UPPSALA UNIVERSITET

ATLAS EXPERIMENT

Hardware tracking for the ATLAS trigger at the High Luminosity LHC and BSM searches with tau leptons in the final state

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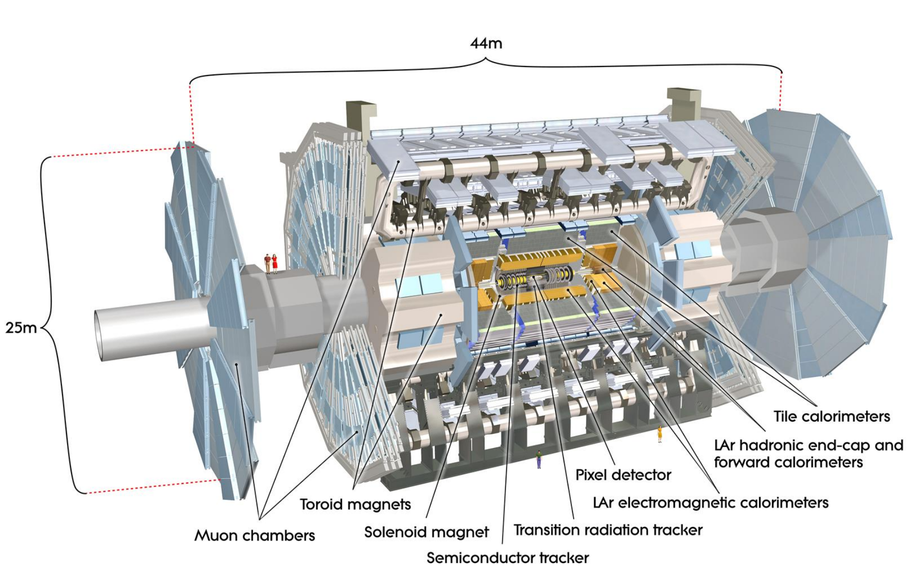
Outline

- Introduction to the ATLAS experiment
- Part 1: BSM with tau leptons in the final state
  - LQ3LQ3 → $b\tau b\tau$ → $b\tau_{had}b\tau_{had}$
- Part 2: Hardware tracking for the ATLAS trigger at the HL-LHC
  - The High-Luminosity LHC
  - The ATLAS trigger at the HL-LHC
  - Hardware tracking for the trigger (HTT)
  - Hough transform FPGA implementation
  - Simulation study: Comparison of pattern matching using Associative Memory and the Hough transform

The ATLAS experiment

- Located at the Large Hadron Collider (LHC), CERN, Geneva.
- General-purpose particle physics experiment.
- Using mainly proton-proton collisions to study the fundamental forces and the structure of matter:
    - Studies the properties of the Standard Model.
    - Searches for physics beyond.

The ATLAS detector

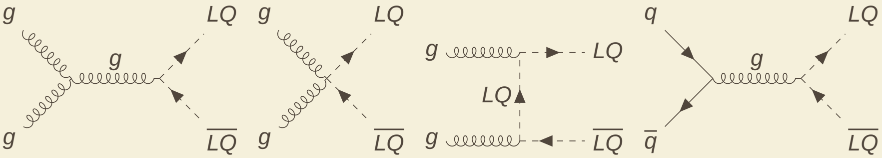


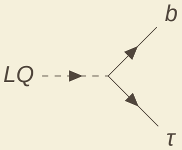
Part 1

BSM searches with tau leptons in the final state

- 3rd gen leptoquark: LQLQ $\rightarrow$ bτbτ

Theory and motivation





- 3rd generation leptoquark, linking lepton and quark sectors.
- Several extensions of the standard model including technicolor, Pati-Salam, and $SU(5)$ GUTs.
- $B \rightarrow \tau\nu$ and $B \rightarrow D(^{*})\tau\nu$ decay rates higher then expected from the Standard Model.
  - Provides potential explanation of 3 σ disagreement seen by BaBar, LHCb, and Belle.

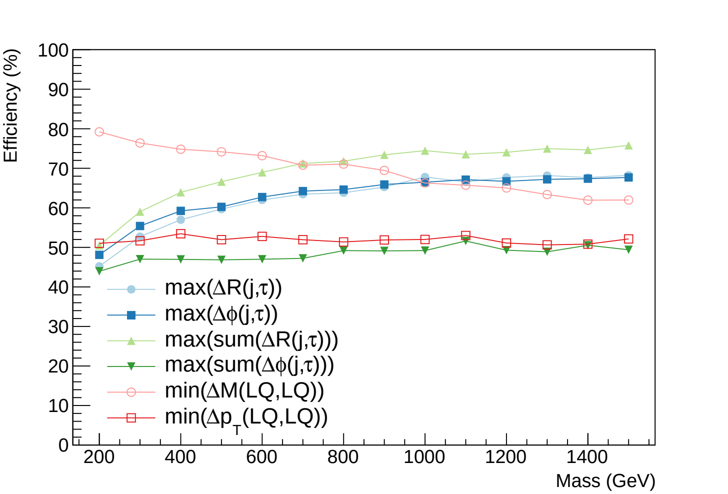
Analysis overview

- Reworking the HH→ bbττ analysis.
  - Pedro and Petar from Uppsala are involved. (Pedro also in LQ3)
- Pair as LQ = bτ instead of H = bb and H = ττ.
- Preselection
  - Single-tau and di-tau triggers.
  - 2 medium taus of opposite sign and 2 or more central jets.
  - $p_T^\tau > 40, 30\,\mathrm{GeV}$, $p_T^j > 45, 20\,\mathrm{GeV}$, and $p_T^{b_0} > 80\,\mathrm{GeV}$
  - $m_{\mathrm{MMC}} > 0\,\mathrm{GeV}$
- I've been looking at strategies of pairing bτ when the tau leptons decay hadronically.

Pairing strategies

- Two ways of pairing jets and taus into LQs:
  - $(j_0\tau_0, j_1\tau_1)$ or $(j_0\tau_1, j_1\tau_0)$
- I've looked at six pairing strategies:
  1. Maximize the sum of $\Delta\phi$ between the jets and taus.
  2. Maximize the sum of ΔR between the jets and taus.
     - $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$
  3. Maximize the $\Delta\phi$ between one jet and one tau.
  4. Maximize the ΔR between one jet and one tau.
  5. Minimize the mass-difference of the two LQs.
  6. Minimize the p_{T}-difference of the two LQs.

Pairing efficiency



Summary and outlook

- Summary
    - Search for 3rd generation leptoquarks decaying to $b\tau$.
    - I have looked at ways to reconstruct the leptoquark by pairing *b*-jets and τ leptons.
    - Minimizing the mass difference is the best one for low mass.
- Outlook
    - Refine cuts, e.g. τ lepton and jet p_T.
    - Move to multi-variate analysis (boosted decision trees).
    - Aiming for publication before Christmas.

Part 2

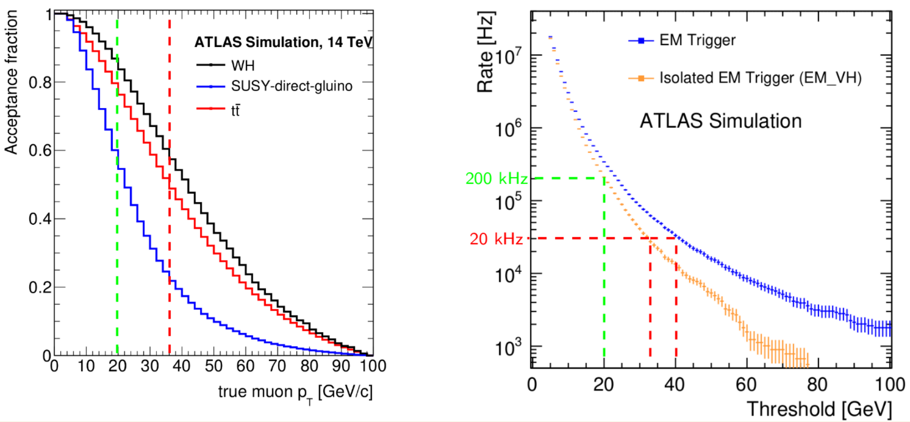
Hardware tracking for the ATLAS trigger at the HL-LHC

- The High-Luminosity LHC
- The ATLAS trigger at the HL-LHC
- Hardware tracking for the trigger (HTT)
- Hough transform FPGA implementation
- Simulation study: Comparison of AM and Hough

The High-Luminosity LHC

- An upgraded version of LHC scheduled to start operation in 2026.
- Physics goals include:
  - Studying the higgs boson, e.g. higgs self-coupling.
  - Studying the quark-gluon plasma.
  - Search for new forces and particles, e.g. Supersymmetry.
- Increase the rate of proton-proton collisions.
- Luminosity increased to $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, a factor of 5-7 compared to the LHC baseline design.

Trigger requirement

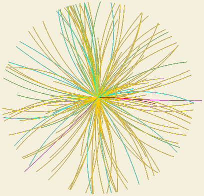


=> If we are forced to increase the trigger p_T threshold to lower the rate, we will not benefit from the higher luminosity!

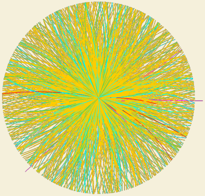
Further reading: LHCC-I-023, LoI for the Phase-II Upgrade

ATLAS at the HL-LHC

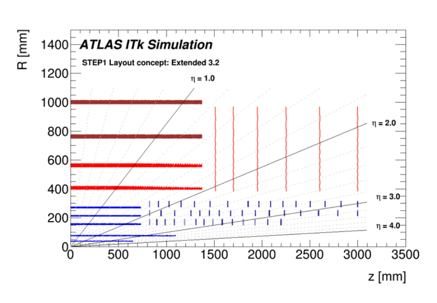
- ATLAS needs to maintain a low trigger p_T threshold to not loose acceptance for interesting processes.
- Introduce fast regional Hardware Tracking for the Trigger (rHTT) with near-offline resolution.
- Using the strip and pixel detectors of the Inner Tracker (ITk).



pile-up 23

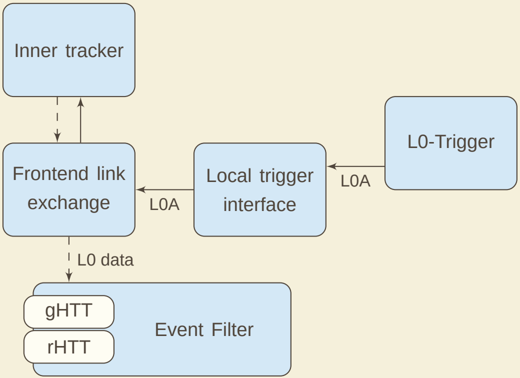


pile-up 200



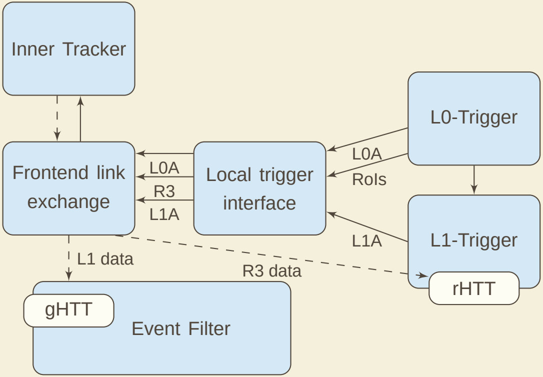
Baseline trigger architecture

- Single-level L0-only mode.
- L0-trigger: muon chamber and EM calorimeter.
- Full detector readout at 1 MHz (max).
- HTT runs as part of the Event Filter.

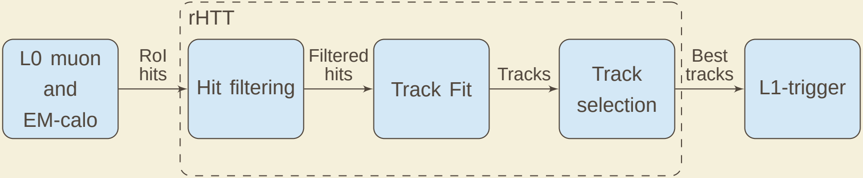


Evolved trigger architecture

- L0A initiates data storage in front-end ASICs.
- 2-4 MHz L0A.
- R3: regional readout request (10 % of ITk volume).
- L1A initiates readout of strips + outer pixels.
- L1 rate = 600–800 kHz (L1A) + 400–200 kHz (10 % of L0A).



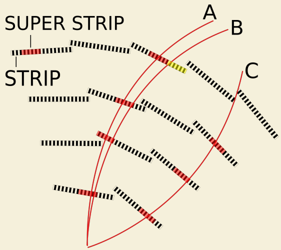
rHTT overview



- Using 8 detector layers of which 1 or 2 are outer pixel layers.
- RoIs of $\Delta\eta = 0.2$ by $\Delta\phi = 0.2$.
- Hit filtering in Associative Memory (AM) chips.
  - Alternatively in Field-Programmable Gate Arrays (FPGAs) using the Hough transform.
  - AM requires custom made ASICs while the Hough transform can be implemented in commercial FPGAs.
- Track fitting in FPGA.

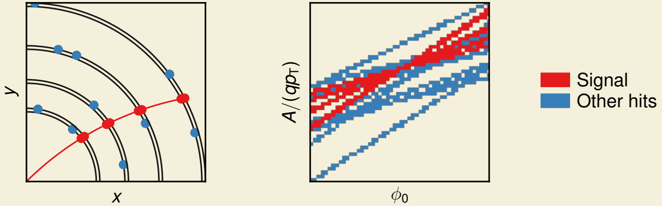
AM pattern matching

- AM chips match input data to pre-defined patterns.
- Pixels and strips are combined to coarser-resolution *super-strips*.
- AMs containing patterns of super-strip hits from simulated tracks.
- 1M patterns per RoI.
- *Don't care bits* and *wildcard layers* can combine similar patterns and account for missing hits.
- Patterns trained using 30M simulated tracks from muons:
    - 1, 2, or $4 < p_{\mathrm{T}} < 400\,\mathrm{GeV}$.
    - $|d_0| < 2\,\mathrm{mm}$.
    - Flat in $1/p_{\mathrm{T}}$, η, ϕ, z_0, and d_0.
- Hits are associated to matched patterns in an external FPGA.

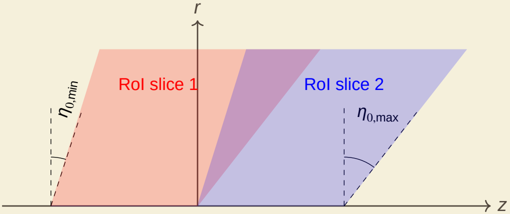


Hough transform

- Alternative to pattern matching using AM. Parallel study.
- Parametrize curves and “accumulate” possible track parameters for all hits: $\frac{qA}{p_{\mathrm{T}}} = \frac{\phi_0 - \varphi}{r}$.



- Background rejection improved by 70 % by slicing up in z_0.



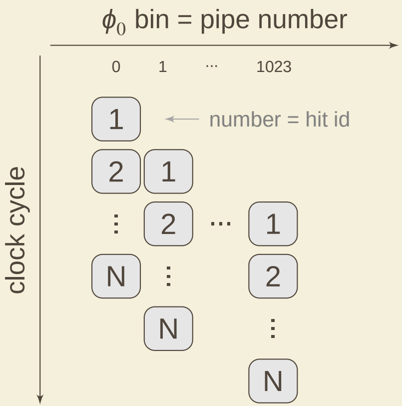
Hough transform in FPGA

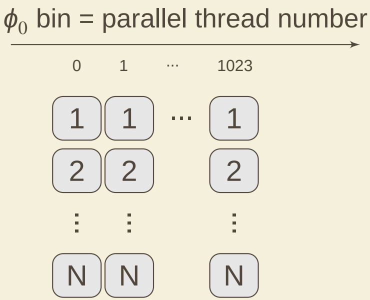
- Implemented the Hough transform in an FPGA using OpenCl.
- Using a Terasic DE1-SoC board with a Cyclone V SoC.
- *Host* code running on on-chip arm32 processor.
  - Inputs hit coordinates to the FPGA.
  - Gets track parameters from the FGPA.
- FPGA *kernel* performs the Hough transform.
- The accumulator is a 2D histogram.
- This study:
  - 32 bins in $(qA)/p_{\mathrm{T}}$.
  - 1 to 1024 bins in ϕ_0.
- Bounds: $p_{\mathrm{T}} > 4\,\mathrm{GeV}$, $0.2 < \phi_0 < 0.5$.
- Each bin consists of 8-bits, 1 bit for each detector layer.

Piped vs. parallel kernel

- Cannot fit a fully parallel kernel when reading in all hit coordinates to local memory. Can I pipe it instead to study performance?

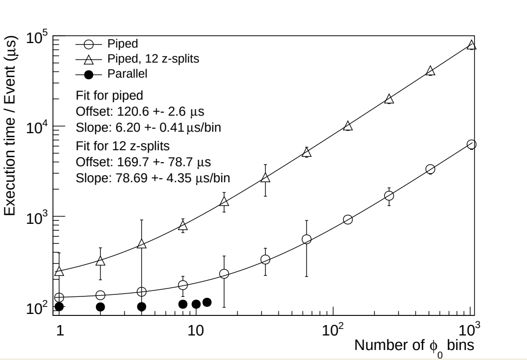
Piped kernel | **Parallel kernel**





Execution time

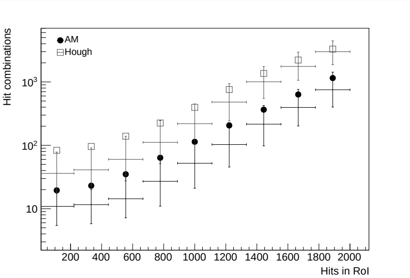
- Single muons embedded in 200 minimum bias events.
- Piped version (with 12 splits in z_0):
  - Execution time increases linearly with number of bins in ϕ_0.
  - 120 µs (170 µs) overhead. Read/write from/to global memory?
  - $6.2\,\mu s/\text{bin}_{\phi_0}$ ($78.7\,\mu s/\text{bin} \approx 6.5\,\mu s/\text{bin}_{\phi_0} \times 12\ \text{bin}_{z_0}$). This is the actual computation.
  - Some large error bars due to 1-2 events taking a long time. FPGA hiccups?
- Parallel version:
  - Cannot fit more than 12 parallel bins in ϕ_0 in this small FPGA.
  - Almost flat execution time of 100 µs.
  - Local memory replicated 4 times => read/write clashes gives 6 µs steps.

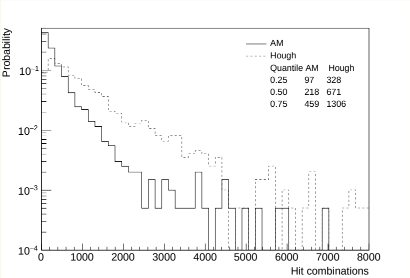


Simulation comparing AM and Hough

- Single muons generated in Geant4:
  - $p_T > 4\,\mathrm{GeV}$, $|z_0| < 150\,\mathrm{mm}$, and $|d_0| < 2\,\mathrm{mm}$.
  - Uniform distributions in $1/p_T$, η_0, ϕ_0, and d_0; gaussian in z_0.
- Minimum bias generated with Pythia8 using `SoftQCD:inelastic` at 14 TeV.
- Detector simulation in Geant4 with the `FTFP_BERT` physics list.
- "Digitization" implemented in C++:
  - Overlay single muon events with 0, 40, 70, 110, 140, 170, 200, 230, and 260 minimum bias events.
  - The total energy deposited in each pixel/strip is calculated and a threshold corresponding to 1 fC is applied.
  - Clusters with 4 or more connected strips/pixels in ϕ are rejected.
  - If an event has muon hits outside the RoI, it is rejected.
- We are using the outer pixel layer and 7 strip layers.

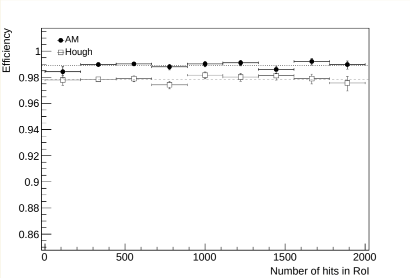
Number of hit combinations

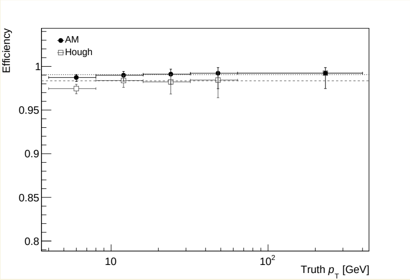




- Combinations: $\sum_g \left(\prod_{l=1}^{8} n_{g,l} \right)$; $n_{g,l}$ is the number of hits in group/pattern g, layer l.
- Right plot shows hit combinations at pile-up 200.
- Left plot shows hit combinations as a function of #hits in the RoI:
  - Circles/squares show the mean. The crosses show the [0.25, 0.50, 0.75] quantiles.
  - The number of hit combinations grow similarly for both methods.
- Hough has more hit combinations than AM.

Muon track finding efficiency

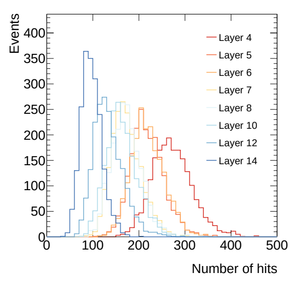




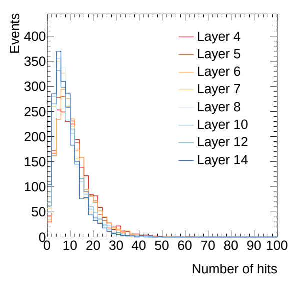
- A muon is considered found if 6 or more hits from the primary muon is found.
- Left plot shows efficiency vs. number of hits, right shows vs. p_T at PU 200.
- The Hough transform i tuned to provide similar efficiency as AM.
- Flat in efficiency vs. number of hits in the RoI.
- Hough slightly worse at low p_T.

Hits per layer

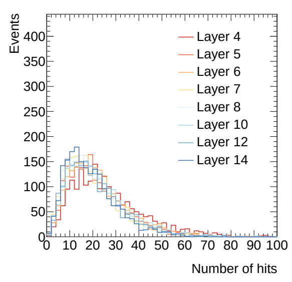
Before hit filtering



After AM

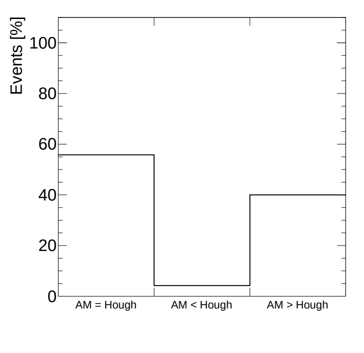


After Hough



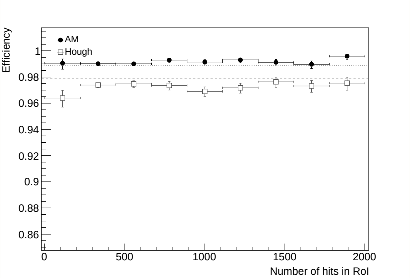
- Shown for single muons overlayed by 200 minimum bias events.
- None of the methods show bias towards any particular layer.

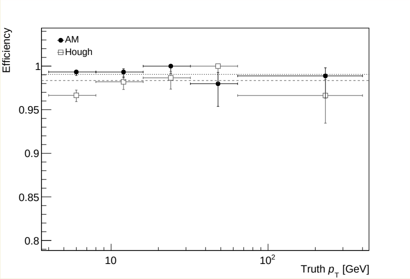
Primary muon hits found



- Shown for single muons overlayed by 200 minimum bias events.
- The AM pattern matching finds more of the primary muon hits than the Hough transform in 40 % of the events.
- The opposite is true in only 5 % of the events.

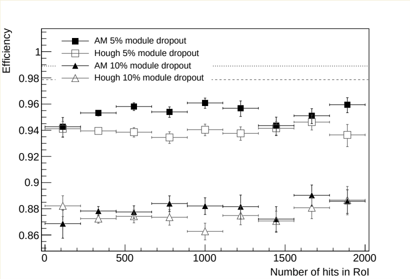
Result when adding addition material

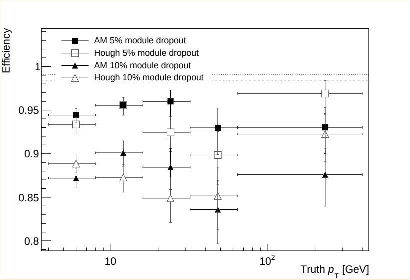




- 50 % more service material.
- The dotted (dashed) line shows the average of the nominal AM (Hough) result.
- The AM methods shows a small overall increase while the Hough transform shows an overall decrease.
- Hough shows a small decrease at low p_T, while AM has an increase.
- However: note the low statistics!

Results with module inefficiency





- Randomly turning of 5 % and 10 % of the modules.
- The dotted (dashed) line shows the average of the nominal AM (Hough) result.
- Dropping 5 % (10 %) reduces the efficiency to approximately 95 % (87 %).
- However: note the low statistics!

Summary and outlook

- Summary
  - The HL-LHC will increase the luminosity by a factor of 5-7 compared to the current run.
  - ATLAS will introduce regional hardware tracking for the trigger to help maintain a low trigger p_T threshold.
  - First stage of the HTT is hit filtering using AM or Hough.
  - Hough transform implemented in FPGA using OpenCL
    - Execution time on the order of 6 μs.
  - Simulation study comparing AM pattern matching and Hough transform
    - AM pattern matching overall better.
    - The Hough transform can be implemented in commercially available FPGAs.
- Outlook
  - Article comparing AM and Hough submitted to JINST
  - Hardware demonstrator

Thank you!

- Publications on track trigger work:
  - Proceeding for Vertex 2016 (poster): PoS(Vertex 2016)069
  - Proceeding for CTD/WIT 2017 (talk): EPJ Web of Conferences 150, 00008 (2017)
  - Article submitted to JINST: arXiv:1709.01034

Questions?