The CMS p_T modules for the Outer Tracker Upgrade: current status and (unexpected) applications

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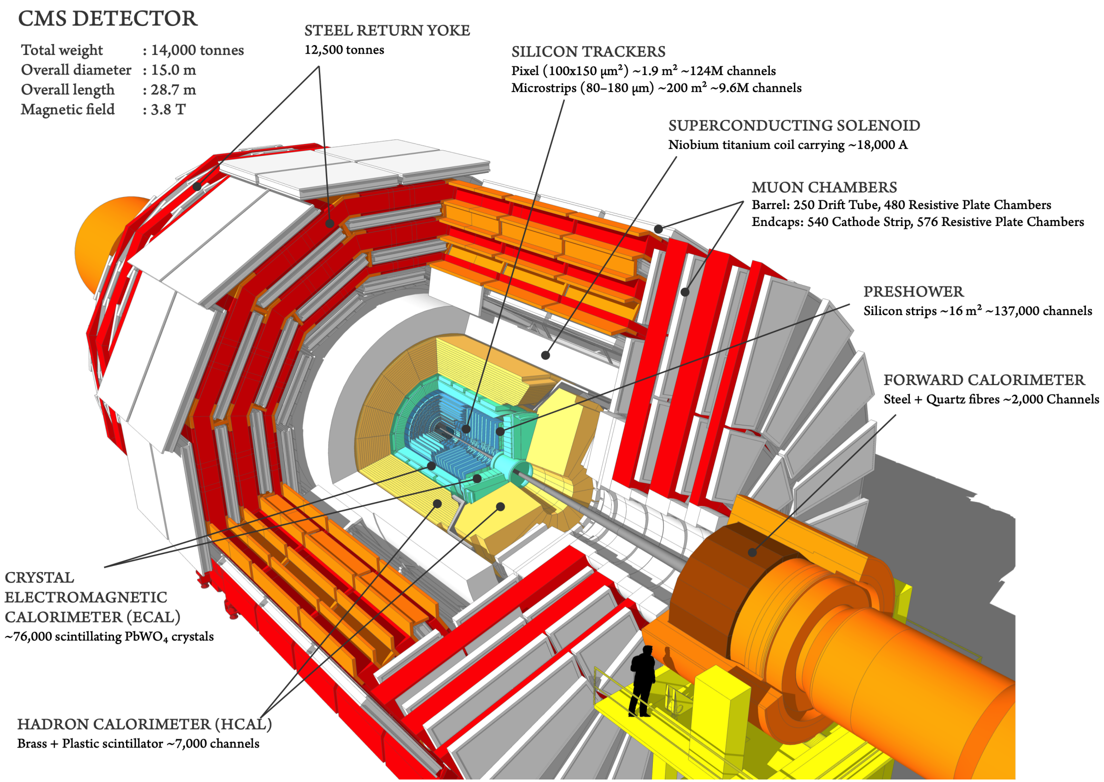
Question I will try to answer

- Why do we need a new tracker?
- What do we want from this new tracker?
- What are the p_T modules?
- Why the p_T modules?
- Are we really building them?
- What are they good for?
- What is MUonE, btw?

Introduction

The CMS experiment at LHC

Designed to study the pp collision at $\sqrt{s} = 13\,\text{TeV}$ produced at $40\,\text{MHz}$ by the LHC.

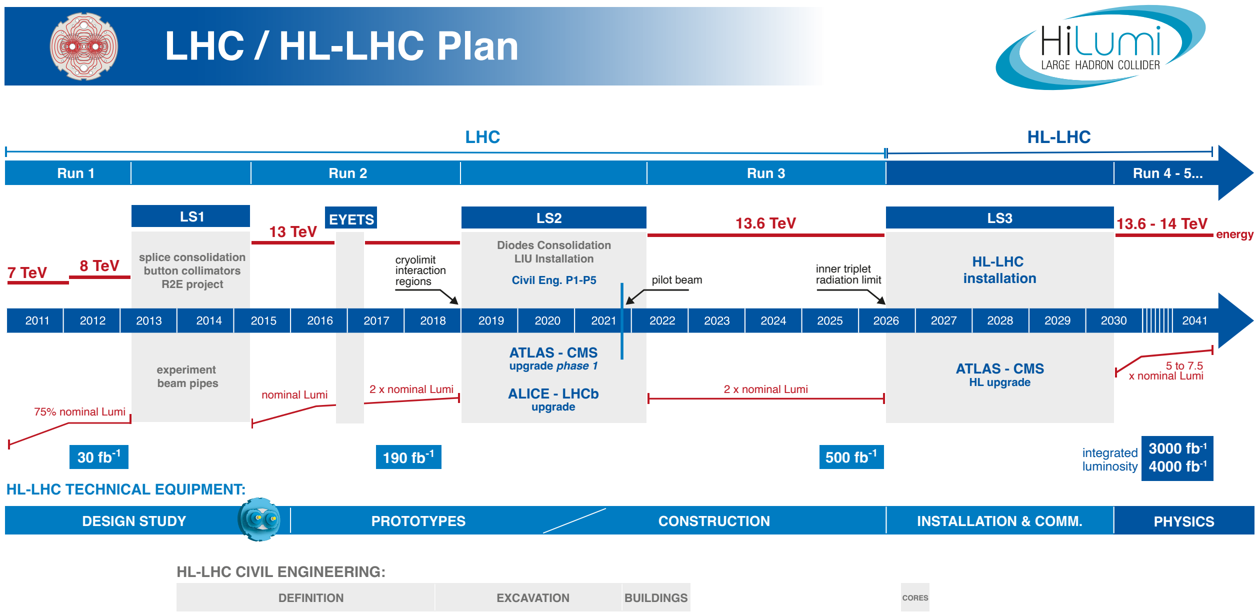


Two stages trigger to select events of interest:

- L1: hardware based, low latency (3.8 μs), uses only simplified informations from calorimeters and muon chambers
  (max accept rate: $100\,\text{kHz}$);
- HLT: software based, uses the whole detector informations to select events to be saved
  (accept rate: $\mathcal{O}(1\,\text{kHz})$).

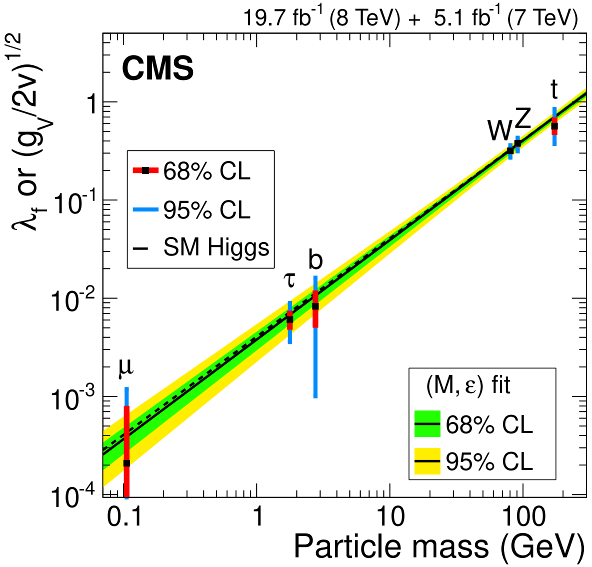
The High Luminosity LHC (Phase II)

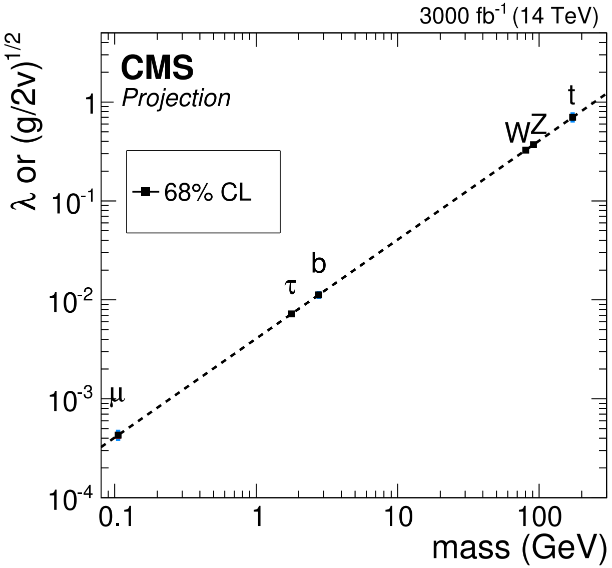
- HL–LHC: 2.3 to 3.4 times the instantaneous luminosity of LHC Run 3;
- Expected integrated luminosty of 3000 fb^{-1} to 4000 fb^{-1} by the end of HL–LHC.



The physics case of High Luminosity LHC

Increased statistics → new opportunities for rare channels searches and precision measurements.





The physics case of High Luminosity LHC

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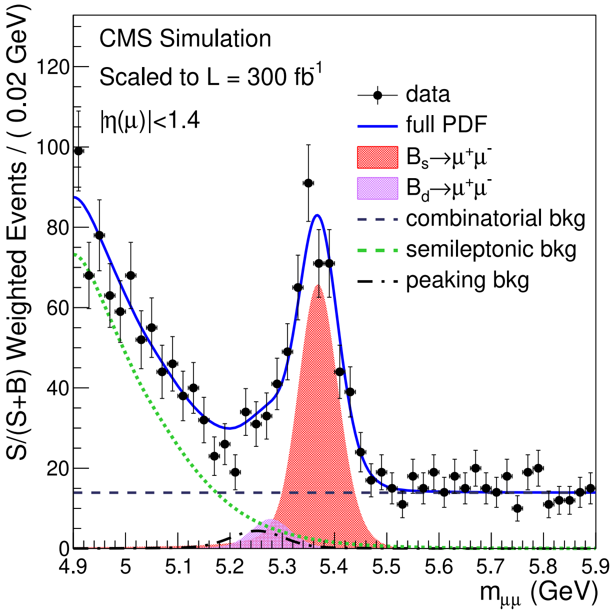
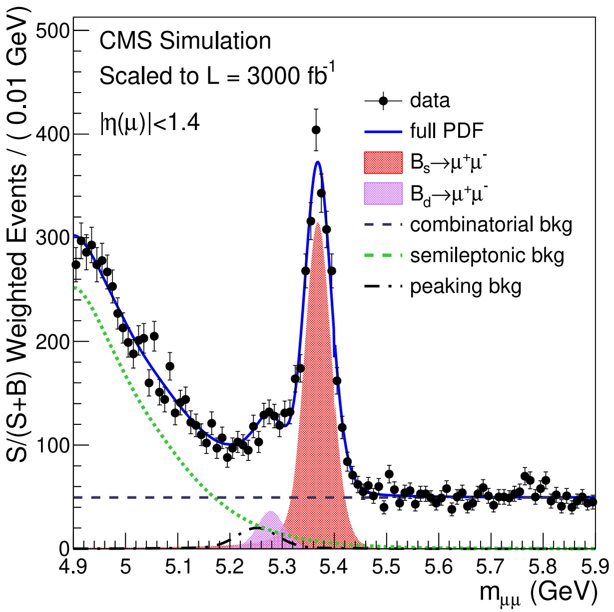


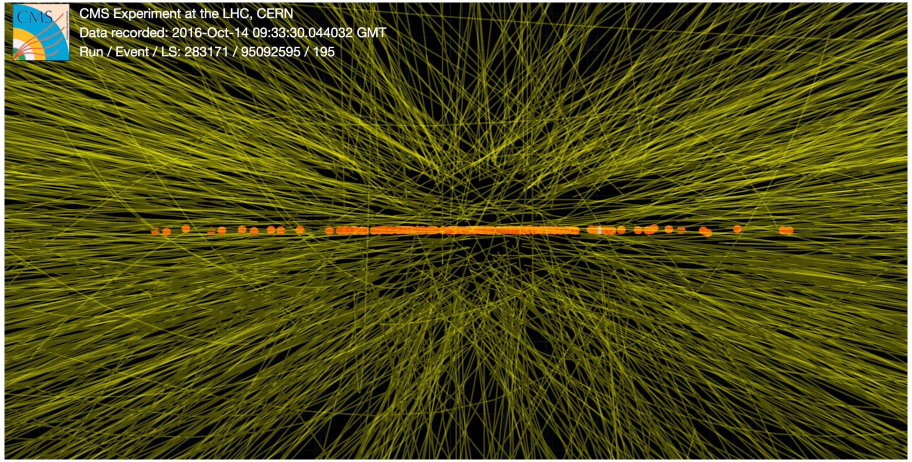


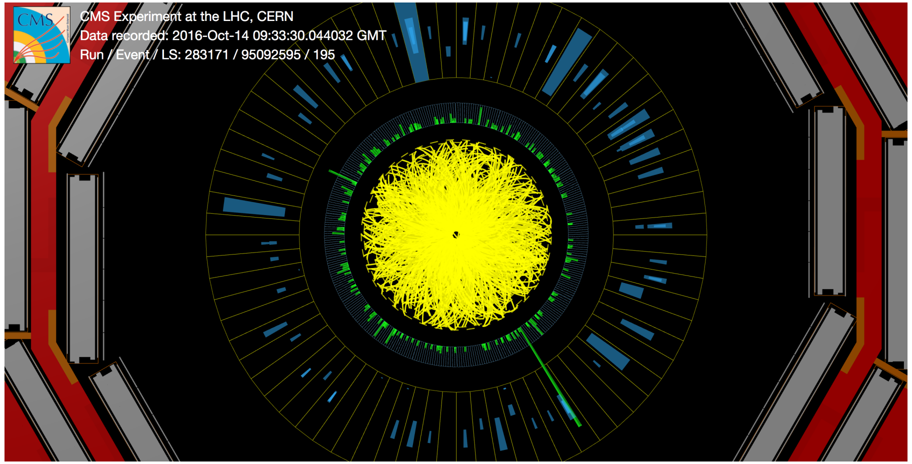
But can we get these results by only increasing the collider performance?

Why do we need a new tracker?

Current tracker was designed for Phase I, not Phase II:

- It cannot withstand the radiation damage of HL–LHC (up to $2.3{\times}10^{16}\,n_{eq}/cm^2$ in innermost layer);
- It is not designed to deal with the high pile–up (140 to 200 vs current 60);





[CMS-PHO-EVENTS-2016-008]

How do we survive?

To take advantage of the HL–LHC opportunity, the new tracker must have these features:

- High radiation tolerance;
- High granularity → Low channel occupancy → Efficient tracking;
- Less material in the tracking volume → Improved momentum resolution;
- Contribution to the L1 trigger ("L1 tracking") → higher selection purity → L1 rate manageable;
- Extra: have 12.5 μs of decision time for the L1 trigger.

p_T modules

The data transmission bottleneck

Let's do a simple back-on-the-envelope calculation:

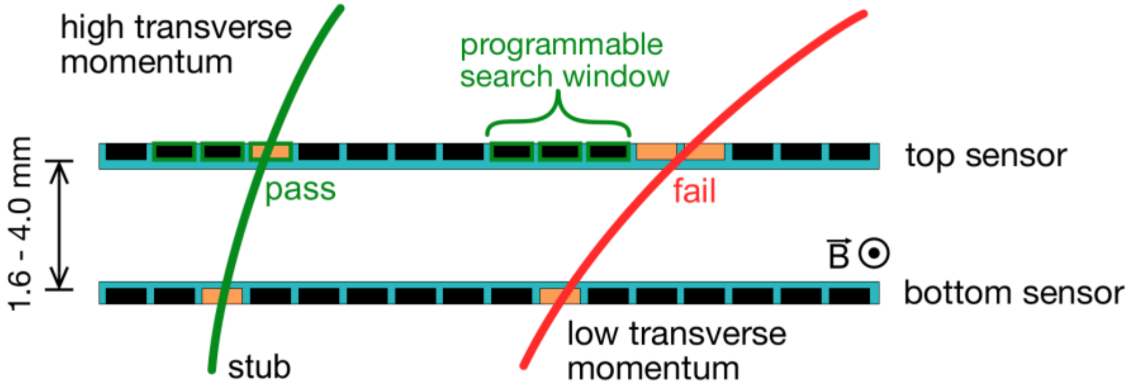
- Consider a reasonable pixel sensor with ≈30000 channels;
- Average channel occupancy at permille level → 30 hits per BX;
- At least 19 bits of information (binary readout) per hit to send via optical link;
- A reasonable header is ≈30 bits (BX time stamp, status bits, ...);

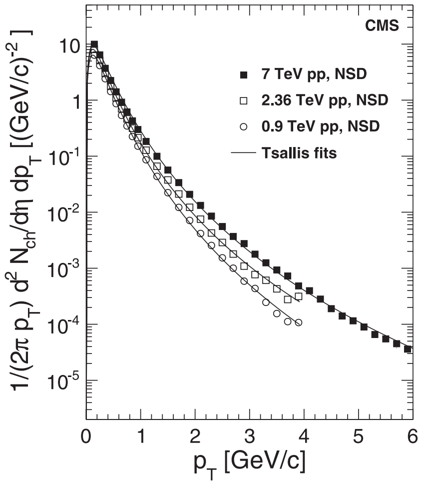
$$(30 \times 19\text{b} + 30\text{b}) \times 40\,\text{MHz} \approx 24\,\text{Gbps}$$

- But our fastest transceiver is at 10 Gbps! [LpGBT]

Low p_T tracks rejection on the frontend: the *stub* concept

Correlation between the two layers *on the front end electronics* → cut on the transverse momentum → rate reduction!

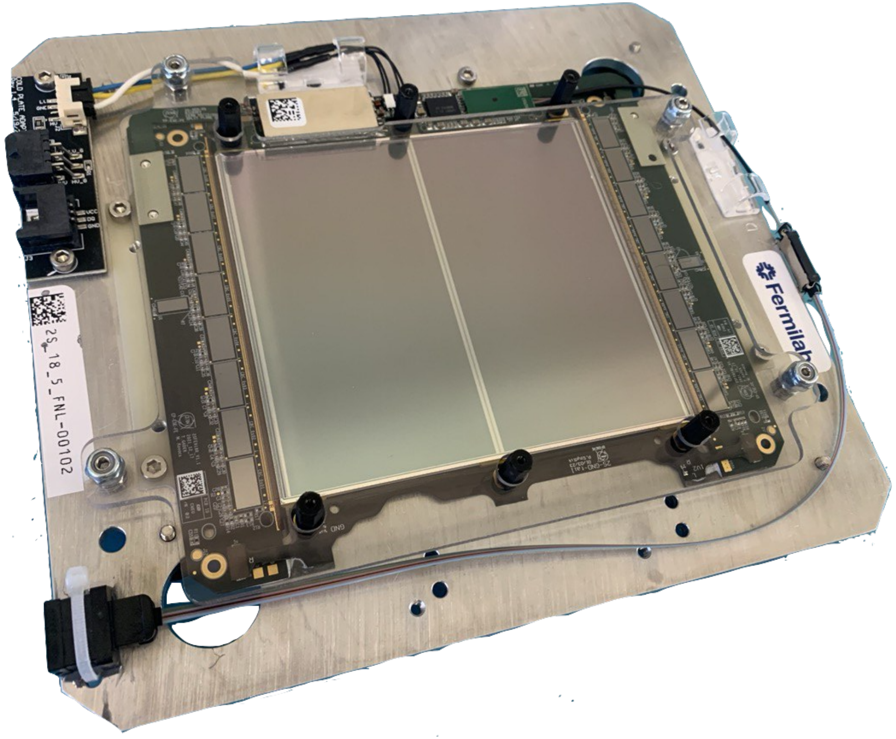




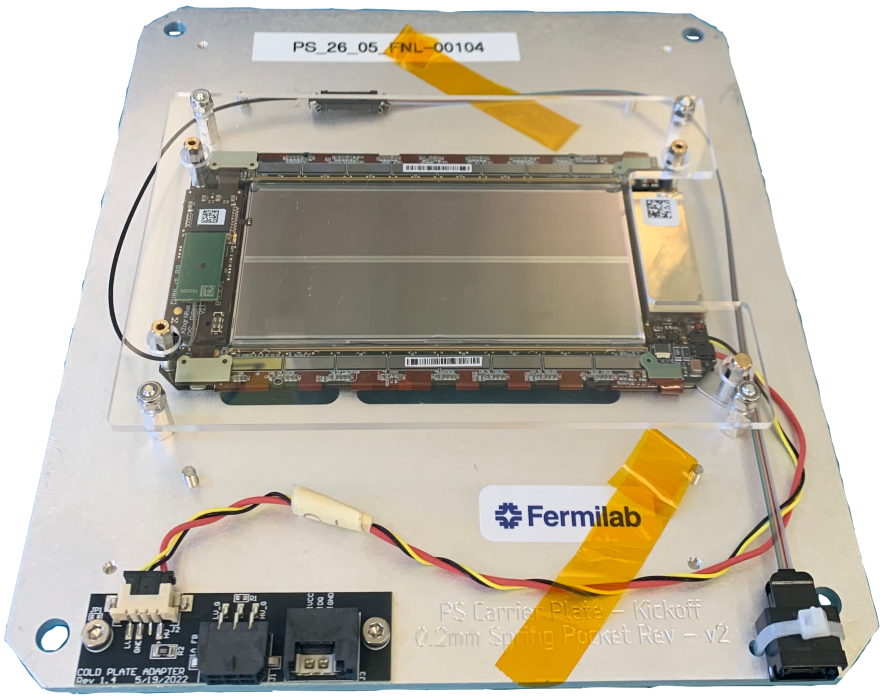
Distribution of non-single-diffrattive (NSD) interactions.

[PhysRevLett.105.022002]

p_T modules

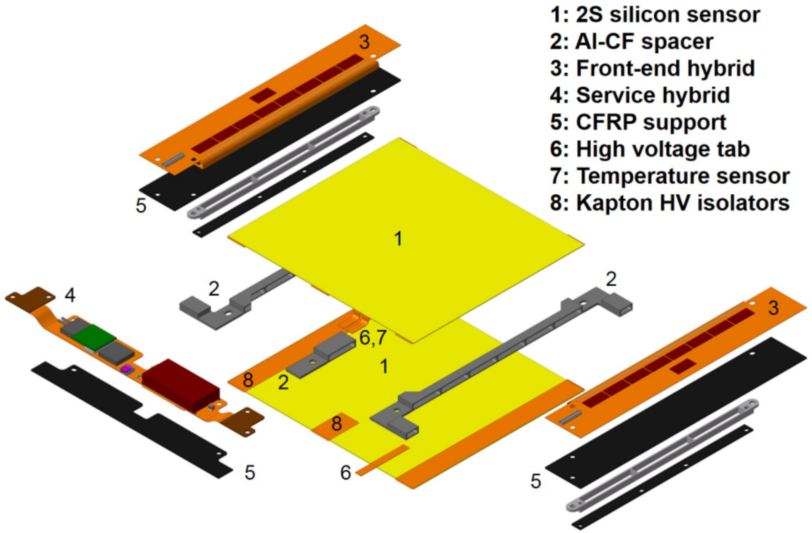


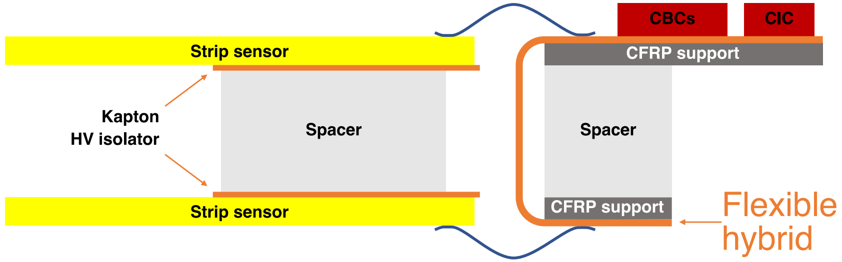
2S (strip + strip) module



PS (pixel + strip) module

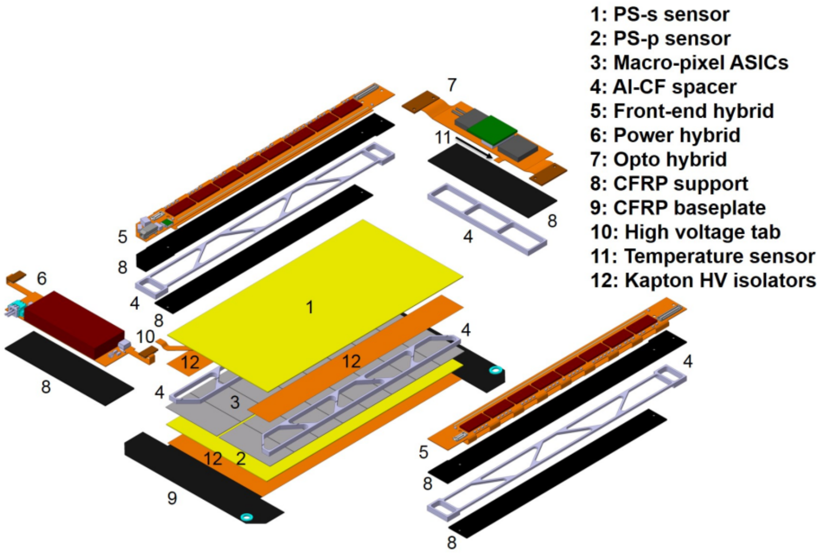
2S module

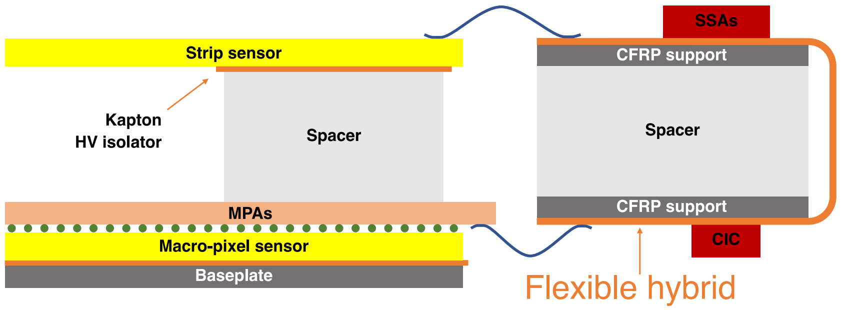




- Two 290 µm thick strips sensors;
- Strip size: 90 µm × 5 cm;
- Sensor area: ≈ 10 cm × 10 cm;
- CBC front end chip wire bonded to both sensors;
- Front end chip data collected by the CIC chip (one per side);

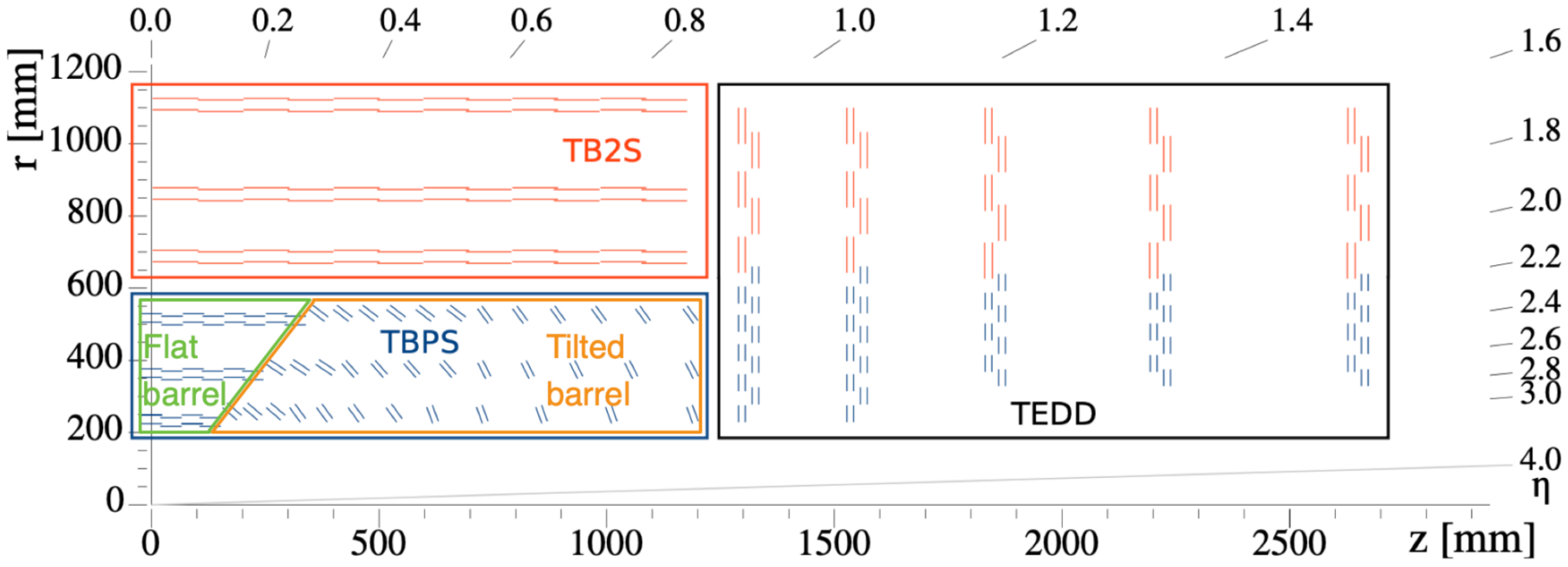
PS module





- One macropixels sensor and one strips sensor;
- Macropixel size: 100 μm × 1 mm; strip size: 100 μm × 2.5 cm;
- Sensor area: ≈ 10 cm × 5 cm;
- MPA front end chip bump bonded to the macropixel sensor;
- SSA front end chip wire bonded to the strip sensor;
- MPA receives from the SSA and sends to the CIC chip;

The Outer Tracker



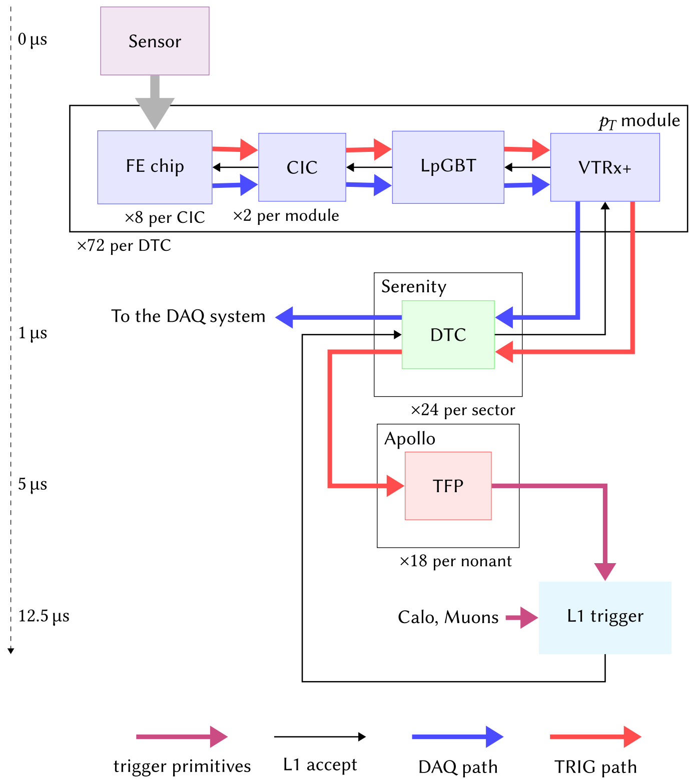
Orange: 2S modules; blue: PS modules.

Data path

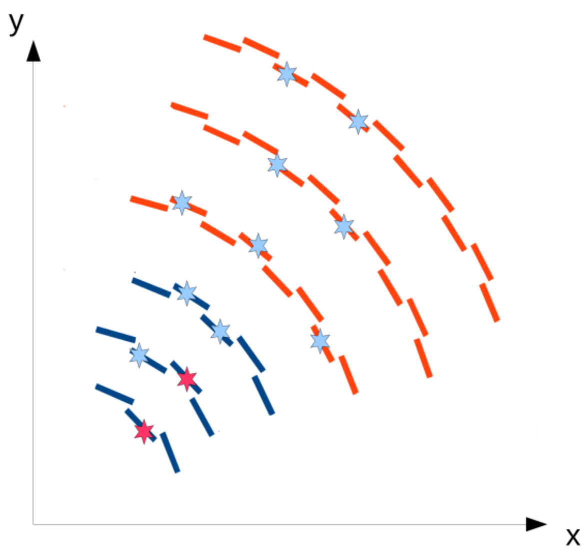
- 2 data streams:
  - Stubs: simplified data, sent at 40 MHz rate to build L1 Tracks primitives;
  - DAQ data: complete data sent when L1 trigger accepts the events (up to 750 kHz rate).
- DAQ data are stored in the Front End chips into 512 events deep pipelines;

9 independent processing regions in ϕ. *Data acquisition, Trigger and Control* (DTC) boards send

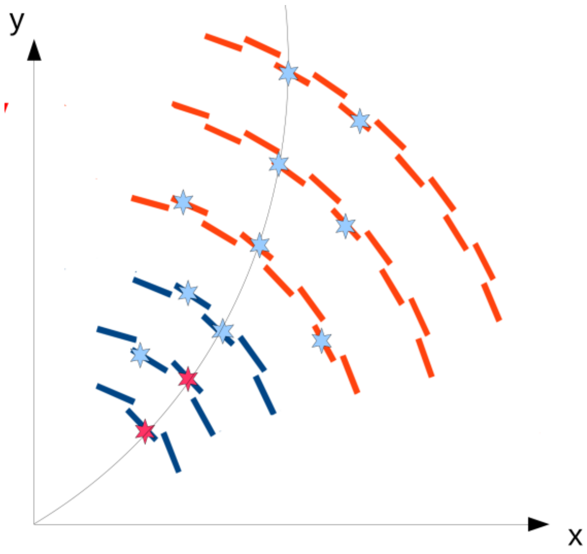
- L1 data to the *Track Finding* (TF) boards;
- DAQ data to the *DAQ and Timing Hub* (DTH) boards.



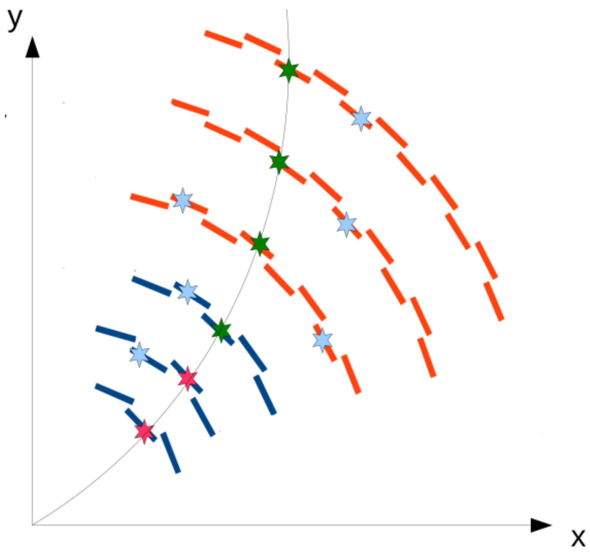
L1 Tracking: the tracklet algorithm



Seeding: doublet of stubs in different layers are used to build a track seed (assuming prompt tracks).



Projecting: using the seed, expected stubs positions for other layers are computed.

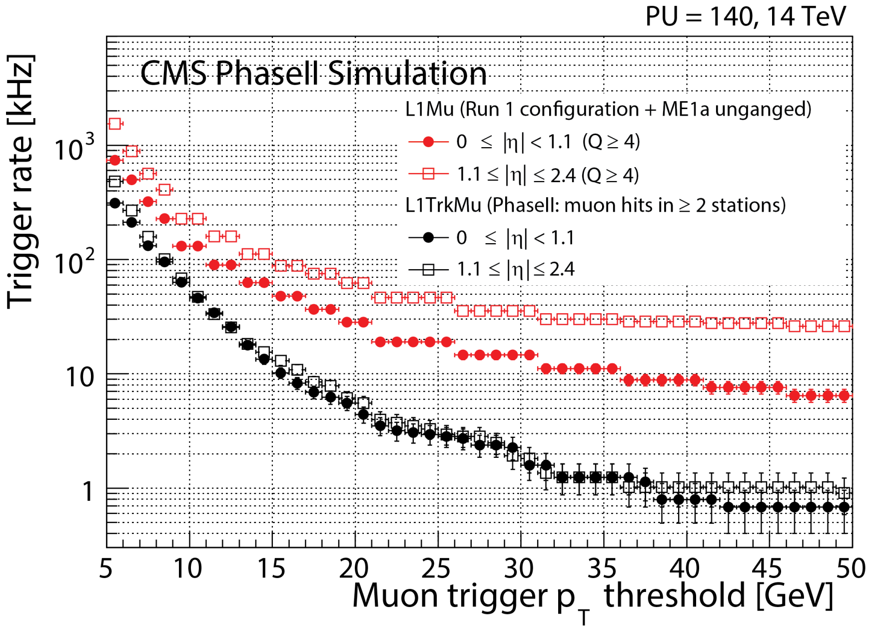


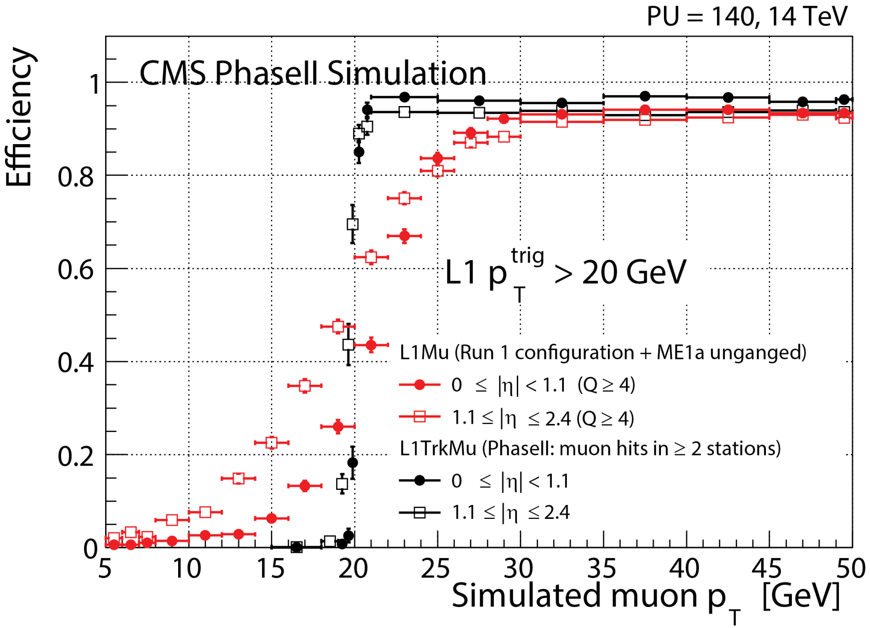
Matching: if stubs are found where expected, the track candidate is accepted.

Kalman filter fit + quality BDT applied to accepted tracks → precise track parameters estimation + enhanced purity.

The effect of L1 Tracking on overall L1 trigger performance

Is sensible!





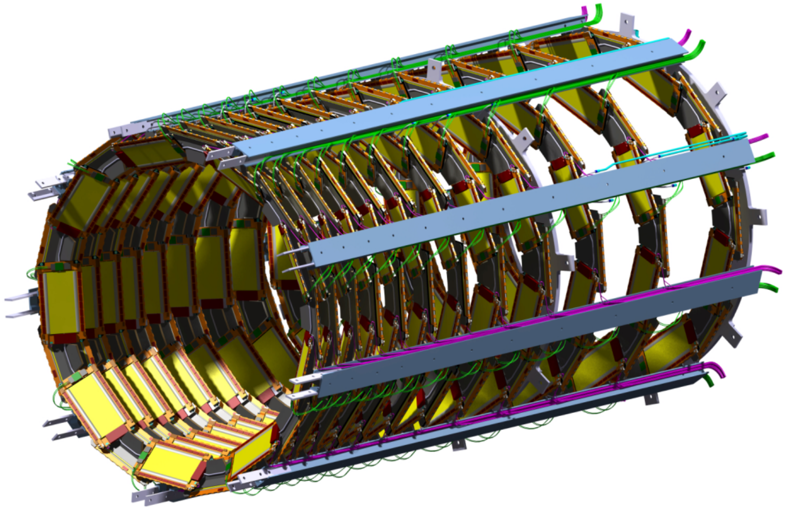
[CERN-LHCC-2015-010]

p_T modules in the wild

Activities in Pisa

INFN section of Pisa is a *burn-in* and *integration* site: PS module are

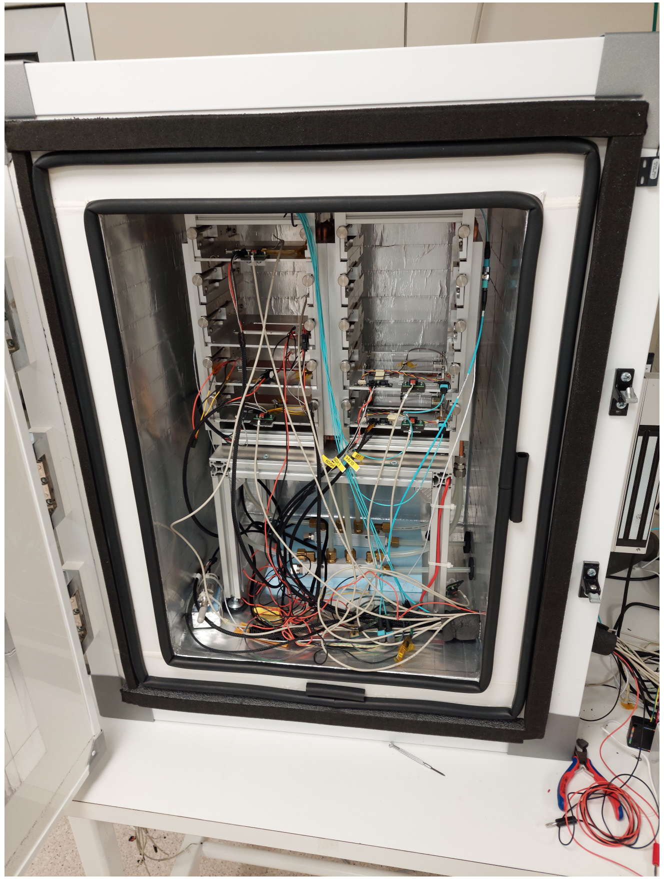
- Received from *assembly* sites (Bari and Perugia) and burn-in tested;
- Integrated in tilted rings and sent to CERN for Tracker integration.[1]



[1] FNAL is an assembly, burn-in and integration site.

Burn-in Box

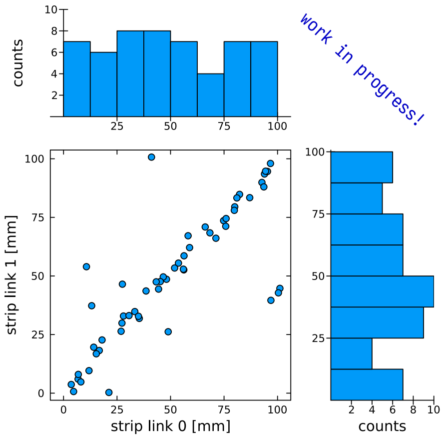
- Developed @ FNAL → at least one for each site;
- Thermal and light insulation for module testing;
- Provides power for FE electronics, HV for sensor (over)depletion, cooling, dry air and optical readout for up to 10 modules;
- Key step in the module qualification;
- $\mathcal{O}(100)$ thermal cycles (room temperature ↔ Phase II cooling temperature $= -35\ ^{\circ}$C) to test the module mechanics and electronics;
- But why limit to these tests?
  We can use it as a cosmic rays telescope!

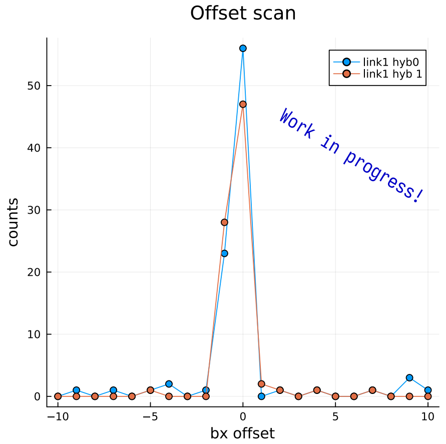


Burn-in Box as a cosmic rays telescope

The self-triggering nature of stubs allowed us to modify readout board firmware to acquire cosmic rays. [Indico 1389895]

- Opened new possibilities to test more aspects of the modules: timing alignment, modules alignment, efficiency, ...
- Still a work in progress.



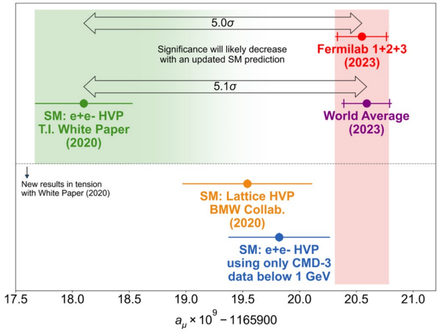


p_T modules outside CMS: the MUonE experiment

The physics of muon $g-2$ in a nutshell

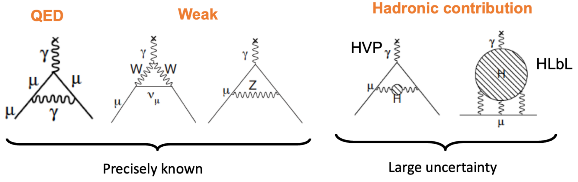
- In 2023, Fermilab Muon $g-2$ Experiment published the most precise measurement (0.20 ppm) of the positive muon anomalous magnetic moment a_μ; [arXiv:2308.06230]

- Experimental result in tension with SM prediction!

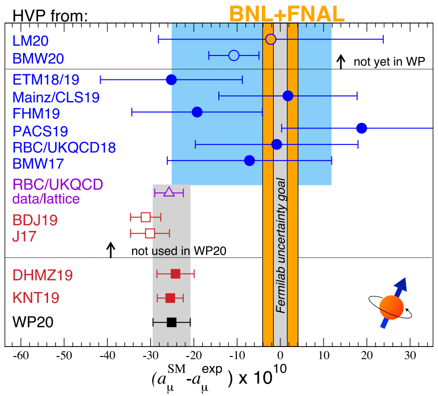


[WIFAI 2024]

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{QCD}$$



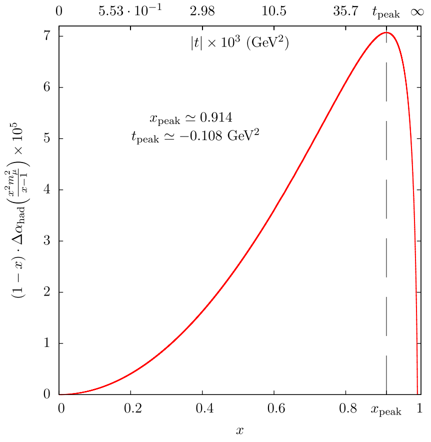
[arXiv:2311.08282]



[arXiv:2203.15810]

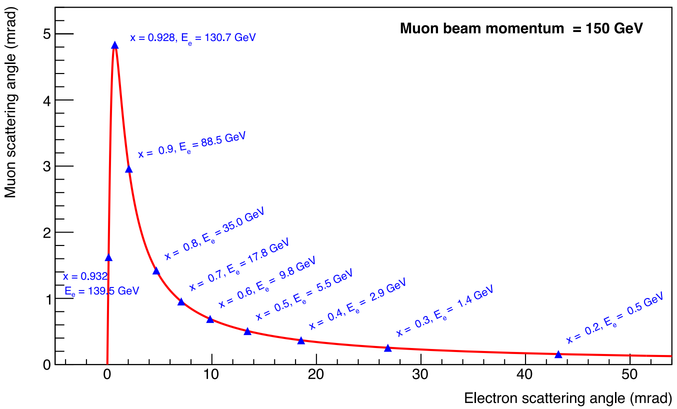
Determine a_μ^{HVP} using $\mu e \to \mu e$ elastic scattering

$$a_\mu^{\mathrm{HVP}} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\,\Delta\alpha[t(x)], \qquad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$



[SPS-I-252]

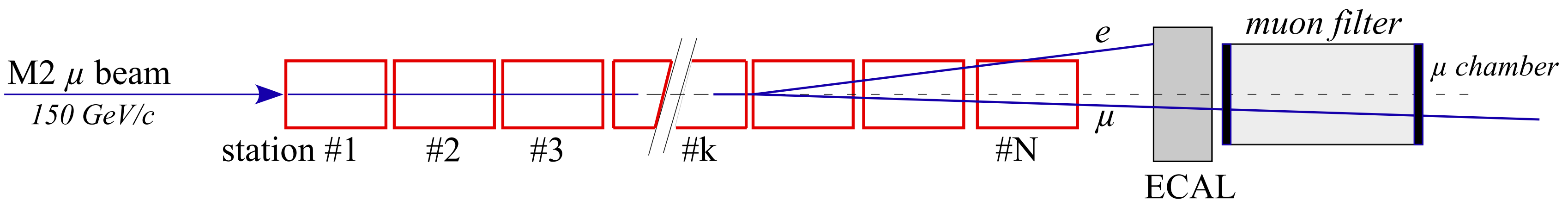
$$\frac{d\sigma_{\mathrm{el}}}{dt} \longleftrightarrow \frac{d\sigma_{\mathrm{el}}}{d\theta}$$

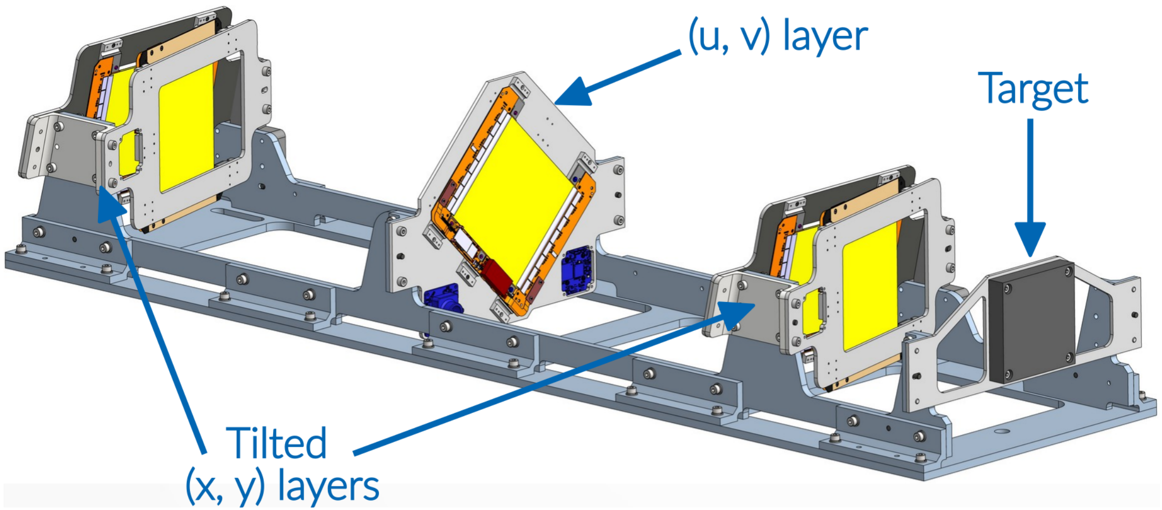


[SPSC-P-370]

We want to measure $\Delta\alpha$ at 10 ppm → we need excellent tracking → 2S modules!

MUonE tracking station

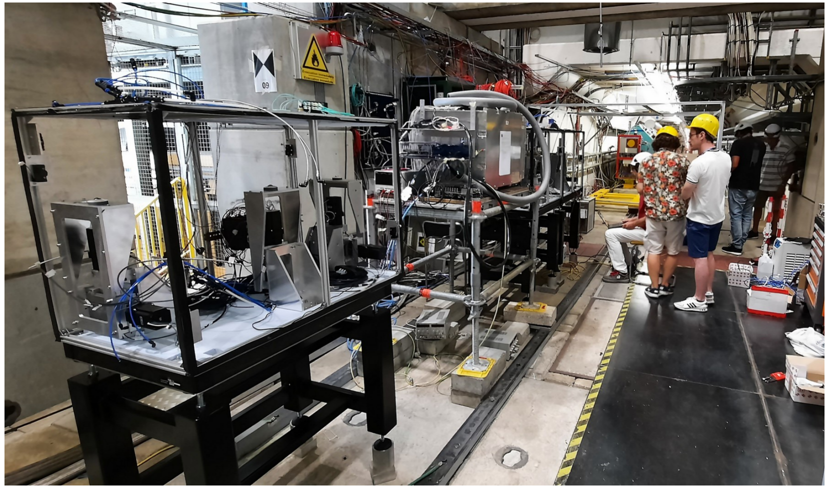


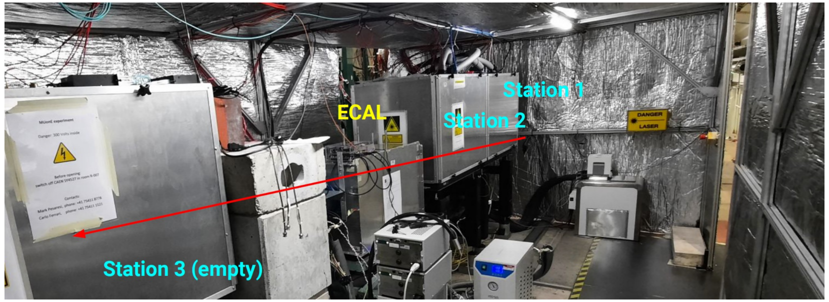


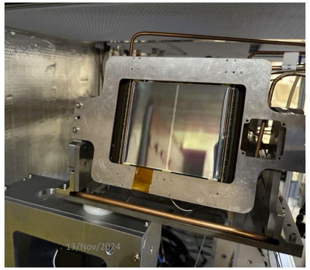
- Low thermal expansion coefficient INVAR frame to improve position stability;
- Tilted modules to improve spatial resolution by charge sharing between adjacent strips;
- U,V modules to solve reconstruction ambiguities;

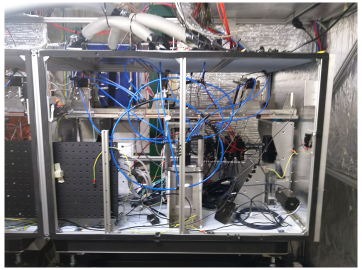
Stubs readout at 40 MHz and online event building (+ online tracking and vertexing! [BTTB12])

2023/24 test beam campaigns





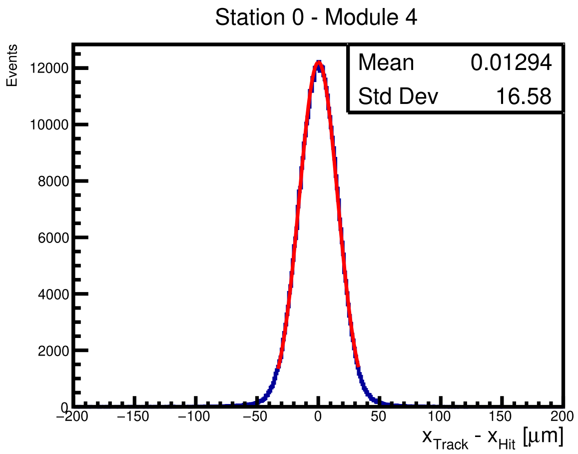




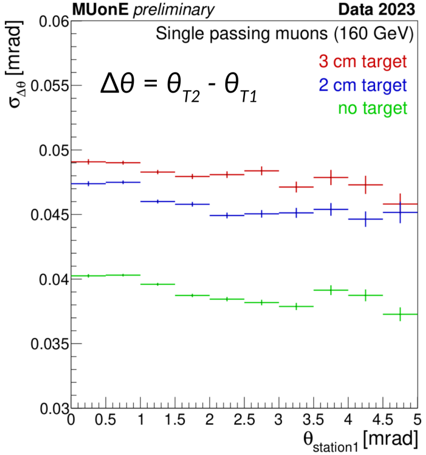
- MUonE Test Run at CERN North Area (M2 beam);
- 2×10^8, 160 GeV muons per 5 s spill;
- 2/3 cm graphite target between the two tracking stations;
- $\mathcal{O}(300\,\text{TB})$ of track+calo data saved to disk $\rightarrow$ $\mathcal{O}(3\times10^8)$ elastic scattering events.

Test beam preliminary reults

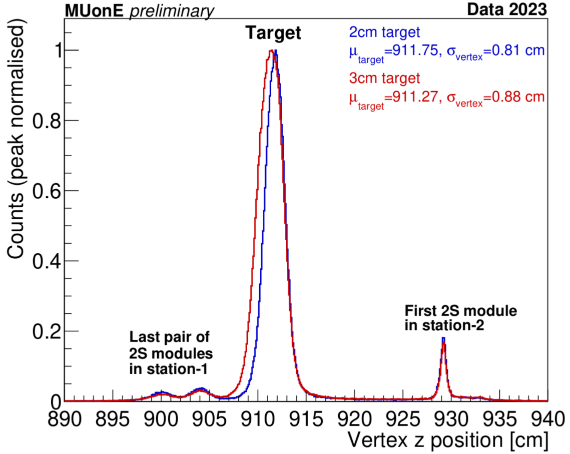
Tracker performance in line with the expectations.



Residuals of the hit in 2S module w.r.t. the fitted track expected hit position.

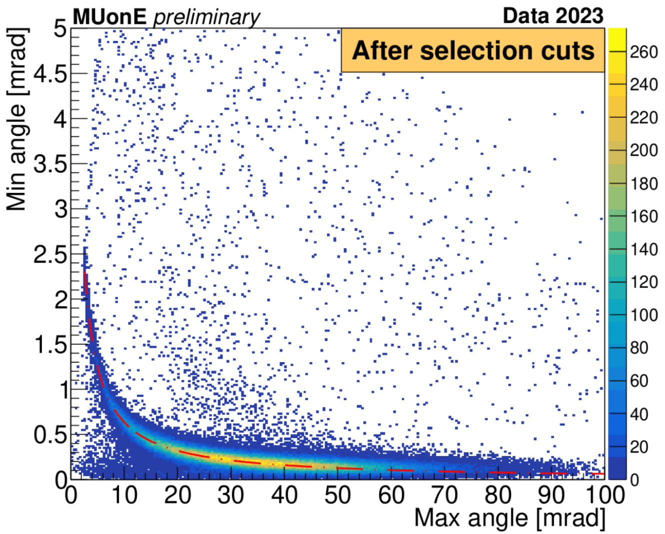


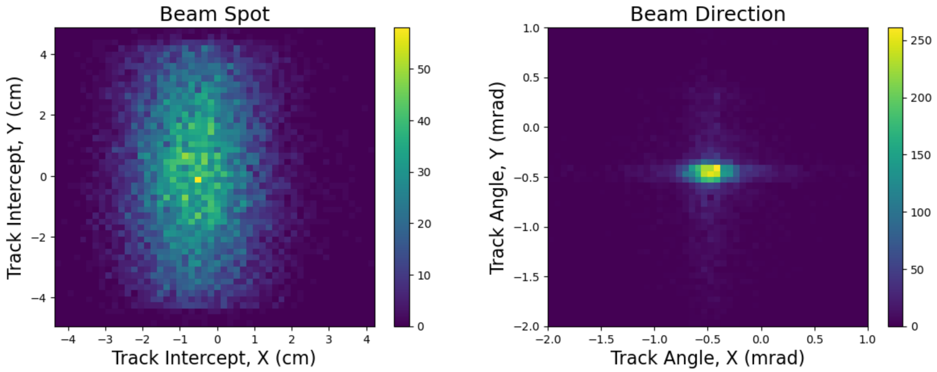
Standard deviation of the distribution of the difference of track direction in the 2 stations.



Vertex z postition for tracks in the second station.

Test beam preliminary reults





This with online tracks!

Phase 1 proposal submitted: aim to request 4 weeks of data taking in 2025.

Conclusions

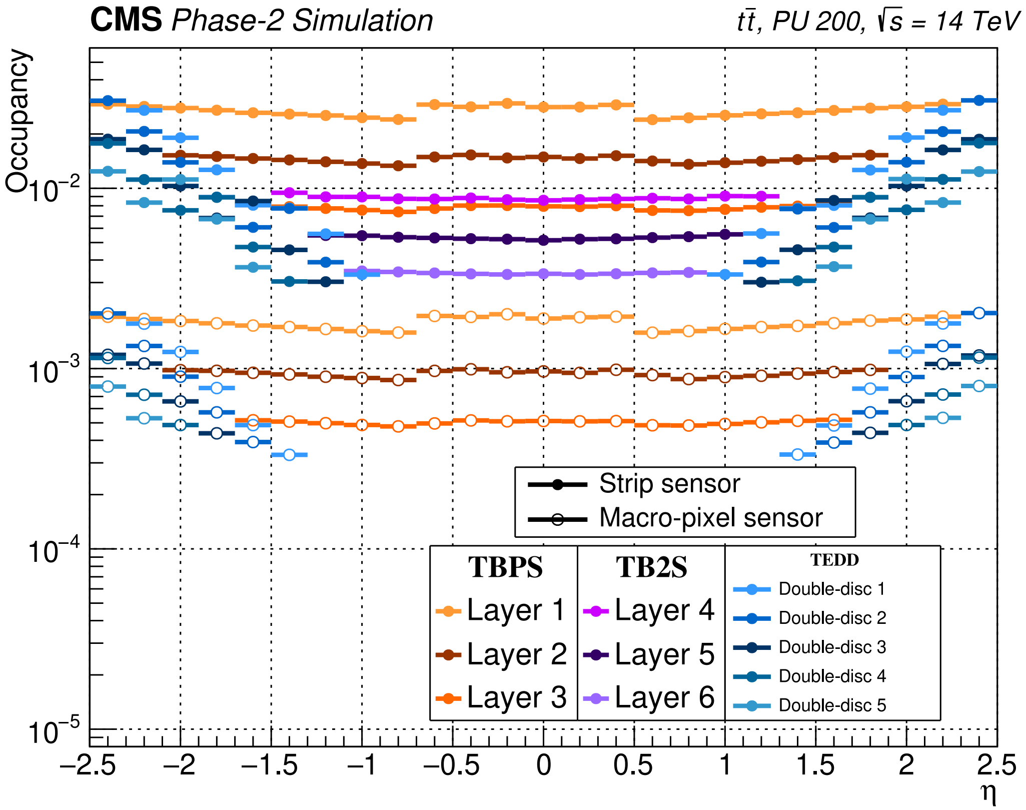
Answers!

- Why do we need a new tracker? To do high precision physiscs even in the more harsh HL–LHC environment!
- What do we want from this new tracker? High granularity, less material, L1 tracking.
- What are the p_T modules? Two silicon sensor layers with a common readout.
- Why the p_T modules? To reduce the data transmission rate.
- Are we really building them? Yes!
- What are they good for? Lot of stuff! Including self–triggering cosmics setups.
- What is MUonE, btw? A new experiment that aims to determine a_μ^{HVP} using 2S modules as tracking modules.

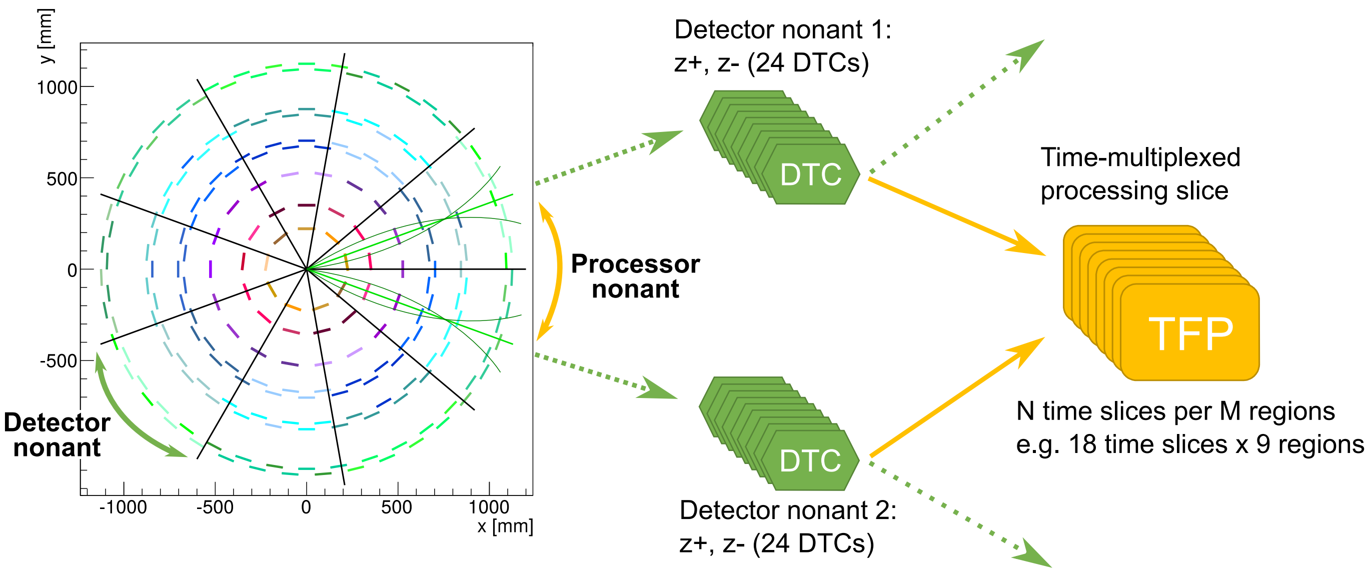
Thank you!

Backup

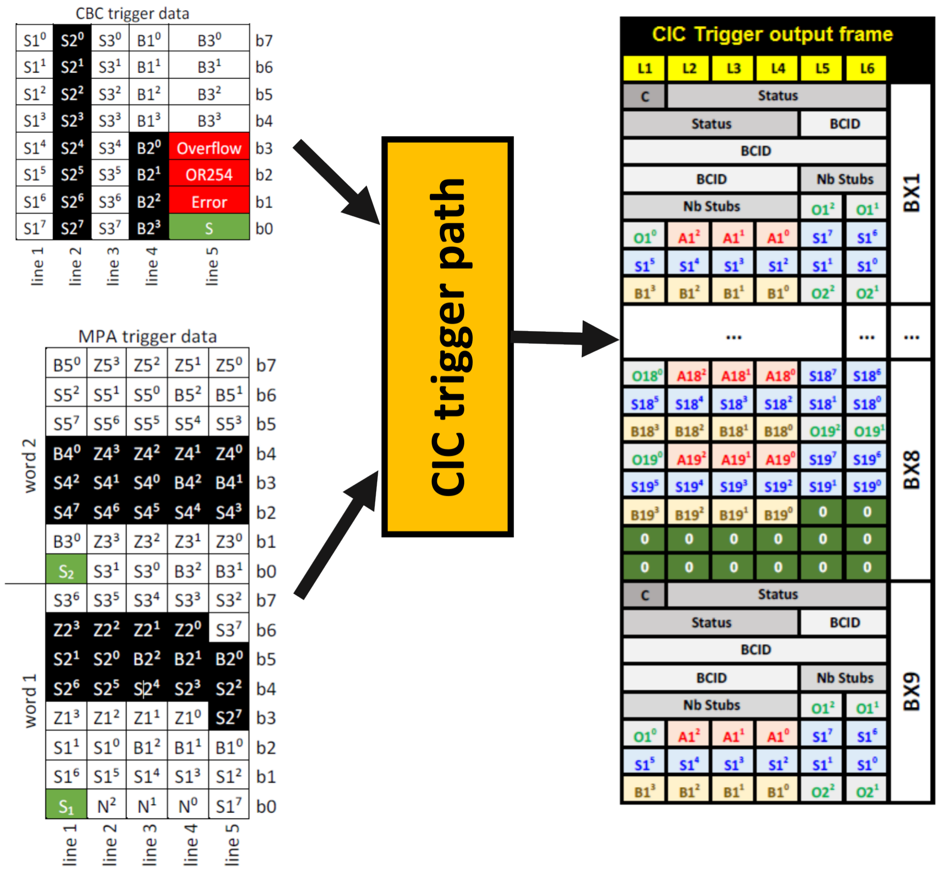
Channel occupancy



Tracker readout sectors

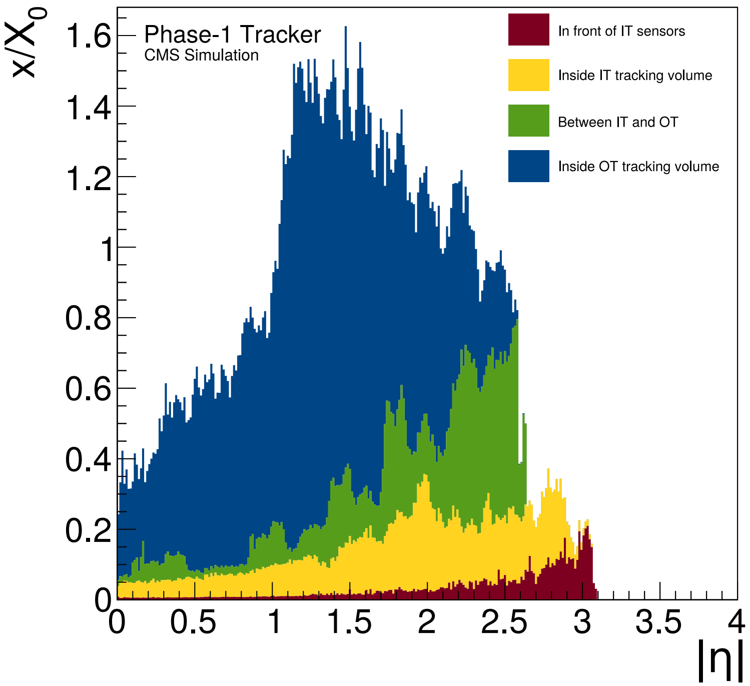


Stub data format

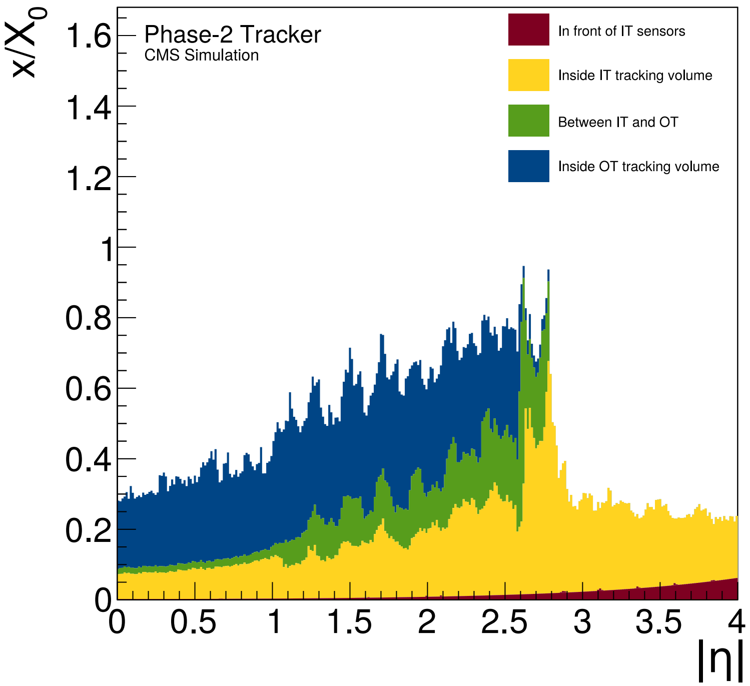


[Indico 688153]

Material Budget

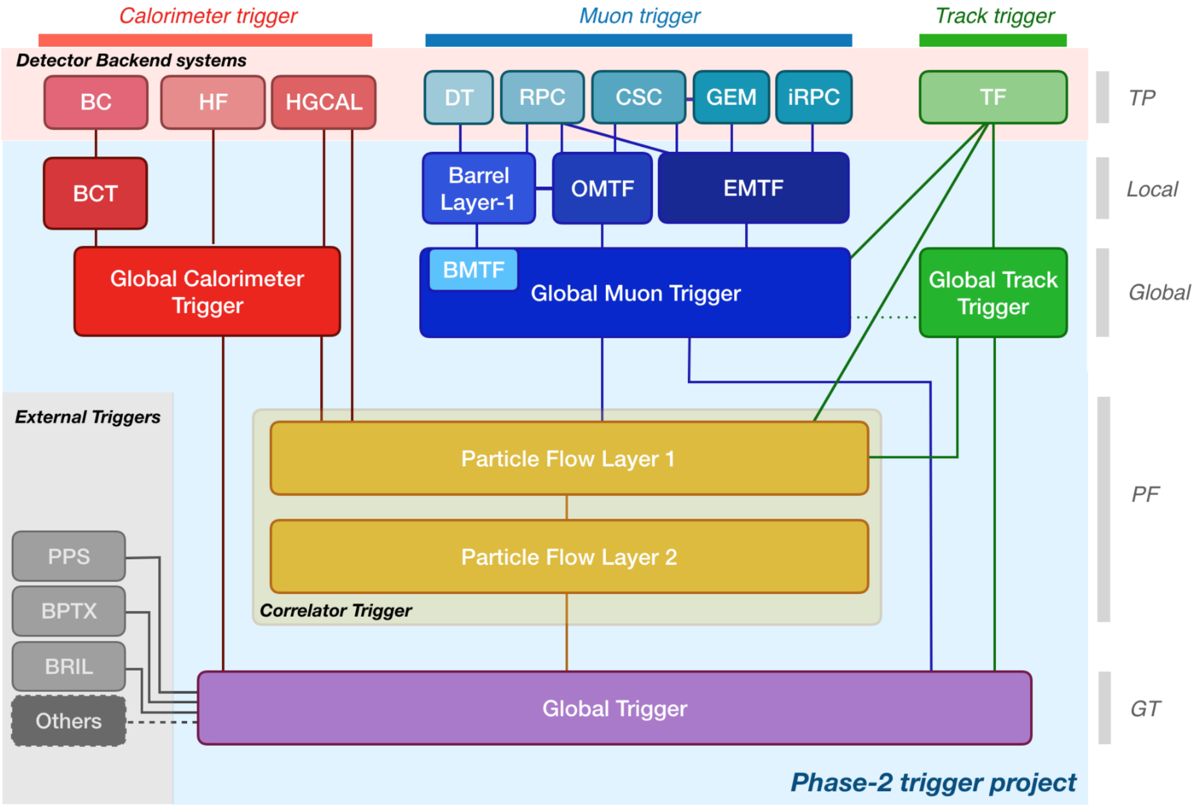


Phase I



Phase II

Phase II L1 Trigger architecture



[CERN-LHCC-2020-004]