Calorimetry Lecture 2

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HCPSS 2024
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Outline

- Reminders
- LHC experience
  - CMS ECAL : APD spikes and endcap radiation effects
  - CMS HCAL : Calibration and (insidious) photosensor aging
- HL-LHC : CMS HGCAL
  - Readout challenges
- Future Higgs Factory : Dual Readout Calorimetry

Reminder : EM vs. Hadronic shower

- EM showers are compact, regular, and homogeneous

$$X_0 \propto (n\sigma_{\text{radiative}})^{-1} \propto \frac{A}{Z^2}$$

- Hadronic showers are extended, irregular, composed of EM and non-EM components, and lose energy to soft neutrals and nuclear break-up

$$\lambda_{\text{int}} \propto (n\sigma_{\text{pN}})^{-1} \propto A^{\frac{1}{3}}$$

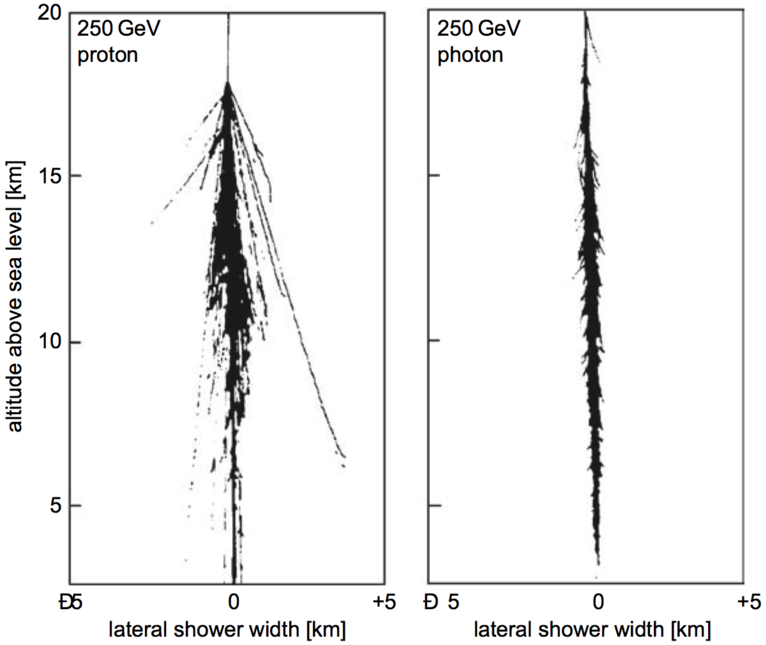
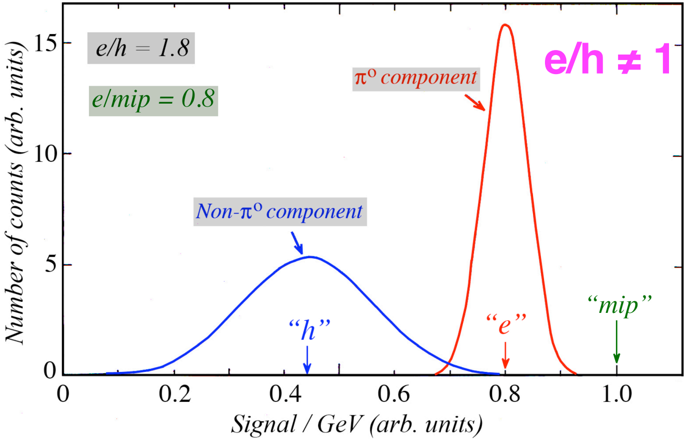
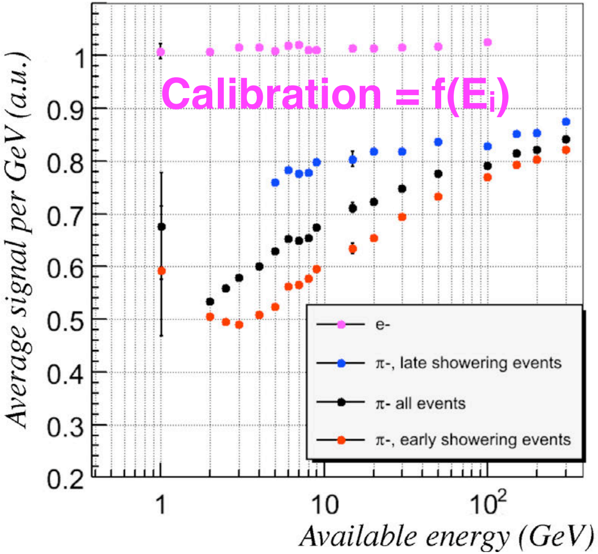


Fig. 8.16. Monte Carlo simulations of the different development of hadronic and electromagnetic cascades in the Earth's atmosphere, induced by 250 GeV protons and photons [51].

Reminder : Challenges of hadronic calorimetry

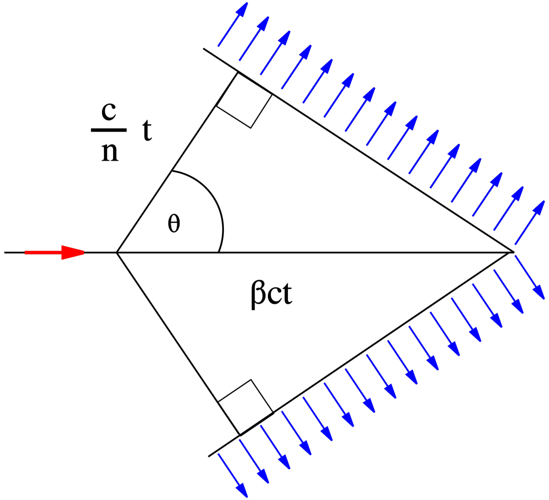
- Large difference in EM and non-EM response (e/h ≠ 1) brings challenges:
  - (e/h ≠ 1) + dependence of **average f_{EM}** on incident energy ➔ calibration depends on incident energy
  - (e/h ≠ 1) + **f_{EM} fluctuations** ➔ degraded resolution





Reminder : Cerenkov radiation

- Cherenkov radiation produced when charged particle travels through medium (with index of refraction n) at faster than local speed of light
  - Often used for PID in flavor physics: measure both velocity + momentum to obtain mass.
- For calorimetry, generally only secondary electrons are sufficiently relativistic to produce Cerenkov
  - For quartz (n=1.485), minimum KE(e) = 0.1 MeV and minimum KE(p) = 220 MeV.
  - Therefore : Cerenkov light dominated by EM component in hadronic showers.



$$\cos\theta = \frac{c}{v\,n}$$

Practical challenges : Radiation and Pileup

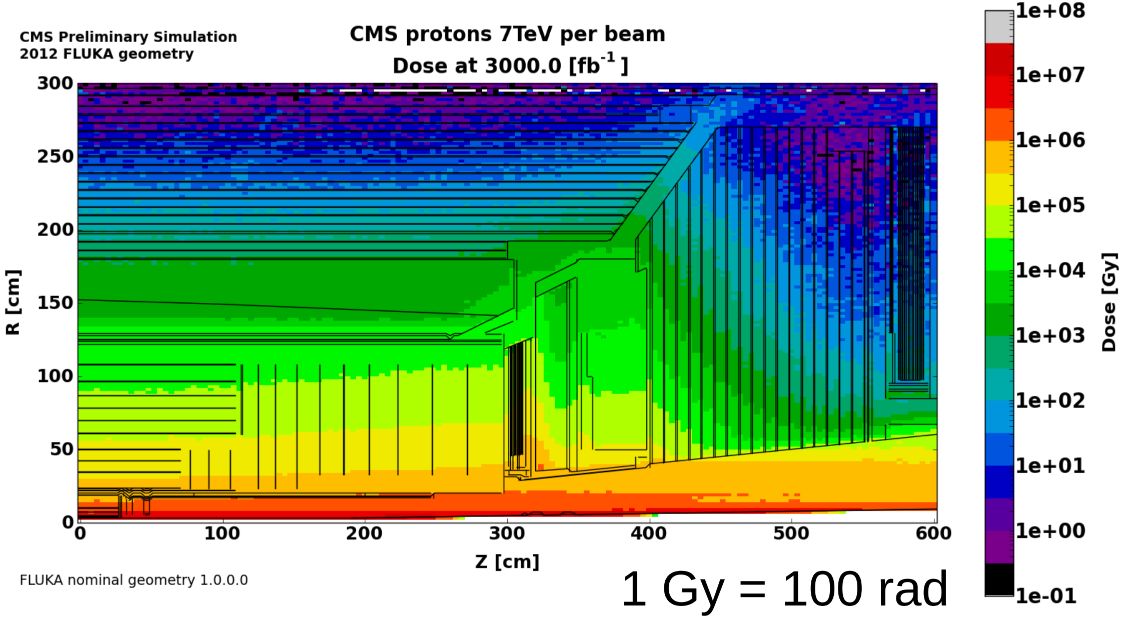
Radiation

Cumulative damage:

- Total ionizing dose (TID)
    - CMOS electronics
    - Scintillator
- Displacement damage from non-ionizing energy loss (NIEL) - silicon sensors

Transient effects:

- Single event effects (SEE) impact operation of CMOS electronics and other components



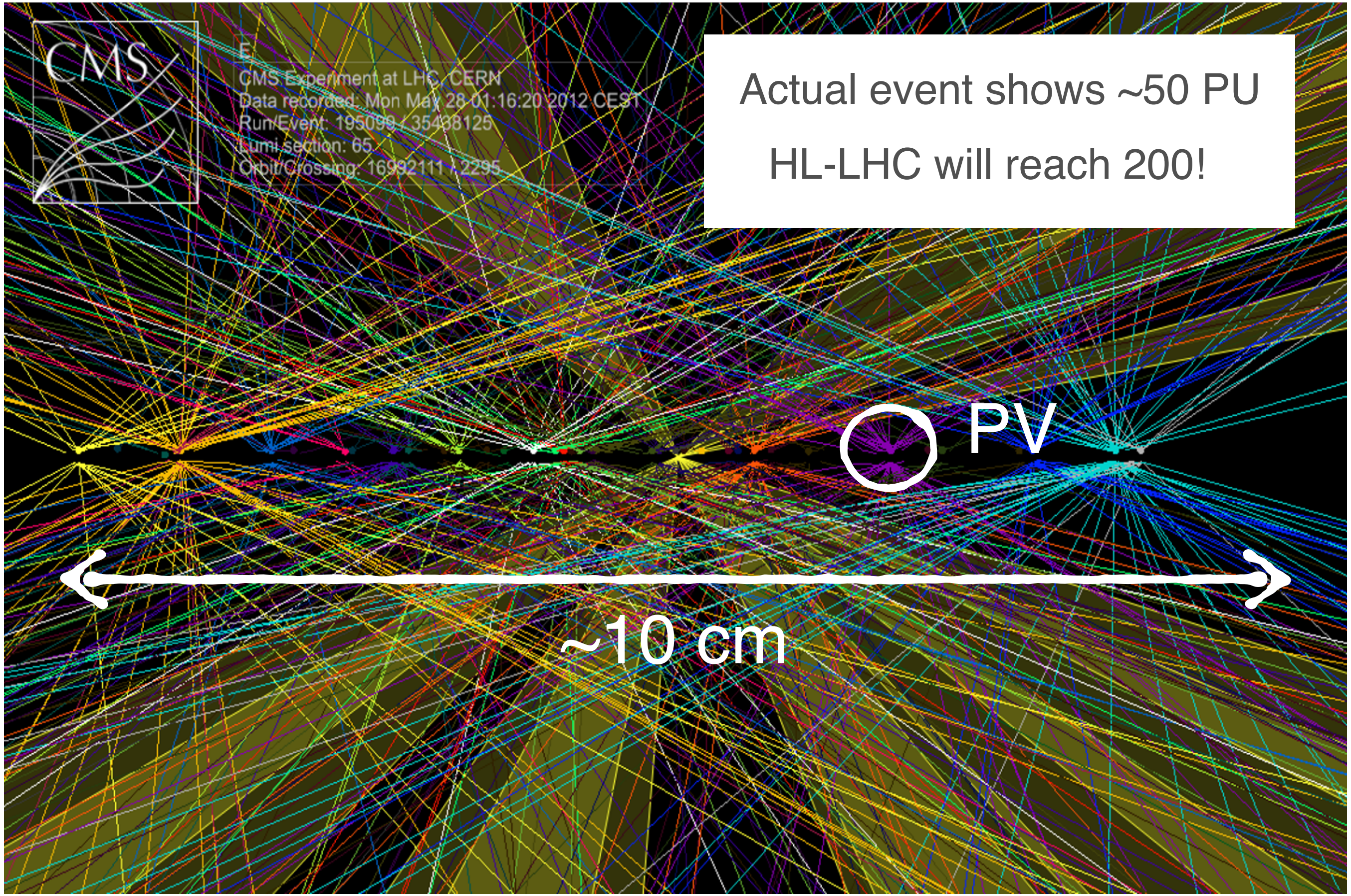
1 Gy = 100 rad

HL-LHC calorimeters:

- TID = 200 Mrad
- NIEL = 10^{16} 1MeV-eq neutrons / cm^{-2}

Pileup

- Pileup : multiple p-p collisions occurring every LHC bunch crossing.
- Remove PU tracks by selecting one primary vertex (PV), but …
- Can’t remove neutrals
- At HL-LHC, vertices will overlap

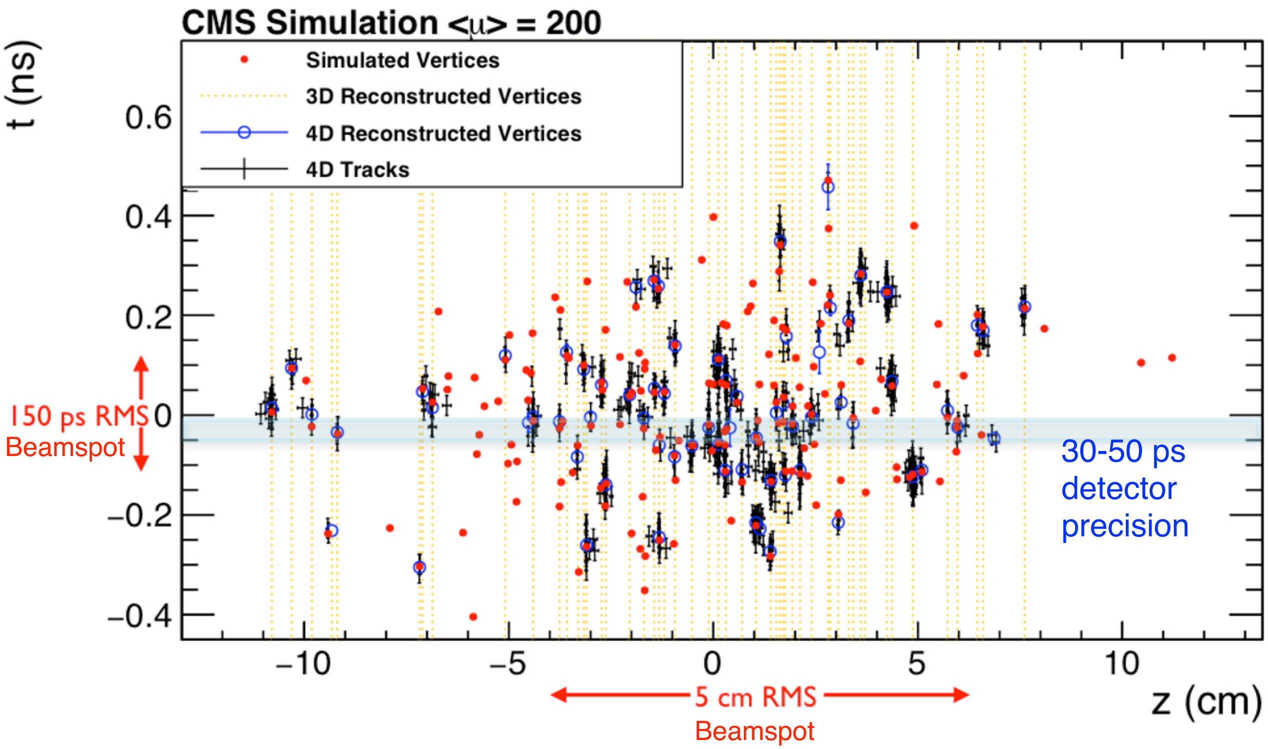


Actual event shows ~50 PU

HL-LHC will reach 200!

Pileup

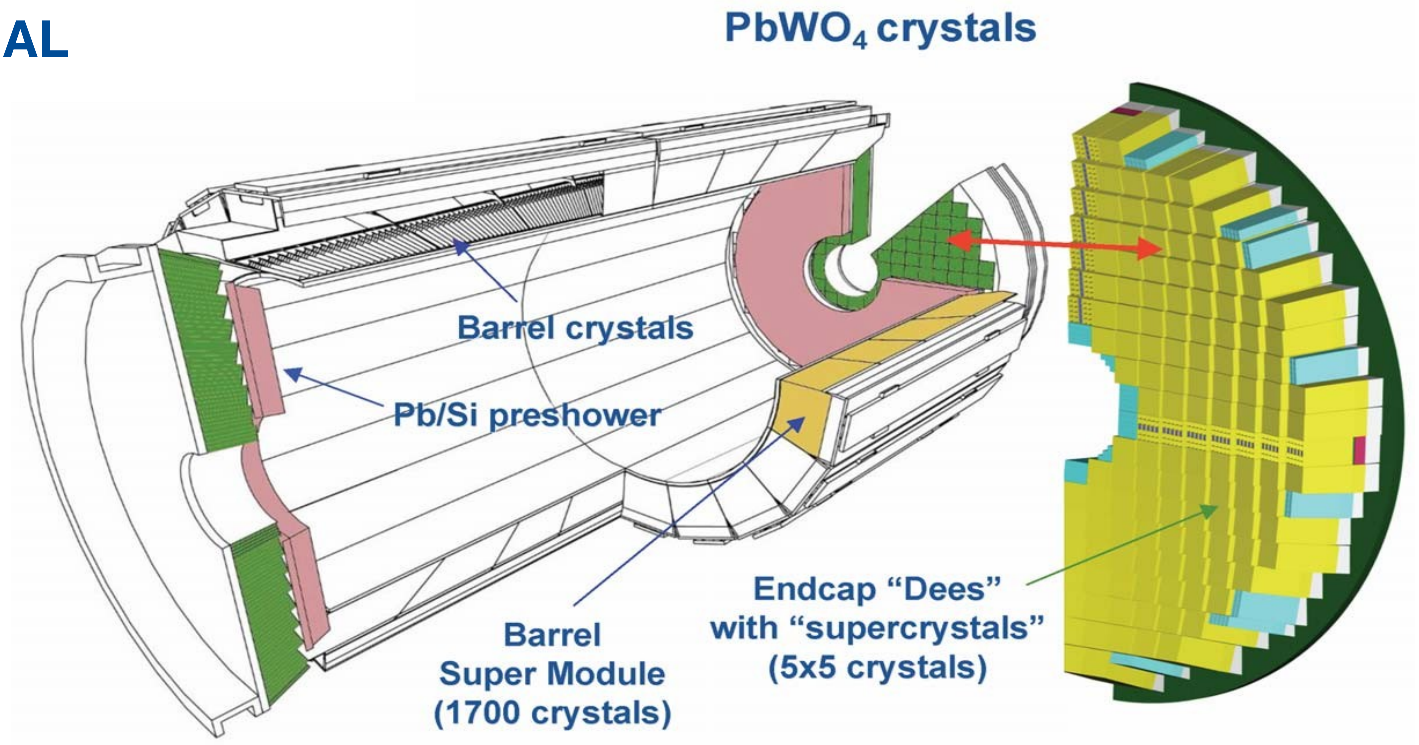
- Use precision timing (~30 ps resolution) to remove tracks **and neutral deposits** not in-time with PV



30-50 ps detector precision

Practical experience : CMS ECAL and HCAL endcap

CMS ECAL

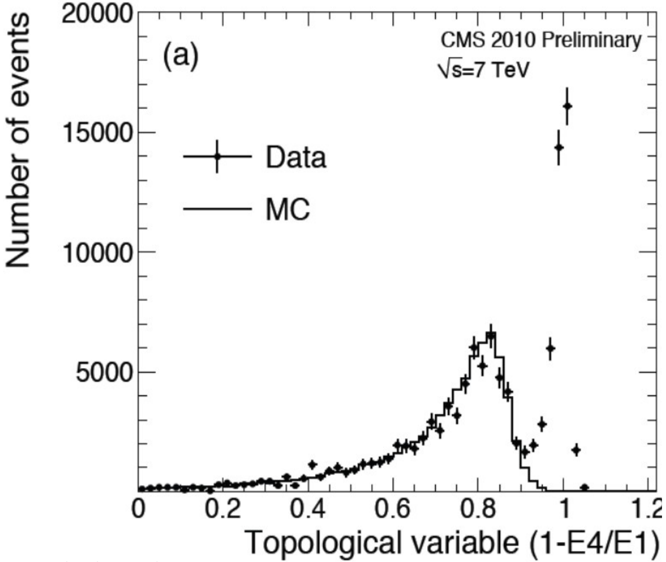


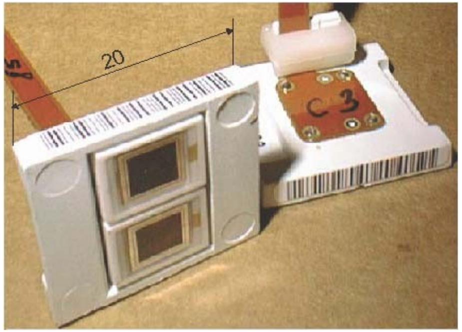
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm^3)

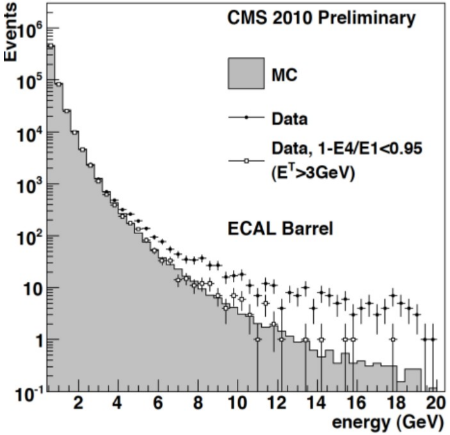
EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm^3)

CMS ECAL APD Spikes

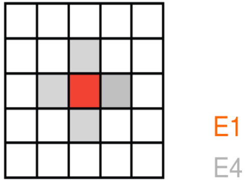
- High energy hadrons interacting in epoxy that binds Avalanche Photodiode sensors to each ECAL crystal eject highly ionizing particles that produce large pulses in APD.
- Identify and reject with unphysical behavior for “Swiss Cross” topological variable.







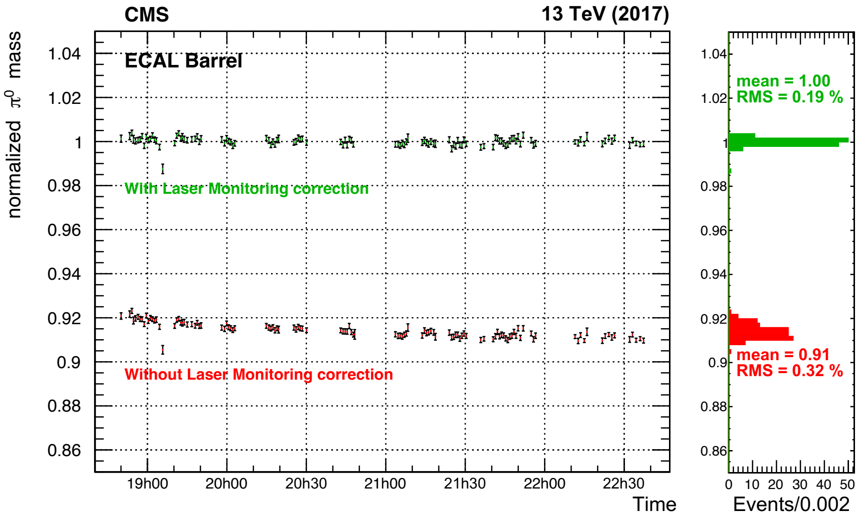
Trigger tower 5 x 5 crystals

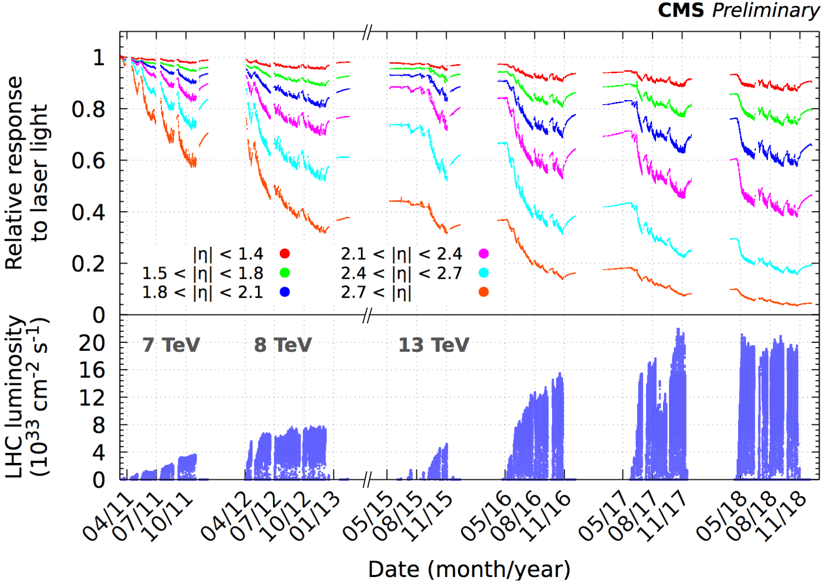


Topological variable: 1 – E4/E1

CMS ECAL Crystal Transparency

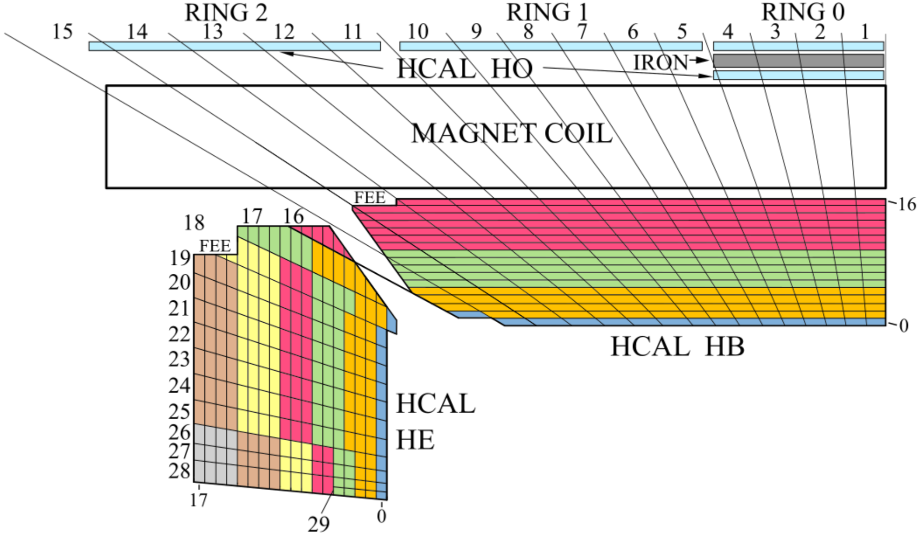
- PbWO4 crystals are darkened by high TID
- Laser calibration during orbit gap + dedicated π^0➔γγ data stream provide real-time measurement and correction
- Response loss is ~1% every 3-4 hours in ECAL barrel; response partially recovers with no beam

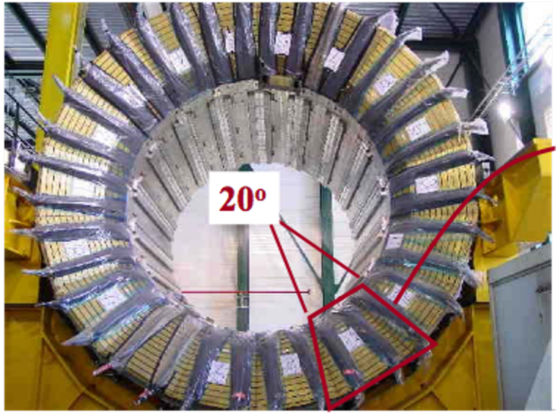


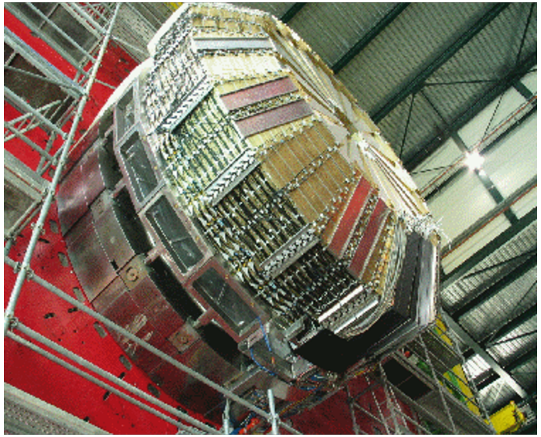


CMS HCAL

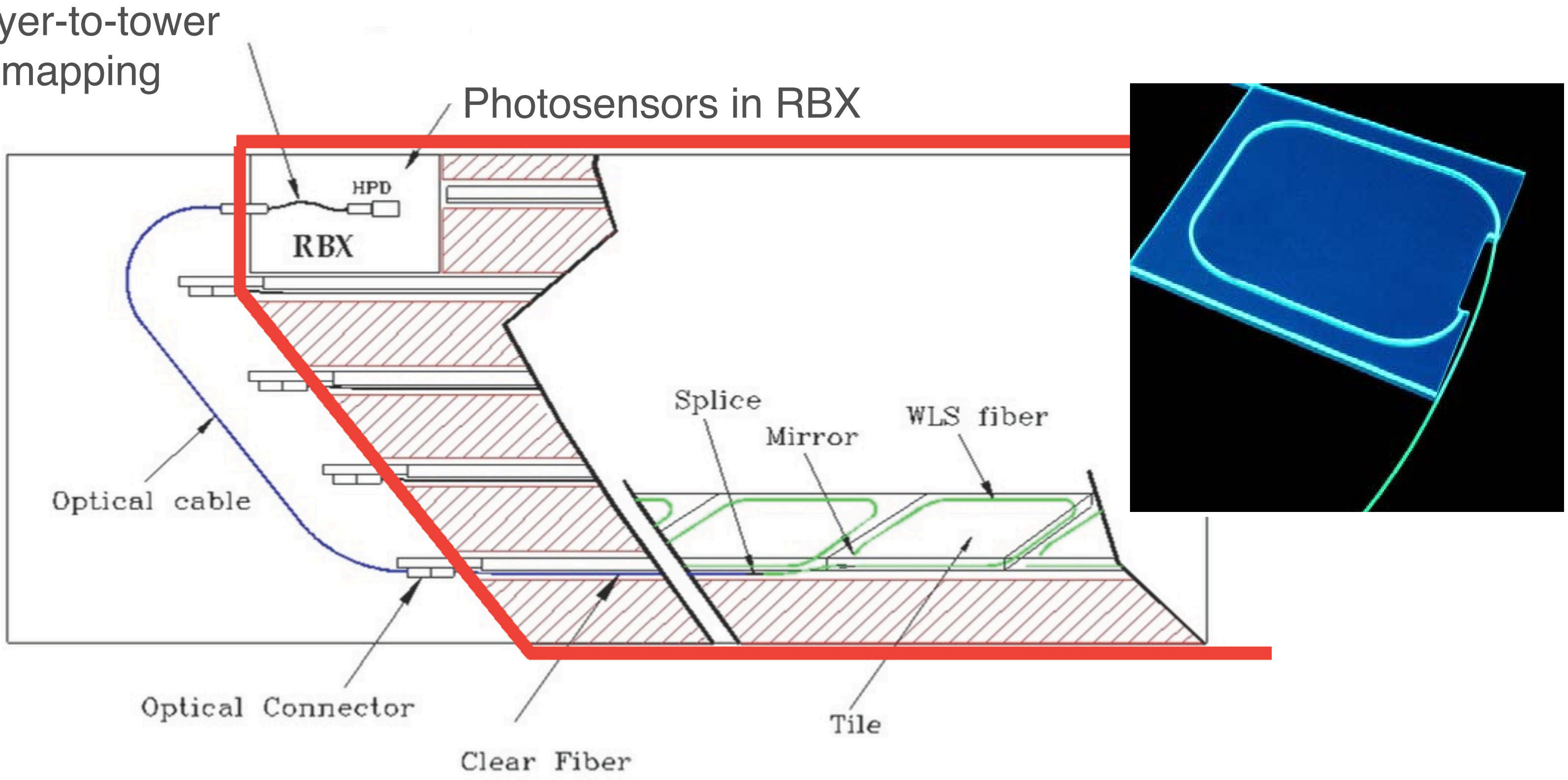
- 17 layer sampling calorimeter : brass (5-8 cm) + plastic scintillator (4mm) + SiPM readout
- Barrel: |η|<1.3, 5.8 λ_{int}, 9216 channels
- Endcaps 1.3<|η|<3, 10 λ_{int}, 6912 channels





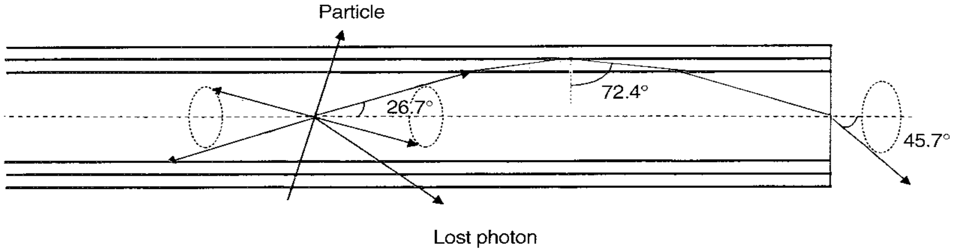


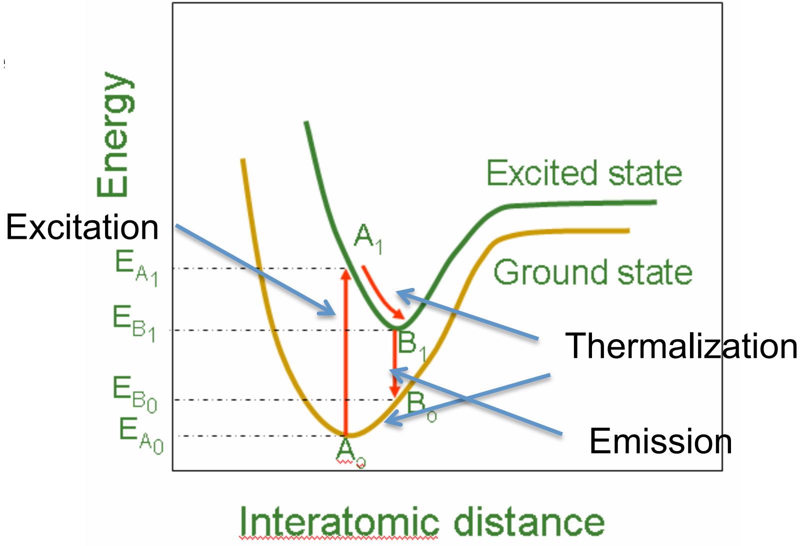
CMS HCAL light path



CMS HCAL wave length shifting

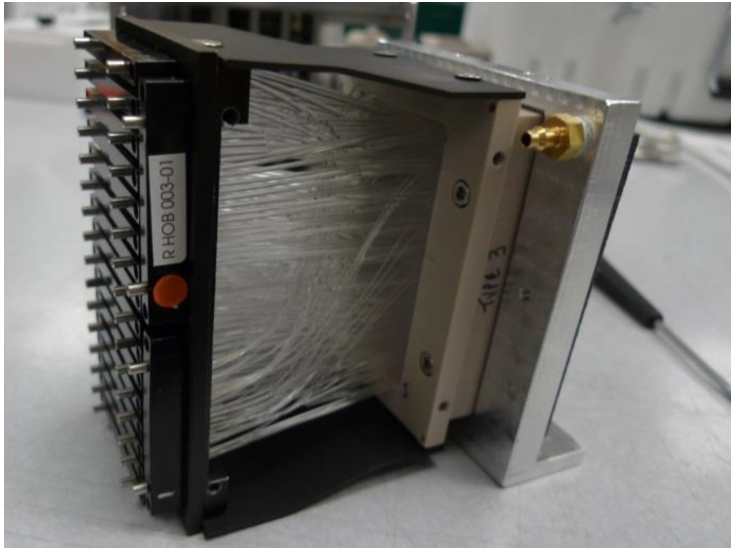
- Scintillation light is emitted isotropically in HCAL tile.
- How do we get it out to the photosensor?
- Optical fiber, but any light that can enter the fiber will also exit the fiber and be lost?
- Wavelength shifting fiber absorbs light internally and re-emits isotropically so that ~5% is captured through total internal reflection.
- Wavelength shifting results from Stokes shift



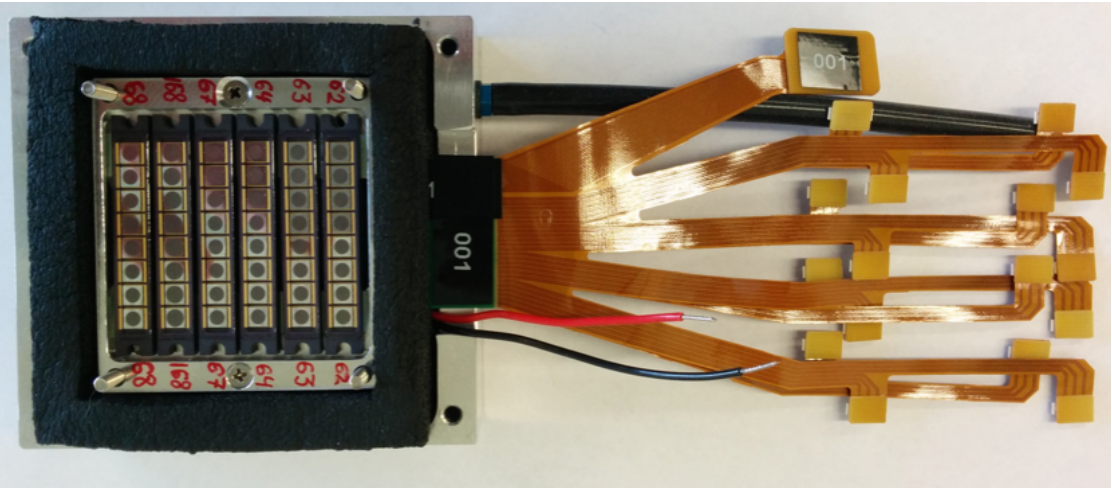


CMS HCAL light path

- Optical Decoder Unit re-maps light from layers into towers on periphery of detector.



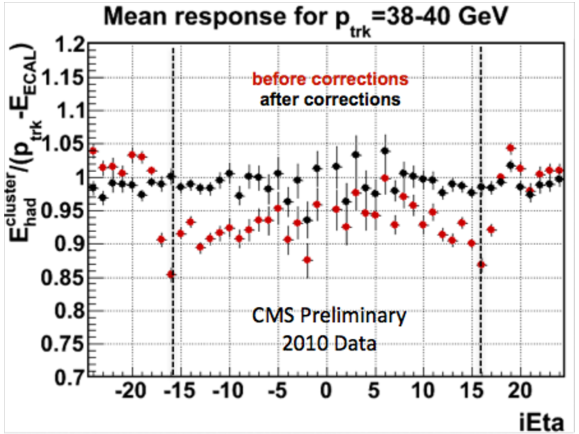
- Photosensors (SiPMs) connect to ODU and convert light into analog electrical signal, which is then digitized by front-end ASIC

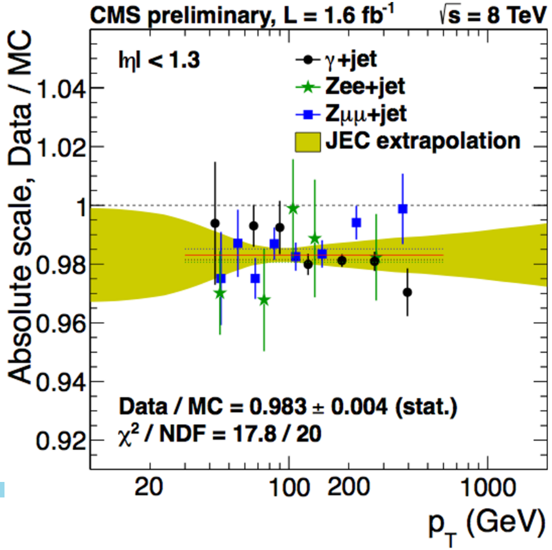


Calibration : CMS HCAL (e.g.)

- Need to **redundantly** understand full chain (**scintillator ➔ optical fibers ➔ photosensors ➔ electronics**) and **each component** of chain.
- Calibration systems not guaranteed to be stable!

- **Test beam** ➔ full chain
- **Cs137 source** routed to each scintillator tile ➔ full chain
- Calibration systems
  - On-detector **LED** ➔ photosensors
  - **Laser**-to-SiPM ➔ photosensors
  - **Laser**-to-scintillator ➔ full chain
  - Internal **charge injection** ➔ electronics
- With data
  - **Muons** ➔ channel-to-channel leveling
  - **Isolated charged pions** ➔ hadronic response
  - **Z+jet, γ+jet** ➔ jet response vs. energy, η, and p_T





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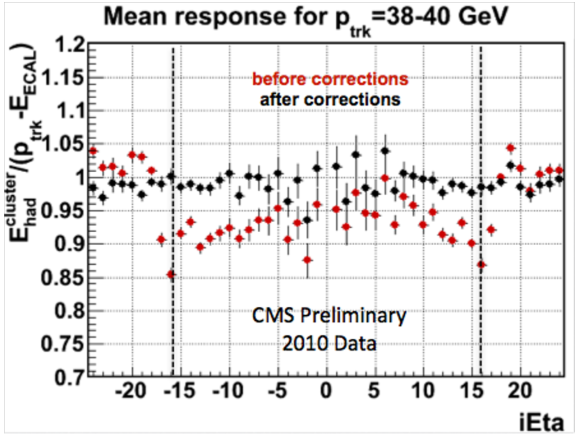
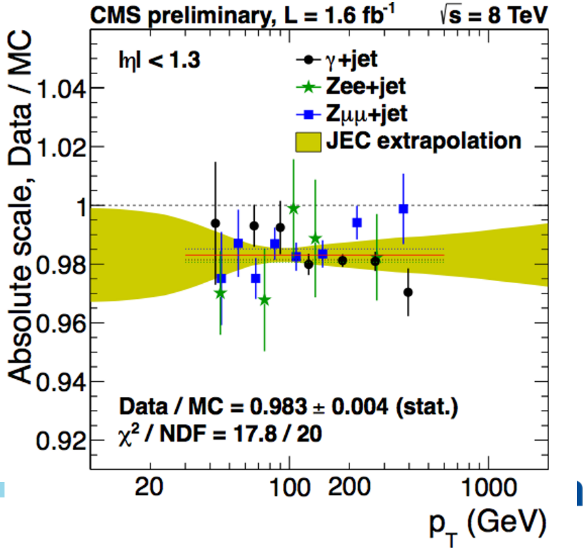
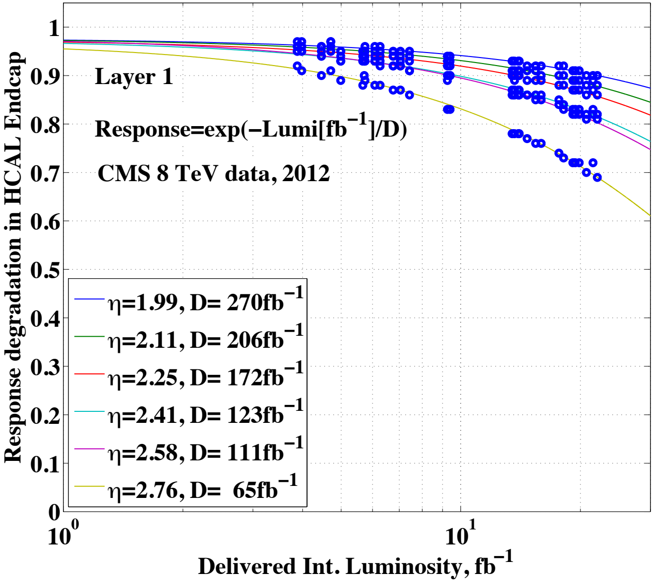
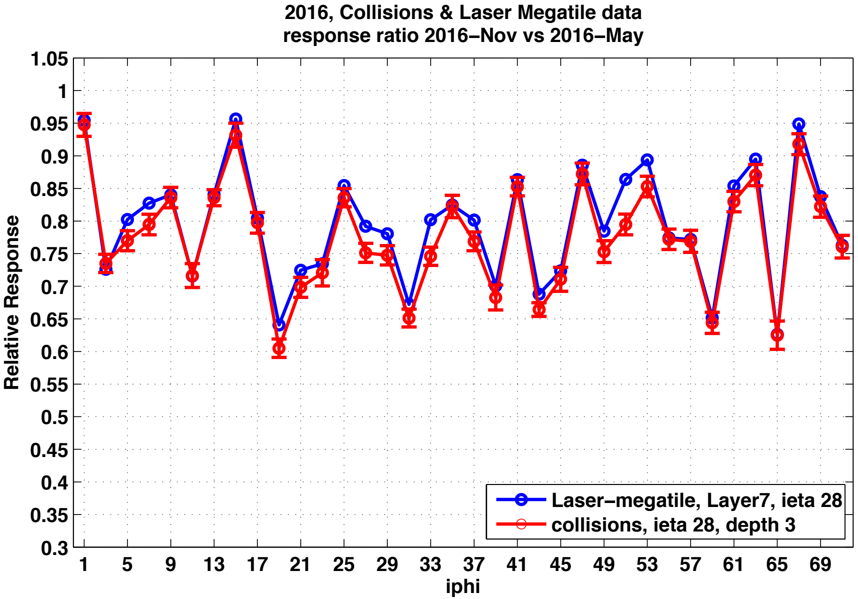




CMS HCAL Hybrid Photodiode Aging

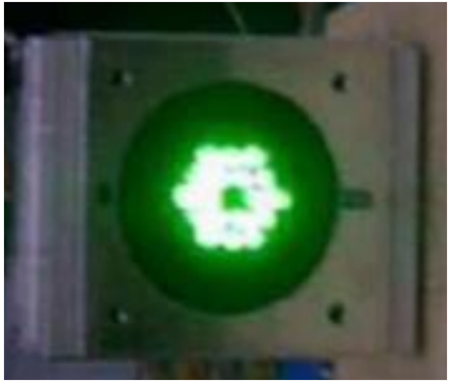
- Observed response loss with dependence on η, layer, delivered lumi ➔ radiation damage
- (Eventually) realized phi dependence ➔ NOT consistent with radiation damage.
- What other sources of aging?

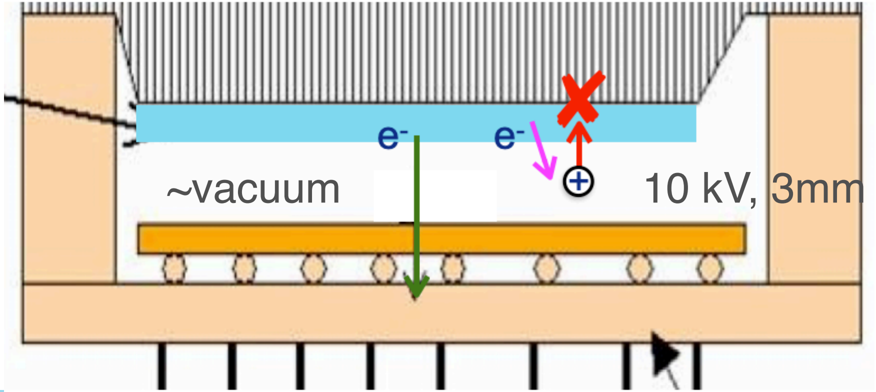


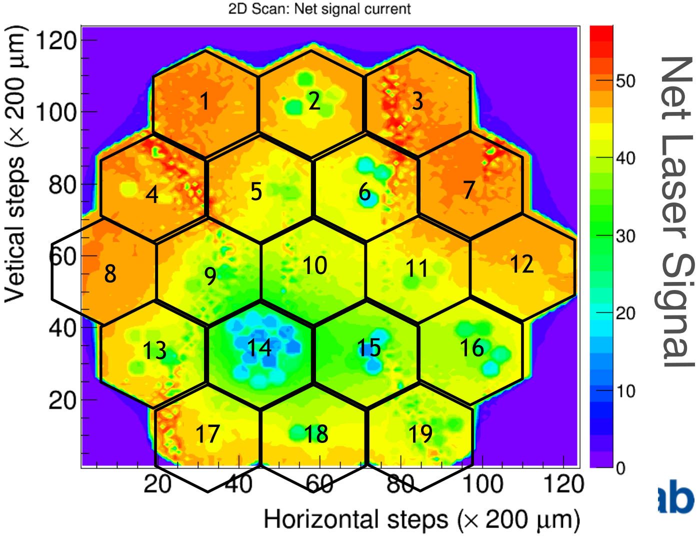


CMS HCAL Hybrid Photodiode Aging (2)

- Checked response of HPDs removed from detector with laser.
- HPD photocathodes showed higher than expected degradation
    - Scaled with level of HPD vacuum ➔ caused by known "ion feedback" mechanism
    - Damage is highly local under fibers from detector ➔ not caught by LED or laser system!
- HPDs replaced with SiPMs in 2017-2019.





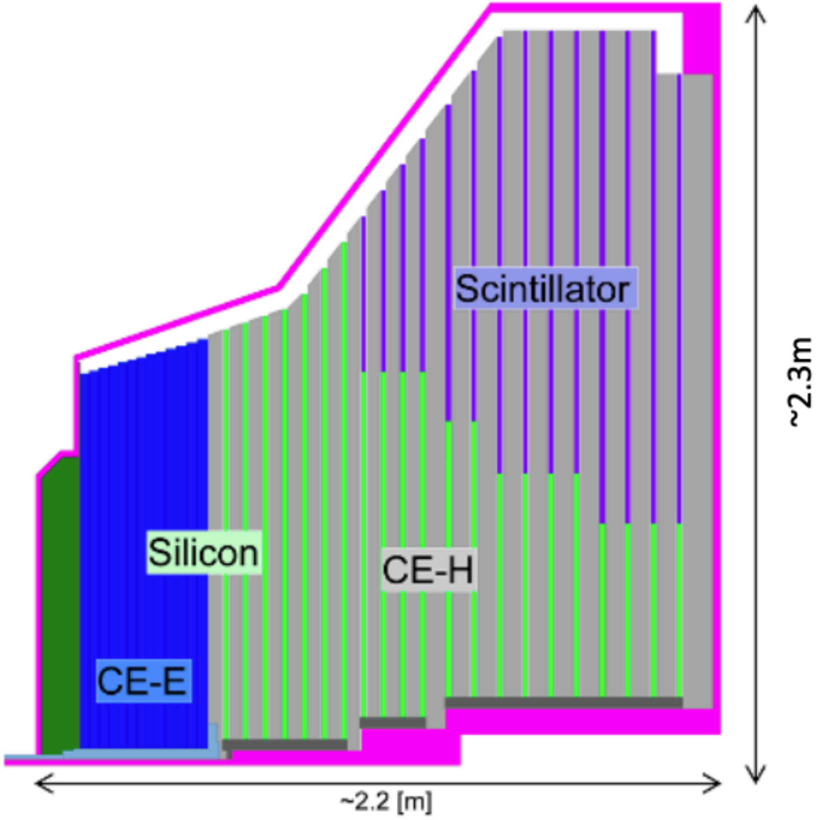


HL-LHC : CMS High Granularity Endcap Calorimeter Replacement

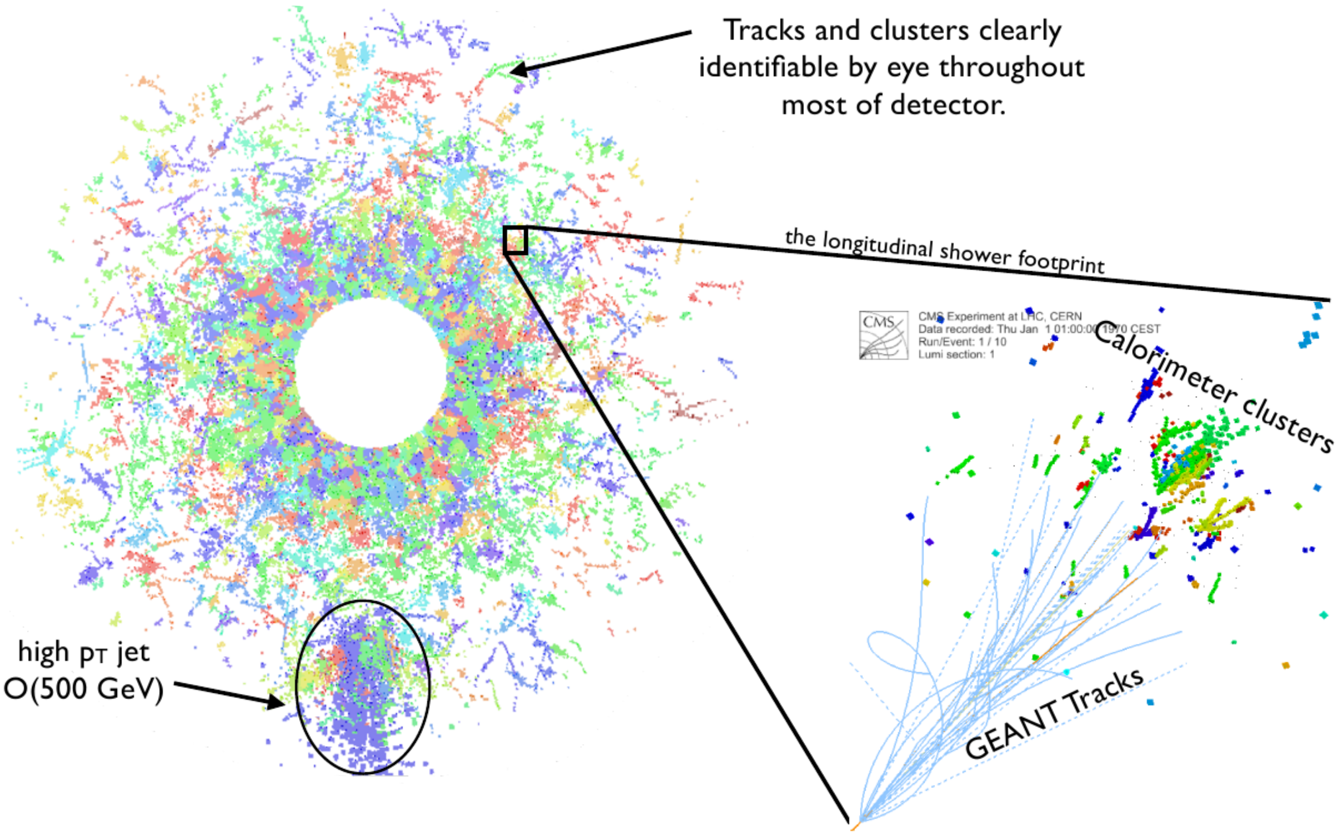
CMS High Granularity Calorimeter (HGCAL)

- Extreme radiation and pileup levels for HL-LHC required total replacement of CMS ECAL and HCAL endcaps.
- HGCAL is a novel "imaging" calorimeter that will reconstruct showers with extreme detail for
  - Separating pileup-related energy deposits from deposits of interest
  - Identifying forward jets from VBF Higgs production

- $1.5 < |\eta| < 3$
- ECAL : 26 layers, Cu/CuW/Pb, 27.7 X_0
- HCAL : 21 layers, steel, 10 λ_{int}
- 620 m^2 Si ➔ 6M channels
- 370 m^2 scintillator ➔ 280k channels!
  - 26k Si / 4k scint modules



CMS HGCAL : imaging calorimeter

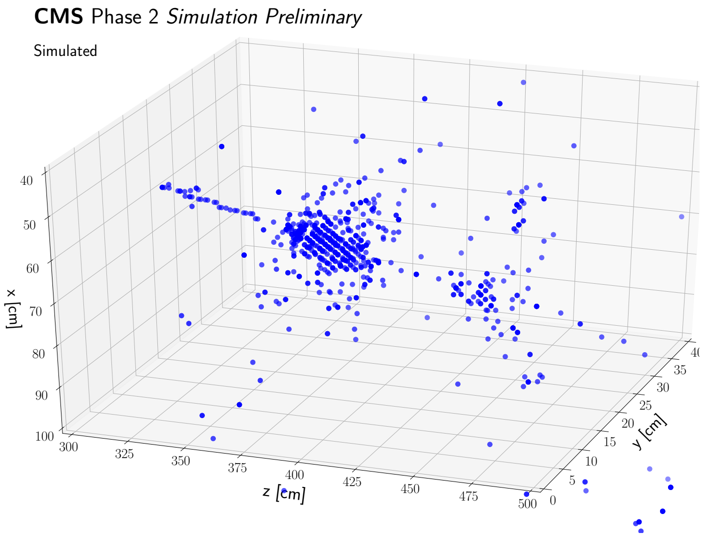


Tracks and clusters clearly identifiable by eye throughout most of detector.

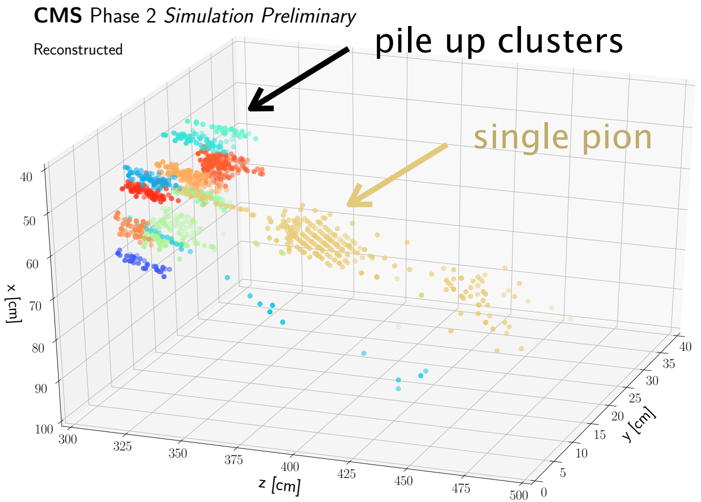
the longitudinal shower footprint

high p_T jet
O(500 GeV)

CMS HGCAL : imaging calorimeter



Simulated hits for single ~50 GeV pion interacting with HGCAL

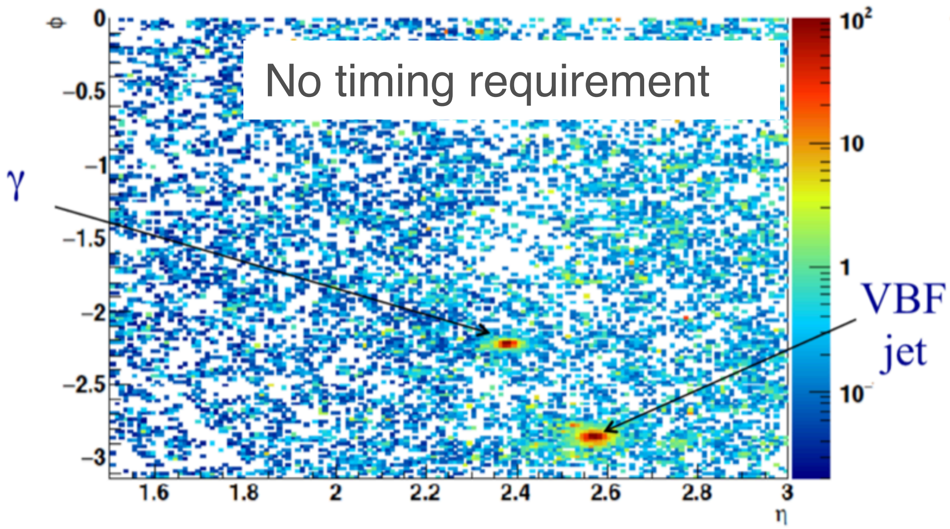


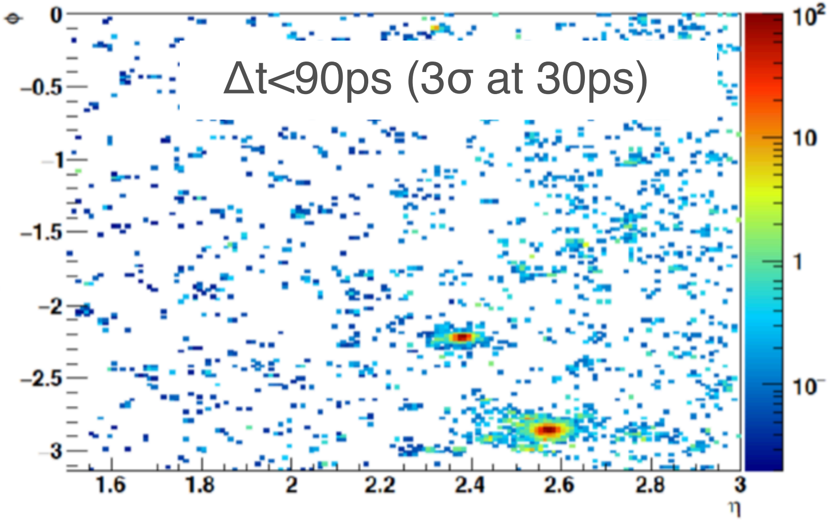
Reconstruction of clusters with 200 PU overlaid on single pion

Jingyu Zhang
ICHEP 2020

CMS HGCAL : Pileup removal with precision timing

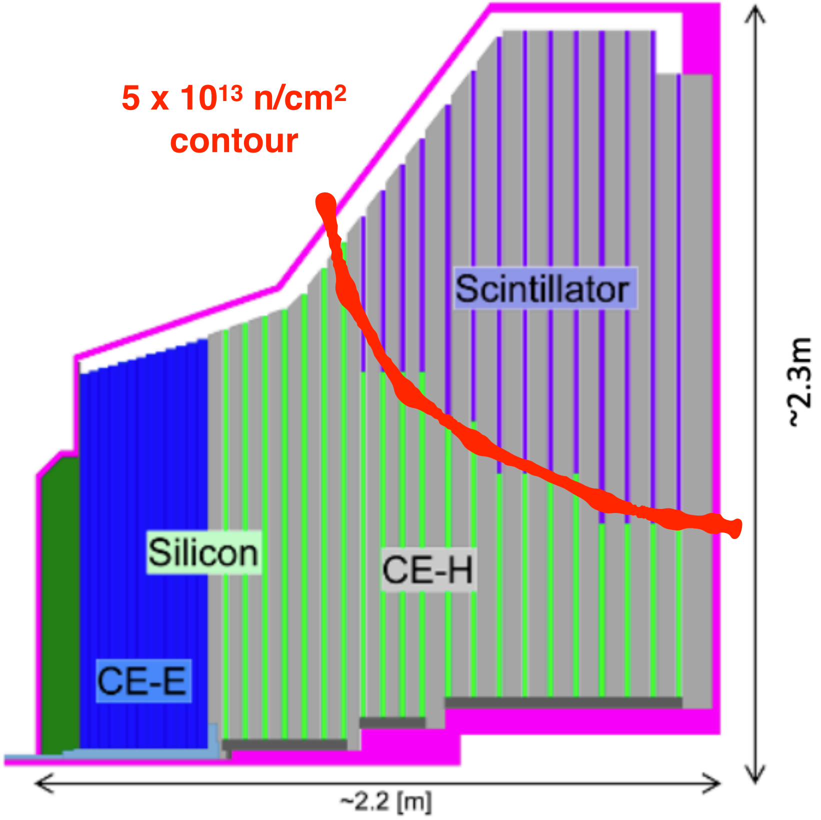
- HGCAL provides ~30 ps precision for multi-MIP energy deposits
- Identify high-energy clusters and then reject out-of-time deposits
- Plots show cells with E > 3.5 MIPs projected to front face with and without timing requirement.
  - Simulation is VBF (H➔γγ) with one photon and one VBF jet in same quadrant


No timing requirement


Δt<90ps (3σ at 30ps)

HGCAL : radiation-based design considerations

- Why both scintillator+SiPM and silicon sections? Why the funny shape of scintillator+SiPM section?
- Scintillator+SiPM is less expensive than silicon, but less radiation tolerant -> se scintillator+SiPM in low radiation regions.
- How to define “low radiation”?
  - We will “level” the response of all 6M HGCAL channels using the MIP as a “standard candle.”
  - Require detector noise to remain at least ~3σ from MIP signal even after irradiation.
  - SiPM radiation-induced noise (dark current) will be unacceptable for good MIP reconstruction after 5 x 10^{13} neutrons / cm^2



HEP data challenge

HEP aims to discover increasingly **more massive particles**, probe **smaller distances**, and study **more rare processes**.

This requires colliders/experiments with increasing **energy** and **luminosity**

- ➔ increasing **detector occupancy**
  - ➔ increasing **detector granularity and precision**
    - ➔ increasing **data volume** produced by detector
      - ➔ **move more data processing to on-detector electronics**
        - ➔ increasing **complexity, power consumption,** and **radiation tolerance**

"The solution to every problem is another problem."
Johann Wolfgang von Goethe

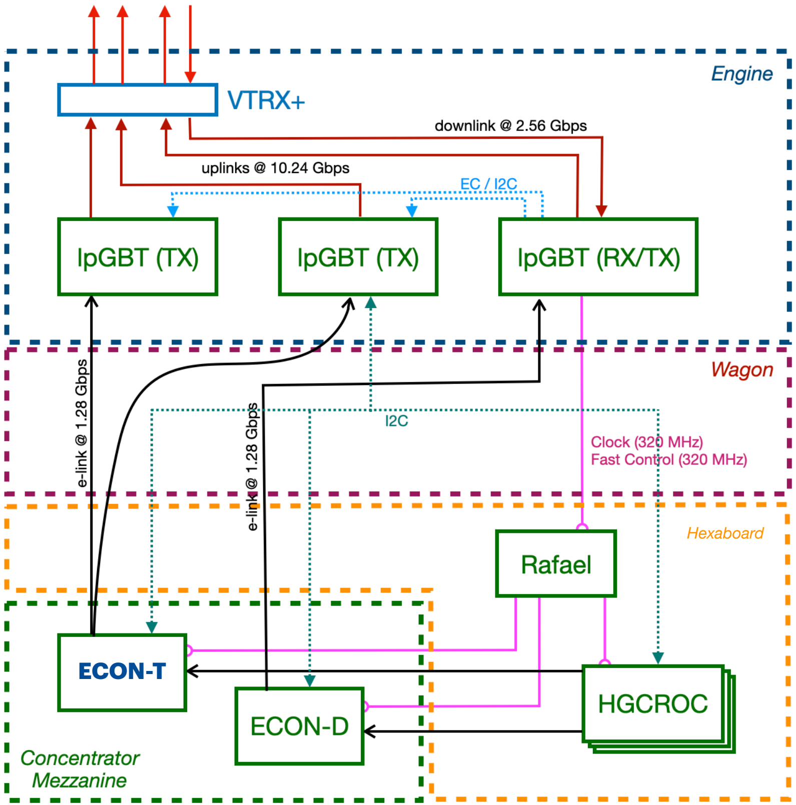
HGCAL data challenge

- Historically, trackers and calorimeters manage data rates with channel count, dynamic range, and readout rate

	channels	Dynamic range	Readout rate	Data rate
Tracker	2E+08	2^4	1 kHz	O(100 Gbps)
Calorimeter	1E+04	2^{10}	40 MHz	O(1000 Gbps)

- This is changing:
  - Trackers will contribute to L1 trigger @ 40 MHz
  - Calorimeters will have ~10M channels

- Readout schemes become more complex ➔ move more complexity onto the detector for processing data at source.



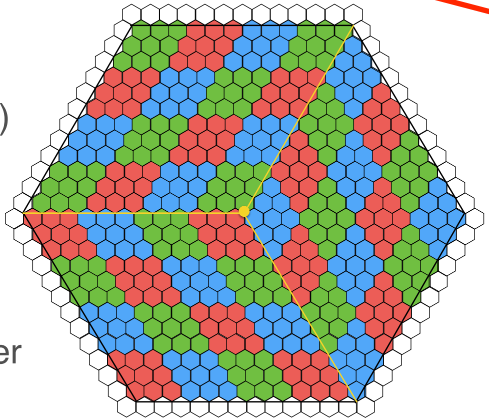
HGCAL Readout Architecture

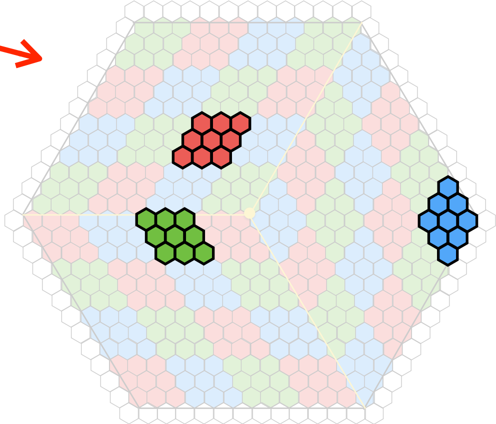
HGCAL data challenge

Trigger path stage	Number channels	bits/ channel	Average Compression factor	Data rate*	# links* (10.24 Gbps)
Raw data	6M	20	1	5 Pb/s	1M
Hardware reduction	1M	7	1	300 Tb/s	60k
Threshold selection	1M	7	7	40 Tb/s	9k

* Assumes 40 MHz rate and 50% link packing efficiency

- 432 Si channels ➔ 48 trigger cells (TC)
- 20b channel ➔ 7b (no timing info)
- Only every-other ECAL layer contributes to trigger





- ECON ASIC selects only 3/48 TC for most of detector!

Calorimeter R&D for Future Colliders

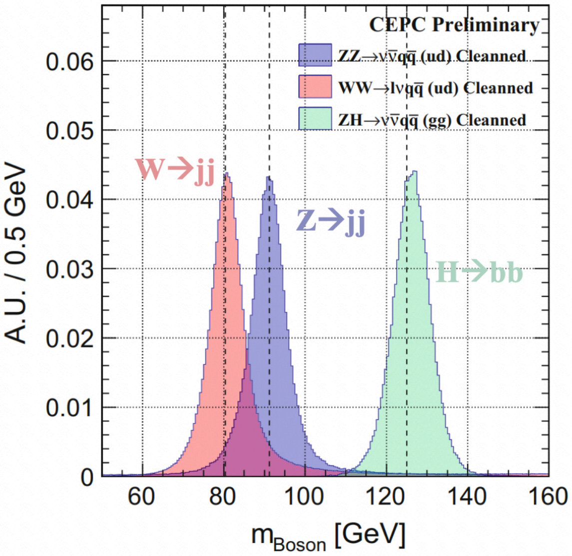
Requirements for future e+e- Higgs factory

- **Jet energy resolution** :
  - Require 3-4% resolution for 100 GeV jets to separate hadronically decaying W and Z bosons
  - Essential for absolute measurement of Higgs total width in e+e- ➔ ZH events.

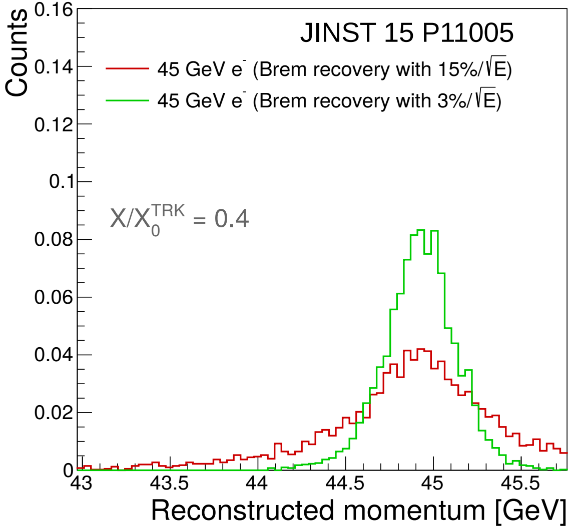
- **EM resolution** remains critical:
  - Precision W/Z boson studies
  - Electron bremsstrahlung recovery

Can we improve jet resolution without harming EM resolution?

EPJC (2018) 78:426



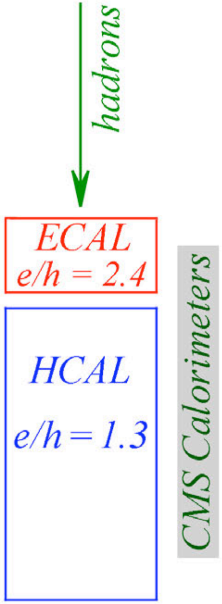
Geant4 simulation



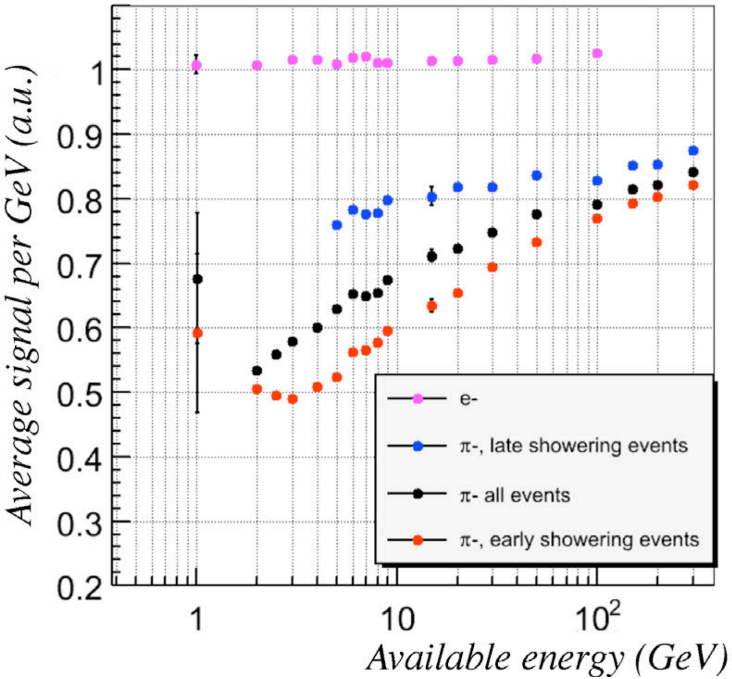
Traditional trade-off : jet vs. EM resolution

- Excellent EM resolution usually harms jet resolution
  - Strong EM response in ECAL leads to **e/h mismatch**.
- Even for well matched e/h, **f_{EM} fluctuations** have a major impact on hadronic resolution.

	ECAL e/h	HCAL e/h	EM res (1/√E)	Had res (1/√E)
CMS	2.4	1.3	3%	100%
ATLAS	1.4	~1.4	10%	50%



- (e/h >>1 in ECAL) ➔ strong calibration dependence on location of shower initiation



Solution : Dual Readout (DR) Calorimetry

- Simultaneous and independent measurements of Scintillation light (S) and Cerenkov light (C) make it possible to measure f_{EM} of hadronic showers event-by-event!

- e/h for S and C are inherently different
  - Hadrons contribute to S but not C
  - Electrons contribute to both S and C

- **RD52 / DREAM** has demonstrated excellent performance for hadron calorimetry and proof-of-principle for EM crystal calorimeter.

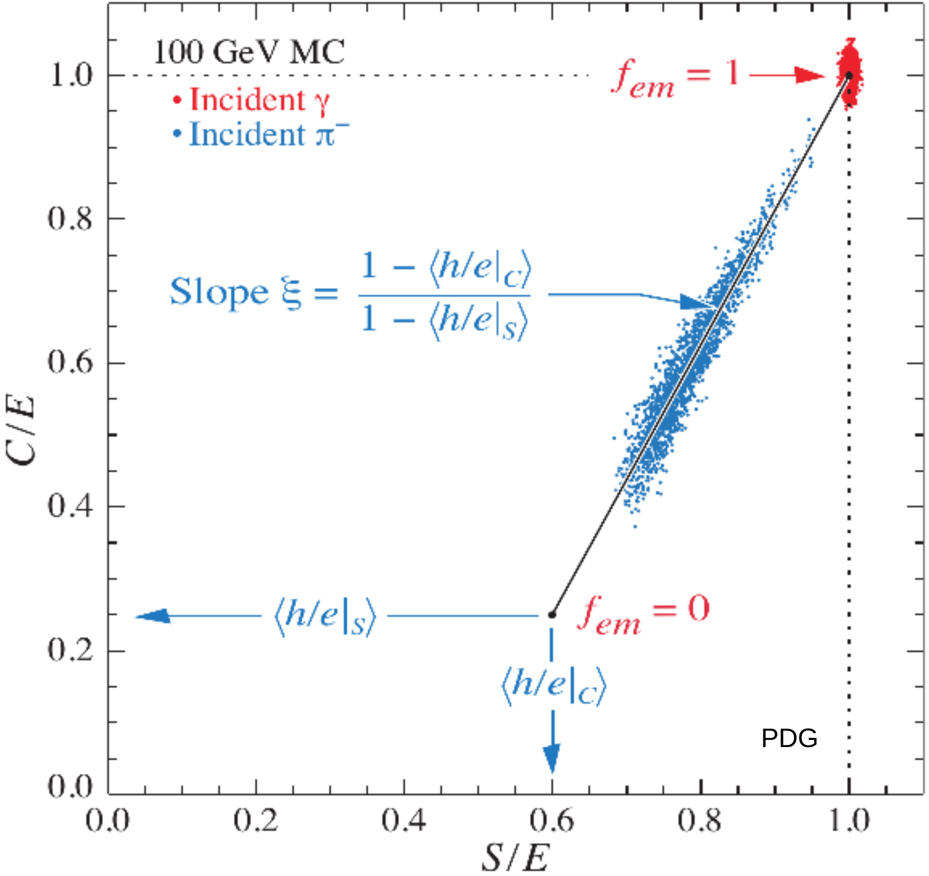
CalVision collaboration goal : demonstrate strong performance of **combined** DR Crystal EM calorimeter + DR HCAL for excellent jet resolution without sacrificing EM resolution.

Dual Readout Method

- Slope of line ξ determined only by e/h values of S and C response
    - ξ is independent of energy and hadron type!
- Energy reconstructed universally as

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

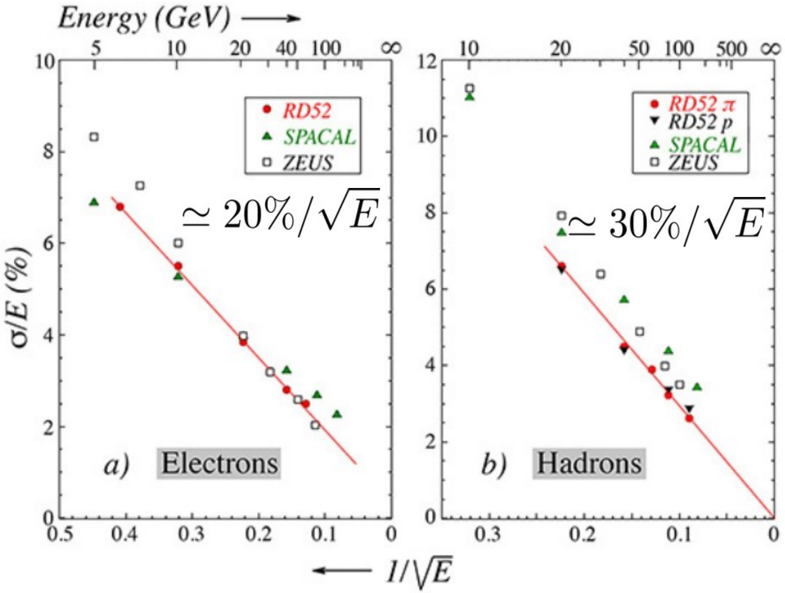
- where S and C are measured event-by-event and ξ is fixed for calorimeter.

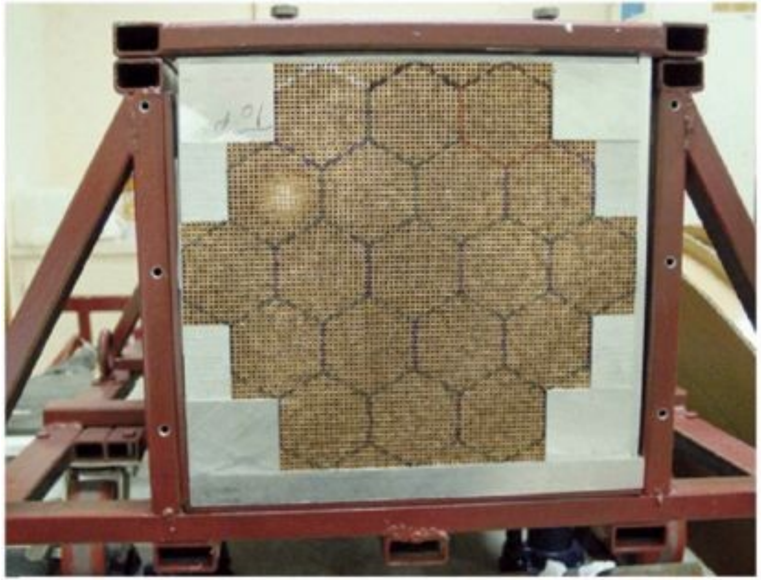


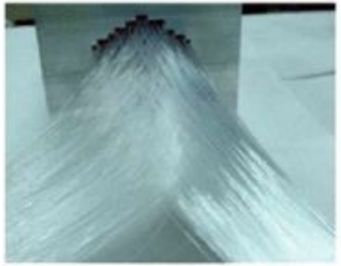
PDG

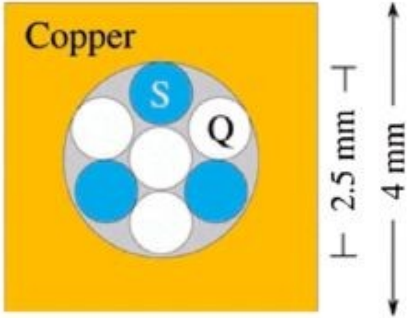
RD52 / DREAM Hadron Calorimeter

- Copper absorber and bundles of scintillating fiber and quartz (no scintillation)
- Excellent hadronic resolution, decent EM resolution.



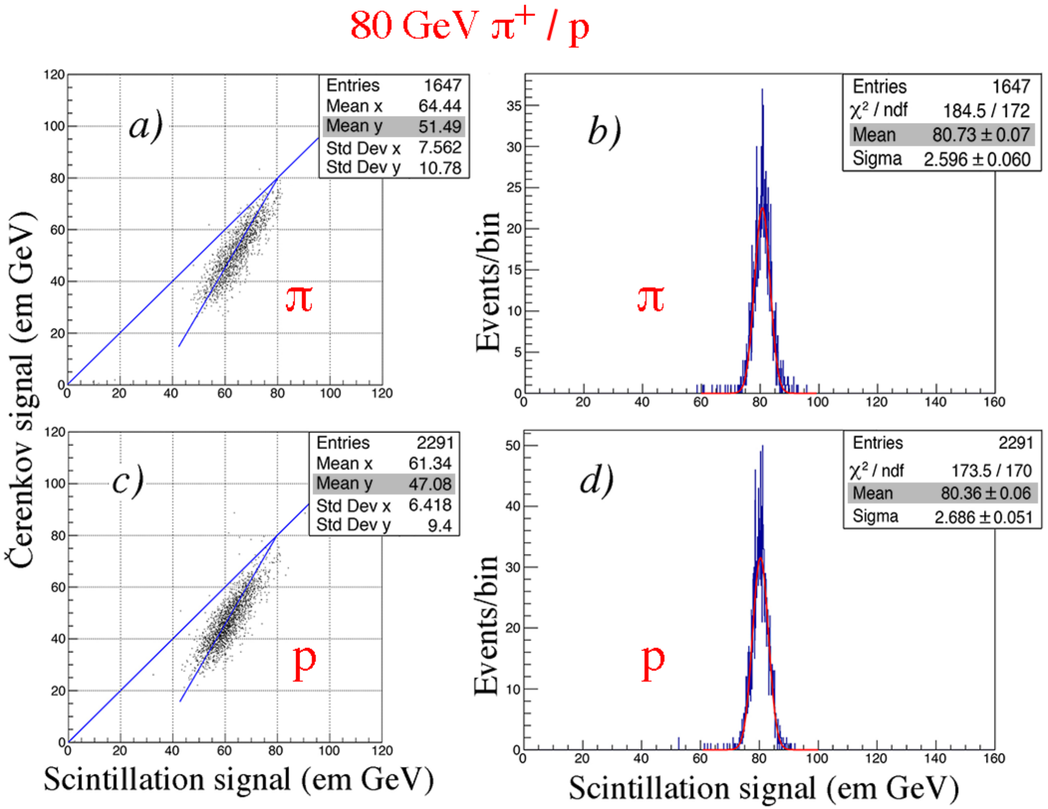






RD52 / DREAM “rotation method”

- Obtained σ/E = 3% for 80 GeV π+ and protons.
- Which is ~30% / √(E)



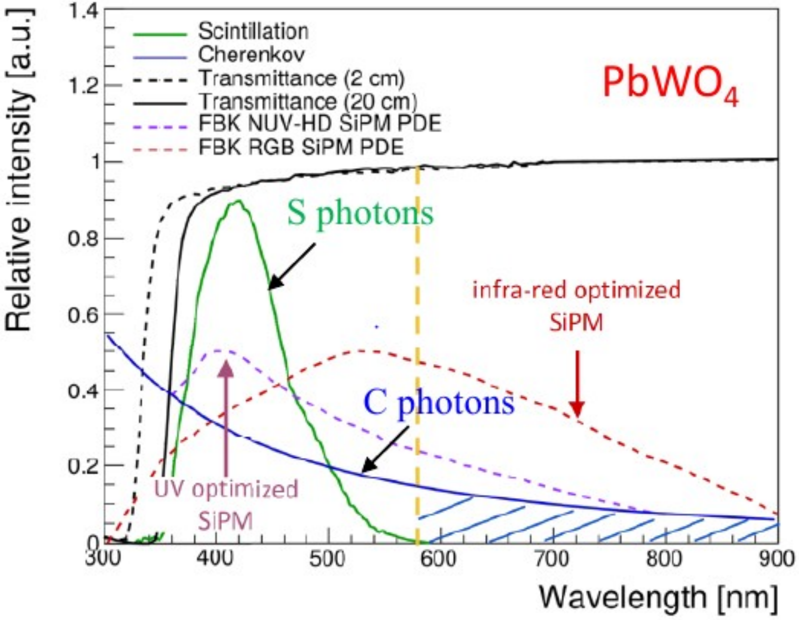
DR crystal calorimeter

- Separate S and C in single monolithic crystal with **wavelength** and **timing/ pulse shape**
- Good performance requires clean separation of S and C components that maintains large S contribution for EM resolution and preserves small C contribution for DR method
  - **Wavelength** : photosensors with near UV sensitivity, optimized filters
  - **Timing** : Fast timing and precise pulse shape discrimination — perform on-detector to avoid “big data” challenges.

Wavelength challenges

- Ideally would take C from its peak at UV wavelengths
    1. Crystals have low transmittance in UV
    2. Photosensors have low efficiency in UV

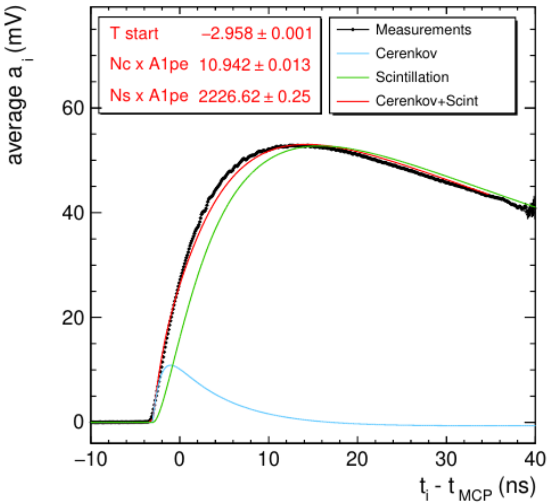
- Instead use filter select long wavelength for C and infra-read optimized SiPM.
- Ongoing R&D:
    - New materials to address (1)
    - Improved photosensors to address (2)



CalVision timing / pulse shapes in beam test

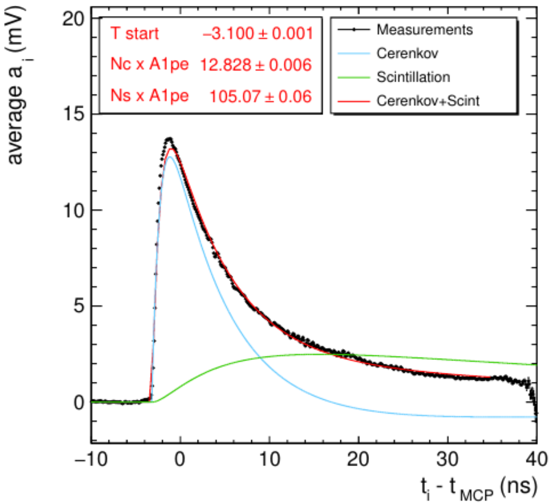
- 120 GeV protons on BGO crystal
  - Select MIP protons - produce both S and C

Front SiPM (no filter)



Large S swamps C despite pulse shape difference

Back SiPM (U330 filter)



Use filter on one SiPM to isolate C

Conclusion

- This is an exciting time for calorimetry
- CMS is deploying a novel and ambitious new HGCAL — will provide an eternal playground for AI/ML!
- Upcoming challenges for extreme precision and radiation tolerance at future e+e- and pp colliders require immediate R&D.
- We are always in need of interested new collaborators — please feel free to contact me!

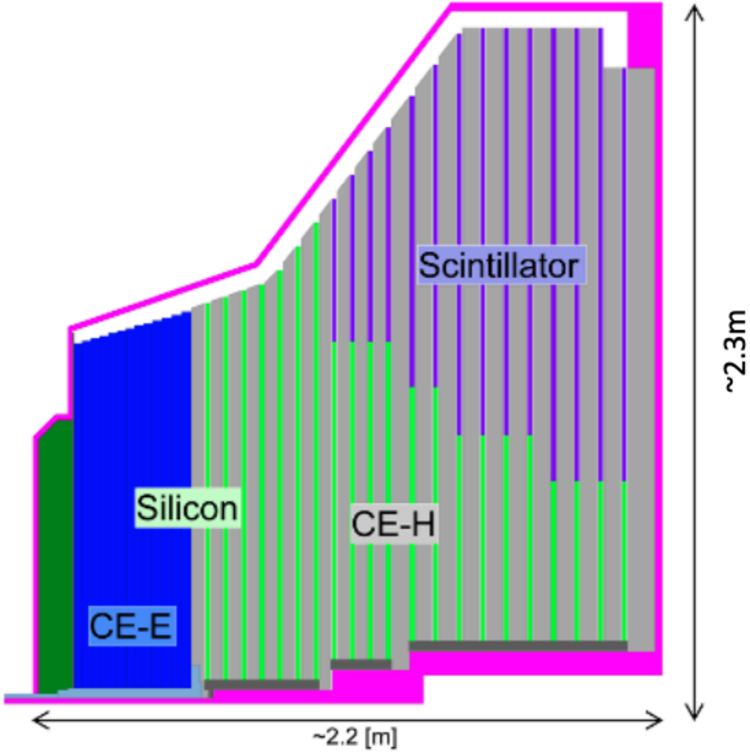
Additional material

CMS High Granularity Calorimeter

Key Parameters:
- HGCAL covers $1.5 < \eta < 3.0$
- **Full system maintained at -30°C**
- **~620 m^2** of silicon sensors
- **~370 m^2** of scintillators
- ~6M Si channels, 0.5 or 1.2 cm^2 cell size (*6M*)
  ~280k scint-tile channels ($\eta-\phi$) 4-30 cm^2
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all in CE-H
- ~26000 Si modules, 3700 Scintillator modules

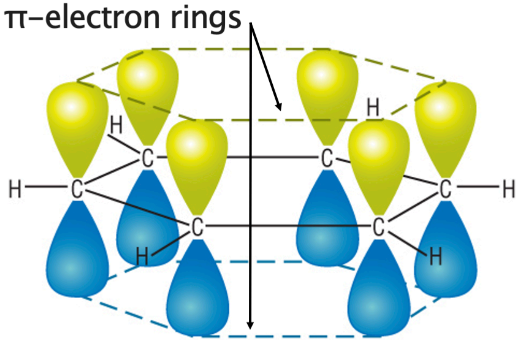
Active Elements:
- Si sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H.
- SiPM-on-Scintillating tiles in low-radiation region of CE-H

Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 26 layers, 27.7 X_0
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, 10.0λ (including CE-E)
~220 tonnes per endcap



Scintillation : plastic scintillator (e.g.)

- **Base material** is excited by ionization at molecular level and emits UV light in de-excitation.
  - In general, base material is nearly opaque to initial UV light.
- **Secondary fluors** absorb primary UV light and re-emit in visible part of spectrum.
- Primary scintillation light (from base) results from excitation and de-excitation of **benzene** rings.
  - S1➔S0 decay is fast scintillation (nsec)
  - S1➔T1 decay is slow phosphoresence (msec)



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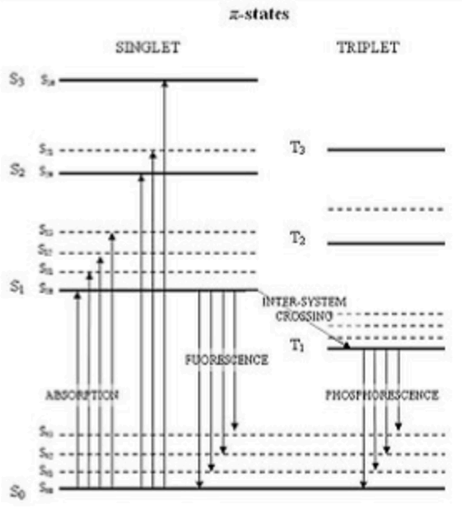
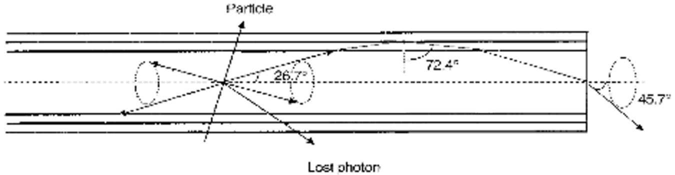
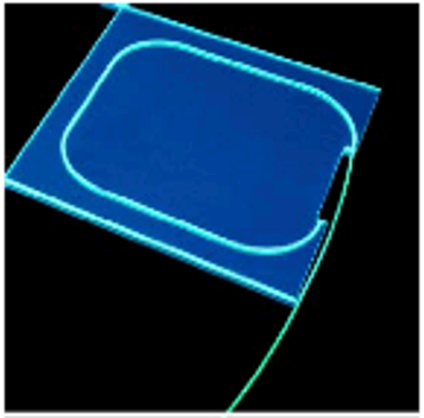
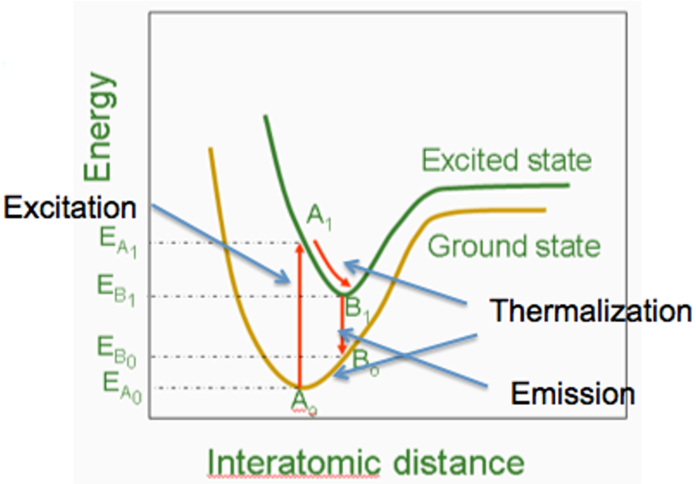


Wave-length shifting



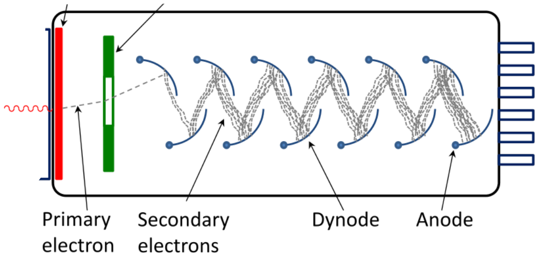
- Scintillation light is **emitted isotropically** in HCAL tile.
- How do we get it out?
  - **Optical fiber**, but any light that can enter fiber can also exit, so
  - **Wavelength shifting fiber** absorbs light and re-emits isotropically at longer wave so that ~5% is **captured through total internal reflection**.
- Wavelength shifting results from **Stokes shift**.





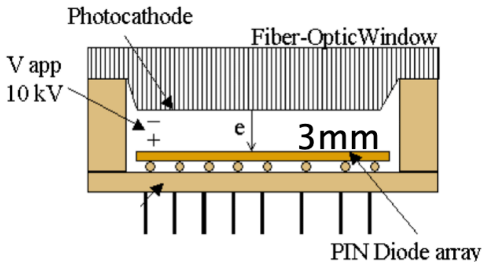
Photosensors

Photomultiplier Tube



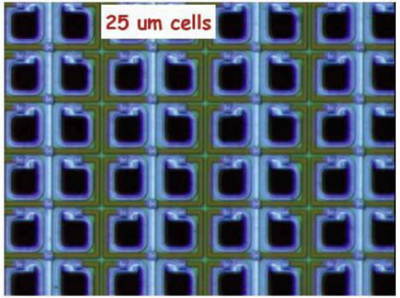
- p.e. accelerated over 2kV into dynode chain
- Secondary emission electrons provide gain 10^6

Hybrid Photodiode



- photoelectron produced in photocathode
- accelerated over 10kV/3mm.
- gain = $V_{app}/3.6$ eV = 2000

Silicon Photomultiplier



- array of binary GAPD,
- gain = C_{GAPD} x ($V_{op}-V_{bd}$)
  = 100 fF (1V) = 10^6

Photosensors

Quantity	PMT	HPD	SiPM
bias voltage	2kV	10kV	50 V
gain (M)	10^6	10^3	10^5-10^6
volume/channel	10cm^3	10cm^3	$< 1\text{cm}^3$
B-field performance	None	Good	Good
High amplitude noise	Fair	Poor	Good
Response stability	Fair	Fair	Good
sensitivity	1 pe	$>$ 1 pe	1 pe
δT for $\delta M/M = 1\%$	3°C	4°C	1°C
$\delta V_b \,/\, V_b$ for $\delta M/M = 1\%$	5×10^{-4}	5×10^{-3}	10^{-3}

Biggest SiPM challenge is radiation-induced dark current

CMS HCAL Hybrid Photodiode Aging (2)