Calorimetry

in particle physics experiments

5.

Calorimeter Technologies

Course roadmap

- **Week 1 (Foundations)**
  - ✓ Lecture 1: Why calorimetry?
  - ✓ Lecture 2: EM shower physics
- **Week 2 (Physics depth)**
  - ✓ Lecture 3: Hadronic shower physics
  - ✓ Lecture 4: Energy resolution from first principles
- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies (real-life EM and Hadronic calorimeters)
  - ✓ Lecture 6: Calorimeter Design
- **Week 4 (Systems & Future)**
  - ✓ Lecture 7: Signal chain, readout, calibration
  - ✓ Lecture 8: Future calorimetry

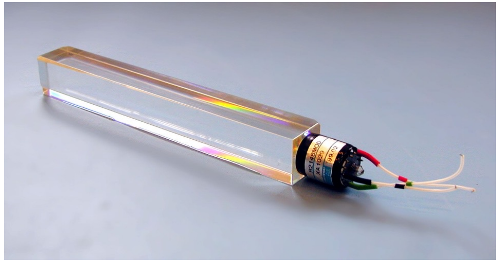
Today's Lecture

- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies (real-life EM and Hadronic calorimeters)
    - *… a.k.a. the technology zoo → which detector families exist, what they are made of, and how they perform.*
    - *5.1 Cherenkov calorimeters*
      - *threshold mechanism; UV-SiPM R&D; CMS HF; Super-Kamiokande; future Cherenkov (Crilin)*
    - *5.2 Scintillation calorimeters*
      - *crystal zoo (NaI→BGO→CsI→$PbWO_4$); LHC crystals; photodetectors (APD, SiPM); LYSO and future*
    - *5.3 Ionization calorimeters*
      - *noble liquids (LAr, LKr); accordion geometry; NA48 LKr; ATLAS LAr, HEC and FCal*
    - *5.4 Semiconductor calorimeters & Si technologies*
      - *e-h pairs in Si; SiPM (APD→G-APD); HEP applications and CMS HGCAL*
    - *5.5 Focus on HAD calorimeter technologies*
      - *always sampling; ZEUS (compensation); ATLAS TileCal; CMS HCAL; ATLAS vs CMS comparison*
  - ✓ Lecture 6: Calorimeter Design
    - *… a.k.a. design principles → why experiments made the choices they did.*

EM technology landscape: 3 (+1) signal types

1. Cherenkov light
    - ✓ Lead glass, PbF2, Water…
    - ✓ Homogeneus
2. Scintillation light
    - ✓ Crystals: NaI, BGO, CsI, PbWO4
    - ✓ Homogeneus
3. Ionization charge
    - ✓ Noble liquids: LKr, LAr
    - ✓ Homogeneus and sampling
4. Electron-hole pairs
    - ✓ Semiconductor
    - ✓ Present & future calorimeters

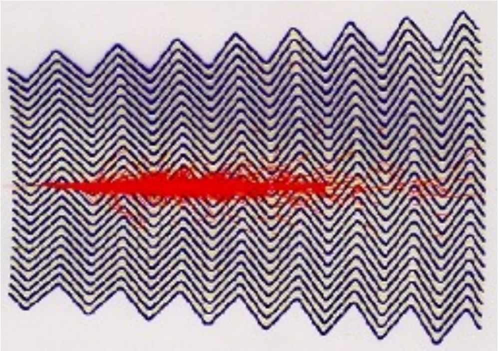
Light ⇒ photoelectrons (by photosensitive device)

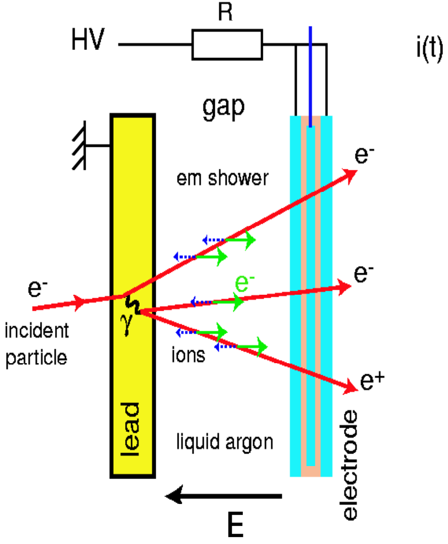


$$\frac{\sigma_E}{E} \propto \frac{\sigma_{N_{\mathrm{pe}}}}{N_{\mathrm{pe}}} = \frac{1}{\sqrt{N_{\mathrm{pe}}}}$$

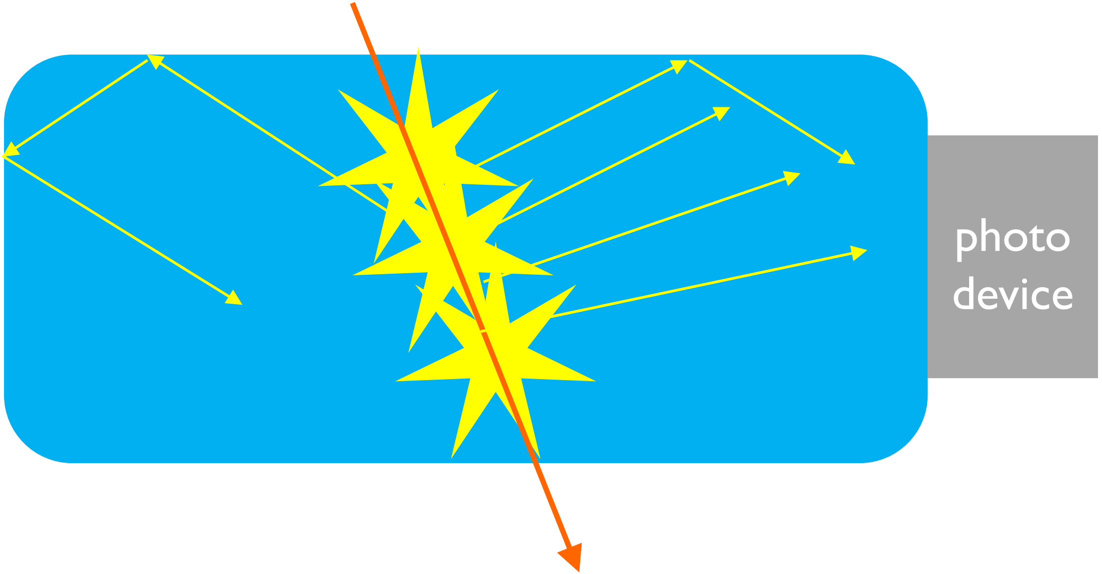
N_{pe} : number of photo electrons

Charge ⇒ current





“Light" calorimetry: key parameters



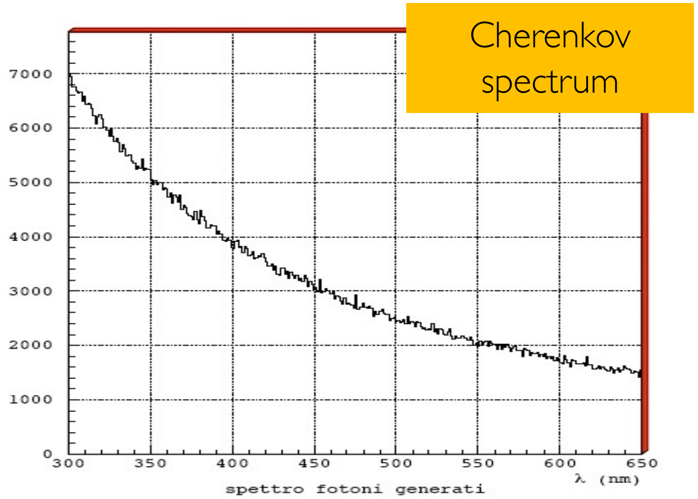
- **Light emission spectrum**
  - ✓ Scintillation and/or Cherenkov
- **Light yield**
  - ✓ Photoelectrons / MeV
- **Decay time**
  - ✓ Time required for the light emission to decrease to 1/e of its maximum (relevant only for scintillation)
- **Refractive index *n***
  - ✓ Determines the transmittance: ratio of the light passing through to medium where light is produced
- **Light transmission curve**
- Quantum efficiency or **Photon Detector Efficiency** PDE(λ) of photodevice

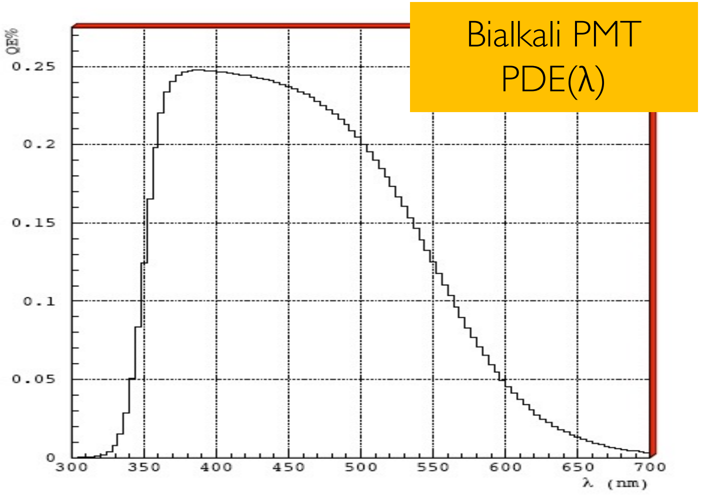
5.1

Cherenkov calorimeters

Cherenkov calorimeters

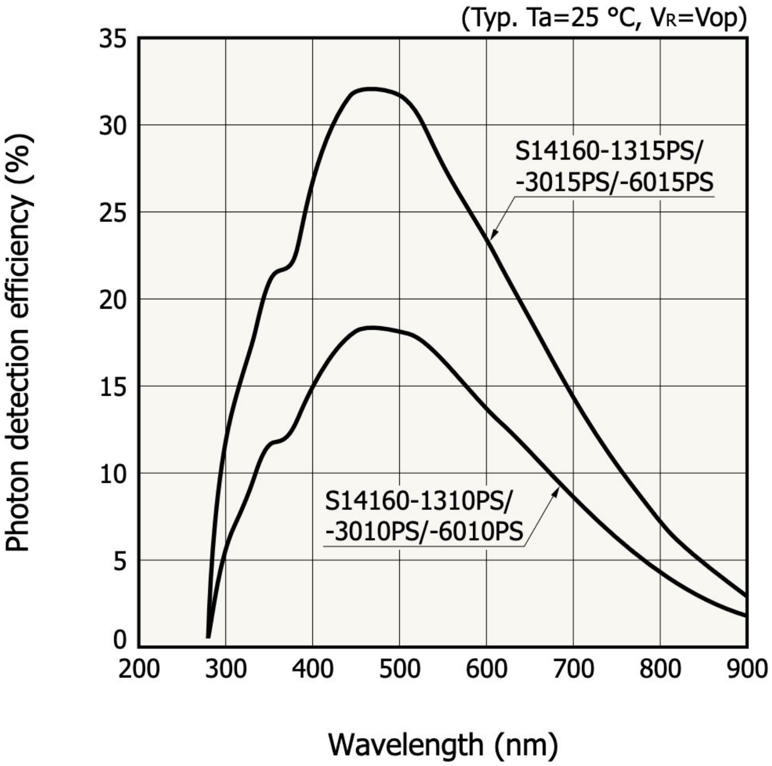
- Usually employed for particle identification
  - ✓ Cherenkov = threshold effect v > c/n
  - ✓ For a given momentum particle speed depends on particle mass
- Can provide calorimetric measure when collecting all light produced by particles in shower
- Very fast signal
- Light yield is very small
  - ✓ 10^4 smaller than scintillation light
  - ✓ Only shower tracks above threshold produce signal
- λ_{Ch} doesn't match well traditional PMT PDE(λ)
  - ✓ Recent R&D of UV-extended SiPM helps…
    - Photon Detection Efficiency @310 nm ~ 30%



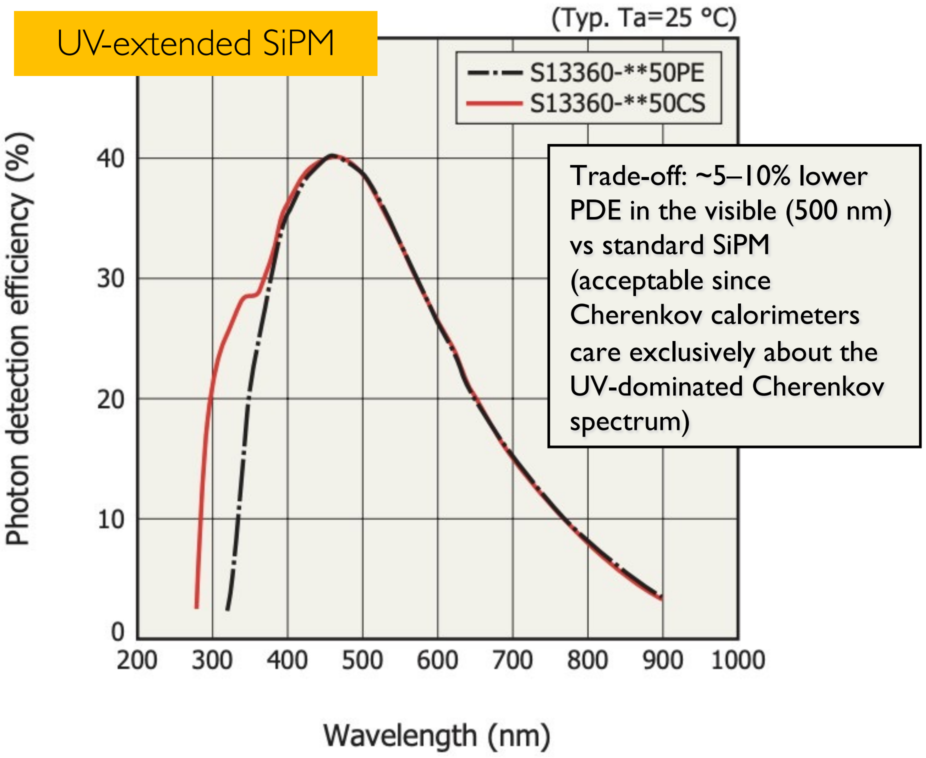


UV-extended SiPM for Cherenkov

- Standard SiPM: PDE peaks at ~420–450 nm; at 310 nm (Cherenkov UV peak) PDE < 3% (essentially blind to Cherenkov light)



- UV-extended SiPM: modified entrance window and anti-reflection coating shift sensitivity into the UV; PDE at 310 nm ~ 30%: ×10 improvement that makes SiPM-based Cherenkov readout viable


UV-extended SiPM

Trade-off: ~5–10% lower PDE in the visible (500 nm) vs standard SiPM (acceptable since Cherenkov calorimeters care exclusively about the UV-dominated Cherenkov spectrum)

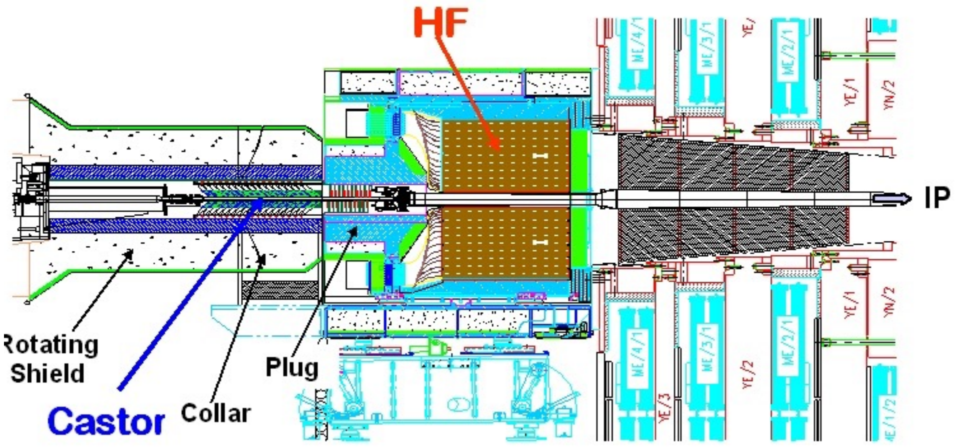
Materials for Cherenkov calorimeters

- **Accelerator-based particle physics**
  - ✓ Lead glass (PbO)
    - Widely used (NOMAD, OPAL)
    - Poor radiation resistance
  - ✓ Quartz
  - ✓ Lead Fluoride (PbF_2)
    - Newer material
    - Smaller radiation length + higher light output + radiation resistant

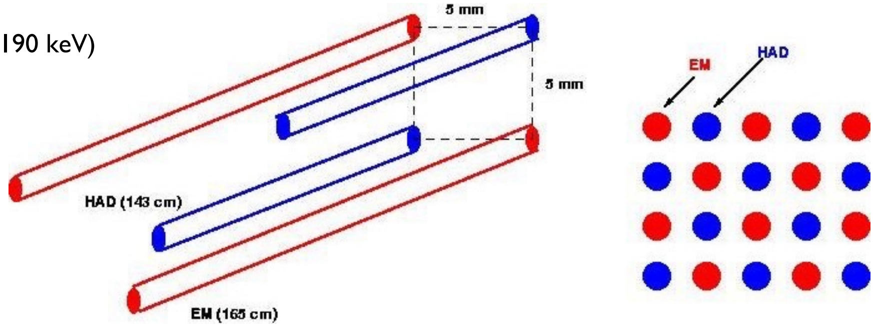
- **Astro-particle physics**
  - ✓ Water (tanks, sea water, polar ice, …)
  - ✓ Air (atmosphere) of the earth
    - For Solar, atmospheric and cosmic neutrinos; ultra high energy particles in cosmic rays

CMS HF: sampling Cherenkov in the very forward region

- CMS Hadron Forward (HF) calorimeter: $3 < |\eta| < 5$
- Why Cherenkov for the forward region?
  - ✓ Radiation up to 10^8 Gy/year at $|\eta|\sim5$
    - >> radiation hardness of any scintillator
  - ✓ Quartz fibers intrinsically radiation-hard
    - no organic molecules to break, no colour centres
  - ✓ Response nearly instantaneous (Cherenkov $\tau \sim 0$)
    - No pile-up integration issue
  - ✓ Low but sufficient light yield (< 1 pe/GeV)
- Design
  - ✓ Steel absorber ($10\ \lambda_I$) with embedded quartz fibres
  - ✓ Non-compensating by design!
    - Sensitive almost only to EM components
      - – Electrons/positrons emitting Cherenkov radiation in quartz ($E \geq 190$ keV)
      - – "Blind" to low energy particles and neutrons
    - Long fibres (run full depth): sample EM + HAD shower
    - Short fibres (start at ~22 cm depth): sample HAD shower only
    - EM energy = (long - short) signal difference
    - HAD energy = short fibre signal
  - ✓ PMT readout (outside high-B-field region)

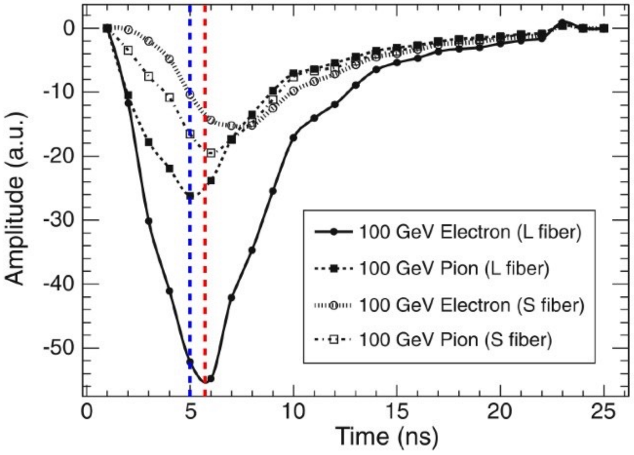


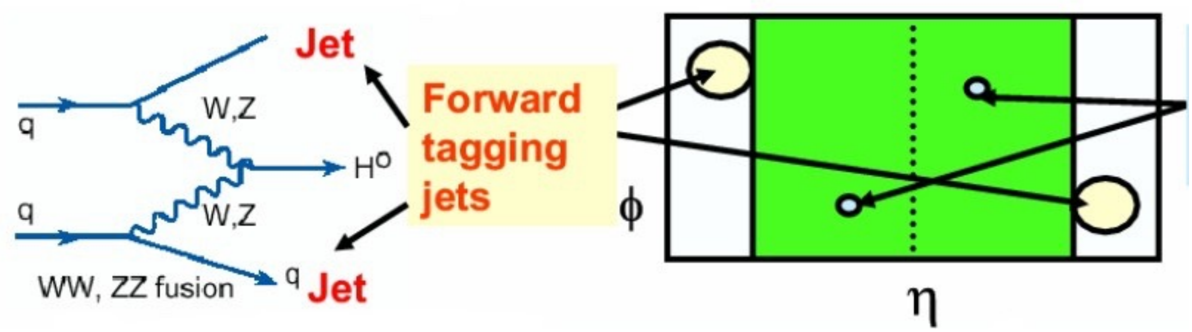
Forward CMS Region



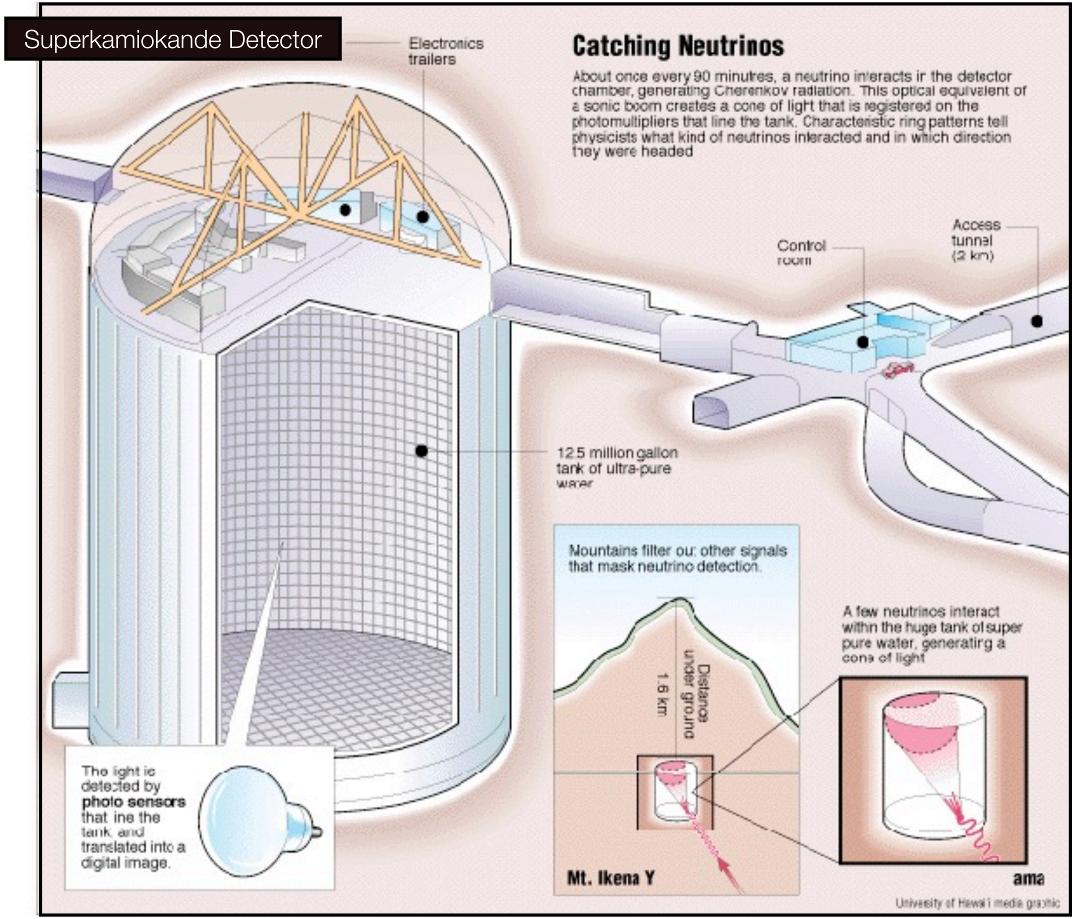
CMS HF: sampling Cherenkov in the very forward region

- Performance
  - ✓ $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 5\%$
    - poor by EM standards, acceptable for forward jets
  - ✓ Fast response: < 5 ns signal
  - ✓ Key role
    - MET measurement (hermeticity to |eta|~5)
    - VBF jet tagging
    - forward BSM signatures





Super-Kamiokande: homogeneus Cherenkov



About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed

Mountains filter out other signals that mask neutrino detection.

A few neutrinos interact within the huge tank of super pure water, generating a cone of light

The light is detected by **photo sensors** that line the tank and translated into a digital image.

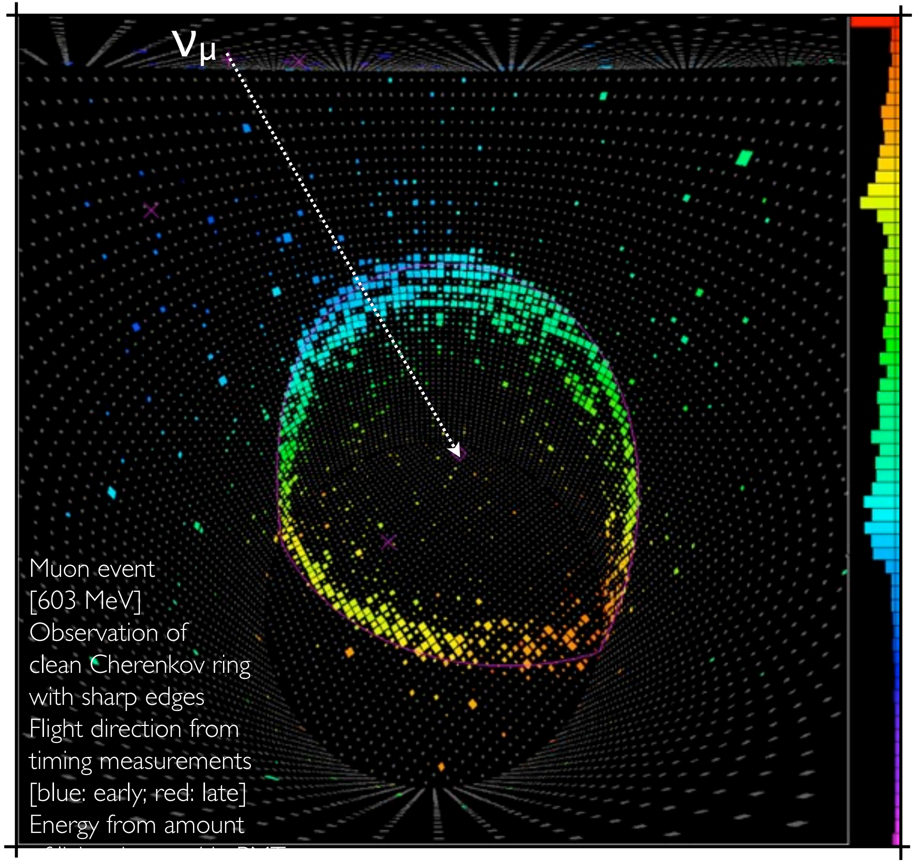
50 kton ultra-pure water
12000 photomultiplier
1000 m underground

Designed to study solar and atmospheric neutrino interactions and neutrino oscillations

Calorimetry sensitive to electrons > 5 MeV (up to TeV)

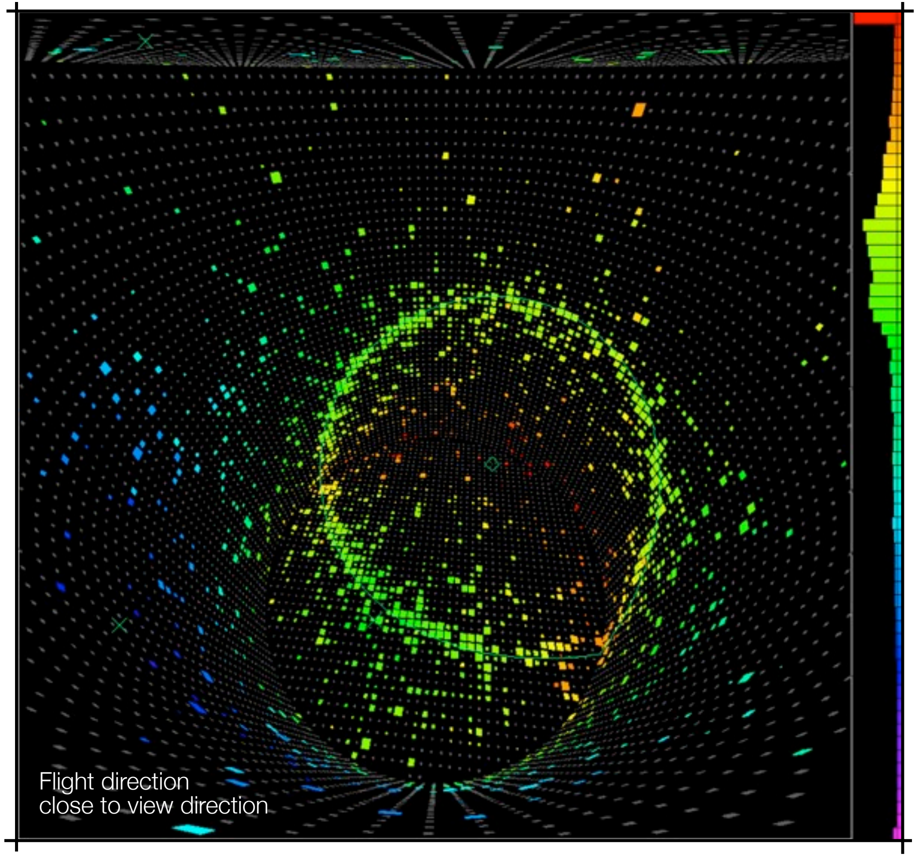
σ_E/E ~ 20% for 10 MeV electrons from neutrinos interactions

Super-Kamiokande



Muon event
[603 MeV]
Observation of
clean Cherenkov ring
with sharp edges
Flight direction from
timing measurements
[blue: early; red: late]
Energy from amount

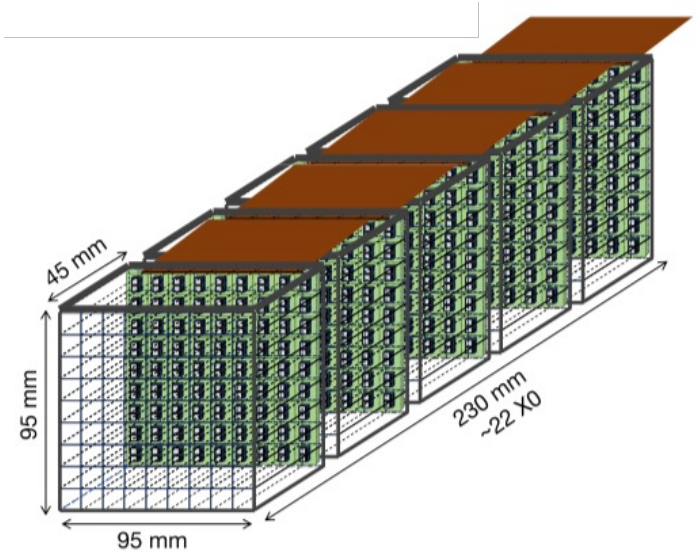
Electron event [492 MeV]
Observation of Cherenkov ring with fuzzy edge from e.m. shower
Flight direction from timing measurements [blue: early; red: late]
Energy from amount of light observed in PMTs

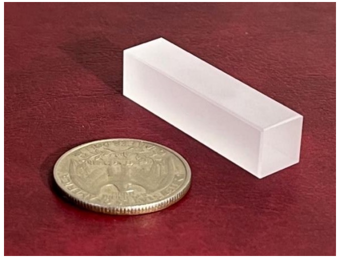


Flight direction
close to view direction

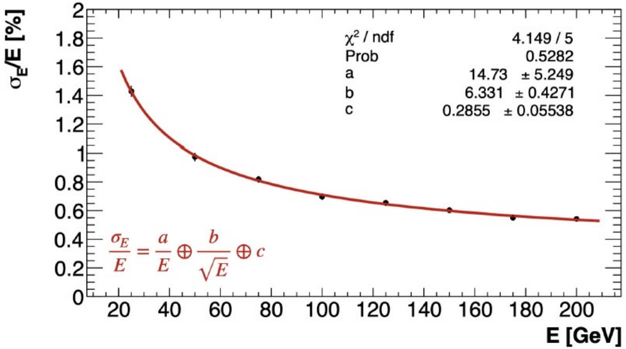
The future of Cherenkov calorimeters

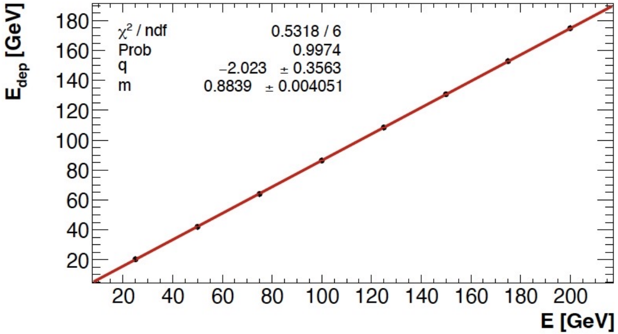
- **Crilin = Crystal Calorimeter with Longitudinal Information**
  - ✓ Semi-homogeneous, longitudinally segmented electromagnetic calorimeter based on high-Z, ultra-fast crystals with UV-extended SiPM readout
    - Lead fluoride (PbF_2)
    - Ultra-fast lead tungstate ($PbWO_4$, PWO-UF)
  - ✓ Candidate solution for Future Muon Collider barrel ECAL, that needs…
    - Ultra-fast reponse: $\sigma_t \sim 80$ ps
    - Longitudinal segmentation
    - Fine granularity
    - Radiation resistance
    - $\sigma_E/E \sim 10\%/\sqrt{E}$





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



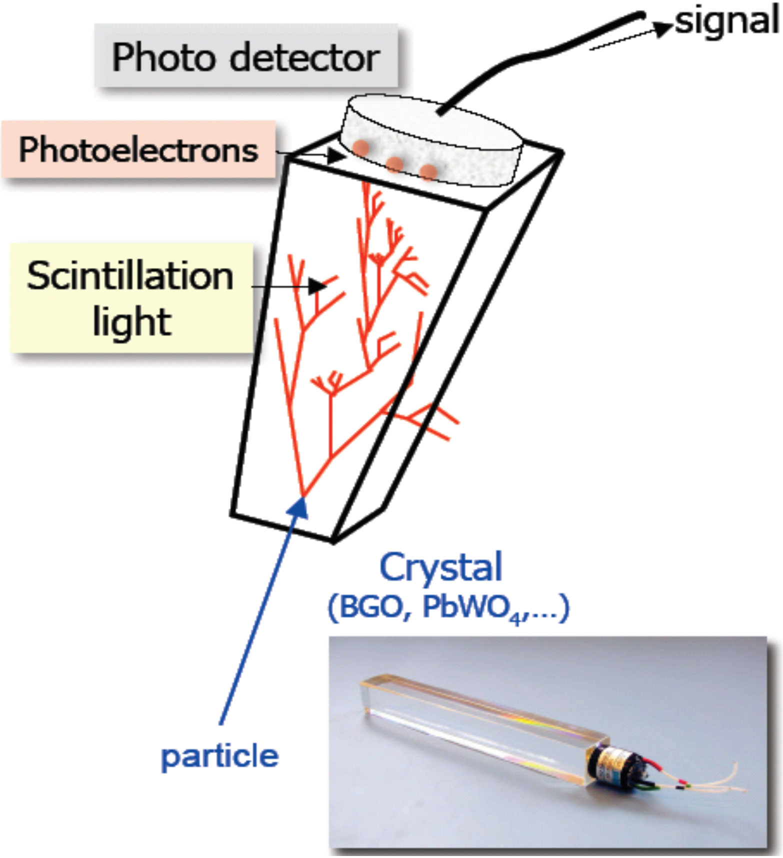


5.2

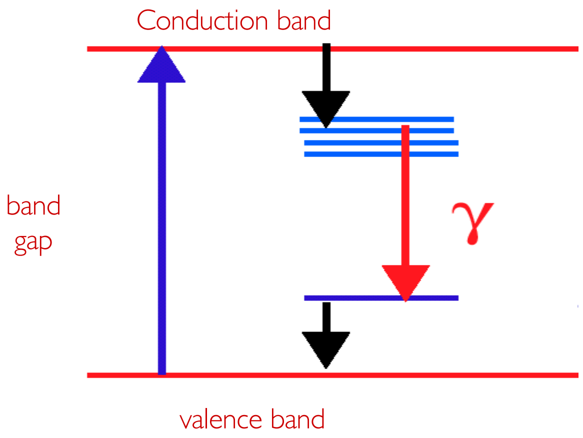
Scintillation calorimeters

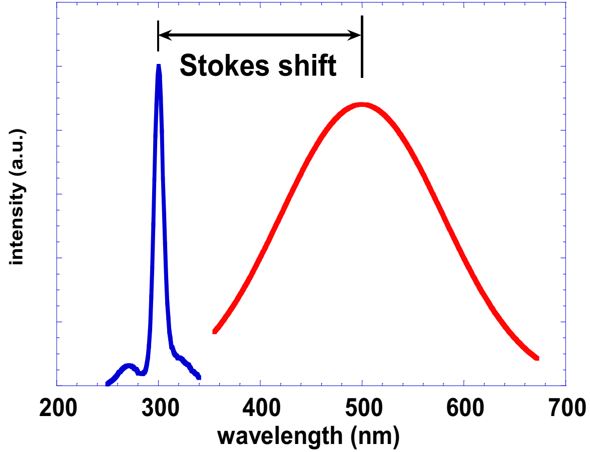
Scintillation calorimetry: crystals as total-absorption detectors

- Scintillating crystals: entire volume is active absorber → no sampling fluctuations
  - ✓ Medium = material in which ionization tracks produce light (fluorescence)
    - Key parameter: light yield [photons/MeV] → higher is better for resolution
    - Stochastic term a: set by Fano factor and number of photons (a ~ 1-3%)
  - ✓ Light transmitted through crystal to reach photodevice
    - Photoelectrons are produces (signal detection)
    - (Fine) longitudinal segmentation almost impossible



Scintillation calorimetry: light emission mechanism





- Variation in lattice (e.g. defects and impurities) create local electronic energy levels in the energy gap
- Electrons excited in conduction band by an incoming particle may enter these centers if they are unoccupied
- Three main types of centers
  - ✓ Luminescence centers: transition to ground state accompanied by photon emission
    - Signal (typically ~3 eV photons)
  - ✓ Quenching centers: radiationl-ess thermal dissipation of excitation energy may occur
    - Signal loss!
  - ✓ Traps: metastable levels from which electrons may subsequently return to conduction band by acquiring thermal energy from the lattice vibrations or fall to valence band by a radiation-less transition
    - Potential delayed photons emission!

Scintillators types

- Organic
  - ✓ Fast response / poor light yield
    - Organic solvent + ≤1% scintillating solute (fluors): molecules excited by the incident charged particles → energy is transferred to solute which produces scintillation light; occasionally wavelength shifter is added; very fast process (ns)
    - Used mainly as active components in sampling calorimeters (not very dense)
    - Inexpensive
    - Medium radiation hardness

- Inorganic
  - ✓ Slow response / large light yield
    - Electron-hole pairs produced in the conduction/valence bands; photons emitted when electrons return to the valence band; large variation in frequency and response time; use of dopants to increase light yield (Thallium)
    - Light yield several order of magnitude better than Cherenkov calorimeter
    - Due to their high density, used in applications where high stopping power or a high conversion efficiency is required.
    - Expensive
    - Radiation hard
    - Drawback: crystals are not intrinsically uniform, lots of effort in calibration and stability control

Crystal requirements for calorimetry

- Crystal requirements for calorimetry
  - ✓ Short radiation length X_0: compact detector
  - ✓ Small Moliere radius R_M: fine transverse granularity possible
  - ✓ High light yield: low stochastic term
  - ✓ Fast scintillation decay time:
    - e.g. compatible with 25 ns LHC bunch crossing (against pileup)
  - ✓ Radiation hardness:
    - e.g. must survive high fluence at LHC

- No single crystal satisfies all requirements perfectly! → technology trade-offs

Scintillating crystals: key properties

Crystal	**X_0 [cm]**	**R_M [cm]**	**Light yield [ph/MeV]**	**τ [ns]**	**dLY/dT [%/°C]**	**Rad. hardness**	**Cost**
NaI(Tl)	2.59	4.84	38,000	250	+0.2	**poor**	**low**
BGO	1.12	2.23	8,500	300	−1.9	**good**	**medium**
CsI(Tl)	1.86	3.57	54,000	1,000	+0.3	**moderate**	**low**
BaF_2	2.03	3.49	10,000/1,400†	630/0.6†	−1.9	**good**	**medium**
$PbWO_4$	0.89	2.00	~100	6–25	−2.1	**excellent** (after optimization)	**medium**
LYSO Lutetium Yttrium Orthosilicate	1.14	2.07	~28,000	40	−0.2	**good**	**high**
GSO Gd2SiO5:Ce	1.38	2.60	~8,000	60/600†	−0.4	**good**	**medium**

† BaF_2 and GSO have fast and slow scintillation components. **Key trade-offs:** $PbWO_4$ — fast & rad-hard, but very low LY → needs APD/SiPM readout (CMS ECAL). CsI(Tl) — highest LY, but too slow for LHC (BaBar/Belle). LYSO — best overall (fast, bright, compact), but expensive.

Scintillating crystals: key properties

Crystal	Use case
NaI(Tl)	**Crystal Ball** (SLAC/DESY), NA48 backup option. The original calorimetry crystal (Hofstadter 1948).
BGO	**L3 at LEP** (11000 crystals, 24 X_0 deep). Best EM resolution at LEP: sigma/E ~ 1.2%/sqrtE (+) 0.8%. Light readout: PIN photodiodes (magnetic field ~ 0.5T in L3).
CsI(Tl)	**BaBar** (6580 crystals) and **Belle** EMC. Compatible with B-factory bunch spacing (~8 ns, but triggered readout). NOT viable for LHC: at 40 MHz bunch crossing, 1 microsecond decay means integrating ~40 crossings.
BaF_2	Fastest scintillator known. Used at **OPAL** (LEP). Fast component ideal for timing; slow component is a nuisance. No major LHC application; relevant for future muon collider or very fast experiments.
$PbWO_4$	Designed FOR the LHC: sacrifices light yield entirely for speed, compactness, and radiation hardness. **CMS** ECAL: requires APD (gain ~50) instead of PIN photodiode to compensate for low LY.
LYSO	The "best of all worlds" candidate for next-generation detectors: high LY + fast + compact + rad-hard. Expensive (Lu content). Under active R&D for future colliders (FCC-ee barrel ECAL concepts). CMS ECAL Phase-2: LYSO/SiPM option for barrel considered vs PbWO4 upgrade.
GSO	Emerging alternative; less studied than LYSO…

Optical characteristics of some crystals

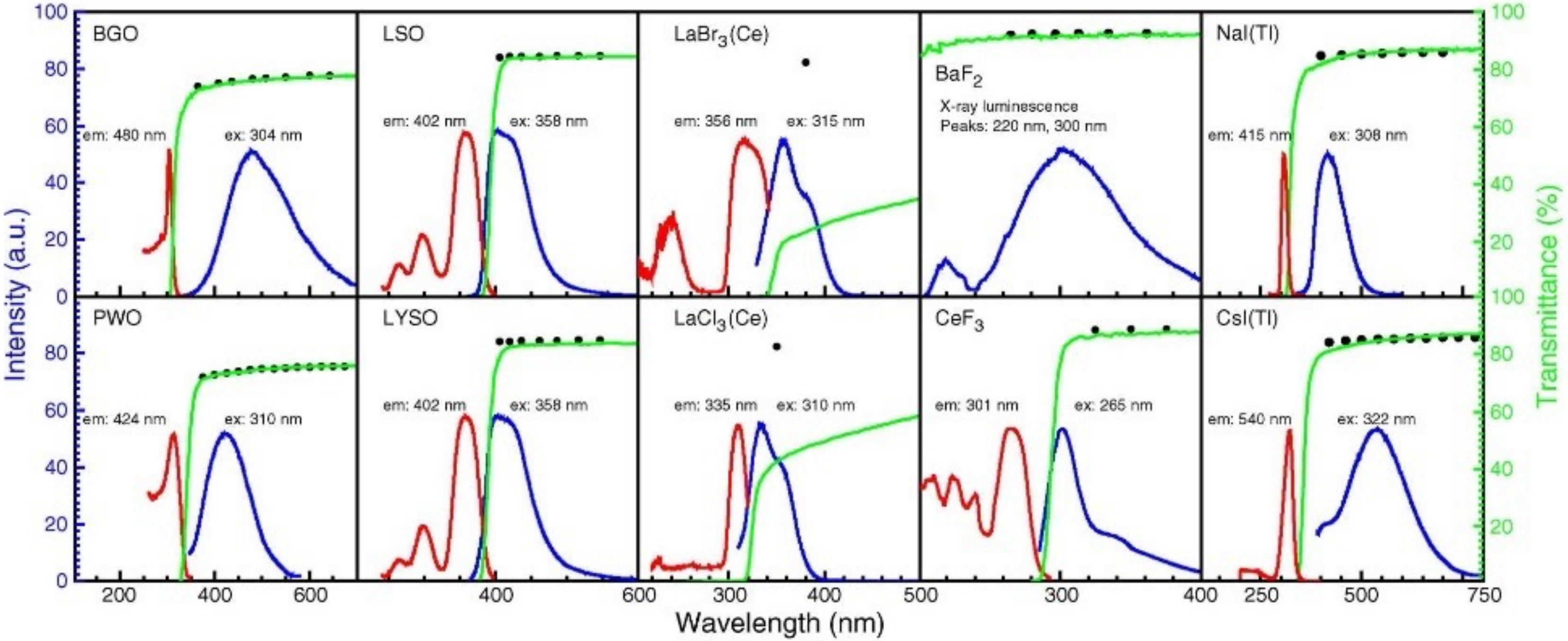
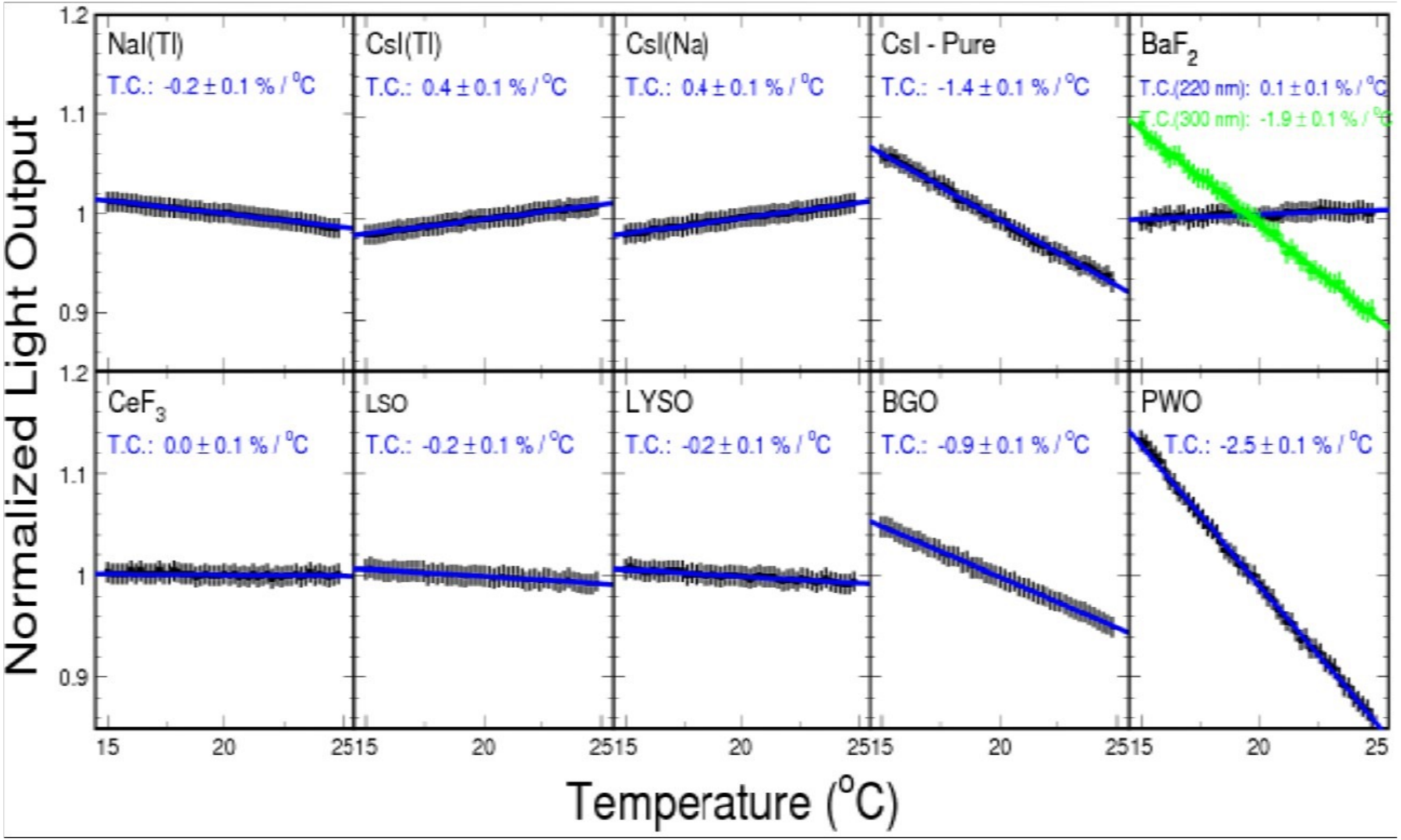
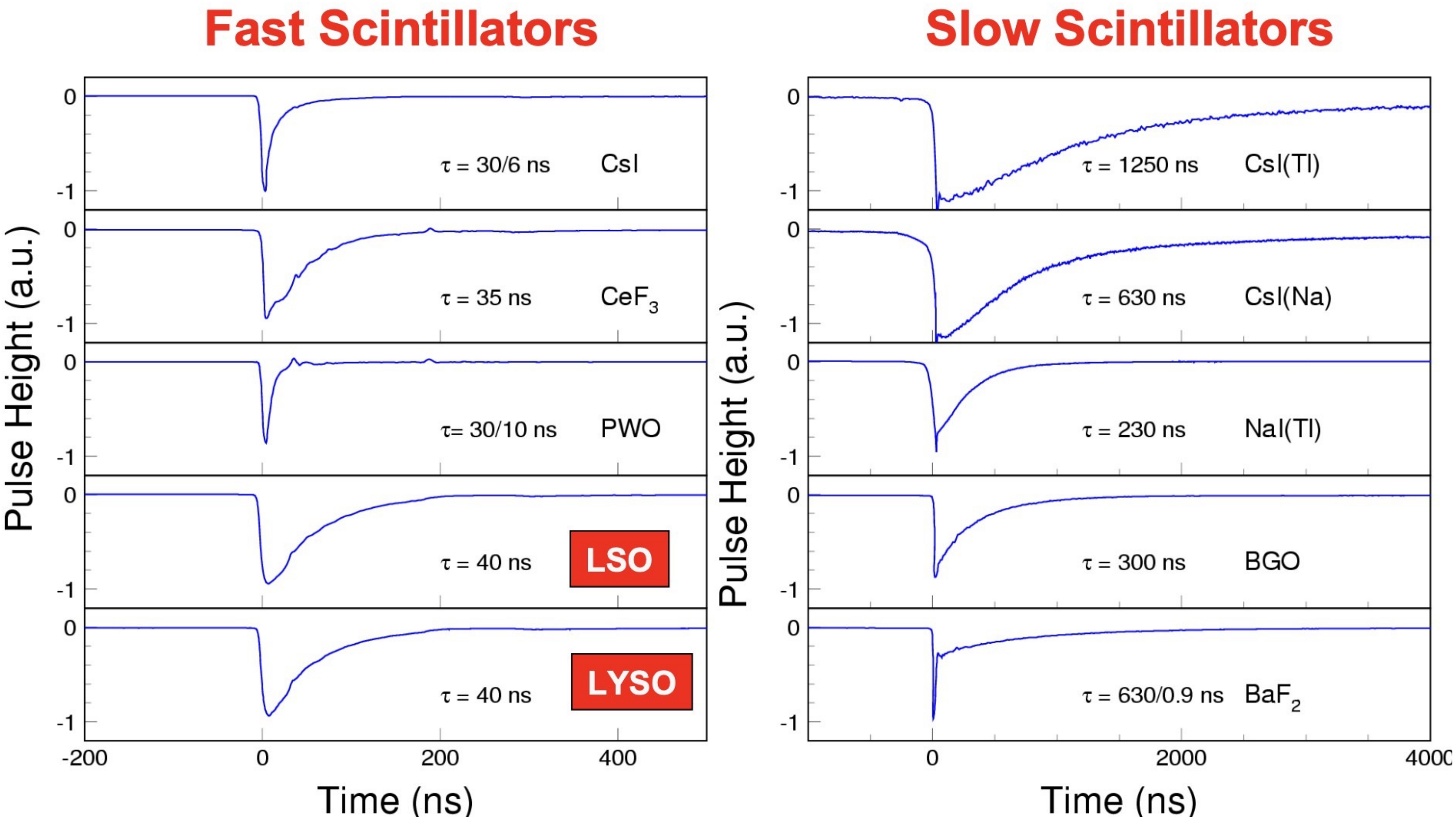


Fig. 2. The excitation (red) and emission (blue) spectra (left scale) and the transmittance (green) spectra (right scale) are shown as a function of wavelength for ten crystal scintillators. The solid black dots are the theoretical limit of the transmittance.

Light Output vs Temperature



Light Decay Time



Crystal calorimeters in particle physics experiments

Experiment	**C. Ball**	**L3**	**CLEO II**	**KTeV**	***BaBar***	**BELLE**	**CMS**
Accelerator	SPEAR	LEP	CESR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	–	0.5	1.5	–	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	–	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	4,000	1	1	50
σ_n/Channel (MeV)	0.05	0.8	0.5	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^5

Crystal calorimeters in particle physics experiments

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Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^5

L3 at LEP
BGO crystals
3x3 cm^2 cross-section

$\sigma_E/E \sim 1.2\%/\sqrt{E} \oplus 0.8\%$

demonstrated BGO potential

BGO light readout: PIN photodiodes (not PMTs)

Crystal calorimeters in particle physics experiments

Experiment	**C. Ball**	**L3**	**CLEO II**	**KTeV**	***BaBar***	**BELLE**	**CMS**
Accelerator	SPEAR	LEP	CESR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
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Number of Crystals	672	11,400	7,800	3,300	6,580	8,800	76,000
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Photosensor	PMT	Si PD	Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	4,000	1	1	50
σ_n/Channel (MeV)	0.05	0.8	0.5	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^5

BaBar ECAL at PEP-II (SLAC): 6580 CsI(Tl) crystals

Tapered crystals 14-17 cm long; asymmetric barrel + endcap

CsI(Tl) very large light output (7000 Pe/MeV)

long decay time (μs) not a problem: rate ~100 Hz

Light readout: silicon PIN photodiodes (magnetic field ~ 1.5 T)

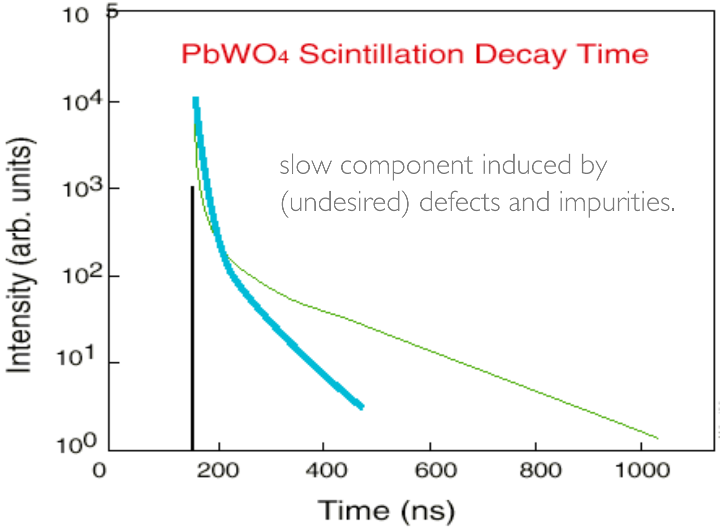
$\sigma_E/E \sim 2.3\%/\sqrt{E} \oplus 1.9\%$

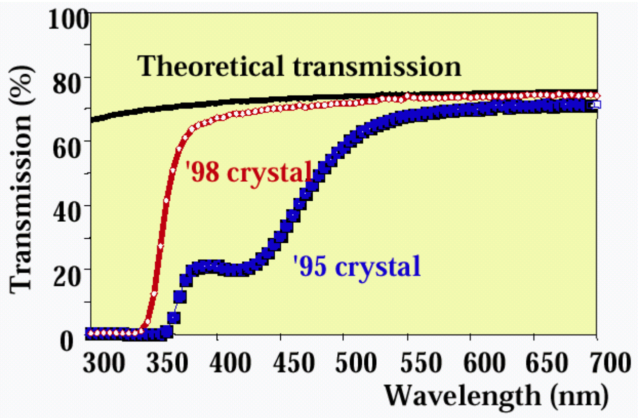
BELLE EMC: similar design to BaBar; CsI(Tl) barrel + CsI(pure) endcap

All non-LHC examples: no radiation damage problem; CsI(Tl) viable

PbWO$_4$: a crystal engineered for the LHC

- **No natural crystal was fast enough, compact enough, and radiation-hard enough for the LHC. PbWO4 was developed specifically**
- **Key property trade-off in PbWO4**
  - ✓ Speed: τ ~ 25 ns → compatible with 25 ns LHC bunch spacing
    - >80% of light collected in one bunch crossing
  - ✓ Compactness: X_0 = 0.89 cm, R_M = 2.0 cm
    - Allows 25 X_0 in ~23 cm radial depth
  - ✓ Radiation hardness: excellent after vendor optimization (Mo/Nb doping controls colour centers)
  - ✓ Light yield penalty: only ~100 photons/MeV (i.e ~400x less than NaI(Tl))
- **Consequence of low light yield: cannot use PIN photodiode (no gain) → use APD (Avalanche Photodiode):**
  - ✓ APD gain ~50 in the 3.8 T CMS solenoid field (PMTs excluded because of high magnetic field)
  - ✓ APD noise temperature coefficient: -2.4%/C → requires crystal temperature stability to 0.1 C (cooling system!)
  - ✓ APD gain radiation sensitivity: monitored continuously with laser system
- **CMS ECAL design around PbWO$_4$**
  - ✓ 75848 crystals (61200 barrel + 14648 endcap)
  - ✓ Crystal cross-section: 22x22 mm2 front face (approximately RM ~ 2 RM)
  - ✓ Barrel coverage: |eta| < 1.479
  - ✓ Endcap: VPT (Vacuum Phototriode) readout instead of APD (lower B field, higher radiation)

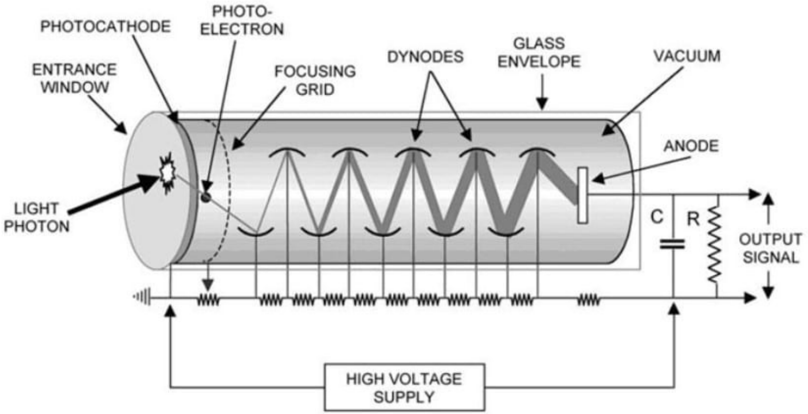




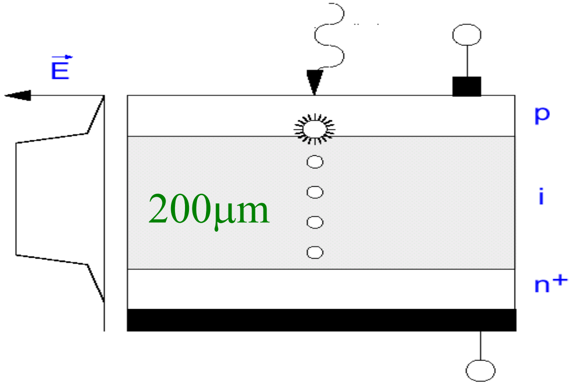
Converting photons to electronic signal

- Photons from crystals must be converted into an electronic signal
  - ✓ If low light yield photon detector should “amplify” light
  - ✓ If calorimeter immersed in magnetic fied: photon detector not sensitive to B
  - ✓ High quantum efficiency for l 400 – 500 nm
  - ✓ Fast and good for high rate (40MHz)
  - ✓ Radiation hard
  - ✓ Not (too) sensitive to charged particles

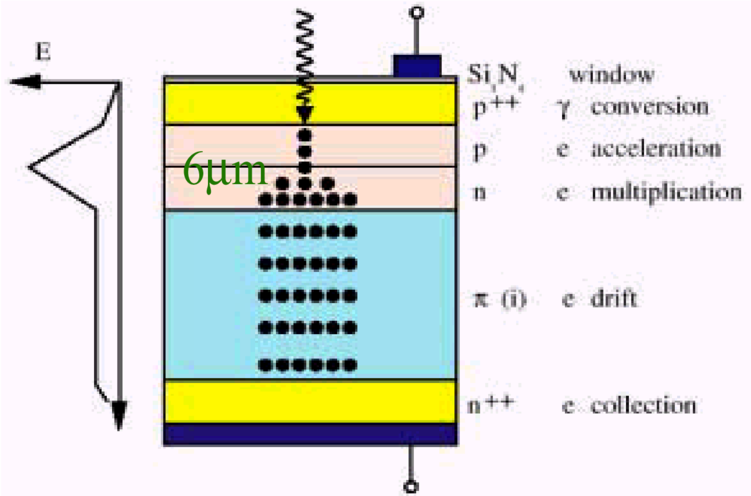
Photomultipliers: affected by magnetic field; large volume

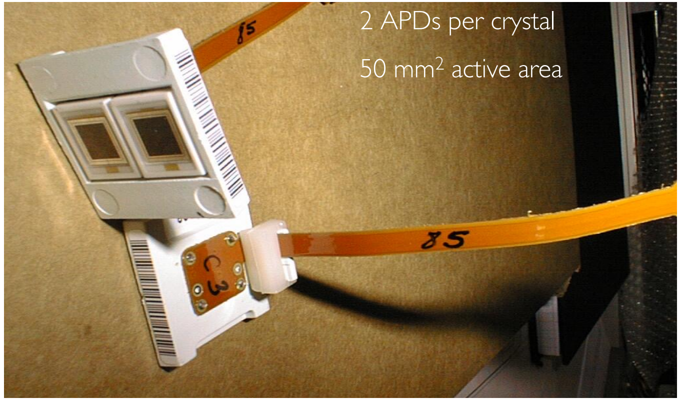


PIN photodiodes: no internal amplification; too sensitive to charged particles (Nuclear Counter Effect)



Avalanche Photodiodes



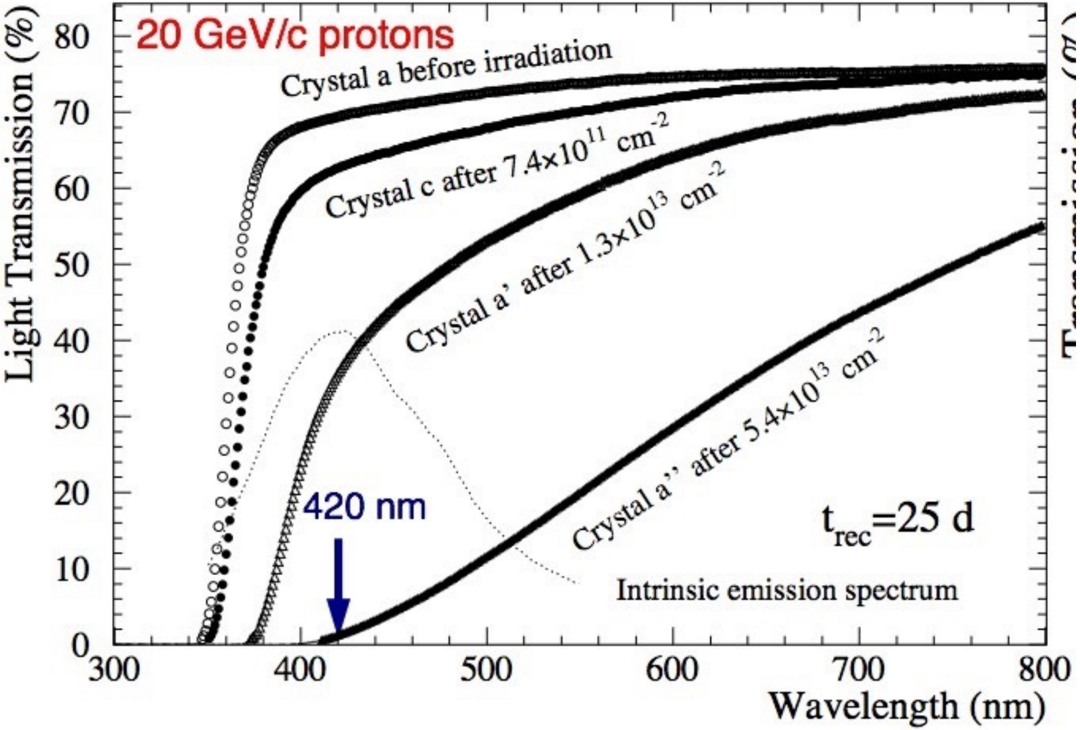

2 APDs per crystal

50 mm^2 active area

- Insensitive to B-field as PIN diodes
- Internal gain (M=50 used for CMS)
- Good match to Lead Tungstate scintillation spectrum (Q.E. ~ 80%)
- dM/dV = 3%/V and dM/dT = -2.3%/oC :
  - ✓ T and V stabilization needed
  - ✓ Changes to be tracked through light injection system
  - ✓ Bulk current increase & recovery with irradiation measured over 1 year before LHC data taking: expect doubling of initial noise after 10 years running (deemed acceptable…)
- Capacitance ~75 pF

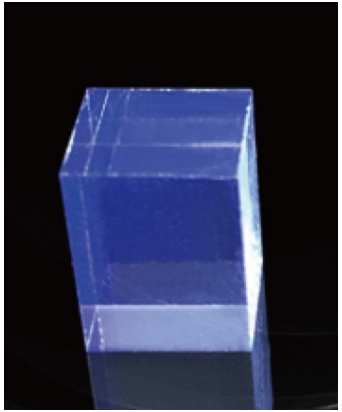
$PbWO_4$ radiation damage

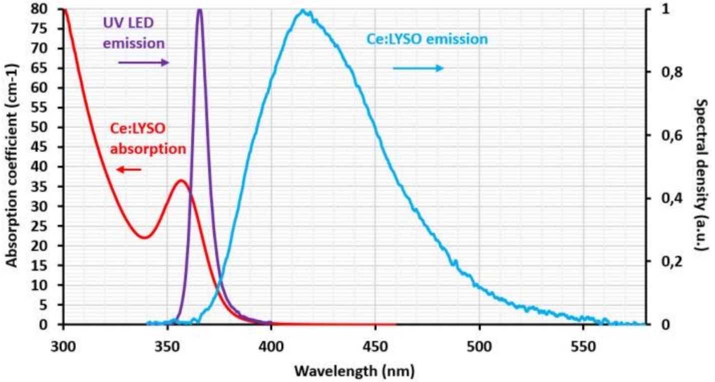
- No damage to scintillation mechanism
- Only transmission properties affected through formation of color centers due to defects
- Changes can be tracked through light injection monitoring system
- Equilibrium (“saturation”) observed, plus recovery (“annealing”)



Future crystal calorimetry: LYSO and beyond

- **LYSO** (Lu2(1-x)Y2x SiO5:Ce) leading next-generation crystal
  - ✓ High light yield: ~30 ph/keV (vs 0.1 for PbWO4)
  - ✓ Fast: τ ~ 40 ns
    - compatible with LHC
    - even faster variants under development
  - ✓ Compact: X_0 = 1.14 cm, R_M = 2.07 cm
  - ✓ Radiation hardness: excellent even at HL-LHC fluences
  - ✓ Temperature sensitivity low: -0.2%/C
  - ✓ Drawback: expensive (lutetium is a rare earth; CERN supply constraints)
  - ✓ Motivations: FCC-ee experiments; Muon Collider ECAL





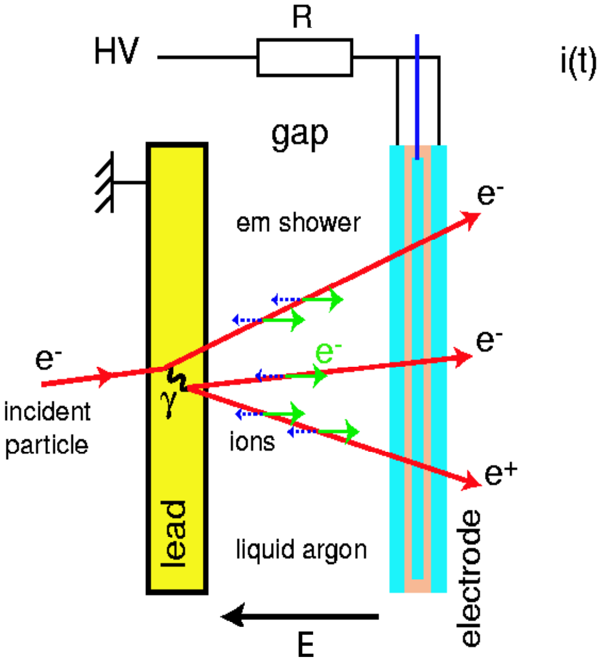
- **Crilin**: longitudinally-segmented semi-homogeneous crystal
  - ✓ PbF2 (Cherenkov-only)
  - ✓ PWO-UF (ultra-fast PbWO4) crystals with UV-extended SiPM
  - ✓ Goal: longitudinal segmentation + timing σ_t ~ 80 ps per layer
  - ✓ Motivation: Muon Collider (BIB rejection requirements)

5.3

Ionization calorimeters

Noble liquids as active media

- Boiling point
  - ✓ LAr (87 K), LKr (121 K), LXe (165 K)
  - ✓ All noble liquid calorimeters need cryogenic system:
    - material in front + cost + complexity (purity)!
- Key properties
  - ✓ high density
  - ✓ excellent charge collection
  - ✓ stable over time and radiation hard
- Signal
  - ✓ In noble liquids charged particles lose ~50% energy in ionization (charge drift → slow signal) and 50% in scintillation (fast signal O(10 ns))



$$N = N_{\mathrm{ion}} + N_{\mathrm{scint}}$$

$$\sigma(N_{\mathrm{ion}}) = \sqrt{N \frac{N_{\mathrm{ion}}}{N} \frac{N_{\mathrm{scint}}}{N}}$$

Fluctuations on N_{ion} from binomial statistics
Variance = np(1-p))

$\sigma(N_{\mathrm{ion}}) \sim 0.4\text{-}0.5 \sqrt{N}$

Factor ~2x better than from pure Poisson statistics

Noble liquids as active media

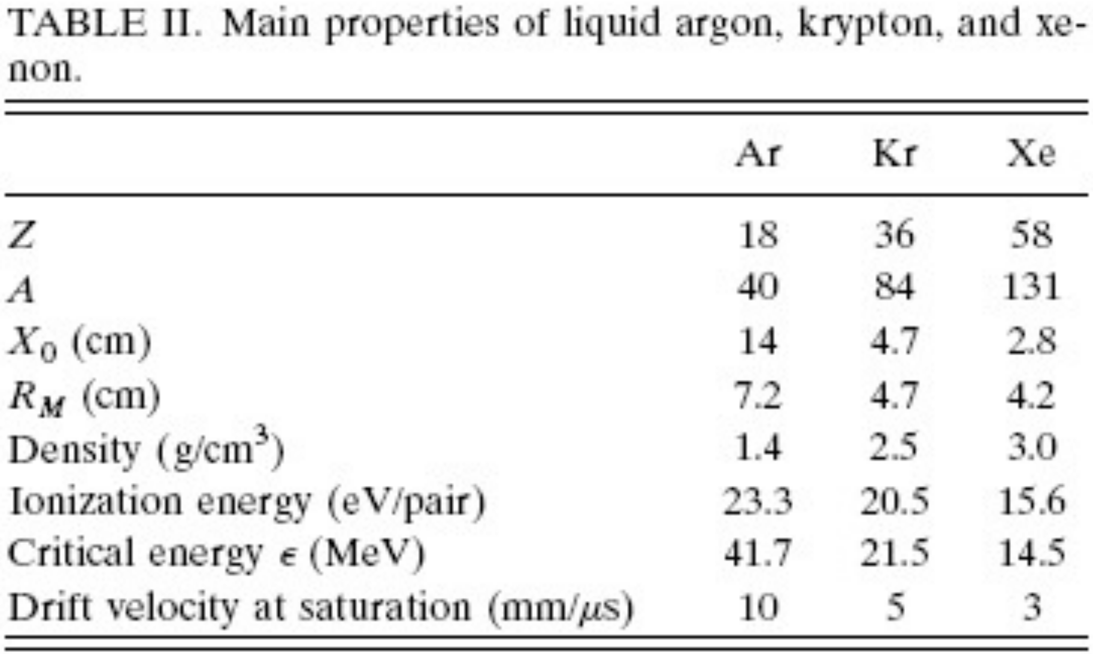
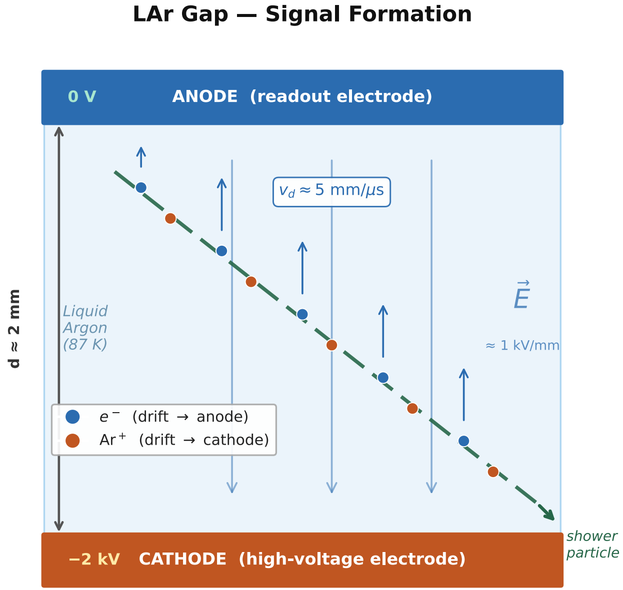


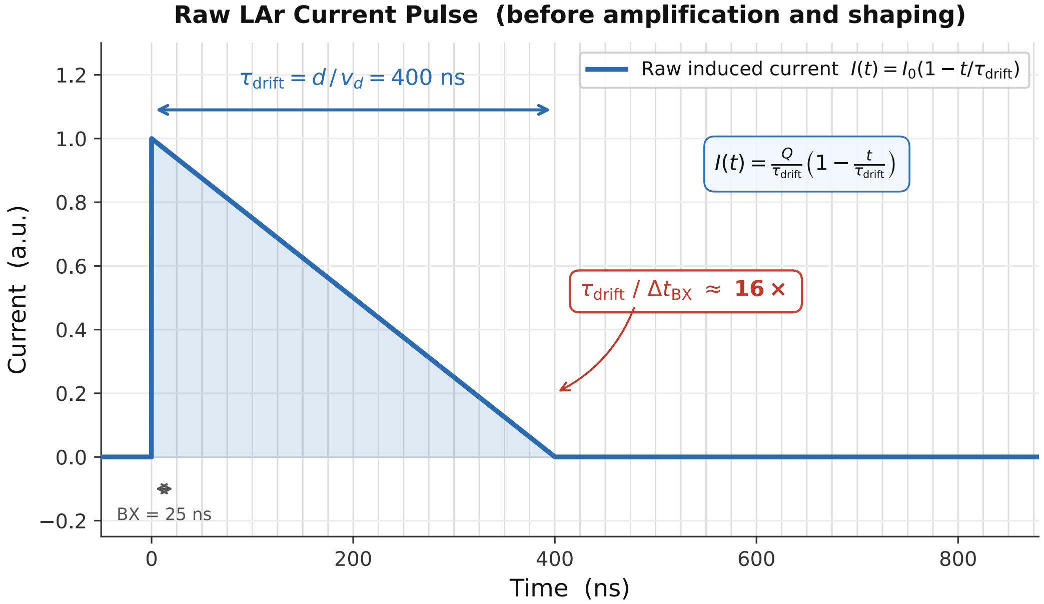
TABLE II. Main properties of liquid argon, krypton, and xenon.

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3

- LAr: cheapest, well-understood, X_0 = 14 cm
  - ✓ Needs high-Z absorber for compact ECAL (ATLAS: Pb)
- LKr: higher Z (36 vs. 18 LAr)
  - ✓ Better shower containment per unit length
  - ✓ NA48 uses quasi-homogeneous LKr
- LXe: highest Z (54), best intrinsic resolution
  - ✓ Expensive!
  - ✓ MEG experiment

Noble liquid ionization signal

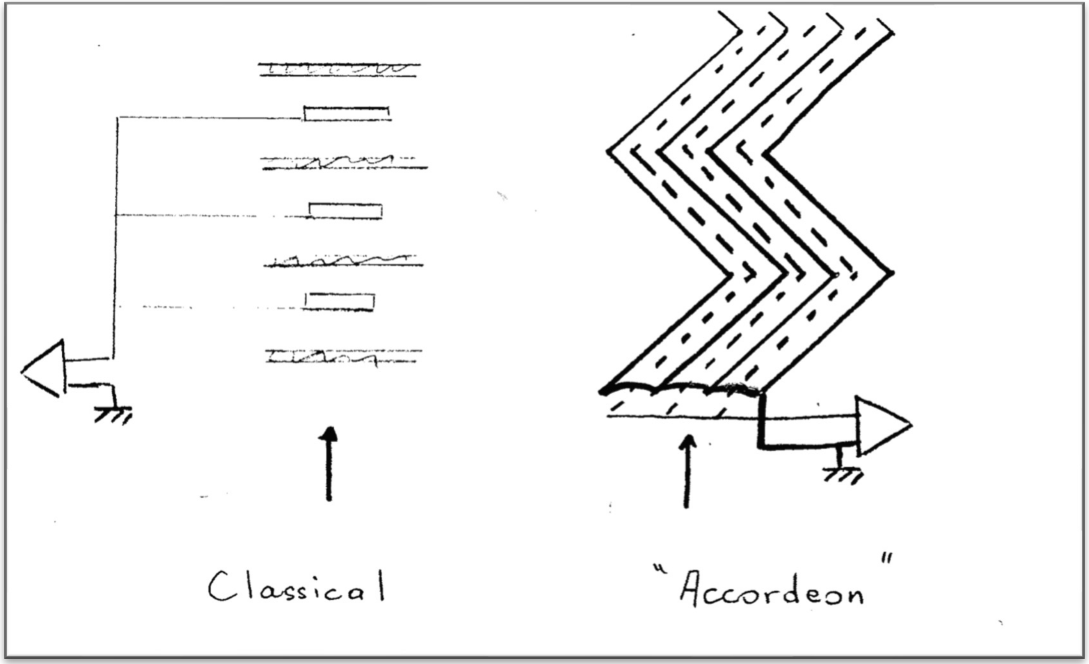




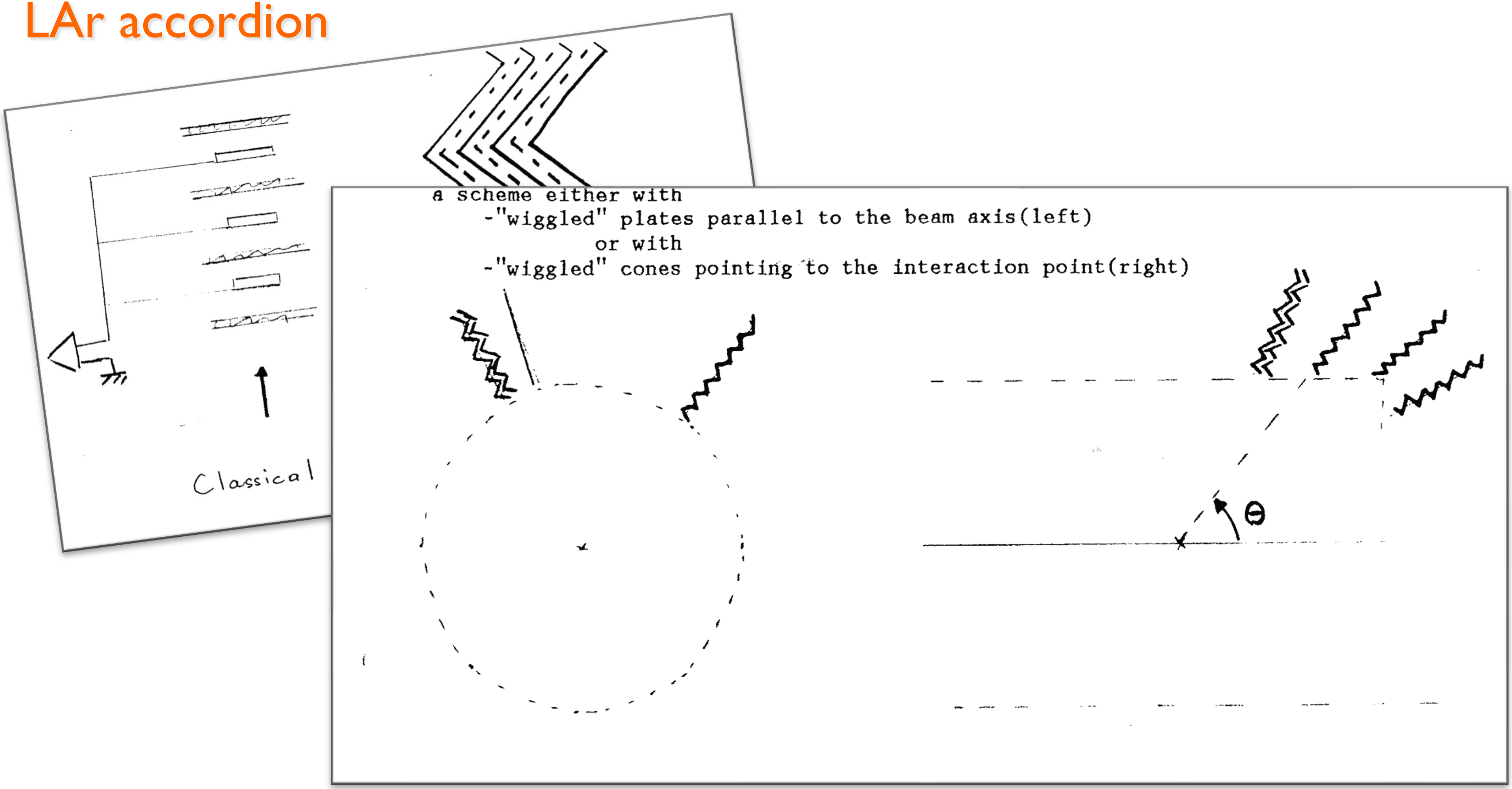
- Signal from drift of ionization electrons
  - ✓ Ions also drifting but speed way slower
- Example: ATLAS LAr ECAL Barrel
  - ✓ d = 2 mm ; HV = 2 kV ; E = 1 kV/mm
  - ✓ $v_d \sim 5$ mm/μs → $\tau_d = d/v_d = 400$ ns
- Signal amplitude proportional to ionization charge
  - ✓ $Q \sim E_{dep}/W_{ion} \sim$ few $\times\ 10^7\ e^-$/cell
  - ✓ Triangular shape assumes uniform ionization along gap (good approximation for a shower); single charge would give rectangular pulse
  - ✓ Preamplifier used before shaping signal (could be "cold" on-detector to minimize noise (or services if on-detector digitization…)

LAr as active medium

- LAr as active medium successfully introduced in early 1970s
  - ✓ LAr as been used in many fixed target and collider experiments
    - R807/ISR, MARK2, CELLO, NA31, SLD, HELIOS, D0, HERA, ATLAS
- In 1990 Daniel Fournier introduced a novel design for a LAr calorimeter with “accordion” shaped absorber
  - ✓ No dead space between towers and provides better uniformity of response and fast signal extraction
  - ✓ ”accordion” was adopted by NA48 (LKr) and ATLAS (LAr)

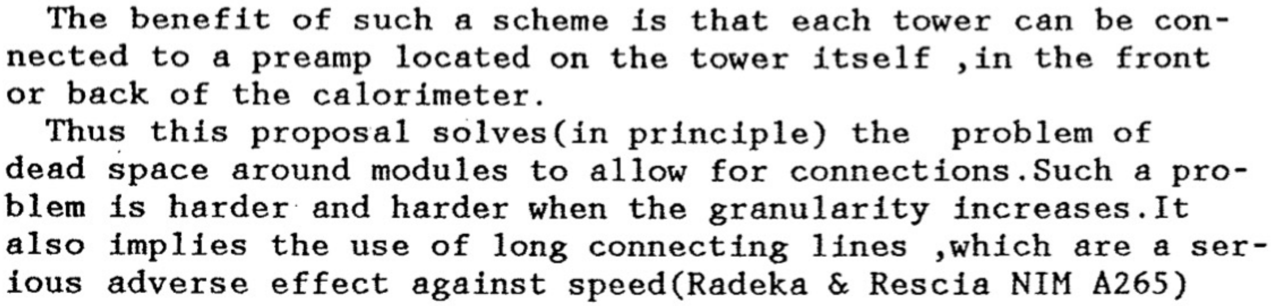


LAr accordion

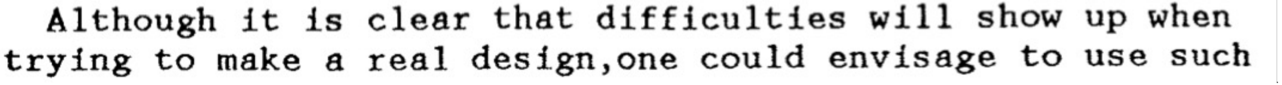


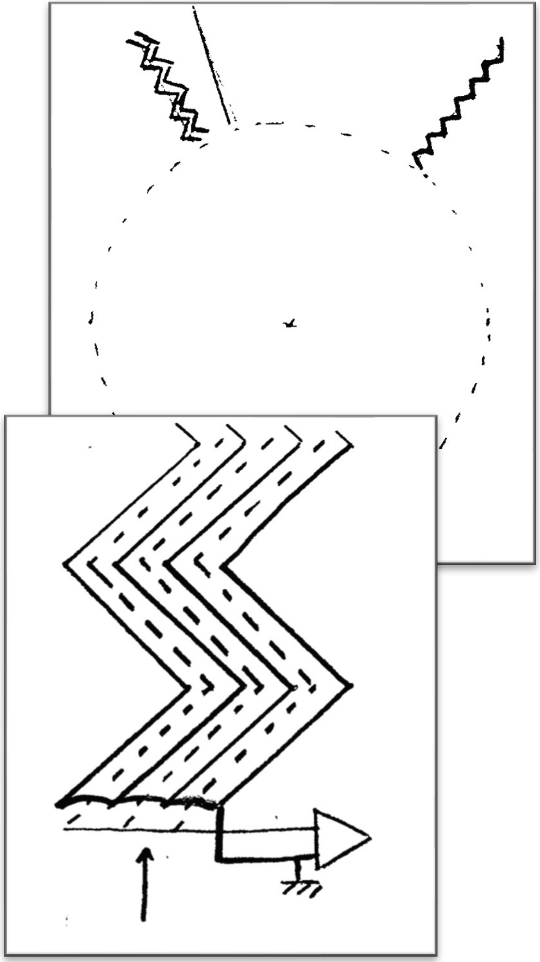
a scheme either with
-"wiggled" plates parallel to the beam axis(left)
or with
-"wiggled" cones pointing to the interaction point(right)

LAr accordion

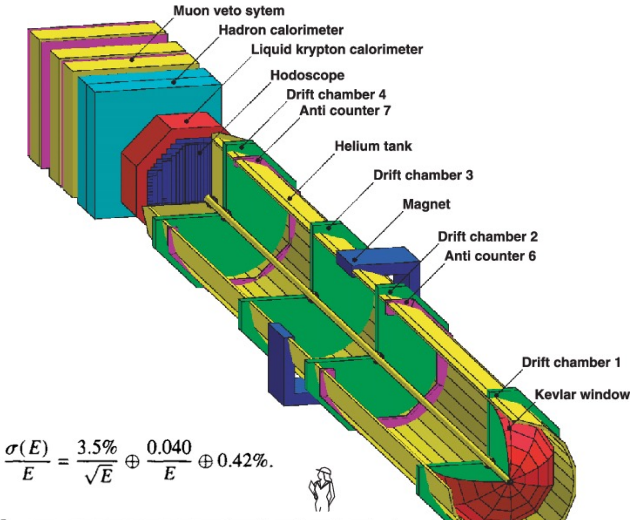

The benefit of such a scheme is that each tower can be connected to a preamp located on the tower itself ,in the front or back of the calorimeter.

Thus this proposal solves(in principle) the problem of dead space around modules to allow for connections.Such a problem is harder and harder when the granularity increases.It also implies the use of long connecting lines ,which are a serious adverse effect against speed(Radeka & Rescia NIM A265)

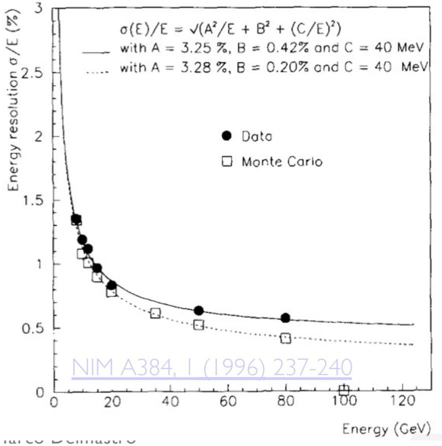

Although it is clear that difficulties will show up when trying to make a real design,one could envisage to use such



NA48 LKr calorimeter: quasi-homogeneous noble liquid

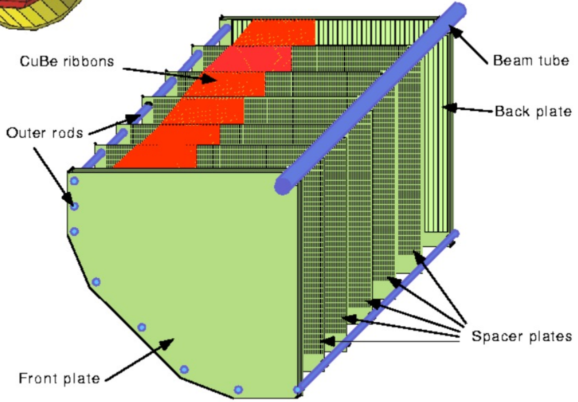


$$\frac{\sigma(E)}{E} = \frac{3.5\%}{\sqrt{E}} \oplus \frac{0.040}{E} \oplus 0.42\%.$$



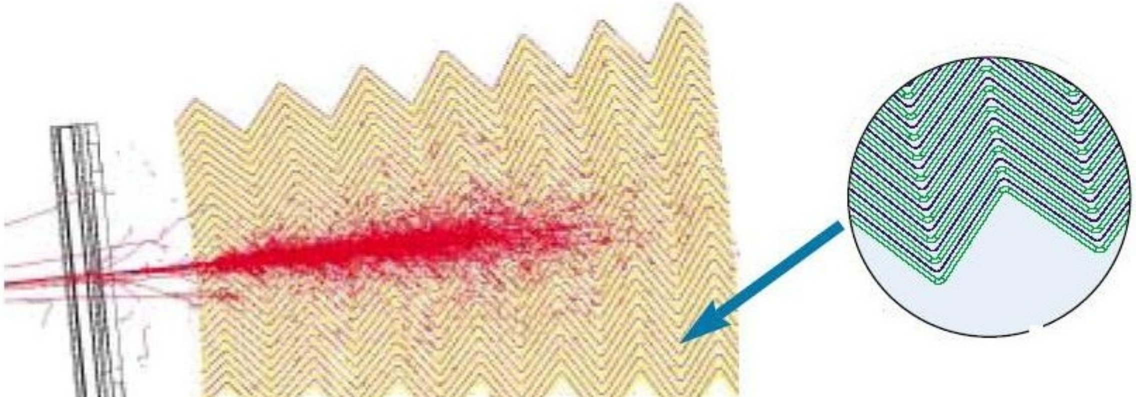
NIM A384, 1 (1996) 237-240

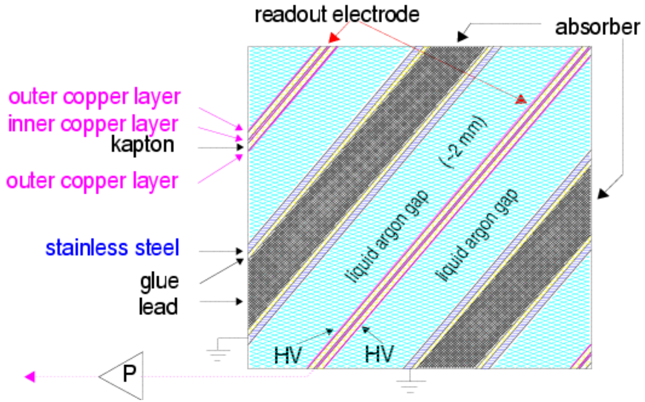
- NA48 at CERN SPS: measurement of direct CP violation in $K^0 \rightarrow \pi^+\pi^-$ and $K^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$
- Required excellent EM resolution: $\sigma(E)/E < 1\%$ at $E > 20$ GeV
- LKr calorimeter: 10000 copper-beryllium ribbon electrodes in liquid krypton
  - ✓ Electrode structure: 1 cm x 1 cm cells, 125 cm deep (~ 27 X0)
  - ✓ Quasi-homogeneous: electrodes are very thin; krypton is both absorber and active medium

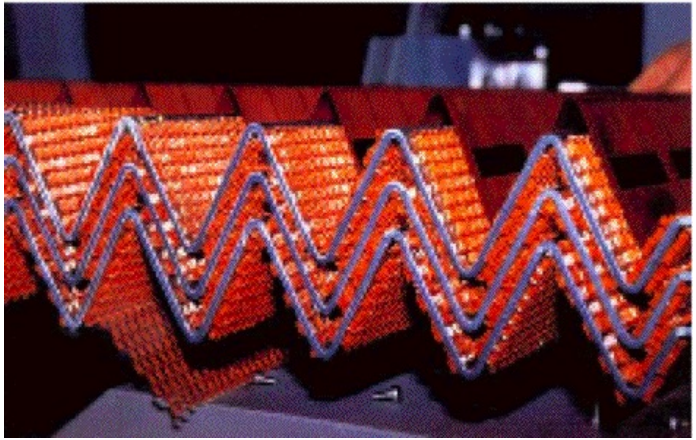


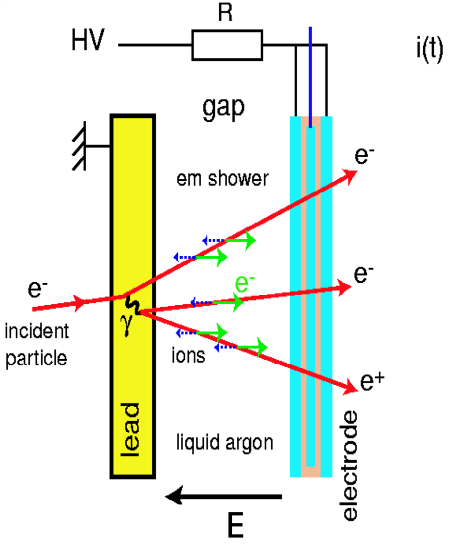
- $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 0.42\%/E \oplus 0.09\%$
- $\sigma_x \sim 1$ mm at 25 GeV
- $\sigma_t < 400$ ps
- Legacy: demonstrated that noble liquid can achieve sub-1% constant term!

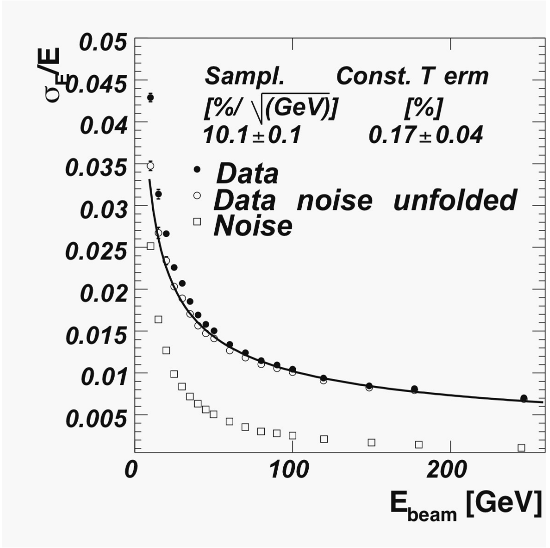
ATLAS LAr EM calorimeter







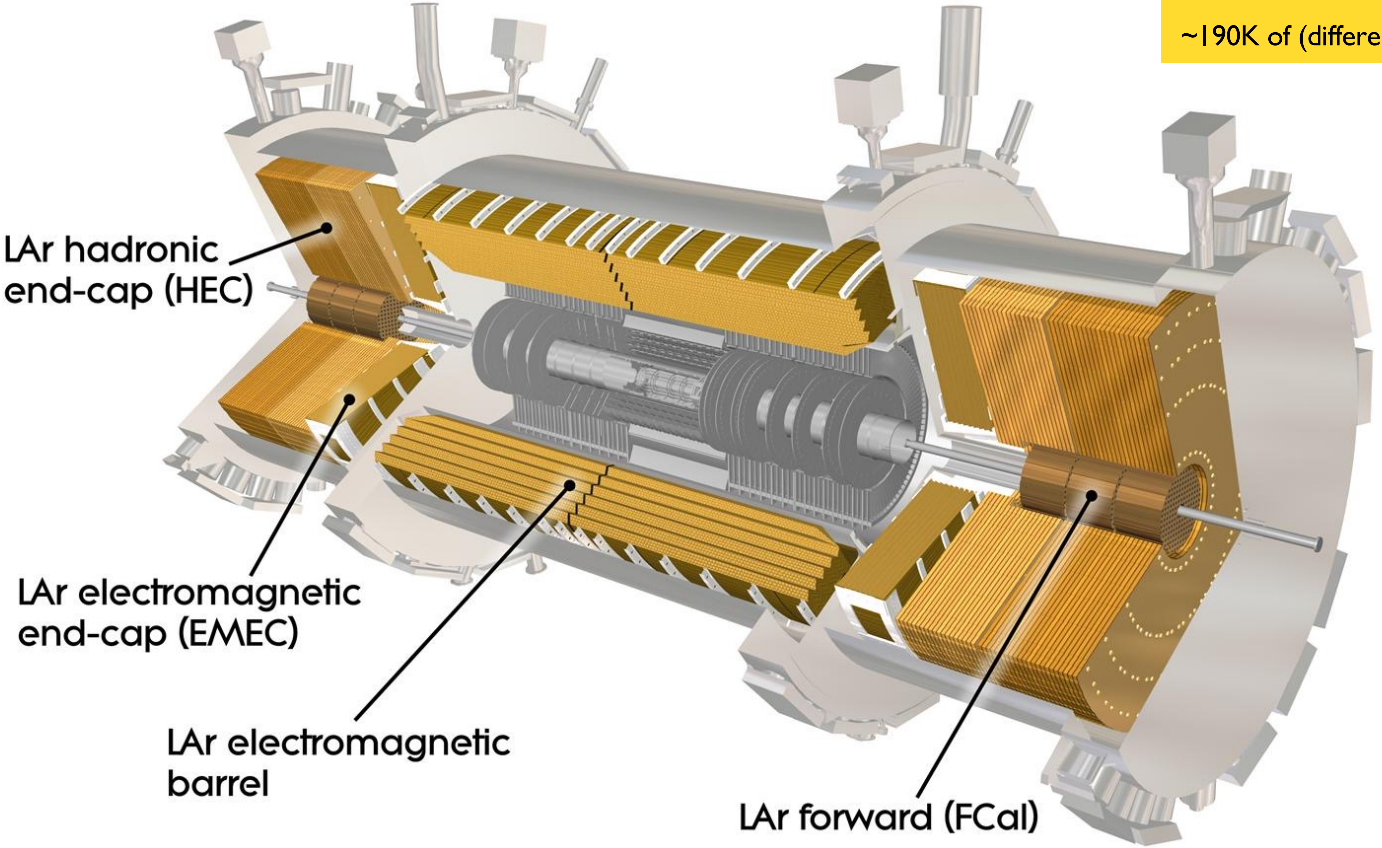




ATLAS LAr calorimeters

- ✓ EM Barrel : (|η|<1.475) [Pb-LAr]
- ✓ EM End-caps : 1.4<|η|<3.2 [Pb-LAr]
- ✓ Hadronic End-cap: 1.5<|η|<3.2 [Cu-LAr]
- ✓ Forward Calorimeter: 3.2<|η|<4.9 [Cu,W-LAr]

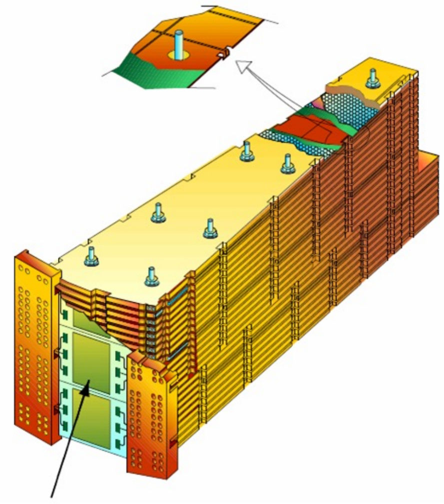
~190K of (different) readout channels



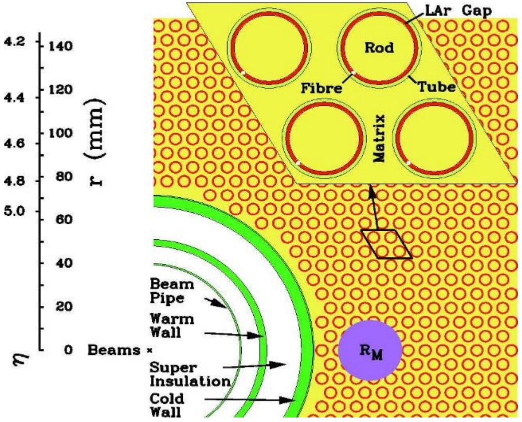
- Same cryogenic infrastructure
- Same signal-chain principle
- Different absorbers and gap geometry

LAr for HAD and forward: ATLAS LAr HEC and FCal

- ATLAS HEC and FCAL sub-systems extend same ionization-in-LAr principle to HAD coverage



- HEC (Hadronic Endcap Calorimeter): $1.5 < |\eta| < 3.2$
  - ✓ Absorber: Cu (non-magnetic, good λ_I and cost)
  - ✓ Gap size: 8.5 mm
    - drift time ~400 ns
    - sampling fraction from 4.4% in first wheel to 2.2% in the second (in EM calo ~20%)
  - ✓ 4 longitudinal sections; total depth $\sim 10\ \lambda_I$
  - ✓ e/h ~ 1.3-1.4 (non-compensating)
  - ✓ $\sigma(E)/E = 70\text{-}85\%/\sqrt{E} \oplus 5\%$



- FCal (Forward Calorimeter): $3.1 < |\eta| < 4.9$
  - ✓ 3 modules: FCal1 (Cu absorber, EM measurement) + FCal2 + FCal3 (W absorber, HAD)
  - ✓ Gap size: 250-375 um
    - Extreme particle and ion current in forward region
    - Standard 2 mm gap would cause LAr to boil!
    - narrow gaps reduce ionization current density
    - Sampling fraction << 1% : very coarse, but sufficient for jet/MET in forward region
  - ✓ Essential for ATLAS hermeticity to $|\eta|$~5

5.4

Semiconductor Calorimeters & Si technologies

Electron-hole pairs in silicon for calorimetry

- Electron-hole pair production
  - ✓ In a semiconductor (Si, Ge, GaAs), ionizing particles produce electron-hole pairs
  - ✓ Mean ionization energy: $\varepsilon_{Si} = 3.62$ eV/pair
  - ✓ **Fano factor: F ~ 0.1 for Si** (<< than scintillation or gas)
    - Intrinsic stochastic term potentially < 1% (if all pairs collected)
  - ✓ Bias voltage collects pairs: electrons drift to anode, holes to cathode

- Si pad/strip sensors for calorimetry
  - ✓ Thickness: 100-500 um
    - thin = small signal
    - thick = more radiation damage trapping
  - ✓ Signal:
    - ~80 electron-hole pairs per um of Si
    - ~3.2 fC per MIP in 300 um
    - Direct electrical signal

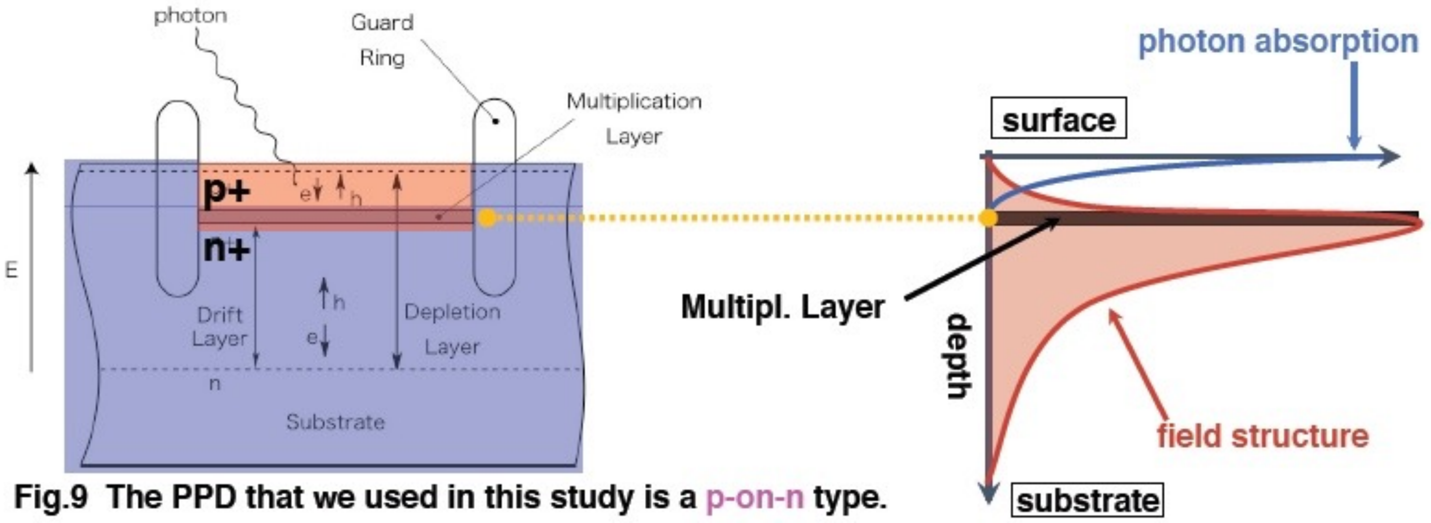
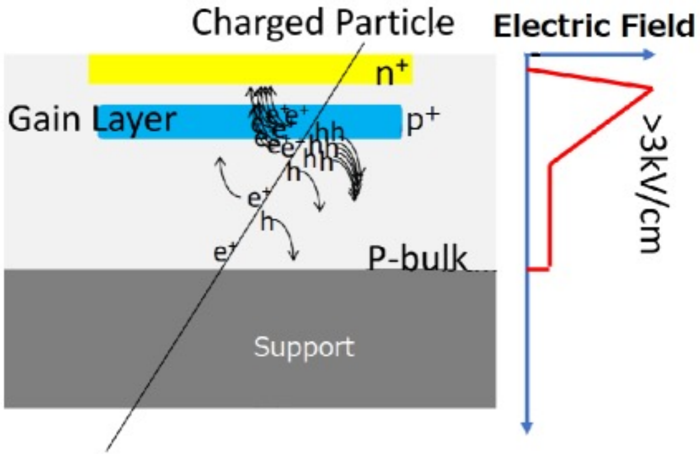


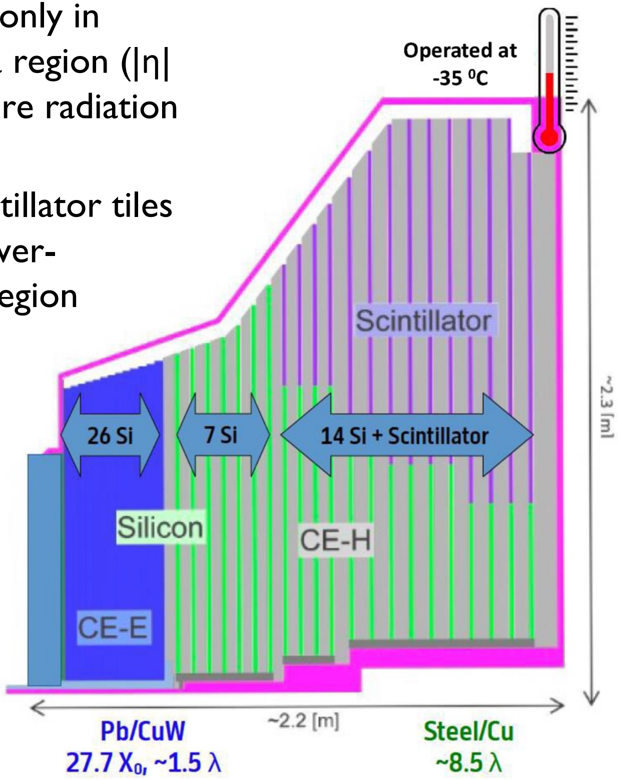
Fig.9 The PPD that we used in this study is a p-on-n type.

Electron-hole pairs in silicon for calorimetry

- Key advantages for (future) calorimeters
  - ✓ Fine lateral granularity: cells can be < 1 cm^2
    - Essential for particle flow
  - ✓ Radiation hardness (up to ~10^{15} n/cm^2 with cooling)
  - ✓ Precise timing: σ_t < 30 ps per hit achievable with LGAD (Low Gain Avalanche Detector) sensors
  - ✓ Compact: dead material mostly from PCB and mechanics, not from sensor



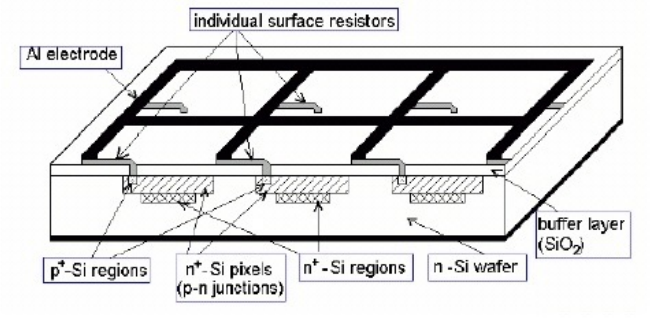
- Current limitation: cost!
  - ✓ e.g. CMS HGCAL uses Si sensors only in highest-eta region (|η| > 2.2) where radiation is severe
  - ✓ Plastic scintillator tiles used in lower-radiation region

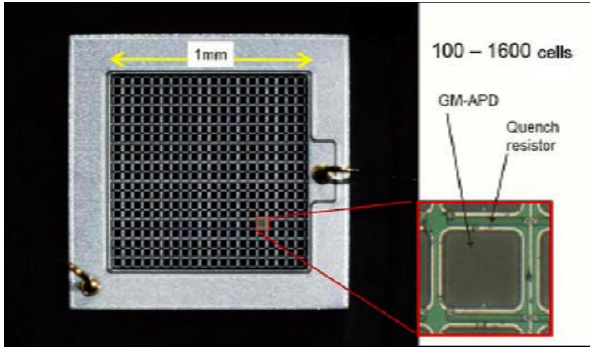


From APD to Silicon Photomultiplier (SiPM)

- Why not PMT or linear APD?
  - ✓ PMT: sensitive to magnetic fields (>1 mT), bulky, high voltage (~1 kV)
  - ✓ Linear APD (gain ~50–500): output proportional to deposited energy → cannot count single photons

- Key next step: Geiger-mode APD (G-APD)
  - ✓ Operate APD above breakdown voltage → single carrier triggers full avalanche (binary signal)
  - ✓ Quenching resistor (R ~ 1–10 MΩ) limits current → cell resets in $\tau \sim R \cdot C \sim 20$–500 ns
  - ✓ Gain: $A_i \sim C/q \times (V - V_b)$ → typical gain 10^5–10^6; overvoltage ~ 2 V above breakdown

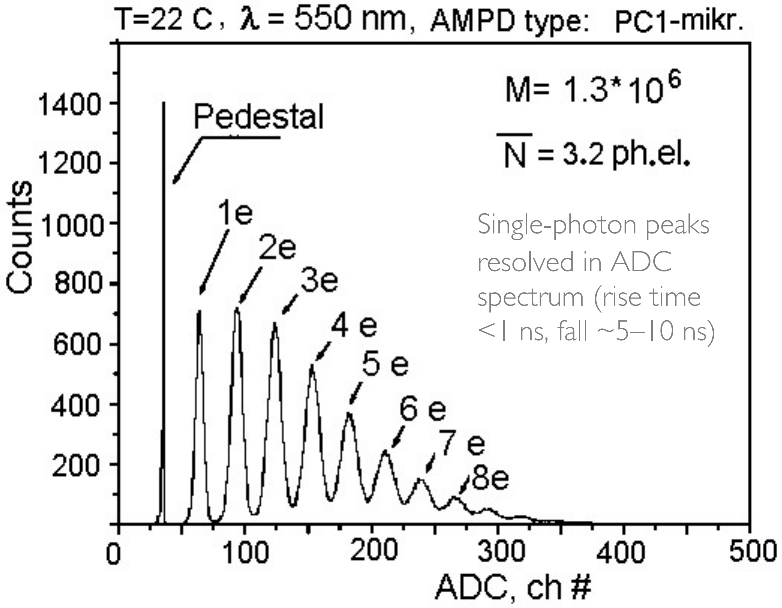




SiPM = array of G-APD microcells in parallel

Pixel size: ~20–30 µm; density: 100–1000 pixels/mm²; single signal line (all in parallel)

Output = Sum pixel signals → analog sum, but each cell is binary → effectively photon counter



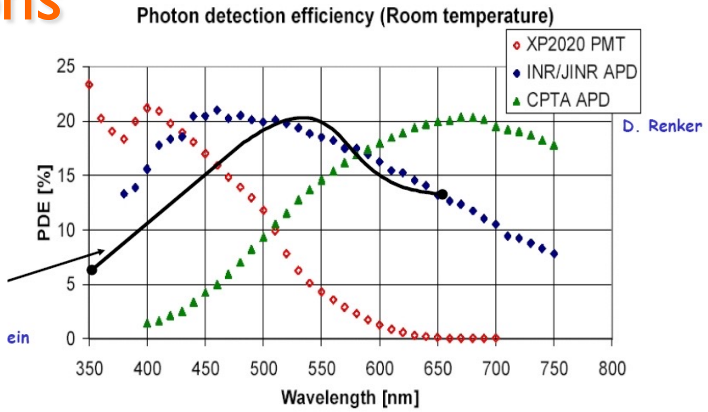
Single-photon peaks resolved in ADC spectrum (rise time <1 ns, fall ~5–10 ns)

SiPM: key properties and HEP applications

- Photon Detection Efficiency (PDE)
  - ✓ PDE = QE × fill factor × P_{ei}^{geo} → typically 20–40%
    - strongly wavelength-dependent
  - ✓ Match SiPM peak response to scintillator emission wavelength
    - blue ~ 400 nm for LYSO
- Noise sources (intrinsic limitations)
  - ✓ Dark count rate: 100 kHz–10 MHz/mm² at 25° C (thermal + tunneling)
    - Reducible by cooling
  - ✓ Optical crosstalk: ~3 photons emitted per 10^5 carriers
    - suppressed by inter-pixel trenches (<10%)
  - ✓ Afterpulses: trapped carriers released over ~100s ns after breakdown
    - fake extra signal
- Gain and PDE stability → must control V and T
  - ✓ Voltage: $\Delta Q/\Delta V \sim 7\%/100$ mV; Temperature: $\Delta Q/\Delta T \sim -4.5\%/K$
    - active stabilisation mandatory!
  - ✓ Radiation damage: dark current ∝ neutron fluence (cooling needed)

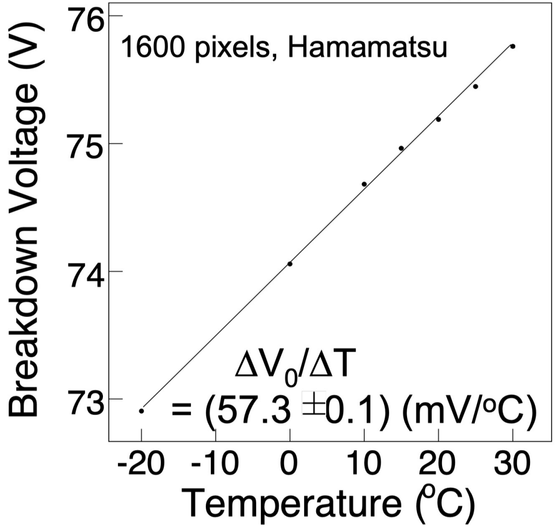
HEP calorimetry applications

CMS HCAL Phase-2: HPD → SiPM in HB/HE (gain stability in B field)
CMS ECAL Phase-2: SiPM option for barrel with LYSO or upgraded $PbWO_4$
CMS HGCAL: SiPM-on-tile scintillator in lower-radiation region



D. Renker

S. Uozumi, Shinshu University, Japan



5.5

Focus on HAD Calorimeter Technologies

Reminder: hadronic calorimeters are always sampling

- Key points
  - ✓ Homogeneous HCAL at collider scale is impossible (cost + size)
  - ✓ HCAL always sampling
  - ✓ $\lambda_{int} >> X_0$: HCAL ~10x larger than ECAL.

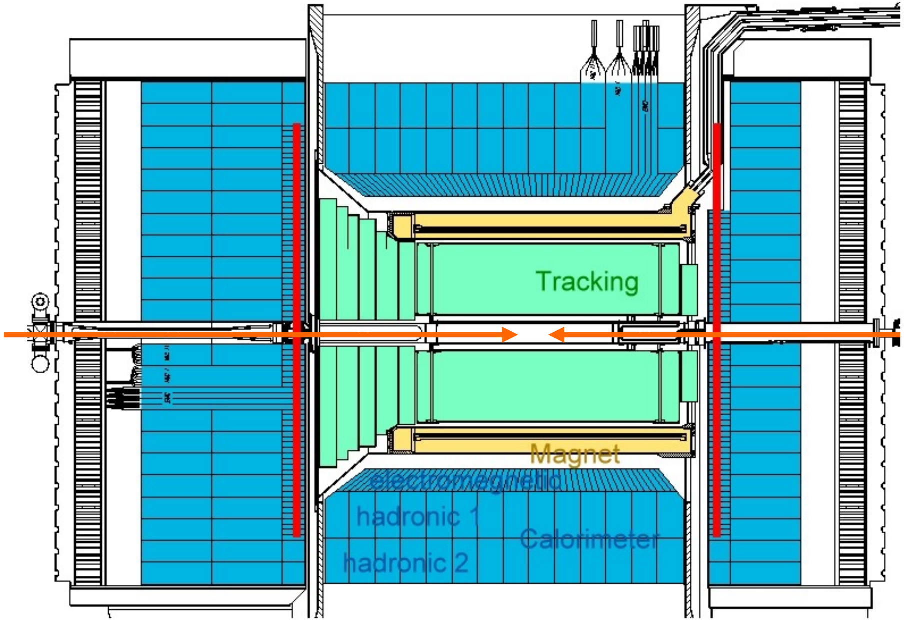
- Signal-type in active sections: HCALs use all four mechanisms just surveyed!

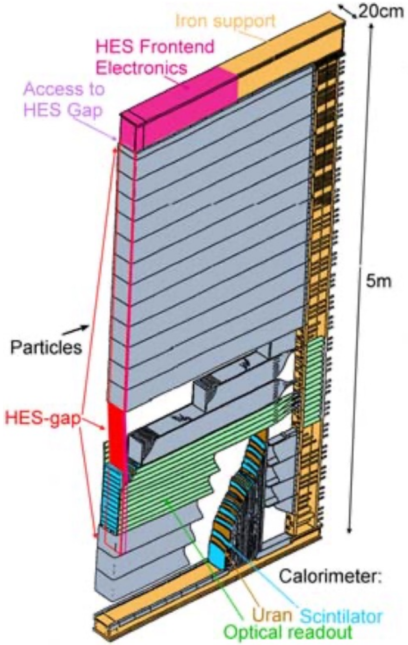
Signal	HCAL	Detector
SCINTILLATION	ATLAS TileCal, CMS HB/HE	plastic scintillator tiles
IONIZATION	ATLAS HEC, ATLAS FCal EM/HAD	LAr gaps, same as EM
CHERENKOV	CMS HF	quartz fibers for radiation hardness in forward region
ELECTRON-HOLE PAIRS	CMS HGCAL (future)	Si sensors (+ scintillation SiPM-tile)

ZEUS: compensation proof-of-concept

- ZEUS at HERA (*Hadron Elektron Ring Anlage* – ep collider): depleted uranium absorber + plastic scintillator compensating calorimeter
  - ✓ e/h = 1.00 ± 0.02 → proof that compensation is achievable
  - ✓ $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons (purely stochastic, no constant term!)

Absorber layer (^{238}U) : 3.3 mm
Scintillator layer: 2.6 mm thick
Readout 2 PMTs per cell; imbalance gives position
Dead material in barrel region: solenoid ($1X_0$; $0.04\ \lambda_{int}$)

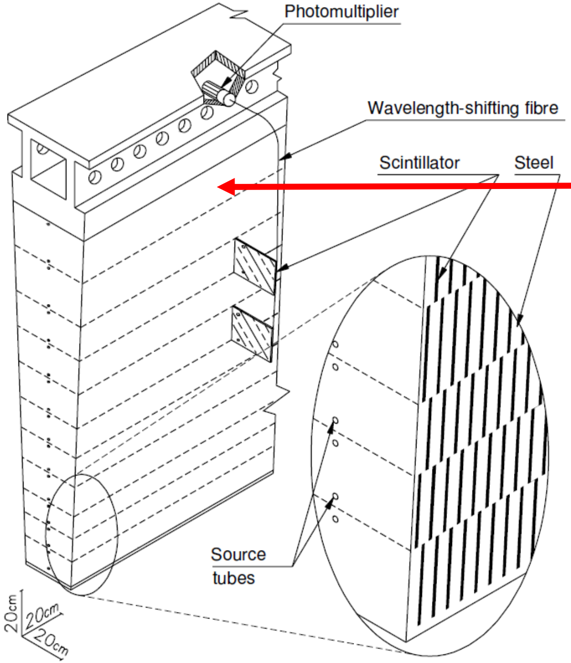


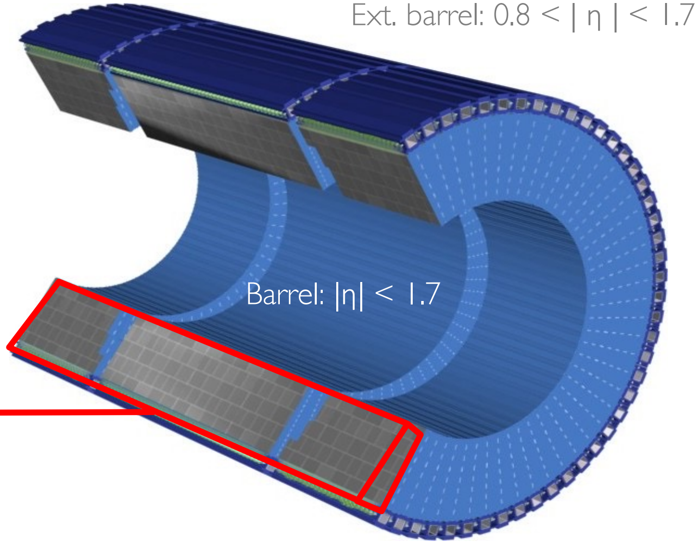


ATLAS TileCal: scintillation signal in a sampling HCAL

- Scintillator: plastic scintillating tiles
  - ✓ polystyrene + PPO + POPOP dopants
- Absorber: iron (steel) plates interleaved with scintillating tiles
- Sampling fraction ~ 3%

- Tile orientation trick:
  - ✓ Tiles are perpendicular to beam axis (not parallel)
  - ✓ This allows WLS fibers to collect light from both tile faces and route it radially outward to PMTs
  - ✓ Result: compact geometry, no dead zones in phi, uniform response
- 3 radial depth samplings
  - ✓ A (1.5 λ_{int})
  - ✓ BC (4.1 λ_{int})
  - ✓ D (1.8 λ_{int})
  - ✓ Total depth: ~ 9.7 λ_{int} (barrel)



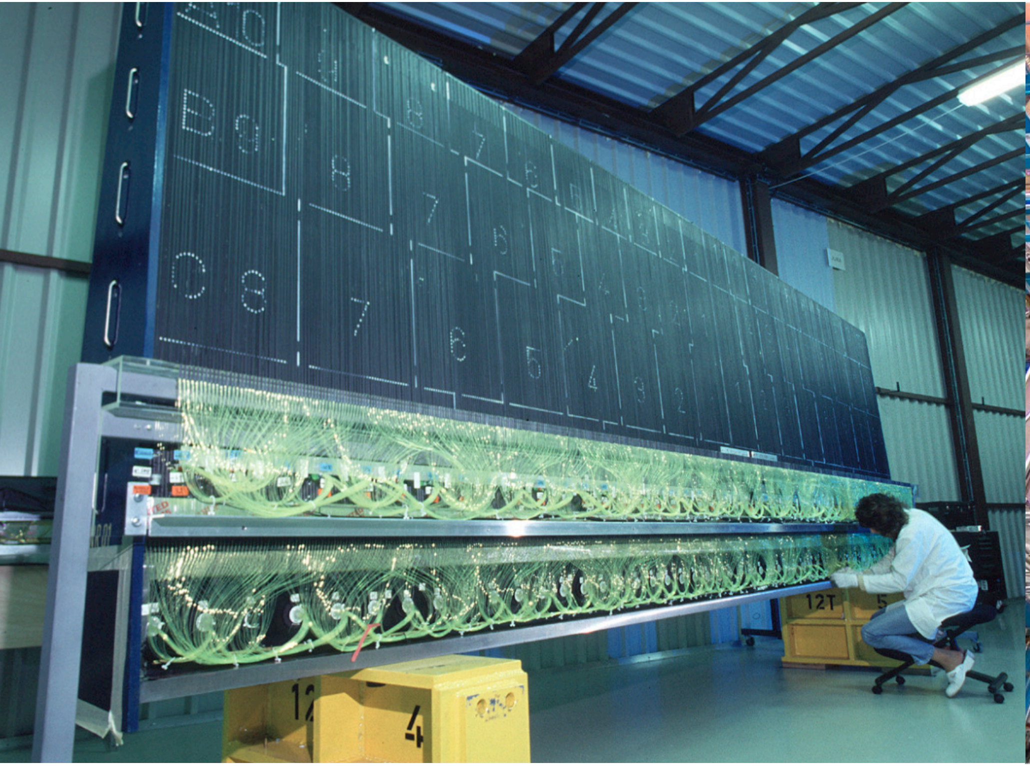


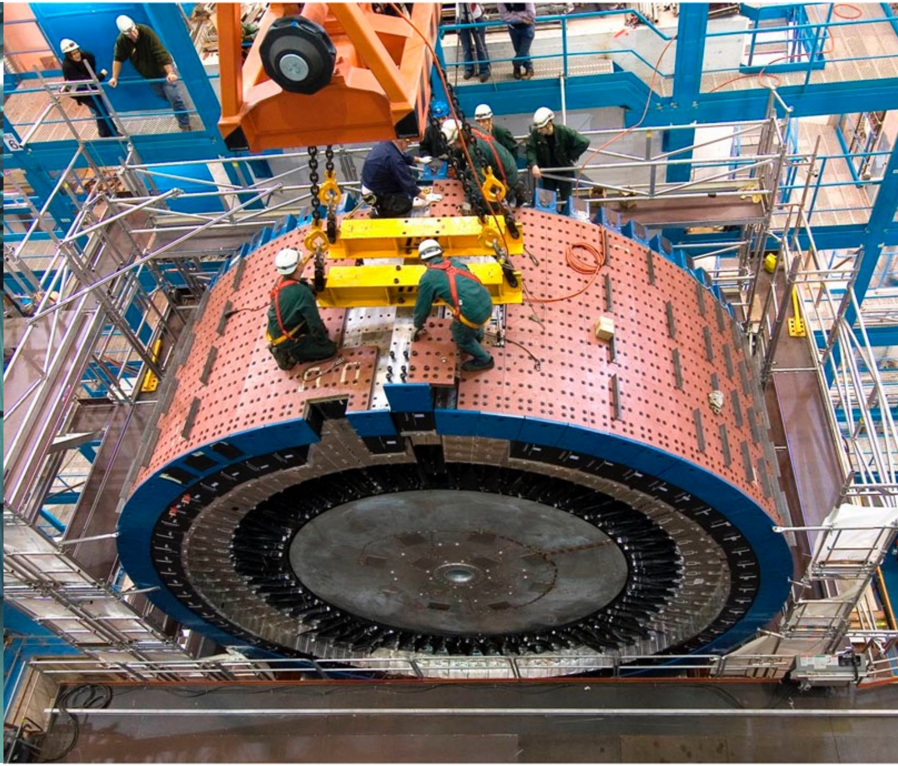
$\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$

e/h ~ 1.37 (non-compensating)

Why iron? Non-magnetic? Cost? λ_{int} vs X0?

ATLAS TileCal





ATLAS TileCal calibration

ATLAS Tile calorimeter is equipped with different calibration and monitoring systems for different components of signal formation

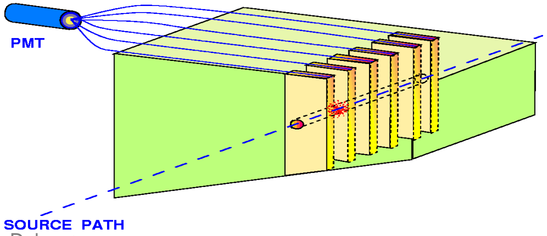
Tiles and fibers → **PMT and optics** → **Electronics**

Cesium

Laser

Charge injection

- A Ce^{137} γ source is transported by hydraulic systems to excite every scintillator tile
- Goal: check quality and uniformity of optical response to known energy deposit



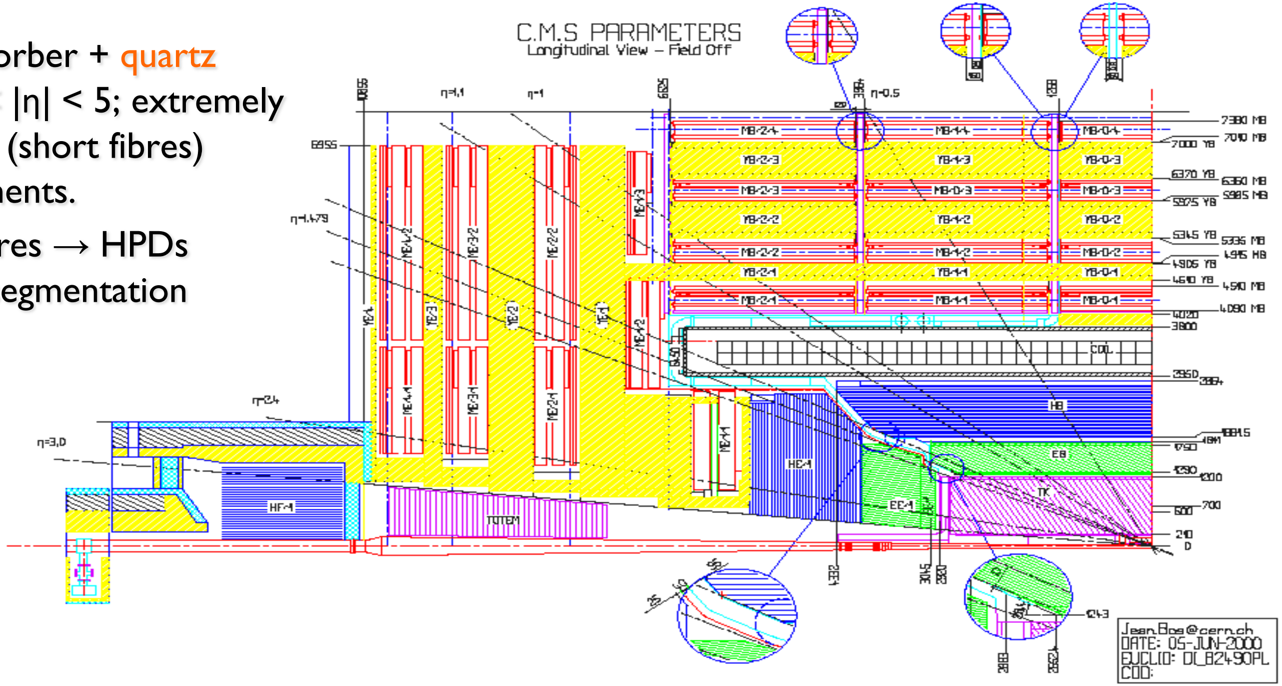
- Lasers monitor PMT stability at a level of 0.5%
- PMT gain corrected by changing HV

- Inject charge from high precision voltage source into calibration capacitors to calibrate and monitor pulse readout electronics at O(1%) level

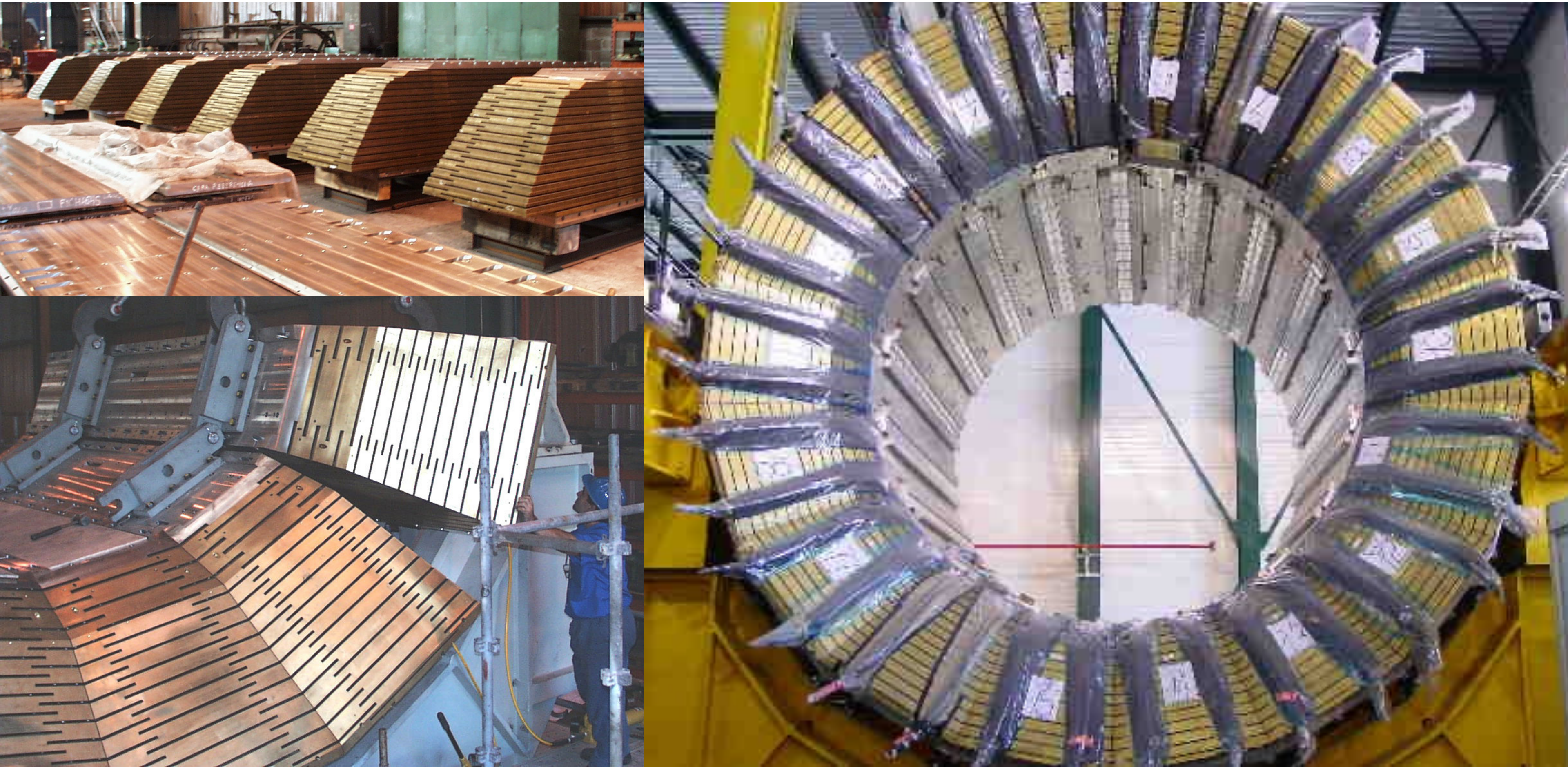
Monitor the evolution of the response ~1% level
Intercalibration of the cell response ~2-3%

CMS HCAL (today…)

- **HB (Hadron Barrel):** brass absorber + plastic scintillator tiles; $|\eta| < 1.3$; 70/30 brass-scintillator by volume
  - ✓ ~5.8 λ_{int} at $\eta=0$ (thin — constrained by solenoid).
- **HE (Hadron Endcap):** brass/scintillator; $1.3 < |\eta| < 3$; ~10 λ_{int}
- **HO (Hadron Outer):** additional scintillator layer outside solenoid at $|\eta| < 1.26$ to catch late-starting showers; uses return yoke as extra absorber.
- **HF (Hadron Forward):** iron absorber + quartz fibres (Cherenkov readout); $3 < |\eta| < 5$; extremely radiation-hard; distinguishes EM (short fibres) from HAD (long fibres) components.
- Readout: wavelength-shifting fibres → HPDs (barrel/endcap) or PMTs (HF); segmentation $\Delta\eta\times\Delta\phi \sim 0.087\times0.087$ (barrel).
- Note: HB+HO together give ~11 λ_{int}, comparable to ATLAS TileCal



CMS HB HCAL



CMS HF: Cherenkov-based forward calorimeter

- HF in the CMS HCAL system:
  - ✓ 4th sub-system (after HB, HE, HO): covers 3 < |eta| < 5
  - ✓ Completes CMS hermeticity to |eta| ~ 5 for MET calculation
  - ✓ Why NOT scintillator? Radiation dose too high for any organic material at |eta| > 3
  - ✓ Cherenkov readout chosen for radiation hardness (quartz fibers survive 10^8 Gy/year)

- HF vs rest of CMS HCAL:
  - ✓ HB/HE/HO: brass + plastic scintillator; sigma/E ~ 65%/sqrt(E) (+) 5%
  - ✓ HF: iron + quartz fibers (Cherenkov); sigma/E ~ 100%/sqrt(E) (+) 5%
  - ✓ HF is coarser: acceptable since forward jets have lower pT threshold for physics

- Why does CMS HCAL use two different signal mechanisms?
  - ✓ A physics-driven choice: best signal type for each radiation environment!

ATLAS HEC and FCal as HCAL sub-systems

- ATLAS HCAL coverage
  - ✓ TileCal (|eta| < 1.7): scintillation; iron absorber; radially outside solenoid
  - ✓ HEC (1.5 < |eta| < 3.2): ionization in LAr; copper absorber; inside end-cap cryostat
  - ✓ FCal (3.1 < |eta| < 4.9): ionization in LAr; Cu (EM) + W (HAD) absorber; very forward

- The fact that TileCal uses scintillation while HEC/FCal use ionization not an inconsistency, again a physics-driven choice:
  - ✓ TileCal is far from the interaction point → scintillator + PMT viable (low radiation)
  - ✓ HEC/FCal share the LAr cryostat with the ATLAS EM endcap → ionization natural extension
  - ✓ FCal needs radiation-hard narrow-gap LAr → uniquely suitable for extreme forward

  - ✓ *Additional benefit: HEC, FCal, and EM endcap share the same signal-chain electronics and common calibration*

ATLAS vs CMS hadronic calorimeters: comparison

- Both experiments made similar fundamental choices for the central HCAL (scintillator tiles + steel absorber) despite very different overall detector geometries.

	ATLAS TileCal	CMS HB+HO
σ/E	$50\%/\sqrt{E} \oplus 3\%$	$65\%/\sqrt{E} \oplus 5\%$
e/h	1.37	1.39
Depth	9.7 λ_{int}	11 λ_{int} combined, but HB alone only ~5.8 λ_{int} HO installed to compensate

- Key difference: ATLAS solenoid before HCAL → more room for HCAL depth;
- CMS solenoid encloses ECAL+HCAL → HB itself is thin (containment issue), needs HO.

Unified EM and HAD technology comparison

- All signal mechanisms deployed in HEP detectors: choice driven by radiation environment, signal speed, and cost.

Mechanism	EM Example	HAD Example	σ/E benchmark	Key Advantage	Key Limitation
SCINTILLATION	CMS ECAL ($PbWO_4$); L3/LEP (BGO)	ATLAS TileCal; CMS HB/HE (plastic tiles)	EM: ~3%/√E ⊕ 0.5% HAD: ~50–65%/√E ⊕ 3–5%	Homogeneous EM → no sampling fluctuations; versatile active medium	Radiation damage (LY loss); T-sensitive (−2%/°C for $PbWO_4$)
CHERENKOV	Lead glass (OPAL, NOMAD); PbF_2 (future, Crilin)	CMS HF (quartz fibres, |η|>3)	EM: ~3%/√E HAD: ~100%/√E ⊕ 5%	Ultra-fast (τ~0); extreme radiation hardness (quartz)	Very low yield (~10^4× below scint.); poor HAD resolution
IONIZATION	NA48 LKr; ATLAS LAr EM accordion	ATLAS HEC (Cu); ATLAS FCal (Cu+W)	EM: ~10%/√E ⊕ 0.3% HAD: ~70–85%/√E ⊕ 5%	Intrinsically stable, hermetic; EM+HAD share same cryostat and signal chain	Cryogenic system (cost, complexity); slow signal (~400 ns drift)
SILICON (e-h pairs)	CMS HGCAL Si sensors (|η|>2.2, Phase-2)	CMS HGCAL (Si + SiPM-on-tile)	Target: few%/√E (design)	Fine granularity (<1 cm^2); σ_t<30 ps; radiation hard to ~$10^{1}5$ n/cm^2	Cost (Si only at high η); Phase-2 technology, not yet tested at full scale

What did we learn today?

- **Week 3 (Technology)**
  - ✓ Lecture 5: Calorimeter Technologies
    - *5.1 Cherenkov calorimeters*
      - *Cherenkov light is threshold-based and ultra-fast but ~10^4× lower yield than scintillation; CMS HF uses quartz fibres for radiation-hard forward calorimetry.*
    - *5.2 Scintillation calorimeters*
      - *Crystal evolution NaI→BGO→CsI→$PbWO_4$ trades light yield for speed and radiation hardness; CMS ECAL (75848 $PbWO_4$ + APD) achieves sub-percent constant term for $H\to\gamma\gamma$.*
    - *5.3 Ionization calorimeters*
      - *Noble liquids (LAr/LKr) provide an intrinsically stable ionization signal; ATLAS accordion eliminates dead zones; HEC and FCal extend the same principle to HAD endcap and forward.*
    - *5.4 Semiconductor calorimeters & Si technologies*
      - *e-h pairs in Si give a direct signal with fine granularity and $\sigma_t<30$ ps; SiPM enables photon counting in B-field; CMS HGCAL demonstrates Si calorimetry at collider scale.*
    - *5.5 Focus on HAD calorimeter technologies*
      - *HCAL is always sampling ($\lambda_I \gg X_0$ means homogeneous HCAL is impossible); ATLAS TileCal and CMS HB both use scintillator+steel; CMS HF uses Cherenkov in the very forward region.*