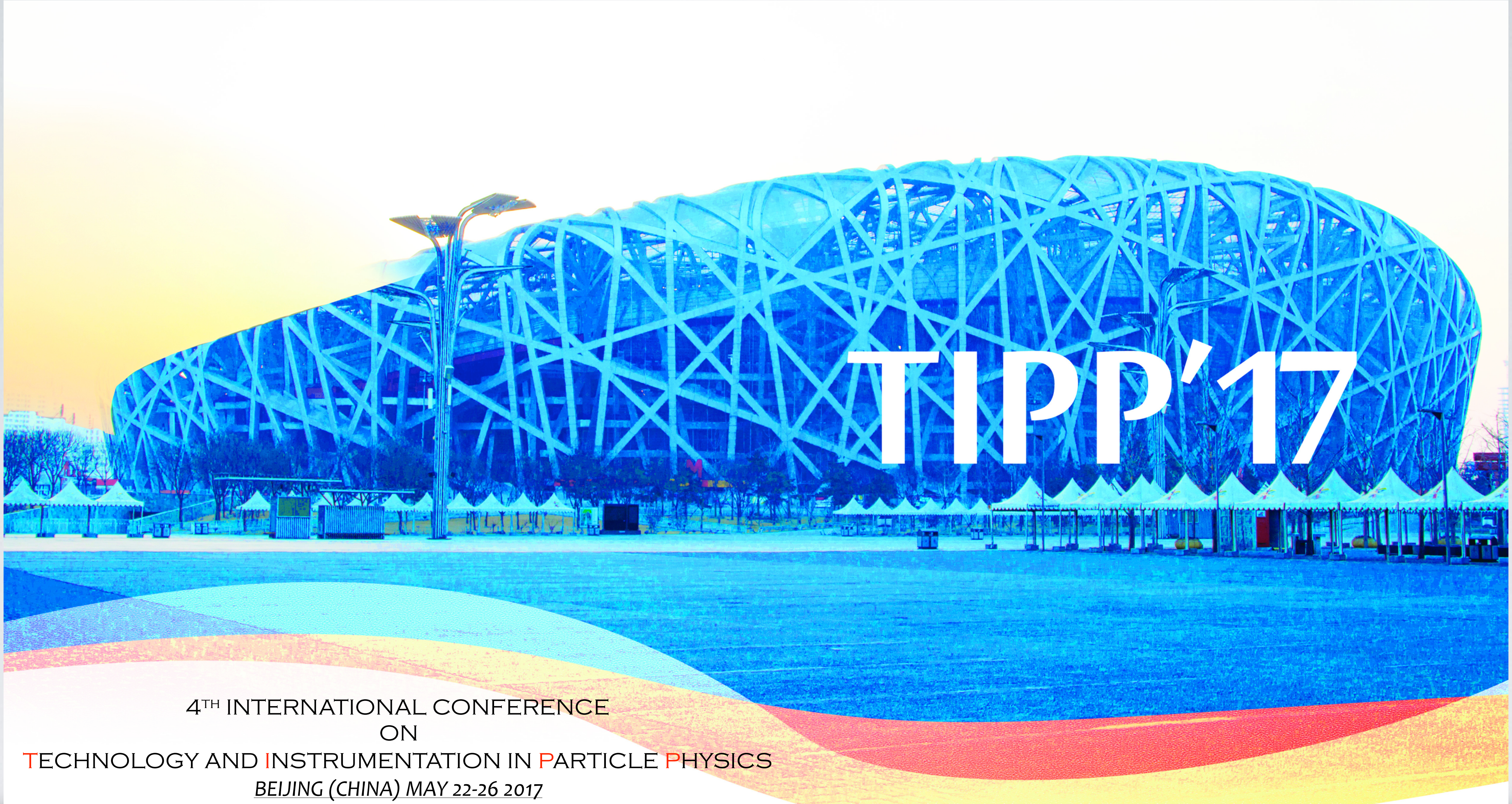


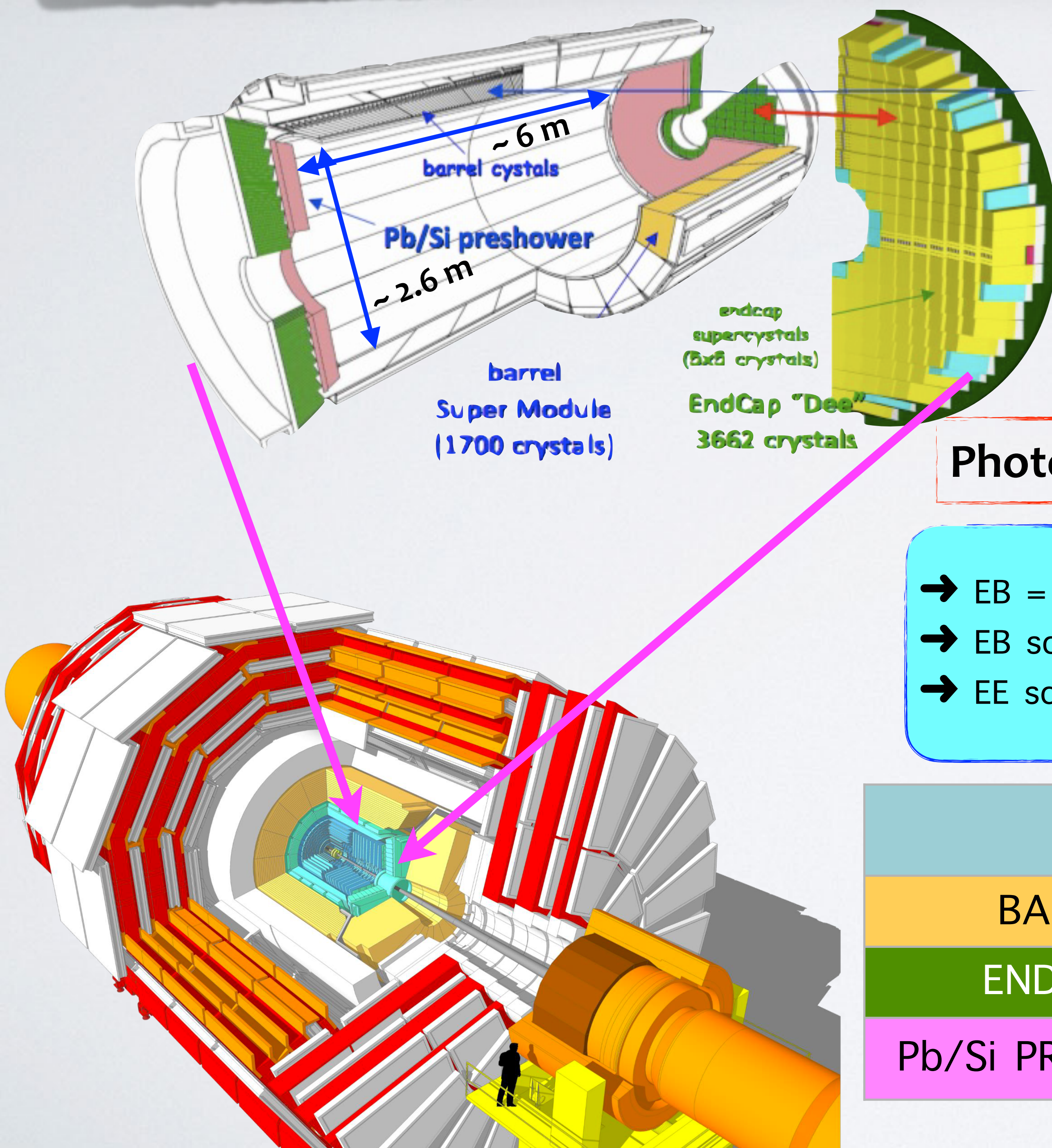

4TH INTERNATIONAL CONFERENCE
ON
TECHNOLOGY AND INSTRUMENTATION IN PARTICLE PHYSICS
BEIJING (CHINA) MAY 22-26 2017

# THE CMS ECAL UPGRADE FOR PRECISION CRYSTAL CALORIMETRY AT THE HL-LHC

PATRIZIA BARRIA
ON BEHALF OF THE CMS COLLABORATION

# THE CMS ELECTROMAGNETIC CALORIMETER (ECAL)

Homogeneous Scintillating Crystal Calorimeter made of Lead tungstate ($PbWO_4$) crystals




**Energy resolution**

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

- **A**: stochastic term
- **B**: noise term
- **C**: constant term

**Photon in CMS: Cluster of energy deposits in crystals**

- ➜ EB = 36 super-modules (SM) of 1700 crystals each
- ➜ EB scintillation light read out by Avalanche Photodiodes (APDs)
- ➜ EE scintillation light read out by Vacuum Phototriodes (VPTs)

| | $\eta$ REGION | # CRYSTALS |
|---|---|---|
| BARREL (EB) | $\lvert\eta\rvert < 1.48$ | 61200 CRYSTALS |
| ENDCAPS (EE) | $1.48 < \lvert\eta\rvert < 3.0$ | 14648 CRYSTALS |
| Pb/Si PRESHOWER (ES) | $1.65 < \lvert\eta\rvert < 2.6$ | |

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# ECAL CURRENT PERFORMANCE

- ECAL energy resolution crucial for Higgs boson and many other CMS analysis

see Chia-Ming Kuo talk

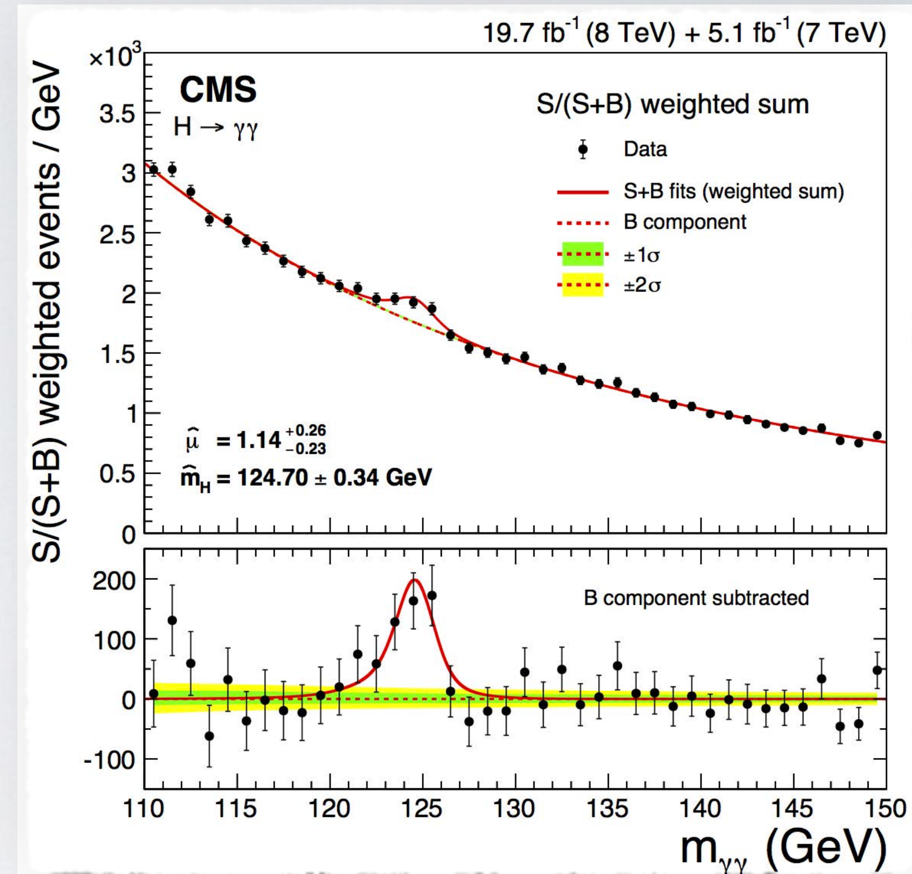
  - $H \rightarrow \gamma\gamma$: Resolution on $m_{\gamma\gamma}$ ~ 1%

- Performance affected by Pile Up (PU) = Overlapping interactions for single bunch crossing (BX)

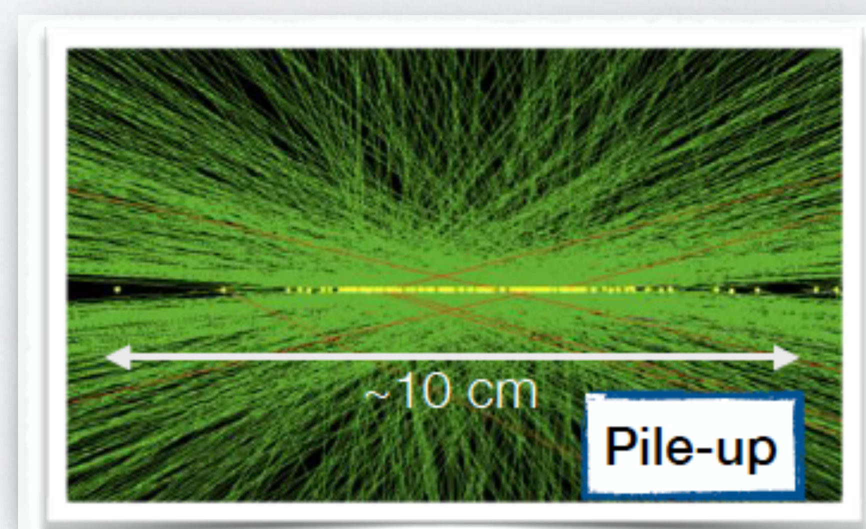
- Improved techniques for LHC Run II (2015-2018) to cope with higher PU (x2 wrt Run I)

Excellent performance of ECAL @13 TeV

**Photon Energy resolution:** 1-3% in EB, 2.5-4.5% in EE




Can we maintain this performance for the future?

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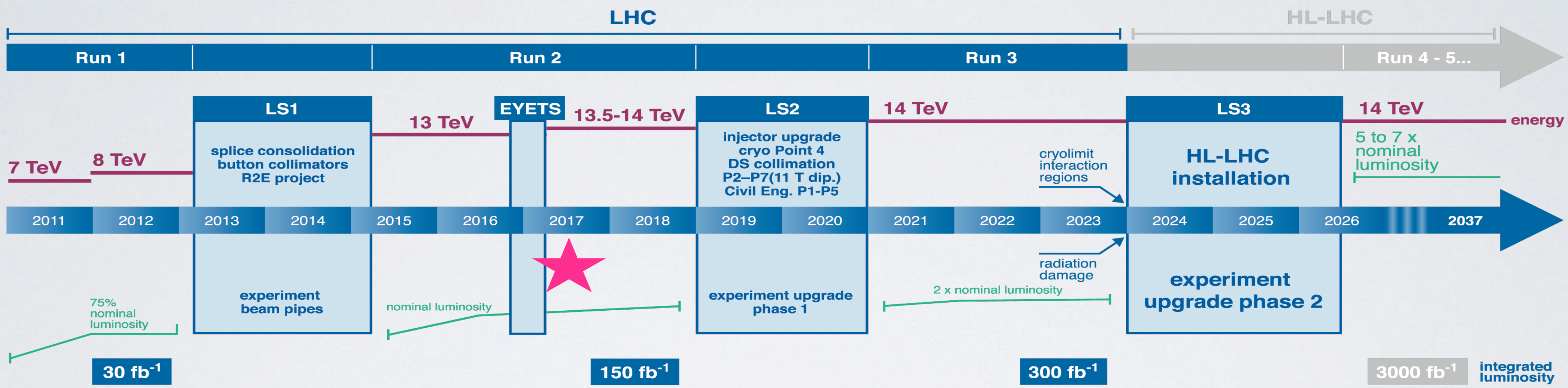
# LHC & HL-LHC SCHEDULE




| | DESIGN | CURRENT STATE | UPGRADED |
|---|---|---|---|
| $E_{beam}$ (TeV) | 7 | 6.5 | 7 |
| $L_{inst}$ ($cm^{-2}$ $s^{-1}$) | $10^{34}$ | $(1.0\text{-}1.4)\times10^{34}$ | $5\times10^{34}$ |
| $L_{int}$ ($fb^{-1}$) 10 years operation | 300 | 40 per year | 3000 |
| $\beta^*$ (cm) | 50 | 40 | 15 |
| PILEUP (PU) | 20 | 37 | 120-200 |

- Higher instantaneous and annual integrated luminosity
- Much higher levels of overlapping events: pile-up (PU)
- Radiation levels will be 6x higher than for LHC

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# CMS ECAL CHALLENGE DURING HL-LHC

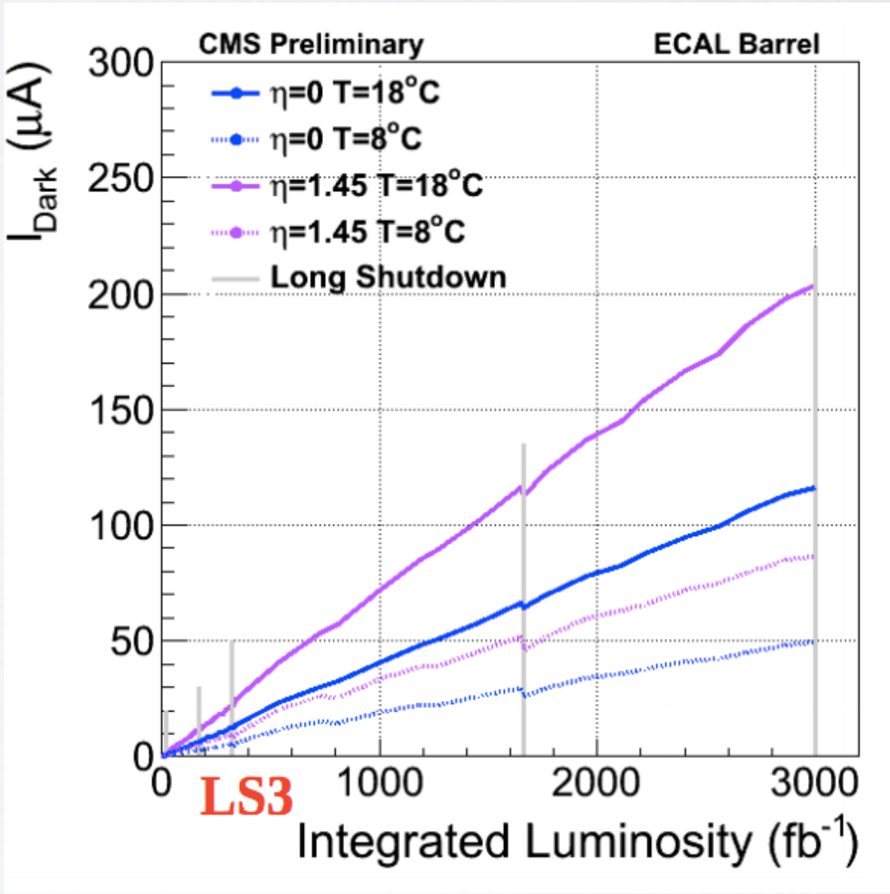
**The HL-LHC conditions = significant challenge to both detector longevity and performance**

- EE difficult challenge ➜ radiation levels change by a factor of 100 between |η| = 1.48 and |η| = 3.0

- Dose & fluence levels result in significant loss to the crystal light transmission and VPT performance ➜ replacement of the Endcap (EE) calorimeter for HL-LHC

- EB: radiation damage not a serious problem
  - increase in APD dark current ➜ dominant effect for $L_{int}$> 1000/fb
  - higher PU
  - increased photodetector (APD) noise

| | | LHC design | HL-LHC prediction |
|---|---|---|---|
| Luminosity [$cm^{-2}s^{-1}$] | | $1\times10^{34}$ | $5\times10^{34}$ |
| Int. Luminosity [$fb^{-1}$] | | 500 | 3000 |
| $\gamma$ **dose rate** [Gy/h] | (EB $\|\eta\| = 1.0$) | 0.2 | 1.0 |
| | (EE $\|\eta\| = 2.6$) | 6 | 30 |
| **hadron fluence** [particle/cm²] | (EB $\|\eta\| = 1.0$) | $12\times10^{11}$ | $7.6\times10^{12}$ |
| | (EE $\|\eta\| = 2.6$) | $3\times10^{13}$ | $2.0\times10^{14}$ |

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# ECAL EB UPGRADE: MOTIVATION

### ACCOMODATE PHASE II TRIGGER

- Current FE and OD readout inconsistent with L1 Phase II requirements

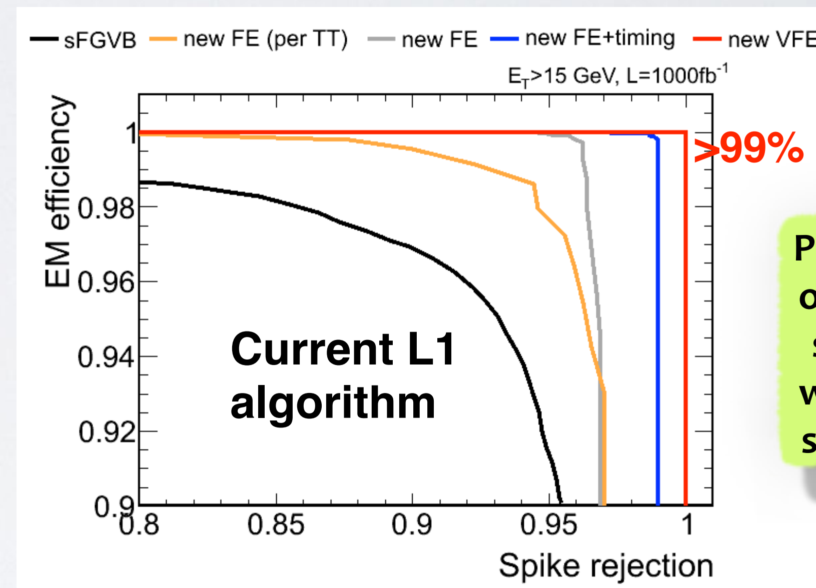
### SPIKES MITIGATION

- **Improved trigger granularity:** 1x1 crystal trigger primitive (TP) vs legacy 5x5 (FE/OD)
- **Timing:** Spikes have different time evolution if compared with scintillation (VFE/OD)

### MAINTAIN PERFORMANCE

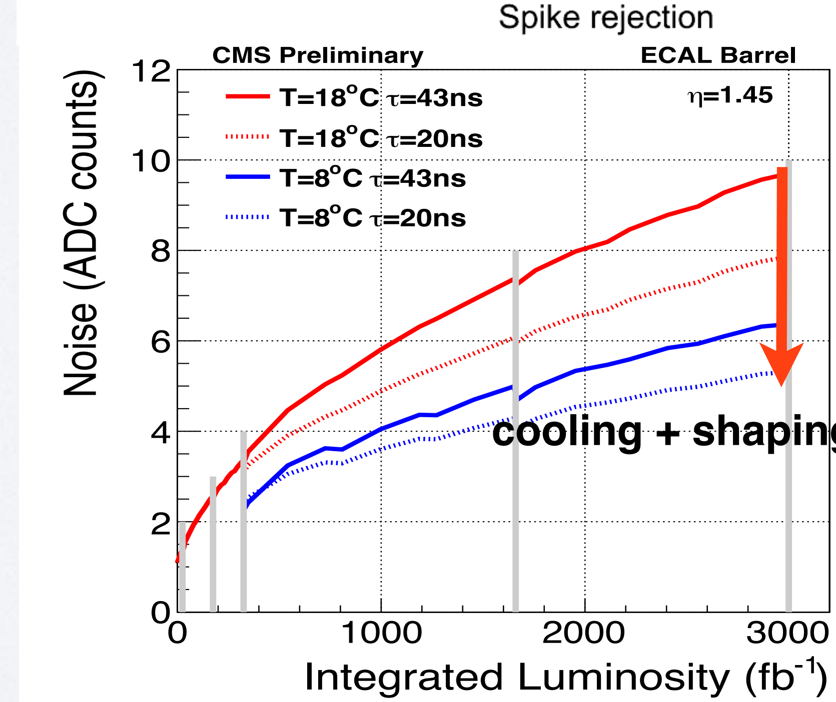
- APD noise increase will significantly degrade EM resolution at HL-LHC
- MANDATORY to mitigate this by cooling the APDs, and optimising pulse shaping (new VFE)

| | L1 ACCEPT RATE | L1 LATENCY |
|---|---|---|
| TRIGGER PHASE II | 750 kHz | 12.5 μs |
| ECAL PHASE I | 150 kHz | 6.4 μs |




>99% spike rejection

Performance of current L1 spike killer will degrade significantly



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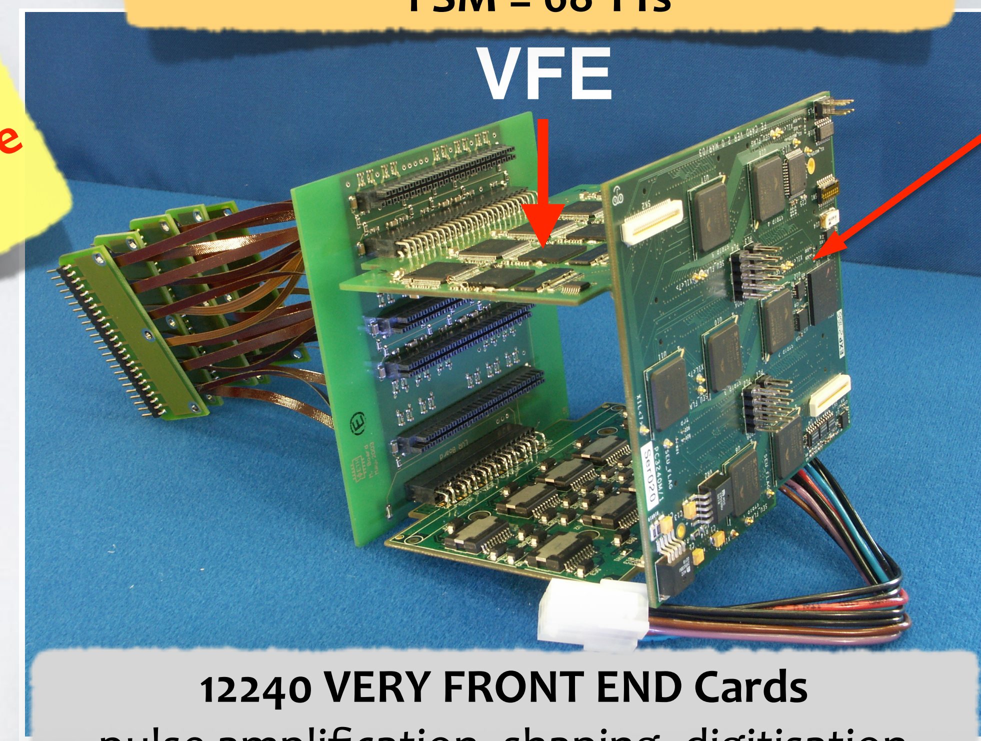
# ECAL BARREL (EB)

**36 SUPERMODULES (SM)**

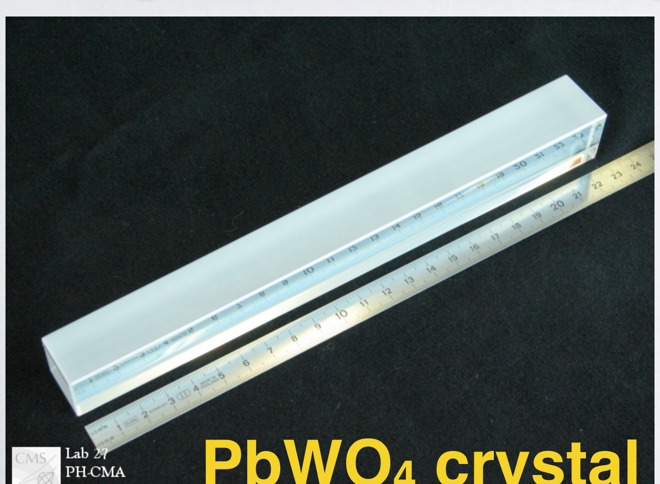

All the SMs will be removed
for the electronics upgrade
MAJOR EFFORT

**2448 TRIGGER TOWERS (TT)**
basic readout unit 5x5 crystals matrix
**1 SM = 68 TTs**

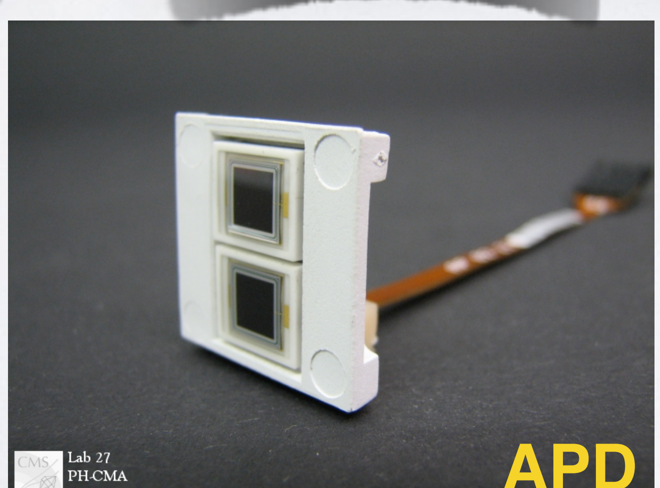



**12240 VERY FRONT END Cards**
pulse amplification, shaping, digitisation

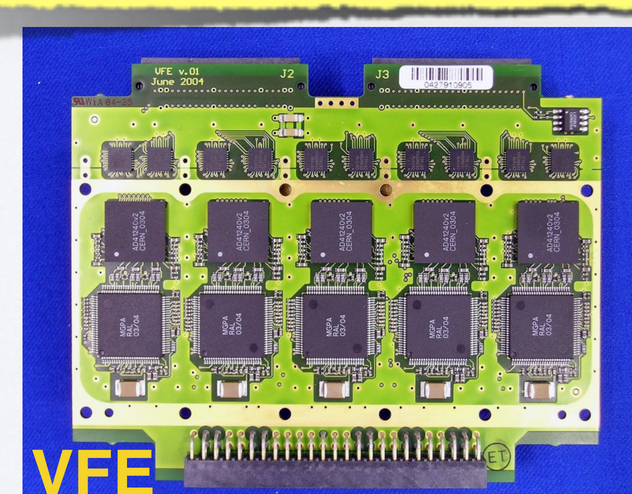
**61200 $PbWO_4$ CRYSTALS**




**61200 APD pairs**




**2448 FRONT END Cards**
data pipeline and transmission, TP formation, clock/control





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# ECAL EB UPGRADE: OVERVIEW

- $PbWO_4$ crystals, APDs, mother boards, & overall mechanical structure **will not change**

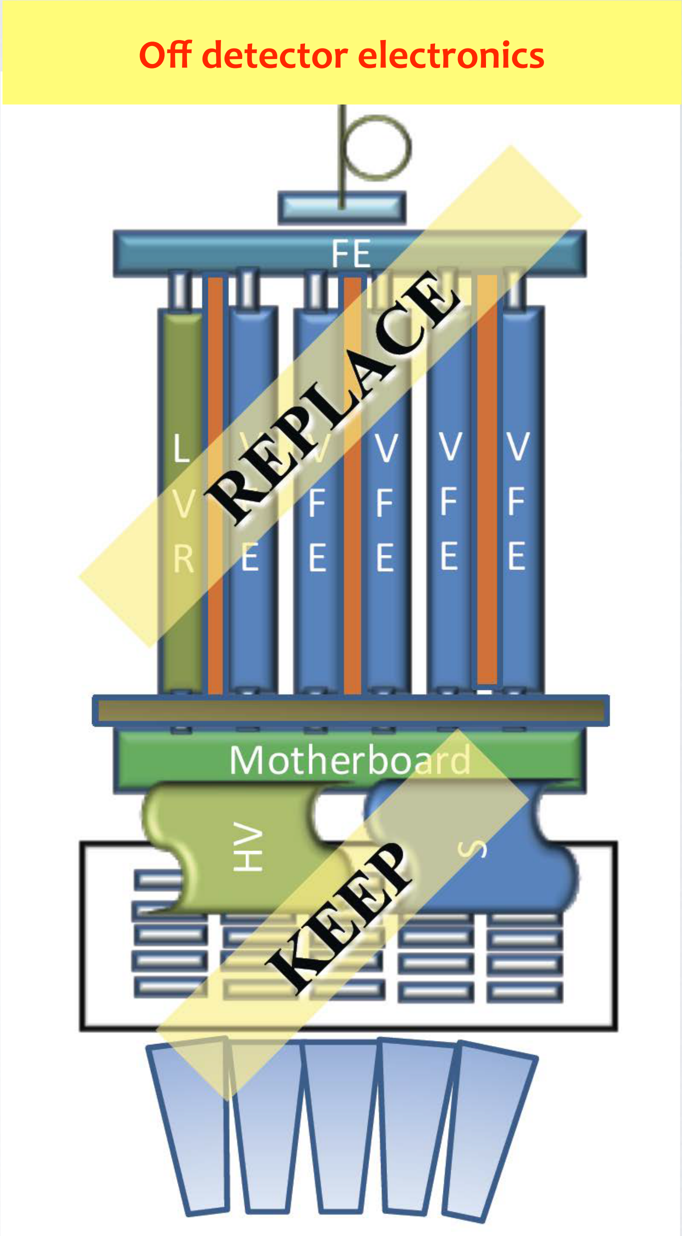
  - **APD dark current strongly dependent on temperature** ➜ by operating **EB colder from 18°C to 8°C ➜ reduce noise by 35%** and dark current by a factor of 2.5

- The **FE** and **VFE electronics readout will be replaced**:
  - ☐ to satisfy the increased **trigger latency** (up to 12.5 µs) and **L1 accept rate** (750 kHz) requirements
  - ☐ to cope with HL-LHC conditions (increased APD dark current, anomalous APD signals, higher PU)

- **VFE** maintains similar purpose, but **reduce shaping time+ digitisation** ➜ reduce out-of-time PU contamination, electronics noise and spikes

- **FE card becomes streaming readout, moving most processing off-detector**

- **Off-detector electronics will be upgraded** to accommodate higher transfer rates and to generate trigger primitives ➜ **Trigger will use single crystal information for spike rejection**

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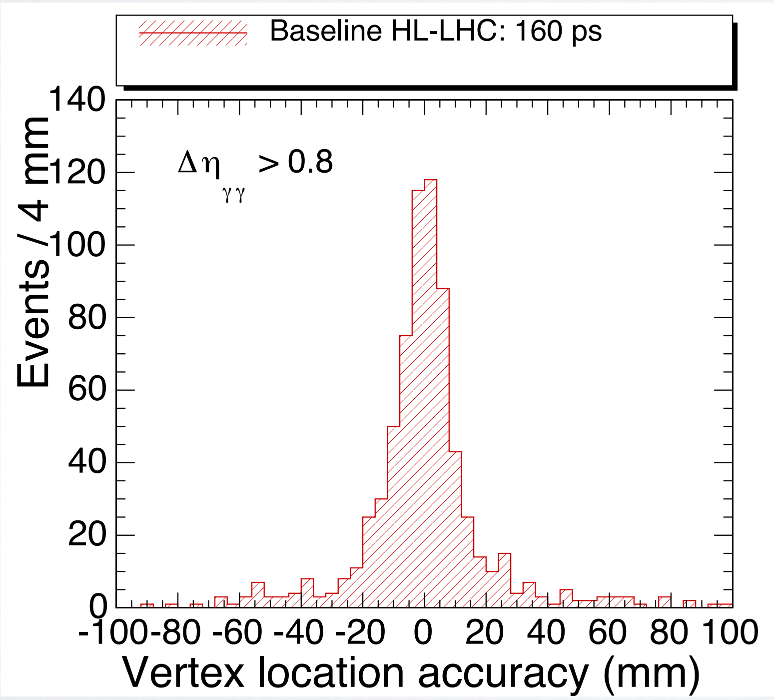
# ECAL EB UPGRADE: PRECISION TIMING

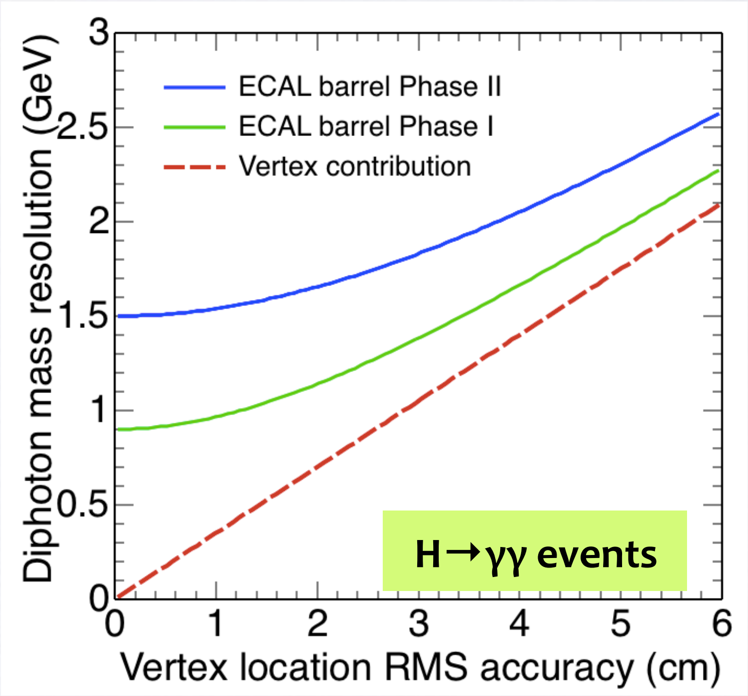
- **PRECISION TIMING** will improve the vertex localisation for high energy photons:
  - **Vertex resolution for H→γγ decays benefits from precise timing**
    - current efficiency of localising vertex (|dz| < 1 cm) is ~70-80%
    - **reduced to < 30% at 200 PU** with current EB timing precision
    - **improves to ~70% for photons with $|\Delta\eta| > 0.8$** for 30 ps timing resolution

see Adolf Bornheim talk

- **Goal: VFE ASIC design, sampling rate, clock distribution should be designed to approach 30 ps timing precision for high energy EM signals**




*Vertex location accuracy at PU=200 assuming 30ps timing resolution*




*Diphoton mass resolution vs accuracy of determining vertex location*

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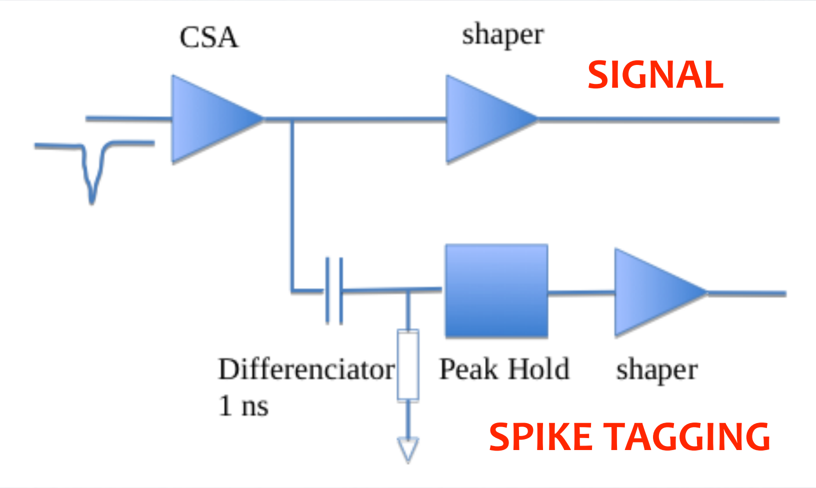
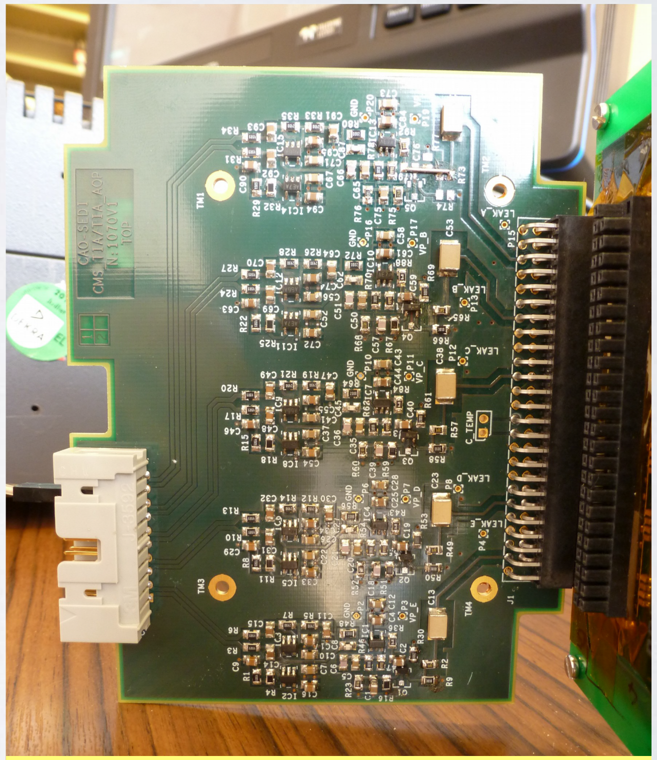
# ECAL EB UPGRADE: VFE

- **New VFE boards with re-designed ASICs:**
  - Optimise shaping time and sampling rate to reduce impact of noise, out-of-time PU, spikes
  - **Precision timing desired**: with **30 ps resolution** H vertex efficiency from 30% to 70% (at 200 PU), PU mitigation removing neutral particles
- Pulse shaper/preamplifier ASIC option:
  - **TIA (Trans-impedance Amplifier)**: Digital design, using trans-impedance amplifiers, **focused on achieving optimal time resolution** (as much as allowed by kapton connections): **160 MHz sampling**
- **ADC:** Require multi-channel ADC with ~12 bit resolution and ability to sample up to 160 MHz



VFE demonstrator w/ TIA

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# TIA: AMPLIFIER FOR ECAL EB @HL-LHC

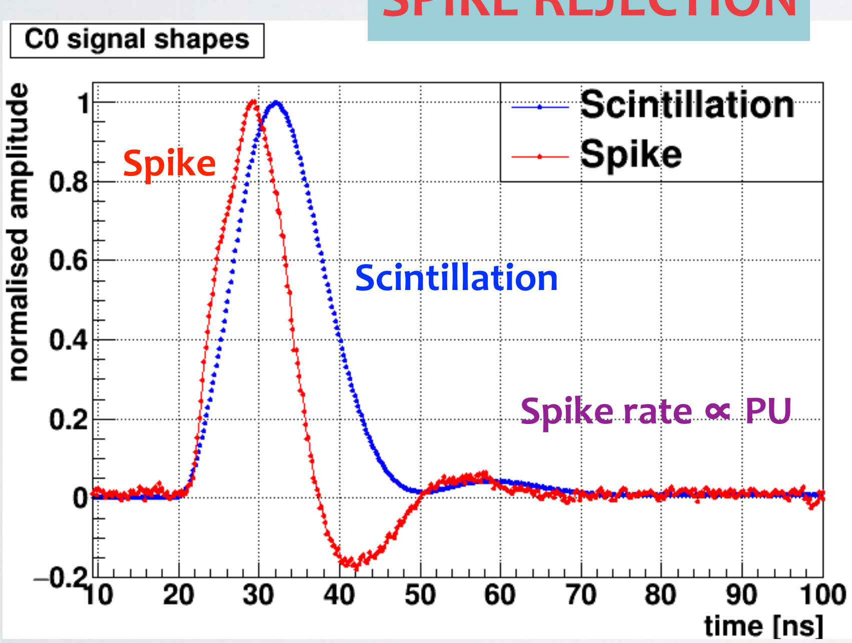
## TIA (Trans-impedance Amplifier):

- No shaping time
- Look directly at APD analog signal with high bandwidth
- Optimised for precision timing measurement of EM shower in ECAL

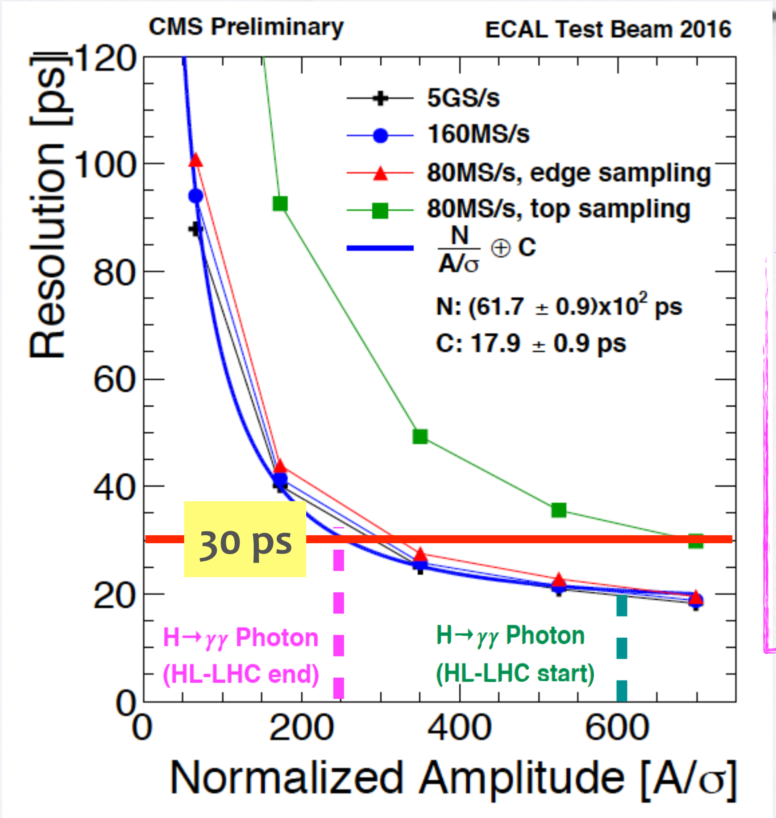
## Performance confirmed @CERN during 2016 Test Beam

- **High energy electrons** (20< Ee < 250 GeV) and **pions**
- $PbWO_4$ crystal matrix read out with prototype VFE with discrete component TIA
- different sampling frequencies can be emulated
- APD timing extracted through template fit to pulse shape

## SPIKE REJECTION




- Pulse reconstruction with fast VFE electronics can flag trigger information
- Spike pulse shape is faster and can be rejected



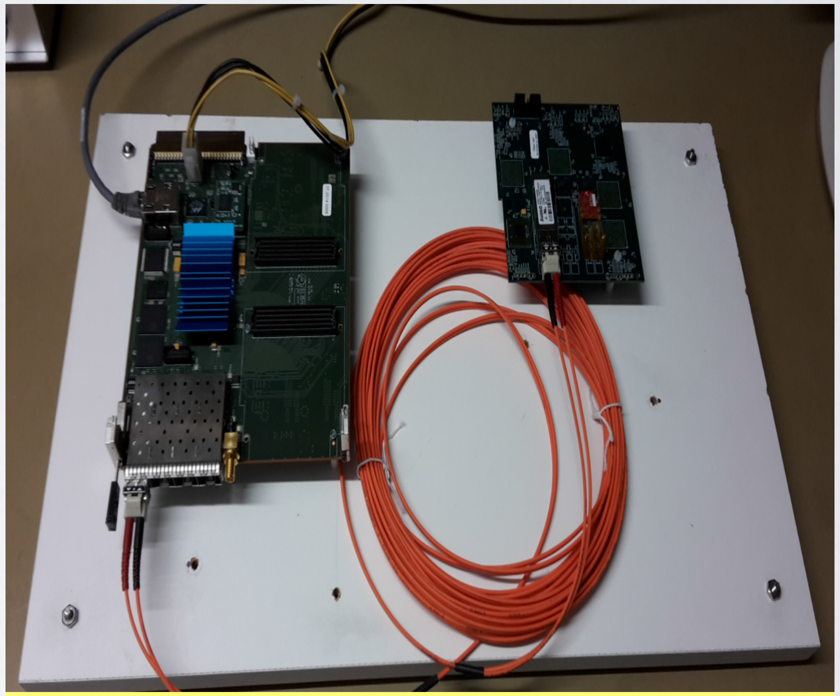

## TIME RESOLUTION

Promising results:

- at 160 MHz σ~30 ps @A/σ=250
  - 25 GeV photon with 100 MeV noise (HL-LHC start)
  - 60 GeV photon with 240 MeV noise (HL-LHC end)

# ECAL EB UPGRADE: FE & OFF-DETECTOR

- REQUIREMENTS:
    - Read data from all crystals
    - Increased trigger latency (12.5 µs) ➜ need longer data pipeline
- FE Changes:
    - Move L1A pipeline off-detector with arbitrary trigger latency
    - Move trigger primitive generation off-detector
- **Data links from detector to readout cards** (in service cavern) **to be updated to Versatile links w/ GigaBit Transceiver (GBT) chipset**
    - GBT bandwidth allows a full-granularity readout for the trigger
    - Potential for more advanced topological filtering of anomalous events
- **Off-detector:** trigger, data & controls may be grouped in single card



FE demonstrator with 5Gb/s links

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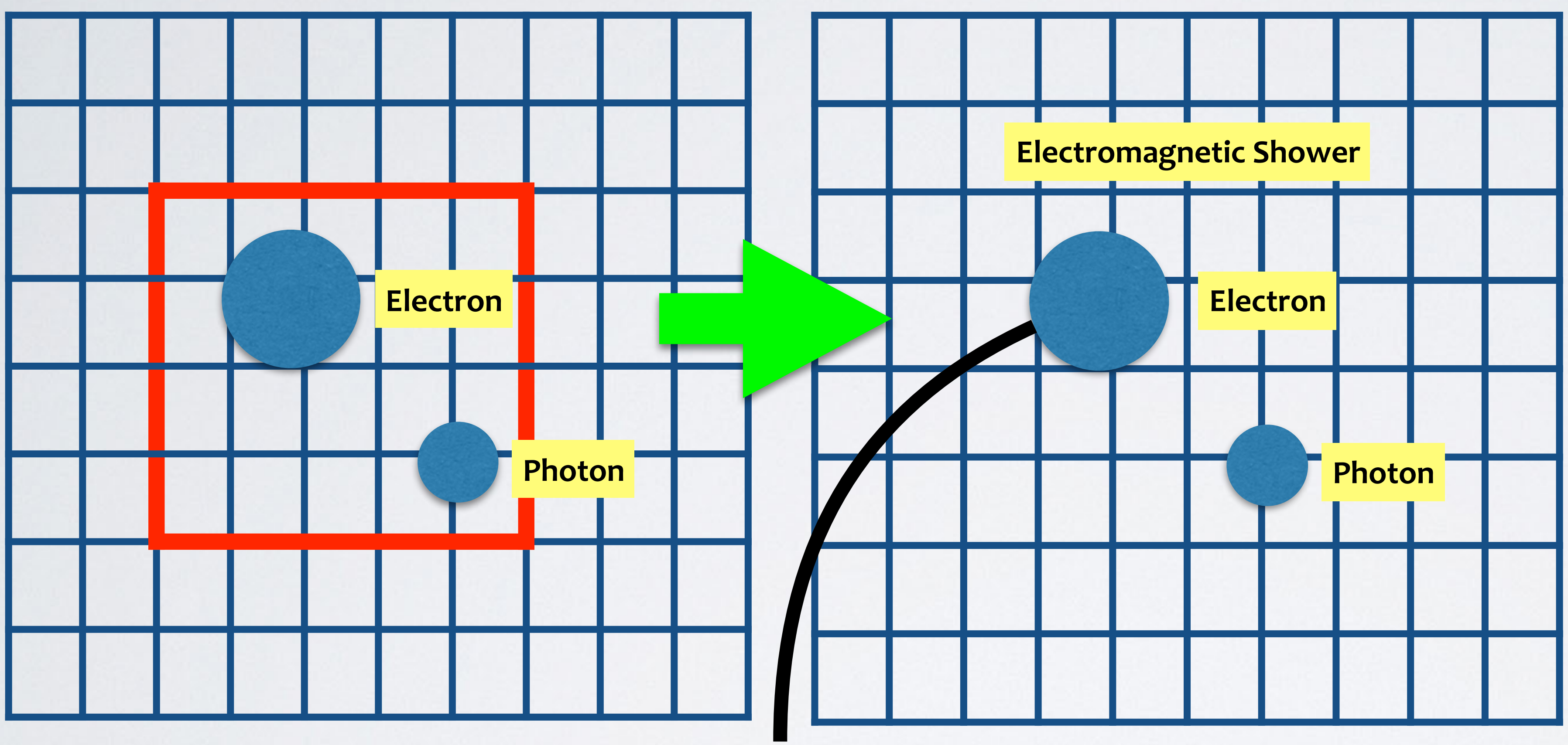
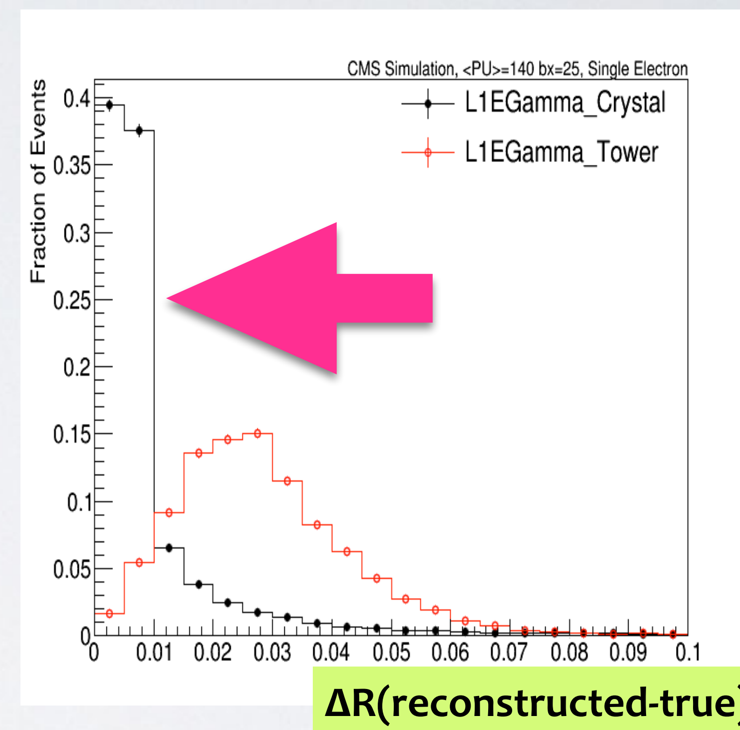
# TRIGGER PRIMITIVE GENERATION OFF-DETECTOR

**LEGACY 5X5 CRYSTAL TP**

**TP NOW 1X1 CRYSTAL**
**Tracks matched to cluster**

**TRIGGER RESOLUTION**
**w/wo single crystal upgrade**




see Fanbo Meng poster

BEFORE UPGRADE


AFTER UPGRADE

global view and full granularity of calorimeters

single crystal information should also allow more efficient track/cluster matching for track trigger

# CONCLUSIONS




### EE COMPLETE REPLACEMENT + EB PARTIAL UPGRADE

- **EE crystals** will suffer large transparency losses ➜ must be replaced in LS3
- **EB crystals** will perform well during HL-LHC (< 50% transparency loss)
- **APDs** remain operational but will have increased noise

### MOTIVATION FOR EB UPGRADE

- **Increased Trigger rate** compared to LHC Run II ➜ **replace VFE, FE and off-detector electronics**
  - **Main motivation :** Phase II requirements: 750 kHz L1 accept rate & 12.5 μs latency (currently 100 kHz & 5 μs)
- **Mitigation of APD noise** (dark current increase due to higher neutron fluence) ➜ **Cooling temperature reduced to 10 or 8℃ (now 18℃)**

### ADDITIONAL IMPROVEMENTS

- **Improved spike rejection** ➜ **single crystal information in trigger + VFE fast shaping**
- **Precision timing for vertex determination & PU mitigation** ➜ **new design for VFE electronics**
  - With precise time-of-flight measurement of photons ($\sigma$~30 ps) same angular resolution in $H(\rightarrow\gamma\gamma)$ analysis as in Run II

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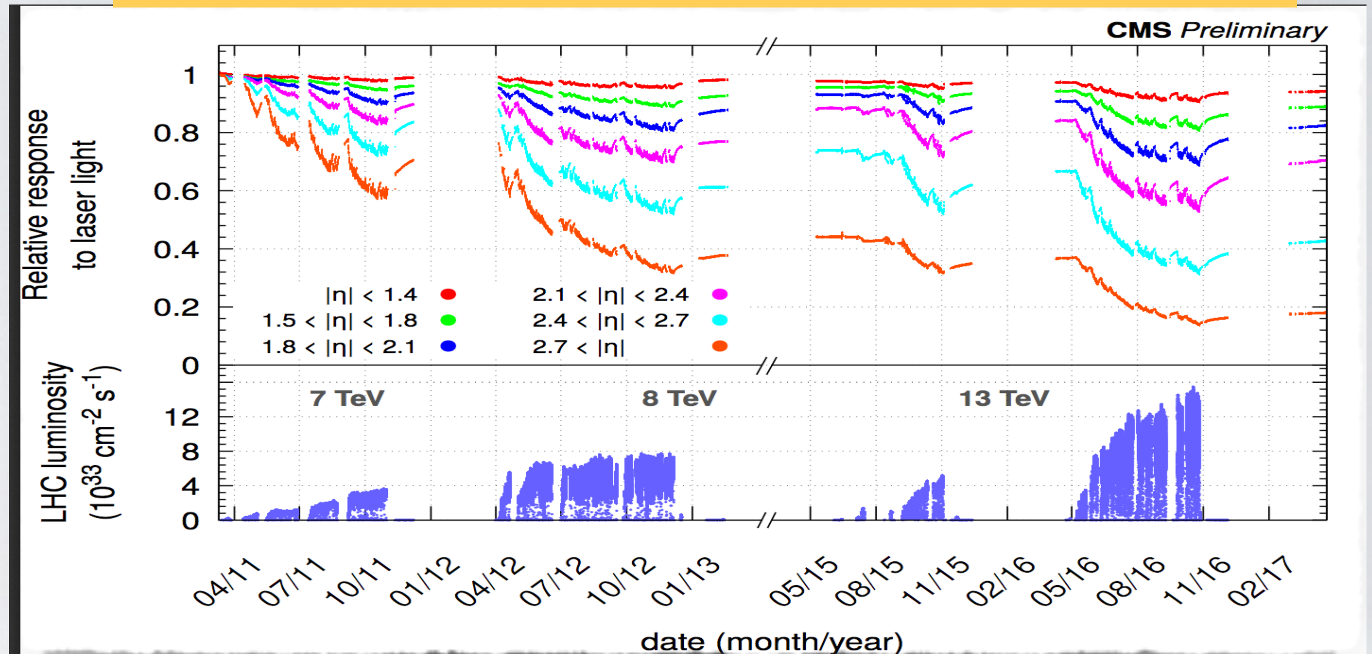
# BACKUP

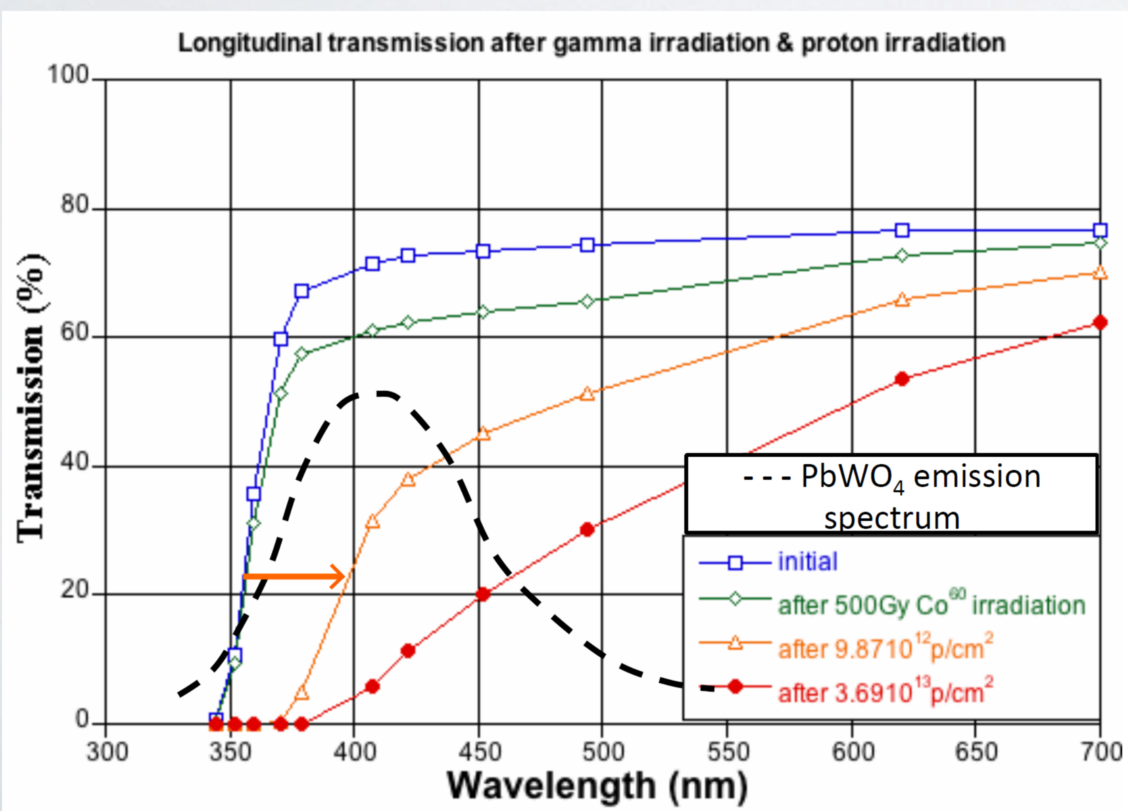
# RADIATION DAMAGE IN $PbWO_4$ CRYSTALS

### IONIZING RADIATION DAMAGE

- It recovers at room temperature (~20°C)
- Light transmission of crystals is constantly monitored in ECAL using laser light
- Evolution of the response is in agreement with expectations

**ECAL relative response to laser light - history plot -**




### HADRON RADIATION DAMAGE

- No recovery at room temperature
- Shift of transmission band edge: cumulative effect
- Will dominate at HL-LHC

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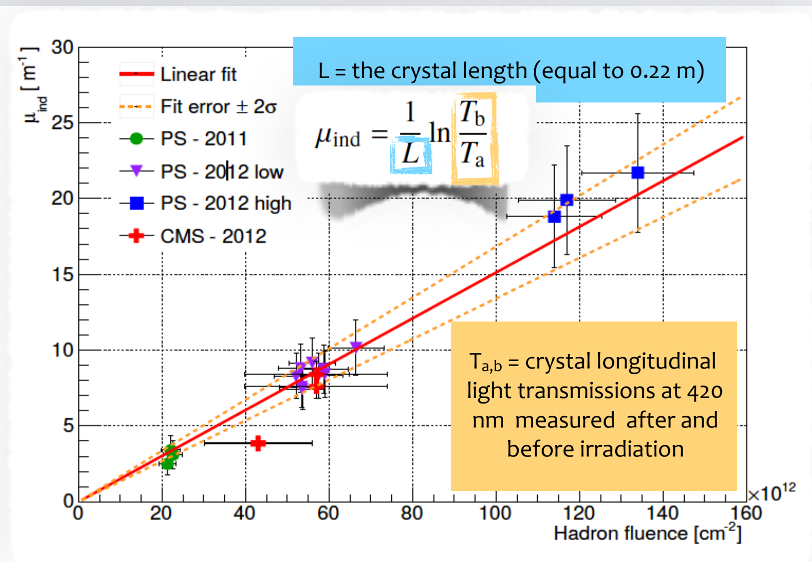
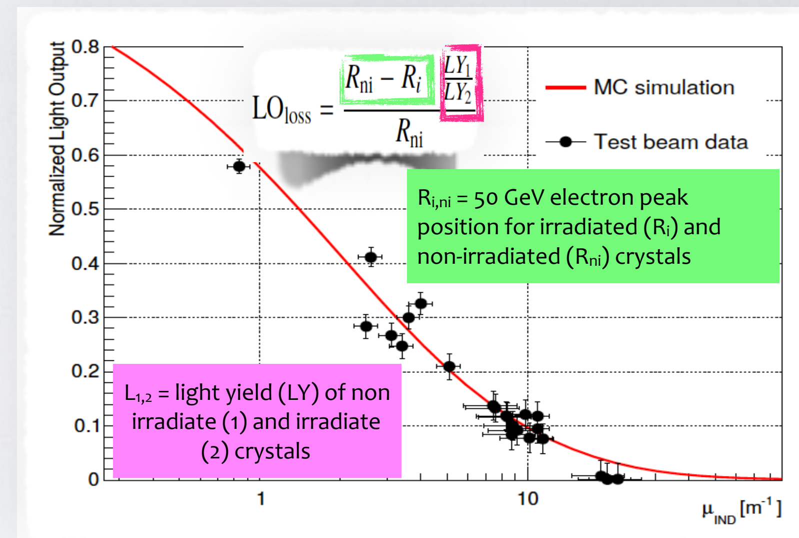
# CRYSTAL IRRADIATION @CERN PS

**$PbWO_4$ crystals irradiated with monochromatic source of 24 GeV protons and inside CMS**

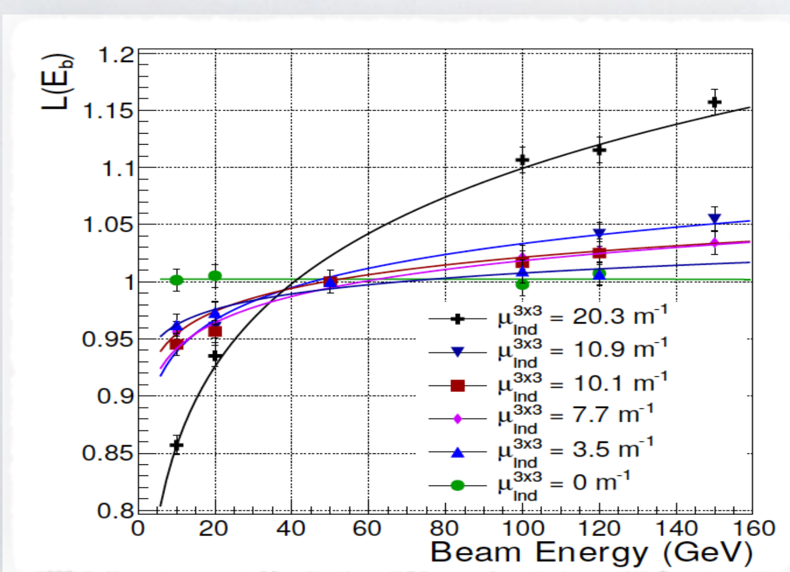
- Defects inside the crystals, due to high-radiation environment, lead to **stronger induced light absorption**



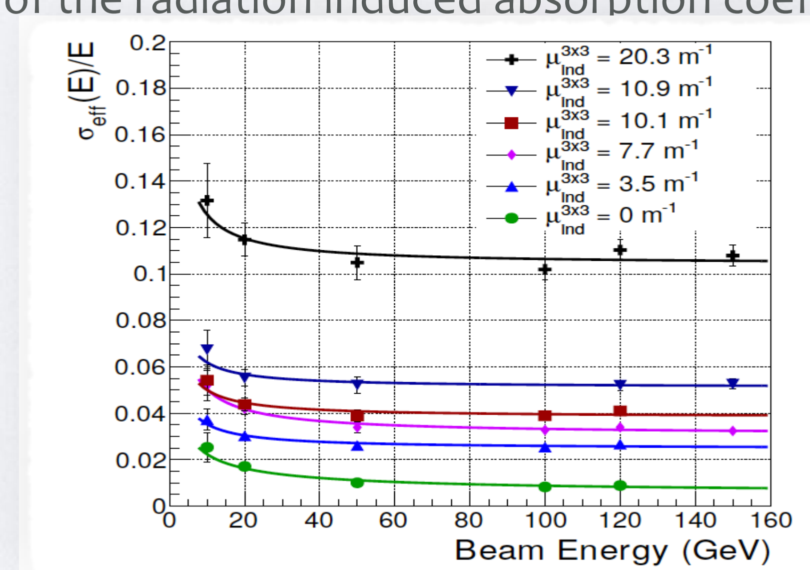

- Induced absorption causes a **light output loss**




- Damaged crystals show a **non-linear response** to electromagnetic showers




- The **constant term of energy resolution increases with higher $\mu_{\text{ind}}$** ( irradiation dose expressed in terms of the radiation induced absorption coeff. $\mu_{\text{ind}}(\lambda)$)

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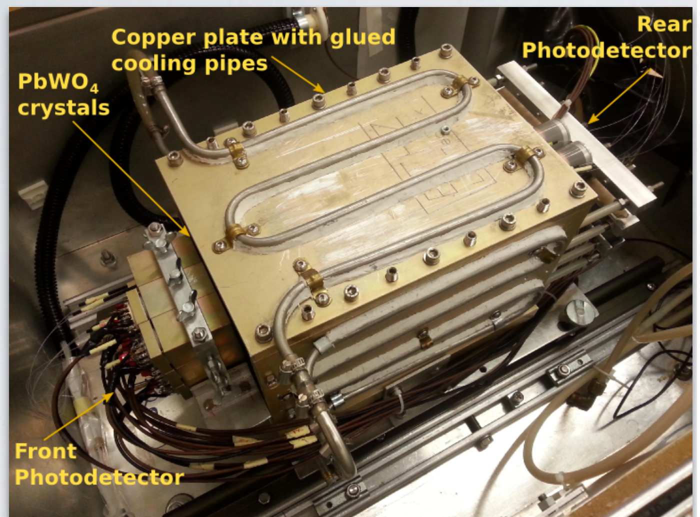
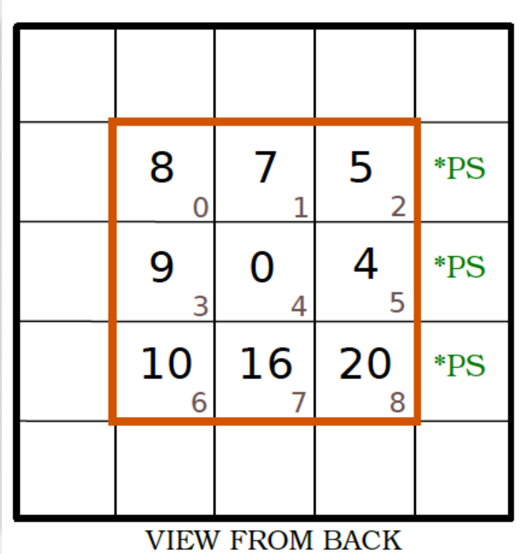
# TEST BEAM: DOUBLE-ENDED READ-OUT TECHNIQUE



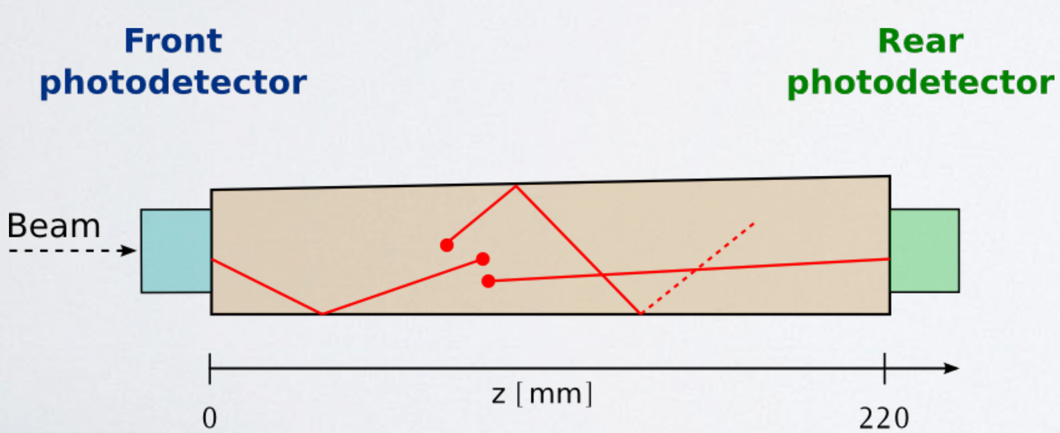




**Experimental setup**

- 9 $PbWO_4$ crystals with different levels of $\mu_{ind}$ (from 0 to 20 $m^{-1}$)
  - Each crystals is instrumented with a front and a rear photodetector
- Study of crystal response to electrons of 20-250 GeV energy

Additional **photodetector on the front face of the crystal** would provide:

- information on shower maximum position and event-by-event shower fluctuations
- better reconstruction of the electron energy by combination of both signals $S_{corr} = \sqrt{R_{sh} \cdot F_{sh}}$

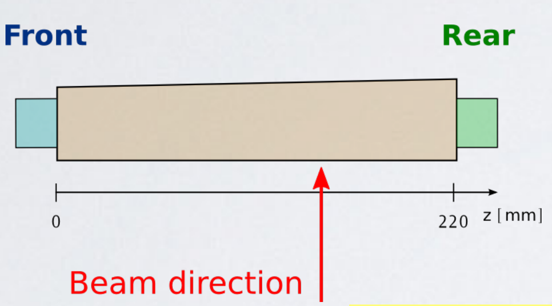



Double-ended read-out

# LIGHT COLLECTION AND SHOWER FLUCTUATION

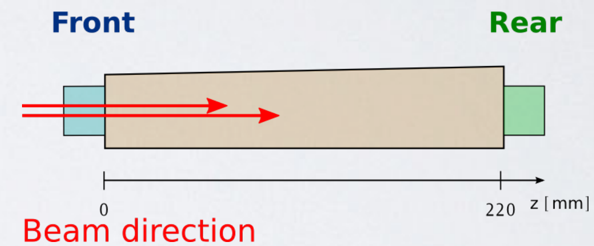
## LIGHT COLLECTION UNIFORMITY

- First measurement of light collection efficiency curves for highly damaged crystals
- **Exponential-like behaviour** with attenuation coefficients proportional to the level of induced absorption $\mu_{\mathrm{ind}}$

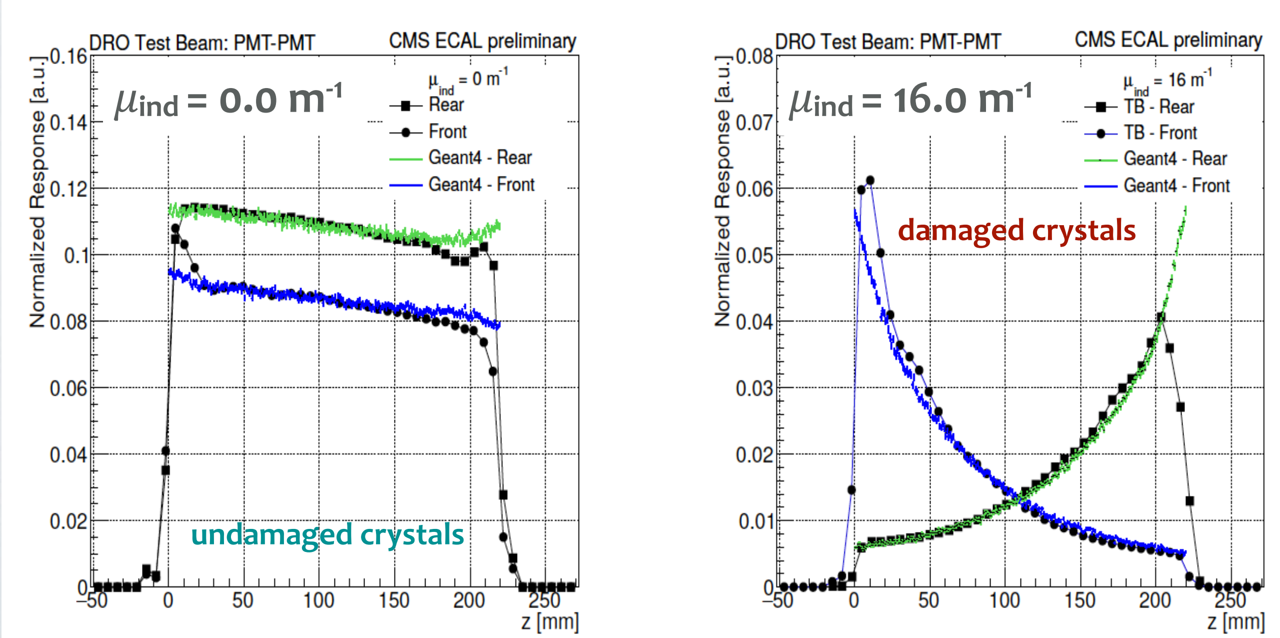



## LONGITUDINAL SHOWER FLUCTUACTIONS

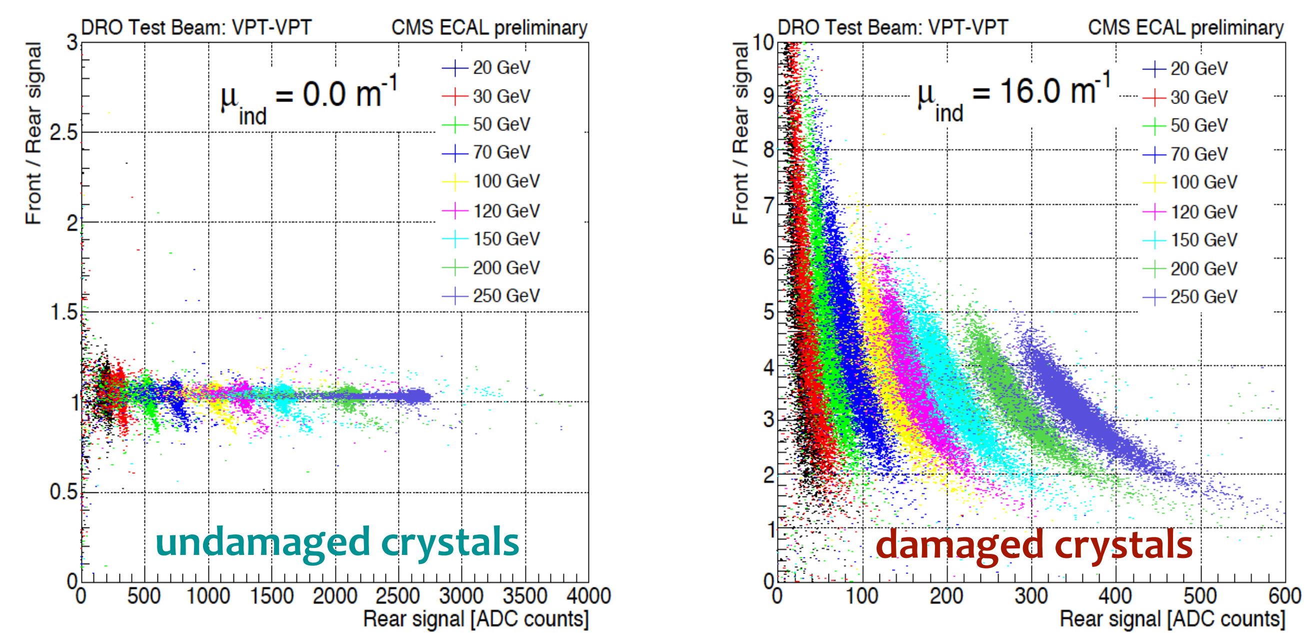
- In **non-damaged crystals** **the ratio of front/rear signal is rather constant for each event at all beam energies**
- **Longitudinal shower fluctuations** become visible in **damaged crystals** due to non-uniformity of light collection efficiency




Light collection efficiency curve




Longitudinal shower fluctuations

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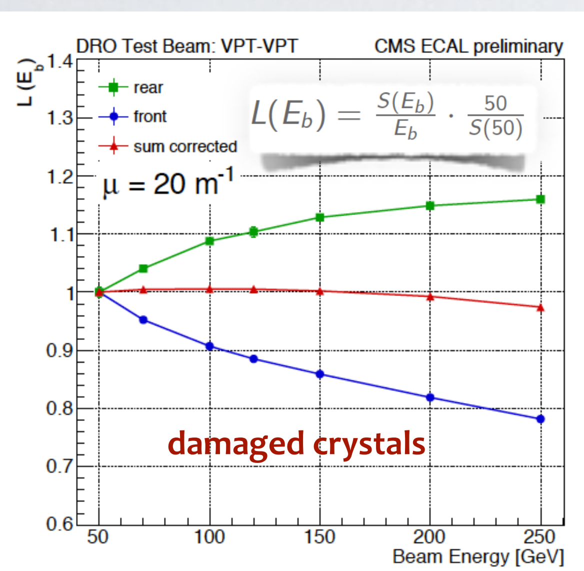
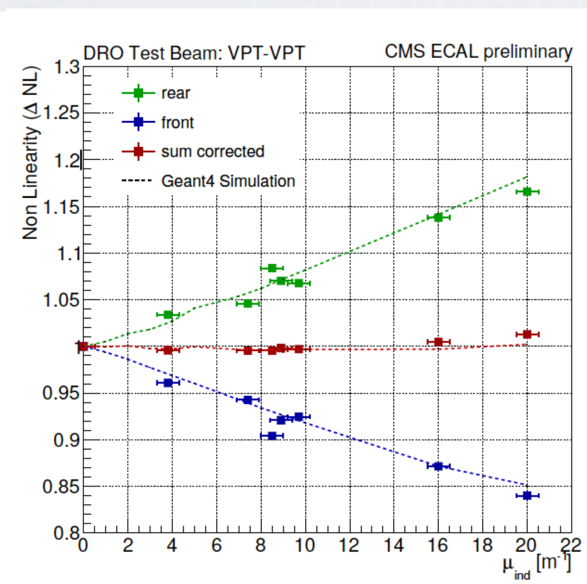
# LINEARITY & ENERGY RESOLUTION

## LINEARITY

- **Linearity: $E_{reco}/E_{beam}$ (normalized at 50 GeV)** is entirely restored if front and rear signals are properly combined [$S_{corr} = \sqrt{R \cdot F}$]



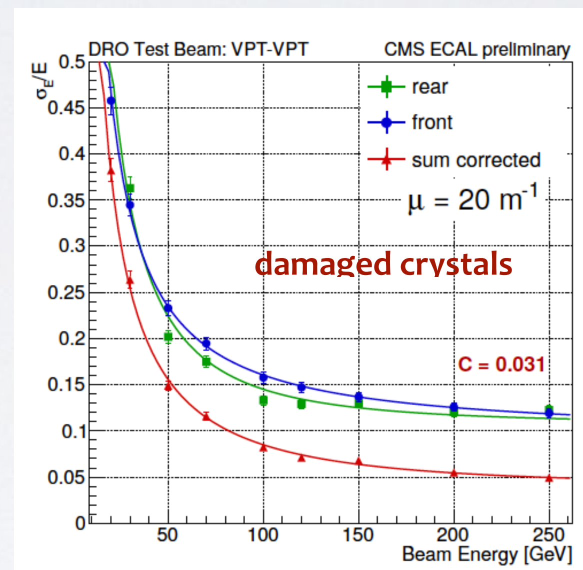



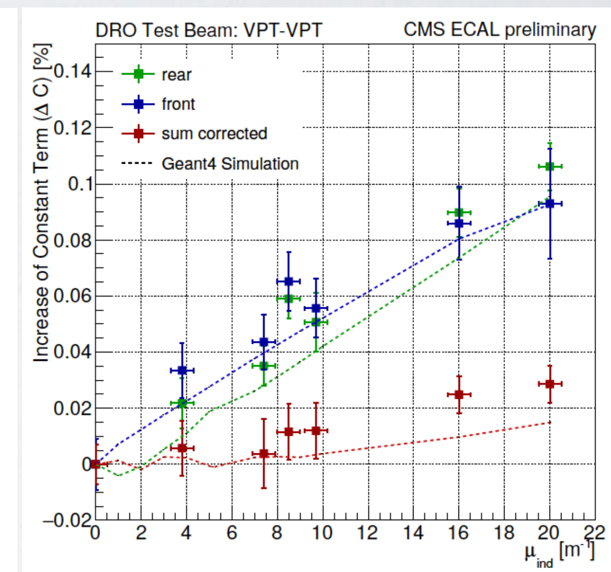

- The non-linear response due to $\mu_{ind}$ can be isolated from longitudinal leakage effects by comparison with a non-irradiated crystal

- **non-linearity estimator** can be defined as the change of linear response between 50 and 250 GeV

## ENERGY RESOLUTION

- Increase of **constant term C is** $\propto$ $\mu_{ind}$ but the combination of front and rear signals allows to strongly mitigate the degradation of constant term C




- Increase of constant term due to radiation damage is defined as

$$\boxed{\Delta C = \sqrt{C^2_{i} - C^2_{ni}}}$$

- Strong mitigation of the constant term also for high levels of $\mu_{ind}$ (from 11% to 3%)



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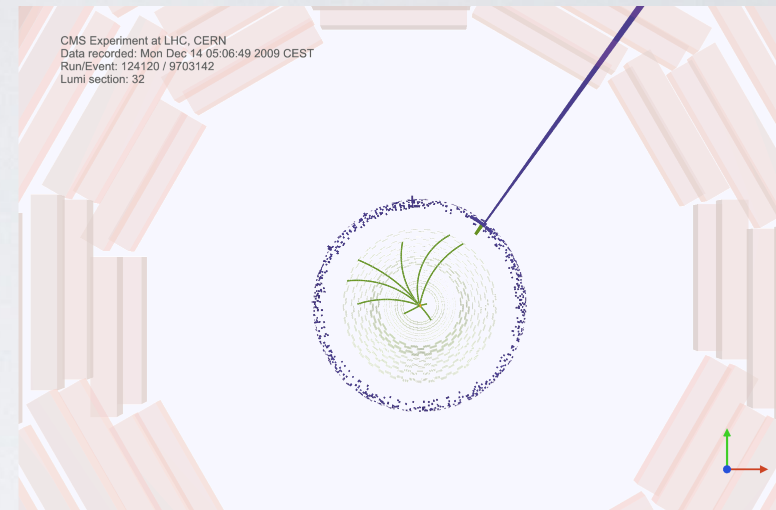
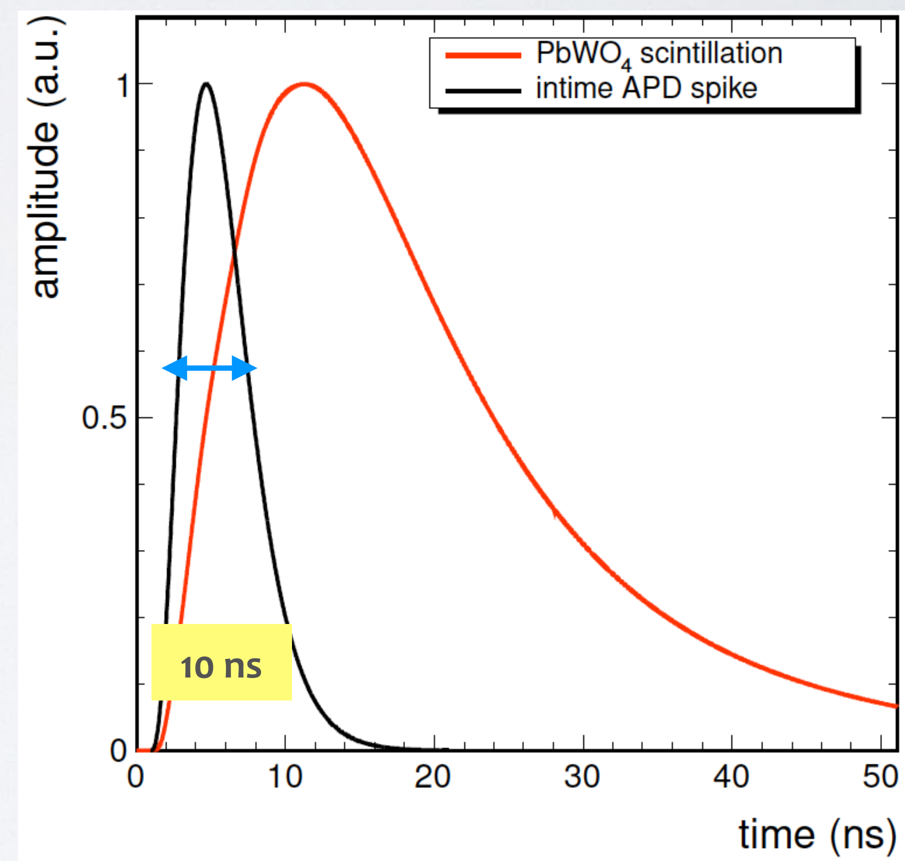
# EB UPGRADE MOTIVATION: SPIKE REJECTION

- Anomalous signals (spikes) are energy deposits directly into APD bulk ➜ create fake EM-like pattern
    - Deposited in a single APD compared to EM shower spread over several crystals
    - Arrive earlier in time + shorter pulse than EM shower
- **Spike rejection:**
    - Currently rejected offline at L1 using coarse topological algorithm
    - Efficiency will degrade to unacceptable levels at HL-LHC due to higher noise & PU
- VFE/FE will be upgraded for better spike rejection, optimising pulse shaping & using finer granularity (single crystal data) @ L1




Charge deposited directly in the APD results in pulses that are shorter in time than pulses generated by scintillation light

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