

Development of FTK Architecture

Fast Hardware Track Trigger for the ATLAS Detector



ATLAS

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(for FTK collaboration)

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THE UNIVERSITY OF
CHICAGO



DPF 2009

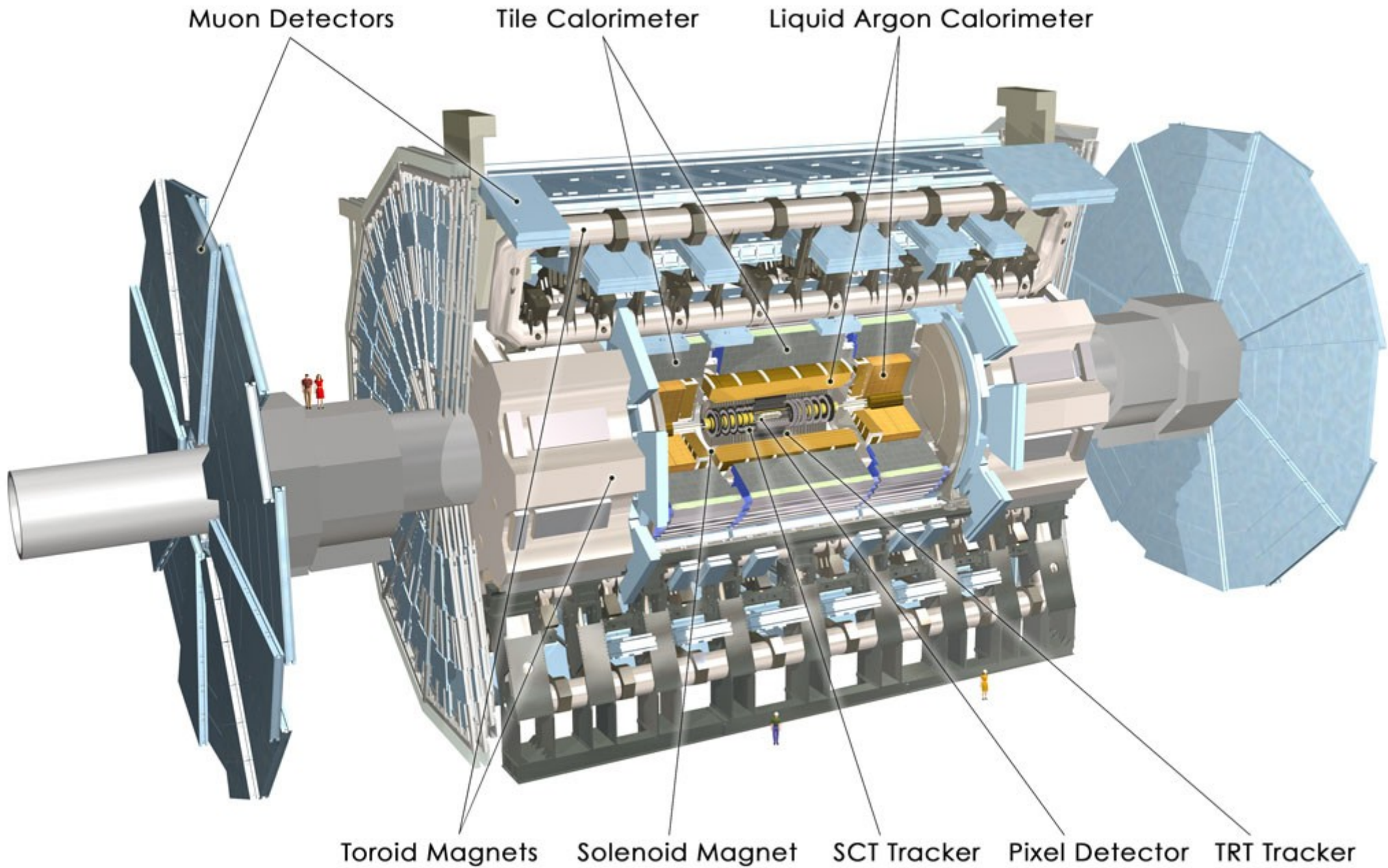
2009 Meeting of the Division of Particles and
Fields of the American Physical Society (DPF 2009)

26-31 JULY 2009

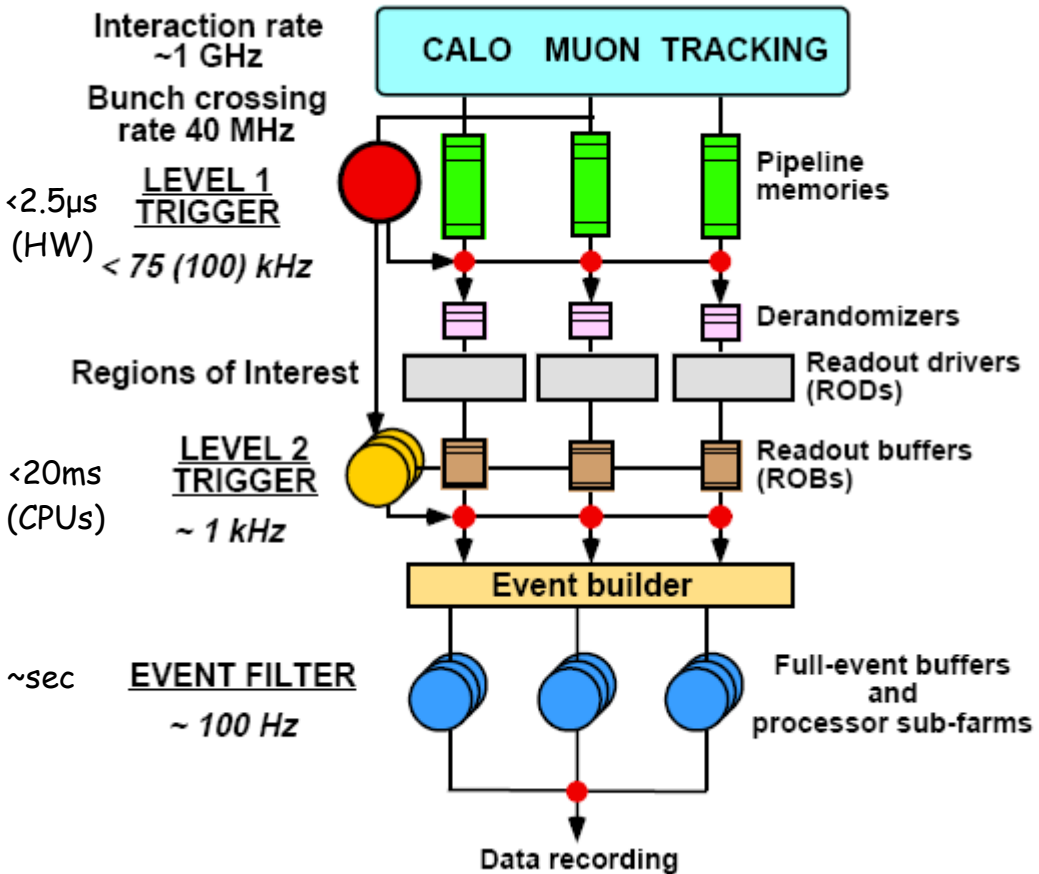
What I will cover

- Introduction
- ATLAS Tracking Detectors
- FTK Approach to Track Finding
- Hardware Considerations
- Expected Performance
- Physics Implications

Introduction I: ATLAS detector



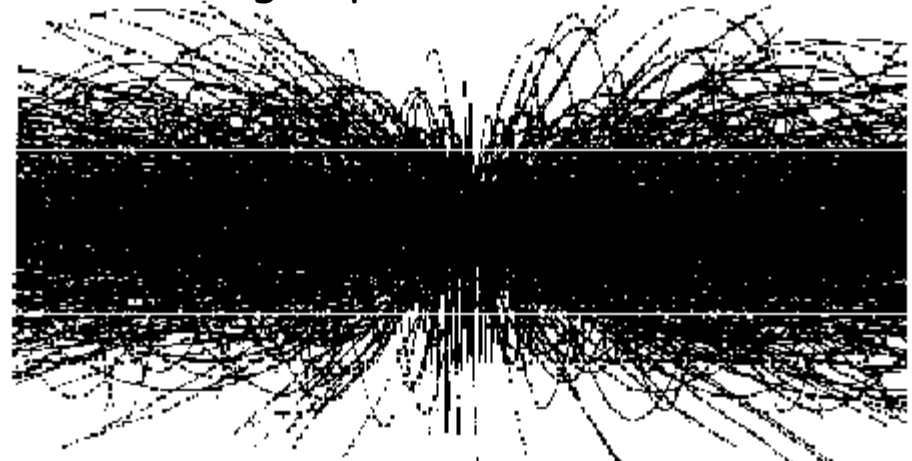
Introduction II: Motivation



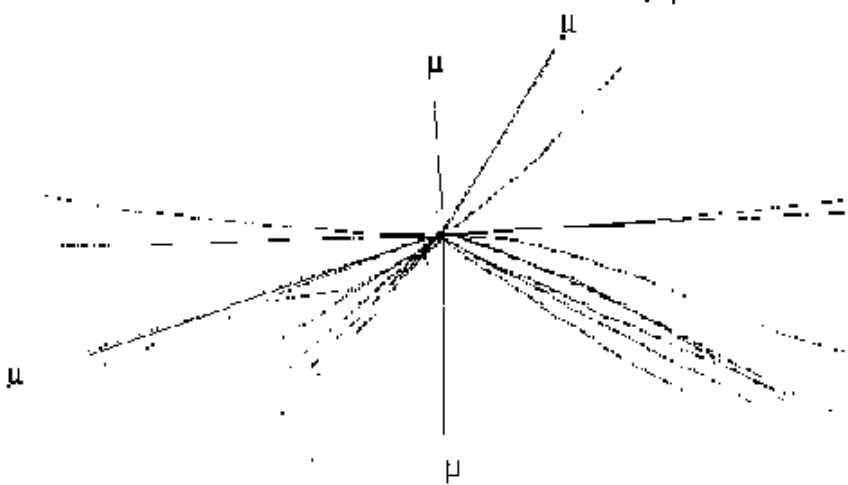
- Data store bandwidth requires rate reduction of 5-6 orders of magnitude, achieved via:
- **L1**: Muon, jet, EM cluster, E_{τ} -miss thresholds
 - **L2**: +Tracking inside Regions of Interests

30 minbias events + $H \rightarrow ZZ \rightarrow 4\mu$

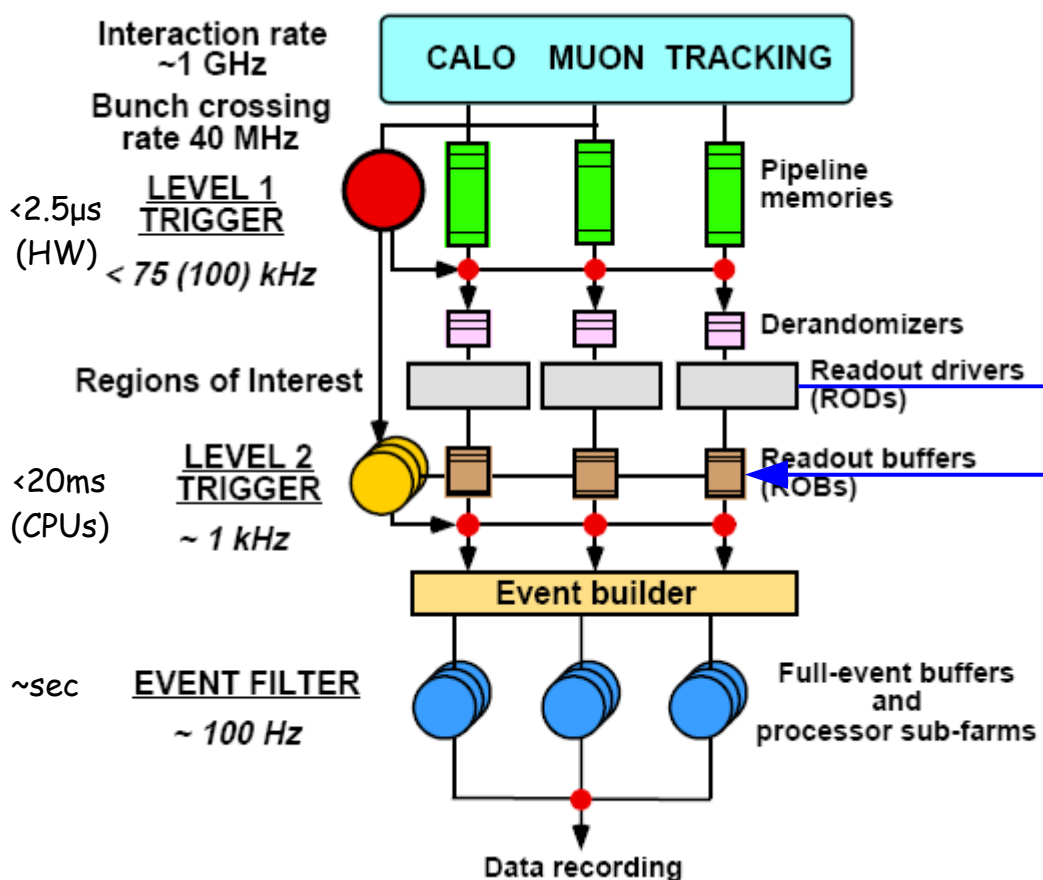
All charged particles with $|\eta| < 2.5$:



Reconstructed tracks with $p_{\tau} > 2.0 \text{ GeV}$



Introduction III: Where FTK fits in



- Tracking ROD output is duplicated and sent to FTK at full L1 rate
- Thus, FTK can noninvasively eavesdrop on ID data

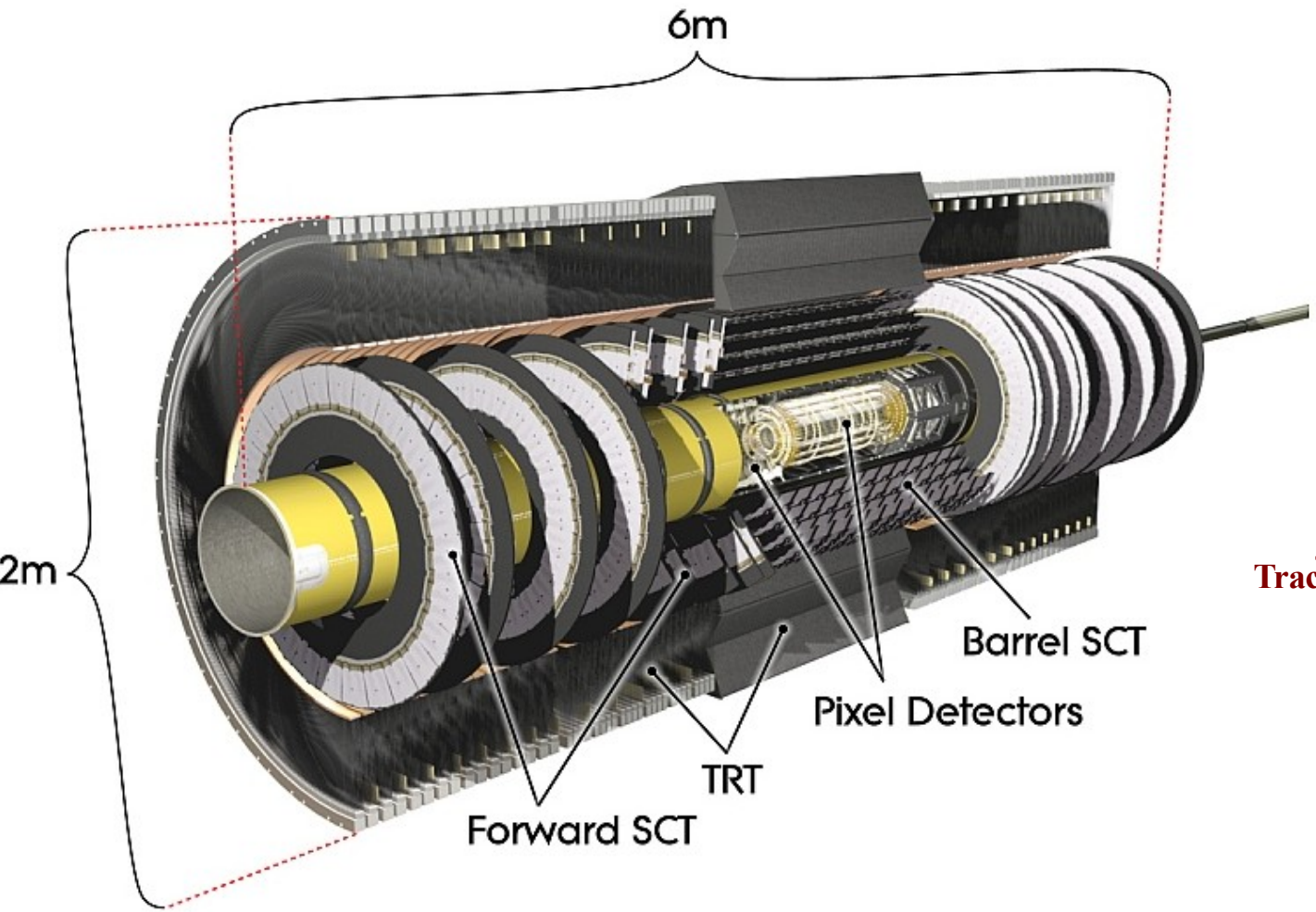
FTK:

- Operates in parallel with silicon readout following each L1 trigger
- Reconstructs tracks over entire inner detector volume (up to η of 2.5) in $\sim 1 \text{ms}$
- FTK provides high-quality tracks by the beginning of L2 trigger processing

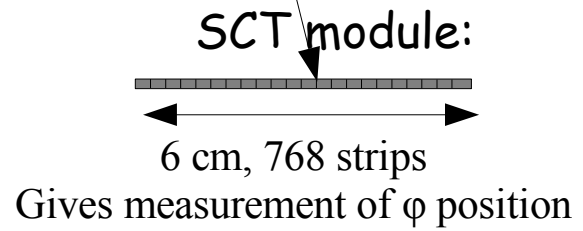
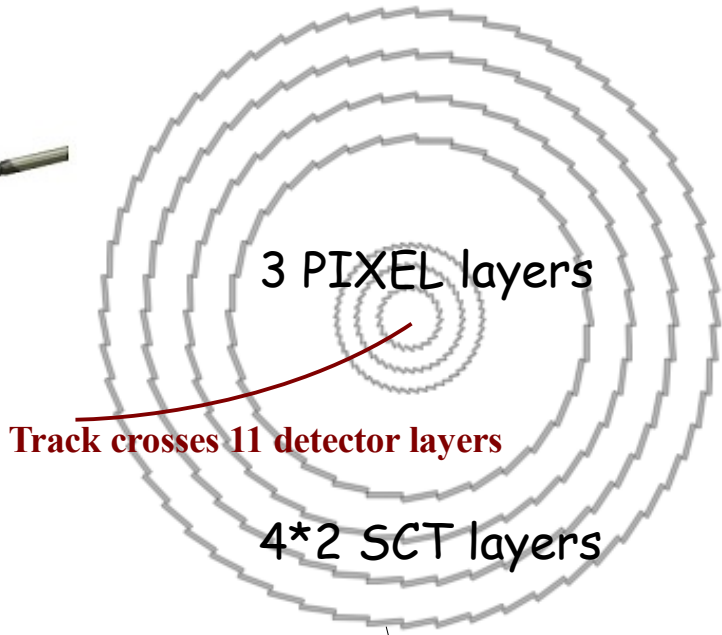
FTK provides the following benefits:

- **L1:** Lower Pt thresholds (since L2 can now reject non-interesting events more quickly)
- **L2:** Freed up from tracking. The extra CPU time is available for more advanced algorithms.

Detectors I: Pixel and SCT Trackers

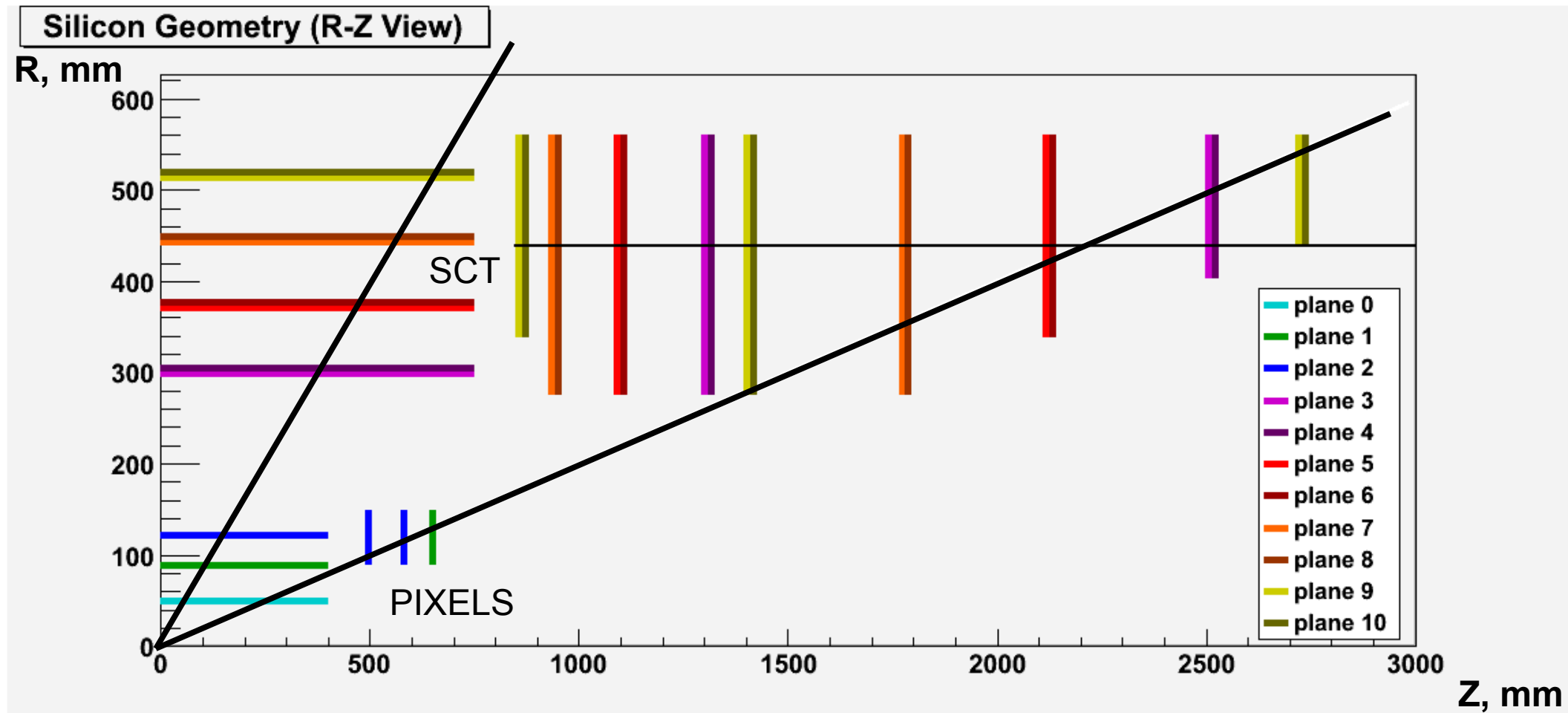


Example:
R-phi view of Barrel region:



Total # of readout channels:
PIXELS: 80 million
SCT: 6 million

Detectors II: 11 tracking layers

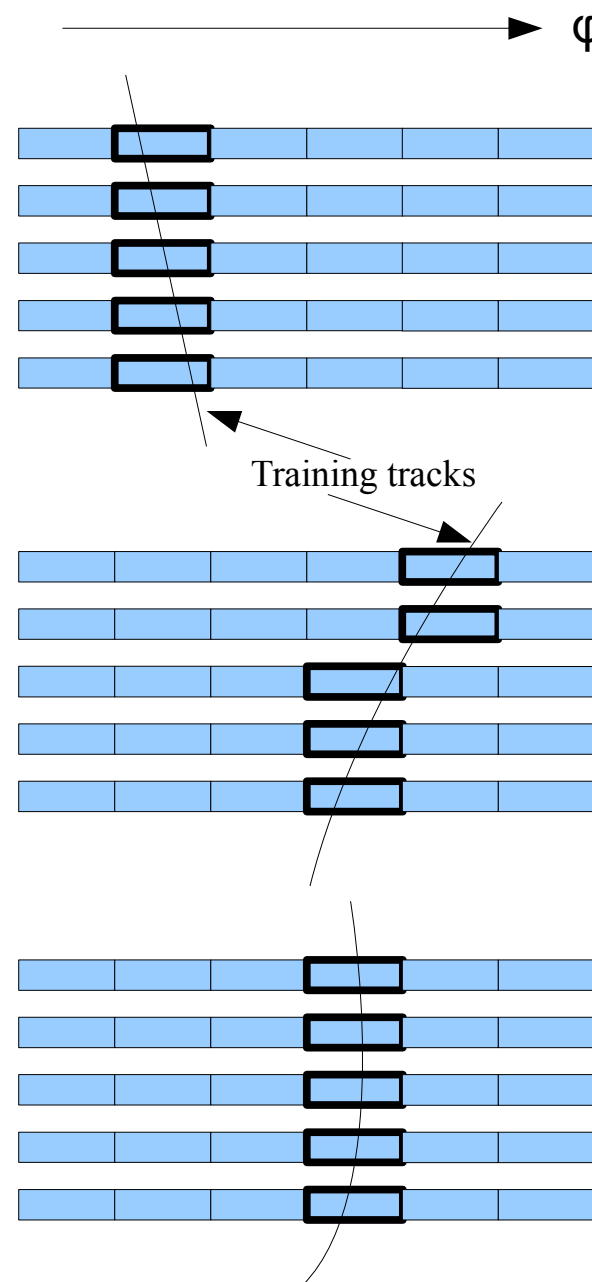


- SCT and PIXEL disks are assigned into one of 11 logical layers
- Assignment aims to reduce overlaps and (almost) eliminate gaps
- These 11 layers are used to do pattern recognition

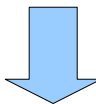
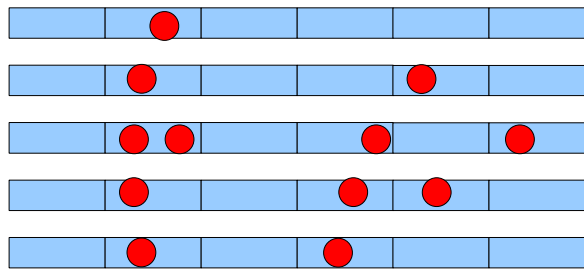
FTK approach I: Associative Memory and Pattern Banks

- Luminosities above $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ combined with 85 million readout channels create a unique combinatorial challenge for tracking
- In fact, even projected future CPU farms won't be able to perform global track reconstruction within L2 time budget ($\sim 10 \text{ ms}$)
- FTK offers a viable hardware solution based on associative memories (AM):
 - A massive, ultra-fast lookup table of all realistic particle paths through 11 layers
 - To keep the AM size under control, detector hit resolution is reduced to coarse superstrips (SS) a few mm across
 - AM bank is precalculated using MC simulation or training events - see figure:

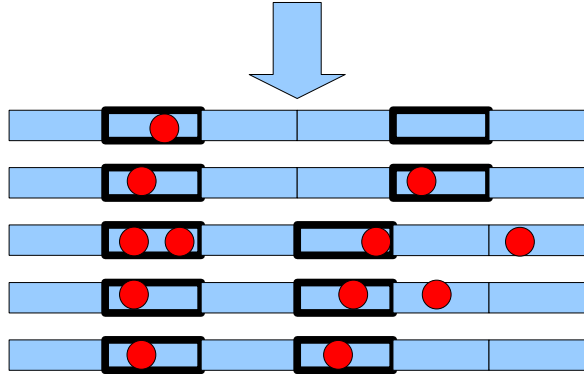
AM bank containing 3 patterns:



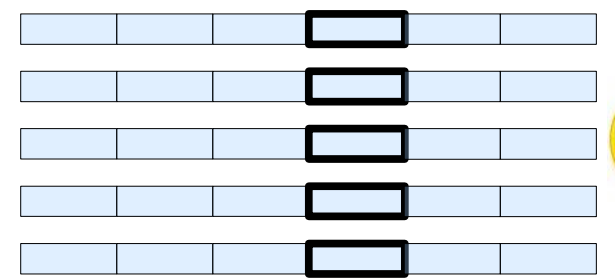
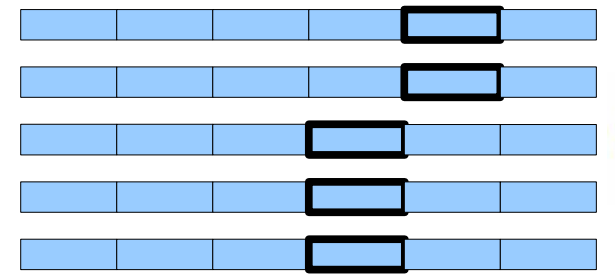
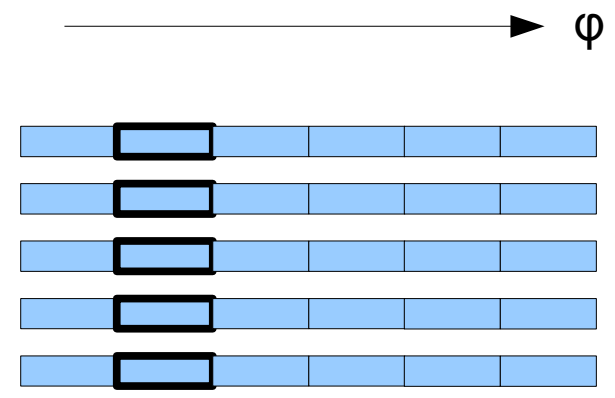
FTK approach II: Pattern recognition with AM's



- Detector hits enter the AM board
- **Simultaneously** compared with **all** stored patterns (~100M)
 - We also allow matches with **1 missing hit**
- Outputs all matched patterns
- Only hits within found patterns go to the next step

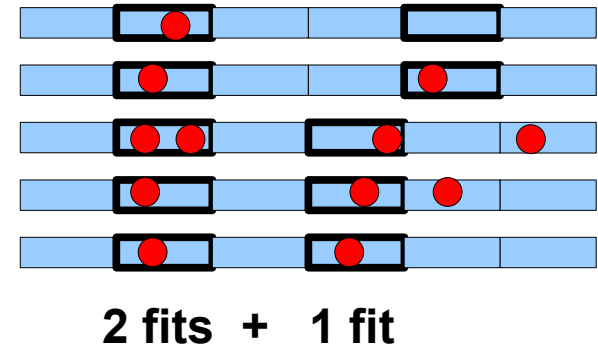


AM bank containing 3 patterns:



FTK approach III: From patterns to final tracks

- 5 track helix parameters (curvature, d_0 etc) + χ^2 quality cut are computed from full-resolution hits within each matched pattern
- Remaining combinatorics (due to multiple hits within a superstrip) is solved by brute-force
- It is possible to group the patterns into geometric groups ("sectors"). Within each sector, the relationship between hit positions and track parameters is approximately linear
 - Linear fitting constants for each sector can be precomputed from training data
 - All detector effects (eg, misalignments) are automatically taken into account
 - Scalar products can be done quickly (1 fit/ns) using DSP units in modern commercial FPGA's

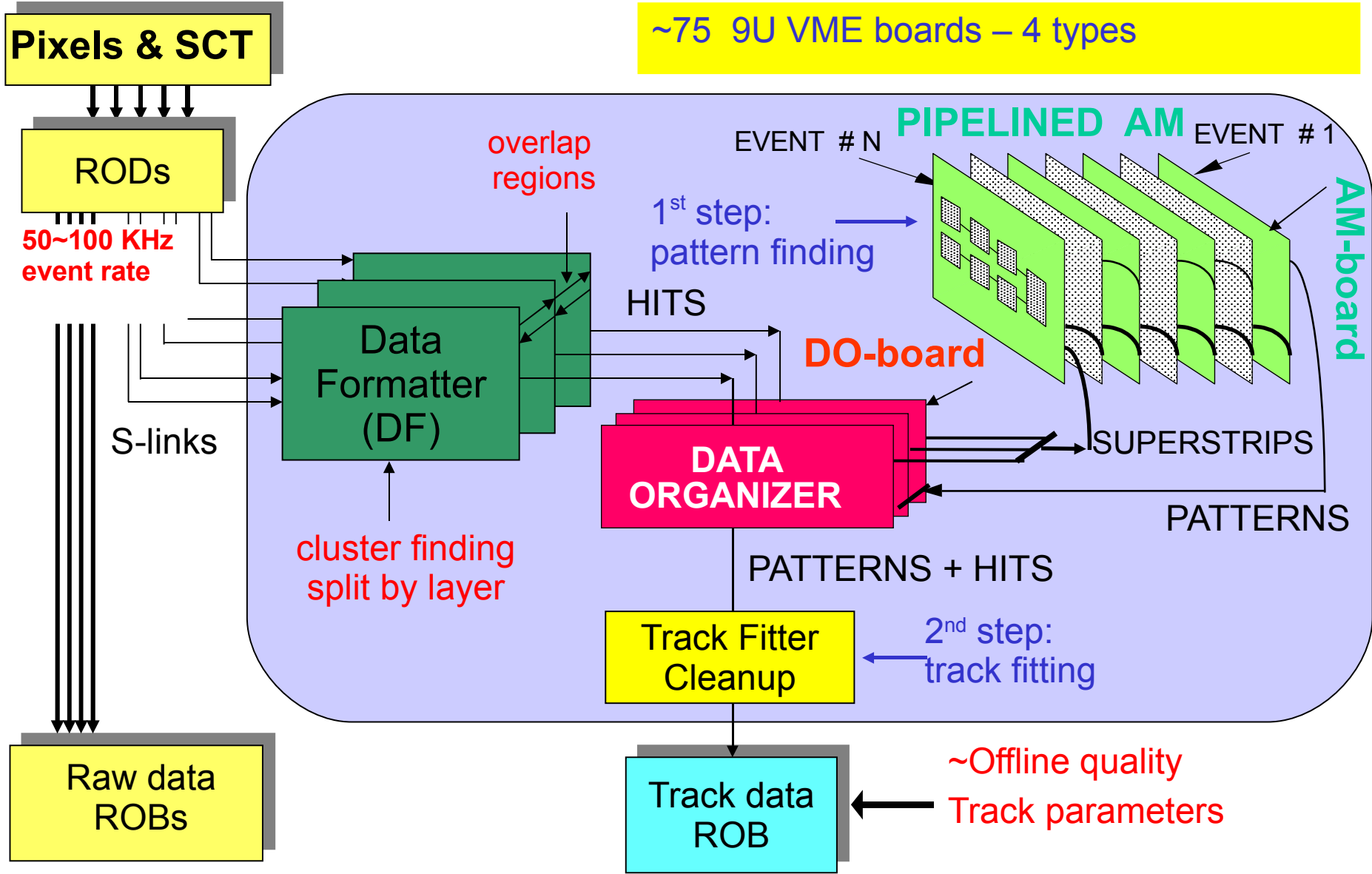


$$p_i = \sum_j C_{ij} \cdot x_j + q_i$$

track parameters p_i are related to hit coordinates x_j through constants C_{ij} and q_i .

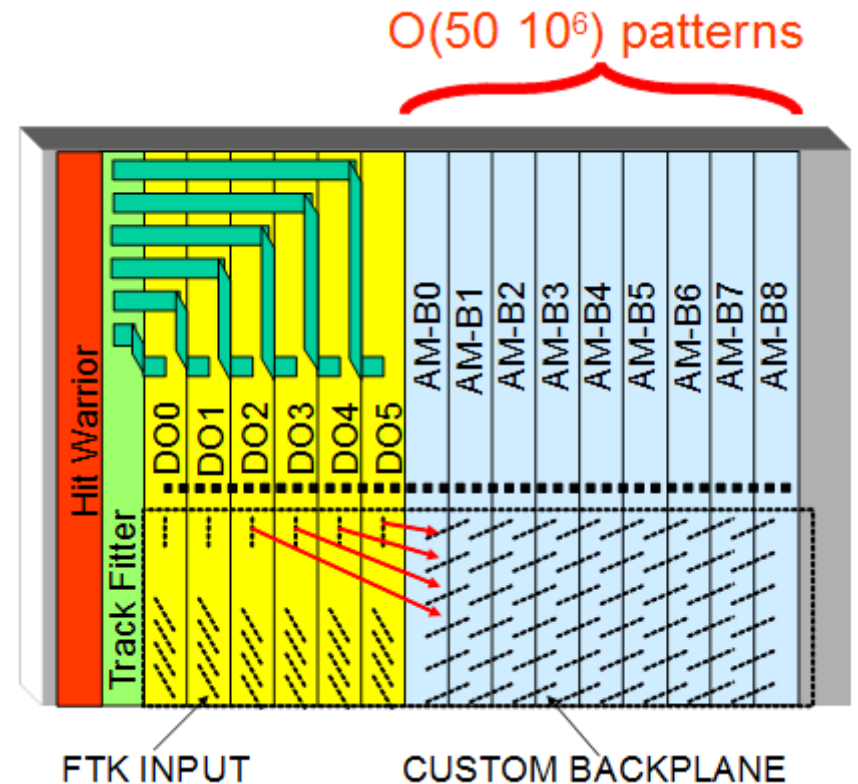
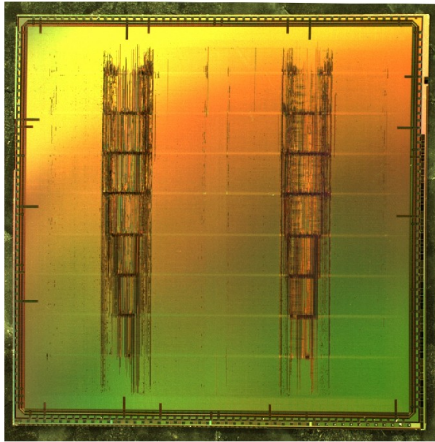


Hardware I: Overview of the System



Hardware II: AM Chip and Crate Structure

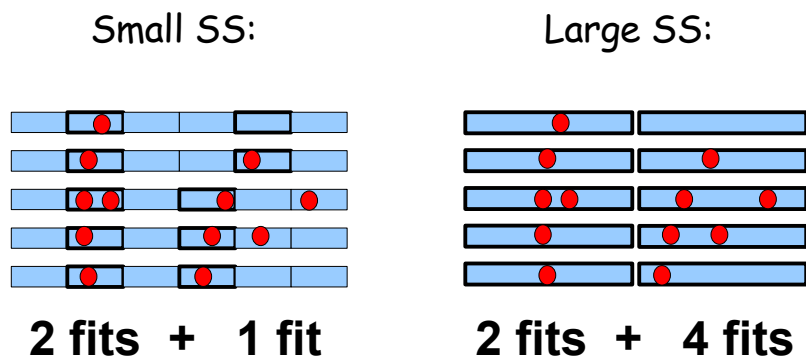
Current AM chip used at CDF:
0.18 μm custom cells with 2500 patterns/chip
IEEE Trans.Nucl. Vol. 53 Pages: 2428-2433



- Using standard cells with 90 nm technology \rightarrow 10k patterns / chip
- If more capacity is needed, we will consider 65 nm technology
- 8 crates covering different ϕ regions
- Patterns are split into several boards
- Track fitter board based on CDF design
- Duplicates cleaned up in HW board

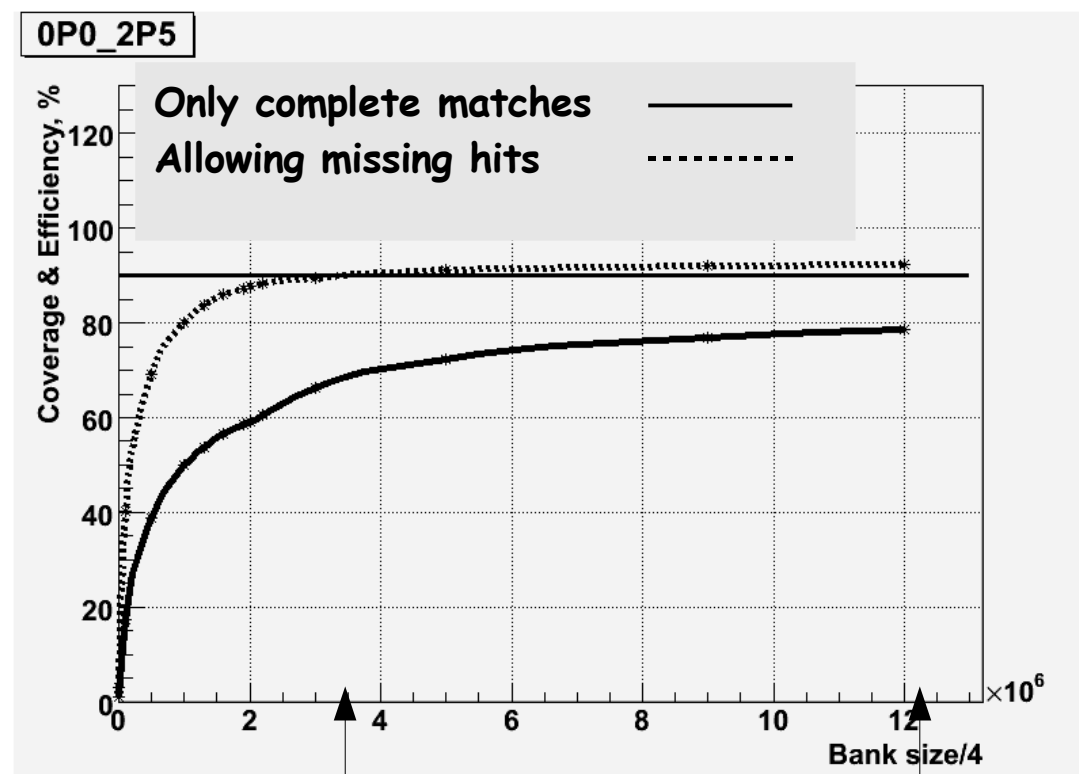
Performance I: Pattern Bank Size and Efficiency

- Many patterns are needed to enumerate all interesting particle paths through 11 detector layers
- Pattern bank size strongly depends on superstrip size. It is a balancing act: **coarser superstrips = fewer patterns**, but many **more fits**:



- If we allow 10/11 pattern matches (when a hit is missing in one layer), efficiency raises much more quickly

Pattern bank efficiency vs bank size
(muon events)
Pixel SS = 3 mm, SCT SS = 5 mm



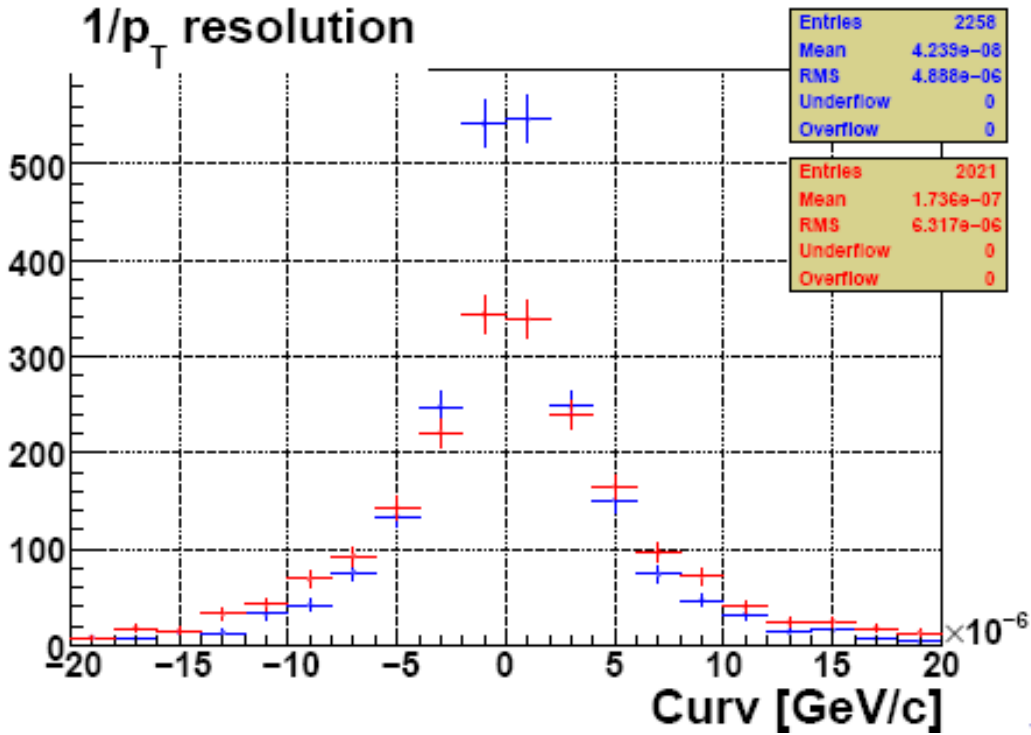
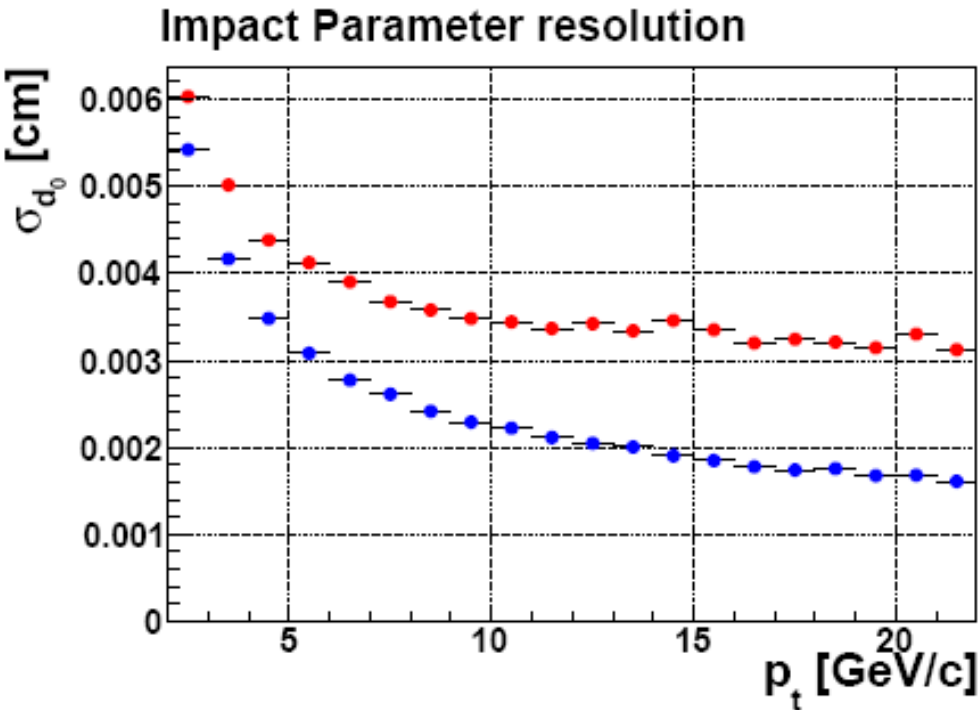
Operating point
(90%)

Maximum bank size
supported by AM

Performance II: Single Muon Events

- We compare **FTK-reconstructed tracks** with an **offline algorithm (IPAT)**:
 - Resolutions are wrt all truth tracks with $p_t > 1 \text{ GeV}$ and $|\eta| < 2.5$
 - Performances are comparable!

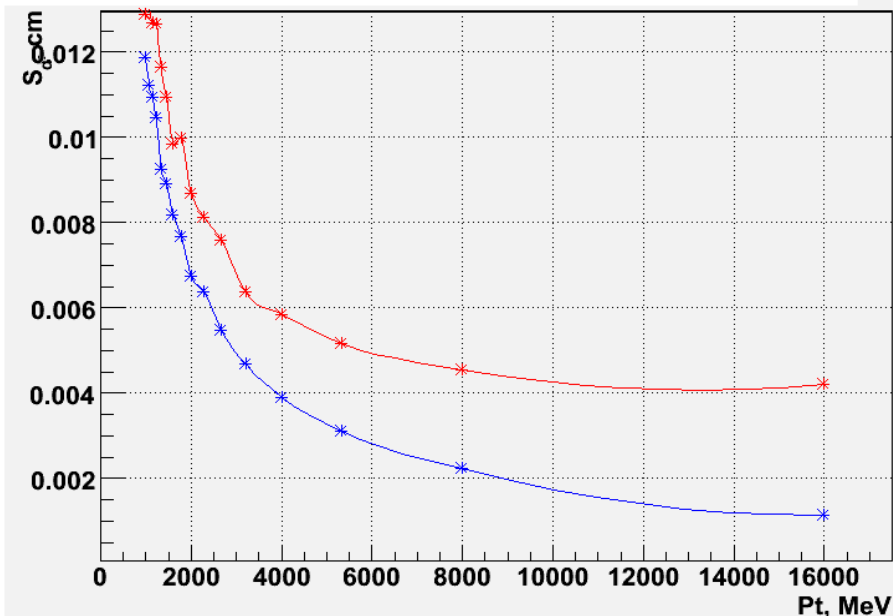
Parameter	$\sigma(\text{FTK})$	$\sigma(\text{OFF})$
$1/(2p_T) [\text{c}/\text{GeV}]$	$7.4 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$
$\phi [\text{rad}]$	$9.5 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$
$d_0 [\text{cm}]$	$5.3 \cdot 10^{-3}$	$3.3 \cdot 10^{-3}$
$\cot(\theta)$	$2.0 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$z_0 [\text{mm}]$	$2.1 \cdot 10^{-2}$	$1.9 \cdot 10^{-2}$



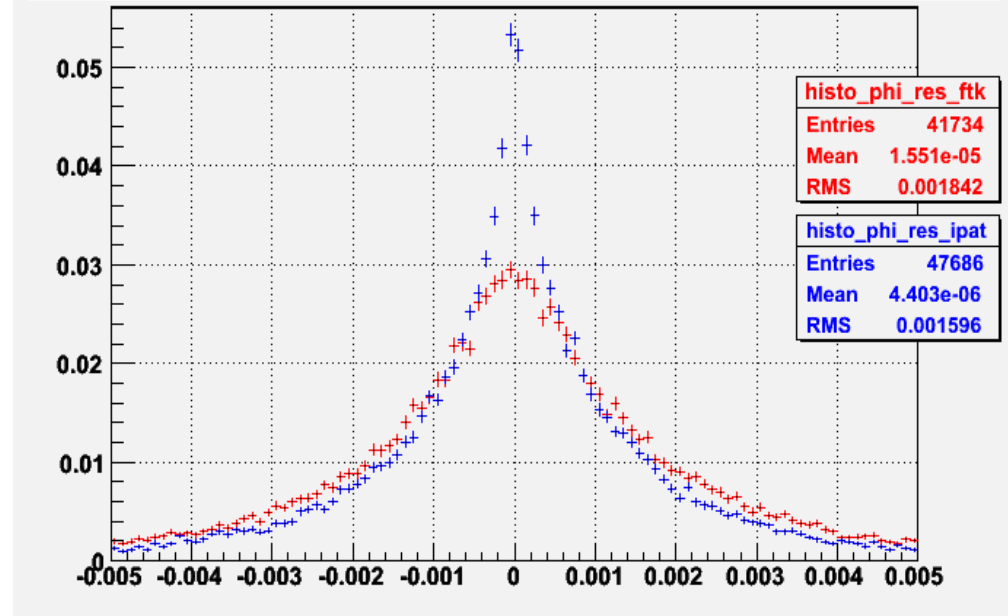
Performance III: $WH \rightarrow bbX$ @ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ events

- **FTK** and **IPAT** resolutions are again similar
- Our current timing estimate is about **1 ms** for a complex event
- At higher luminosities with their large inner detector occupancy, the # of fits could become excessively large. This can be dramatically reduced by narrowing the superstrip width and modifying the pattern recognition and fit strategy. Studies are underway to find the optimal strategy.

Impact Parameter Resolution, cm

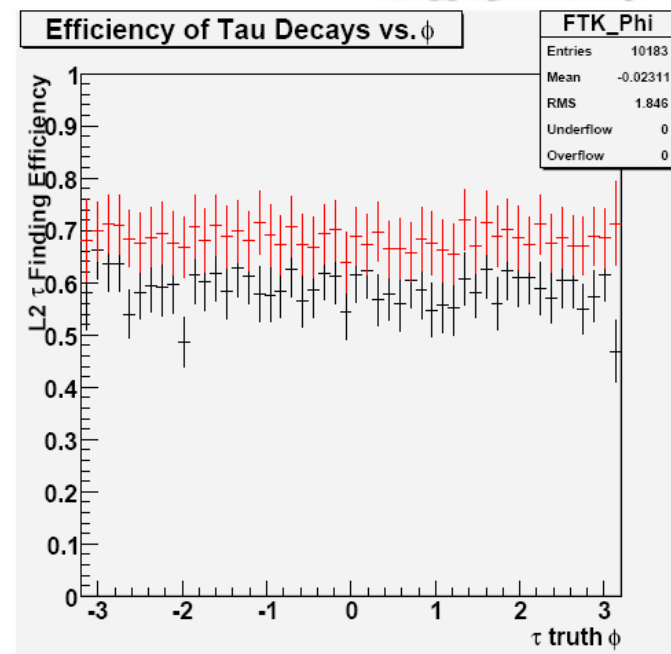
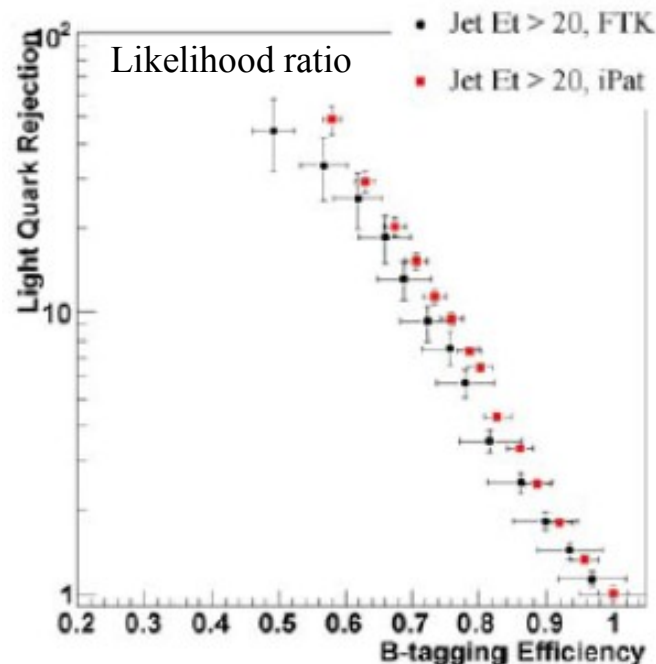


Phi resolution (normalized to unity)



Physics Implications (Preliminary)

- b-jets
 - Offline-quality b-tagging efficiency and light quark rejection can be achieved by using the savings in tracking time to apply more sophisticated Level-2 b-tagging algorithms.
 - Expanded physics reach for channels with b-quarks in the final state (eg, $bbH/A \rightarrow bbbb$)
- electrons and muons
 - Isolation using tracks from the hard scatter vertex can reduce the dependence of lepton efficiency on luminosity
- taus
 - Identification based on an isolation region devoid of tracks surrounding a small cone containing no more than 3 tracks



Summary

- FTK performs global track reconstruction at Level-1 trigger rate
- Using massively parallel *Associative Memories*, FTK will provide a complete list of 3D tracks at the beginning of Level-2 processing
- Time saved by FTK can be used in Level-2 for more advanced algorithms
 - Bonus: access to tracks outside the Regions of Interest
- FTK easily integrates with current ATLAS DAQ
- Builds on success of Silicon Vertex Trigger (SVT) at CDF

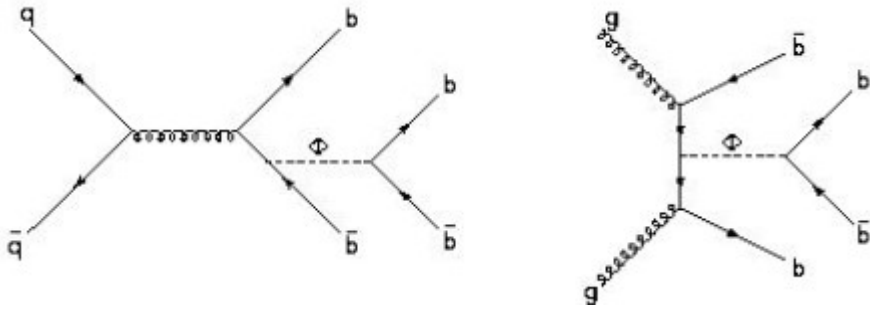
Project timeline:

- TDR in the fall 2009
- First board prototypes in 2010
- Completion of the system prior to LHC Phase I shutdown

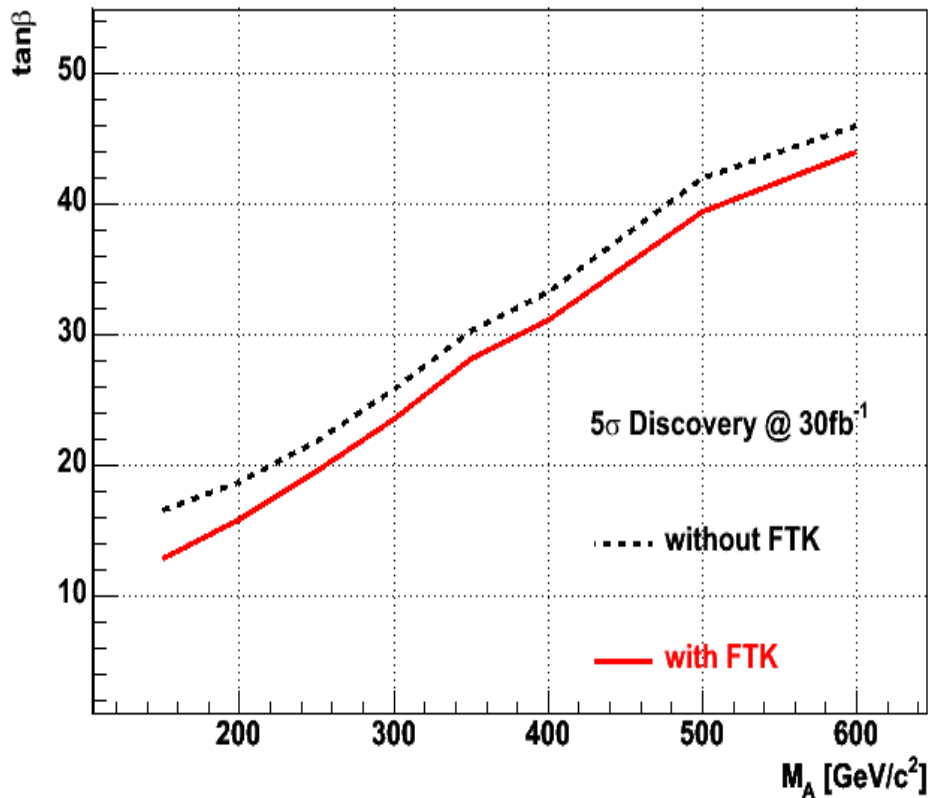
THANK YOU

Additional information about FTK:
<http://www.pi.infn.it/~orso/ftk/>

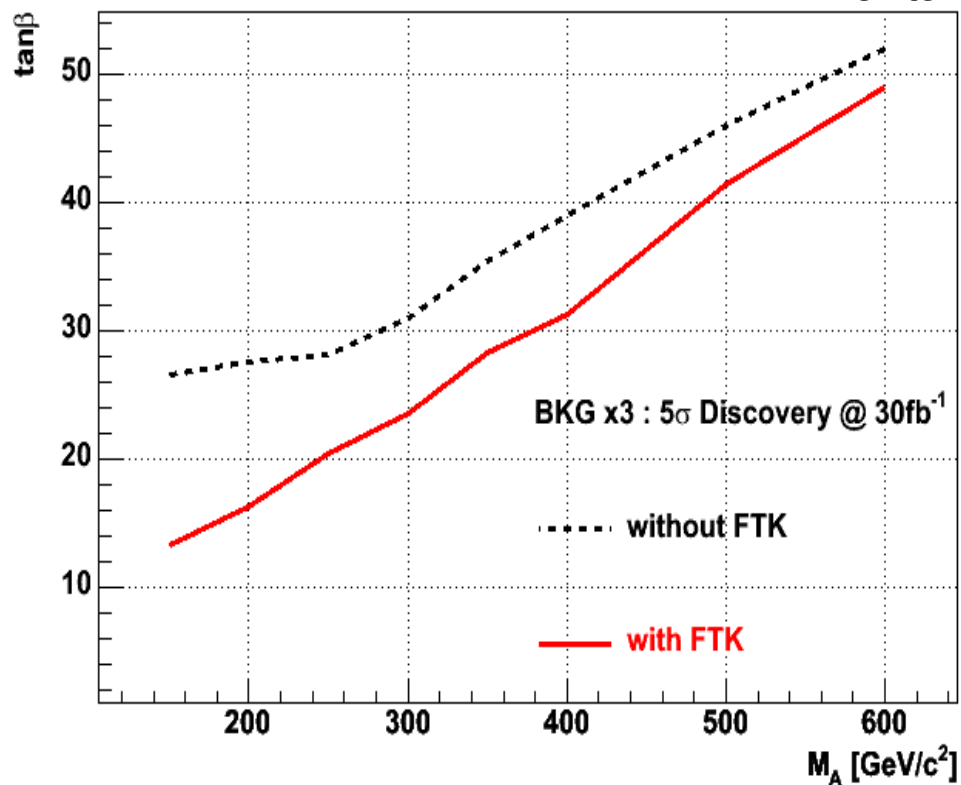
FTK with high backgrounds



H/Abb $\bar{\text{b}}$ ->4b channel



H/Abb $\bar{\text{b}}$ ->4b channel

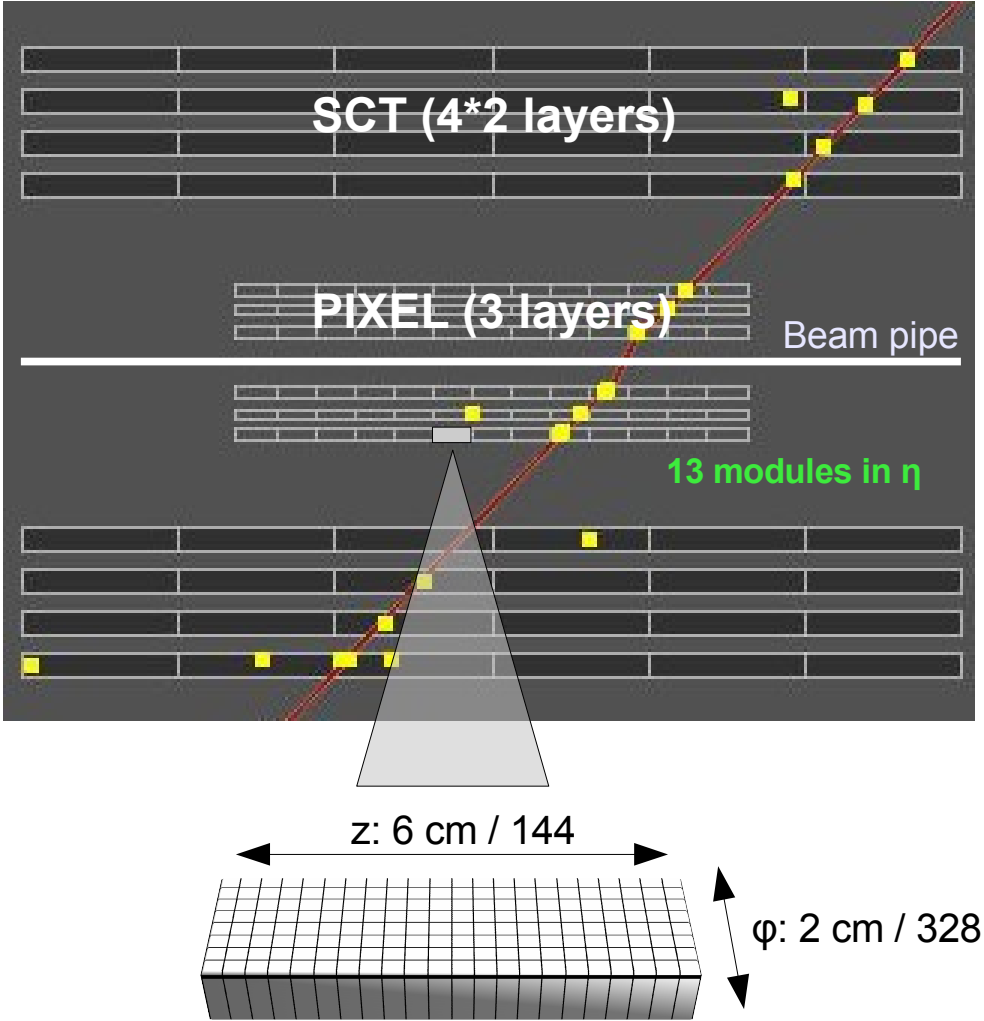


K. Yorita

Even if background rate is much higher due to high lumi or wrong MC tuning (in this case x3), FTK can provide almost the same sensitivity!
 -> without FTK, physics reach is weaker at high backgrounds (dotted line.)

Silicon Tracker geometry (central barrel)

r-z view:



r- ϕ view:

