The MUonE DAQ: Online Track-finding and Event Selection in Hardware at 40 MHz

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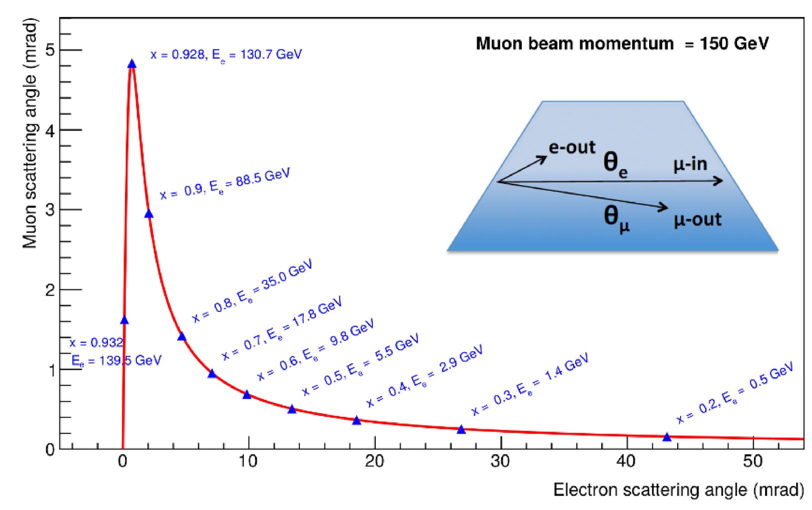
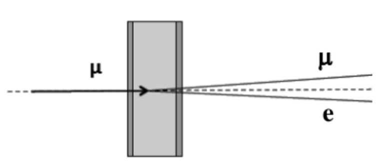
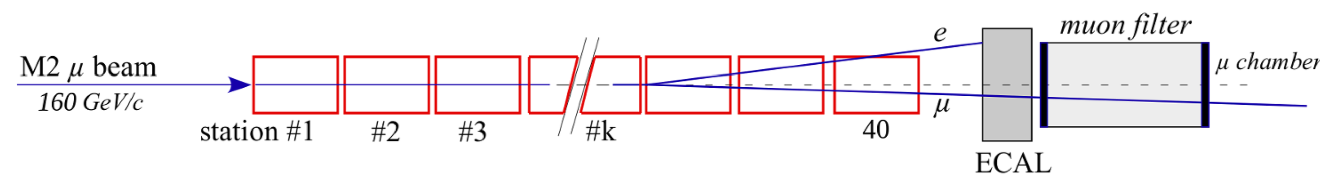
MUonE experiment

- Extraction of $\Delta\alpha_{had}(t)$ from the shape of the $\mu e \rightarrow \mu e$ differential cross section [1, 2]
- Compute a^{μ}_{HLO} using data from one single experiment.
- proposed at CERN using the M2 muon beam on fixed target electrons [3].
- The correlation between muon and electron angles allows for selection of elastic scattering events and rejection of background (μ N → μ N e+e-).
- Tracking system: 3 pairs of silicon strip detectors (CMS Phase-II 2S modules[4])



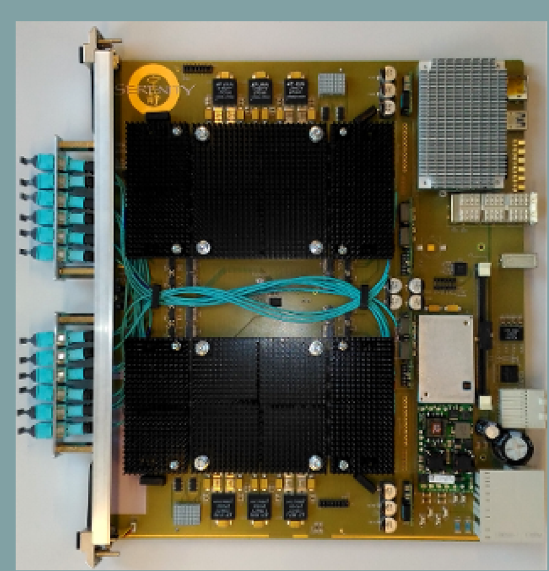


$$= \frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}}=0)} \sim 1 + 2\Delta\alpha_{\mathrm{had}}(t)$$



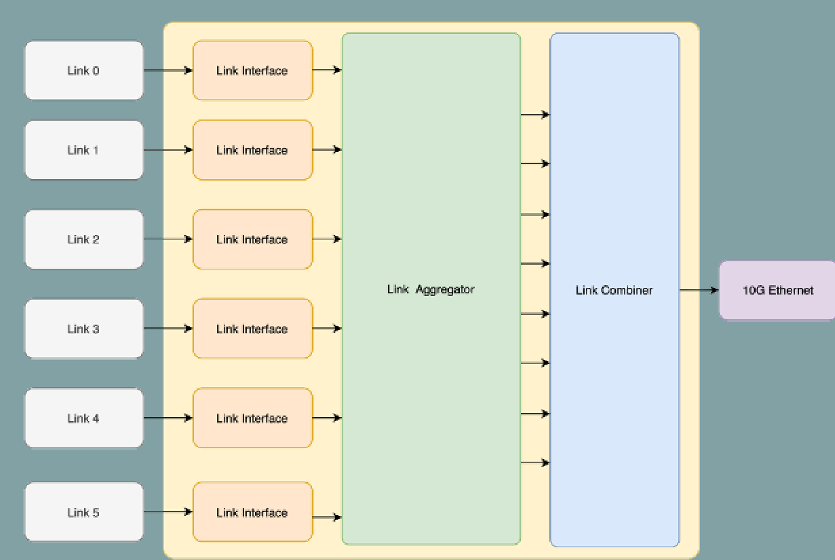
Hardware

- Ingestion of data and configuration of modules is handled by the Serenity [5] card
- Prototype ATCA-class processing card developed for CMS Phase-II upgrade
- Generic, composed of up to 2 AMD-Xilinx Ultrascale+ FPGAs and 144 optical transceivers for I/O
- Also includes a System on Module (SoM) for management (Intel i5-based CoM-Express)
- Data transferred onward via 10 Gbps ethernet links to commercial PCs
- PCs consolidate and chunk the data, before transfer to EOS for long-term storage and analysis
- Direct link to EOS from experimental hall at 2 x 100 Gbps
- No local buffering, data streamed live



Firmware

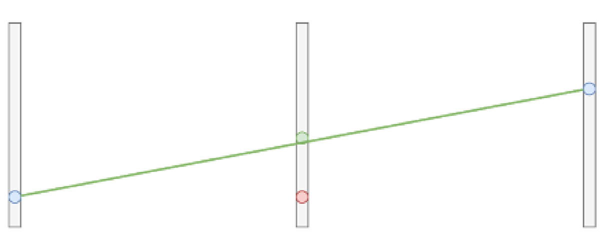
- EMP framework developed for CMS Phase-II upgrade
- Abstracts infrastructure (links, clocks) away from algorithm
- Link interface firmware is common to CMS Phase-II tracker upgrade, rest of firmware custom to MUonE
- Stubs are collected by their clock ID across all modules and aggregated based on bx (link aggregator), each collection sent sequentially to ethernet link (link combiner)



Strategy for Hardware Track Finding

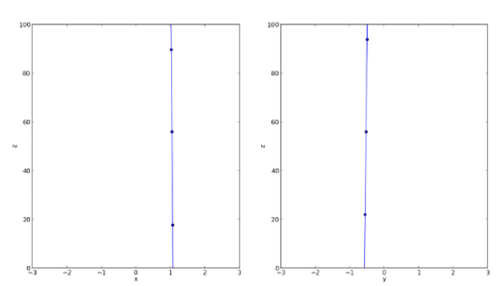
- 40 MHz triggerless readout: online track selection will be necessary for final system to reduce rate sufficiently. Process still to be implemented, previewed in three stages:

Candidate events



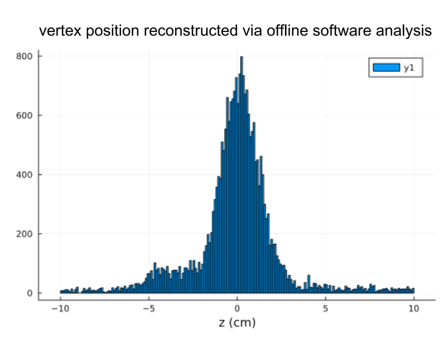
- Combinations of hits increases exponentially, necessary to form candidate sets of stubs within event
- x and y axes can be considered independently for initial selection
  - Tracks can be formed from 3 hits: 1 hit at start of station, 1 hit at end, 1 "virtual" hit generated from combination of u,v planes
  - Candidate sets obtained by propagating straight line made from outer hits to the u,v plane, then iteratively searched for compatible hits
  - Possibility to programmatically tune acceptance window to maximise efficiency at given occupancy
- 10% reduction in rate

Fitting



- Least Squares fit implemented using HLS (tool for C++ code -> VHDL, highly effective for rapid prototyping and complex operations)
- Fitting performed independently in each axes, then 2D tracks are combined to form a 3D track
  - 2D tracks which share u,v hits are merged
- High latency (~2us) per candidate set -> necessary to buffer event data for this time: foreseen multiple fitters in the FPGA to parallelise stage.

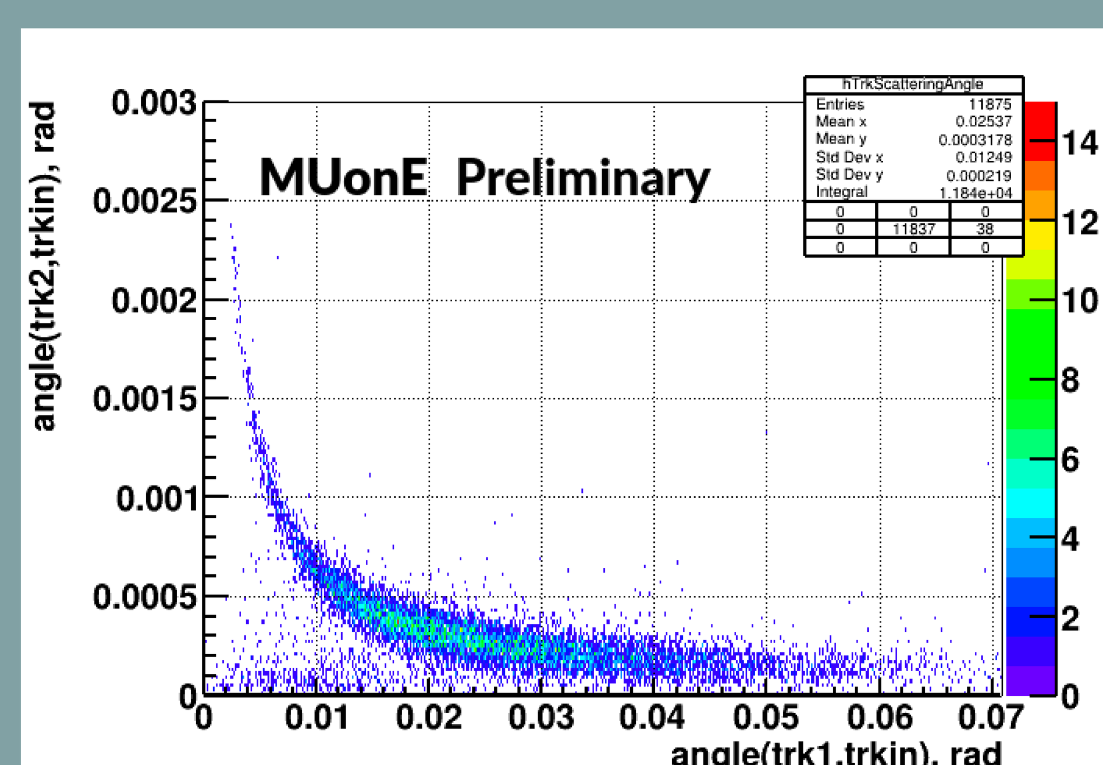
Event selection



- Vertexing: search for two tracks with intersection
- Should offer ~6x reduction in data rate
- PID: opportunity to use ML, in particular online
- hls4ml project provides framework to translate trained networks into VHDL for use on an FPGA for inference

2023 Test Run

- Test run 2023 setup:
  - 2 stations, fully equipped
  - Readout with final daq system
  - Environmental condition system readout
  - Online monitoring - directly from Serenity FPGA via SoM
  - Offline monitoring for tracking related quantities
- First offline vertexing performed:
  - Events with 1 stub per module in 1st station + 2 stubs per module in 2nd station
  - Hits are arranged to tracks assuming two not crossing tracks
  - Two combinations to match X and Y
  - UV hits are attached to each track candidate as closest solution in UV planes
  - pair of tracks (from 2 candidate) is selected by best χ2 sum of UV hits residual
- mu-e elastic scattering on target observed via offline software analysis



[1] G. Abbiendi et al., "Measuring the leading hadronic contribution to the muon g-2 via mu-e scattering", Eur. Phys. J. C 77 (2017) 139
[2] G Abbiendi. Status of the MUonE experiment. Physica Scripta, 97(5):054007, apr 2022.
[3] MUonE Collaboration, Letter of Intent: the MUonE project", CERN-SPSC-2019-026 / SPSC-I-252
[4] CMS Collaboration. The Phase-2 Upgrade of the CMS Data Acquisition and High Level Trigger. Technical report, CERN, Geneva, 2021
[5] Andrew Rose et al. Serenity: An ATCA prototyping platform for CMS Phase-2. PoS, TWEPP2018:115, 2019