Calorimetry – part 3

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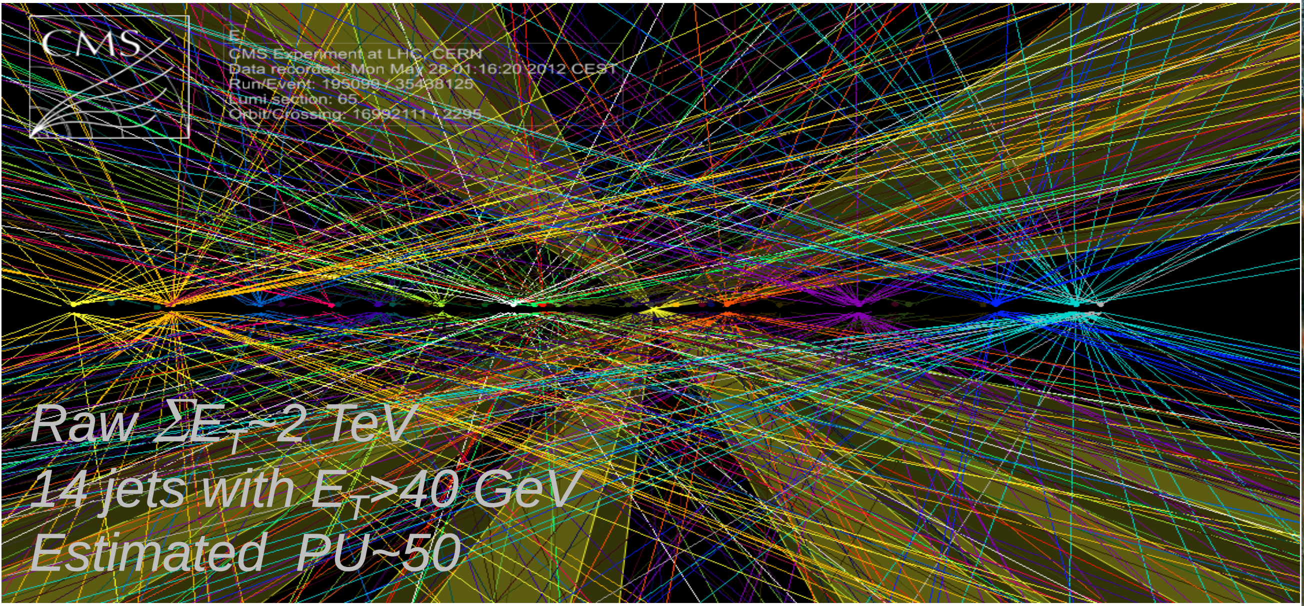
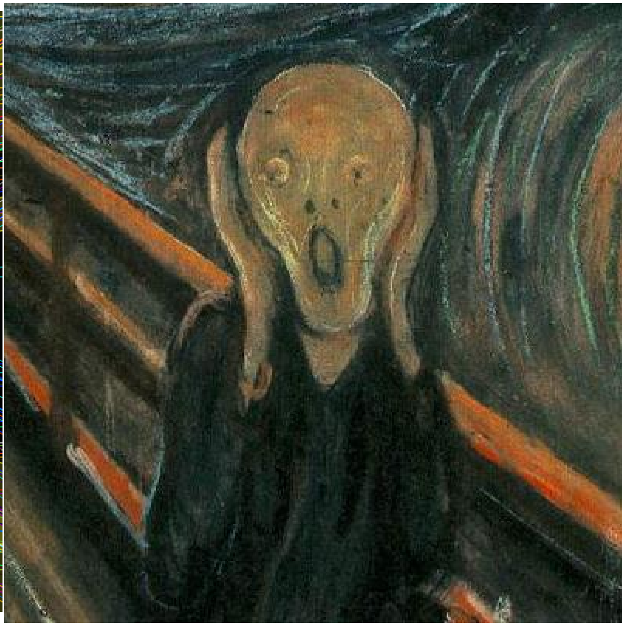
Outline

- R&D for future calorimeters:
  - High granularity (CALICE)
  - Dual readout (DREAM)
- The HL-LHC and upgrade of CMS calorimeters
- PU mitigation with precise timing



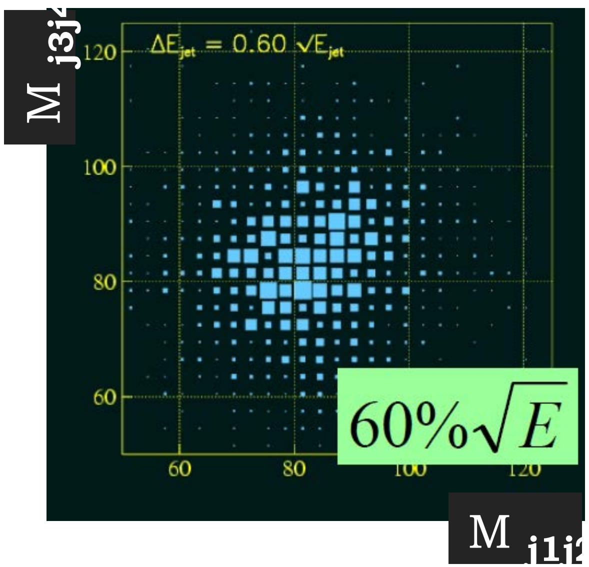


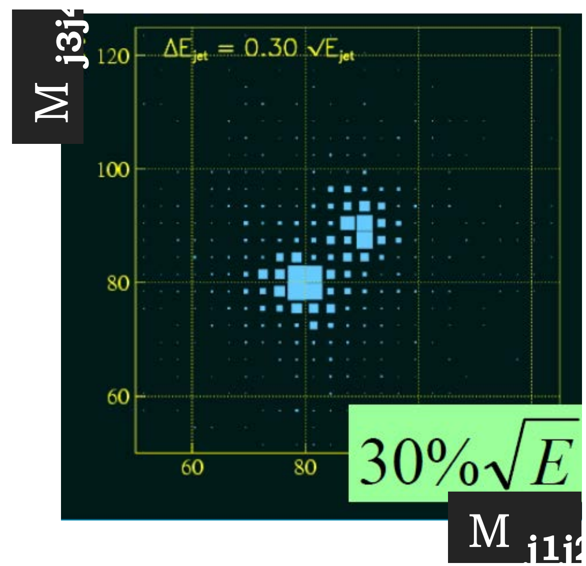
~ 10 cm

R&D for future calorimeters

R&D for future calorimeters

- One of the goal for linear collider hadronic calorimeter: W/Z separation in hadronic decays





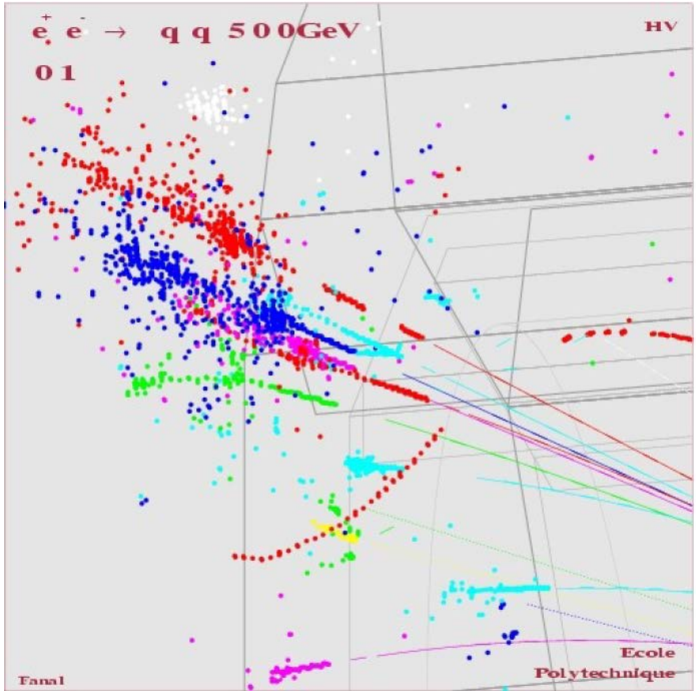
σ_{Ejet}/E_{jet} ~ 3%-4% @ ~50 GeV → σ_{Ejet}/E_{jet} ~ 25-30%/√E

Two mainstream R&Ds:

- High Granularity (Particle Flow)- Calice activity since ~10 years
- Dual Readout – Dream and RD52 project

A detector designed on PF algorithm

Needs large B field and R, transversal and longitudinal granularity for shower tracking



Emphasys on tracking capabilities of calorimeters
Use granularity to correctly assign hits to showers
60% of jet energy measured with tracker
30% of jet energy measured in ECAL
10% of jet energy measured in HCAL

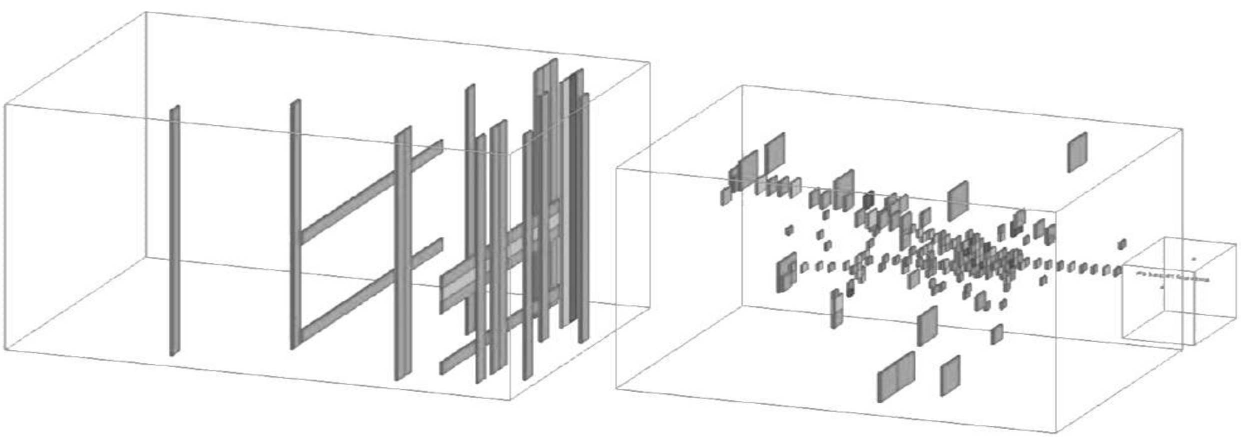
cluster mixing/double counting

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

- The resolution on jets depends anyway on the good performance of σ_{ecal} and σ_{hcal} which should be always take care of, especially systematics effects.
- The correct association of clusters to tracks relies on energy-momentum matching
- The minimization of $\sigma_{confusion}$ might not be enough to reach the goal $\sigma_{Ejet}/E_{jet} \sim 30\%/\sqrt{E}$

CALICE Collaboration

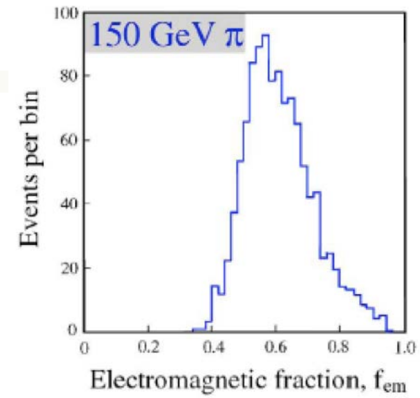
- CAlorimeter for LInear Collider for Electrons
- Different read-out technologies are under investigation
  - Tungsten - Silicon for em-part
  - Tungsten/Iron - Silicon and scintillating tiles (SiPM readout) for hadronic part



Dual Readout Calorimeter (DREAM)

How to improve energy measurement in hadron calorimeters?

Eliminate the main source of fluctuation (e/h≠1) measuring the electromagnetic fraction (f_{em} , also depends on energy) of hadronic showers event by event



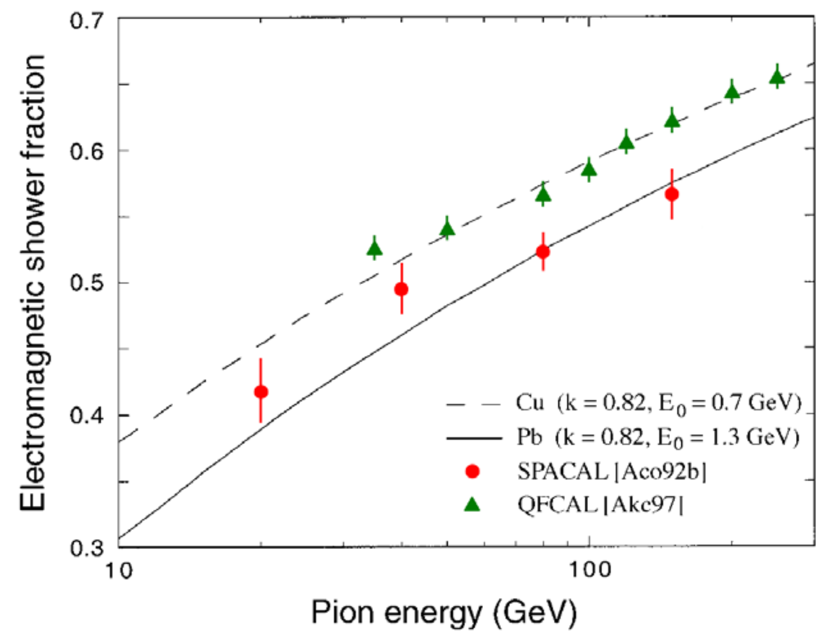
DUAL READOUT

Sample shower energy with both

Čerenkov radiator: sample em part of the shower

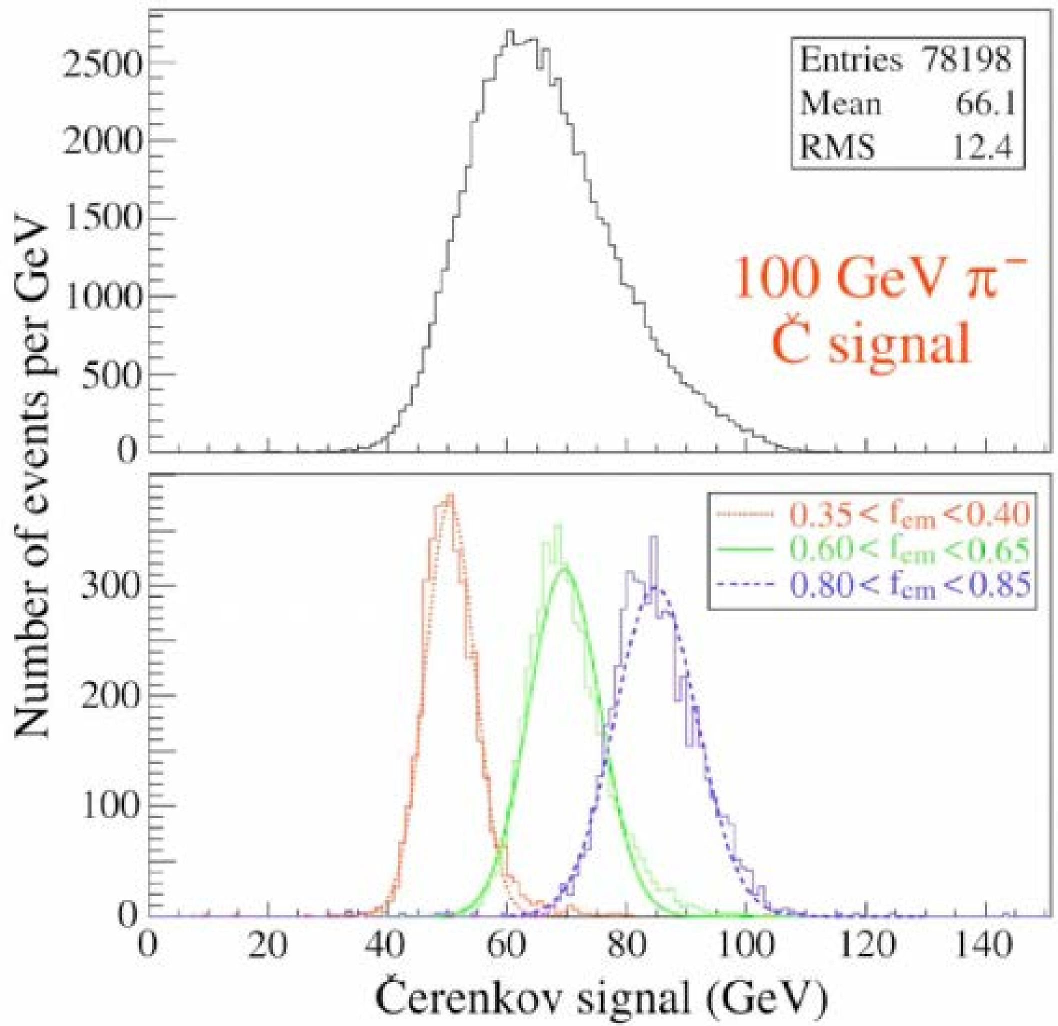
Scintillator: sample all components

Combine information and extract f_{em} and E



R&D on this concept going on since 2002, DREAM project (RD52). Applied to fiber calorimeters and also to crystals.

Dual Readout Calorimeter (DREAM)



Č/S signal ratio measures f_{em} event by event!

→ Elimate effects of f_{em} fluctuations on performance of hadron calorimeters

Dual Readout Calorimeter (DREAM)

Measure F_{em} event by event using Čerenkov light emission

Čerenkov light emission threshold: **$\beta>1/n$**
e.g. quartz n=1.45 E_{th} = 0.2 MeV for electrons, 400 MeV for protons
Enhance electromagnetic response (in a quartz fiber calorimeter e/h ~ 5)

DUAL READOUT

Cerenkov radiator:
sample em part of the shower

Scintillator:
sample all components

Take electrons signal as reference

$$\boxed{C = [f + c(1-f)]\,E} \quad c = (h/e)_C$$

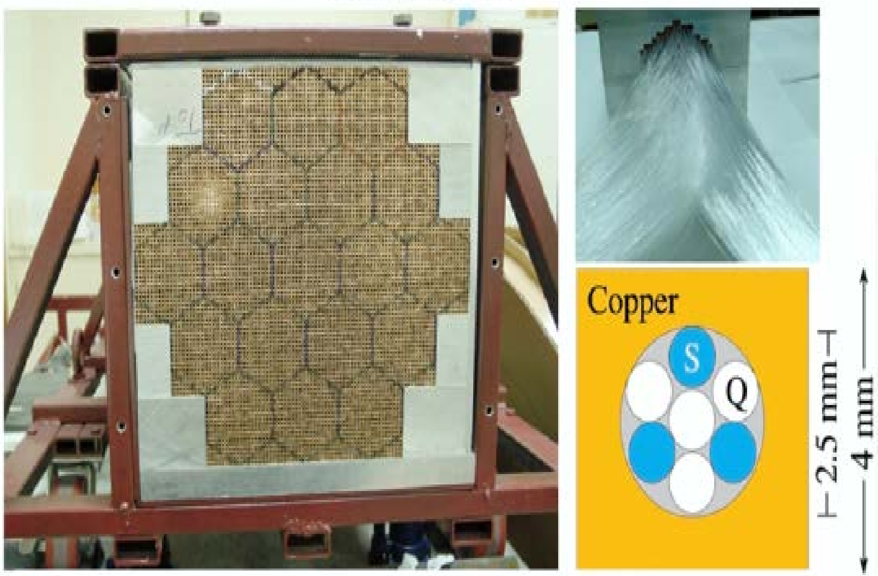
$$\boxed{S = [f + s(1-f)]\,E} \quad s = (h/e)_S$$

Combine information and get F_{em} (f) and E !

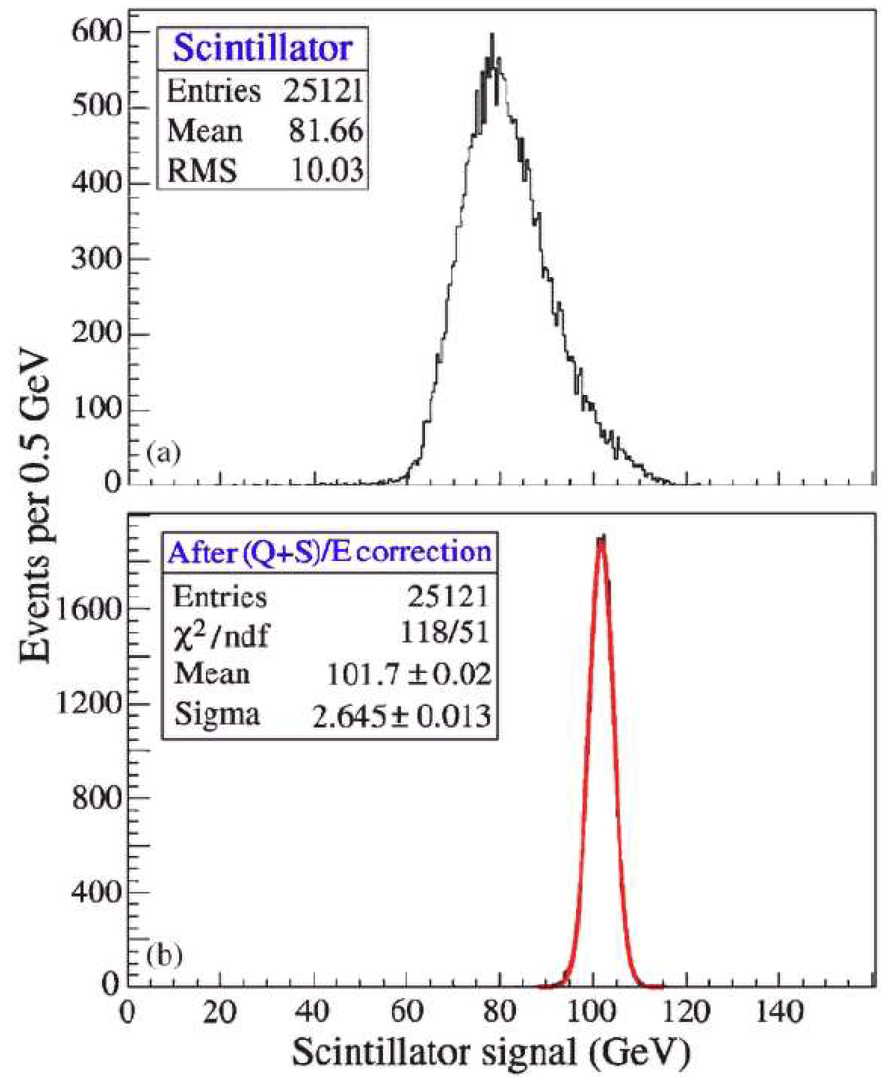
$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)} \qquad E = \frac{S - \lambda C}{1-\lambda} \qquad \lambda = \frac{1-s}{1-c}$$

Constant of the calorimeter

Dual Readout Calorimeter (DREAM)

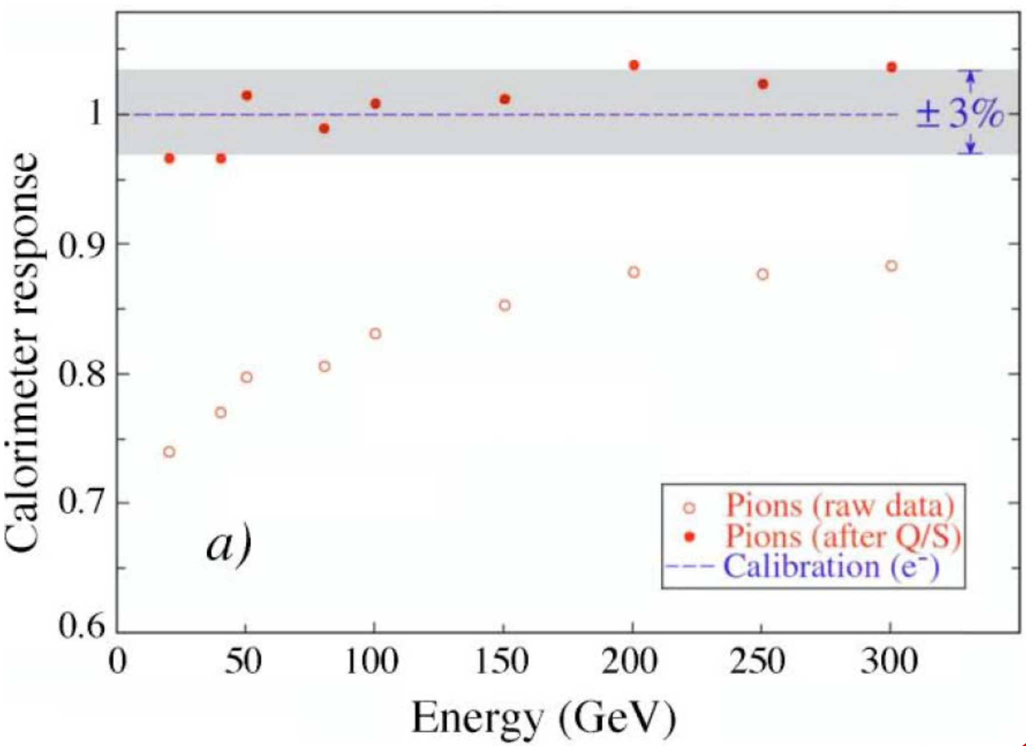


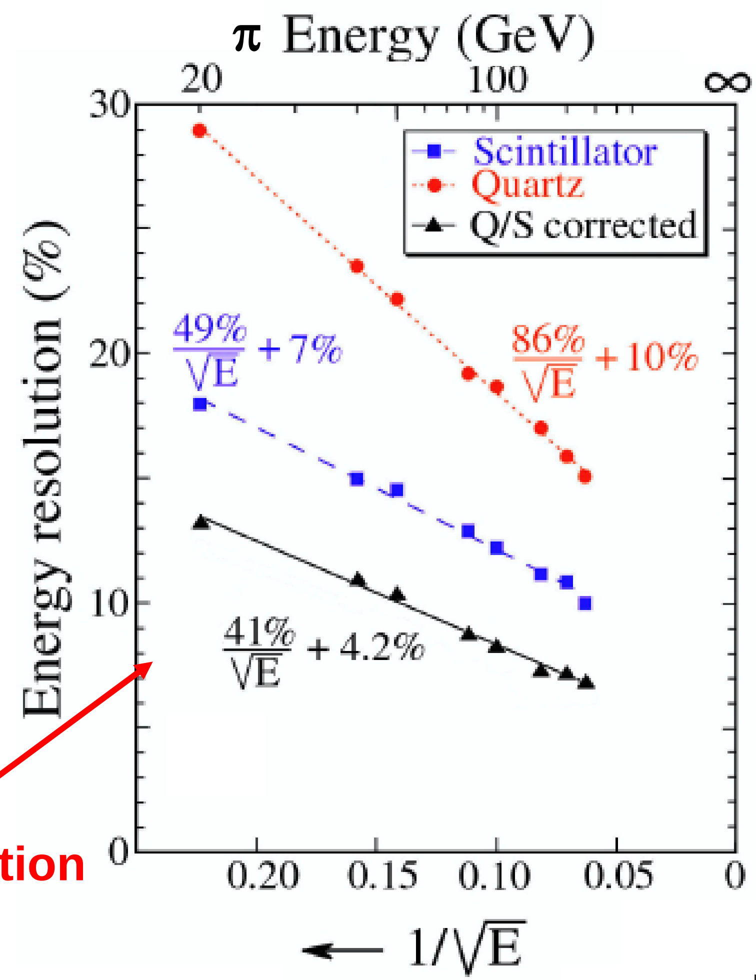
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs



Dual Readout Calorimeter (DREAM)

Hadronic response after C/S correction

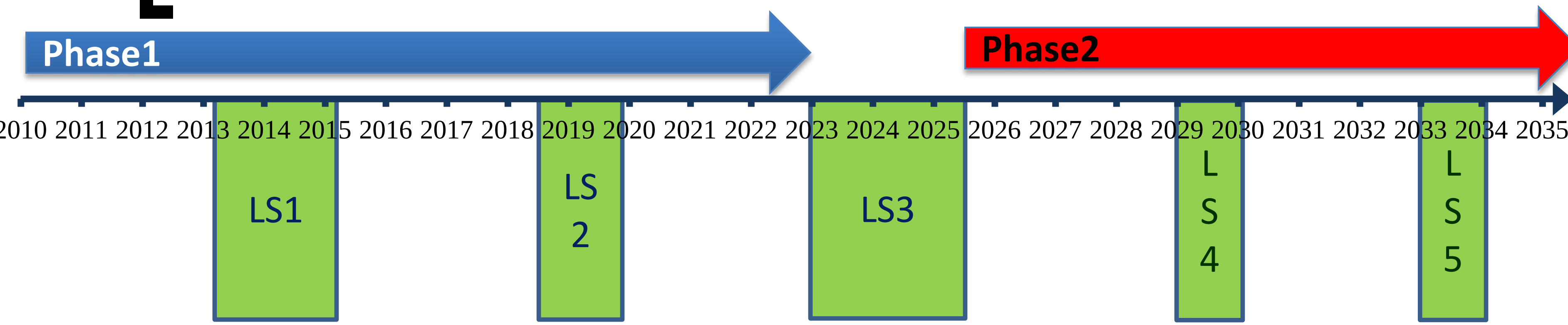




NB contains leakage contribution

Upgrade of the CMS calorimeters for the High-Luminosity LHC

LHC and HL-LHC



Phase 1: E = 13-14 TeV
$L=1\text{-}2 \cdot 10^{34}\ cm^{-2}s^{-1}$
<PU> ~ 40-60
$\geq 50 fb^{-1}$ per year
by the end of Phase1
$300 - 500\ fb^{-1}$

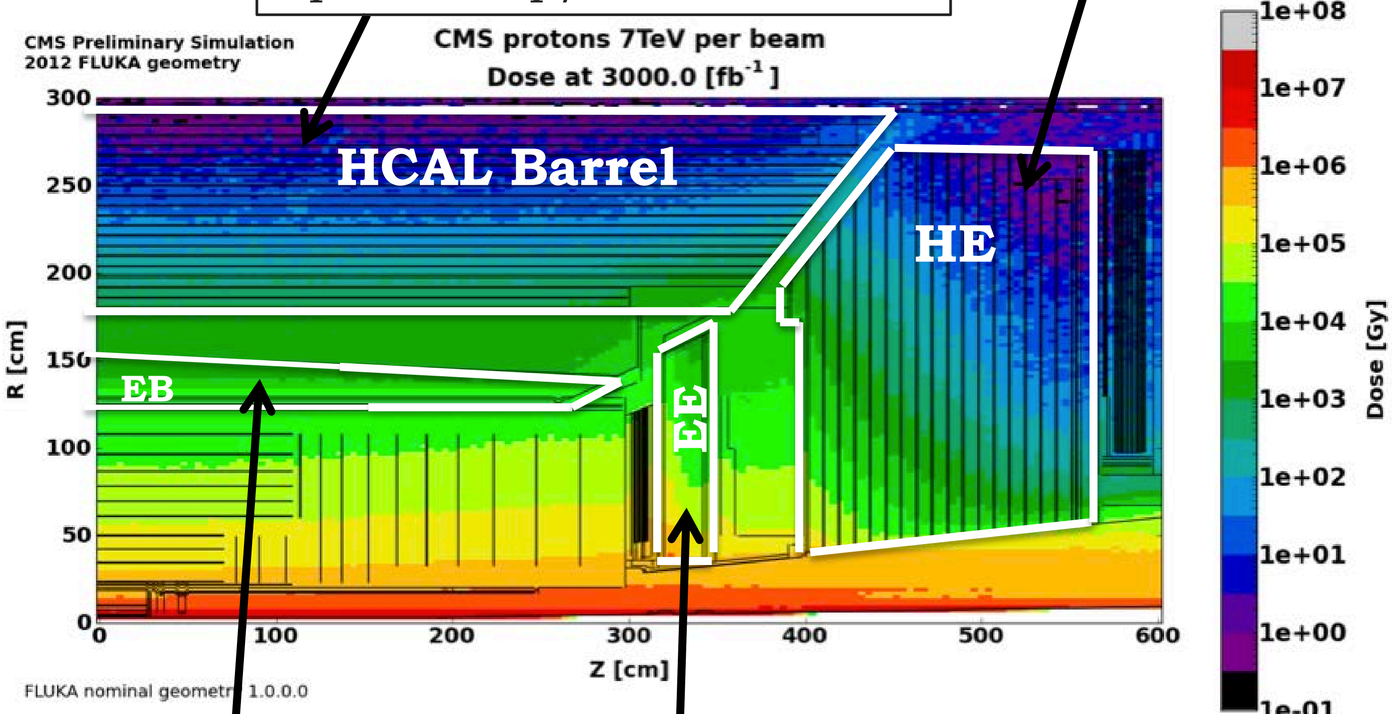
HL-LHC:
$L=5 \cdot 10^{34}\ cm^{-2}s^{-1}$
<PU> ~ 140 events
$250\ fb^{-1}$ per year
by 2035 → $3000\ fb^{-1}$
In Run1 we have collected ~1% of the total data expected!

- **~25 years of operation since installation instead of anticipated 10 years.**
- **We will see that while the ECAL barrel will perform well to $3000\ fb^{-1}$, the ECAL endcaps must be upgraded at the end of LHC Phase I**

Radiation Environment

HCAL barrel: 0.3 Gy/h and up to 10^{11} p/cm^2

HCAL endcap: up to 20 Gy/h and 10^{13} p/cm^2



HL-LHC

$L=5 \cdot 10^{34}$ cm^{-2}s^{-1}

$\int L dt = 3000$ fb^{-1}

ECAL barrel: 3 Gy/h and 2×10^{12} p/cm^2

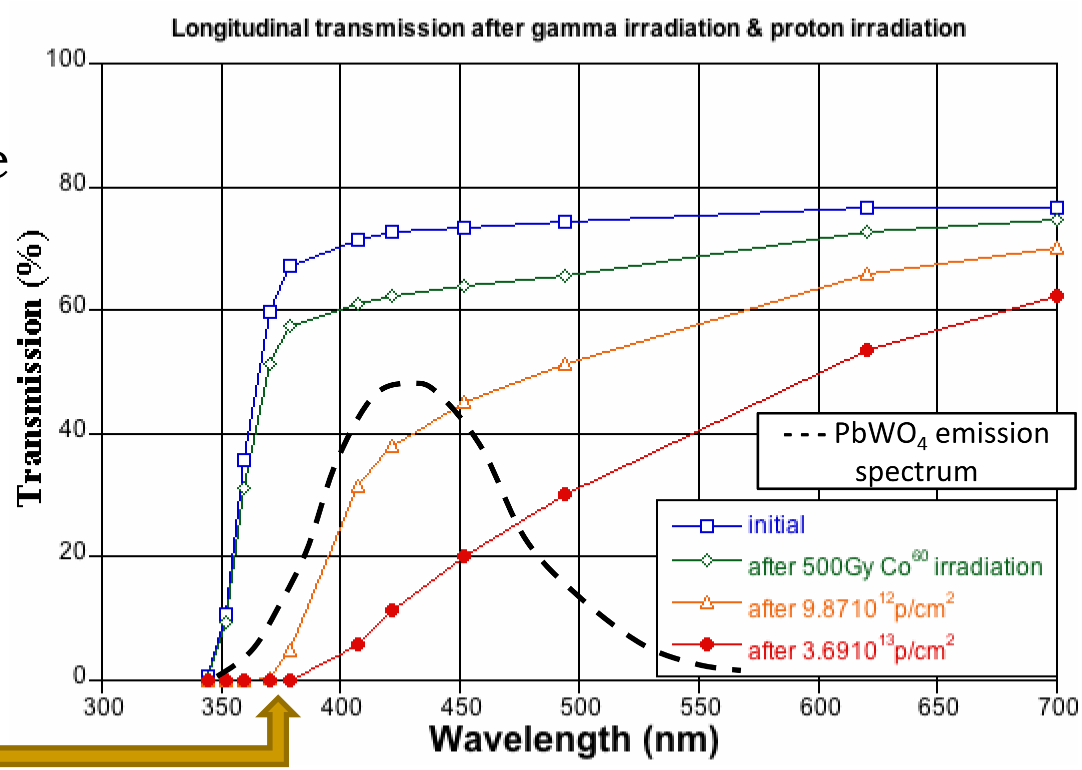
ECAL endcap at η=2.6: 65 Gy/h and 2×10^{14} p/cm^2

1 Gy = 1 Joule/kg
~ 3×10^9 mips/cm^2
across the medium

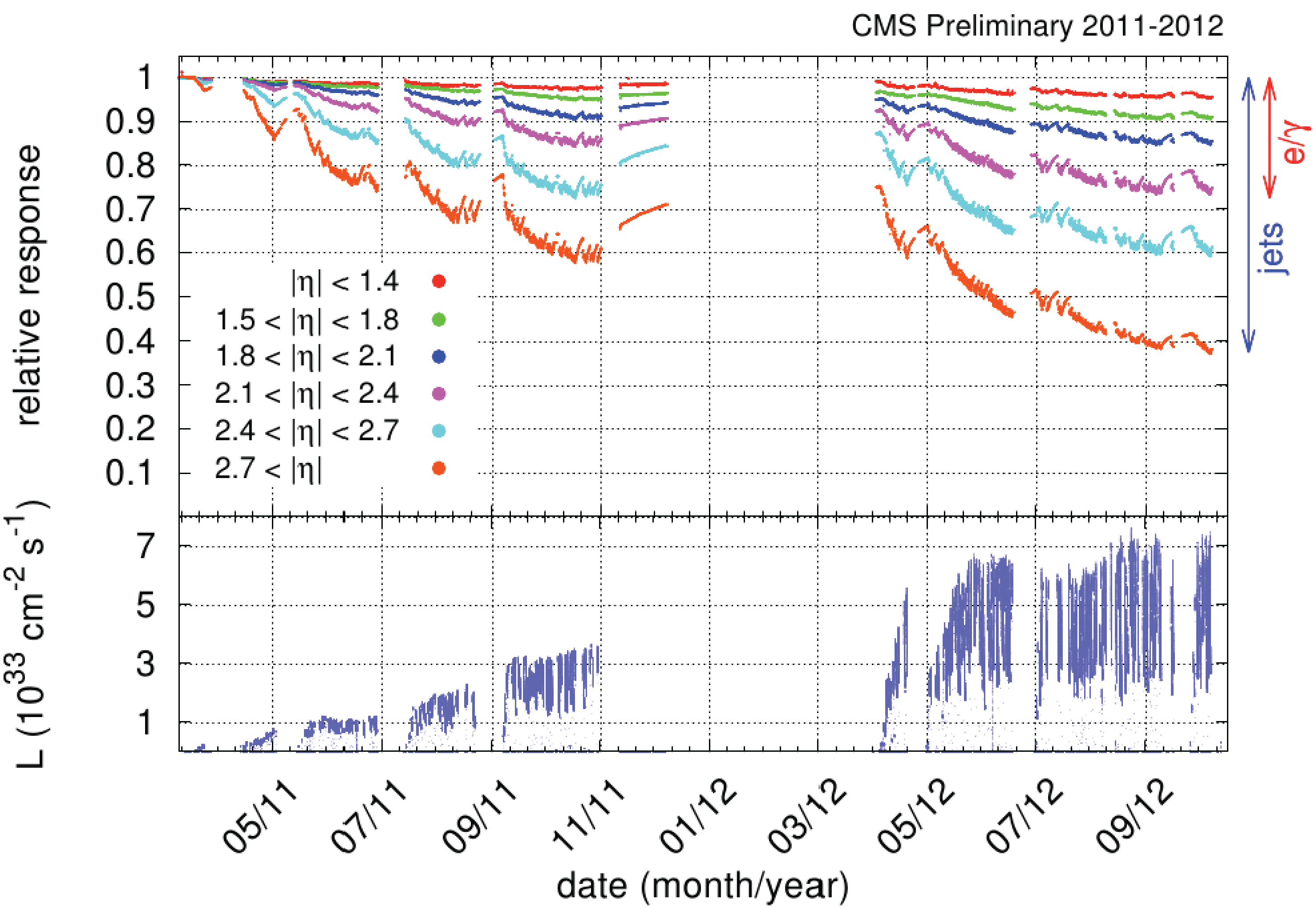
Radiation damage to $PbWO_4$ crystals

Crystals are subject to two types of irradiation:

- Gamma irradiation damage spontaneously recovers at room temperature.
- Hadron damage creates clusters of defects which cause light transmission loss. The damage is permanent and cumulative at room temperature. Hadron damage causes band-edge shift at low wavelengths of the $PbWO_4$ emission spectrum (orange and red curves).



Partial recover during 2011-2012 data taking

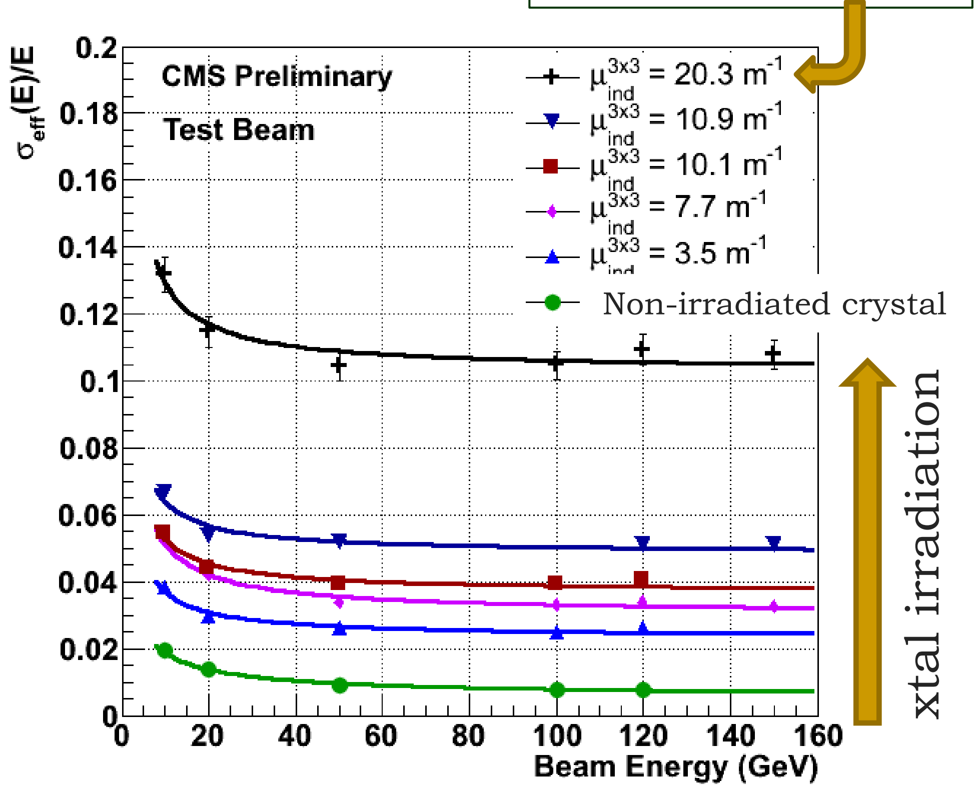


Energy Resolution

Deterioration of ECAL response strongly affect all the contribution to the energy resolution.

$$\frac{\sigma(E)}{E} = \frac{s}{\sqrt{E}} \oplus \frac{n}{E} \oplus c$$

Dose equivalent to end of HL-LHC at |η| = 2.6



Reduction of light output causes:

- Worsening of stochastic term
- Amplification of the noise term
- light collection non-uniformity and deviation from linearity impact on the constant term

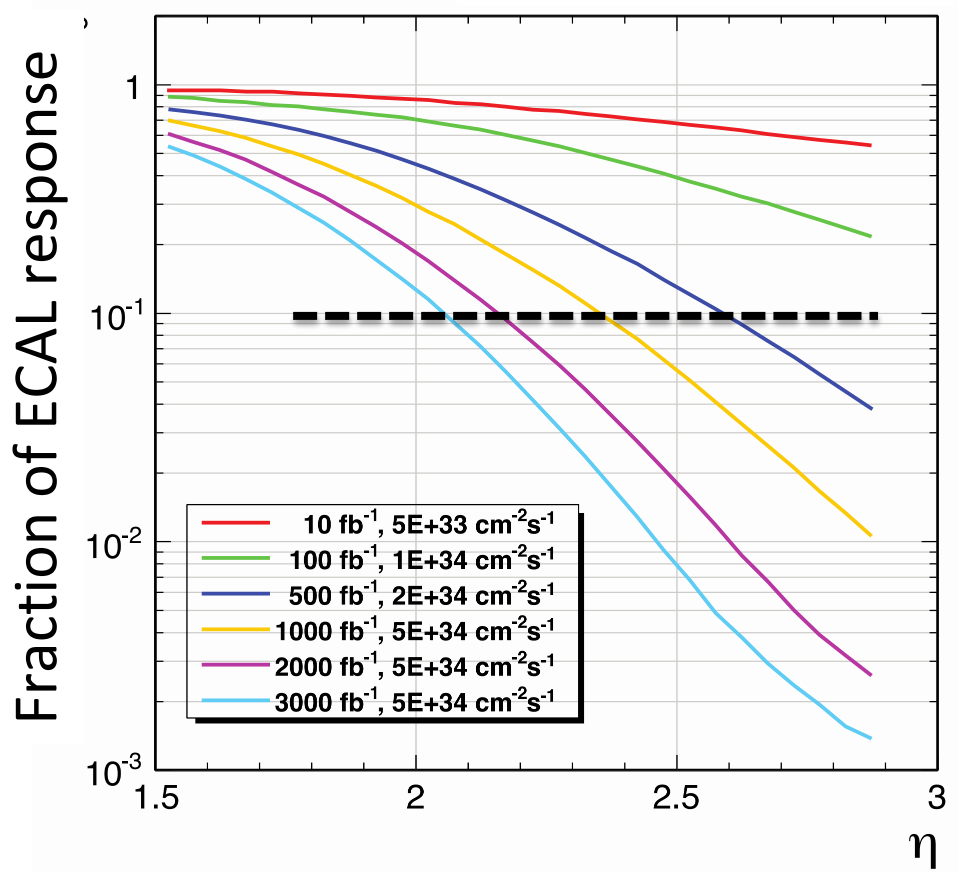
ECAL Endcaps response evolution

Evolution of progressive deterioration of ECAL response vs pseudorapidity (damage on photodetector included)

Energy resolution for e/γ is still acceptable with ECAL response greater than ~ 10% of the non-damaged detector.

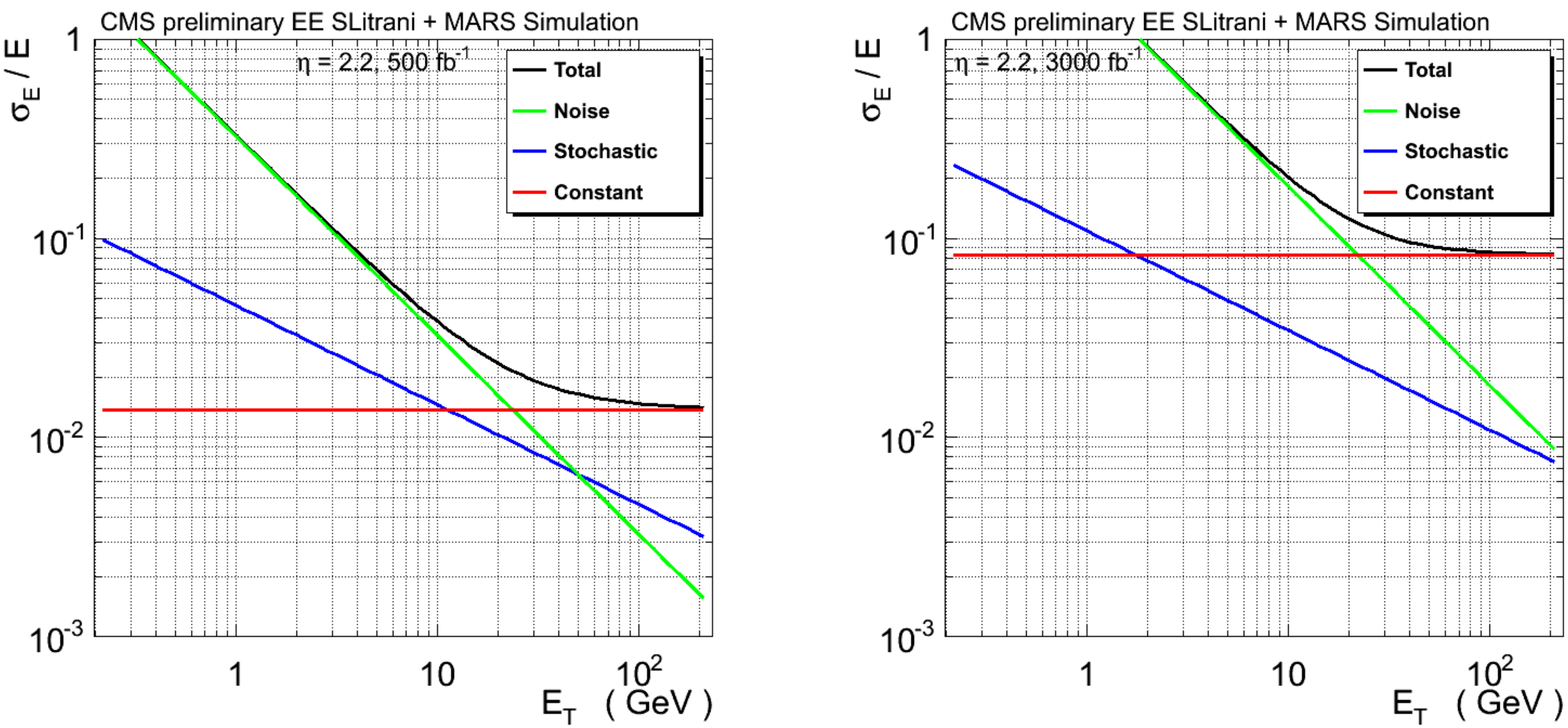
- 500 fb^{-1}: ECAL coverage to $\eta<2.6$ (i.e. full TK fiducial area)
- 1000 fb^{-1}: ECAL coverage to $\eta<2.3$
- 3000 fb^{-1}: ECAL coverage to $\eta<2.1$

Simulation 50 GeV e-



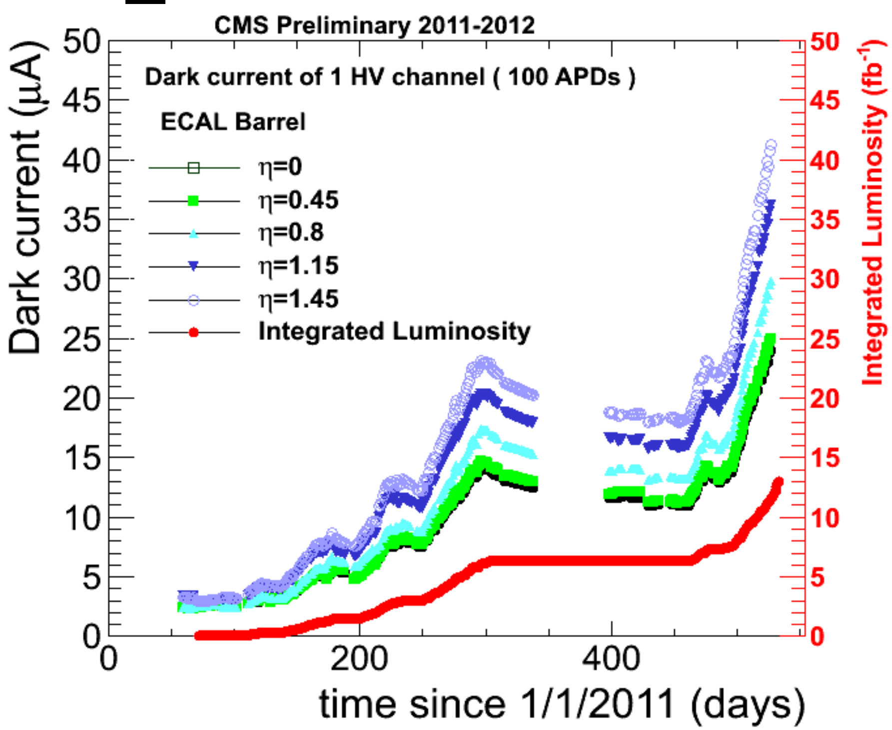
- ECAL endcaps to be replaced after 500 fb^{-1} (during LS3)

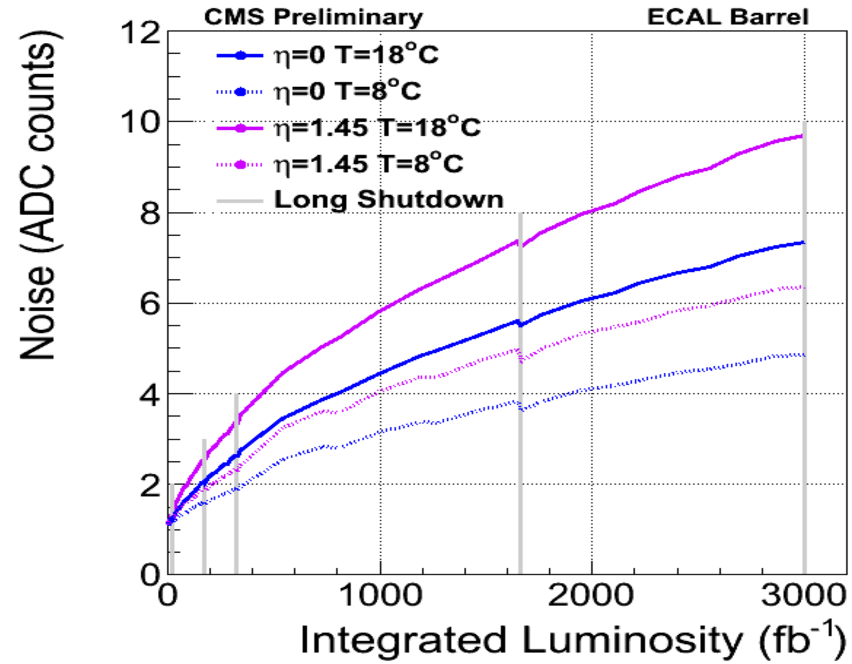
Energy Resolution



- Performance for e/γ is acceptable on the right (~1/2%) while unsustainable on the left (~10%)

APD dark current and noise in ECAL barrel





The dark current evolution in time during the 2011 and 2012 is shown.

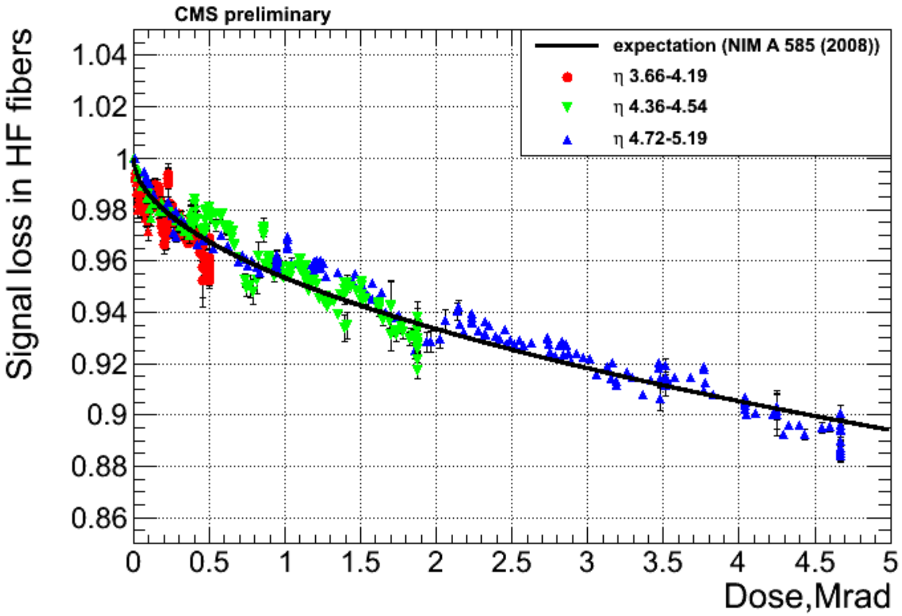
- The APD dark current increases linearly with neutron fluence (which depends on pseudorapidity).

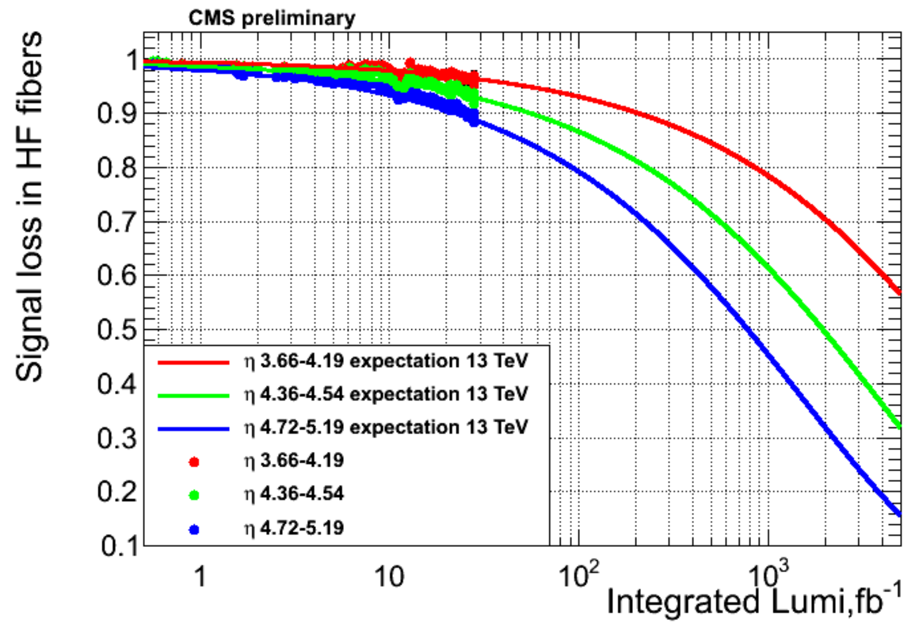
Single channel noise extrapolation.

- Dark current and noise measured for several APDs irradiated at the ENEA up to the HL-LHC expected fluence.
- Goal: energy resolution not overwhelmed by noise from dark current.
- 5 ADC counts equivalent to~ 200 MeV

The dark current can be mitigated by cooling the EB to 8 °C.

Radiation damage to HF



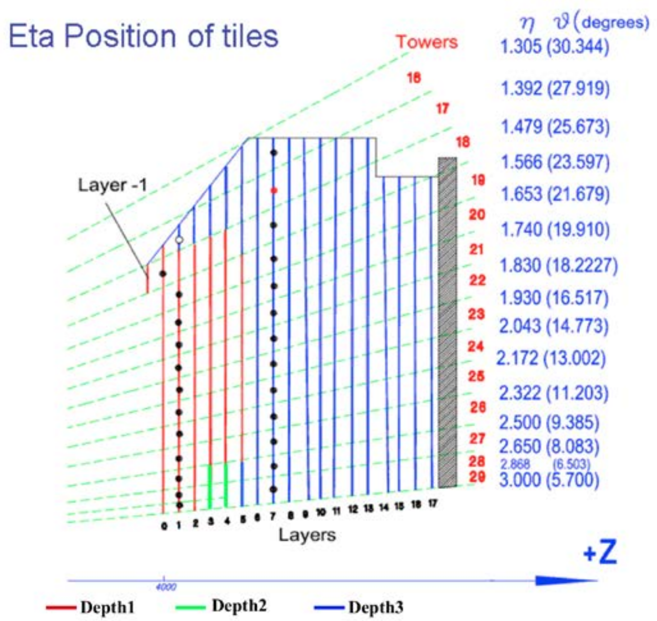


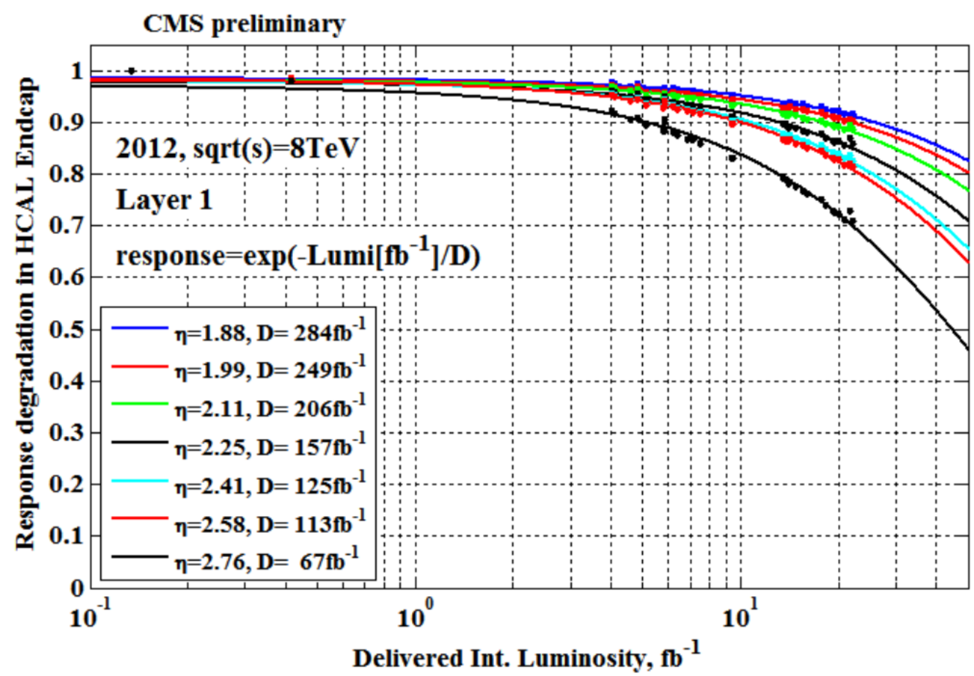
Signal loss in HF due to the radiation induced reduction of quartz fiber transparency.
Laser data shown: 2011+2012 (29 fb^{-1})
Black line is the expectation (not a fit) based on simulation.

Expected loss of signal for up to 3000 fb^{-1}
In the highest η region, signal reduction by factor x3-x4 is expected and can be compensated by re-calibration.
HF will survive 3000 fb^{-1}, at least up to $\eta < 4.5$.

No upgrade of HCAL Forward is planned for LS3

Radiation Damage to HE



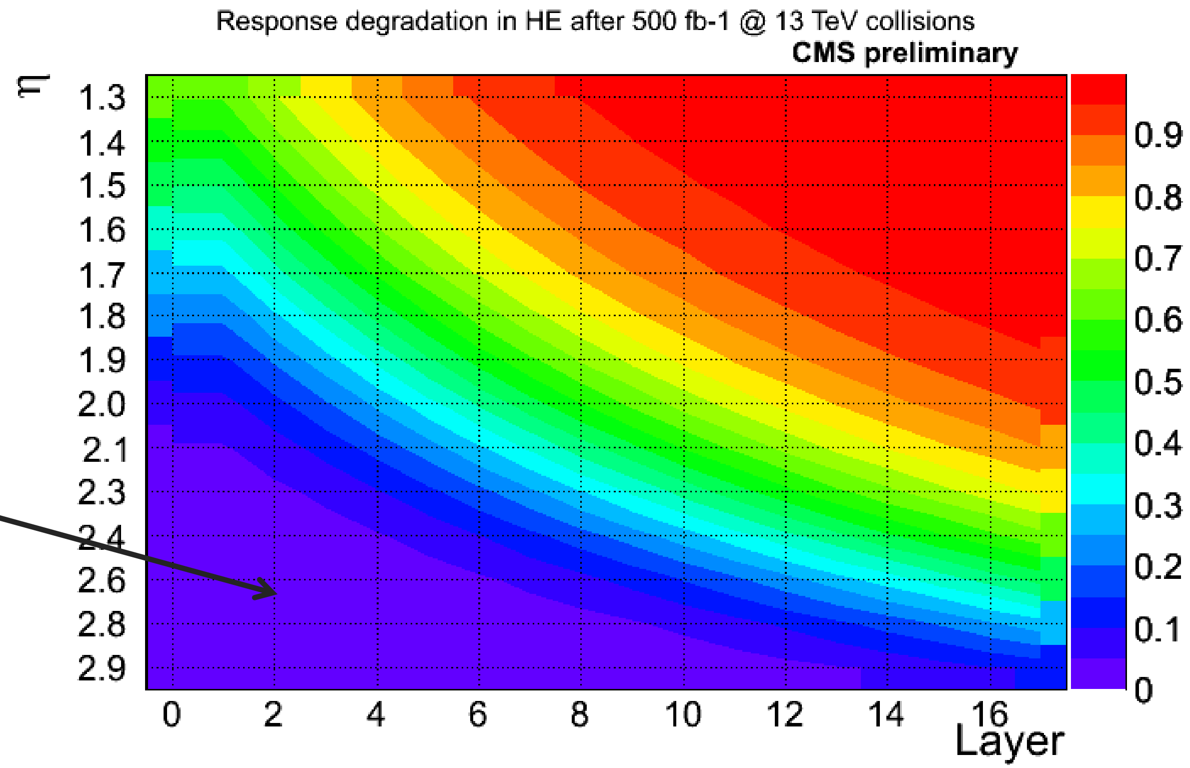


Degradation of signal (loss of scintillation and reduced transmission of light) in CMS HCAL Endcap in 2012 for the first sampling layer.

A signal reduction of ~ 30% is observed at the highest pseudorapidity region (η=3).

Extrapolated signal degradation in HE

Here signal drops to (less than) 5% of the original value.



- Extrapolation of degradation based on the 2012 data.
- HCAL Barrel will be highly performant to 3000 fb-1
  HCAL Endcaps will be replaced after 500 fb^{-1} (during LS3)

The two scenarios for the Endcap Calorimetry

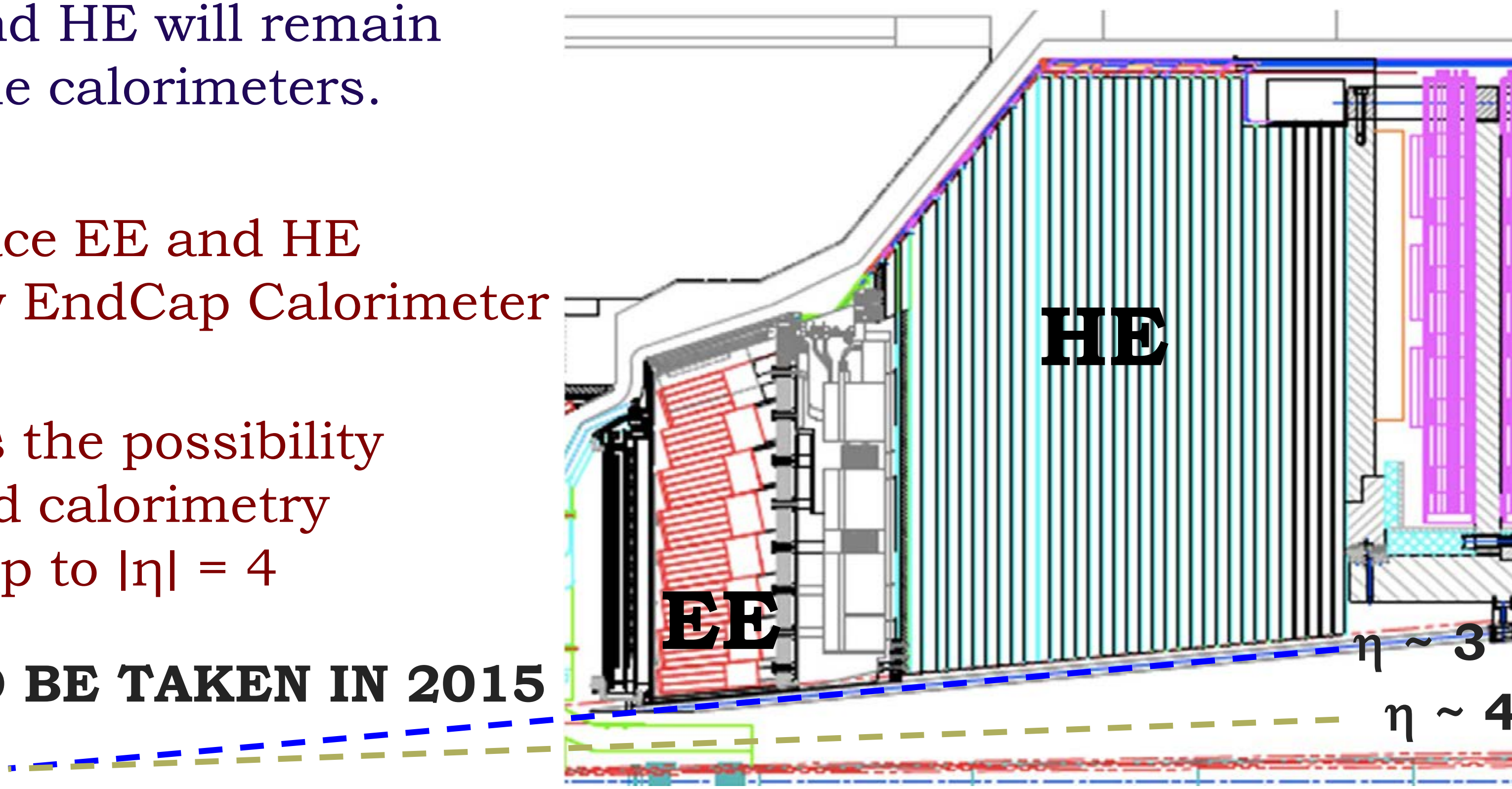
- CMS plan is to replace the Endcap calorimeters in LS3

SCENARIO 1:

- Maintain present geometry
- New EE and HE will remain stand-alone calorimeters.

SCENARIO 2:

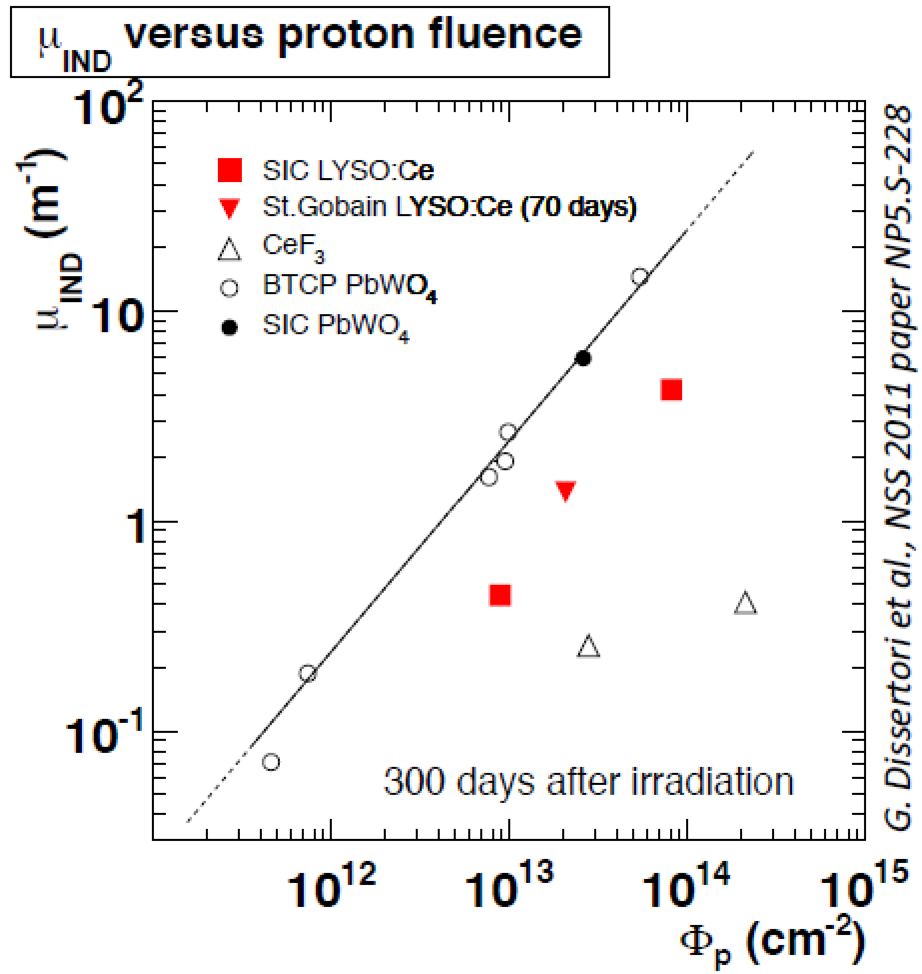
- Fully replace EE and HE with a new EndCap Calorimeter system.
- This opens the possibility of extended calorimetry coverage up to |η| = 4



DECISION TO BE TAKEN IN 2015

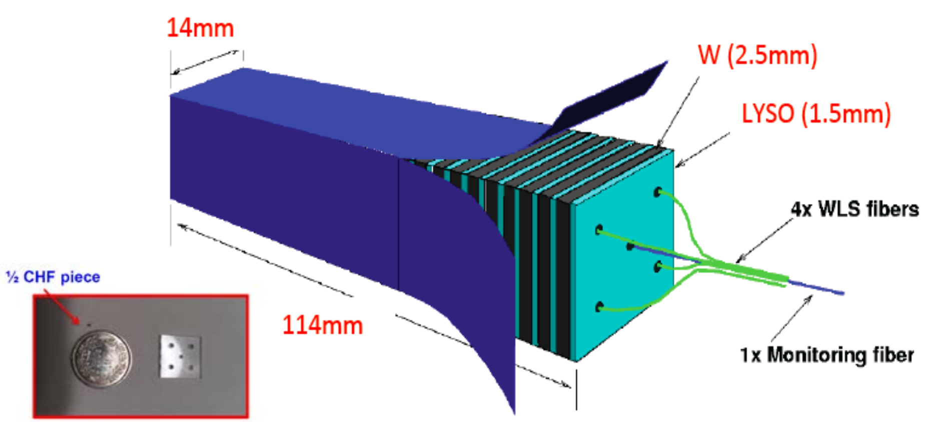
R&D on new scintillators

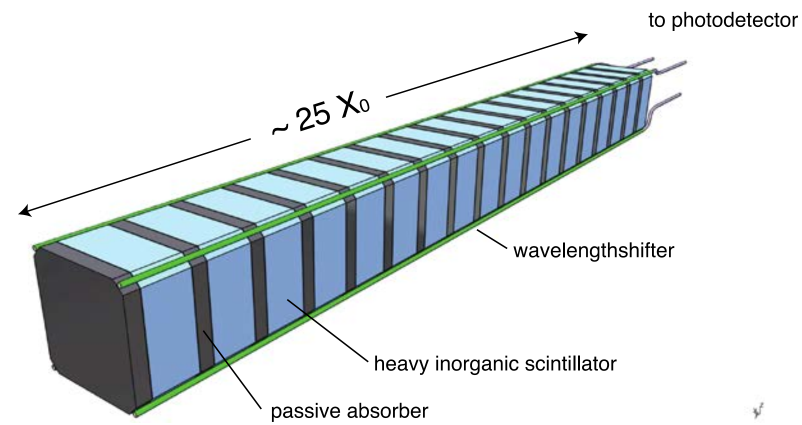
- R&D on new crystal materials and new growing techniques are ongoing.
- Key points are:
  - radiation hardness, especially for hadron damage
  - light emission spectrum matching to WLS fibers or rad-hard photo-detectors



Scenario 1: new standalone ECAL Endcap

- **Sampling calorimeter**
  - Rad-hard inorganic scintillator e.g. LYSO or CeF_3 and tungsten as absorber
  - Light readout with wavelength shifting fibers (WLS) in a shashlik configuration or running along chamfers





- $\Delta E/E \sim 10\%/\sqrt{E} + 1\%$

- *<u>Challenges</u>: rad-hard fibers, photo-detectors, mechanical mounting (tolerances)*

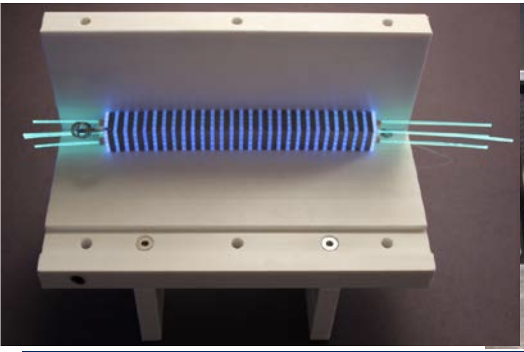
Prototype test beam

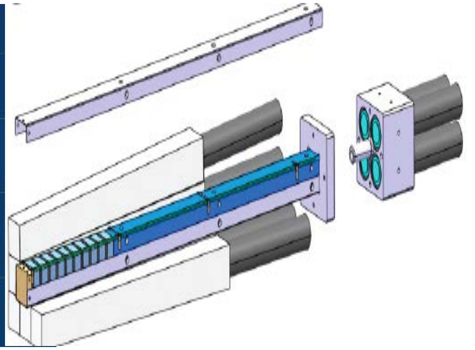
LYSO test beam in Fermilab:

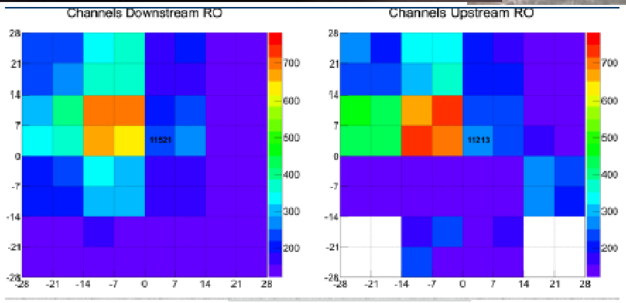
- 4x4 module prototype, 364 LYSO xtals
- WLS readout at both ends with SiPMs
- Laser calibration in central fiber
- proton, electron and pion beams
- beam energy up to 120 GeV

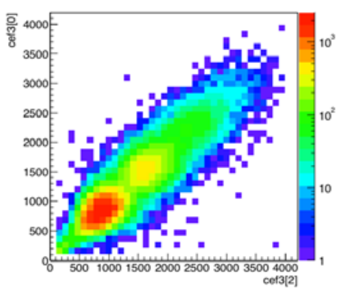
CeF3 test beam in Frascati:

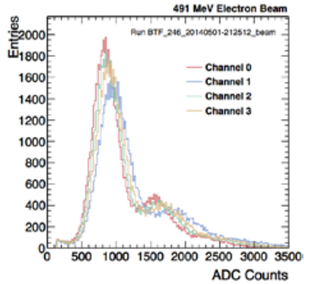
- 10 x (3.1 mm W + 10 mm CeF3)
- Scintillating fiber readout with PMTs
- 8 BGO surrounding crystals
- electron beam at 490 MeV









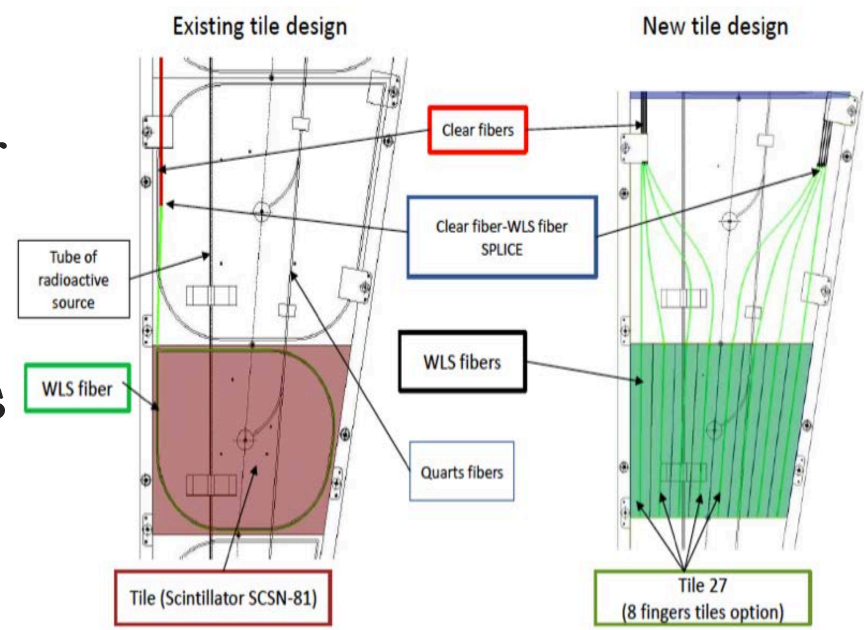


Data analysis on going

Higher energy test beam scheduled at the end of october in the H4 area at Cern

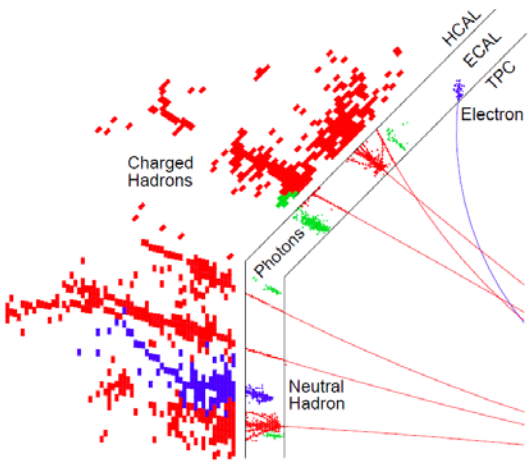
Scenario 1: replacement of HE active readout

- Option considered:
  modification of the layout of wavelength shifting (WLS) fiber within scintillator tile to shorten light path length
- Ongoing R&D:
  - Replacement of scintillator material with radiation tolerant version
  - Replacement of WLS fibers with quartz capillaries



Scenario 2: new combined Endcap Calorimeter

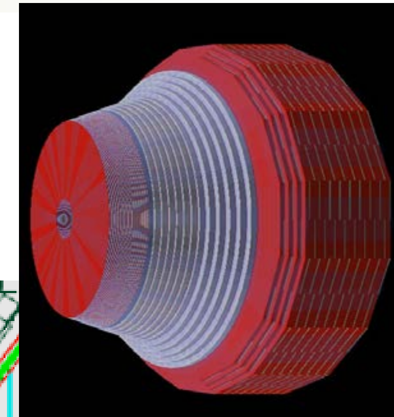
- **High Granularity Calorimeter (HGCAL)**: measure charged particle momentum with the inner tracker, and neutrals in the calorimeter (Particle Flow)
- Key point: resolving/separating showers through a finely granulated and longitudinally segmented calorimeter.
- Planes of Si separated by lead/Cu or brass
- *Challenges:*
  number of channels and data transmission, compact and inexpensive electronics, L1 trigger, cooling, high pile-up, mechanical mounting

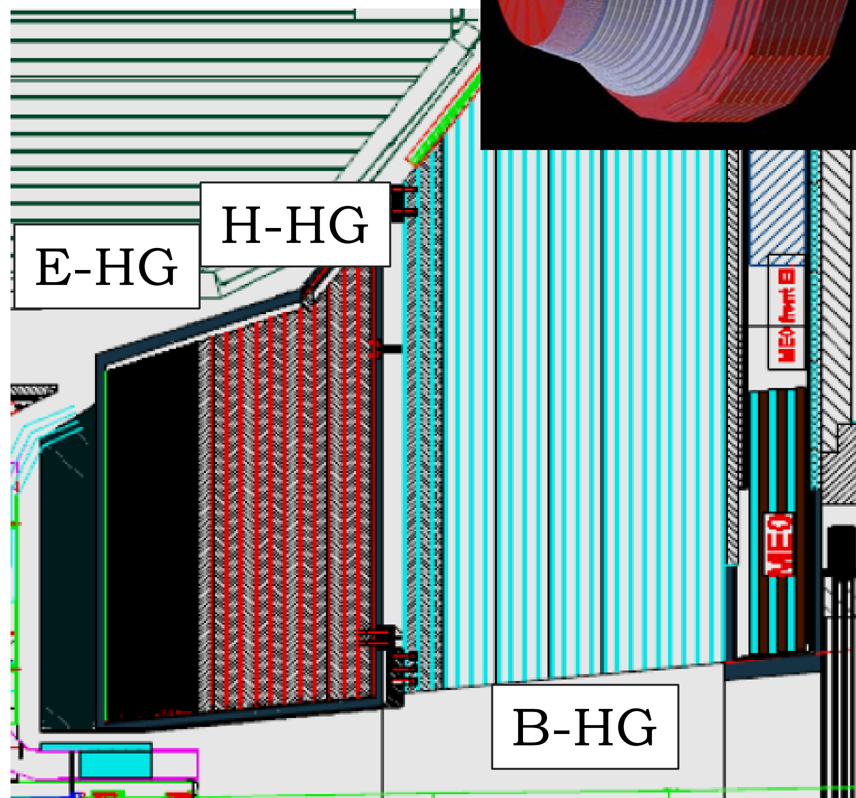


HGCAL concept

High Granularity Calorimeter

- E-HG: ~33 cm, 25 X_0, 1λ, 30 layers:
  - 10 planes of Si separated by 0.5 X_0 of tungsten/lead
  - 10 planes of Si separated by 0.8 X_0 of tungsten/lead
  - 10 planes of Si separated by 1.2 X_0 of tungsten/lead
- H-HG: ~66 cm, 3.5λ:
  - 12 planes of Si separated by ~0.3λ of brass absorber
- E-HG + H-HG:
  - Fine grain pads 0.45 and 0.9 cm^2
  - 9M channels and 660 m^2 of silicon
- B(back)-HG as HE re-build 5λ
- $\Delta E/E \sim 20\%/\sqrt{E}$
  3D shower reconstruction
  - Use shower topology to mitigate PU effect





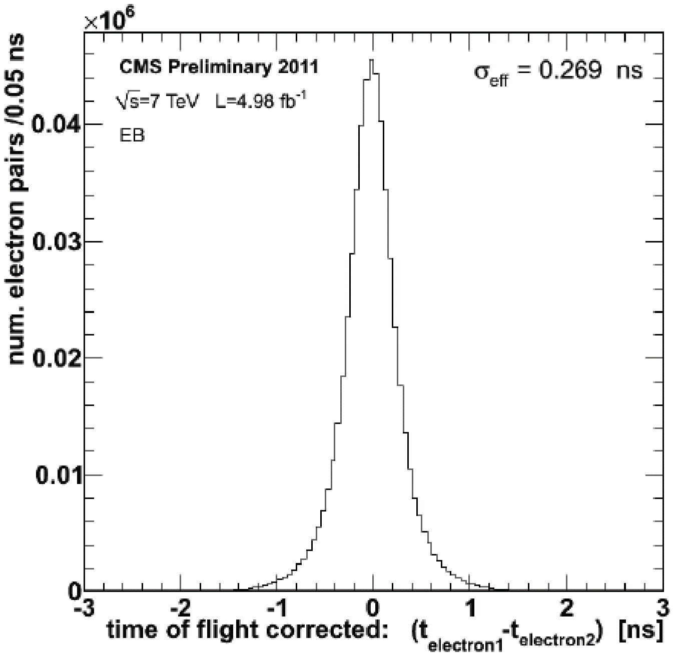
Pile-up mitigation with precise timing

Pile-Up Mitigation

- PU particles overlap with main event objects spoiling resolution (bad energy measurement) and reconstruction (fake objects are created).
- 30-40% of the energy in a jet is coming from **photons** or **neutral hadrons** (→ so no tracker information for PU cleaning).
- Pile-up is most critical in the forward region
- Upgrades must aim at optimizing forward detector for high pile-up condition

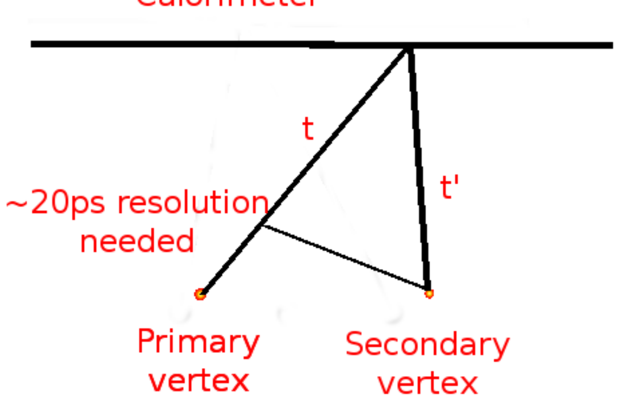
Two areas of study :

- Increased granularity and segmentation may help to separate out pile-up activity from primary event physics objects.
- High precision (pico second) timing may help in pile-up mitigation.
  The subdetector providing the precision timing may best be associated to precise and finely segmented detector → ECAL
  - Object reconstruction
  - Object-to-vertex attribution



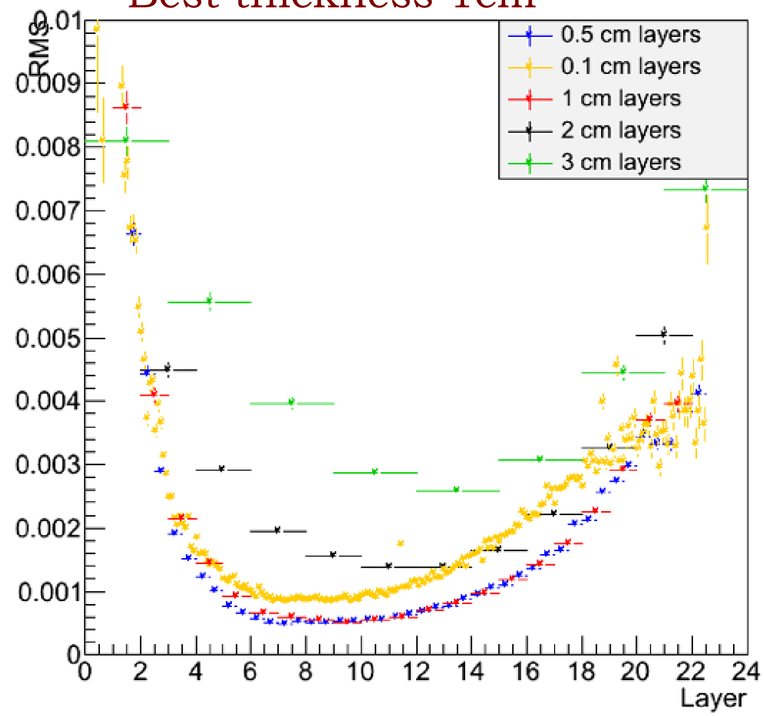
Pile-Up Mitigation with precise timing

- Desired time resolution is 20-30 ps (~ 1 cm in vertex resolution)
- Generic R&D on MicroChannelPlates and fast timing Si (highly doped) sensors. R&D also on timing with LYSO crystals.



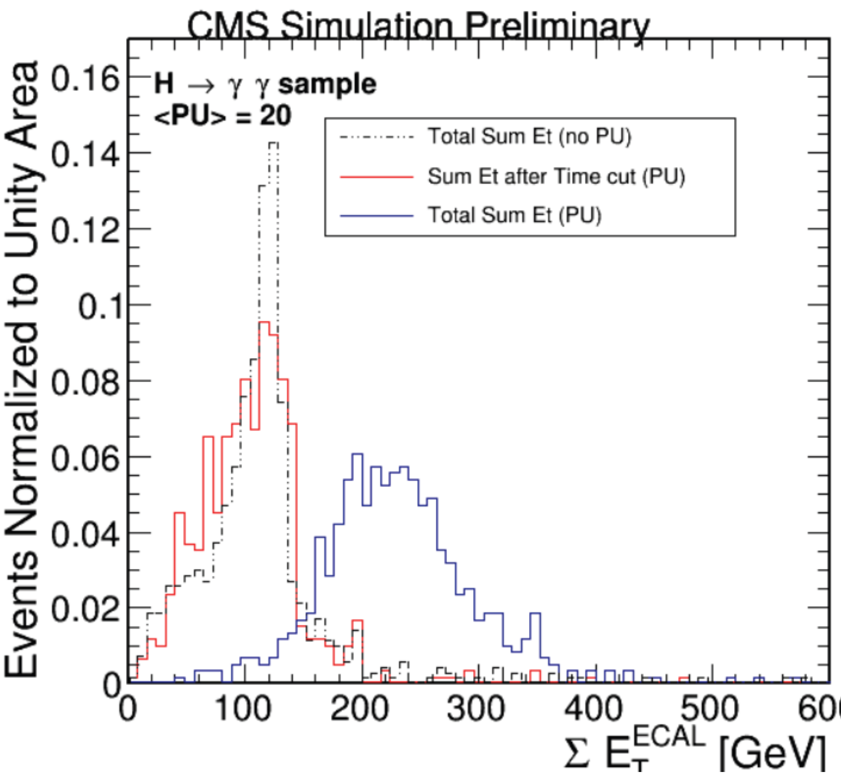
GEANT4 toy simulation with *"crystal slices"* to study detector configuration (25 GeV photons)

- Best resolution at 7-8 X_0
- Best thickness 1cm



Pile-Up Mitigation with precise timing

- **Effect of timing cut** on ΣE_T^{ECAL} variable
  - sum of all ECAL hits with E > 1GeV.
- O(30 ps) resolution detector simulated
- Require ECAL timing (time-of-flight subtracted) within a **90 ps window**
- Most of the **PU extra energy gone**
  - able to almost recover no PU conditions
- Timing-based selection looks **promising for high PU environment**



In summary

- Modern calorimeters at the LHC already shown excellent performance in terms of stability, energy resolution, timing, etc.
- They played a crucial role in the discovery of the Higgs Boson and will be fundamental in Run2 as well.
- The HL-LHC poses severe requirements to detectors in terms of performance and rad-hardness.

In these lectures I mainly discussed LHC calorimeters, with a brief overview to other HEP calorimeters. But calorimetry is also important in many other fields: space experiments, neutrino experiments, medical applications, etc.

Six more hours (…and another speaker… ☺) would be needed to cover everything.

THANK YOU