Search for Lepton Flavour Unitarity Violation in top-quark events at ATLAS and development of the Global Trigger system

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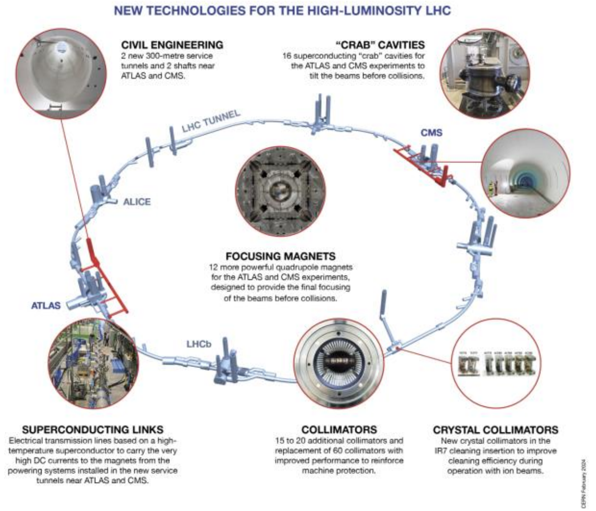
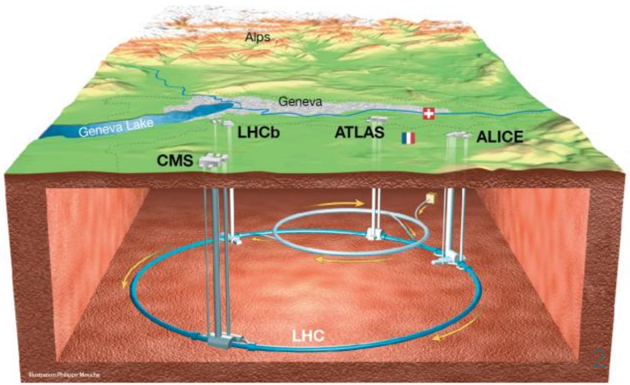
ATLAS EXPERIMENT

UKRI Science and Technology Facilities Council
Particle Physics

CERN and High-Luminosity LHC

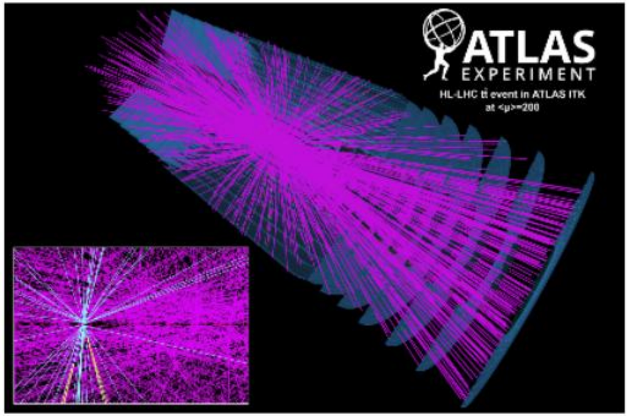
- ATLAS is one of the two ‘general purpose’ detectors at the Large Hadron Collider at CERN
  - Located on the Franco-Swiss Border near Geneva
- Designed to capture and analyse a full range of physics processes generated by the high intensity proton-proton collisions of the LHC
- From 2026-2030, LHC will undergo a major upgrade to significantly increase the collision intensity (luminosity) and allow us to take much more data for analysis
  - ‘High-luminosity’ LHC (HL-LHC) will then run in this configuration through to ~2041 (with some shutdowns along the way for maintenance and optimisation)
- To be ready for HL-LHC, ATLAS and CMS are working on a major programme of upgrades
  - LHCb and ALICE upgrades on different timescales
  - Significant challenges to handle the increase data rates and event complexity, commonly described in terms of ‘pileup’, which is the average number of proton-proton interactions that happens each time the LHC beams collide
  - In Run 3 (now) the average pileup is ~60, for HL-LHC it may reach 200



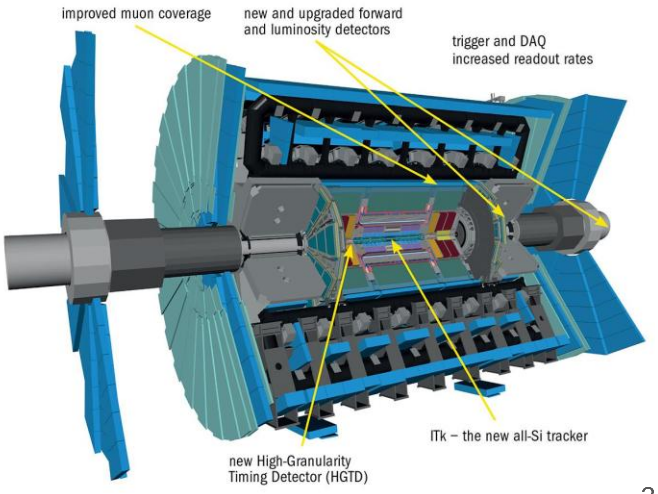


ATLAS in HL-LHC

- ATLAS is laid out in the classic ‘onion’ formation
  - Inner tracking detector close to the beam pipe, surrounded by calorimeters and then an outer muon layer
- Key parts of the HL-LHC upgrade
  - Inner tracking detectors will be replaced by a new all-silicon system called ITk
  - A new high performance timing detector on each endcap (HGTD) will help further reduce backgrounds in these regions
  - Muon and forward detectors updated with increased coverage
  - Fully upgraded Trigger and Data Acquisition (TDAQ) system to handle increased rates and complexity

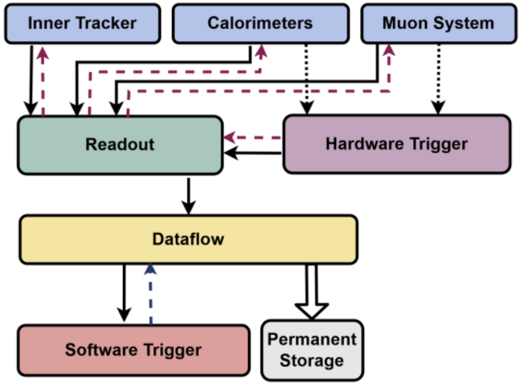


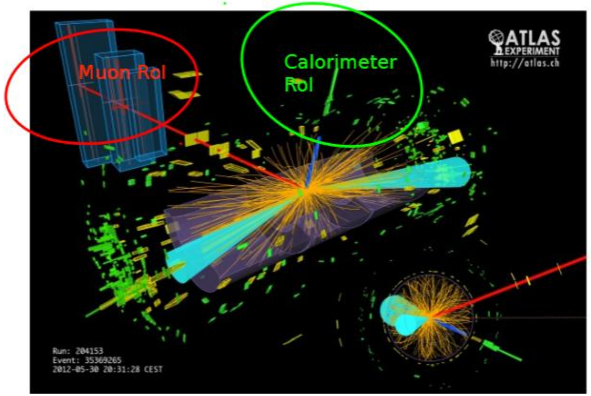
Simulated 200 pileup event



ATLAS TDAQ in HL-LHC

- The ATLAS Trigger System selects interesting events for further study as they are produced by the LHC
- System split into two main components
  - Low-level hardware-based trigger for high-speed selection
    - Typically based on custom hardware featuring application specific integrated circuits (ASICs) or field programmable gate arrays (FPGAs)
    - Rate reduction from 40 MHz LHC collision rate to 100 kHz now, 1 MHz for HL-LHC
    - Needs to decide on each event within 2.5 μs (10 μs in HL-LHC), a time known as the 'latency'
  - High-level software-based trigger, running on a farm of standard computers
    - More complex processing
    - Further rate reduction, from 100 kHz to 1.5 kHz now, 10 kHz for HL-LHC
    - Needs to decide on each event within 0.5-1s (similar in HL-LHC)
- Based on 'Regions of Interest'
  - Deposits in the Calorimeter of Muon systems that fall above given energy/momentum thresholds.
  - Processed in hardware trigger, then interesting events passed to software trigger where tracking information is incorporated for more accurate selection.

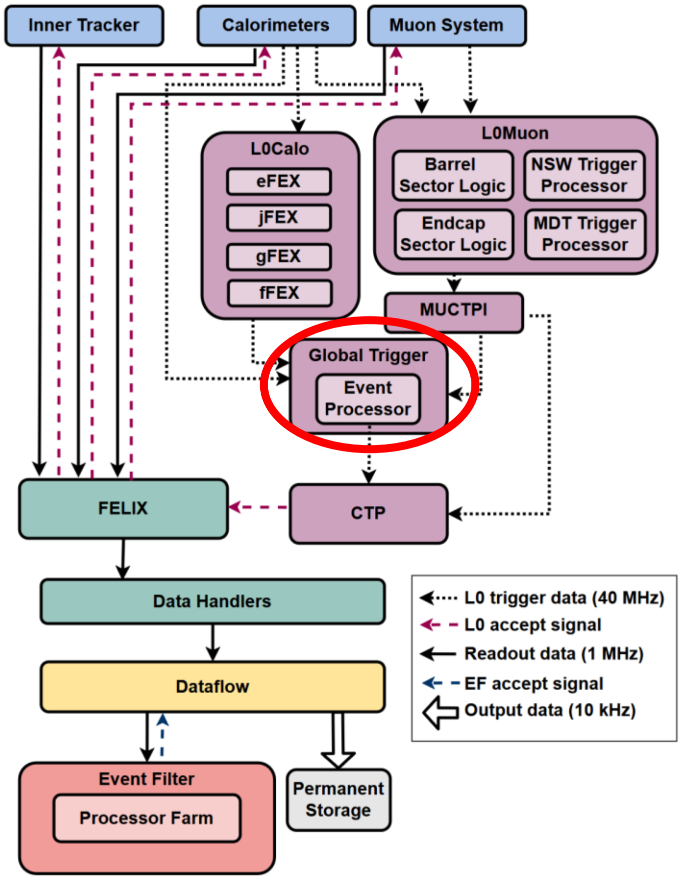




ATLAS Event Display from Run 1 showing Muon and Calorimeter RoIs

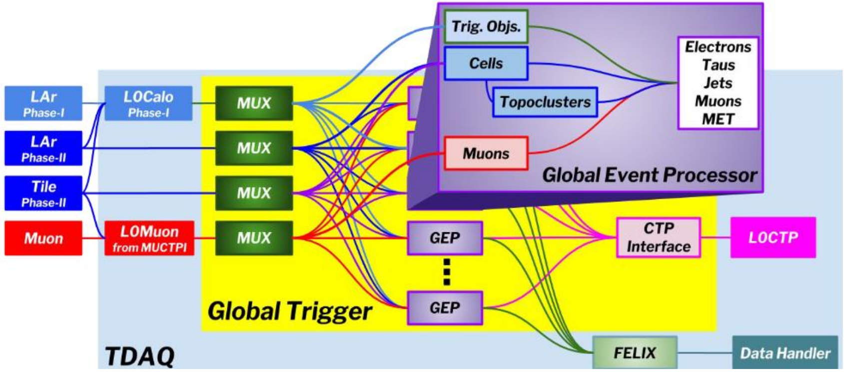
ATLAS TDAQ in HL-LHC

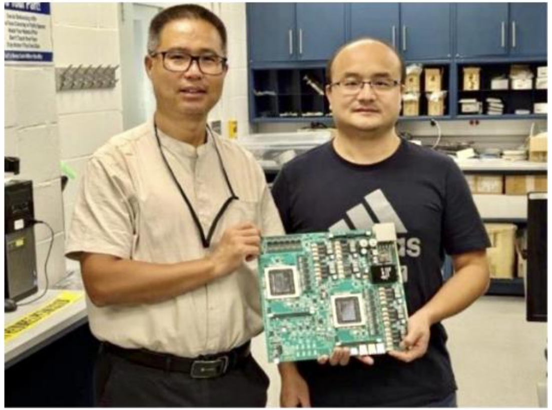
- TDAQ for HL-LHC will feature:
  - Upgraded calorimeter and muon trigger systems
    - New and upgraded hardware, FPGA firmware, software
  - All-new Global Trigger system
  - Upgraded readout (FELIX and Data Handlers) and dataflow systems
    - Transport all data from events passing hardware trigger selection to software trigger (known as Event Filter)
  - Upgraded Event Filter (software trigger farm), potentially incorporating GPU or FPGA-based acceleration



Global Trigger

- In the ATLAS trigger, events arrive split over all the different systems which contributed detecting them
  - Typically only fully stitched together in the software trigger, where there is enough time to study them within the latency budget
- Improved technology, facilitating among other things a longer latency window, means more advanced techniques can be deployed for HL-LHC
- The Global Trigger is based on a concept known as 'time multiplexing'
  - Concentrate calorimeter and muon data from each event onto one processing node to allow more complex analysis within latency budget
  - Essentially moving software trigger-like functionality into the hardware trigger
- Implemented as a farm of around 50 custom-made FPGA-based processing boards (Global Common Modules)
- Receiving approximately 50 Tb/s of data across all inputs
- Input stage multiplexes all data from a given event onto one processing module
  - Can then run advanced algorithms (including Machine Learning) for optimal selection power

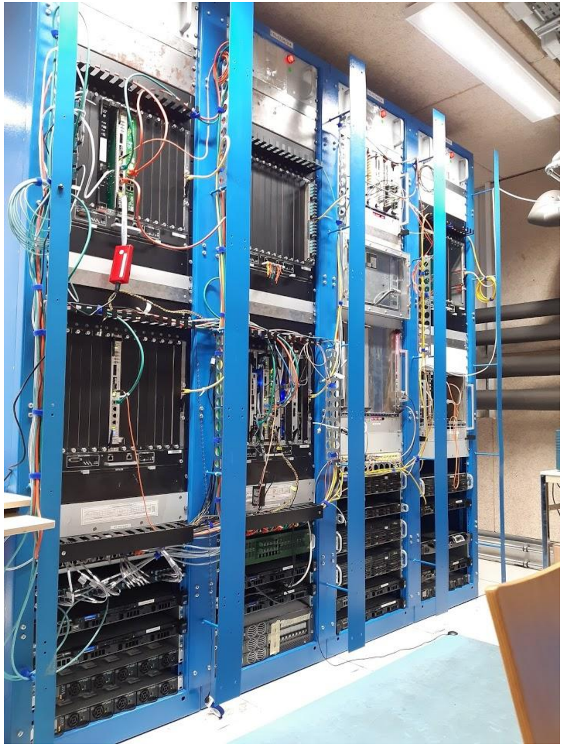




Global Common Module Prototype Testing

Working with Global

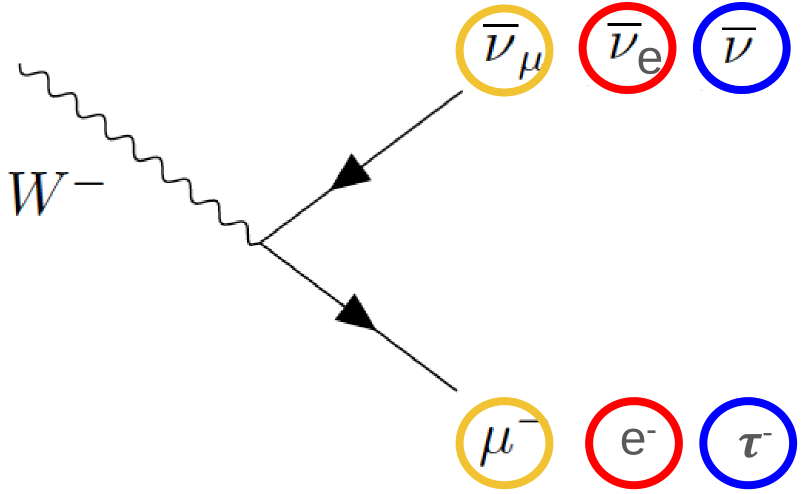
- As part of the Global Trigger team, you will contribute to the development of the software needed to operate the processing farm
    - Working with latest generation AMD Versal FPGAs with ARM-based System-on-chip
- Opportunity to contribute to integration and commissioning of the final system, based in the labs both at RAL and CERN
- You'll be part of a large international team working together to deliver a key component of ATLAS TDAQ for HL-LHC



Surface Test Facility at CERN

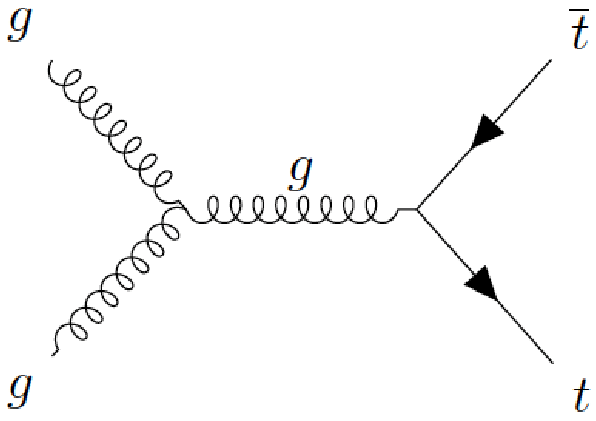
Lepton Flavour Universality (LFU)

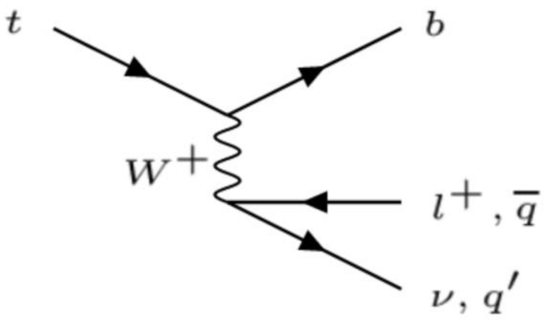
- One of the foundational principles of the Standard Model: electroweak interactions of charged leptons (e, μ, τ) are identical
  - Differences from masses lead to slightly different rates



Lepton Flavour Universality (LFU)

- Tested at ATLAS using top anti-top quark events and on-shell W bosons:





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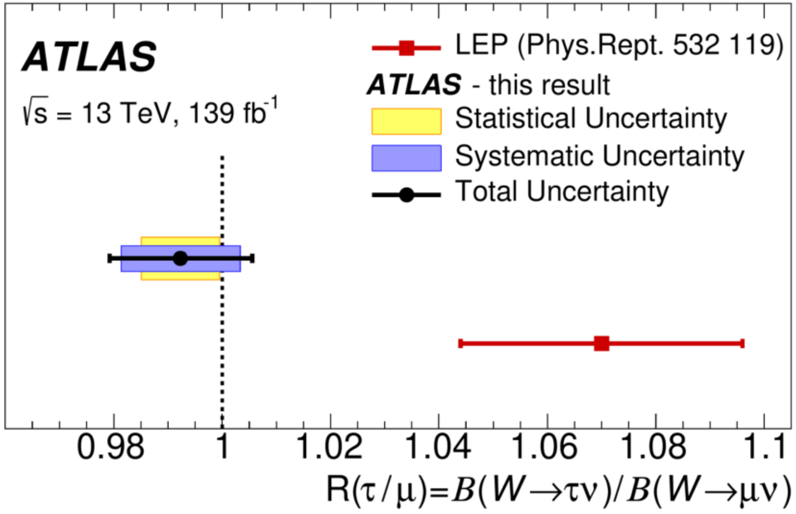

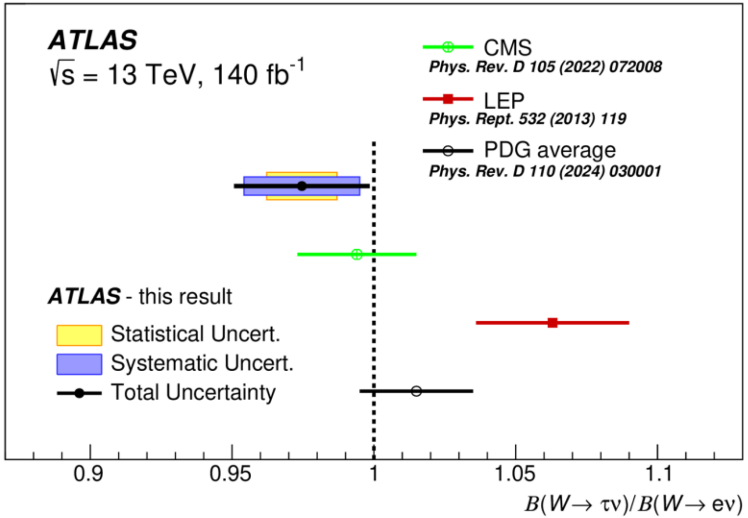

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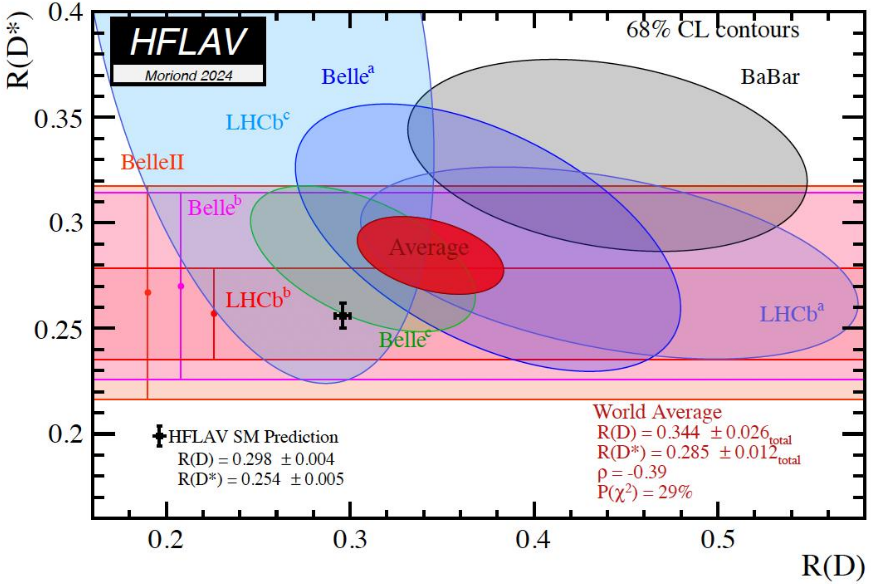
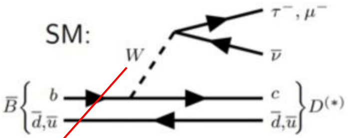
Submitted to JHEP

Lepton Flavour Universality (LFU)

- Tested at B factories using off-shell W bosons: combination has 3.2σ tension with SM value



SM:

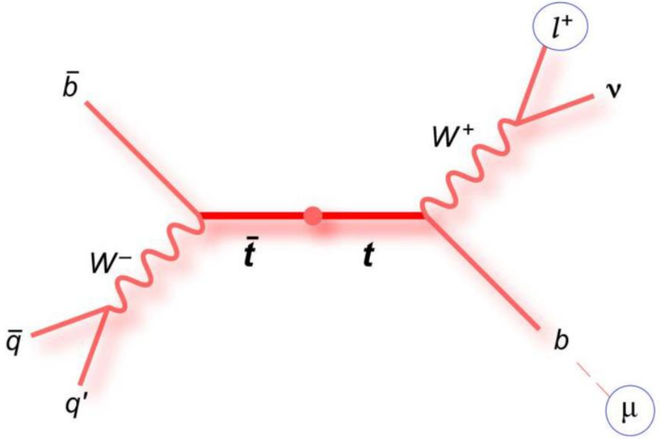


X: might violate LFU → look for new physics!

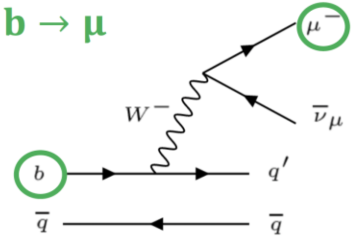
Search for LFU Violation at ATLAS

- Use top anti-top quark events and select b-quark jets containing a muon
- Count how often the muon is directly from the b vs from a τ that came from a b

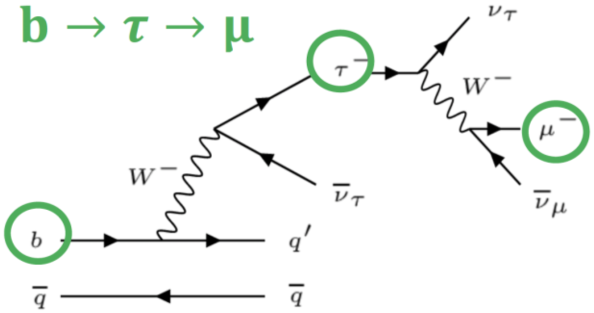
$$\mathcal{R}(\tau/\mu) = \frac{N[b \to \tau \to \mu]}{N[b \to \mu]}$$



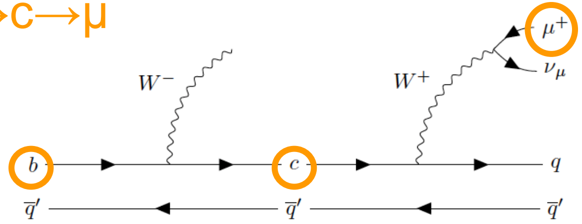
b → μ



b → τ → μ



b→c→μ



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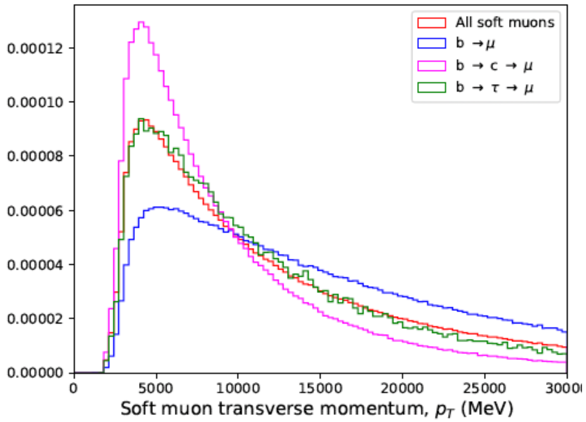
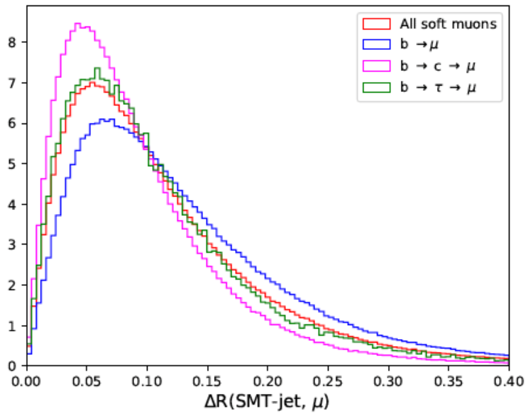
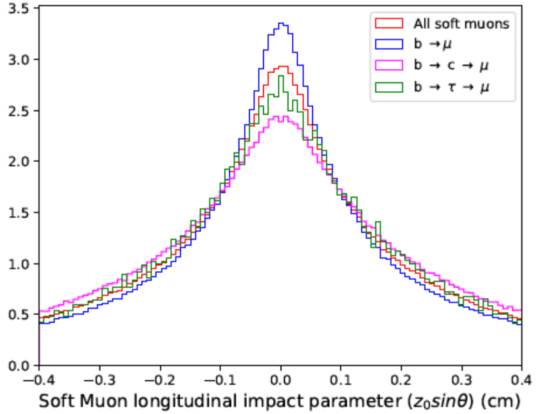
Search for LFU Violation at ATLAS

- Use Machine Learning to distinguish where the muon came from:



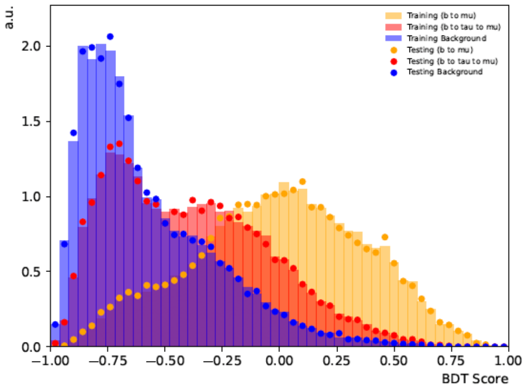


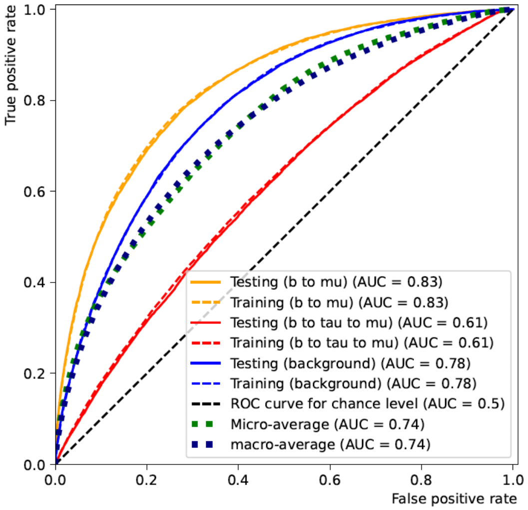


Feasibility study

Search for LFU Violation at ATLAS

- For example: Multi-Class BDT





Feasibility study

Search for LFU Violation at ATLAS

- Using the Run 2 dataset from ATLAS we expect:
  - Statistical uncertainty of 0.6%
  - Measurement likely to be dominated by systematic uncertainties
  - Vs Theoretical uncertainty from SM of 2%
  - Vs LHCb22 R(D*) has total uncertainty of 10.7% (6.4% statistical uncertainty)

$$\mathcal{R}(\tau/\mu) = \frac{N[b \to \tau \to \mu]}{N[b \to \mu]}$$

- For this analysis we plan:
  - To use Run 2 and Run 3 datasets
  - Find a good Multi-Class ML method to identify the muons
  - → brand new analysis in ATLAS/CMS, competitive with other B-factories, search for new physics!

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Conclusion

- Come and be part of one of the biggest commissioning projects in science in the UK!
- Participate in exciting searches for new particles!
- Look forward chatting with you this afternoon!