Validation of the CMS Barrel Timing Layer and searches for $HH \rightarrow bb\tau\tau$

XXXIV International School "Francesco Romano"

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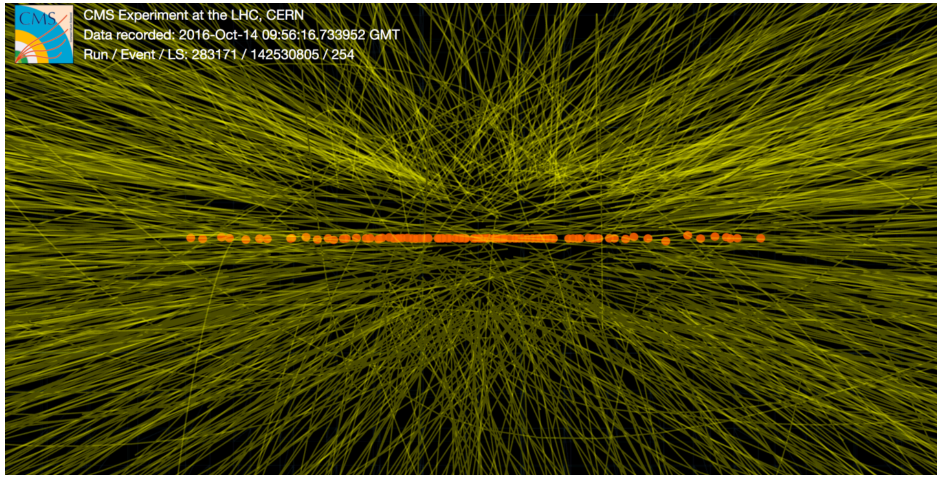
Precision timing in CMS for High Luminosity LHC



- New High Luminosity phase of LHC

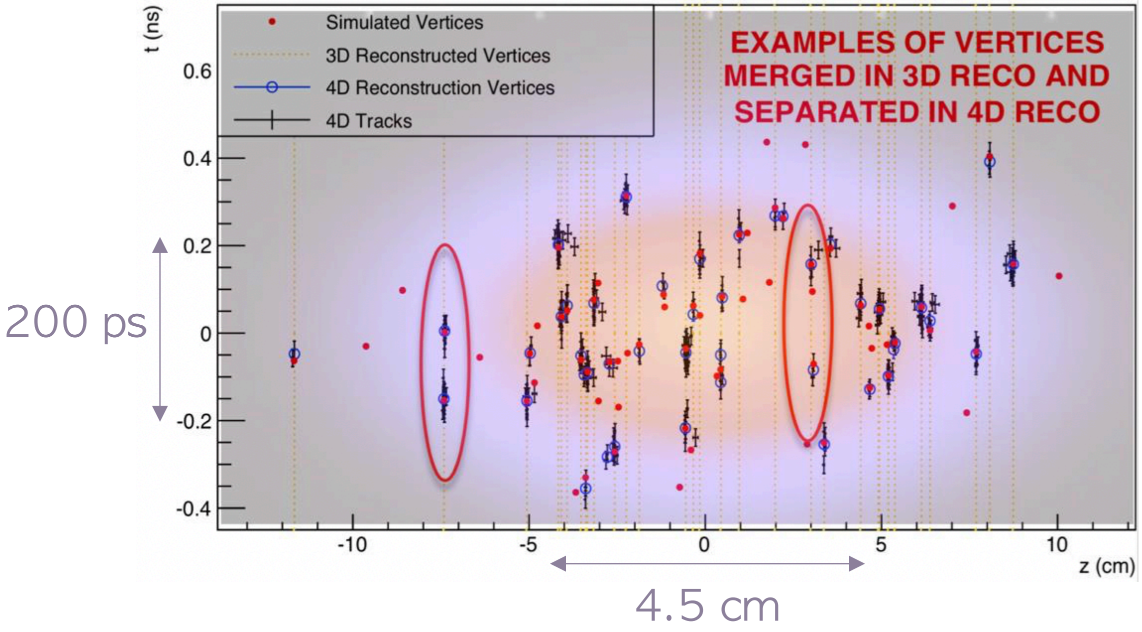
  → $\mathcal{L}_{ultimate}$ up to ~ 7 x 10^{34} cm^{-2} s^{-1}

  ⇒ higher vertex density (up to x5) will lead to increases in:

  - Radiation damage
  - Pileup

- CMS is undergoing major upgrades to withstand such harsh conditions:

  - MIP Timing Detector will enable the measurement of the time of arrival of charged particles

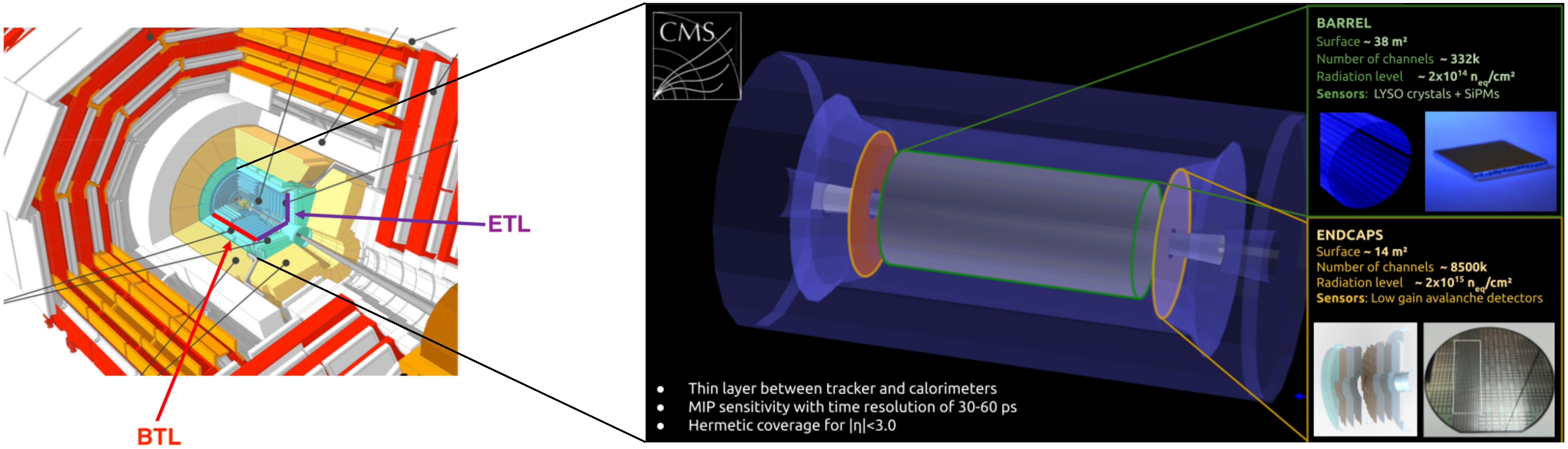


MTD design

Thin and hermetic detector ($|\eta|<3$) between the tracker and the calorimeter with different specifications contingent on radiation dose

⟶ employing diverse technologies to equip the barrel and the endcap areas of CMS:

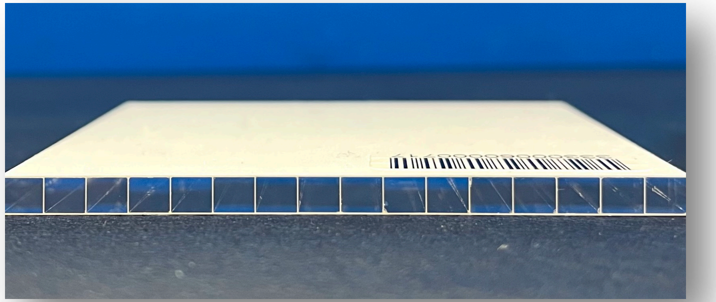
- **Endcap Timing Layer** (ETL): modules of Low Gain Avalanche Detectors (LGADs)
- **Barrel Timing Layer** (BTL): arrays of LYSO crystal bars readout at both ends by SiPMs



BTL sensors

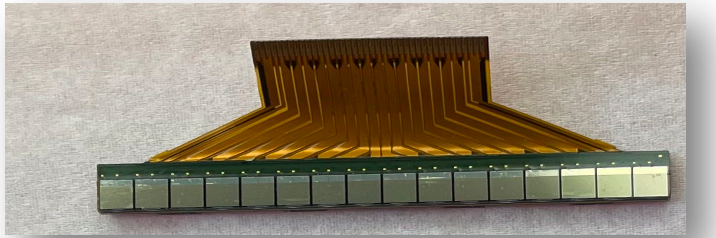
LYSO:Ce crystal

- large LY, fast scintillation rise time (<100 ps), short decay time (~40 ns)
- bar-like geometry: 3 x 3 x 52 mm^3



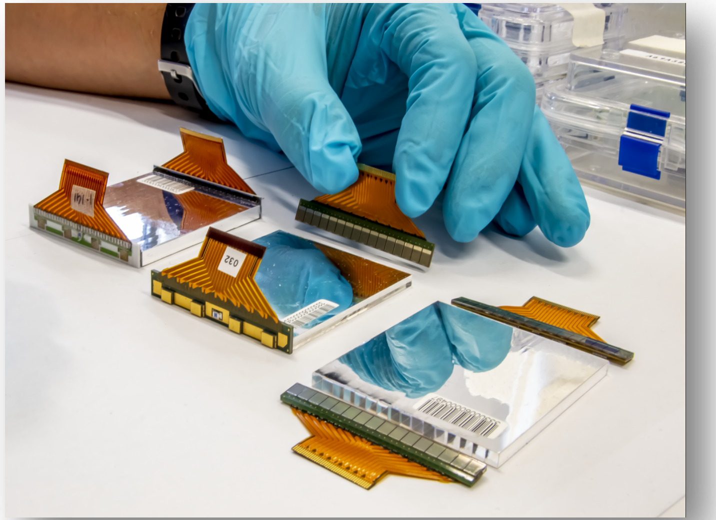
SiPM

- fast timing properties, magnetic field tolerant, compact and robust
- 15 µm cell size (initial design)



Module

- array of 16 crystal bars coupled to a pair of SiPMs through optical glue
- modules will be exposed to an accumulated radiation levels of 50 kGy of ionizing dose and a neutron fluence of 2×10^{14} n_{eq}/cm^2
    - No other large area experiment has ever used SiPMs in such a harsh radiation environment



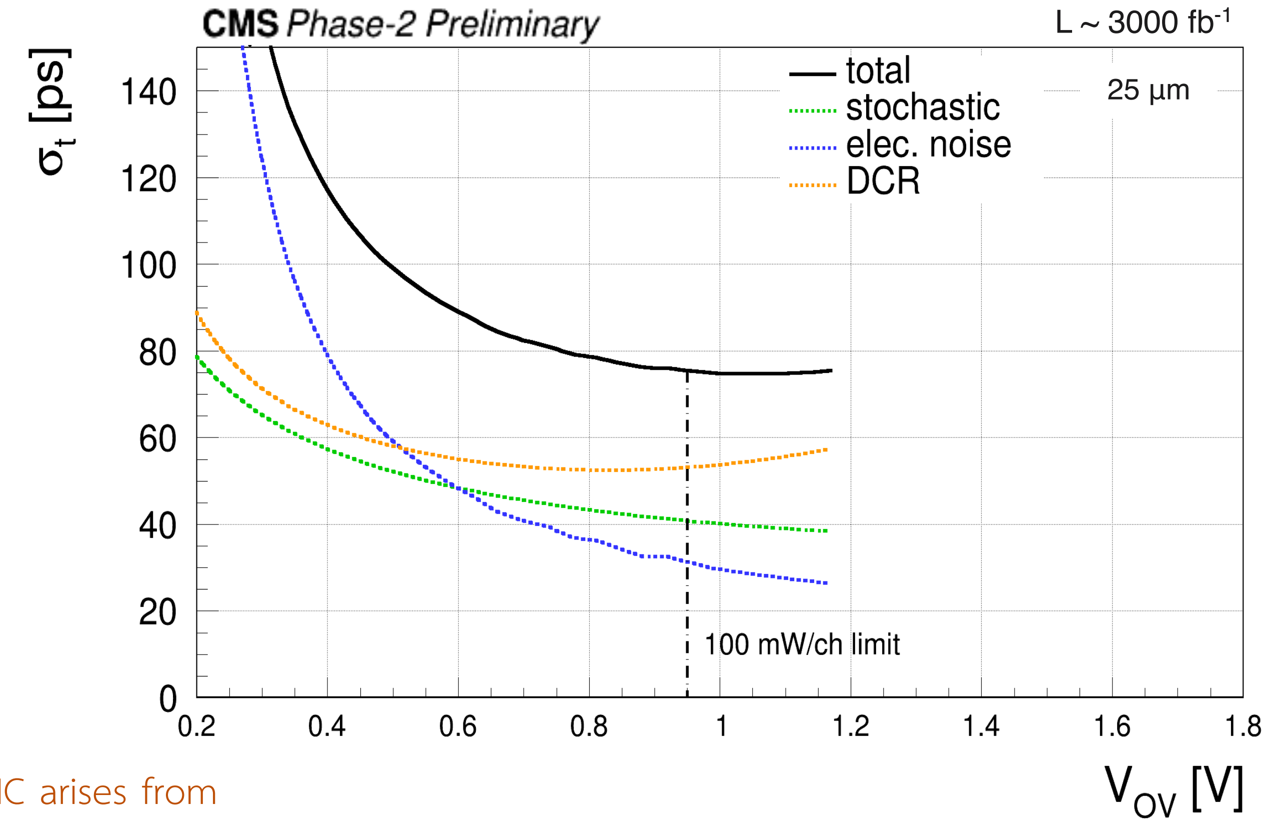
BTL performance

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

$$\sigma_t^{ele} \propto \frac{1}{dI/dt} \propto \frac{1}{N_{phe}}$$

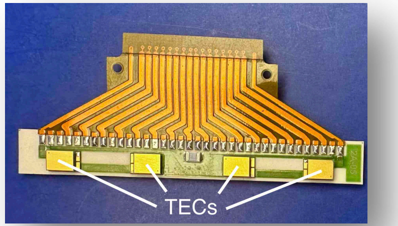
$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_d}{N_{phe}}}$$

$$\sigma_t^{DCR} \propto \frac{\sqrt{DCR}}{N_{phe}}$$



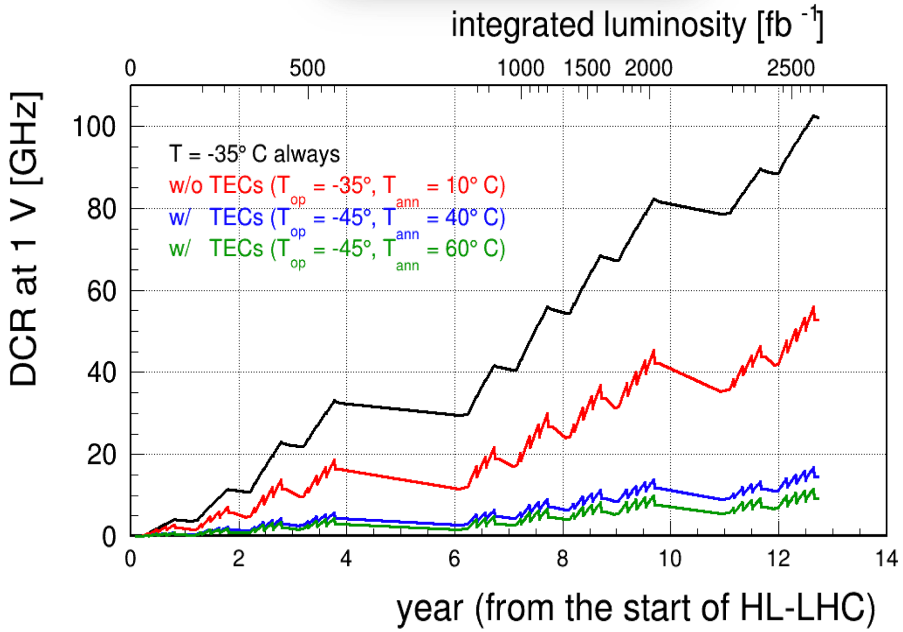
Significant impact towards the end of operations in HL-LHC arises from radiation-induced damage to SiPMs : Dark Count Rate ~ 10-30 GHz

Tackling Hi-Lumi challenges in BTL



Decreasing dark count rate

- *Thermo-Electric Coolers integration* on the SiPM packaging: lower operational temperature and higher annealing temperature



Reducing electronic noise contribution

- *SiPMs with a larger cell size*: increase in gain and PDE, faster rise time

Increase number of photoelectrons produced

- *Increasing module thickness*: increase in energy deposit (~25%)

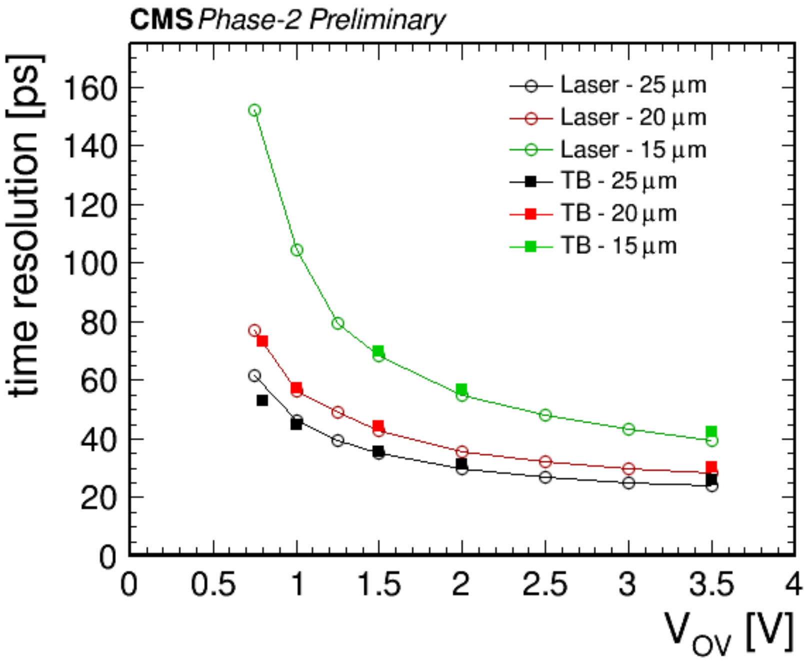
→ intense laboratory and test beam measurements focused on the validation of these studies

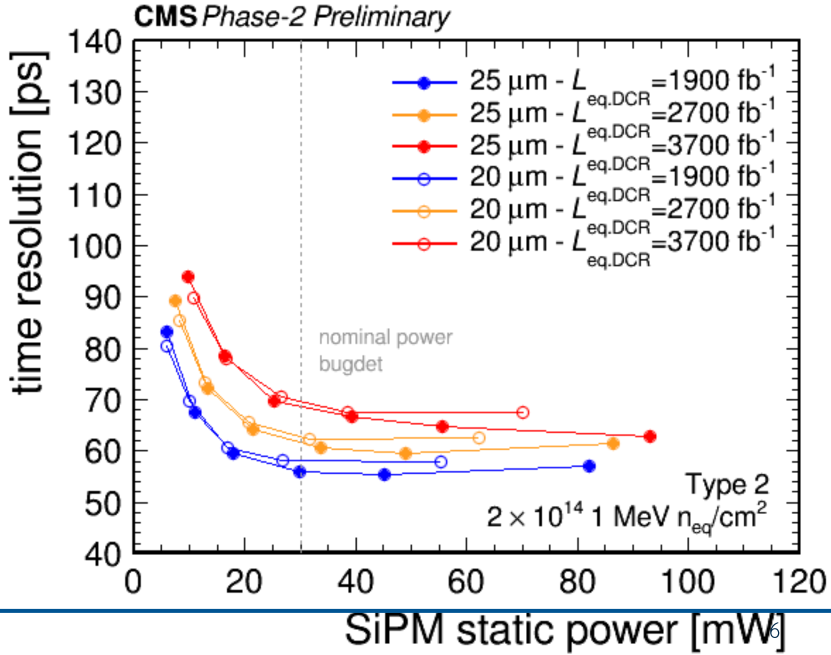
Larger cell size SiPMs

- Modules with larger cell sizes confirmed to achieve the **best performance**
  - Good agreement between test beam and laboratory measurements

- Some SiPM arrays **irradiated to the total radiation level** expected at the end of HL-LHC operation (2×10^{14} n_{eq}/cm^2)
  - assembled with LYSO arrays into sensor modules and tested at various temperatures to emulate different points of HL-LHC lifetime in terms of DCR

- Time resolution of **~ 65 ps** achieved with both modules, within the available power budget



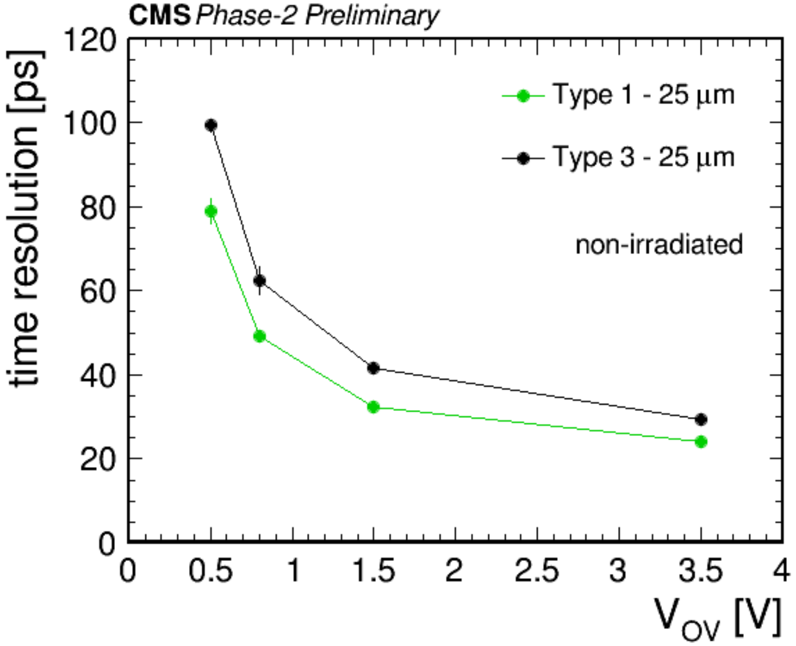


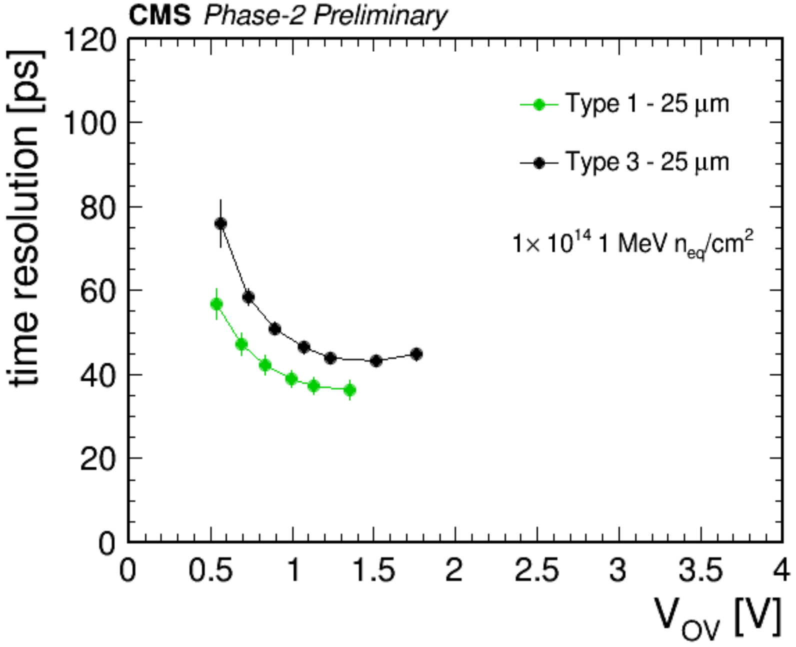
Thickening

- Non-irradiated SiPMs with a cell size of 25 μm were coupled to LYSO arrays
  - **Significant enhancement** in time resolution observed from type 3 to **type 1**

- When subjected to irradiation, SiPMs with larger active area exhibit high DCR and increased power consumption ⟶ crucial to evaluate irradiated modules with different thicknesses

- Both T1 and T3 SiPMs, featuring a 25 μm cell size, underwent irradiation to half of the total radiation level (1 x 10^{14} n_{eq}/cm^2)
  - **Enhanced performance of the thickest** modules was validated also in the case of **irradiated** SiPMs

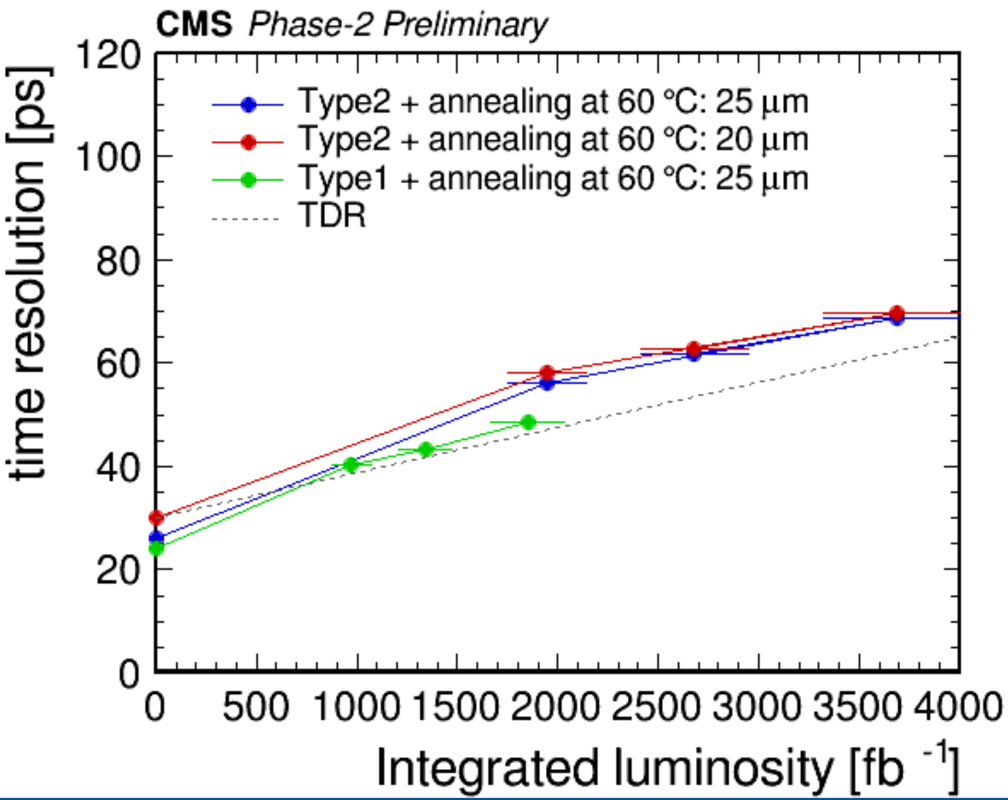




Validation

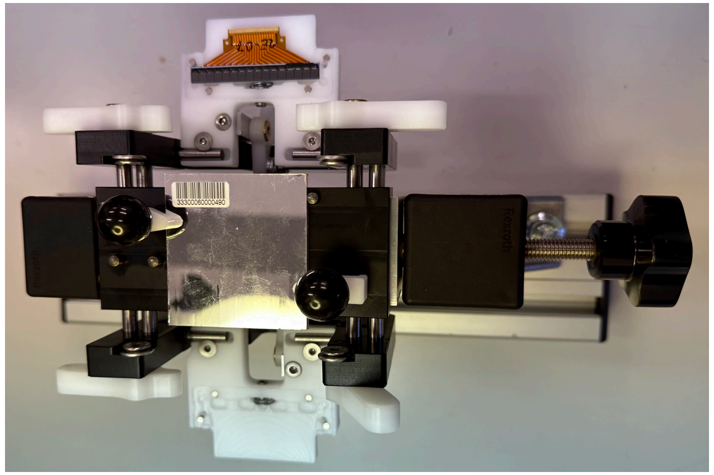
- BTL prototyping phase now concluded
- Innovations in sensors design:
  - ❑ TECs integration: reduced DCR ⟶ improved performance
  - ❑ 25 μm cell size SiPM: improved performance compared to 15 μm
  - ❑ Thickest module: better timing performance both at BoO and EoO

✓ Performance of the final prototypes aligned with the design target

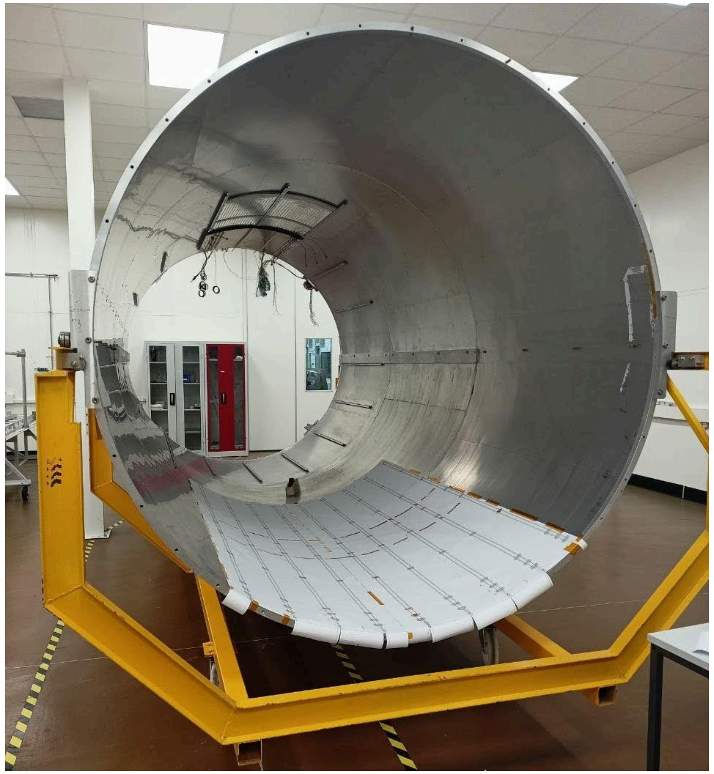


Towards the assembly

Prototyping phase concluded, ready for production!



- *4 BTL Assembly Centers* (Milano-Bicocca, Caltech, U. Virginia and Peking U.)
- *Common tools* for module assembly (e.g. gluing tools and tester boards) are being finalized



- *2 trays/month* production and testing @ each BAC, then shipment to CERN
- *Tray integration @ Tracker Integration Facility* + tray test

- *Final installation* in the BTL Tracker Support Tube by Summer ***2025***

Commissioning in CMS starting in 2027

Impact of MTD on the CMS physics

- Reduced number of tracks from PU vertices that are incorrectly associated with the PV
    - Improved reconstruction performance of ~ all physics objects and, thus, significance of some benchmark cases such as Higgs boson self coupling
    - Since timing information not available until HL-LHC, now focusing on analysis of Run 2 data

35 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.38	1.52	1.60
$bb\gamma\gamma$	1.70	1.75	1.85	1.90
Combined	2.31	2.40	2.57	2.66

50 ps BTL, 50 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.36	1.44	1.50
$bb\gamma\gamma$	1.70	1.72	1.78	1.80
Combined	2.31	2.37	2.47	2.53

70 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.92	0.94
$bb\tau\tau$	1.30	1.38	1.36	1.44
$bb\gamma\gamma$	1.70	1.75	1.76	1.81
Combined	2.31	2.40	2.41	2.51

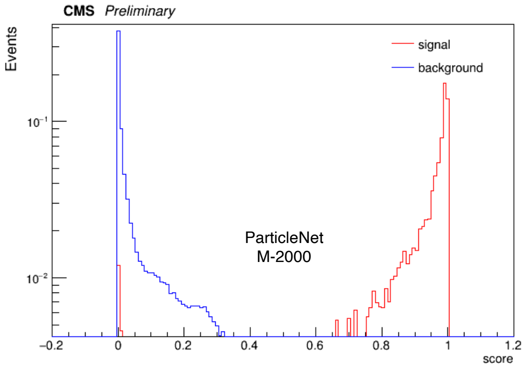
Preliminary studies on efficiencies

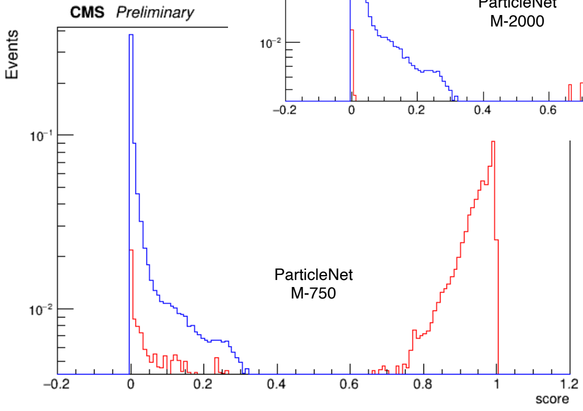
- Defining the score from a GNN indicating a jet as a bb originating from a H as:

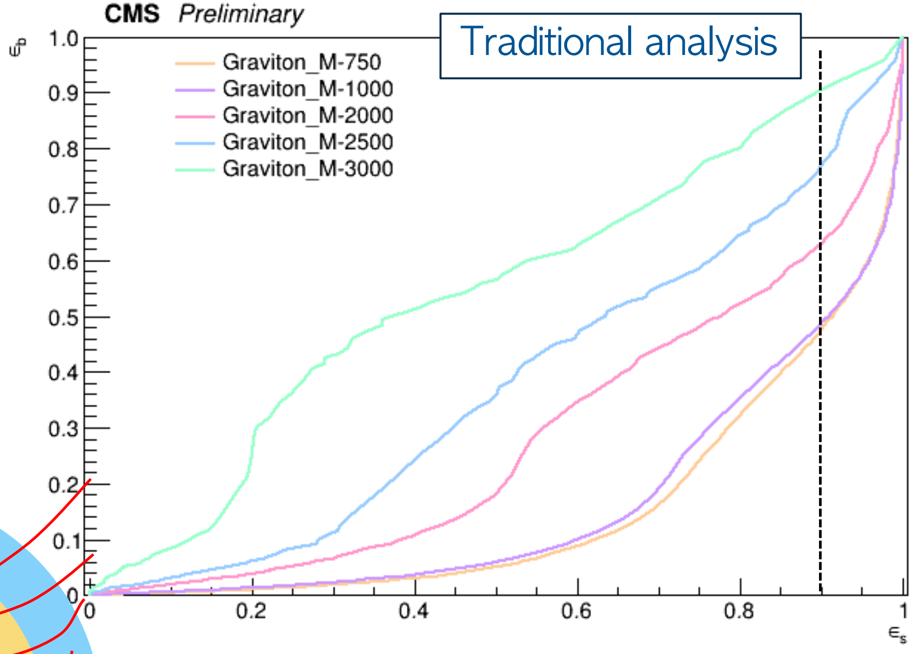
$$score^{traditional} = \frac{(prob_b + prob_{bb} + prob_{lepb})^{subjet1} + (prob_b + prob_{bb} + prob_{lepb})^{subjet2}}{2}$$

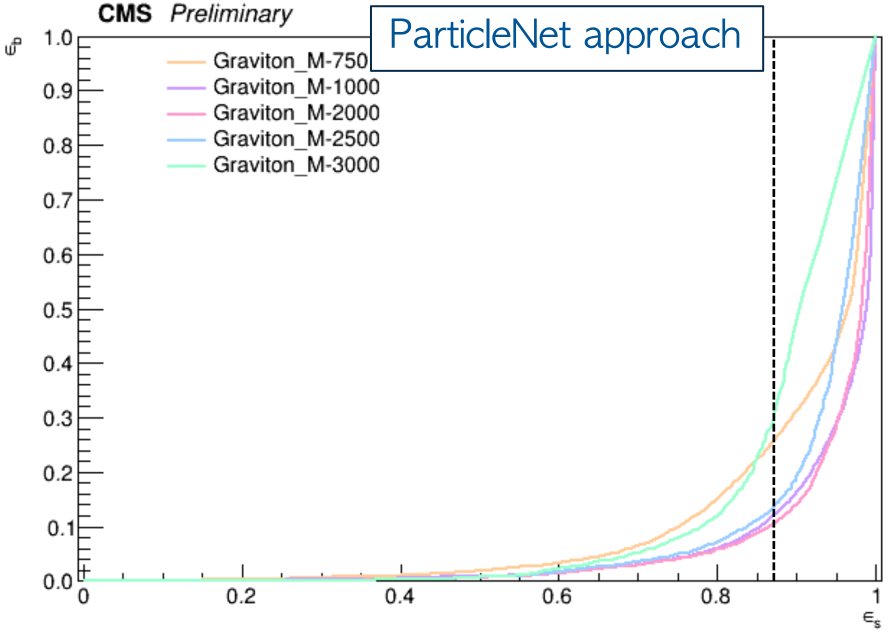
$$score^{ParticleNet} = \frac{prob_{Hbb}}{prob_{Hbb} + prob_{QCD}}$$

- we then computed the corresponding ROCs







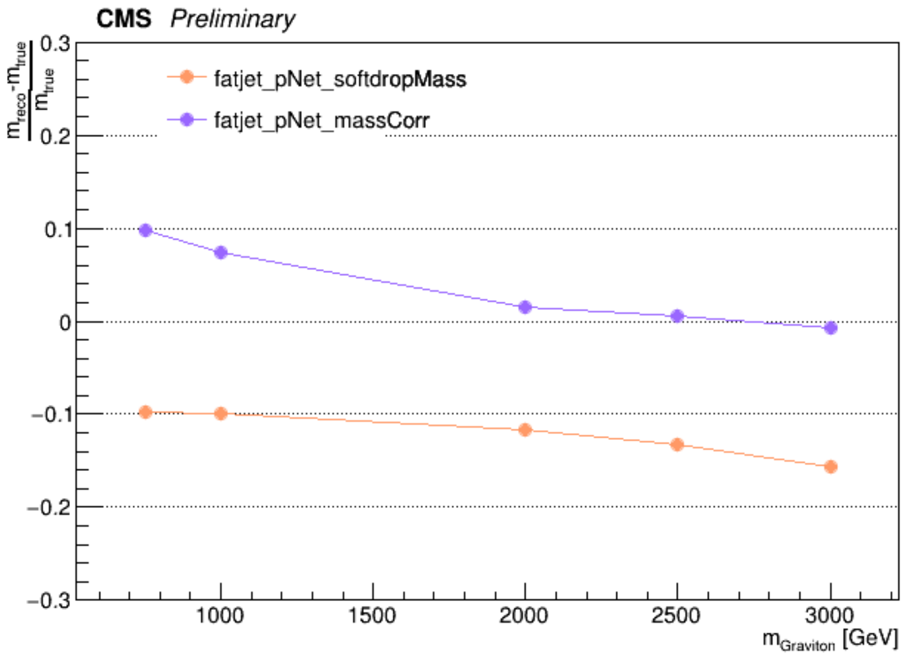


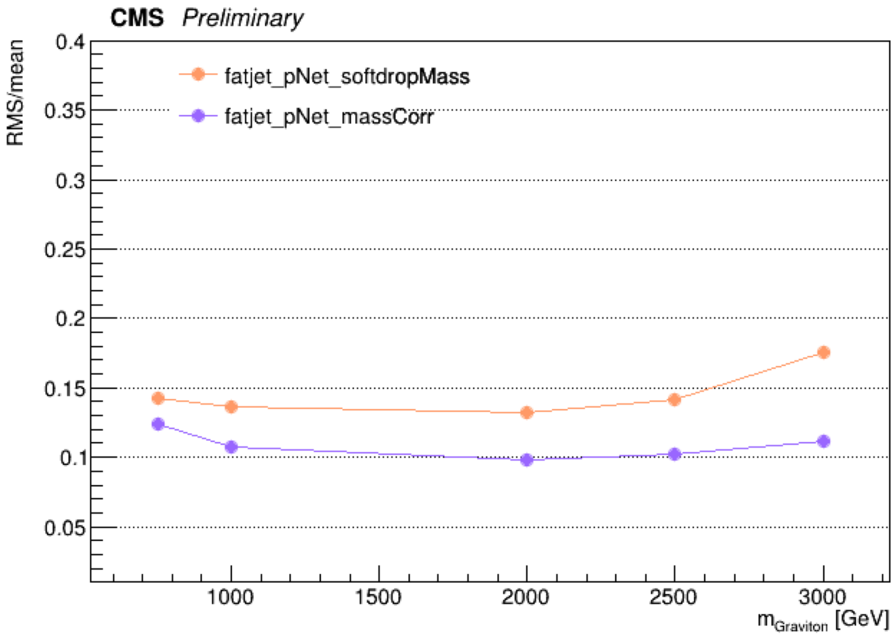
Fixing 90% signal efficiency for graviton with mass [1,3] TeV, ParticleNet allows a **reduction of a factor 2-3** of the backgrounds coming from DY and ttbar.

Preliminary studies on jet mass correction

- Traditional analysis reconstructed the jet mass through Soft Drop declustering
  - which recursively removes soft wide-angle radiation from a jet

- Exploiting the jet mass correction, we achieve **improved precision** in terms of both **resolution** and **mass** values
  - This allows both for a background reduction since we will be asking m(jet) ~ m_H and, in perspective, an improved reconstruction of the mass resonance





Next step

- MTD:
  - Final design validated
  - Procedures for assembly and quality control are now being finalized
    - Ready for assembly

- HH:
  - ParticleNet information (already available in MiniAOD) now included in the production of big-ntuples
  - I am currently assessing the potential increase in significance by incorporating ParticleNet for b-tagging
  - Perspectives for Run 3, contributing to:
    - Inclusion of ParticleNet information for tau leptons tagging in NanoAOD
    - Development of a new framework

Thank you!