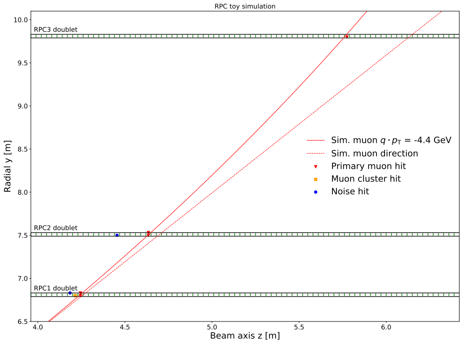
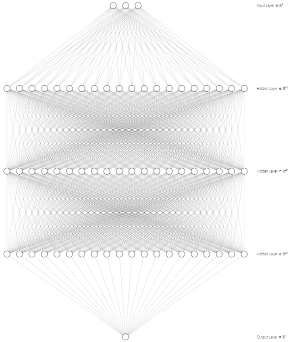
Study of FPGA-based neural network regression models for the ATLAS Phase-II barrel muon trigger upgrade





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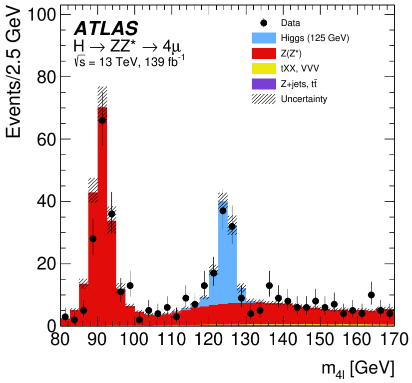
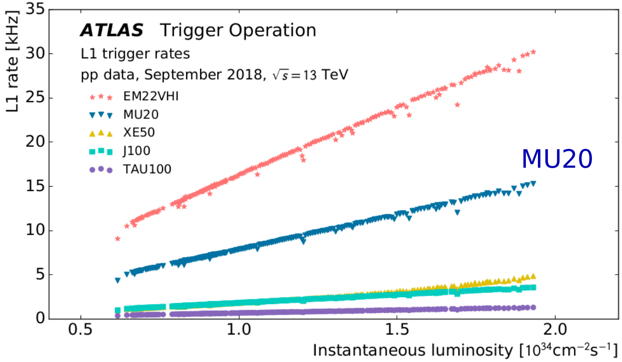
Motivation

- Muons are important signature for the physics programme of the ATLAS experiment at the LHC
  - Electroweak studies with W & Z bosons, Higgs boson measurements, searches for new phenomena...
  - Muon trigger signatures contributed $\sim$ 10% of the total 100 kHz bandwidth of the Level-1 hardware trigger (L1)



Level-1 trigger (L1) rates vs. instantaneous LHC luminosity

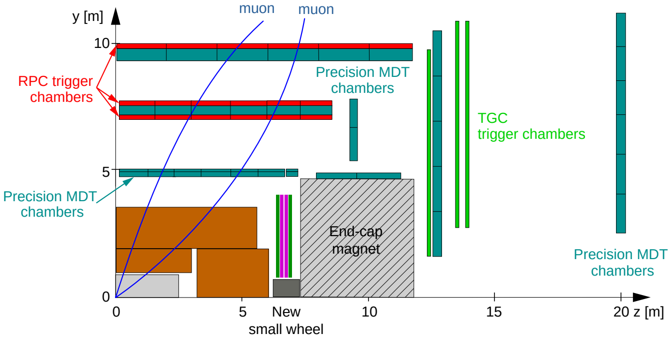


Outline

1. ATLAS muon spectrometer (MS) and RPC detector
2. ATLAS L1 muon barrel trigger
3. Muon spectrometer upgrades for the High Luminosity LHC (HL-LHC)
4. Neural network regression model for RPC muon trigger
5. FPGA implementation and simulation

ATLAS muon spectrometer (MS)

- 2 fast detectors for L1 trigger with position resolution of ~ 1 cm:
  - Resistive plate chambers (RPCs) in the barrel region ($|\eta| < 1.05$) - *subject of this talk*
  - Thin gap chambers (TGC) in the endcap region ($1.05 < |\eta| < 2.4$)
  - Fast measurements of muon transverse momentum (p_T) within the 2.1 μs latency of the L1 trigger
- 2 precision detectors for high-level trigger (HLT) and offline muon reconstruction:
  - Muon Drift Tubes (MDT) for $|\eta| < 2.7$ with position resolution of ~ 80 μm
  - Cathode Strip Chambers (CSC) $\rightarrow$ replaced with New Small Wheel detectors



- 1 barrel and 2 endcap air-core toroid magnets
- Toroidal magnetic field of ~ 0.5 T
- Barrel: 1.5 to 5.5 Tm of bending power
- Muon p_T resolution: $\Delta p_T / p_T \approx 4\%$
- Calorimeters stop energetic hadrons

Resistive Plate Counters

- RPCs were developed by Santonico and Cardarelli in early 80s

  Careful study of different designs and many materials to arrive at a working prototype

- Two parallel electrodes producing high uniform electric field

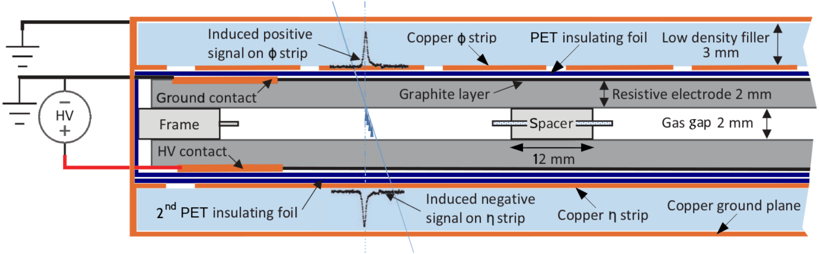
  Free electron $\rightarrow$ avalanche $\rightarrow$ streamer

- High bulk resistivity reduces surface area for ionisation discharge $\rightarrow$ suppresses streamers
  - $\rightarrow$ RPCs use phenolic resin known as bakelite - first synthetic plastic invented in 1907
  - $\rightarrow$ $\mathcal{O}(100\ \text{Hz/cm}^2)$ counting rates and $\mathcal{O}(1\ \text{ns})$ time resolution

- RPCs are low-cost detectors covering large surface areas and using gas at room pressure
  - $\rightarrow$ RPCs are used at the LHC by the ATLAS and CMS muon trigger systems
  - $\rightarrow$ Multi-gap RPCs are used as time-of-flight detectors, e.g. reaching $\sim$ 40 ps resolution with 10 gaps for ALICE

ATLAS Resistive Plate Chambers

- Parallel resistive plates (bakelite with $2 \times 10^{10}\ \Omega \cdot cm$) are separated by 2 mm with insulating spacers
- Induced signal is read out using orthogonal η and ϕ copper strips with 23-35 mm pitch
- $\sim$ 1 ns total time resolution $\rightarrow$ excellent separation of proton bunches that are 25 ns apart
- 320 MHz clock for detecting raising edge of the amplified avalanche signal $\rightarrow$ 3.125 ns wide time bins
- RPC operate in avalanche mode with average applied voltage of 9.6 kV $\rightarrow$ working at the efficiency plateau

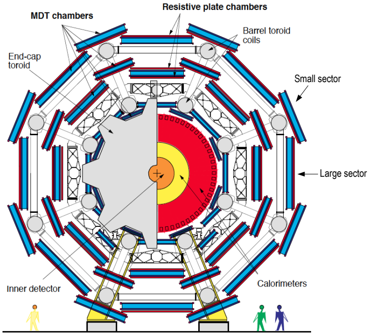


- Non-flammable low-cost gas: tetrafluorethane $C_2H_2F_4$(94.7%), iso-butane C_4H_{10}(5%), sulphur hexafluoride SF_6(0.3%)
- This mixture is a potent greenhouse gas $\rightarrow$ currently being phased out in EU $\rightarrow$ raising costs and environmental impact

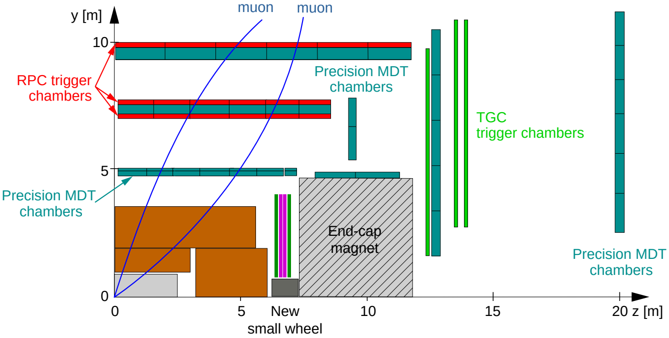
ATLAS RPC detector

- 3 concentric cylindrical shells of double-layer (doublet) chambers located at radii of 7, 8 and 10 meters
- $\sim$ 3700 gas volumes with the surface area of $\sim 4000 m^2$ with $\sim$ 360k readout strips
- Provide 6 measurements in bending (r, z) plane and 6 measurements in non-bending (x, y) plane

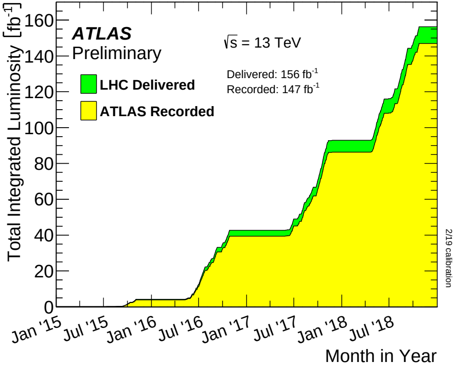
Non-bending (x, y) plane - RPC ϕ strips



Bending (r, z) plane - RPC η strips



Performance of RPC detector with proton-proton collision data at 13 TeV



LHC delivered a half of the originally designed number of collisions

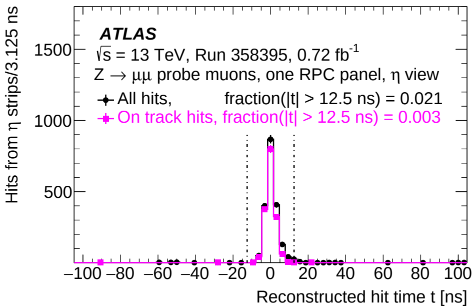
→ Study RPC detector performance to check for possible aging effects

→ RPC performance paper using 2018 data: JINST 16 (2021) P07029

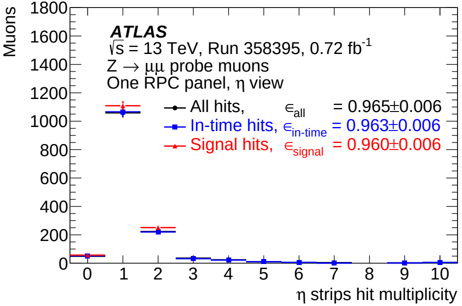
RPC detector response

- Measure RPC detector response with offline probe muons produced in pp collisions
  - Use Z boson decays to 2 muons - one muon is tag and second is probe
  - Propagate probe muons in magnetic field to predict an impact point on the RPC surface
  - Offline probe muon candidates are reconstructed using primarily the MDT detector
- Detect hits associated with muon induced avalanche $\rightarrow$ hit time and multiplicity
  - Hit is a signal induced in one strip which is above a tunable threshold of the front-end electronics

Calibrated hit time for one RPC module
Zero corresponds to time of pp collisions

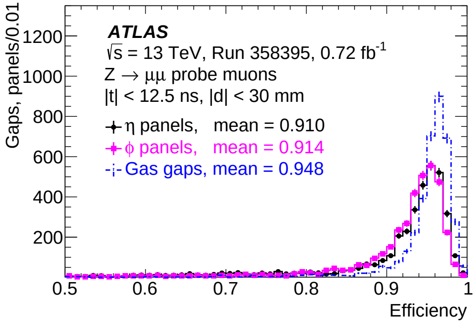


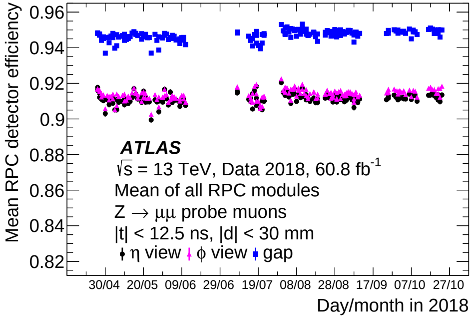
Hit multiplicity in response to muon passage for one RPC module
Efficiency is a fraction of events with at least one detected hit



RPC detector efficiency

- Muon detection efficiency = probability to detect avalanche with ≥ 1 hit
  - Measured using events containing a muon predicted to pass through a given chamber
  - Gas gap efficiency = probability to detect a muon induced avalanche using either η or ϕ strips
- Average RPC detector efficiency to detect a muon is $\sim 94\%$
  - Excellent detector stability during data taking in 2018
  - About 10% of RPCs were off in 2018 due to gas leaks - these chambers are not shown below

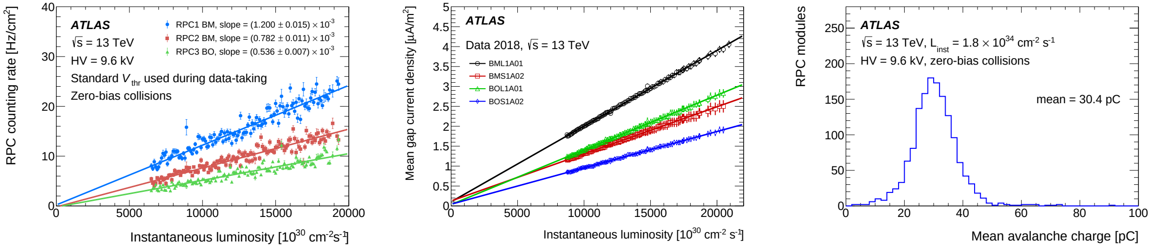




RPC counting rates and ionisation currents

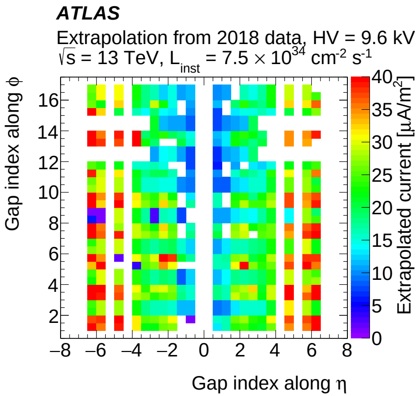
- Measured RPC ionisation currents and counting rates as a function of instantaneous luminosity
  - Scale linearly with instantaneous luminosity, as expected
- Also measured the mean avalanche charge $= I/R_{\text{counts}} \approx 30$ pC
  - Consistent with test beam results → confirmed with the full RPC detector

Counting rates (R_{counts}) at different radii | Ionisation currents (I) at different radii | Mean avalanche charge $= I/R_{\text{counts}}$



RPC integrated charge limits

- RPC detector was certified for up to 0.3 C/cm^2 integrated charge
  - This corresponds to about 10 years of LHC operations at $\mathcal{O}$(100 Hz/cm^2), equivalent to 30 μA/m^2
  - Some chambers at high $|\eta|$ will exceed this limit for High Luminosity LHC $\rightarrow$ reduce HV and replace some RPCs

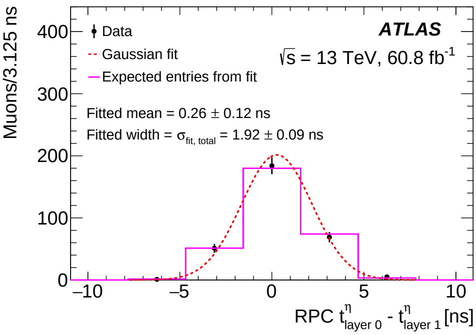


$\rightarrow$ RPC ionisation currents extrapolated to the HL-LHC instantaneous luminosity

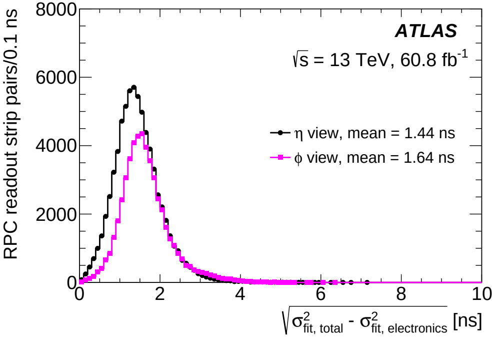
RPC detector time resolution

- Measure time resolution using time differences of muon signals recorded by two parallel RPC layers
  - Two layers are separated by $\sim$ 20 mm $\rightarrow$ negligible muon time-of-flight
  - Subtract time resolution component of the front-end electronics which is measured in-situ
- Average measured RPC time resolution: $\sigma_{RPC}/\sqrt{2} \sim 1$ ns
  - Small differences between η and ϕ time resolution is due to differences in construction

$t_{\text{layer 0}} - t_{\text{layer 1}}$



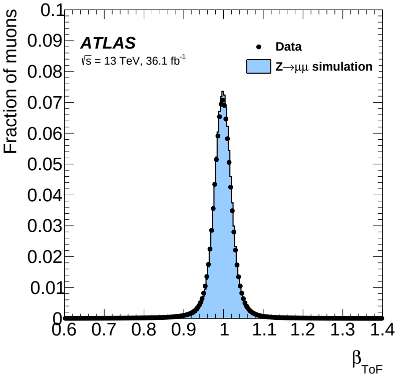
σ_{RPC}



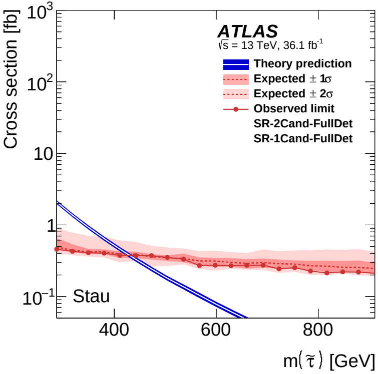
Search for slow-moving stable charged particles

- Time-of-flight and dE/dx energy loss are used to search for heavy stable charged particles
  - RPC is the most sensitive detector for measuring muon time-of-flight
- Search for production of supersymmetric particles (stau, chargino, gluino, R-hadron)
  - Sensitive to other models producing heavy stable charged particles

RPC has most precise β_μ resolution of $\sim 2\%$

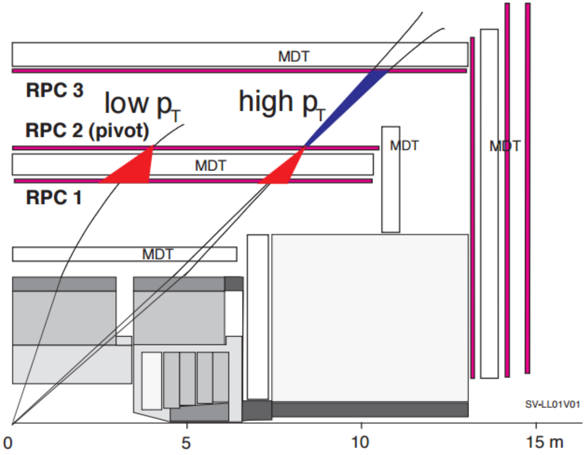


Exclusion limit on stau production



ATLAS L1 muon barrel trigger

Level 1 muon barrel trigger

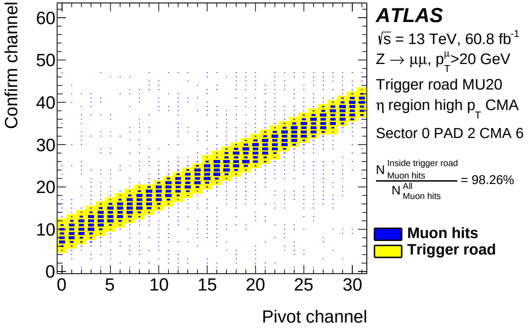


- L1 muon barrel trigger uses RPCs to detect muon trigger candidates at 40 MHz rate
  - Custom-built on-detector electronics making decision within 2.1 μs
  - 3328 detector regions with $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$
- 3 low p_T thresholds:
  - 3/4 coincidence within trigger road in the two inner doublet layers (RPC1 and RPC2)
- 3 high p_T thresholds:
  - Require highest low-p_T trigger plus 1-out-of-2 coincidence in the outer doublet layer (RPC3)

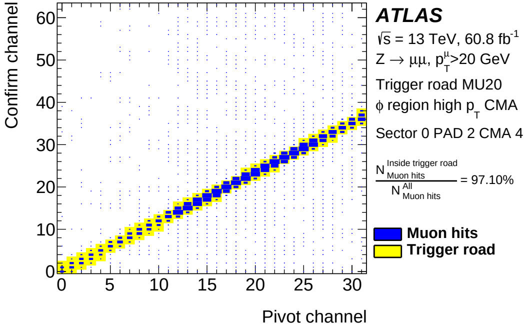
L1 muon barrel trigger: coincidence matrix

- Coincidence matrix ASIC (CMA)
  - Application-specific integrated circuit (ASIC) to check coincidence of hits between two RPC layers within a cone
  - 6 programmable roads (cone sizes) correspond to 6 trigger thresholds for muon p_T

High-p_T MU20 road for **bending** η coordinate
Road width is determined by muon curvature in magnetic field



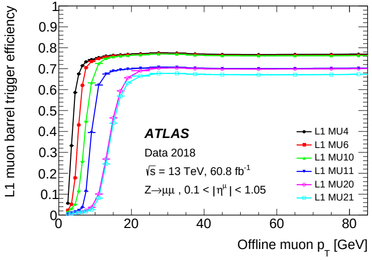
High-p_T MU20 road for **non-bending** ϕ coordinate
Road width is determined by RPC strip width



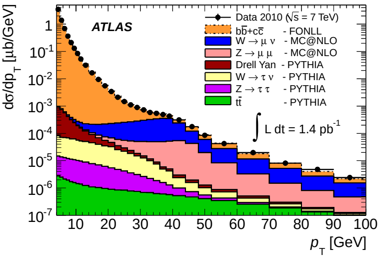
Level 1 muon barrel trigger: efficiency

- MU20 is the primary L1 muon trigger threshold for selecting muons with $p_T > 20$ GeV for physics data taking
  - Highly efficient for detecting muons produces in decays of W and Z bosons
  - RPC acceptance holes and detector inefficiency lead to the efficiency plateau at 70% for MU20 trigger
  - Steepness of the efficiency curve determines trigger rates → dominated by muons with mismeasured p_T
- Steepness of the efficiency curve determines trigger rates
  - Accepted MU20 events are dominated by low-p_T muons produced in $b\bar{b} + c\bar{c}$ events

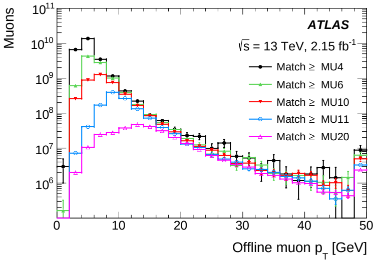
L1 barrel muon trigger efficiency $\epsilon_{\text{trigger}}$ vs. p_T



Inclusive muon p_T spectrum $P_\mu(p_T)$ at 7 TeV



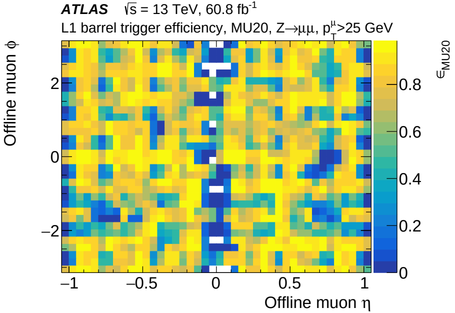
p_T of accepted MU20 events $= \int \epsilon_{\text{trigger}} \cdot P_\mu(p_T)$



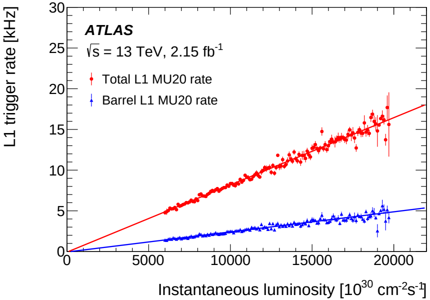
L1 muon barrel trigger: (in)efficiency and rates

- RPC acceptance holes and detector inefficiency lead to the efficiency plateau at 70% for MU20 trigger
  - Will install three new RPC layers in the inner barrel region for HL-LHC operations to increase acceptance
- RPC muon trigger rates are dominated by low-p_T muons with mismeasured momentum
  - New Small Wheel detectors will reduce the endcap muon trigger rate by a factor of ~ 3
  - Barrel RPC muon trigger rates would then contribute a significant fraction of L1 events
  - *Our study aims to improve p_T resolution of the future RPC trigger by using a neural network regression*

MU20 trigger efficiency in (ϕ, z) plane



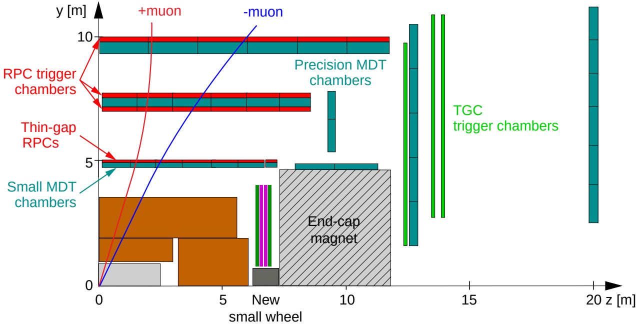
Muon trigger rate vs p_T



Muon spectrometer upgrades for High Luminosity LHC

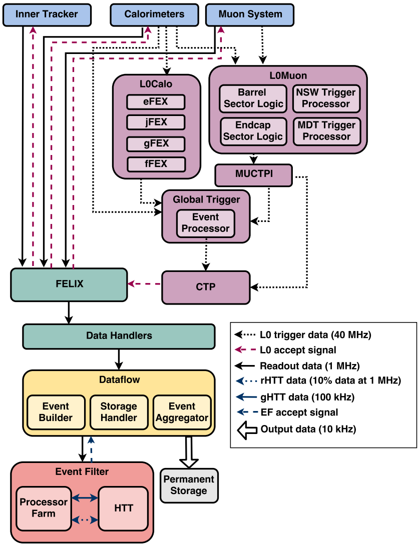
Muon spectrometer upgrades for High Luminosity LHC

- Current RPC:
  - 6 layers with $\eta \times \phi$ grid of 3 cm wide strips
  - Custom ASICs for muon trigger electronics
  - Total L1 bandwidth is 100 kHz
  - L1 latency to process an event: 2.1 μs
- After HL-LHC upgrades in 2025∼2026:
  - Higher background $\rightarrow$ higher trigger rates
  - 3 new inner RPC layers with better time resolution $\rightarrow$ Thin-gap RPCs in inner barrel (BI)
  - L1$\rightarrow$L0: 1 MHz bandwidth & 10 μs latency
  - *New FPGA-based electronics for L0 muon trigger*
  - MS Phase-2 Upgrade Technical Design Report
  - TDAQ Phase-2 Upgrade Technical Design Report



FPGAs in future ATLAS trigger system

- Field-programmable gate array device (FPGA)
  - Integrated circuit configurable after manufacturing
  - Programmable logic blocks and interconnects
  - *Use software to programme computing hardware*
- L0 muon trigger:
  - Input: $\sim$ 0.1 MB at 40 MHz $\approx$ 4TB/s
  - Fixed L0 muon latency $\sim$ 4 μs $\rightarrow$ too fast for CPUs
  - *Use FPGAs for hardware trigger algorithms*
- High-level software-based trigger system (HLT) :
  - Input: $\sim$ 2 MB at 1 MHz
  - Partial event reconstruction in regions of interest
  - *R&D to use FPGAs to accelerate HLT algorithms*



Neural network regression model for RPC muon trigger

Neural network regression model: goals

1. Our first goal is to measure muon q/p_T in order to improve $|p_T|$ resolution of the RPC trigger
   - Idea is to include muon charge $q \rightarrow$ narrower trigger road $\rightarrow$ better p_T resolution and smaller background
   - Essentially, we use the neural network regression model to fit q/p_T

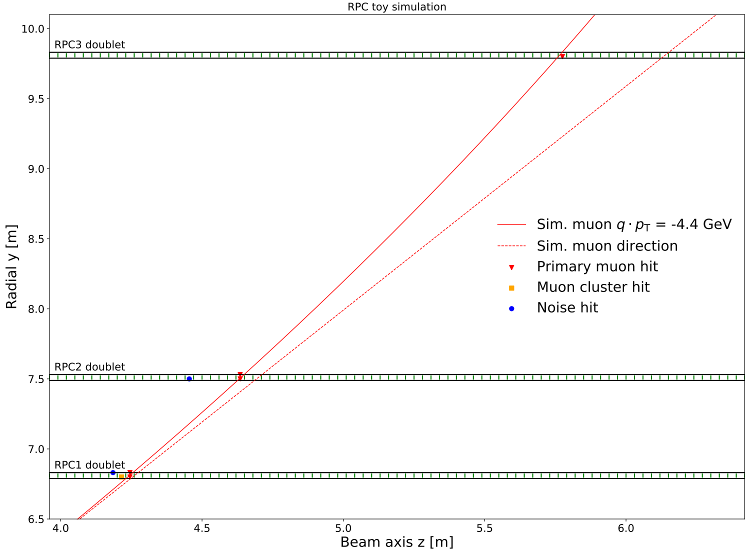
2. Design requirements
   - Aim for fast enough network with small FPGA resource usage $<<$ resources of proposed XCVU13P FPGA
   - Aim for neural network latency $<<$ 10 μs latency of the future L0 trigger system
   - *If these goals can be achieved, neural networks can be also used for new exotic triggers - long lived particles, etc*

3. Advantages of using neural networks for hardware trigger
   - Machine learning algorithms allow to reach higher signal efficiency and smaller background acceptance
   - Same circuit can be used for different detector elements $\rightarrow$ differences encoded via training weights
   - Same circuit can be used for different triggers, for example to trigger on long lived particles

- Collaboration with Prof. Changqing Feng, and Wenhao Dong, Wenhao Feng, Kai Zhang, Shining Yang
  - Preliminary results reported at CHEP 2021, today showing updates from our upcoming paper
  - Ours is different approach than Convolutional Neural Networks $\rightarrow$ presented at CHEP 2019 by Stefano Giagu

RPC toy simulation model

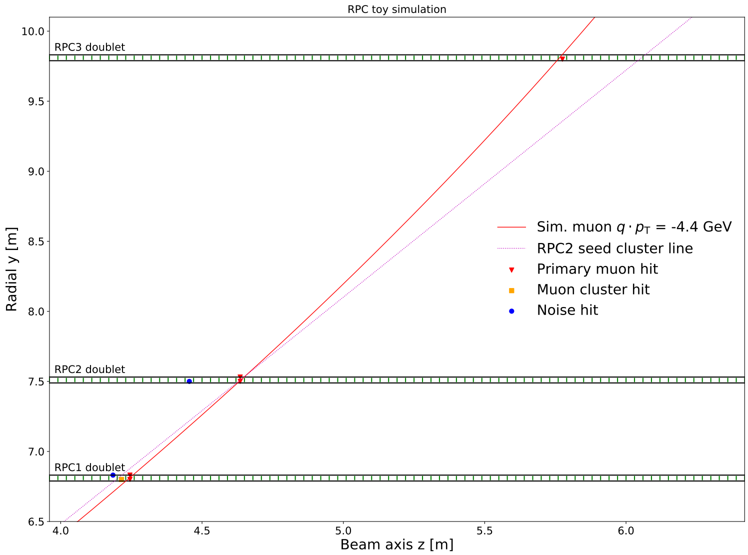
- RPC detector toy model for first studies:
  - Model existing RPC with perfect acceptance (for easier comparisons with ATLAS data)
  - Uniform 0.5 T toroidal B-field
  - 6 RPC layers with 3 cm wide strips
  - Only bending (η) detector view
  - 95% efficiency to produce muon hit
  - 25% prob. to produce 2-strip muon cluster
  - 0.1% prob. per strip to make noise hit
  - No detector material (multiple scattering is small because of the air-core toroids)
- Muon simulation parameters:
  - Flat muon p_T: 3 to 30 GeV
  - Flat muon angle: 50 to 85 degrees to z-axis
  - Python code in GitHub: https://github.com/rustemos/MuonTriggerPhase2RPC



Candidate muon reconstruction

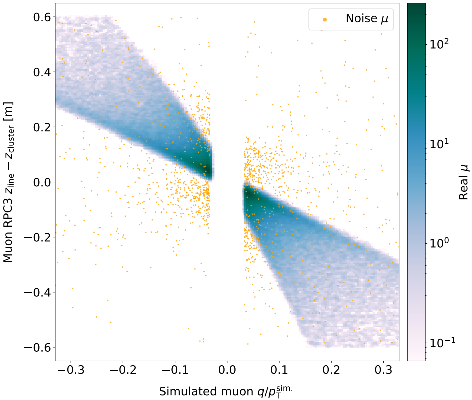
1. In each single layer, reconstruct nearby contiguous hits as one cluster
2. In each doublet layer, merge overlapping single-layer clusters into one super-cluster
3. In RPC2 doublet layer, draw a straight line through each RPC2 super-cluster (seed line)
   - 3.1 *In RPC1 and RPC3 doublet layers, select super-cluster closest to this line*
   - 3.2 *If the selected super-clusters are within* ± 20 *strips to seed line, make a muon candidate*

- With a window of ± 20 strips to make candidates, muons with $p_T < 3$ GeV bend outside this window
- 2 candidates when a noise hit is reconstructed as a muon cluster



Candidate muon reconstruction: muon deflections

- Deflections from the straight line are due to muon curvature in the magnetic field
  - Computed with respect to the straight line from the collision point (origin) to the RPC2 seed cluster
- RPC3 deflections from the seed line are plotted below as a function of muon qp_T

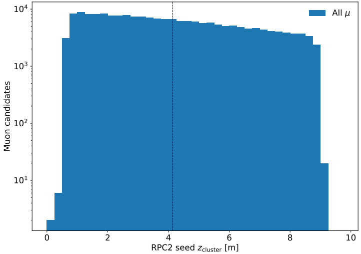


→ RPC3 muon deflections start to be comparable to strip width of 3 cm for $p_T \gtrsim 10$ GeV

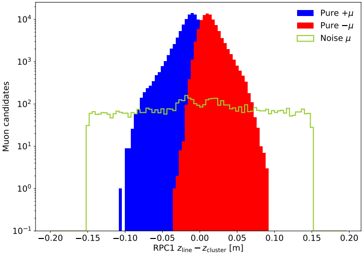
Neural network inputs

- 3 inputs for the neural network training:
  1. RPC2 seed cluster z position (gives muon angular direction to NN)
  2. RPC1 cluster Δz to seed line for $|\Delta z| < 0.15$ m
  3. RPC3 cluster Δz to seed line for $|\Delta z| < 0.6$ m
  - *Using differences improved NN convergence and performance*

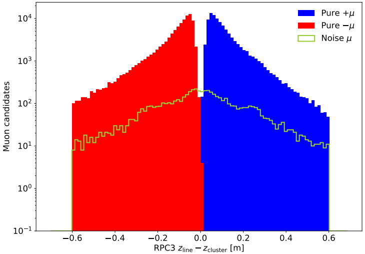
z position of RPC2 seed cluster



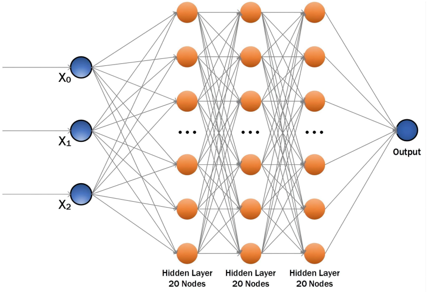
RPC1 differences between $z_{cluster}$ and seed line



RPC3 differences between $z_{cluster}$ and seed line

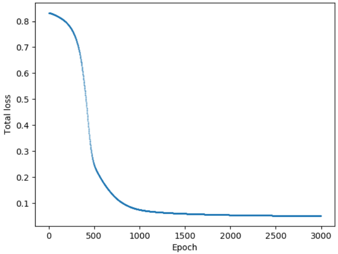


Neural network regression model: design



- Scan several network architectures
  - → *Select 3 hidden layers with 20 nodes each & ReLU activation*
- Network size is driven by RPC resolution with 3 cm wide strips
  - → *Little benefit from a larger network size*
- Linear loss function to improve training convergence
  - → *Mean of |differences| between simulated and predicted* q/p_T
- Network training with PyTorch:
  - 100k events without noise to improve convergence & performance

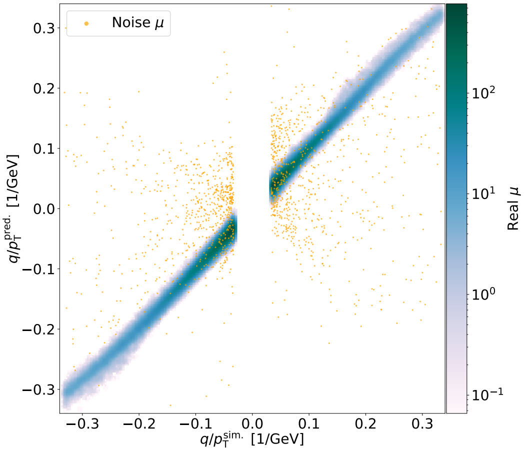
Loss function vs. training epoch



Neural network performance

- Excellent performance for predicting q/p_T for pure muons
  - Noise μ shown in orange
  - Evaluated with statistically independent events
  - Contributions from noise muons are small
  - Also developed quality criteria to suppress noise muons

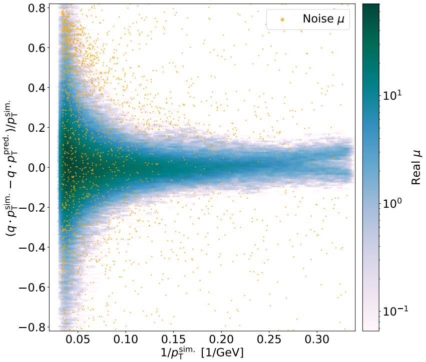
Predicted vs. true q/p_T



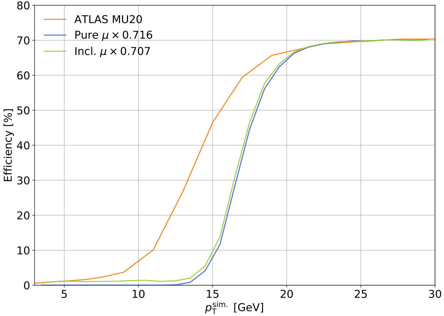
Neural network performance: trigger efficiency

- Compute efficiency for selecting muon candidates with $p_T > 20$ GeV:
  - Compare to MU20 trigger efficiency in data as shown earlier
  - Toy simulation has perfect acceptance $\rightarrow$ scale efficiency curve to match the data plateau
- Obtained much steeper efficiency curve than data - potentially leading to lower muon trigger rates
  - Missing many effects present in the real RPC detector $\rightarrow$ still looks interesting enough to study further...

Relative p_T error vs. true q/p_T
Achieved about 20% p_T resolution at 20 GeV



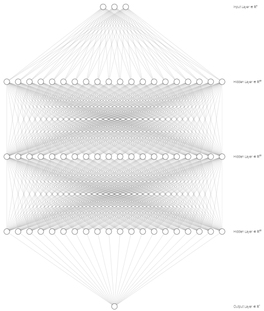
Efficiency to trigger muon with $p_T > 20$ GeV
Scale efficiency curve to match the data plateau

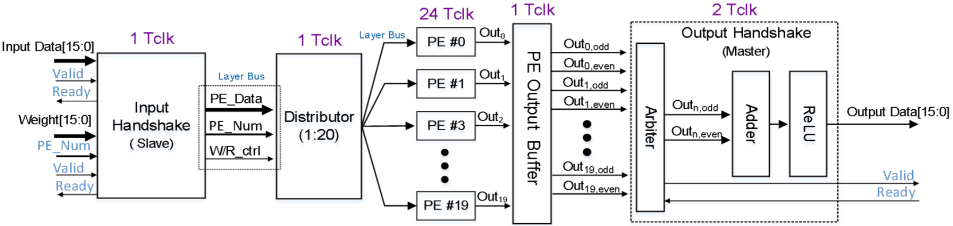


FPGA implementation and simulation

FPGA implementation

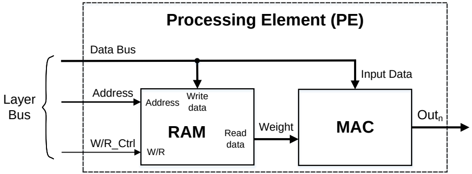
- Implemented the full neural network regression model in Vivado HDL
  - Data processing logic not yet implemented - important for final prototype
- Serial data pipeline between layers
  - Reduce a number of connections between layers using distributor → smaller latency
  - 5 clock cycles for signal handshake, final adder & ReLU operations and transmission
- Process in parallel 20 neurons of each layer
  - Processing element (PE) implements logic for one neuron node → next page



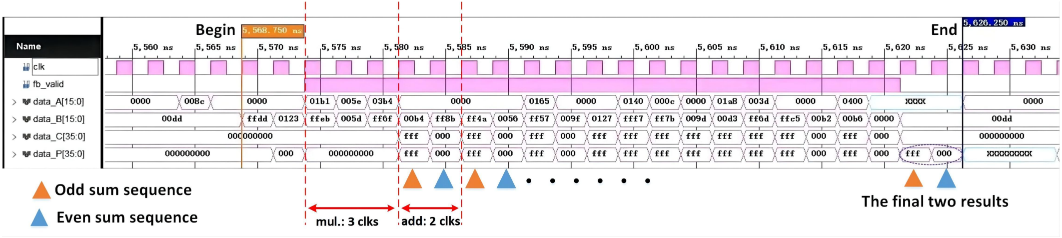


FPGA implementation: neuron processing element

- Neuron node is implemented in processing element (PE):
  - Output $= \text{ReLU}(\sum_{i=1}^{20} x_i \cdot \text{weight}_i + \text{bias})$
  - Process serially 20 data inputs from the previous layer
  - Latency $= (N_{\text{input}} + 4) \times \Delta t_{\text{clock}} = 24 \times \Delta t_{\text{clock}}$
- Multiply-add-accumulate (MAC) unit:
  - Implemented using one digital signal processor (DSP)
  - 3 clock cycles for multiplication and 2 clock cycles for addition
  - Odd/even inputs are processed independently: $IA_i * W_i + AC_{i-2}$



PE simulation



FPGA implementation: latency and resource usage

- Latency for the full network: 98 clock cycles

  245 ns @400 MHz $<<$ 10 μs latency of L0 trigger system

- Deadtime for the full network: 24 clock cycles

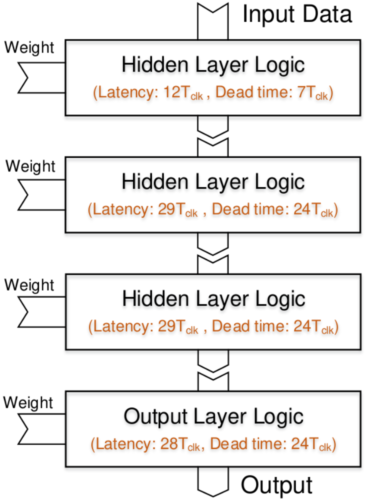
  60 ns @400 MHz $<$ 3 LHC bunches $=$ 75 ns

- Resource usage for implementation on Xilinx FPGA XCKU060:

LUTs	Registers	DSPs
9949 (3.15%)	10257 (1.55%)	68 (2.36%)

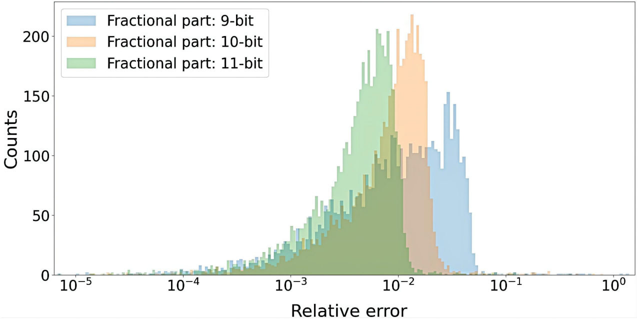
- This corresponds to $\sim$ 0.5% of resources of XCVU13P FPGA
  - 32 such devices will be used for muon barrel trigger upgrade

- Much lower resource usage than hls4ml with $\times$3 latency
  - Latency can be further reduced by using more DSPs



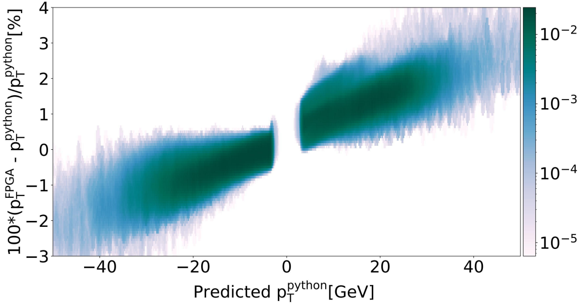
FPGA implementation: fixed point arithmetic

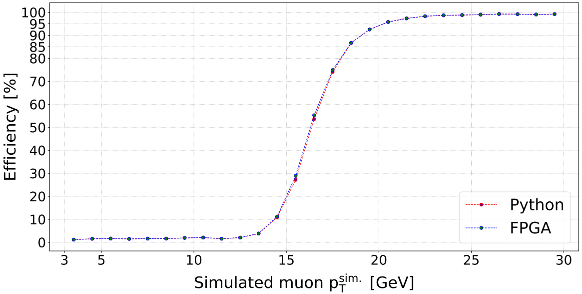
- Our FPGA implementation uses 16-bit binary fixed-point numbers
  - Scan several options for fractional part precision
  - Compute relative p_T error between full precision and fixed-point precision - plotted below
  - *Chosen 10 bits for the fractional part and 6 for the signed integer part*



FPGA simulation

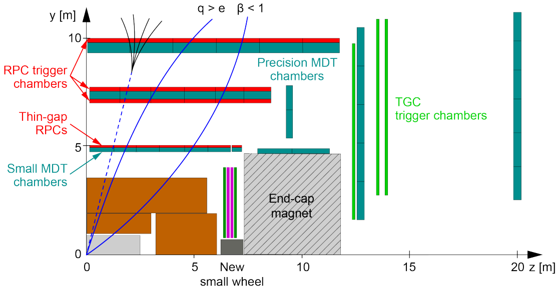
- Full neural network circuit has been tested using simulation:
  - Simulation test project was developed using Questa Advanced Simulator and SystemVerilog
- Compare results from PyTorch and FPGA simulation for the same events:
  - Percent level errors from using fixed point 16-bit arithmetic
  - Efficiency curve for the FPGA implementation is nearly identical that obtained with PyTorch





Potential applications for FPGA-based neural networks

- HL-LHC searches for long lived particles (LLPs)
  - L1 trigger was optimised for detecting SM particles
  - FPGAs allow development of dedicated exotic triggers
  - *Can neural networks be used to trigger on exotic signatures? LLP decays, slow-moving LLPs, highly ionising LLPs*
- Hardware accelerators for ATLAS High Level Trigger (HLT)
  - HLT runs on a large CPU farm that will process events accepted by L0 at 1 MHz rate
  - *Is it possible to use FPGAs or GPUs to accelerate CPU-intensive (track) reconstruction steps?*
  - Ongoing R&D to answer this question by 2025, plan to use commercial FPGA or GPU cards plugged in PCIe slots
  - Main points: cost, power, cooling, flexibility, usability



Summary and outlook

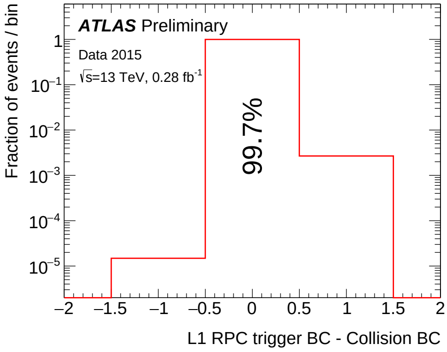
- Effective trigger selection of muon candidates is crucial for the ATLAS physics programme
- Excellent performance of the ATLAS RPC detector and L1 muon barrel trigger with 2018 data
- Extensive muon spectrometer & trigger upgrades are planned for the HL-LHC
- All new FPGA-based L0 muon trigger electronics will allow more sophisticated trigger algorithms
- *We developed resource efficient FPGA-based neural network regression model*
  - Regression model is trained with toy RPC simulation to measure muon q/p_T
  - Promises better performance than the current L1 system $\rightarrow$ steeper muon efficiency curve
  - Implemented this neural network in FPGA code: 245 ns latency and very low resource usage
- Results look promising and warrant further studies using more accurate simulation
  - Plan to develop dedicated triggers to search for new long-lived particles using the muon spectrometer

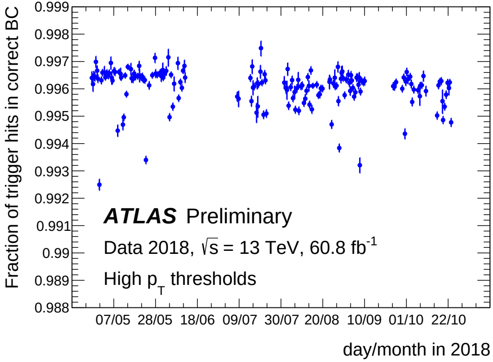
Thank you for your attention!

BACKUP

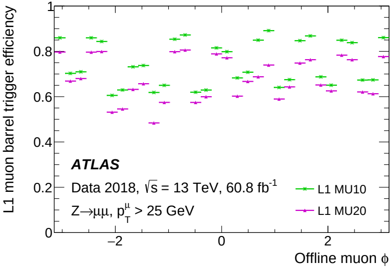
Trigger timing calibrations

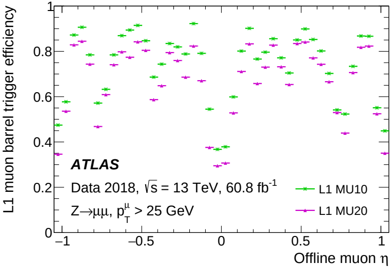
- RPC hits (muon signals) are calibrated online with 3.125 ns step
  - More than sufficient to identify individual LHC bunch crossings with 25 ns spacing
- 99.7% of muon candidates arrive within expected 25 ns time window
- Excellent stability of timing calibrations during data taking period

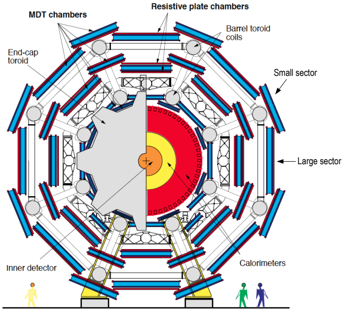


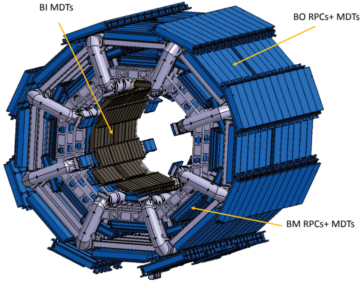


RPC trigger efficiency is reduced by ≈ 20% by detector support structures

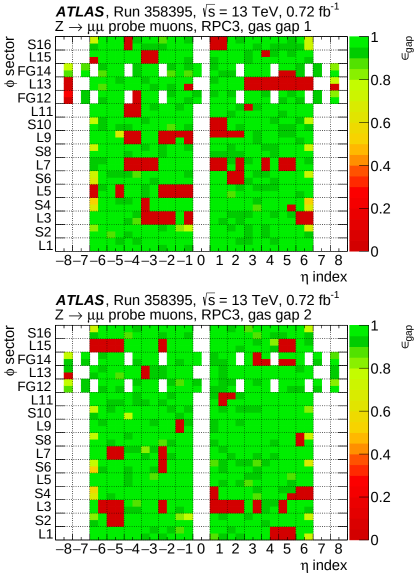


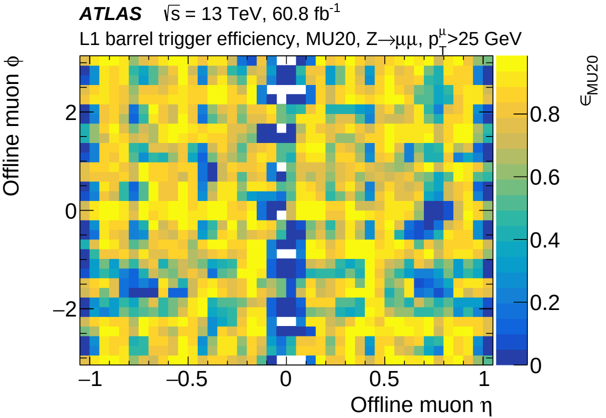






RPC trigger efficiency is reduced by another ≈ 10% by inefficient modules (left plots)

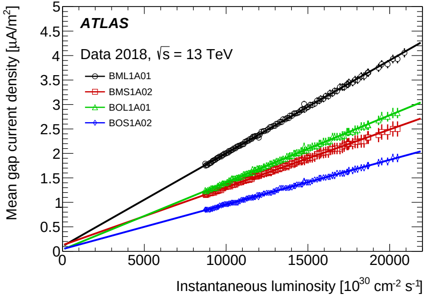




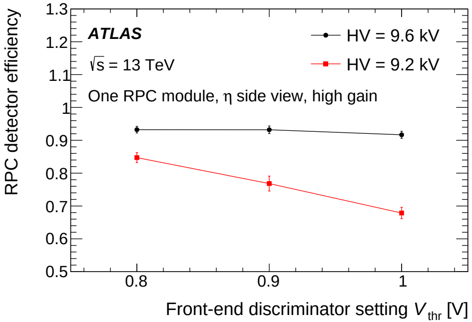
HL-LHC studies

- RPC upper limit on current density is $30\mu A/m^2$ for HL-LHC at $\mathcal{L} = 7.5 \times 10^{34} cm^{-2}s^{-1}$
- Extrapolate current LHC data to high luminosity to study expected performance
  - Chambers with smaller radius and at high $|\eta|$ will exceed these limits
  - Plan to reduce HV to 9.2 kV and decrease front end thresholds to regain $\sim 10\%$ efficiency
- Scan FE discriminator thresholds at 9.6 kV (nominal) and 9.2 kV (proposed for HL-LHC)

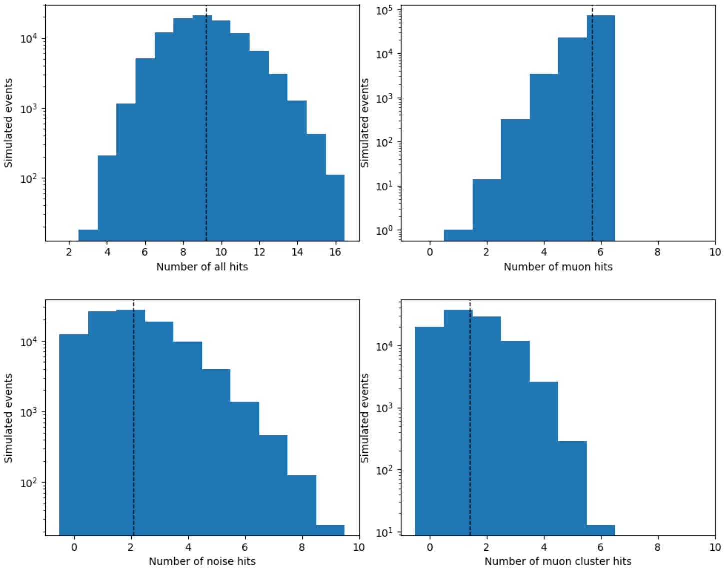
RPC detector currents at different $|\eta|$ stations versus instantaneous luminosity



RPC detector efficiency versus discriminator V_{FE}



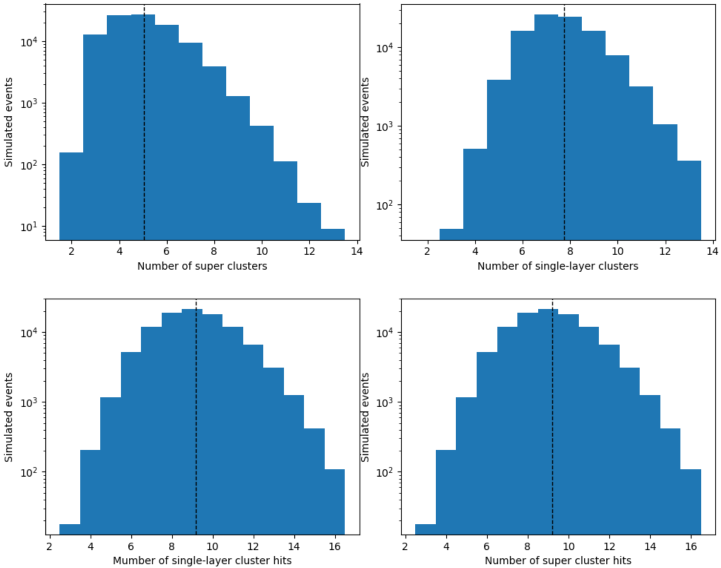
RPC toy simulation: hit multiplicity



- On average, about 9 total hits per event
- On average, about 2 noise hits and 1.8 cluster hits

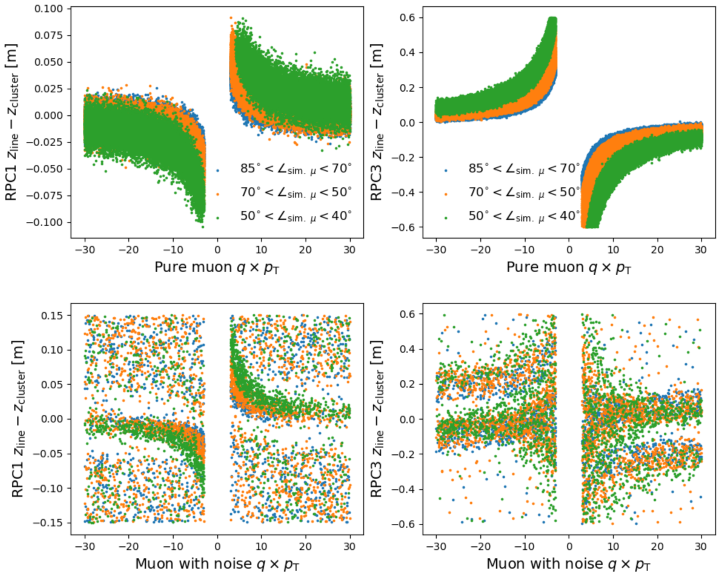
Neural network simulation: cluster multiplicity

- Super-clusters are reconstructed from single-layer clusters in one doublet layer that are within 1.5 × strip width
- On average, about 8 single-layer clusters
- On average, about 5 super (double-layer) clusters
- Check: same number of hits for both cluster types



Neural network simulation: super-cluster position differences

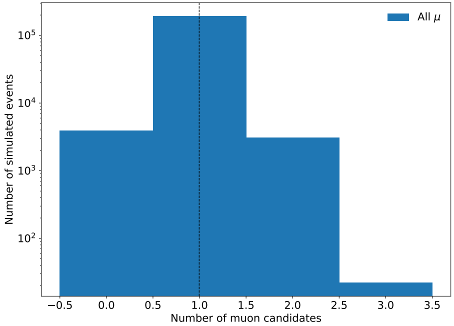
- Muon candidates:
  - Require $\geq$ 1 clusters per RPC1, RPC2 and RPC3
  - Make muon candidate for each RPC2 (seed) cluster
  - Draw line through each RPC2 seed cluster
- Clear correlations between p_T and Δz for muons without noise hits
- As expected, random deviations for muons containing noise hits



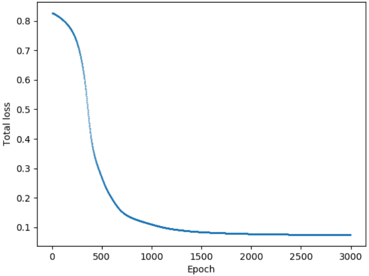
Candidate muons

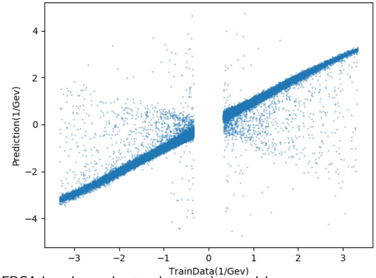
- On average, we reconstruct 1 muon candidate per simulated event
  - 0 candidates when one doublet layer is inefficient
  - 2 candidates when a noise hit is reconstructed as a cluster
  - In later plots, noise muon candidate (noise μ) contains at least one noise cluster

Number of muon candidates per event

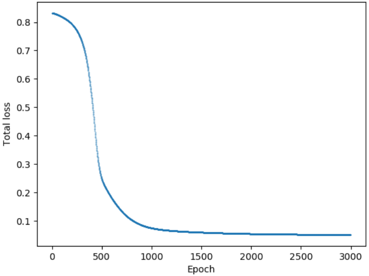


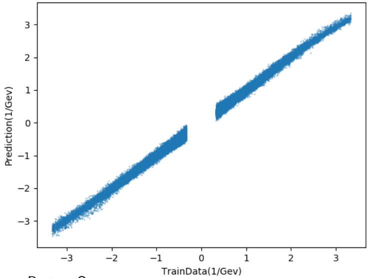
Training events with noise





Training events without noise





FPGA implementation: multiply-add-accumulate (MAC) unit

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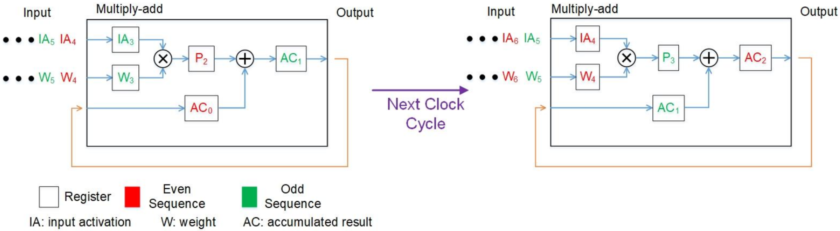
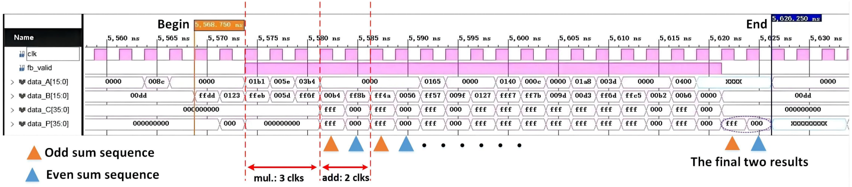
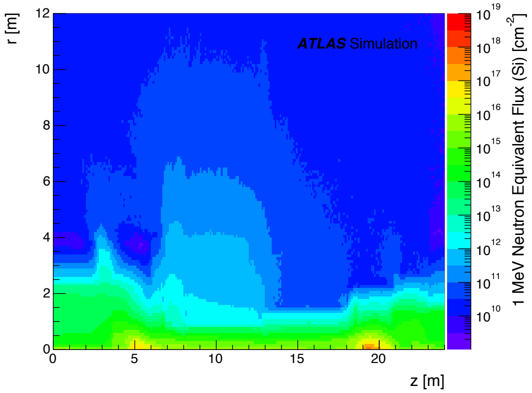
- Odd and even input data elements are processed in parallel and independently: $IA_i * W_i + AC_{i-2}$



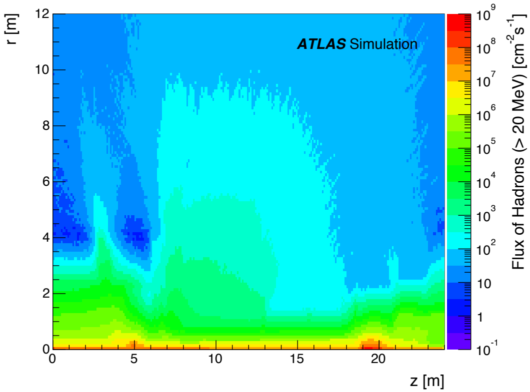


Simulated dose and particle flux

Neutron equivalent flux



Hadrons flux



HL-LHC upgrades of RPC detector and trigger

- For HL-LHC data-taking, RPC will provide up to 9 measurements of $\eta \times \phi$
- Inner barrel RPCs will increase detector acceptance
- MDT will be included in hardware muon trigger $\rightarrow$ refine p_T measurement for candidates accepted by RPC
- Order of magnitude better time-of-flight resolution with new on-detector electronics and faster thin-gap RPCs