The tau lepton studies at the ATLAS

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Tel **A**viv **U**niversity

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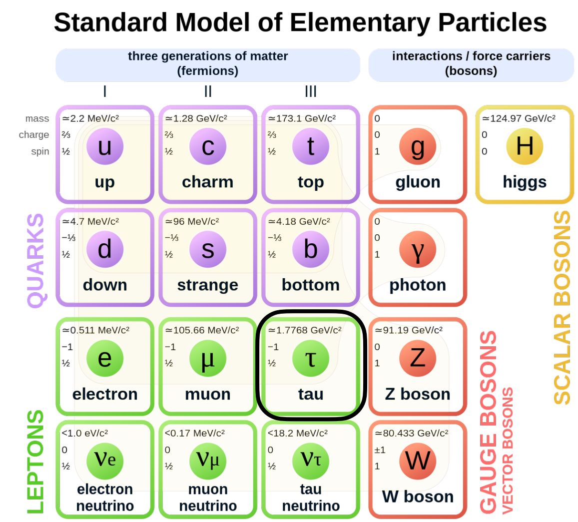
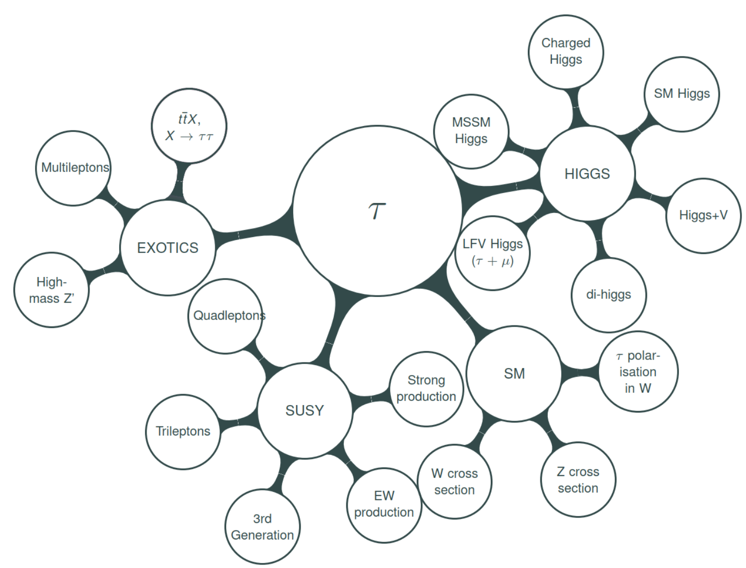
TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Introduction and motivation

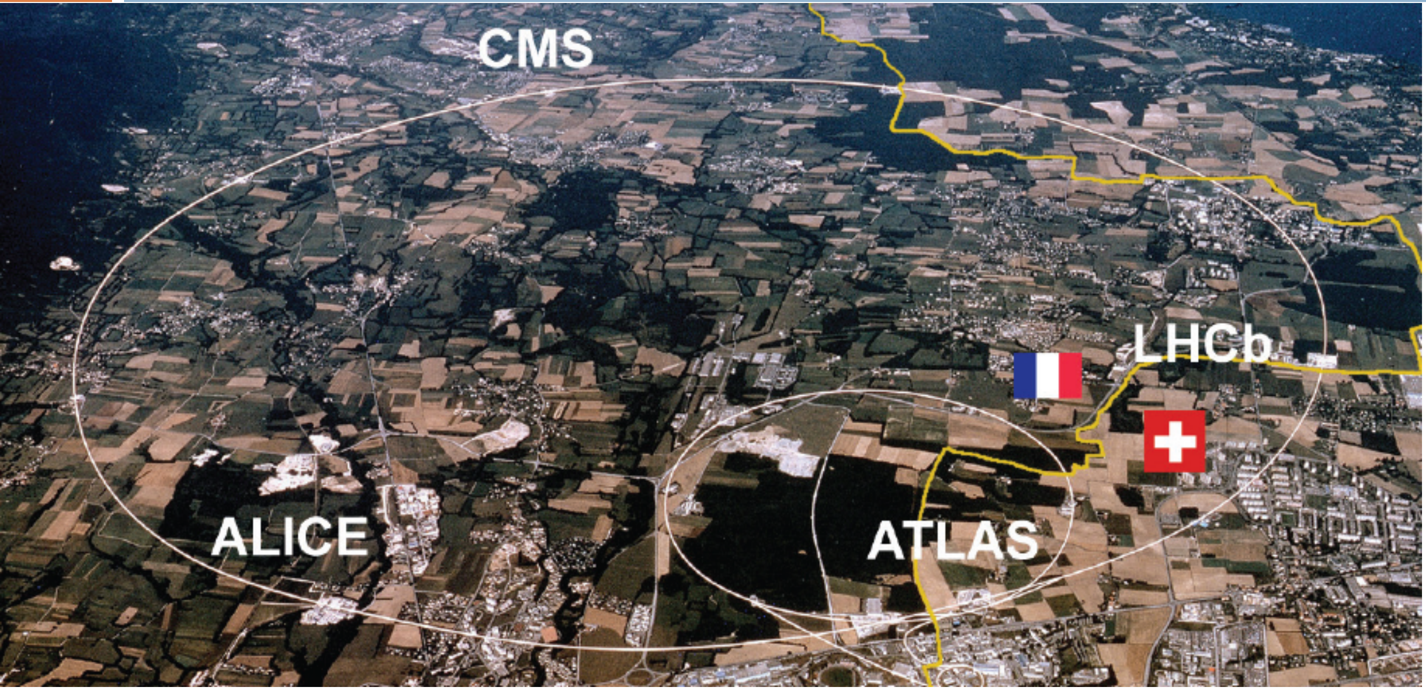
- Why tau?
  - Heaviest **lepton**, decay to **hadrons**(~65%)
  - Study new physics/SM with tau
  - …
  - We are TAU(**T**el **A**viv **U**niversity)!



- Single τ algorithm in ATLAS
- New boosted di-τ tagger
- **Trigger upgrade study for τ**

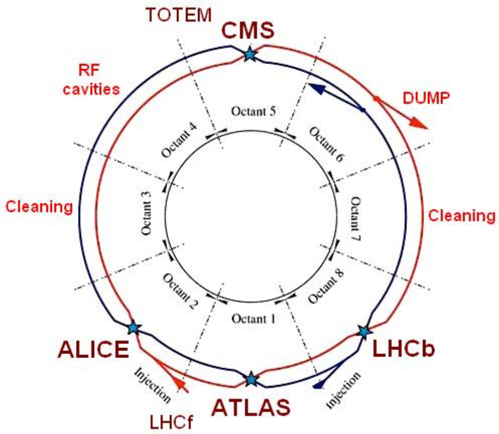


Large Hadron Collider(LHC)



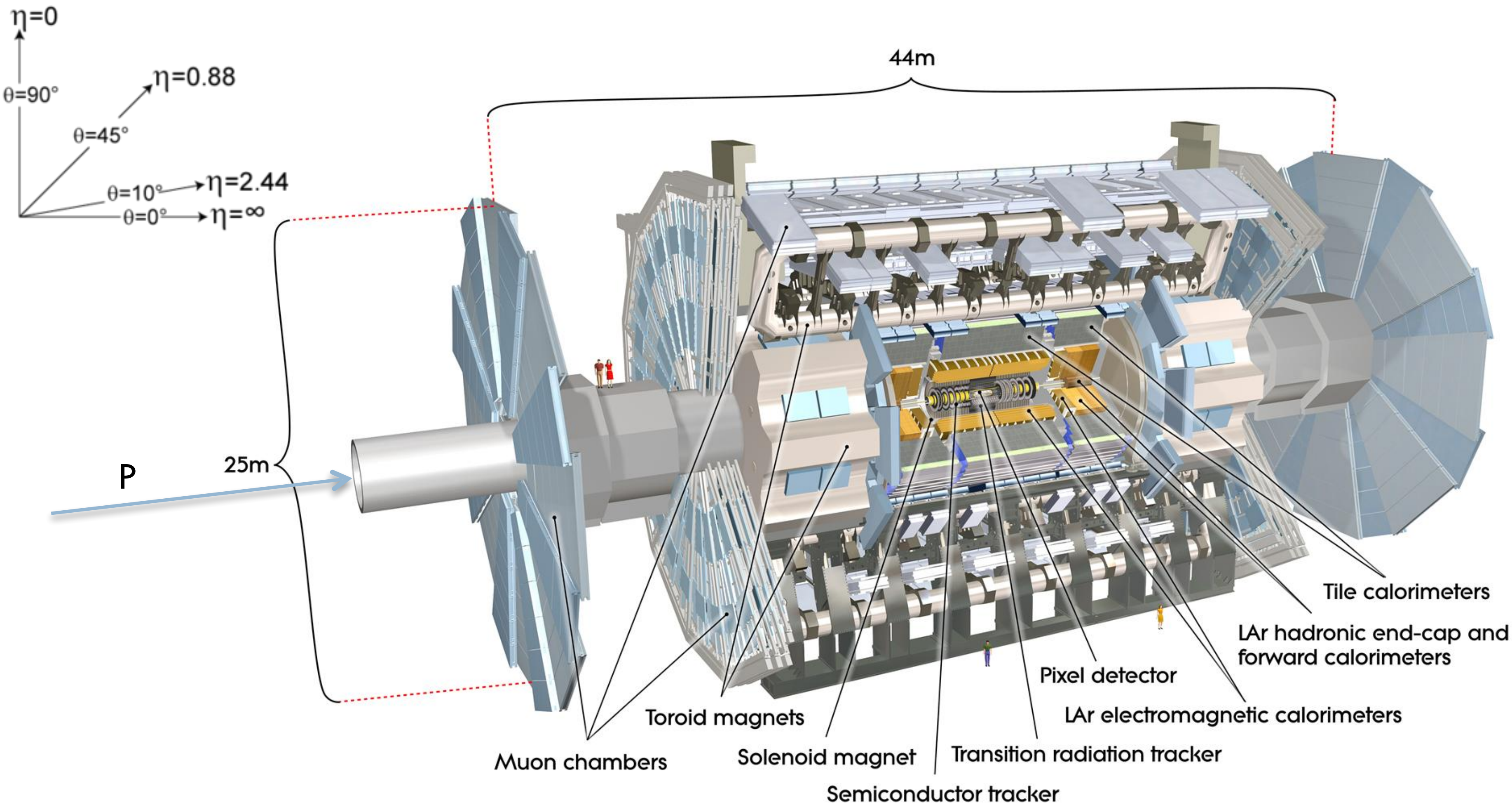
- 27 kilometers in circumference
- 175 meters beneath the France–Switzerland border
- Four crossing points

- Largest and most powerful particle collider in the world
- Collides proton beams(Lead–lead and proton-lead collisions one month per year)
- ATLAS: study Higgs boson & search for evidence beyond Standard Model



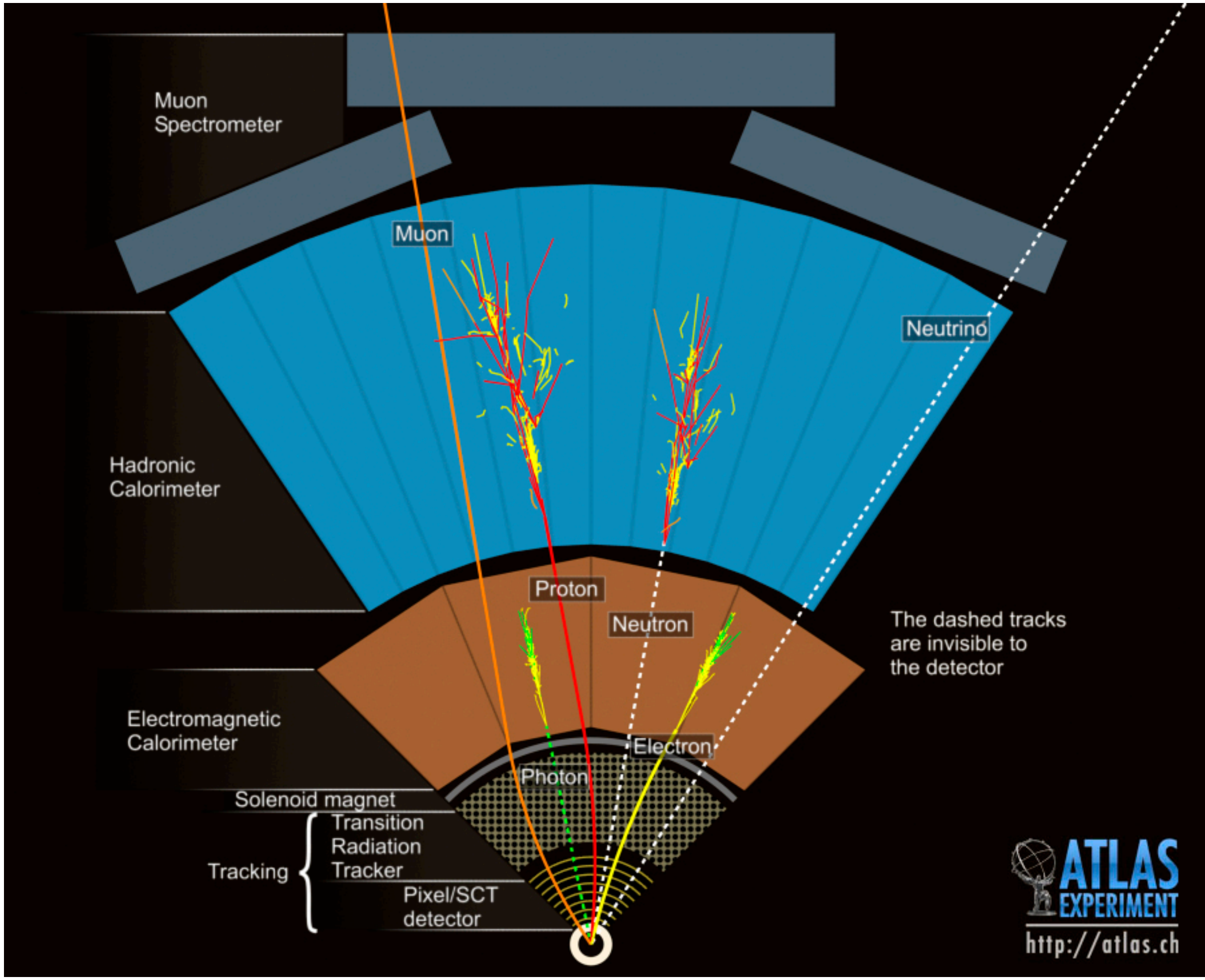
A Toroidal LHC ApparatuS(ATLAS)

Pseudorapidity: $\eta=-\ln[\tan(\theta/2)]$, θ: polar angle in spherical coordinate

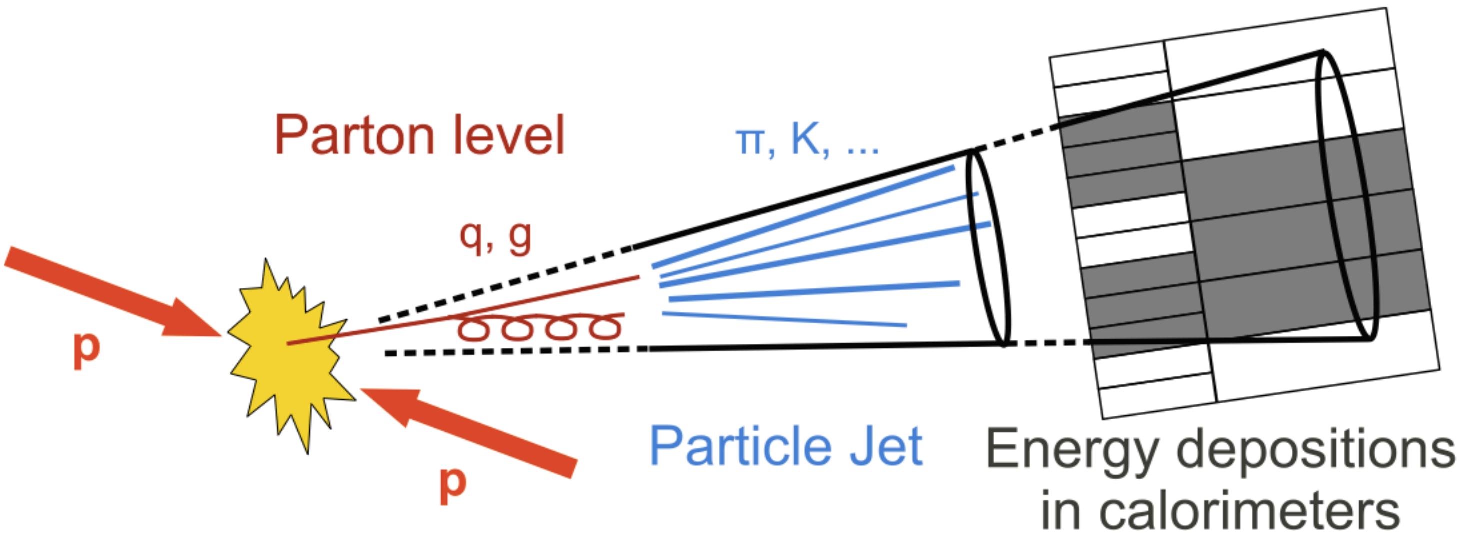


Cross section of ATLAS

- Muon Spectrometer
  - Detect muon and its momentum
- Hadronic Calorimeter
  - Energy of hadron
- Electromagnetic Calorimeter
  - Energy of photon and charged particle, stop photon and electron
- Tracking
  - Momentum, charge and direction of charged particle



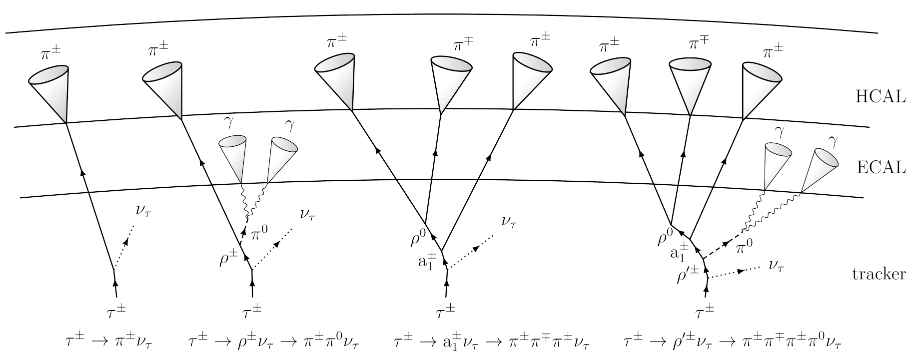
Jet



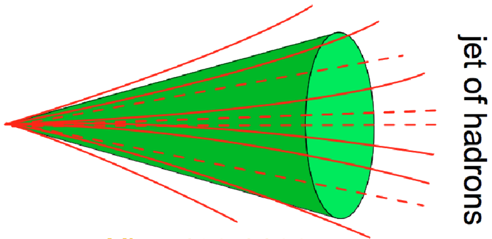
High energy quark and gluon will produce ionization shower.
A much heavier particle, W/Z/H/t … if its energy is high enough, the final decay products will merge together.

New single τ algorithm

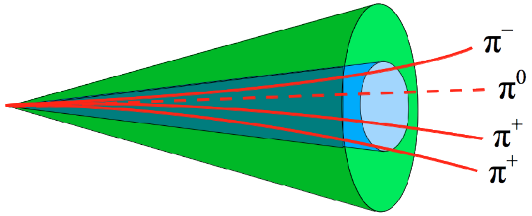
- The τ had-vis candidates are seeded by jets formed using the anti-kt algorithm, with a distance parameter of 0.4. ATL-PHYS-PUB-2022-044
- τ identification:
  - Track identification: RNN: 4 categories: τ track; conversion track; isolation track; fake track; Run 2: boosted decision tree (BDT)
  - τ id: RNN: same as run 2 with new tracks from above
  - Electron discrimination: RNN; Run2 BDT
  - Decay mode classification: DeepSet



https://tikz.net/tau_decay/



arXiv:1409.2699

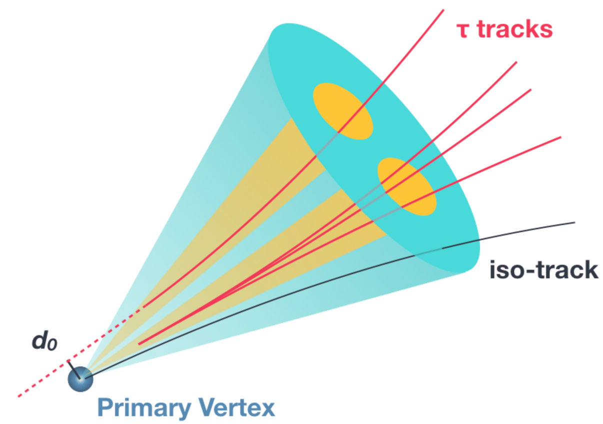


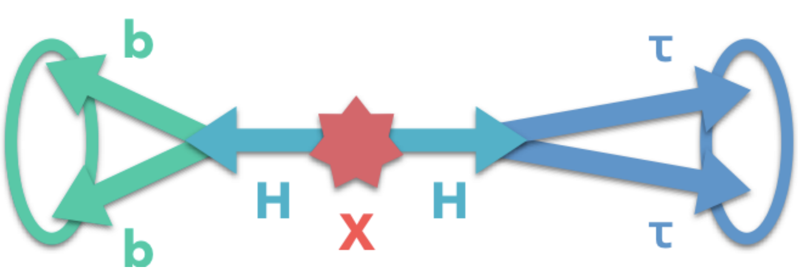
Boosted di-τ

- The reconstruction fails when two τ are merged together(from a boosted object, like Higgs boson)
- Instead of two jets, using one large-R jet
  - Useful for high energy region, or low pT & low mass resonance region
- Four boosted di-τ channel:
  - High(low)-pT $\tau_{Had}\tau_{Had}$
  - High(low)-pT $\tau_{\mu}\tau_{Had}$

High pT boosted di-τ

- The di-τ candidates are seeded by jets formed using the anti-kt algorithm, with a distance parameter of 1.
  - With at least two R=0.2 subjets
- BDT is trained for the identification
  - Inputs: track, subjet, large-R jet
- Search in the heavy resonance -> HH->bb$\tau\tau$





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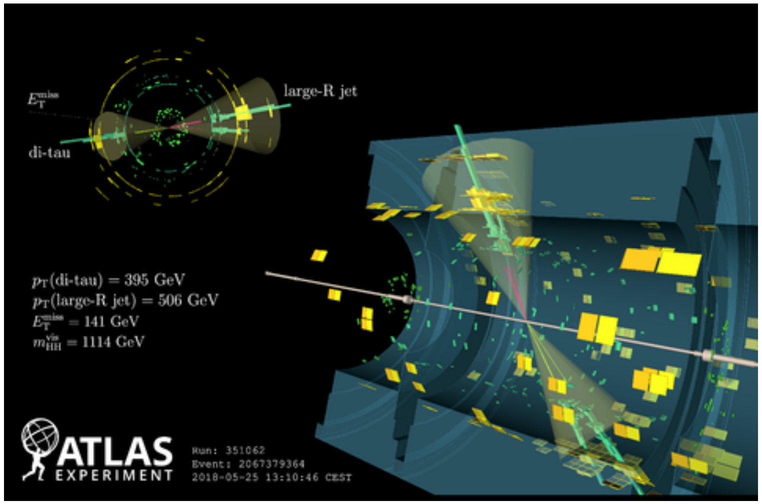
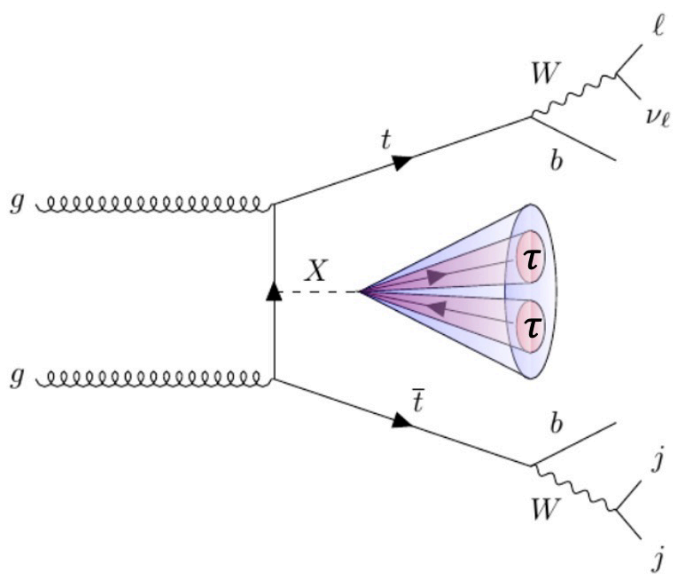
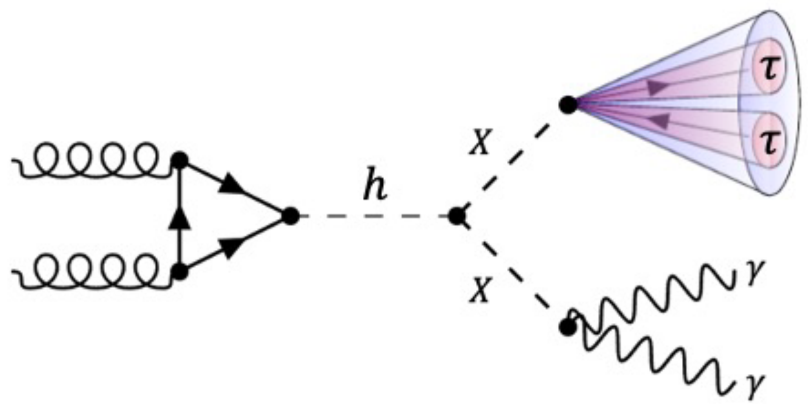


Low pT boosted di-τ analysis

- No discovery for the heavy resonance…How about low mass?
- Two analyses using the low pT
  - $ttX(X \to \tau\tau)$ and $H \to XX \to \tau\tau\gamma\gamma$, X mass: [10GeV, 60GeV]
- Still working on the tagger

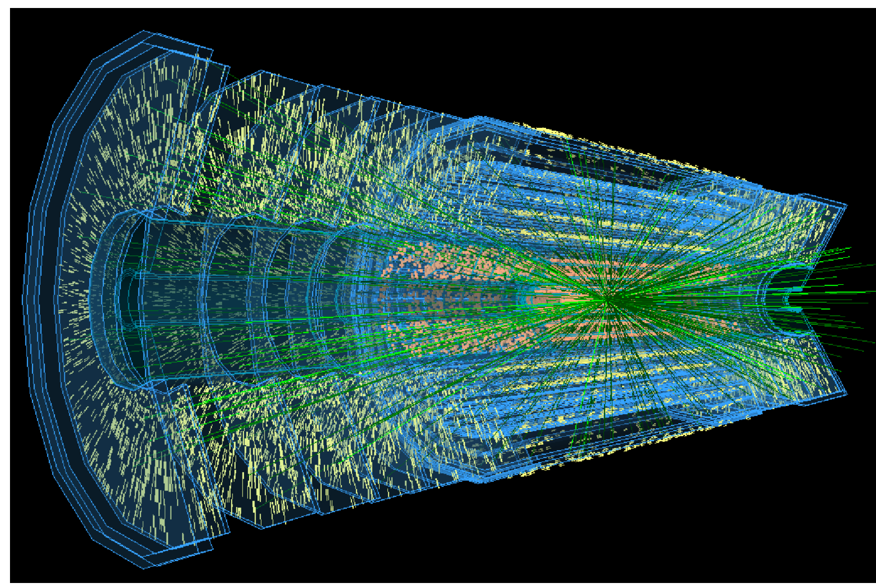




Trigger study for τ

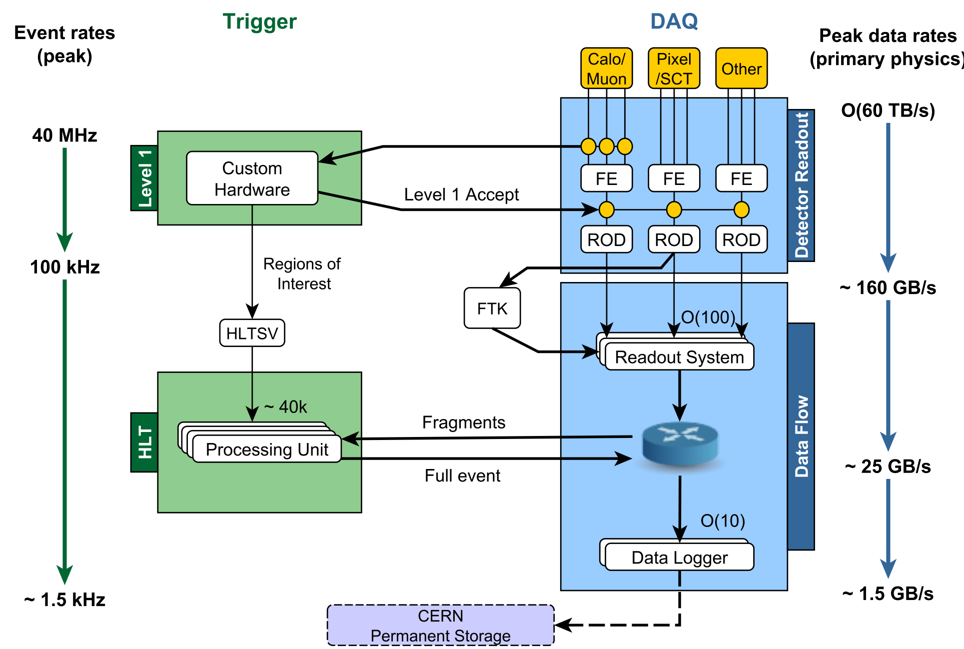
Schedule

- Run1
  - 2011, 2012
- Run2
  - 2015-2018
- Run3(phase 1 upgrade)
  - 2022-2024
- Run4(high luminosity LHC, phase 2 upgrade)
  - 2027?



ATLAS run 2 trigger system

- Too many data!
  - ~1.7b pp collision / s
- Trigger
  - Event selection system
- Two level
  - First-level(L1) hardware trigger
    - Located on the detector
    - Using subset(calorimeter, inner detector, muon) of the information from the detector
  - High level trigger(HLT), software
    - Data passing L1 trigger as input
    - Using information for full detector
    - Running with ~40000 cpu
- Only ~0.0025% will be stored

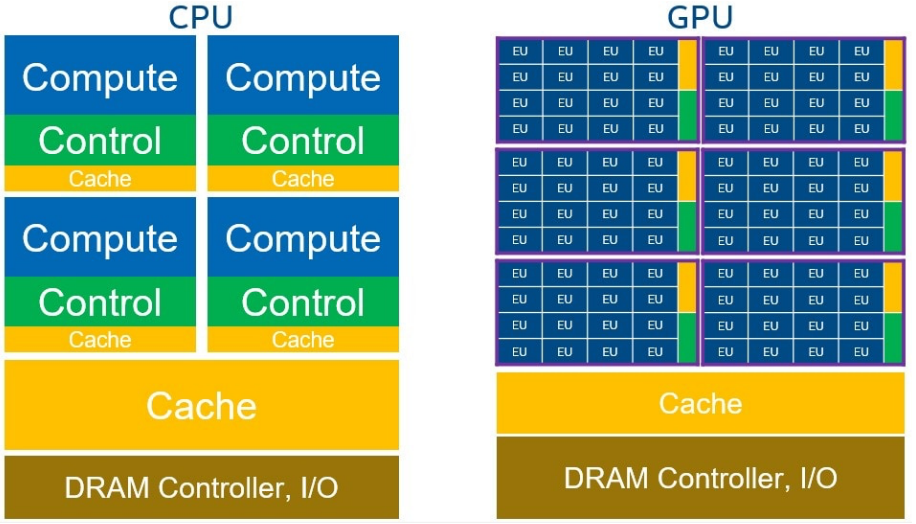


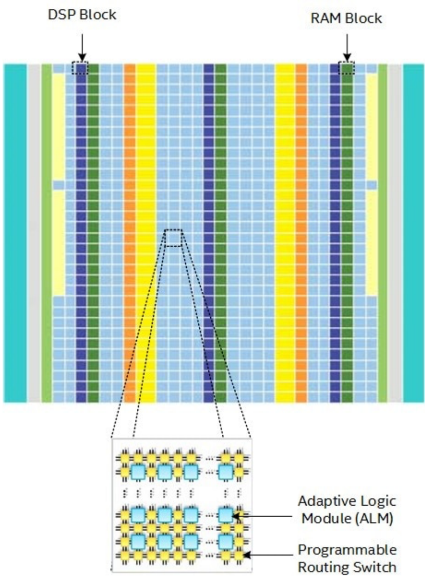
https://twiki.cern.ch/twiki/pub/AtlasPublic/ApprovedPlotsDAQ/tdaqFullNew2017.pdf

Hardware trigger upgrade

- The field-programmable gate array (FPGA) is used since Run 2
- More powerful FPGAs are used for Run3 and Run4

- CPU vs GPU vs FPGA
- CPU: good at doing complicated job but not parallel
- GPU: good at doing many simple jobs
- **FPGA**: different from CPU&GPU, but difficult to use, while cost much less power



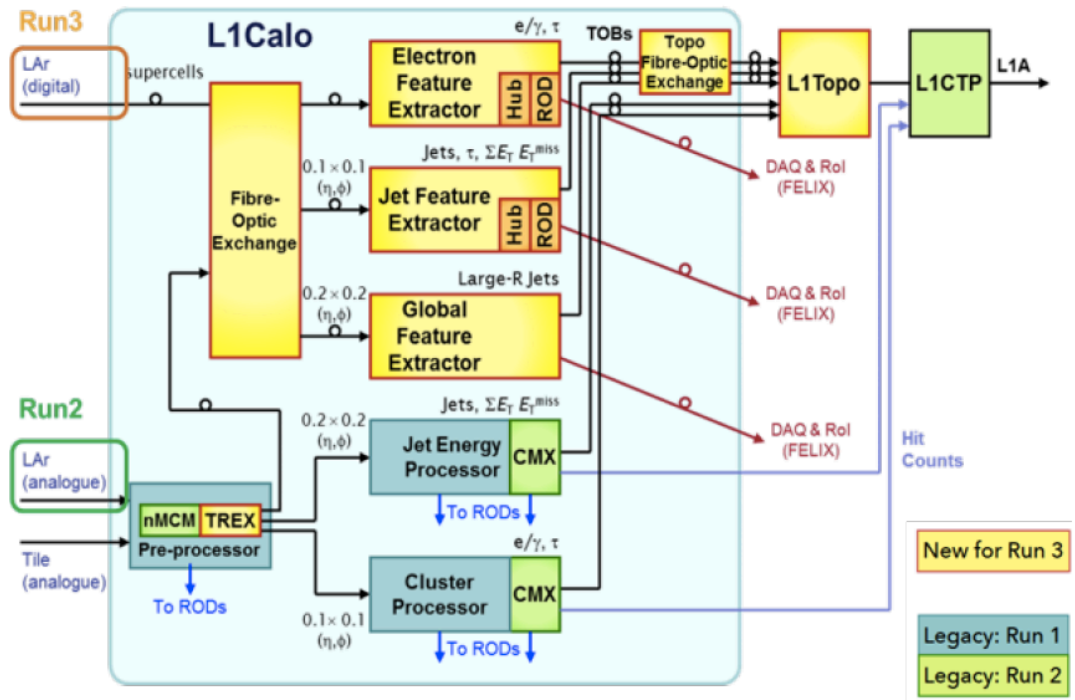


Intel

Run 3 trigger system upgrade

- Three new machines
  - Electron Feature Extractor(efex)
  - Jet(jfex)
  - Global(gfex)

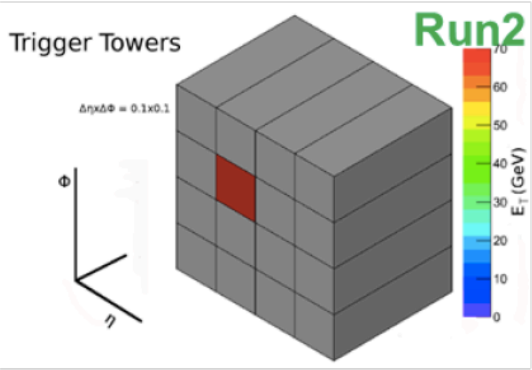
- New FPGA for the efex, jfex, gfex
  - Possible to read more data(higher granularity)
  - Run more complicated algorithm(machine learning, like BDT)

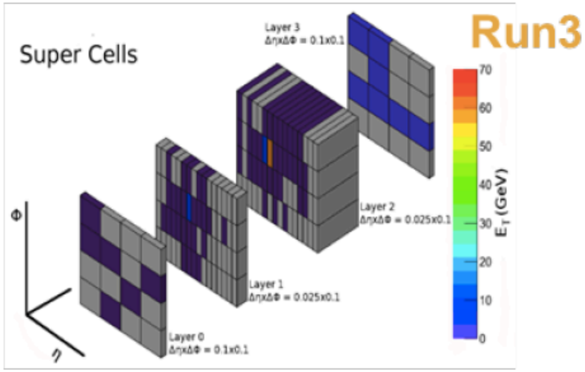


[ATL-DAQ-PROC-2020-015]

Run 3 trigger input upgrade

- Run2 input: trigger tower 0.1x0.1 for η and ϕ
- Run3 input: supercell, higher granularity
  - Electron magnetic calorimeter 0 layer(EM0, or presampler): 0.1x0.1
  - EM1&**EM2**: 0.025x0.1
  - EM3&Had: 0.1x0.1

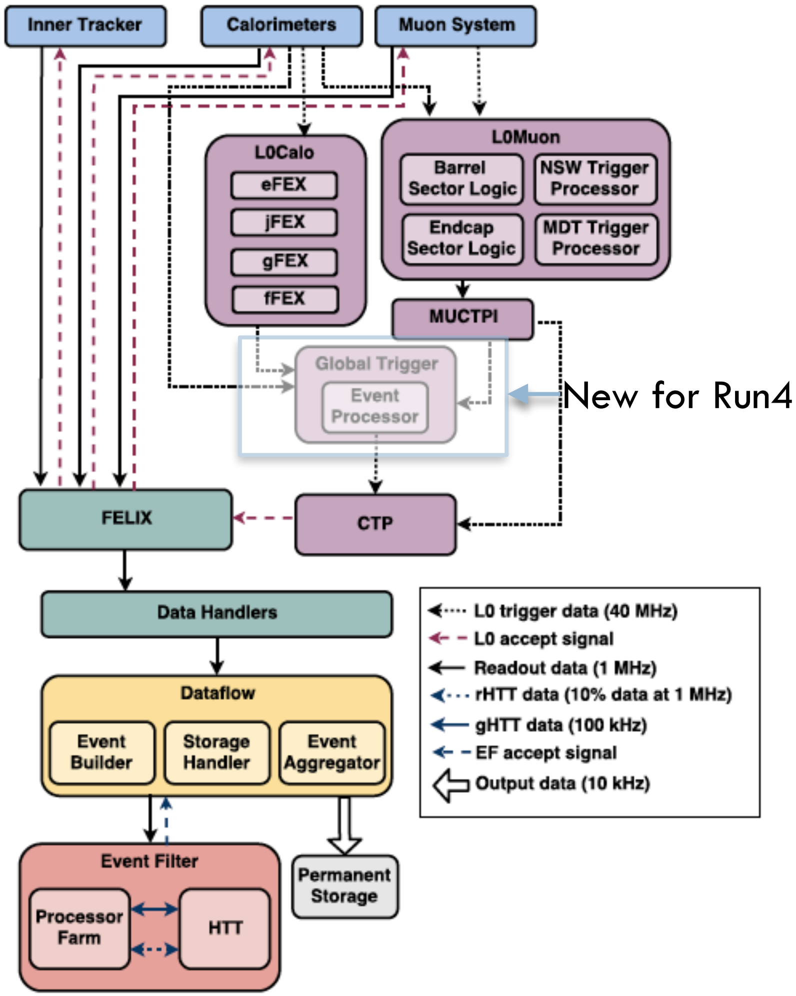




ATL-DAQ-PROC-2020-015

Run 4 trigger system upgrade

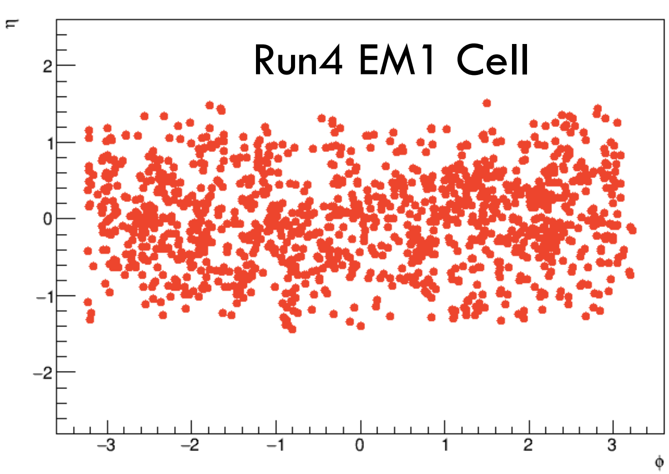
- New for Run 4: Global trigger
  - Input from L0Calo and **Calorimeters**
  - Able to access all the sensor in calorimeters(higher granularity)
  - Even more complicated algorithm(neural network)

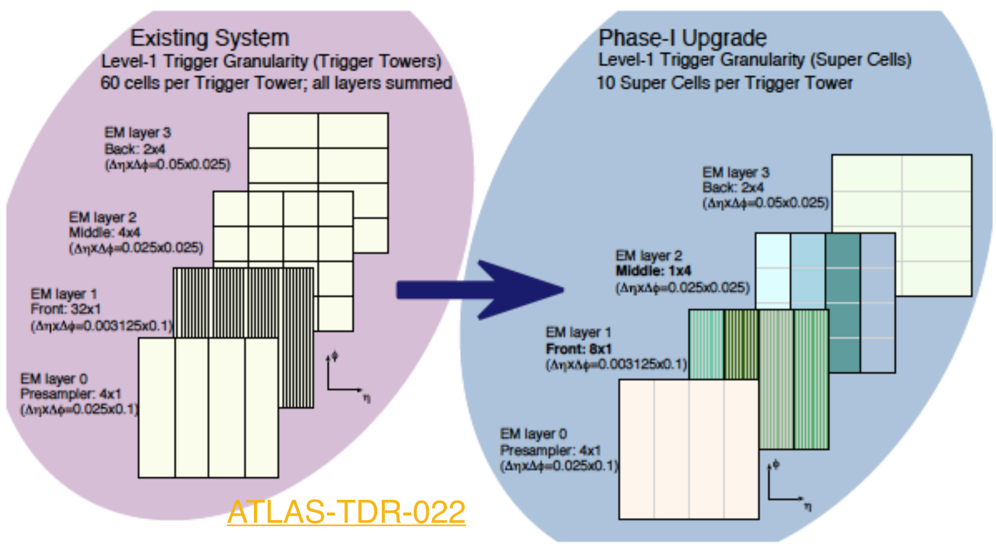


Run 4 trigger input upgrade

- Run2: Trigger tower vs Run3: Supercell vs Run4: Cell

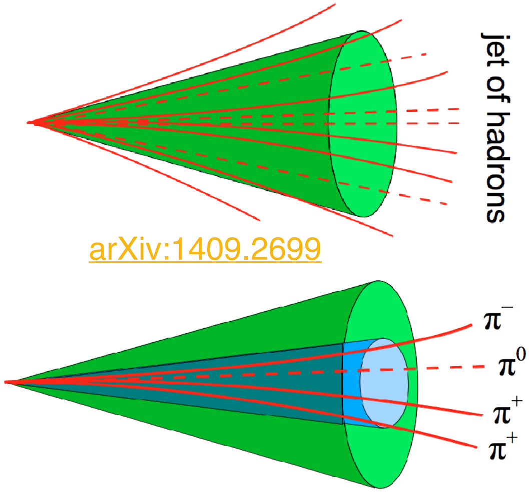
$\eta \times \phi$	Run2	Run3	Run4
EM0	0.1x0.1	0.1x0.1	0.025x0.1
EM1	-	0.025x0.1	0.003125x0.1
EM2	-	0.025x0.1	0.025x0.025
EM3	-	0.1x0.1	0.05x0.025
Had	-	0.1x0.1	0.1x0.1



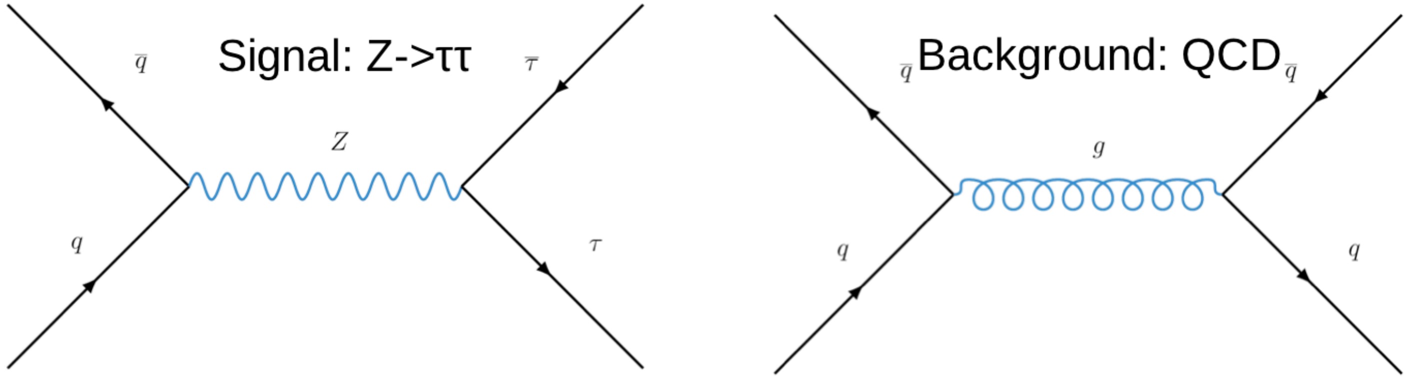


ATLAS-TDR-022

Hadronic τ and jet

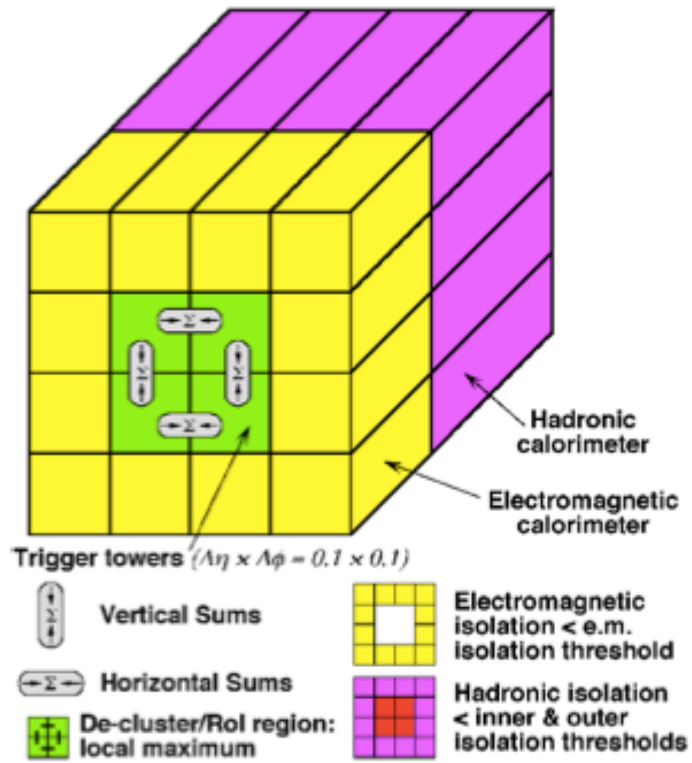


- Hadronic $\tau(65\%) \rightarrow \tau$ jet in calorimeter
- τ trigger: distinguish between τ jet and QCD jet
- Signal: $Z \rightarrow \tau\tau$, background: qcd events



ATLAS Run2/3 τ trigger algorithm

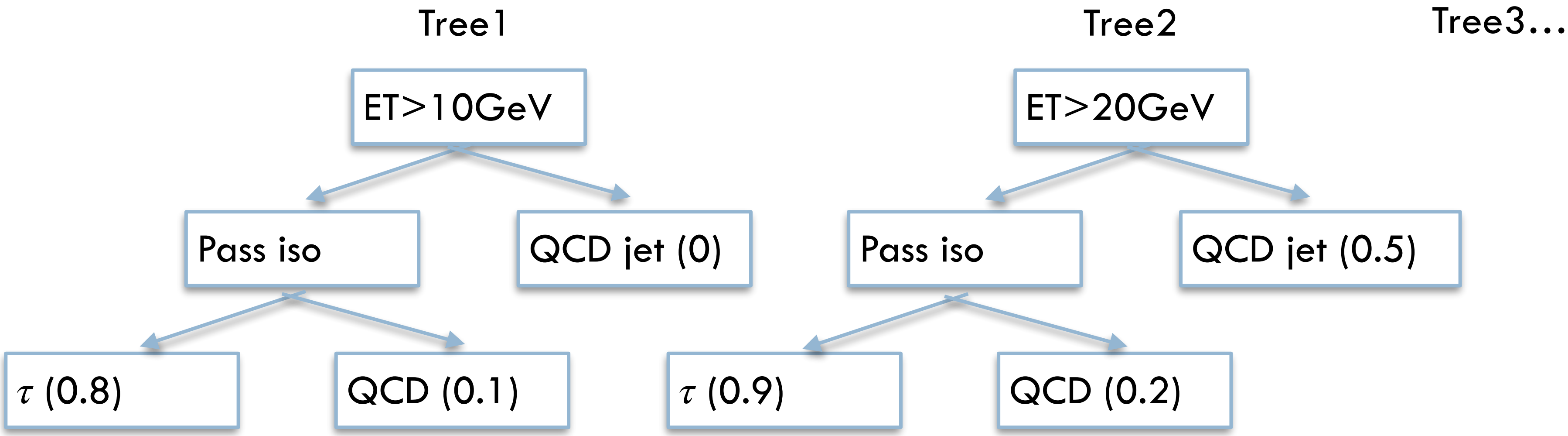
- Seed with cell $E_T > 4\sigma$, σ: noise
- Run2 trigger object(TOB)
  - Green: calculate τ energy
  - Yellow: isolation region
- Run3 TOB
  - 0.3x0.3: calculate τ energy
  - 0.5x0.5 for isolation region
- Isolated TOB
- Run2 algorithm:
  - EM: Maximum energy of two adjacent towers in green
  - Had: Sum of 2x2 grid
  - $E_T = E_T^{EM} + E_T^{Had}$
- If $E_T > 12.5$ GeV, identified as τ candidate



arXiv:0810.0465

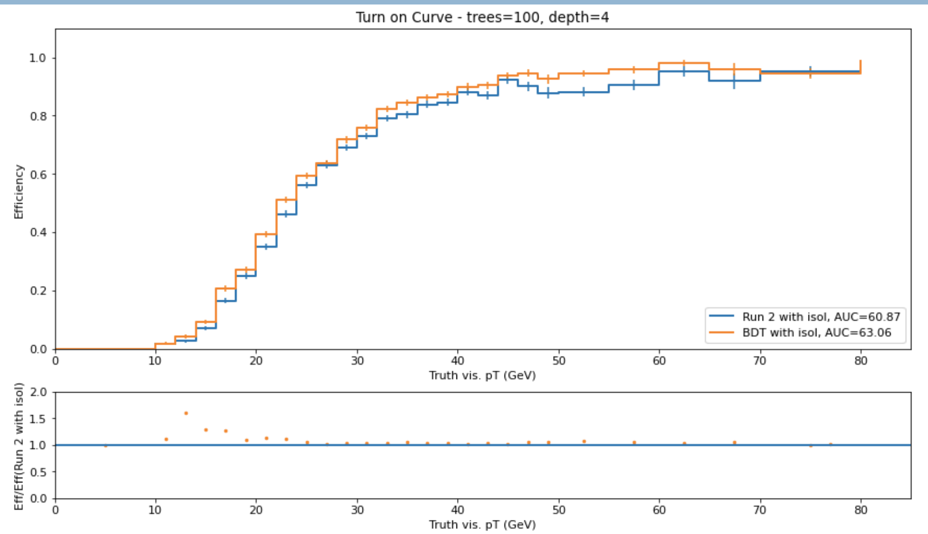
Alternative Run3 τ trigger algorithm

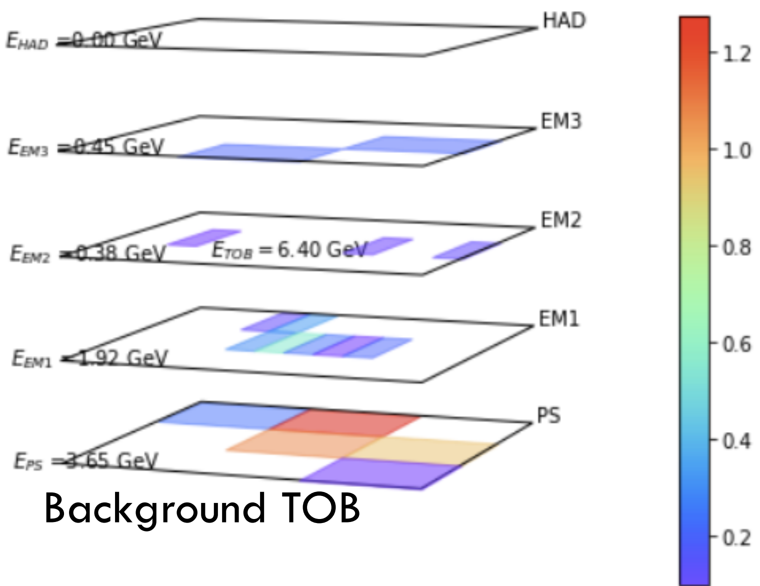
- Boost decision tree (BDT)
- Two parameters
  - Number of tree
  - Maximum depth of the tree
- Simple and powerful, sometimes beat neural network
- Highly parallelizable(running fast)
- Small and simple, use little resource



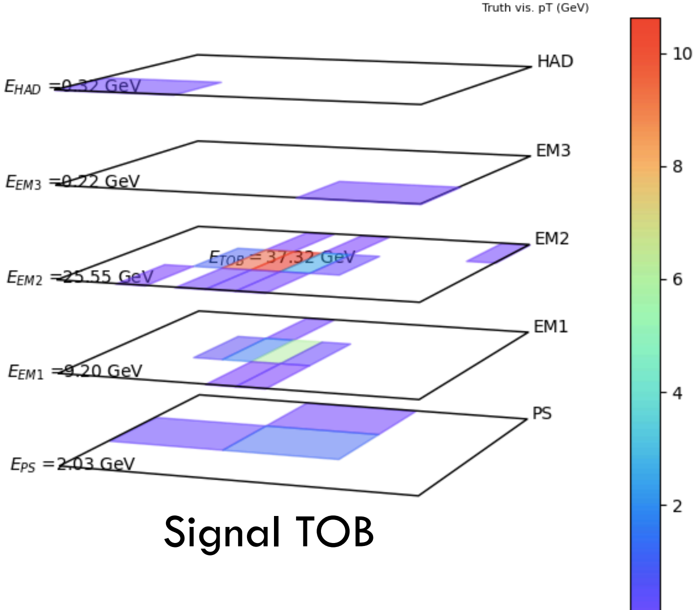
Run3 BDT performance

- Turn on curve: signal efficiency for the Run2 τ trigger background rate





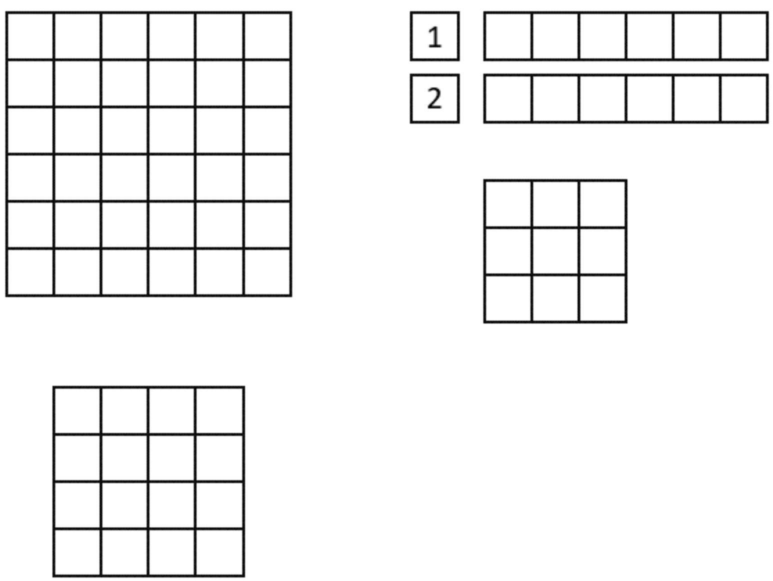
Background TOB

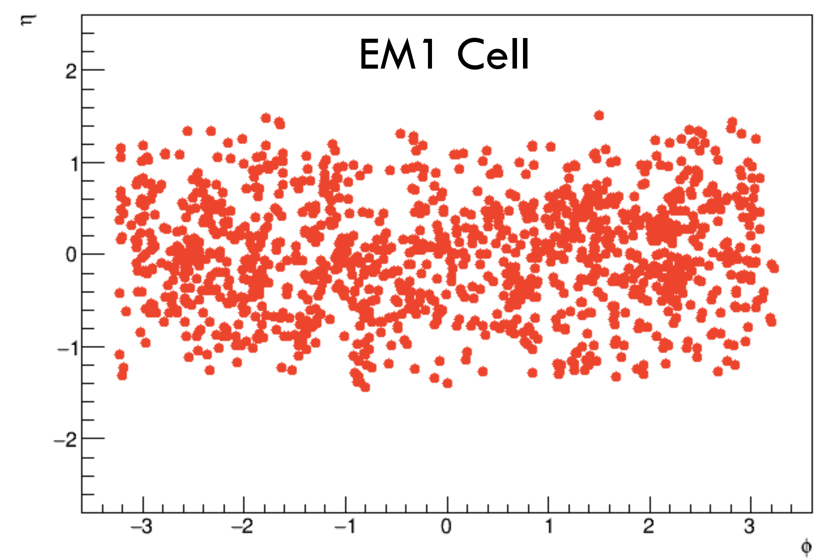


Signal TOB

Run4 τ trigger algorithm

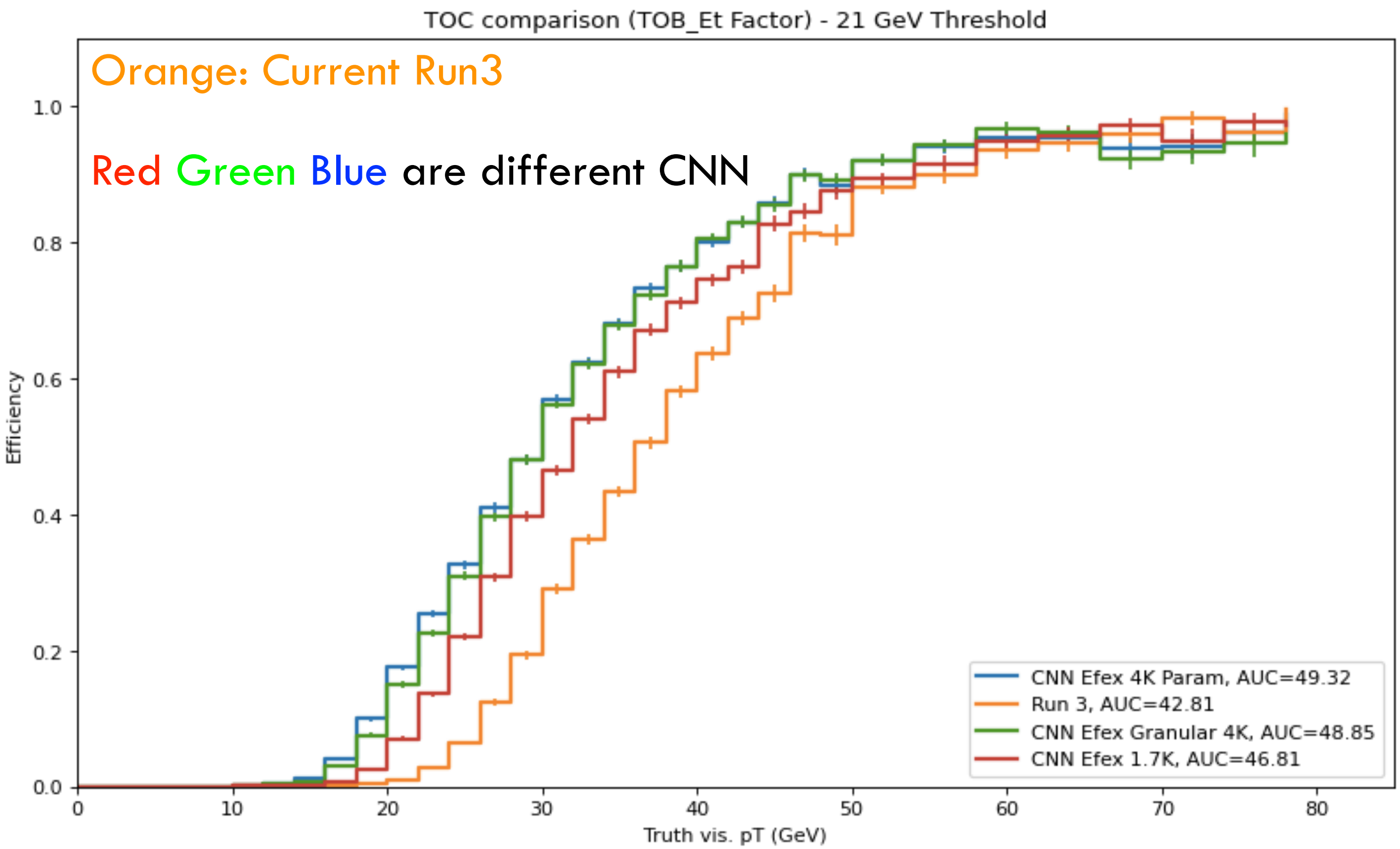
- More powerful hardware for Run4 (better FPGA)
- Detector is just like a camera -> image identification algorithm
- More complicated algorithm, like neural network (**CNN**, deepset…)
- With higher pile-up, much more noise, so neural network may perform better





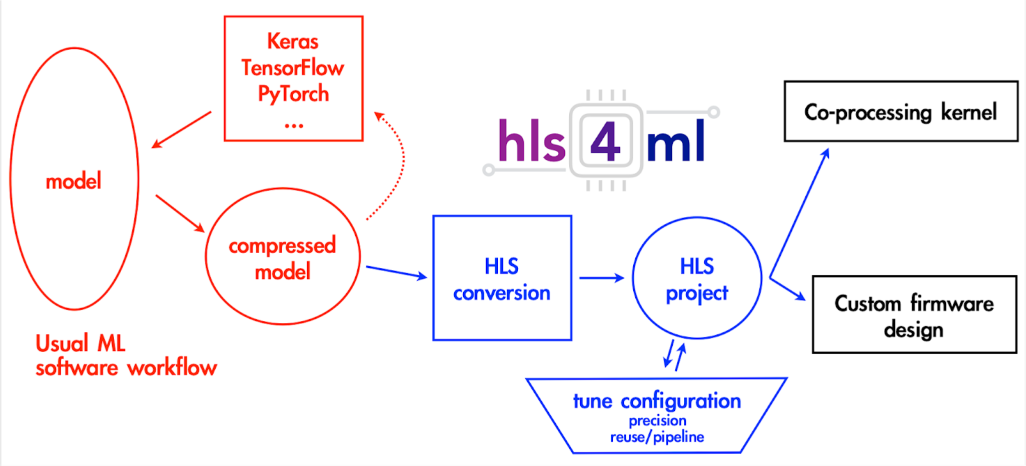
Run4 CNN performance

- Performance: much better than Run3 algorithm



Implement to hardware

- NN/bdt model->hls4ml->C++ code->HLS->Vivado->FPGA
- Timing: Latency: ~3 us
- Still working to optimize the NN




```
+ Timing:
    * Summary:
    +--------+---------+----------+------------+
    |  Clock |  Target | Estimated| Uncertainty|
    +--------+---------+----------+------------+
    |ap_clk  | 5.00 ns | 4.366 ns |    0.62 ns |
    +--------+---------+----------+------------+

+ Latency:
    * Summary:
    +---------+---------+----------+----------+-----+-----+----------+
    |  Latency (cycles) |  Latency (absolute) |  Interval | Pipeline |
    |   min   |   max   |    min   |    max   | min | max |   Type   |
    +---------+---------+----------+----------+-----+-----+----------+
    |      563|      564| 2.815 us | 2.820 us |  141|  491| dataflow |
    +---------+---------+----------+----------+-----+-----+----------+
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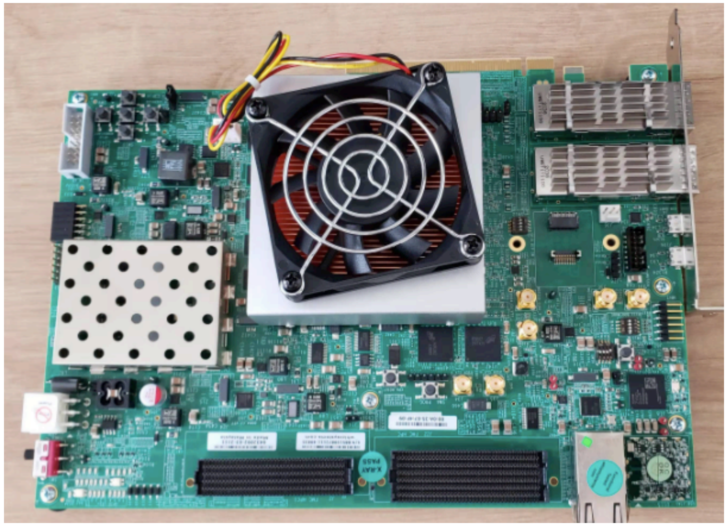

Summary

- ATLAS τ algorithms are presented
- Much better hardware for future ATLAS trigger
- Possible to implement neural network in hardware trigger level