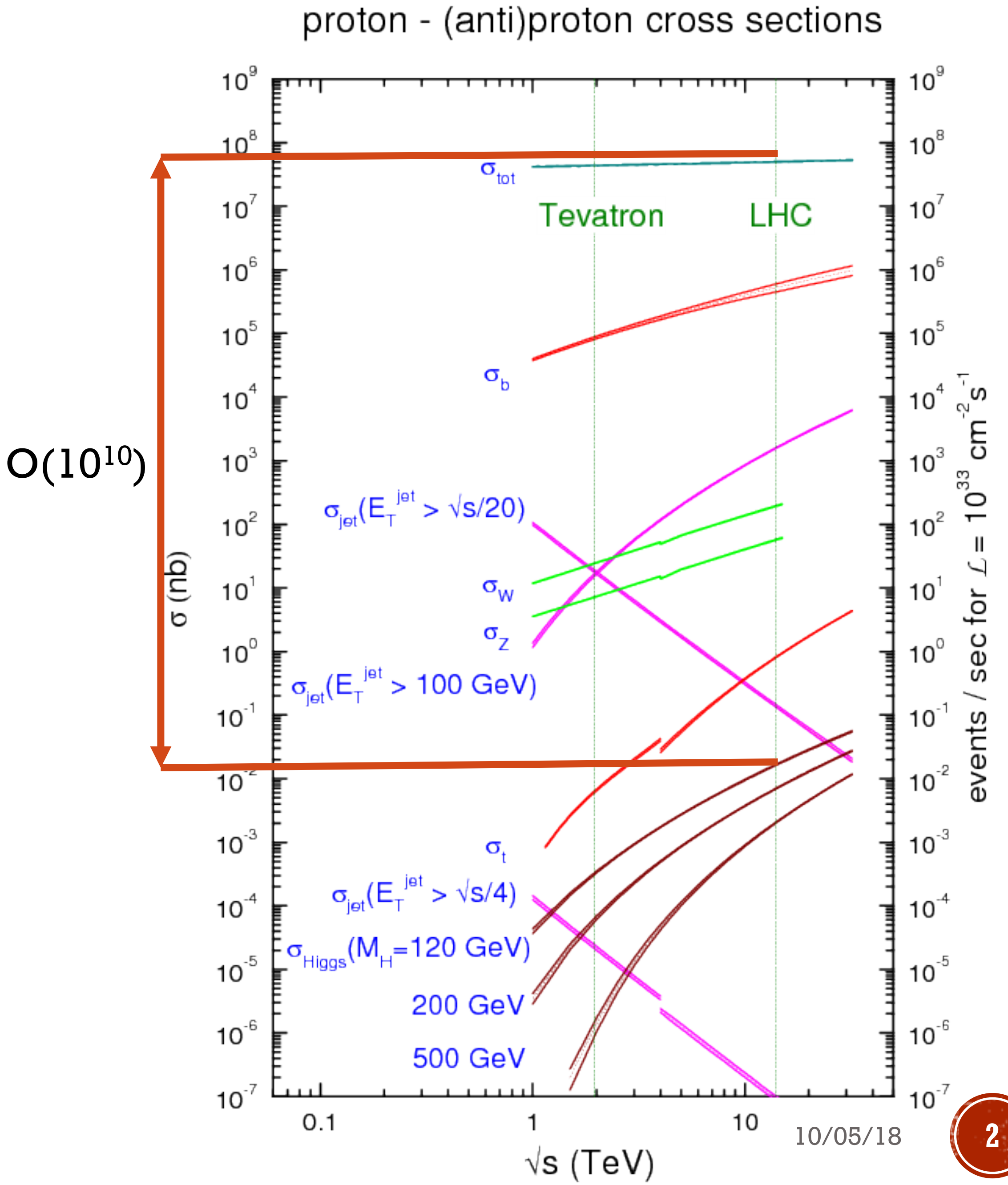
FTK: AN HARDWARE BASED TRACKER FOR THE ATLAS EXPERIMENT

Simone Sottocornola

Young Researchers Workshop 2018

TRIGGER @ LHC

- Very rare events
  - $\sigma_{Higgs} < 10^{-10}\sigma_{tot}$!
- Output limit ~1KHz
  - Storage and analysis capability limited!
- Trigger: online selection of interesting events rejecting the background
  - The events rejected are lost forever!!



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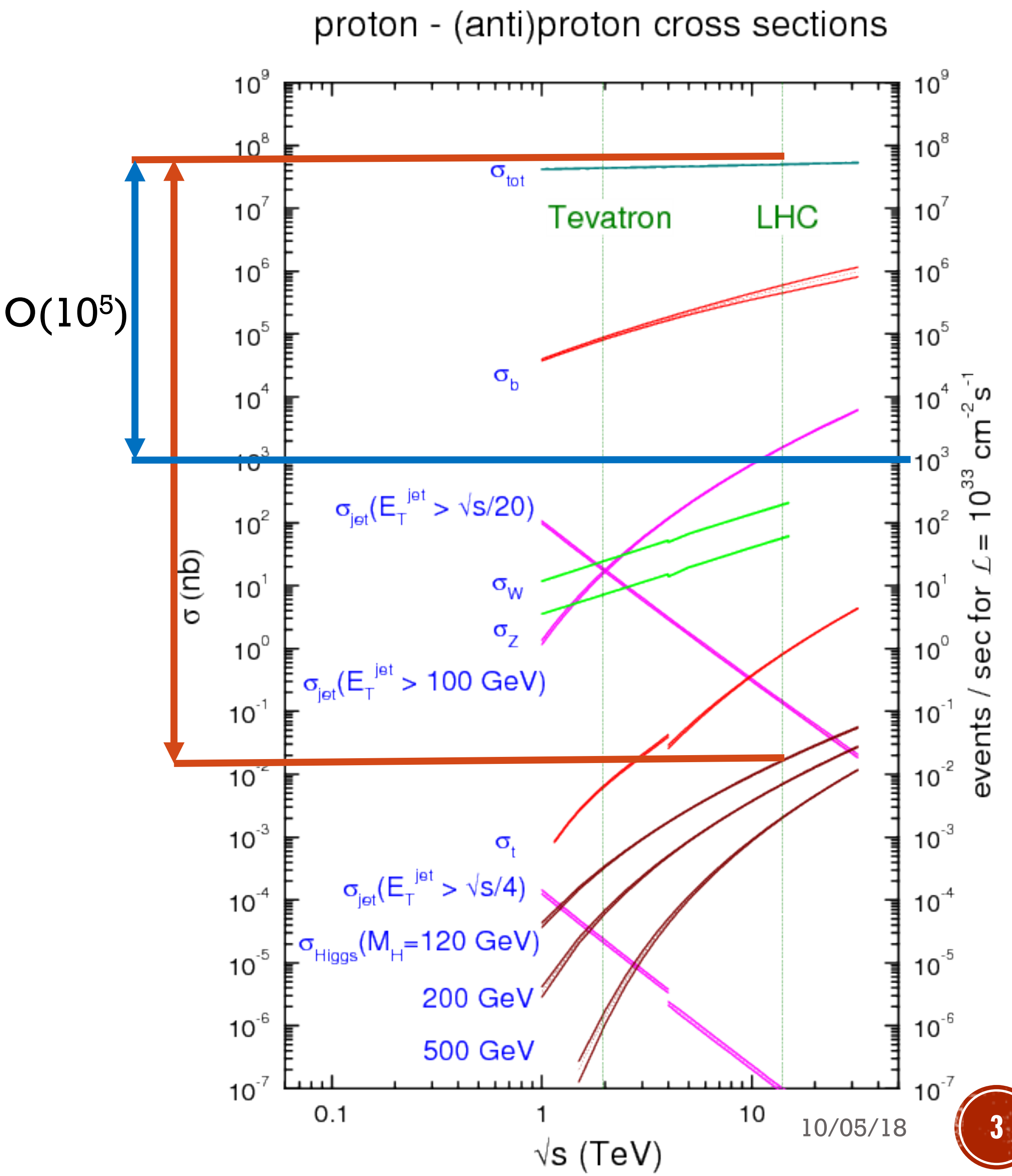

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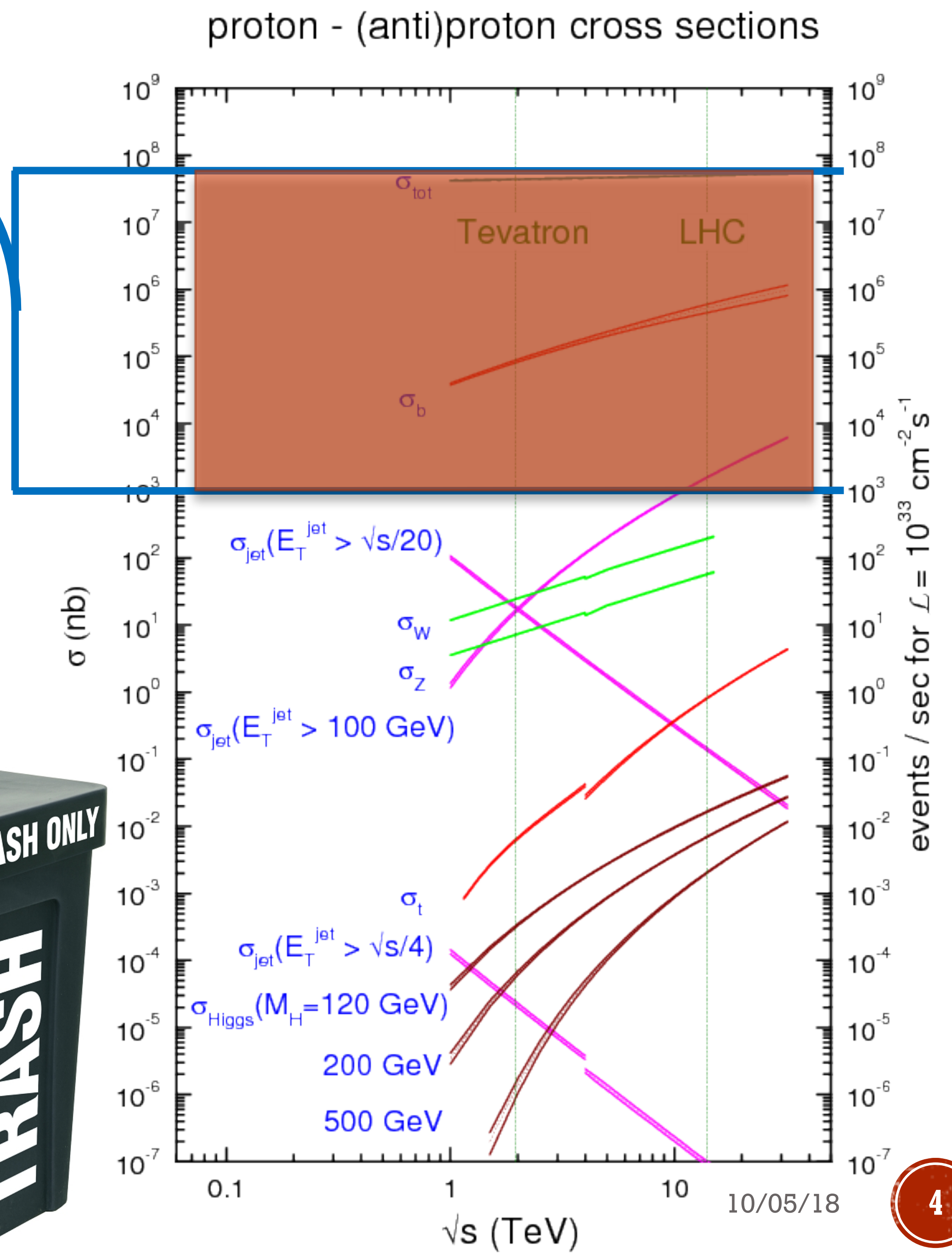
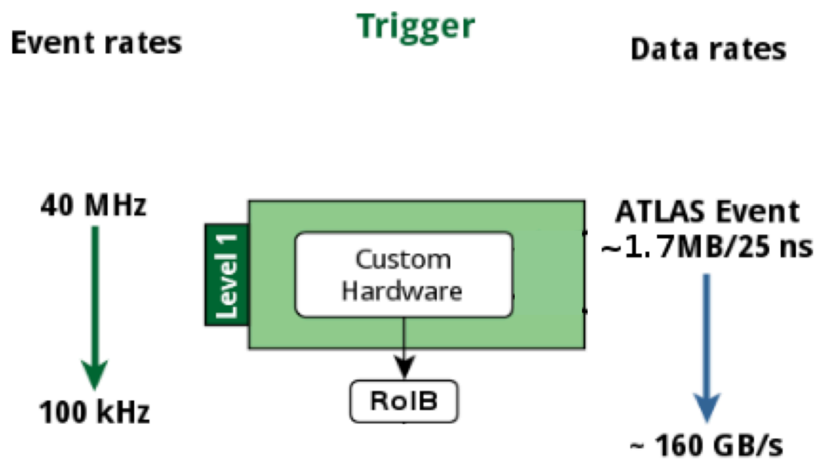


TRIGGER @ LHC

- Rate reduction $\sim$ 40000
  - Multilevel architecture
- Level 1:
  - Hardware-based
  - Low resolution data from calorimeters and muon spectrometer (no Inner Detector)
  - Rate reduction $\sim$ 400 in $2.5\mu s$
- HLT:
  - Software-based
  - Full resolution data from all the detectors
  - Rate reduction $\sim$ 100 in $200ms$ avg

ATLAS trigger



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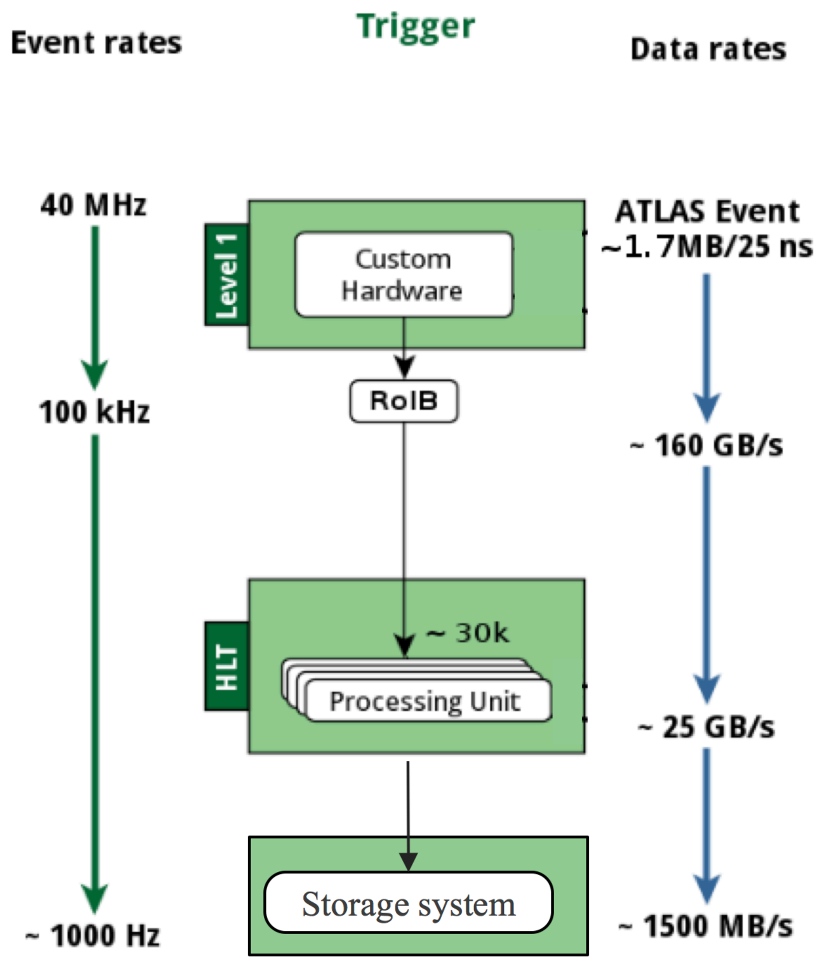
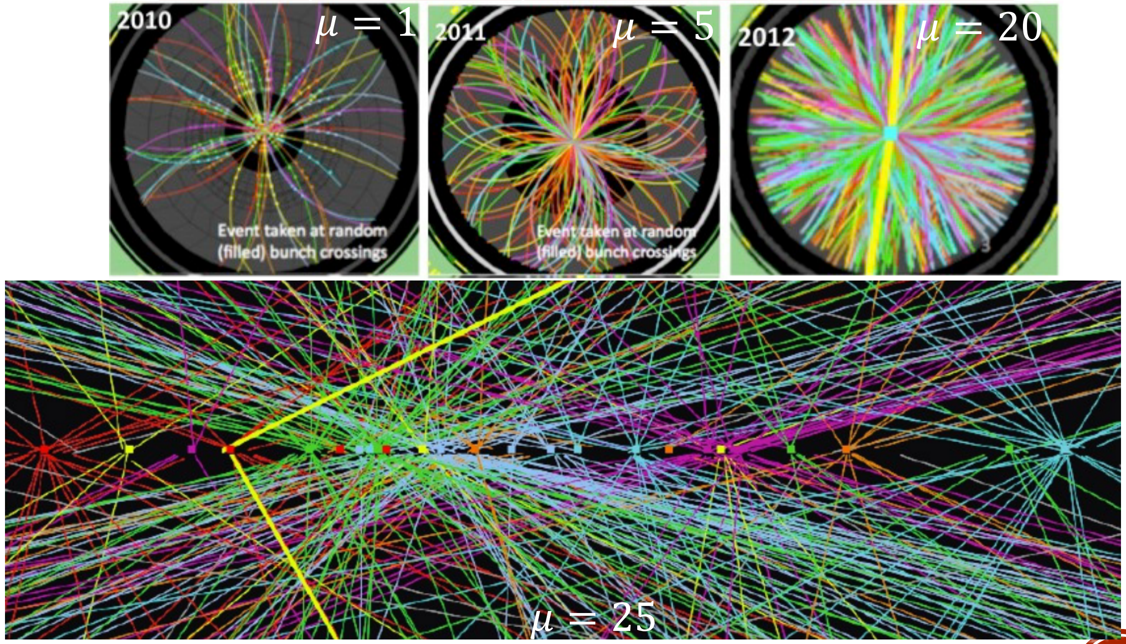


LHC UPGRADE

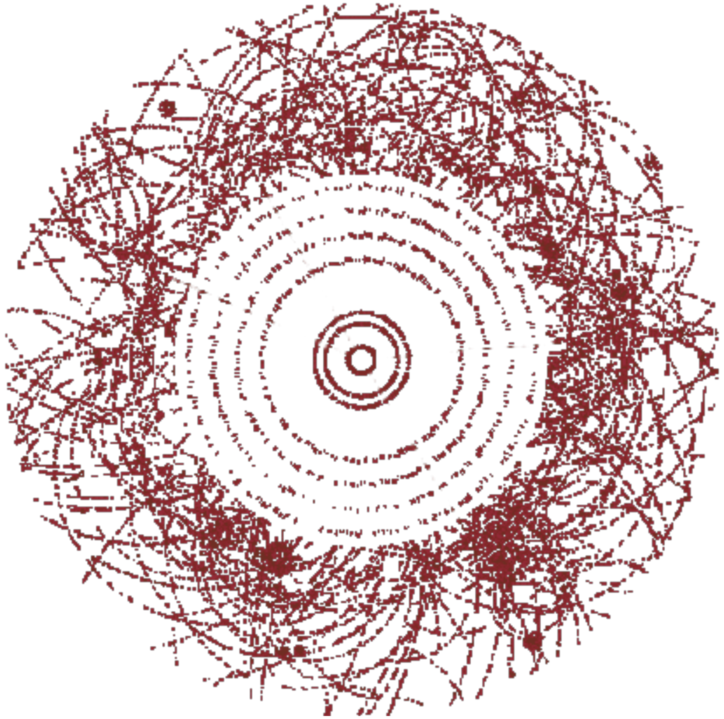
Run	Anni	L ($cm^{-2}s^{-1}$)	Pile-up
1	2010-12	~$7x10^{33}$	~20
2	2015-18	~10^{34}	~25
3	2021-23	~$3x10^{34}$	~80
4	2026-…	~ $5\text{-}7 \, x10^{34}$	~ 140-200

- Luminosity increased to collect more statistics -> improve discovery potential
- Problems:
  - Increase in the number of superimposed events (pile-up)
  - Output rate to be kept ~1(10) kHz
  - Trigger working condition critical!!
- Track-based trigger selection fundamental!!
  - Less pile-up dependent

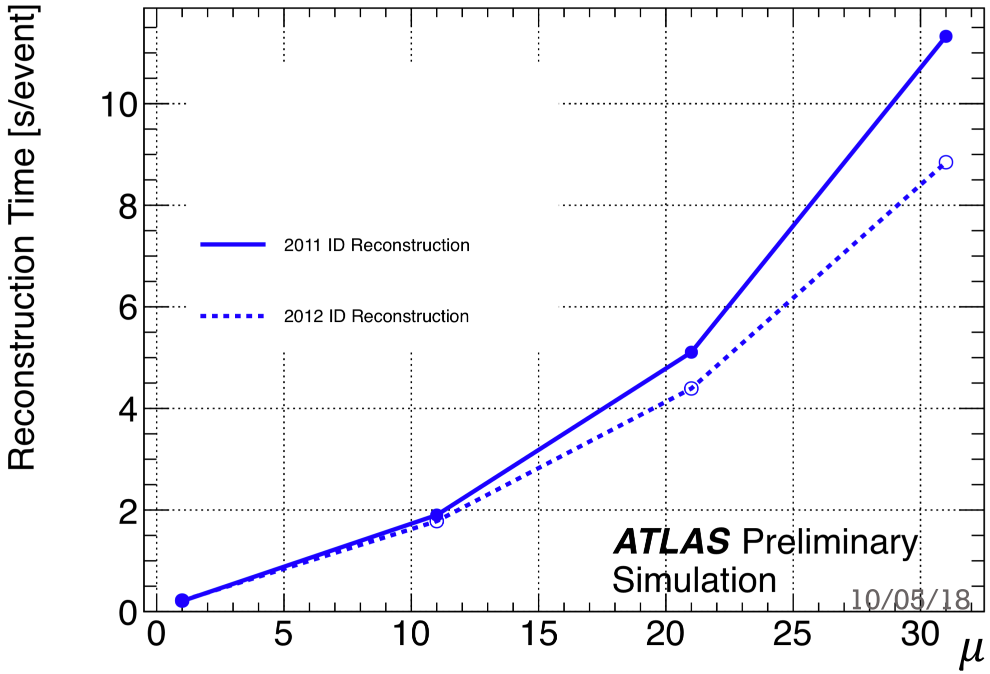


THE TRACKING CHALLENGE

- Track reconstruction performed "connecting the dots"
- Combinatorial problem
  - CPU Processing time does not scale (linearly) w/ luminosity
  - Already now, full tracking only executed for a small subset of the events
- Possible solutions:
  - Increase the cuts at the upper level (L1) to reduce HLT input
    - LOOSE GOOD EVENTS!!
  - GPU usage (brute-force approach)
  - Fast TracKer (hardware-based approach)



ATLAS-CONF-2012-042



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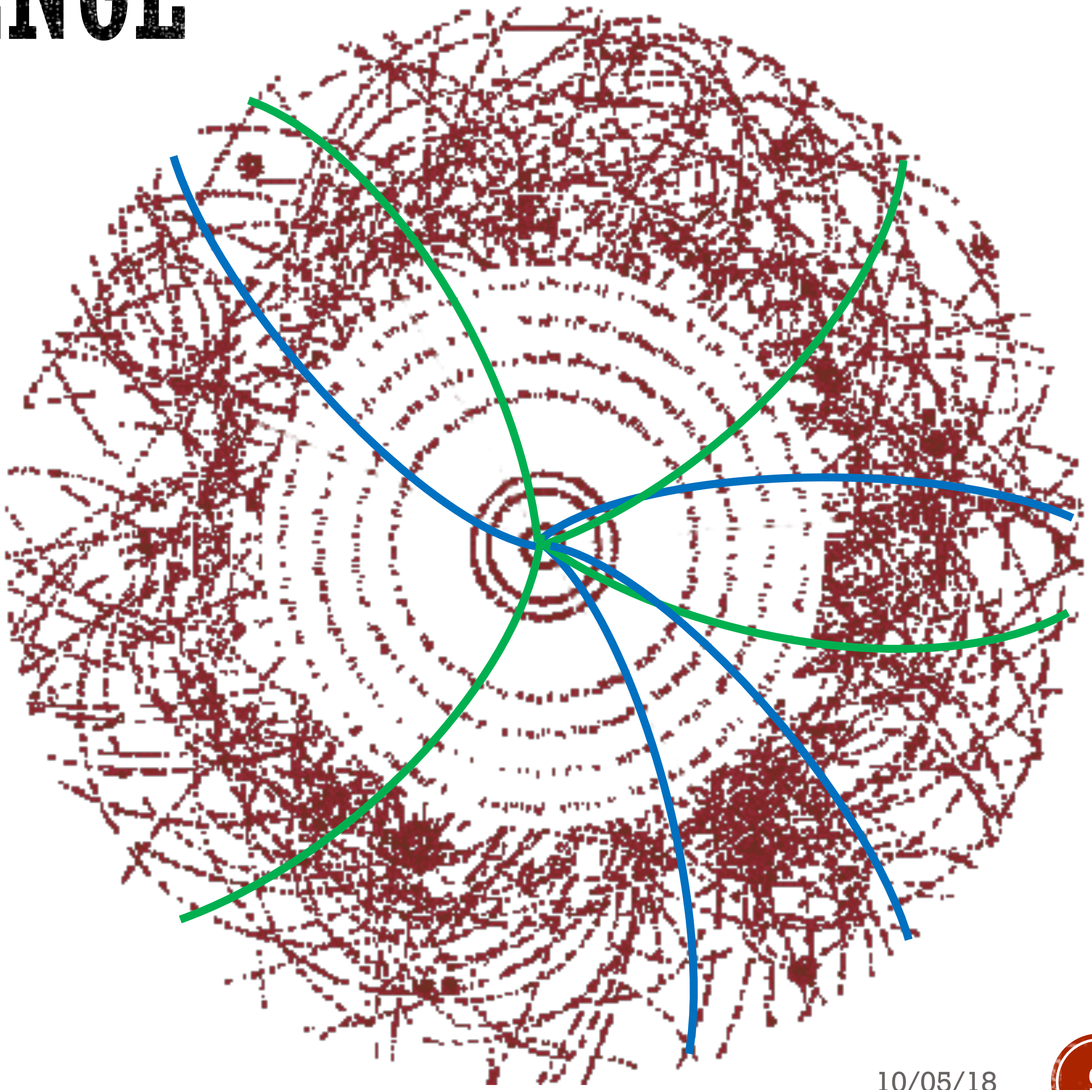
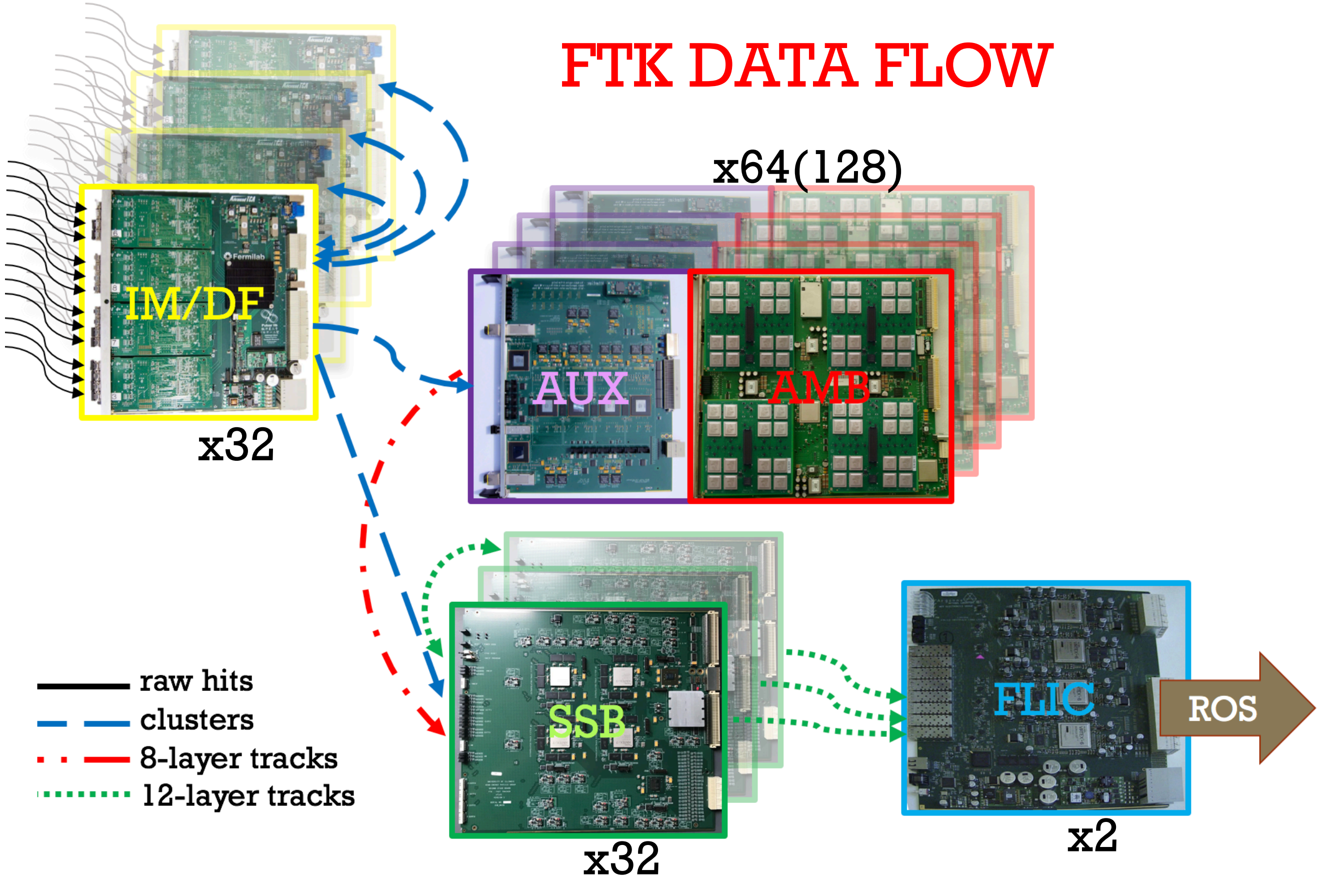


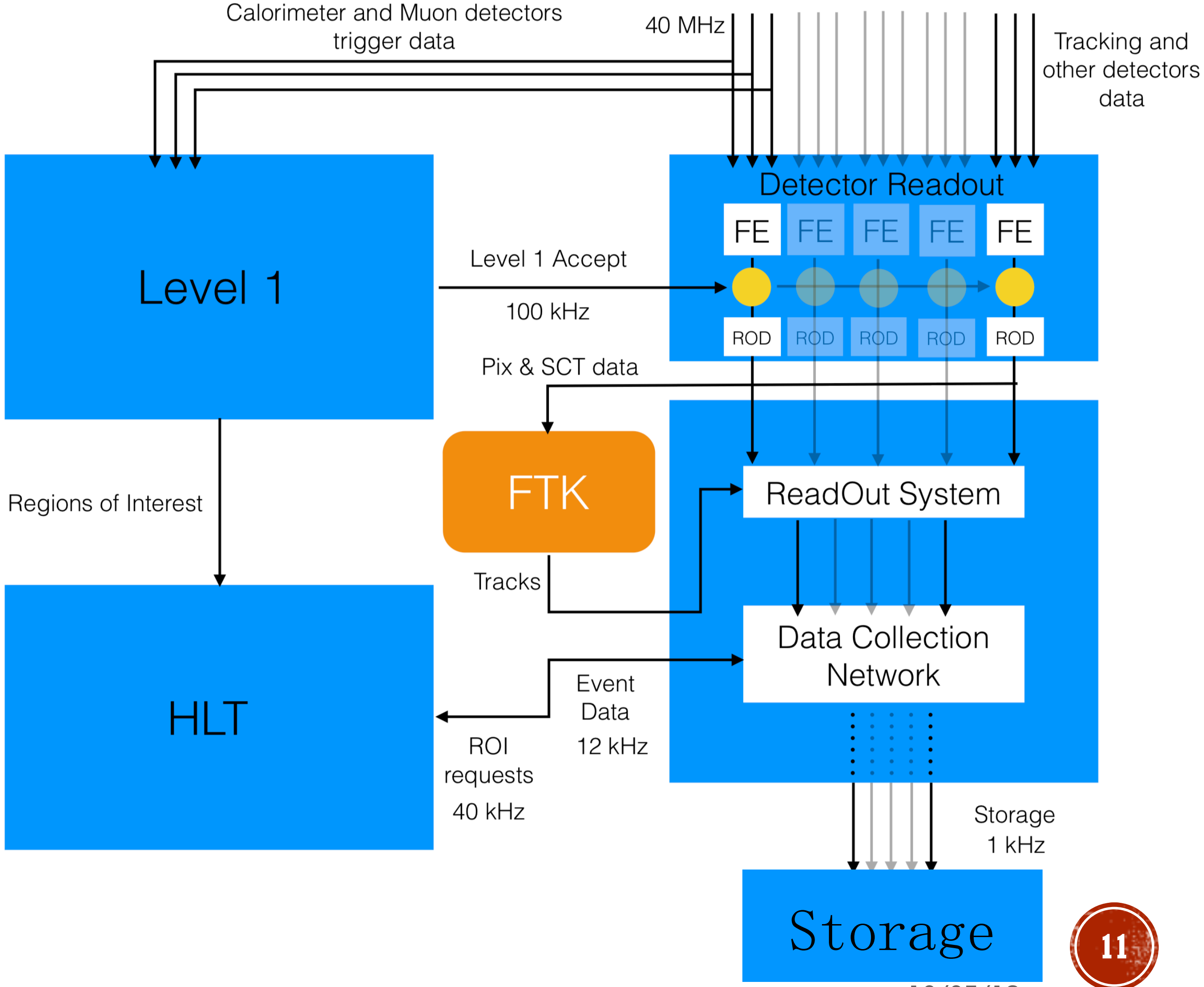
THE ATLAS FAST TRACKER

- Fast TracKer:
  - Highly parallel processing system
  - Hardware-based, able to perform global tracking in the whole Inner Detector
- Based on:
  - Custom Associative Memory (AM) chips for pattern matching
  - FPGAs: track fitting, data preparation, ambiguity resolution …
- Very complex system:
  - **> 450 boards, 8k AM chips, 2k FPGAs, highly parallel!**



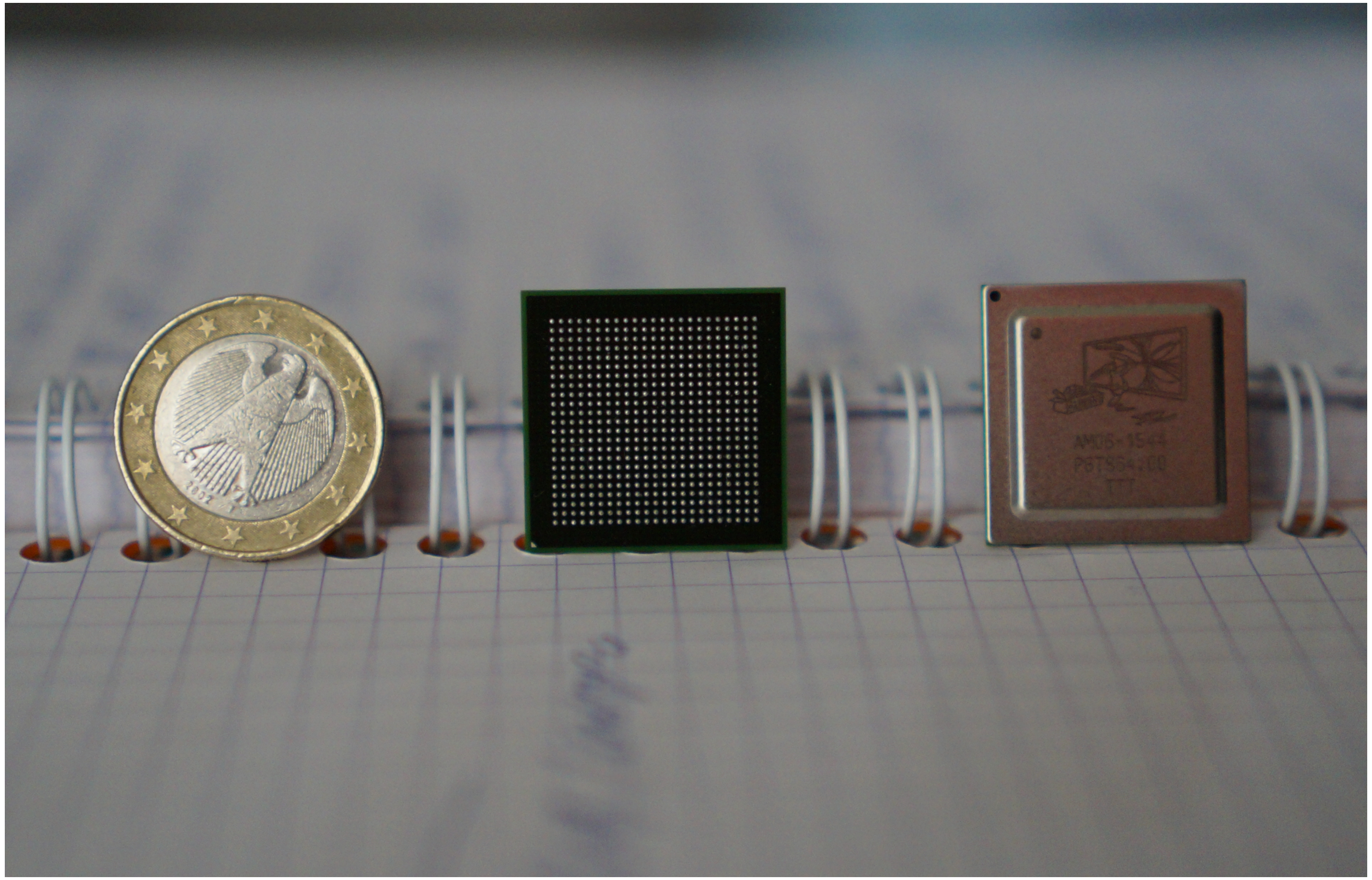
THE ATLAS FAST TRACKER

- HLT: tracking information currently used in small Region of Interest for a subset of events
- FTK reconstructs all tracks ($p_T > 1\ GeV$) for all L1 accepted events
- Tracks provided at HLT in $\sim 100\ \mu s$ at the L1 rate ($100\ kHz$)



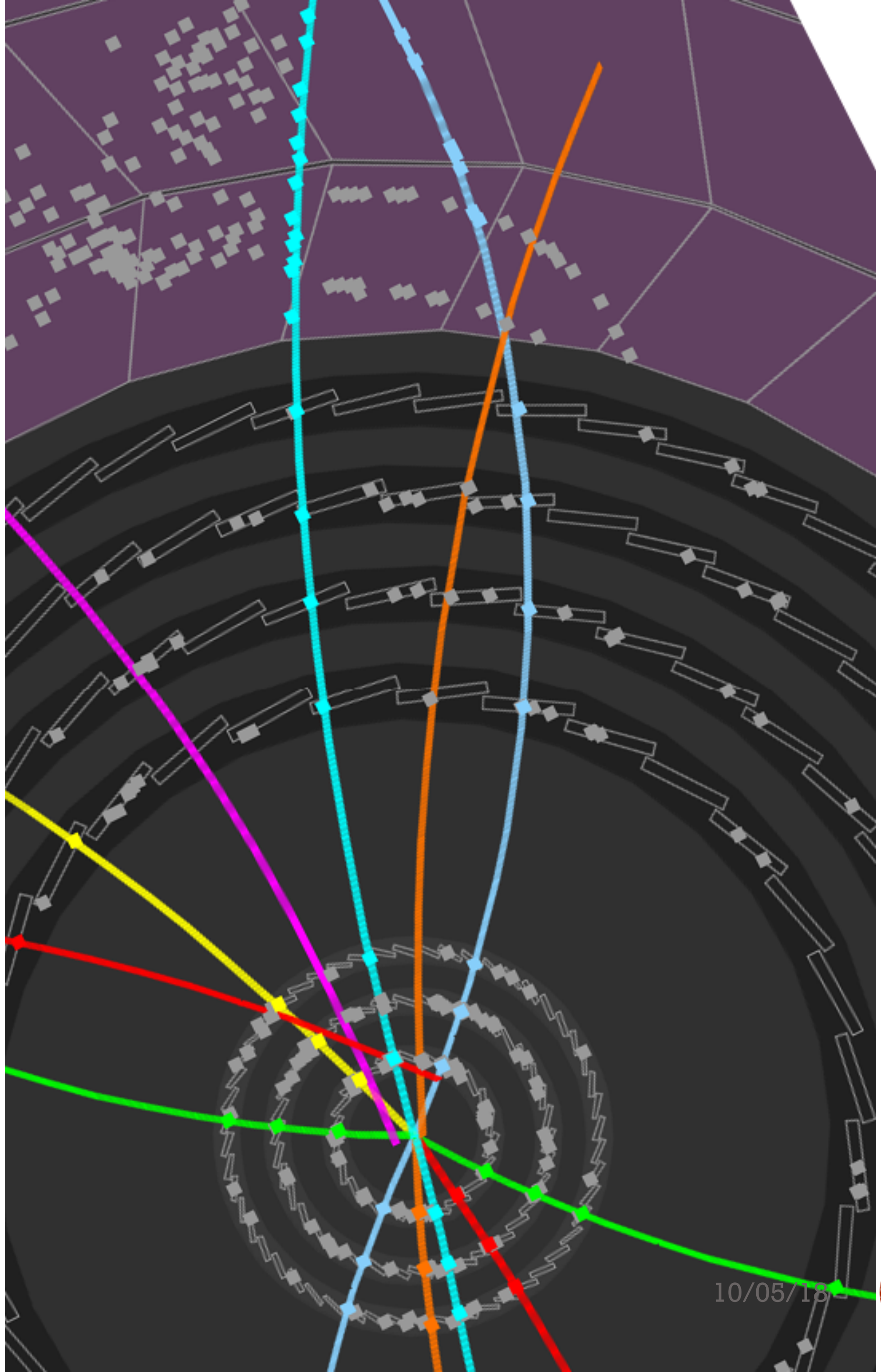
THE HEART OF FTK: ASSOCIATIVE MEMORIES

- Why so important??
- Random Access Memory
  - Data searchable by address: from the address to the data
- Content Adressable Memory
  - Data searchable by content **in a single clock cycle**: from the data to the address!
- Highest possible level of parallelism
  - instantaneous pattern recognition



FTK WORKING PRINCIPLE

- Detector geometry: concentric layers
  - Channels grouped and merged in bins: granularity reduction
- In each event: different collections of bin hits
- Comparison performed between the set of bin hits and the precomputed patterns
  - Candidate tracks selected (road)
- Hits found in the road Fitted by FPGA
  - Final tracks sent to the HLT



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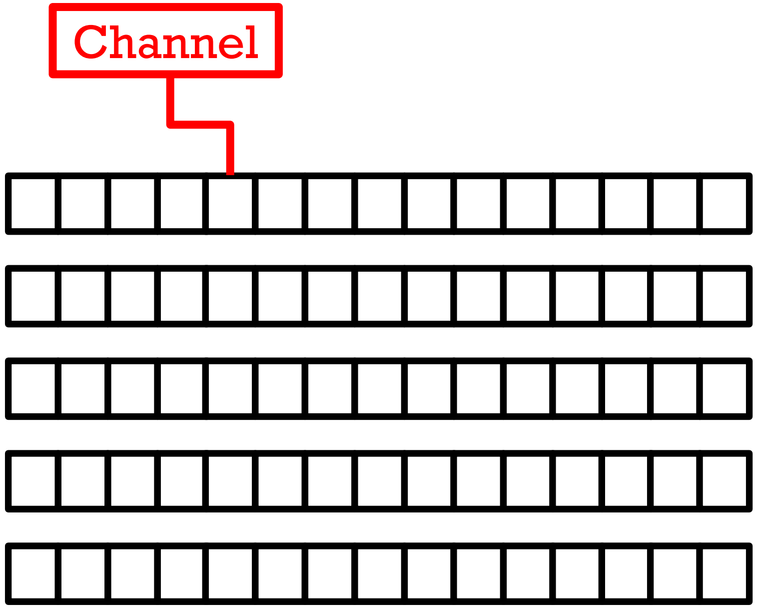

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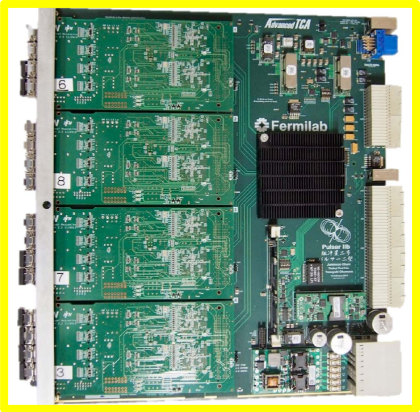

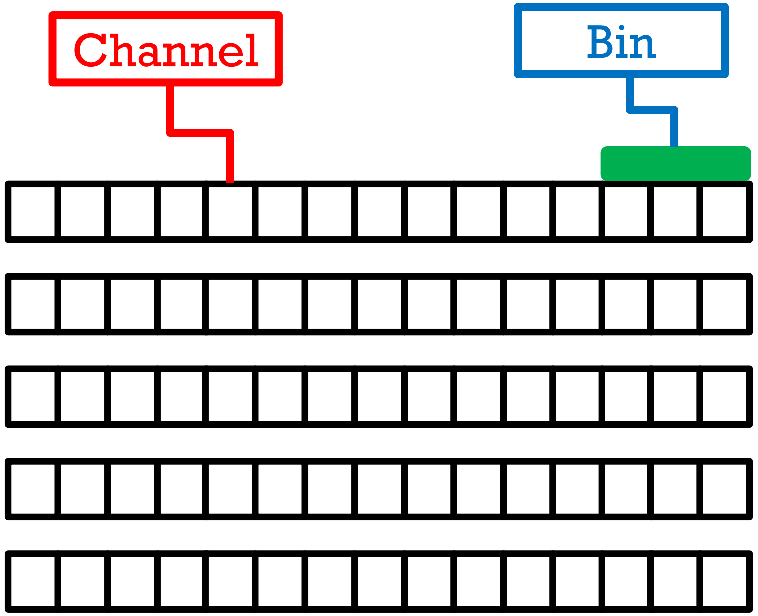

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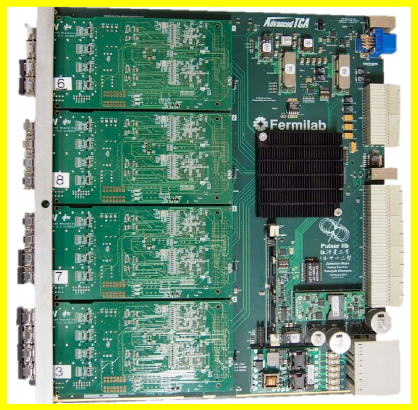

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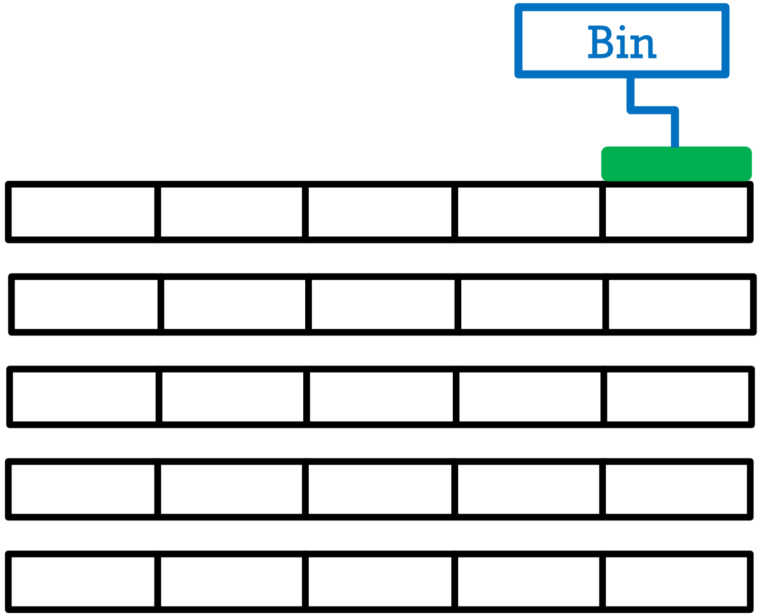

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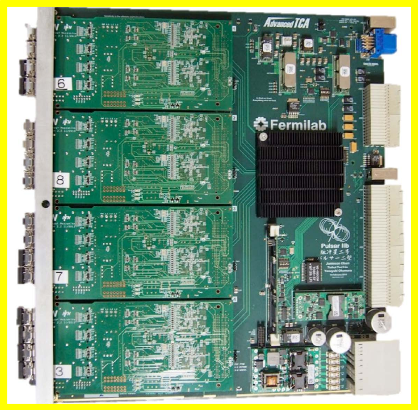

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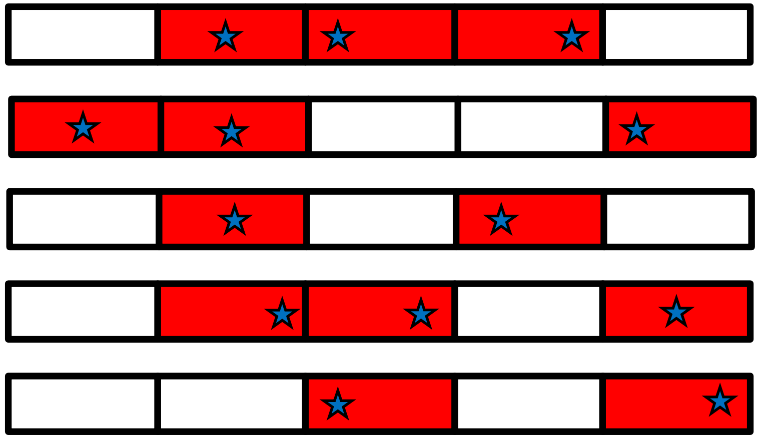

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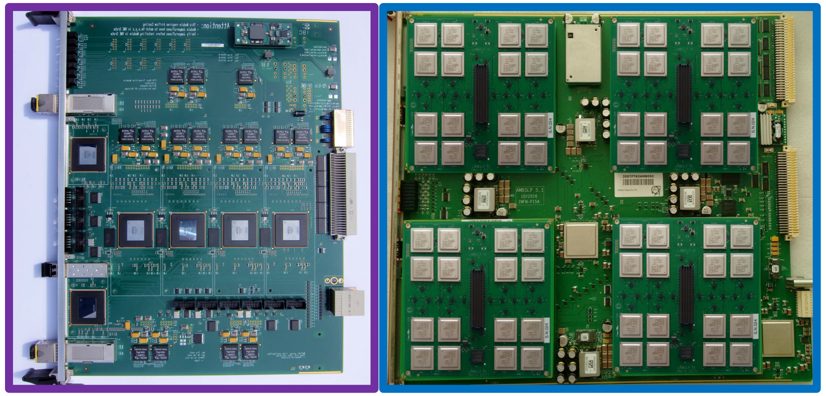

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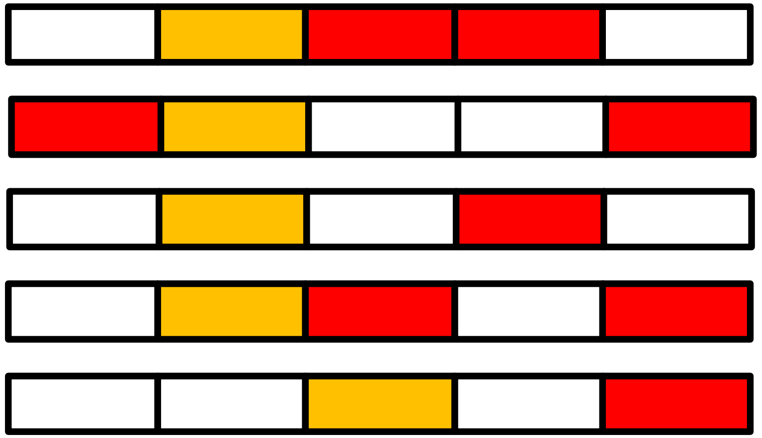

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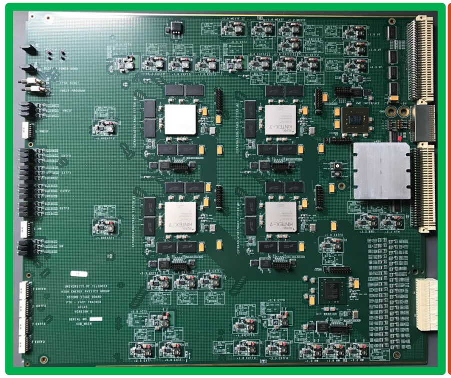

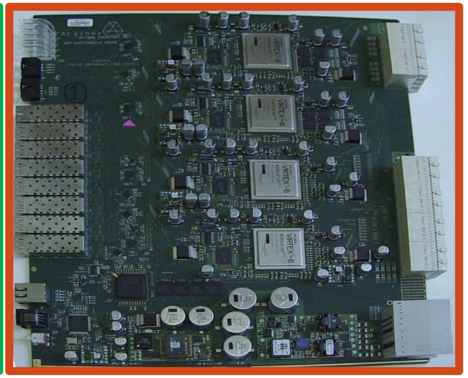

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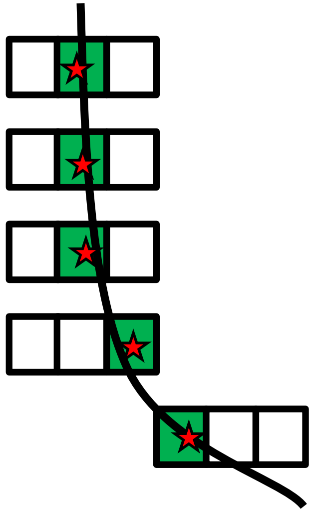
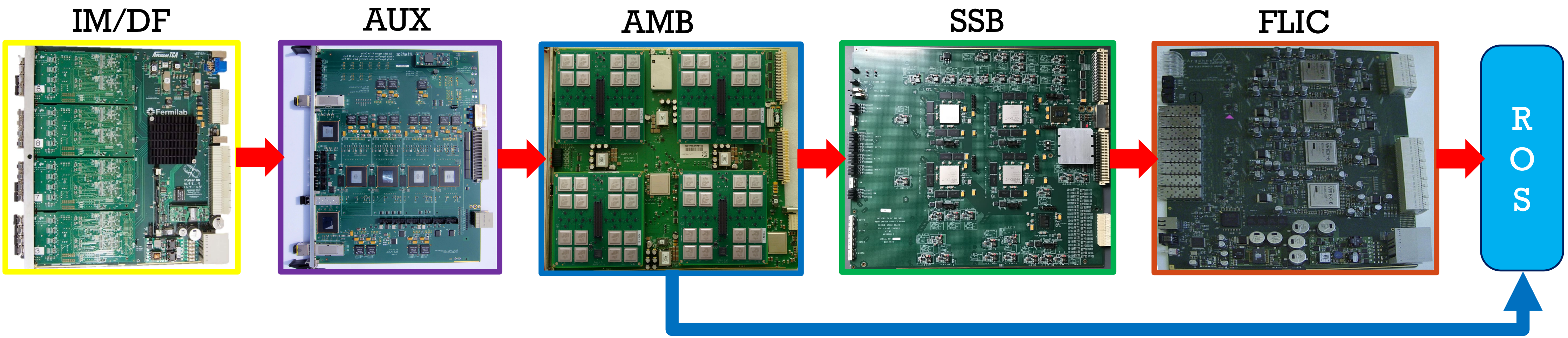


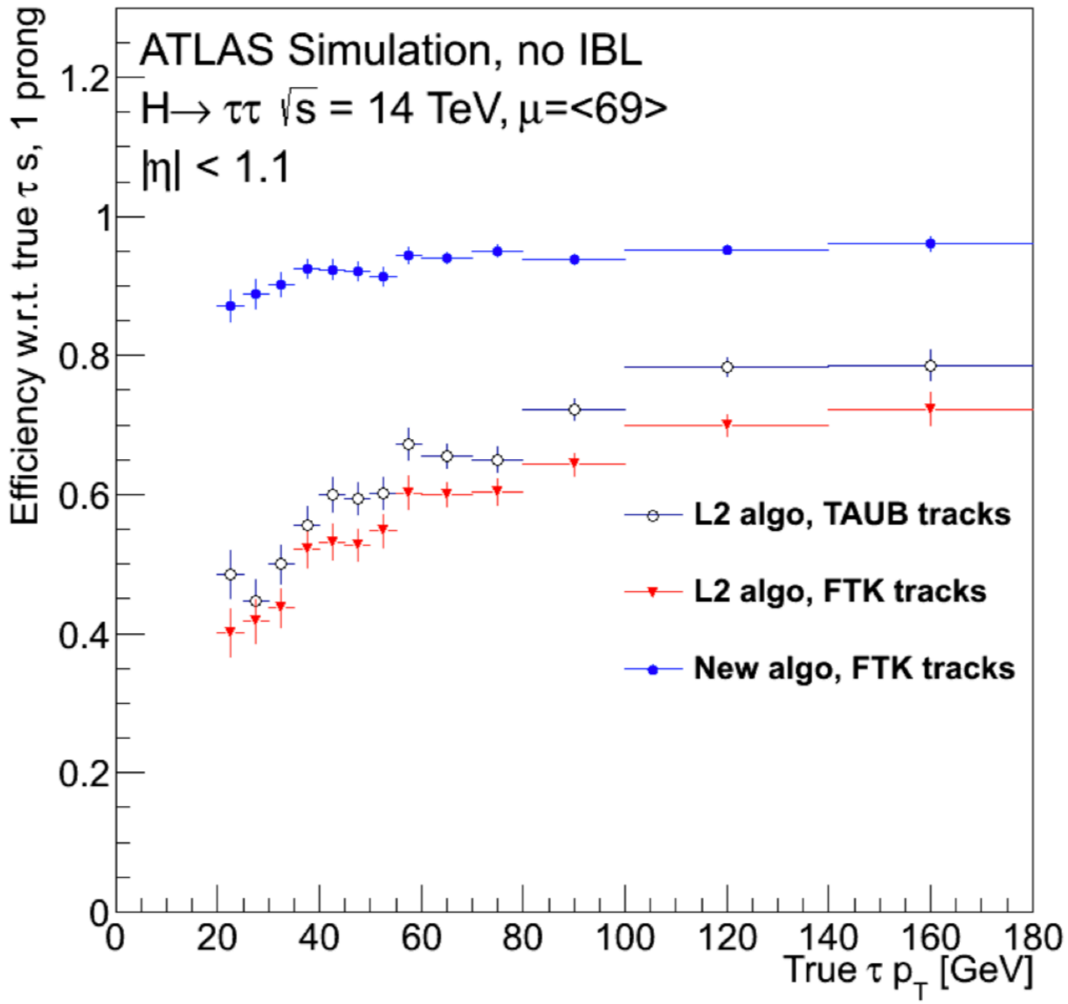
COMMISSIONING STATUS



- FTK system currently under commissioning
- System already integrated in ATLAS:
  - SliceA: 1 complete FTK slice, providing 12-layer traks
  - Slice2: 1 slice up to AMB, providing 8 layers traks
- Half of the system expected to be integrated by the end of the year
  - FTK not used for trigger selection before Run3

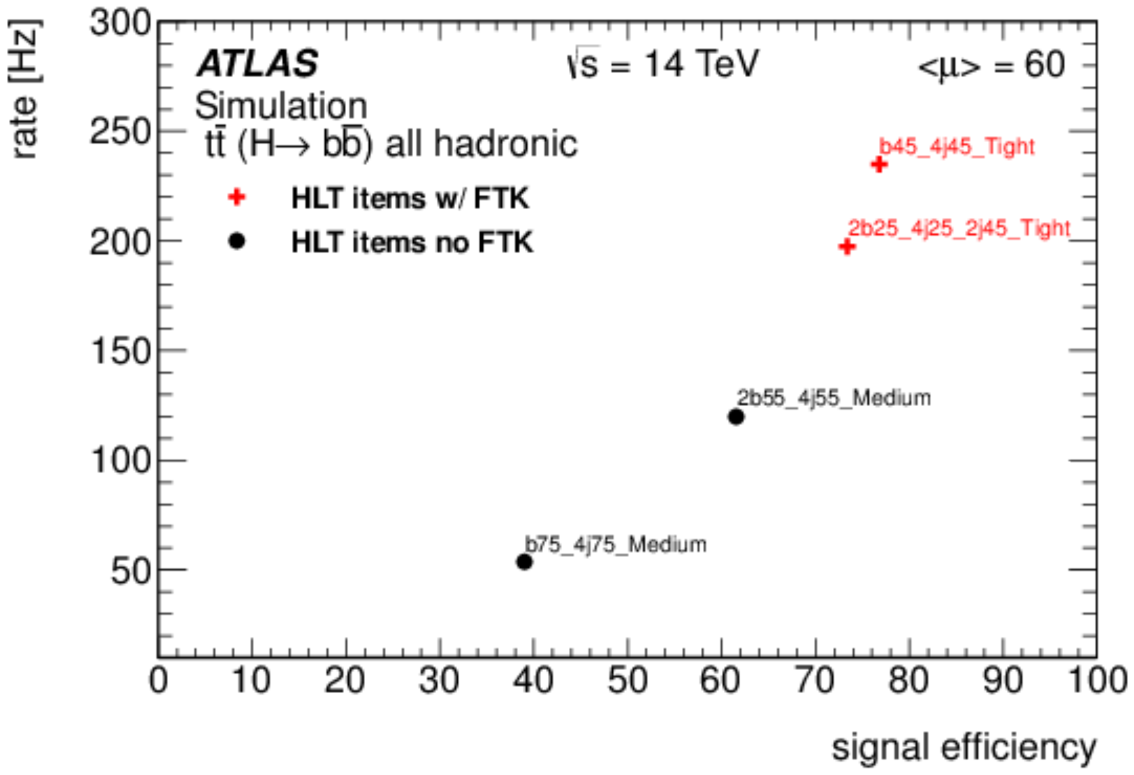
TAU PERFORMANCE

- Current tau identification:
  - Calo preselection
  - MultiVariate Analysis after tracking inside the RoI
- Most of the HLT time spent for tracking
- With FTK:
  - All tracks fed to HLT
  - No need of Calo preselection (pile-up affected)
  - Possible use of more sophisticated algorithms not usable before
- Tau selection efficiency as in offline reconstruction!



b PERFORMANCE

- b trigger identification based on MultiVariate Analysis
  - Relies on tracking information
- Without FTK:
  - Not possible to reconstruct all the b-candidates identificated at L1
  - Increase of the L1 threshold required
  - Selection efficiency dramatically reduced in future Runs
- Significative increase in efficiency foreseen with FTK



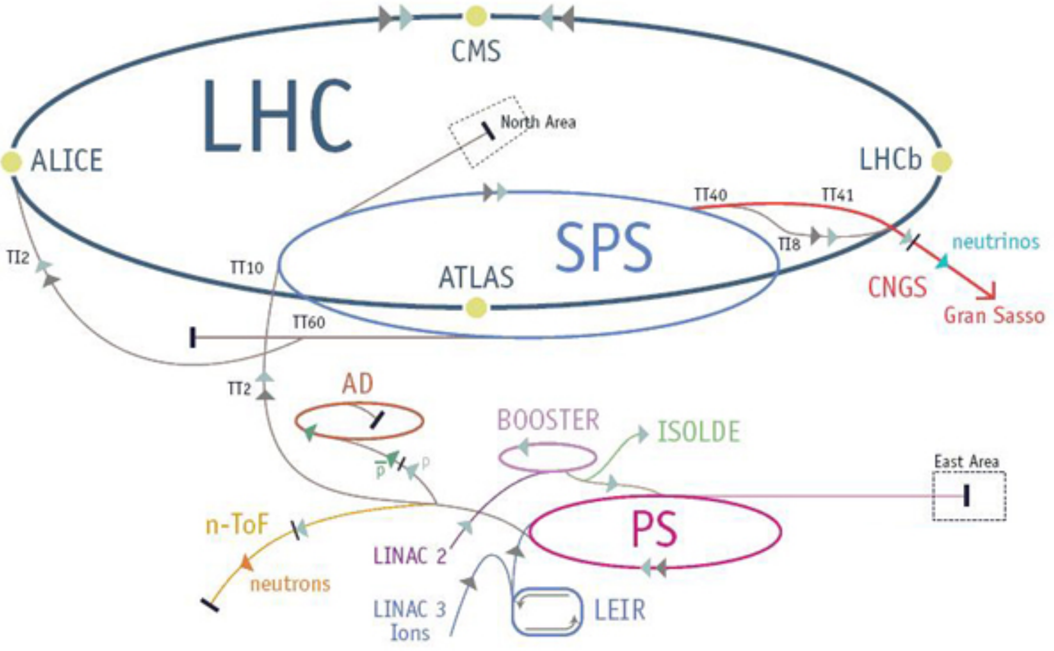
CONCLUSIONS

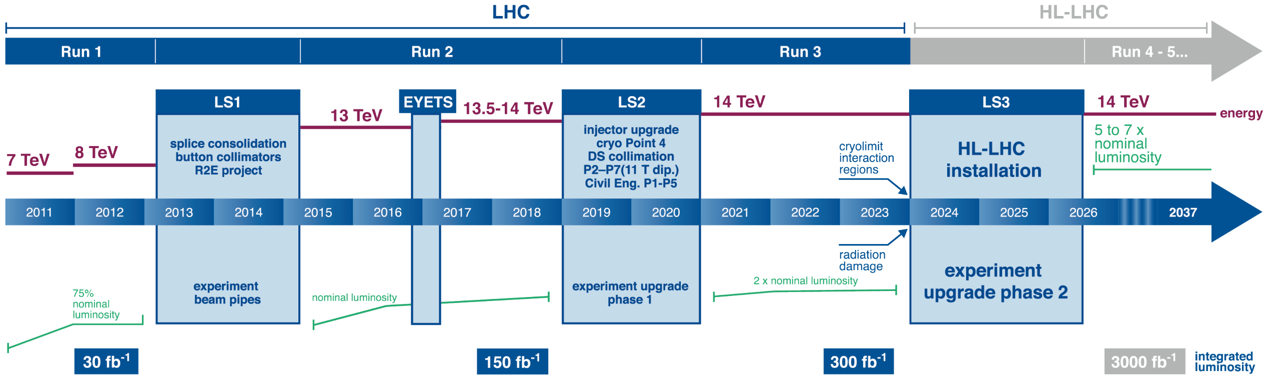
- LHC Run II & III will have a lot of challenging physics to be explored
- Only the wider use of tracking information in the trigger will allow to achieve the research goals prefixed
  - Without loose profit from the increase of statistic provided by the luminosity upgrades
- The Trigger is a challenging environment for tracking
  - High rates, short times, requirements for high efficiency and low fake rates
- FTK uses an highly parallel, hardware-based solution to solve the problems of tracking at high luminosity
  - Very good performance with respect to software-based tracking

BACKUP

LHC

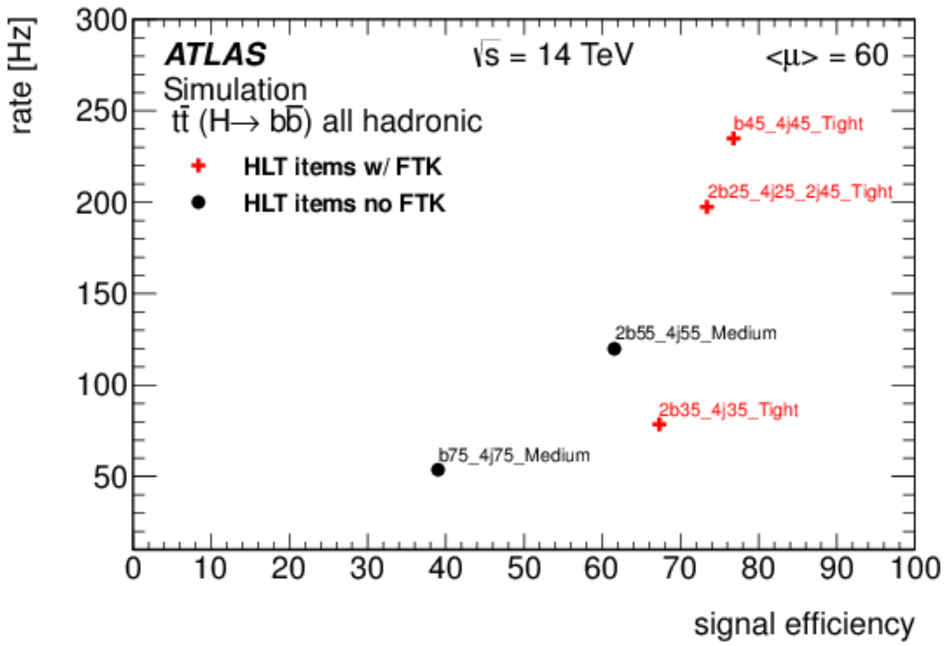
- Run 1 main results:
  - Higgs boson found @ 125 GeV
  - High precision measurements of the SM
  - No new physics observed!
- Run 2 and beyond:
  - Measure the properties of the new boson
  - Search wider, further and deeper for new physics
- Increase in luminosity foreseen

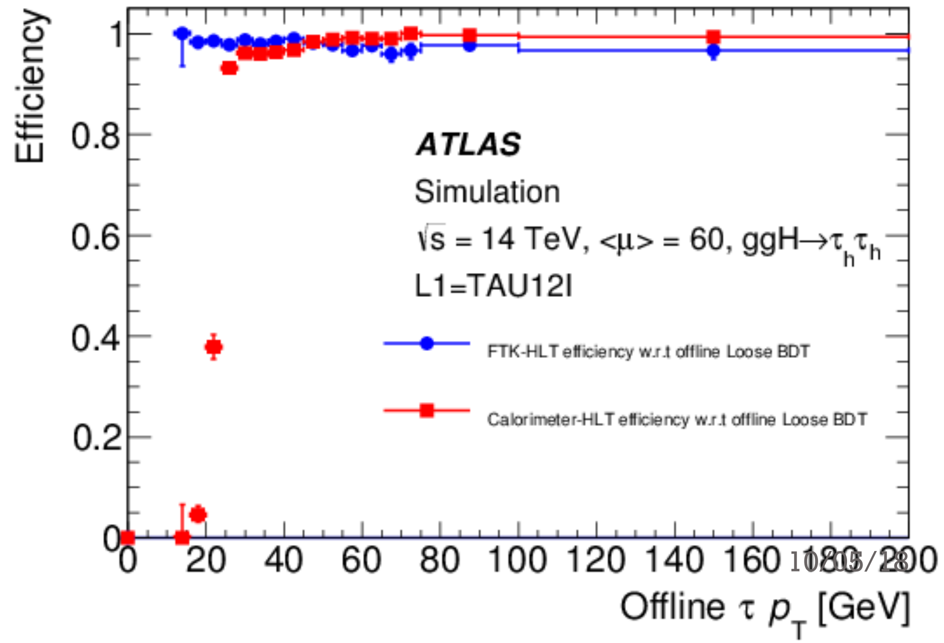




WHY TO USE FTK?

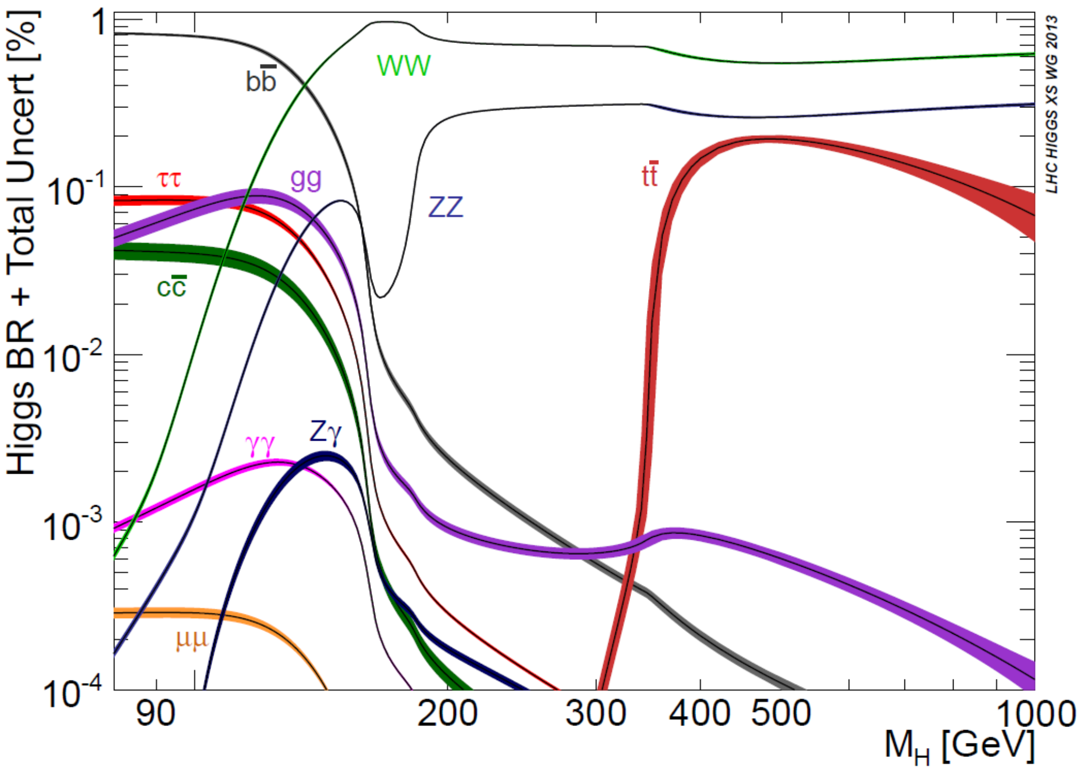
- Measure Higgs Properties
  ex: are fermionic-couplings SM-like?
  - Final states with b-quarks and τ-leptons important but with very large backgrounds from light quark and gluon jets
  - FTK trigger chains can identify b-quarks by finding displaced vertex
  - FTK trigger chains can identify τ leptons by providing tracks in jet cones
- SUSY sparticles can decay to medium energy b and τ which are difficult to trigger without FTK
- …





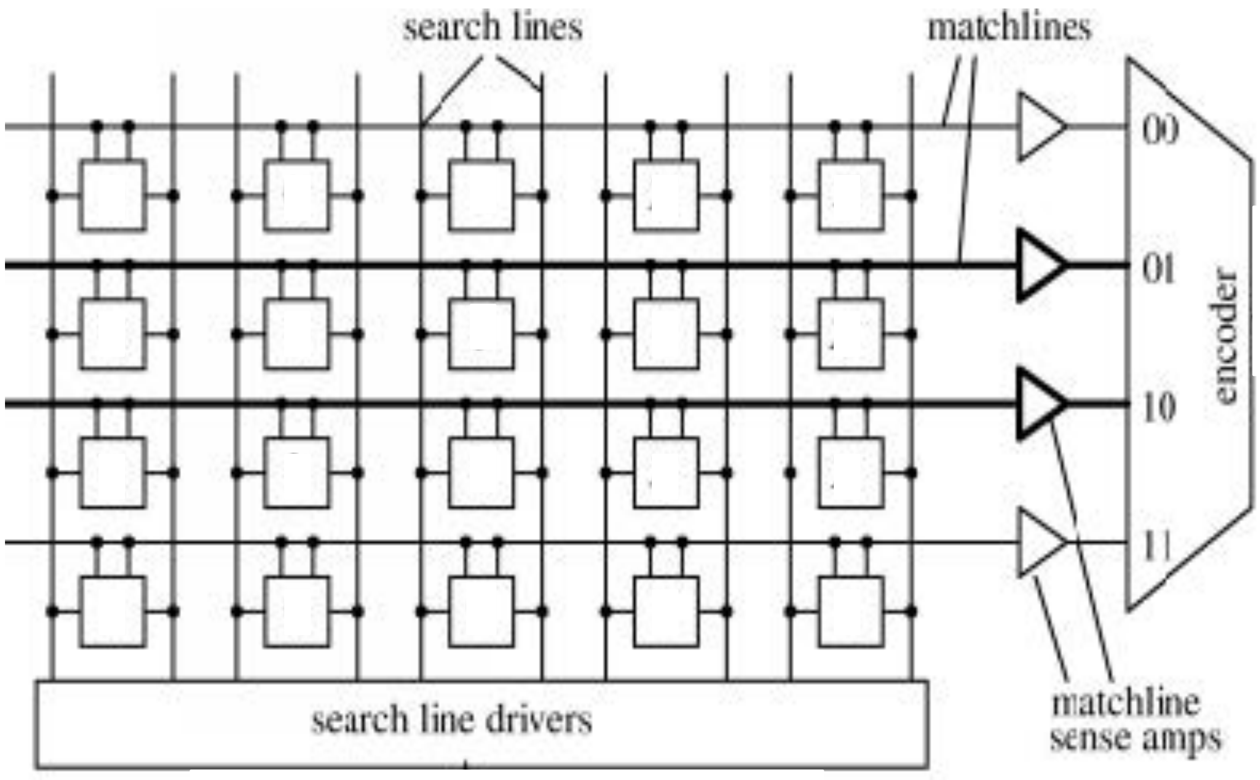
HIGGS FERMIONIC COUPLING

- Higgs Boson couplings
  - SM gives accurate coupling predictions
    - $\propto m_f$ for Fermions
    - $\propto {m_B}^2$ for Bosons
  - Powerful indication on the nature of Higgs boson: SM, or subtly different?
- $H \rightarrow \tau\tau \;\; H \rightarrow b\bar{b}$
  - Only two channels available to study the Yukawa coupling @ LHC
  - Online identification of both tau and b very challenging
    - Based on tracking information!



THE HEART OF FTK: ASSOCIATIVE MEMORIES

- Configuration:
  - AM pattern loading
    - From MonteCarlo
- At work:
  - Collisions data sent in parallel to all the lines
  - Match: pattern found in the ones loaded
  - Found pattern address sent in output
- Pattern bank dimensions scalable!
  - Adding more AM



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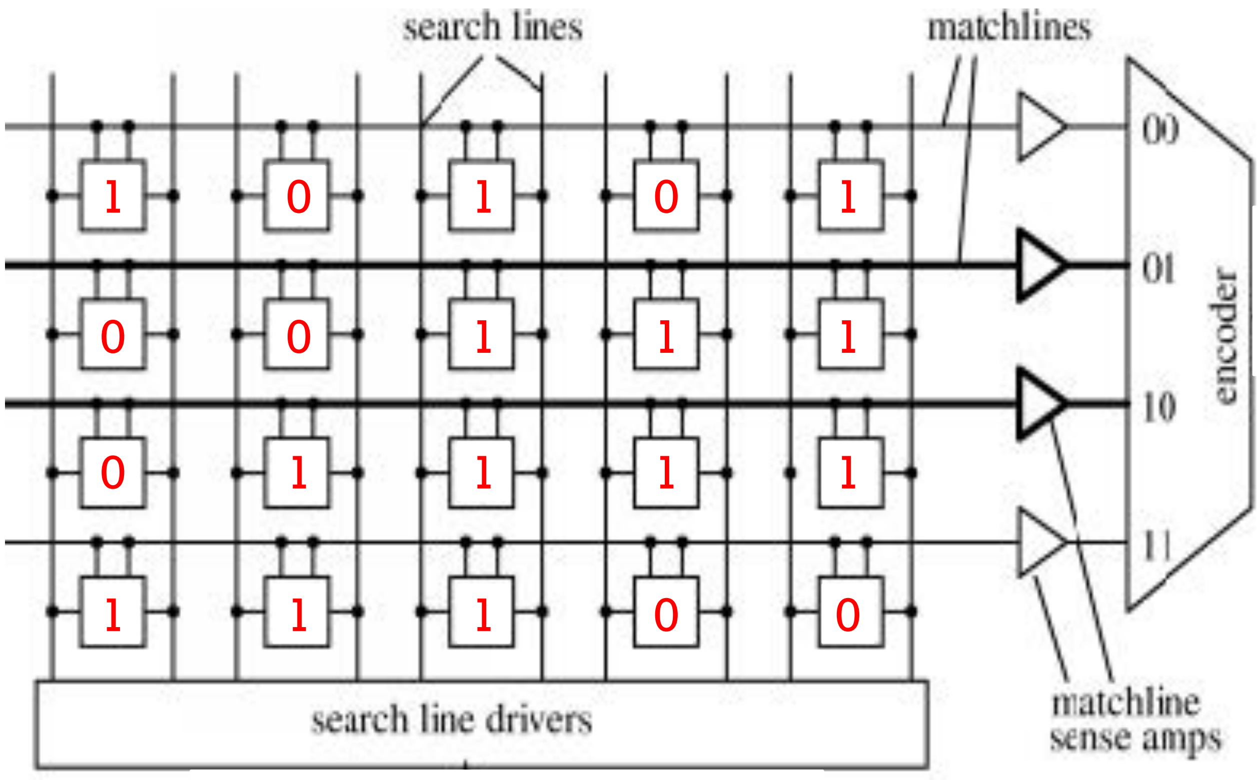

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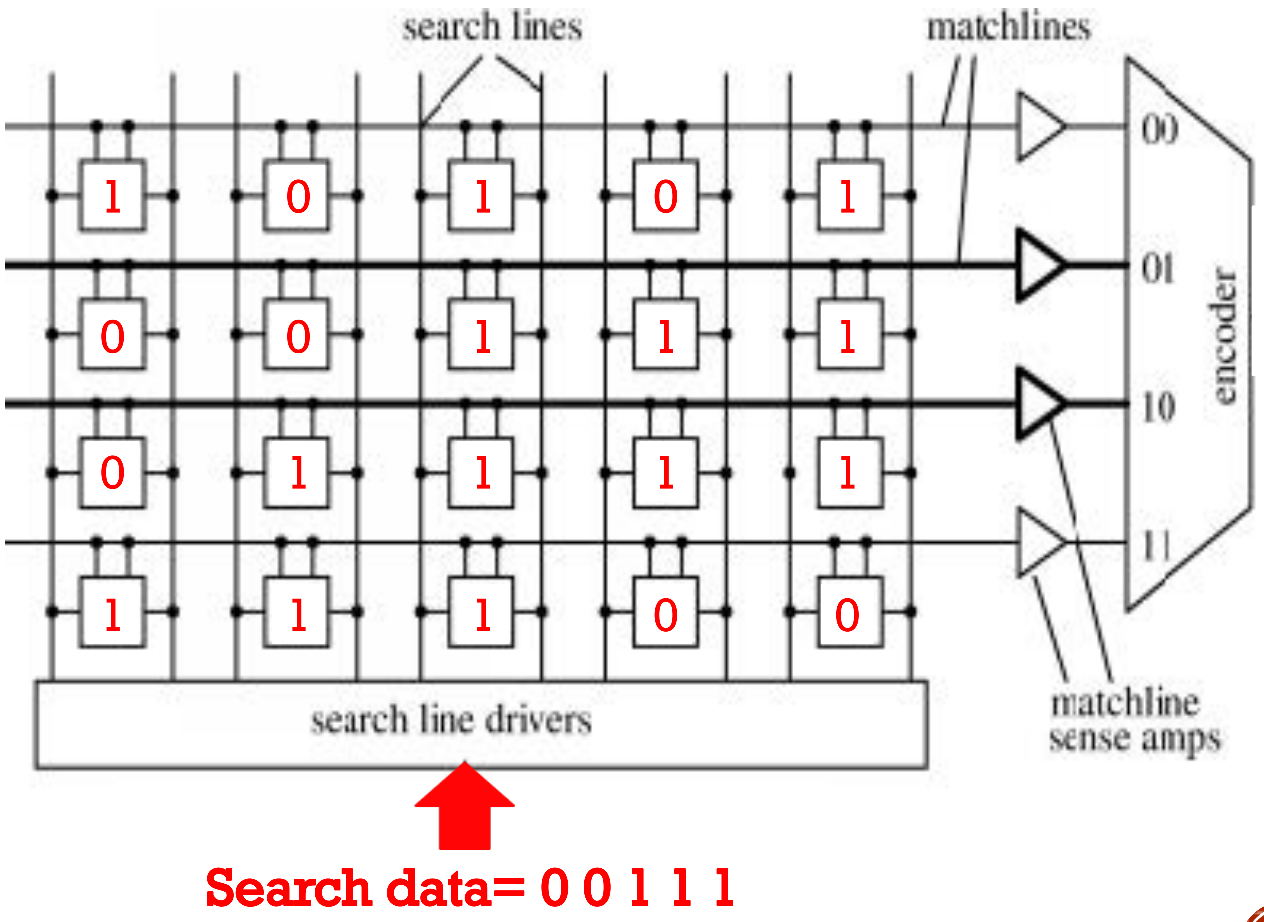

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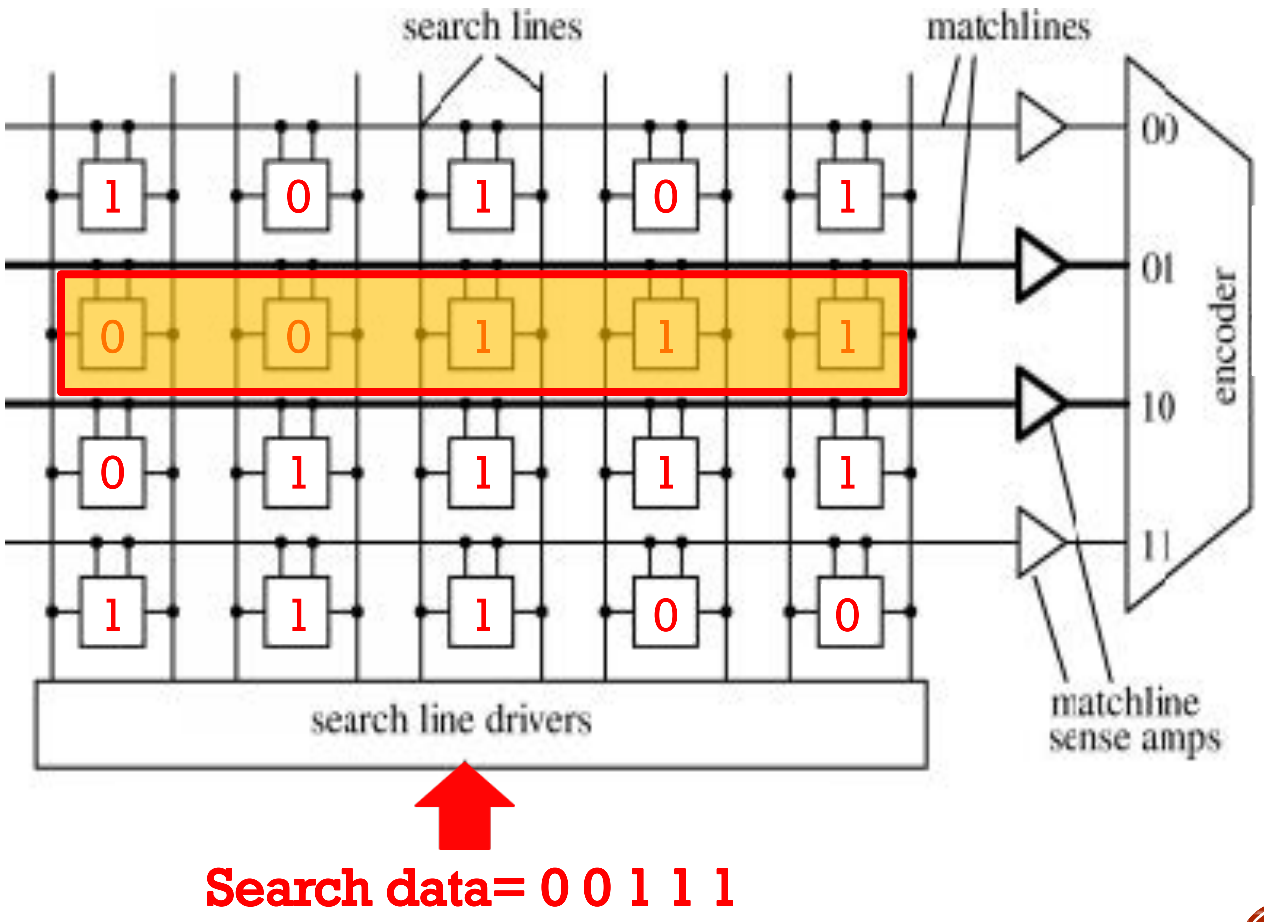

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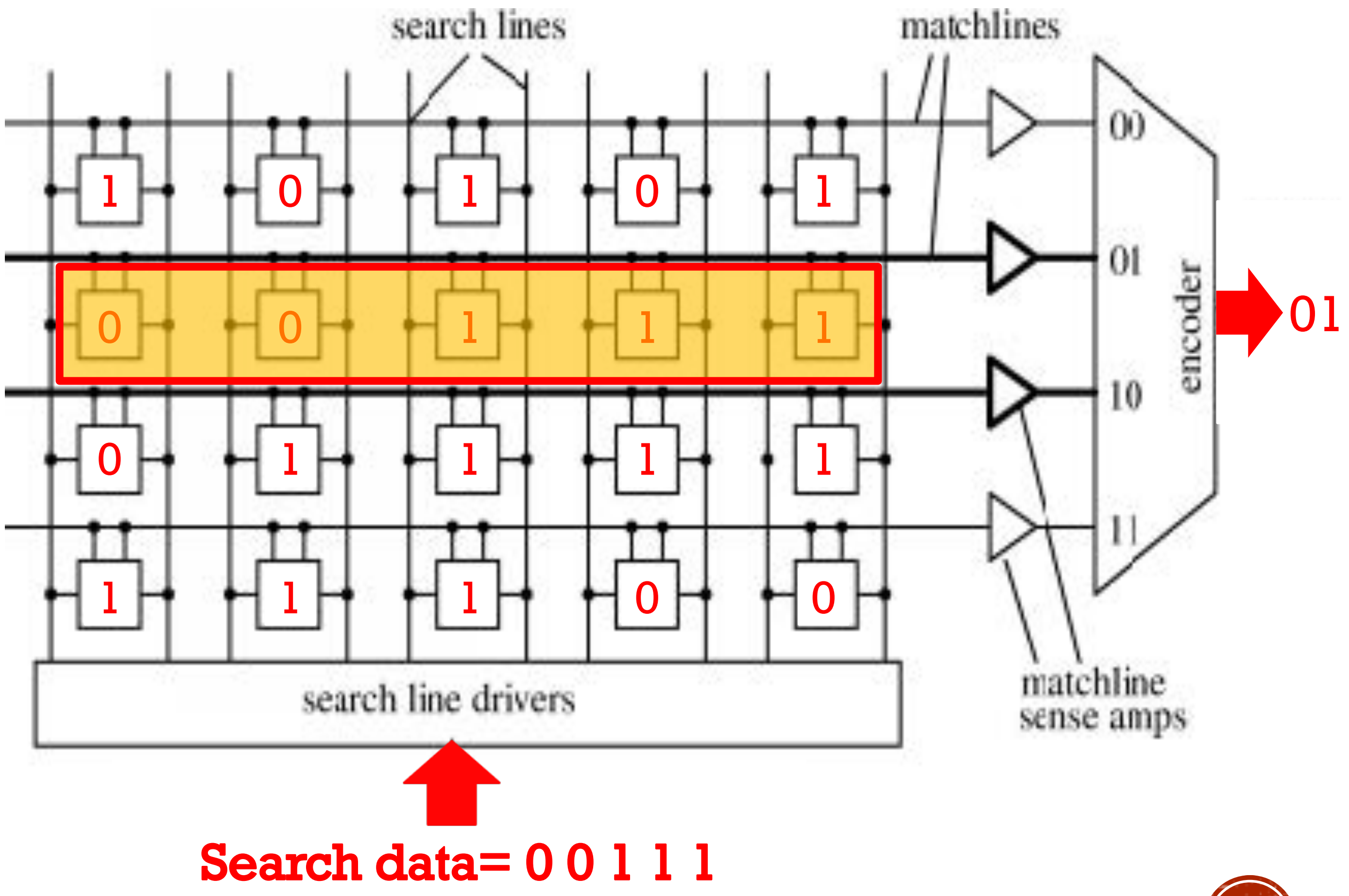
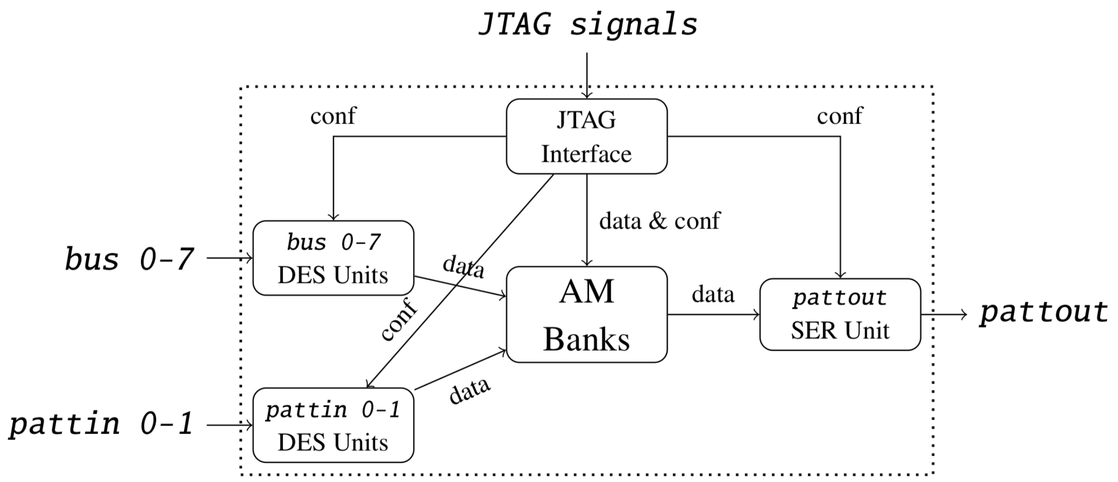


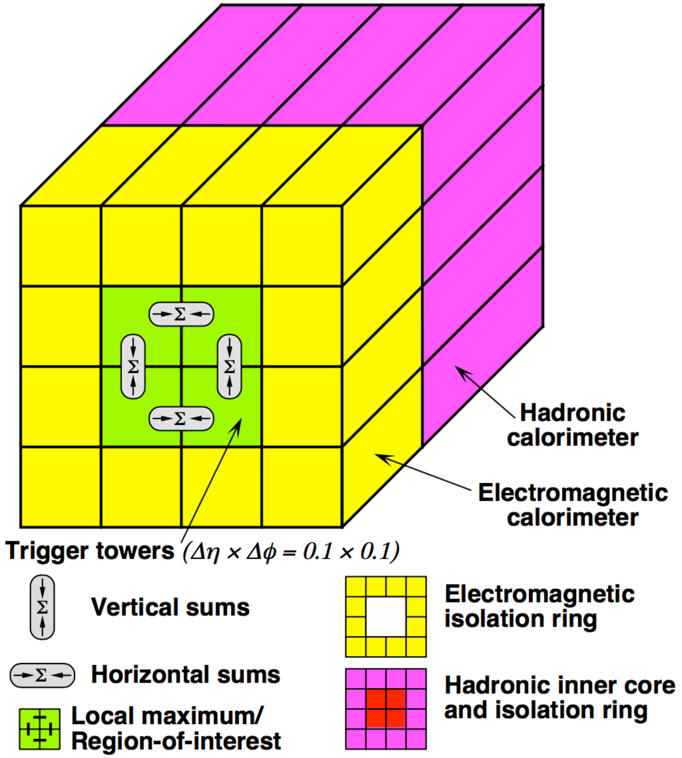
THE HEART OF FTK: ASSOCIATIVE MEMORIES

Version	*Design approach*	*Technology*	*Area*	*Patterns*	*Package*
1	Full custom	700 nm		128	QFP
2	FPGA	350 nm		128	QFP
3	Std cells	180 nm	100 mm^2	5 k	QFP
4	Std cells + Full custom	65 nm	14 mm^2	8 k	QFP
mini-5	Std cells + Full custom	65 nm	4 mm^2	0,5 k	QFP
5	Std cells + Full custom + IP blocks		12 mm^2	3 k	BGA
6	**Std cells + Full custom + IP blocks**	**65 nm**	**168 mm^2**	**128 k**	**BGA**

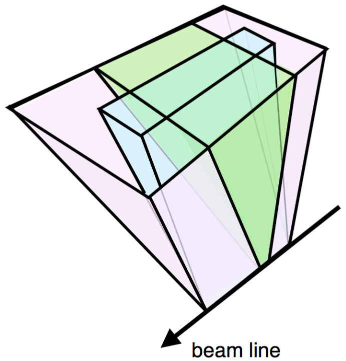


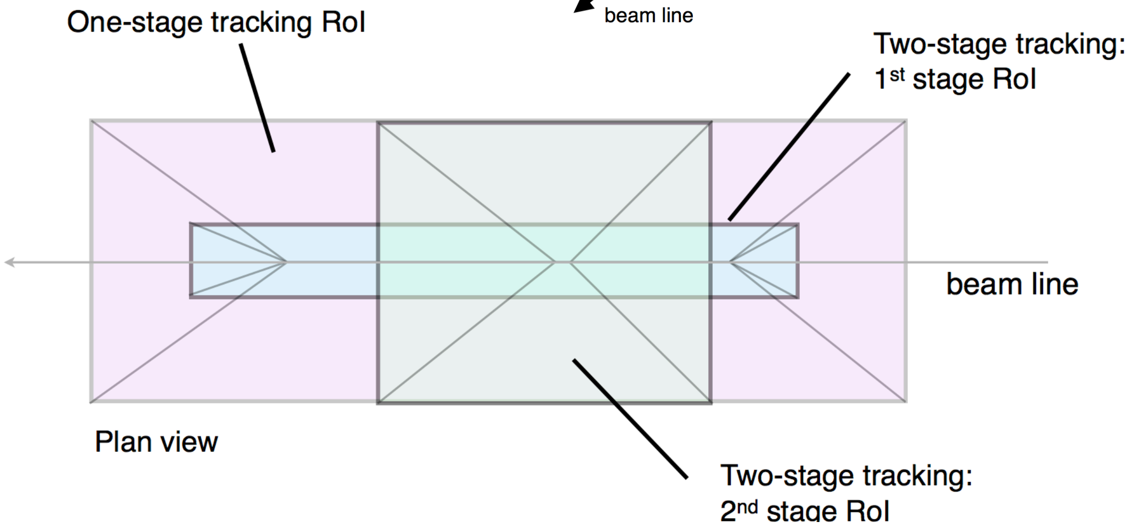
L1-CALO AND HLT CALO-PRESELECTION

- L1 CALO:
  - Hardware based
    - Energy deposits in EM and HAD calo
    - Granularity $\Delta\eta\times\Delta\phi = 0.1\times0.1$
  - Selection of RoI as 2x2 tower clusters
    - Energy of 2x1 EM and 2x2 HAD > threshold
    - Energy of insulation EM and HAD rings < threshold
- HLT:
  - Calo-only preselection:
    - Reconstruction from Calo informations (full granularity)
    - Energy calculated in a cone of $\Delta R < 0.2$



HLT: TRACK PRESELECTION

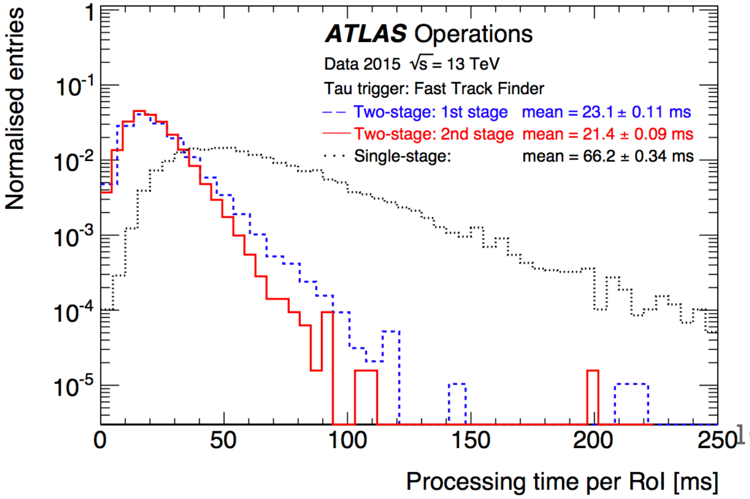




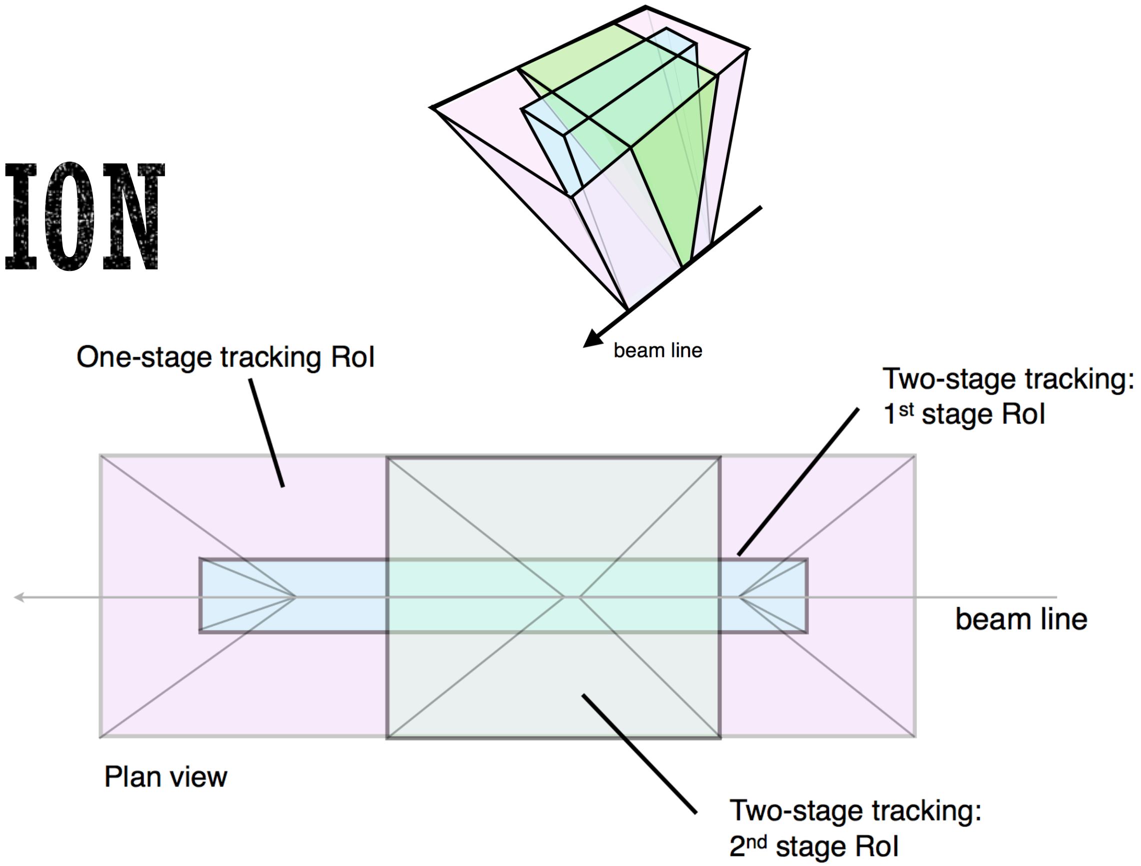
- Z position not know
  - Not possible to track the full RoI
- Two stage fast tracking algorithm:

1) Leading track sought ($p_T > 1GeV$)
   - RoI: narrow cone ($\Delta R < 0.1$) along the beamline ($|z| < 225\ mm$)
   - If no tracks: τ rejected

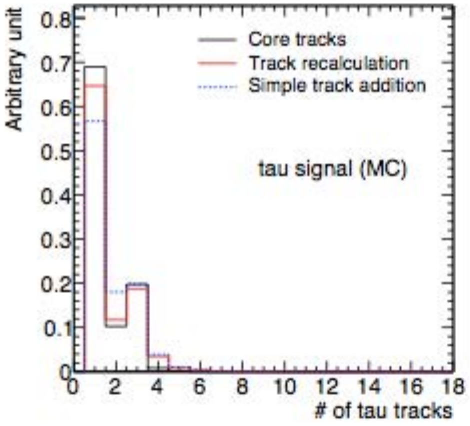
2) All other tracks reconstructed
   - RoI: larger cone ($\Delta R < 0.4$) shorter in the beamline ($|z| < 10\ mm$)

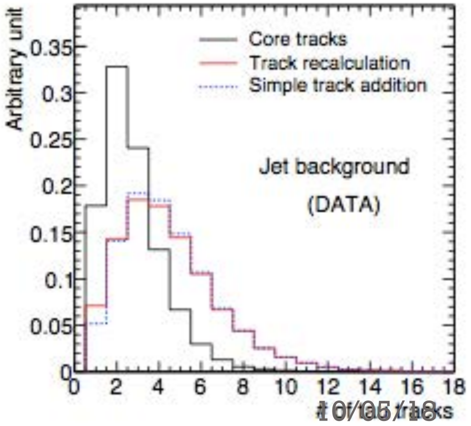


HLT: TRACK PRESELECTION



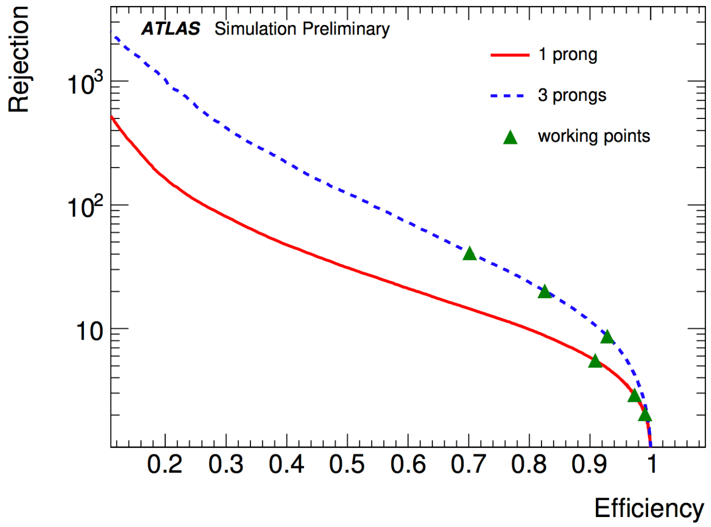
- Used the track multiplicity to perfome the selection
- Tracks multiplicity computed
  - N_{core}^{trk} for $\Delta R < 0.2$
  - N_{isol}^{trk} for $0.2 < \Delta R < 0.4$
- Candidate finally accepted if $0 < N_{core}^{trk} < 4$ and $N_{isol}^{trk} < 2$





HLT: OFFLINE-LIKE SELECTION

- High precision tracking performed on pre-selected tracks
- Final tracking and calo information used to compute identification variables
- Variables feed to a BDT for the final selection



Variable	Description
f_{cent}	Central energy fraction
$f^{-1}_{\mathrm{leadtrack}}$	Leading track momentum fraction
R_{track}	Track radius
$\lvert S_{\mathrm{leadtrack}}\rvert$	Leading track impact parameter significance
$f^{\mathrm{track}}_{\mathrm{iso}}$	Fraction of p_{T} from tracks in the isolation region
ΔR_{Max}	Maximum ΔR
$S^{\mathrm{flight}}_{\mathrm{T}}$	Transverse flight path significance
m_{track}	Track mass
$f^{\mathrm{track-HAD}}_{\mathrm{EM}}$	Fraction of EM energy from charged pions
$f^{\mathrm{EM}}_{\mathrm{track}}$	Ratio of EM energy to track momentum
$m_{\mathrm{EM+track}}$	Track-plus-EM-system mass
$p^{\mathrm{EM+track}}_{\mathrm{T}}/p_{\mathrm{T}}$	Ratio of track-plus-EM-system to p_{T}

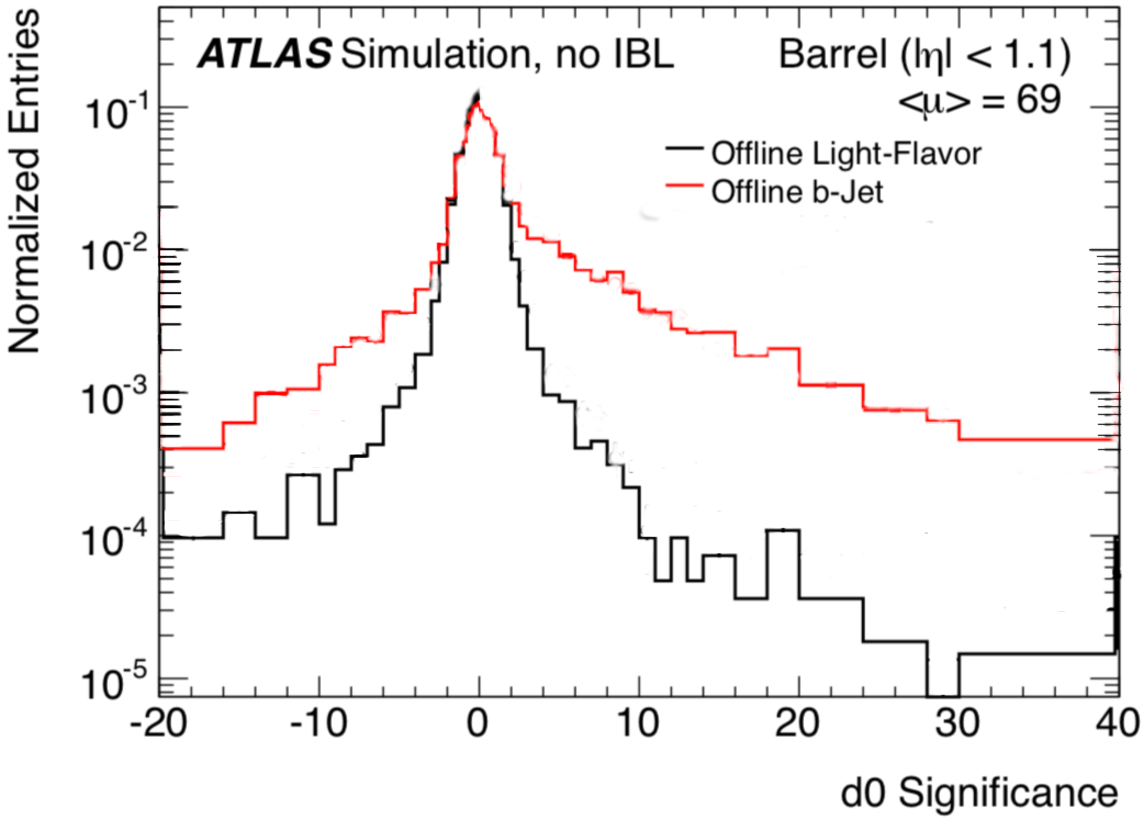
TAU-JET OFFLINE DISCRIMINATION

- Topology features used to discriminate between jets and taus
- Challenge: quantify these features in a way that is suited to the analysis technique
- Example: cut based analysis
  - $|\eta_{j1} - \eta_{j2}| > 6.0$
  - $\phi_\tau < \phi_{E_T^{miss}} < \phi_l$
  - $\eta_{j1} < \eta_l < \eta_{j2}$ or $\eta_{j1} > \eta_l > \eta_{j2}$ etc…
- Problem: few signal events look good after full reconstruction
  - Detector effects, efficiencies, pure random fluctuations …

- Compromise required to accept more signal still rejecting the backgrounds
  - Difficult to be done in cut based analysis
- Definition of new discriminating variables
  - Useful to help for discrimination
- Example:
  - Core energy fraction $f_{core} = \frac{\sum_{i \in all}^{\Delta R_i < 0.1} E_{T,i}}{\sum_{j \in all}^{\Delta R_j < 0.2} E_{T,j}}$
  - Ring isolation $f_{iso} = \frac{\sum_{i \in had}^{0.1 < \Delta R_i < 0.2} E_{T,i}}{\sum_{j \in had}^{\Delta R_j < 0.2} E_{T,j}}$
  - …

b PERFORMANCE

- b trigger selection based on BDT
  - Relies on tracking information
- Without FTK:
  - Not possible to reconstruct all the tracks selected at L1
  - Increase of the L1 threshold required
  - Selection efficiency dramatically reduced in future Runs
- No loose of efficiency foreseen with FTK



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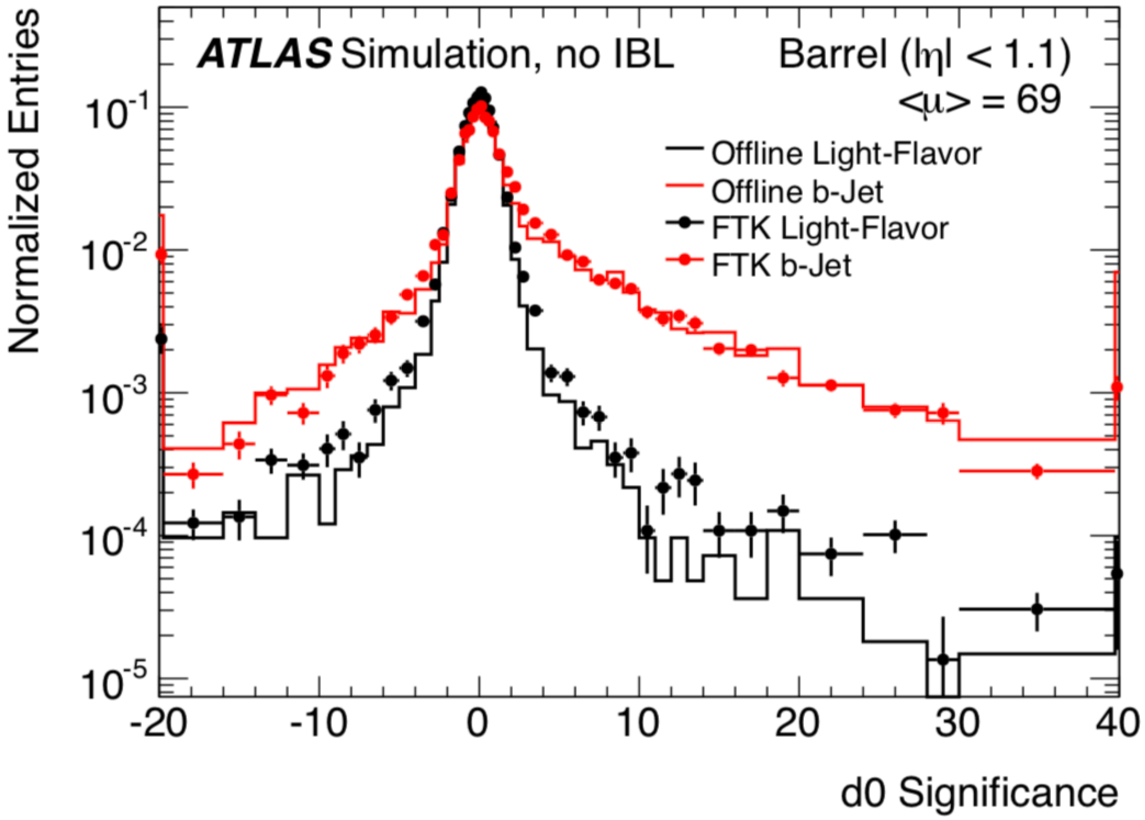

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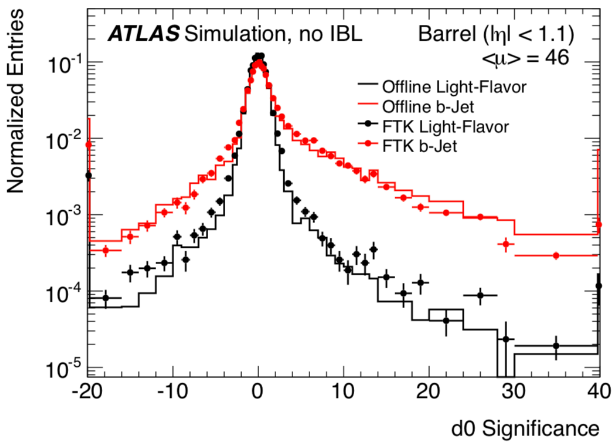

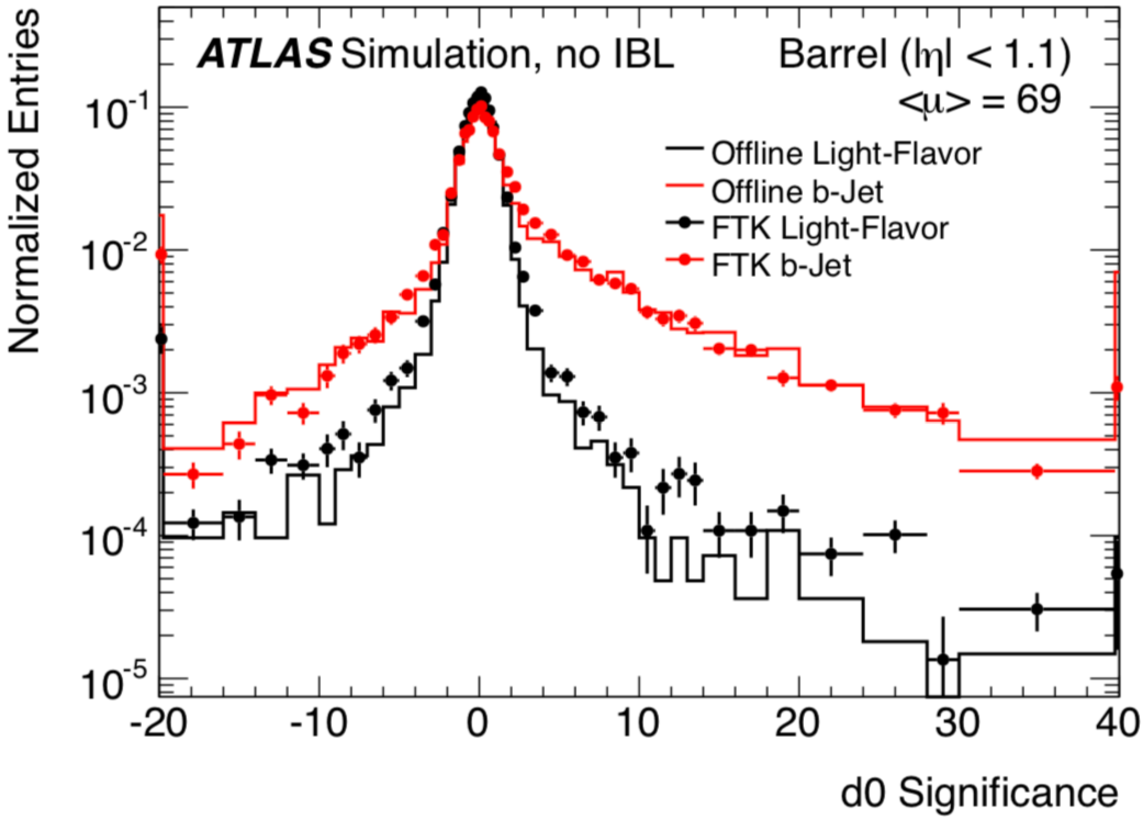

It doesn't degrade with pileup!