Real-time reconstruction of long-lived particles at LHCb using FPGAs.

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on behalf of the LHCb Collaboration
Tracking at LHCb-Upgrade

- **Long track**: reconstructible using VELO + UT + T stations. → beauty and charm core physics
- **Downstream track**: reconstructible using UT + T stations. → crucially to reconstruct for LLPs.
- **T-track**: reconstructible using T stations. → first stage of downstream tracks reconstruction.
A crowded event in 2018 (L=4x10^{32})

An average of about 150-200 tracks per event, up to a maximum of 400-500 tracks per event, is expected at the LHCb-Upgrade conditions L=2x10^{33} cm^{-1}s^{-1} (LHC Run3 and Run 4).
Downstream tracking

- Algorithm used for reconstructing standalone T-tracks in the SciFi sub-detector, called seeding, is crucial for reconstructing tracks generated by long-lived particles (LLPs), such as $K_S, K_L, \Lambda$.

- Seeding is a very intensive pattern recognition task and requires a significant amount of CPU-time to be executed, i.e. about 500 μsec (*) per event [LHCb-PUB-2017-005].

  - Adding UT hits to form a “downstream track” requires a total CPU-time even larger.

- The total budget for the LHCb-Upgrade tracking sequence, in Run 3, is expected to be 33 μsec per event, assuming 1000 Event Filter Farm nodes [LHCB-TDR-016, LHCb-PUB-2017-005] → at the moment finding tracks downstream of the magnet at the earliest trigger level is not part of the baseline trigger scheme.

See C. Fitzpatrick’s talk (Track 1) for details on the LHCb-Upgrade Tracking Sequence.

(*) measured using a setup different from the official throughput test setup.
The Downstream Tracker

- R&D work in the context of the Future LHCb Upgrades (LHC Run 4 and beyond), to realize a downstream tracking unit that can be integrated in the DAQ architecture and act as an “embedded track-detector”.

- This would make event reconstruction primitives immediately available to the event-building, and to the high-level-trigger farm.

- FPGA is the appropriate technology: aim for high bandwidth and low latency, comparable with that of other elements in the detector DAQ.

This talk: specifically aimed at the reconstruction of standalone T-tracks, the first and most expensive part of the reconstruction of downstream tracks.
Scintillating Fibre Tracker (SciFi)

- 3 tracking stations (T1, T2, T3) of scintillating fibre.
- 4 layers per station (x-u-v-x)
  - u/v layers tilted by a stereo angle of +5°/-5°.
  - Electronic readout at 40MHz.
  - Hit spatial resolution: ~100 μm.
  - High occupancy: an average of about 300 hits per layer, up to a maximum of 800 hits per layer.
- A small component of magnetic field (fringe field) is present in the SciFi region. Tracks are well approximated as parabola in x-z view, and as straight lines in y-z view.
- For this study SciFi divided in 4 independent quadrants. Negligible loss of efficiency because of tracks crossing different quadrants.
A biologically inspired architecture: the Retina Algorithm

Massively parallel architecture. Similarities with Hough transform and associative memories for pattern matching.

- **Step 0** - Discretize space of track parameters (pattern cells) and generate track intersections with detector planes (receptors) and connect them to cells (mapping).

- **Step 1** - Detector hits are distributed (Switching Network) only to a reduced number of cells according the mapping of Step 0 (LUT).

- **Step 2** - A logic unit (engine) for each cell accumulates a Gaussian weight proportional to the distance with the receptors.

- **Step 3** - Tracks are identified as local maxima of accumulated weights, above a certain threshold, over the cells grid.

Conceived for parallelism: processing before the event building.
DAQ integration

- The LHCb-Upgrade Event Builder is made by about 500 interconnected PCs nodes, each of one equipped with a DAQ-board. Events are built and sent to the Event Filter-Farm server nodes, where the HLT will be running [LHCb-TDR-016].

- Event Builder PC nodes (of interest) have to be instrumented with a “tracking board” equipped with a modern FPGA connected to the node through a PCIe card (100 Gbit/s).

- A single tracking board performs both hits distribution and template matching. A Patch Panel is needed to distribute hits inter boards.

- Reads small detector portion, outputs small parameter space.

- Easier to implement large global bandwidths.

- May use standard commercial PCIe express FPGA boards.

156 DAQ boards will receive raw data from SciFi sub-detector, half from the axial layers (6 layers providing x-coordinates) and half from the stereo layers (6 layers providing u- and v-coordinates).

### Table 3.1: Number of Event Builder PC nodes for each LHCb Upgrade sub-detectors

<table>
<thead>
<tr>
<th>Sub-detectors</th>
<th>VELO</th>
<th>UT</th>
<th>SciFi</th>
<th>RICH</th>
<th>Calorimeter</th>
<th>Muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB node</td>
<td>56</td>
<td>72</td>
<td>156</td>
<td>114</td>
<td>55</td>
<td>30</td>
</tr>
</tbody>
</table>

**Figure 3.4: Integration in LHCb DAQ.**

**Figure 3.5: Integration scheme of the Downstream Tracker into the LHCb Upgrade Event Builder system.**

**3.4 Implementation details**

The architecture described in previous sections is flexible and largely scalable. Without significant loss of generality, we will in the following make reference to straight

51 Number of Event Builder PC nodes

...
Reconstruction of 3D tracks

- Reconstruction of T-tracks is factorized in two stages.

- **Pattern recognition:** find the x-z track projection using only axial layers.
  - tracks approximated as straight lines (2-dim Retina).
  - for each local maximum found, a linear $\chi^2$ fit to a parabola is executed (on DSP blocks of FPGAs) over a limited number of combinations of the two closest hits to the receptors, in order to kill ghost tracks and evaluate parabola parameters.

Reconstruction of 3D tracks
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- **Stereo association:** x-z projection of axial track candidate is used as “seed” to extract y-coordinates from u/v layers and associate y-z track projection. The same firmware of axial Pattern Reco stage is used, but with much lower granularity.
Tracking 6-layers of SciFi

- Axial retina track parameterization:
  - \( x_0 \) (\( x_{11} \)) \( x \)-coordinates of the intersection between the first (last) axial layer;
  - similar for the stereo association \( y_0 \) (\( y_{11} \)).

- Interesting physics tracks (Long and Downstream) distributed over the diagonal region, being \( x_0 \approx x_{11} \).

- About 25k cells per quadrant, for a total of about 100k cells for the whole SciFi sub-detector.

- Cells granularity of axial retina is the minimal to ensure the presence of the true track hits within the two closest hits of each receptor, once a local maximum is found.
Axial retina at work

- Efficiency above 95%.
- Ghost rate ~ 90% (for instance 150 true-matched reconstructed tracks correspond to 1350 “fake” reconstructed tracks).

Excitation level $W_A > 4$

- Efficiency ~ 80-90%. (approaching 90% with some minimal momentum request).
- Ghost rate ~ 15% (comparable with standard offline seeding algorithm).
Stereo Association

• For each reconstructed axial tracks candidate, the u/v-hits from tilted layers are transformed in y-coordinates and accumulated into the corresponding stereo retina \((y_0, y_{11})\).

• Same processing of the x-z view is performed (hits distribution, accumulation, search of local maxima and linear fit of the combinations of hits accumulated in the local maxima).

• The y-hits combination with the best \(\chi^2\) is promoted as the y-z track projection.

Each stereo tracking board hosts at least 3 stereo retinas (355 cells each), for a total of 355 x 3 \(\approx\) 1k cells per FPGA.
Hardware prototypes

• First prototypes assembled and tested within the INFN Retina CSN5 project.

• Used an ASIC prototyping board by DiniGroup equipped with two large FPGA's:
  - 2 Stratix V (28 nm), 1M of LEs, with (0.6+0.6)Tb/s I/O bandwidth, and maximum clock of 700 MHz;
  - on-board CPU, DDR memory;
  - 96 inter-FPGA LVDS connections;
  - 96 high-speed SerDes I/O (12 Gb/s).

• Switch and engine can be tested in basic standalone configurations, but more are possible connecting other boards through optical fibers.

• Can be used as building block for an entire tracker. Results on this prototype therefore readily extrapolate to real systems size.
Measured performance

- Various configurations tested. Here, results on 6 axial layers of Scintillating Fibre Tracker as a function of retina occupancy (#track/#cell).
- Achieved a throughput above 30MHz and latencies <1μs.
- Determined engine size: about 1k LEs.
  - Pattern Reco. (axial): needed about 100k engines distributed over 78 FPGAs, corresponding to ~1.2M LEs per FPGAs.
  - Stereo Association: needed about 78k engines distributed over second half of EB PC nodes, corresponding to ~1M LEs per FPGAs.
- Such a specialized processor is already cost effective and can be built today using FPGAs off the shelf.
  - Hardware cost < 0.1 €/KHz of tracks.
  - Power cost: 0.2 mW/kHz of tracks.
Physics performance

- Simulated realistic pp collisions at the LHCb-Upgrade conditions:
  - sqrt(s)=14 TeV;
  - LHC bunch spacing = 25 ns;
  - L=2 x 10^{33}cm^{-2}s^{-1};
  - v = 7.6

- Events processed using the official LHCb-Upgrade simulation of the Scintillating Fibre sub-detector (energy deposits, spillover, noise, inefficiencies, light attenuation in the fibre, clustering, read-out electronic chain, etc.)

- Performances comparable with those obtained with the offline seeding algorithm. Efficiency within the 80-90% range, approaching the 90% level with a minimal momentum threshold.

<table>
<thead>
<tr>
<th>Track type</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>hasT</td>
<td>75.0</td>
<td>71.4</td>
<td>74.4</td>
</tr>
<tr>
<td>hasT, p &gt; 1GeV/c</td>
<td>77.6</td>
<td>73.9</td>
<td>77.7</td>
</tr>
<tr>
<td>hasT, p &gt; 3GeV/c</td>
<td>87.0</td>
<td>83.0</td>
<td>85.9</td>
</tr>
<tr>
<td>hasT, p &gt; 5GeV/c</td>
<td>90.3</td>
<td>85.7</td>
<td>88.2</td>
</tr>
<tr>
<td>Long</td>
<td>81.7</td>
<td>78.8</td>
<td>84.1</td>
</tr>
<tr>
<td>Long, p &gt; 1GeV/c</td>
<td>81.7</td>
<td>78.8</td>
<td>84.1</td>
</tr>
<tr>
<td>Long, p &gt; 3GeV/c</td>
<td>87.3</td>
<td>84.2</td>
<td>87.1</td>
</tr>
<tr>
<td>Long, p &gt; 5GeV/c</td>
<td>90.6</td>
<td>86.9</td>
<td>88.1</td>
</tr>
<tr>
<td>Down</td>
<td>80.1</td>
<td>77.7</td>
<td>83.0</td>
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<tr>
<td>Down, p &gt; 1GeV/c</td>
<td>80.1</td>
<td>77.7</td>
<td>83.0</td>
</tr>
<tr>
<td>Down, p &gt; 3GeV/c</td>
<td>87.0</td>
<td>84.4</td>
<td>87.1</td>
</tr>
<tr>
<td>Down, p &gt; 5GeV/c</td>
<td>90.5</td>
<td>87.5</td>
<td>88.8</td>
</tr>
<tr>
<td>Down strange</td>
<td>-</td>
<td>-</td>
<td>84.7</td>
</tr>
<tr>
<td>Down strange, p &gt; 1GeV/c</td>
<td>-</td>
<td>-</td>
<td>84.7</td>
</tr>
<tr>
<td>Down strange, p &gt; 3GeV/c</td>
<td>-</td>
<td>-</td>
<td>89.4</td>
</tr>
<tr>
<td>Down strange, p &gt; 5GeV/c</td>
<td>-</td>
<td>-</td>
<td>93.0</td>
</tr>
<tr>
<td>ghost rate</td>
<td>12.1</td>
<td>15.7</td>
<td>16.3</td>
</tr>
</tbody>
</table>

\[ \varepsilon_{A} = \text{efficiency of finding axial projection of the track} \]

\[ \varepsilon_{AS} = \text{efficiency of finding 3D track} \]
Conclusions

- Reconstruction of standalone tracks in the forward LHCb SciFi sub-detector in realtime at 30MHz, with latencies of the order of 1 μs, is doable with a system based on modern commercial PCIe FPGA cards.

- Such a specialized processor is cost effective and might be built already today using FPGAs off the shelf.

- Achieved a crucial milestone in the R&D development for a future realization of a downstream tracking unit to operate during LHC Run 4 (2026-2029) and beyond.
Backup
Selected list of references

• R. Cenci et al. First results of an "artificial retina" processor prototype, 2016 https://doi.org/10.1109/MOCAST.2016.7495111.
• G. Punzi et al., A Specialized Processor for Track Reconstruction at the LHC Crossing Rate, 2014, JINST 9, C09001 (2014).
• A. Abba et al., A specialized track processor for the LHCb upgrade, 2014, LHCb-PUB-2014-026.
• F. Lazzari, Development of a real-time tracking device for the LHCb Upgrade 1b, 2017, CERN-THESIS-2017-442.
• A. Piucci, Reconstruction of tracks in real time at high luminosity environment at LHC, 2014, etd-06242014-055001.
LHCb timeline in the next decades

The LHCb Upgrade I will enable to integrate about 22 fb\(^{-1}\) by end of Run 3 and 50 fb\(^{-1}\) by end of Run 4.
Intensity frontier

- LHCb Upgrade Ia in Run-3 (2021-2023)
  - \( \text{L}_{\text{inst}} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \).
- LHCb Upgrade Ib Run-4 (2026-2029)
  - Integrate 50 fb\(^{-1}\) by the end of Run 4.
  - Profit from LS3 for a “consolidation”.
- LHCb Upgrade II in Run 5 (2031-2033) and beyond.
  - New experiment to be installed in LS4 to integrate > 300 fb\(^{-1}\).

### Table 2.1: LHC parameters of pp runs from 2010 to 2033.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{cm}} ) (TeV)</td>
<td>( 7 - 8 )</td>
<td>( 13 )</td>
<td>( 14 )</td>
<td>( 14 )</td>
<td>( 14 )</td>
</tr>
<tr>
<td>LHC ( L_{\text{peak}} ) (cm(^{-2}) s(^{-1}))</td>
<td>( 7.7 \cdot 10^{33} )</td>
<td>( 1.7 \cdot 10^{34} )</td>
<td>( 2 \cdot 10^{34} )</td>
<td>( 7 \cdot 10^{34} )</td>
<td>( 7 \cdot 10^{34} )</td>
</tr>
<tr>
<td>LHCb ( L_{\text{peak}} ) (cm(^{-2}) s(^{-1}))</td>
<td>( 2 - 4 \cdot 10^{32} )</td>
<td>( 2 - 4 \cdot 10^{32} )</td>
<td>( 2 \cdot 10^{33} )</td>
<td>( 2 \cdot 10^{33} )</td>
<td>( &gt; 10^{34} )</td>
</tr>
</tbody>
</table>

This talk: R&D developed in the context of the LHCb Upgrade Ib (LHC Run 4 and beyond), specifically aimed at the reconstruction of long-lived particles.
LHCb Upgrade 1 (Run 3)

**Upgrade (current) Conditions**
- visible interactions=5.5 (1.1)
- $\sqrt{s}=14$ TeV (13 TeV)
- lumi: $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ ($4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$)
- expected integrated lumi: 50 fb$^{-1}$ (8 fb$^{-1}$)

**Key Changes**
- VERTex LOcator
  - From strip sensors to hybrid pixel detectors
  - Closer to the beam (from 8.2 mm to 5.1 mm)
  - CO$_2$ cooling in micro-channel substrate
  - New RF box
  - Fluence in the innermost region $8 \times 10^{15}$ MeV neq cm$^{-2}$

- Upstream Tracker
  - 4 planes (x-u-v-x) of Si strips sensors
  - Staves staggered: overlap in x
  - Closer to the beam pipe
  - Finer granularity
  - Bi-phase CO2 cooling in stave support

- SCIntillating Fibres
  - Scintillating fibres as active detector elements
  - 3 stations with 4 detection layers (x-u-v-x)
  - $2 \times 2.5$ m long modules with mirror in the middle
  - Readout with SiPMs at the outer edge

- Silicon Inner Tracker will be removed.

Major upgrade of the electronics to allow the read-out of all sub-detectors at 40MHz.
LHCb acceptance of LLPs

- Considering only VELO, LHCb il long about 50 cm.
- First UT layer is 2.3 m from the interaction point.
- Assuming an average momentum of 20GeV for LLPs, LHCb acceptance increases
  - $K_S$: $N_{DD} \approx 1.3 \, N_{LL}$ (x2.3 in stat.)
  - $K_L$: $N_{DD} \approx 3.4 \, N_{LL}$ (x4.4 in stat.)
  - $\Lambda$: $N_{DD} \approx 1.7 \, N_{LL}$ (x2.7 in stat.)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (MeV)</th>
<th>$\tau$</th>
<th>$L = \beta \gamma c \tau$ (at $p=20$GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>1864</td>
<td>123μm</td>
<td>1.3mm</td>
</tr>
<tr>
<td>$B^0$</td>
<td>5279</td>
<td>456μm</td>
<td>1.7mm</td>
</tr>
<tr>
<td>$K_S$</td>
<td>497</td>
<td>2.7cm</td>
<td>108cm</td>
</tr>
<tr>
<td>$K_L$</td>
<td>497</td>
<td>15.3m</td>
<td>615m</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1115</td>
<td>7.9cm</td>
<td>141cm</td>
</tr>
</tbody>
</table>

Long Lived Particles at LHCb
LHCb-Upgrade readout system

Figure 2.23: The architecture of LHCb Upgrade-I readout-system.
DAQ Integration

Table 3.1: Number of Event Builder PC nodes for each LHCb Upgrade sub-detectors.

<table>
<thead>
<tr>
<th>Sub-detectors</th>
<th>VELO</th>
<th>UT SciFi</th>
<th>RICH</th>
<th>Calorimeter</th>
<th>Muons</th>
<th>EB node</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB node</td>
<td>56</td>
<td>72</td>
<td>156</td>
<td>114</td>
<td>55</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 3.5: Integration scheme of the Downstream Tracker into the LHCb Upgrade Event Builder system.

3.4 Implementation details

The architecture described in previous sections is flexible and largely scalable. Without significant loss of generality, we will in the following make reference to straight
Envisioned architecture

- 156 Event Builder PC nodes dedicated to the SciFi tracker.
  - half receives raw hits from the x-layers and the second half receives raw hits from the tilted u/v-layers.

- Each EB node has to be instrumented with a “tracking board” equipped with a modern FPGA (at least ~1MLEs per chip is needed) interconnected through PCIe card (100 Gbit/s).

- Two optical Patch Panels and Switching Networks needed to distribute x-hits and u/v-hits inter boards.

- The axial retina ($10^5$ cells) is distributed over 78 tracking boards (left side), while each stereo tracking board (right side) should host at least 3 different stereo retinas ($355$ cells each).

- Once axial tracks are ready, they are sent (green arrows) to the corresponding stereo retinas for the “stereo association”, with a total latency of the process of $\sim 1 \mu s$, well below the Event Builder timing constraints.
Track model

- A small component of magnetic field (fringe field) is present in the SciFi region.

\[ \frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B} \]

- Assuming \( B_y \) small and constant over the x-z plane:

\[ x(z) = x_0 + t_x(z - z_0) + \frac{q B_y}{p} \left( z - z_0 \right)^2 \]

- Assuming null \( B_x \) and \( B_z \) components:

\[ y(z) = y_0 + t_y(z - z_0) \]
A biologically inspired architecture: the Retina Algorithm

Massively parallel architecture. Similarities with Hough transform and associative memories for pattern matching.

- **Step 0** - Discretize space of track parameters (pattern cells) and generate track intersections with detector planes (receptors) and connect them to cells (mapping).

- **Step 1** - Detector hits are distributed (Switching Network) only to a reduced number of cells according the mapping of Step 0 (LUT).

- **Step 2** - A logic unit (engine) for each cell accumulates a Gaussian weight proportional to the distance with the receptors.

- **Step 3** - Tracks are identified as local maxima of accumulated weights, above a certain threshold, over the cells grid.

Conceived for parallelism: processing before the event building.
LHCb-Upgrade SciFi Simulation

- Official LHCb-Upgrade simulation:
  - pp collisions with PYTHIA;
  - Particle interaction with detect layers usign GEANT4 toolkit;
  - Accurate simulation of hits digitization (energy deposits, spillover, noise, inefficiencies, light attenuation in the fibre, clustering, read-out electronic chain, etc)

- Simulated LHCb-Upgrade conditions:
  - $\sqrt{s} = 14$ TeV;
  - LHC bunch spacing = 25 ns;
  - $L = 2 \times 10^{33} \text{cm}^2\text{s}^{-1}$;
  - $\nu = 7.6$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Nb. Events</th>
<th>Decay Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>1,000</td>
<td>Minimum-Bias</td>
</tr>
<tr>
<td>Sample 2</td>
<td>1,000</td>
<td>$D^{<em>+} \rightarrow D^{</em>+} \rightarrow D^{0}\pi^{+} \rightarrow [K^{0}_{S}\pi^{+}\pi^{-}]\pi^{+}$</td>
</tr>
<tr>
<td>Sample 3</td>
<td>1,000</td>
<td>$B^{0}_{s} \rightarrow \phi\phi \rightarrow [K^{+}K^{-}] [K^{+}K^{-}]$</td>
</tr>
</tbody>
</table>

![Simulation graphs](image)
Occupancy

Figure 4.1: Distribution of the number of hits for the first axial layer (n. 0x) and the last stereo layer (n. 10v) of the SciFi subdetector.
Tracking indicators

Efficiency:

\[ \varepsilon_{\text{Tracking}} = \frac{\text{reconstructed & matched}}{\text{reconstructible}} \]

Ghost rate:

\[ \text{ghost rate} = \frac{\text{reconstructed not matched}}{\text{reconstructed}} \]

A reconstructed track is said to be “truth-matched” to a simulated track if both the axial and stereo maxima are contained in a 3x3 square centered at the true track parameters position.

<table>
<thead>
<tr>
<th>Name</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>hasT</td>
<td>reconstructible in SciFi</td>
</tr>
<tr>
<td>down (or downstream)</td>
<td>reconstructible in SciFi and UT</td>
</tr>
<tr>
<td>long</td>
<td>reconstructible in VELO and SciFi</td>
</tr>
<tr>
<td>noVelo</td>
<td>not reconstructible in the VELO</td>
</tr>
<tr>
<td>strange from B</td>
<td>daughter of a strange particle (( K^0 ), ( \Lambda ), ..)</td>
</tr>
<tr>
<td>strange from D</td>
<td>belongs to the decay chain of a ( b ) hadron</td>
</tr>
<tr>
<td></td>
<td>belongs to the decay chain of a ( c ) hadron</td>
</tr>
</tbody>
</table>

Table 5.1: Selections used by the performances indicators.
Number of combinations

Axial

Stereo

Entries 2916
Mean 7.19
Std Dev 8.97

Entries 4652
Mean 56.5
Std Dev 74.1
Remove axial false positive

![Histogram of axial track $\chi^2_A$](image)

- **Entries**: 1719
- **Mean**: 5.38
- **Std Dev**: 9.24

$\chi^2_A < 20$

Truth-matched tracks

False positive tracks

axial track $\chi^2_A$
Figure 6.1: Graphical representation of the extraction of the y\(_{u/v}\)-coordinate intersection, given the x\(_{measured, u/v}\) coordinate of the \(u/v\)-hit of a stereo SciFi layer and the predicted x\(_{pred, u/v}\)-coordinate of the reconstructed axial track candidate. The y\(_{u/v}\)-coordinate (red dot) comes from the intersection of the \(u/v\)-hit (green line in the bottom figure) with a straight line parallel to the y axis and passing through the x\(_{pred, u/v}\)-coordinate (vertical black dashed line in the bottom figure). Only \(u/v\)-hits compatible with the axial track projection (transparent red band in the bottom figure) are sent to the stereo retina.
Stereo retina

Figure 6.4: Excitation level of two stereo retinas filled with SciFi subdetector hits from fully simulated LHCb Upgrade events. True tracks (yellow stars), reconstructed track candidates (red dots), and truth-matched reconstructed track candidates (black dots) are superimposed.