Status and perspective of the Barrel Timing Layer project for the Phase II upgrade of the CMS detector

Flavia Cetorelli (INFN Milano Bicocca, CERN)
on behalf of the CMS Collaboration

FAST2023:
13th Workshop on Picosecond Timing Detectors, Electronics and Applications
28 May-1 Jun 2023, La Biodola, Elba (Italy)

31-05-2023

Introduction to MIP Timing detector

As shown in Federico's talk

The **Mip Timing Detector** is included in the Phase II Upgrade of the Compact Muon Solenoid (CMS) detector:

- **Upgrade of the CMS detector** needed to cope with harsh High Luminosity (HL) LHC conditions, such as:
  - higher amount of interactions per bunch crossing (~200)
  - higher radiation damage (integrated particle fluences of ~ 2 10^{14} 1 MeV n_{eq}/cm^2)

- MTD inserted between the tracker and the ECAL:
  - Cover both **Barrel** and Endcap of CMS
  - Time resolution:
    - **30-40 ps** at the beginning of its operation (BoO)
    - **50-60 ps** at the end of operation (EoO) due to radiation damage
  - Perform **4D reconstruction of vertices** to maintain the actual CMS reconstruction performance

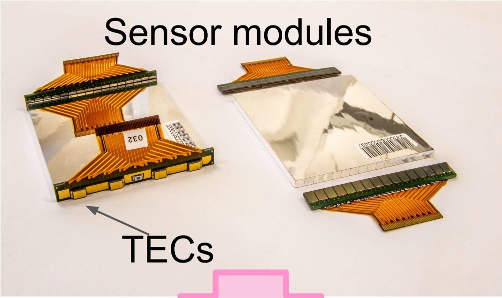
In this talk

Results on the **characterization of the module sensor prototypes** obtained with laser in the laboratory, and during the recent test beam campaigns.

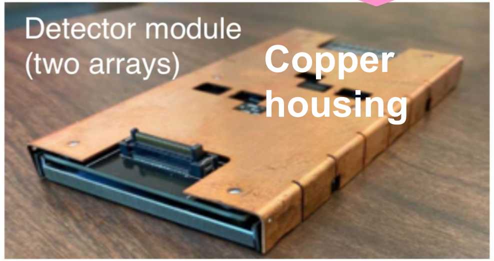
Barrel Timing Layer: Sensor module

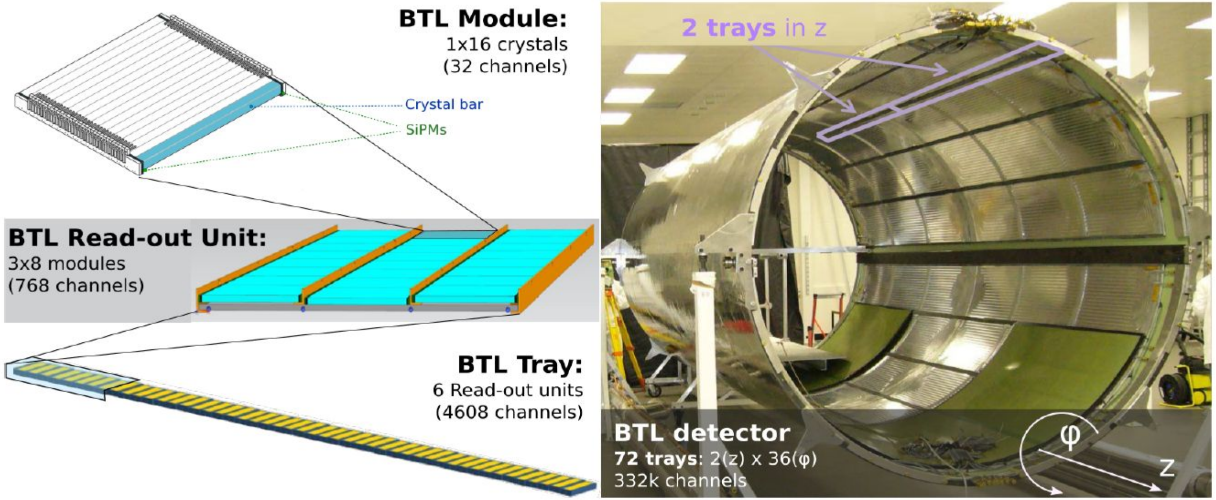
16 bars of LYSO:Ce (54.7 mm length x 3.12 mm width x different thickness) coupled at each end with **Silicon Photon Multipliers (SiPMs)**

Three different regions in η, crystal thickness varies from 3.75 to 3.0 and 2.4 mm.



Readout by **TOFHIR** ASIC and encapsulated in





Towards BTL **construction**: starting in **early 2024**!

Time resolution

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$

Electronic noise

Scaling with the steepness of the rising edge of electronic signal the as **1/(dI/dt)**

Photo-statistics

Scaling with the Light Output (LO) as **$1/\sqrt{LO}$**

non-irradiated modules

Dark Current

Expected integrated fluence: $2\ 10^{14}\ n_{eq}/cm^2$ → radiation damage induces

$\sigma_t^{DCR} \propto \sqrt{DCR/LO}$

Mini Thermoelectric Cooler (TECs) to work at -45 °C

In-situ **annealing** up to 60 °C during shutdown / technical stops

To reduce DCR

irradiated modules

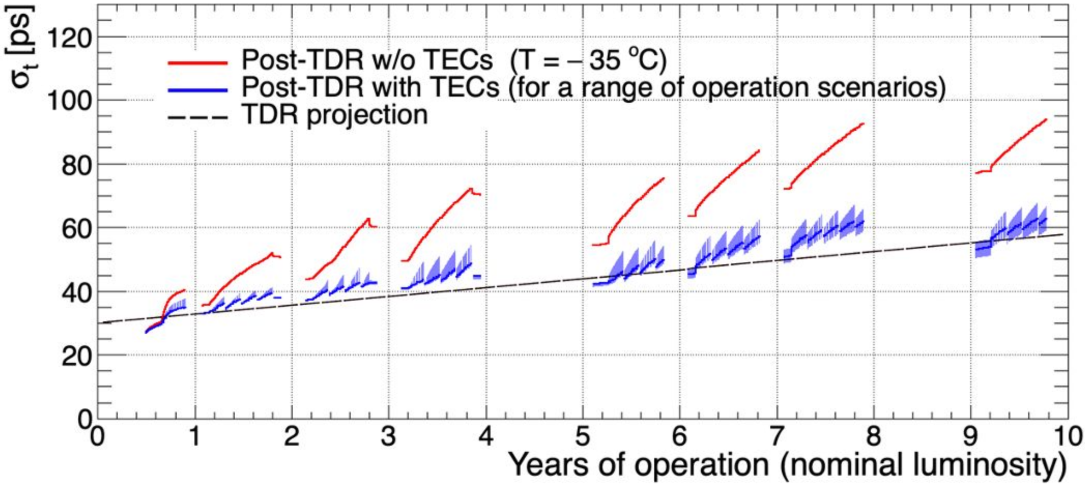
Optimization

- **Packaging**:
  - glue amount reduced, improved **LO** ~ 10%
- **SiPMs**:
  - comparing the performance of **15-20-25-30 μm**
  - larger cell size → higher **PDE** and **gain**, steeper **rising edge**
  - larger cell size → higher **DCR** can be controlled with **operation at lower temperature** and **accelerated annealing** at high local (SiPM) temperature.

TECs

Laboratory and **beam test** measurements to assess the performance of different options

- **Crystals of different thickness**
  - **type 1:** 3.75 mm
    type 2: 3 mm
    type 3: 2.4 mm
  - **LO** $\propto$ **thickness**



Test Beam campaigns

★ **March 2019 @ Fermilab**
- first proof-of-concept with single bars + SiPMs + custom electronics

★ **October 2021 @ SPS CERN**
- first test of module sensor with TOFHIR

★ **June-July 2022 @ SPS CERN**
- characterization of module sensor + new version of TOHFIR
- optimized package validated

★ **March 2023 @ Fermilab**

Preliminary laboratory measurements with laser

- Non-irradiated SiPMs with different cell-size (15-20-25 μm) → BoO performance

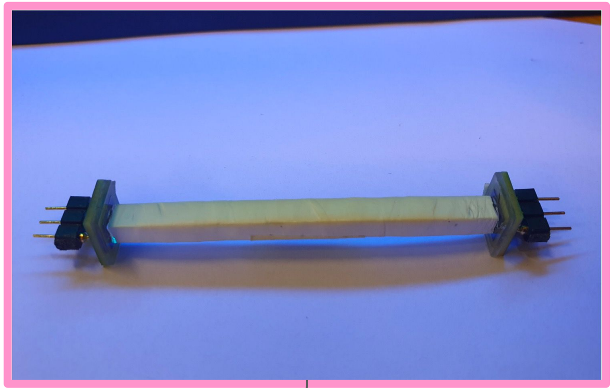
★ **May 2023 @ SPS CERN**
- Irradiated SiPMs with different cell-size (15-20-25 μm) → EoO performance

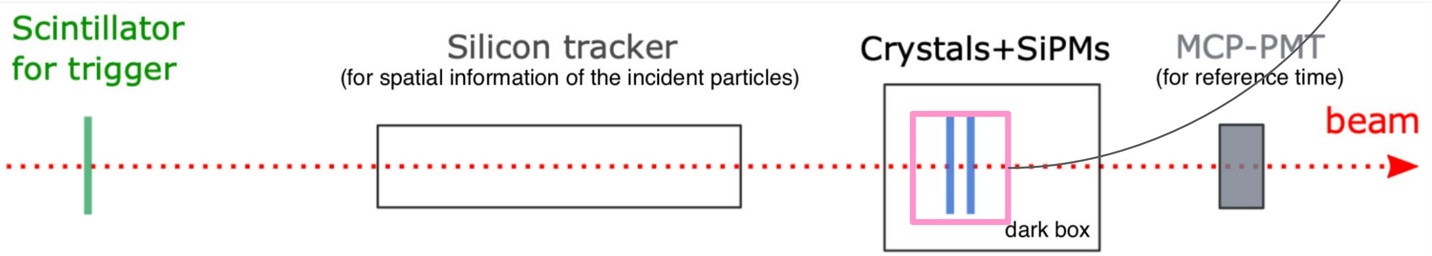
Fermilab 2019: Experimental setup

First proof-of-concept of the BLT sensor layout @ Fermilab Test Beam Facility in 2019:

- 120 GeV protons in batches of 20-50 k particles
- Tested:
  - LYSO:Ce bars of different thickness (2, 3, 4 mm) with a geometry close to the reference design and coupled to ...
  - ... SiPMs from Hamamatsu (**HPK**) 3x3 mm^2 active area and Fondazione Bruno Kessler (**FBK**) 5x5 mm^2 active area
  - Custom electronic boards to apply SiPMs bias and readout signals

DOI 10.1088/1748-0221/16/07/P07023





Fermilab 2019: Results

DOI 10.1088/1748-0221/16/07/P07023

Measured the different contributions to time resolution.

Time resolution estimated from a Gaussian fit of $t_{diff} = t_L - t_R$

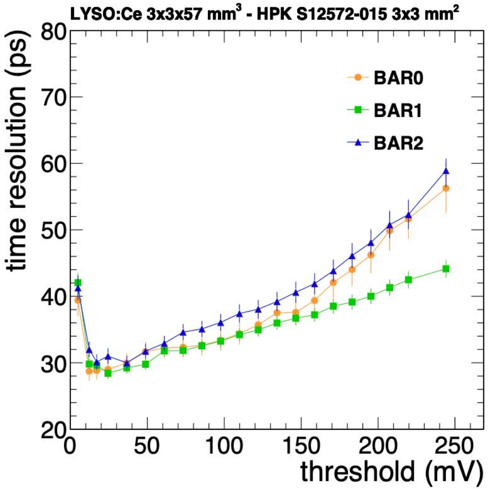
$$\frac{1}{2}\sigma_{t_{diff}} = \frac{1}{2}\sqrt{\sigma^2_{t_{left}} + \sigma^2_{t_{right}}} = \sigma_{t_{average}}$$

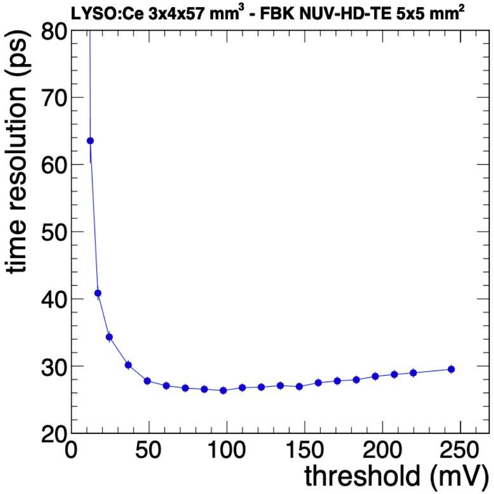
Measurements were made with single unpackaged bars and SiPMs operated at OV that cannot be used in situ.

σ_t **= 28 ps** for MIPs crossing a 3 mm thick crystal bar corresponding E_{dep} ~ 2.6 MeV

σ_t **= 22 ps** for the E_{dep} ~ 4.2 MeV deposition expected in the BTL: to match the required performance, **a high PDE of the photosensors is key.**

OV of 6 V and 36% PDE



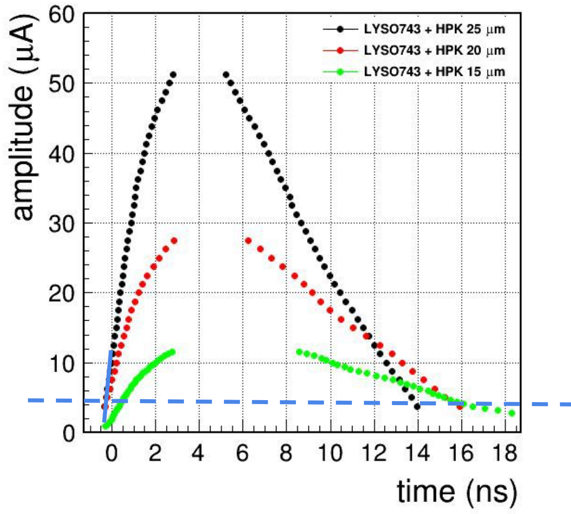


Laser measurements: set up

UV Laser with tunable intensity to induce scintillation in the crystals, tested:

- Non-irradiated Type 2 **LYSO** array grease-coupled to **HPK SiPM** with cell sizes 15 , 20, 25 µm
- Readout performed with **TOFHIR** ASIC
- **Laser intensity** tuned to reproduce expected N_{phe} at 3.5 V
  - LO ~1250 phe/MeV for optimized LYSO+15µm SiPMs
- Performed scans in OV = V_{bias} -$V_{breakdow}$ to test time resolution (noise + photo-statistics) for different operating conditions.

Noise scales with the slew rate (SR)
SR = dI/dt at timing threshold



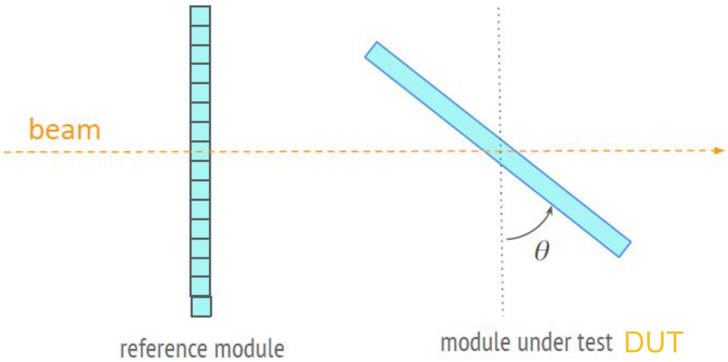
OV of the SiPM decreased during the detector lifetime from 3.5 V to about 1 V to maintain the **DCR to 35–55 GHz** (SiPM dependent) at a cost of a reduction in PDE

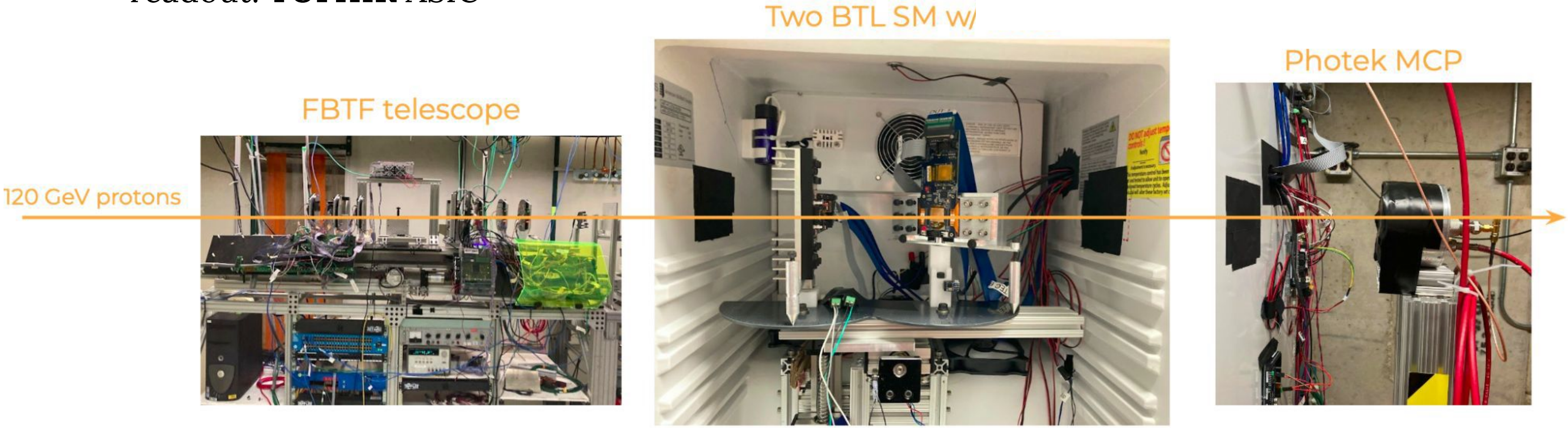
Fermilab 2023: Experimental setup

Assess the **BoO** time resolution with **non-irradiated** SiPMs:

- 120 GeV protons
- Tested 6 modules with **new large cell-size HPK SiPMs** and **LYSO** arrays of **different thickness**
- Modules and boards placed **inside cold box**, operating temperature stabilized to **12 °C with TECs**
- readout: **TOFHIR** ASIC

90° rotation of DUT wrt Ref module

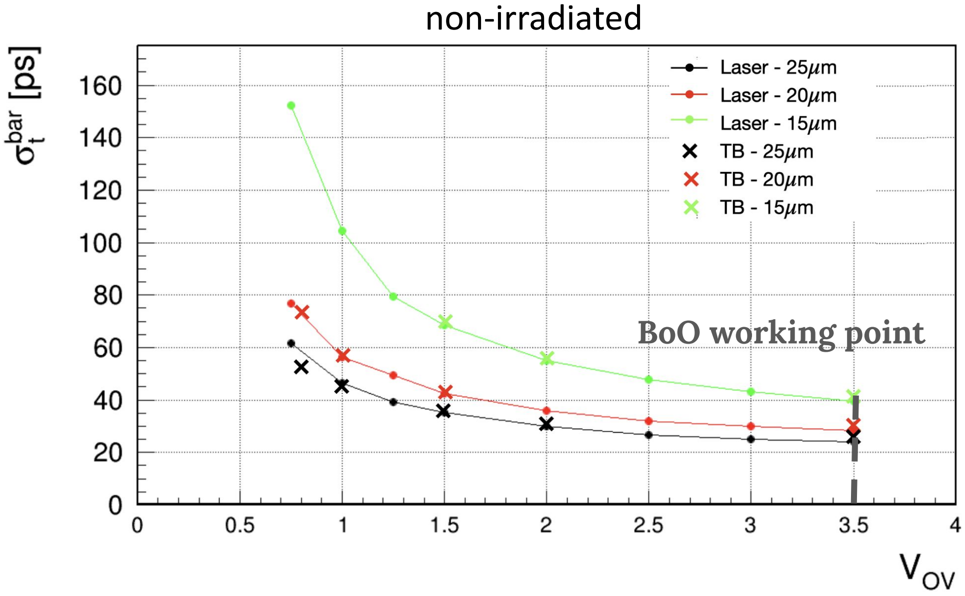




Different cell size SiPMs

Module under test tilted wrt beam of θ **= 52°** to represent the MPV energy deposition of MIPs in BTL **~ 4.2 MeV**

- Good agreement between laboratory measurements with laser and test beam (TB) results with non-irradiated SiPMs.
- **Time resolution** for TB is the average over a bar.
- Electronic noise and photo-statistics contribution **smaller** for **25 µm** cell-size SiPMs over all the OV range.

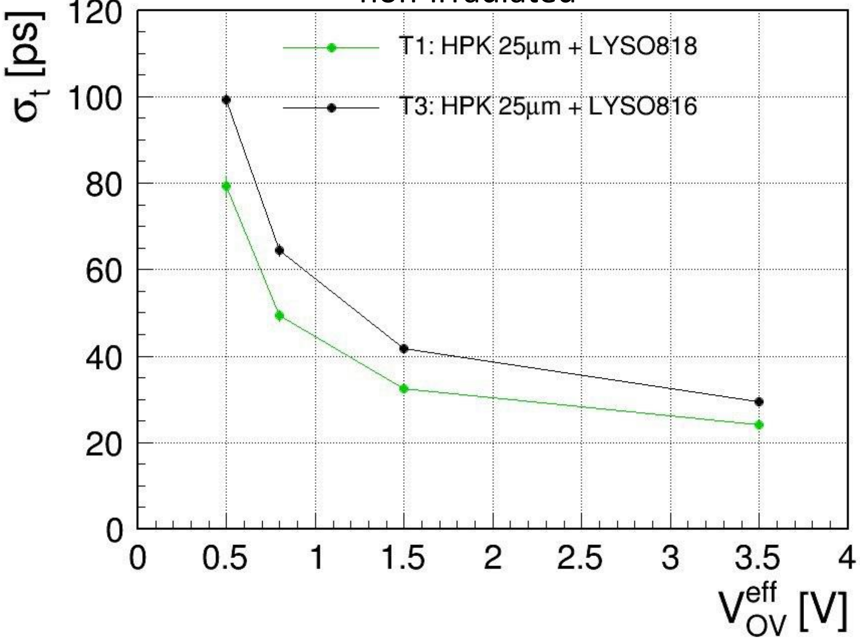


Different geometry crystals

Module with **thicker crystals (T1)** show a **better time resolution**.

Confirmation with **irradiated modules** in progress.

non-irradiated



Under study: Possibility to implement thicker T1 type modules in all RUs to achieve **better performance**:

- within cost and power envelopes;
- with negligible impact on ECAL;
- with no impact on mechanical aspects.

Test beam May-June @ SPS CERN

Test beam measurements have been performed during 10-24 May @CERN on irradiated modules

- crystals of different thickness
  - → to test possibility to enhance thickening of crystals in the 2nd/3rd η regions
- SiPMs of different cell-sizes
  - → to confirm expectations of better performance with larger cell-size

Different operating temperatures have been tested to provide idea of different BTL operating conditions

The analysis of these data will provide the **final characterization** of the **EoO performance**.

↓

Inputs for the final procurements of LYSO and SiPMs arrays

Summary

The MTD will provide time information to maintain the actual reconstruction performance of the CMS detector during the HL-LHC.

The BTL prototype testing campaign is reaching its end:

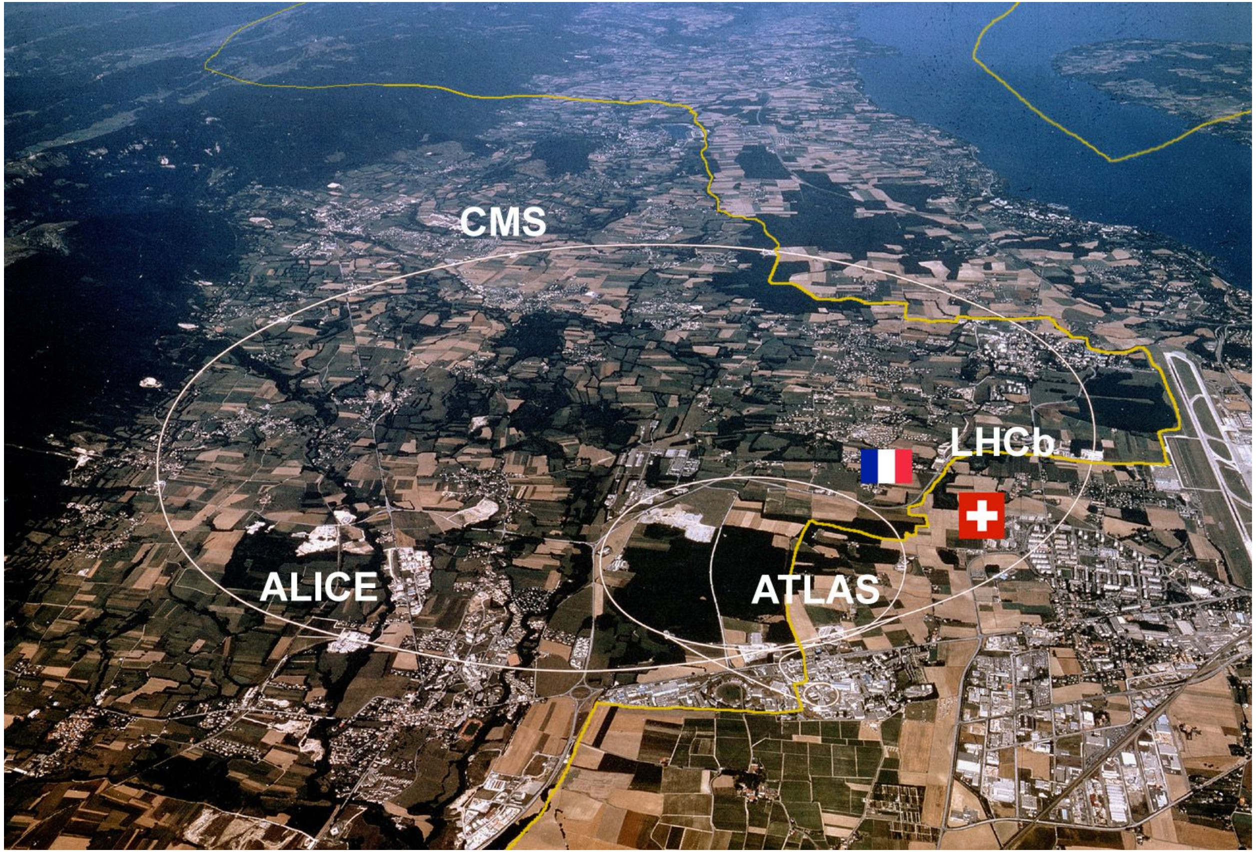
- many studies performed in laboratory and in beam test to optimize the **performance** of **BoO and EoO**
  - recent test beam at Fermilab confirmed the expected time resolution at BoO
  - ongoing test beam analysis at SPS CERN to assess the performance of EoO.

- Tests of **full-tray** (6 RUs) will be carried out at CERN Prevessin site and CERN Tracker Installation Facility:
  - **thermal tests** for validation of the **CO_2 cooling**
  - integration of the **front-end** and **back-end electronics** to verify the final readout chain

Towards BTL **construction**: starting in **early 2024**!

Backup

Large Hadron Collider (LHC)



LHC in summary:

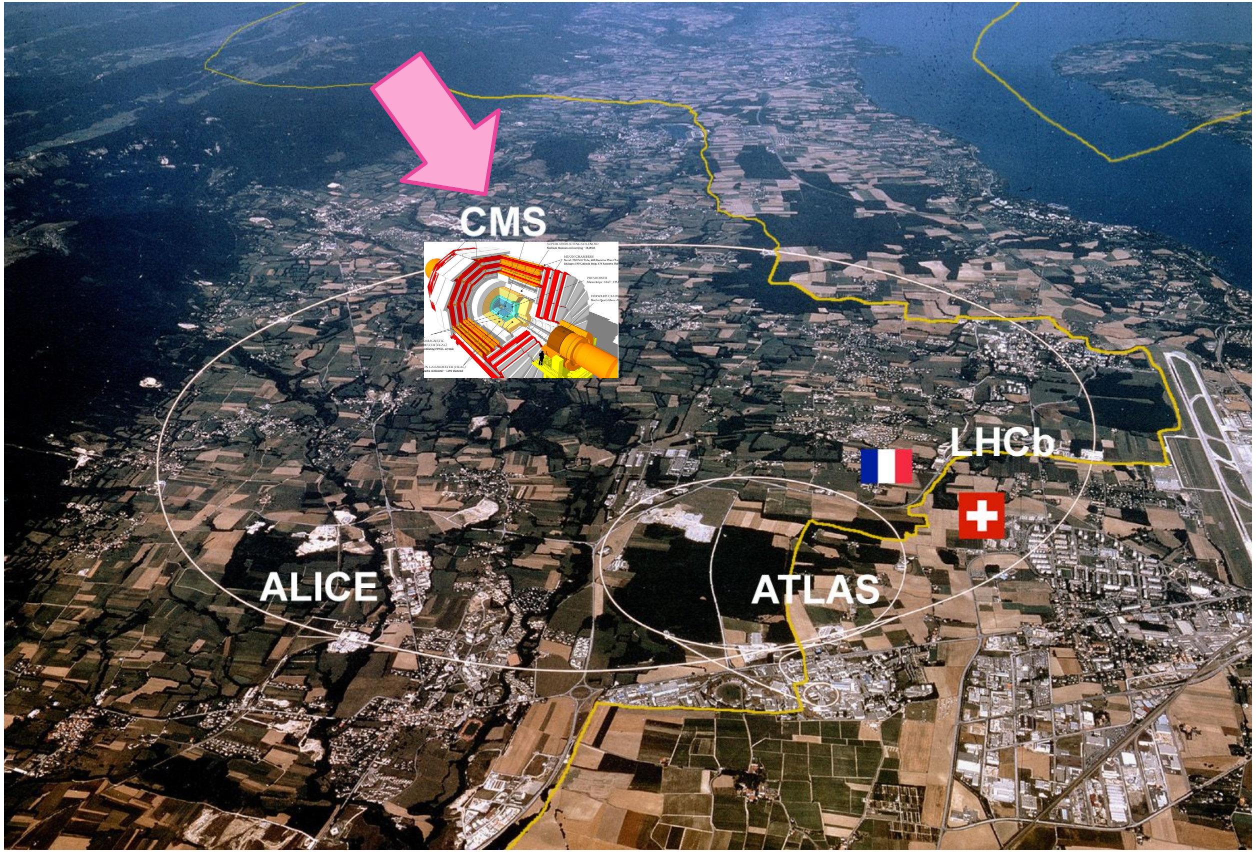
Circumference:
27 km

Proton-proton (ion-ion) collisions

Center-of-mass energy:
13 TeV

4 collision points
4 main experiments

Large Hadron Collider (LHC)



LHC in summary:

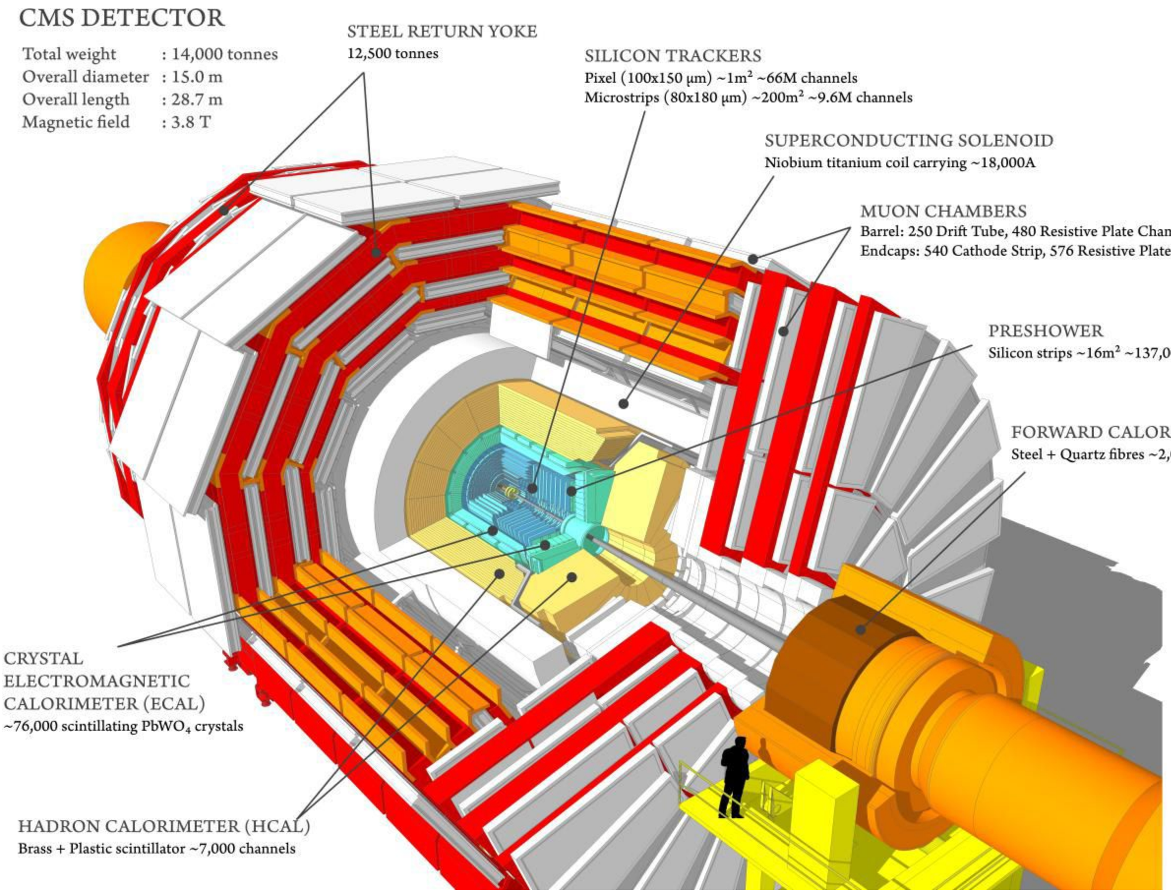
Circumference:
27 km

Proton-proton (ion-ion) collisions

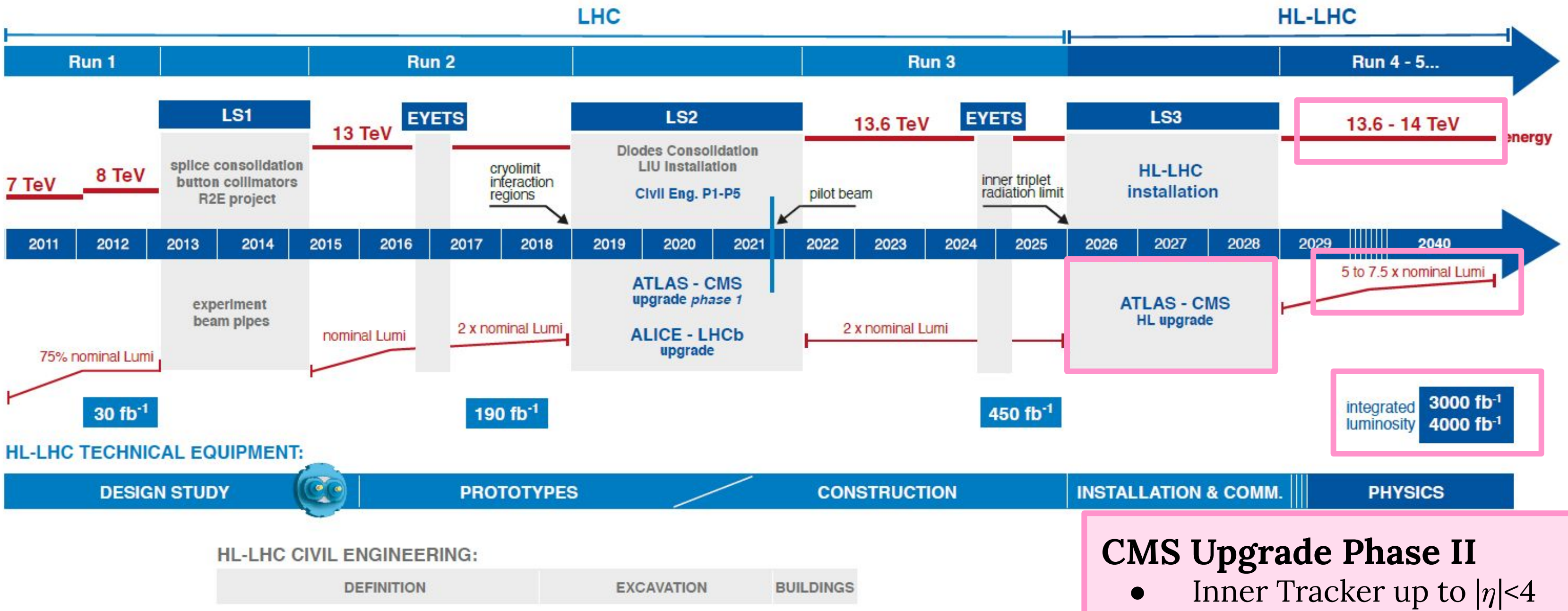
Center-of-mass energy:
13 TeV

4 collision points
4 main experiments

Compact Muon Solenoid (CMS) detector



LHC / HL-LHC Plan



CMS Upgrade Phase II

- Inner Tracker up to $|\eta|<4$
- Muon system coverage improved
- **MTD timing layer**
- High Granularity endcap calorimeter
- DAQ and trigger systems (L1 and HLT -7.5 kHz)

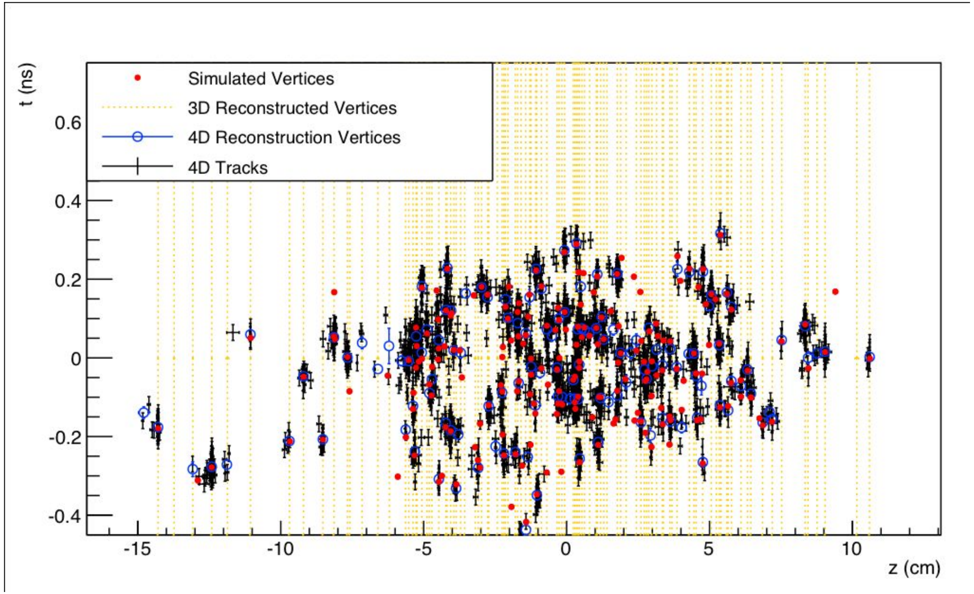
The MIP Timing Detector

The **Mip Timing Detector:**

- inserted between the tracker and the ECAL
- cover both **Barrel** and Endcap of CMS
- achieve a time resolution of about **30-40 (60-70) ps** at the beginning (end) of its operation.

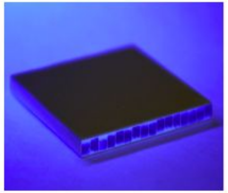
→ Needed to cope with the about **200 interactions per bunch crossing** at HL-LHC

The time information is exploited to make a **4D reconstruction** of interaction vertices:
→ Disentangle lots of 3D-reconstructed merged vertices and maintain the **current performance** of the CMS detector

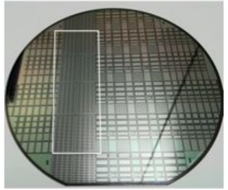


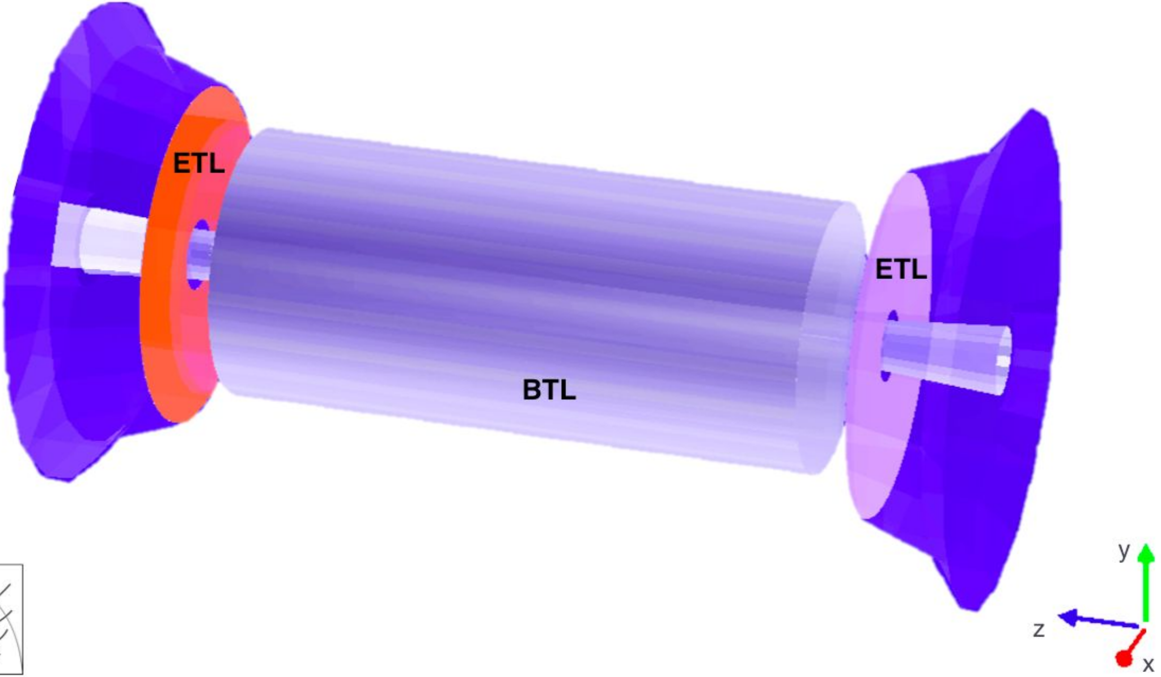
Mip Timing Detector

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2





The Barrel Timing Layer

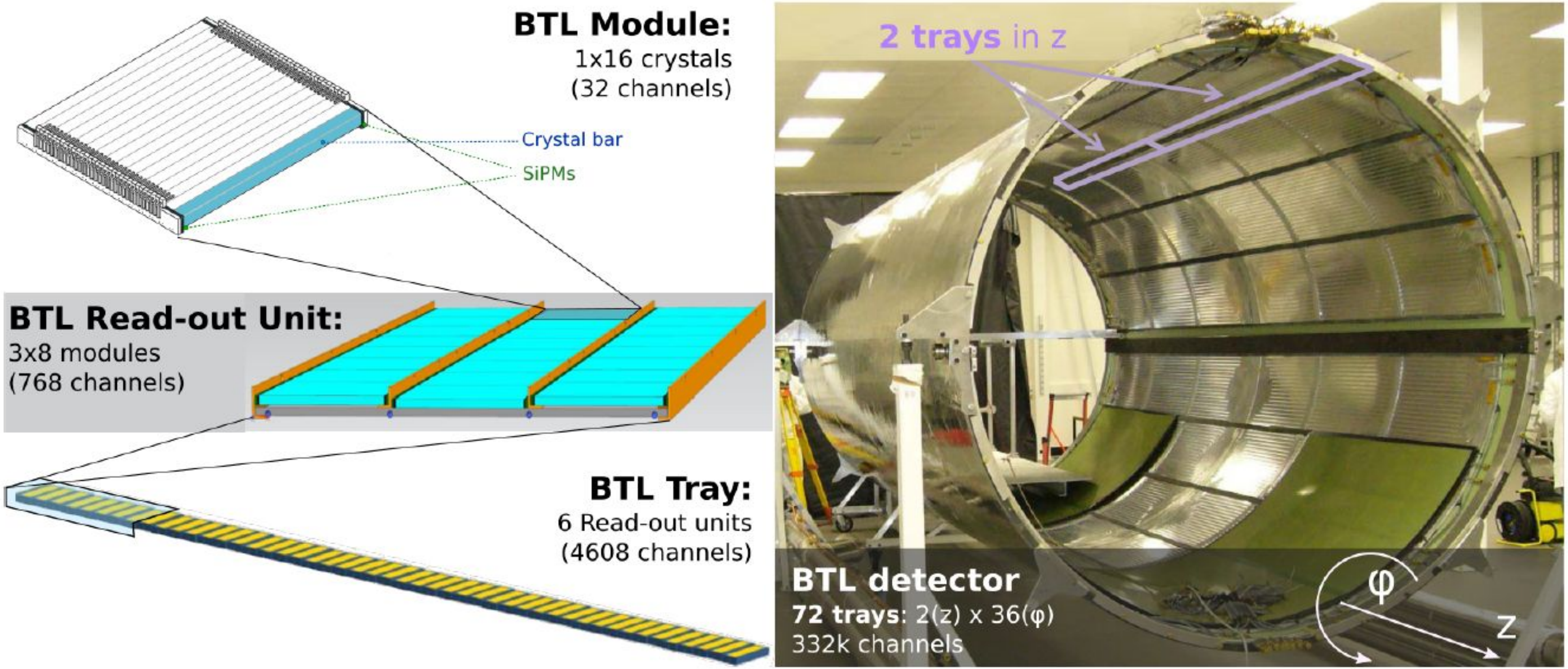


Photo-statistics contribution

Dependance of the photo-statistics term on the BTL parameters

$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{dep} \cdot LY \cdot LCE \cdot PDE}},$$

τ_r = rise time of scintillation pulse ~ 100 ps
τ_d = decay time of scintillation pulse ~ 40 ns

$\mathbf{N_{phe}}$ = Number of photoelectrons, depending on:

- E_{dep} = Energy deposited in the crystals by the MIP
- LY = Light Yield
- LCE = Light Collection Efficiency
- PDE = Photon Detection Efficiency