Detector optimization and physics performance of the CMS Phase-2 Endcap Timing Layer

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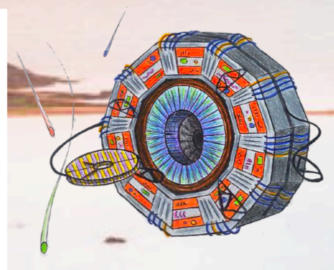
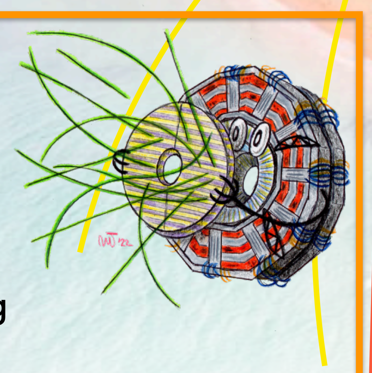


My PhD thesis on CDS

The CMS Phase-2 Upgrade



High Luminosity LHC will produce in the CMS experiment:

- pileup increase bringing to 140-200 proton-proton collisions per bunch crossing
  → Hard to distinguish overlapped collision
- radiation levels reaching 10^{16} n_{eq}/cm^2 in some subdetectors

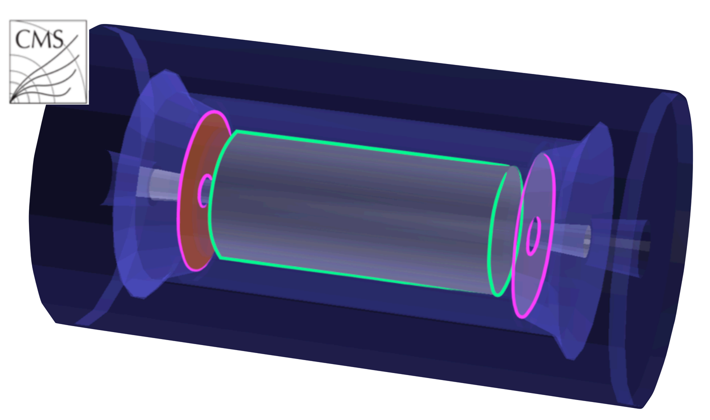
To maintain its present performance, CMS will feature important changes with the Phase-2 Upgrade

The MIP Timing Detector (MTD) will provide 4D tracking by adding track time information to separate events overlapped in space but happening at different times

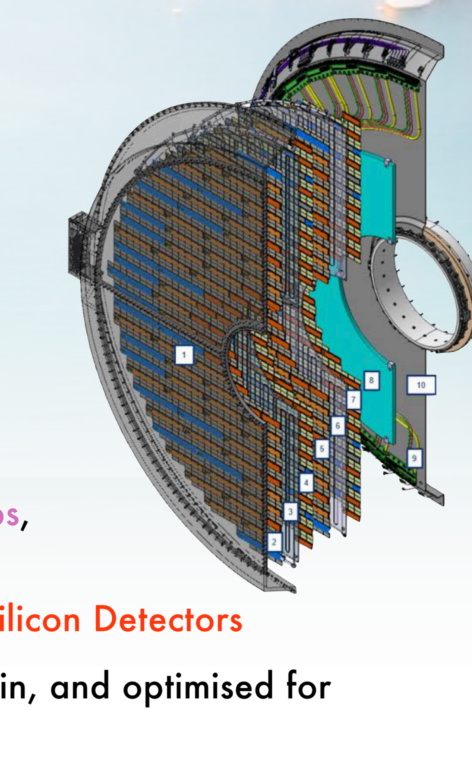
MTD will be made of two parts: the Barrel and the Endcap Timing Layer (BTL and ETL)

MTD will improve reconstruction by:

- reconstructing time information for charged particles by combining tracker and MTD measurements
- providing a timing resolution $\sigma_t \sim 30-40\ ps$ at the start of HL-LHC



The Endcap Timing Layer



Instrumented with Low Gain Avalanche Diodes + ASIC readout
Radiation $\sim 10^{15}$ n_{eq}/cm^2

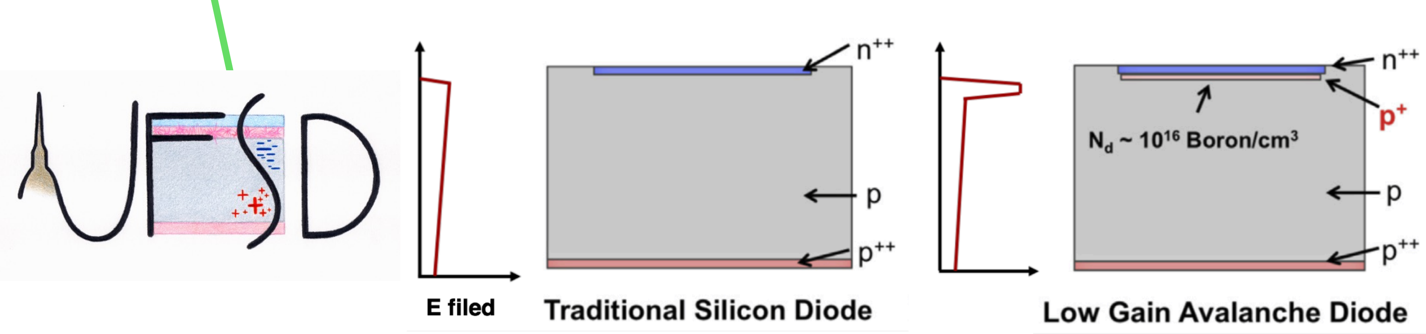
Each endcap is made of two disks covered in silicon sensors on both sides, for a total active area of 7 m^2 per endcap, hermetic coverage for $1.6 < |\eta| < 3.0$

Time resolution per track <35 ps thanks to single hit resolution <50 ps
ETL will contribute in maintaining present CMS performance

ETL requirements: sensors with segmentation of $\sim 1mm^2$, time resolution 30-40 ps, radiation field 1.7×10^{15} n_{eq}/cm^2

An innovative type of silicon detectors matches these requirements: Ultra-Fast Silicon Detectors

UFSDs are based on Low Gain Avalanche Diodes, with a moderate internal gain, and optimised for precise timing measurements



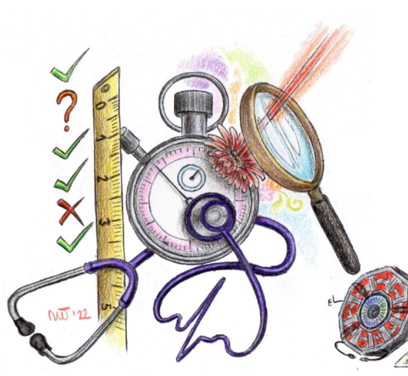
Towards the final ETL sensor: from R&D to prototyping

ETL requirements for LGADs considering the best time resolution conditions:

- High hit efficiency and excellent gain uniformity
- Low single pad leakage current to limit power consumption and noise
- High gain and low noise producing >8 fC when new, >5 fC after highest irradiation point
  → Excellent time resolution 30-40 ps
- High fill factor: narrow no-gain area (50 μm) and edge width (500 μm at most)
- Long term stability, avoidance of failure modes due to increase of bias with fluence

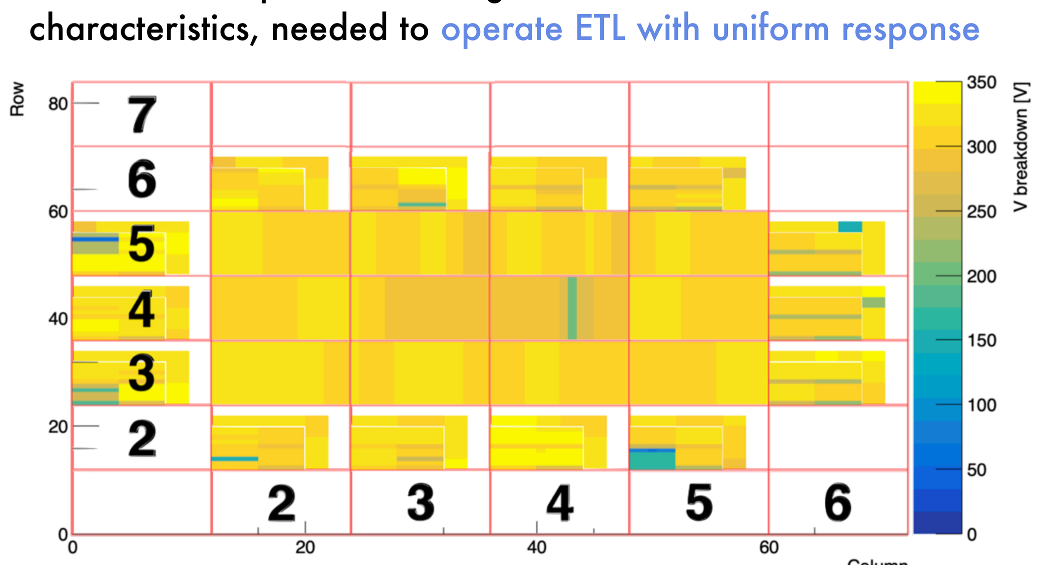
Extensive laboratory measurements performed in the Laboratory for Innovative Silicon Sensors in Torino on several LGAD productions to define the characteristics of the perfect sensor for ETL:

- Yield and gain uniformity studies
- No-gain width measurements
- Interpad resistance
- Gain curves and charge collection
- Time resolution: jitter component and total resolution
- Micro-discharges
- Single event burnout studies
- ETL bias granularity

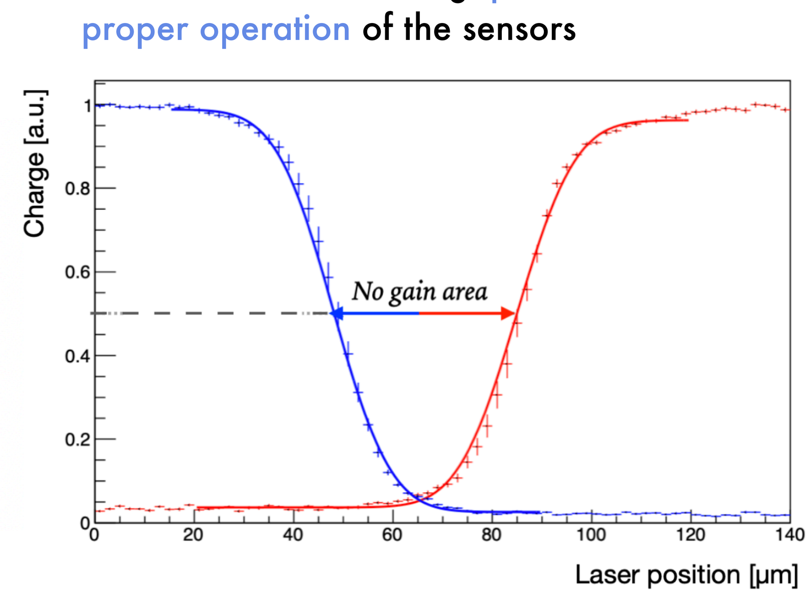


Measurements in purple performed by me

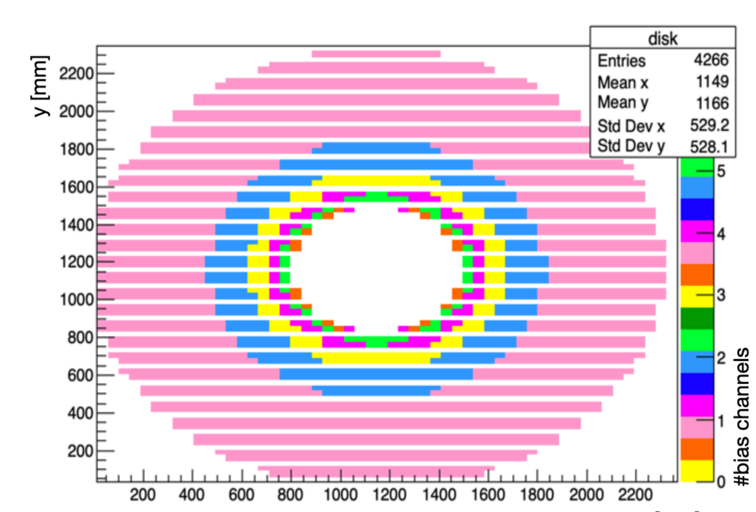
Breakdown map of pads in an FBK UFSD4 wafer used to compute the sensors yield and uniformity, used to evaluate the quality of a production and the capability of different vendors to produce large sensors with the same characteristics, needed to operate ETL with uniform response



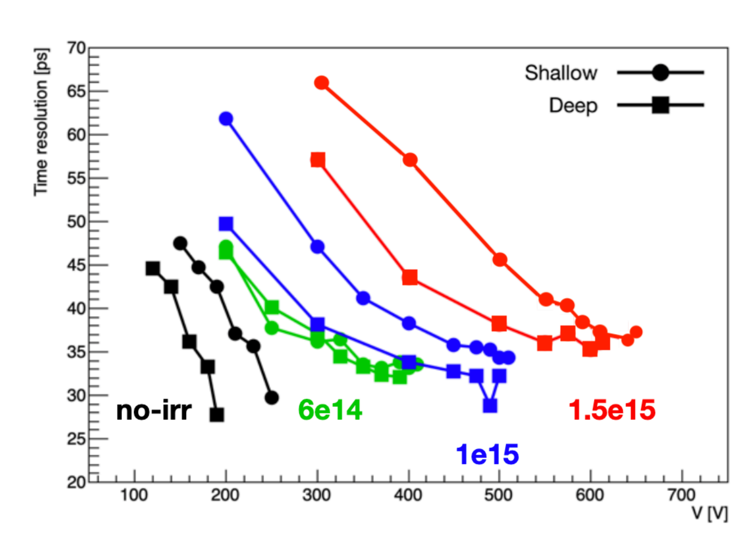
Charge collected by two adjacent pads shot with a laser to measure the no-gain distance. The goal is to reach the narrowest no-gain distance while ensuring pad isolation and proper operation of the sensors

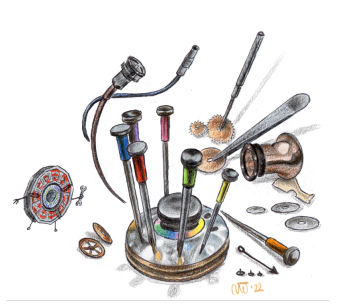


Bias granularity map for FBK UFSD3.2 W19 to maintain a delivered charge of 10-15 fC at 3000 fb^{-1}. Used to define the best gain layer implants for the ETL



Time resolution for sensors with two different gain implants from FBK UFSD4. UFSDs should reach 40 ps below 700 V after irradiation to avoid single event burnout



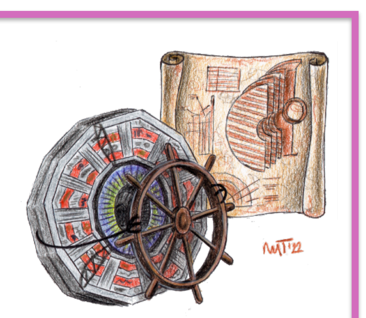


Results of these and other studies performed within the Torino group have been collected to:

- The sequence of tests needed to fully characterise a UFSD production has been defined and shared with other ETL centres, producing consistent and comparable results
- A subset of these tests has been selected for the Market Survey, considering the importance of the results for ETL and the reduced time at disposal in the MS process

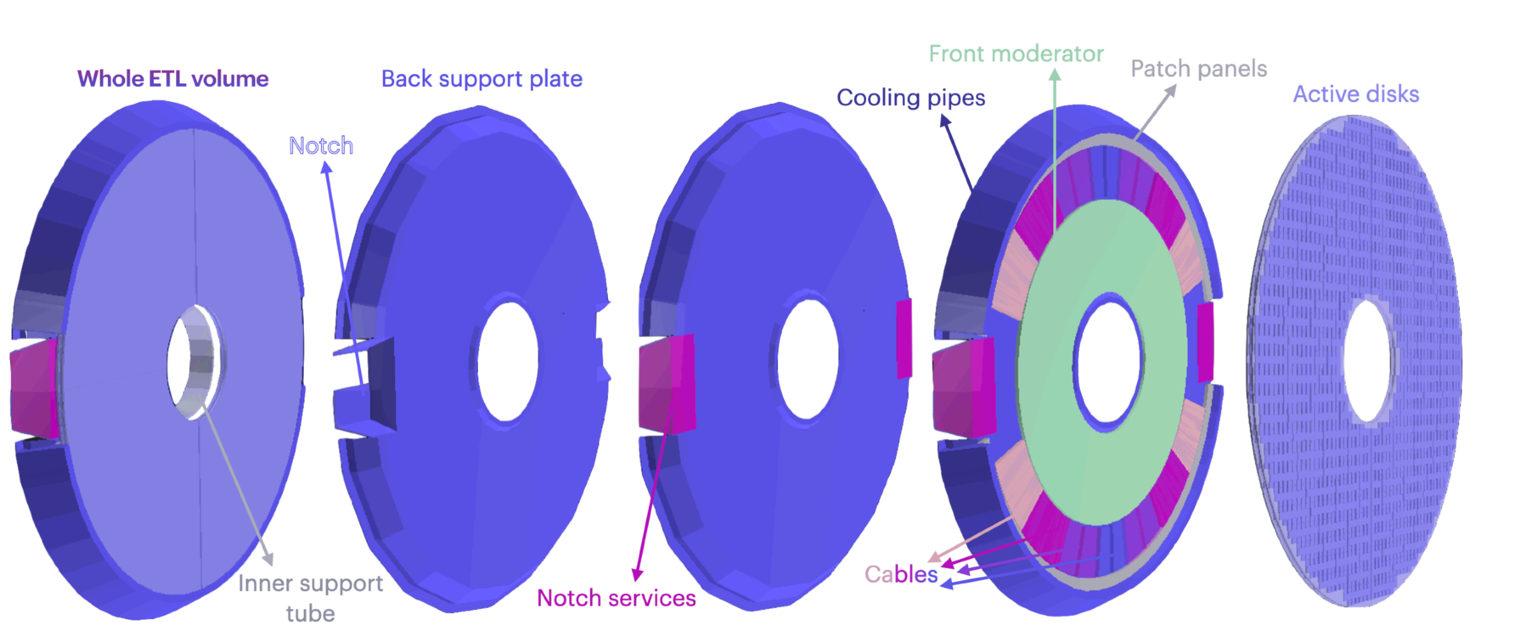
The testing is being finalised and the results on the qualification of the vendors within the Market Survey will be soon made available

The ETL geometry design



As MTD is a new detector, ETL geometry needs to be implemented in the CMS software environment (CMSSW)

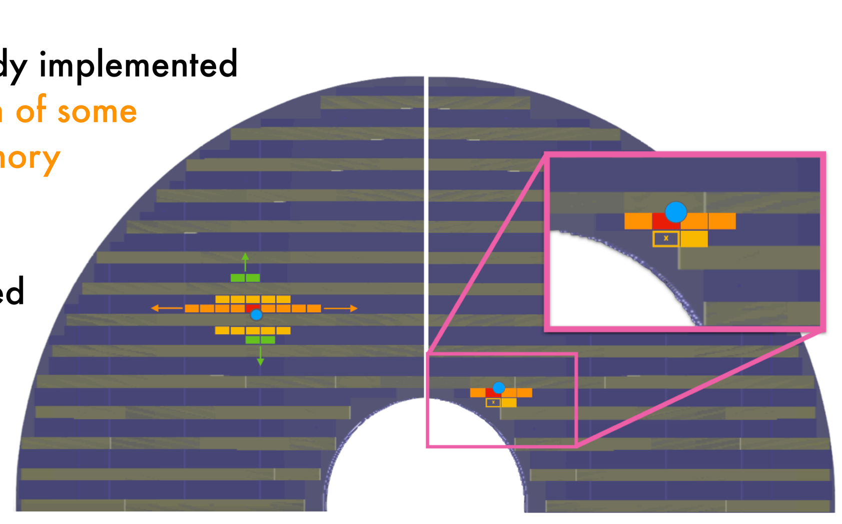
The latest ETL version implemented in CMSSW at the moment is ETL v7, included in CMS geometry from scenario D86, based on the engineering drawings from end 2020/beginning 2021



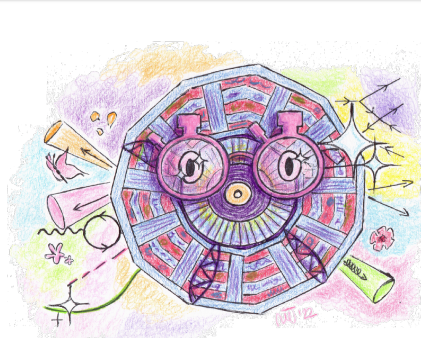
The ETL Navigation Algorithm is used by the reconstruction algorithms to identify the ETL modules compatible with a track

The search for compatible modules was already implemented in an existing code, but it caused the exclusion of some compatible modules and used a time and memory consuming procedure

Development of a new efficient algorithm based on the definition of a new dedicated modules order and row-by-row search



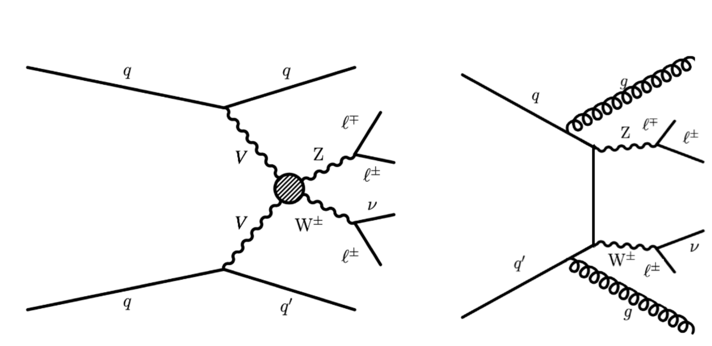
The impact of MTD on CMS analysis



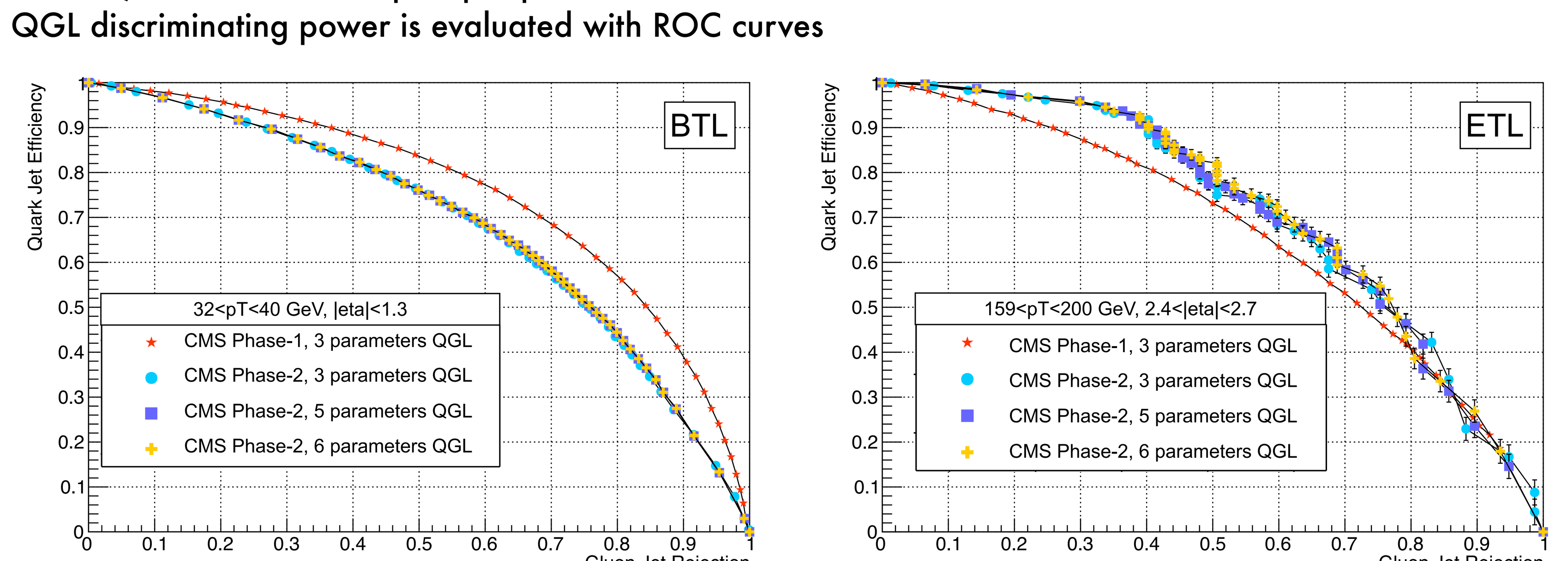
Processes with final states the forward region are significantly improved with CMS Phase-2, particularly with ETL
Vector Boson Scattering identified as a case study to verify the improvements brought by MTD

MC samples simulated with the latest CMS Phase-2 geometry at 14 TeV and 200 PU for:

- Signal: VBS with $W^{\pm}Zjj \rightarrow \ell^{\pm}\nu\ell^{+}\ell^{-}jj$ final state
- Background: QCD-induced di-boson production with gluon-jets in the final state



Quark-Gluon Likelihood can be used in the endcap region in CMS Phase-2 (was used only in the barrel in Phase-1) and benefit from pileup rejection from MTD
QGL discriminating power is evaluated with ROC curves



QGL performance slightly degrades in the barrel region moving from Phase-1 (JME-22-003) to the high pileup of Phase-2, but significant improvements are noticeable in the forward region with respect to CMS Phase-1 performance

No improvements observed in VBS significance, but the new QGL variable can be used in MVA to increase the sensitivity in rare processes, such as single polarised cross-section of WZ