Commissioning and study of a CMS 2S module with 40MHz readout

Martin Delcourt on behalf of the joint CMS Tracker Group-MUonE test beam analysis group

15th of April 2024

12th Beam Telescopes and Test Beams Workshop

CMS tracker upgrade

- The CMS silicon strip tracker will be undergoing a major upgrade for the High-Luminosity LHC

Now

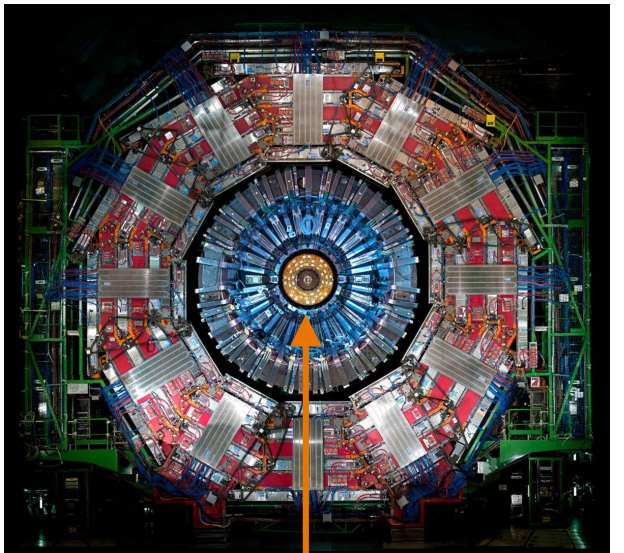
$$\mathcal{L}_{peak} \sim 2 \cdot 10^{34} cm^{-2} s^{-1}$$
$$\langle PU \rangle_{peak} \sim 60$$

~ 2030

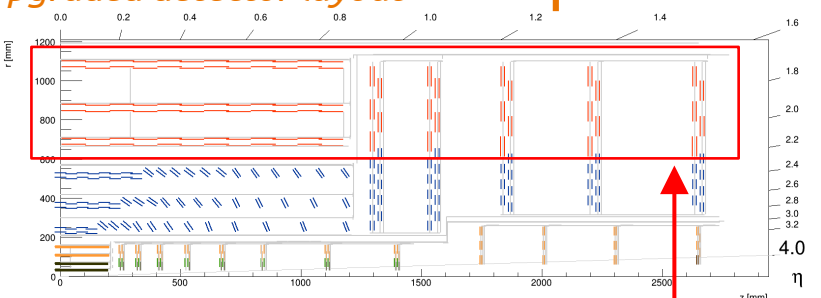
$$\mathcal{L}_{peak} \sim 5 - 7.5 \cdot 10^{34} cm^{-2} s^{-1}$$
$$\langle PU \rangle_{peak} \sim 140 - 200$$

- The goal is to maintain its outstanding performance under
  - A higher **instantaneous** luminosity
  - A higher **integrated** luminosity
- Main requirements of the new detector
  - Improved granularity
  - Radiation hardness
  - Participate in L1 trigger decisions

Current CMS detector



Upgraded detector layout

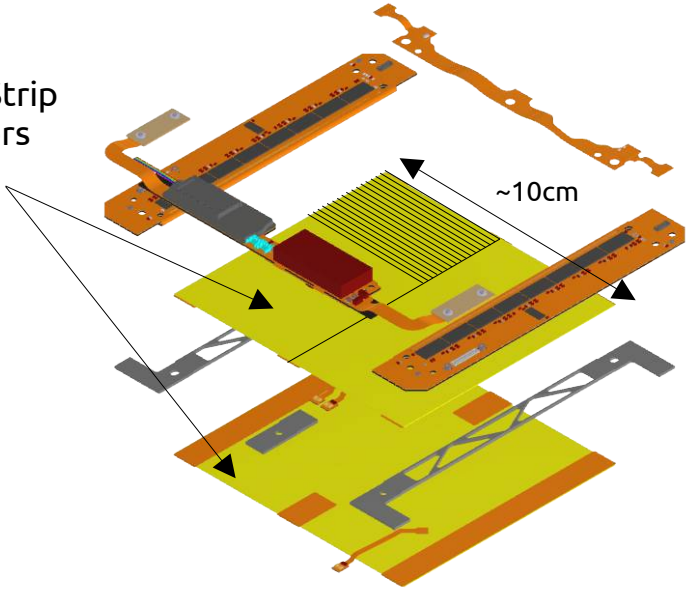


Modules for this talk

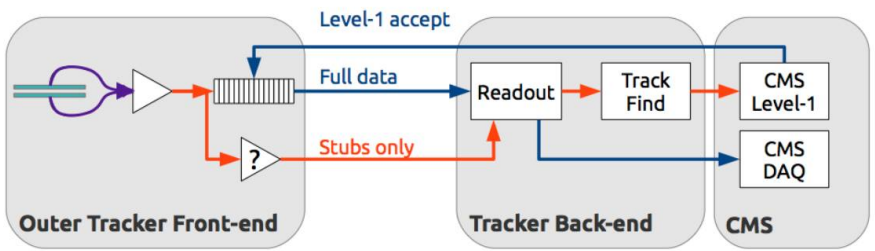
More info in the Tracker upgrade TDR

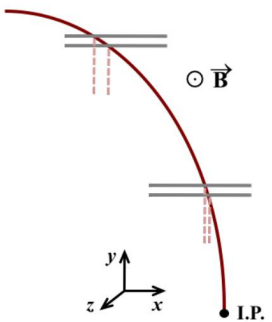
2S modules

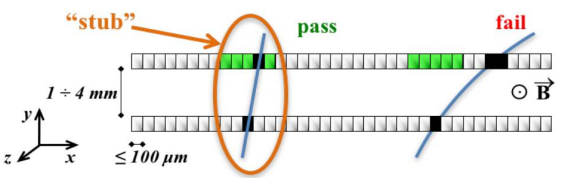
- The outer-layers of the upgraded detector will be populated by "**2S**trip **modules**"
  - Two 320μm silicon strip sensors
    - → 2 rows of 1016 90μm x 5cm strips each
  - Binary read-out
  - Sensor correlation to select "**stubs**" compatible with high transverse momentum particles



- Two simultaneous data-streams
  - Stub read-out at the full 40MHz rate
  - Full data read-out at up to 750kHz





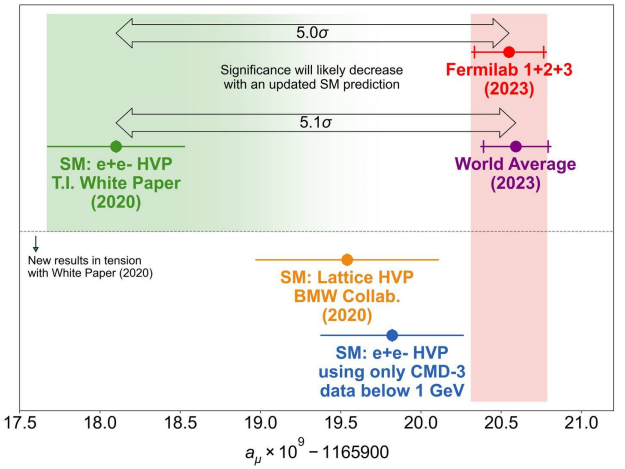


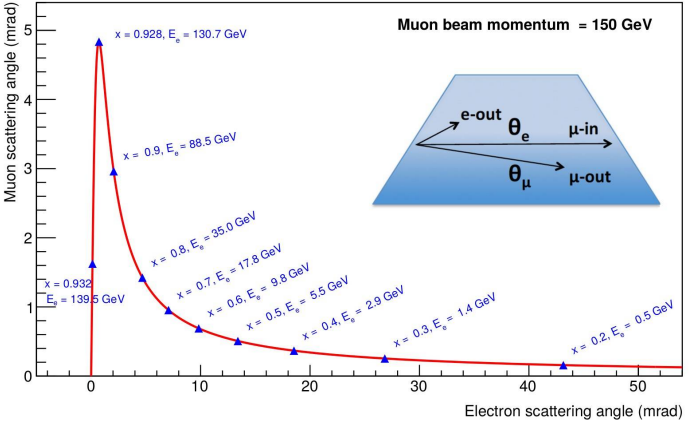
2GeV cut → ~10x data reduction

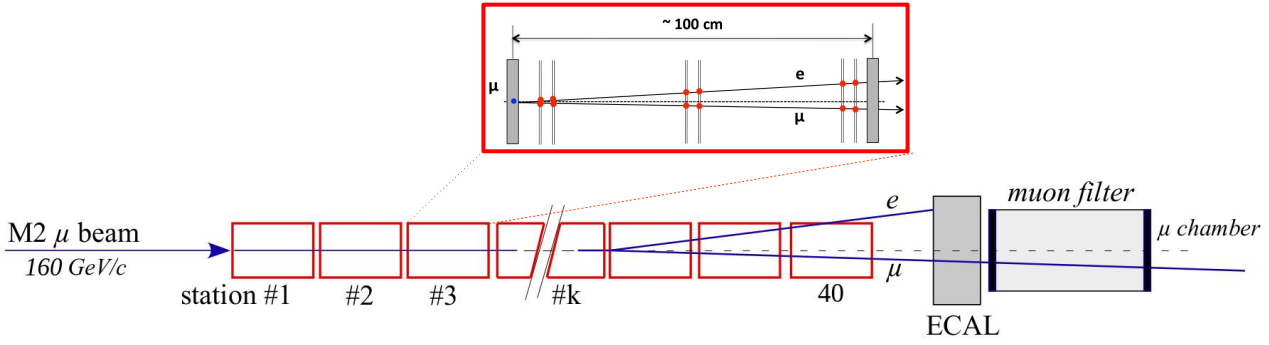
More info in the Tracker upgrade TDR

MUonE experiment

- The **MUon ON Electron elastic scattering** experiment (**MUonE**) is proposing an independent evaluation of a_μ^{HLO}
  - Longstanding tensions in muon anomaly $a_\mu = \frac{g-2}{2}$
    - Theoretical prediction limited by leading-order hadronic contributions
  - A precise measurement of the shape of the eμ → eμ cross section allows the extraction of $\Delta\alpha_{\rm had}(t)$
- The experiment would use the SPS M2 beam at CERN
  - 40 tracking stations with a target and 6 detector planes
  - Calorimeter and muon filter for particle identification







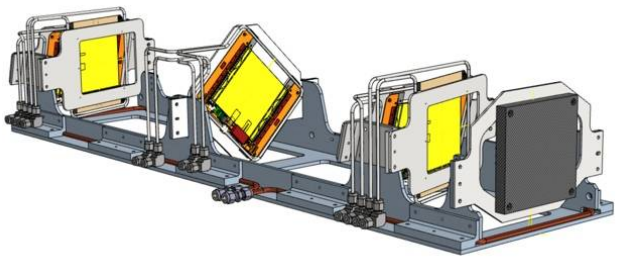
More info in Phys. Scr. 97 (2022) 054007

Synergies between CMS-TK and MUonE

- 2S modules seem like a great choice as tracking detectors
  - High granularity
  - Low material budget
  - Stub stream sufficient to record all events

Memorandum of Agreement
for the execution of the MUonE Test Run
between the
CMS-Tracker Group (CMS-TK)
and the
MUonE Collaboration (MUonE)
collectively named the Signatories

- Valuable for the CMS Tracker Group
  - Allows for DAQ & Commissioning tests of a “slice” of the detector
  - First results using 2S modules

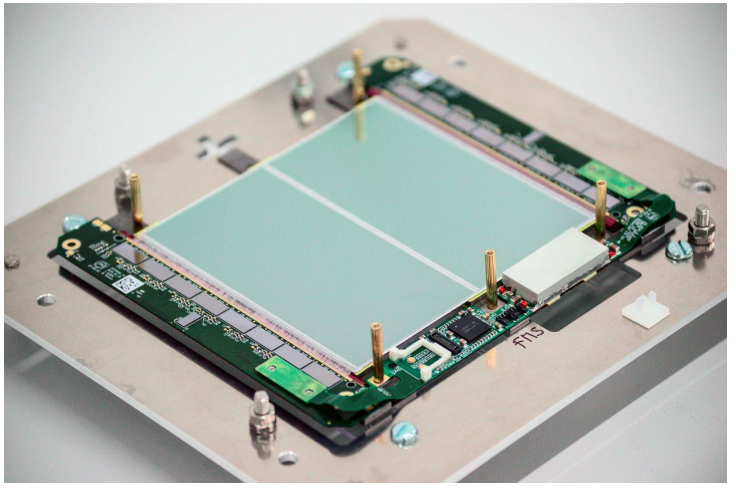


- Extends physics impact using existing module production lines

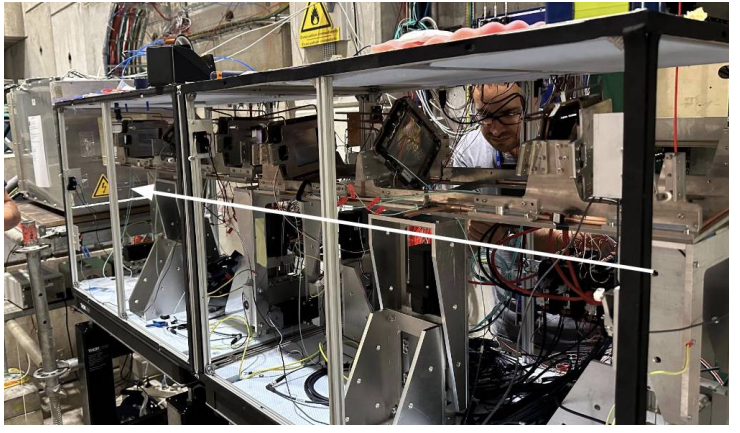
- Some key differences:
  - Stub stream used as analysis data, not only for triggering
  - Very different geometry and beam properties
  - **Beam in M2 is asynchronous, while in-time at the LHC**

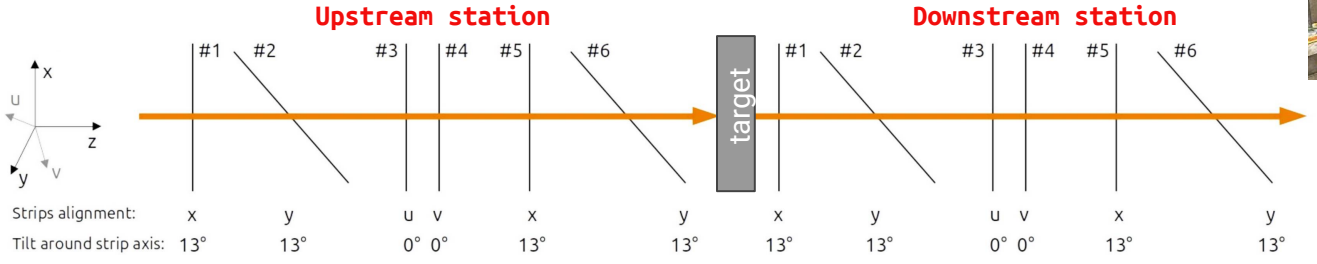
Beam tests

- A series of test runs were carried-out
  - Up to twelve prototype 2S modules in two stations
  - Either perpendicular to beam, or at a 13° tilt to maximize charge sharing
  - “x,y” orientation, or rotated 45° in “u,v” orientation



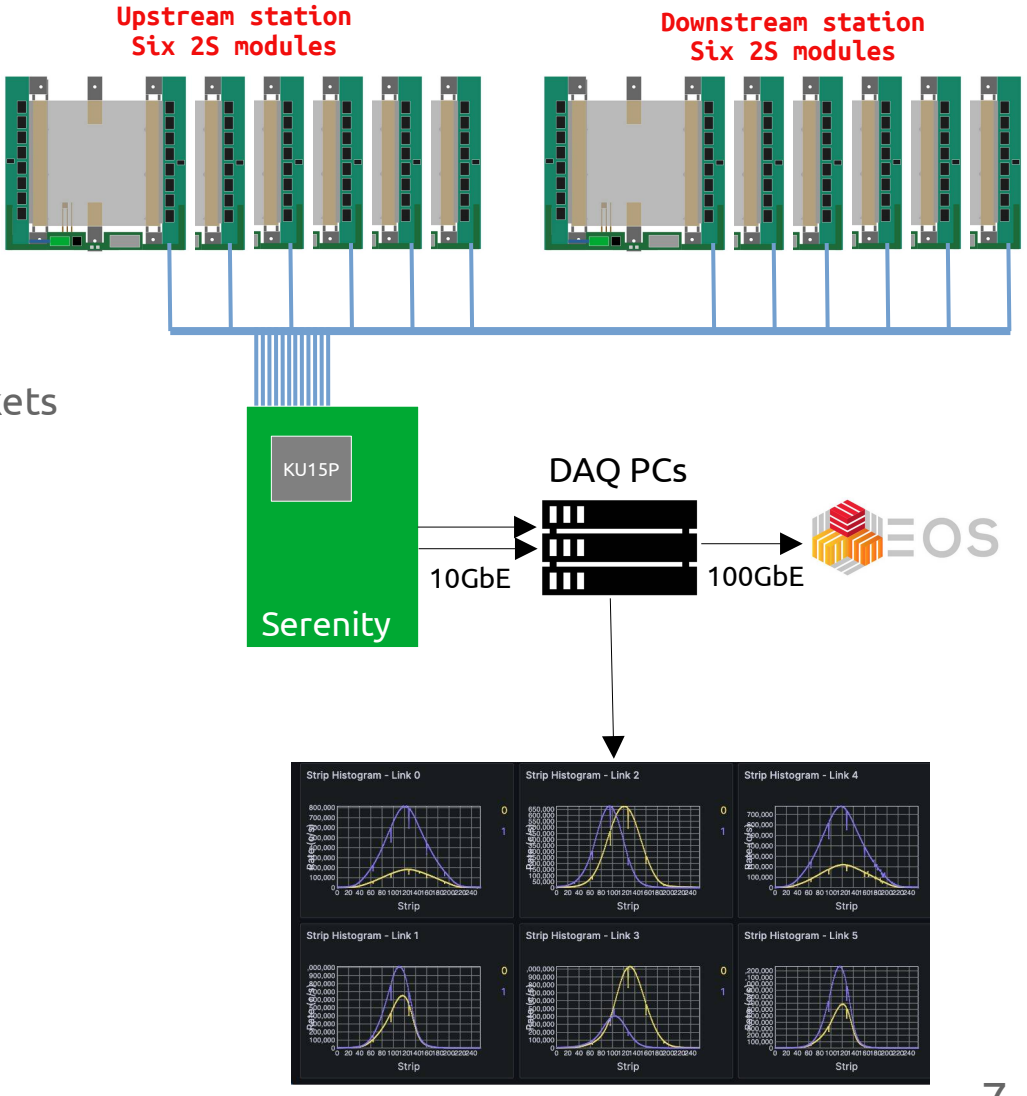
- Beam used
  - 160 GeV muons
  - In spills of a few seconds, asynchronous
  - Average rate of up to ~1 muon every 25ns





Read-out

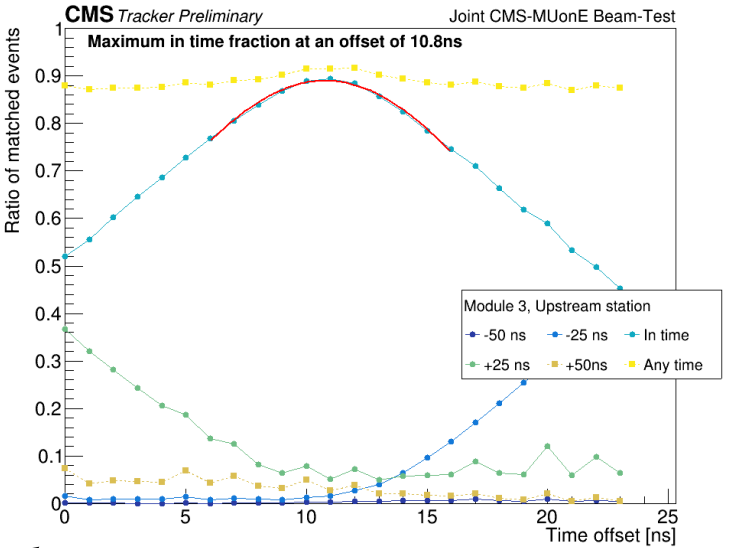
- Front-end electronics:
  - Generate hits from signals crossing thresholds within 25ns bins
  - Two sensors combined to generate stubs
  - Each module side aggregates stubs in 200ns packets
  - Module read out by a single optical fiber pair
- Acquisition boards:
  - Serenity boards with KU15P FPGA
  - Up to 36 optical links (12 used)
  - Multiple 10GbE links to DAQ (2 used)
- DAQ computers:
  - Buffering, packaging, DQM, shipping
  - Direct 100GbE connection to EOS



Commissioning – Timing scan

- In order to operate optimally, the module timing is tuned
  - To be **in time** with particles **at the LHC**
  - To be **synced** with other modules **in M2 beam**

- The internal module clock can be offset in steps on 1ns
  - Scanning all modules but the first, used as reference
  - Looking at **events with a single stub in reference**, isolated in time
  - Computing fraction of events with **a stub measured in given module**

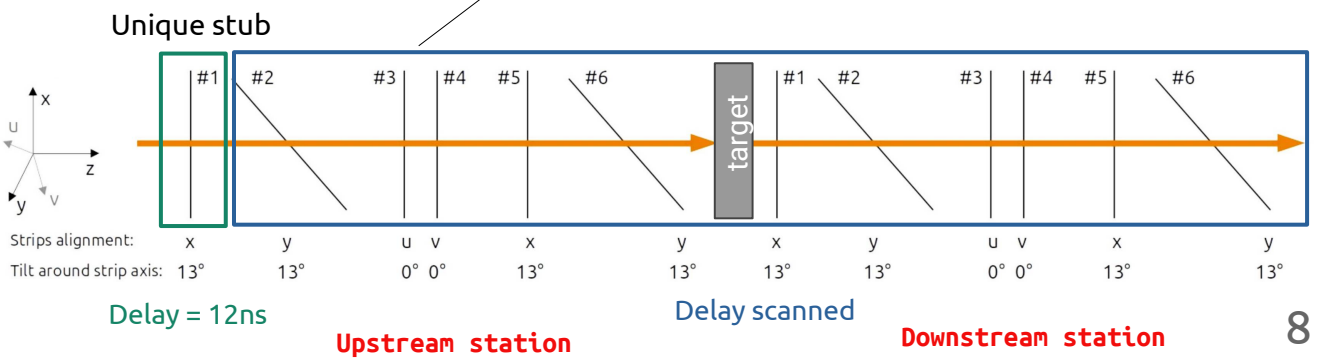


Probability of seeing a stub

A single scan gives us all timing offsets

The ratio of matched events is impacted by timing even for "Any time" selection (yellow)

→ **Time induced inefficiency?**

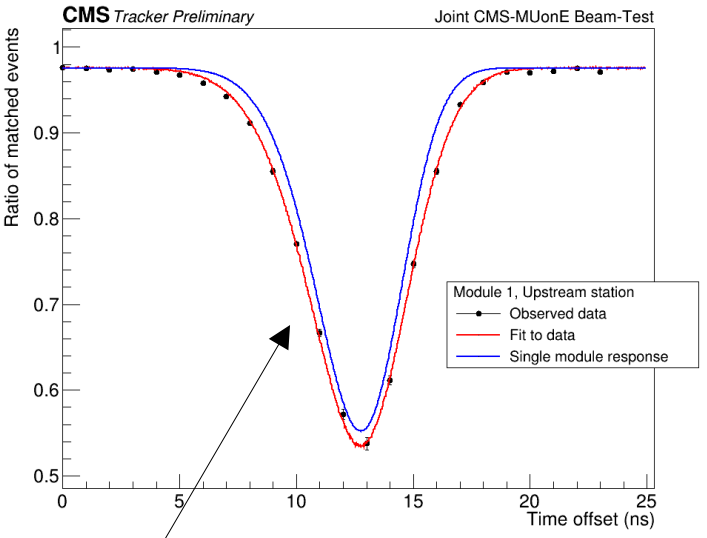


Commissioning – Timing scan

- Why do we see less stubs when modules aren't synced?
  - Modules configured to generate hits when signal crosses threshold
    → **Hits generated in different time bins will not create stubs**
    → **Time walk and noise will generate inefficiencies**
  - *In this configuration*, we expect **dead-time at the 40MHz clock edges**
    → Caused by internal hit detect logic
- This was measured directly
  - Selecting events with a stub in modules 2 & 3 with $\Delta t = \pm 25\text{ns}$
    → Selceting particles passing near the clock edge
  - No other module sees more than one stub
- Single module response extracted from simulation
  - Toy MC assuming all modules identical
  - Assumes time response modelled as error functions

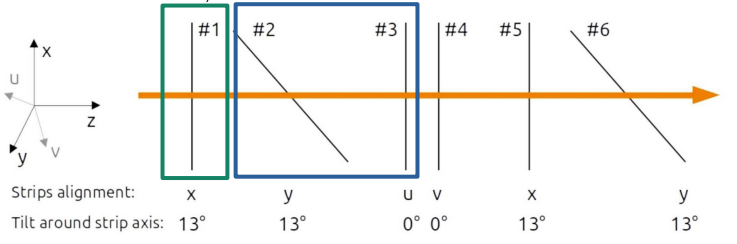
Useful for CMS to model out-of-time inefficiencies

Useful for MUonE to understand how to best configure and tune the modules



Probability of seeing a stub

Single stubs with $\Delta t = \pm 25\text{ns}$



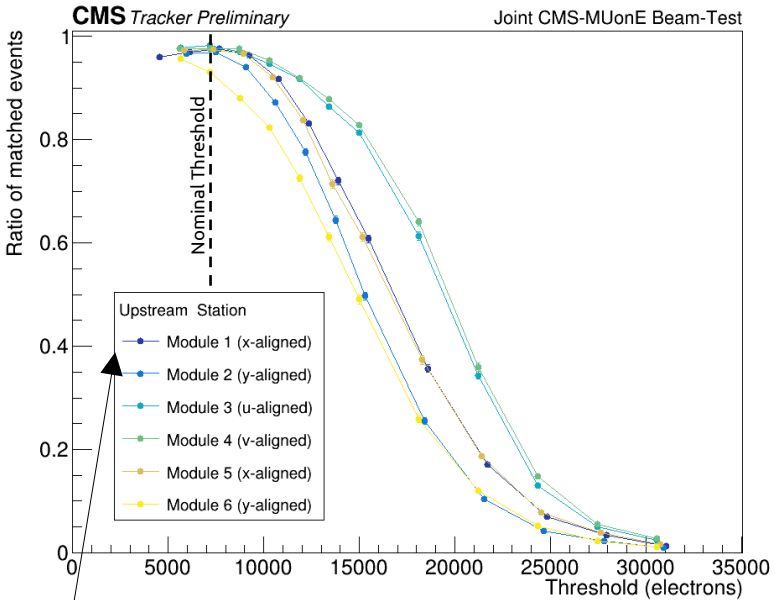
Delay = 12ns

Delay scanned

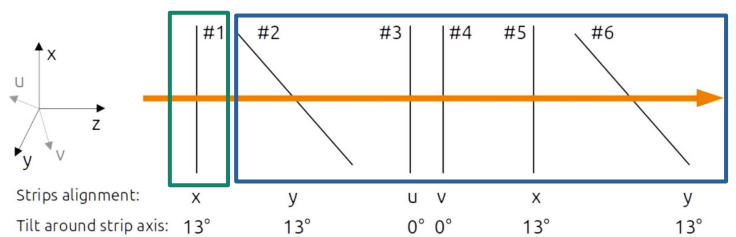
Upstream station

Commissioning – Threshold scan

- 2S modules are binary detectors
  - The charge threshold to generate hits has to be tuned
  - Most straightforward way: **maximise stub efficiency**
- Requires other modules to be used as reference
  - A single module can be scanned at a time…
    Twelve modules here, many more in final system
- For events with a single stub in all other modules
  - **Probability of seeing at least a stub in scanned module**



Probability of seeing a stub



Peak can be used to tune the setup

Modules grouped by geometry!

Acceptance effect and different angles leading to different charge sharing

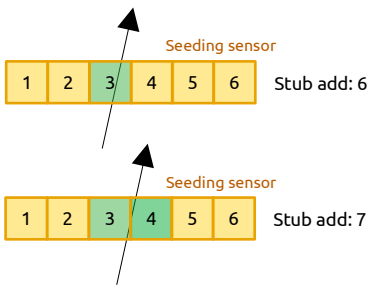
Threshold scanned

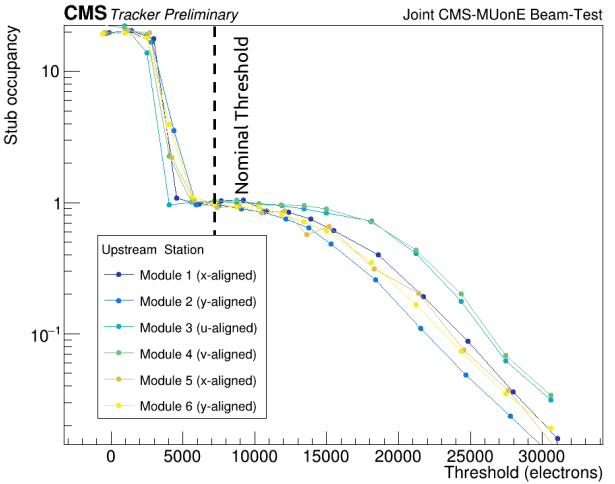
Nominal threshold

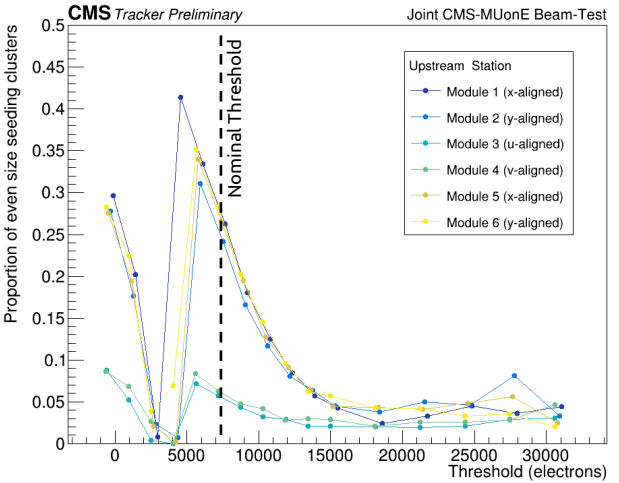
Upstream station

Commissioning – Threshold scan, alternative methods

- Other methods explored to tune threshold
- Stub occupancy used to determine lowest acceptable threshold
- *Stub parity* used to get ideal resolution
  - Stub address is the position, in half-strip units of seeding cluster
  - We can use this to know if the seeding cluster is of
    - Odd size : 1 or 3 strips fired
    - Even size : 2 or 4 strips fired
  - Ideal resolution when odd fraction = even fraction = 50%





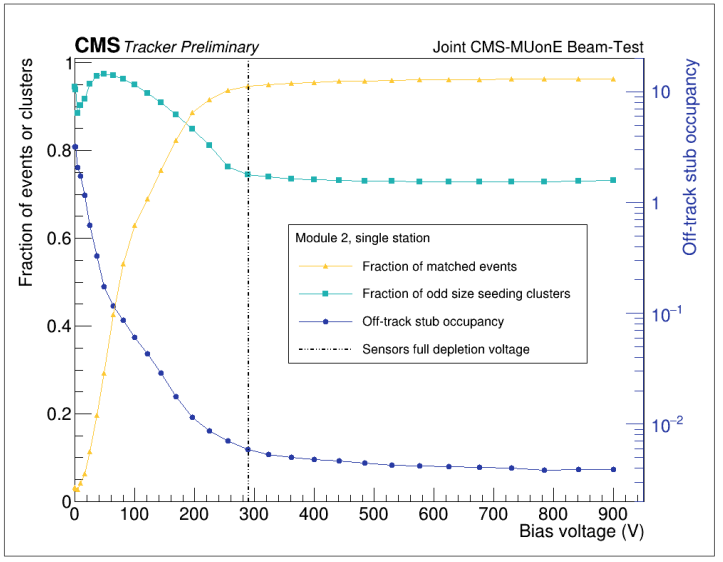


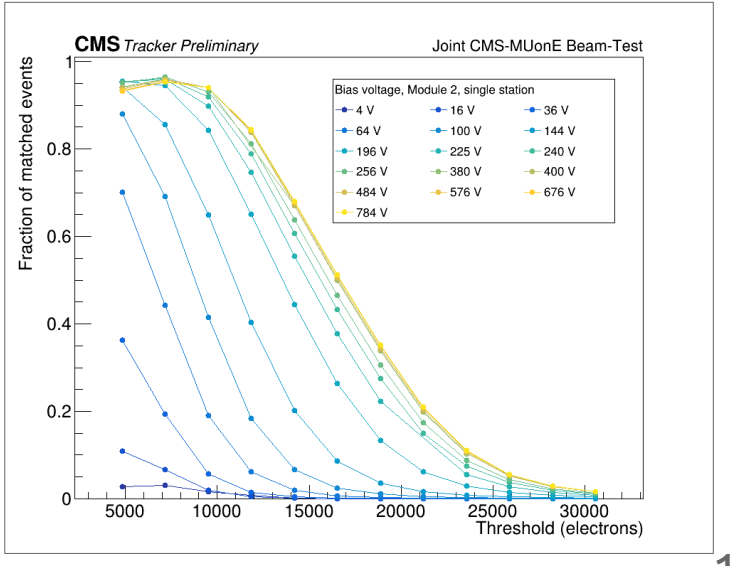
Three different ways to tune threshold

All yield similar values

Commissioning – Bias scan

- Similarly, bias voltage has to be tuned
  - Regularly required during operations to compensate for radiation damage
- Three observable assessed
  - Fraction of matched events
    - Bias → depletion depth → charge → detection probability
  - Off-track stub occupancy
    - Lower bias → higher bulk capacitance → higher noise
  - Fraction of odd seeding clusters
    - Higher bias → depletion → wider clusters → less single strip clusters
    - **Doesn't require other modules**
      → Can be done with a single slow ramp using stub stream
- Impact of threshold on bias scan
  - Threshold scans for different biases performed
  - Similar results for any bias bigger than the ~290V full depletion voltage





Conclusion

- The CMS Silicon Strip Tracker will be upgraded for the HL-LHC
- The MUonE experiment is proposing to use 2S modules to shed light on muon g-2 anomaly

- A joint beam-test campaign is underway
  - Great success for CMS:
    - **First full 40MHz readout of 2S modules in beam**
    - **Valuable test system to better understand detector**
  - Great success for MUonE:
    - **Very promising results from test run**
    - **Hints at possible better module configuration for this beam**
    - **Continuous progress in integration, DAQ, alignment, reconstruction …**
      - See Michael McGinnis poster on 40MHz track fitting Wednesday

- And much more to come!

More results from MuonE *here*


Thank you