LDMX Trigger Scintillator: Firmware Design and S30XL Implementation

HEPCAT Annual Meeting, 11/2/24

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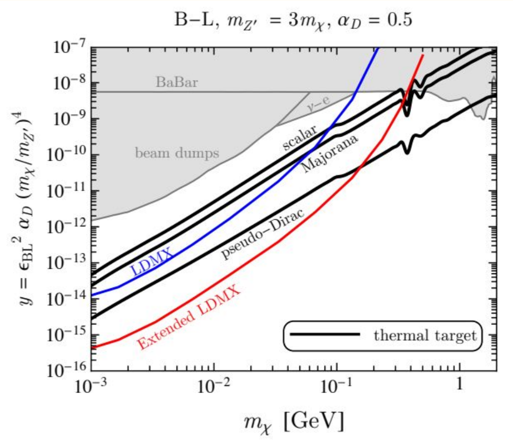
Intro: Thermal Relic Dark Matter and LDMX

If current DM is a freeze-out relic of the early universe (**the thermal model**), we can predict production probability as a function of DM mass.

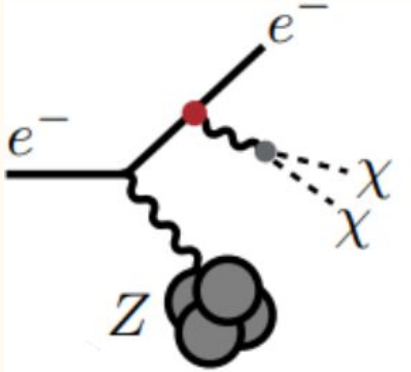
LDMX will find or eliminate thermal relic DM in the MeV-GeV mass ranges.

It is built around a tungsten target wherein a DM bremsstrahlung is meant to occur.

It should detect this event occurring at rates down to the neutrino floor.



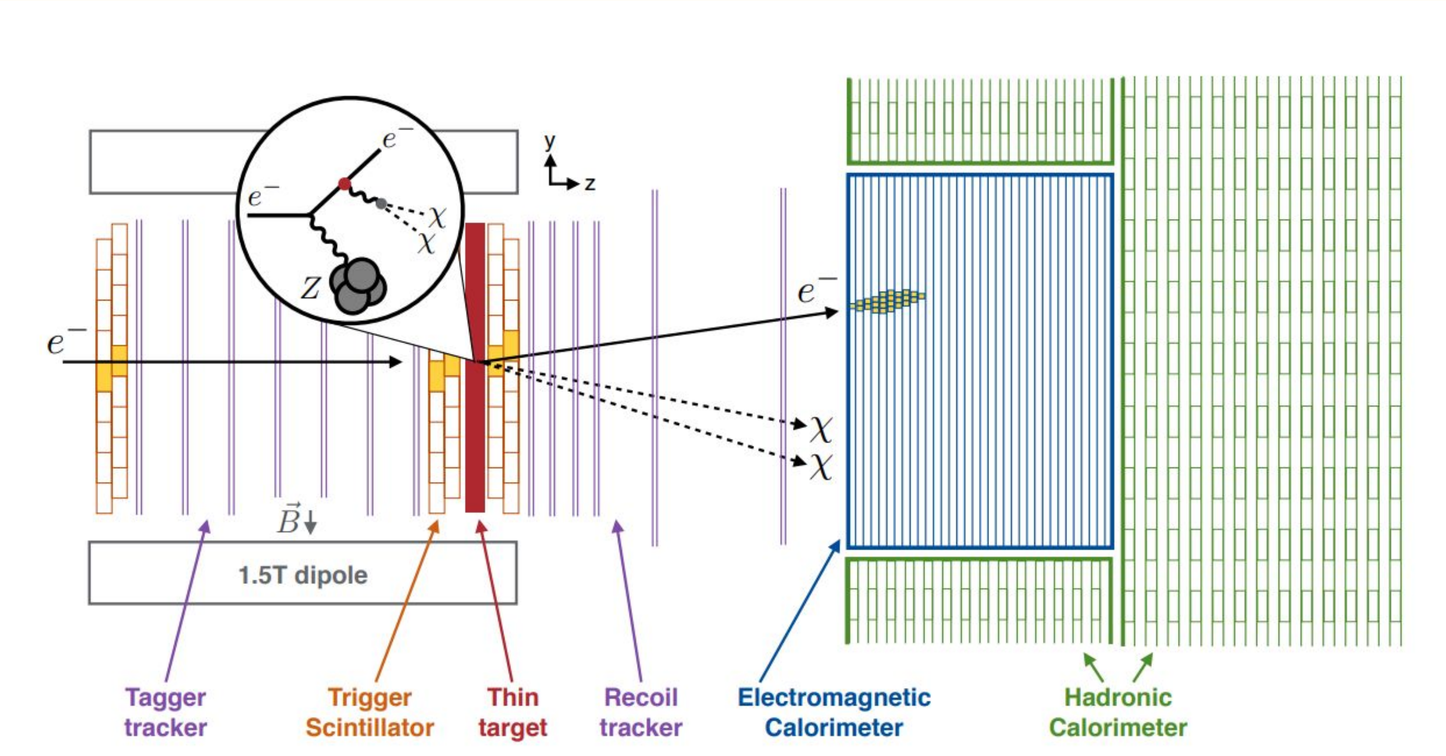
Thermal Relic Dark Matter curves (black) over already excluded parameter space (grey). LDMX reach is overlaid (blue and red) [1].



Example of a dark bremsstrahlung decay against a tungsten atom. [3].

Intro: Thermal Relic Dark Matter and the LDMX

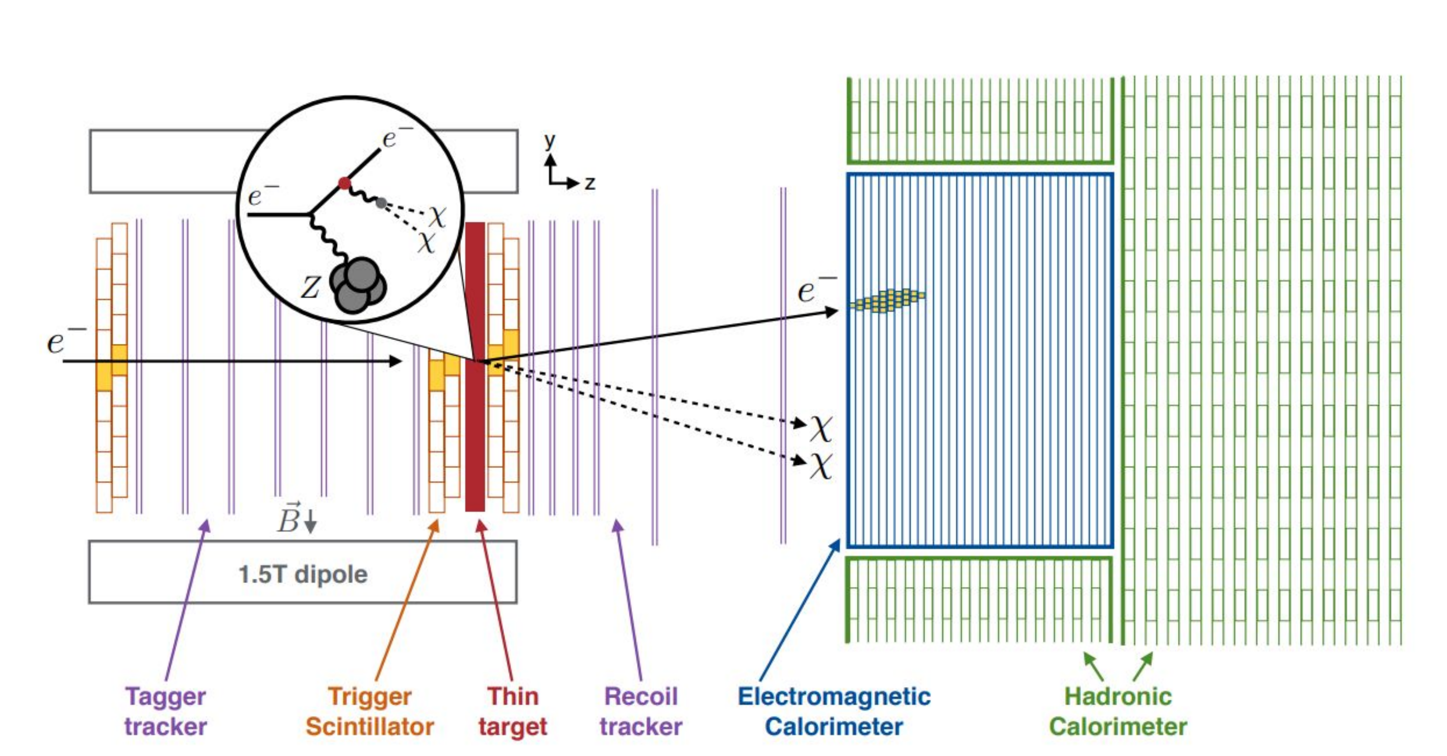
The signature of most DM in accelerator experiment is missing energy; the DM carries it away invisibly. In **LDMX,** this could look like this:



Sourced from [3].

Intro: Thermal Relic Dark Matter and the LDMX

One advantage of the LDMX is its acceptance; it will see any non-neutrino SM particle that passes through it. If something disappears, we will notice.



Sourced from [3].

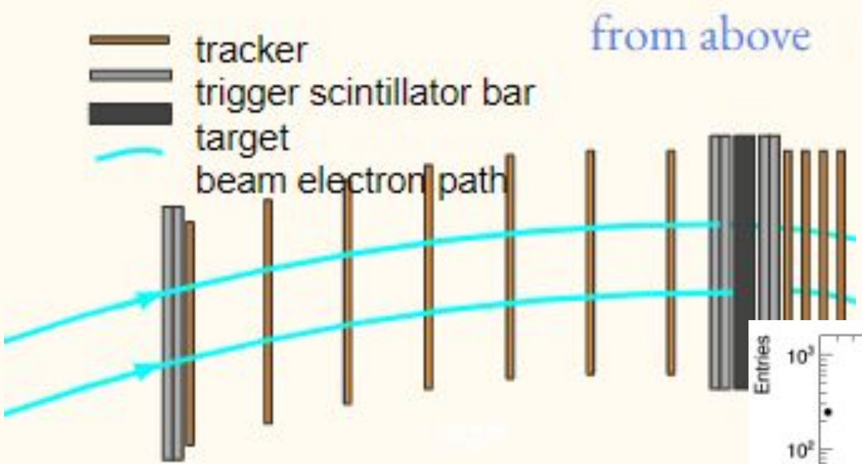
LDMX Global Trigger: A Clarifying Example

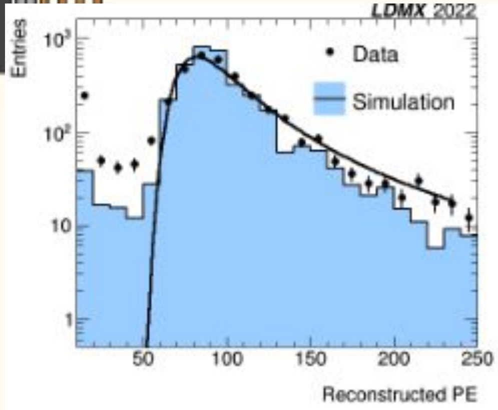
Two Electrons Pass Through the TS Bars, as shown.

They deposit >50 PE (Photo-Electrons) in each bar they cross.

The TS registers

$$e^{-}_{TS}=2$$





Example event Above and Data TS energy counts for 4 GeV electrons below [4].

LDMX Global Trigger: A Clarifying Example

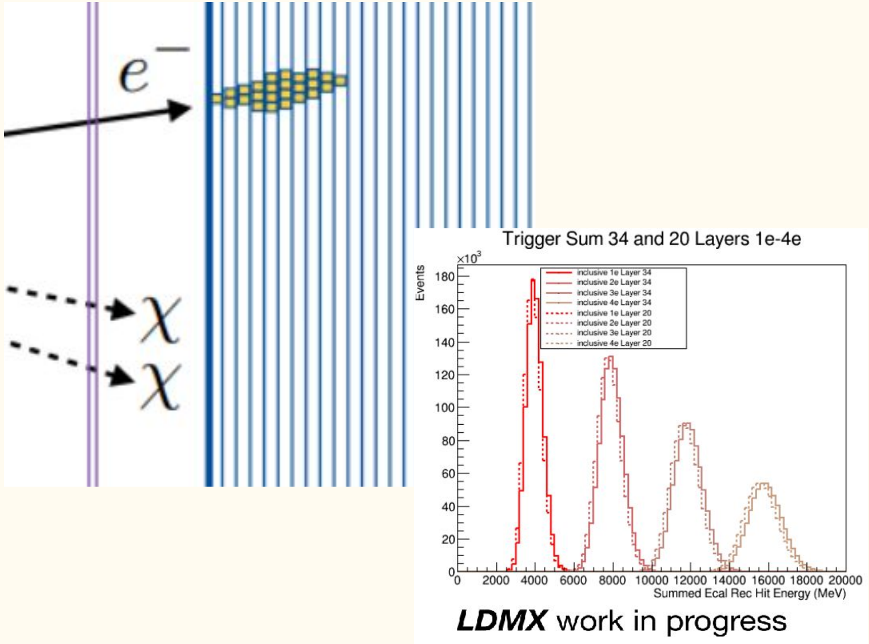
The ECal only counts 4.3 GeV worth of energy in its crystals.

This is in the energy distribution for 1 election, ot sets $e^{-}_{ECal}=1$.

We have

$e^{-}_{ECa} < e^{-}_{TS}$

Trigger!!



Sample event with Dark Matter in ECal, Simulated ECal energy counts for 4 GeV electrons. [6].

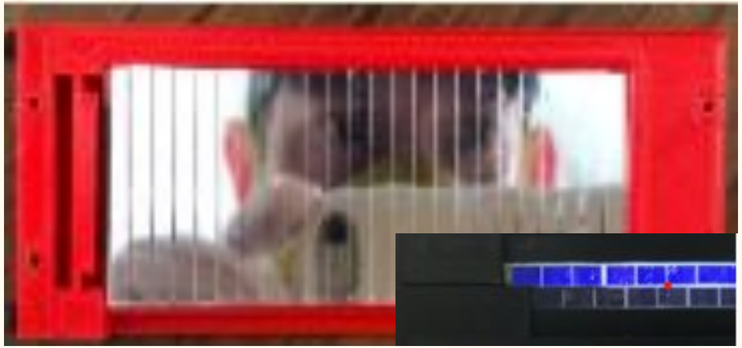
The Trigger Scintillator System

The **Trigger Scintillator** consists of 3 arrays of 48 20x4x3mm bars arranged as in Slide 5 (and shown in this pic).

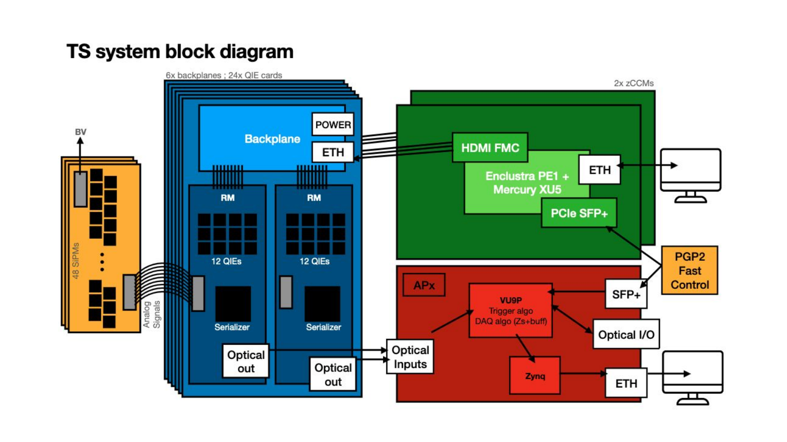
Each set of 12 bars are serviced by a backplane board with QIE11 integrators; these are then connected to an APX board and DAQ.

The APX holds our FPGA chip; it will house the TS Firmware.

This is passed to the Global Trigger.



TS Pad; two (scaled) profiles. [2]



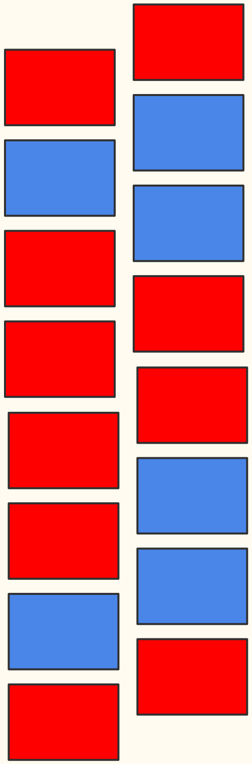
TS system block diagram for the LDMX configuration. [2]

The Trigger Scintillator System: Clustering

For clustering in the TS firmware, we check if a channel exceeds a threshold.

This is done simultaneously for all channels.

A “cluster” is one channel above threshold or it and a neighbor. Some hits are in multiple clusters.



Step 1: Identify above threshold channels

The Trigger Scintillator System: Clustering

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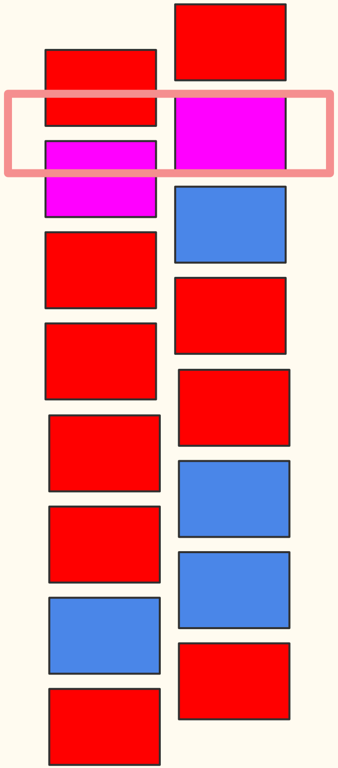

Step 2: Identify single channel above threshold clusters.

The Trigger Scintillator System: Clustering

For clustering in the TS firmware, we check if a channel exceeds a threshold.

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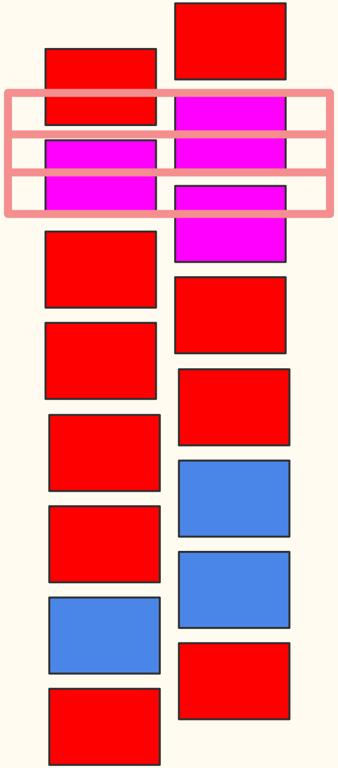


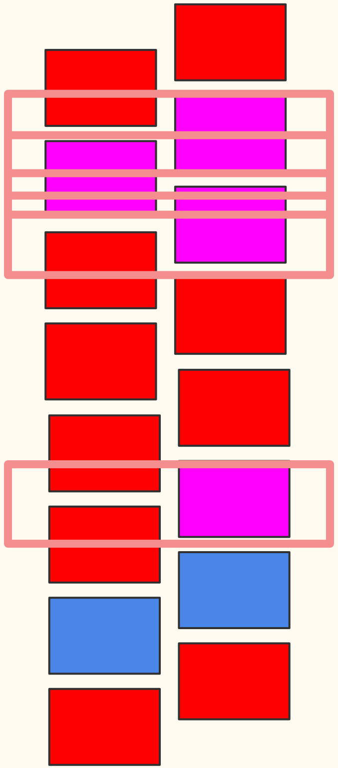
Step 2: Identify clusters with two neighboring above threshold clusters.

The Trigger Scintillator System: Clustering

For clustering in the TS firmware, we check if a channel exceeds a threshold.

This is done simultaneously for all channels.

A “cluster” is one channel above threshold or it and a neighbor. Some hits are in multiple clusters.



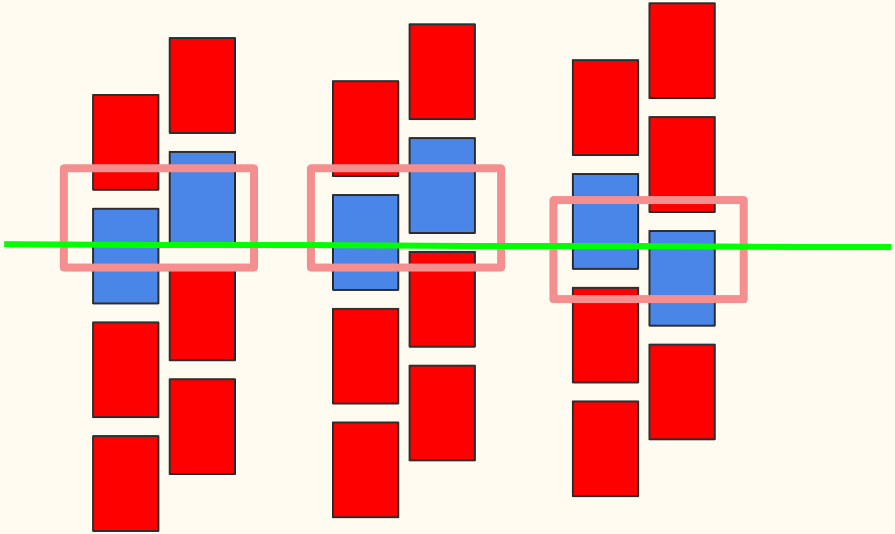
Step 3: Propagate throughout detector

The Trigger Scintillator System: Tracking

We now have a collection of clusters.

At the *exact same time* (i.e. clock cycle) we use a Look-Up Table (LUT) which matches triplets of clusters along the 3 TS modules into tracks.

We don't perform shared hit/cluster removal until the very end*; its complexity exceeds this talk.



Tracking Step

Firmware HLS Implementation and Test Vectors

The first pic shows the HLS resource usage/specs of clustering implementation.

We generate input and output objects (clusters to tracks) in MC, and feed input into firmware.

We can then event-by-event validate the firmware, checking for extra tracks or poor positions.

Latency(cycles)	Latency(ns)	Pipelined	FF(%)	LUT(%)
5	35.000	yes	~0	7

Resource usage for clusterer as percentage (and latency), ~0 is on the order of several 1000 flip flops

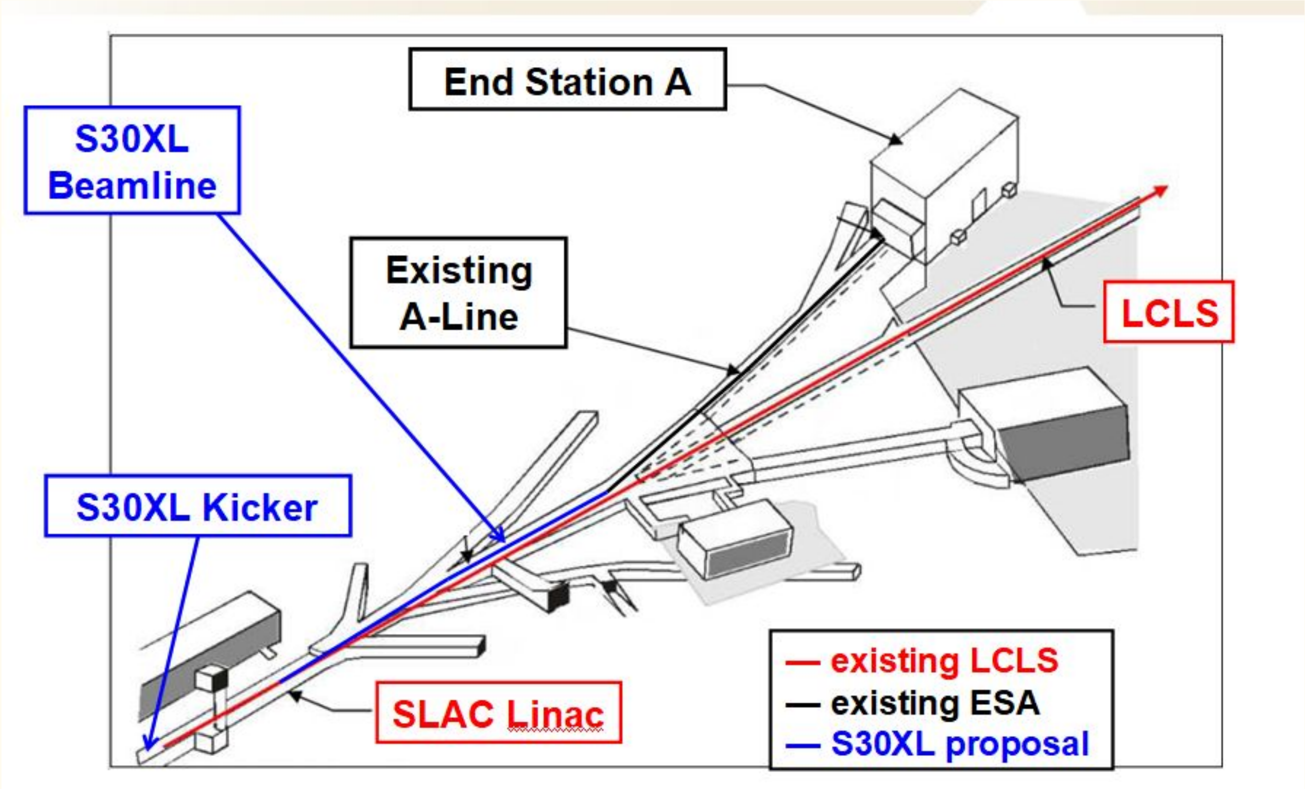
```
First Firmware Cluster Centroids:
37
858
2161
2300

Now Simulated Cluster Centroids:
37
858
2161
2300
```

Hypothetical test vector pass for cluster reconstruction.

Shifting Gears: S30XL Testbeam Studies

SLAC Site Geography

I have borrowed diagrams from Thomas Markiewicz (source)

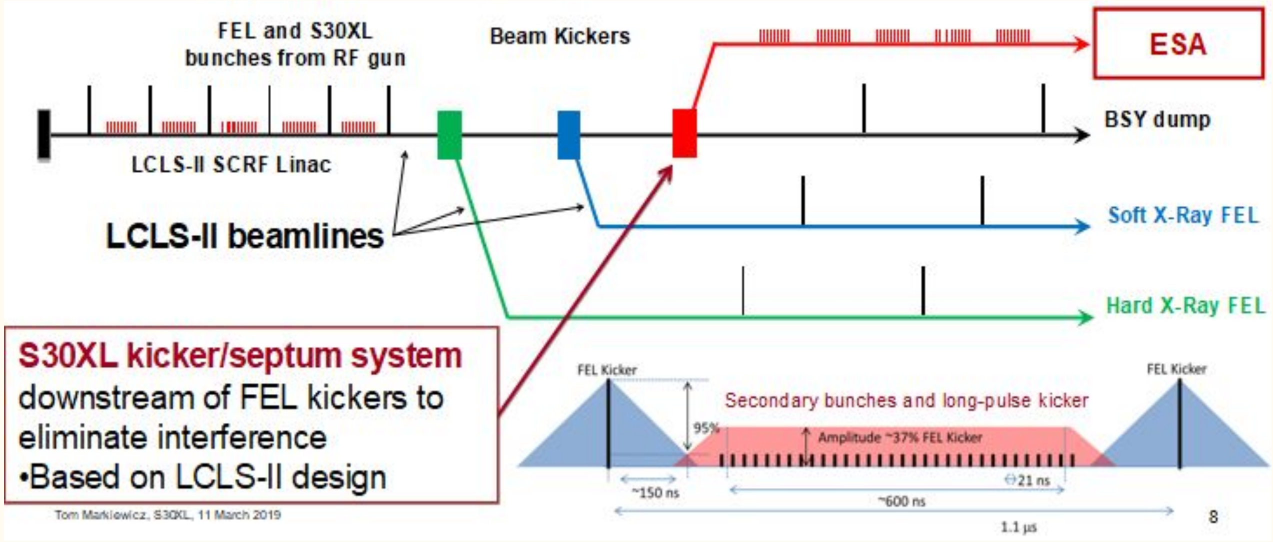


For LDMX, current HLS firmware would handle ~5 e-/24 ns.

The S30XL exceeds this rate; we could only measure the dark current.

This rate may be achieved by decreasing the plateau length of the kicker * to ~24 ns, our in time pileUp will be still be too high.

S30XL Beamline Design



Intro

The S30 transfer line takes to dark current from LCLS II to Hall A and into LDMX.

Now that S30XL has been built, we may test LDMX's TS (trigger scintillator) system with beam currents and energies similar to those we'd see in the experiment's environment.

We have been building a working prototype of the TS' DAQ (data acquisition) system since August and are waiting for our period to install.

The aforementioned hit reconstruction firmware will be evaluated in an upcoming testbeam.

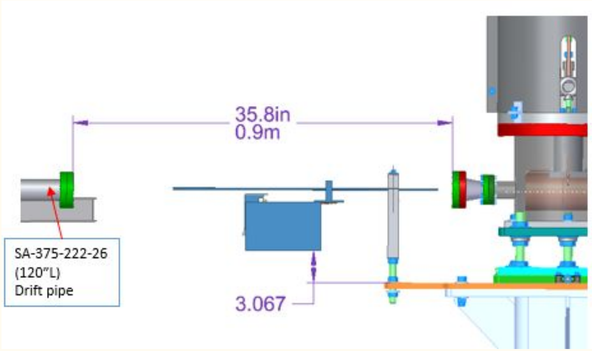


Diagram of TS location w.r.t. The dump

Picture of dump taken while evaluating wired cables to S30

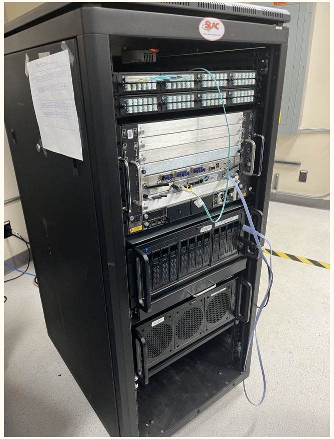
What Has Been Done?

We have set up and communicate with the APx switch and with the QIE11 board.

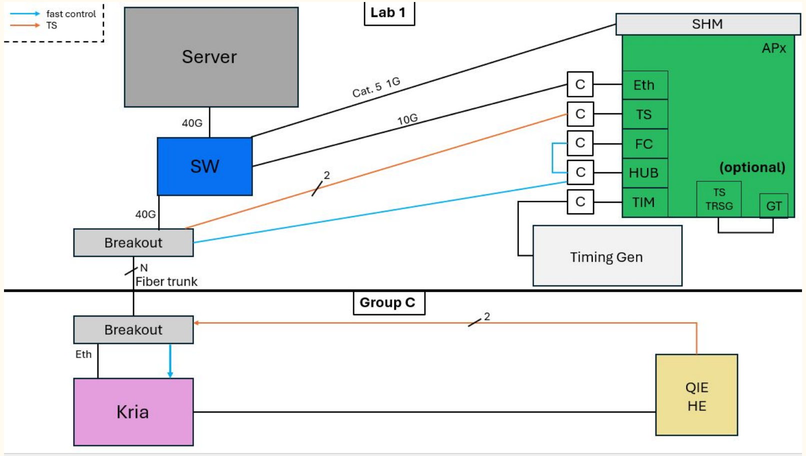
We have setup the physical connections between the APx and the QIE11; we could begin testing w.r.t. cosmics in the near future.

We have completed (much of) the triggering firmware and the surrounding DAQ firmware architecture.

We must get a zCCM running (for the purpose of syncing LCLS II and the local clock), after whose incorporation we can begin the validation necessary before installation.



Old image of APx switch crate. The breakout board has now been populated and routed to a Lab C with the QIE11 boards.



Most on the LHS of this diagram is done, on the RHS zCCM and some DAQ firmware work is required

Conclusion

We have shown how one develops a triggering system through the TS detector in the LDMX experiment; namely how a 37 MHz clock rate pushes physicists to be clever about how they design firmware to realize electron counting for triggering.

We will evaluate the performance of the TS detector at SLAC's S30XL testbeam.

We have built much of the surrounding DAQ system (zCCM, APX board, etc.) and are running test bench studies on it now.

We plan on evaluating an early prototype of the LDMX TS Trigger and DAQ system at S30XL in early January.

Citations

[1]. *Light Dark Matter eXperiment*. Akesson, Torsten et. al. https://arxiv.org/abs/1808.05219

[2]. Courtesy Andrew Whitbeck

[3]. *Current Status and Future Prospects for the Light Dark Matter eXperiment*, Akesson, Torsten. Et. al. https://arxiv.org/abs/2203.08192

[4]. Courtesy Lene Kristian Bryngemark

[5]. *Simulation of a prototype of the LDMX hadronic calorimeter and analysis of test beam data.* Gyorgy, Peter.

[6]. Courtesy Megan Loh

BACKUP

APx Board For Trigger Decision

The captan board with FPGA in center;

Connected to backplane QIE1 cards by optical fiber

COMPARE / Reset	XCVU9P
System Logic Cells (K)	2,586
DSP Slices	6,840
Memory (Mb)	345.9
GTY/GTM Transceivers (32.75/58 Gb/s)	120/0
I/O	832

Specs for the FPGA onboard the APx board.

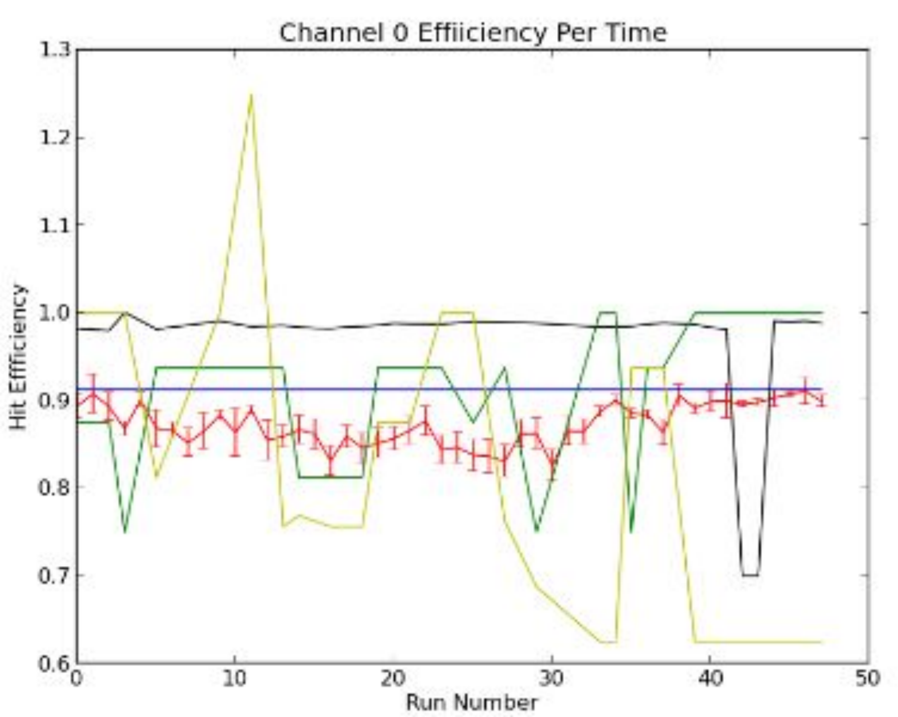
Overview of Data

Some calibration studies took in all ~300 runs, with muon, pion, or electron beam types.

The remaining studies used 48 ‘good’ runs which underwent reprocessing -better timed hit reconstruction windows.

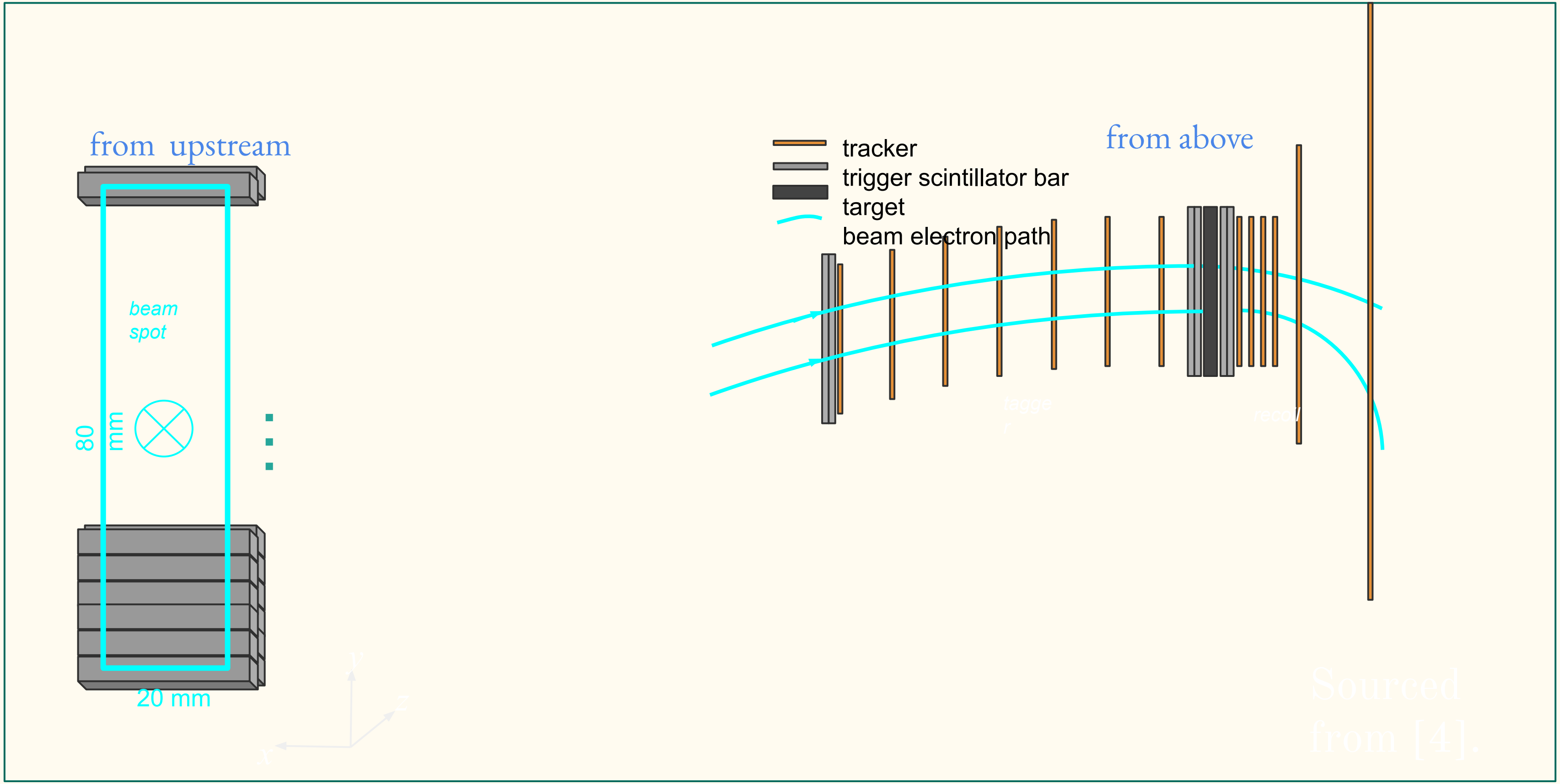
These runs number ~1e5-1e6 events each.

The beam energy ranges from .2 to 8 GeV (yellow). The gain was relatively constant at a multiplier of 2e6. Green is beam type (electrons at .82, muons at .875, pions at .925, and other points were unlogged).



In this plot we have beam energy (yellow), type (green), gains (black), data efficiency (red) and MC efficiency (blue)

Some (Other) Geometric Perspectives of the LDMX TS



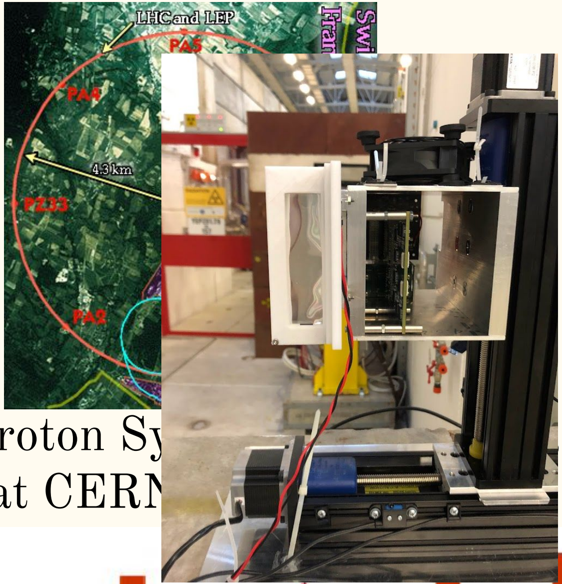
Testing a First Iteration of the TS System: T9 Testbeam

The PS, the smallest of the many rings at CERN's LHC, feeds our T9 Testbeam

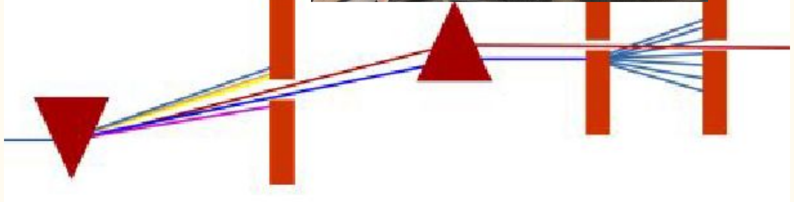
It accelerates protons to ~24 GeV before latter rings take them to ~13 TeV.

We smashed these 12 GeV protons into aluminum foil at the T9 Testbeam area.

The resultant stream of muons, electrons, and pions were sorted by the Dipole array so that we keep particles at a known energy.



PS (Proton Sy... SPS in Cyan at CERN...



Beam Purifier and Dipole Array at PS T9 Testbeam. [5].

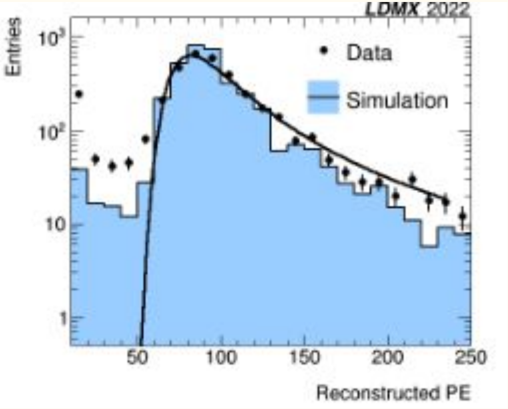
LDMX Global Trigger: A Brief Description

Step 1: Count the number of electrons worth of energy in Ecal. This can be done via a diagram to the right.

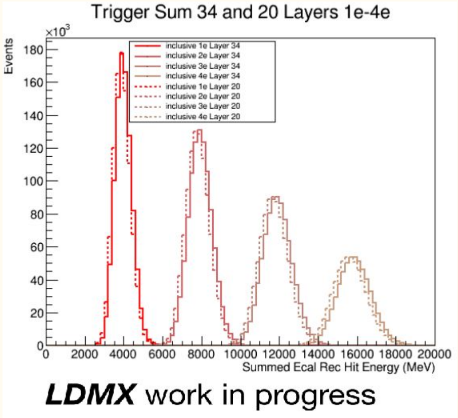
Step 2: Count the number of electrons in the TS. This is down by reconstructing tracks as in Slide 5 and counting tracks.

Step 3: If $e^-_{Ecal} < e^-_{TS}$, trigger!

On the next slide, we give a description of this TS track reconstruction firmware.



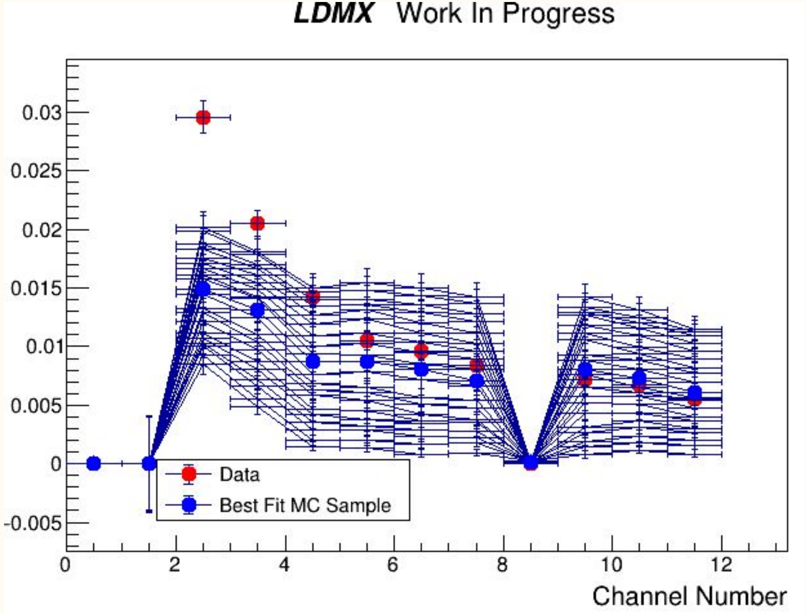
Data TS energy counts for 4 GeV electrons [4].

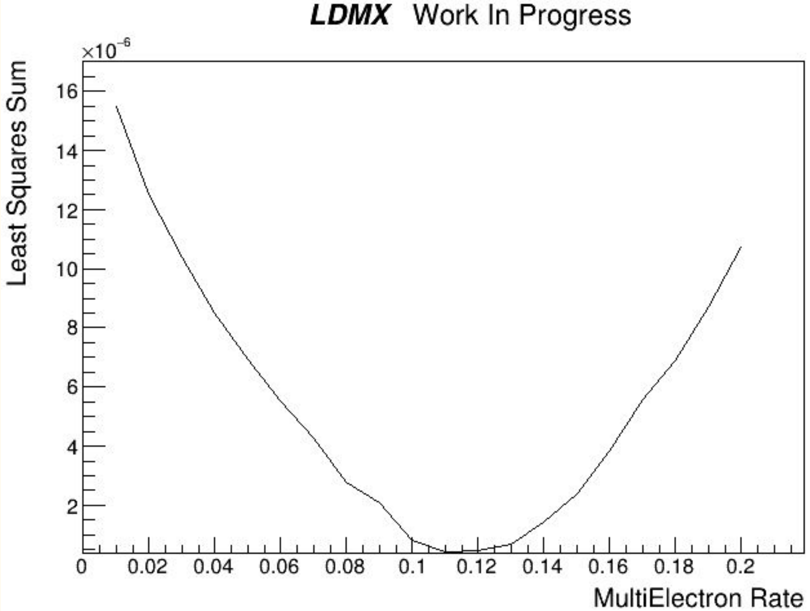


Simulated ECal energy counts for 4 GeV electrons. [6].

How is Secondaries Fitting Performed?

We generate a sample of single and double electrons passing through our in situ measured detector and consider a mixture of events established by the MultiElectron Rate. We then fit against the last 6 channels, whose rate will not include secondaries.





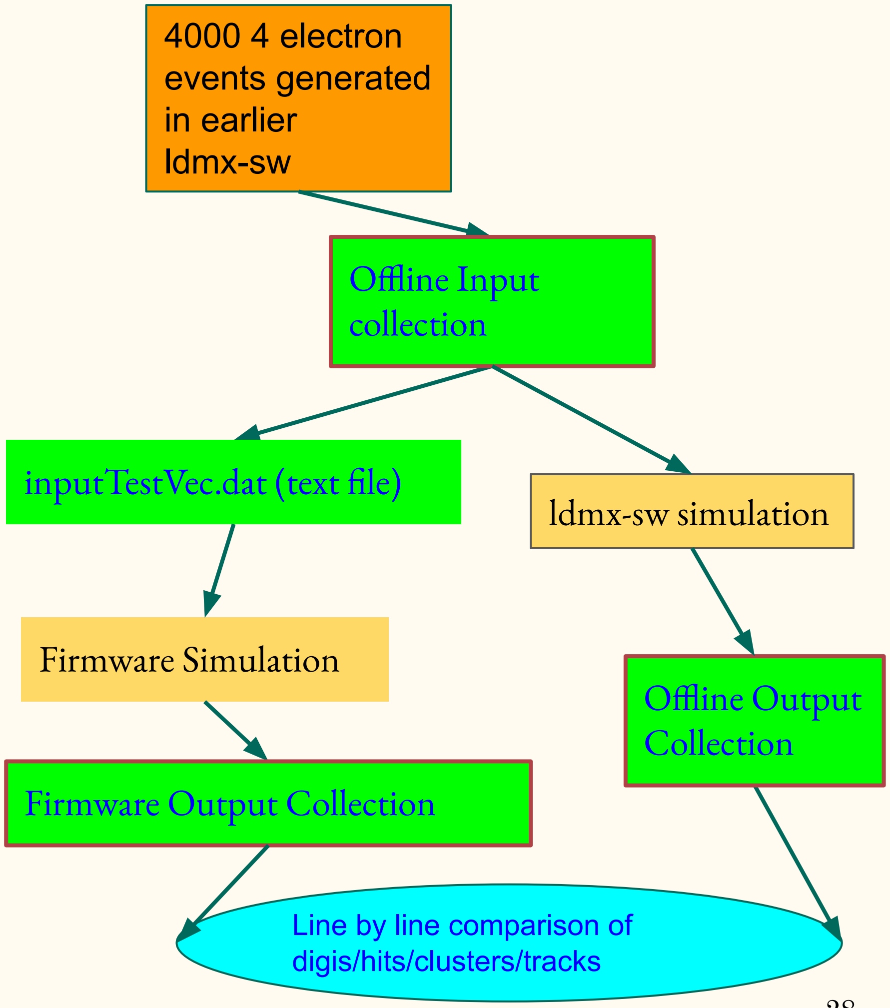
Firmware HLS Implementation

We have existing software, ldmx-sw, is which performs reconstruction in MC.

For test beams and in practice, this must be put into **Firmware;** this is a special language which directly builds circuits.

I used **vitis HLS** for this task: it synthesizes firmware from C^{++} and allows me to directly compare to ldmx-sw firmware (as shown right).

In the next slides I will briefly describe the new firmware way of performing reconstruction in the LDMX TS



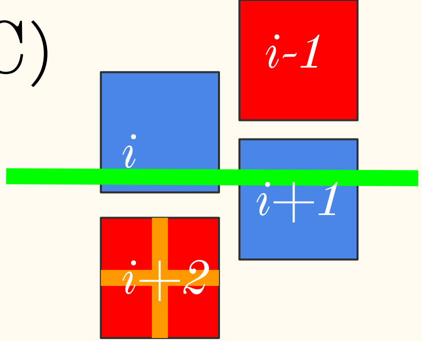
Tag and Probe Hit Efficiency Metric (MC)

We can check TS efficiency *in situ* as the layers are redundant.

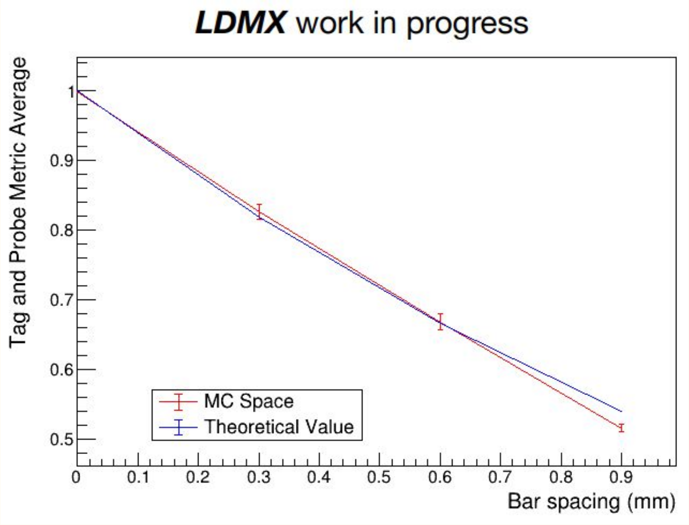
The Tag and Probe efficiency metric tags on seeing a hit in i+1 to probe the efficiency of channel i.
We condition further on not seeing a hit in i+2; this implies we either register a hit in i or an e$^-$ passes through a gap.

This metric is sensitive to bar gaps, though we can model this in MC.

The lower plot demonstrates how hit efficiency decreases in MC should bar spacing increase.



Probing i conditioned on i+1 and **not** i+2

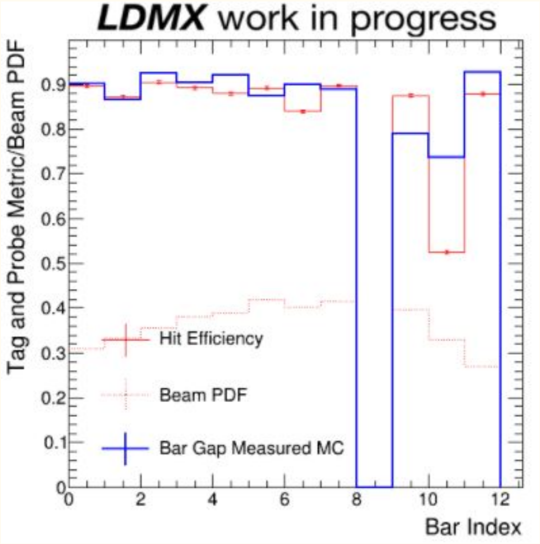


Hit Efficiency Metric on Data

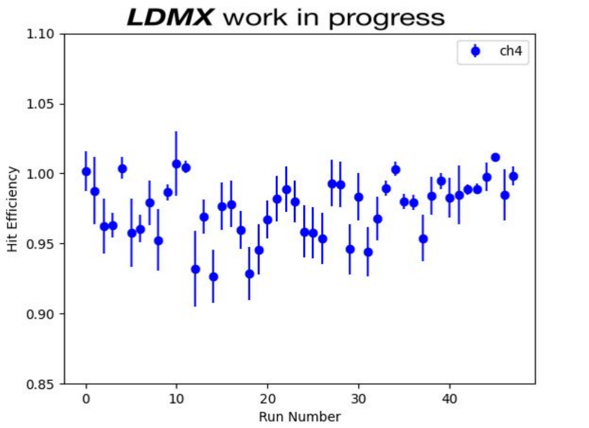
The first 8 bars of the TS (up to a dead channel) all had good agreement in hit efficiency metric with the MC determined value (Top Plot). Channels 9,10, and 11 show some discrepancies.

The MC to Data Ratios for most channels is statistically indiscernible from 1.0 (Bottom Plot).

We understand well how detector geometry affects our efficiency metric; our measured value of ~90% is due to the .3 mm bar gaps.



Hit Efficiency per bar for a single run of the April Testbeam.



Hit efficiency data MC ratio over all good runs for channel 3.

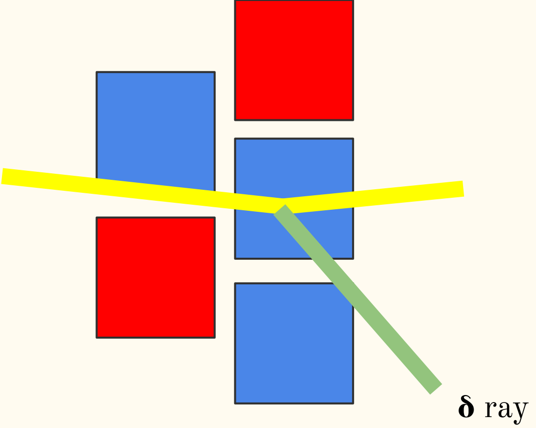
Secondary + Cross-Talk Rates

When e⁻ pass through scintillating material, they can sometimes knock off an electron and form a delta ray.

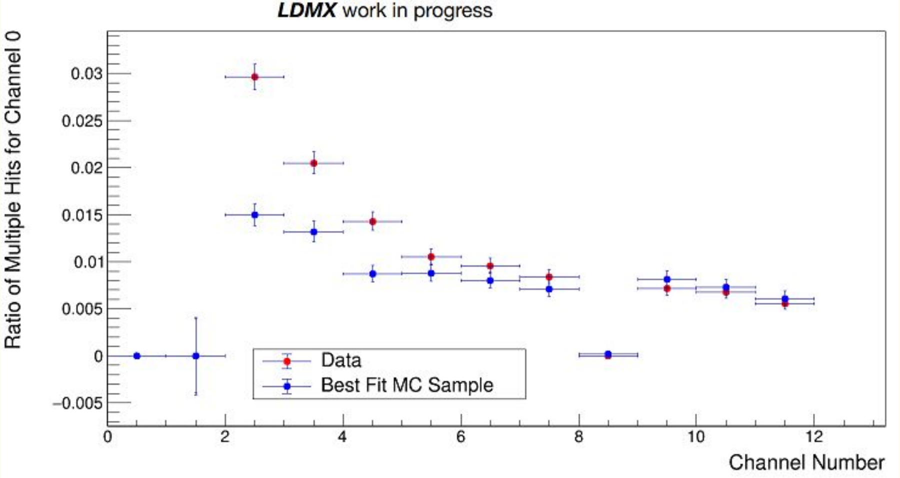
These can make it look like we have more electrons than we do, inducing a false trigger.

To count the rate of delta rays (and additional) cross talk, we can condition on seeing a hit in channel 0 and scan for hits in other channels.

This would count that rate of genuine multiple electrons plus delta rays; from fitting we determined 11.0(5)% multi-electron rate and 3.0(5)% delta ray/cross talk.



Geometry of a delta ray event



Closest fit secondary metric for MC (blue) and data (red)

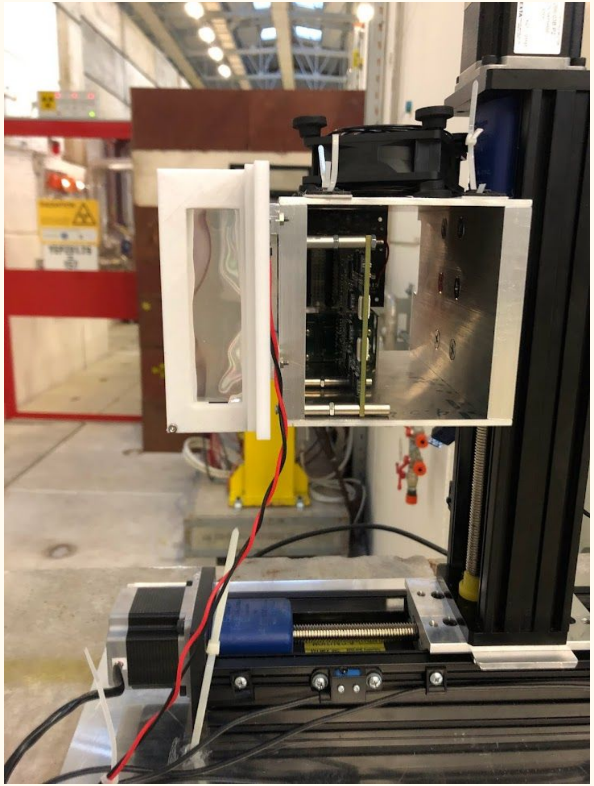
Testing a First Iteration of the TS System: T9 Testbeam

The PS, the smallest of the many rings at CERN's LHC, feeds our T9 Testbeam

At this testbeam, we exposed a 12 bar TS prototype to several beam types over 300 runs over a month long run in April/May 2022.

Each run included between 1e5 and 1e6 events, including muon, pion, and electron interactions.

For these beams, beam energies from 500 MeV to 8 GeV was employed (the LDMX environment is ~8 GeV).



TS 12 bar setup at the T9 testbeam. Note that Slide 1 in Back Up has more run details.