Upgrade of the CMS Forward Calorimetry

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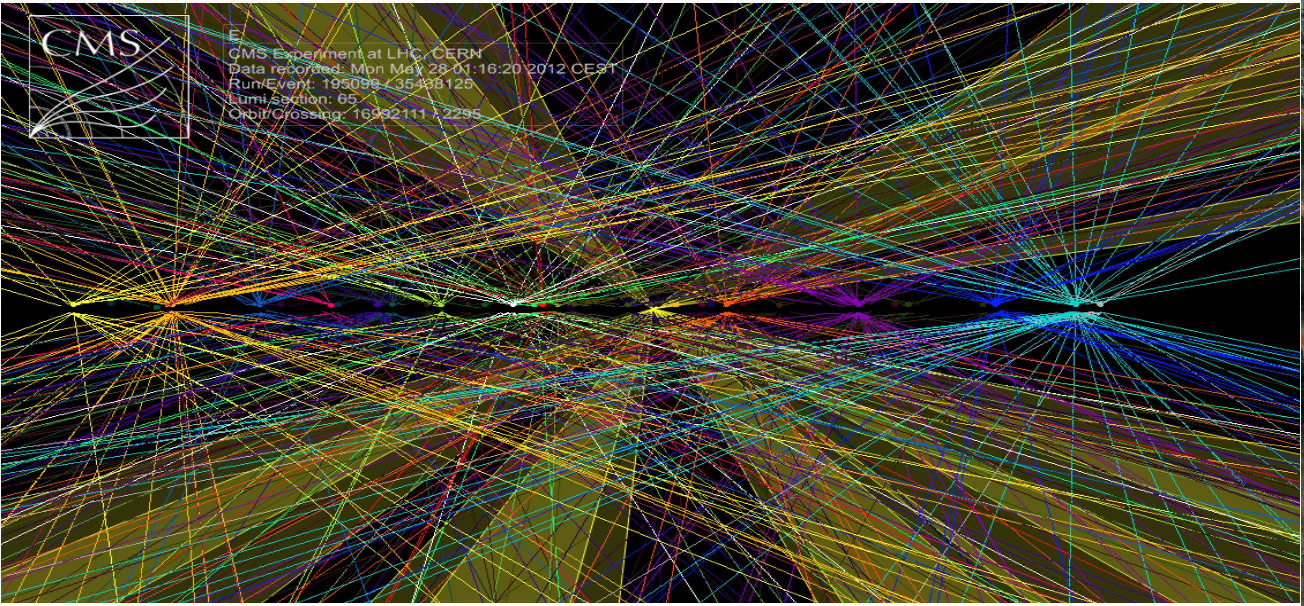
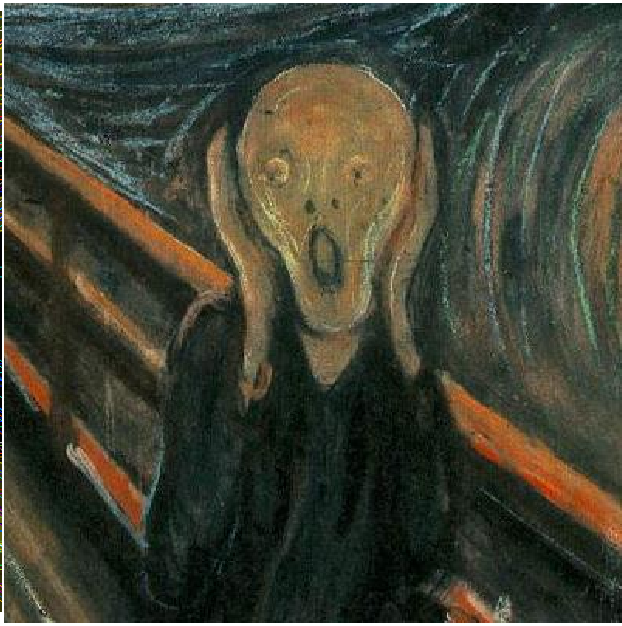
Outline

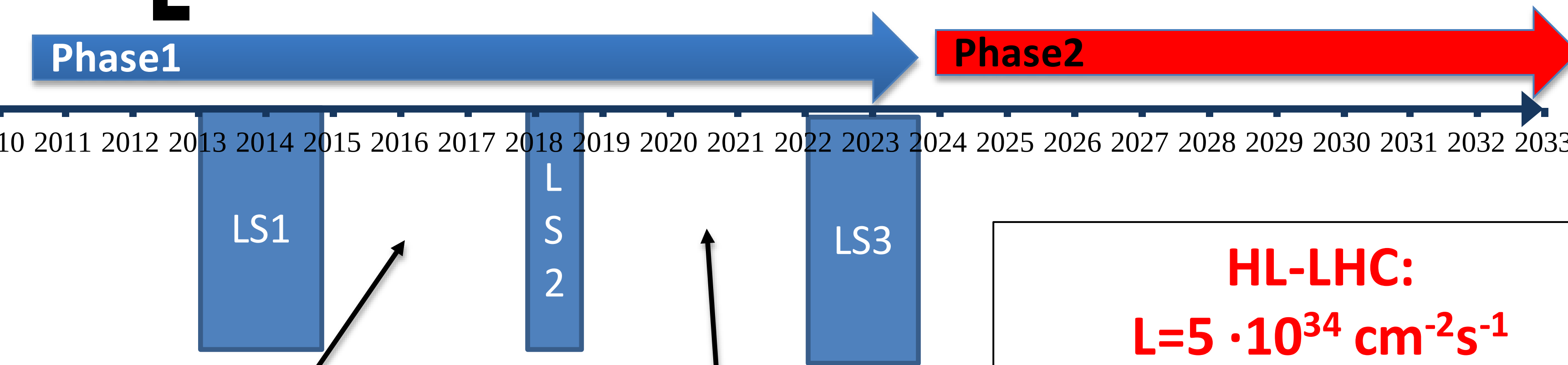
- Radiation damage at HL-LHC
- ECAL and HCAL performance at high luminosity
- Pile-Up mitigation
- Scenarios for the new Endcap Calorimeter.





The scream (E. Munch 1893)

LHC and HL-LHC

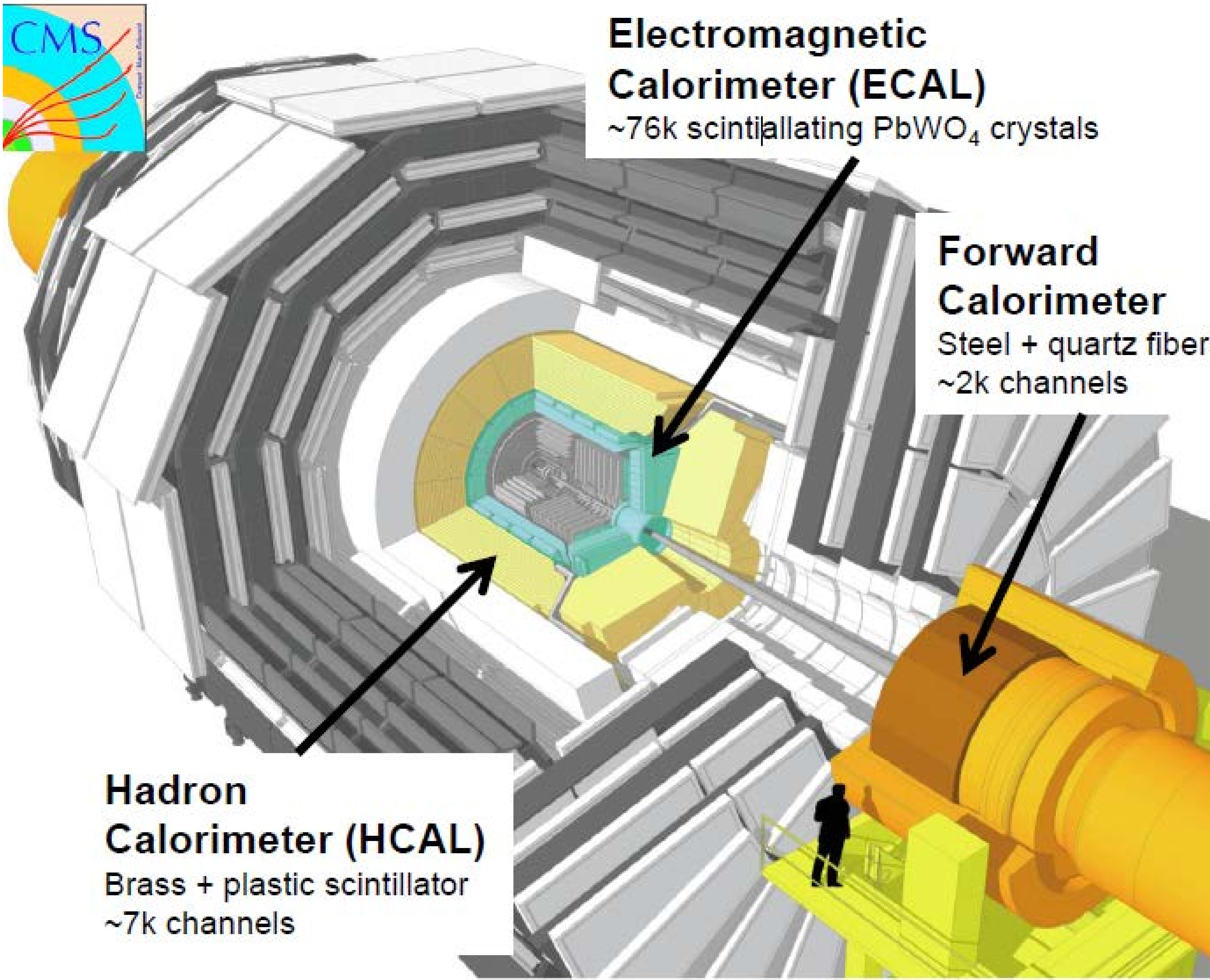


E = 13 TeV
L=1 $\cdot 10^{34}$ cm^{-2}s^{-1}
<PU> ~ 40
50 fb^{-1} per year

L=2 $\cdot 10^{34}$ cm^{-2}s^{-1}
<PU> ~ 60
≥50fb^{-1} per year
by the end of Phase1
300-500 fb^{-1}

HL-LHC:
L=5 $\cdot 10^{34}$ cm^{-2}s^{-1}
250 fb^{-1} per year
by 2033 → 3000 fb^{-1}
<PU> ~ 140 events
spread in *z* over ~ 5 cm

- **~25 years of operation since installation instead of anticipated 10 years.**
- **We will see that while the barrel calorimeters and forward calorimeter (HF) will perform to 3000 fb-1, the endcap calorimeters must be upgraded in LS3**

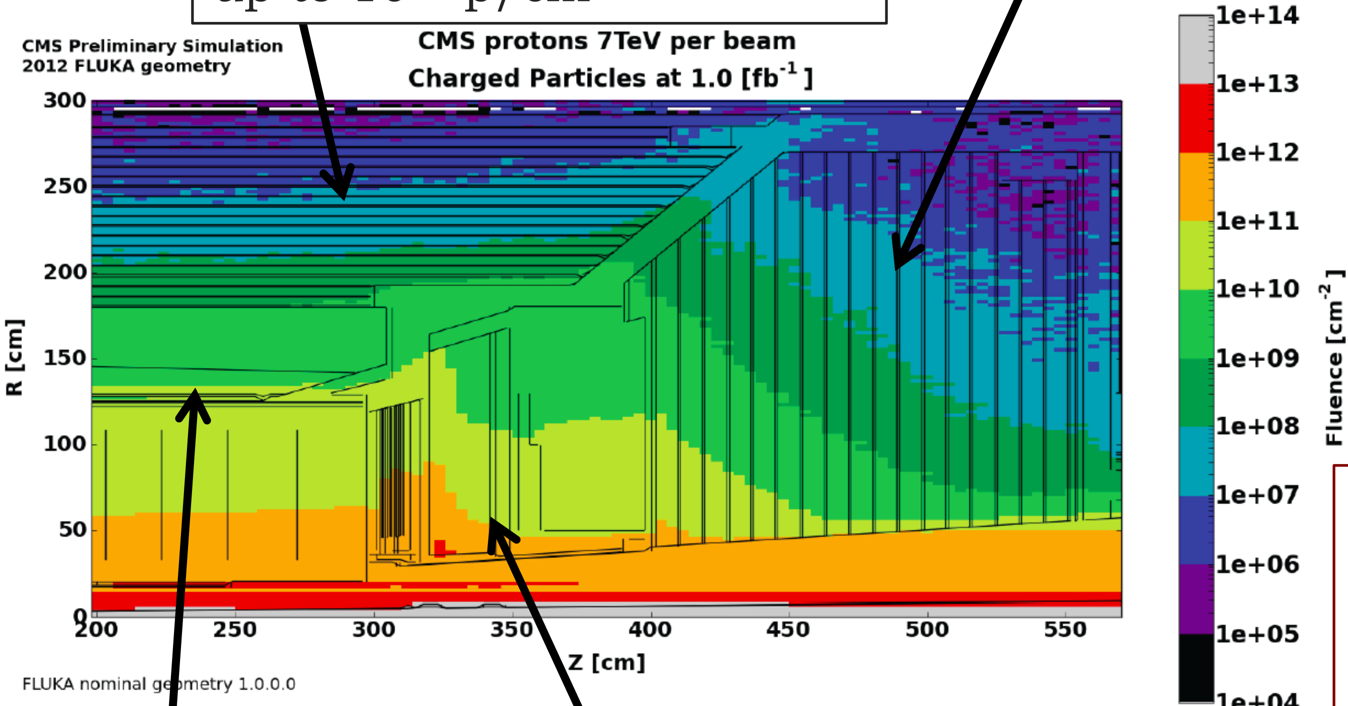


CMS
Electromagnetic
Calorimeter (ECAL)
~76k scintiallating $PbWO_4$ crystals
Forward
Calorimeter
Steel + quartz fibers
~2k channels
Hadron
Calorimeter (HCAL)
Brass + plastic scintillator
~7k channels

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



1 Gy = 1 Joule/kg = 3x 10^9 mips/cm^2 of material with unit density

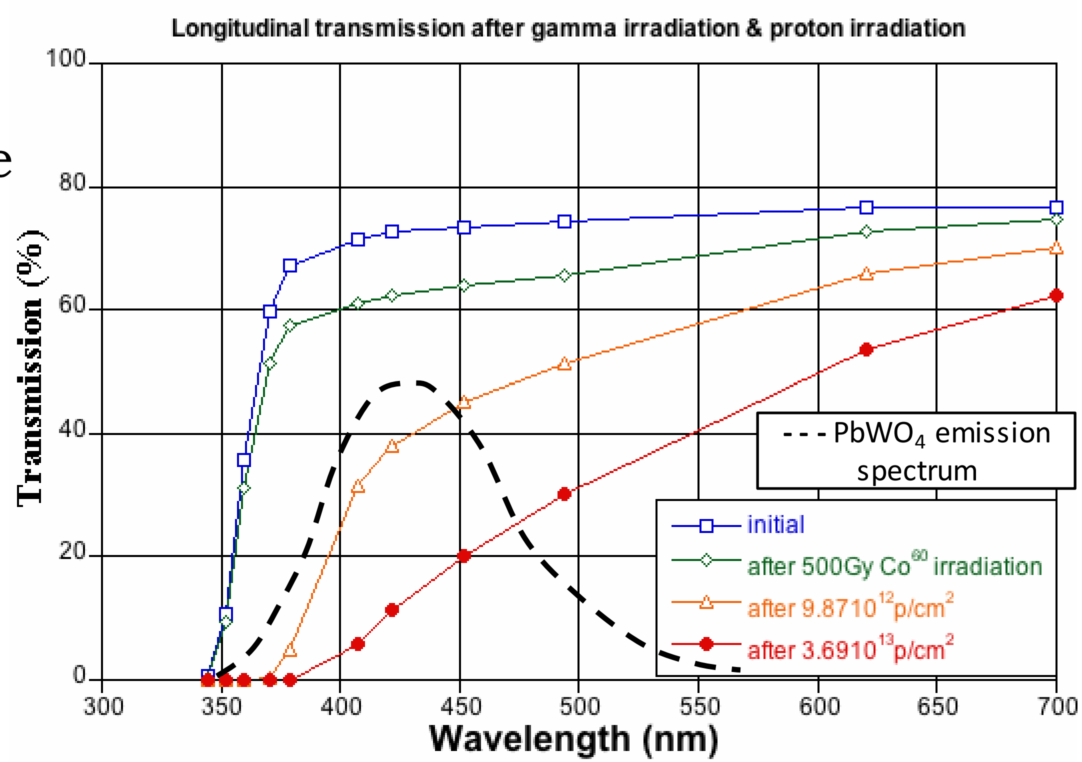
ECAL barrel: 3 Gy/h and 2x10^{12} p/cm^2

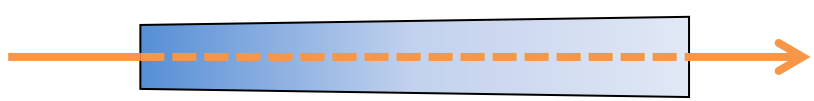
ECAL endcap at η=2.6: 65 Gy/h and 2x10^{14} p/cm^2

Radiation damage to $PbWO_4$ crystals

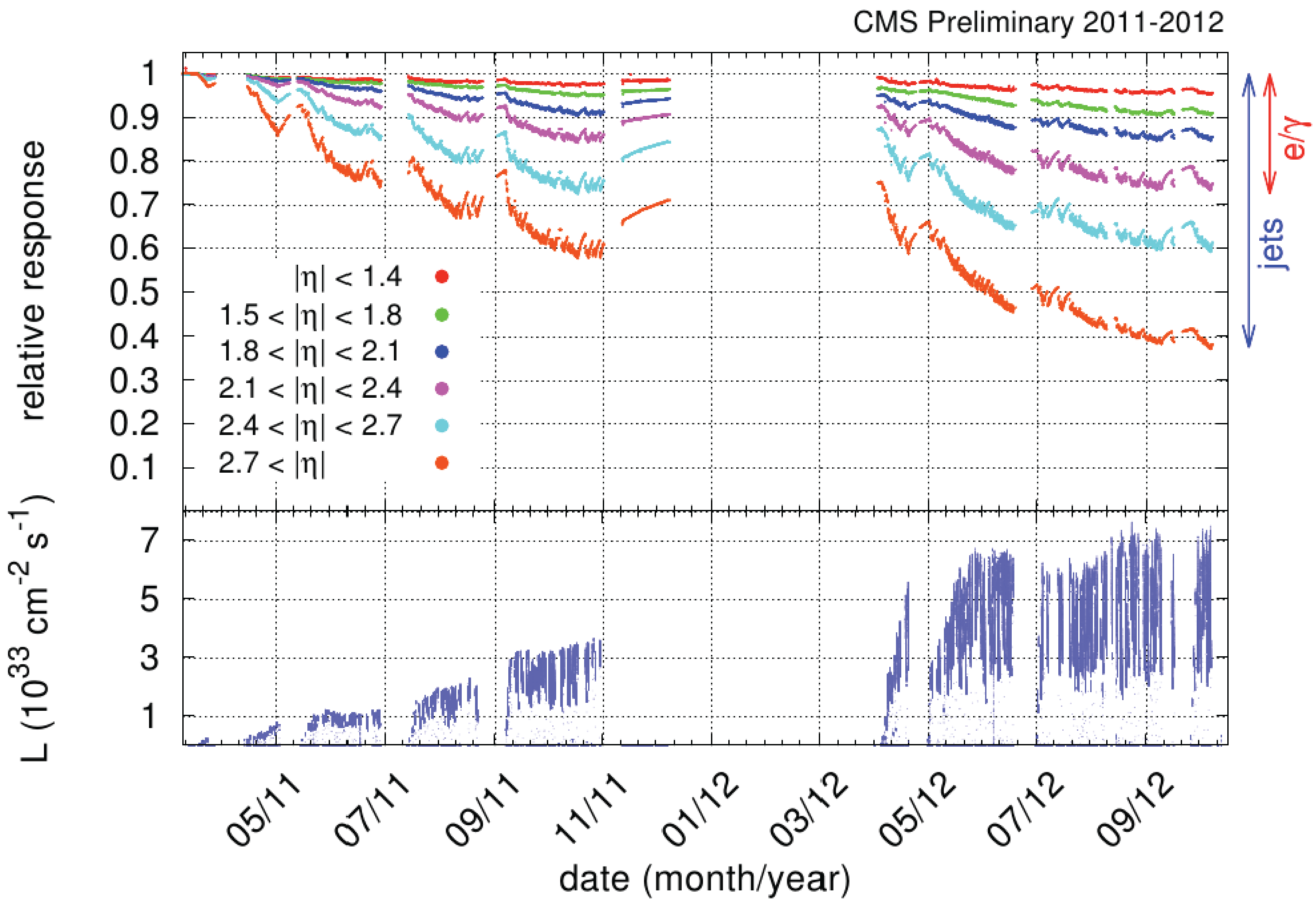
Crystals are subject to two types of irradiation:

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





ECAL monitoring response in 2011-2012



ECAL Endcaps response evolution

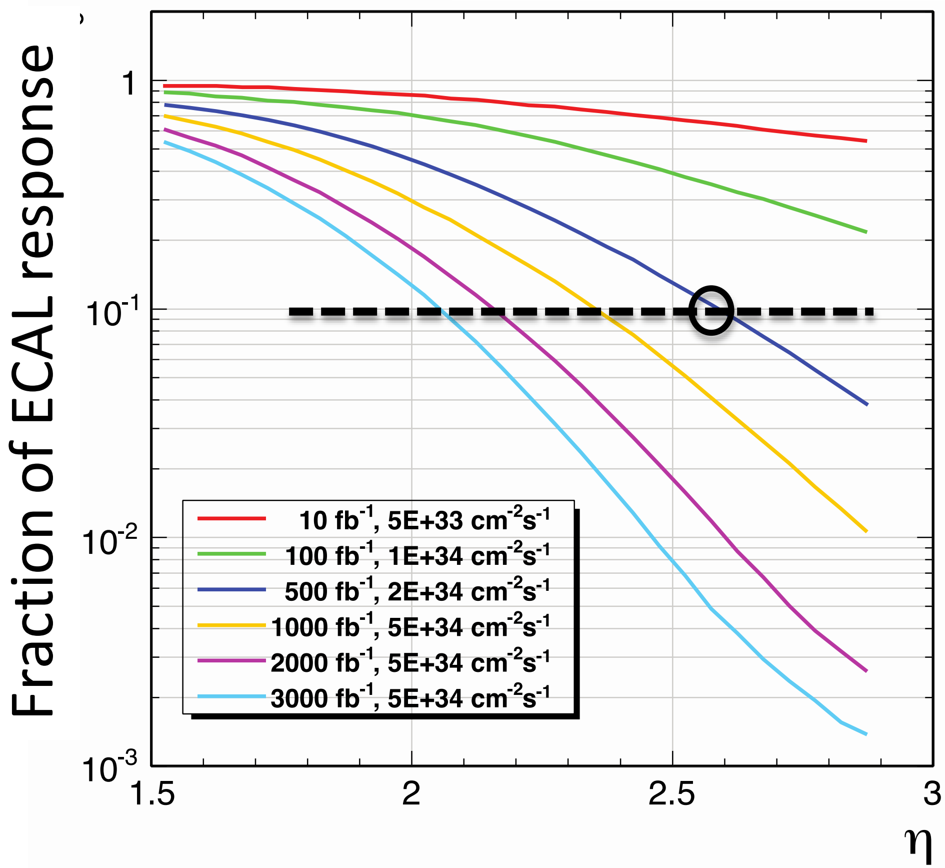
Progressive deterioration of ECAL response with strong η dependence

The 10 fb^{-1} curve is in quite good agreement with the July 12 signal loss in the previous slide.

Threshold at 10% light remaining:

- 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-



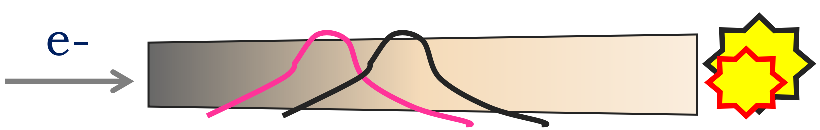
Energy Resolution

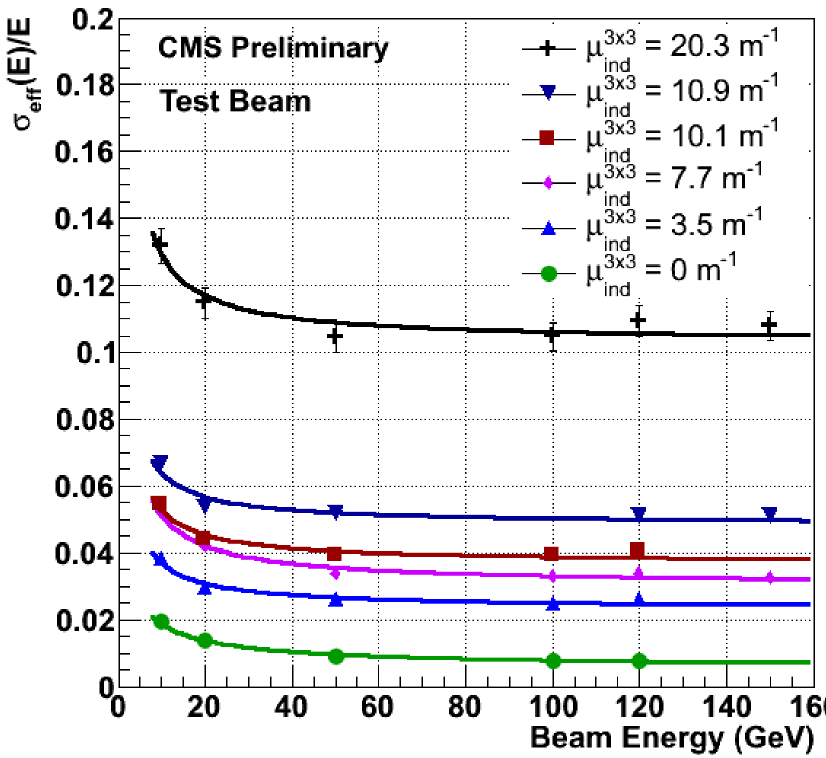
Deterioration of ECAL response strongly affect all the contribution to the energy resolution.

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

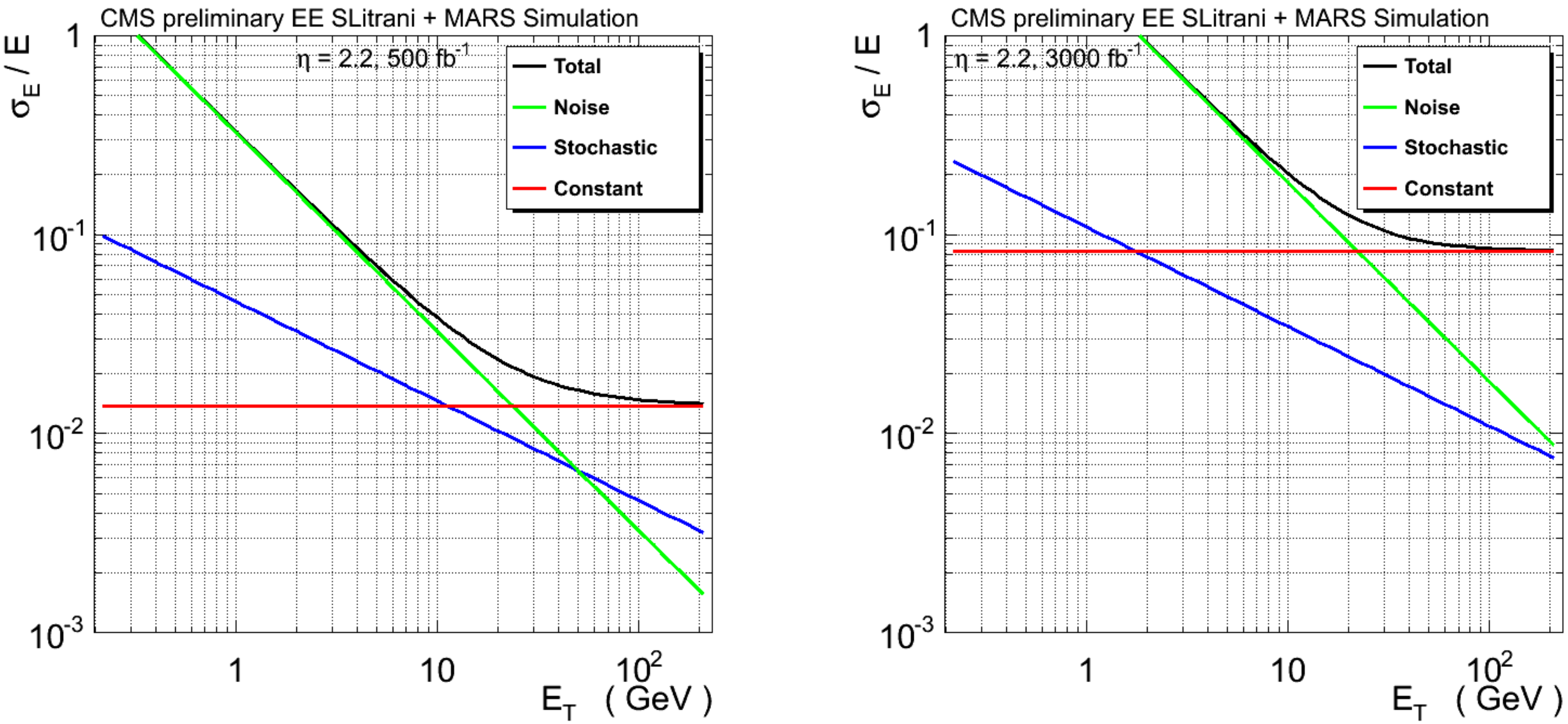
Reduction of light output causes:

- Worsening of stochastic term
- Amplification of the noise
- light collection non-uniformity (impact on the constant term)



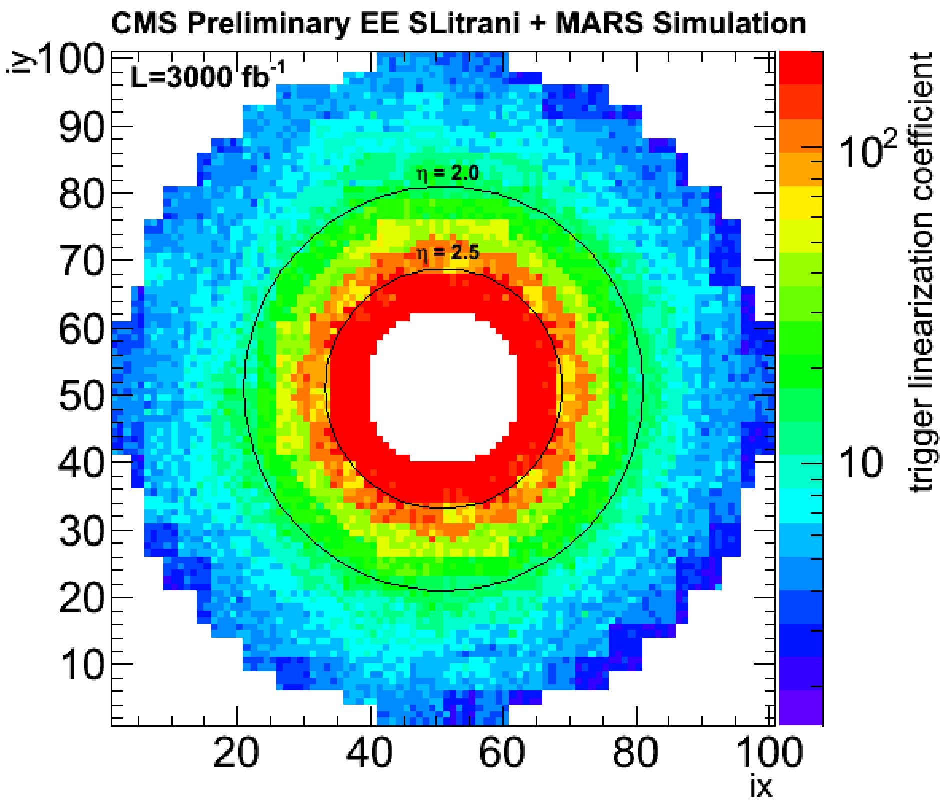


Energy Resolution



- Performance for e/γ is acceptable on the right (~1/2%) while unsustainable on the left (~10%)
- ECAL endcaps to be replaced after 500 fb^{-1} (during LS3)

Triggering on EE after 3000 fb^{-1}

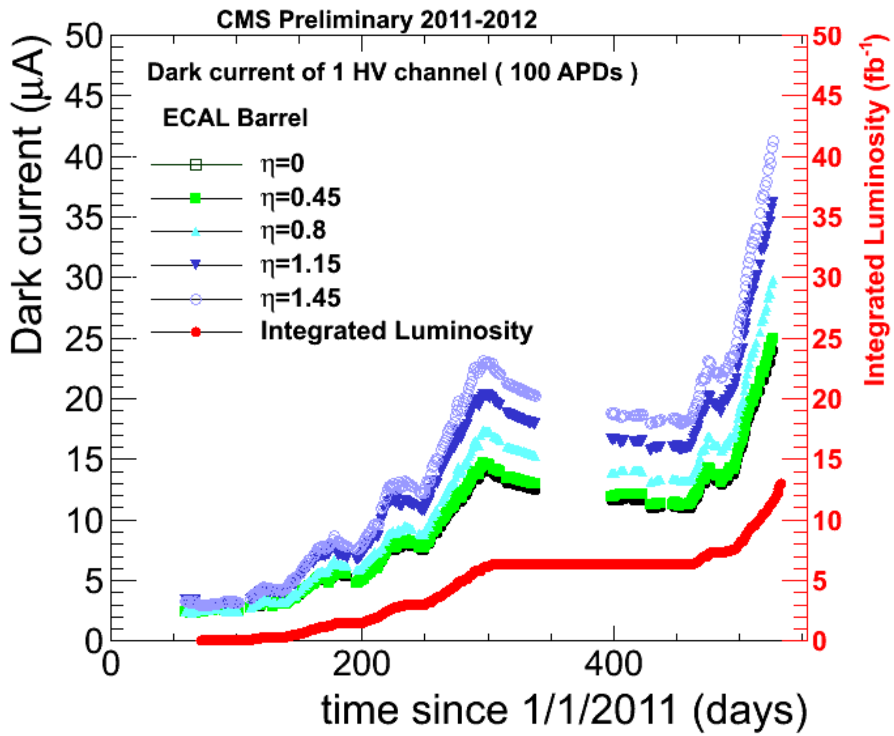


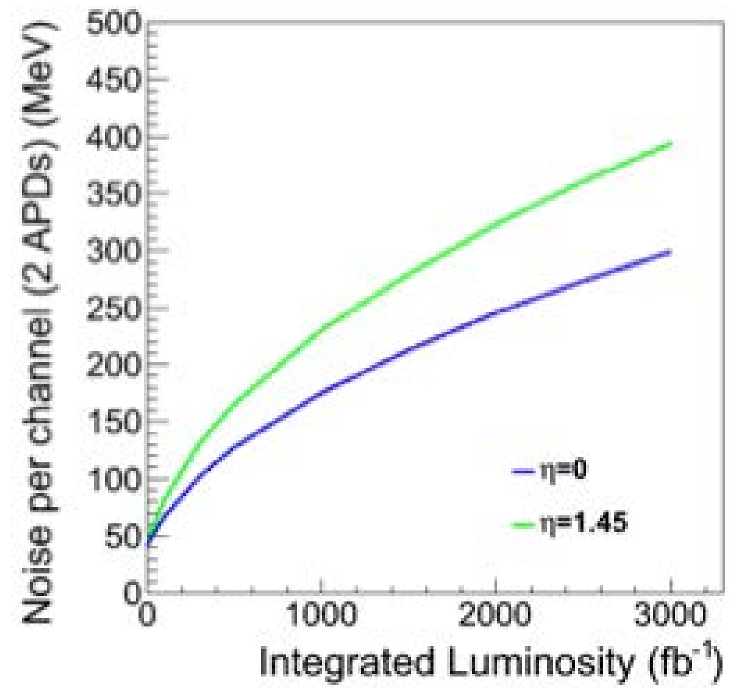
At 3000 fb^{-1} significant regions of EE have calibration factor x 100 to adjust for light output loss

Effective noise will be 12 GeV per crystal that is 60 GeV in 5x5 trigger tower.

In Phase II we would progressively lose the ability to trigger on increasingly large parts of EE

APD dark current and noise in ECAL barrel



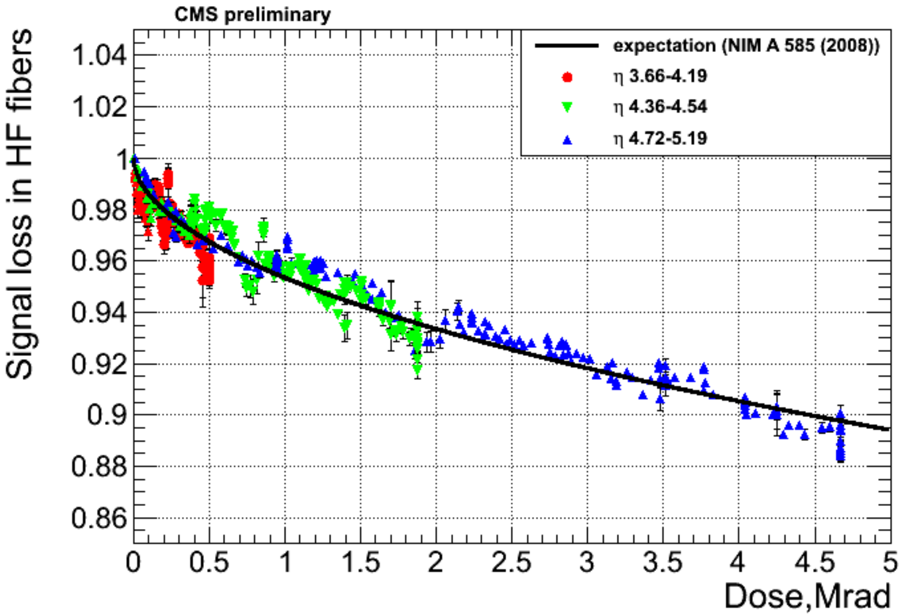


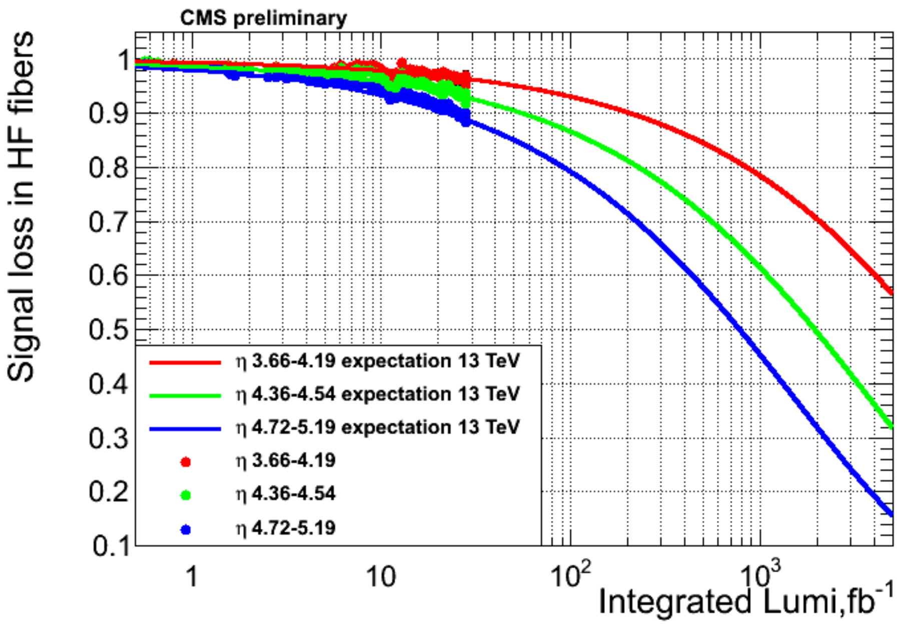
The APD dark current increases linearly with neutron fluence (which depends on pseudorapidity).
The dark current evolution in time during the 2011 and 2012 is shown.

<u>As a consequence there will be an increase in noise in EB.</u>
This increase would worsening the needed capability of rejecting spikes at trigger level.

<u>The dark current can be mitigated cooling the EB.</u>

Radiation damage to HF



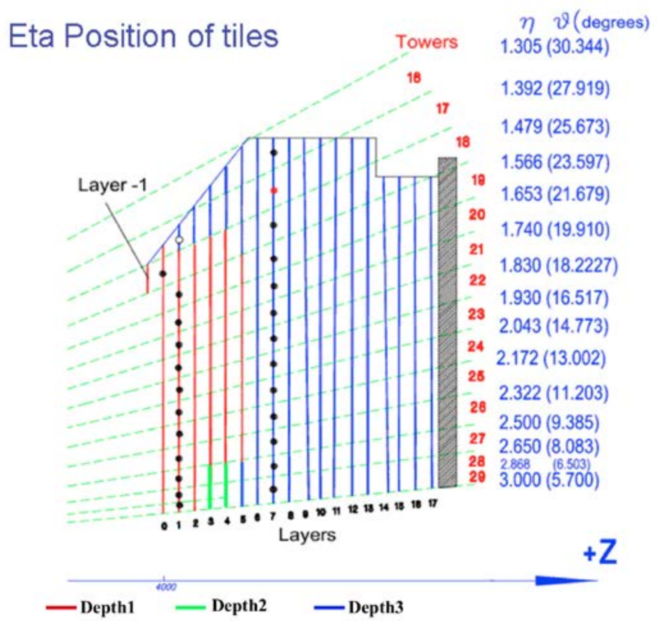


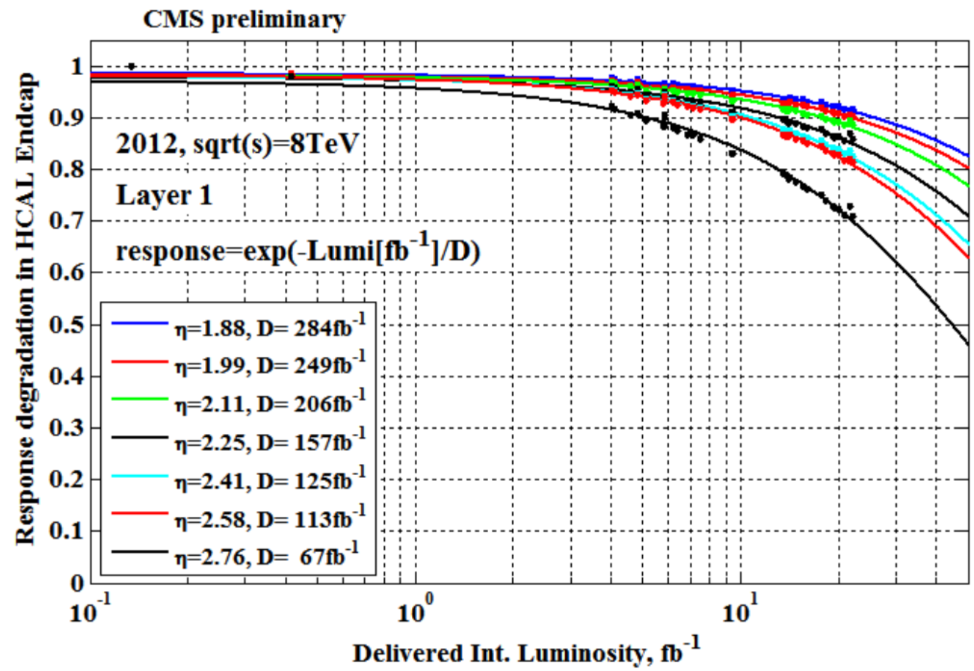
Signal loss in HF due to the radiation induced reduction of quartz fiber transparency.
Laser data shown: 2011+2012 (29 fb^{-1})
Black line is the expectation (not a fit) based on simulation.

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 $\eta < 4.5$.

<u>No upgrade of HCAL Forward is planned for LS3</u>

Radiation Damage to HE

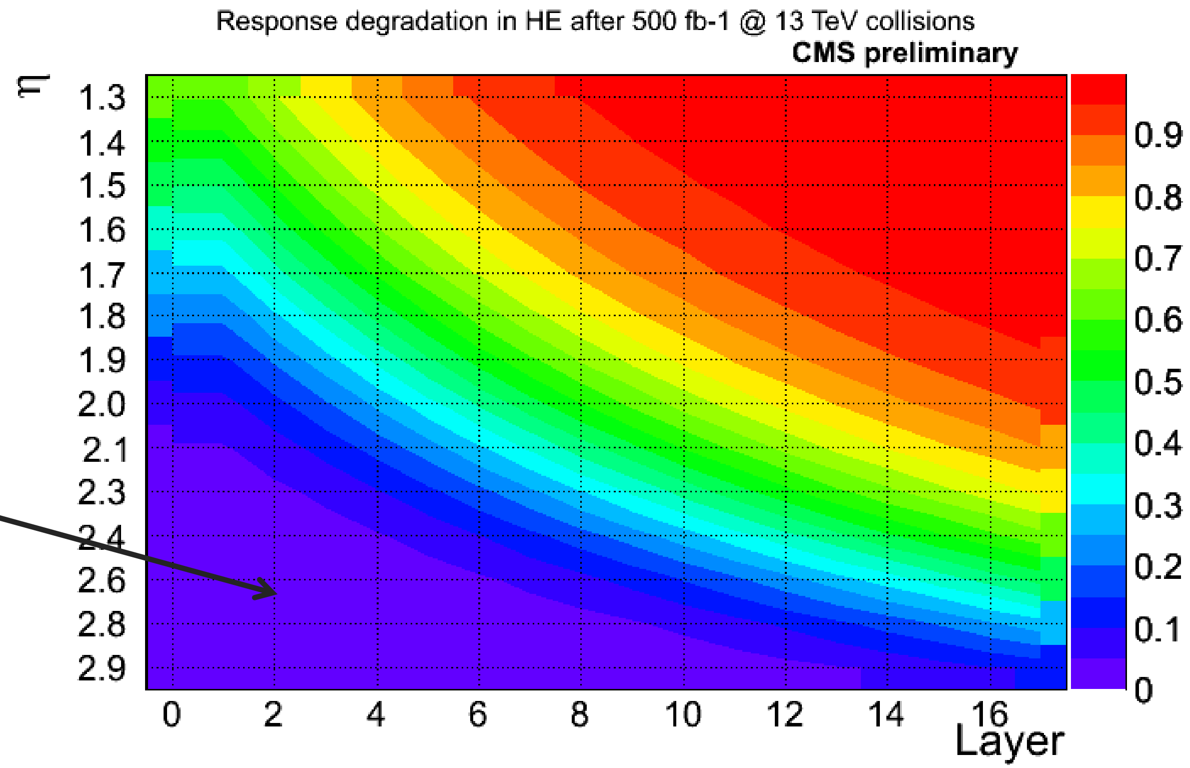




Degradation of signal in CMS HCAL Endcap in 2012 for the first sampling layer.

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

Extrapolated signal degradation in HE



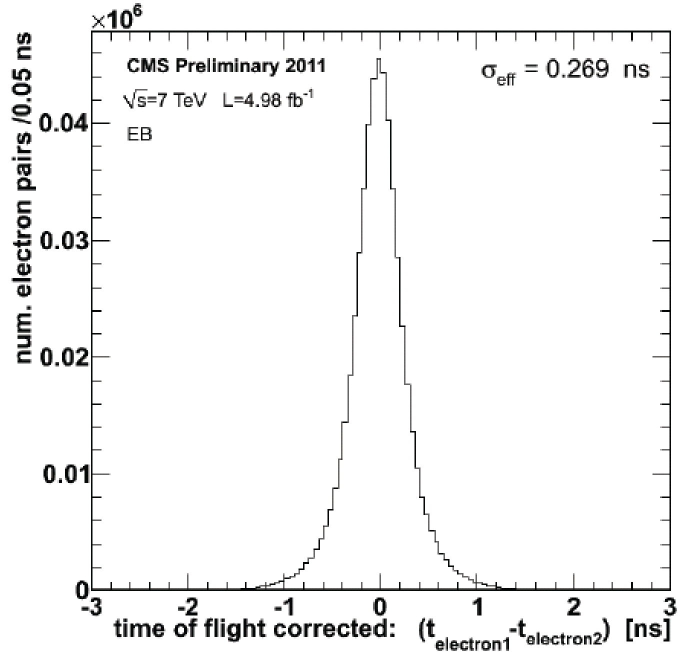
Here signal drops to (less than) 5% of the original value.

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

Pile-Up Mitigation

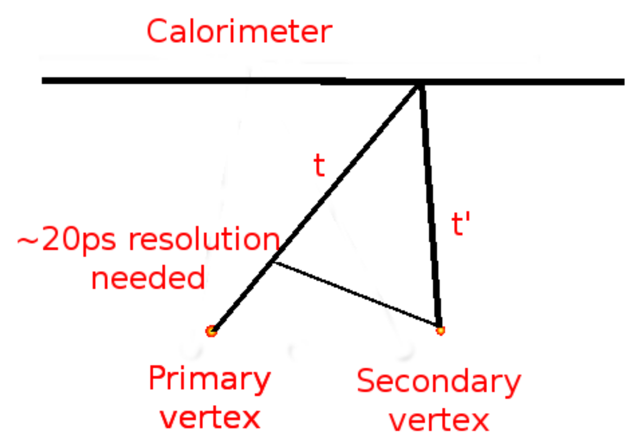
Pile-up is most critical in the forward region

- 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
- Desired resolution is 20-30 ps.

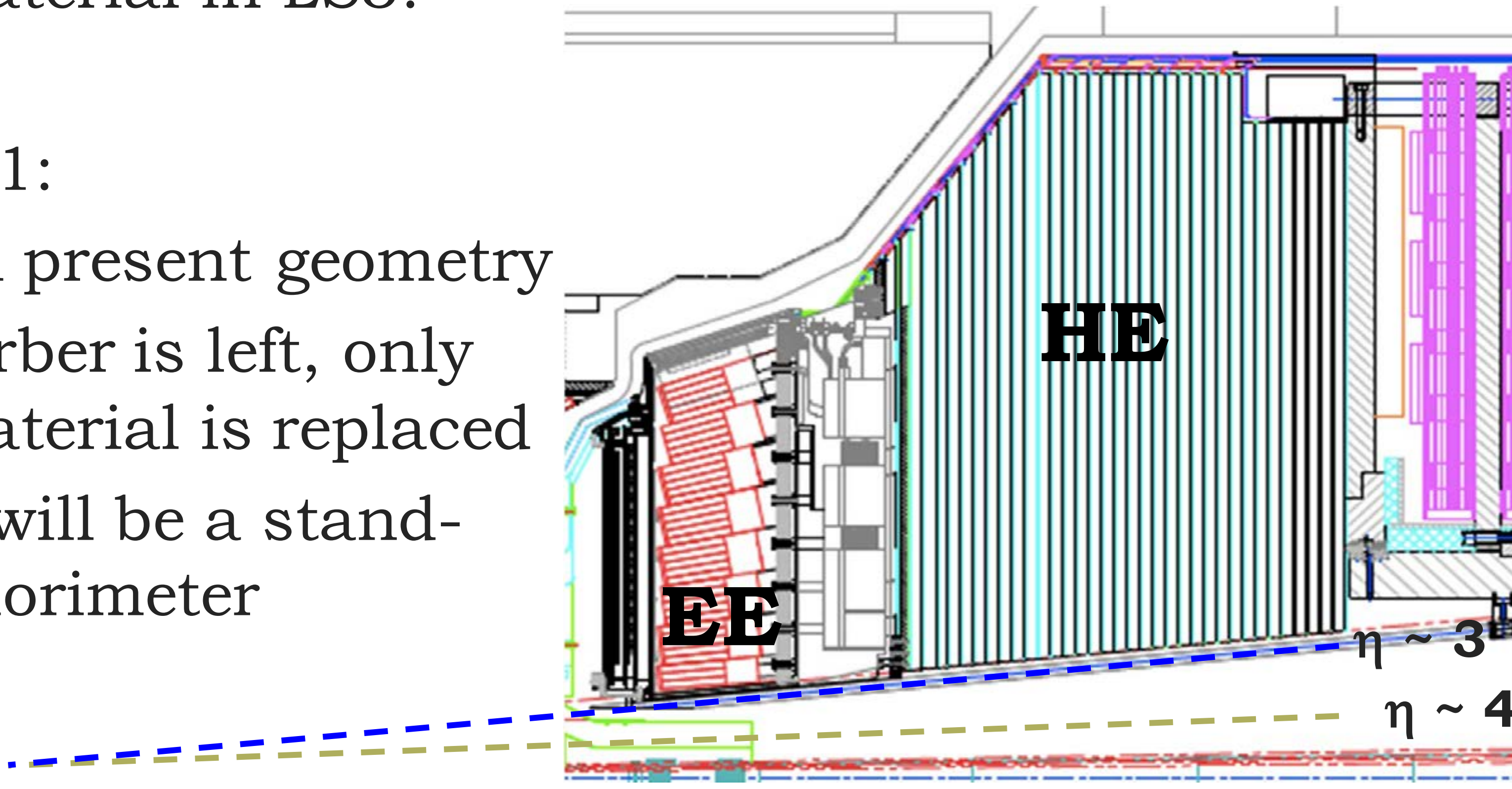


The two scenarios for the Endcap Calorimetry

- ECAL plan is to replace the Endcap calorimeters in LS3
- Hadron calorimeter endcaps (HE) need to replace the active material in LS3.

SCENARIO 1:

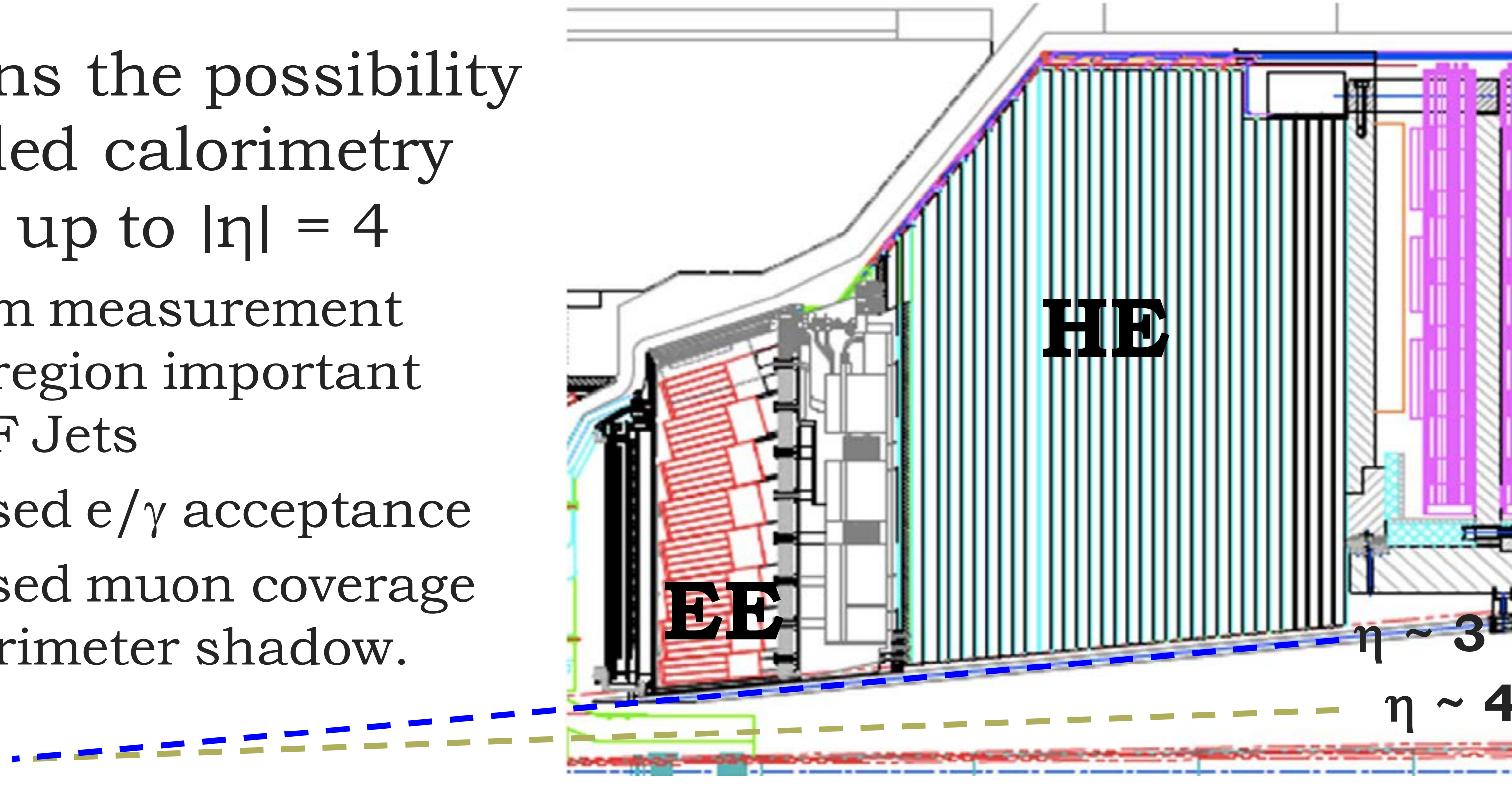
- Maintain present geometry
- HE absorber is left, only active material is replaced
- New EE will be a stand-alone calorimeter



The two scenarios for the Endcap Calorimetry

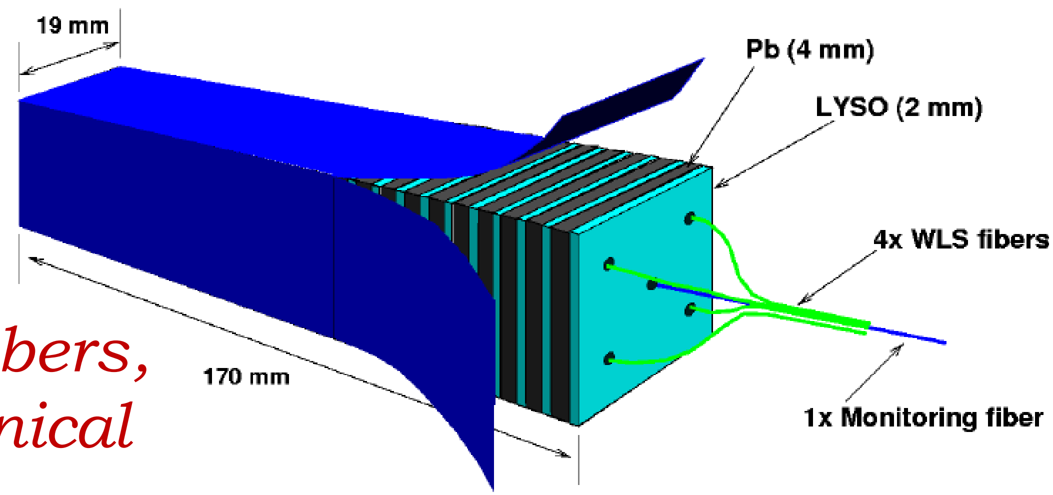
SCENARIO 2:

- Fully replace EE and HE with a new EndCap Calorimeter system.
- This opens the possibility of extended calorimetry coverage up to $|\eta| = 4$
  - Uniform measurement in the region important for VBF Jets
  - Increased e/γ acceptance
  - Increased muon coverage in calorimeter shadow.



Scenario 1: standalone Endcap ECAL

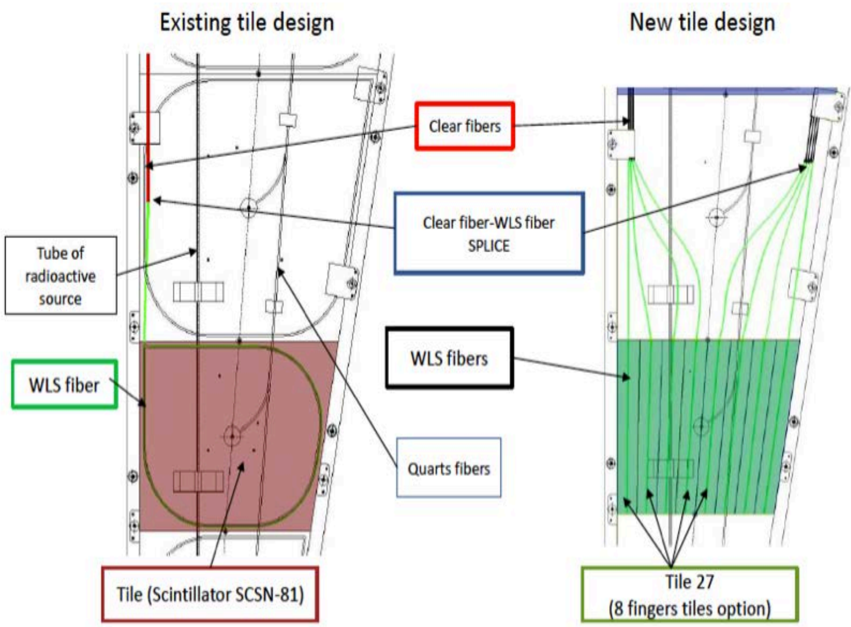
- **Sandwich calorimeter** in sampling configuration
  - Rad-hard inorganic scintillator e.g. LYSO or CeF_3
  - Pb or W as absorber
- Possible light readout solutions
  - wavelength shifting fibers (WLS) in a shashlik configuration
  - photon sensors on the sides



- *Challenges: rad-hard fibers, photo-detectors, mechanical mounting (tolerances)*

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

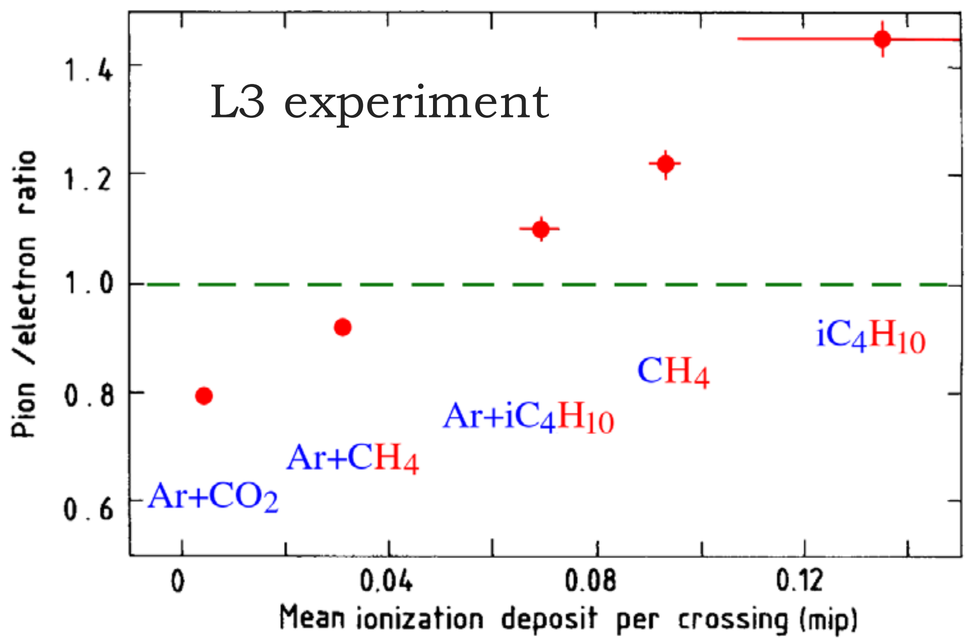


Compensation

- A not negligible fraction of hadronic energy does not contribute to the calorimeter signal (e/h>1):
  - energy to release nucleons from nuclei
  - muons and neutrinos from pi/K decays
- The calorimeter response to hadrons is generally smaller than to electrons of the same energy (**π/e < 1**).
- Degradation in energy resolution (the energy sharing between em and non-em components varies from one event to another) and linearity (the em fraction of hadron-induced showers increases with energy, so π/e does).

Compensation

- Low energy neutrons contribute to the calorimeter signal through elastic scattering with nuclei.
- The energy transfer is strongly Z dependent and much larger in active material (low Z) than in passive material (high Z)
- Tuning the hydrogen presence in the active layer allows to tune the e/h ratio.



Compensation

Compensation: equalization of the response to the electromagnetic and non-em shower components (e/h = 1).

Even better is to measure the em fraction event by event and correct offline.

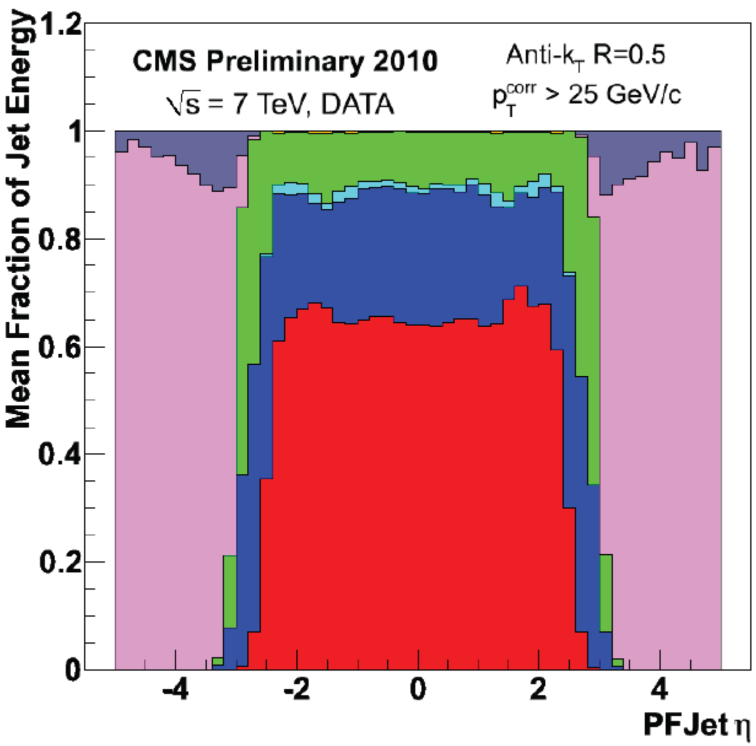
Compensation with dual readout:

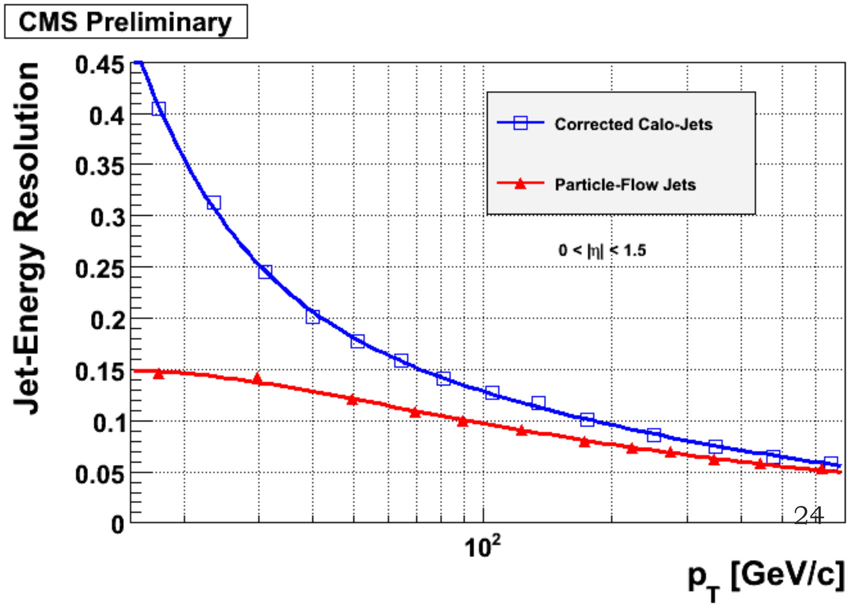
- Production of Cherenkov light in hadron showers is due to em component.
- Comparing the amounts of Cherenkov light with the scintillation light allow to estimate the em fraction.
- Measure the two component independently.

Energy Flow

- Measure charged particles with tracker, photons with ECAL and neutral hadrons with HCAL.
- Fine granularity

Intensively used in CMS
Strong benefit on Jet and Met resolution.

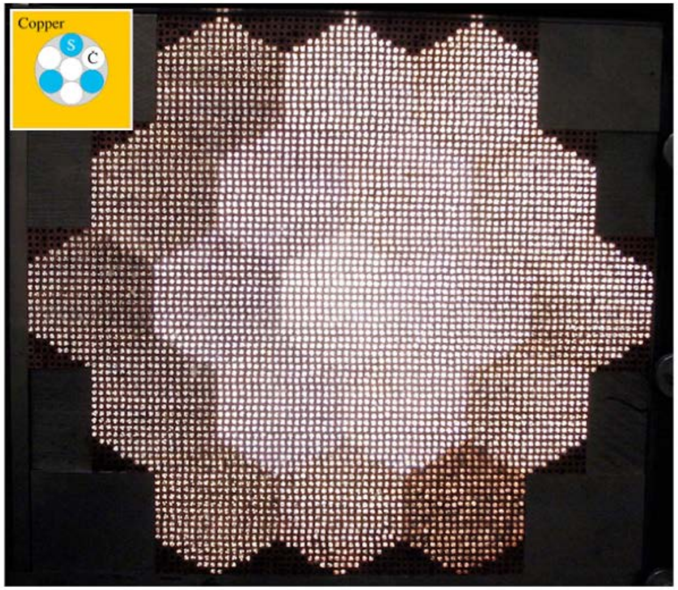




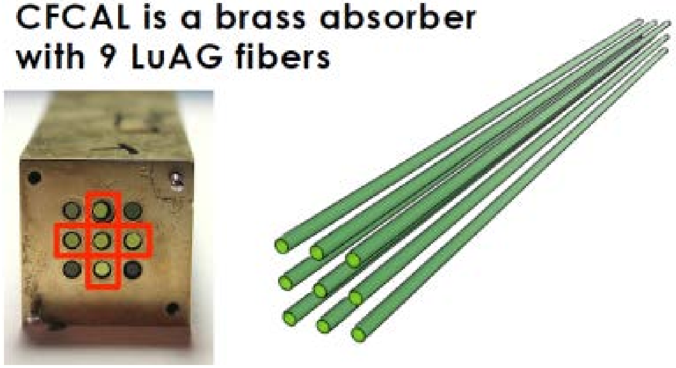
Scenario 2: Dual Readout Calorimeter

- **Dual Readout**: simultaneous measurement of the Cerenkov and scintillation signal in the calorimeter in order to correct for intrinsic fluctuations in the hadronic and e.m. component (γ,π^0,η) of the hadronic showers
  - (Dream / RD52 Collaboration)
- Other ideas: inorganic crystal fibers, e.g. LuAG
- <u>*Challenges:*</u> *rad-hard fibers, photo-detectors*

The original DREAM calorimeter

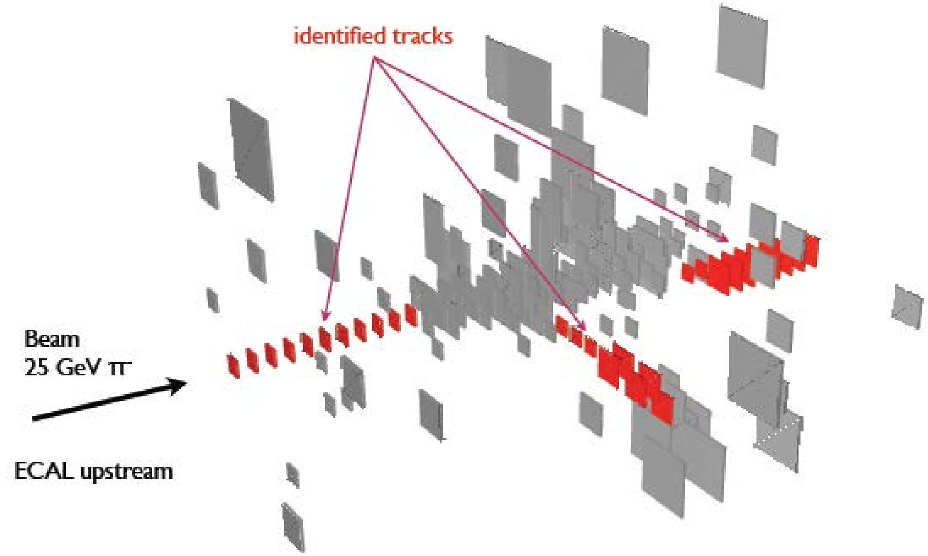


CFCAL is a brass absorber with 9 LuAG fibers



Scenario 2: Imaging calorimeter

- **High Granularity Particle Flow (PFCAL)/Imaging calorimeter**: measure charged particle momentum with the inner tracker, and neutrals in the calorimeter (following work of CALICE)
- Key point: resolving/separating showers through a finely granulated and longitudinally segmented calorimeter.
- High rates in CMS in the endcaps region drive the detector choice.
- *<u>Challenges:</u>*
  number of channels, compact and inexpensive electronics, trigger, cooling, performance in high pile-up, linearity
- Test beams are foreseen in 2014-15 for Dual Readout and PFCAL



Conclusions

- The HL-LHC poses severe requirements to detectors in terms of performance and rad-hardness.
- HF, ECAL and HCAL barrels will survive up to 3000 fb^{-1} providing good performance also during LHC phase 2.
- ECAL and HCAL endcaps should be replaced at the end of the LHC phase1 (after 500 fb^{-1}).
- New calorimeter options are being studied. Key points are rad-hardness, granularity and segmentation.
- Timing resolution may add important information for pile-up mitigation.

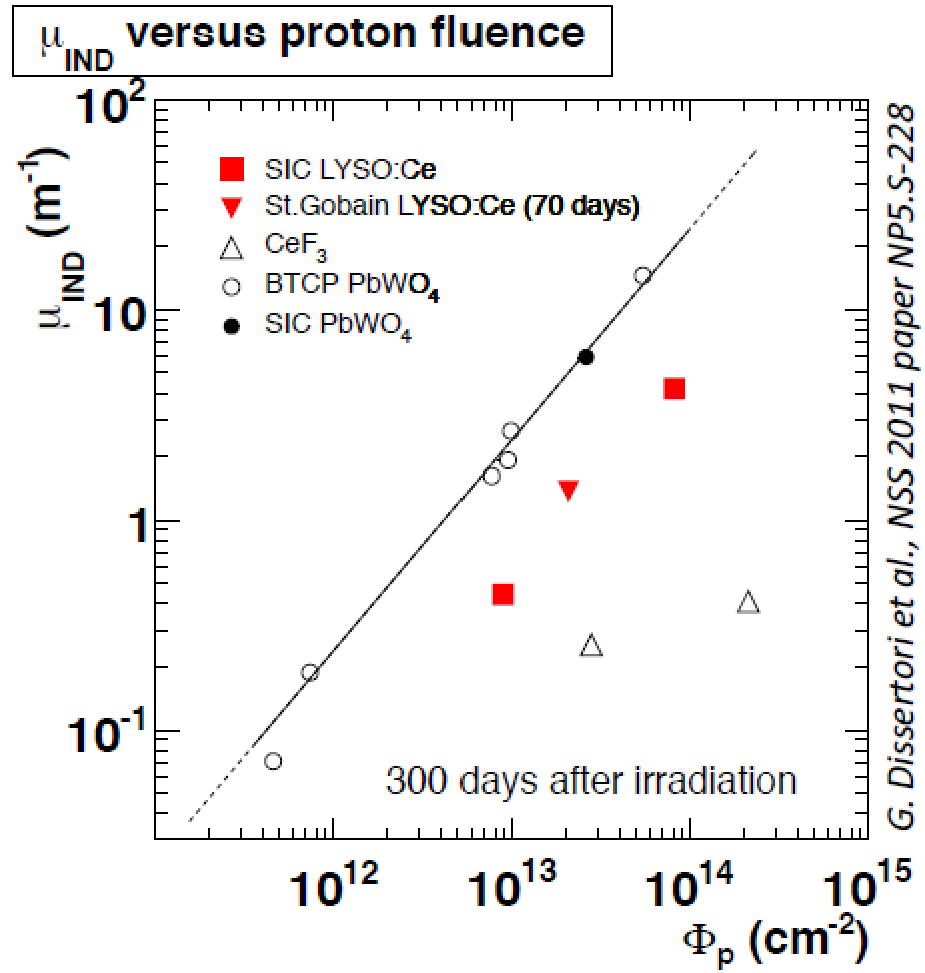
Many thanks to the organizers for the very appreciated invitation to IPMLHC2013 and for the excellent hospitality.

Backup

R&D on new scintillators

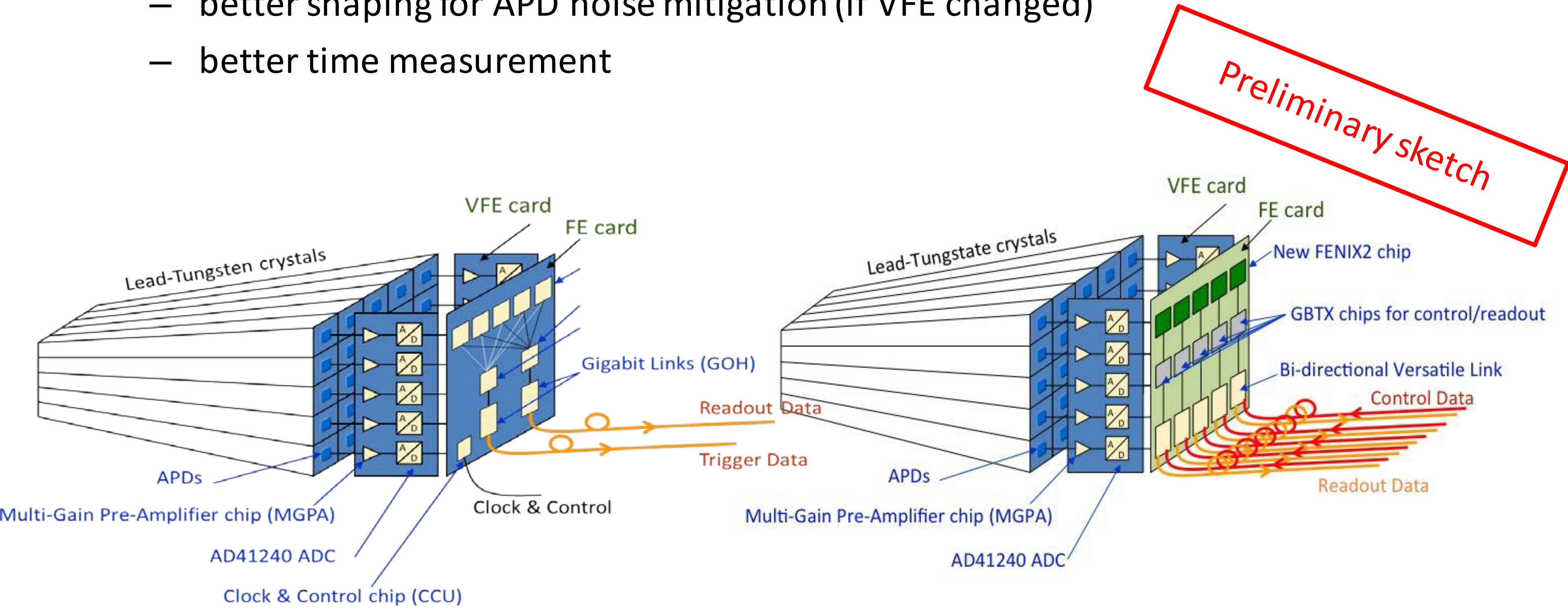
- R&D on new crystal materials and new growing techniques are ongoing.

- Key points are:
  - radiation hardness, especially for hadron damage
  - Light emission spectrum matching to WLS fibers or rad-hard photo-detectors



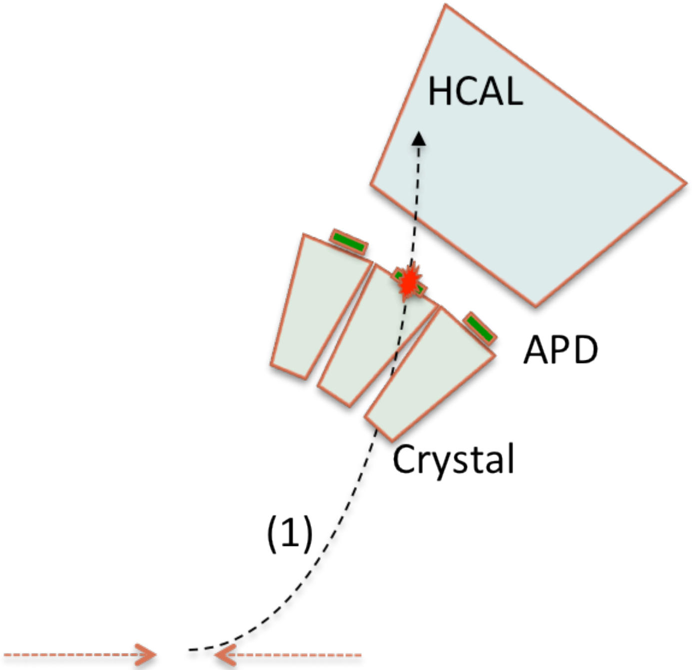
New EB electronics

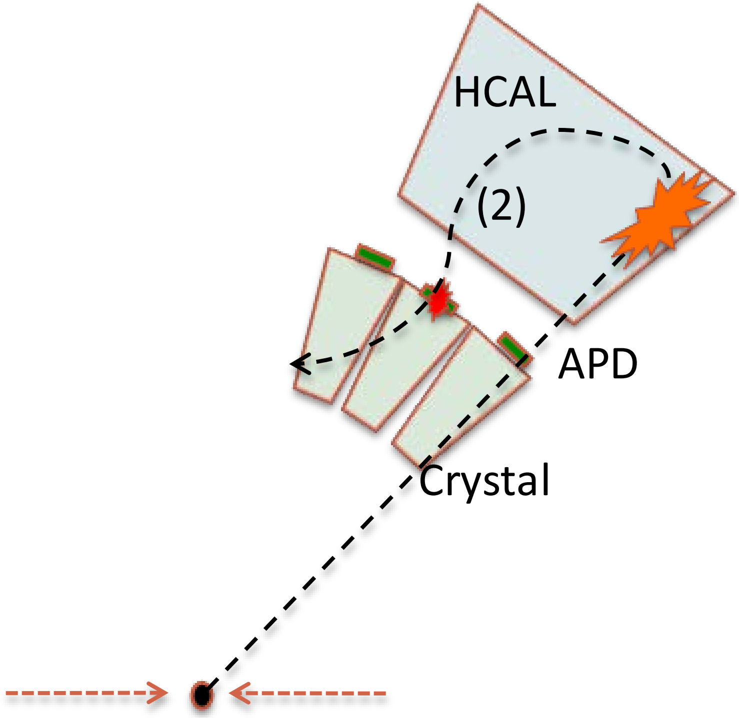
- EB electronics may profit of new electronics to provide single-crystal information sent out at 40MHz for
  - better efficiency in matching with tracks for electron selection and π^0/γ separation at L1
  - better APD anomalous signal rejection at L1
  - better shaping for APD noise mitigation (if VFE changed)
  - better time measurement



Spikes

Reminder: Hadrons interacting with the APD's causing anomalous high E deposits

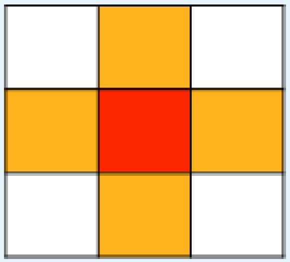




Hadrons come from primary interaction and backsplash

Spike Rejection

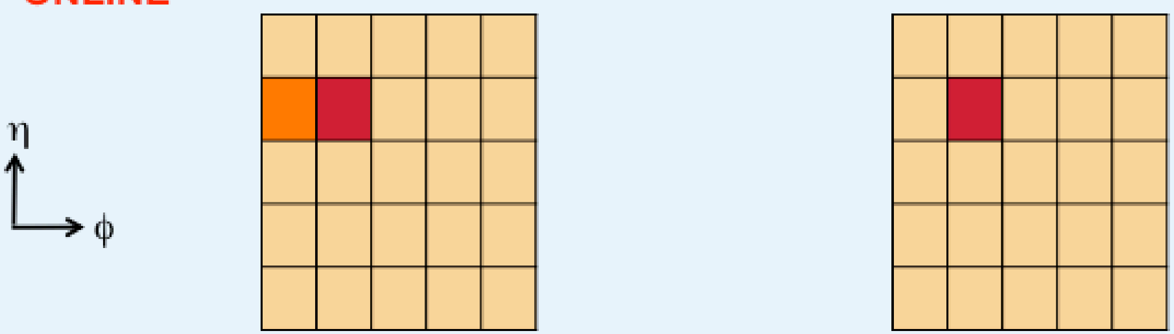
OFFLINE



« **SwissCross** » : **($1 - E_4 / E_1$)**
→ EM shower energy : ~80% in 1 crystal
→ Spike : single crystal

Timing cut : particle directly hitting the APD
→no decay constant of scintillation light (~10ns)
→spike pulses appear earlier than shower pulses

ONLINE



Real EM shower (VetoBit=1)
if 2 crystals in a strip **>** T_1
(**B**+Bremsstrahlung ⇒ φ spread)

Spike (VetoBit=0)
E_T(tower) **>** T_2
⇒ tower set to 0 GeV

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