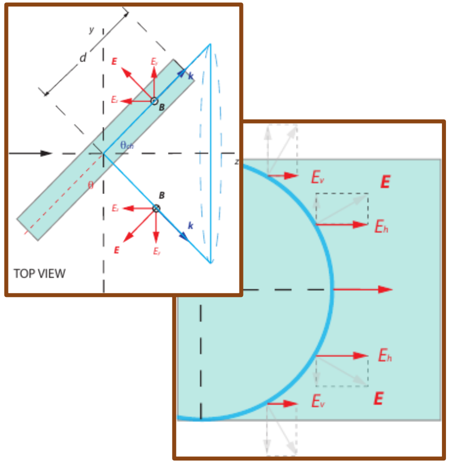


R&D plans

Fiber HCAL







- SiPM and dSiPM, materials characterization
- Develop GEANT4 simulation framework
- Reconstruction algo studies
- Material properties studies
- Explore timing performance using fast lasers

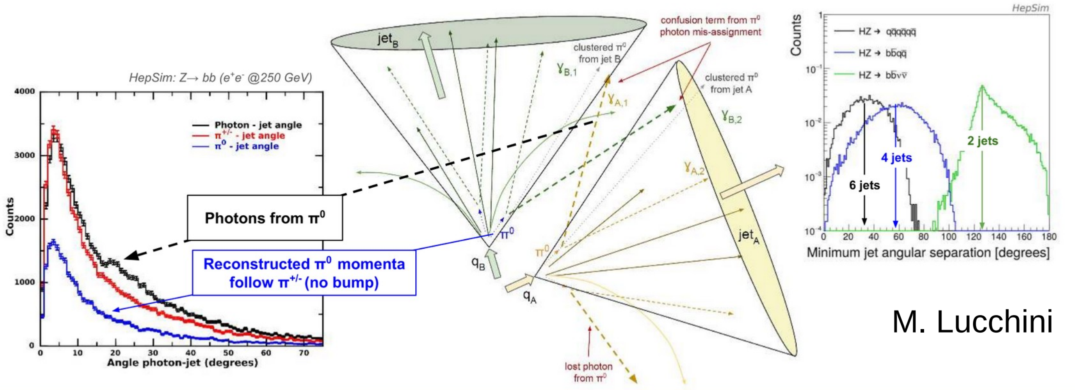
- Scale readout electronics to ~512 channels
- High energy test beams, evaluate performance of fiber types
- Analyze measured waveforms for longitudinal segmentation with timing
- ML studies for on-detector RECO

- Focus on test beam with fast readout capabilities
- Expand channel count
- Develop scalable calibration methods

R&D plans

Full detector

- An overall simulation plan spans 3 years of the proposal
- Develop Hybrid Dual-Readout calorimeter simulation on DD4HEP
- PF/ML/AI studies: neutral hadron clustering, sampling optimizations, deep learning for clustering
- Homogenous HCAL (HHCAL) frame work and studies
- Develop carbon fiber crystal mechanics and large scale structure assemblies



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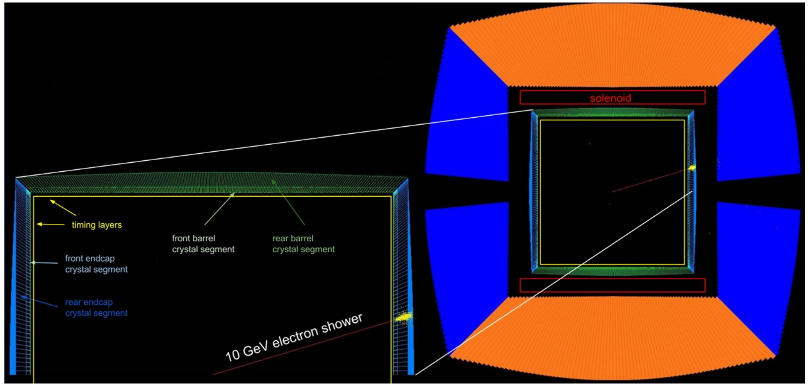

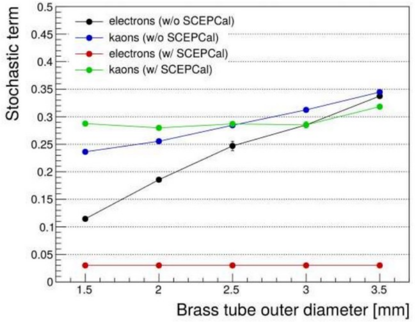

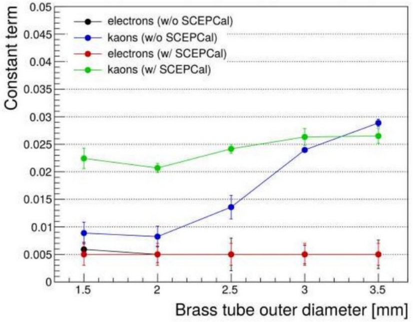

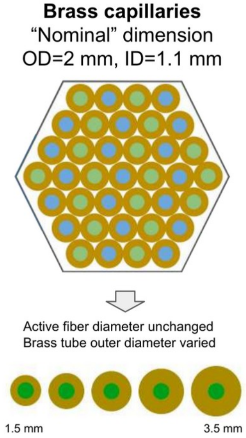

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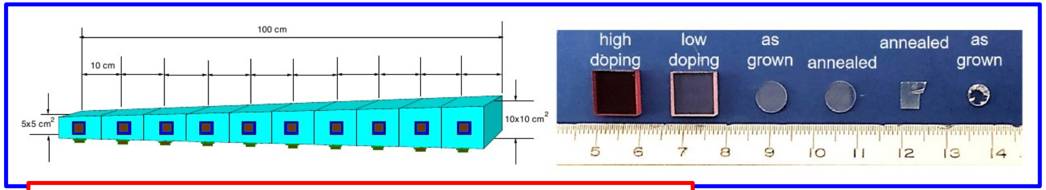
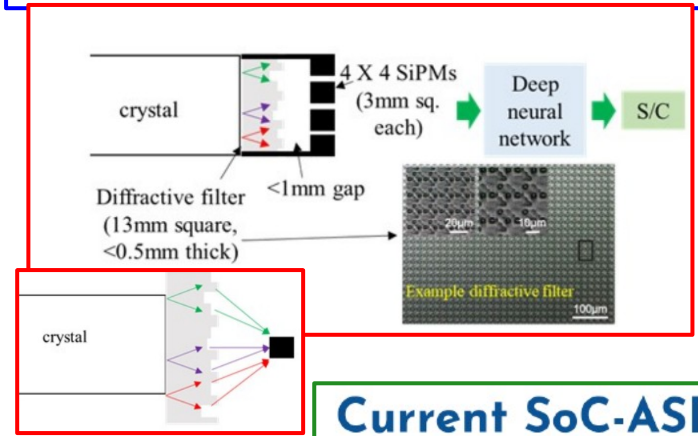
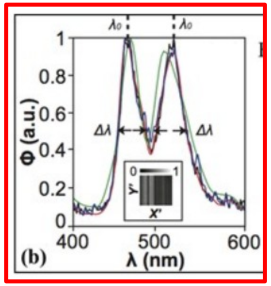
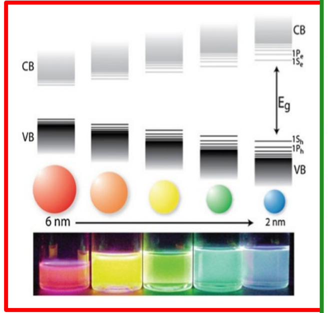
R&D plans

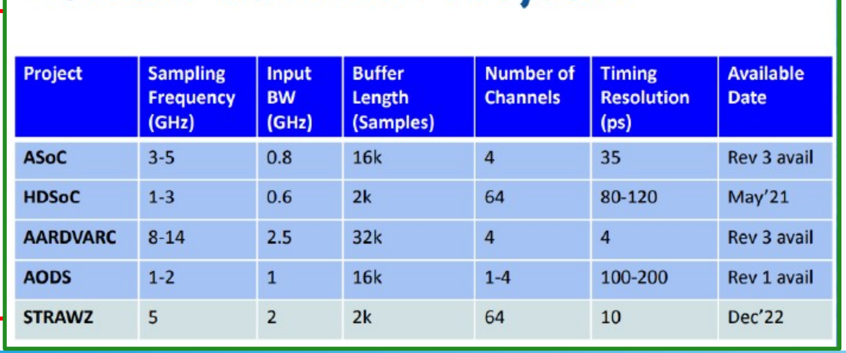
Blue sky











Current SoC-ASIC Projects

Project	Sampling Frequency (GHz)	Input BW (GHz)	Buffer Length (Samples)	Number of Channels	Timing Resolution (ps)	Available Date
ASoC	3-5	0.8	16k	4	35	Rev 3 avail
HDSoC	1-3	0.6	2k	64	80-120	May'21
AARDVARC	8-14	2.5	32k	4	4	Rev 3 avail
AODS	1-2	1	16k	1-4	100-200	Rev 1 avail
STRAWZ	5	2	2k	64	10	Dec'22

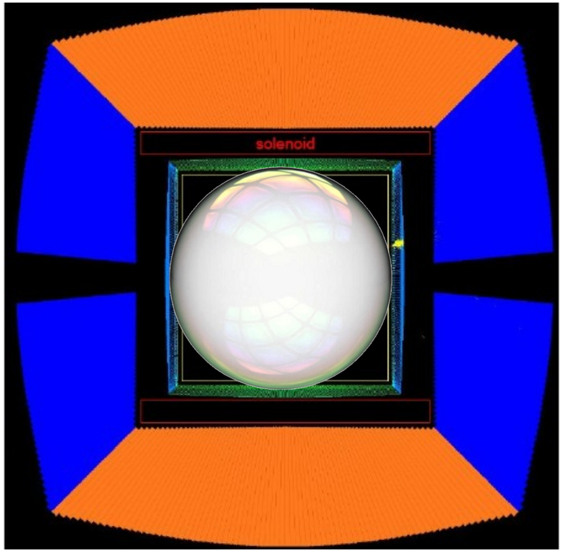
- Survey of potential cost effective inorganic scintillators for HHCAL concept (eg Gd loaded heavy glasses)
- Characterization of test samples, iterate with producers on properties and feasibility of large size samples

- Enhancement studies for C/S light separation, evaluating:
  - Quantum dot waveshifters
  - Interference filters
  - Engineered diffraction filters
  - Field-Programmable Analog Arrays (FPAA) System-on-Chip ASIC platforms
  - Waveform digitizers for real-time processing and classification

- **ASoC**: Analog to digital converter System-on-Chip
- **HDSoC**: SiPM specialized readout chip with bias and control
- **AARDVARC**: Variable rate readout chip for fast timing and low deadtime
- **AODS:** Low density digitizer with High Dynamic Range (HDR) option
- **STRAWZ:** Streaming Autonomous Waveform-digitizer with Zero-suppression

Conclude

A dual readout calorimeter with a crystal ECAL is an attractive option for future Higgs factories.



- When combined with the DRO fiber HCAL, state of the art EM energy resolution can be achieved (~3%/√E), while the hadron energy resolution is consistent with a pure DRO hadronic calorimeter
- Significant R&D effort is needed to demonstrate DRO capability of a segmented crystal ECAL through simulation, cosmic ray and beam tests
- Plans include integration with the IDEA detector concept in the simulation to optimize the design of the crystal ECAL
  - The DRO crystal ECAL could also be combined with a high granularity HCAL
- New materials and technologies are developing rapidly, maintain ‘blue sky’ initiatives for possible performance/cost benefits
- The CALVISION R&D program is (just) started, NEED TO GROW!
  - Lot’s to do, including major efforts in next gen materials, real-time signal analysis, readout, optical interfaces and sensors, full/fast simulation and physics performance, ...

Additional slides

Some references

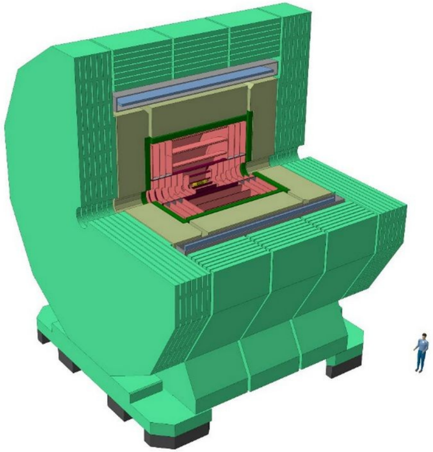
- Dual-Readout Calorimetry for Future Experiments Probing Fundamental Physics
  - 2203.04312
- New Developments in Calorimetric Particle Detection
  - 10.1088/1748-0221/15/11/P11005
- Dual-Readout Calorimetry
  - 10.1103/RevModPhys.90.025002 (https://arxiv.org/pdf/1712.05494.pdf)
- New perspectives on segmented crystal calorimeters for future colliders
  - 10.1088/1748-0221/15/11/P11005
- Detection of electron showers in dual-readout crystal calorimeters
  - 10.1016/j.nima.2012.04.092
- Dual-readout calorimetry with a full-size BGO electromagnetic section
  - https://doi.org/10.1016/j.nima.2009.08.074

Detector Concepts

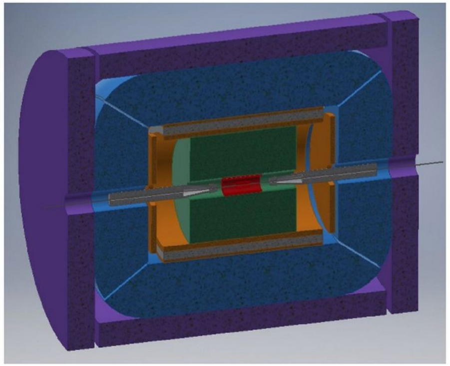
Background on calorimetry options: **granularity**

- Particle Flow Algorithm (PFA) calorimeter (ILC, CLIC, FCC-ee, CEPC) ~ high O(100M ch)
- Dual Readout (DRO) calorimetry (FCC-ee, CEPC) ~ moderate O(10M ch)

Both PFA and DRO calorimetry are optimized to achieve a jet energy resolution of 3 − 4% at ~100 GeV, allowing for the separation of $W \to q\bar{q}'$ and $Z \to q\bar{q}$ decays.



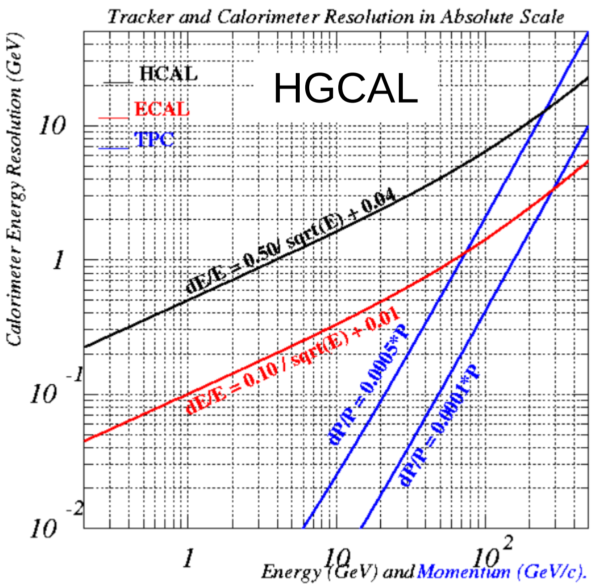
CLD proposed for FCC-ee
(PFA EM+HAD calorimetry)



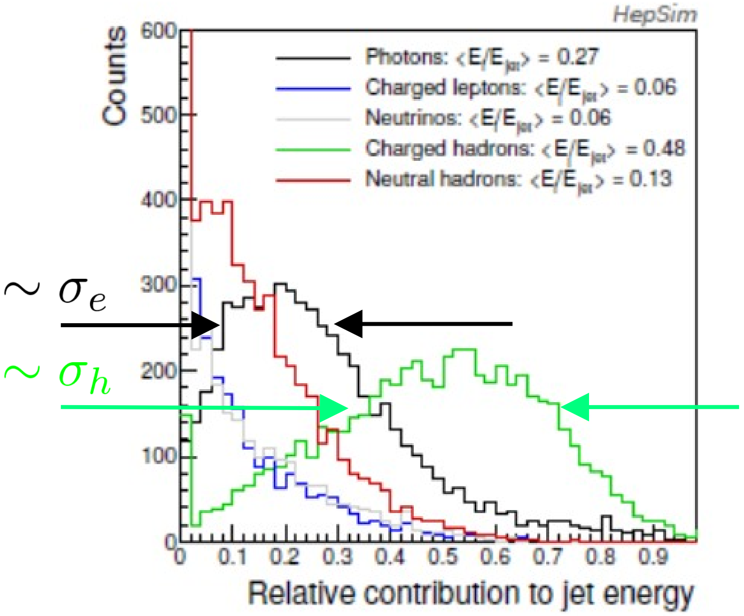
IDEA proposed for FCC-ee and CEPC
(DRO single calorimeter)

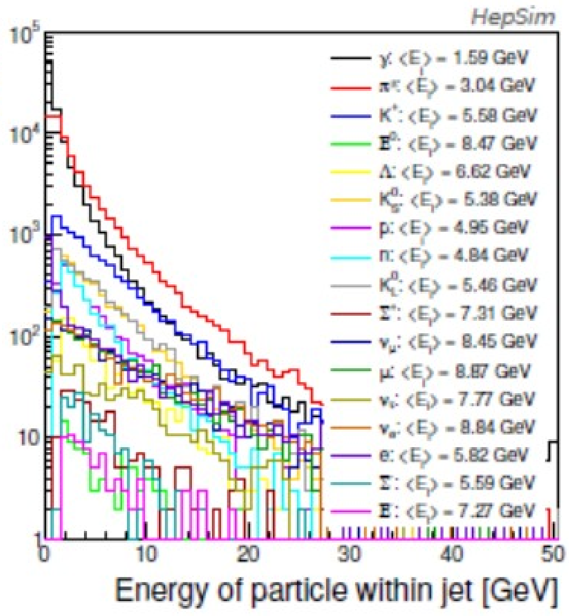
Sampling calorimeters => limit ultimate EM resolution wrt homogeneous EM calo

Fluctuations => limit calorimeter resolution



$$\sigma_{Jet} = \sqrt{\sigma^2_{Track} + \sigma^2_{Had.} + \sigma^2_{elm.} + \sigma^2_{Confusion}}$$





"Simple" physics handles to improve performance:

- Improve sampling (lower stochastic terms)
- Response linearity, uniformity, address e/h

(simultaneous) Calorimeter resolution requirements: **much better** than 50% HAD and 10% EM stochastic terms is where we all want to take the state of the art

PFA Calorimetry

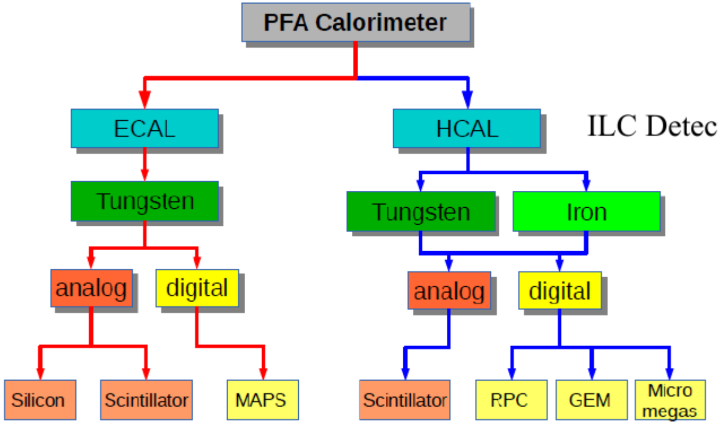
Sampling calorimeter, reconstruction and identification of individual particles in showers, measuring energy in the most suitable sub-detector for the particle type:

- Charged particles in the tracking detector
- Photons in the electromagnetic calorimeter
- Neutral hadrons in the hadronic calorimeter

Extensive R&D by the
CALICE Collaboration

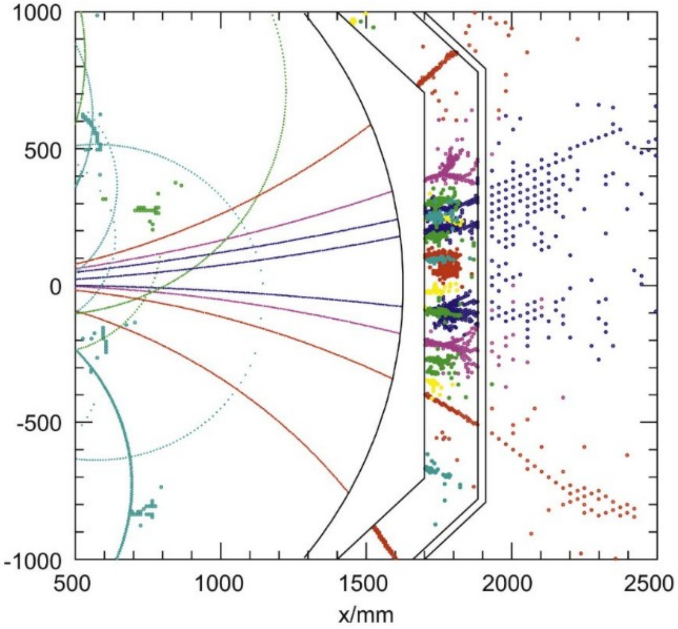
Characteristics:

- High granularities ⇒ large channel count
- relatively small sampling fractions



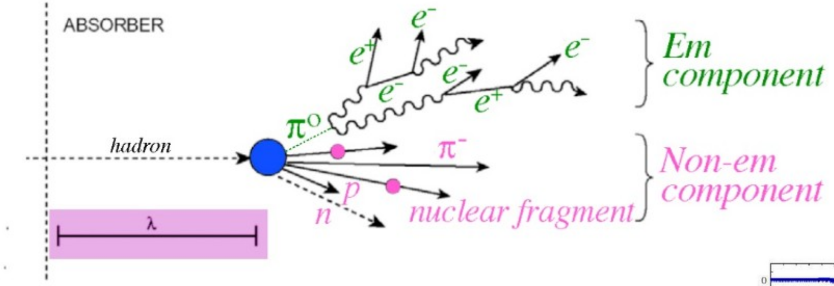
PFA Calorimeter
- ECAL
  - Tungsten
    - analog
      - Silicon
      - Scintillator
    - digital
      - MAPS
- HCAL
  - Tungsten
  - Iron
    - analog
      - Scintillator
    - digital
      - RPC
      - GEM
      - Micro megas

ILC Detector TDR

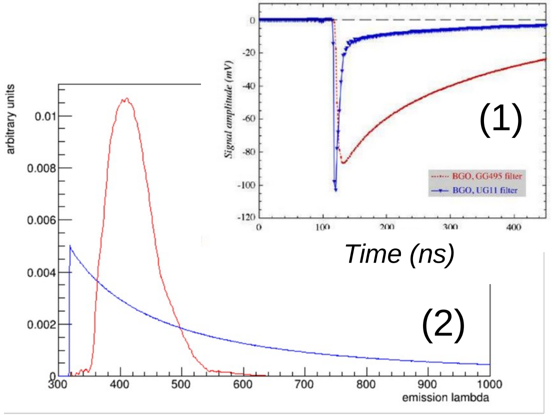


Dual readout

(Sampling) calorimeter, reading out both scintillation and Cherenkov light to disentangle EM and hadronic components shower-by-shower
=> allows corrections for different EM and hadronic responses



- Cherenkov – relativistic charged particles, mostly electrons
  - Fast (1), UV to IR light (2)
  - Few photons: requires sensing w/ high eff, large area, directionality?
- Scintillation – sensitive to dE/dx energy loss ⇒ charged particles
  - Slower response, scintillator characteristic τ
  - Large signals: smaller, cheaper sensors?

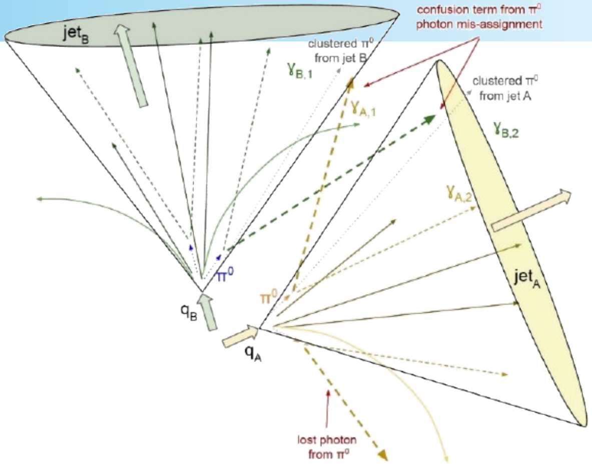


DREAM/RD52/IDEA: using DR, achieve sampling terms ~30% for hadrons*

- Use Cherenkov light to measure, shower-by-shower, the fraction of the shower energy in pizeros.
- Use scintillation light to measure all ionizing energy deposits.
- Apply a scale correction that depends on this ratio.

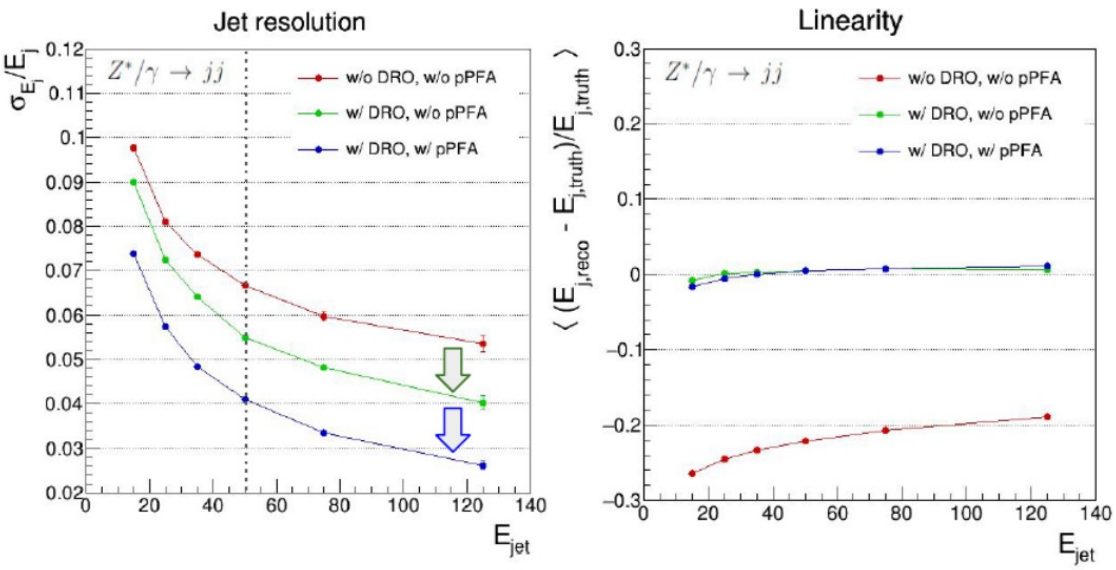
*See eg: arXiv:1807.03853

Adding particle flow



The crystal ECAL is "particle-flow friendly"

- Relatively compact showers
  - O(1 mm) transverse segmentation for timing layers
  - O(1 cm) transverse segmentation for ECAL
  - High EM resolution for π^0 clustering
- Improve 'confusion term'
- Timing and dual-readout information for additional handling of particle ID
- Maximally exploit object identification,
  high resolution and
  linear response provided by the crystal ECAL to improve the tracker-calorimeter hit matching in PFA

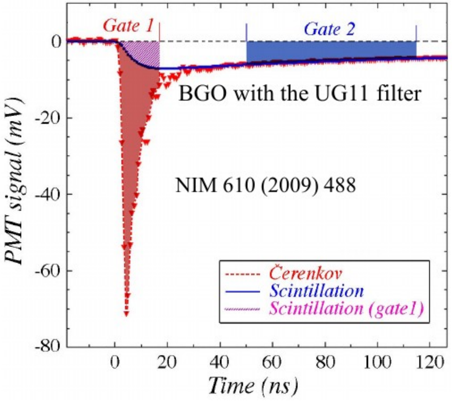


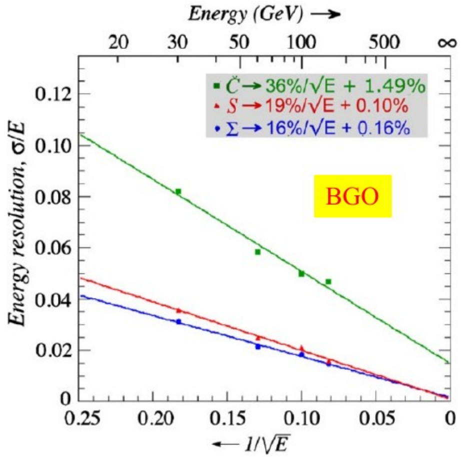
Previous DREAM/RD52 results on DRO Crystal Calorimeter

DREAM/RD52 has previously investigated DRO of crystals with PMTs using BOTH optical filters and timing to separate C and S signals (NIM 686 (2012) 125)

A proof of principle for a DRO crystal calorimeter, but

- Worse electron energy resolution (~15-30%/√E) than best xtal calorimeters (~3%/√E)
- Resolution dominated by limited statistics for # of photons detected (only a small fraction of C and S photons are selected)
- Not pursued further:
  - Cost with PMT readout
  - Limited wavelength sensitivity
  - ‘acceptable’ EM resolution demonstrated in fiber calorimeter





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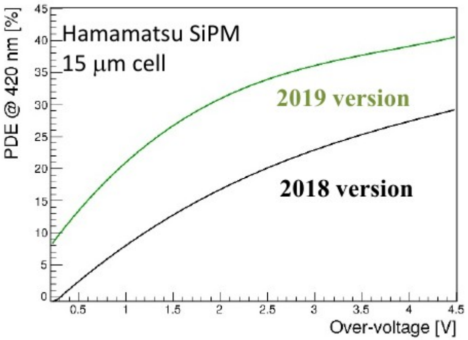
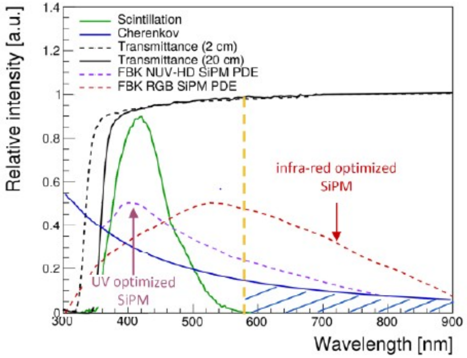
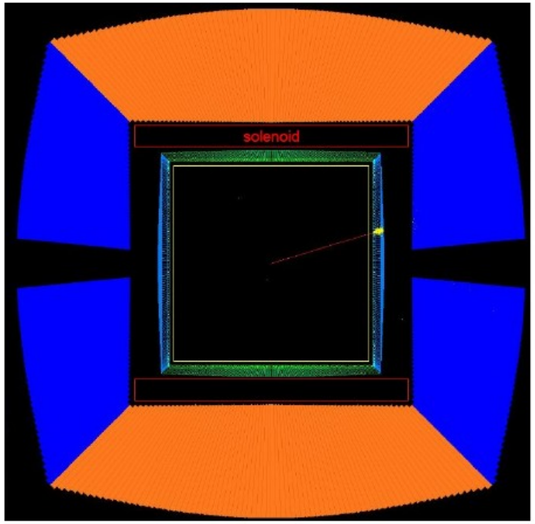
Today: SiPM performance has vastly improved

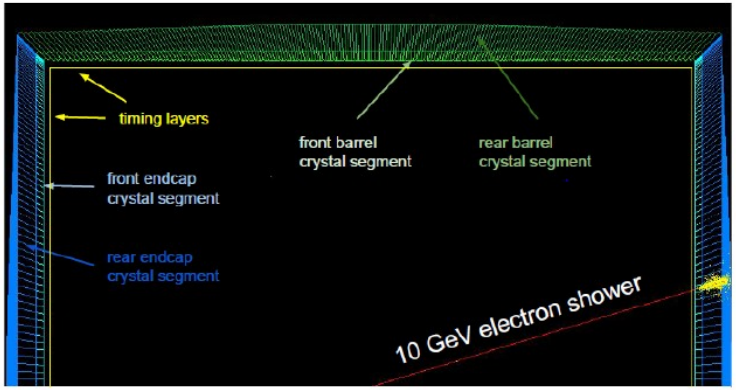




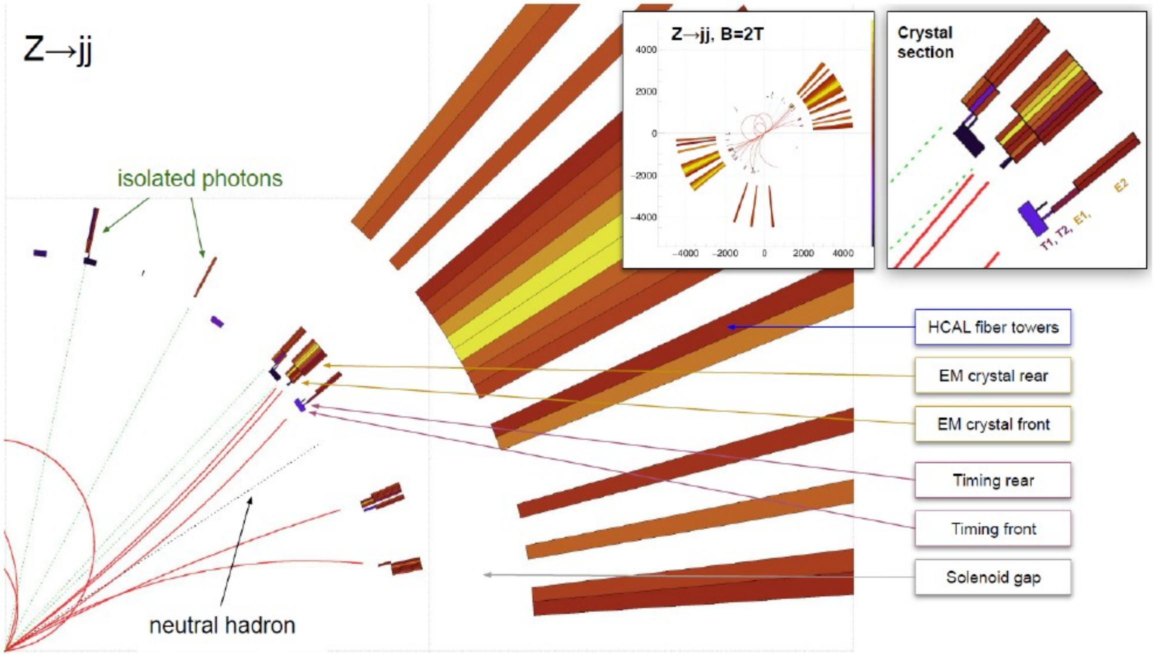
Fast, affordable, tunable λ sensitivity

GEANT Simulation: Z->jj Event Display

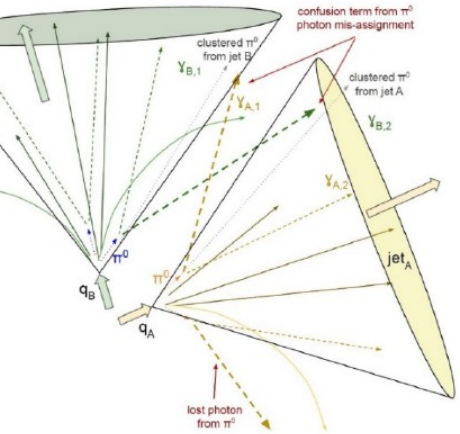




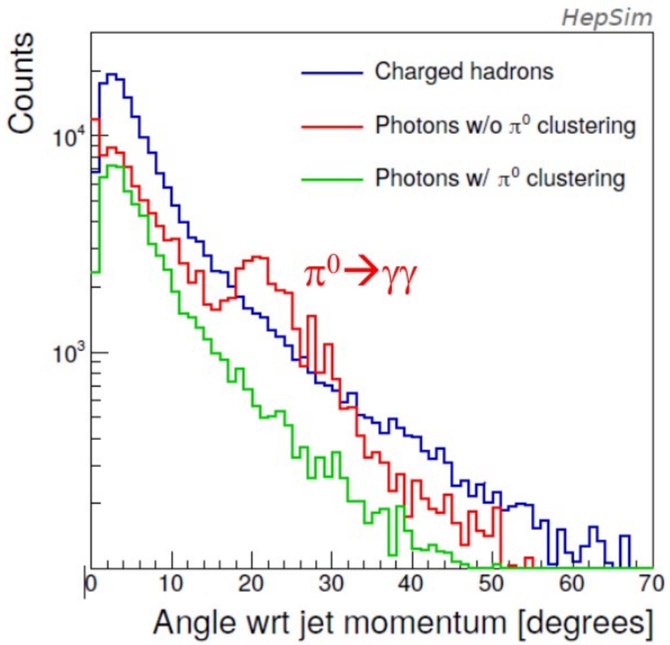
Lucchini, EPS-HEP Conf 2021

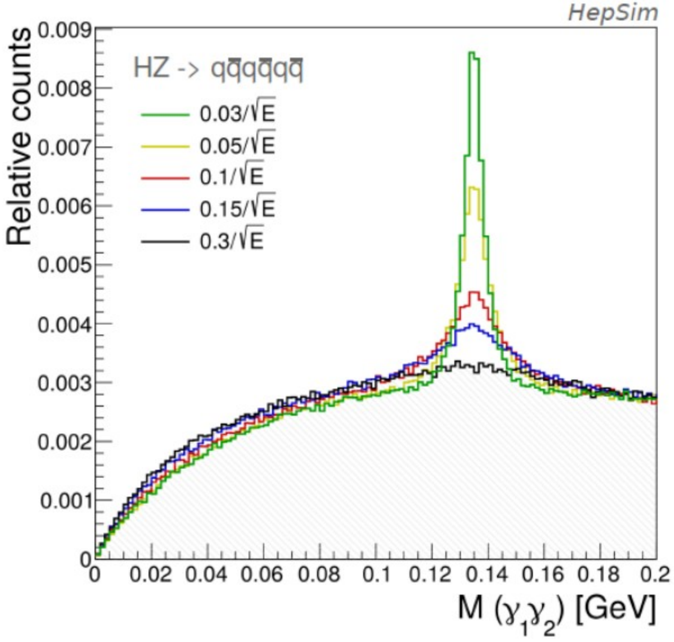


Advantages with a high-resolution EM Calorimeter



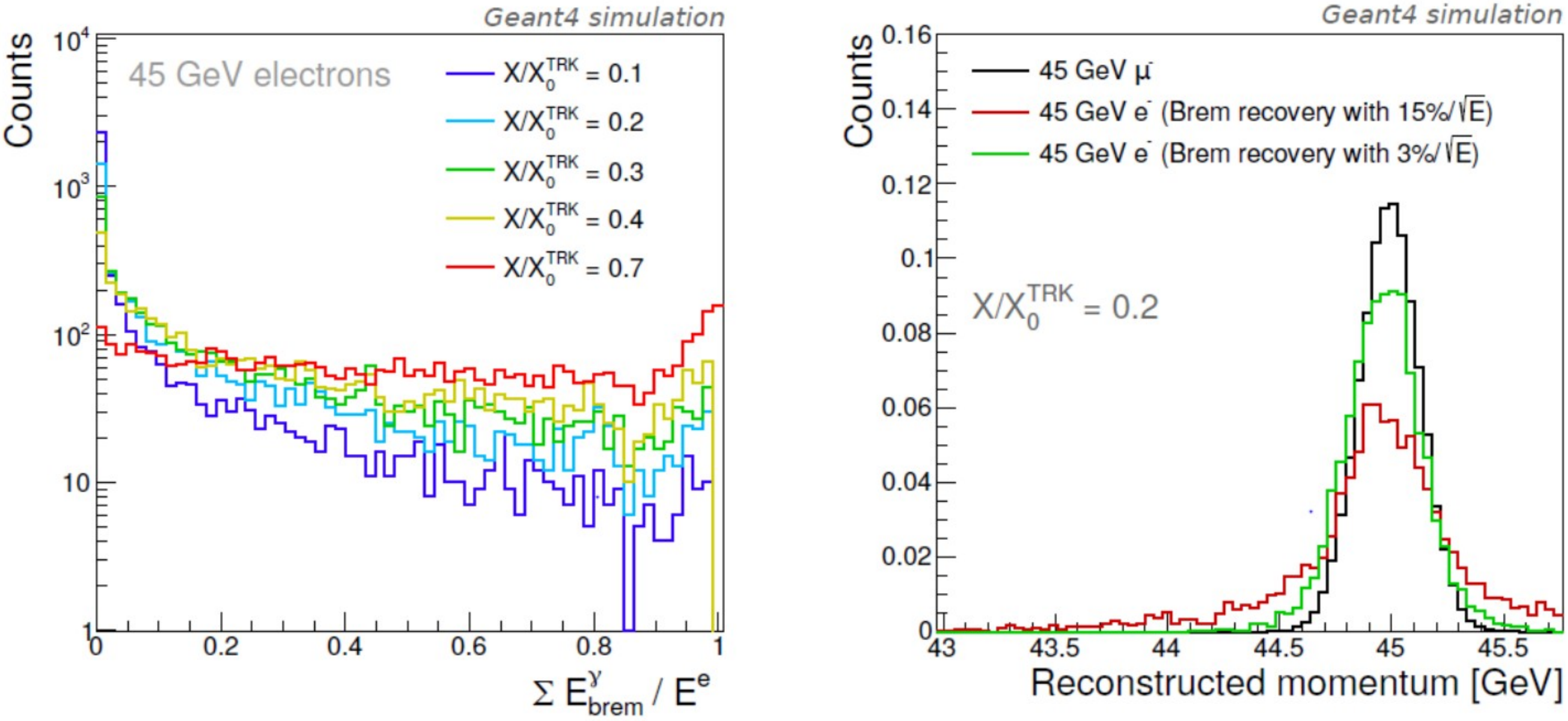
- In hadronic showers, π^0 is a significant component of neutral particles. Good EM resolution is critical for the π^0 reconstruction and therefore is important for correctly clustering γ's into the right jets





Advantages with a high-resolution EM Calorimeter

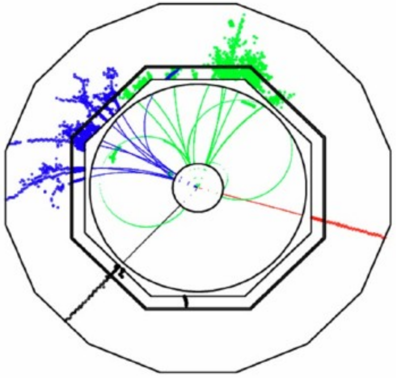
- Recovery of photons from bremsstrahlung

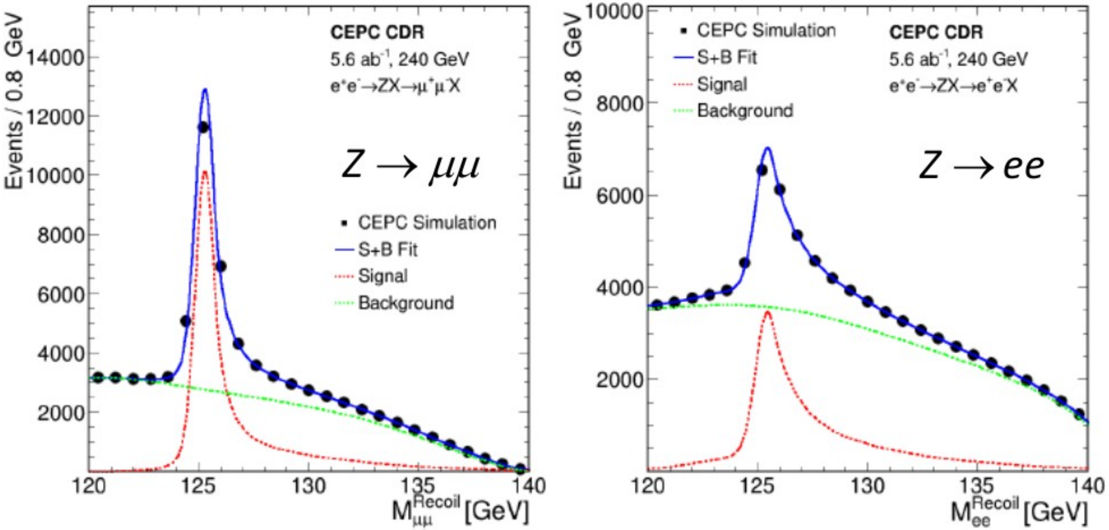


Electrons: tracker measurement + photons

Advantages with a high-resolution EM Calorimeter

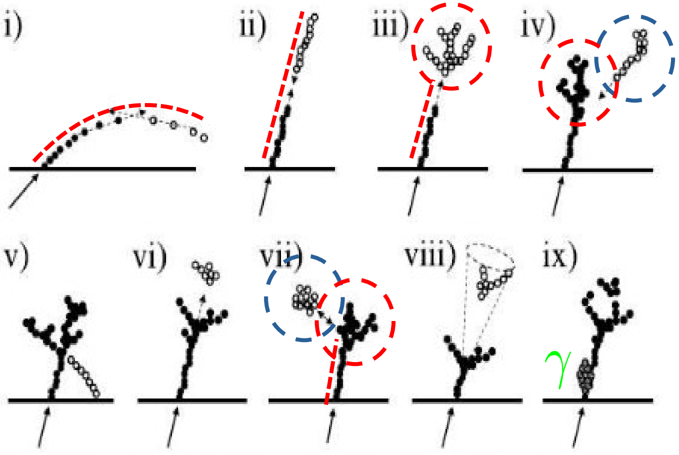
- Improve Higgs tagging: the Higgs boson from the $e^+e^- \rightarrow ZH$ process can be identified through the recoil mass of the Z boson → identify the Higgs boson without looking at the Higgs boson





Much worse recoil mass resolution in the Z → ee channel due to bremsstrahlung radiation, need to have good EM resolution for the radiation recovery

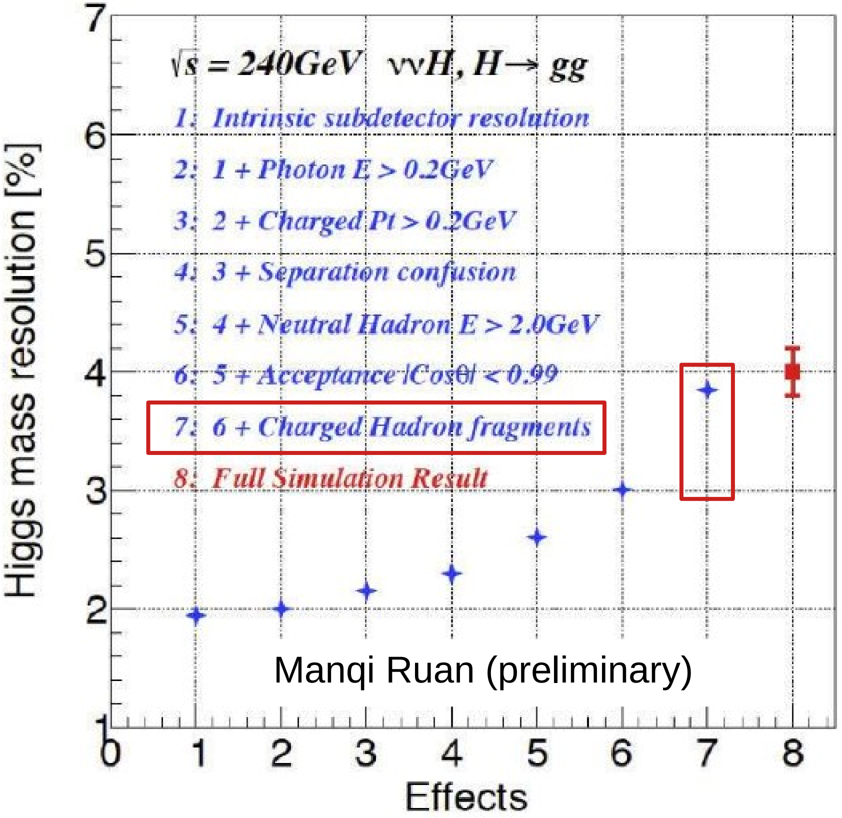
Example from PFA fast simulation



Topological clustering with high granularity calorimetry
Tracks, charged and neutral calo clusters, associated photon radiation

Reliance on pattern recognition/track matching for precision measures

Moderately good resolution achievable
~50% HAD and 10% EM stochastic terms



Manqi Ruan (preliminary)

- Pattern recognition is challenging
- Advantages/ complications of large channel counts
- Hadronic resolution remains a leading driver