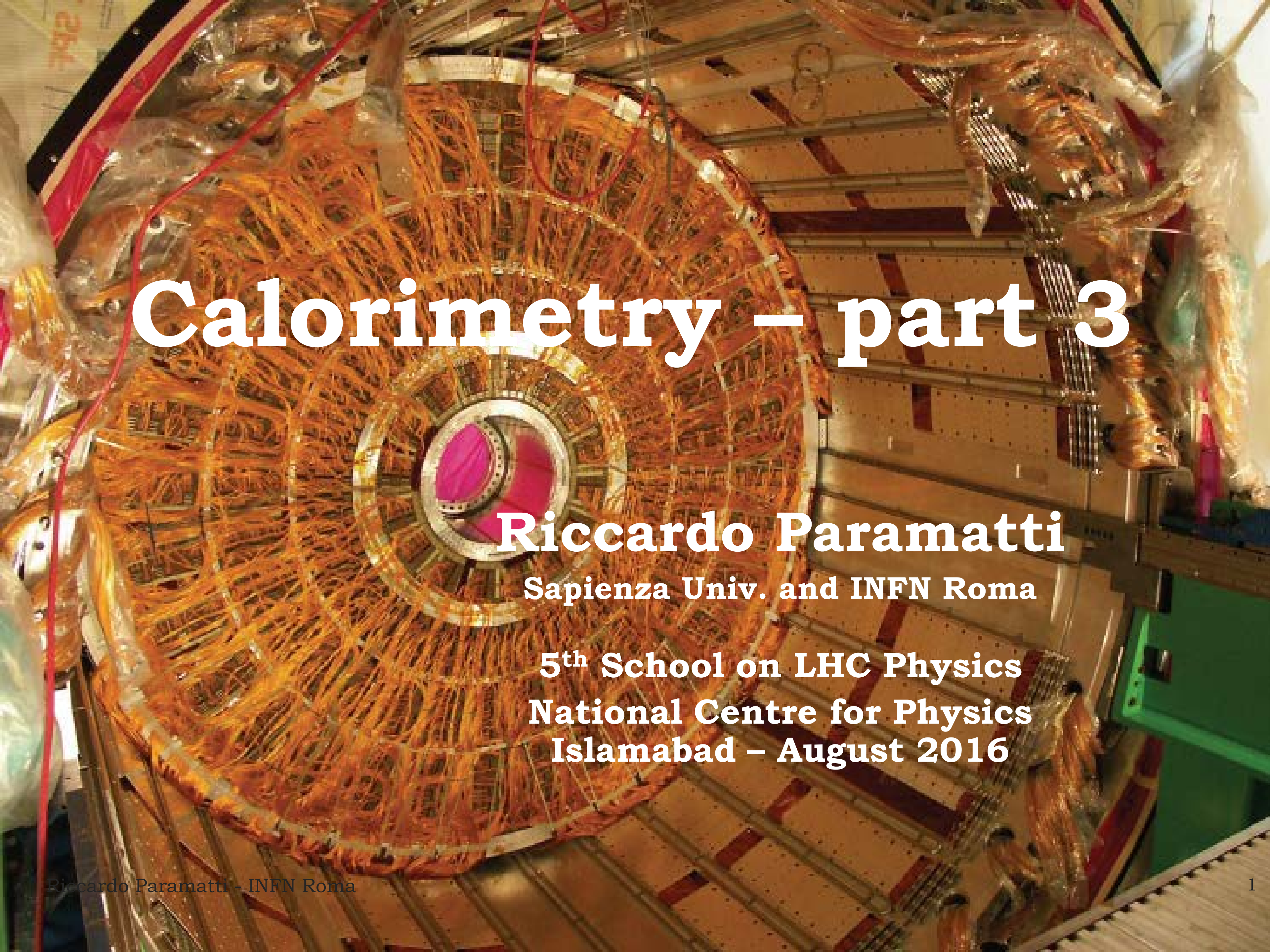

Calorimetry – part 3

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5th School on LHC Physics
National Centre for Physics
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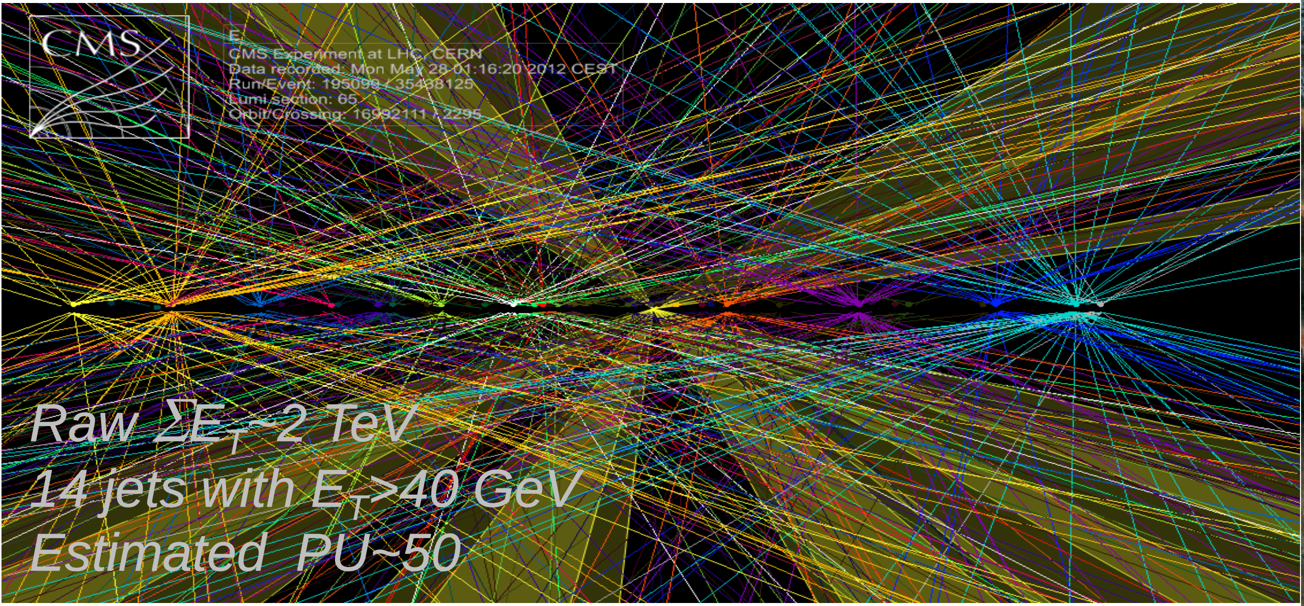
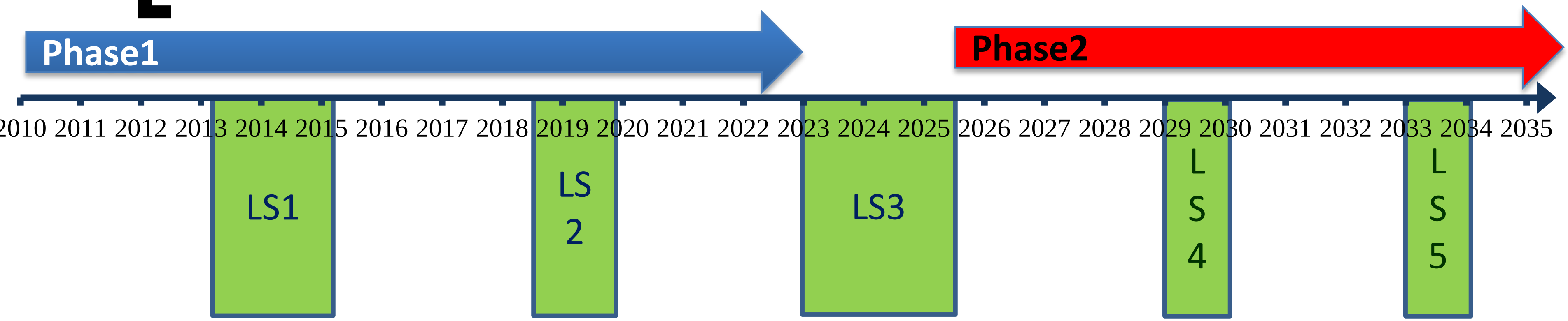
Outline

- The HL-LHC and upgrade of CMS calorimeters
- PU mitigation with precise timing



~ 10 cm

LHC and HL-LHC



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

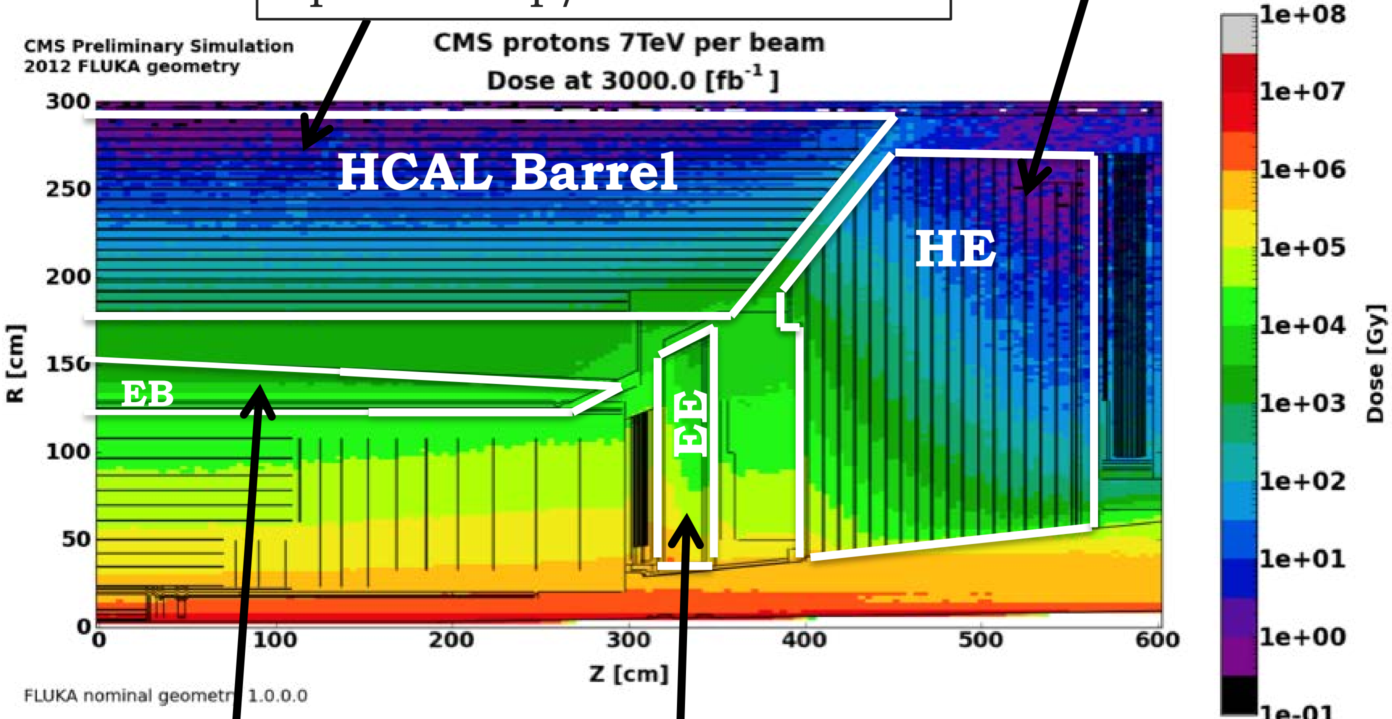
HL-LHC:
L=5 ·10^{34} cm^{-2}s^{-1}
<PU> ~ 140 events
250 fb^{-1} per year
by 2035 → 3000 fb^{-1}
In Run1 we have collected ~1% of the total data expected!

- **~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 2x10^{12} p/cm^2

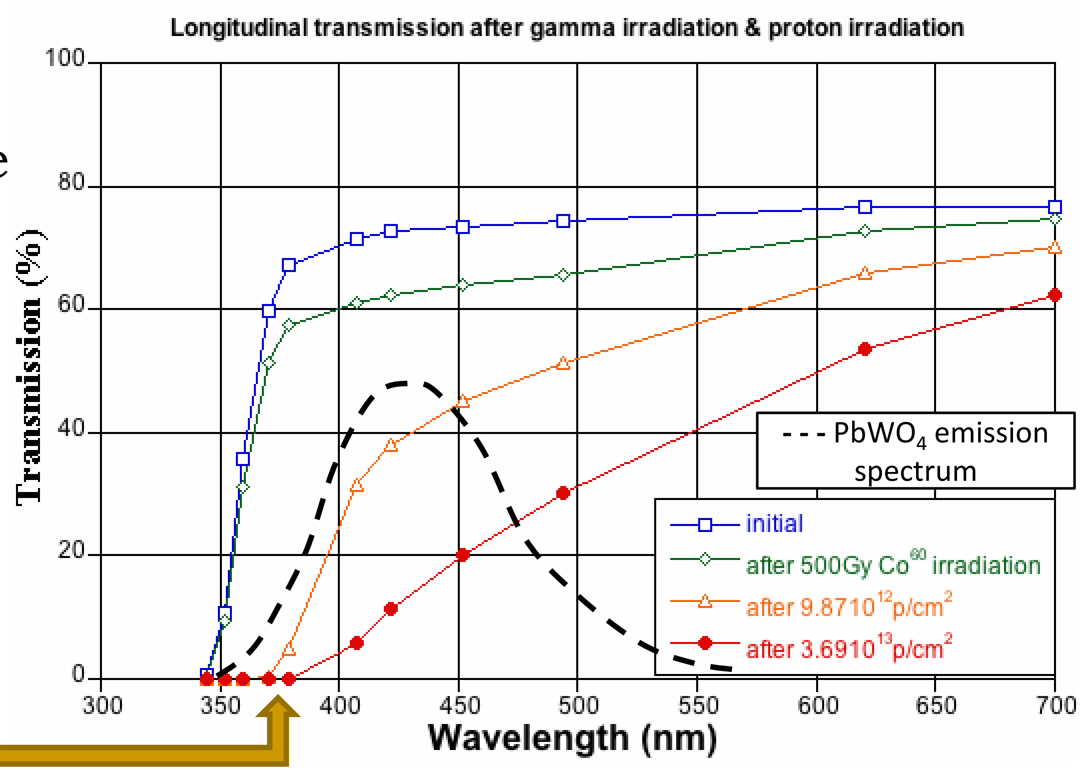
ECAL endcap at η=2.6: 65 Gy/h and 2x10^{14} p/cm^2

1 Gy = 1 Joule/kg
~ 3x10^9 mips/cm^2
across the medium

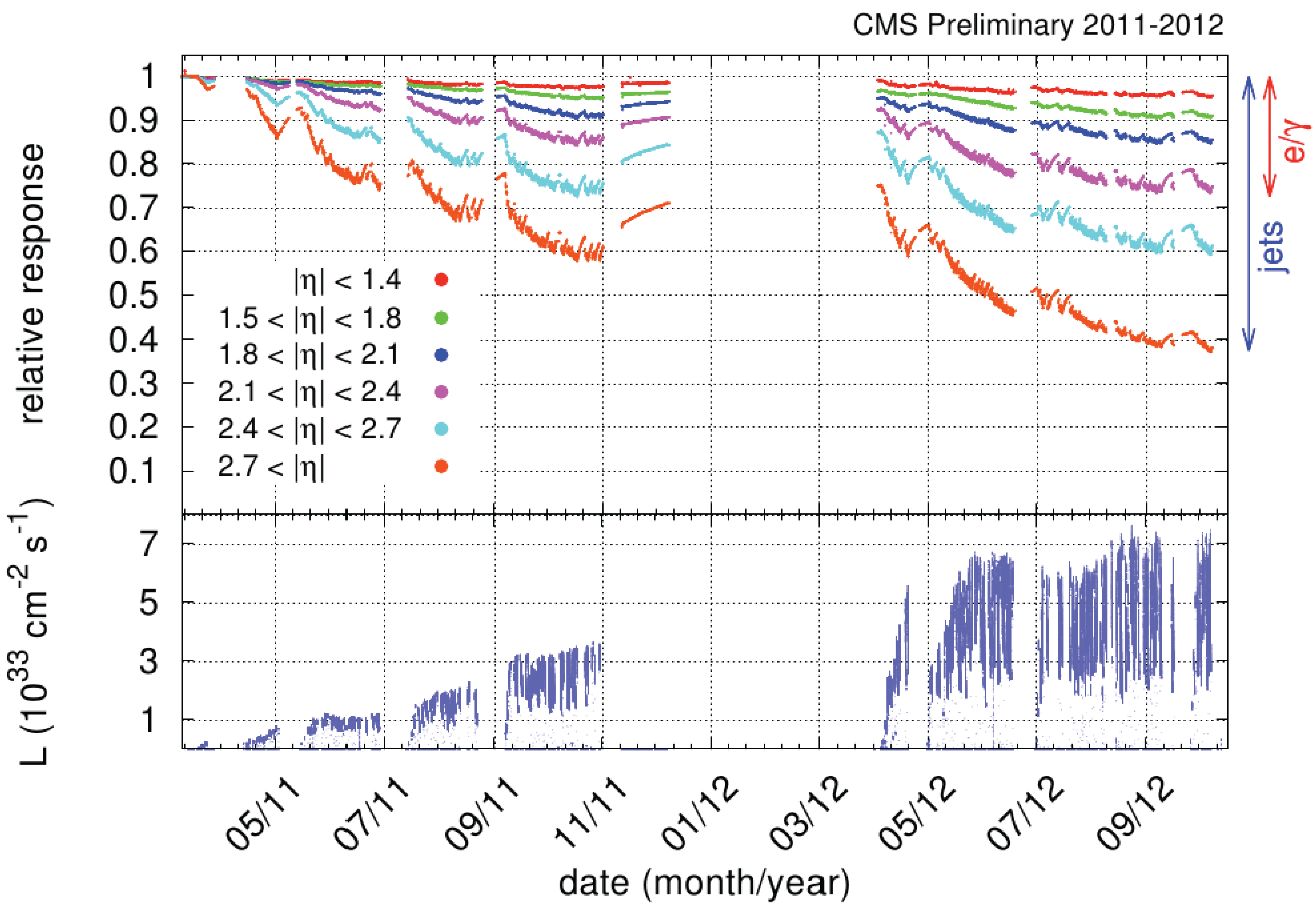
Radiation damage to $PbWO_4$ crystals

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

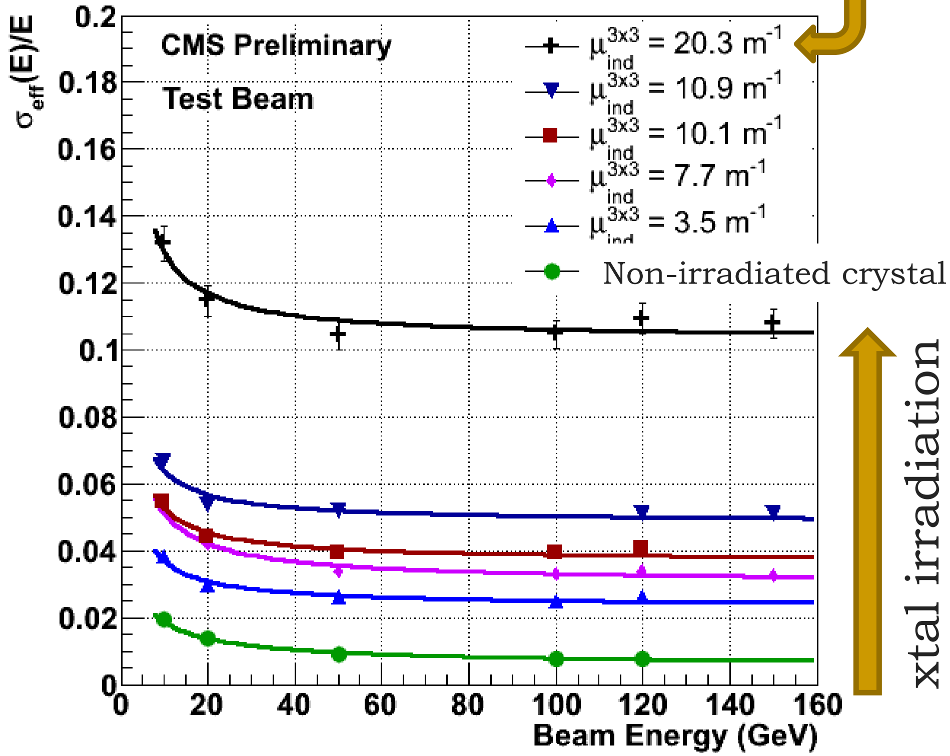
Deterioration of ECAL response strongly affect all the contribution to the energy resolution.

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

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

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

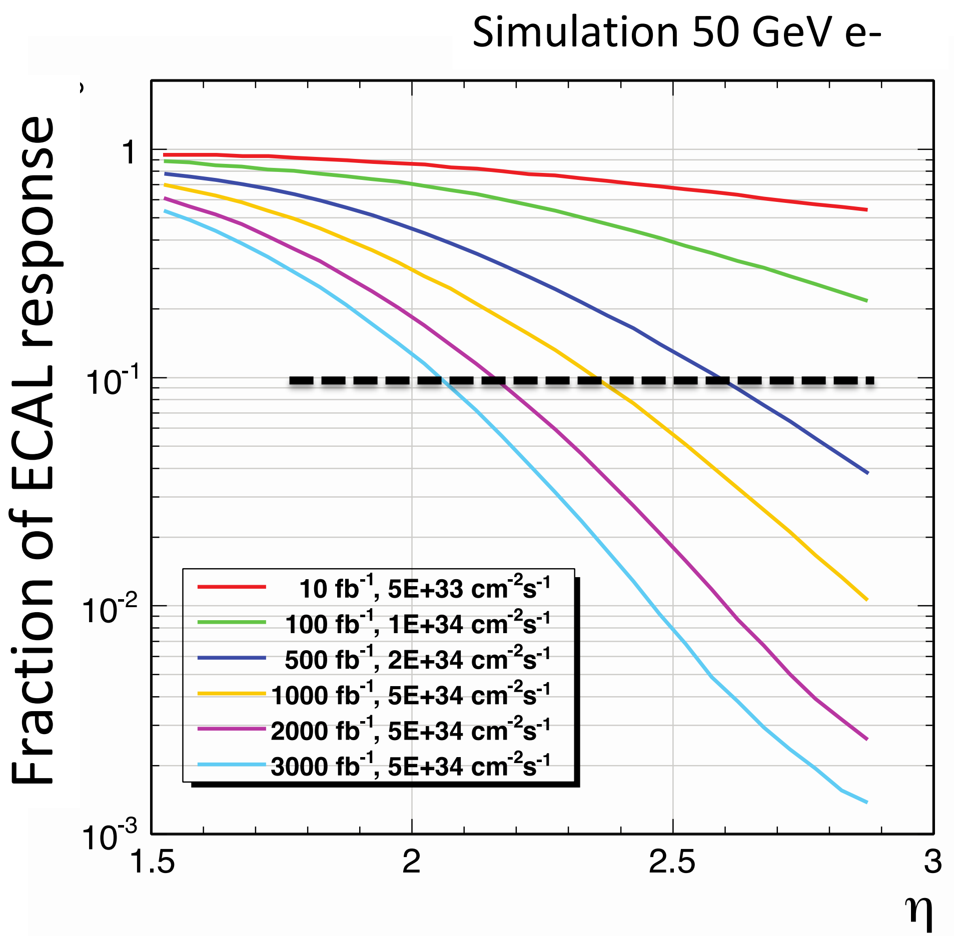


ECAL Endcaps response evolution

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

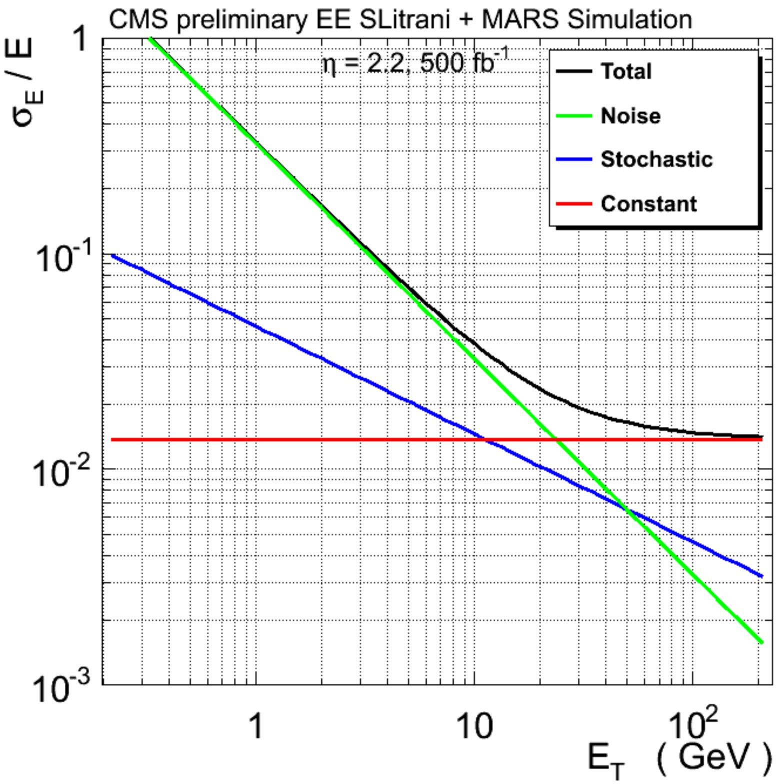
Energy resolution for e/γ is still acceptable with ECAL response greater than ~ 10% of the non-damaged detector.

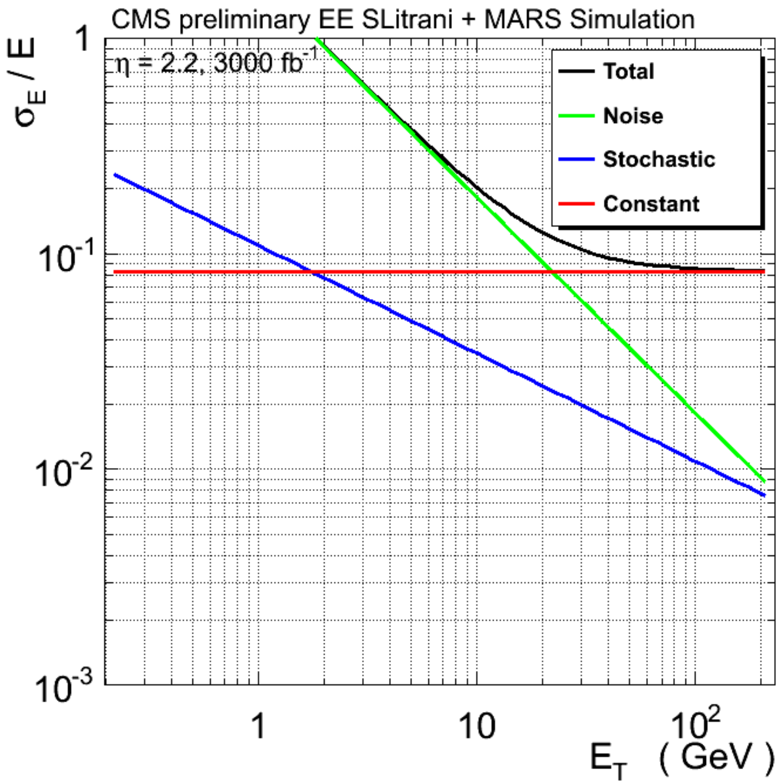
- $500\ fb^{-1}$: ECAL coverage to $\eta<2.6$ (i.e. full TK fiducial area)
- $1000\ fb^{-1}$: ECAL coverage to $\eta<2.3$
- $3000\ fb^{-1}$: ECAL coverage to $\eta<2.1$



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

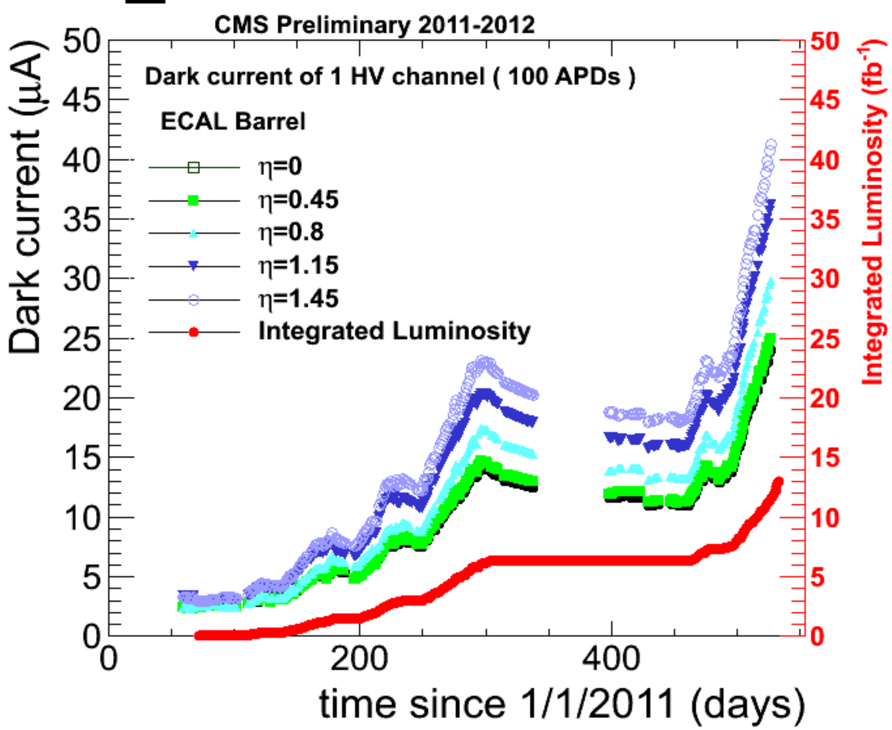
Energy Resolution

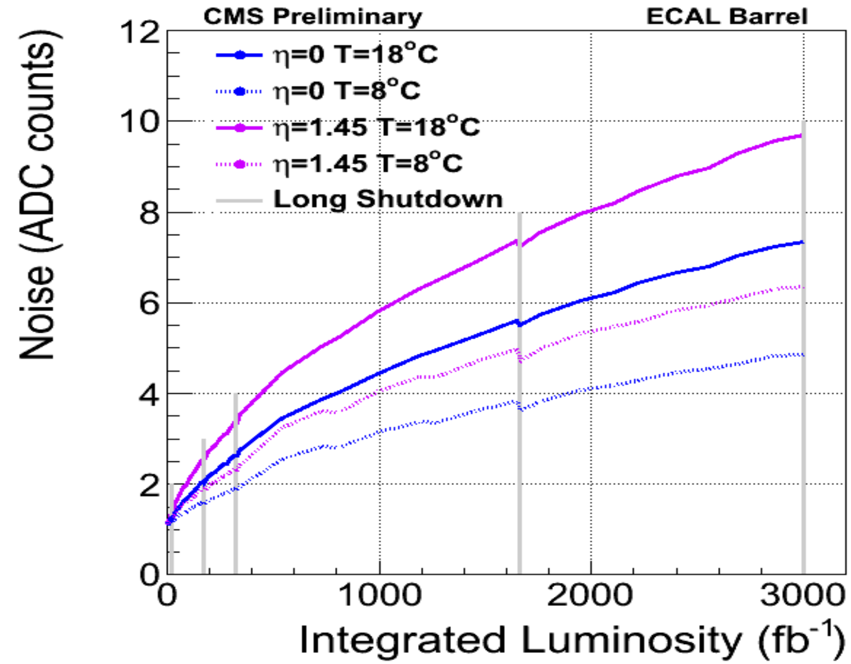




- Performance for e/γ is acceptable on the right (~1/2%) while unsustainable on the left (~10%)

APD dark current and noise in ECAL barrel





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

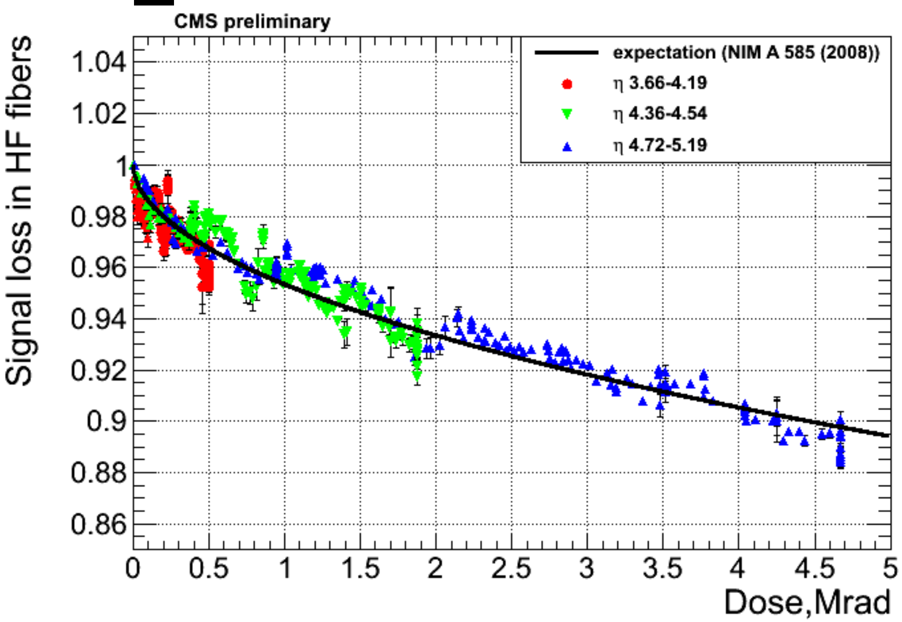
- The APD dark current increases linearly with neutron fluence (which depends on pseudorapidity).

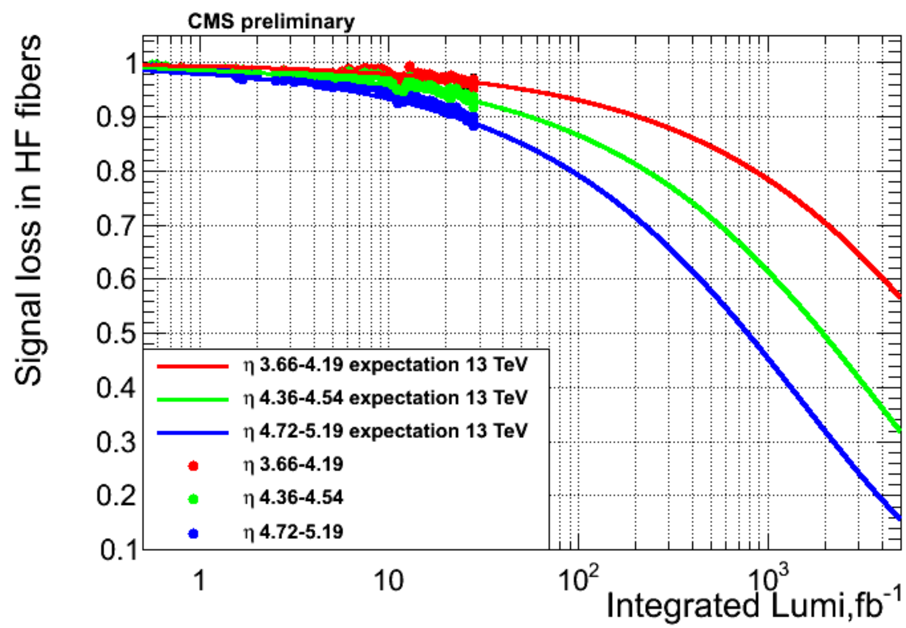
Single channel noise extrapolation.

- 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



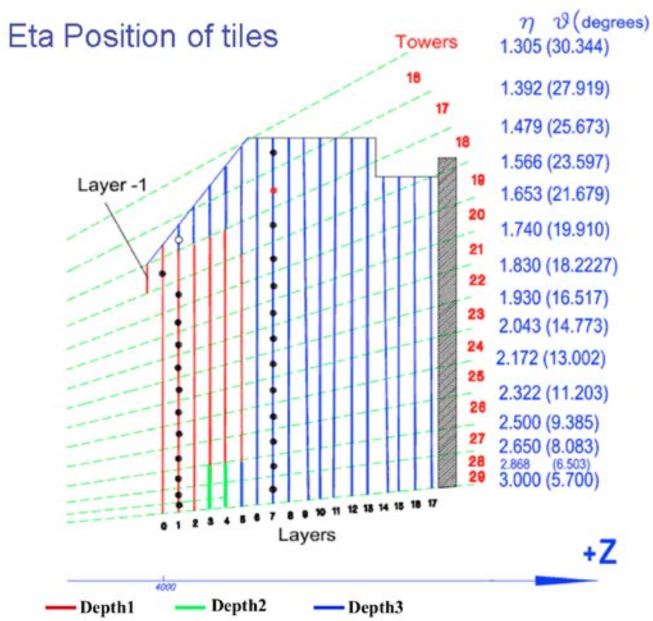


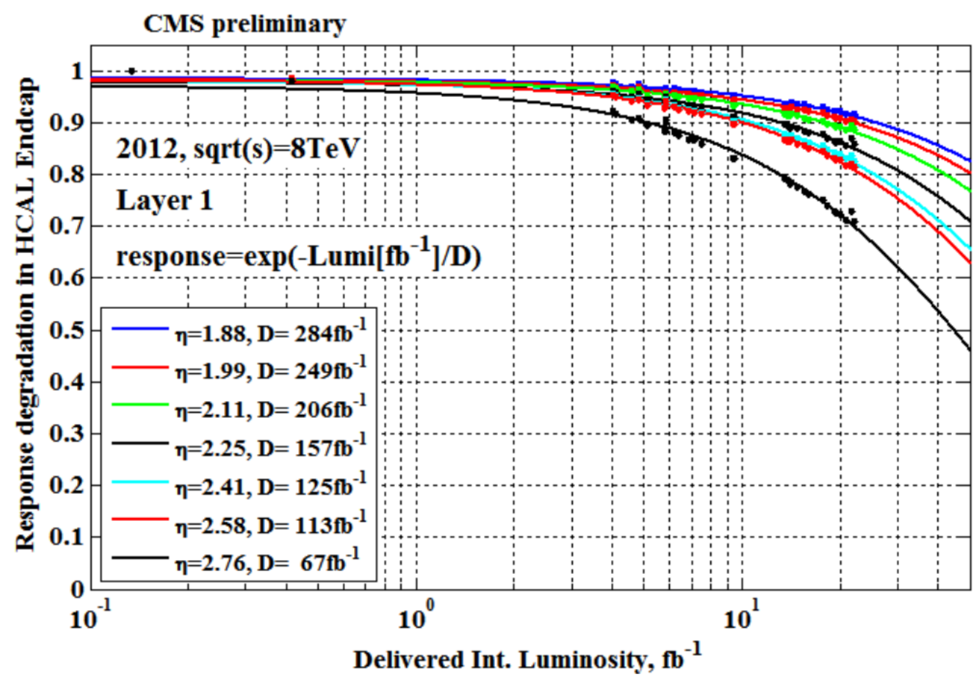
Signal loss in HF due to the radiation induced reduction of quartz fiber transparency.
Laser data shown: 2011+2012 (29 fb^{-1})
Black line is the expectation (not a fit) based on simulation.

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

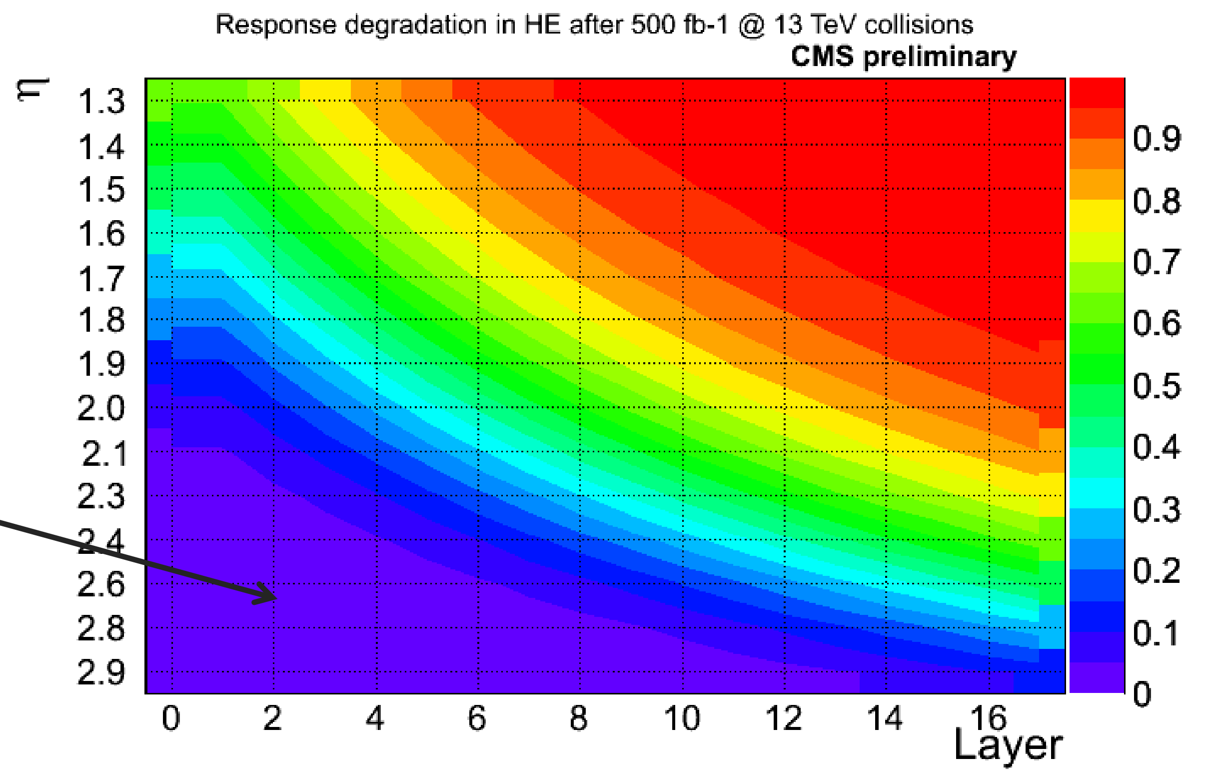




Degradation of signal (loss of scintillation and reduced transmission of light) in CMS HCAL Endcap in 2012 for the first sampling layer.

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

Extrapolated signal degradation in HE

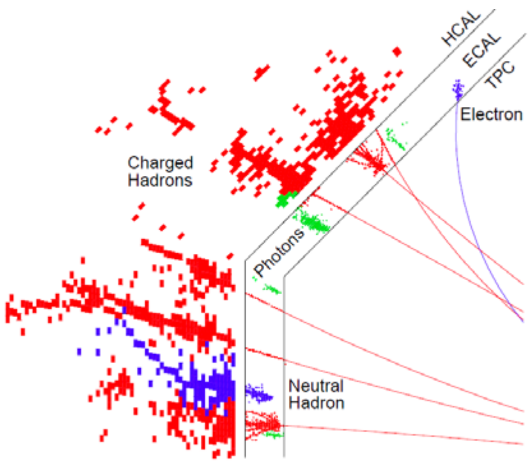


Here signal drops to (less than) 5% of the original value.

- 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)

A 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
- <u>*Challenges:*</u>
  number of channels and data transmission, compact and inexpensive electronics, L1 trigger, cooling, high pile-up, mechanical mounting

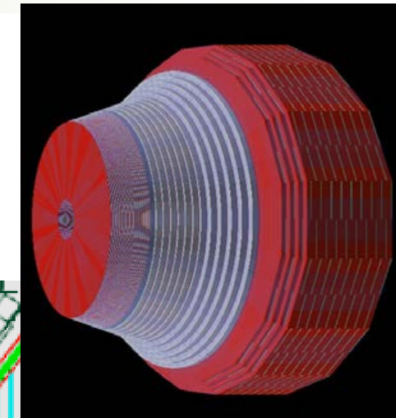


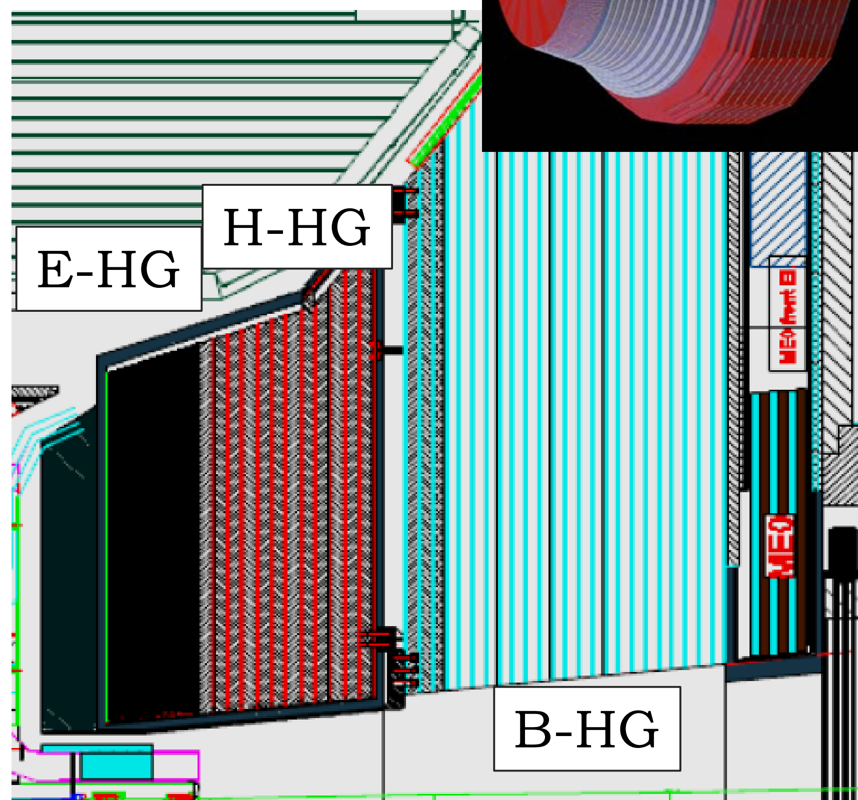
HGCAL concept

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





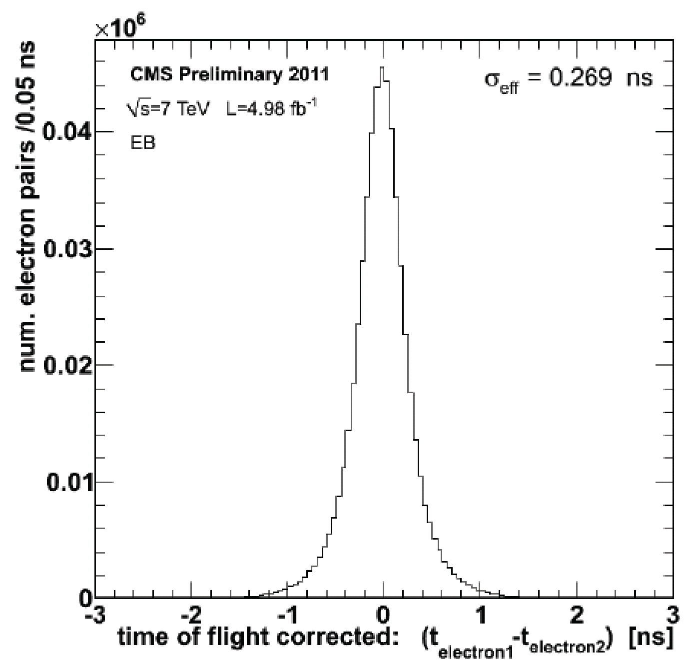
Pile-up mitigation with precise timing

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

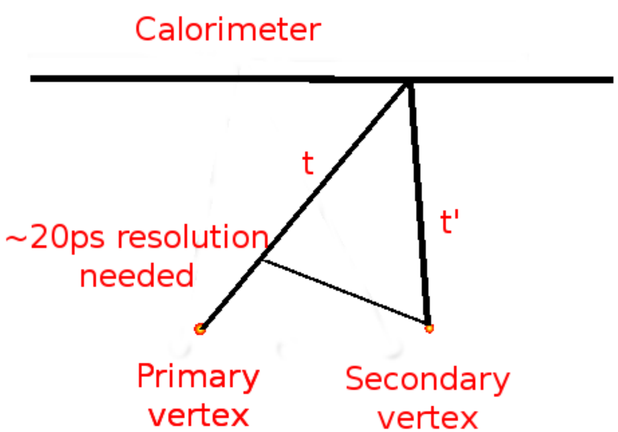


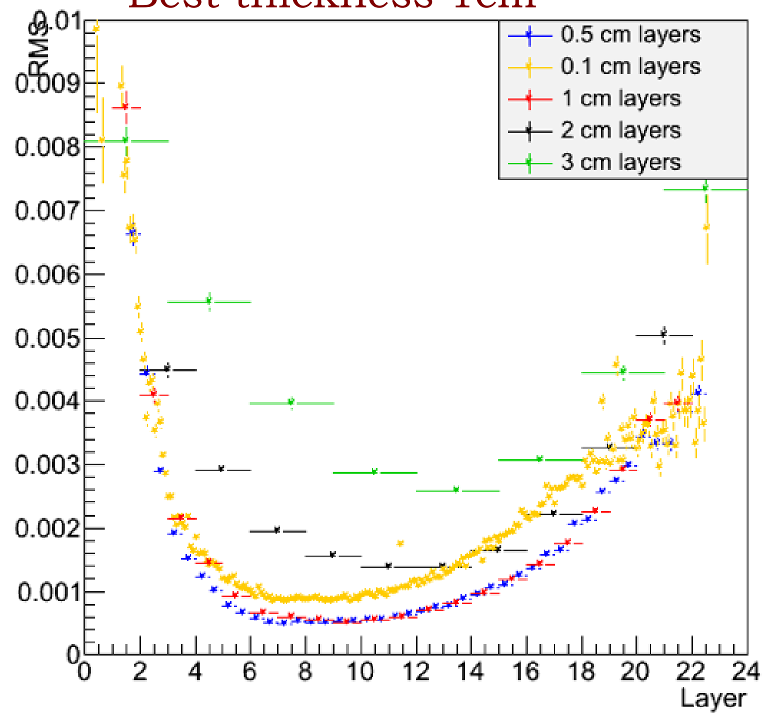
Pile-Up Mitigation with precise timing

- 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)

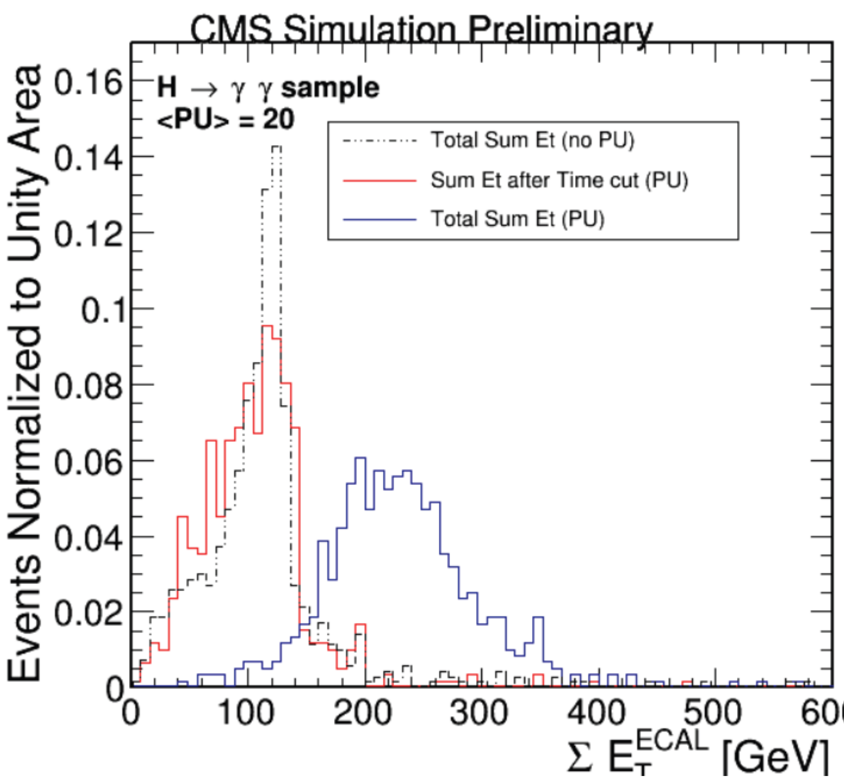
- Best resolution at 7-8 X_0
- Best thickness 1cm





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.

Calorimetry is also very important in many other fields: space experiments, neutrino experiments, medical applications, etc.

THANK YOU