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Evolution studies of the CMS ECAL endcap response and upgrade design options for High-Luminosity LHC

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on behalf of the CMS Collaboration

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Outline

- **Evolution of ECAL endcap response**:
  - LHC schedule and data-taking conditions after LS3
  - effects of **crystal transparency loss**
  - performance in **high-pileup** conditions

- Detector **Phase-II upgrade options**:
  - **Shashlik** sampling EM calorimeter + HE rebuild
    - LYSO
    - CeF_3
  - High-granularity calorimeter (**HGCal**)

Present ECAL configuration

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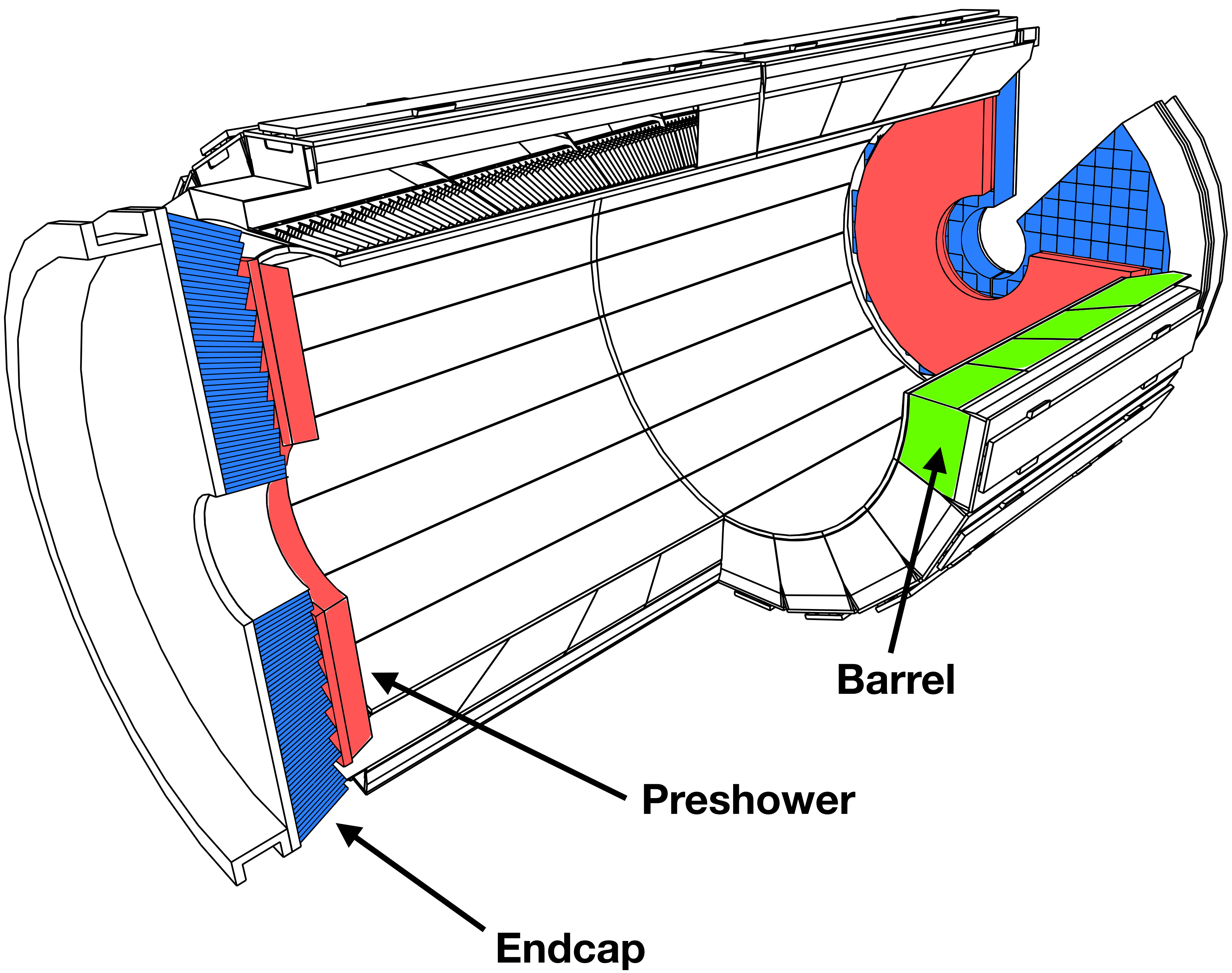
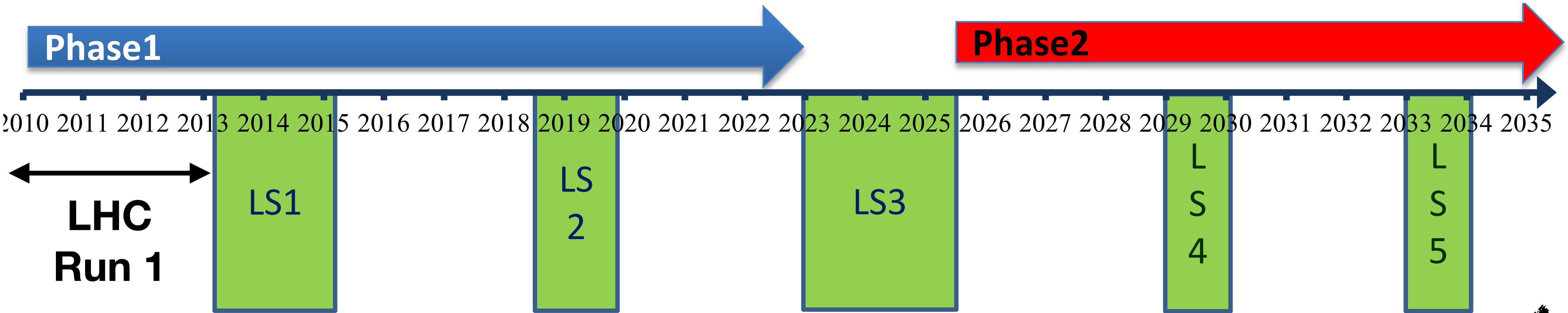
- Lead tungstate ($PbWO_4$) homogeneous crystal calorimeter
  - Barrel (EB):
    - 36 supermodules, 1700 crystals each
    - $|\eta|<1.48$
    - APD photodetectors
  - Endcap (EE):
    - 2 endcap sides, 7324 crystals each
    - $1.48 < |\eta| < 3.0$
    - VPT photodetectors
  - Preshower (ES):
    - sampling calorimeter (lead, silicon strips)
    - $1.65 < |\eta| < 2.6$



LHC schedule



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

HL-LHC:
L=5 $\cdot 10^{34}$ cm^{-2}s^{-1}
<PU> ~ 140 events
250 fb^{-1} per year
by 2035 → 3000 fb^{-1}

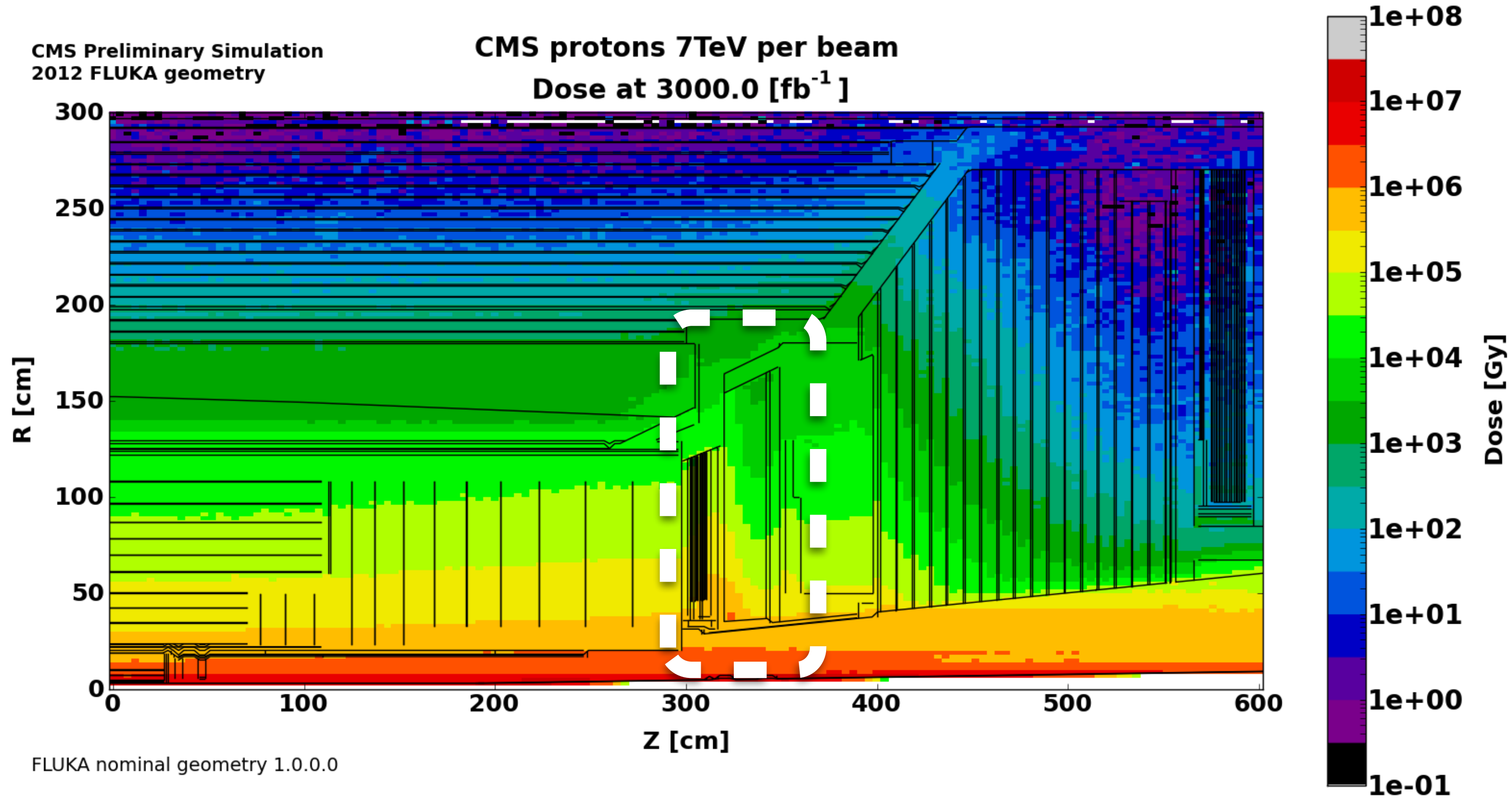
Data-taking conditions

	2012	Design	HL-LHC
cms energy [TeV]	8	13	13
Luminosity [$cm^{-2}s^{-1}$]	7×10^{33}	1×10^{34}	5×10^{34}
Int. Luminosity [fb^{-1}]	23	500	3000
γ **dose rate** [Gy/h]	0.2 (EB) 4 (EE)	0.3 (EB) 6.5 (EE)	1.5 (EB) 30 (EE)
hadrons fluence [cm^{-2}]	1.8×10^{10} (EB) 1.4×10^{11} (EE)	4×10^{11} (EB) 3×10^{13} (EE)	2.4×10^{12} (EB) 1.8×10^{14} (EE)

Photon dose rate

Energetic hadrons fluence

- **Absorbed dose and hadron fluence significantly beyond design** in HL-LHC conditions
- Strong radiation gradient as a function of |η|



Transparency loss in Run 1

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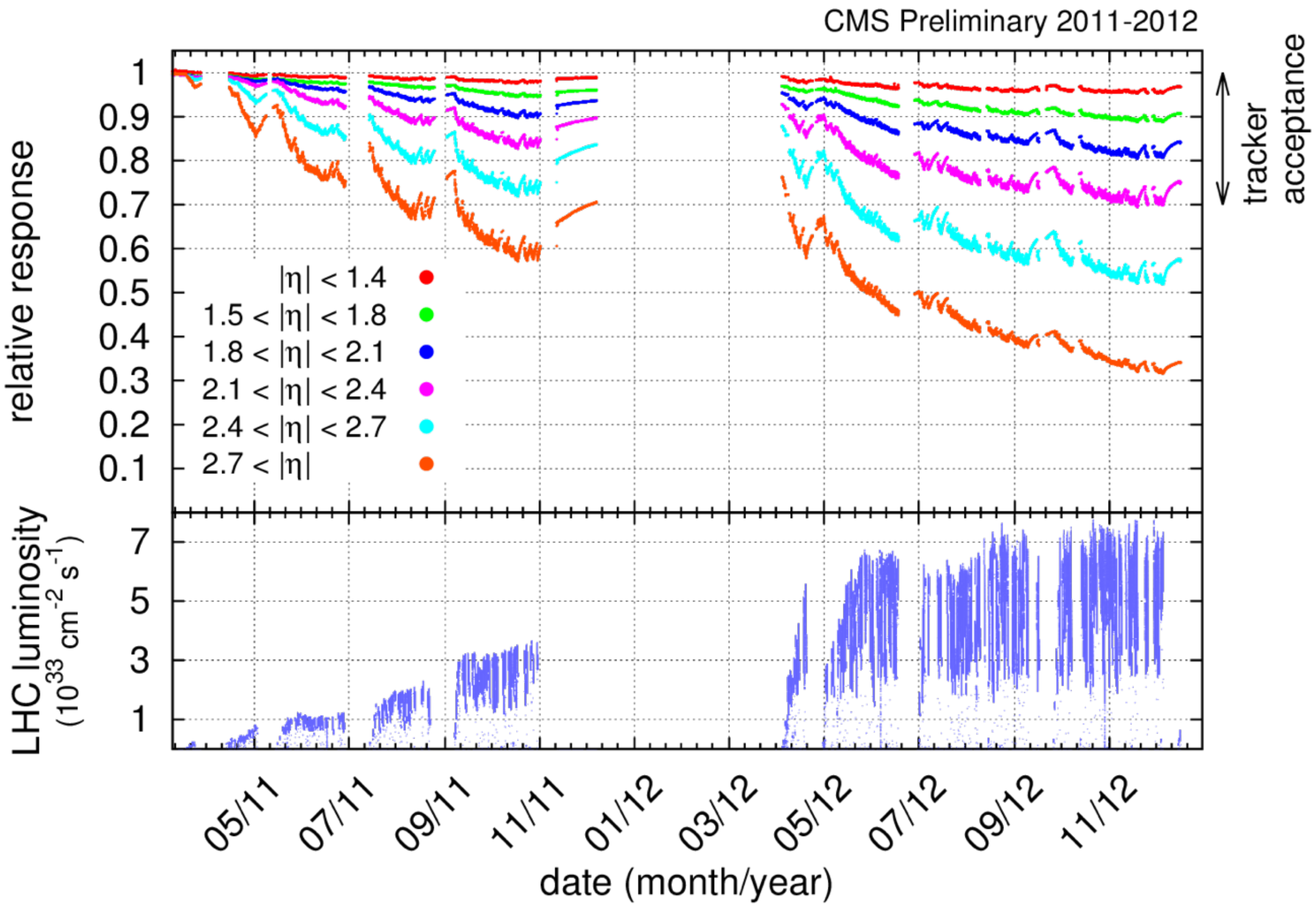
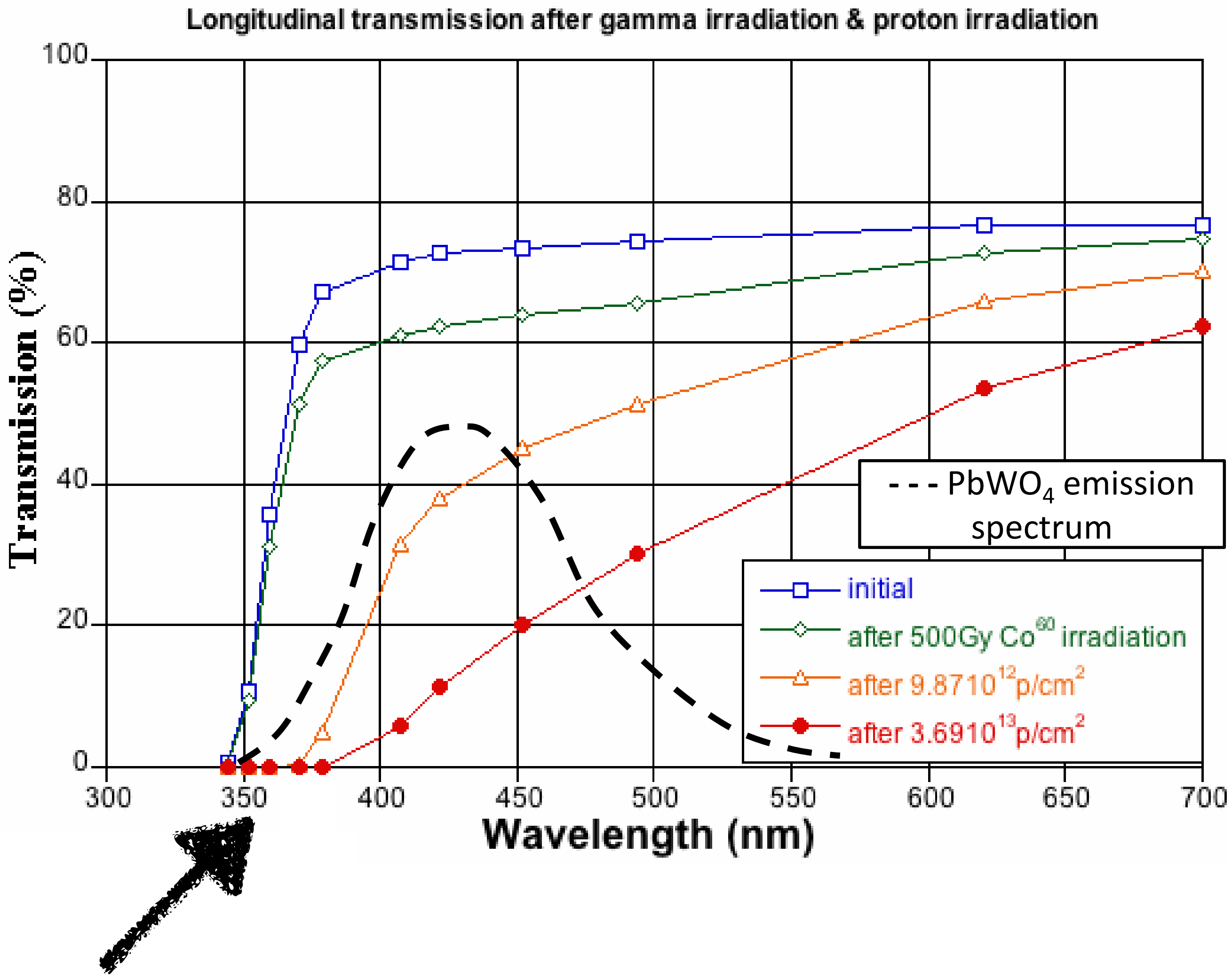
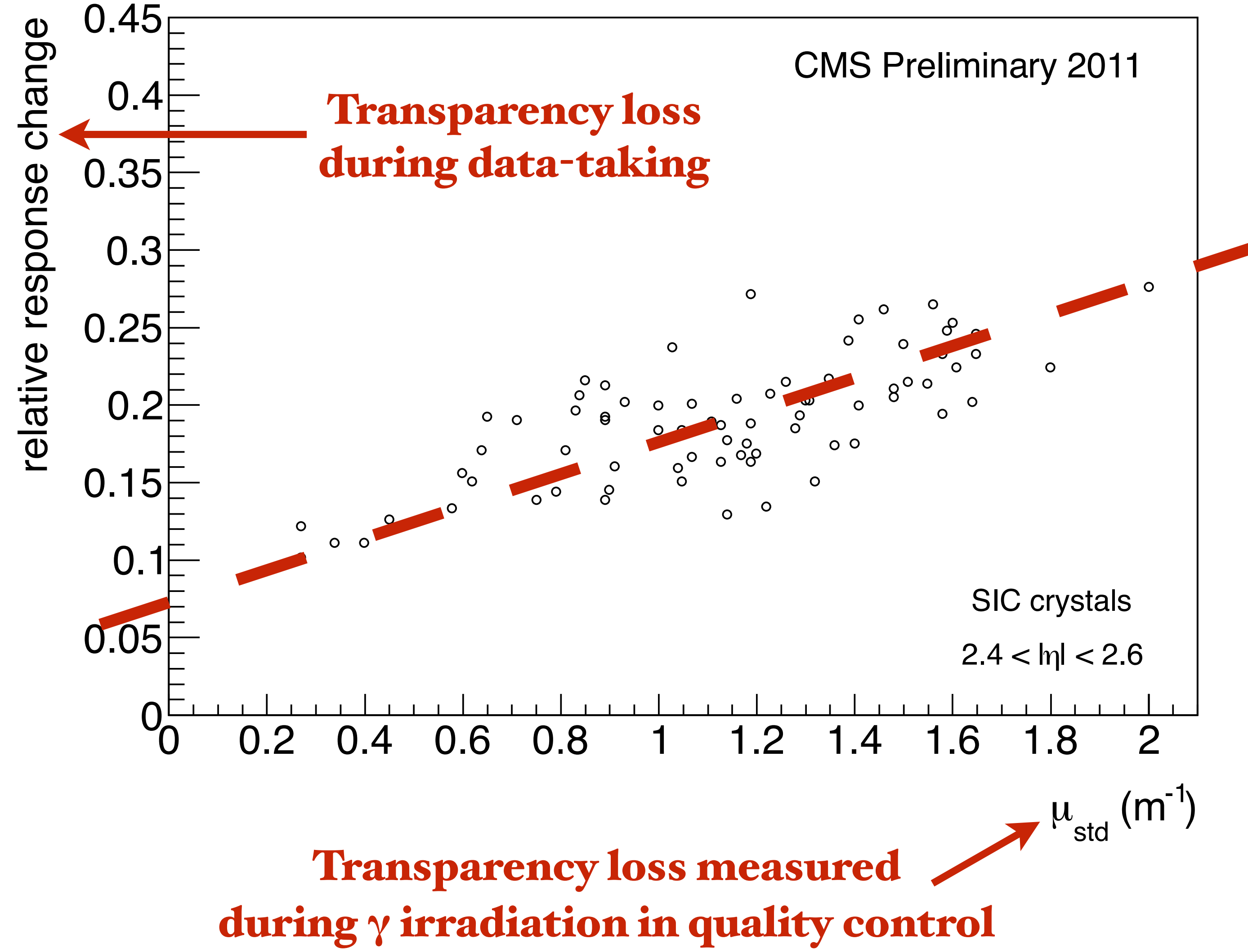


- Crystal transparency loss mainly due to **ionizing radiation** which causes color centers to form
- This component rapidly **recovers** when irradiation stops

- **Laser light injection** successfully used for **monitoring the effect and correcting for it** in Run 1 dataset

$PbWO_4$ radiation hardness





- Crystal **ionization damage recovers with time**
- **Hadron damage does not recover**, and **builds up** during data-taking
  - will become dominant as integrated luminosity increases
  - causes band edge shift and transparency loss across the emission region

Evolution of ECAL resolution

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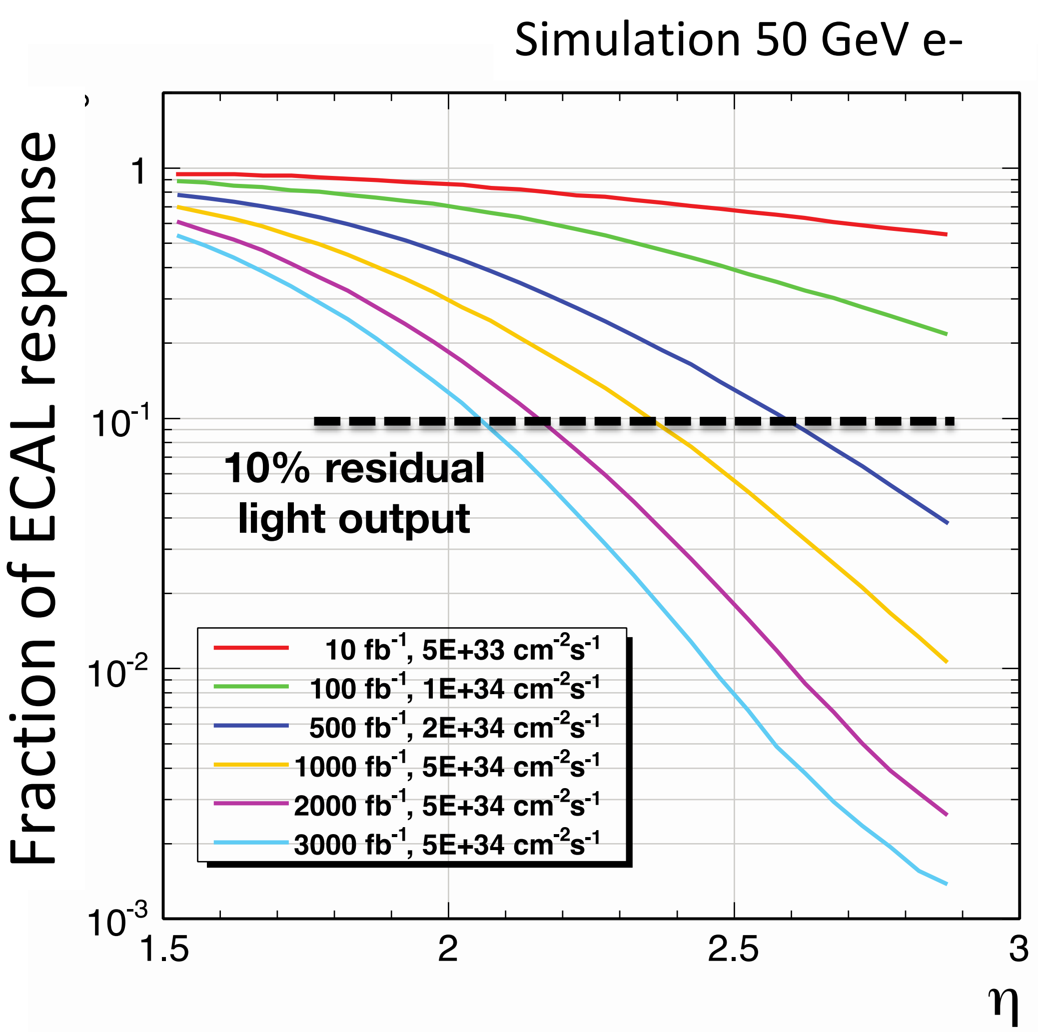
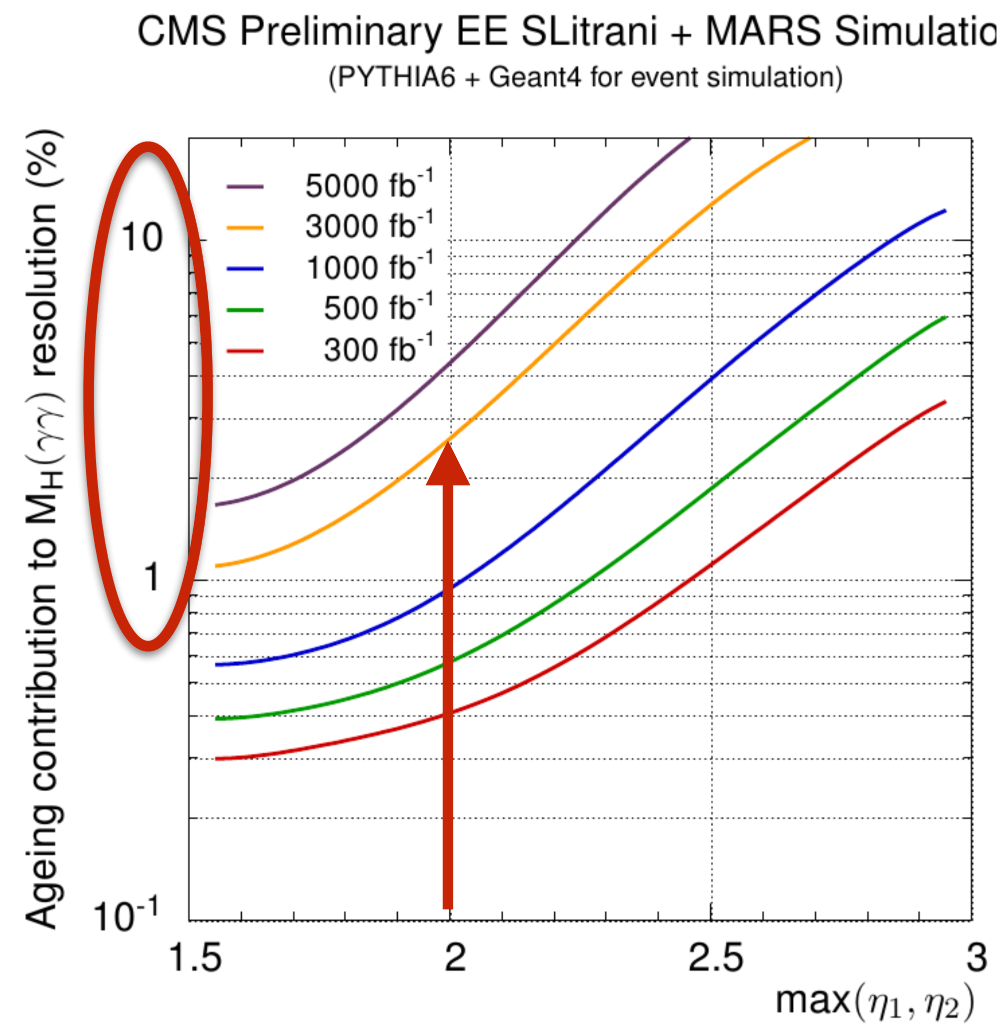
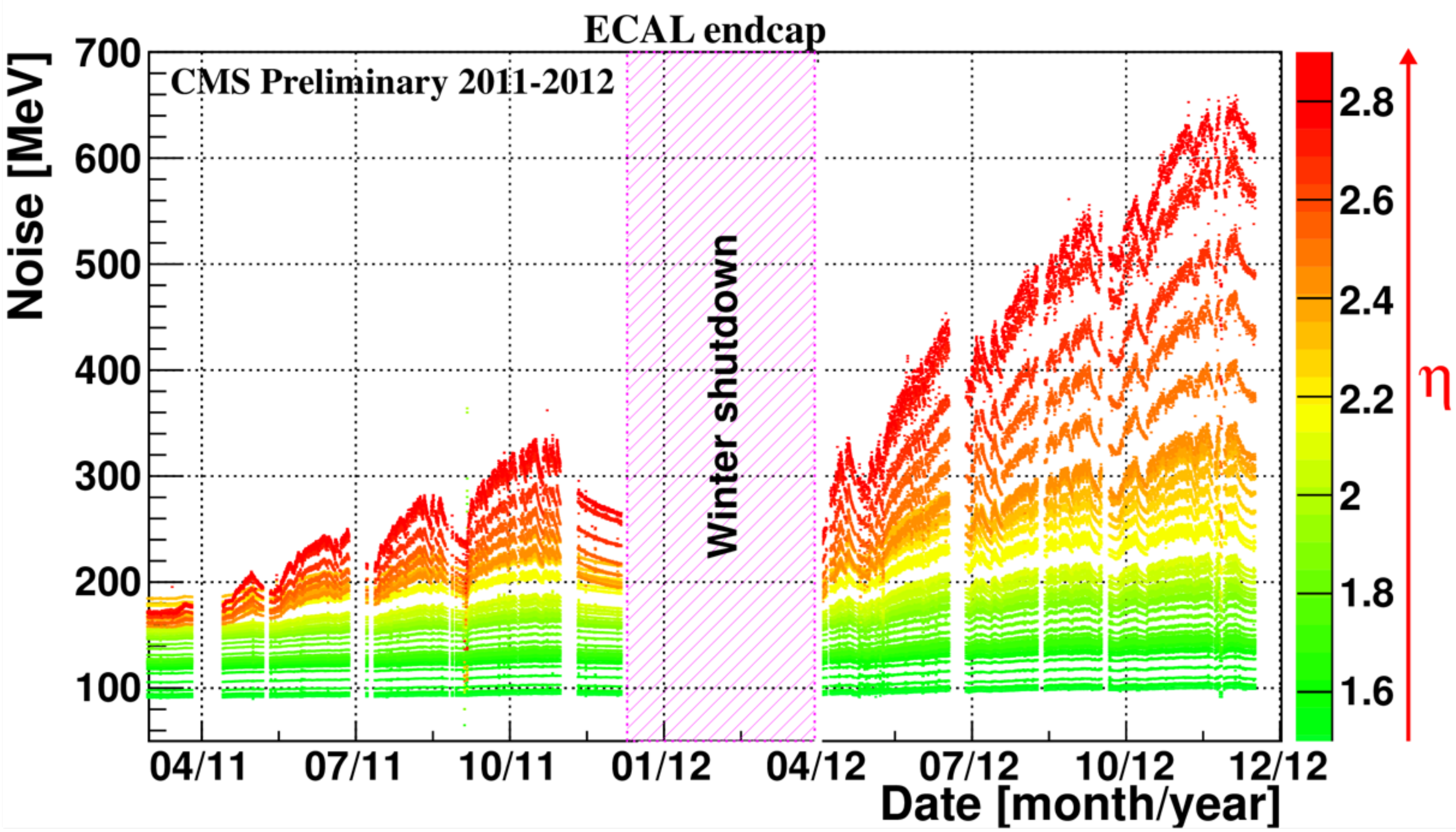
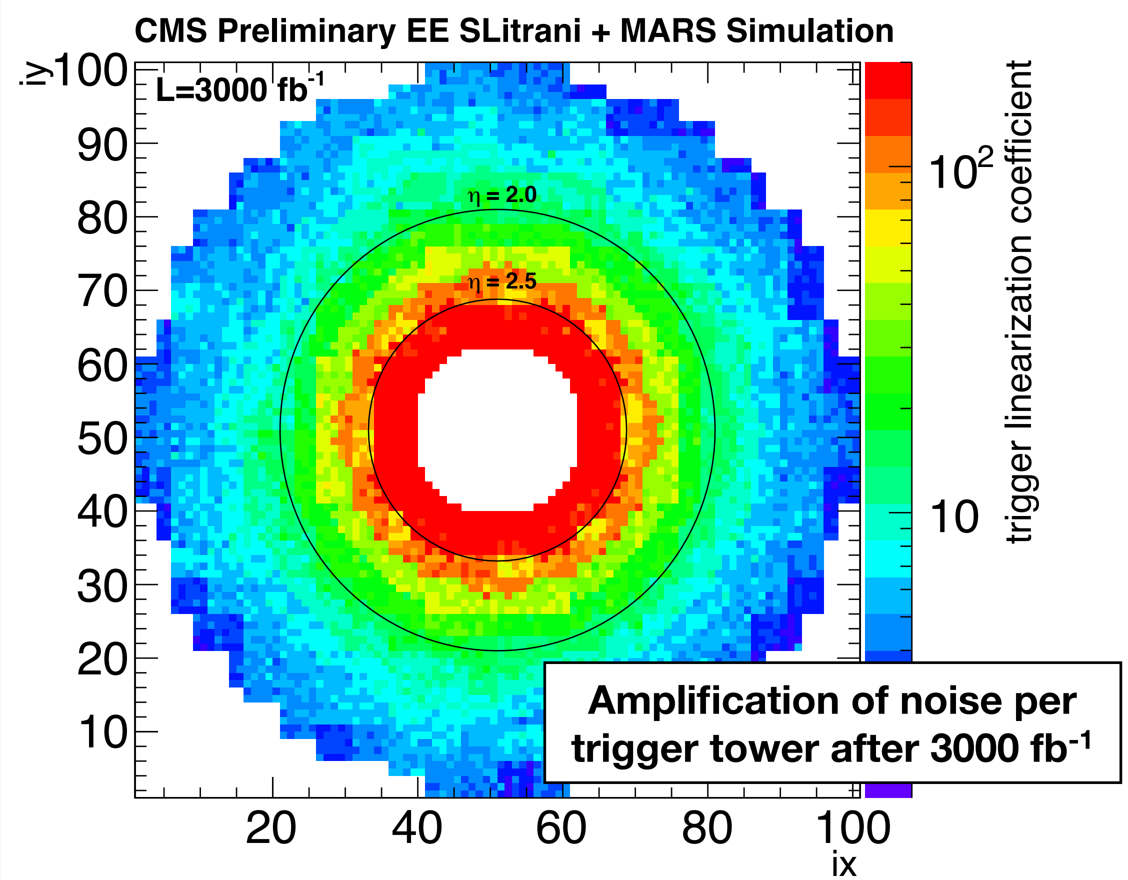




- At very high integrated luminosities, the ECAL response is **progressively degraded in the high-η region**
- Results in a strong **loss of physics performance for |η|>2** (transparency loss stays acceptable in the barrel region)
- **Need for ECAL endcap replacement during LS3**

Amplification of effective noise

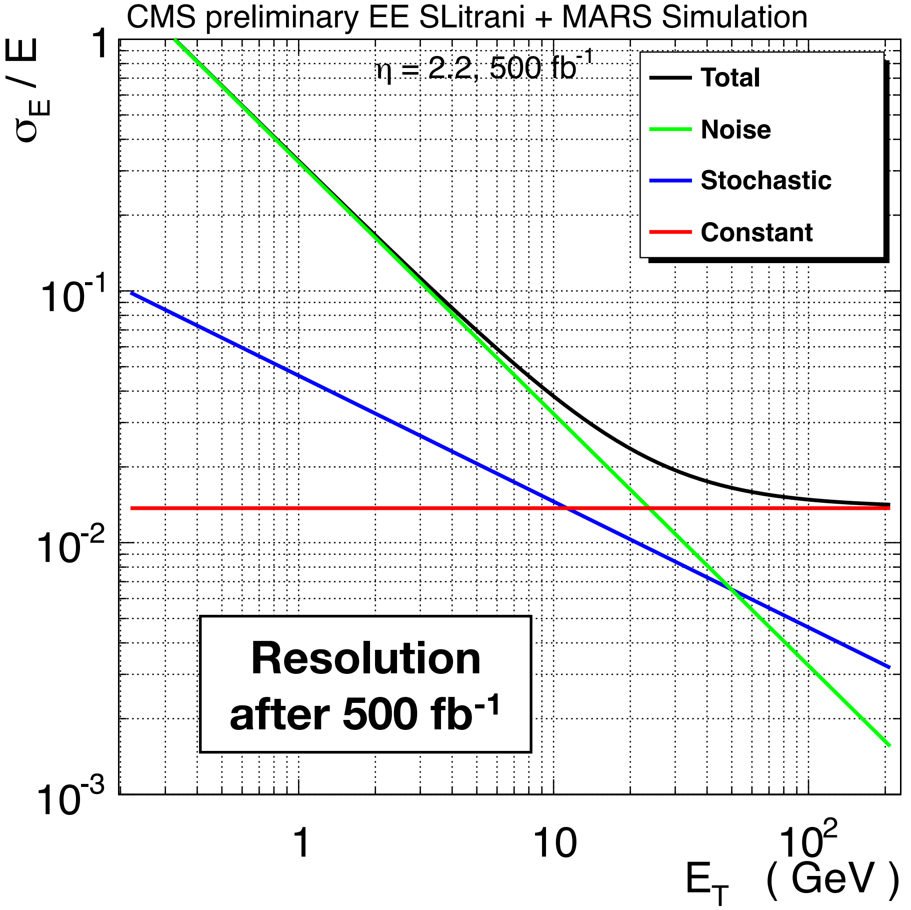


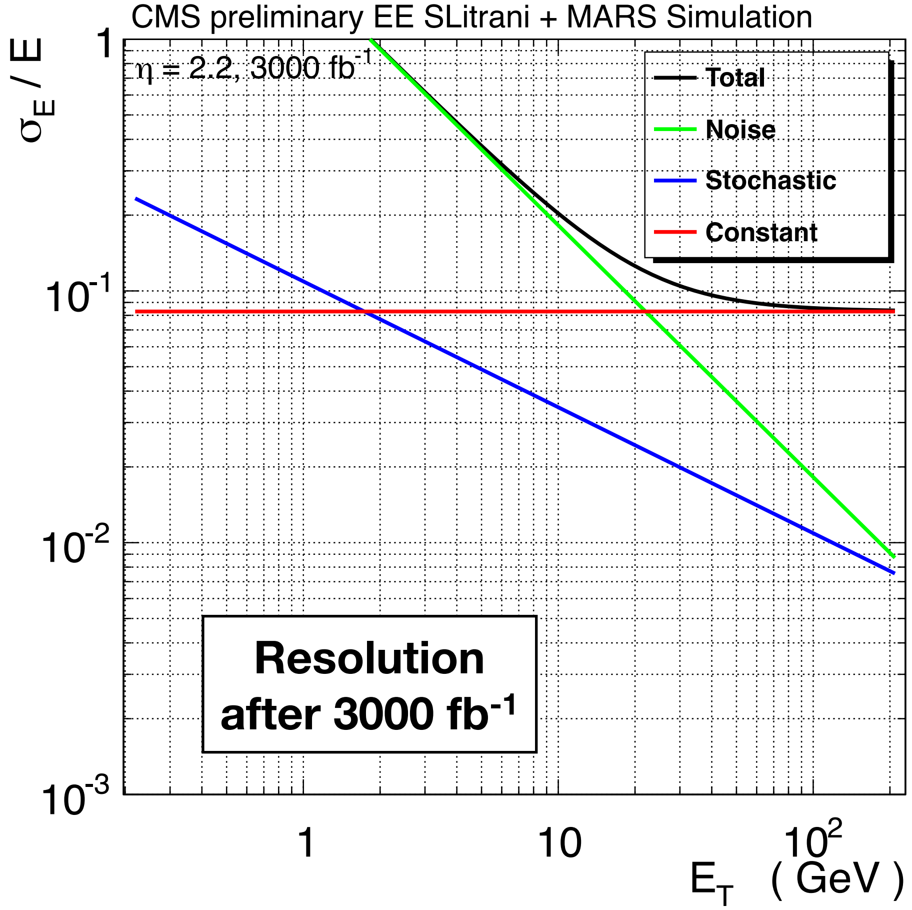


- Additional effect: **amplification of effective noise**
  - Already observed during LHC Run 1
  - <u>Noise measured in ADC counts stays constant, amplified by per-crystal transparency correction factors</u>
  - Amplified noise in trigger tower readout <u>prevents triggering on low E_T electrons and photons</u> in the endcap region

$$E_{e,\gamma} = \mathcal{G}\ \mathcal{F}_{e,\gamma} \sum_i \boxed{c_i s_i(t) \mathcal{A}_i}$$

Performance evolution

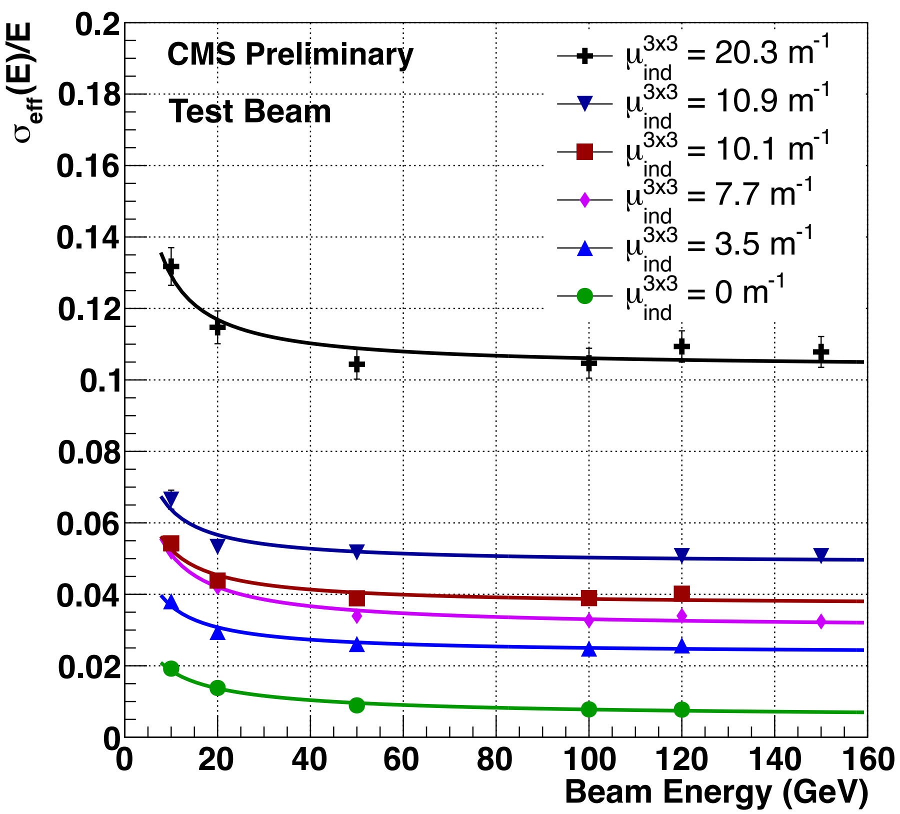




$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

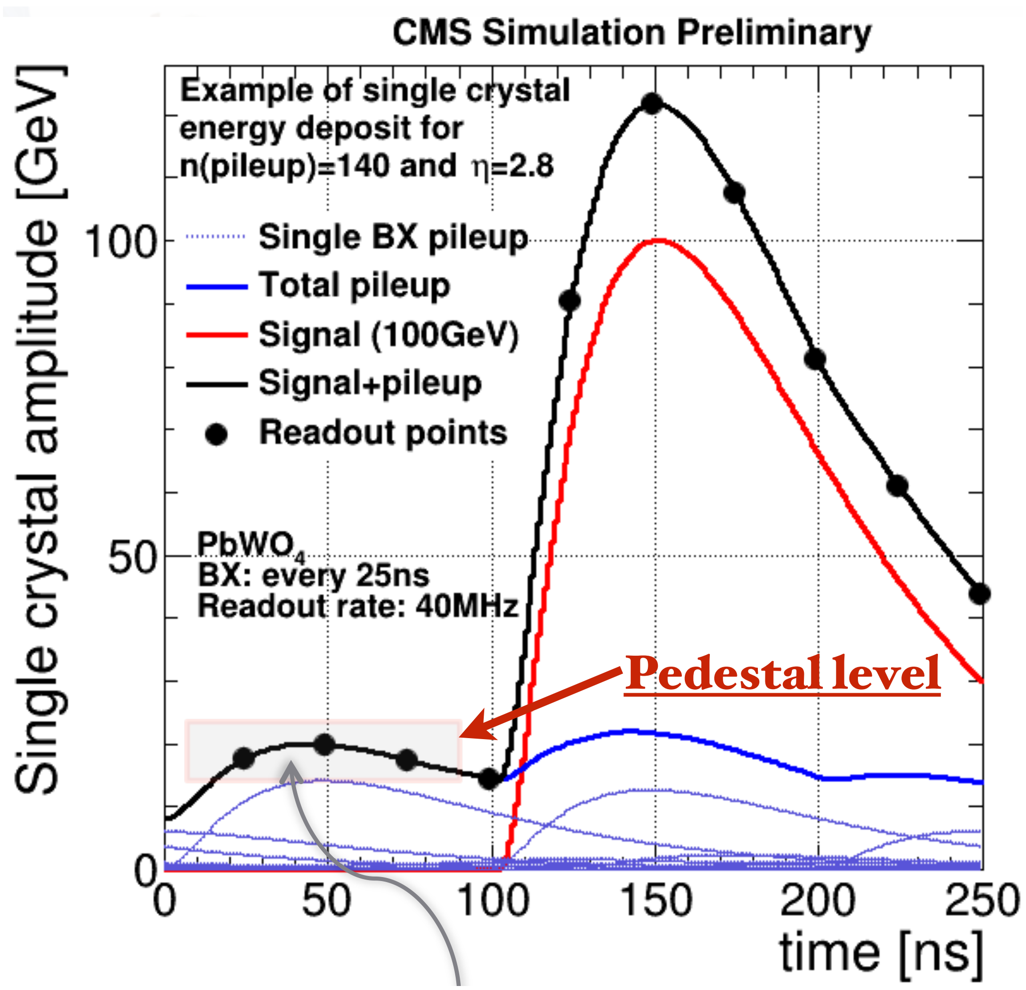
$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

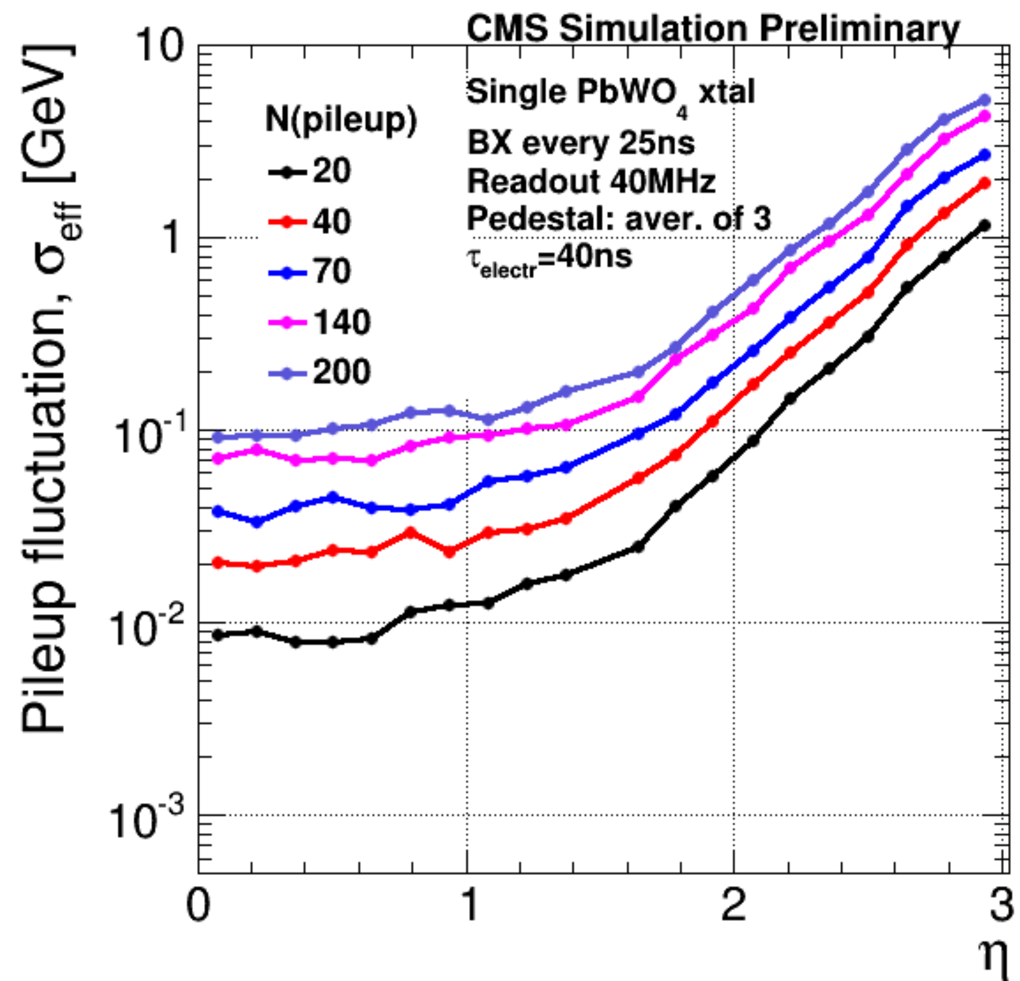
Reference:
crystal matrix resolution
in test beam data



- Worsening of **all terms of ECAL resolution:**
  - **stochastic term** from transparency loss
  - amplification of **noise term**
  - effects from non-uniformity of light collection and non-linearity on the **constant term**
- **Evolution model checked in irradiated crystals**

Effect of pileup in ECAL





- ❖ Energy deposition in ECAL crystals based on pulse shape
- ❖ Dynamic pedestal subtraction used to subtract the noise
- ❖ With high pileup, **overlapping energy deposits from adjacent bunch crossings**
- ❖ Effect **scales with detector occupancy**:

➠ **Main tool for fighting the effects of pileup is granularity**

Precision timing

- Additional handle available: **precision timing in ECAL**
  - identify photon clusters from pileup vertices
  - identify pileup jets
  - vertex choice in $H\rightarrow\gamma\gamma$ events

- Resolution needed:
  20 - 30 ps = 1 cm at vertex
  (contribution to $\gamma\gamma$ mass reconstruction comparable to energy measurement)

- Generic R&D ongoing:
  direct measurement, or dedicated layer with MCP or fast Si sensor

Calorimeter upgrade options

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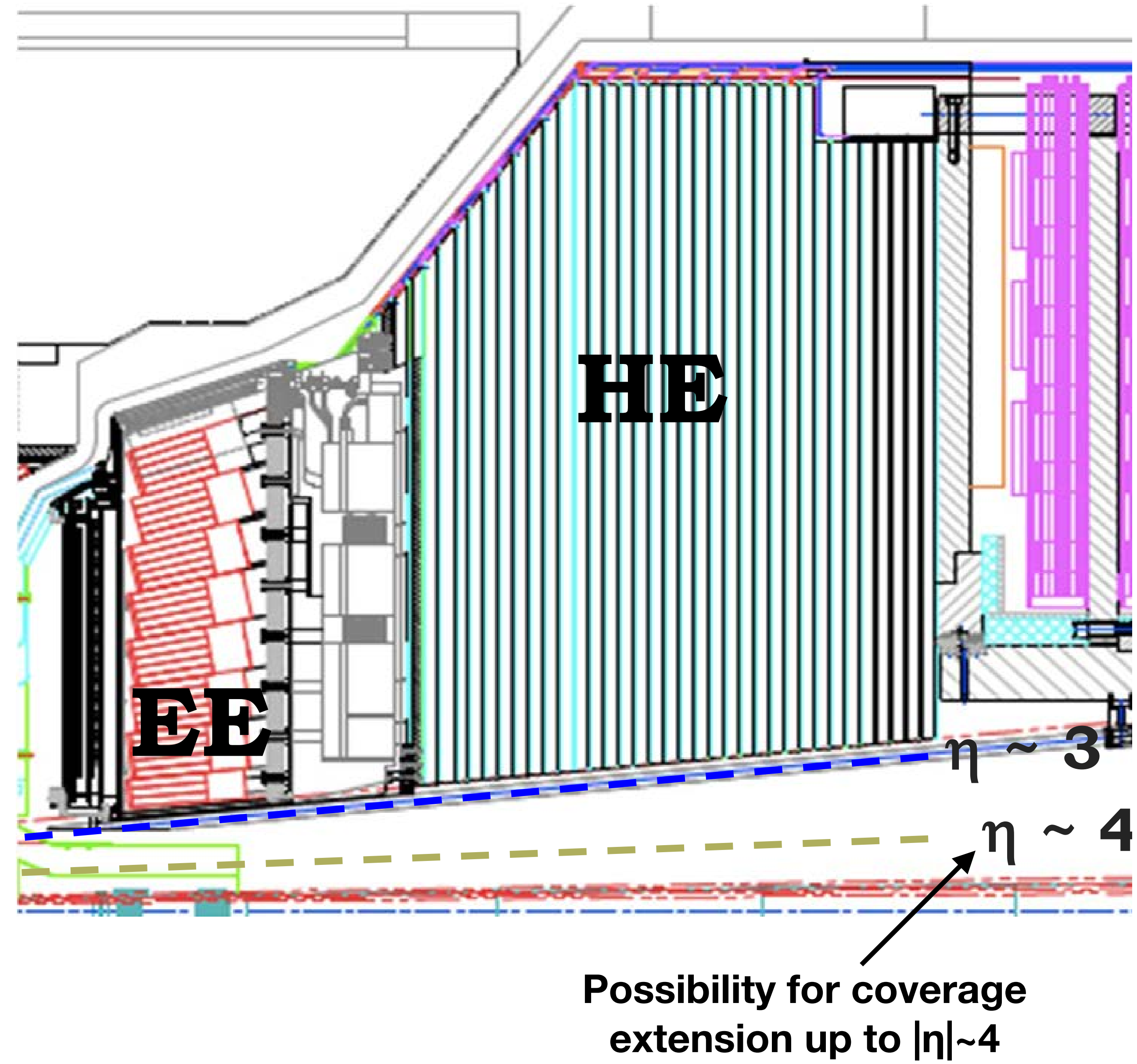
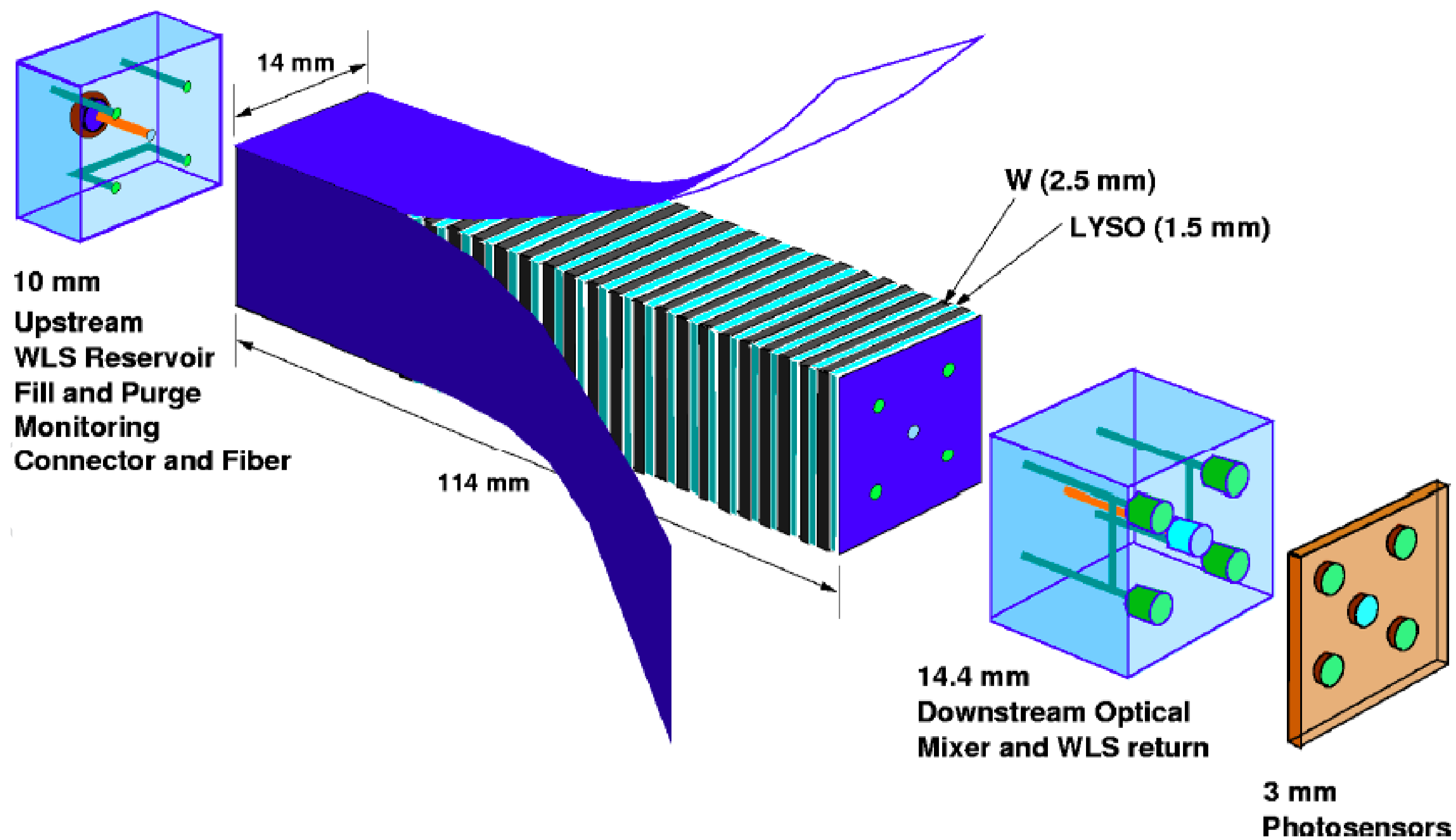
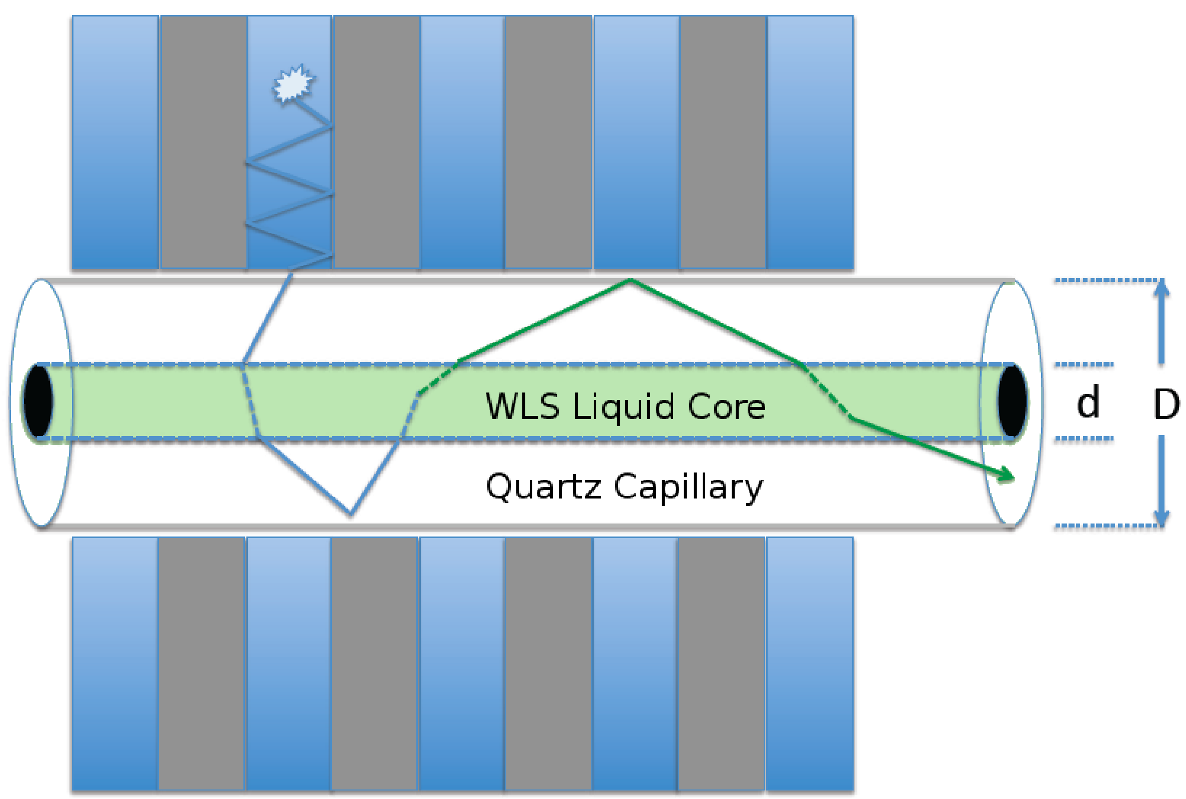
- ❖ Requirements for HL-LHC:
  - ✦ improved **radiation hardness**
  - ✦ **resilience to high-pileup**
- ❖ **Options for ECAL + HCAL endcap calorimeters replacement in LS3:**
  - ✦ **Maintain current scheme**, with separate EE and HE
    - ▸ new detector technologies
  - ✦ **Replace EE and HE with a new endcap calorimeter**



Shashlik option

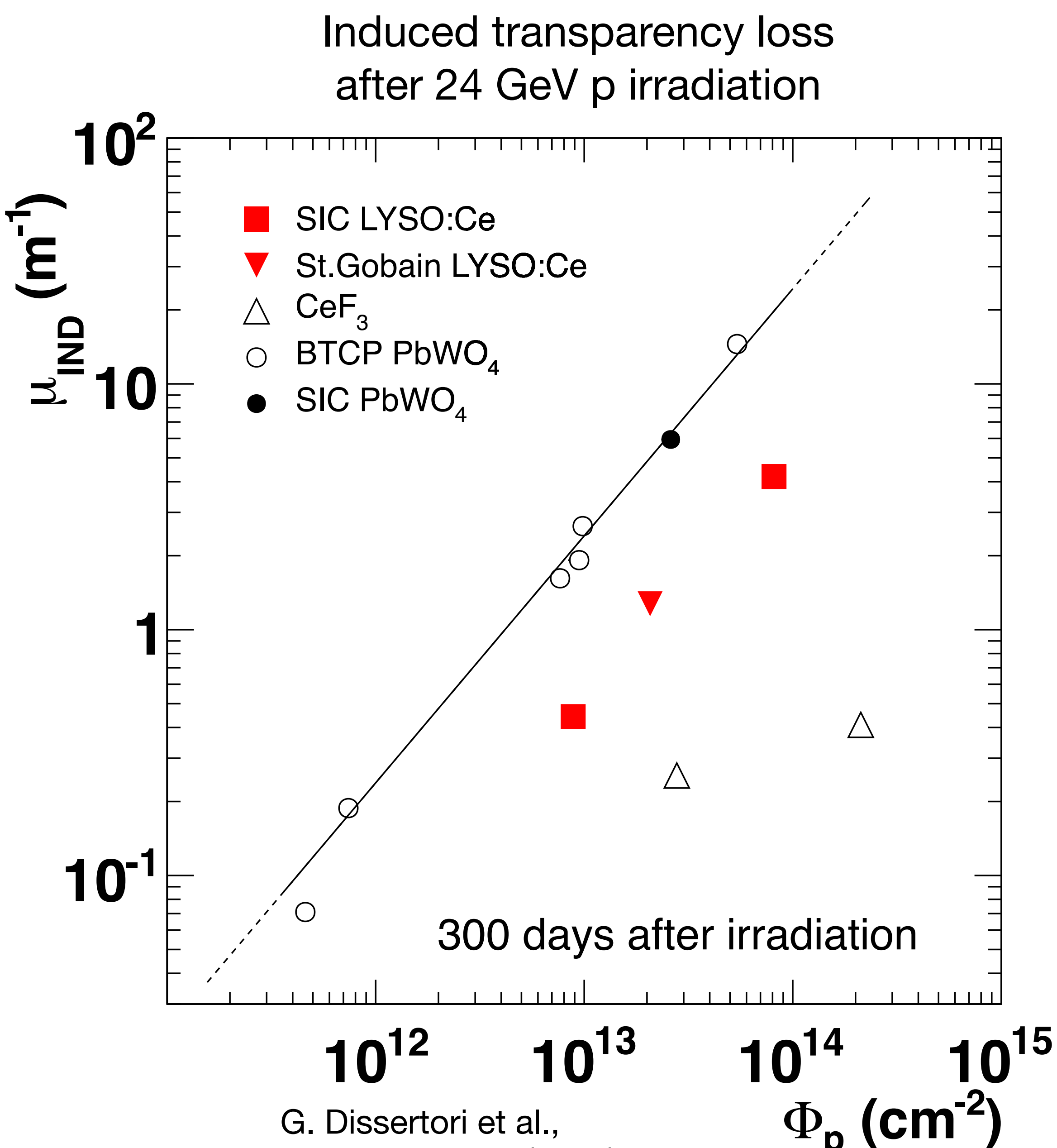
- ❖ **Sampling calorimeter**
  - ✦ radiation-hard inorganic scintillator (**LYSO, CeF_3**)
  - ✦ heavy absorber (W)
  - ✦ **light extraction through WLS fibers or capillaries**
  - ✦ **ΔE/E ~ 10%/√E**





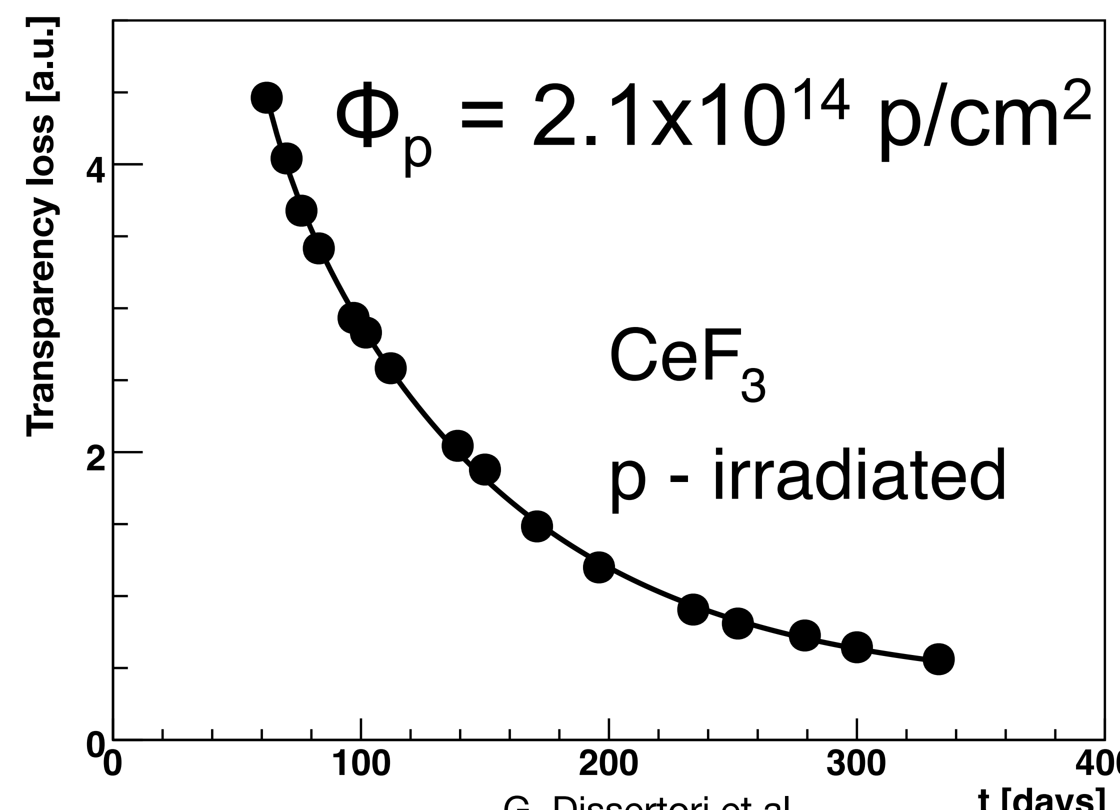
- ❖ Main challenges:
  - ✦ radiation-hard fibers
  - ✦ photodetectors
  - ✦ light output after WLS

Alternative scintillators



G. Dissertori et al.,
Nucl. Instr. Meth. A 745 (2014) 1-6

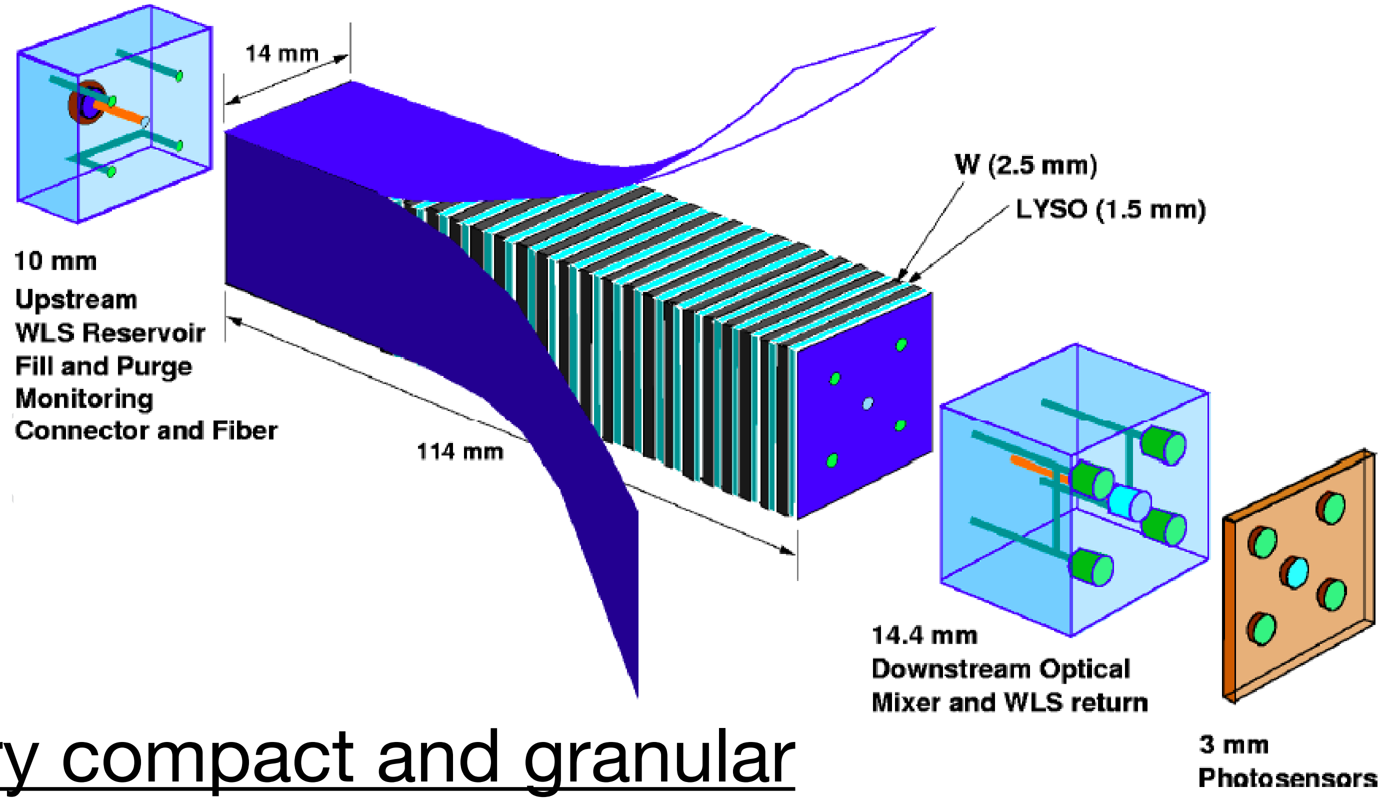
- Alternative scintillators under consideration:
  - **LYSO**
  - **CeF_3**



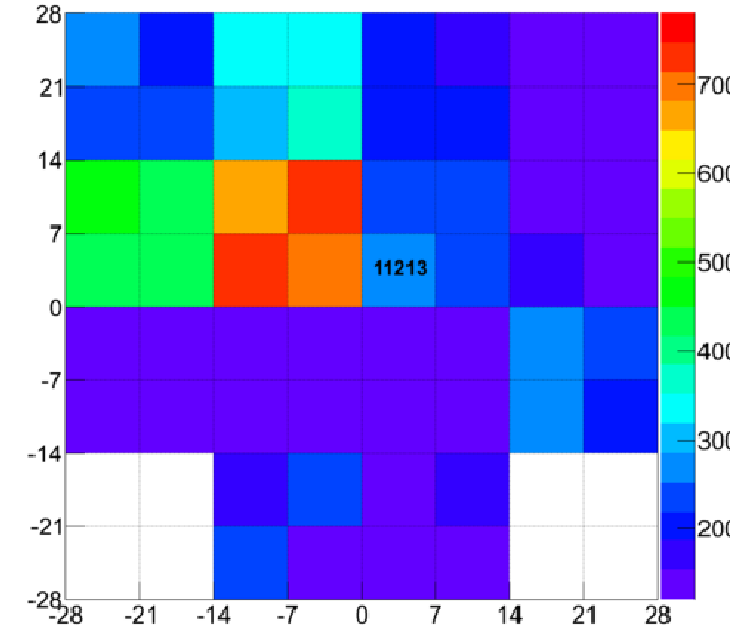
G. Dissertori et al.,
Nucl. Instr. Meth. A 622 (2010) 41-48

- Lower hadron damage than $PbWO_4$, or even capable of spontaneous recovery

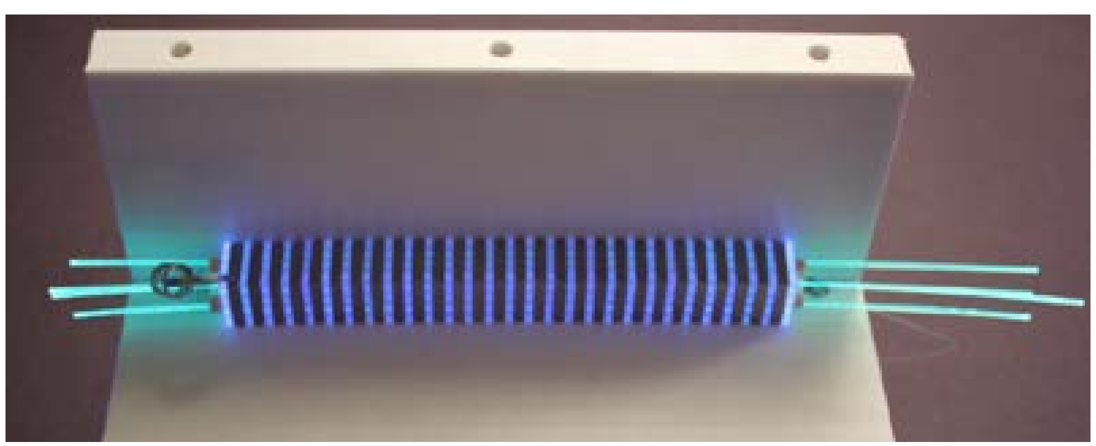
LYSO design and test beam



Example of matrix readout in test beam

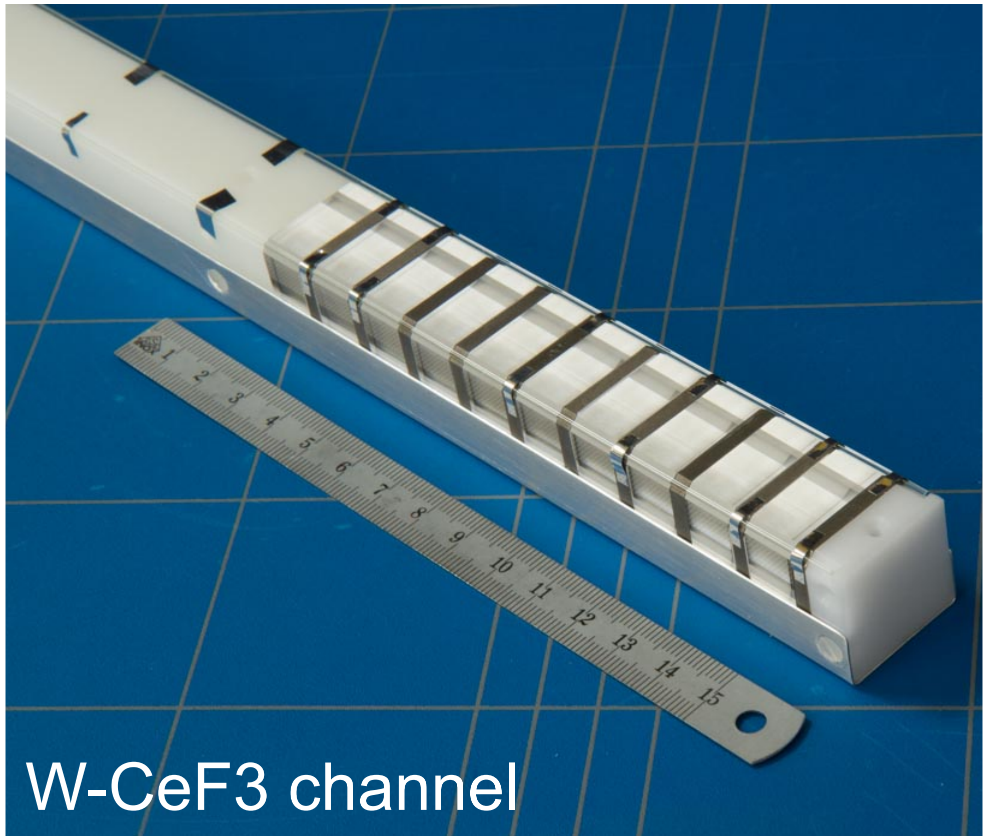


- <u>Very compact and granular (R_M~14 mm)</u>
- 4 readout WLS fibers,
  1 fiber for light injection
- SiPM readout at both ends

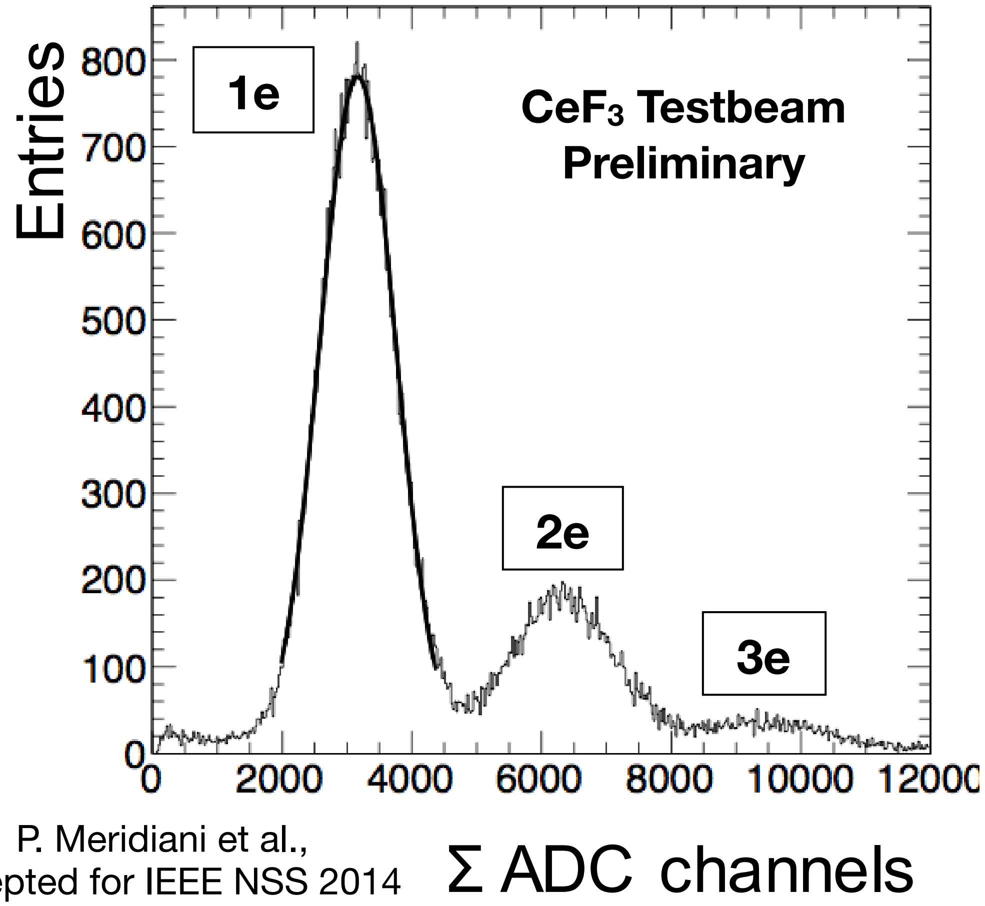


CeF_3 design and test beam

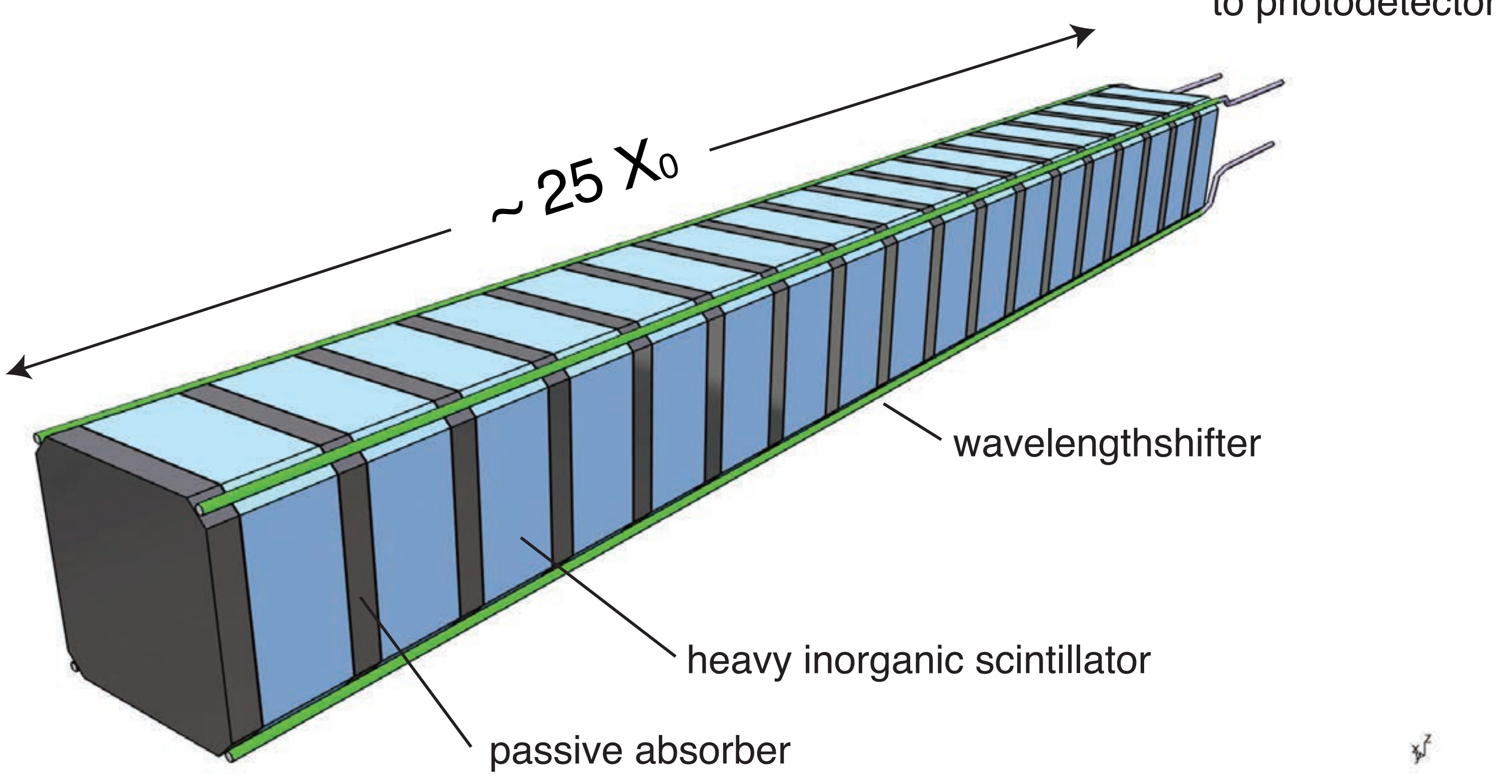
- **CeF_3** scintillating crystals, tungsten absorber plates
- **Wavelength-shifting fibers on channel corners** to extract light
- Test beam with BGO crystals for lateral shower energy containment



F. Nessi-Tedaldi, Proc. Calor 2014

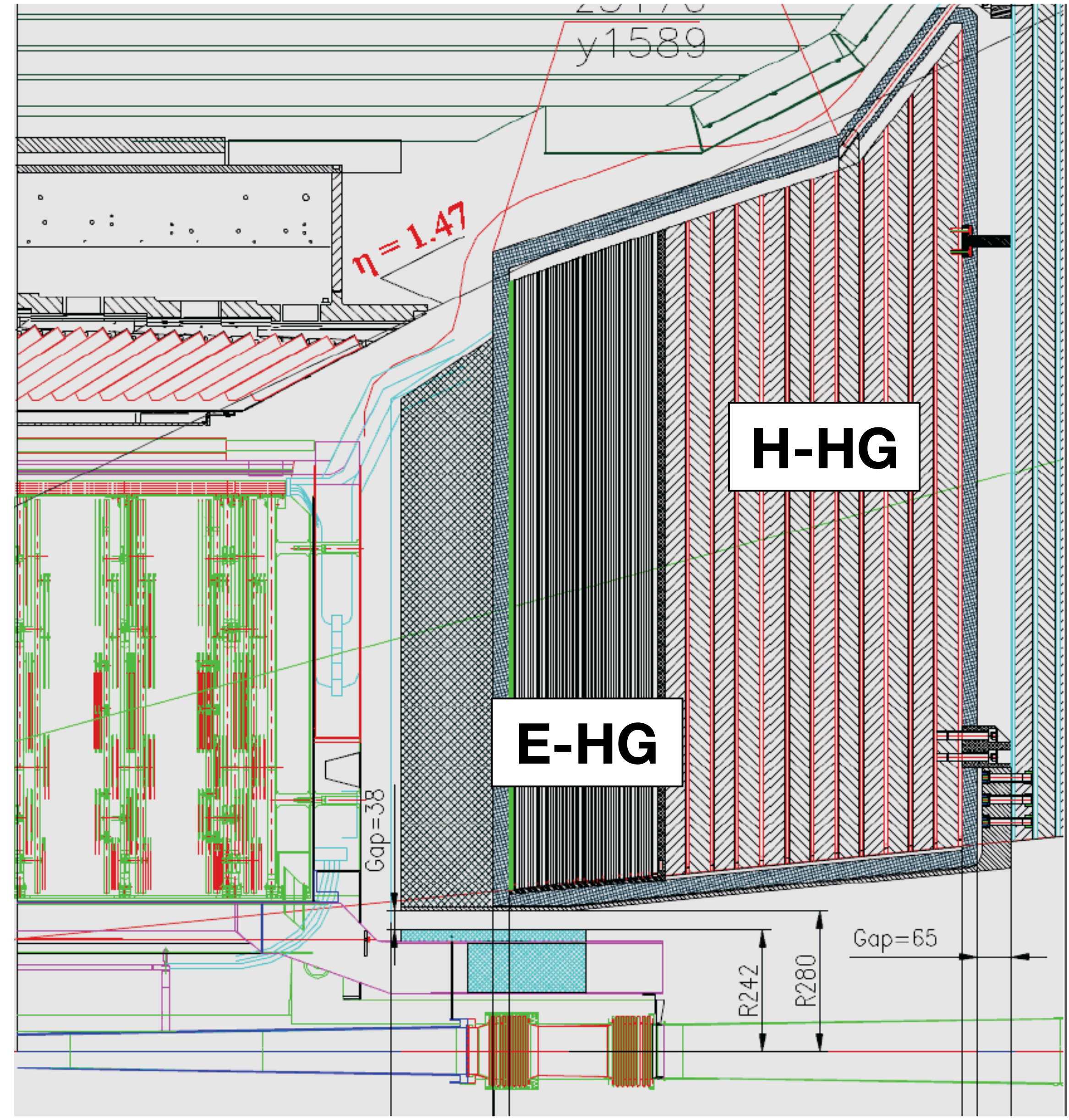


P. Meridiani et al., accepted for IEEE NSS 2014



HGCal option

- **Planes of Si separated by absorber (Cu or brass)**
- Focus on **very fine granularity and longitudinal segmentation for 3D shower profile reconstruction**
- E-HG: 25 X_0, 1 λ depth
  - 10 Si layers separated by 0.5 X_0
  - 10 Si layers separated by 0.8 X_0
  - 10 Si layers separated by 1.2 X_0
- H-HG: 3.5 λ depth
  - 12 Si layers separated by 0.3 λ
- B-HG as HE rebuild, 5.5 λ depth
  - finer granularity than current HE
- In total: ~ 9M channels, 600 m^2 Si



- Main challenges:
  - number of channels, readout and event reconstruction
  - electronics and cooling (-30 °C)

HGCal option

- **Planes of Si separated by absorber (Cu or brass)**
- Focus on **very fine granularity and longitudinal segmentation for 3D shower profile reconstruction**
- E-HG: 25 X_0, 1 λ depth
  - 10 Si layers separated by 0.5 X_0
  - 10 Si layers separated by 0.8 X_0
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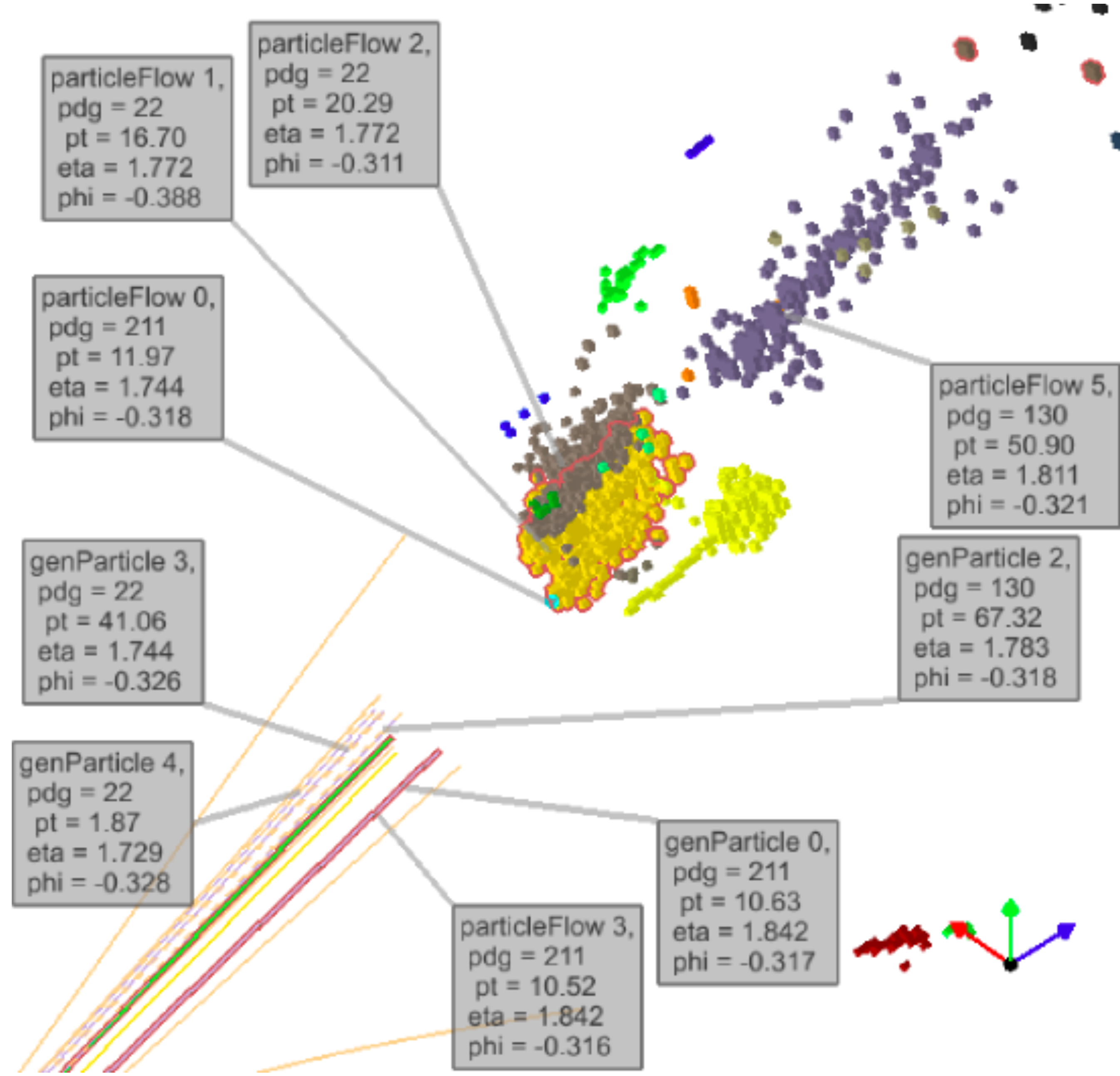
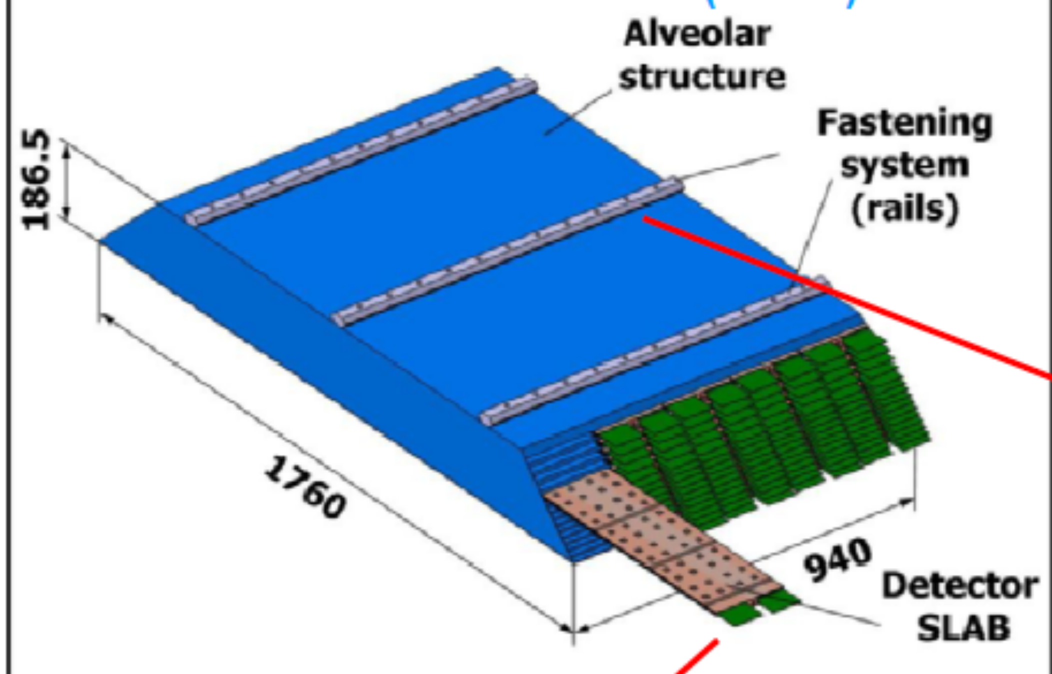


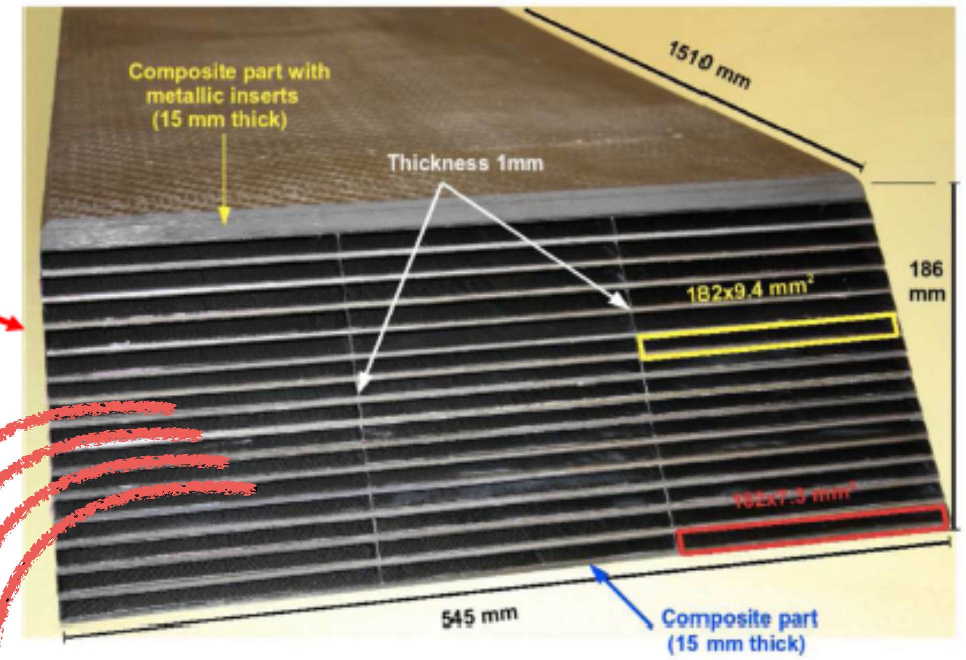
- **ΔE/E ~ 20%/√E**
- **3D shower reconstruction**

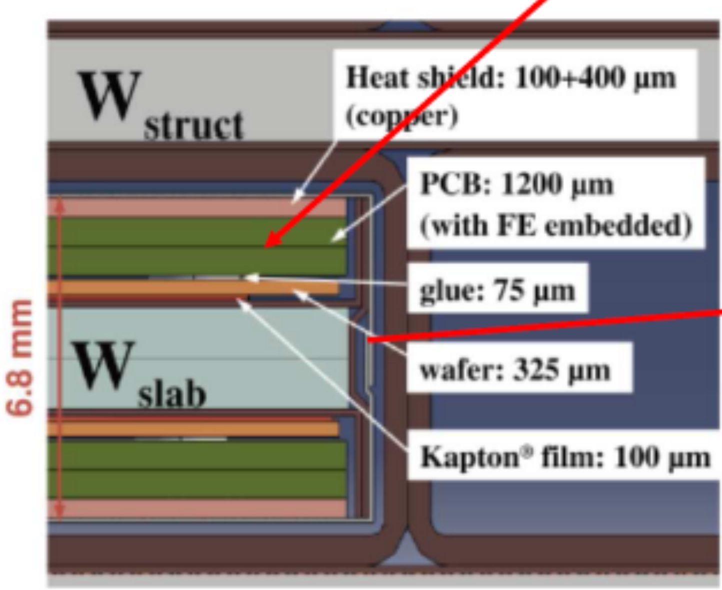
HGCal design

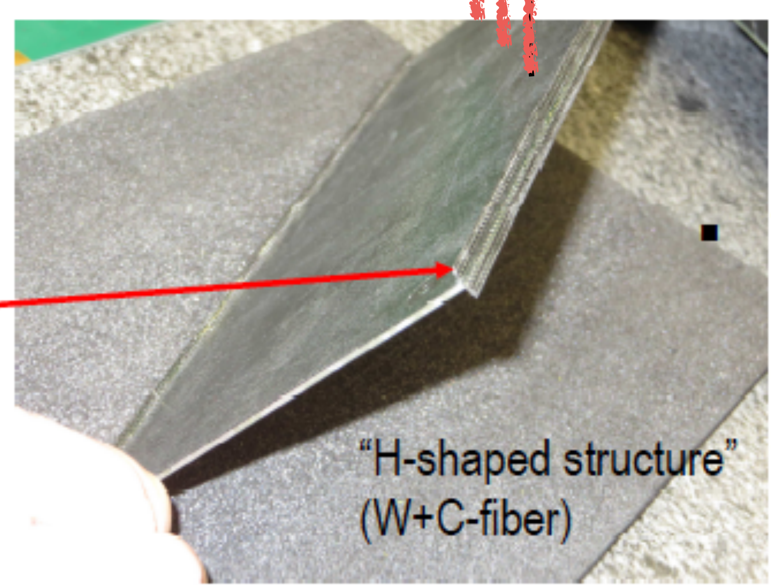
CALICE ECAL module (barrel)

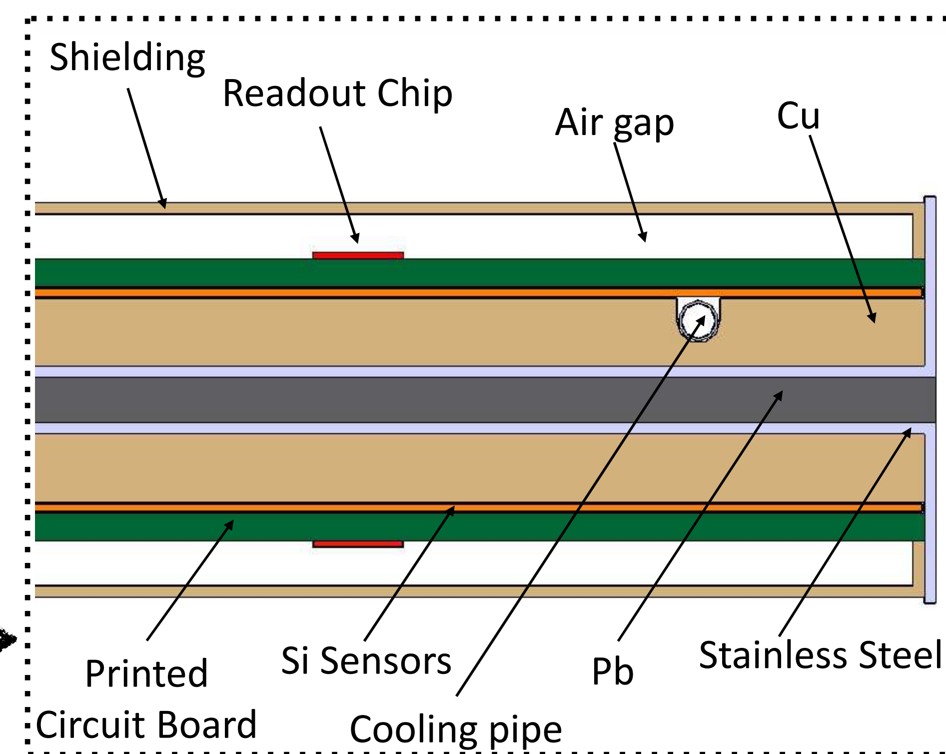


- Half of the tungsten plates is incorporated into a self-supporting **alveolar composite structure** (carbon)







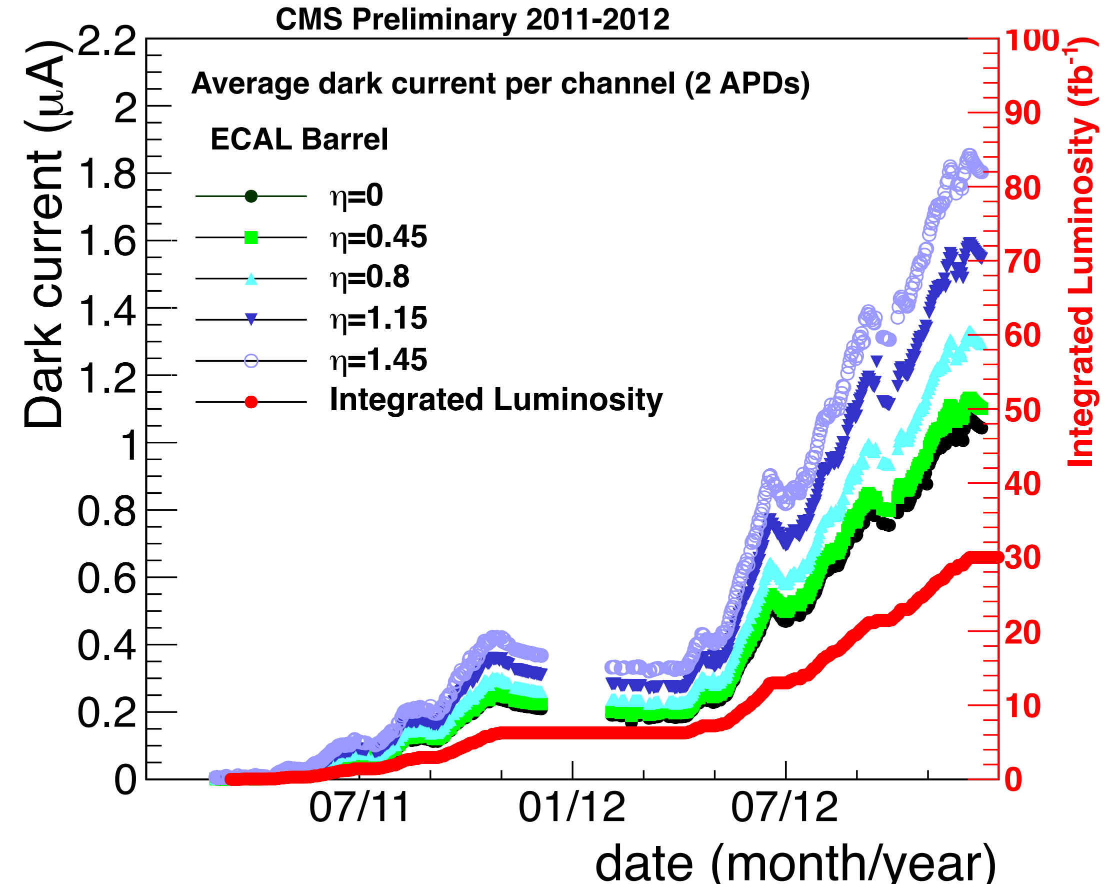


Conclusions

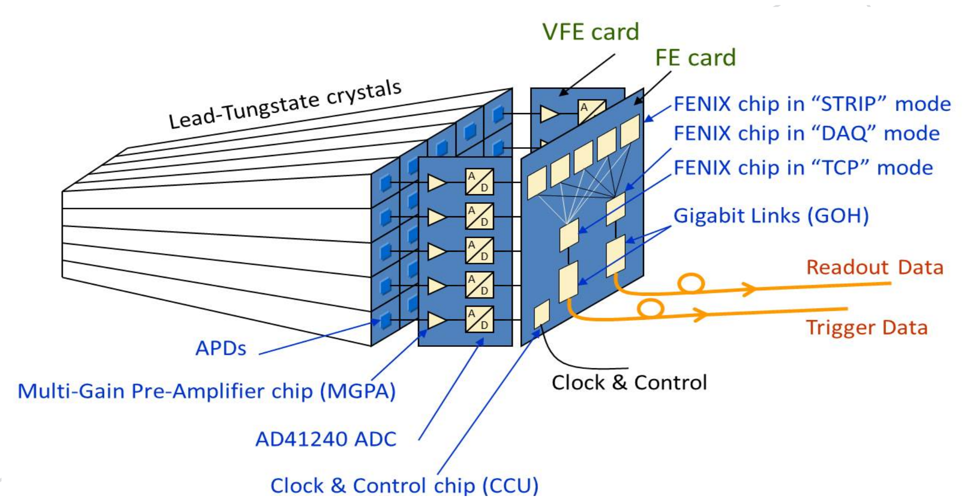
- Data-taking conditions at the HL-LHC significantly beyond design in terms of instantaneous luminosity (radiation, pileup)
- Mechanisms of **radiation damage** to $PbWO_4$ and other scintillating crystals studied in detail, evolution models validated in test beam data
- Challenges to physics performance:
  - loss of transparency (loss of light output, increased effective noise)
  - high pileup → need for more granularity
- While barrel crystals can maintain good performance after LS3, the **ECAL endcaps have to be replaced**
- Upgrade options under consideration (decision in ~ 1 year):
  - **Shashlik LYSO/CeF_3** sampling ECAL + HE rebuild
  - **Silicon-based high-granularity** endcap calorimeter

ECAL barrel upgrade

- Crystals capable of standing HL-LHC radiation environment in the barrel region
- **Damage to APD photosensors: increase of dark current**
  - worsening of effective readout noise
  - limited by lowering the temperature (→ 8 °C)



- **Upgrade of electronics** to fit the new L1 trigger requirements
  - single-crystal information available at L1
  - improved spike rejection, time measurement



Preliminary sketch of upgraded configuration