Triggering the Future: Fast Muon Detection for the HL-LHC Era

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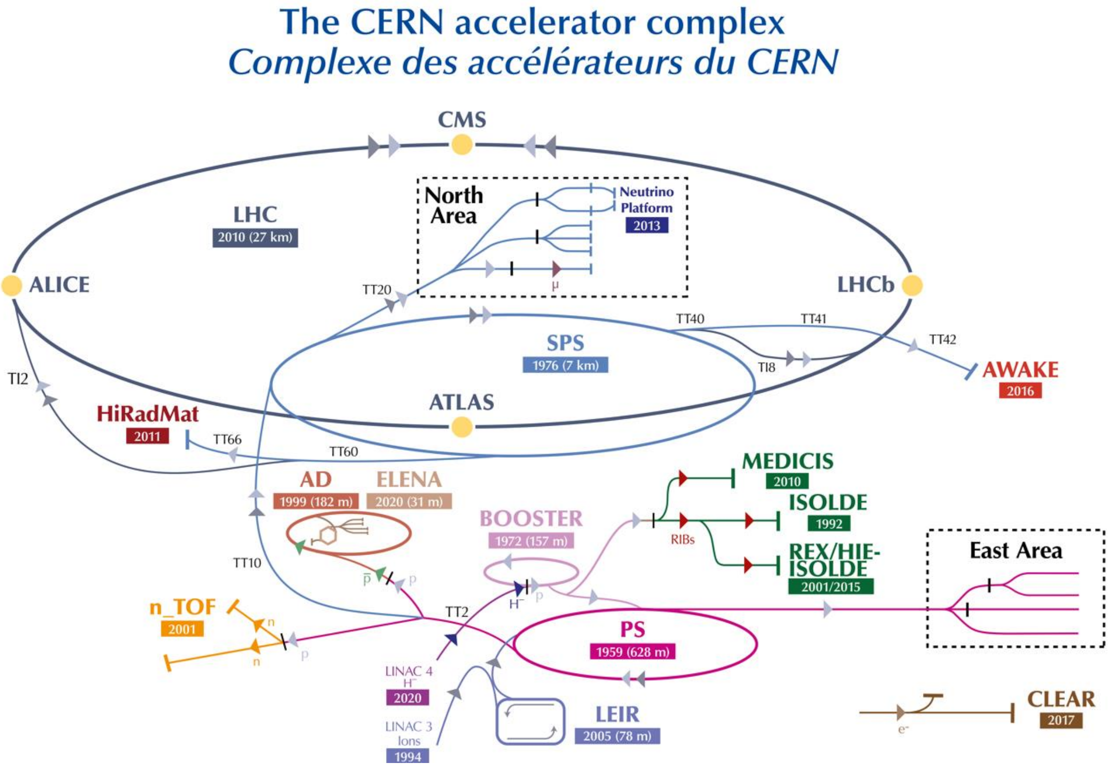
The Large Hadron Collider

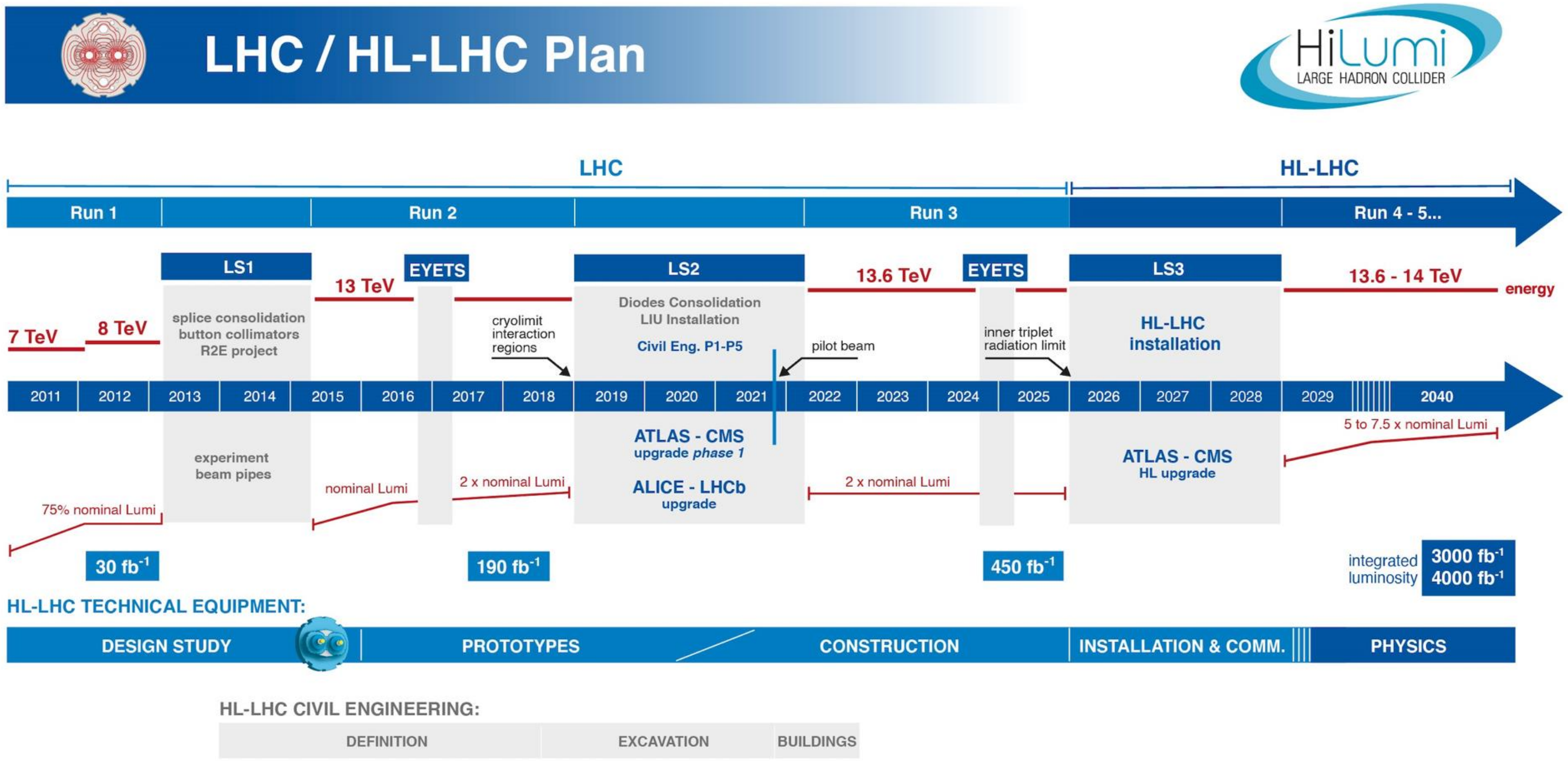
- The Large Hadron Collider (LHC) @ CERN is the largest proton-proton and ion-ion collider in the world.
- Underground 27-km ring, where particles collide every 25 ns with $\sqrt{s} = 13.6$ TeV.
- It aims at exploring the fundamental interactions, test the Standard Model (SM) and search for new physics beyond the Standard Model (BSM).
- **2012:** Discovery of the Higgs boson from the ATLAS and CMS experiments → Nobel Prize to Higgs and Englert



LHC and HL-LHC plan

Hi-Lumi LHC project web page

- Upgrade of the LHC collider during the next Long-Shutdown (LS3).
- Higher energy → 14 TeV
- Higher luminosity → more collisions → new physics potential!



What does this mean on the detector side?

Experiments @ HL-LHC

Benefits

- Instantaneous luminosity ($N_{collisions}$ per second per cm^2) up to $7.5 \cdot\ 10^{34}\ cm^{-2}s^{-1}$ @ 14 TeV (x7.5 the design LHC value)
- Integrated luminosity of $4000\ fb^{-1}$
- Enormous statistics
- Precision physics in the Higgs sector
- Access to rare or new processes?

New detector challenges

- Increased average number of interactions per bunch crossing (pile-up)
- Higher background
- Stringent detector and trigger requirements
- High rate of detector data to be handled
- Enormous amount of fully-reconstructed events to be stored.

Phase-II ATLAS upgrade

New **RPC (Resistive Plate Chambers)** and **sMDT (small Monitored Drift Tubes)** muon detectors in the barrel inner region.

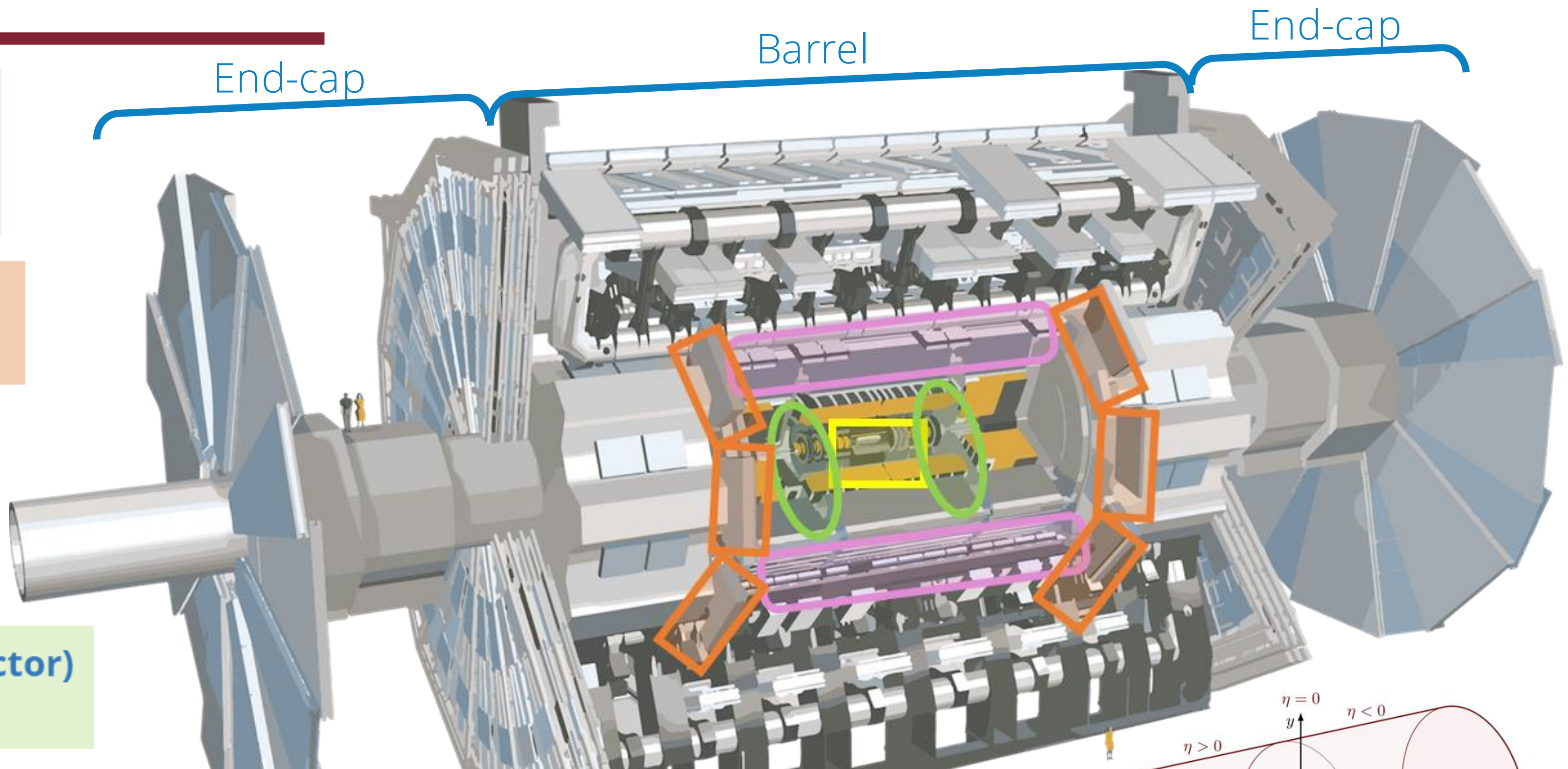
New **sTGCs (small Thin Gap Chambers)** in the end-cap inner region.

New **ITk (Inner Tracker)** silicon inner tracker (pixels + strip detector) with eta coverage up to 4.

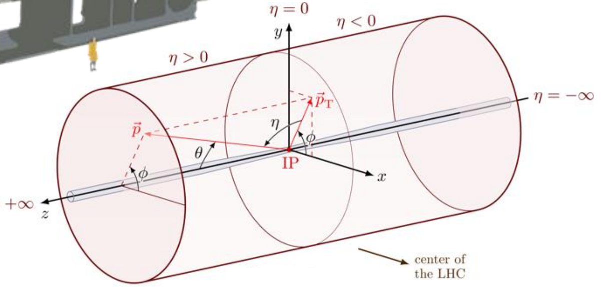
New **HGTD (High Granularity Timing Detector)** in the forward region.

New TDAQ off-detector electronics:

- **Level-0** FPGA-based **hardware trigger.**
- **FELIX readout** for all ATLAS detectors.
- **Event Filter processor** farm and hardware tracking.

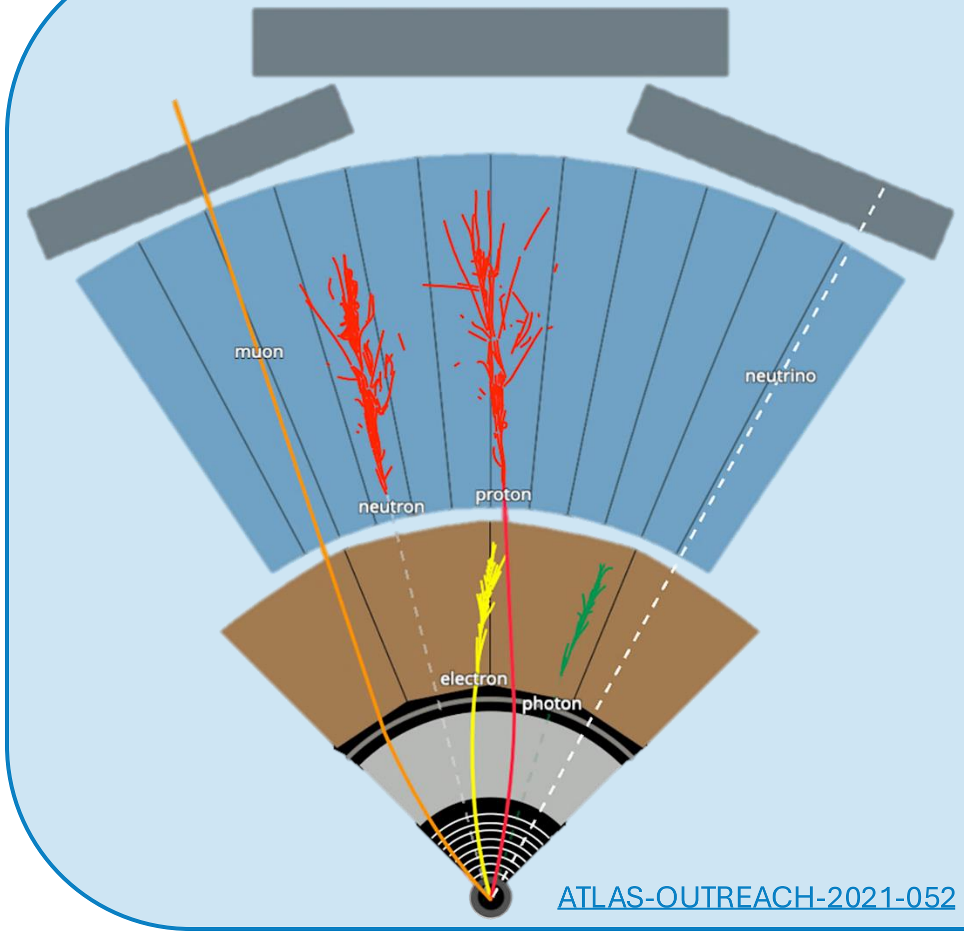


$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$



[ATLAS Collaboration Web page]

Muon spectrometer



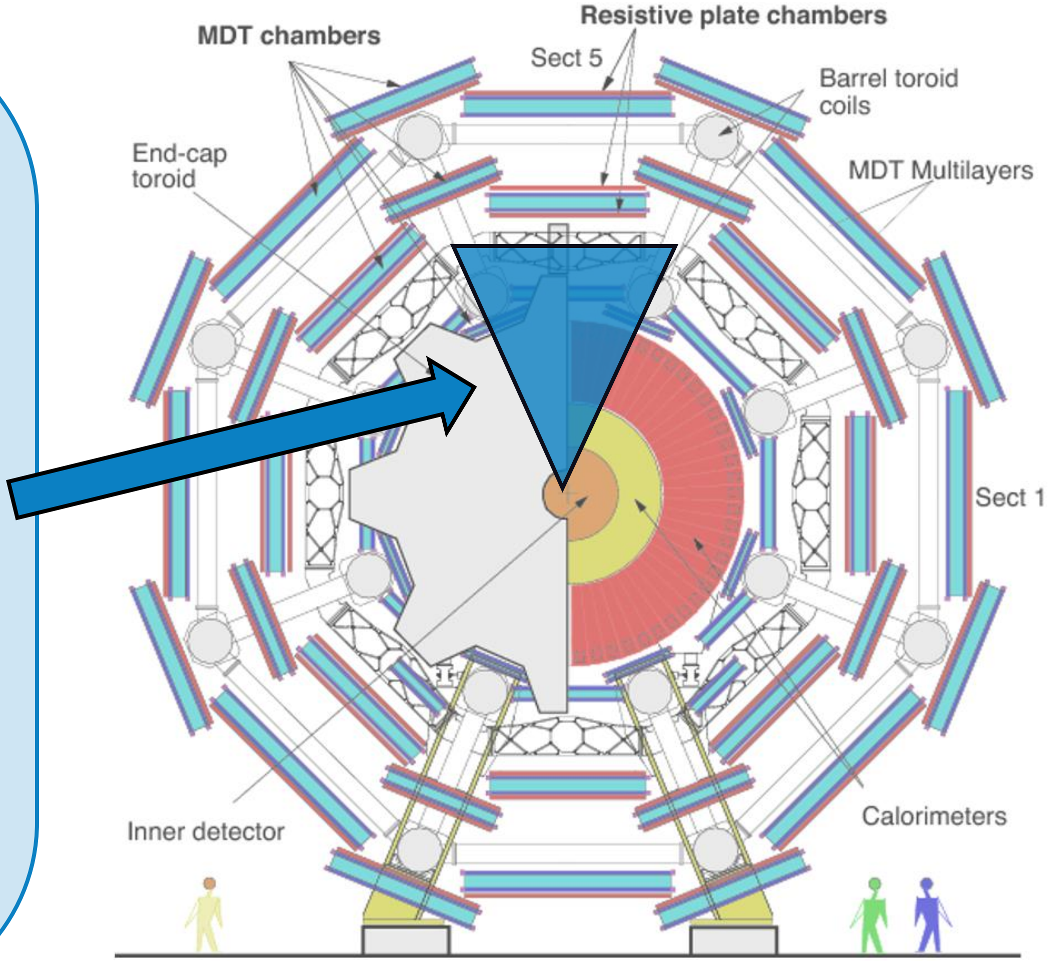
ATLAS-OUTREACH-2021-052

Muon spectrometer (MS)

Hadronic calorimeter

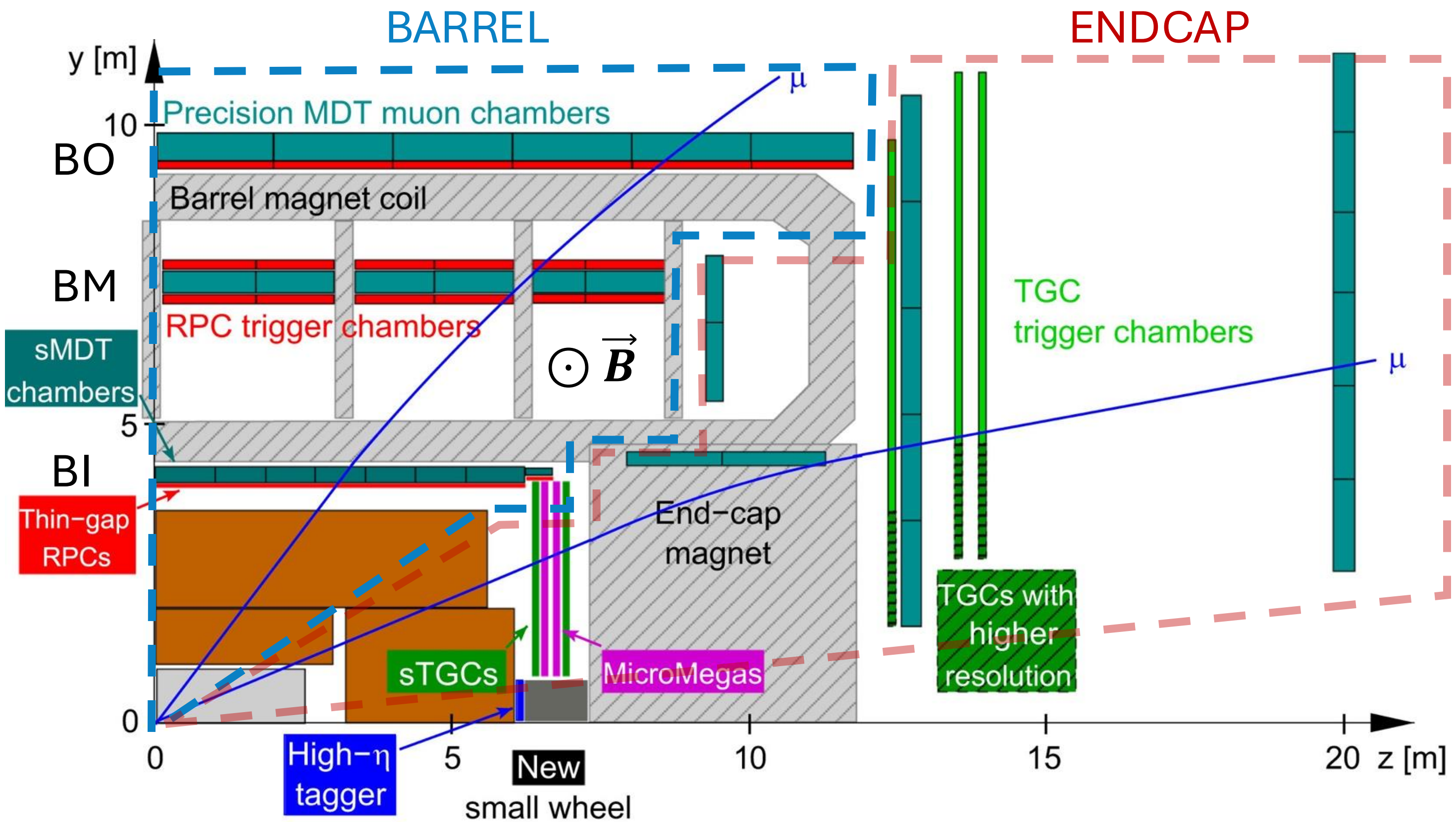
Electromagnetic calorimeter

Inner tracker



CERN-PH-EP-2010-045

Muon spectrometer



j.nima.2016.06.065

16 independent sectors along ϕ direction for both barrel and encap regions per each half of the detector (32 sectors in total)

BARREL: MDT, RPC
(trigger: RPC)

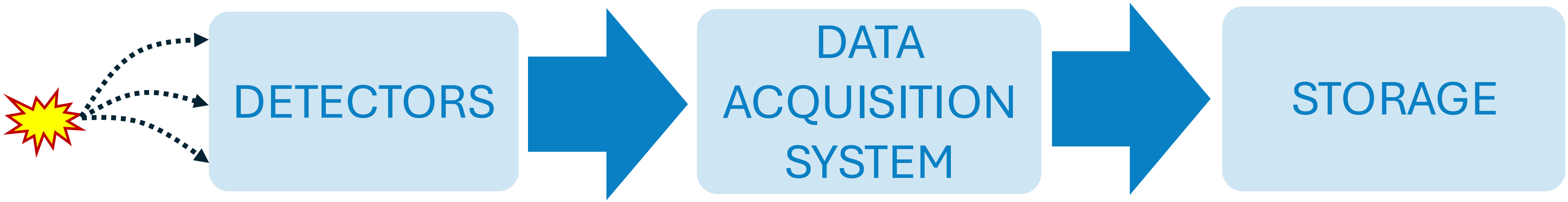
ENDCAP: sTGC, MM, TGC, MDT
(trigger: sTGC, MM, TGC)

Innermost BI (Barrel Inner) MDT layers will be replaced by sMDTs and BI RPCs and additional sTGC in the endcaps.

Reduction of trigger fake rate, and increase in geometrical coverage and trigger performances

ATLAS Trigger System

IDEAL CASE



ATLAS Trigger System

REAL CASE

Why do we need a trigger system?

- Collisions every 25 ns → millions of collisions per second, but only a few interesting events (e.g., ~1 Higgs Boson per second!)
- Too many PB of data!

$$40\ MHz \cdot 1.5 \frac{MB}{event} \sim 60 \frac{PB}{s}$$

ATLAS Trigger System

The trigger system selects interesting events reducing the amount of data passed to the storage disks

Two-level trigger → hardware and software

Algorithms with low latency and low consumption of the hardware resources

Collisions @ 40 MHz

Hardware Trigger (Level-1/0)

First-selection data @ 100 kHz

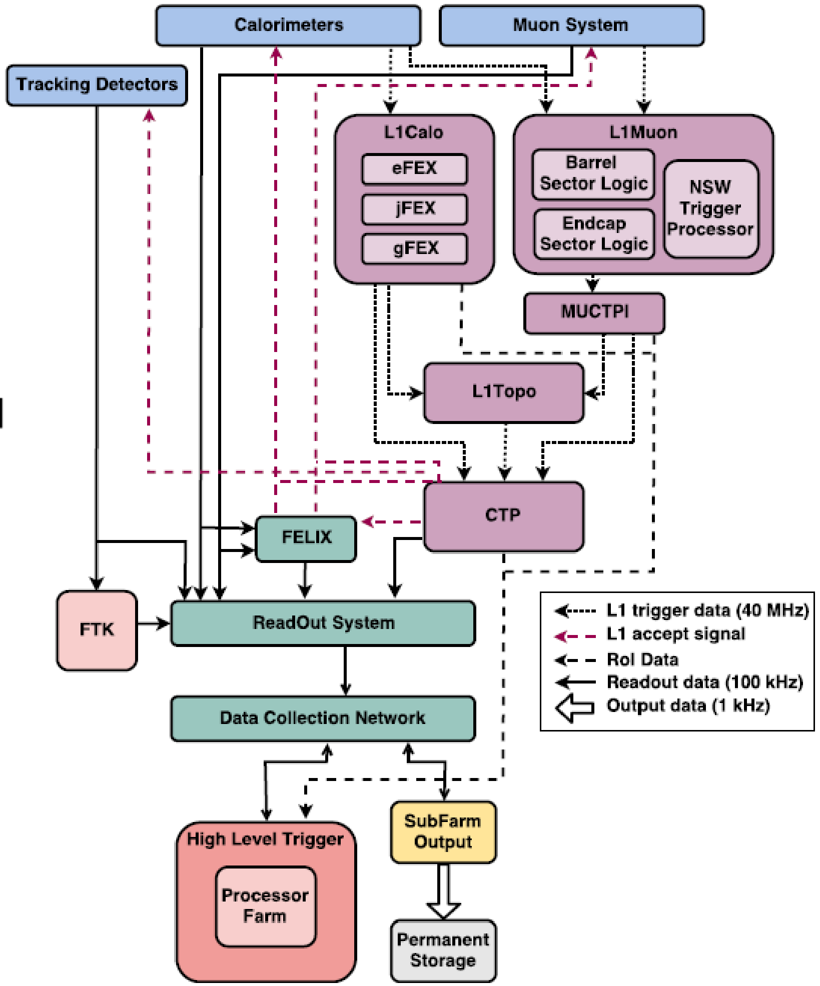
High-Level Trigger/ Event Filter

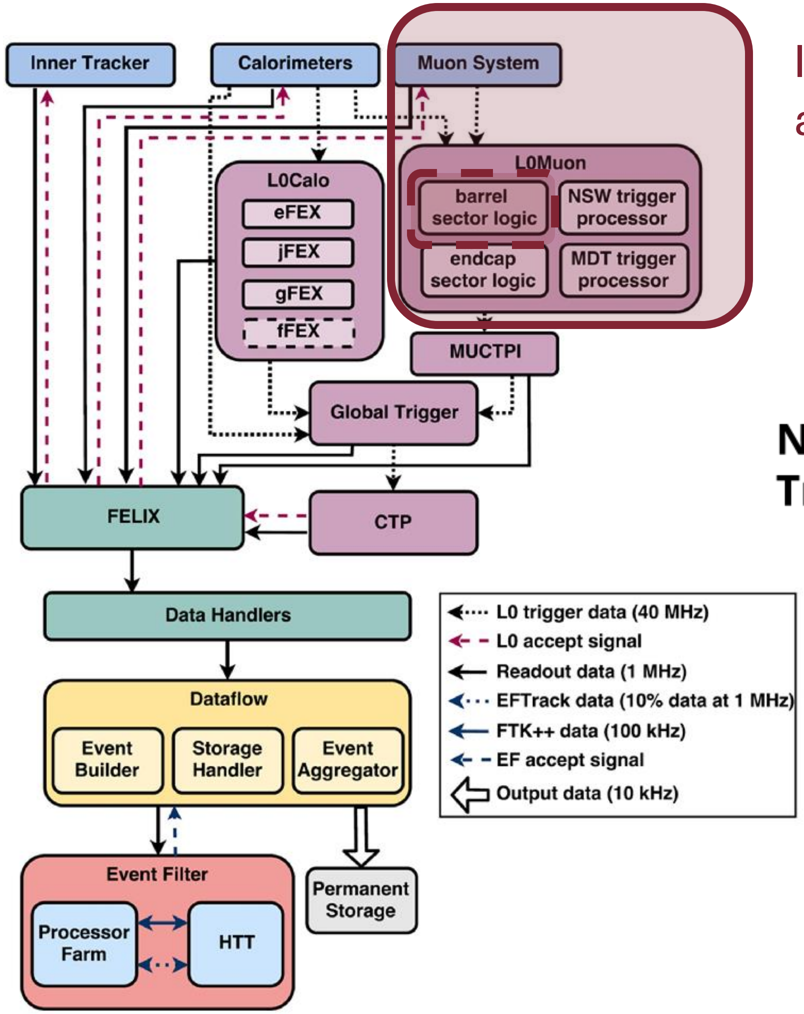
Accepted events @ 10 kHz

Storage Disks

Current/New Trigger

Current Level-1 Trigger System





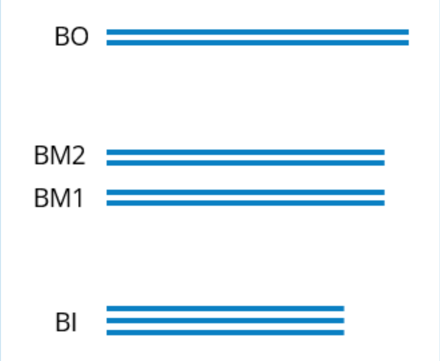
INFN RomaI and Sapienza

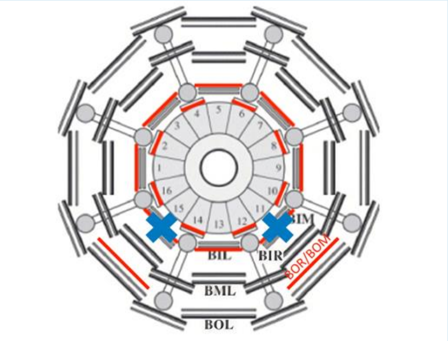
New Level-0 Trigger System

L0Muon Barrel Trigger

Phase-II MS Barrel Layout

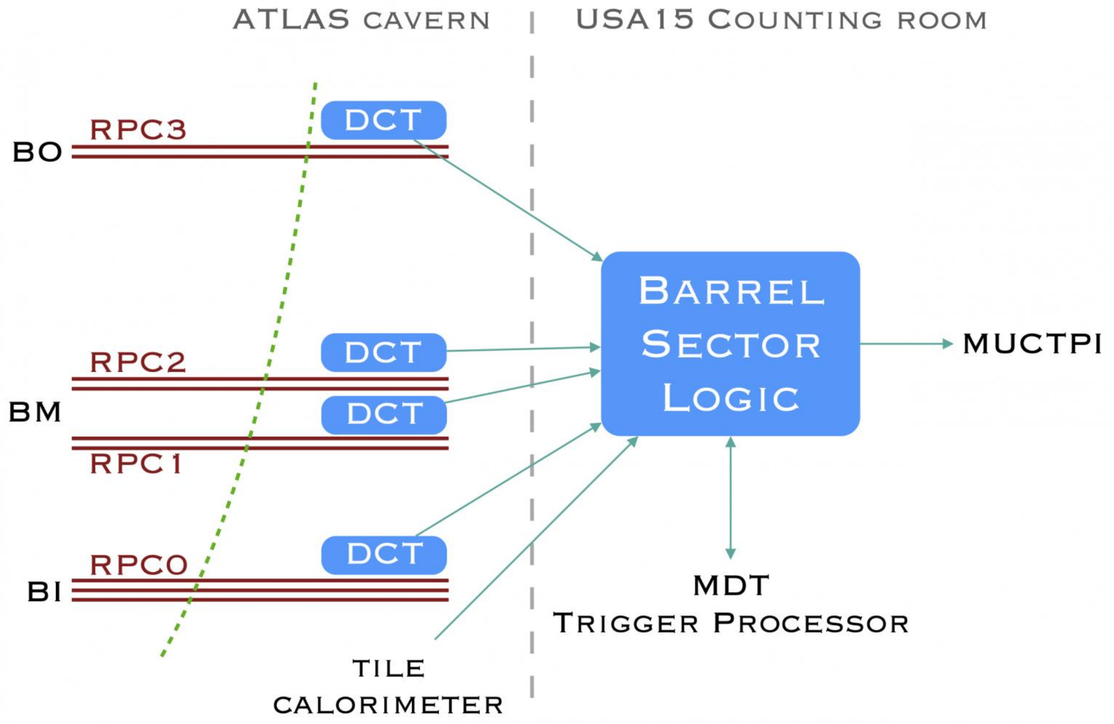
- 9 RPC concentric layers in each Phi-sector.
- BM and BO have strips in both eta and phi direction.
- BI only have eta strips with front-end electronics on both sides → phi coordinate is obtained through centroid calculations.
- In the regions with the detector support structure, “feet”, i.e., sector 11 and 15, no BI stations, but additional BO chambers.





ATL-UPGRADE-PROC-2022-003

(On-detector) (Off-detector)



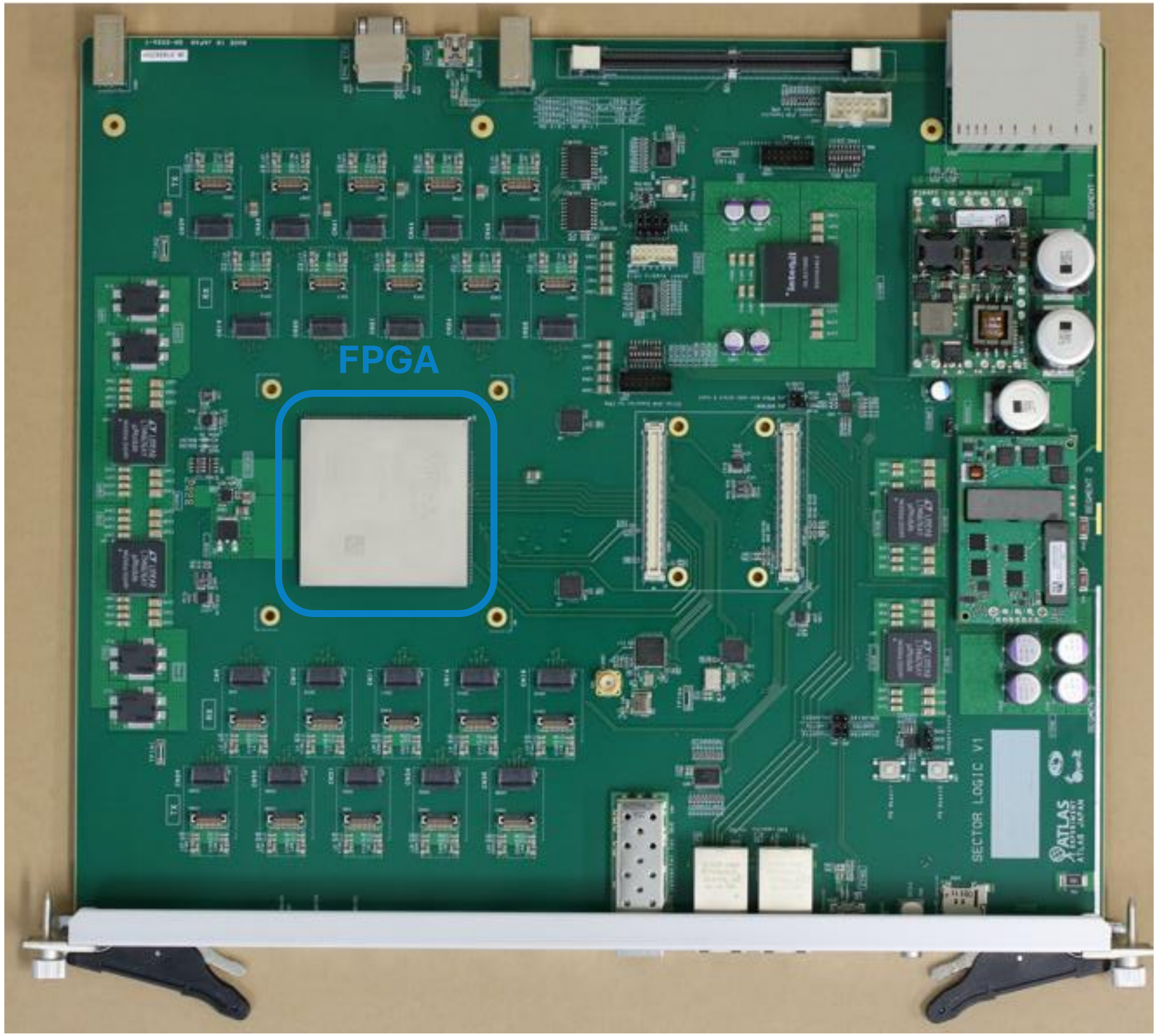
ATLAS Roma I Web page

Increased geometrical acceptance from ~75 % to ~95%.

New on-detector electronics and off-detector full digital read-out @ 40 MHz.

Barrel Sector Logic

- 32 FPGA-based off-detector boards.
- Each board (Sector Logic, SL) receives hits from the RPC detectors in a given ϕ-sector of the MS.
- Latency: ~390 ns.
- Clock: 320 MHz

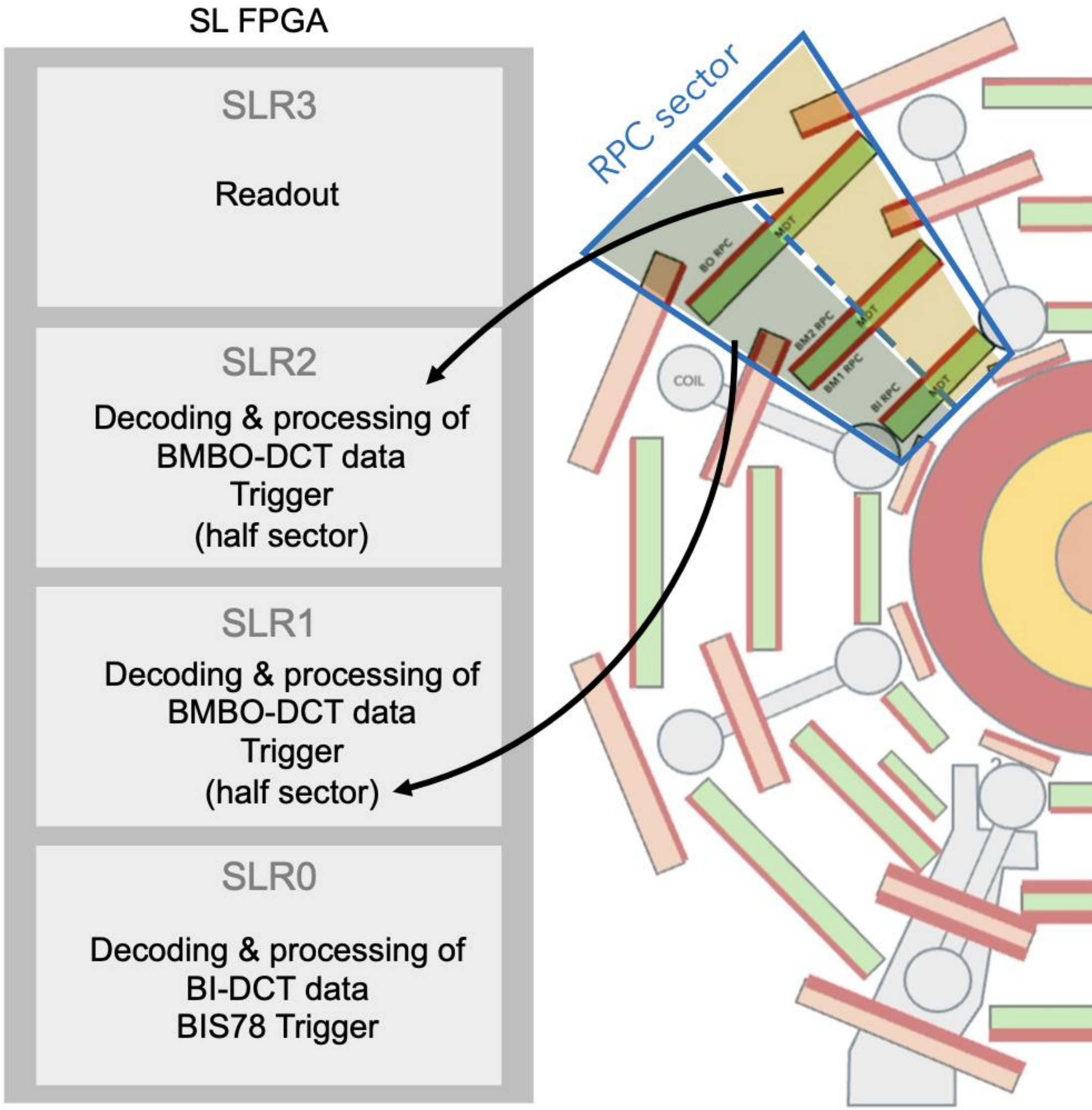


(from F. Morodei's slides)

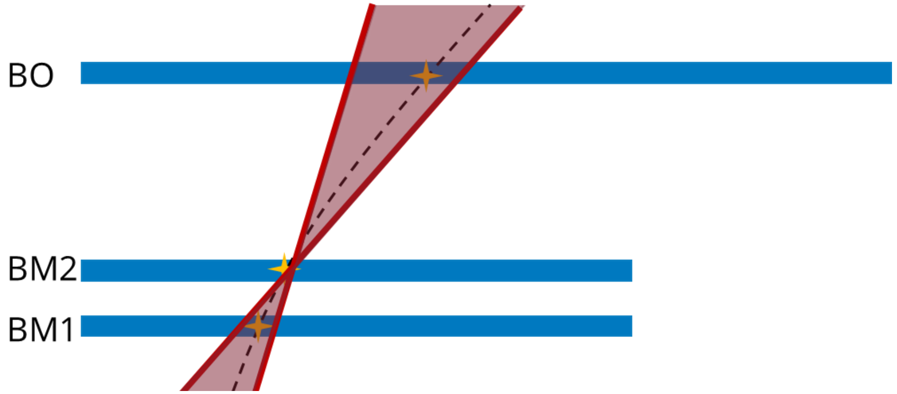
SL FPGA Firmware

XCVU13P **FPGA** divided into 4 Super Logic Regions (SLRs)

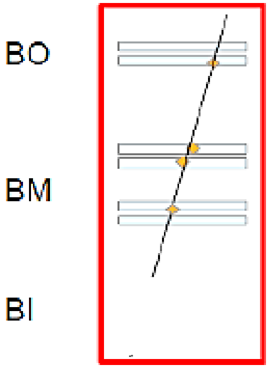
- All BI-DCT data → SLR0 → SLR1/SLR2
- ½ BMBO-DCT data → SLR1 → trigger algorithm
- ½ BMBO-DCT data → SLR2 → trigger algorithm
- All DCT data → SLR3 → readout
- The trigger algorithm runs independently for the two halves of the sector in SLR1 and SLR2.



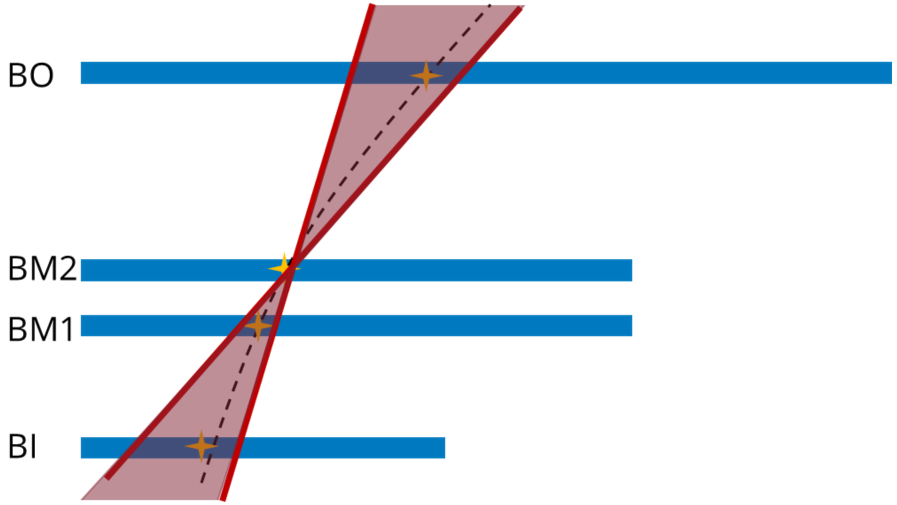
Trigger logic



Current trigger algorithm exploits a 2/3 (Barrel Medium (BM) + Barrel Outer (BO)) coincidence logic within a coincidence window around a pivot candidate (BM2).



Trigger logic



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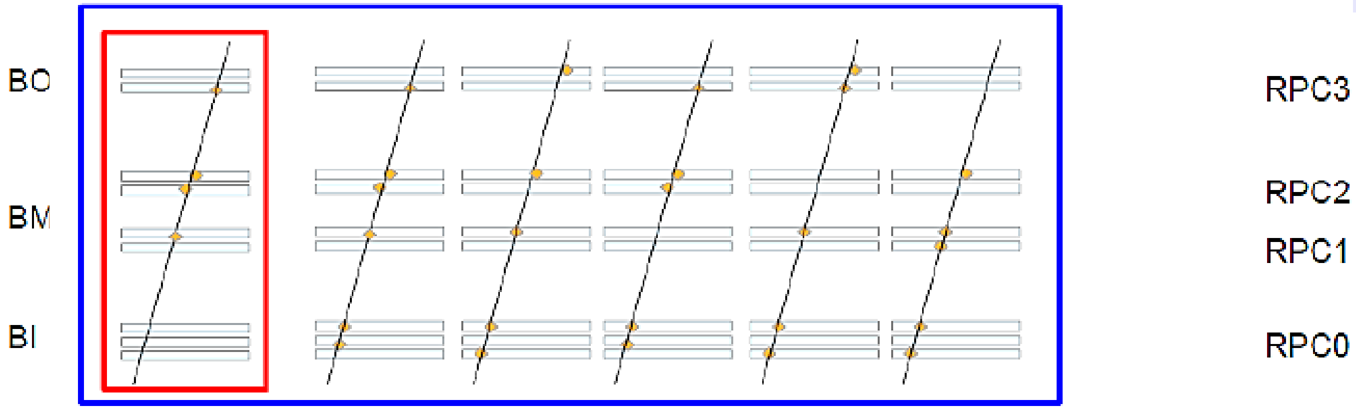
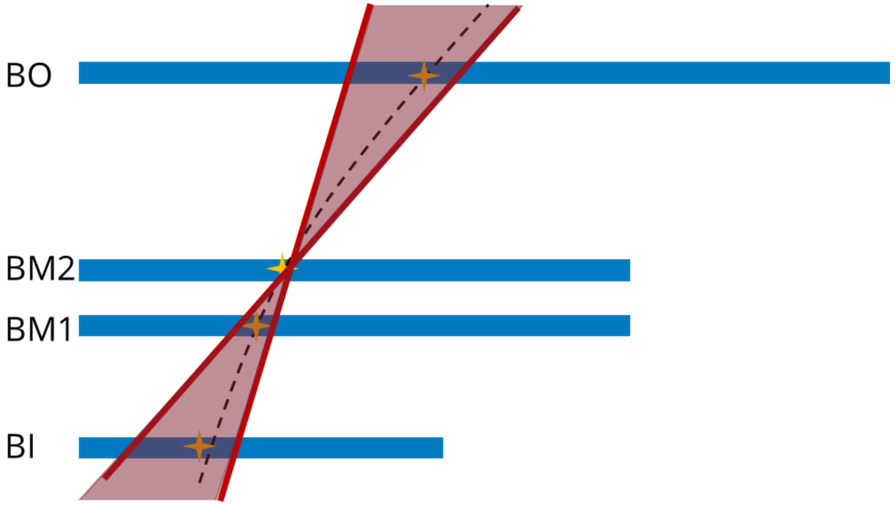
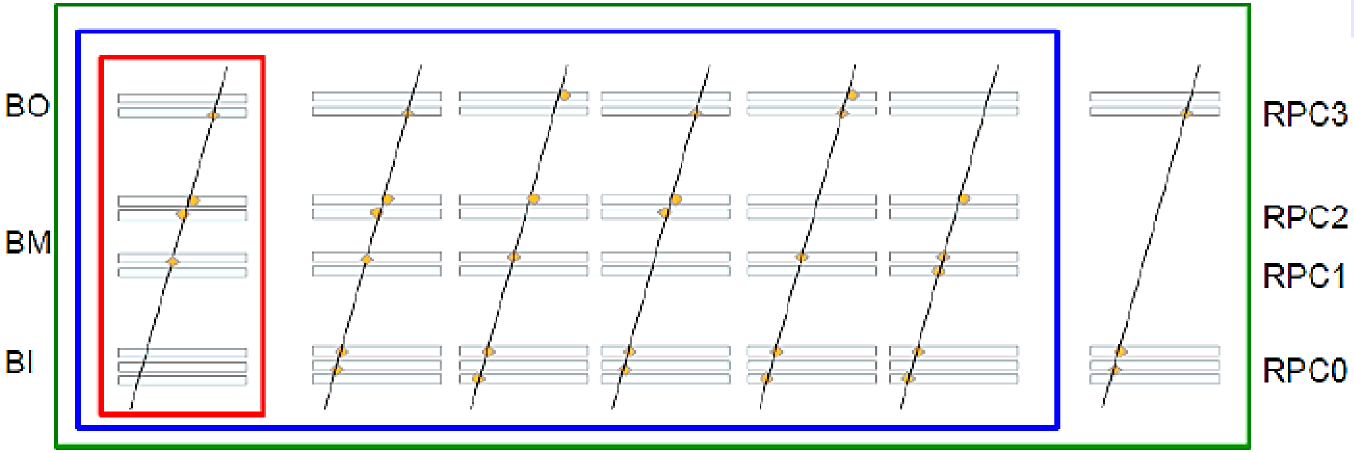
The straightforward extension of this trigger logic is to use 3/4 coincidence logic without any pivot candidate (all combinations are allowed!).



Trigger logic





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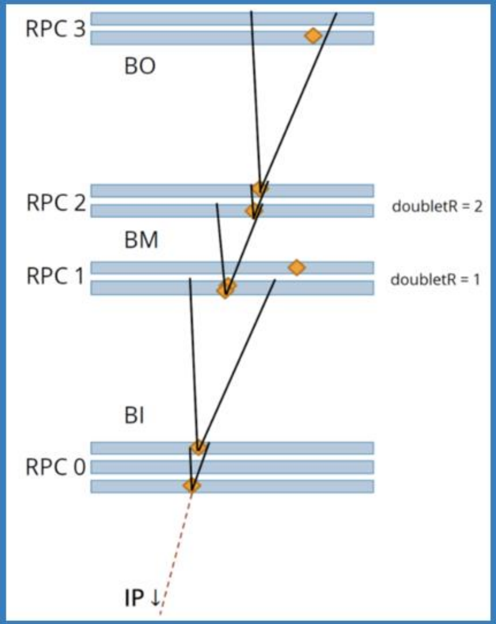
The straightforward extension of this trigger logic is to use 3/4 coincidence logic without any pivot candidate (all combinations are allowed!).

The final decision is to use the 3/4 without pivot + (BI & BO) logic to maximize geometrical acceptance.

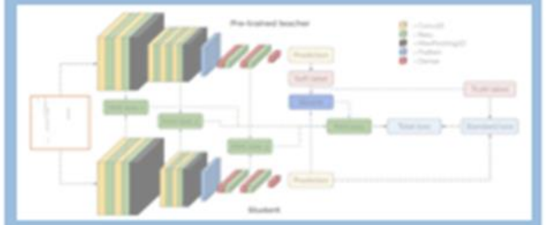
Trigger logic

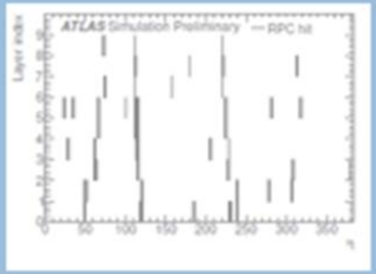
PatFinder



ATLAS-TDR-026

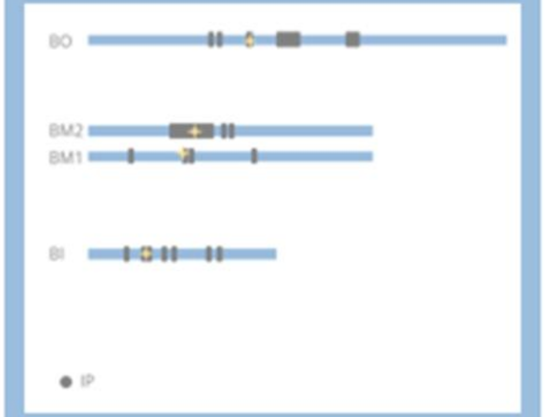
CNN and Q-CNN





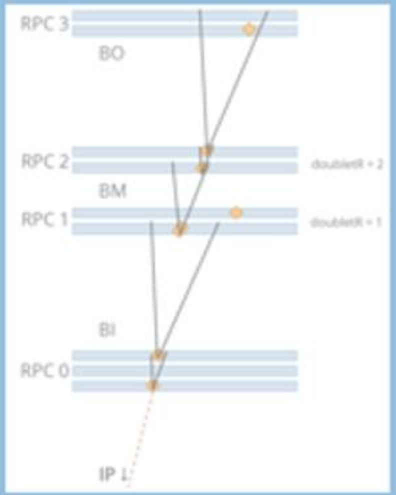
ATL-COM-DAQ-2019-189

Pattern-Matching



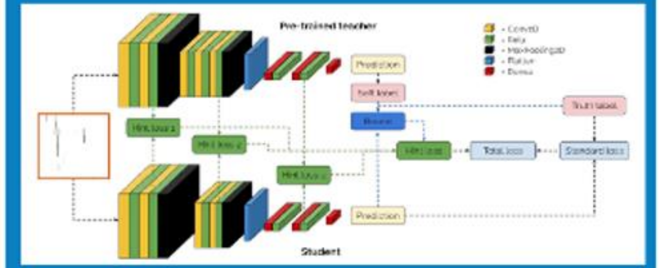
Trigger logic

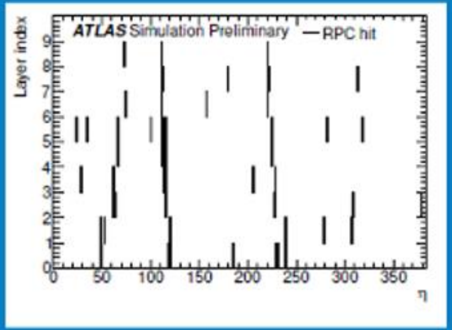
PatFinder



ATLAS-TDR-026

CNN, Q-CNN, GNN

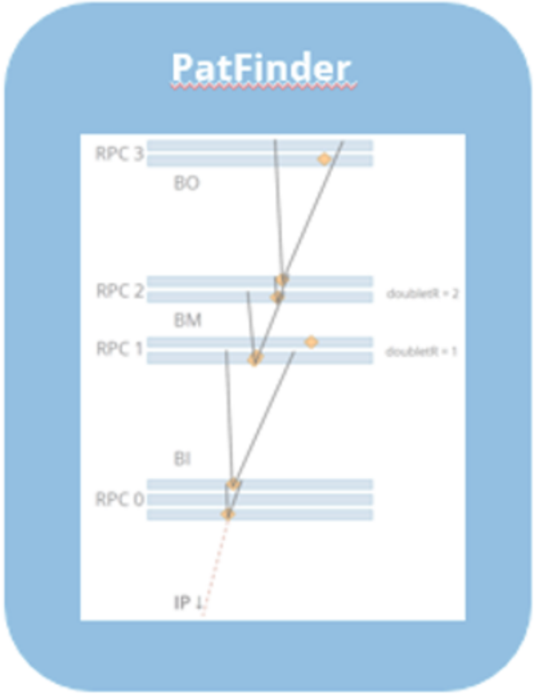




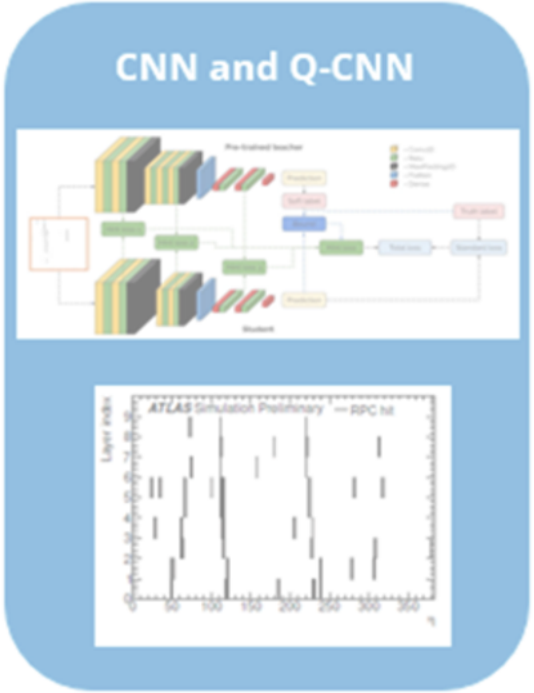
ATL-COM-DAQ-2019-189

Pattern-Matching

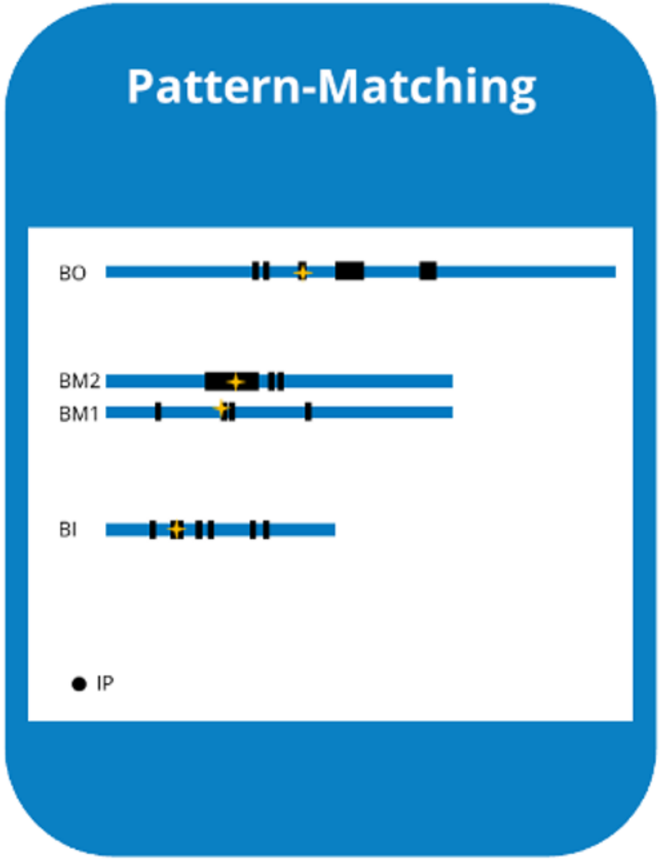
Trigger logic



ATLAS-TDR-026



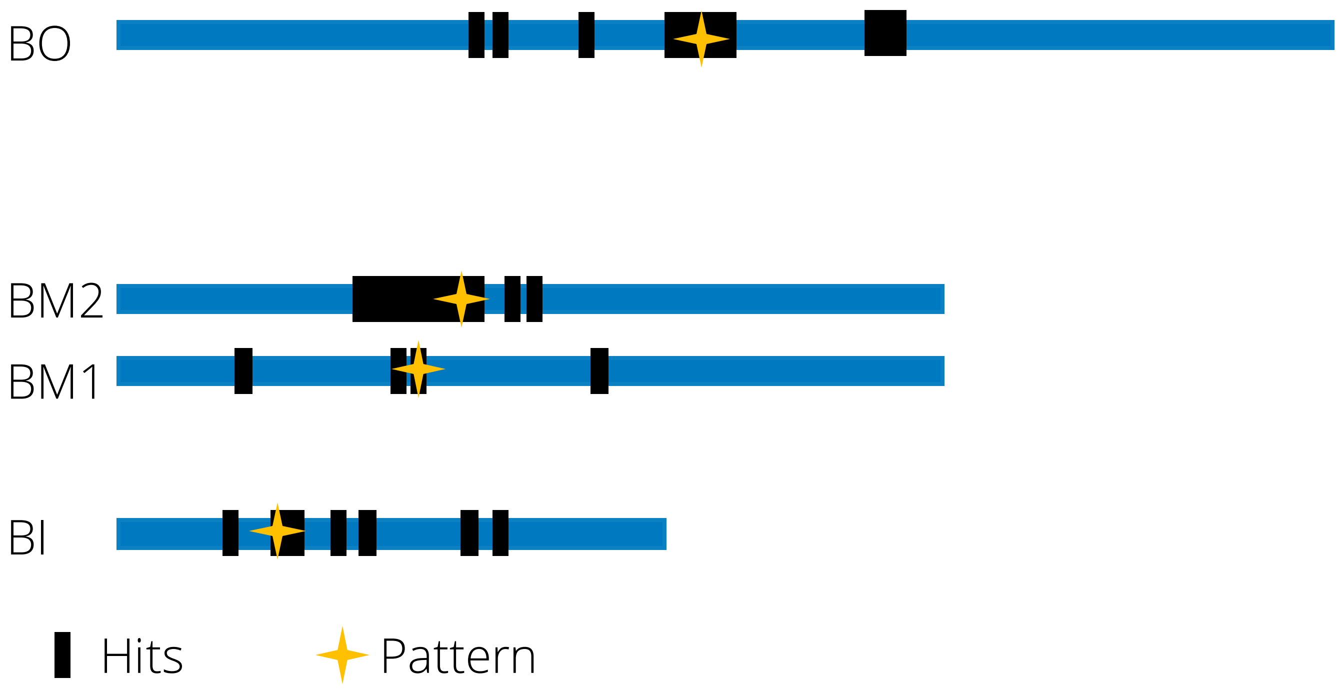
ATL-COM-DAQ-2019-189



Pattern-Matching

IDEA: look-up table of patterns.

- MC single-muons samples with uniform momentum distribution and 100% RPC efficiency.
- The OR of the two layers for doublets and the 2/3 majority for triplet BI stations is considered.
- 2 look up tables: eta and phi.

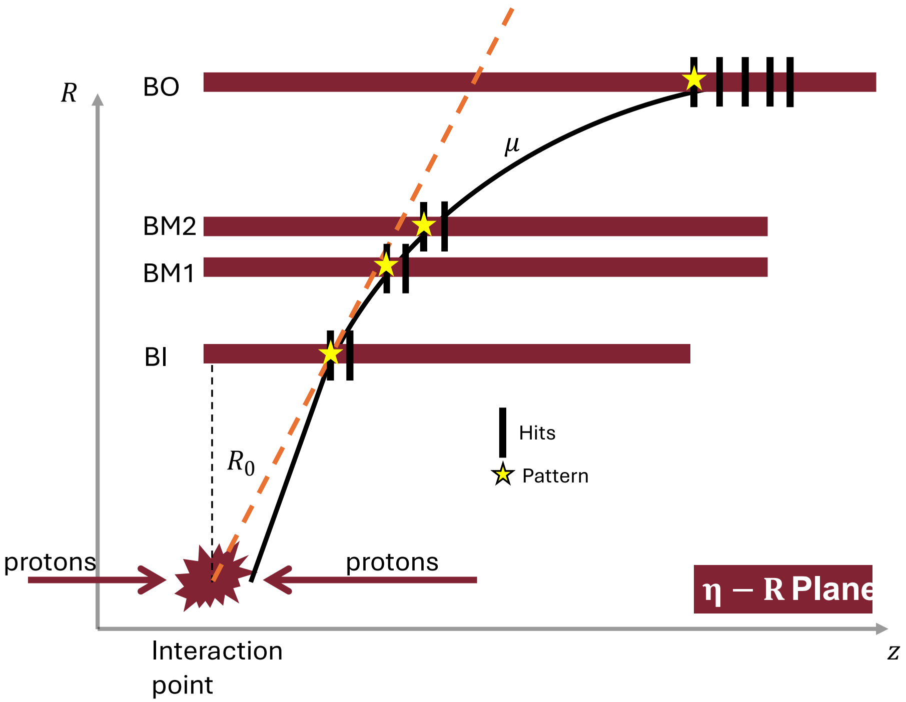


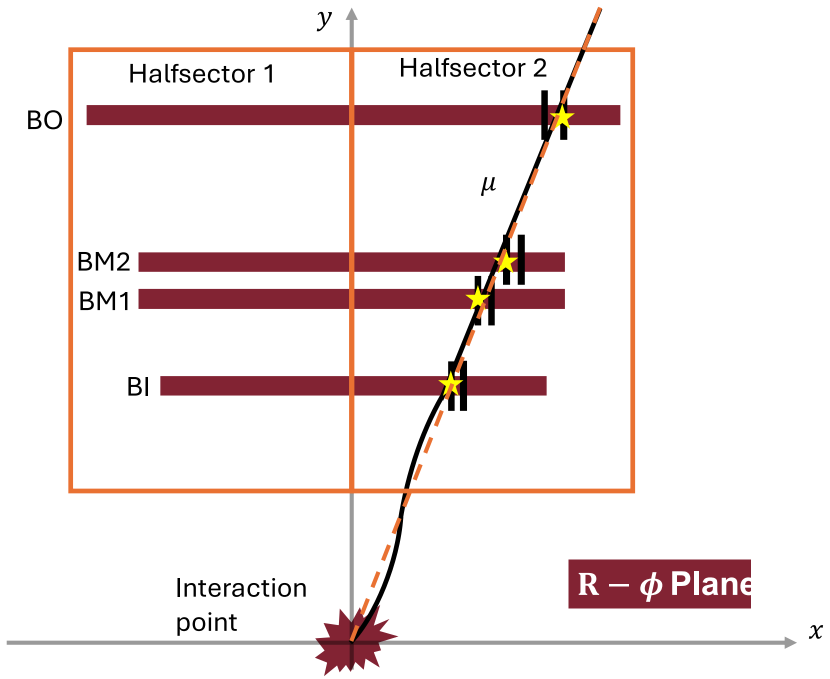
Pattern-Matching

Two separate tables of patterns in the $\eta - R$ and $\phi - R$ planes with the following structure:

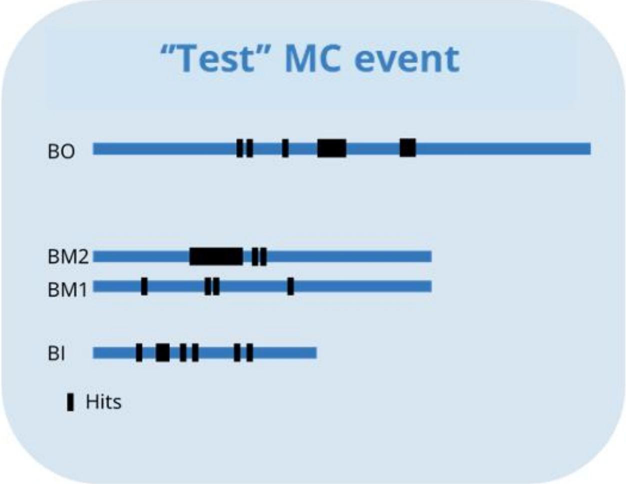
- Pattern η = [strip BI, strip BM1, strip BM2, strip BO] + chambers + average p_T + charge.
- Pattern ϕ = [strip BI, strip BM1, strip BM2, strip BO] + chambers + ϕ coordinate.

Each strip is identified via an integer number which is unique in each RPC station.





Pattern-Matching



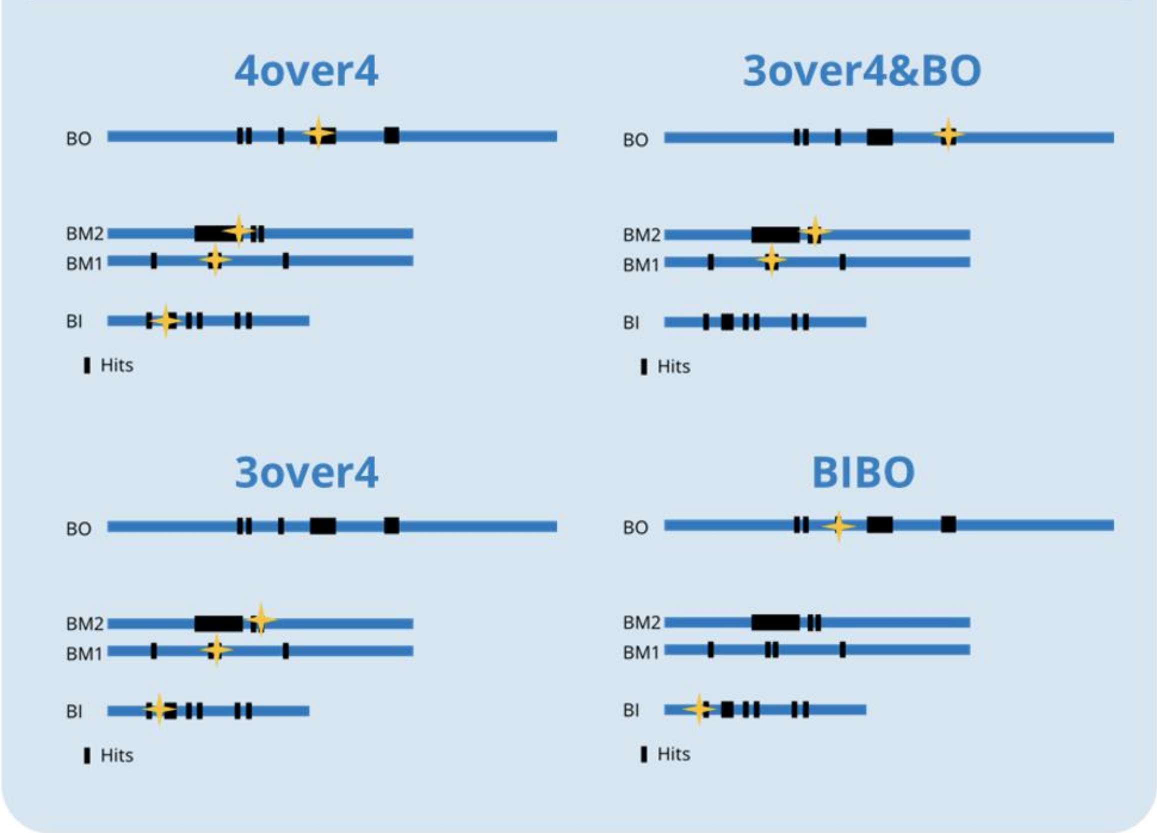
+

Pattern Database

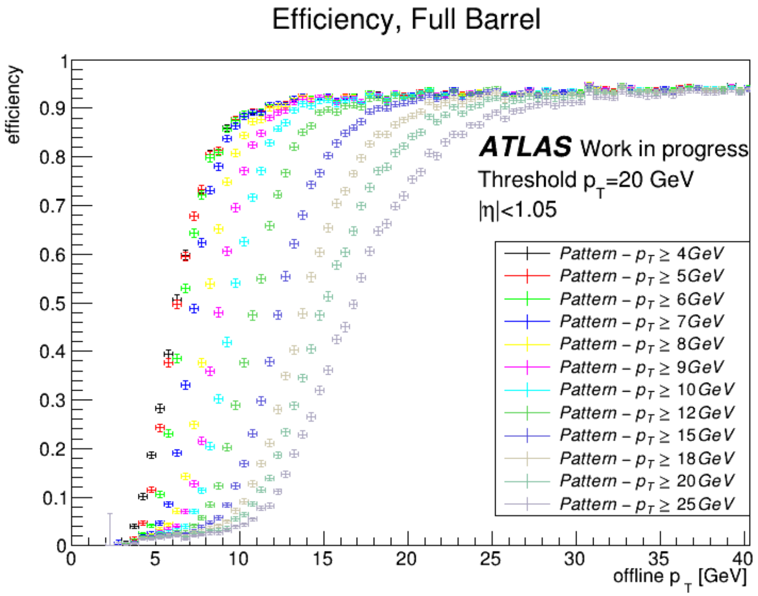
=

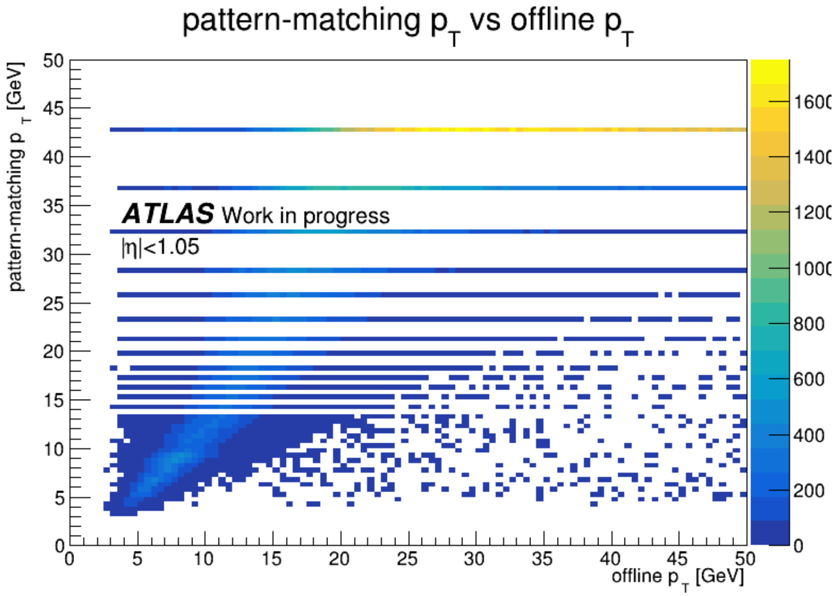
Matching failed

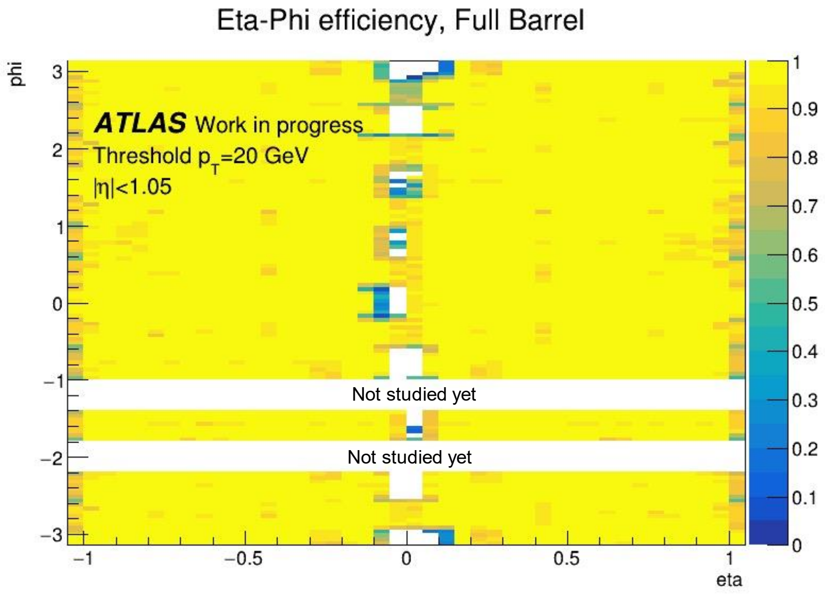
Successful matching – *'Priority'*



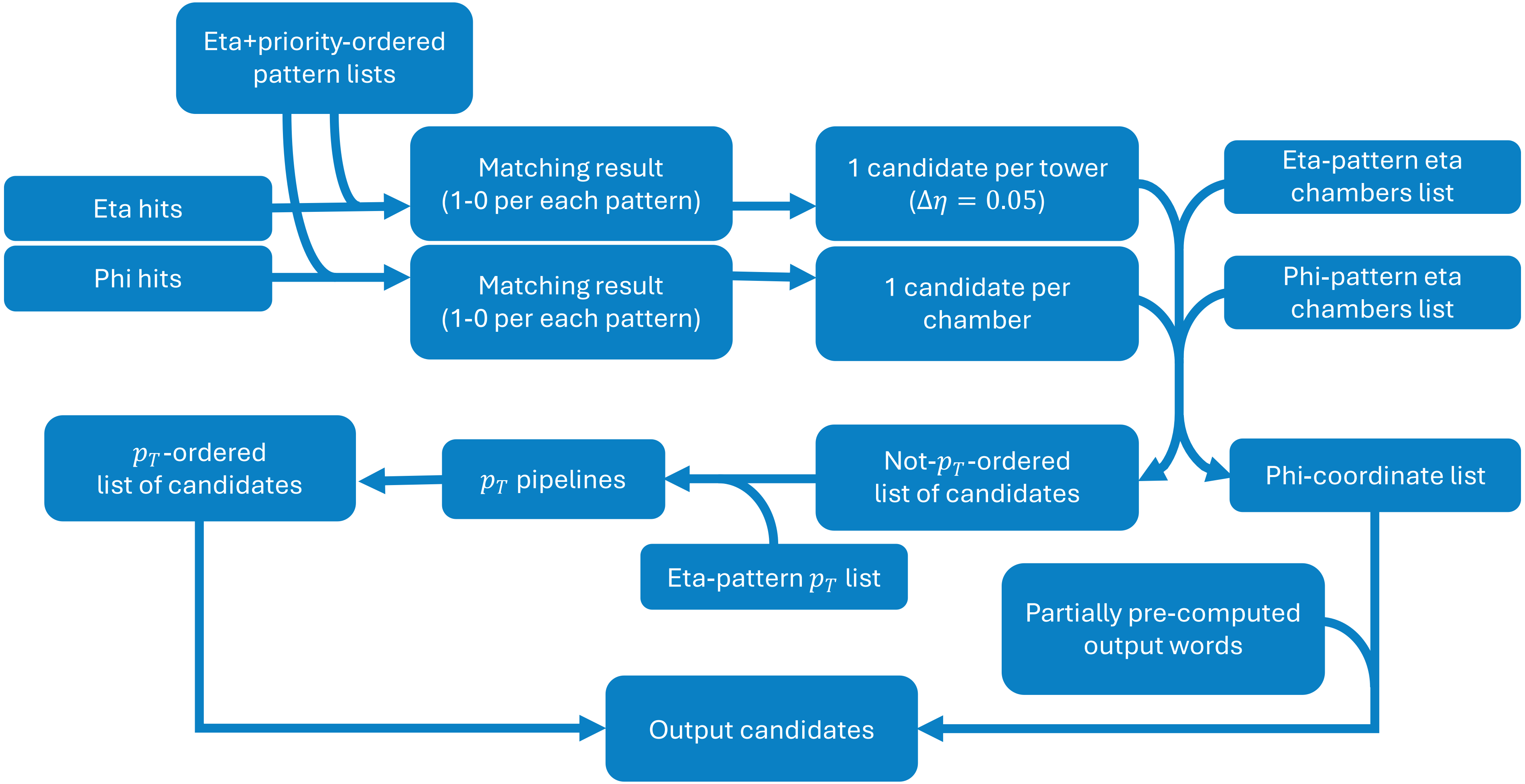
Simulated performance





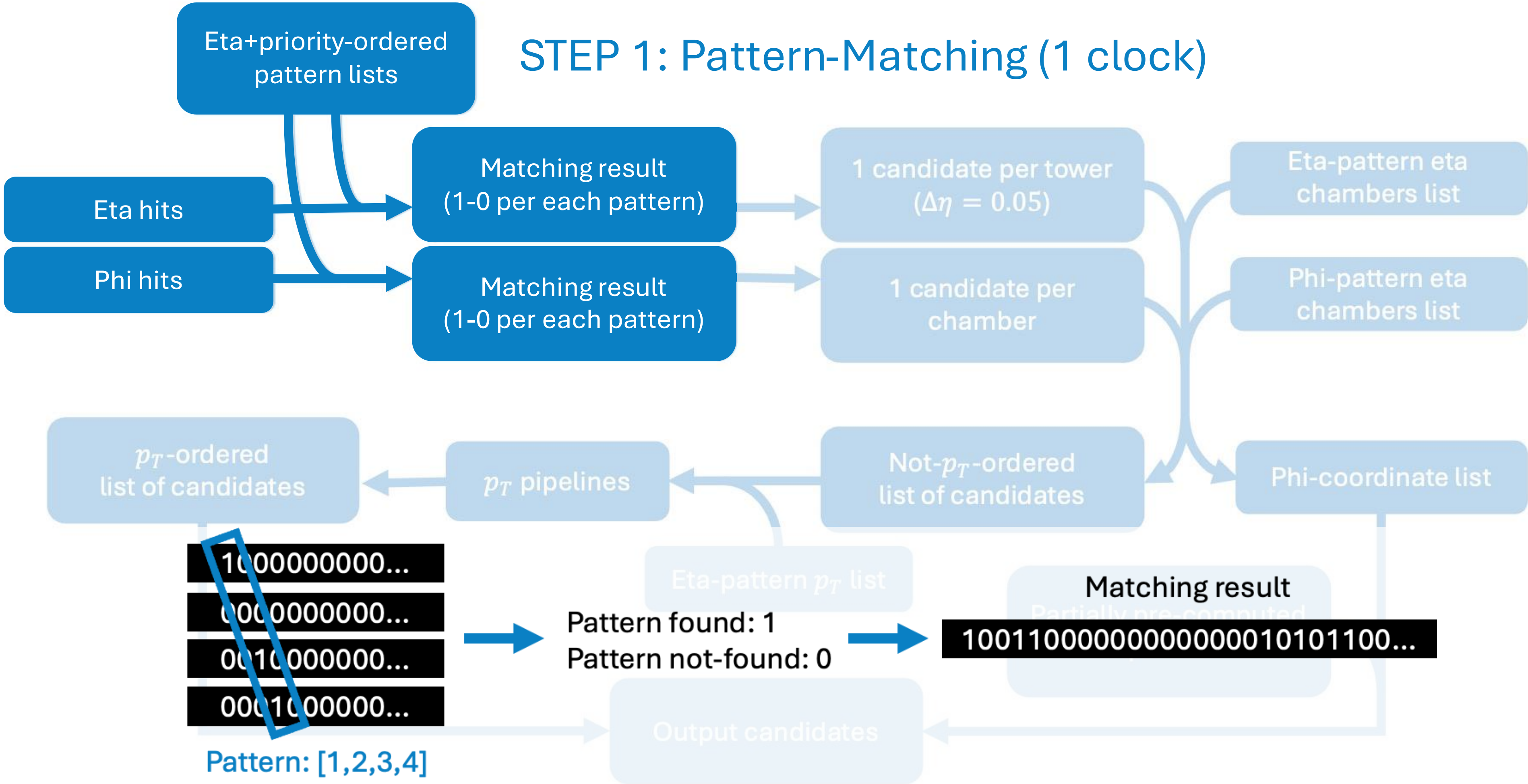


On the FPGA


Eta+priority-ordered pattern lists
Eta hits
Phi hits
Matching result (1-0 per each pattern)
Matching result (1-0 per each pattern)
1 candidate per tower ($\Delta\eta = 0.05$)
1 candidate per chamber
Eta-pattern eta chambers list
Phi-pattern eta chambers list
Phi-coordinate list
Not-p_T-ordered list of candidates
p_T pipelines
p_T-ordered list of candidates
Eta-pattern p_T list
Partially pre-computed output words
Output candidates

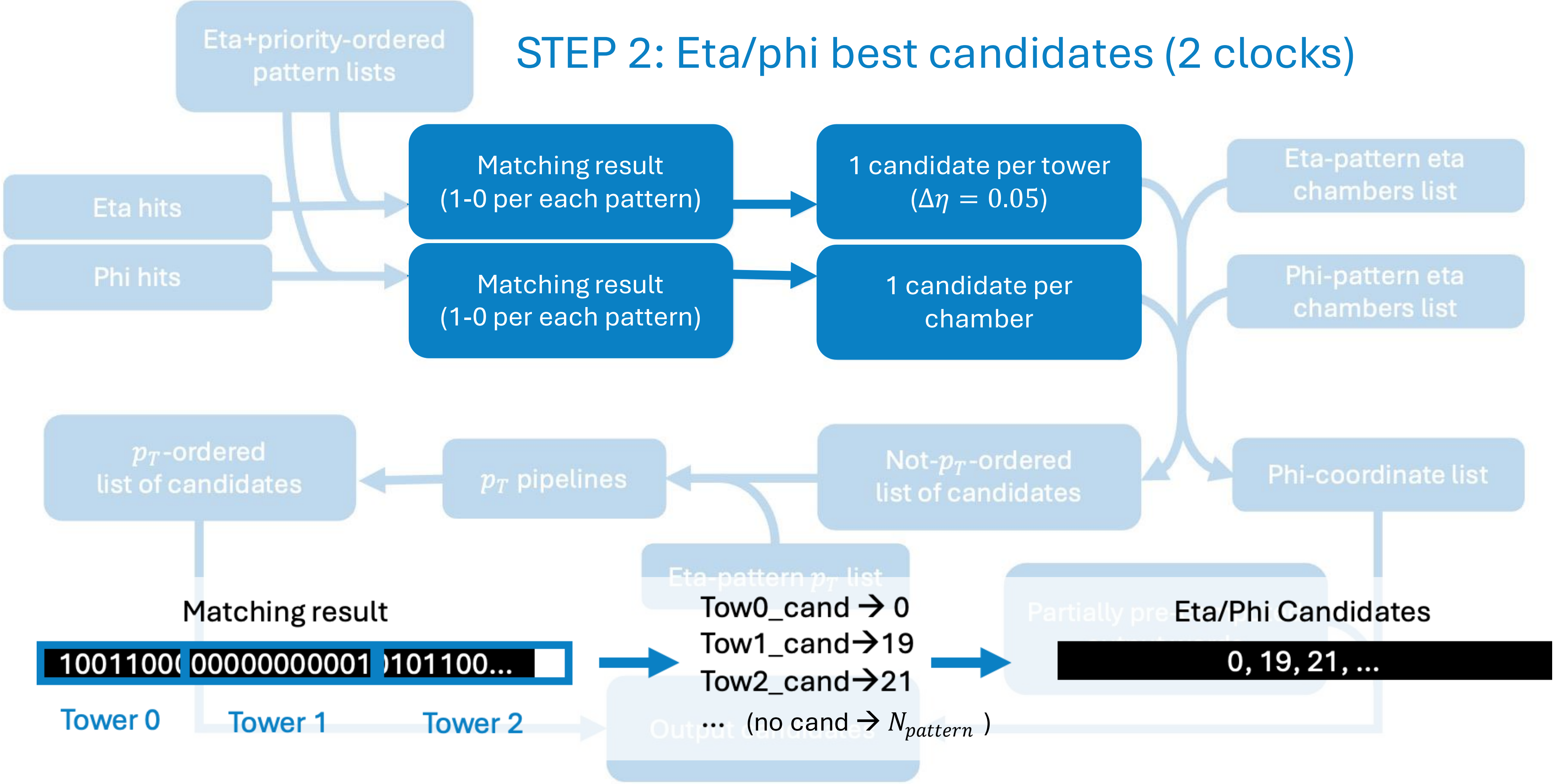
On the FPGA

STEP 1: Pattern-Matching (1 clock)



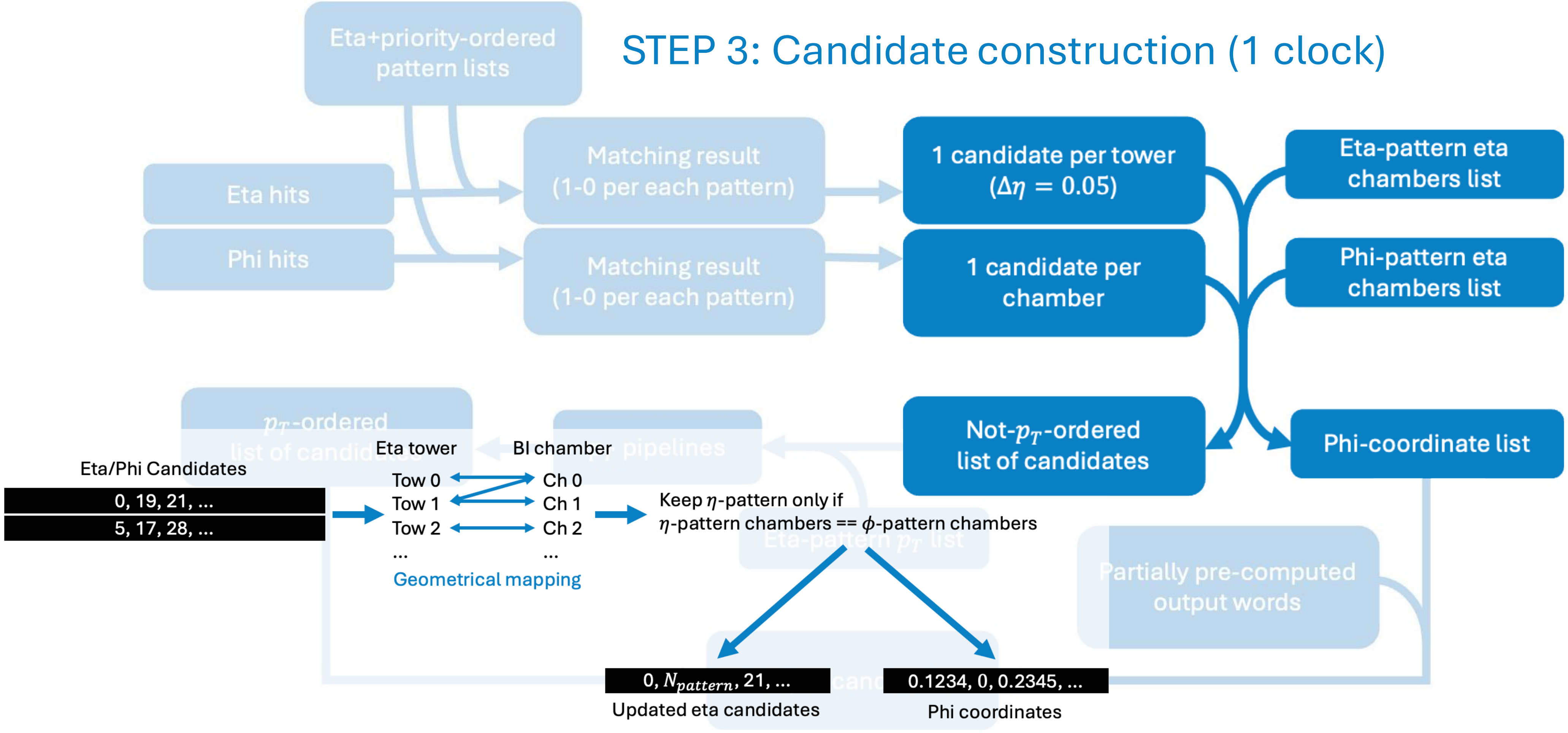
On the FPGA

STEP 2: Eta/phi best candidates (2 clocks)



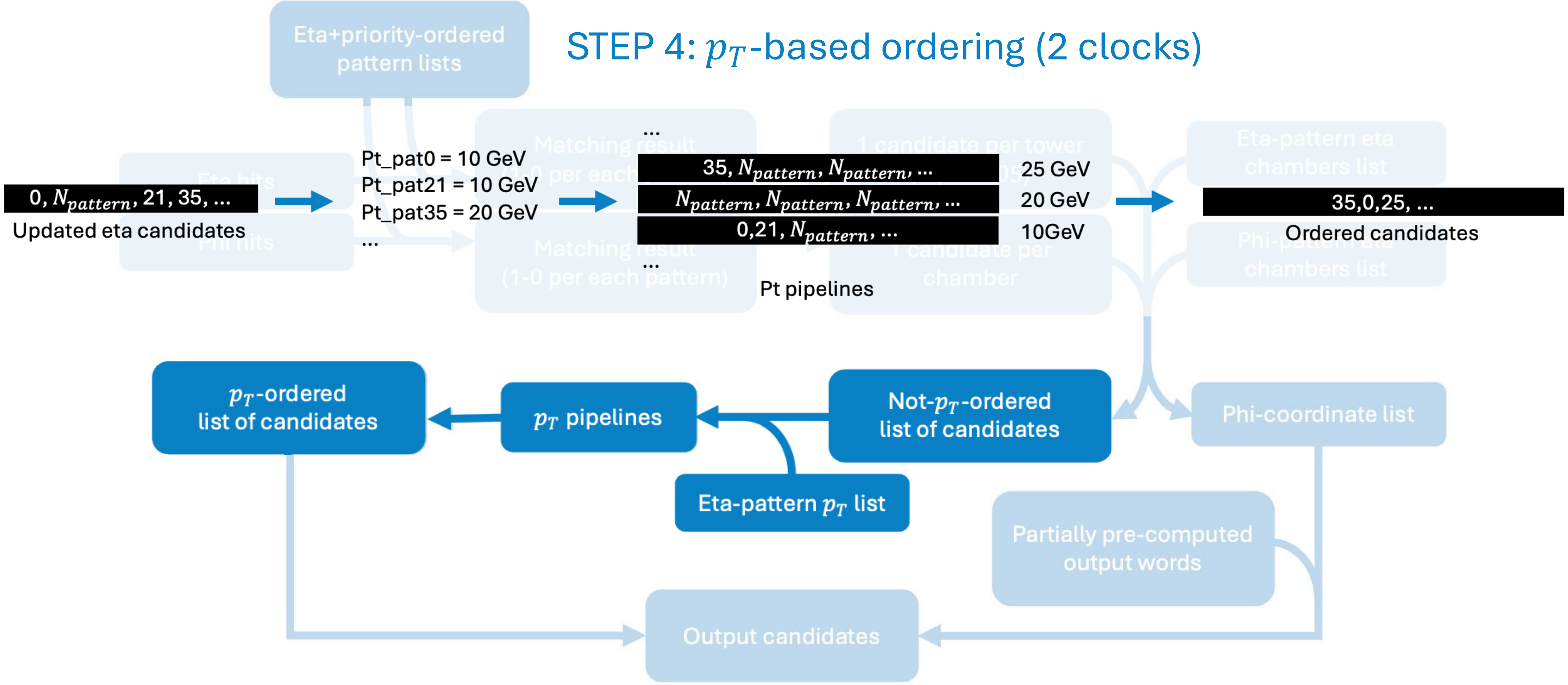
On the FPGA

STEP 3: Candidate construction (1 clock)

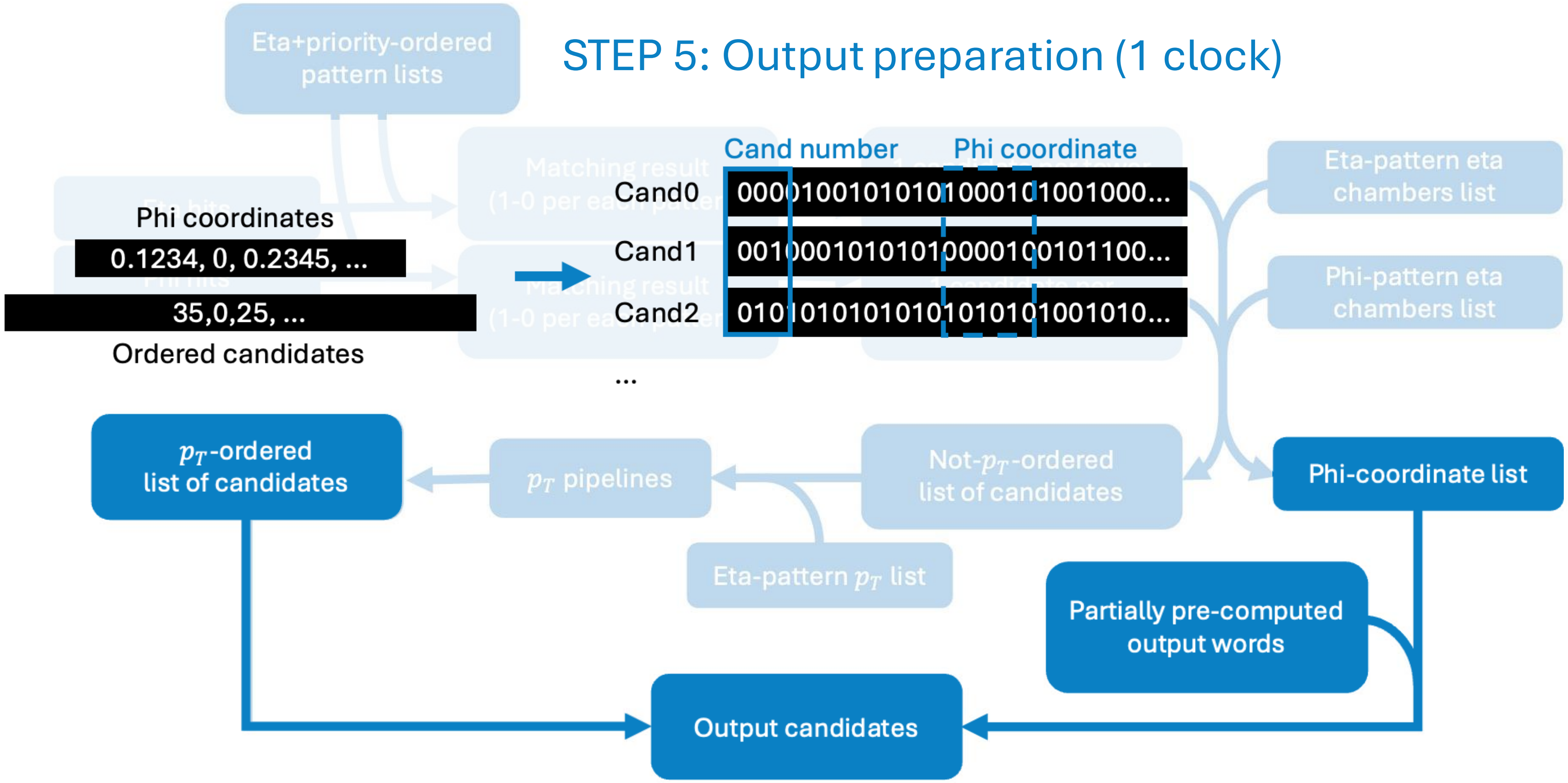


On the FPGA

STEP 4: p_T-based ordering (2 clocks)



On the FPGA

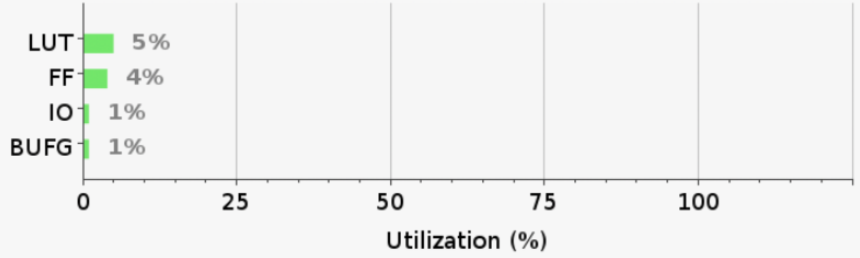


Eta+priority-ordered pattern lists
STEP 5: Output preparation (1 clock)
Cand number
Phi coordinate
Phi coordinates
0.1234, 0, 0.2345, ...
35,0,25, ...
Ordered candidates
Cand0 000010010101010001001001000...
Cand1 001000101010100001000101100...
Cand2 010101010101010101010100101...
...
Eta-pattern eta chambers list
Phi-pattern eta chambers list
p_T-ordered list of candidates
p_T pipelines
Not-p_T-ordered list of candidates
Phi-coordinate list
Eta-pattern p_T list
Partially pre-computed output words
Output candidates

FPGA occupancy

Utilization Post-Synthesis | **Post-Implementation**

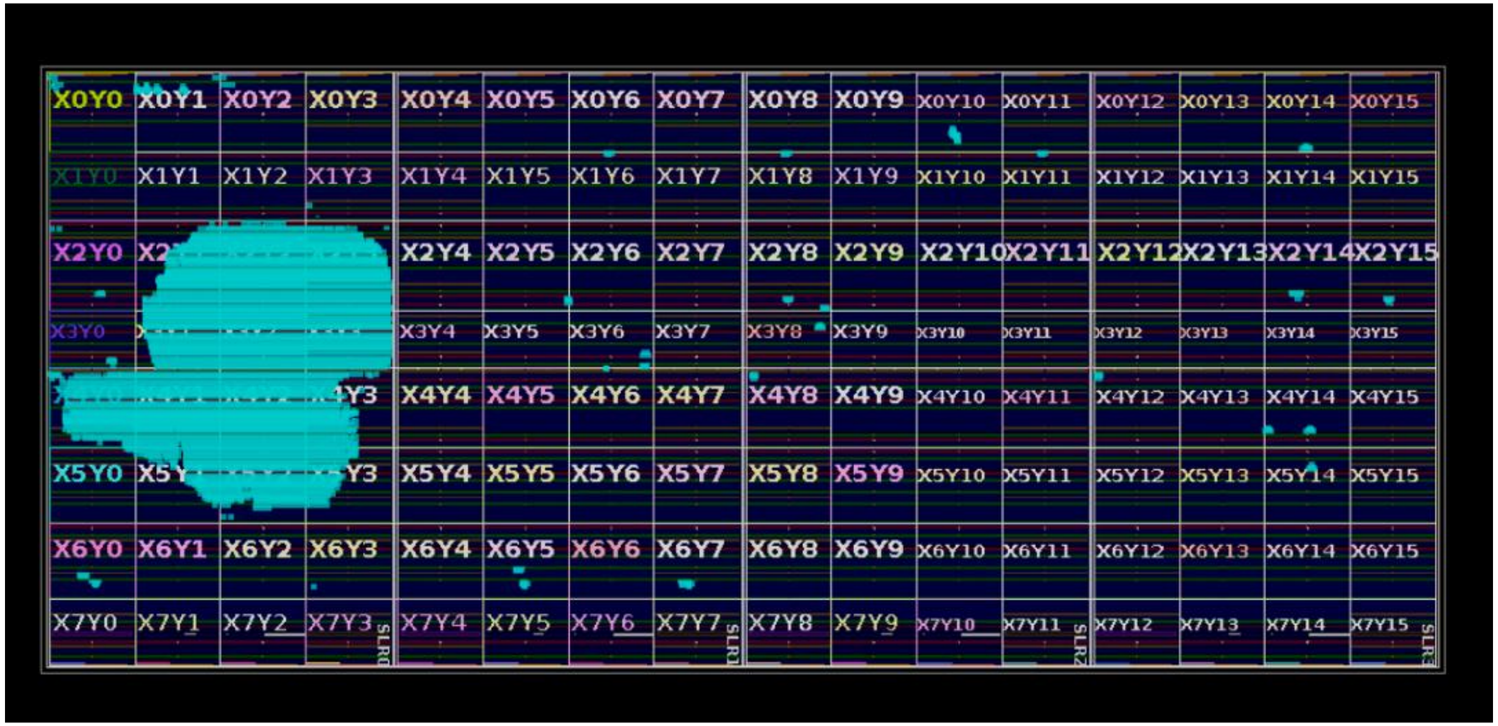
Graph | Table



Utilization Post-Synthesis | **Post-Implementation**

Graph | **Table**

Resource	Utilization	Available	Utilization %
LUT	81755	1728000	4.73
FF	143156	3456000	4.14
IO	1	448	0.22
BUFG	1	1344	0.07



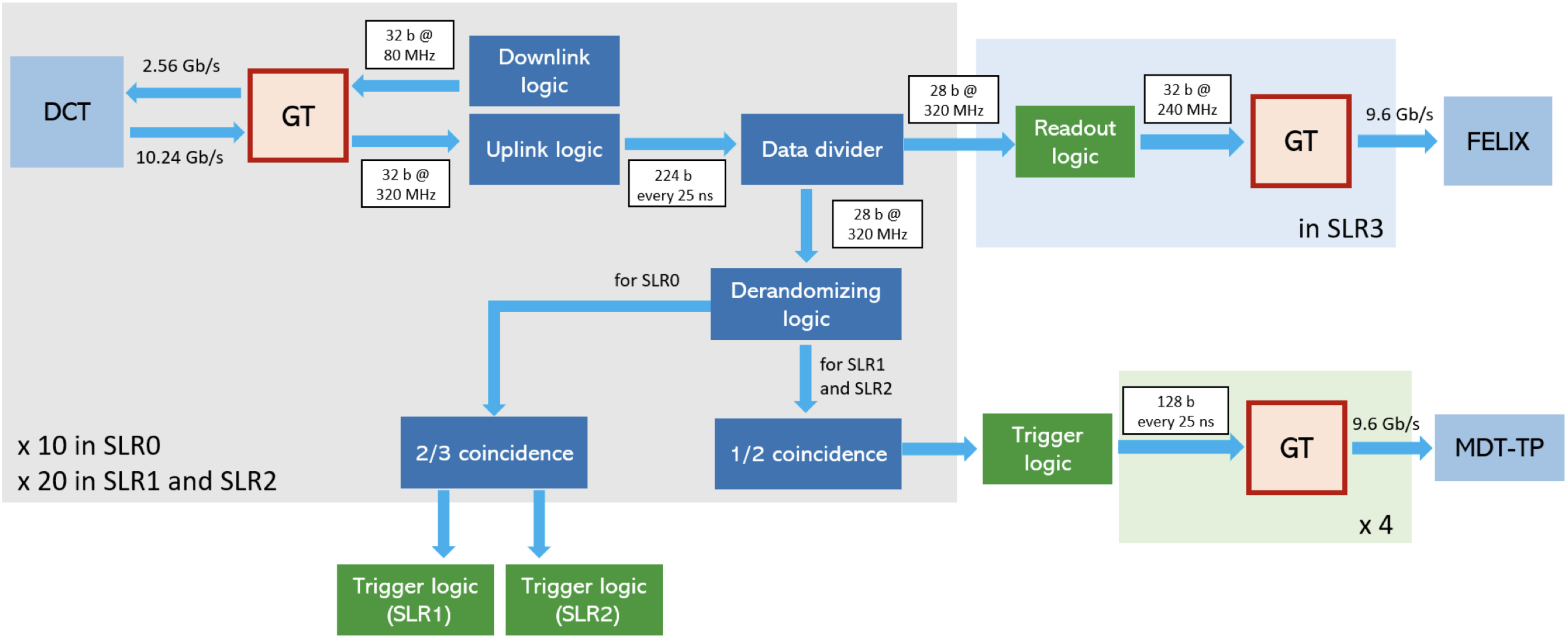
Preliminary algorithm-only latency: 7 clock cycles

Conclusions

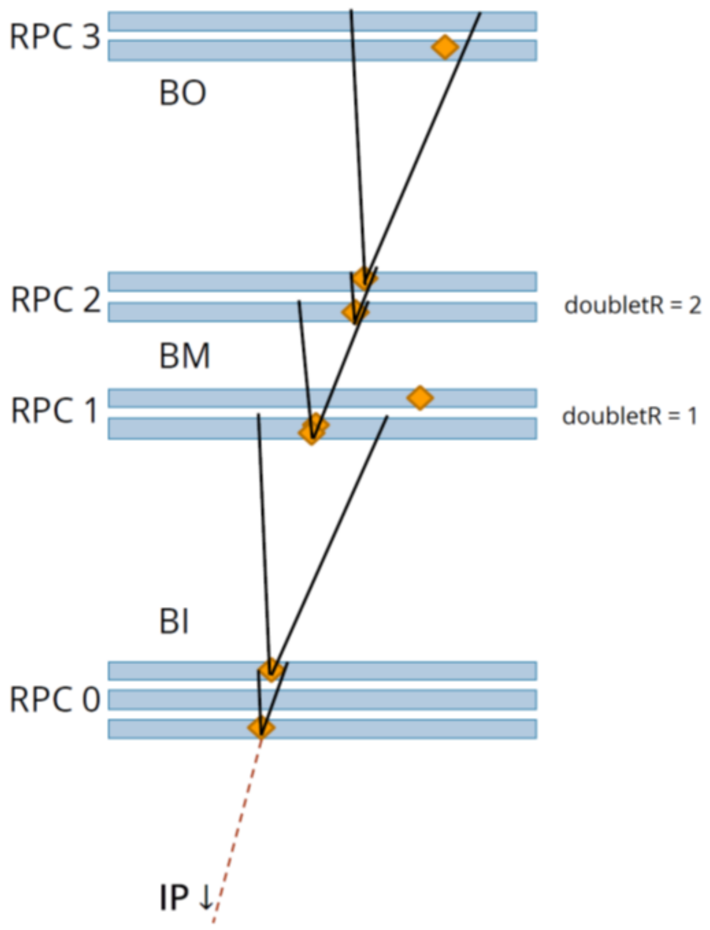
- HL-LHC will provide higher luminosity, providing more statistics to the experiments at CERN.
- The Phase-II ATLAS upgrade will handle the high luminosity environment from HL-LHC.
- The L0Muon Barrel Muon Trigger will provide increased geometrical acceptance and exploit SL FPGAs to run fast trigger algorithms.
- The pattern-matching algorithm is a valid candidate for the Phase-2 L0Muon Barrel Trigger.
- There are ongoing studies on simulation/performance testing and implementation in the FPGA firmware.
- Pros and cons:
  - ✓ low latency;
  - ✓ Changeable pattern lists;
  - ✓ Pre-computed p_T and output words to the next steps in the trigger chain;
  - \- A huge number of patterns are to be stored in the FPGA → it looks like they can fit.
  - ✗ The amount of patterns makes the logic more complex.

Backup

Interface logic



The PatFinder Algorithm



- The algorithm starts looking for hits in the innermost RPC layer: if no hit is found, the search continues in the following layer.
- Starting from one of these hits, a coincidence window (i.e. η/ϕ bins) is opened in the following layers. Whenever the algorithm finds a new hit, it is added to the array containing all previous hits.
- If more hits lie in the same coincidence window, only the one that is closest in η and ϕ to the line connecting the first hit and the interaction point (IP).
- Per every hit in the innermost layer a pattern of hits is produced.
- Patterns may contain up to 9 hits.
- The p_T estimate comes from the deflection of the candidate pattern from the previous straight line.

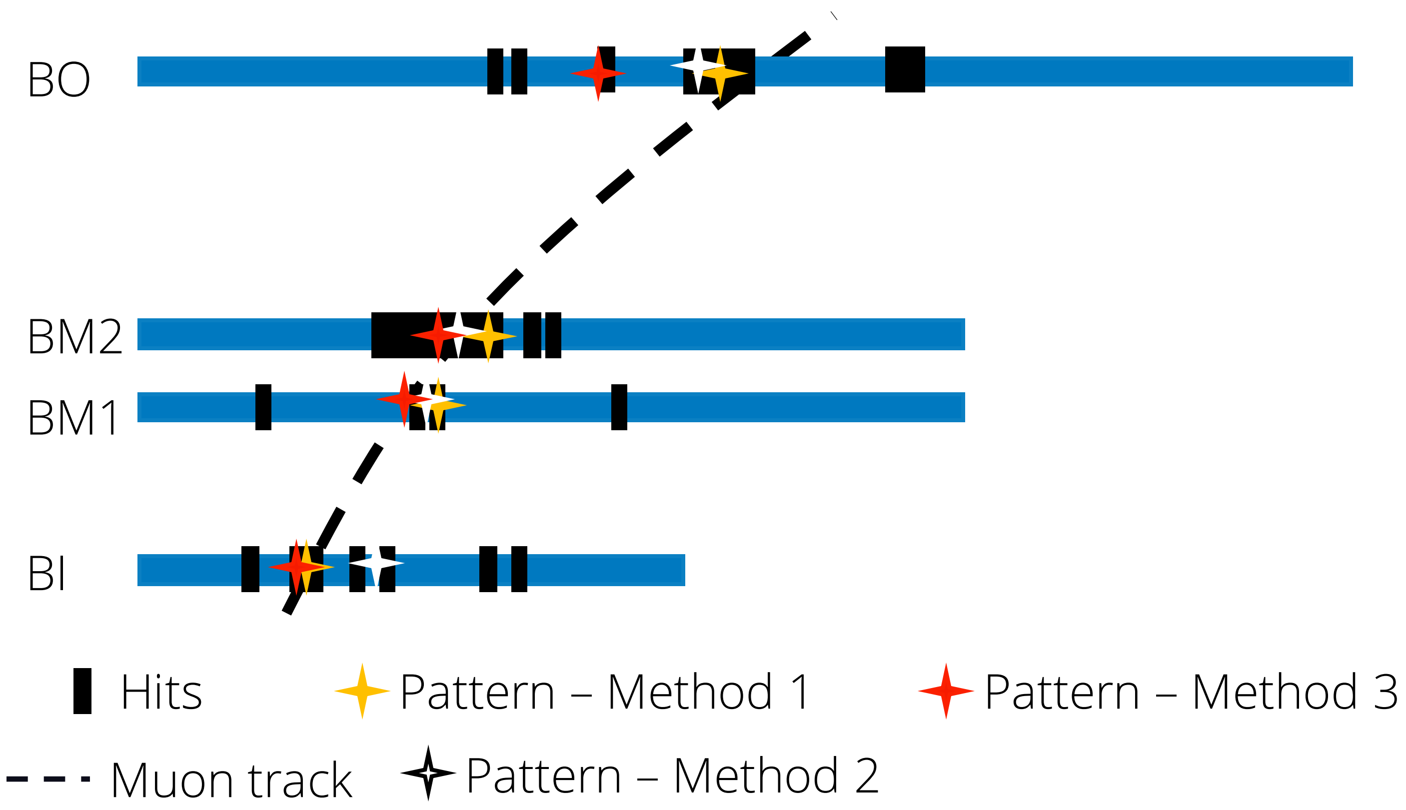
Creation of the pattern database

Muon track

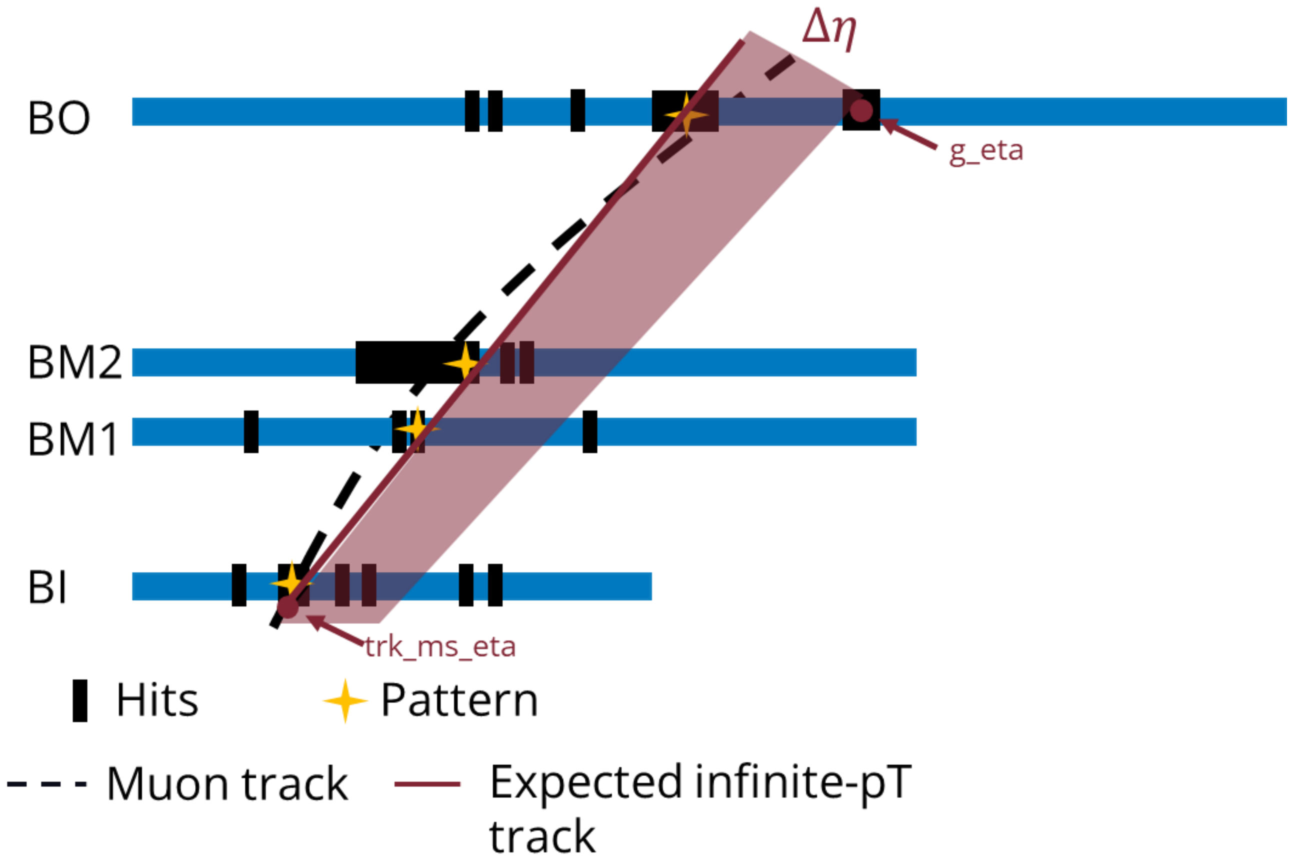
- Pattern 1
- Pattern 2
- Pattern 3
- …
- Pattern N

- Muon 1
- Muon 2
- Muon 3
- …
- Muon M

Pattern



Creation of the pattern database



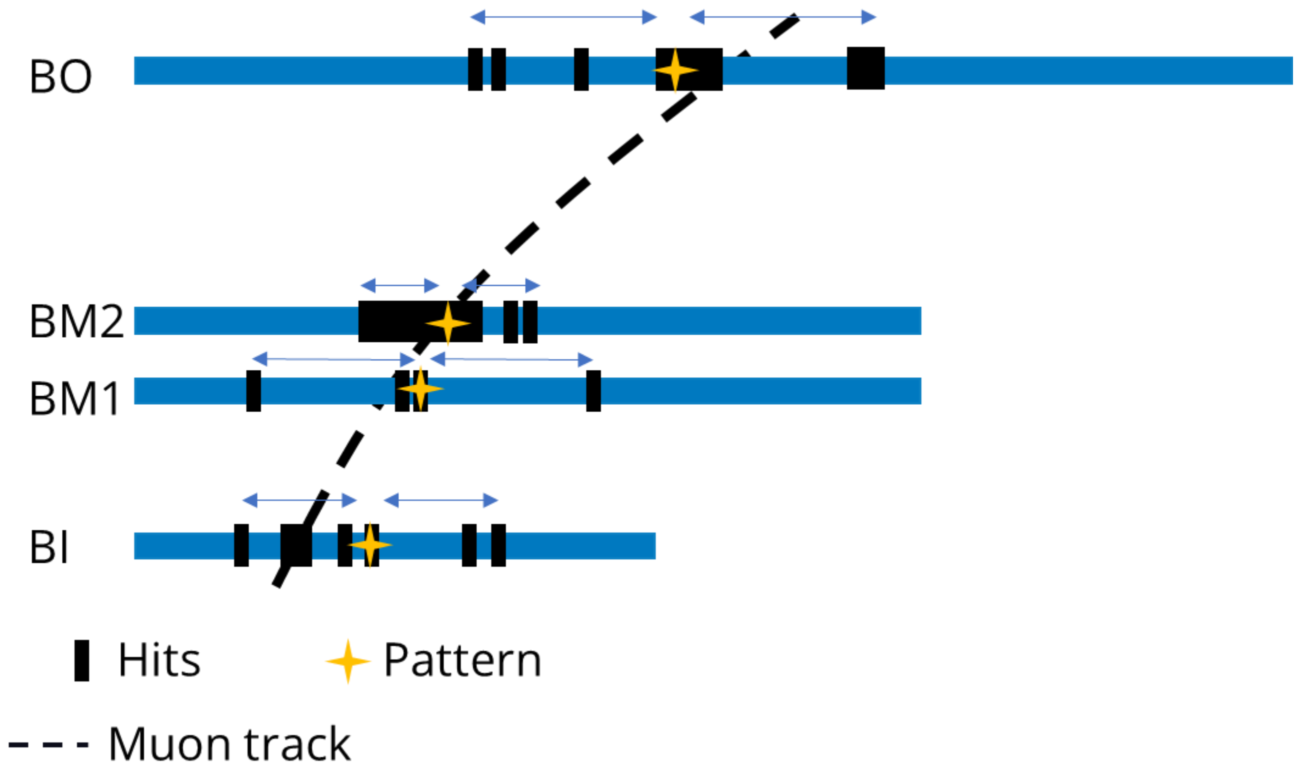
Method 1 : minimize $|g\_eta - trk\_ms\_eta|$

- Simulations provide information about the global eta coordinate (g_eta) of each hit and the eta coordinate of the muon entering the spectrometer (trk_ms_eta).
- The strips included in the pattern are the closest to trk_ms_eta.

Method 2 : central hits

Method 3 : infinite-pT track

Creation of the pattern database



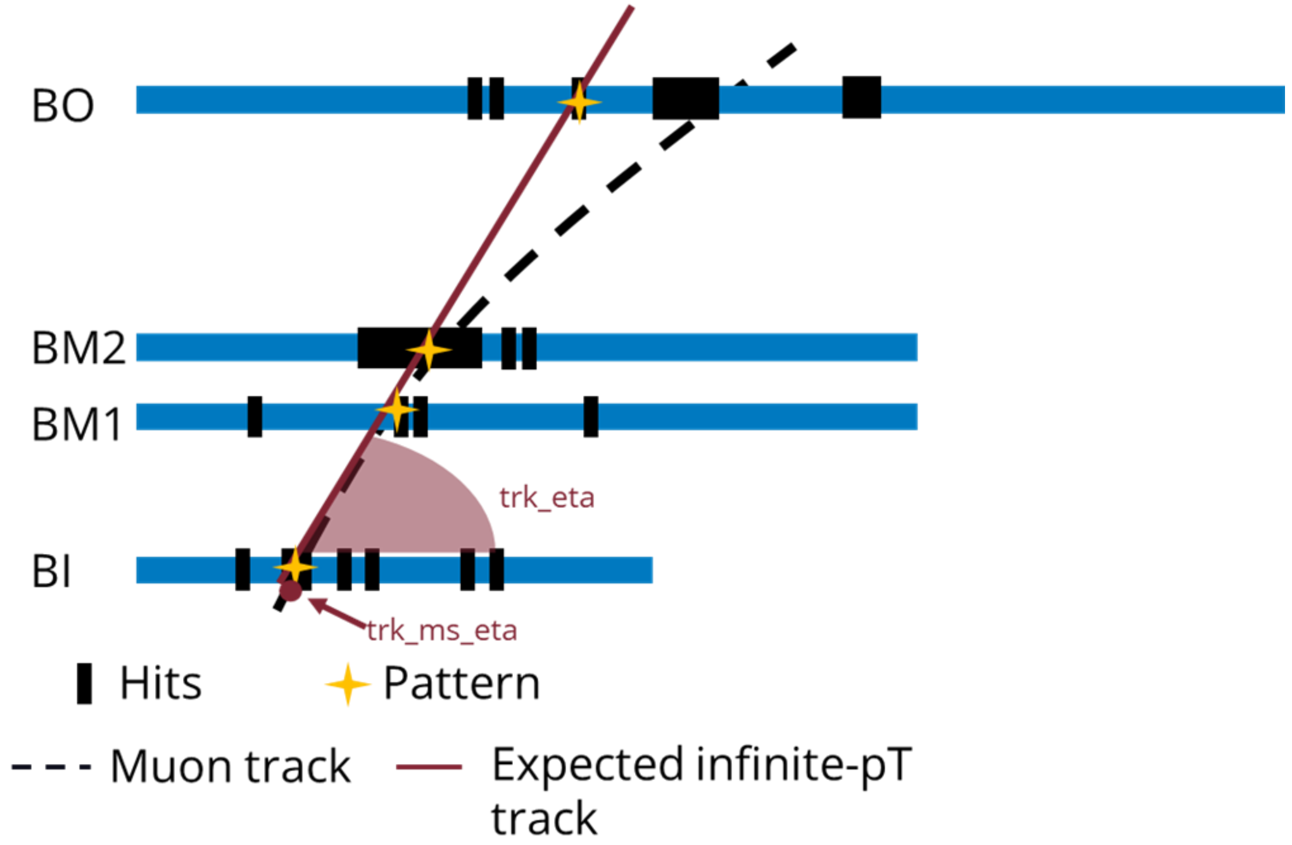
Method 1 : minimize |*g_eta – trk_ms_eta*|

Method 2 : central hits

- Simulations provide the global z coordinate of each hit (g_z).
- Strips in the pattern are the closest to the center of the g_z distribution per each station.

Method 3 : infinite-pT track

Creation of the pattern database



Method 1 : minimize |*g_eta – trk_ms_eta*|

Method 2 : central hits

Method 3 : infinite-pT track

- Simulations provide information about all global coordinates of the hits (g_x, g_y, g_z), trk_ms_eta, and the angle of the muon track extrapolated to the interaction point (trk_eta).
- Reconstruction of the expected infinite-pT track starting from the BI or BM1 strip closest to trk_ms_eta:

$$z(R) = R_0 \frac{e^{2 \cdot \text{trk\_ms\_eta}} - 1}{2 \cdot e^{\text{trk\_ms\_eta}}} + (R - R_0) \frac{e^{2 \cdot \text{trk\_eta}} - 1}{2 \cdot e^{\text{trk\_eta}}}$$

- Strips in the pattern are the ones closest to the predicted z coordinate.

Creation of the pattern database