Just the Beginning: The Post-Higgs Discovery LHC

Lauren Tompkins

Outline

- Vital Stats
- High Energy Particle Physics in a Nutshell
  - The Physics
  - The Physicists
- What my group does, specifically.
- Unsolicited advice ;)

Hello!

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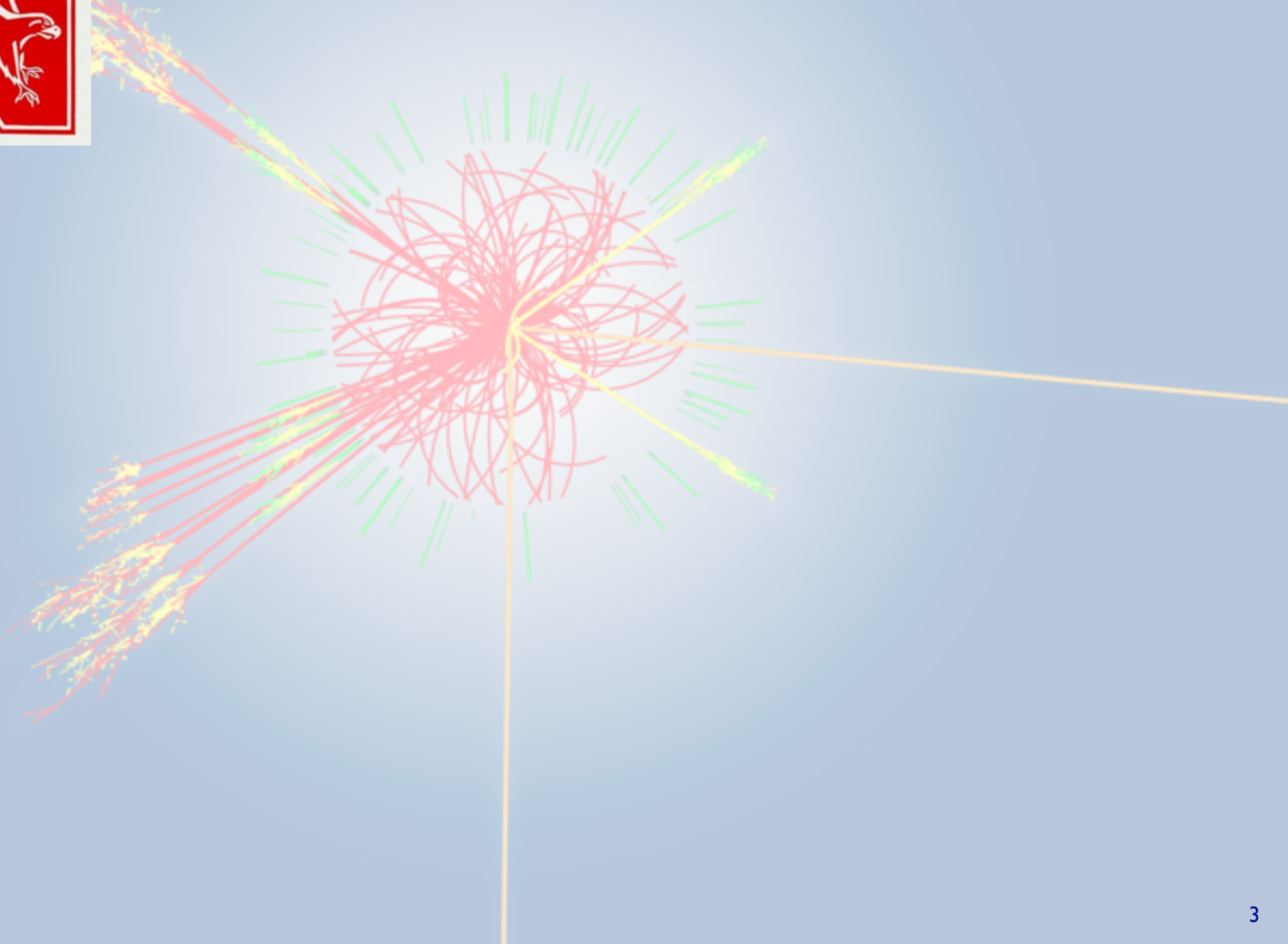

Hello!

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Steve McConnell / UC Berkeley

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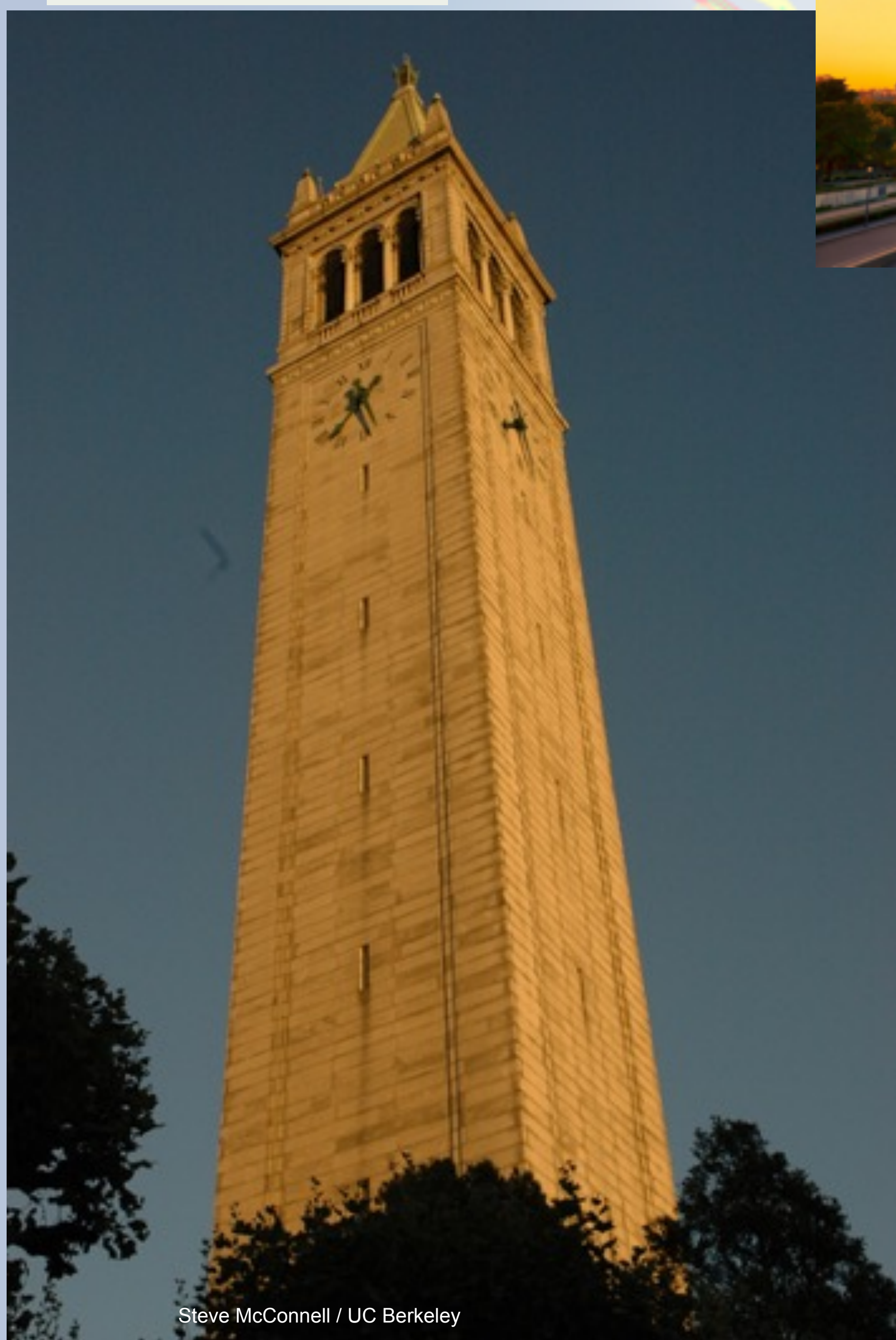

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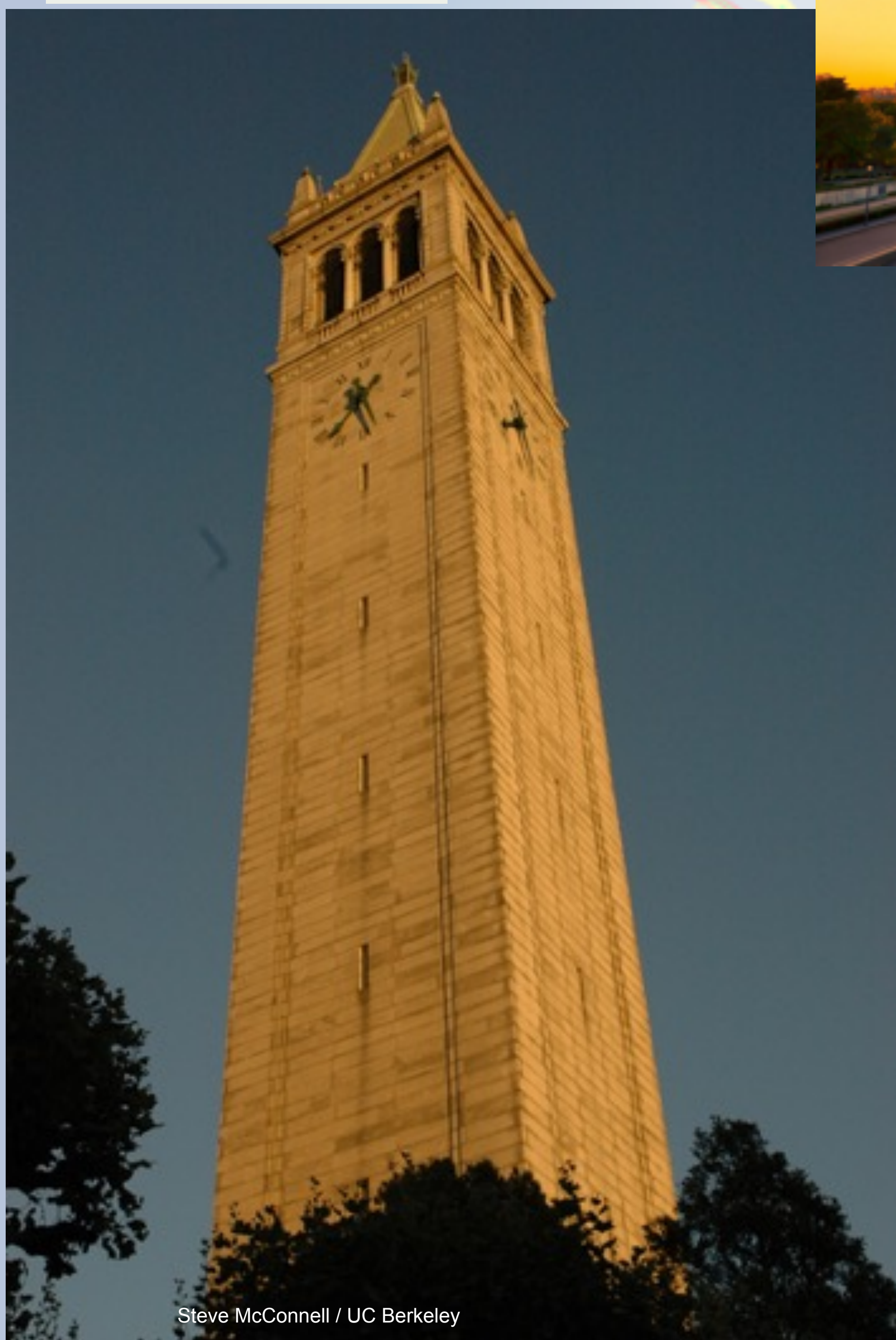

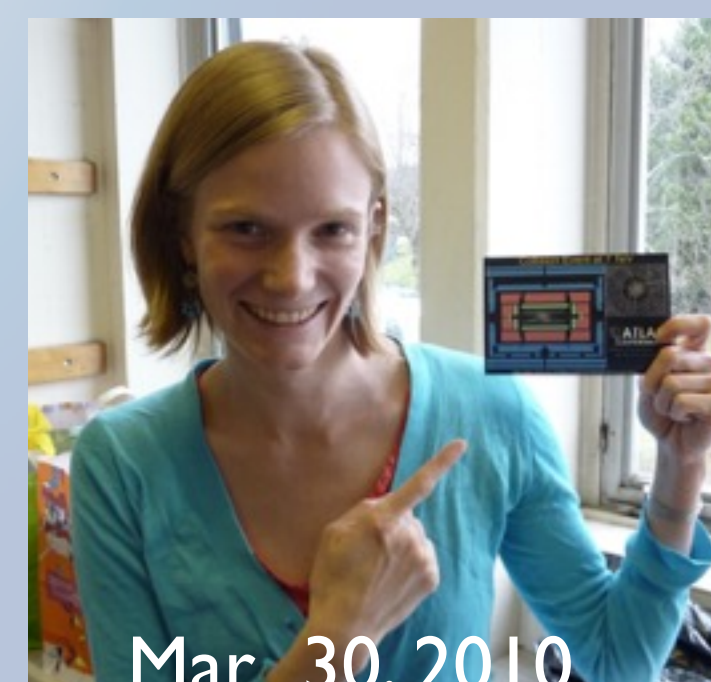

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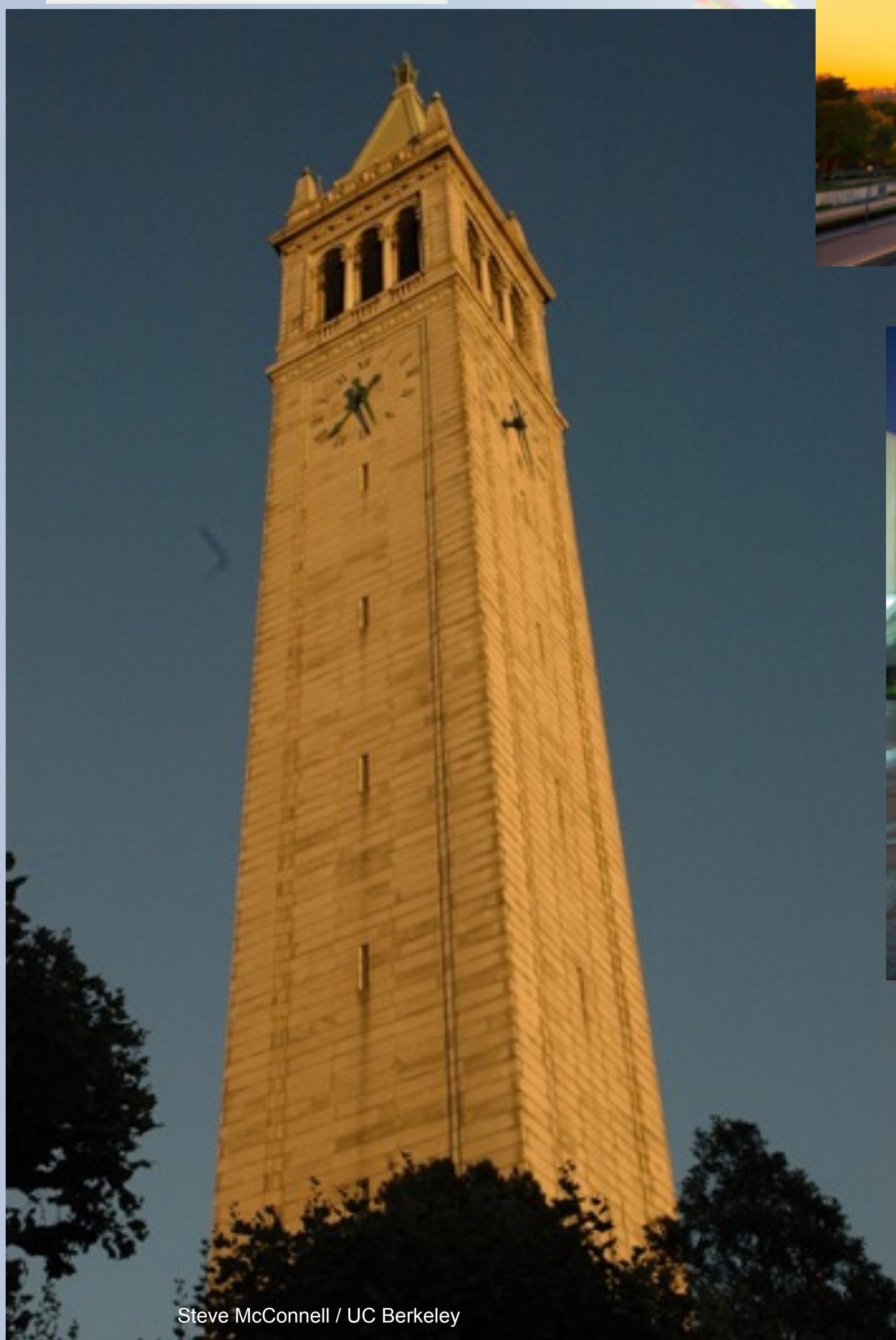

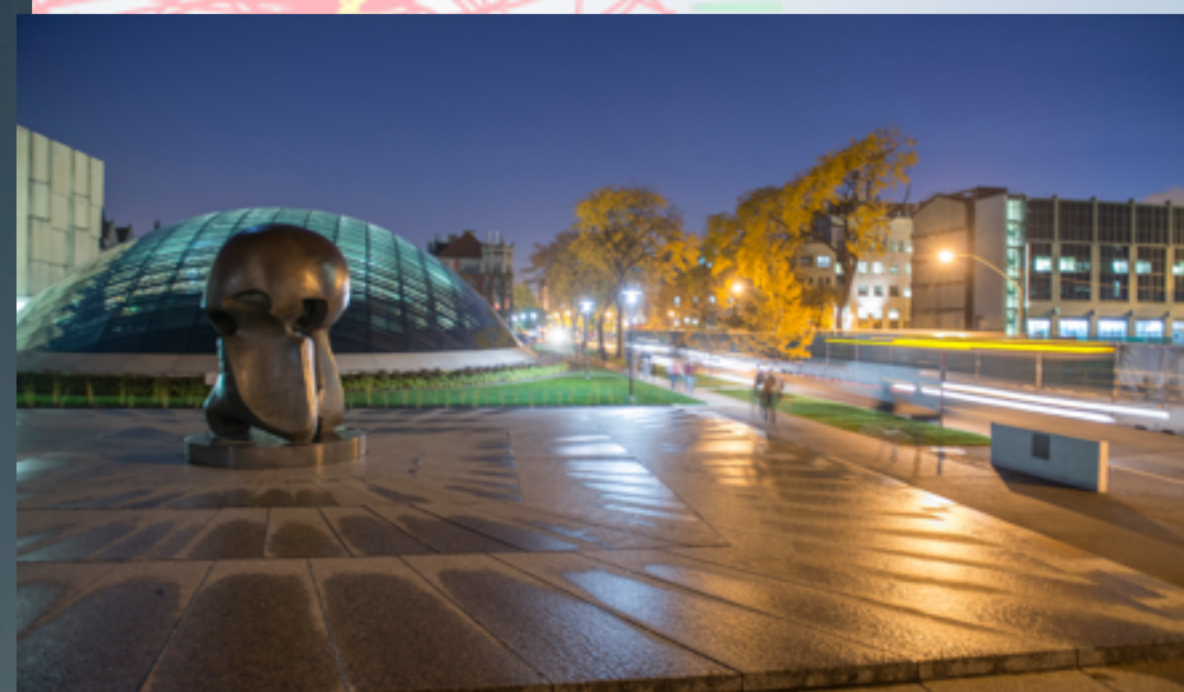

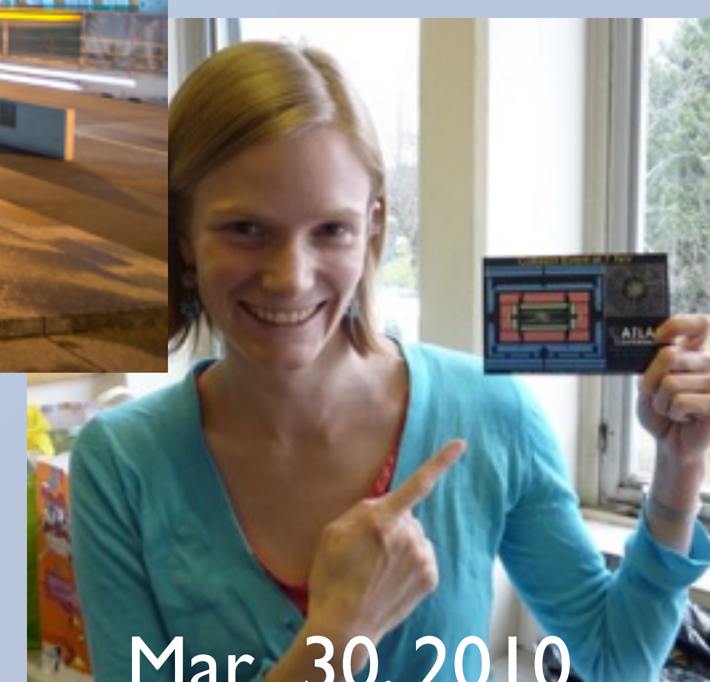

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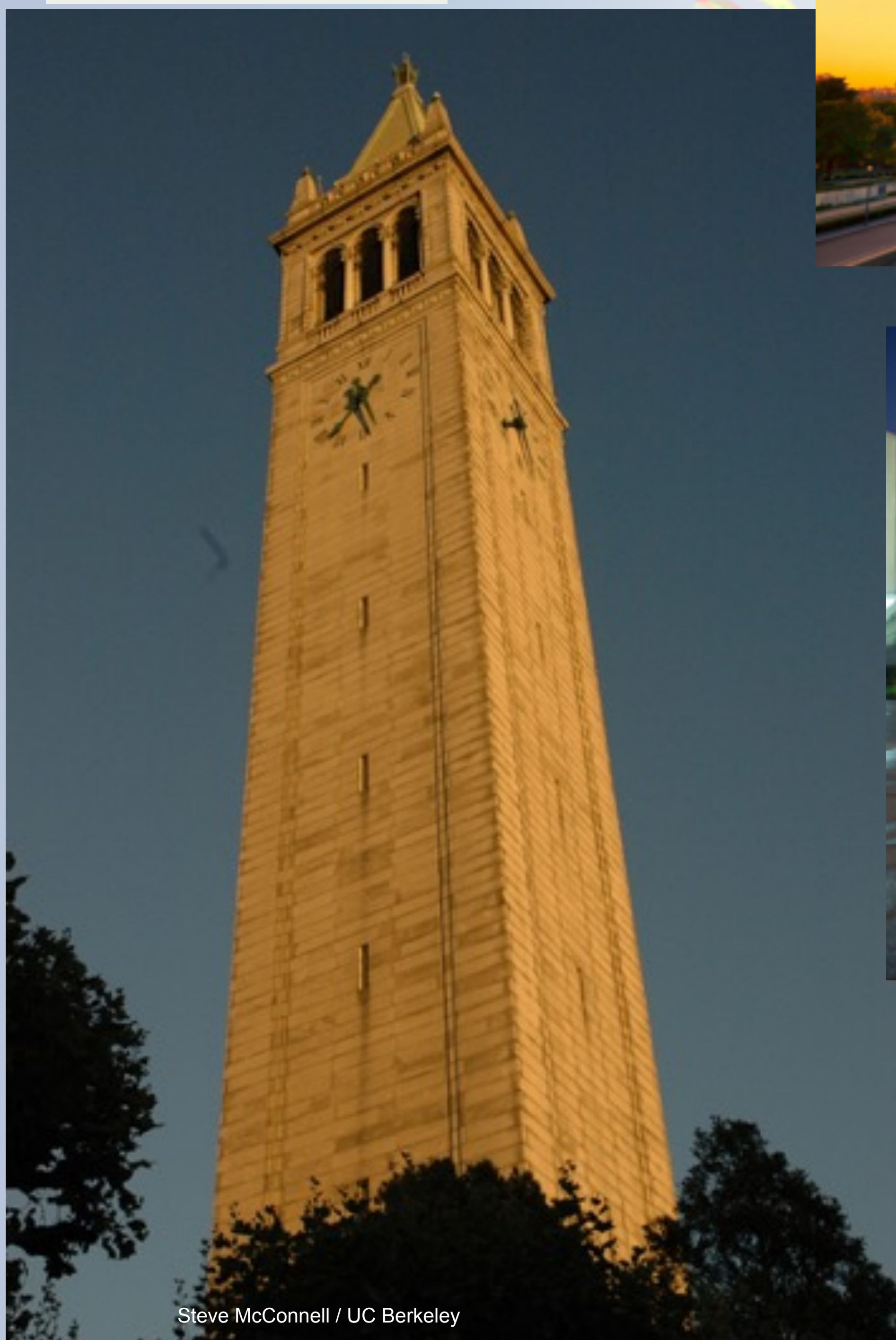
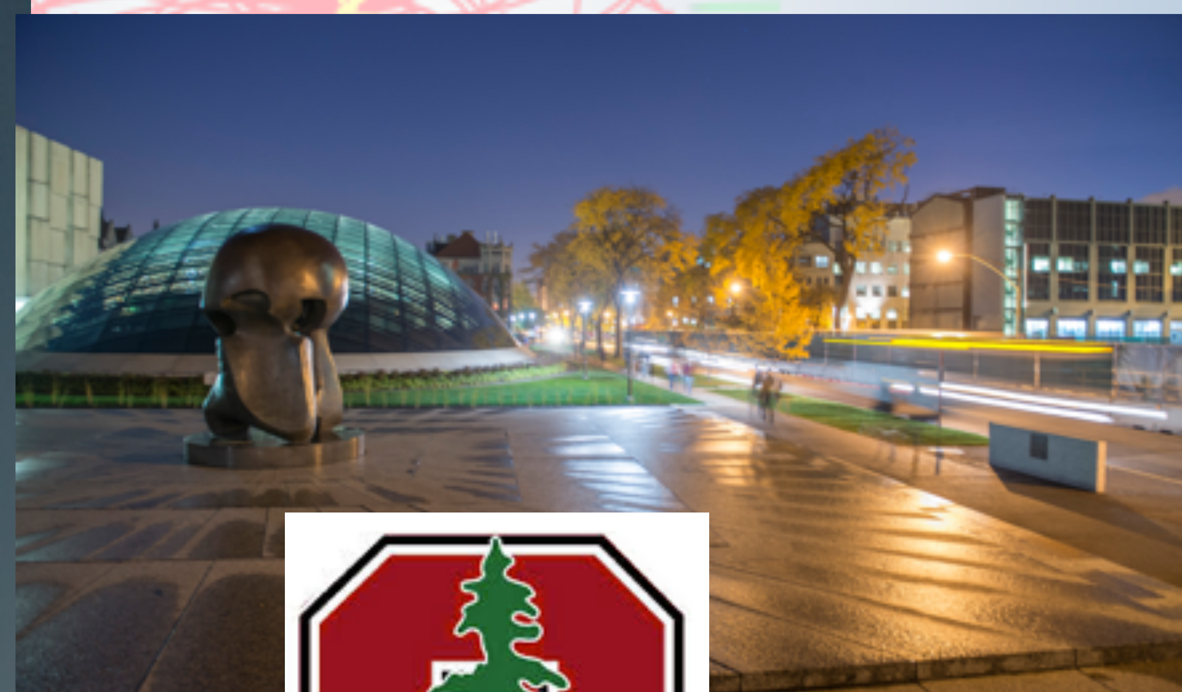
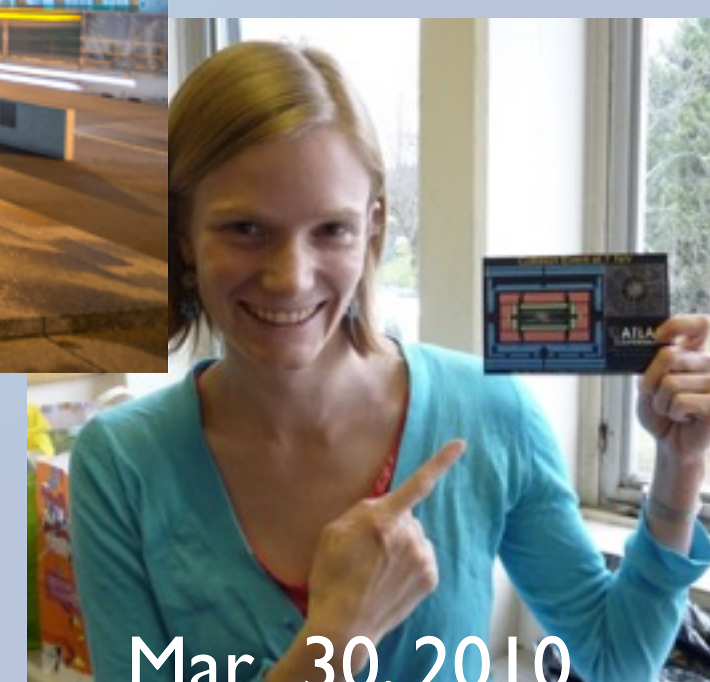
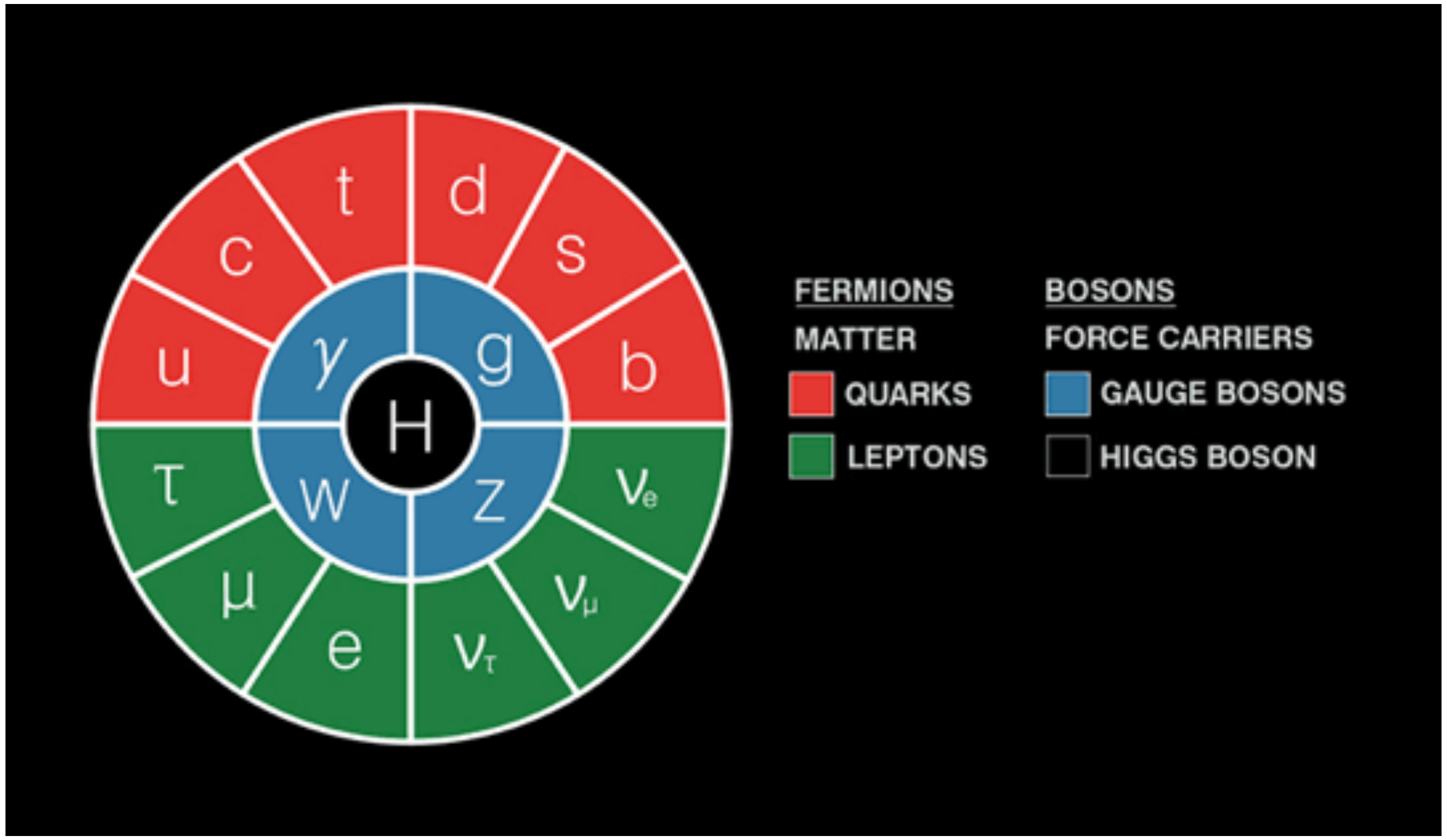


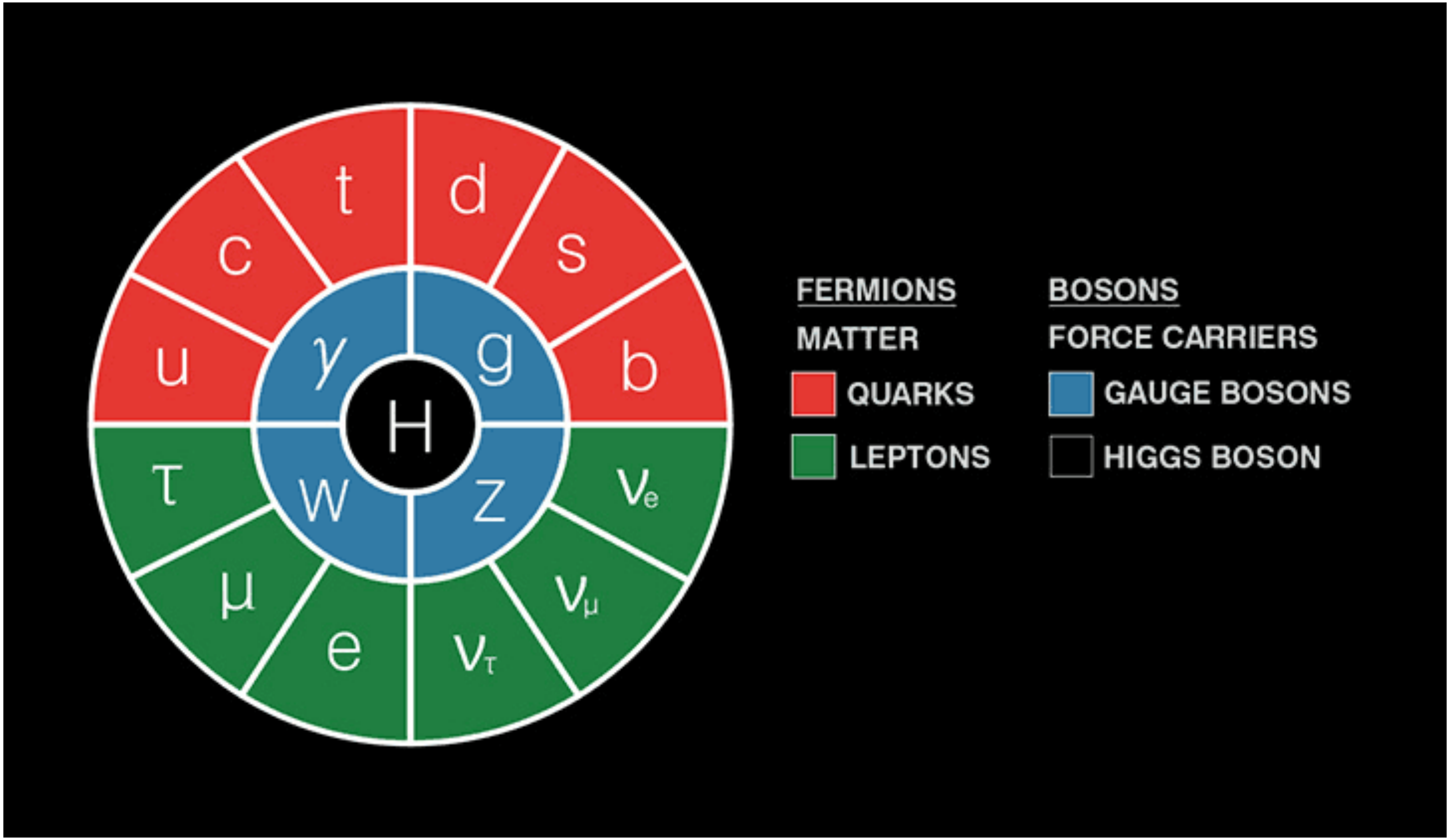




What's important to me



The Standard Model and The Higgs Boson



Where is Gravity?

- Gravity doesn't "fit" into the Standard Model
- It's way too ***weak!***
  - 10^{-36} times weaker than electric force!

What do particle physicists want to find out?

- Why do particles have mass?
  - We've found the Higgs, but is the mass mechanism more complicated?
- Why are the particles so different from each other?
- Can we find some way to unify the way the particles interact?
- Are there more particles and forces that we haven't discovered yet?

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Possible answers: Extra dimensions, mini-black holes, and … pink elephants.

How do we study it?

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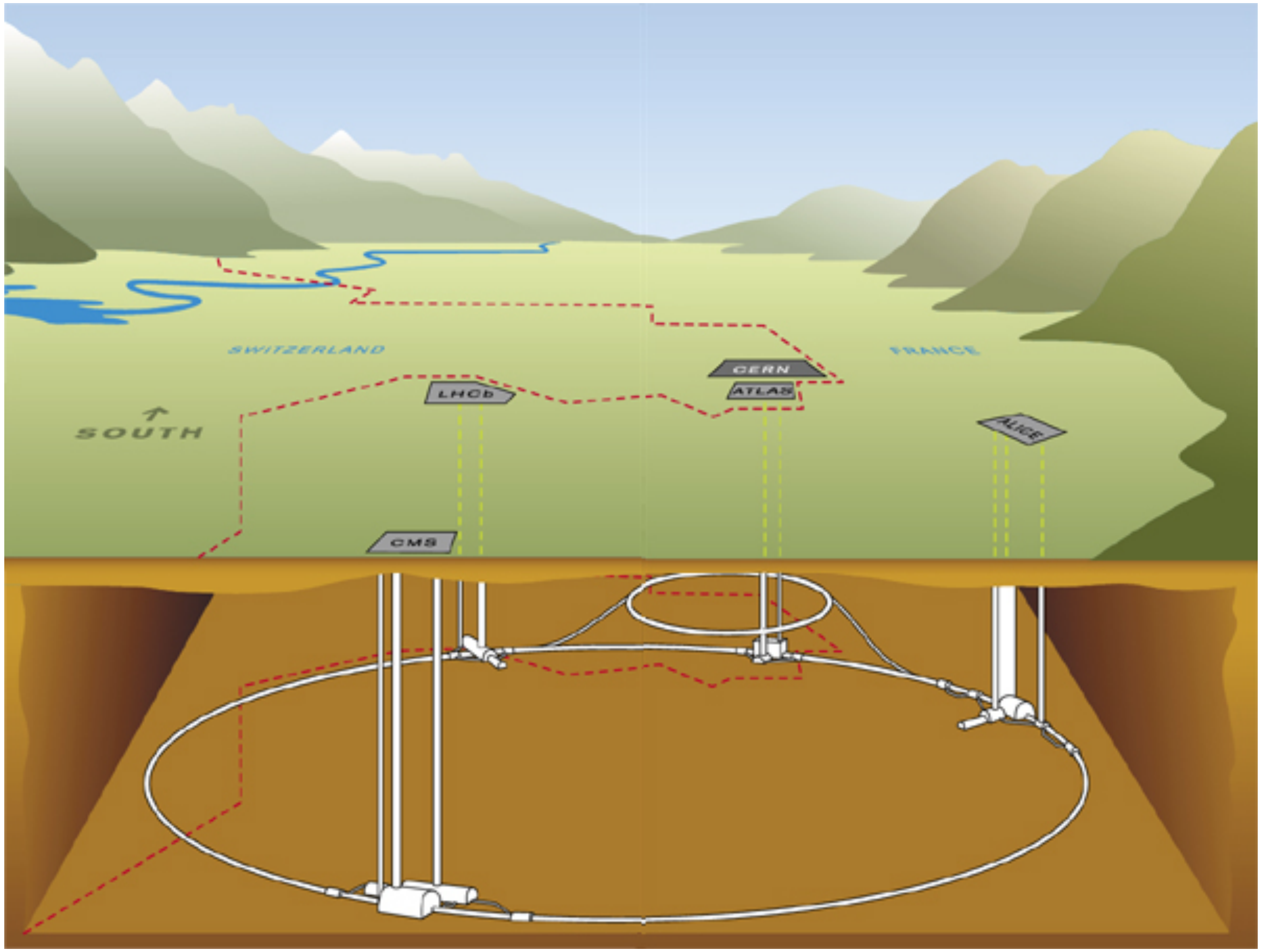
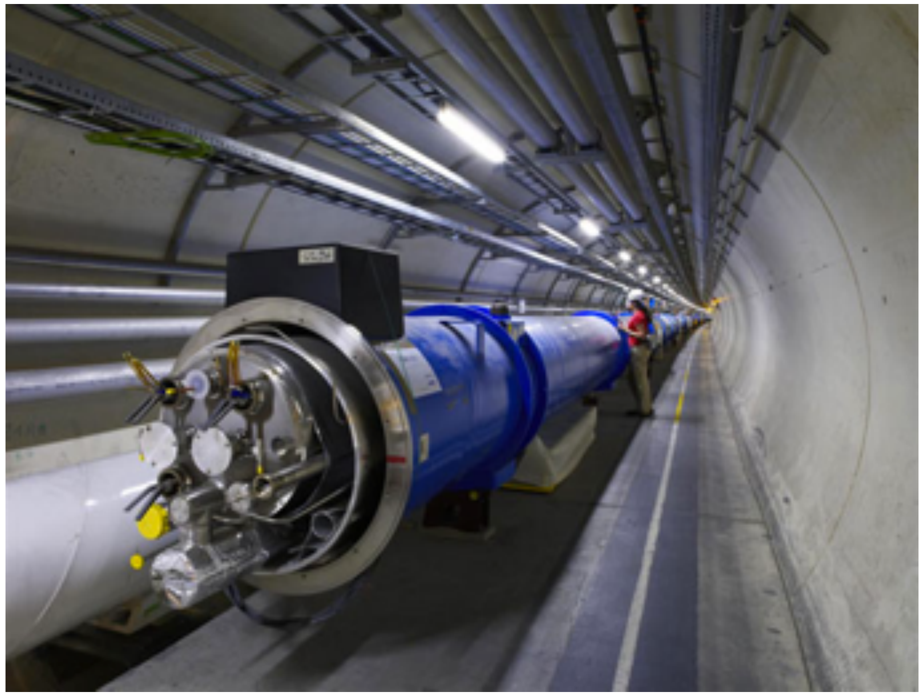
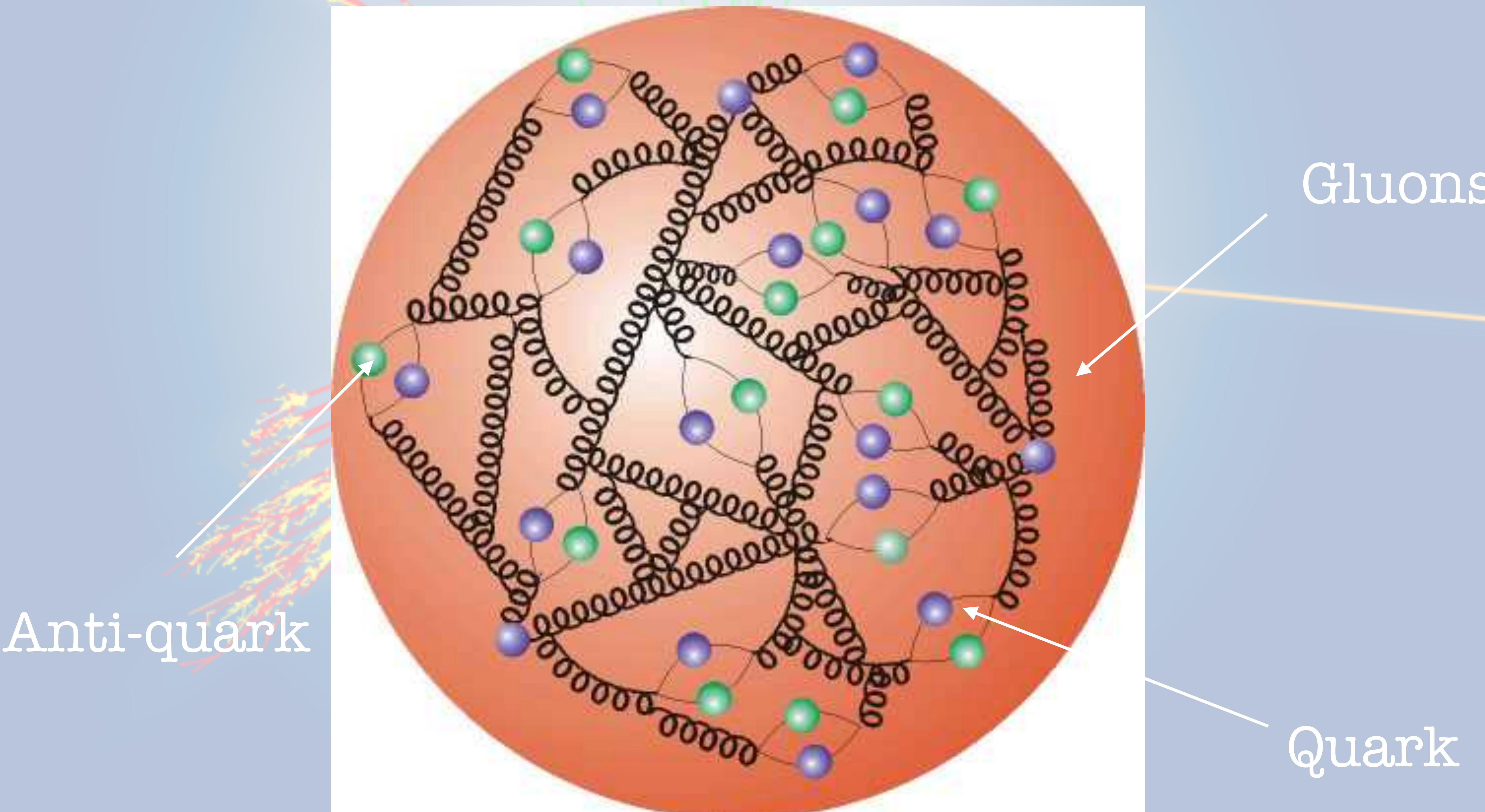
LHC in a nutshell



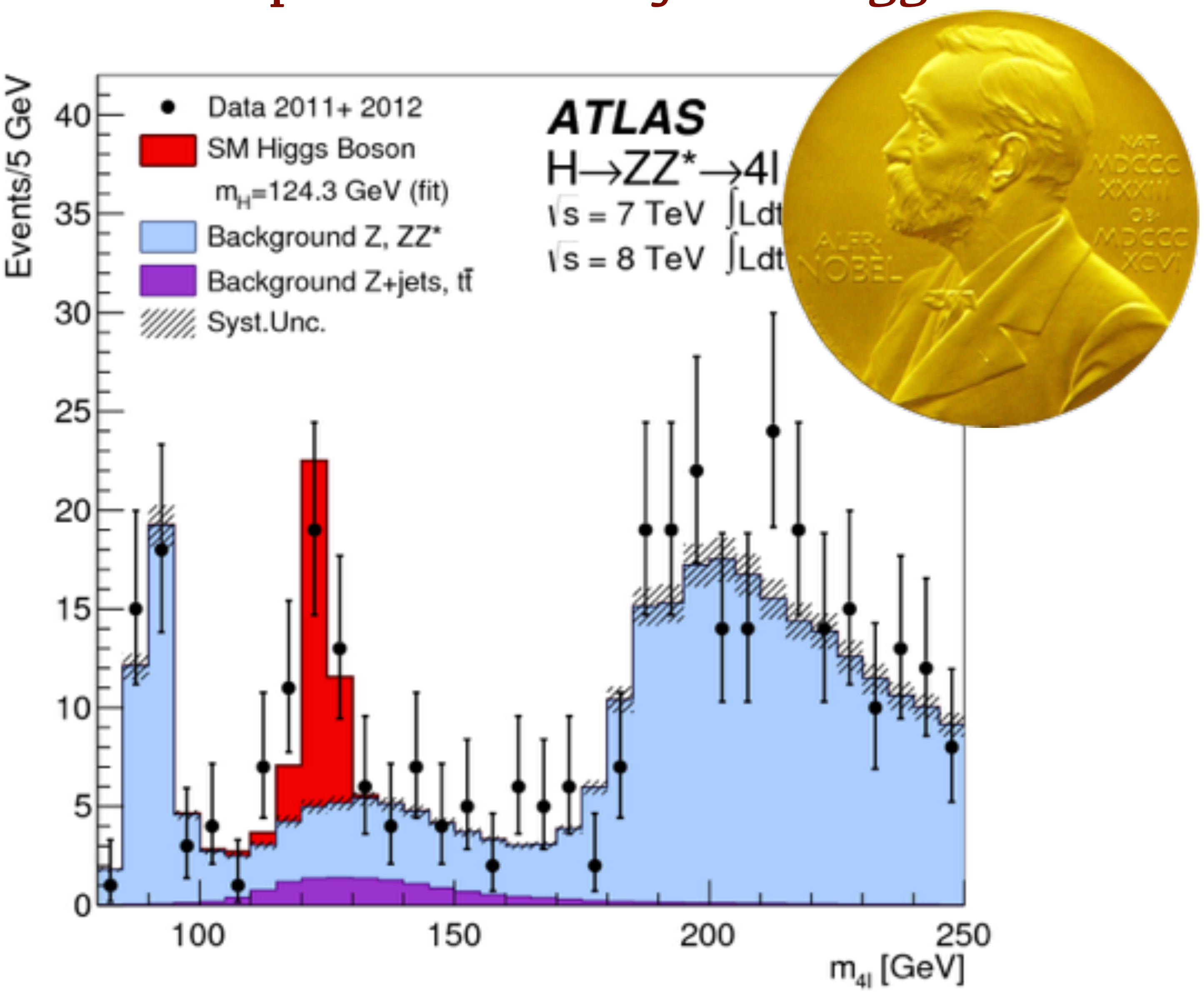


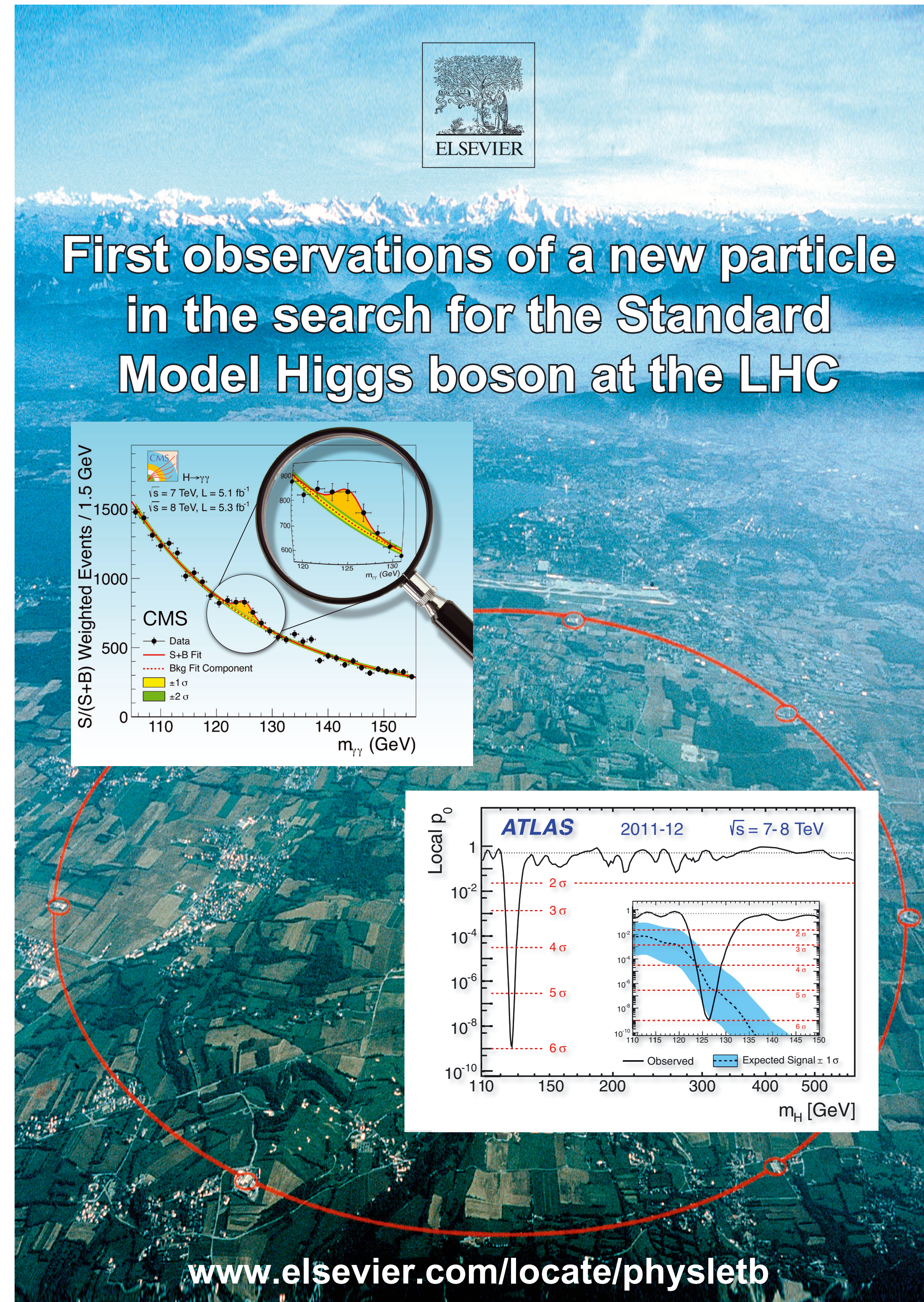
The messy world of protons



The Large Hadron Collider So Far

- Triumphant discovery of a Higgs boson





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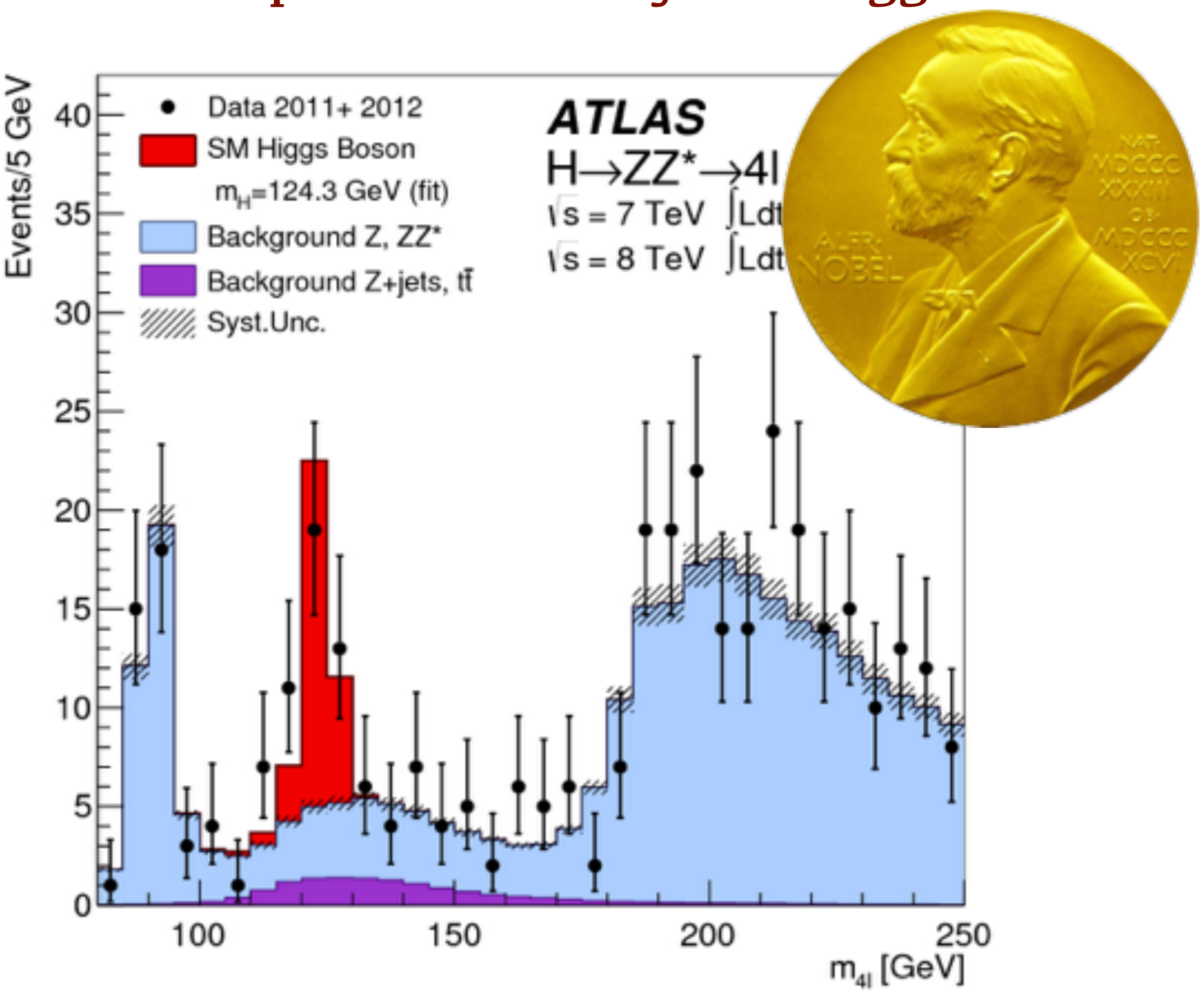

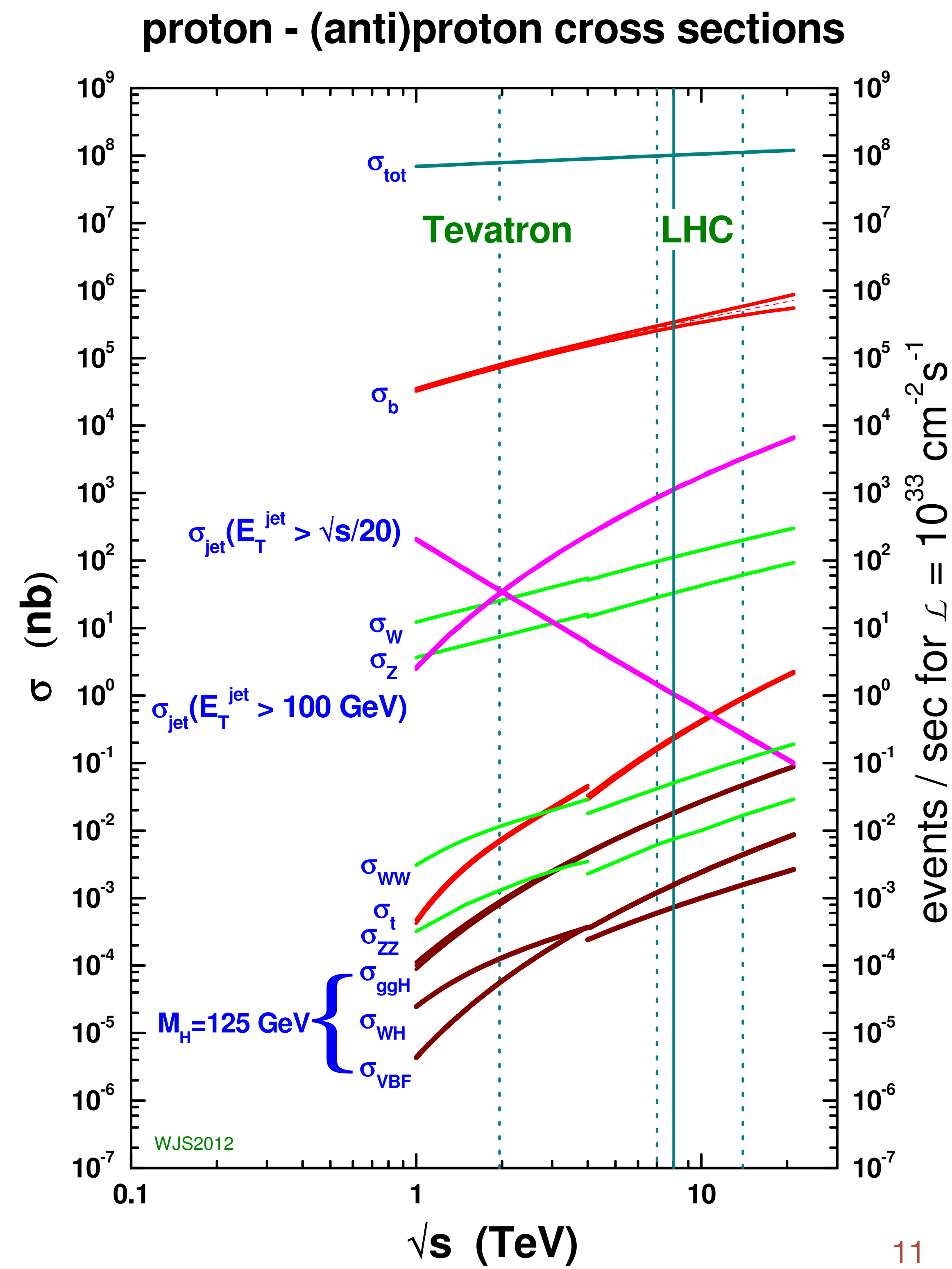

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- **What** is Dark Matter?

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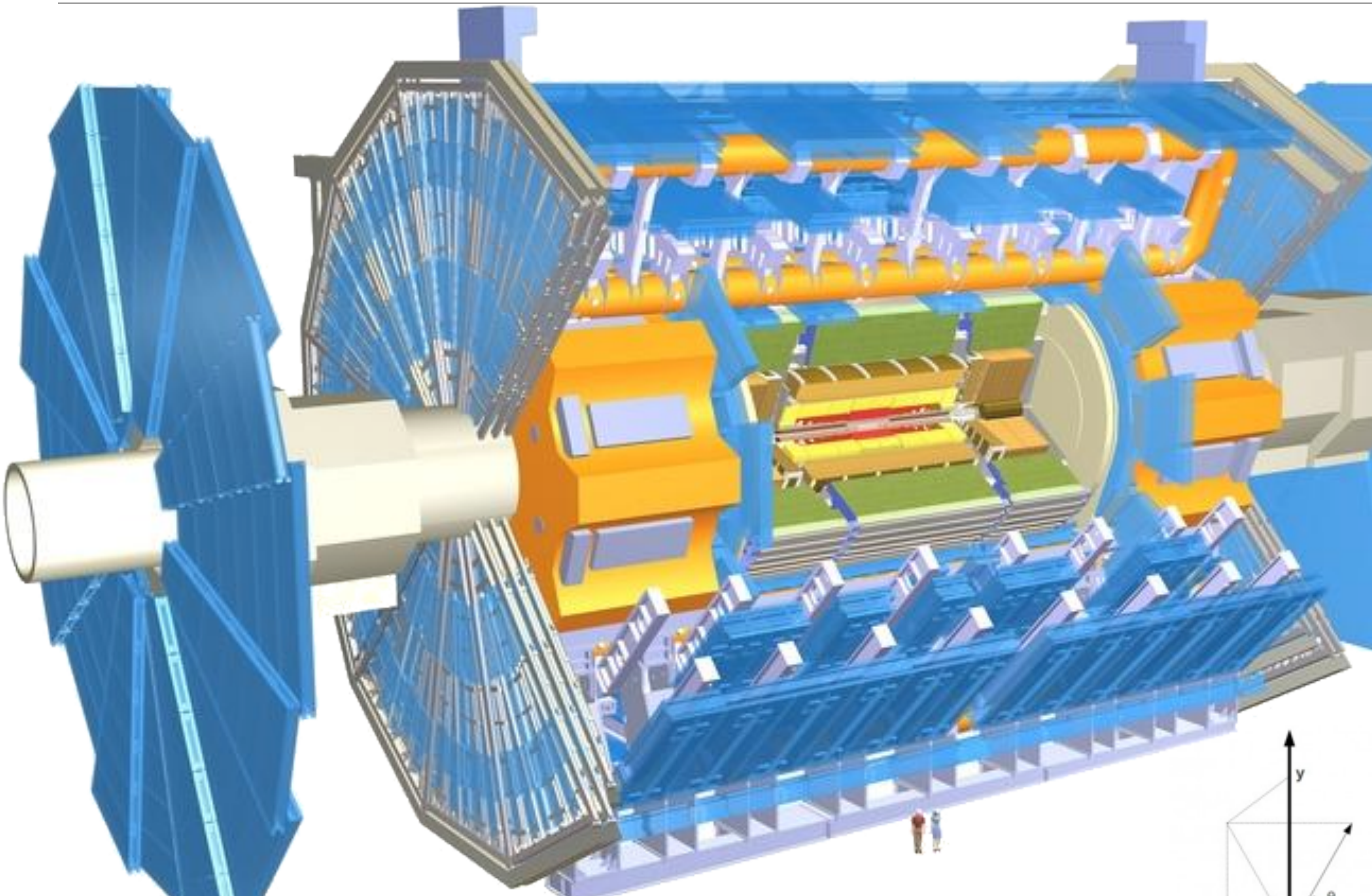
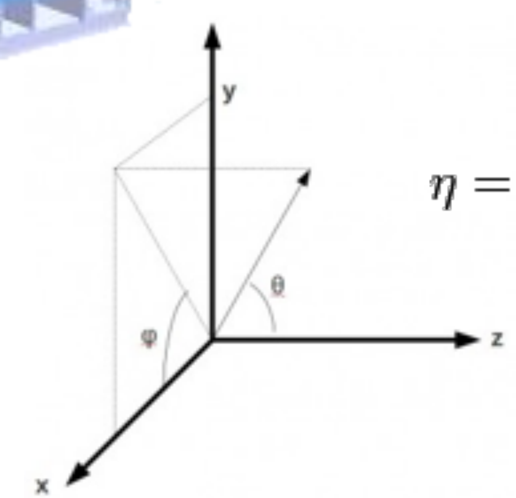
- **Why** is the Higgs mass much lower than the Planck scale?
- **What** is Dark Matter?
- **Are there any other particles we haven't discovered yet?**

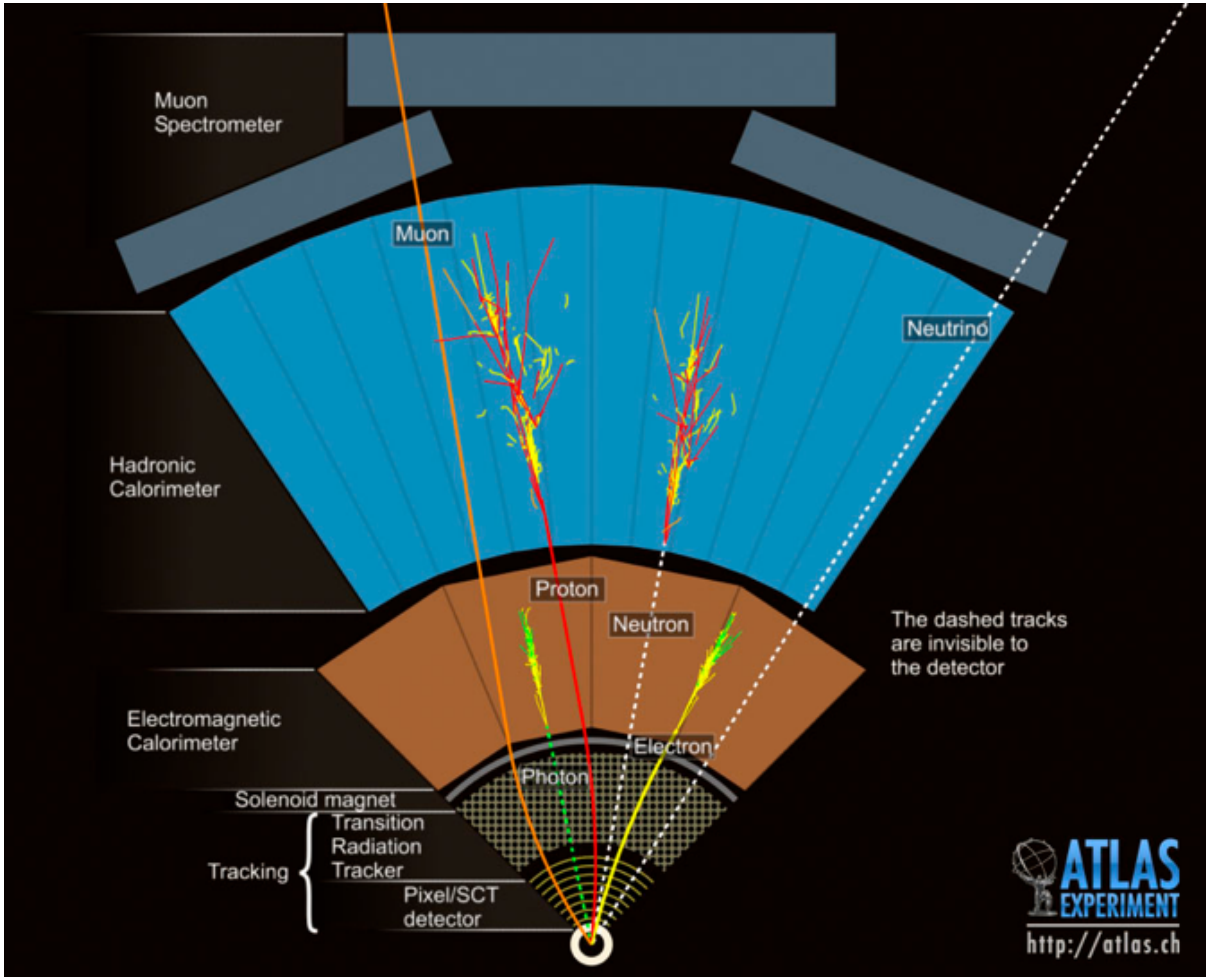
ATLAS



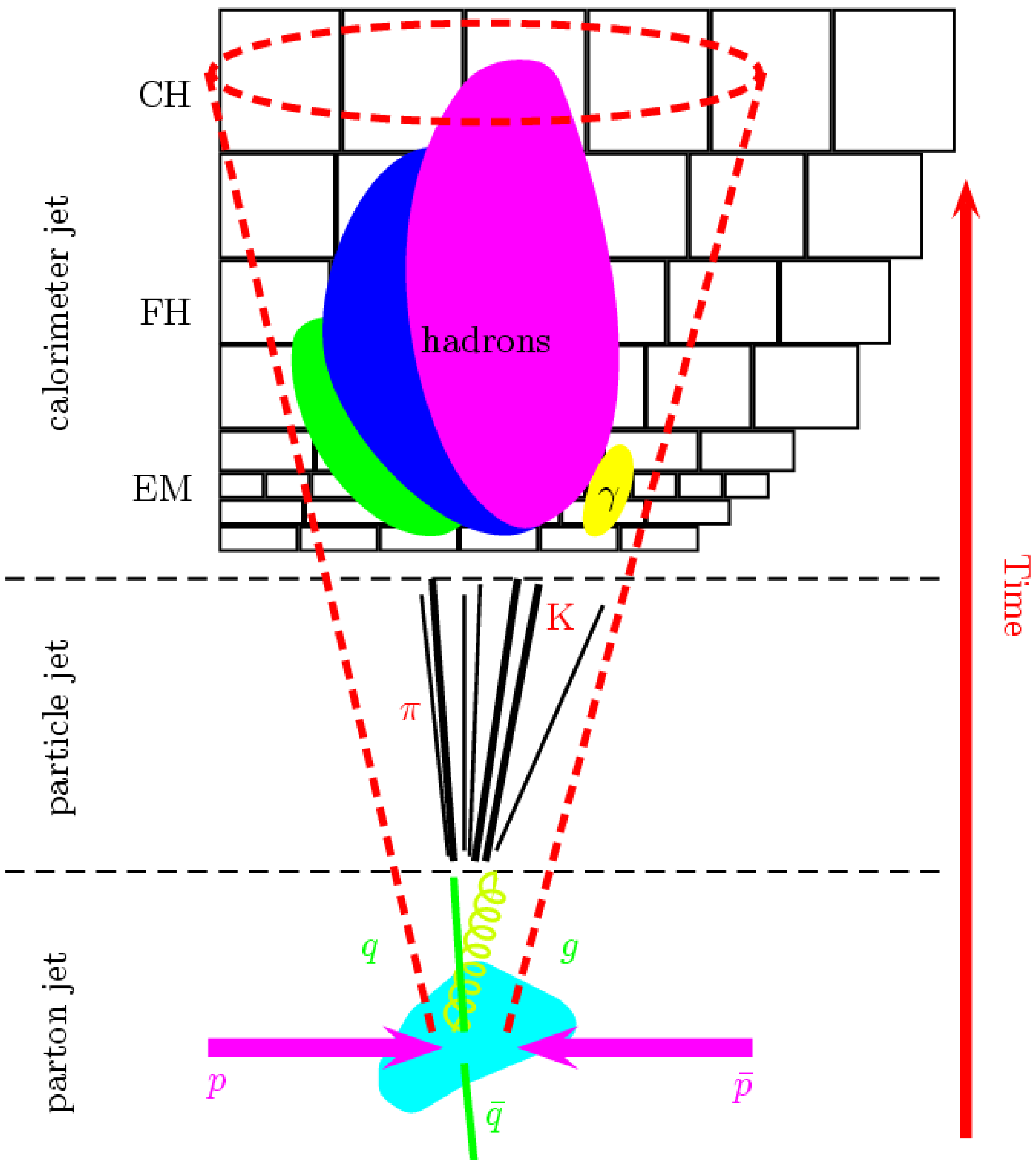


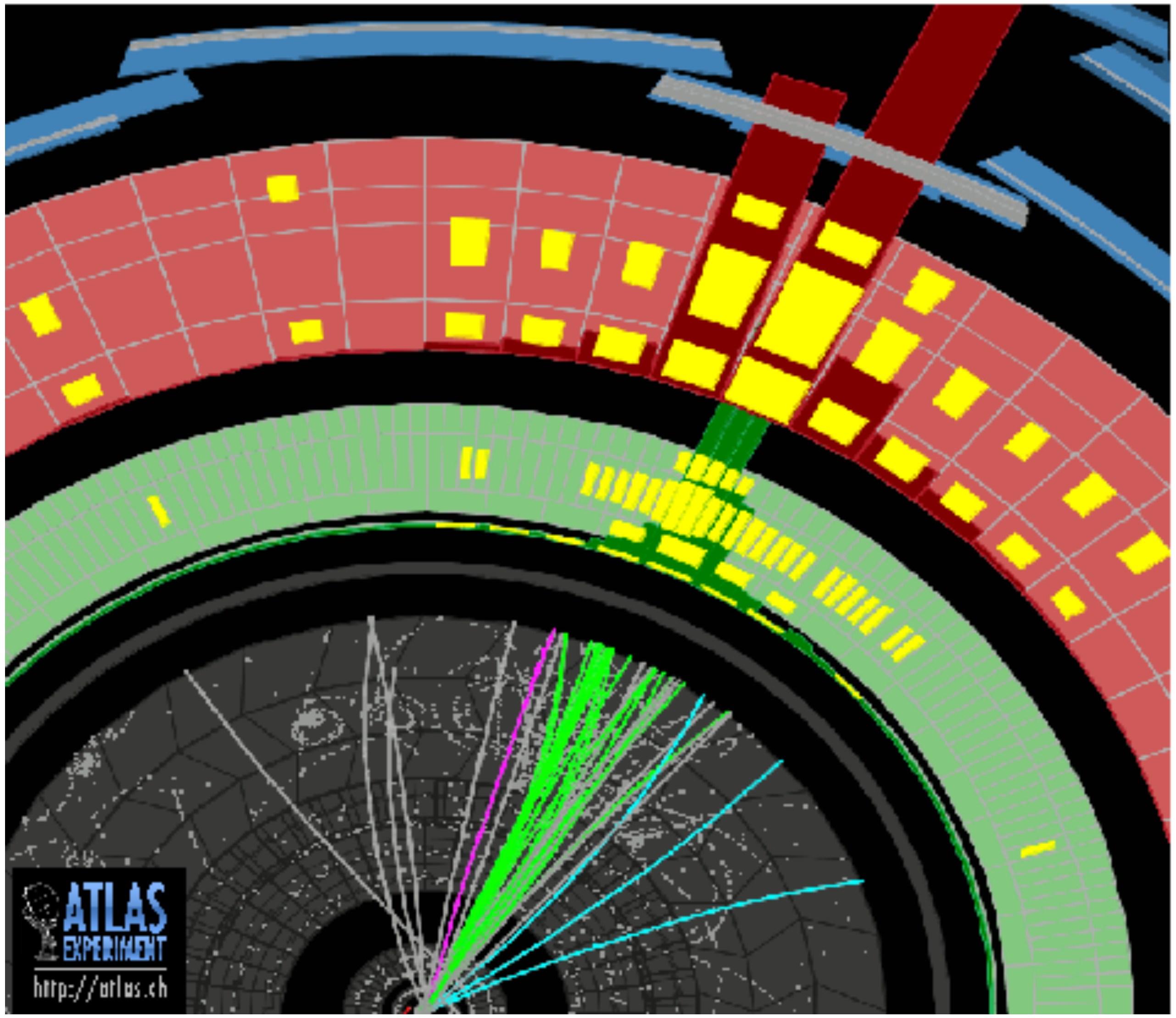
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Particles in ATLAS



Quarks and Gluons





Jets

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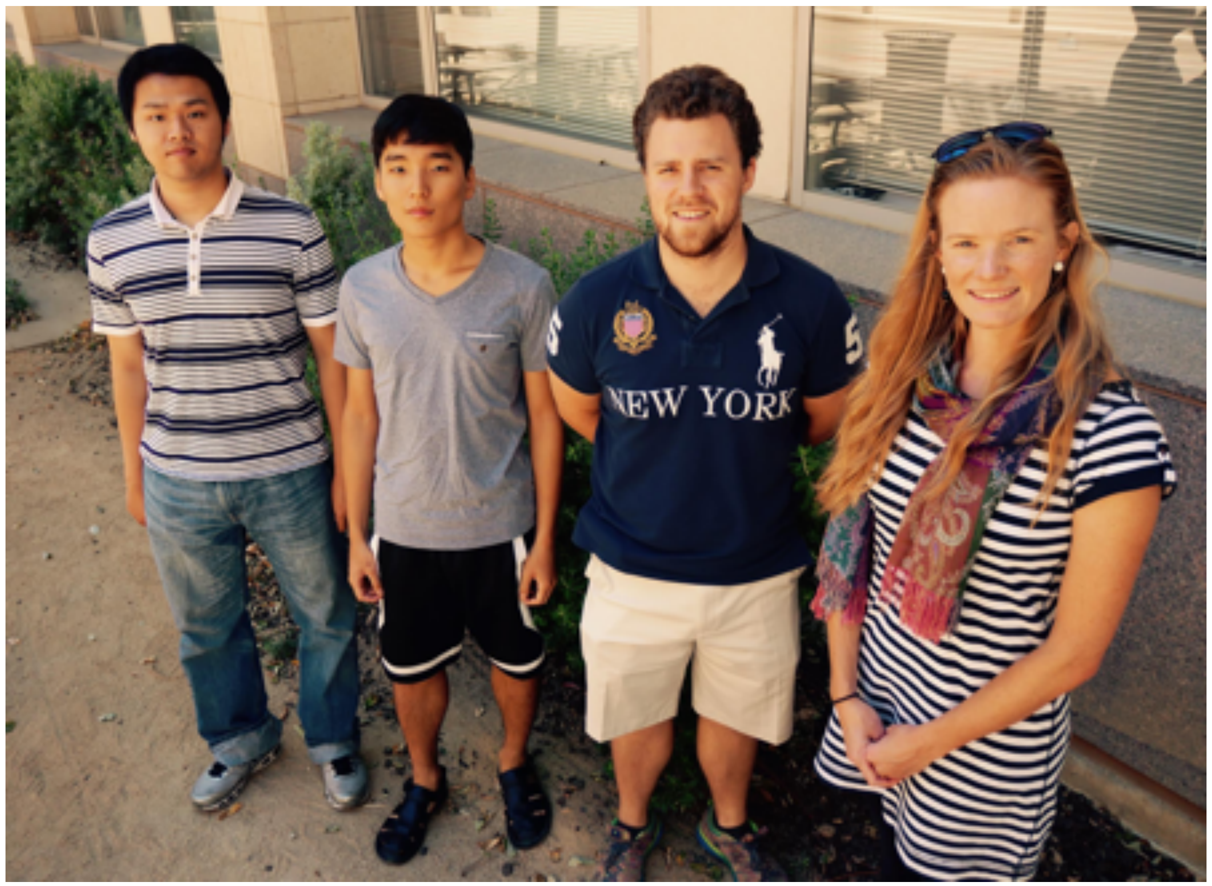
- THIS IS NOT A FIELD FOR INDIVIDUAL GLORY

ATLAS @ Stanford (& CERN)

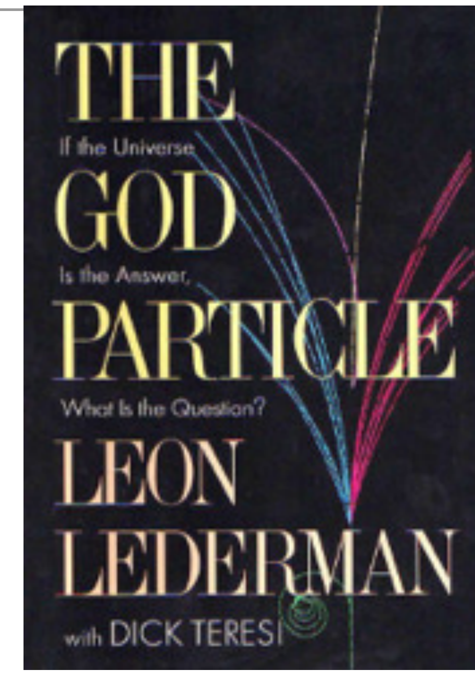


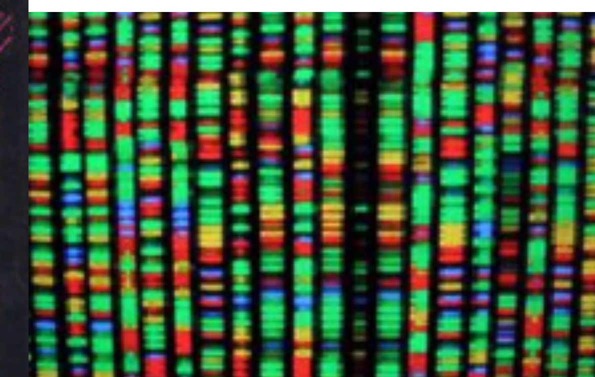
- Digital electronics for better data acquisition
- Using the Higgs as a probe for new physics
- Currently: 1 faculty, 1 graduate student (Zihao Jiang), 1 postdoc (Nikolina Ilic), 1 masters student (Victor Ruelas, Cal State Fresno), 1 research assistant (Rex Brown)

Data Deluge

Data Deluge

- Each event is ~ 1.25 MB
  - 1MB ~ 500 page book
  - Human genome = 800MB





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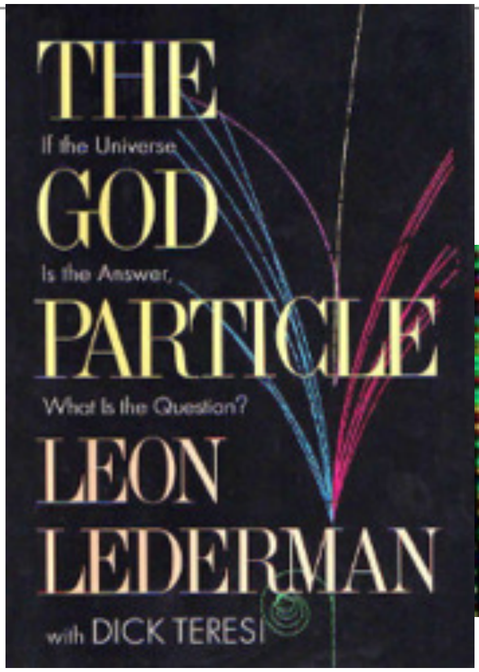

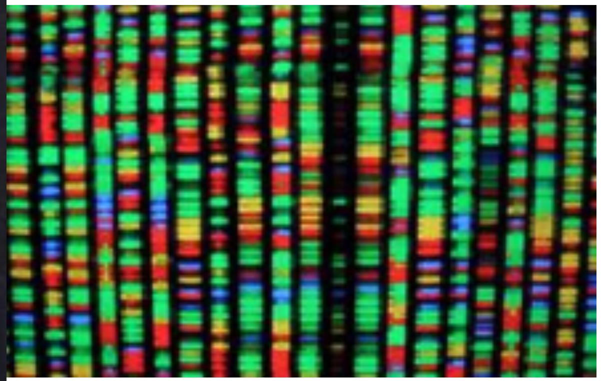

- 40 million events per second = 50 TB/second
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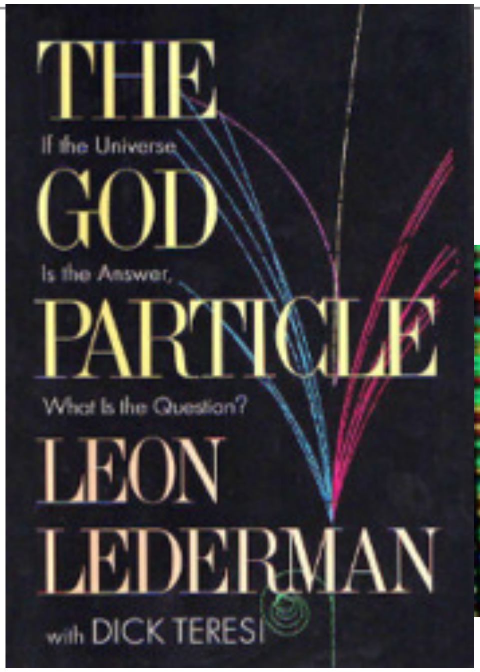

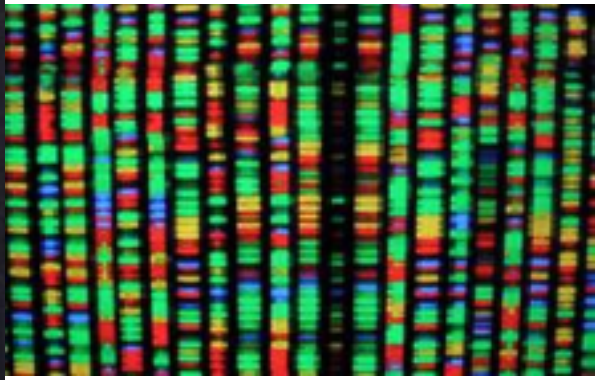

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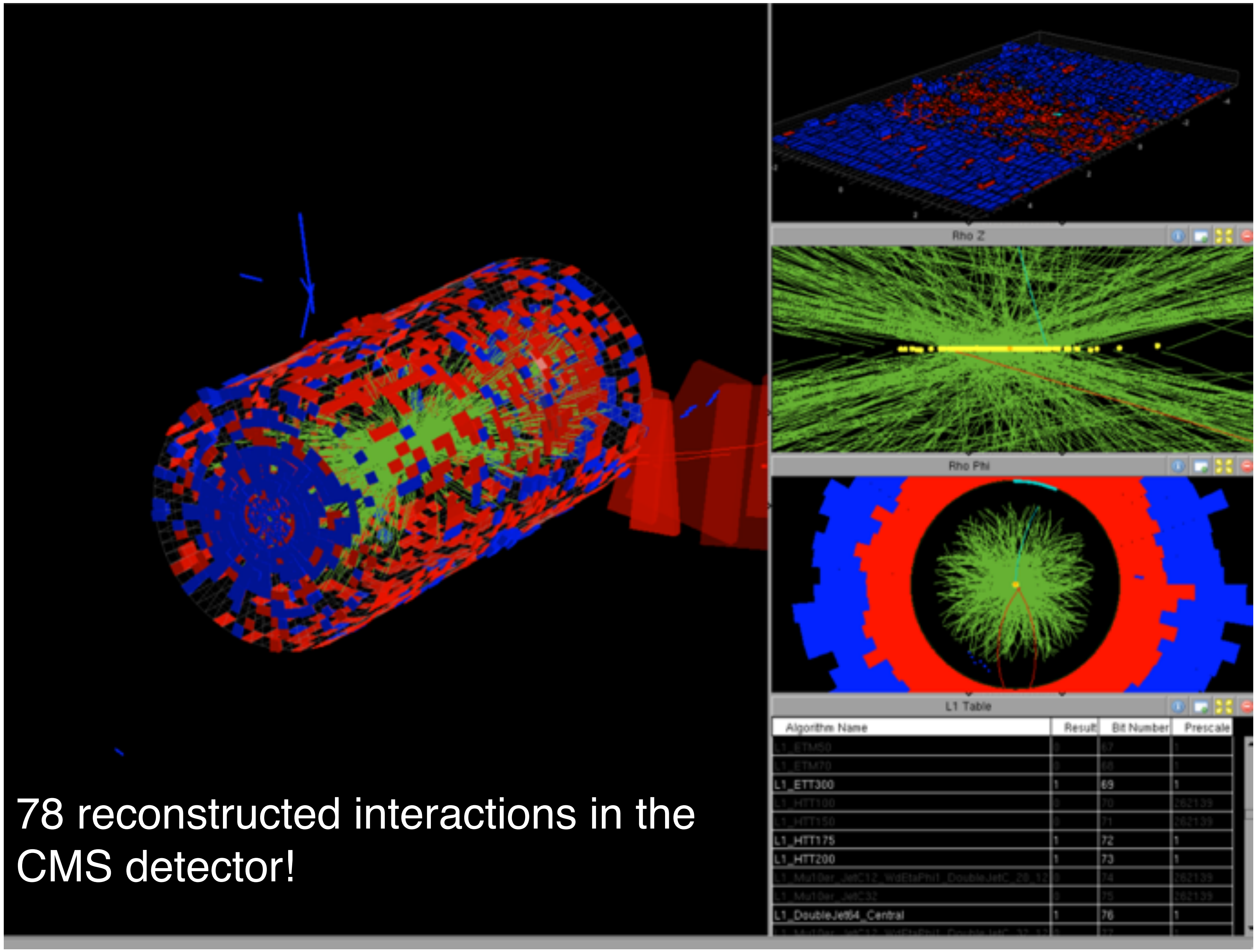
- **WAY TOO MUCH!**

Runs II&III: Challenges



- **Run II (2015 to 2017)**: mean of 45 simultaneous interactions
- **Run III (2018-2021)**: mean of up to 80 simultaneous interactions

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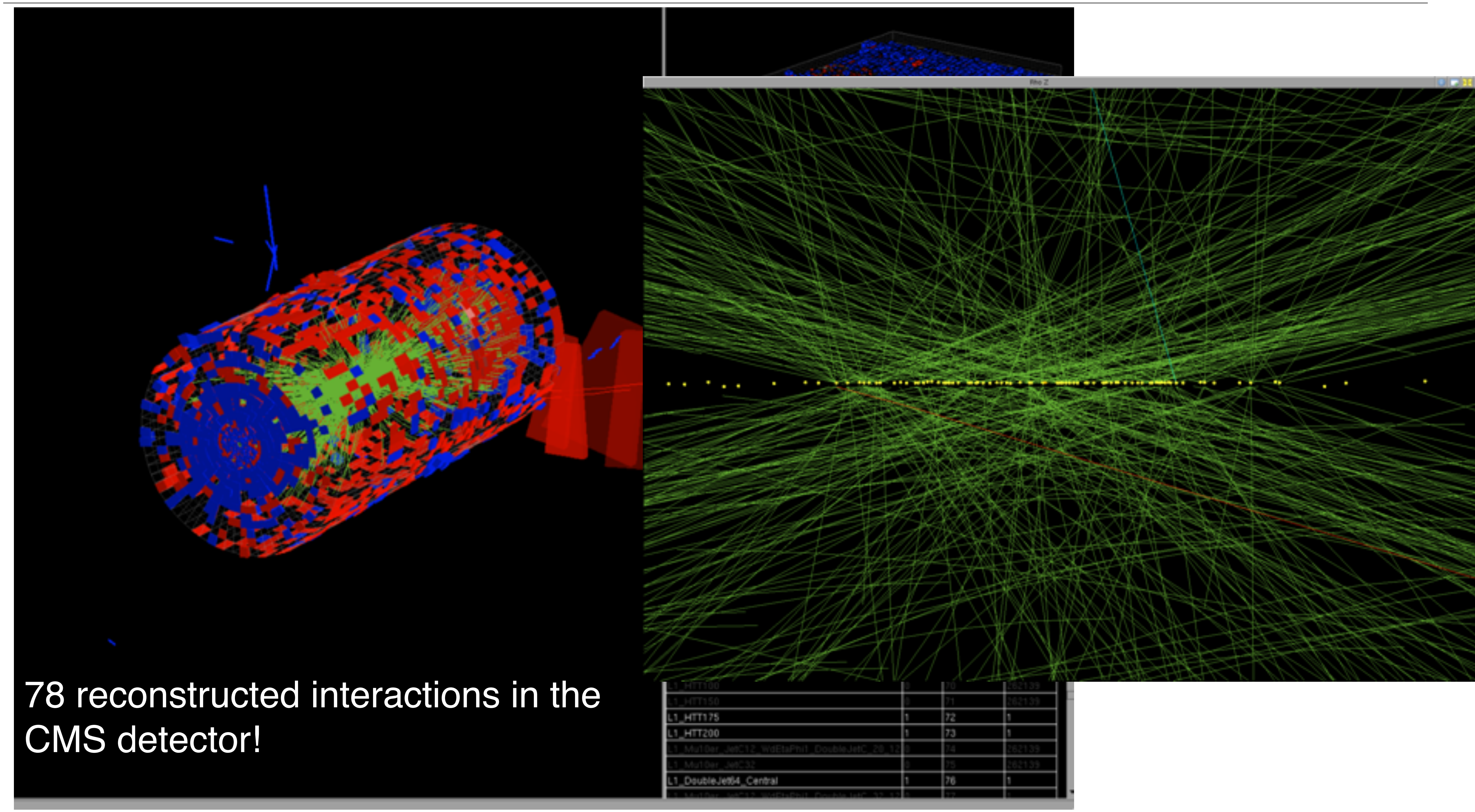

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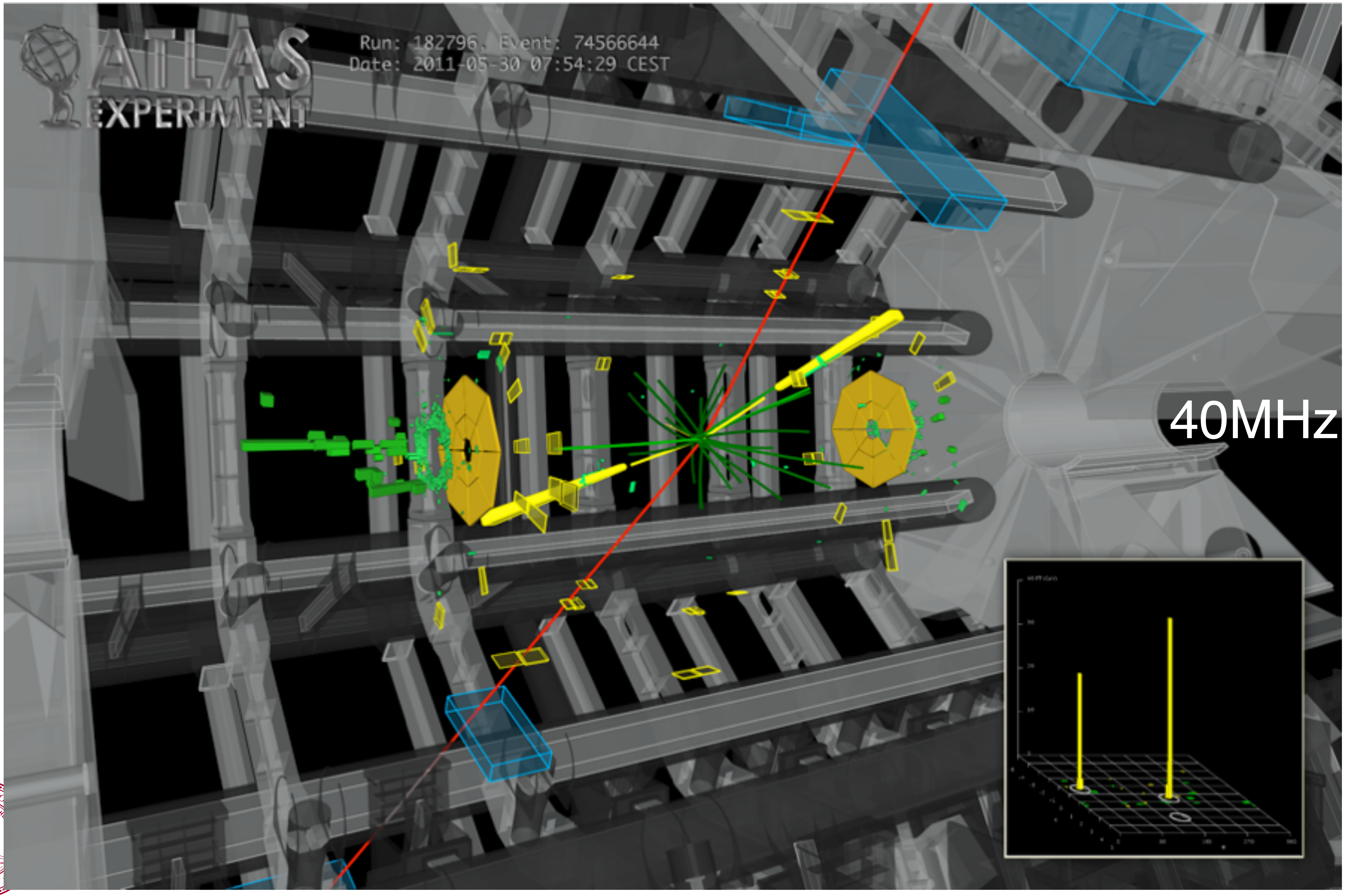
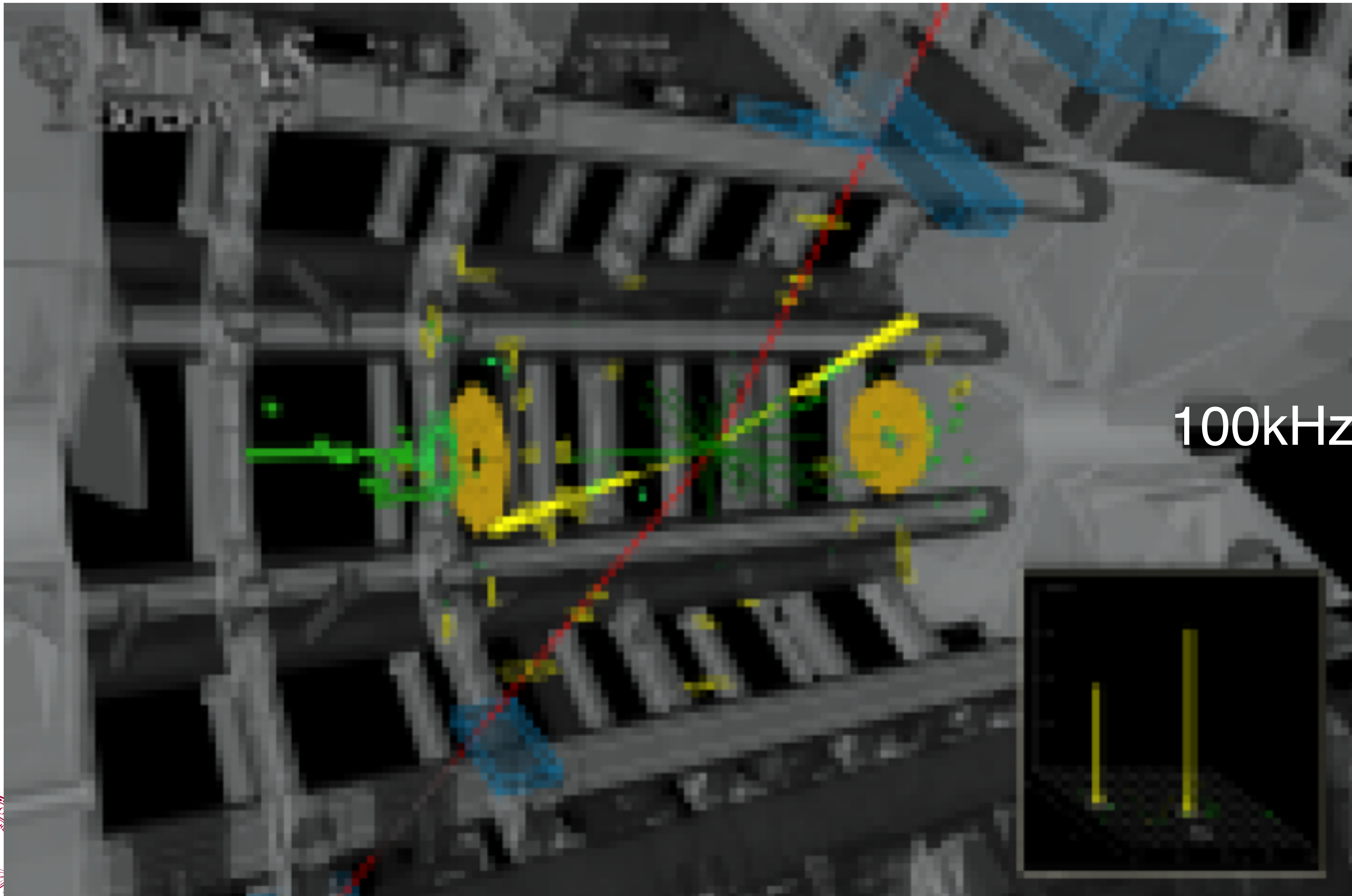
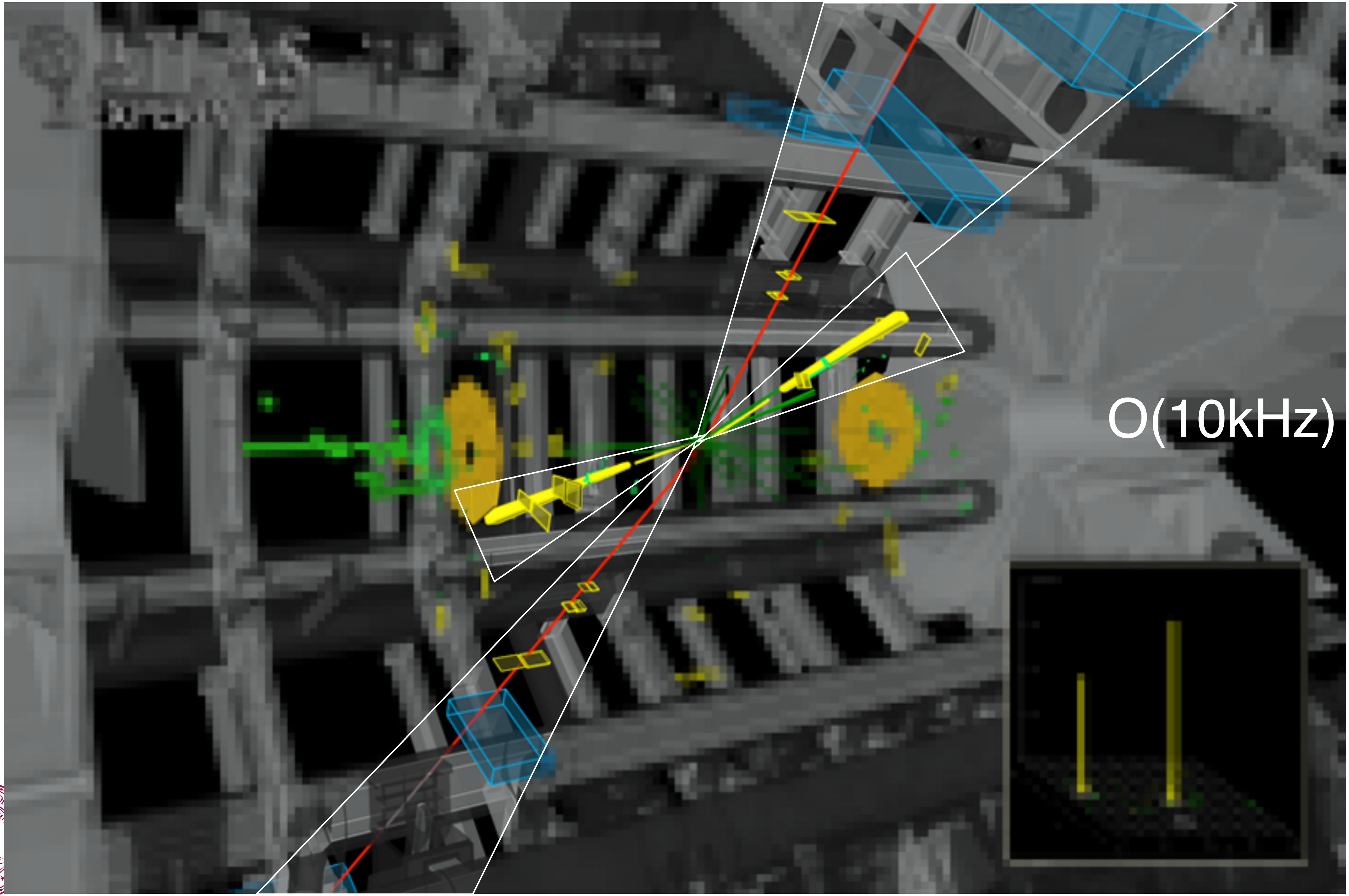
Recording The Data: Multi-Step Approach



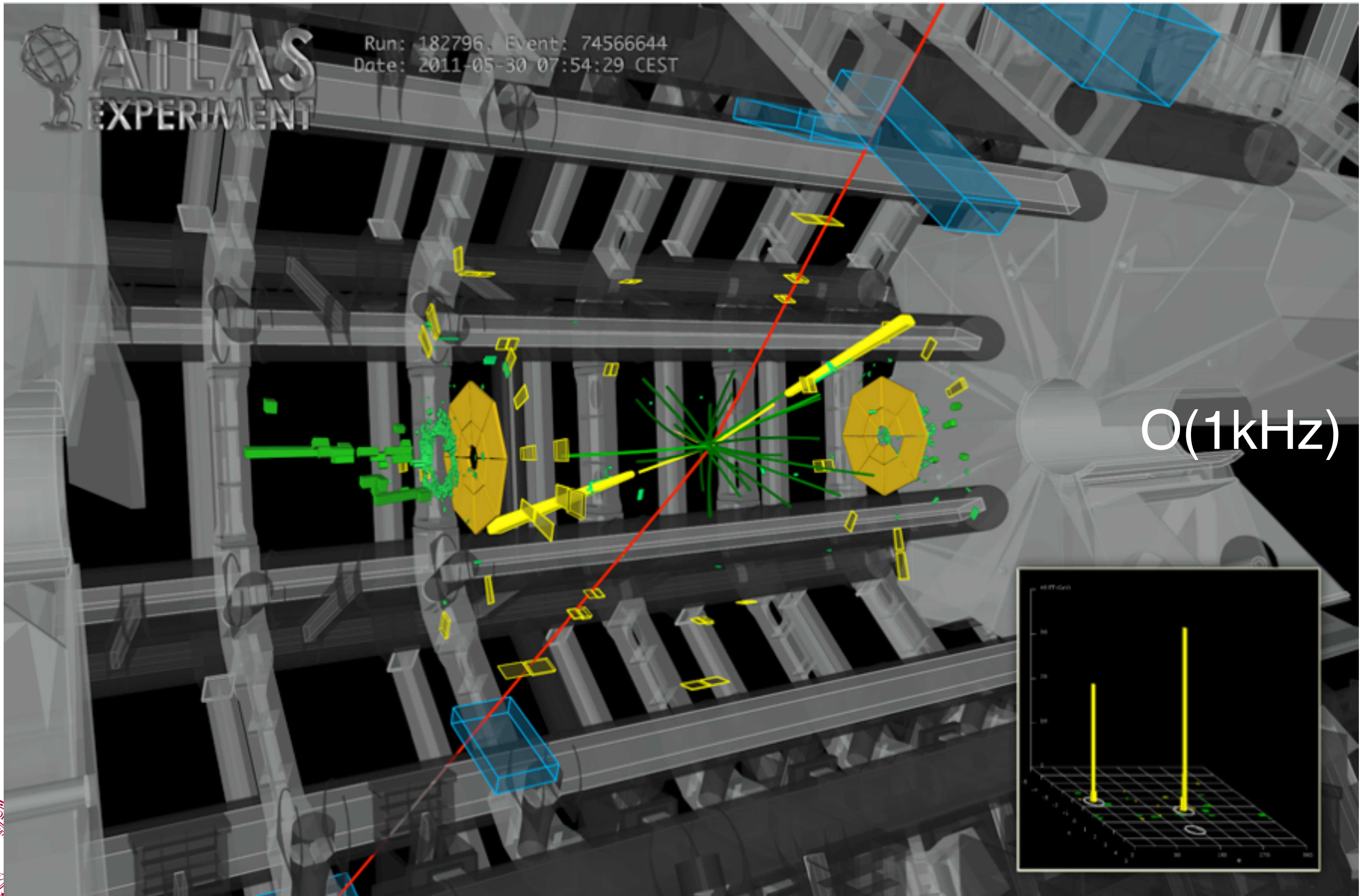
Step 1: Quick and Dirty



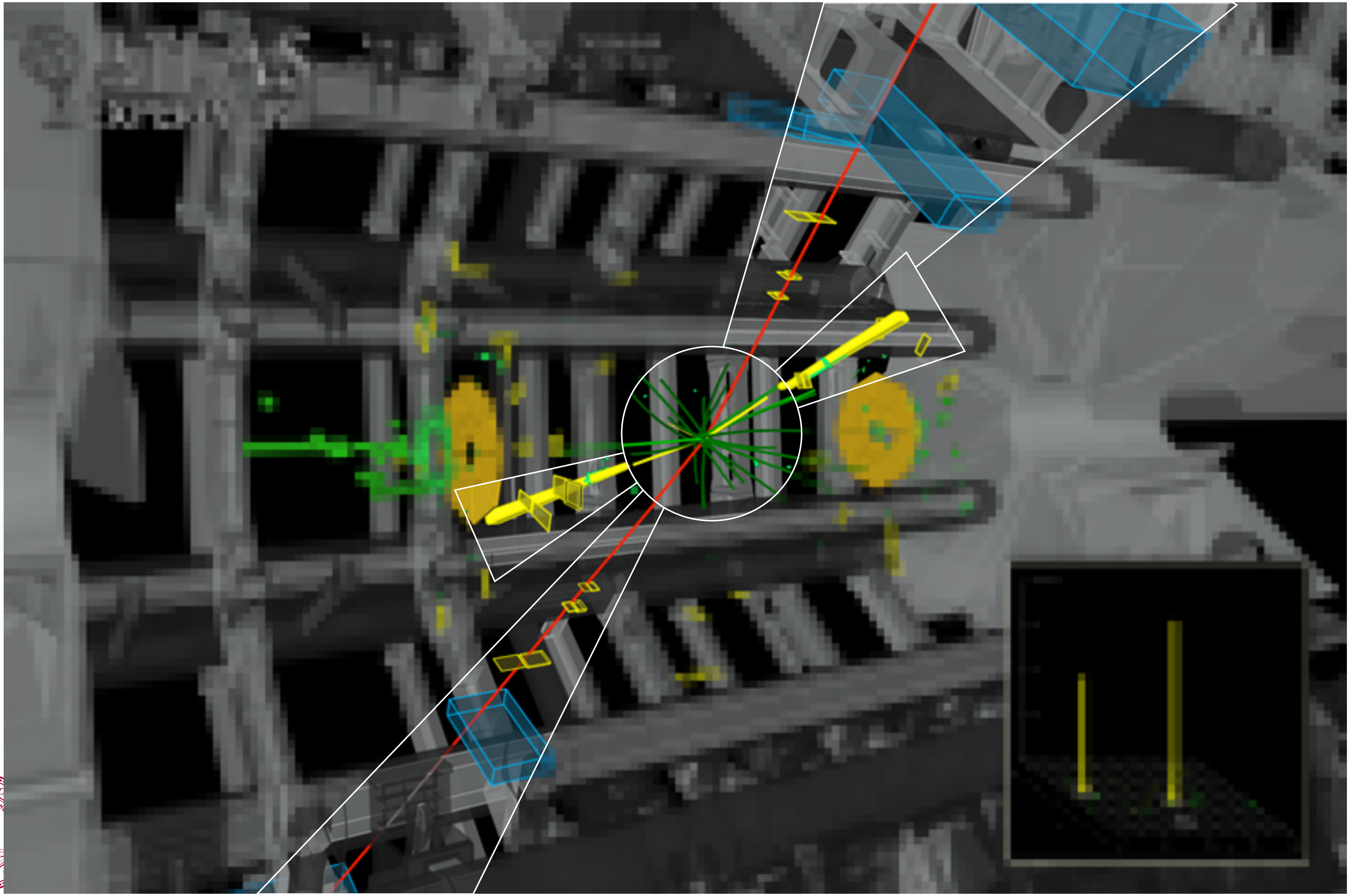
Step 2: Selective Sight



Step 3: The Full Picture (Almost)



The Atlas FastTracKer Steps Up



How we do it: BINGO!

- Hits are ganged together into coarse resolution hits

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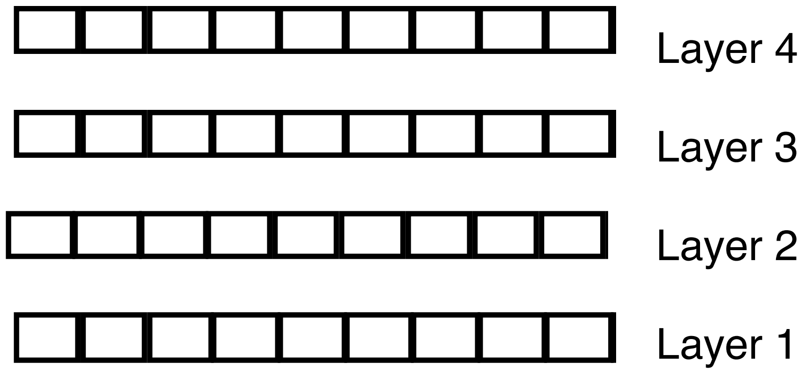

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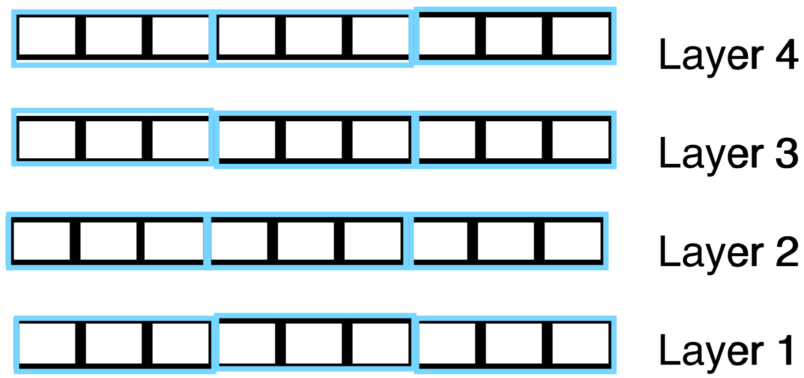

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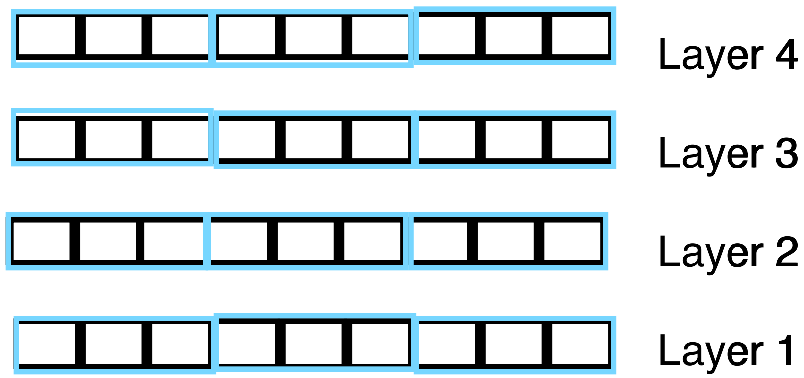

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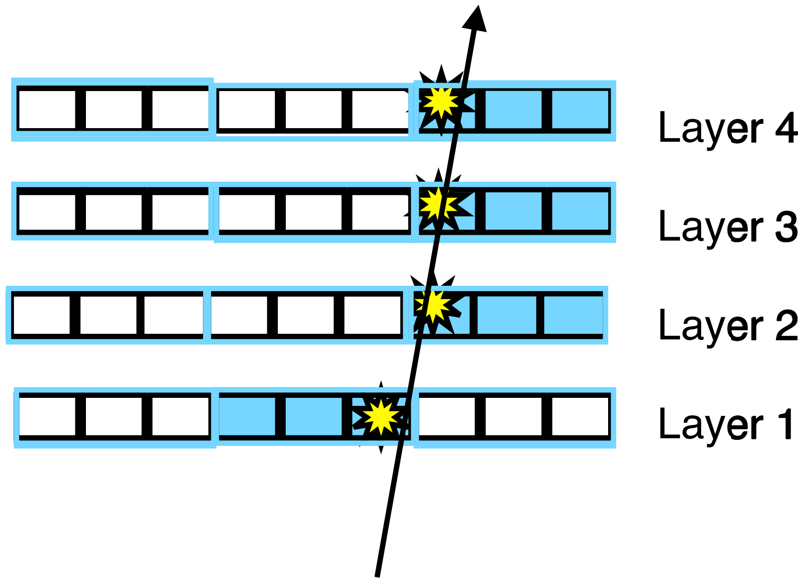

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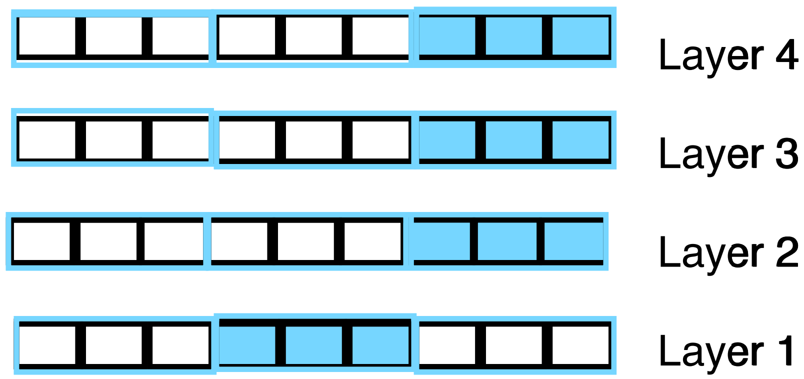

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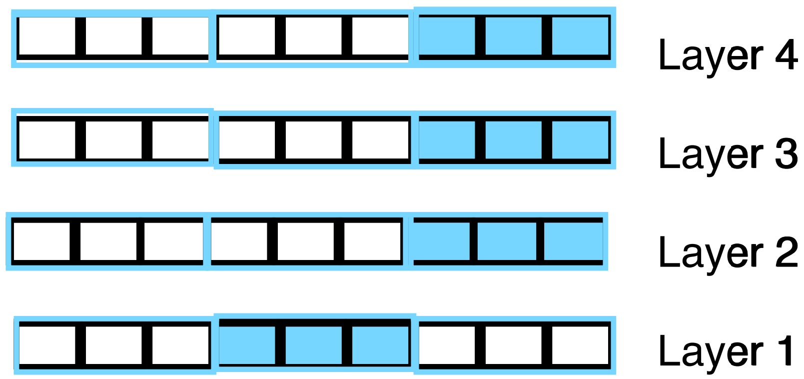

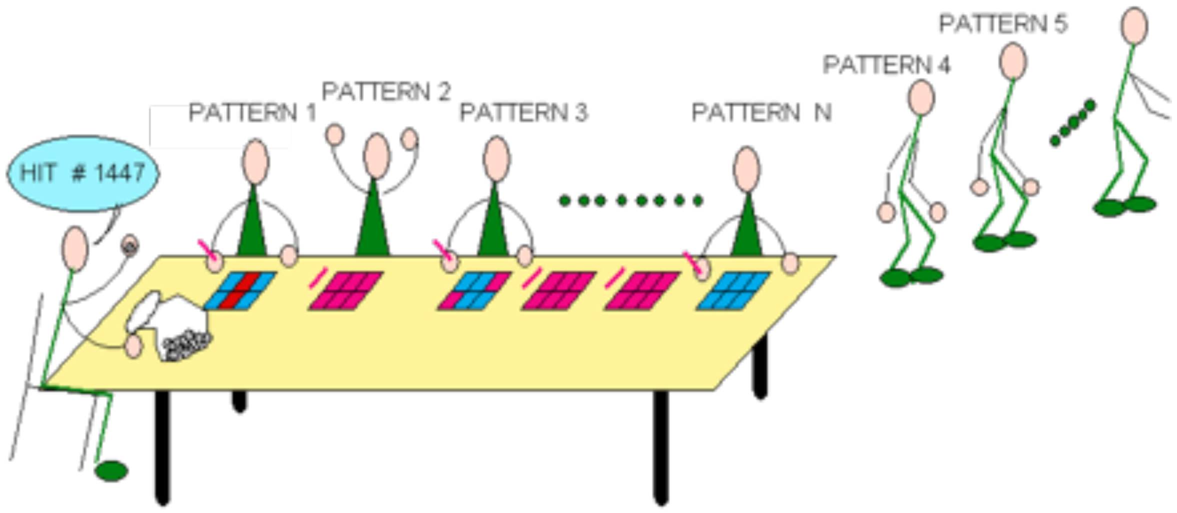

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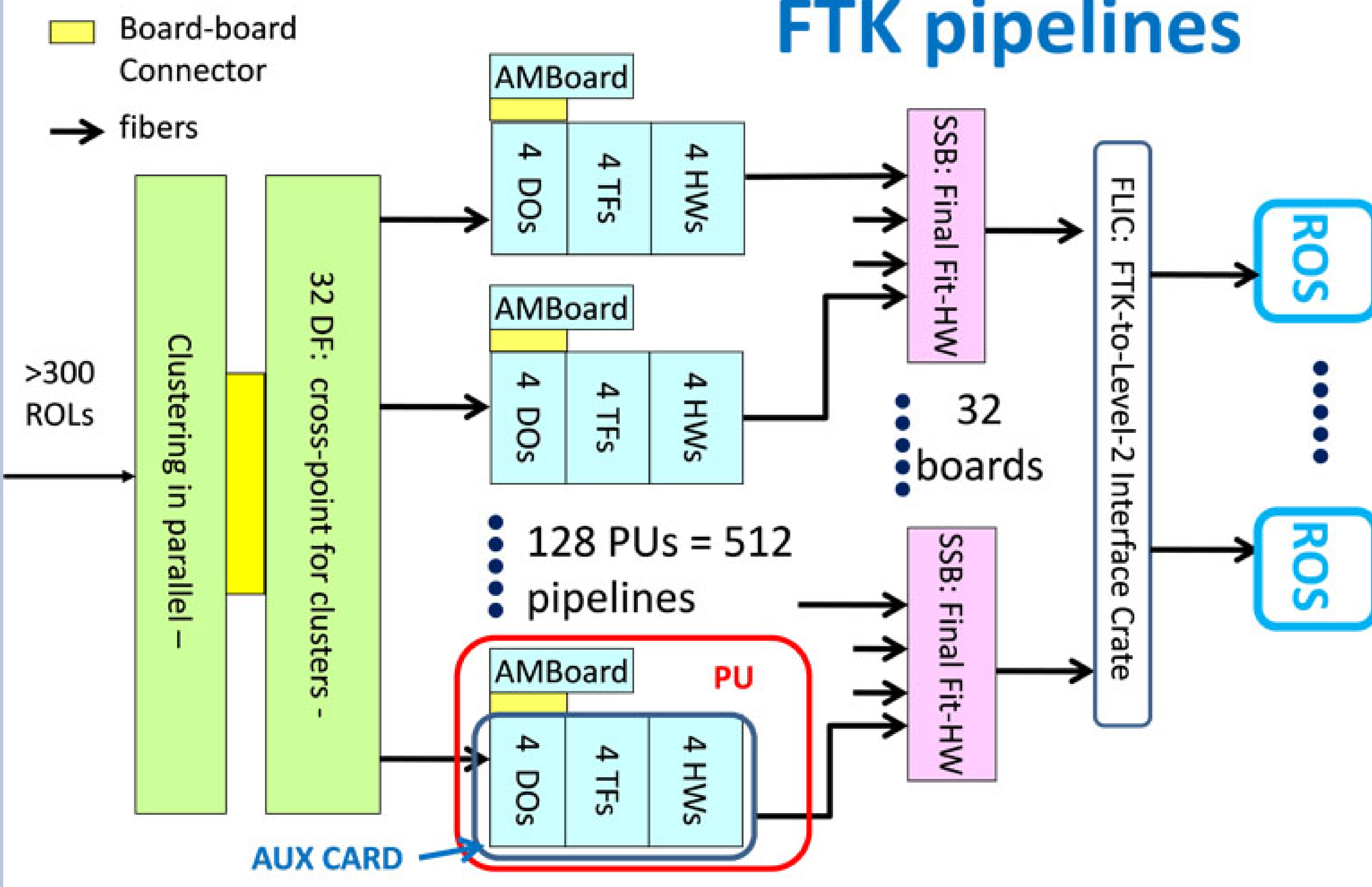
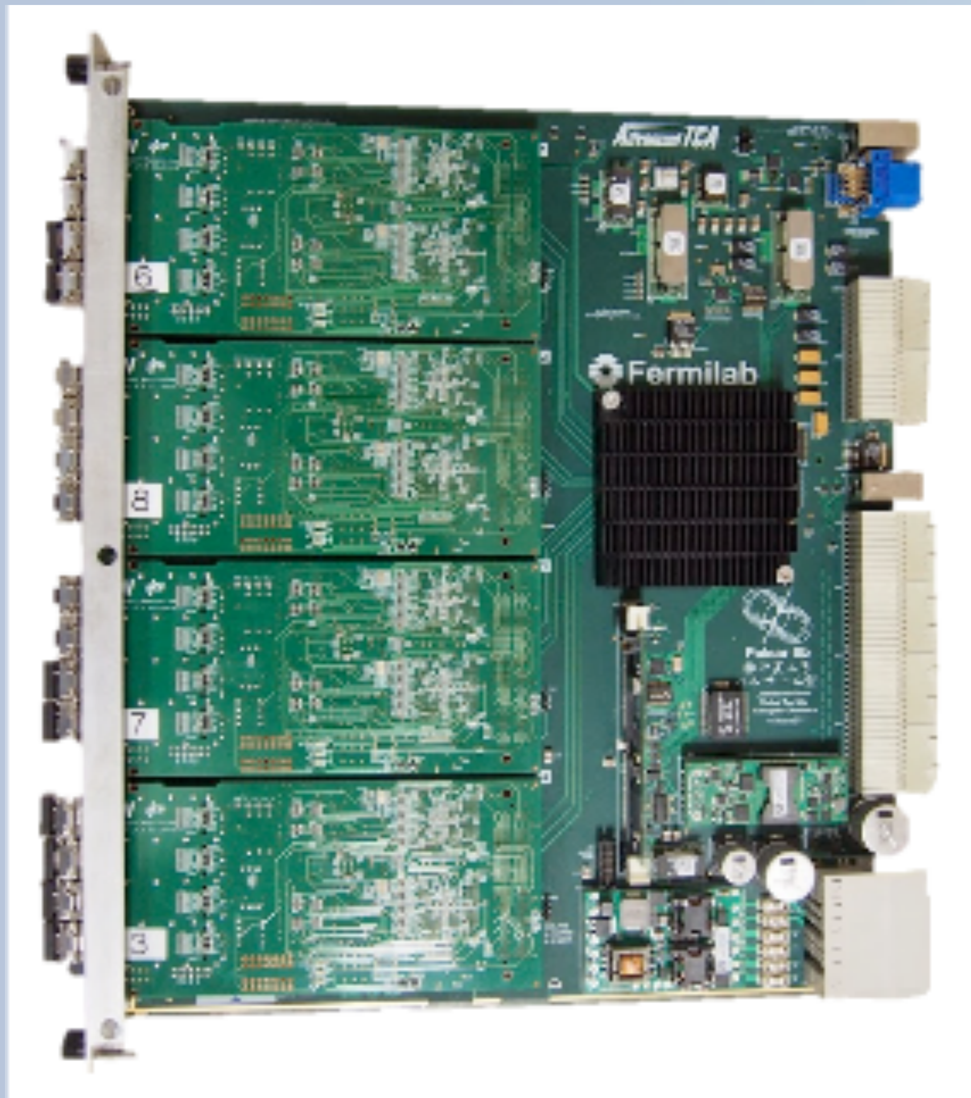
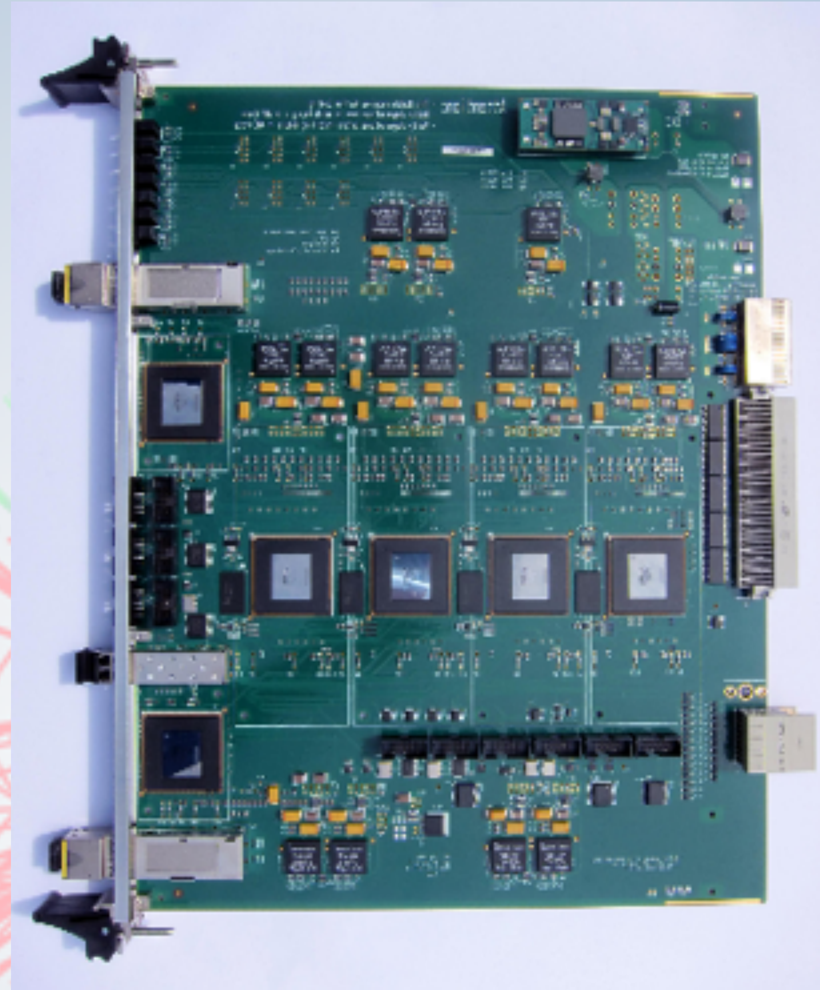
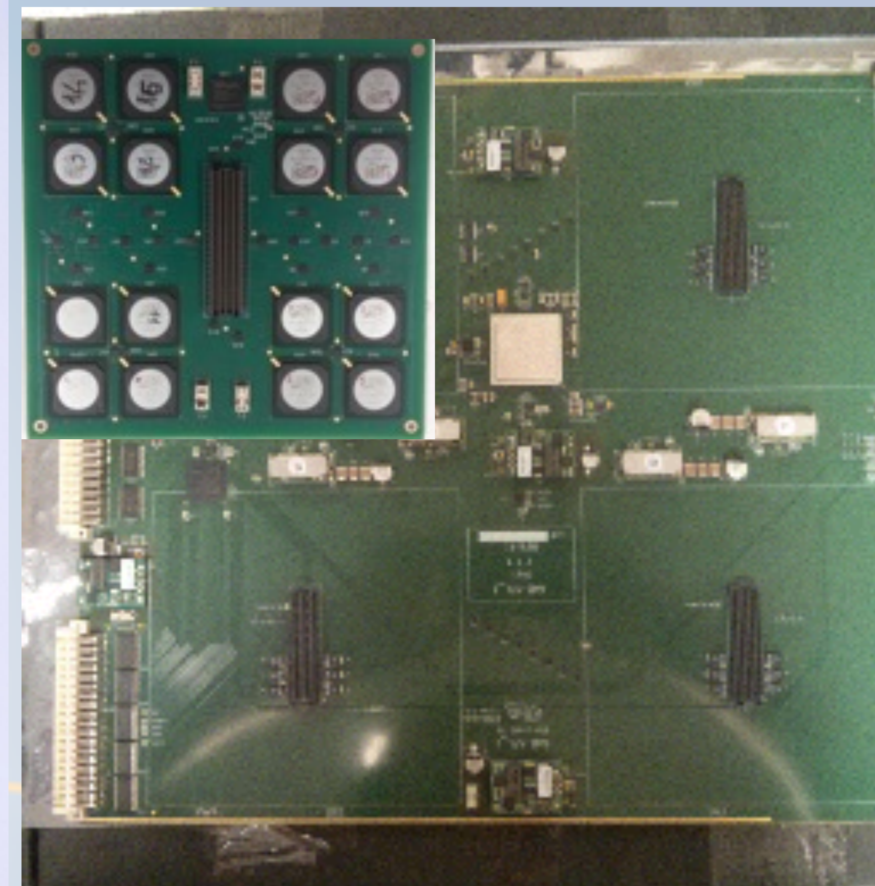
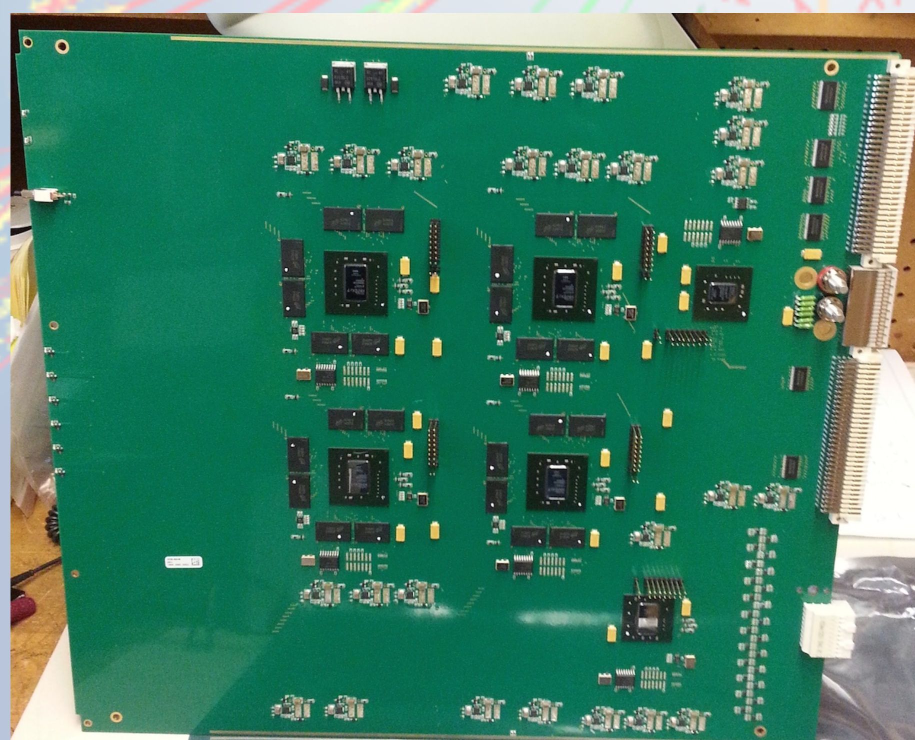
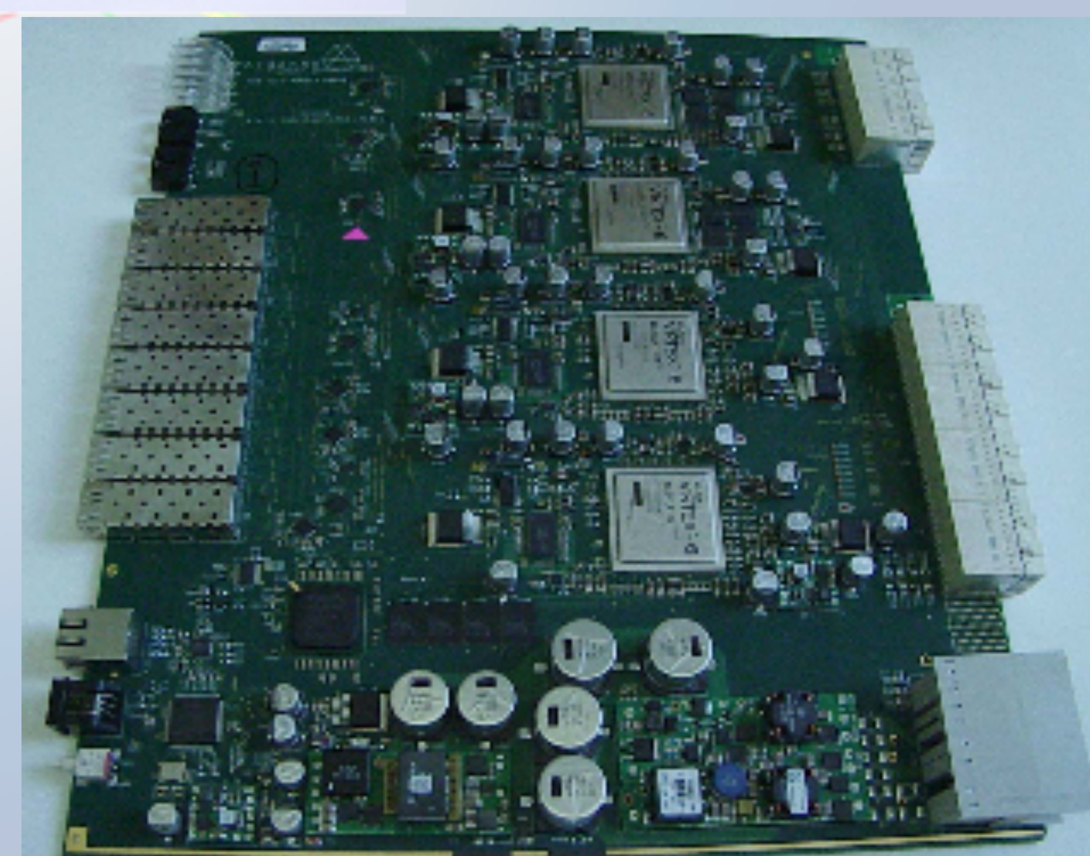
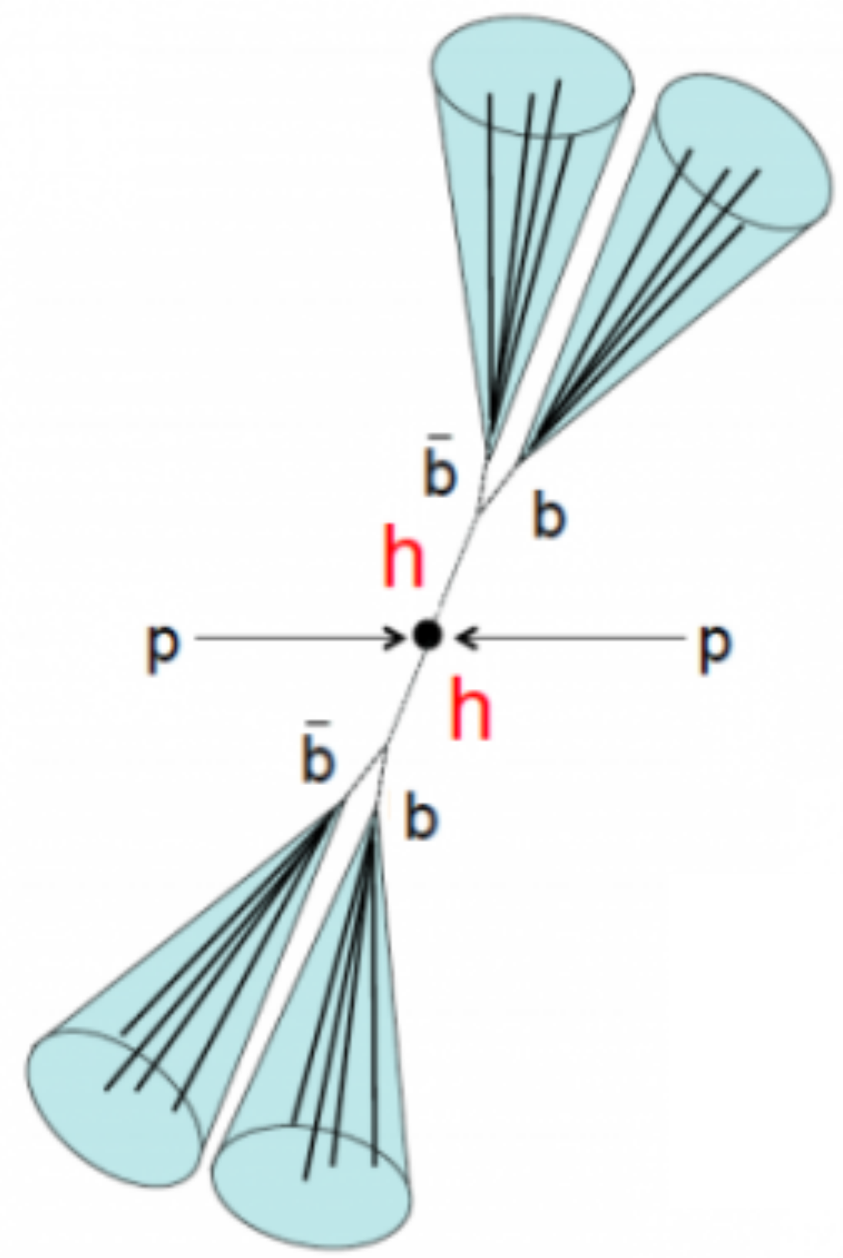
FTK pipelines




Fermilab





Analysis topics

- Higgs as a probe for new physics!
  - New particles can decay to Higgs, let's go look for them
- Boosted decays of Higgs to b-quarks
  - Understanding the modeling of b-quarks in boosted like topologies
- Pretty much anything else including b-quarks, tau leptons, or which would use FTK.
- Will be taking 1 more student in next 1-2 years

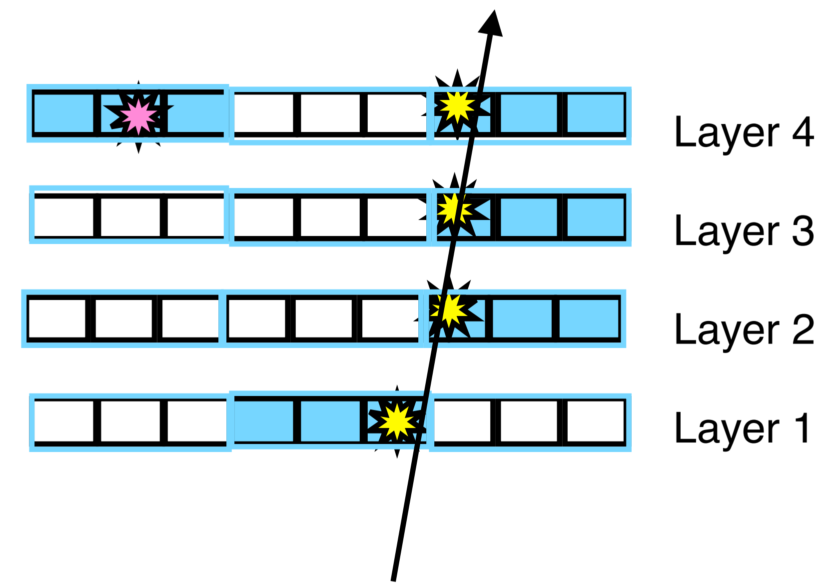


Unsolicited Advice

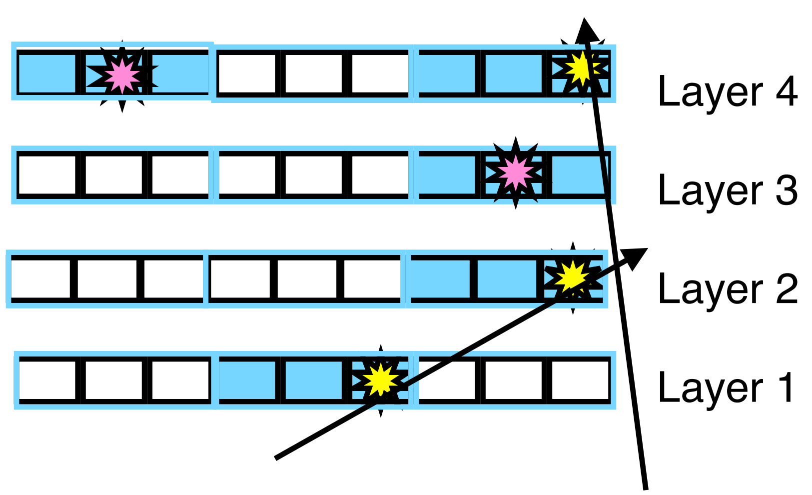
Just a little bit

Track Fitting

- Problem: >90% of matched patterns (BINGOs) are from random association of hits

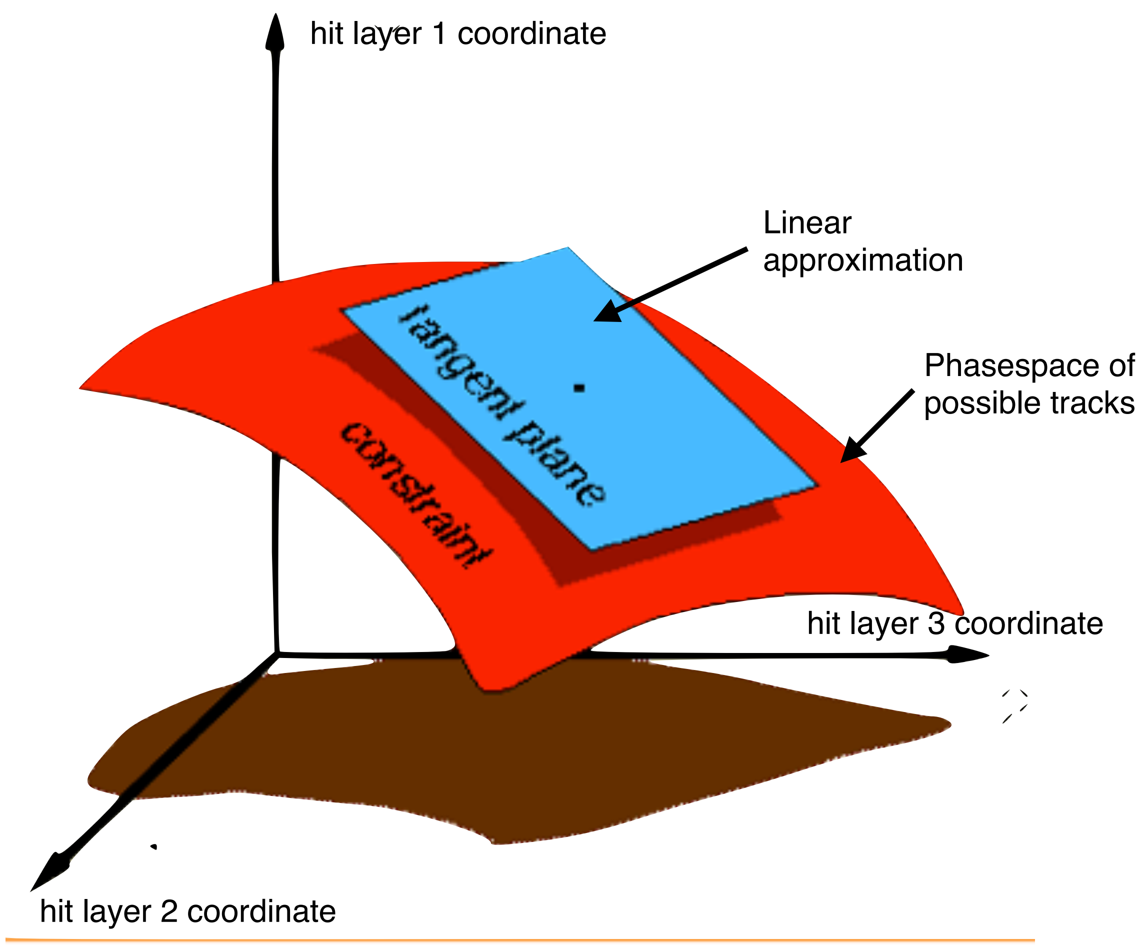


- Solution: check if **full resolution** hits in matched patterns are compatible with a single charged particle



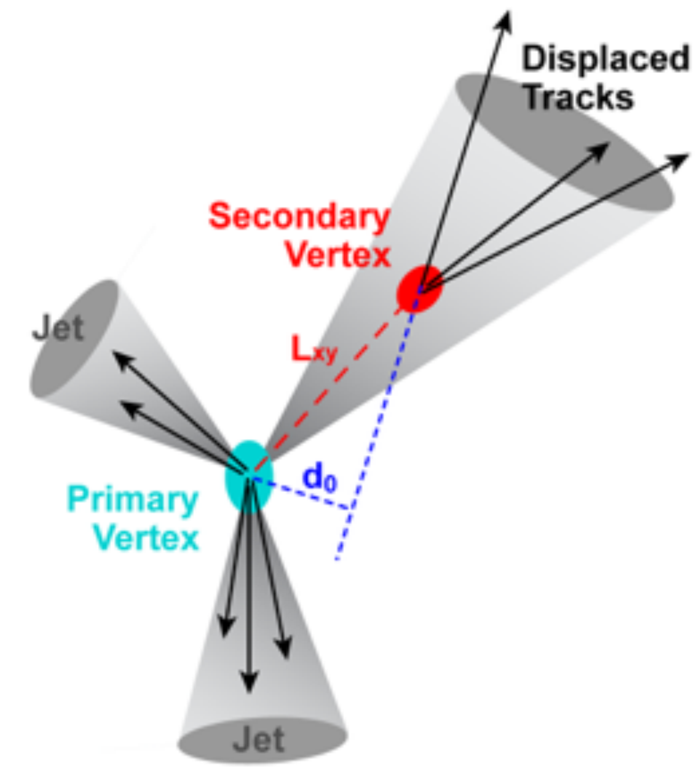
5 Picosecond Track Fitting

- Linearized fits on FPGAs:
  - Determine phasespace of possible tracks (χ^2)
  - Linear approximation calculated and defined by sector
  - FPGAs multiply and add coordinates by constants to get χ^2
- Keep roads with at least 1 good track
- Fit 1 track / ns (1 track every 5 ps for full system)!

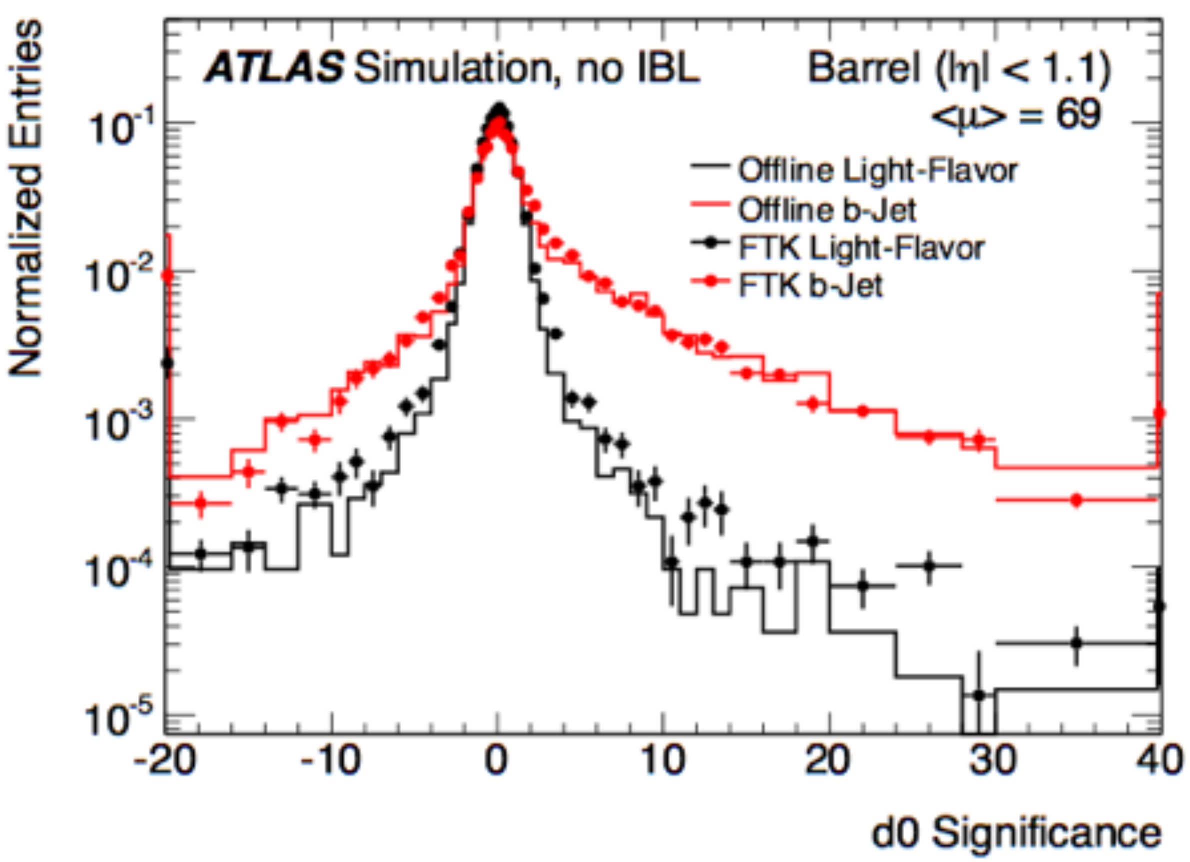


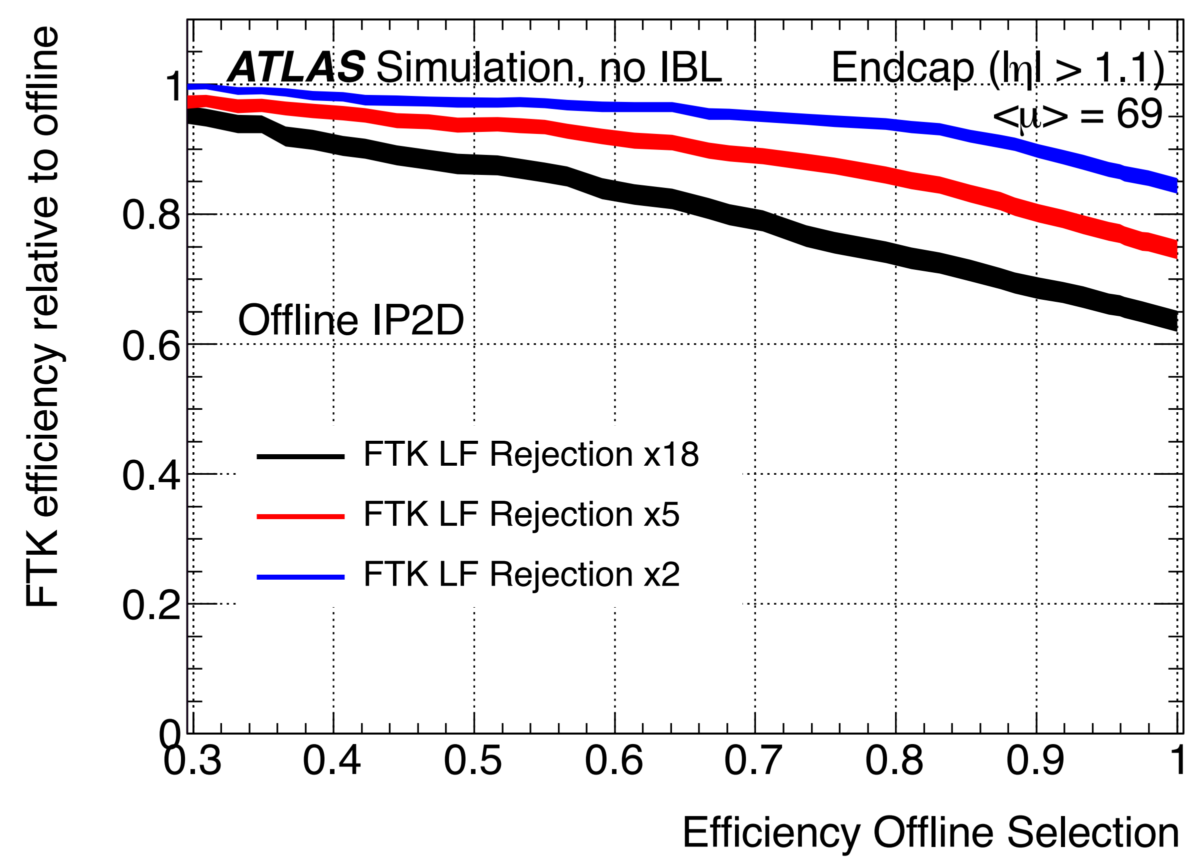
$$\chi_i = \sum_{j=1}^{N_c} S_{ij} x_j + h_i; i = 1, \ldots, N_\chi$$

Performance: B-tagging

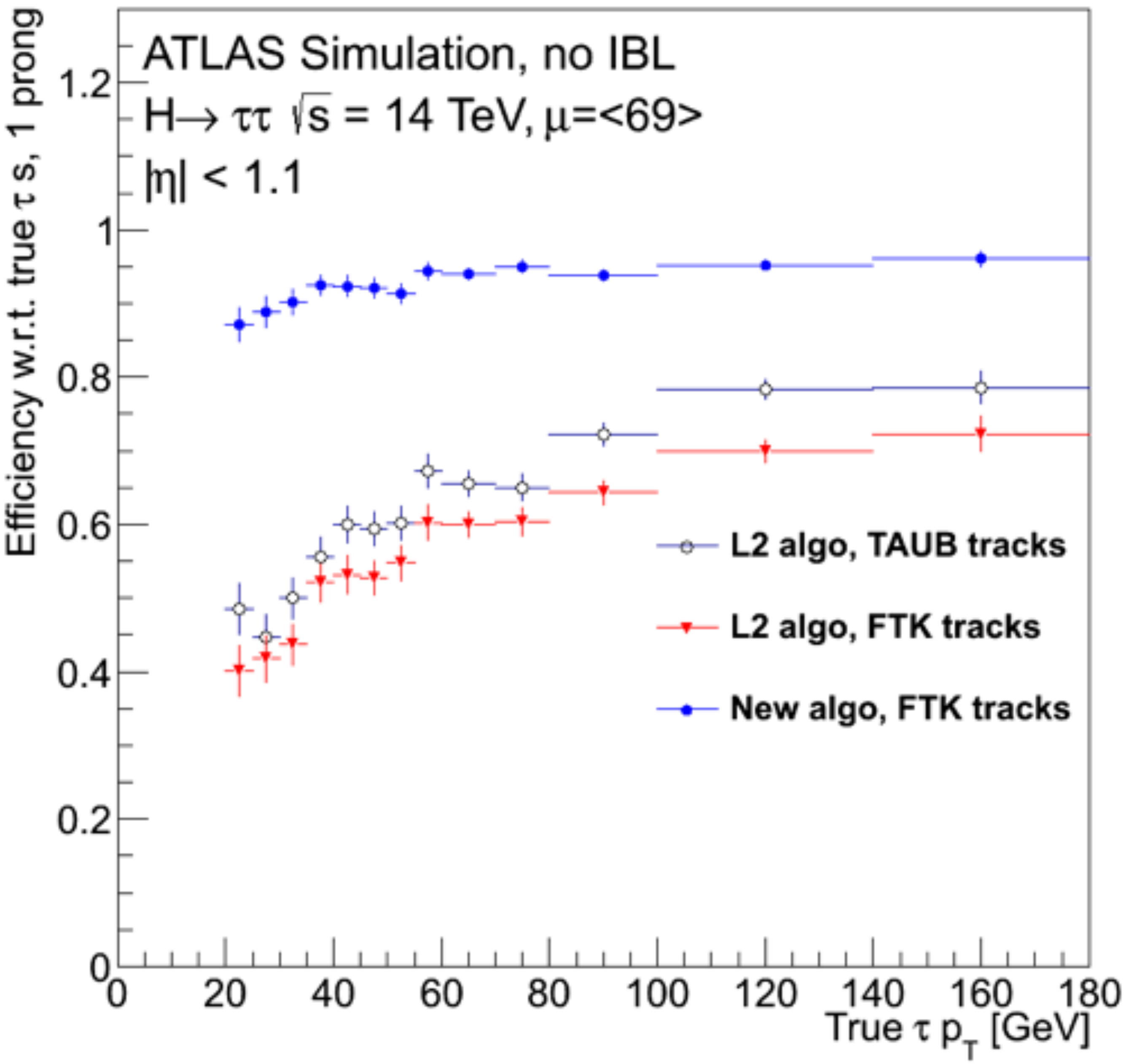


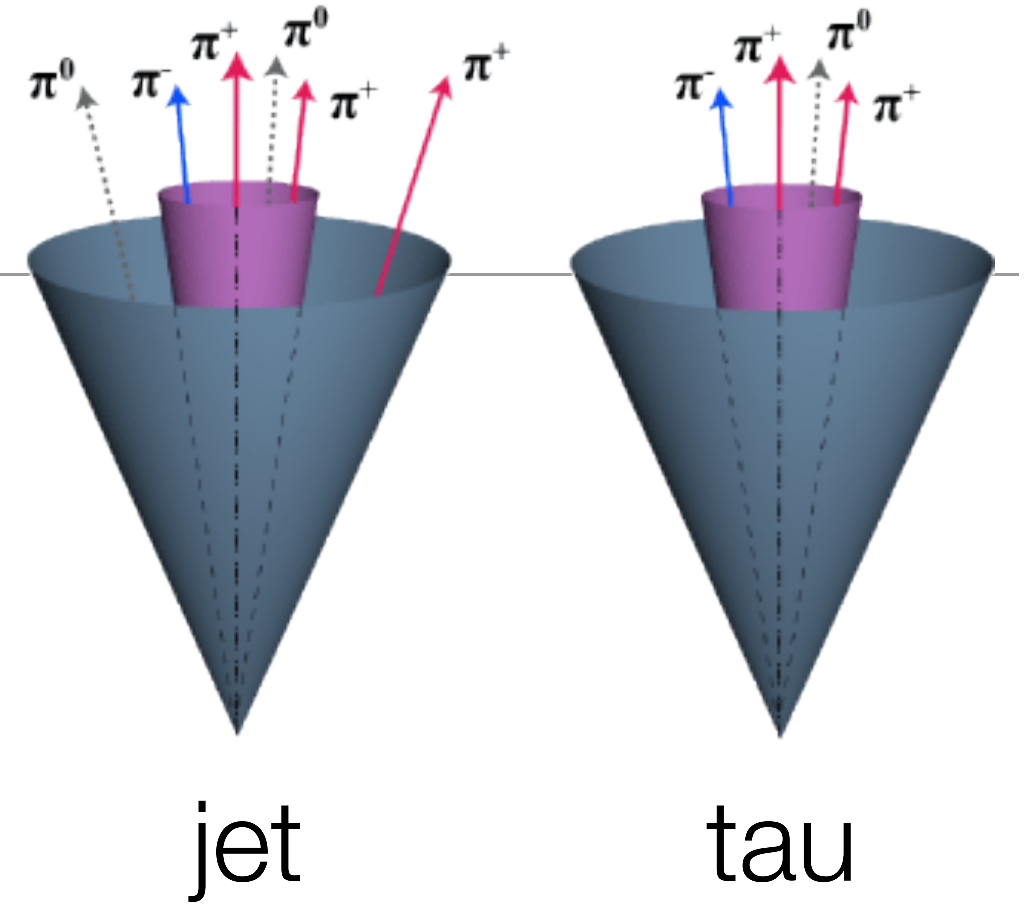
- Use simple 2D Impact parameter significance b-tagger
- For 80% offline point can get 70% or higher relative FTK efficiency
  - Many improvements already implemented, not shown here





Performance: Taus



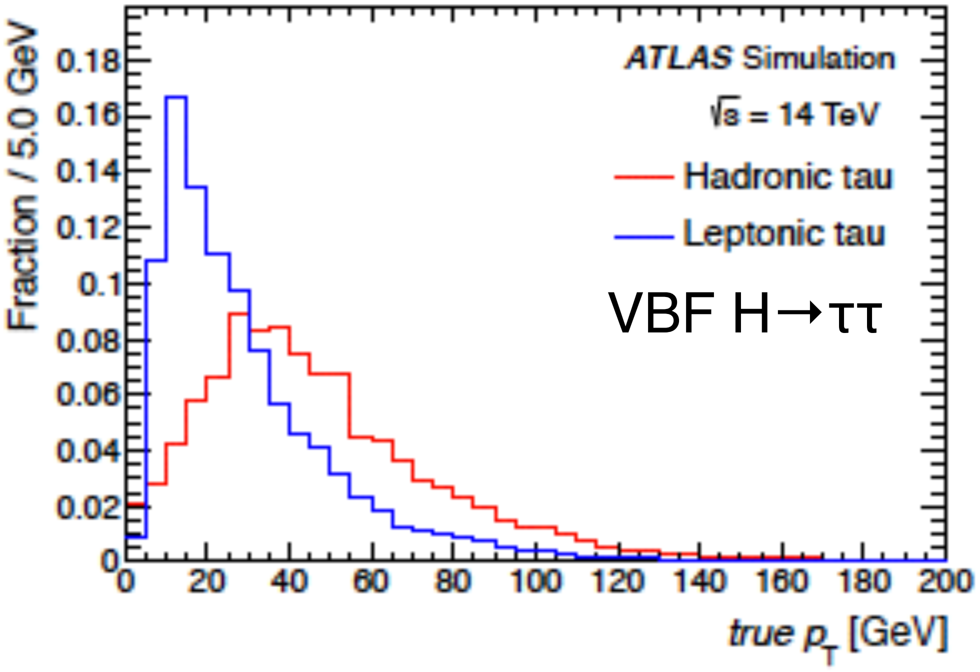


- Tau algorithms run calo selection first, then tracking b/c of tracking time costs
- Integrate tracking from start
  - Then run more sophisticated calorimeter algorithms (not shown here)
  - Need to re-optimize offline in this case!

What FTK Buys Us

- More events with lower energy b-jets:
  - Unless boosted, Higgs events have moderate p_T b-jets: ~50 GeV
  - W/o FTK jet algorithms will apply jet energy threshold before b-tagging—loose efficiency!
  - W/FTK can afford to tag all events which get past first level trigger
  - Improvements for all b-jet physics cases, particularly for VBF Higgs, multi-b jet triggers

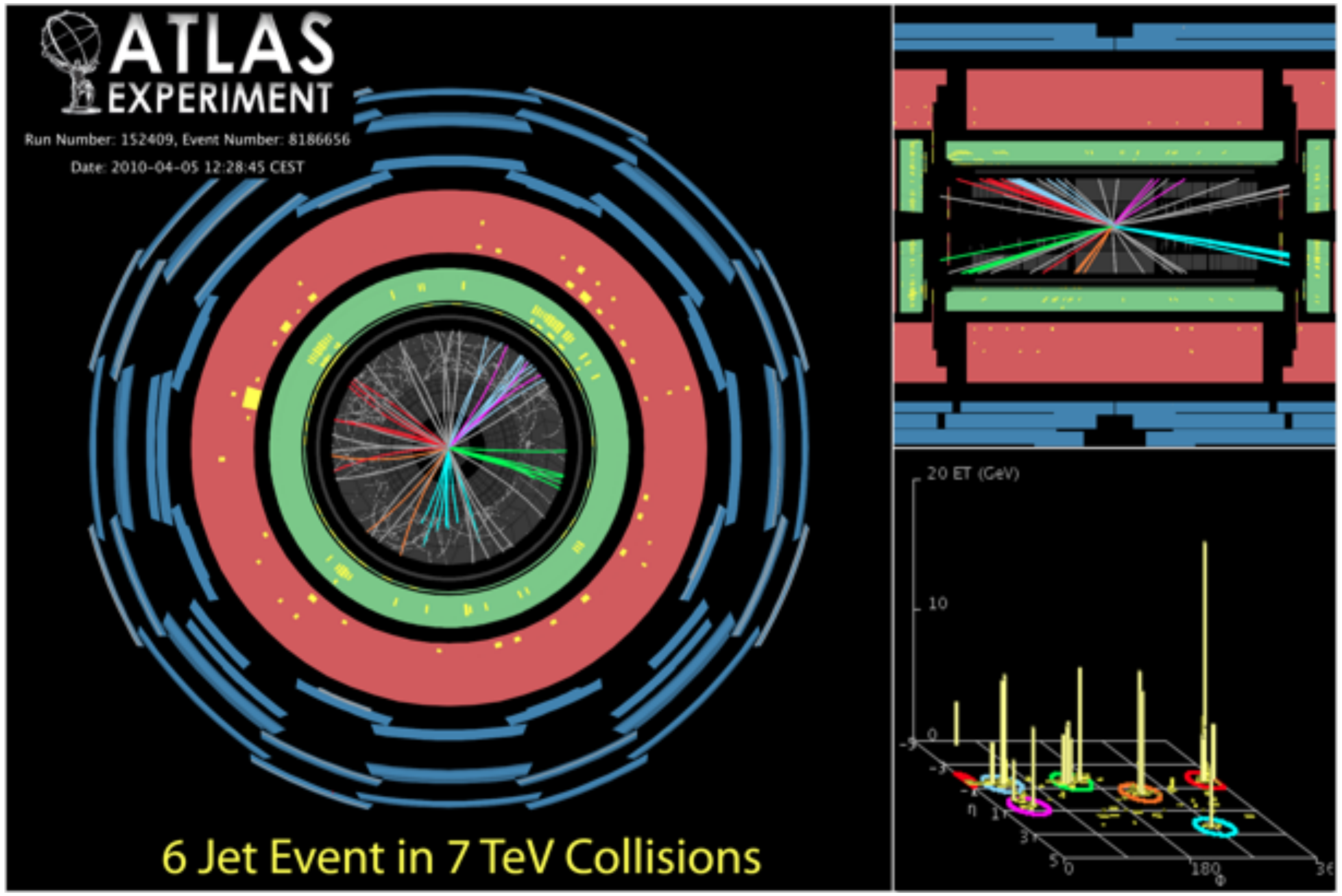
- More taus from Higgs:
  - More efficient selections (at least 30% increase over 2012 selections in VBF Higgs events from preliminary studies)
  - Lower thresholds:optimization in progress, expect reduction of ~15 GeV.



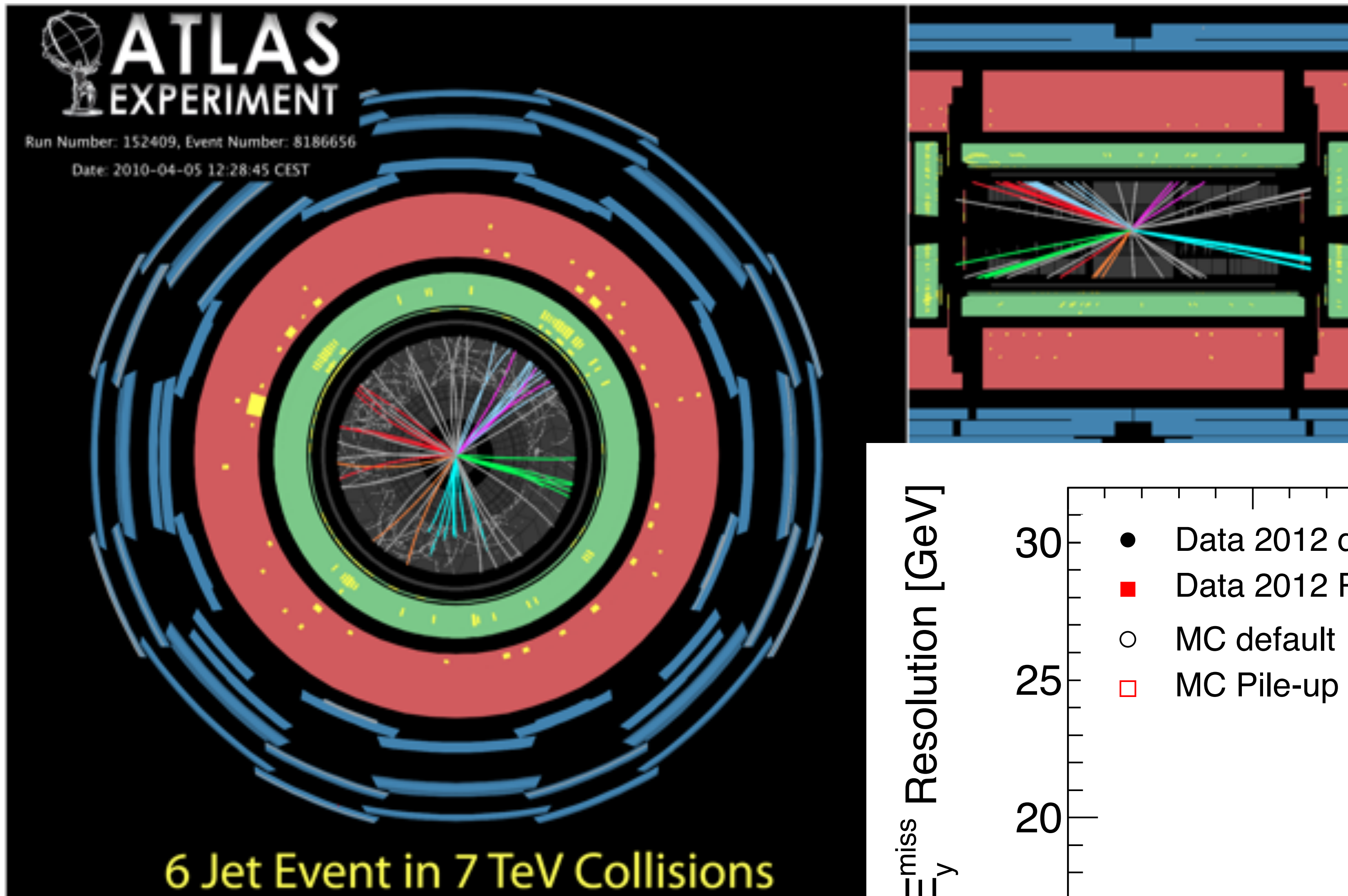
ATLAS-TDR-023

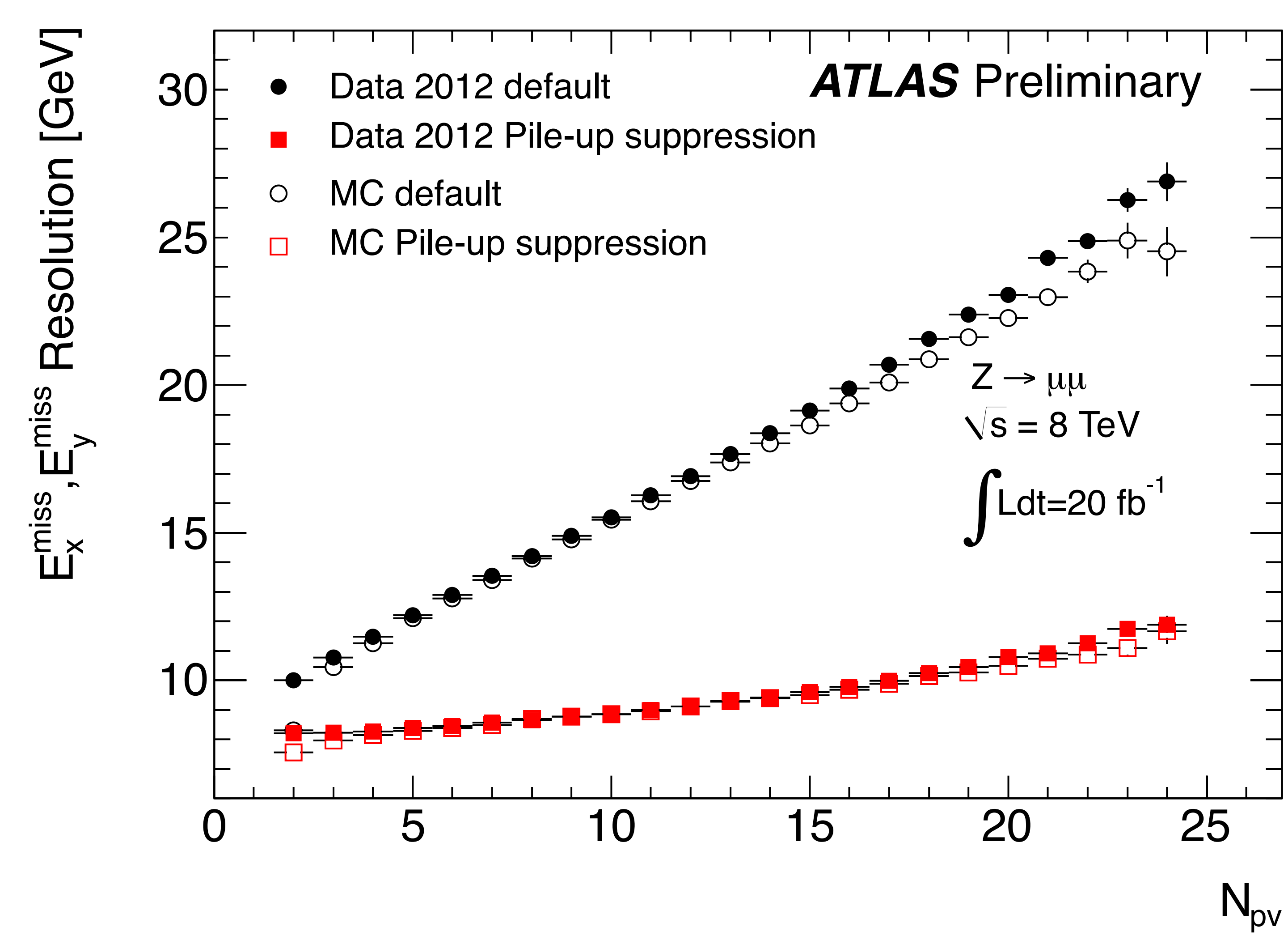
Other FTK Applications

Other FTK Applications



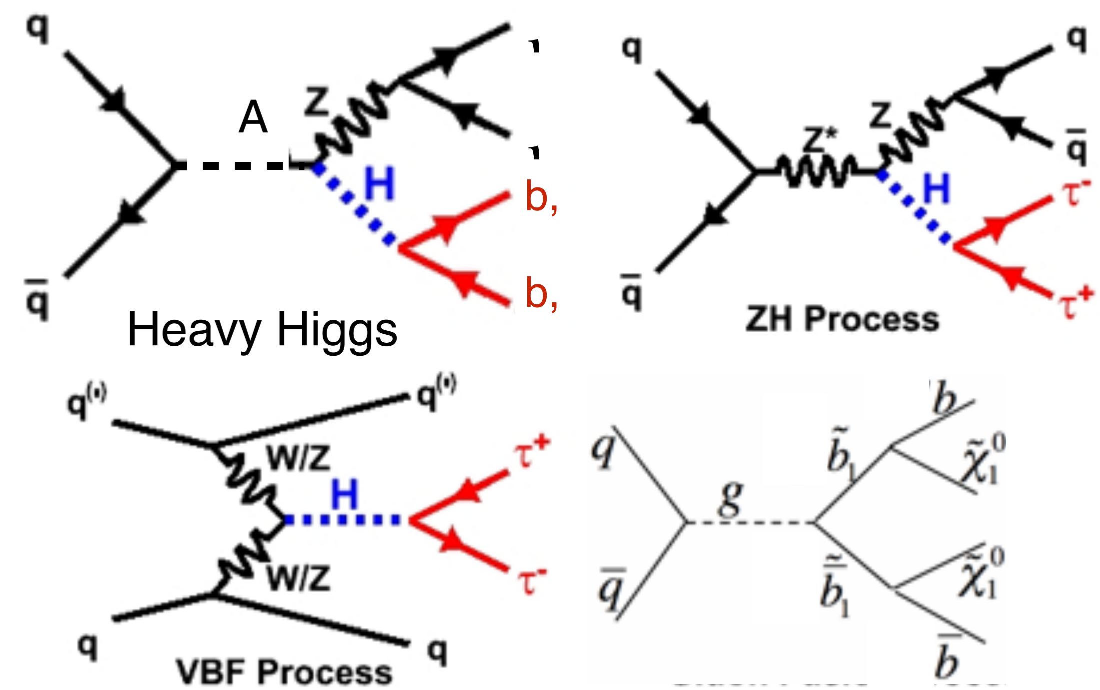
Other FTK Applications

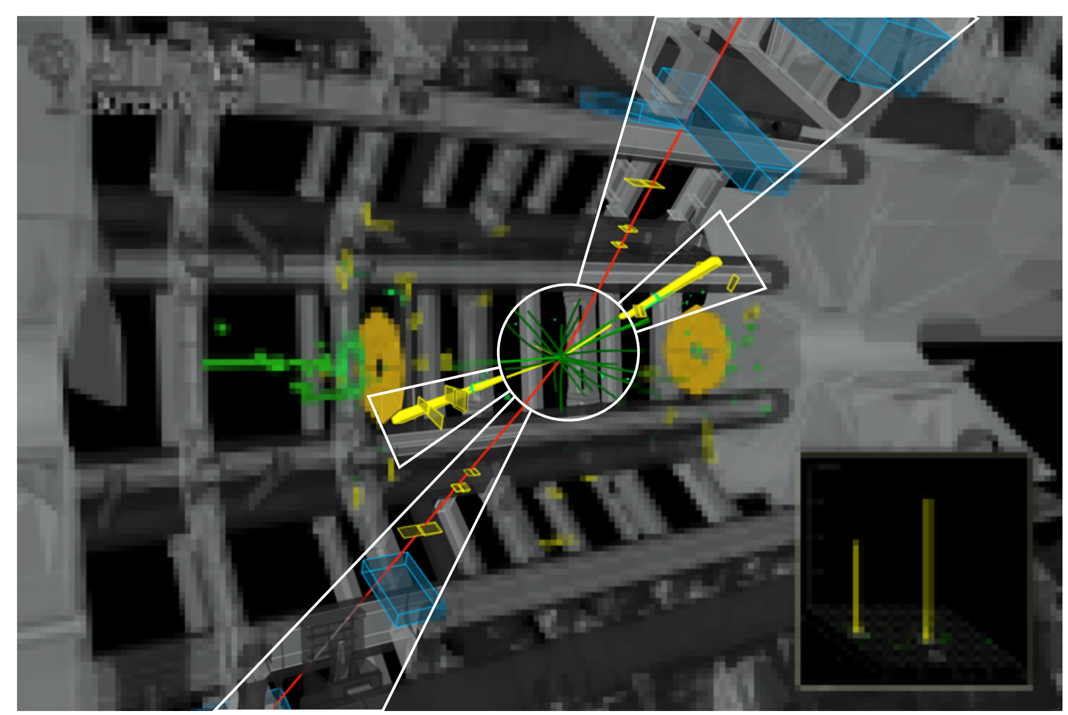




Conclusions

- LHC Run I was a fabulous success but left many questions to be answered
- The Higgs observation opens up new window into physics beyond the standard model
  - Non standard couplings, Multiple Higgses, New resonances decaying to Higgs
  - Third generation particles will be key to exploring the new landscape & answering those questions
- The rest of the LHC lifetime will be a challenging environment
  - Up to an average of 80 simultaneous interactions
- FTK will allow ATLAS to cope with the challenges of RunII&III and will be critical for final states with bs and taus

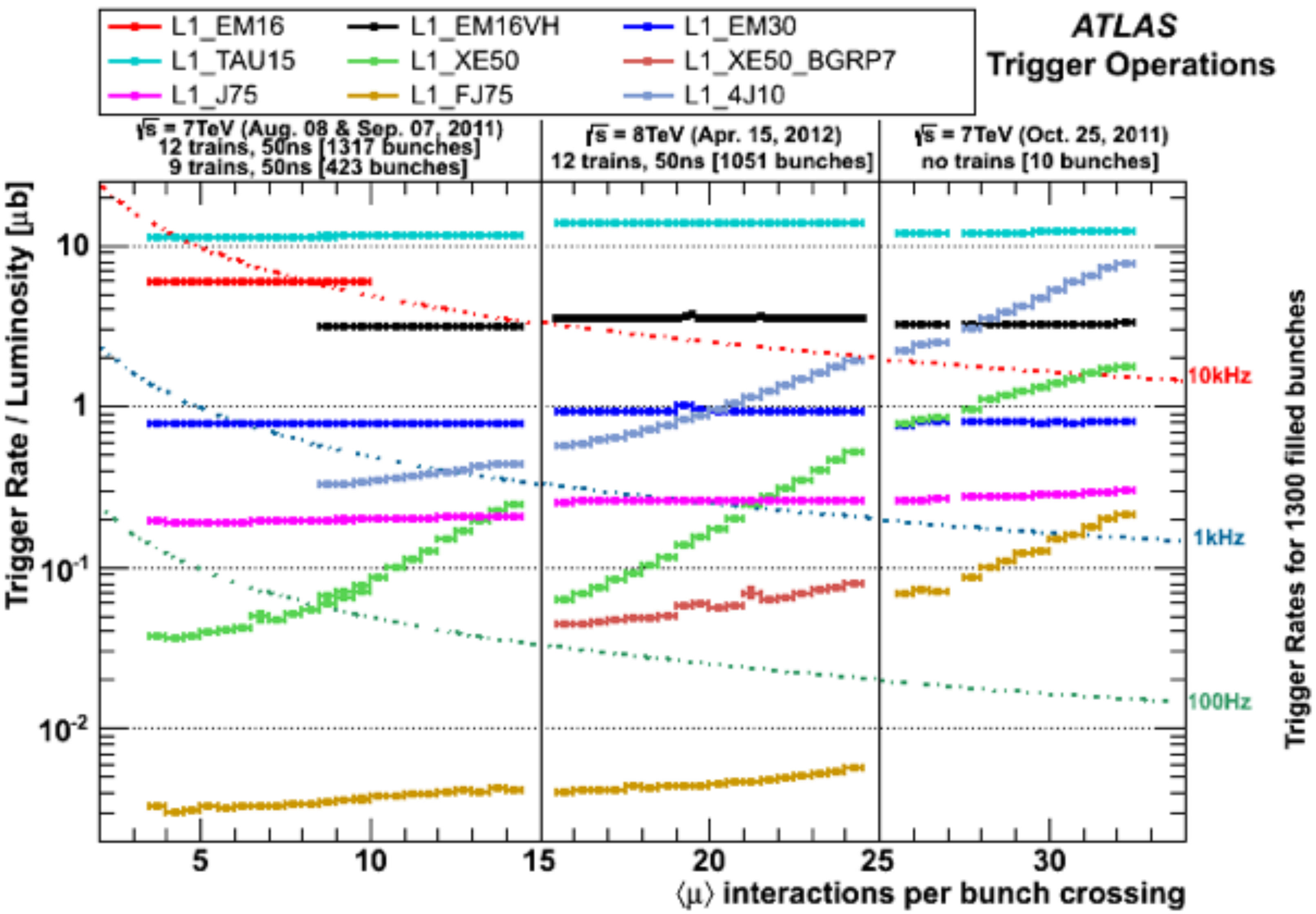




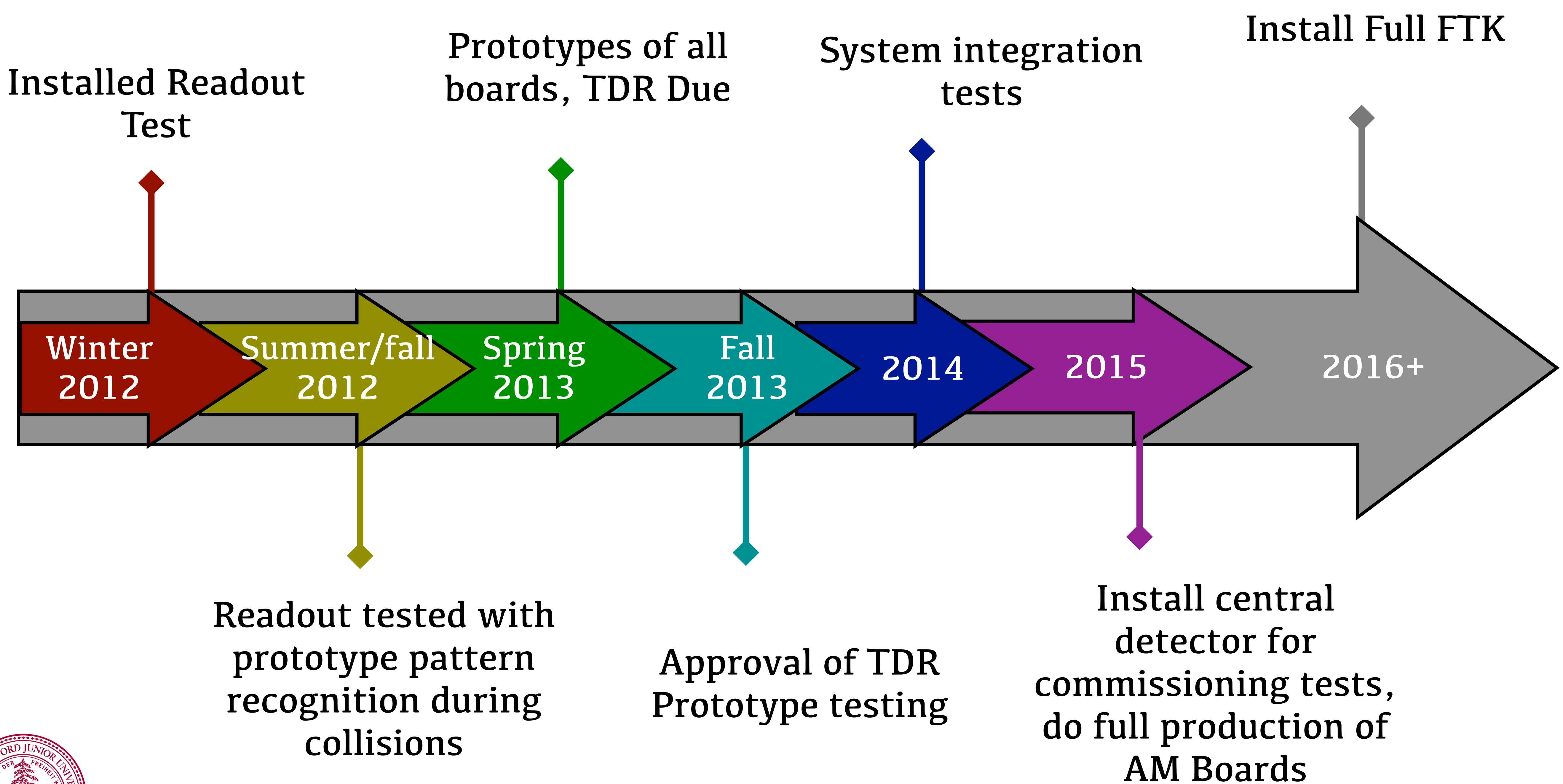
Back-up

Triggering: A major challenge

- At 40-80 interactions per crossing, triggering is very hard!
  - $W \to l\nu$ has 1kHz rate @ 80 PU : Saturates output rate!!
- Particularly a problem for triggers with missing energy, multi-jets

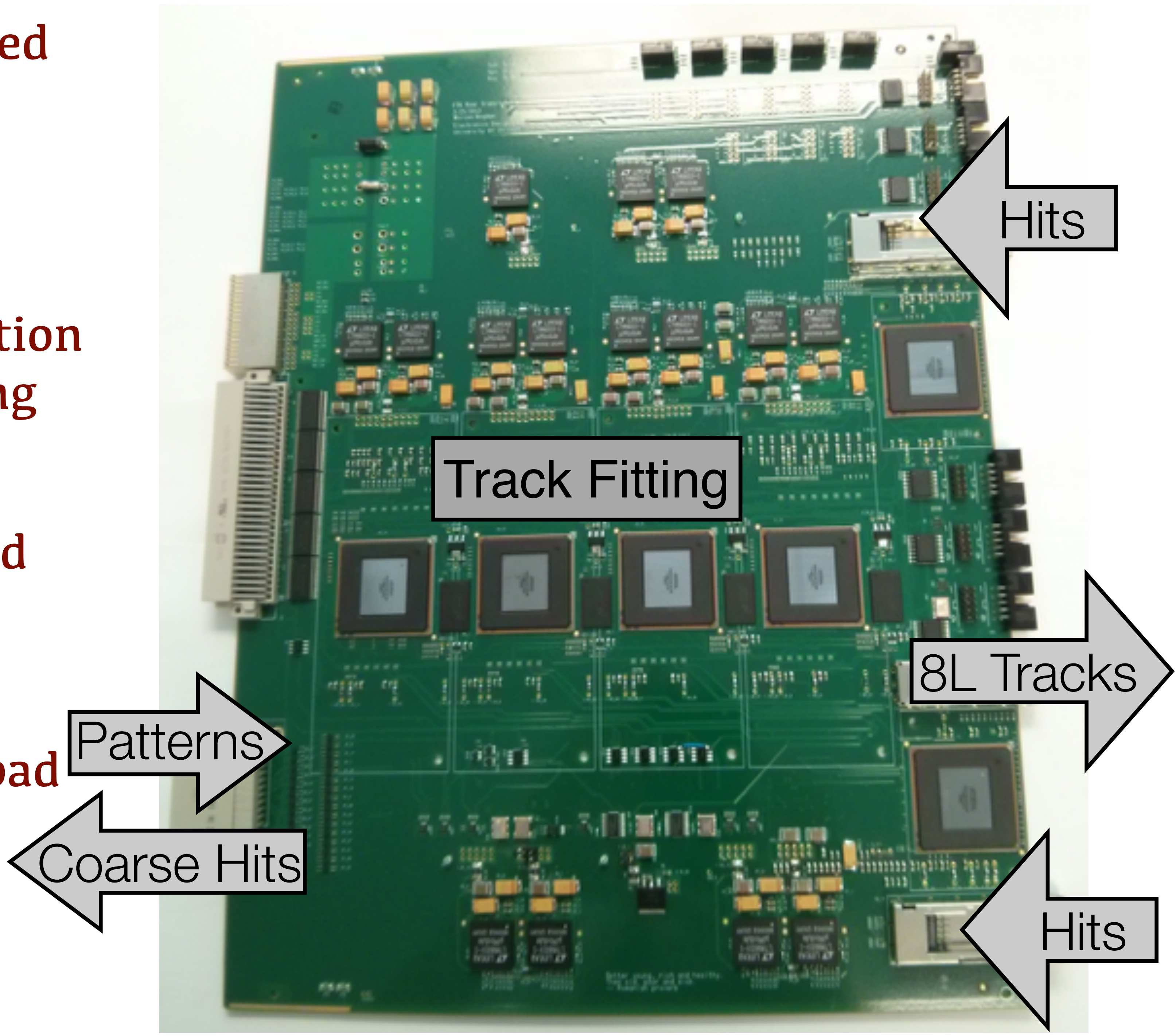


FTK Status and Plans



The AUX Card

- Track fitting (and more!) carried out in Auxiliary Card
  - 128 in entire system!
- Converts hits to coarse resolution hits, sends to pattern matching
- Receives matched patterns and fetches full resolution hits
- Performs 8 layer fit to reject bad patterns
- Sends hits to 12 layer fit



What Have We Learned about this Higgs Boson?

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- It's a **scalar** particle

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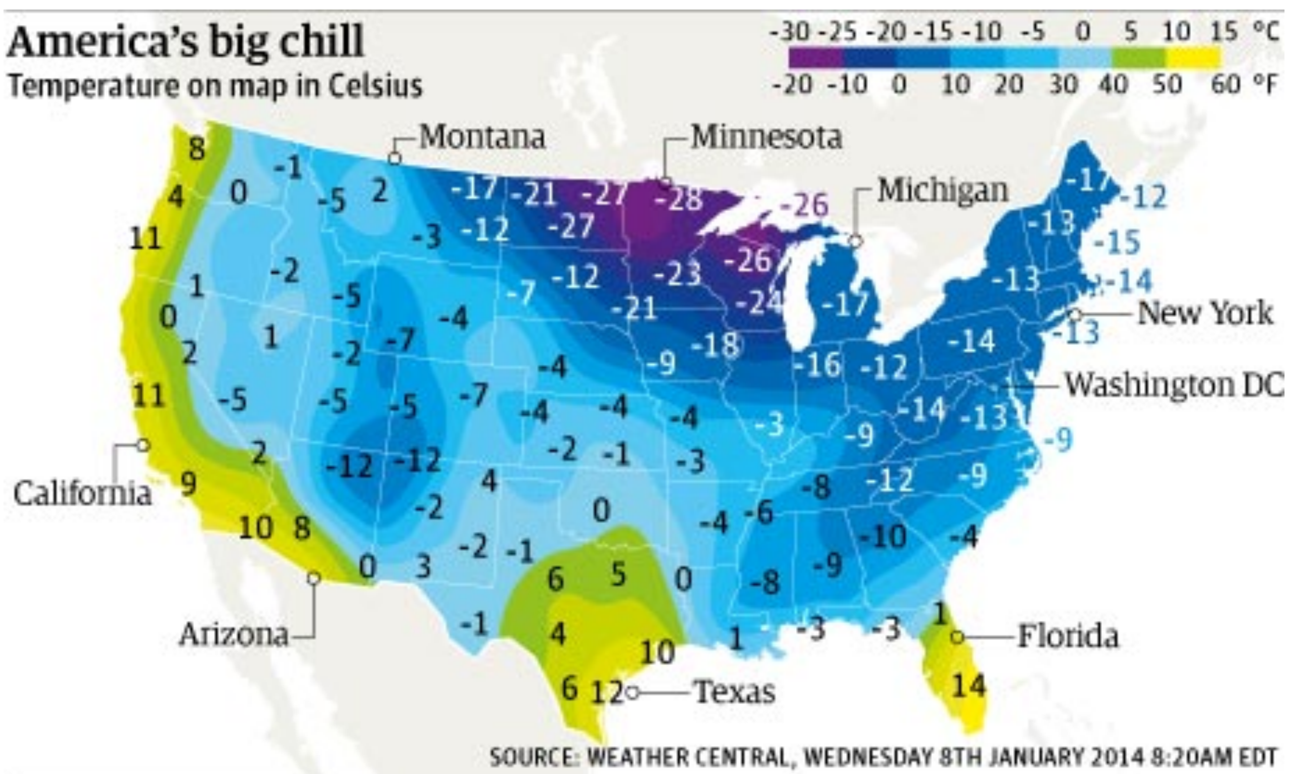
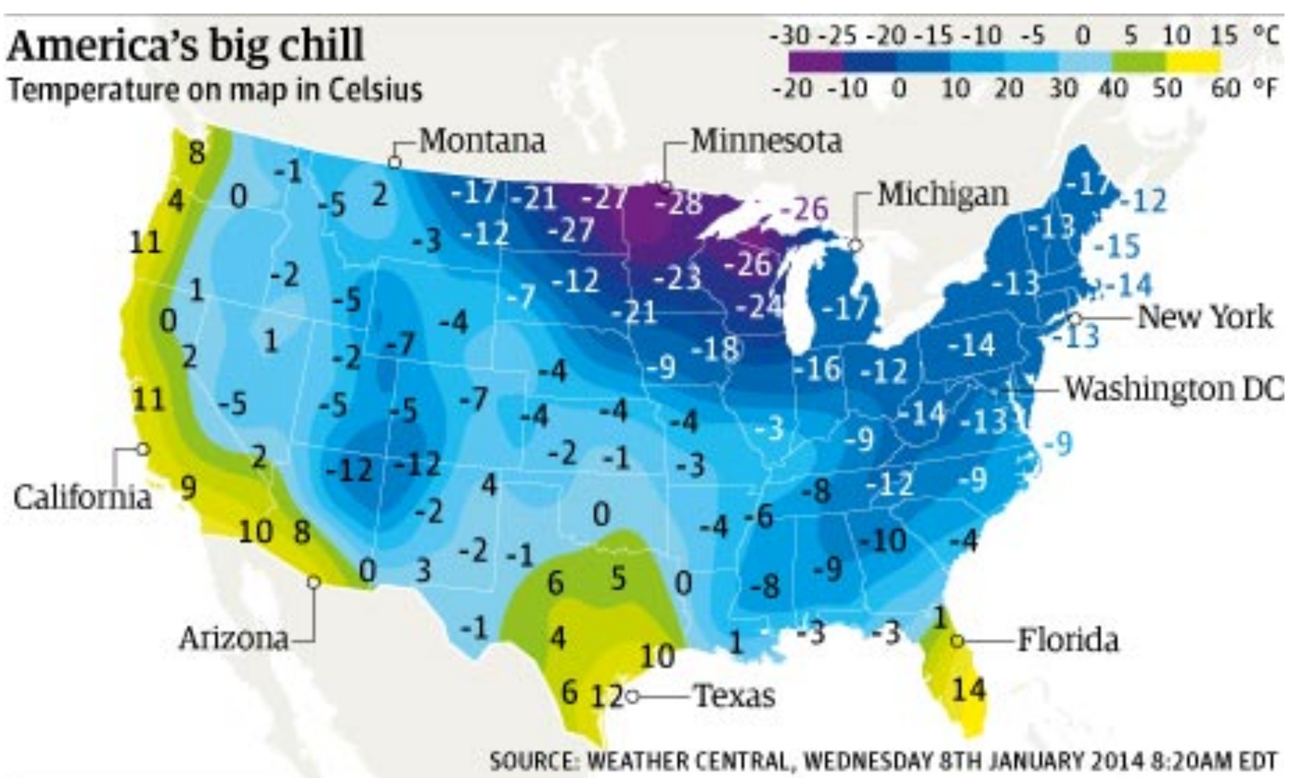
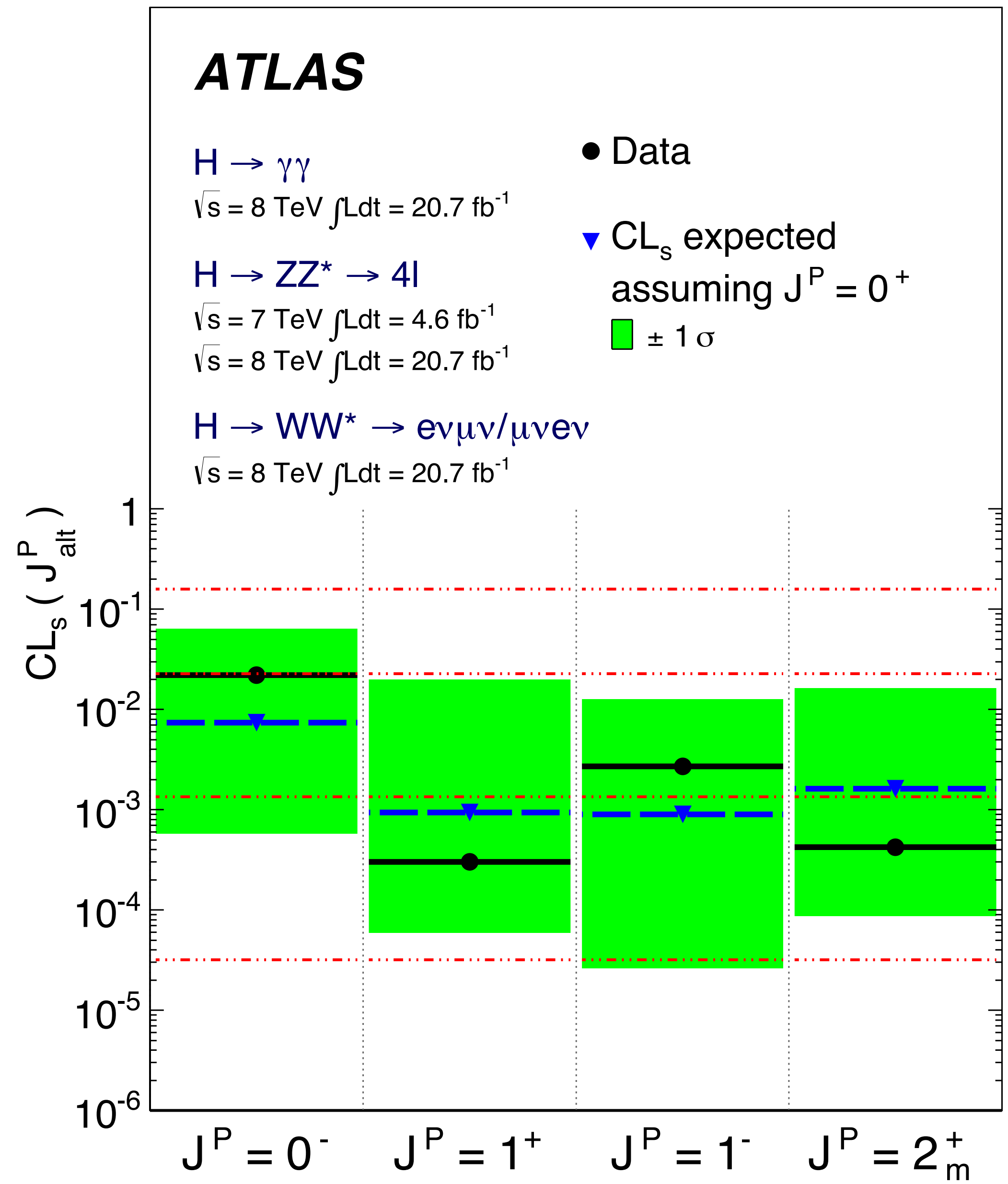


What Have We Learned about this Higgs Boson?

- It's a **scalar** particle





LHC Plan*

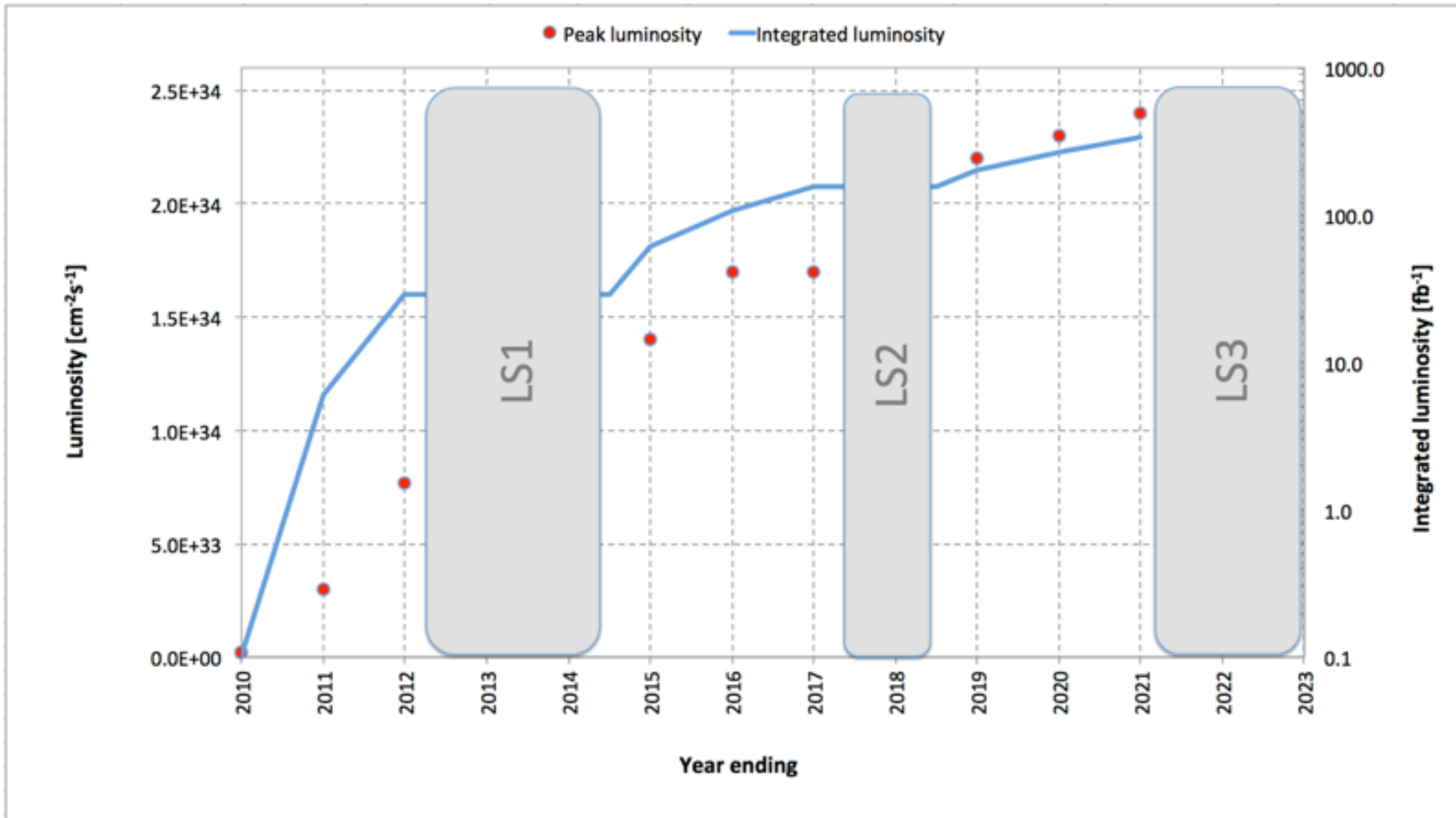
- Experiments request: 25 ns running with no significant 50ns dataset
- Machine reality: 50ns is easier/safer and will be used for 13 TeV commissioning before moving to 25 ns.
- Plan:
  - Low intensity for first 2 months, low number of bunches
  - Intensity ramp up with 50 ns (1-2months)
  - 50ns nominal running at <mu> of 40 to characterize machine
  - 25ns commissioning
- May have to run at lumi-leveled 50ns operation if 25ns has problems
- Stable operations possibilities:

Scheme	N_b	ppb (10^{11})	β^* [cm]	emittance [μm]	peak	pile-up	$\mathcal{L}$ [fb^{-1}]
25 ns	2760	1.15	55/43/189	3.75	9.3e33	25	24
25 ns BCMS	2760	1.15	45/43/189	1.9	1.7e34	52	45
50 ns	1380	1.65	42/43/189	2.3	1.6e34	87	40†
50 ns BCMS	1380	1.6	38/43/189	1.6	2.3e34	138	40†

See Talk by O.Bruning for details

*Evian Summary †Lumi-leveled

Run II and III conditions



7 TeV 8 TeV ~13 TeV 13-14 TeV

2015+ ATLAS Trigger System: Simplified

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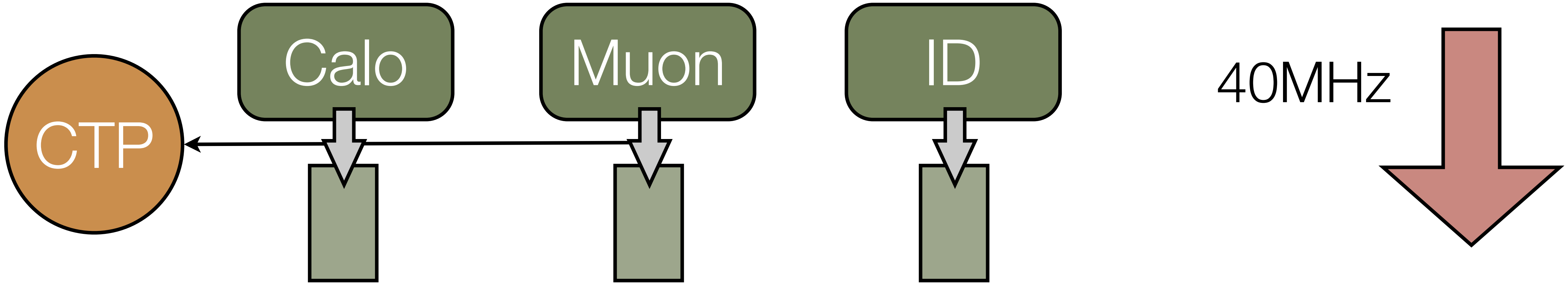
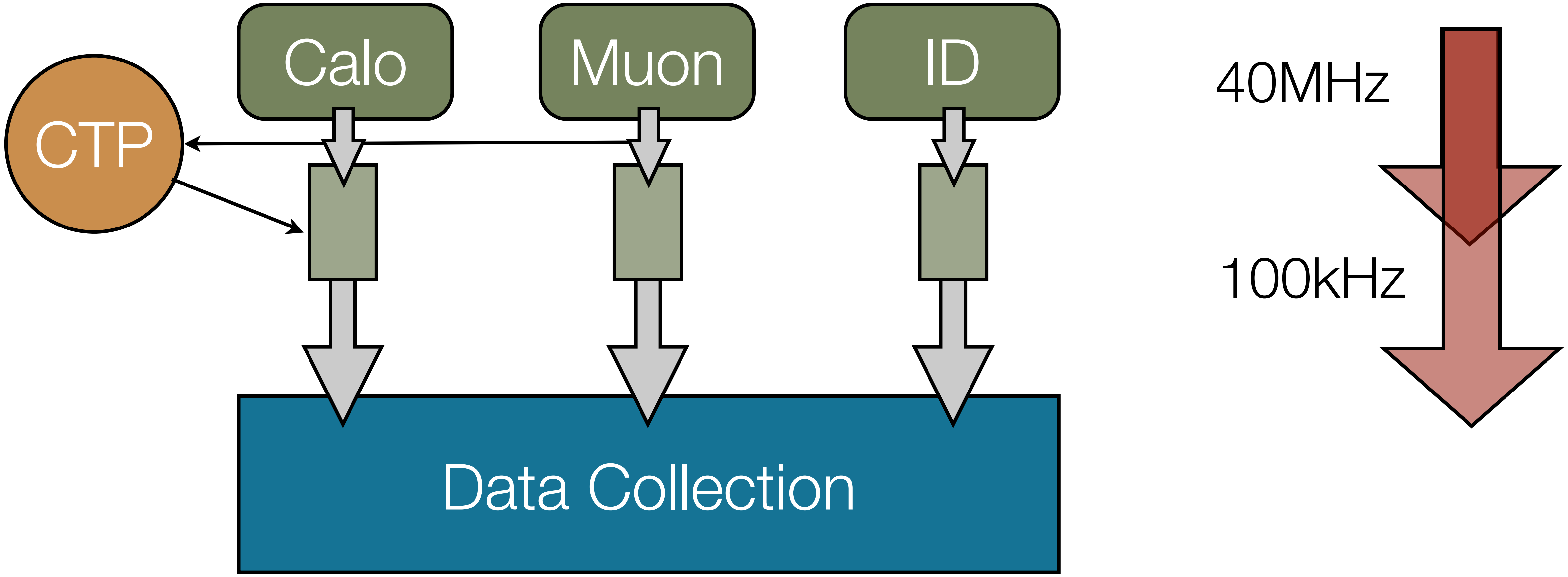


2015+ ATLAS Trigger System: Simplified



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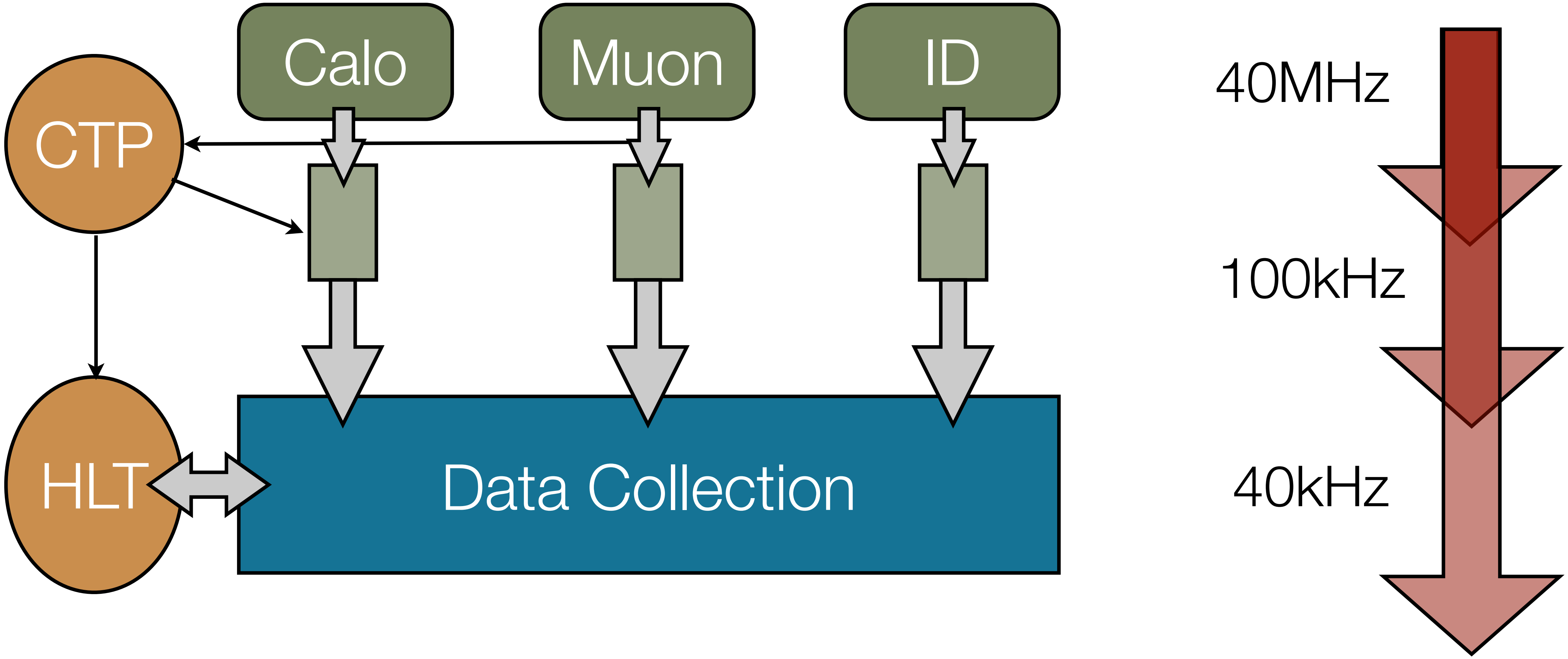

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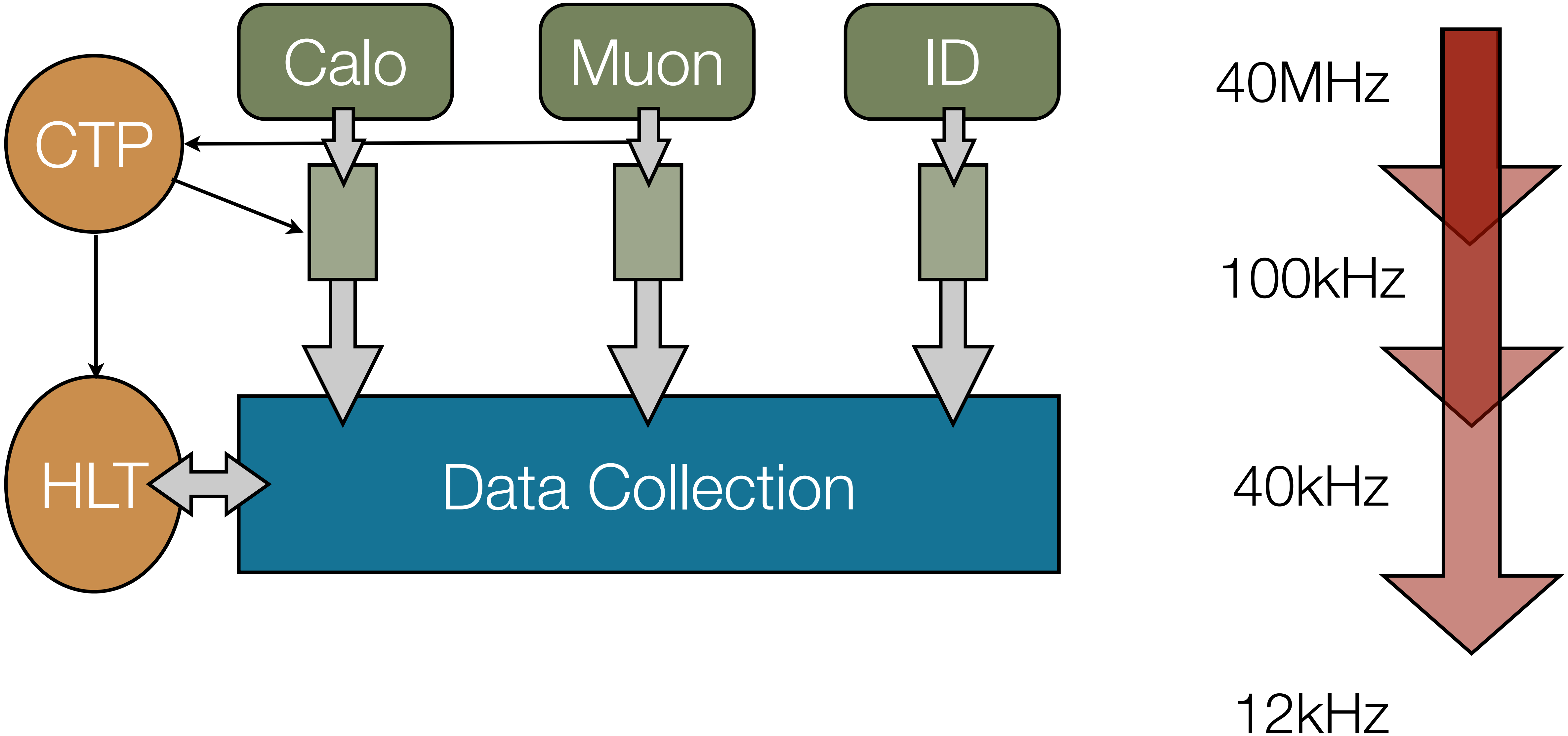

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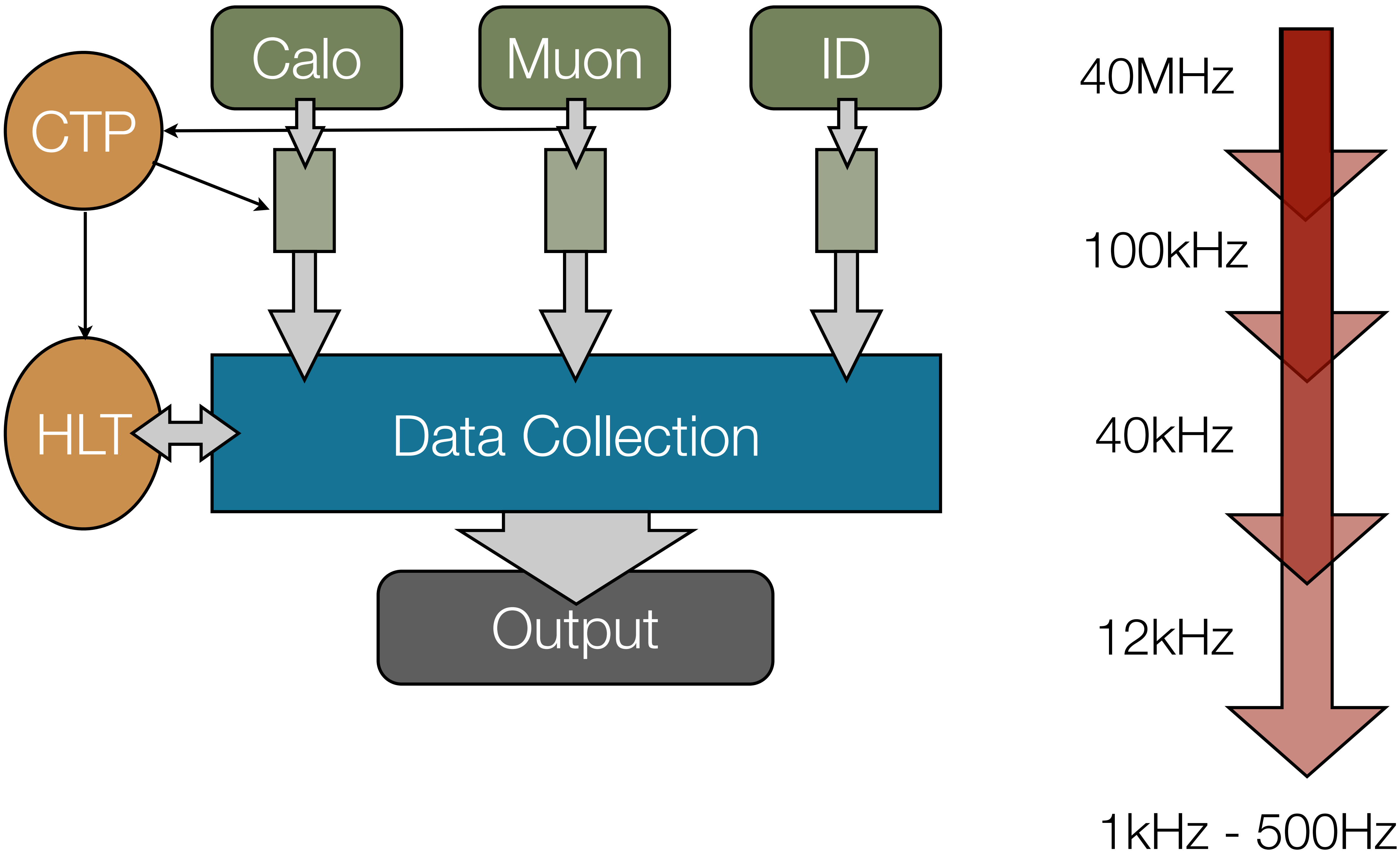

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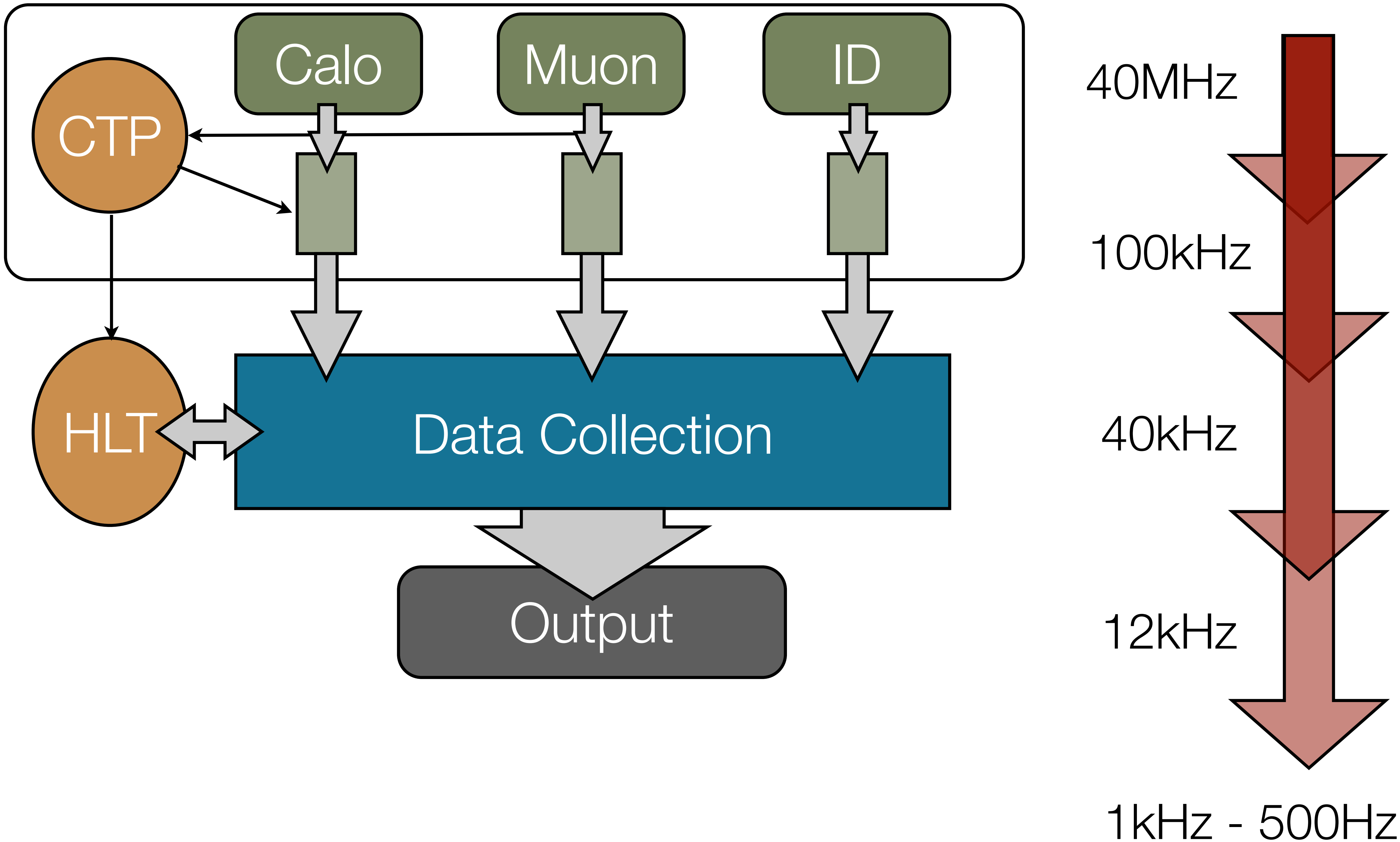
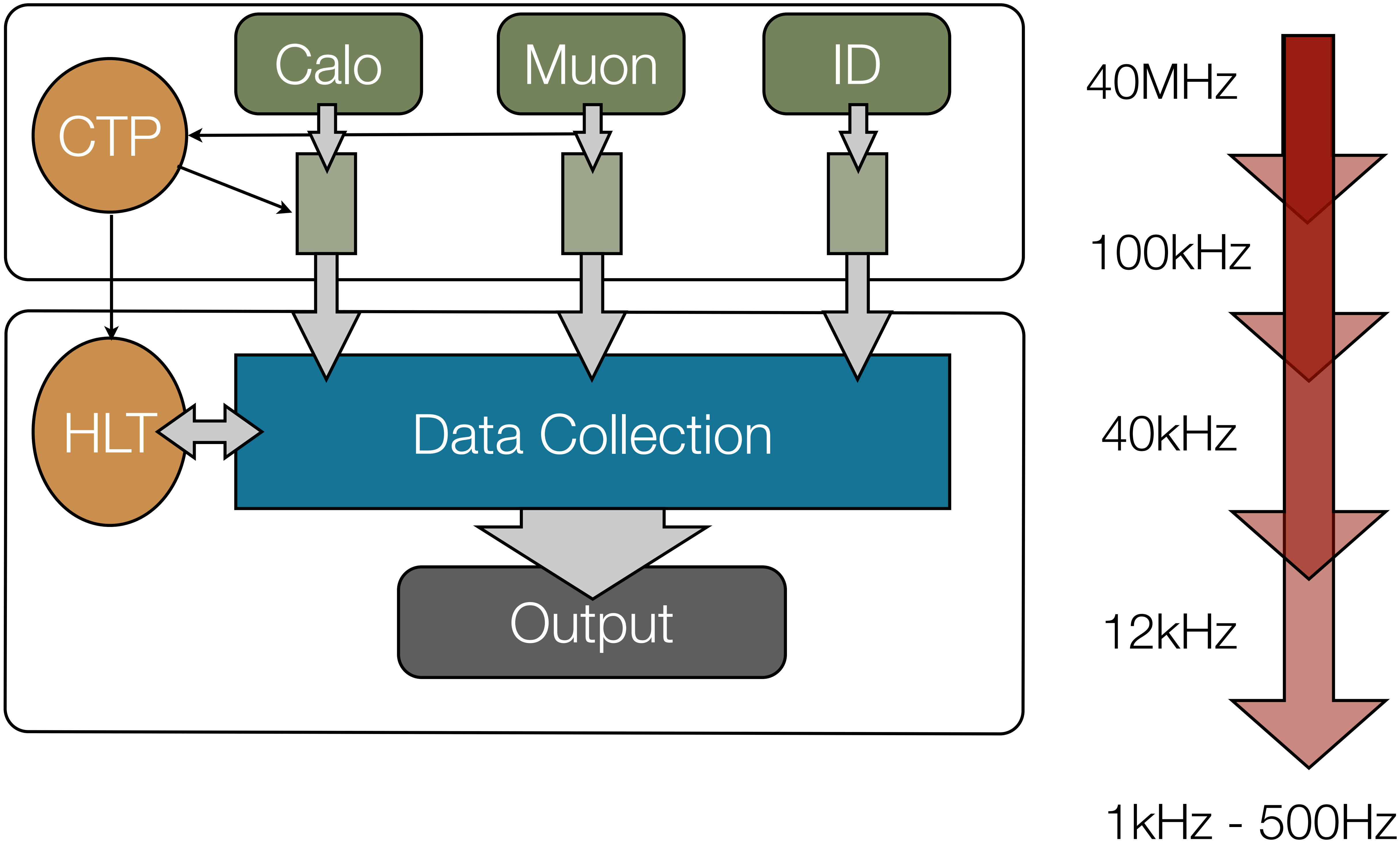
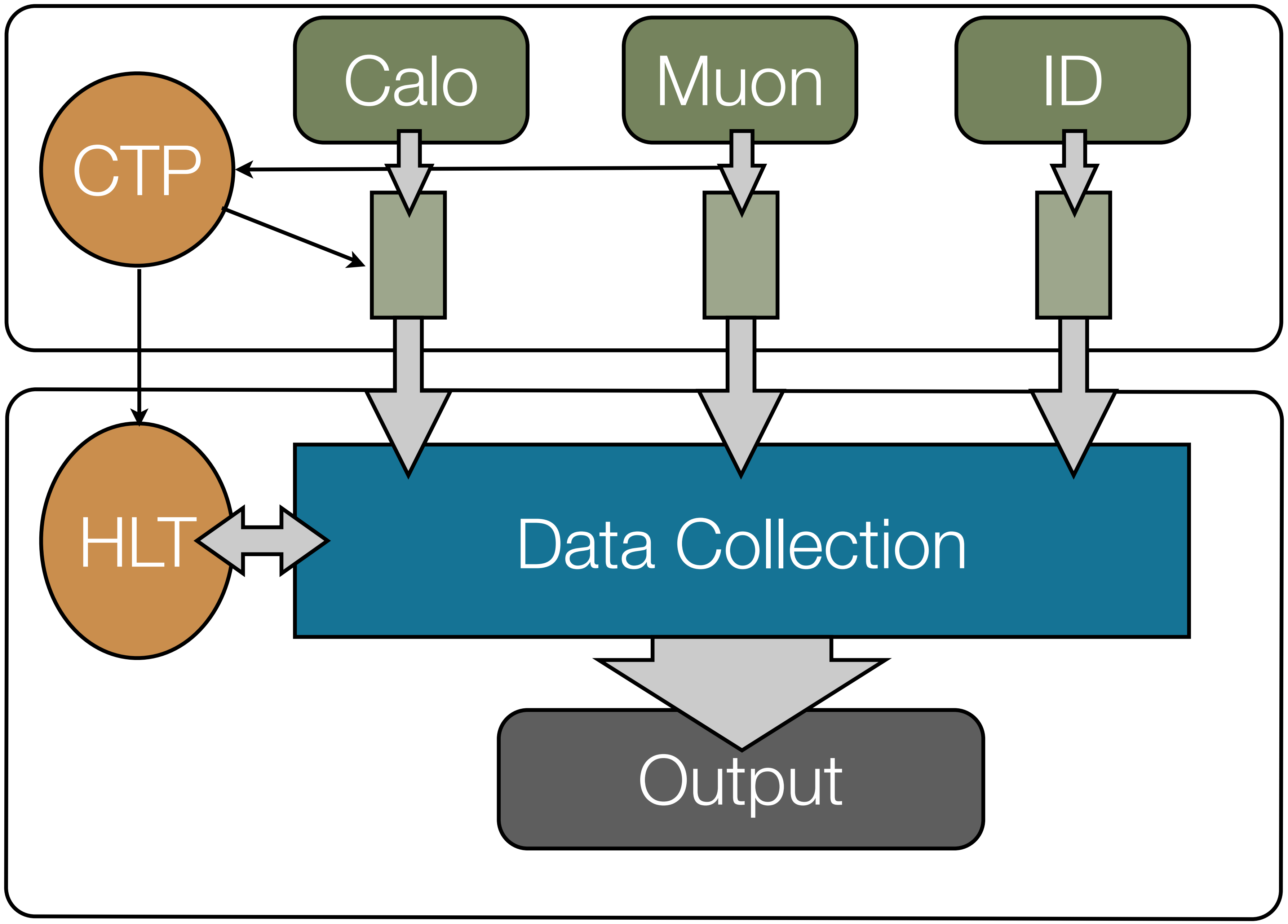


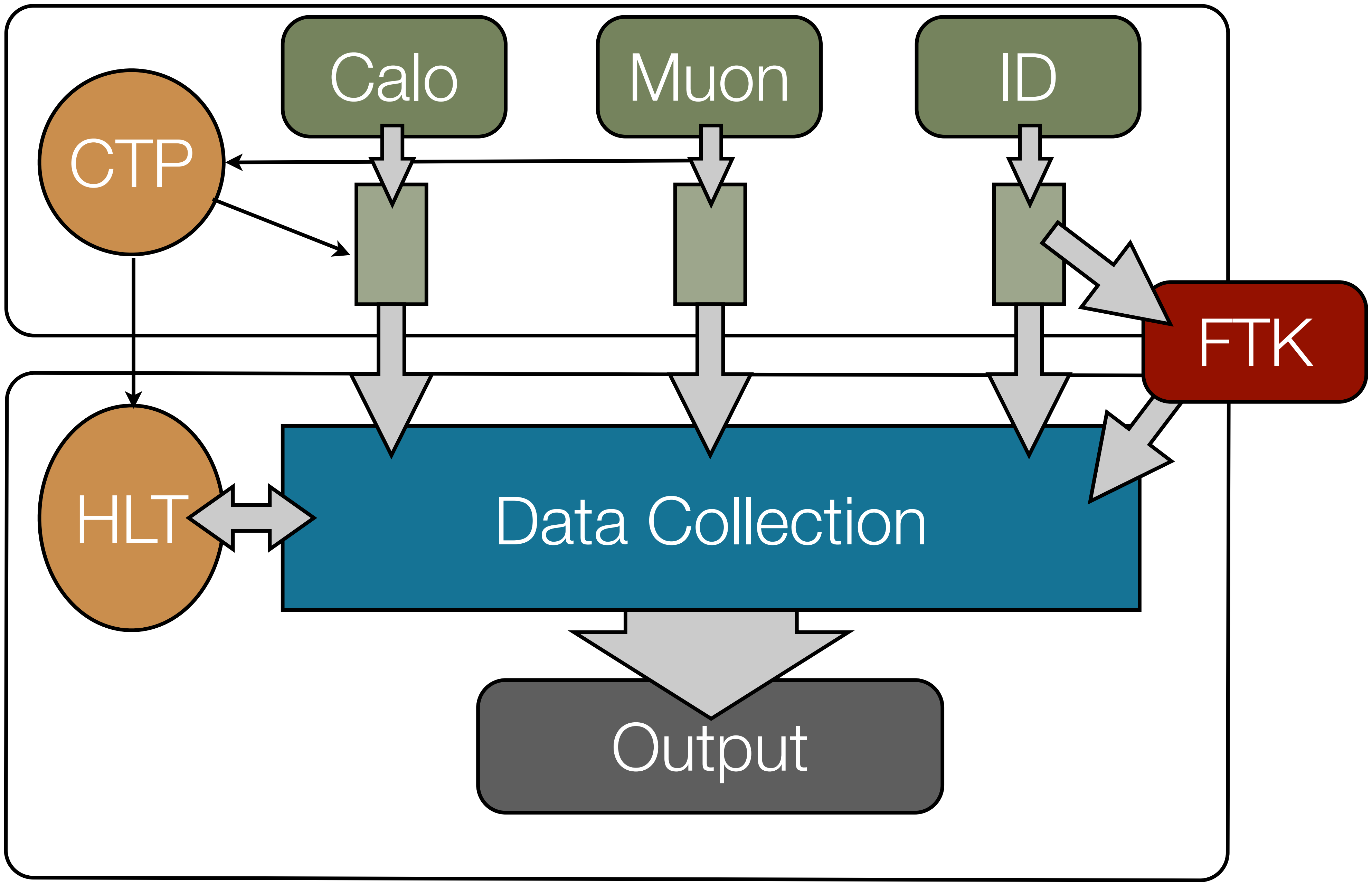
2015+ ATLAS Trigger System: Simplified



FTK in the ATLAS Trigger System

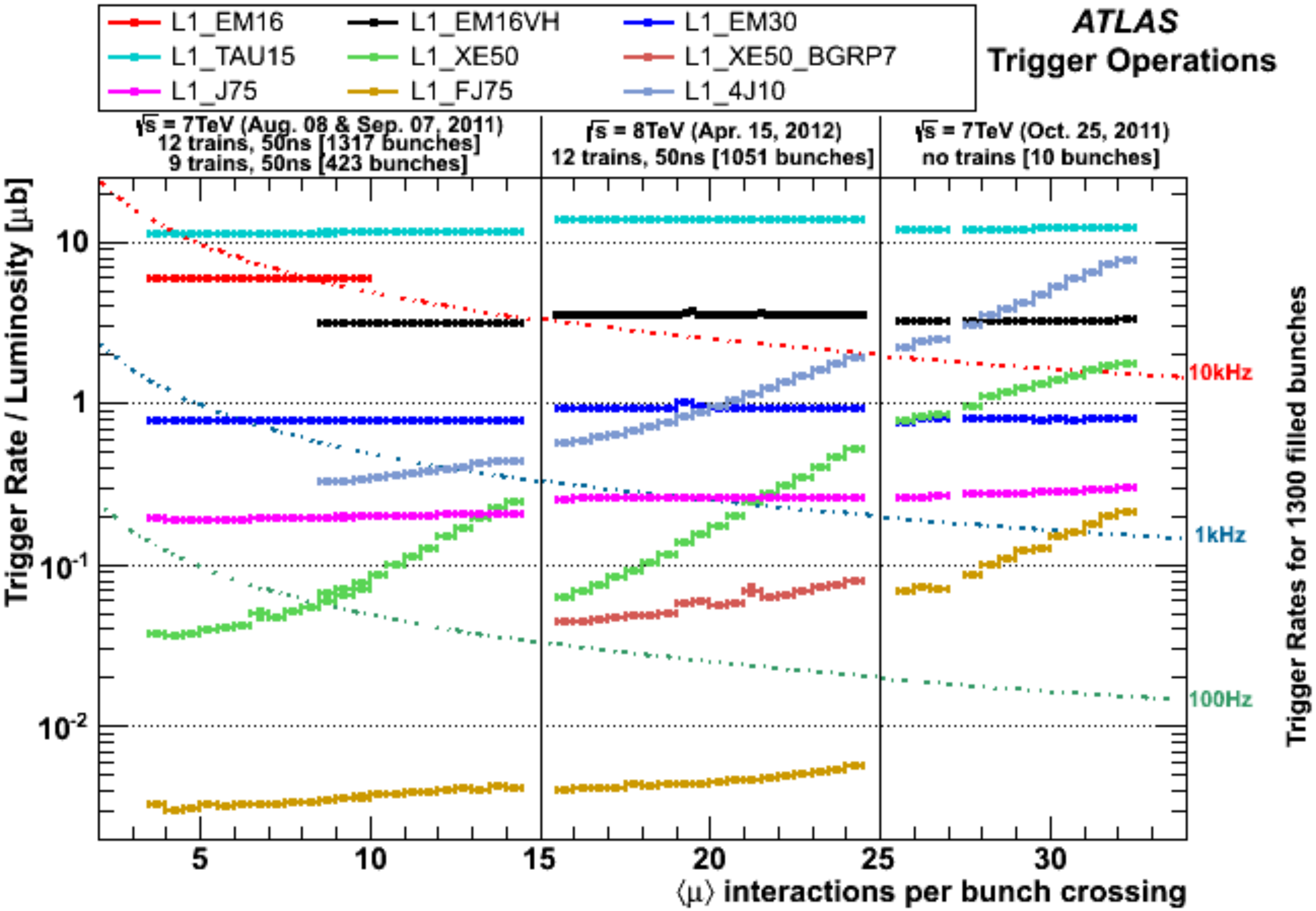


FTK in the ATLAS Trigger System



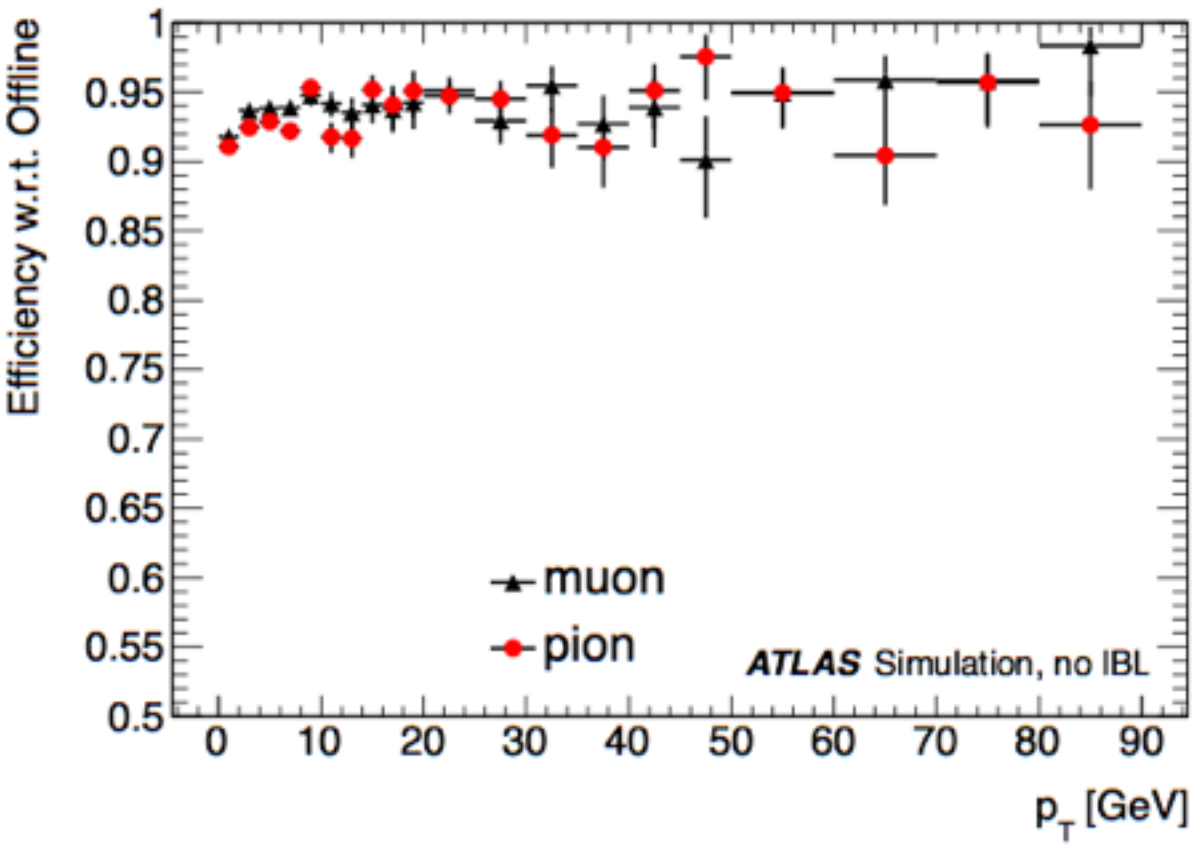
100kHz
Latency:
O(100μs)

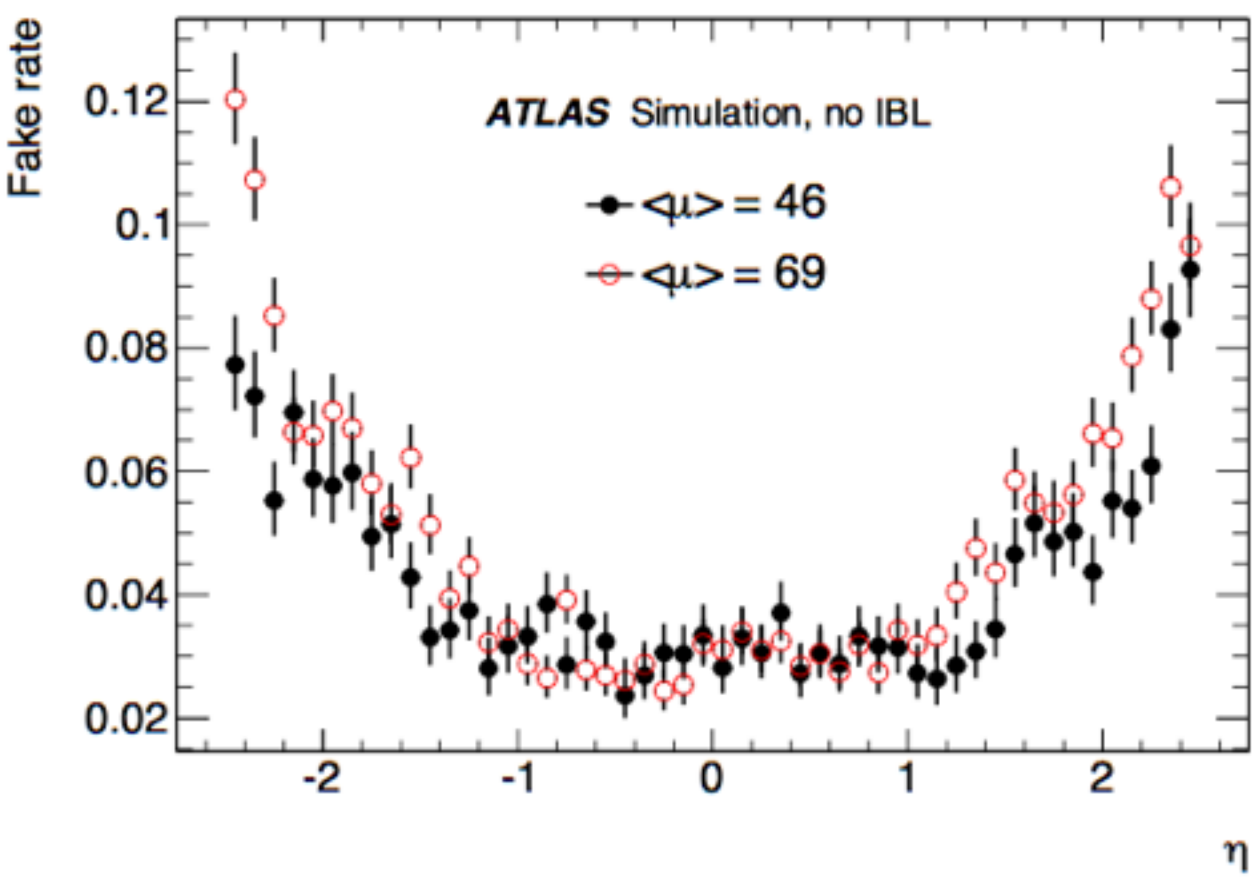
Trigger rate evolution



Efficiencies & Fake Rates

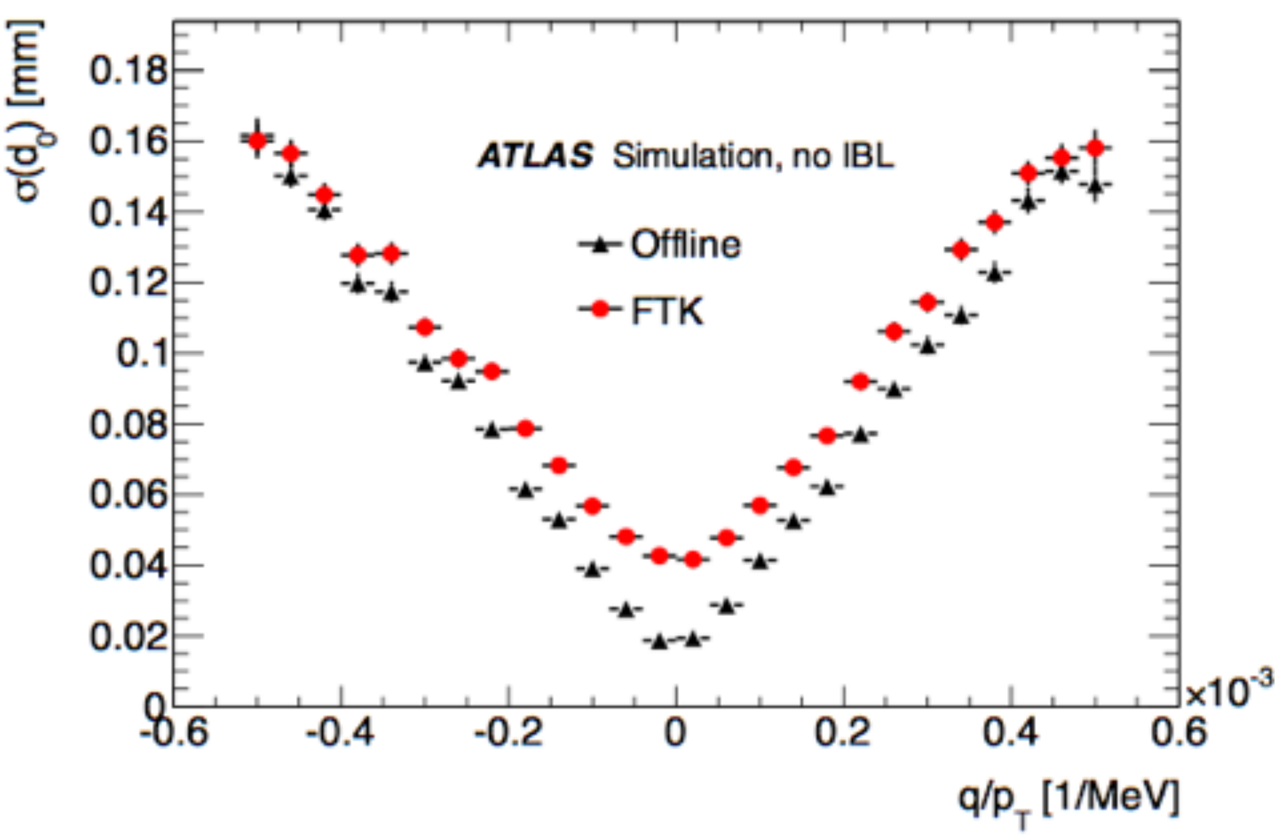
- 93-94% efficiency with respect to offline tracks
- 3% fake rate at central eta, up to 10% at high eta

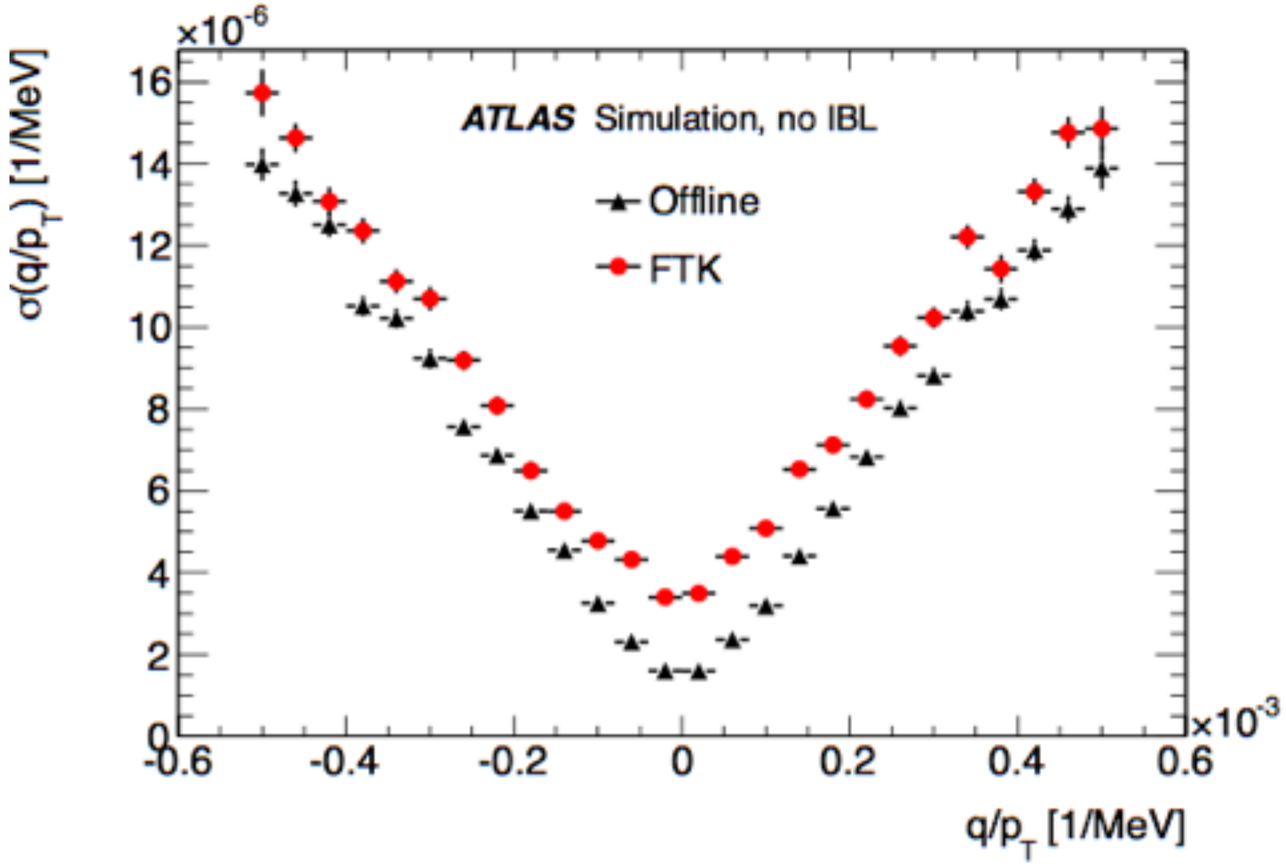




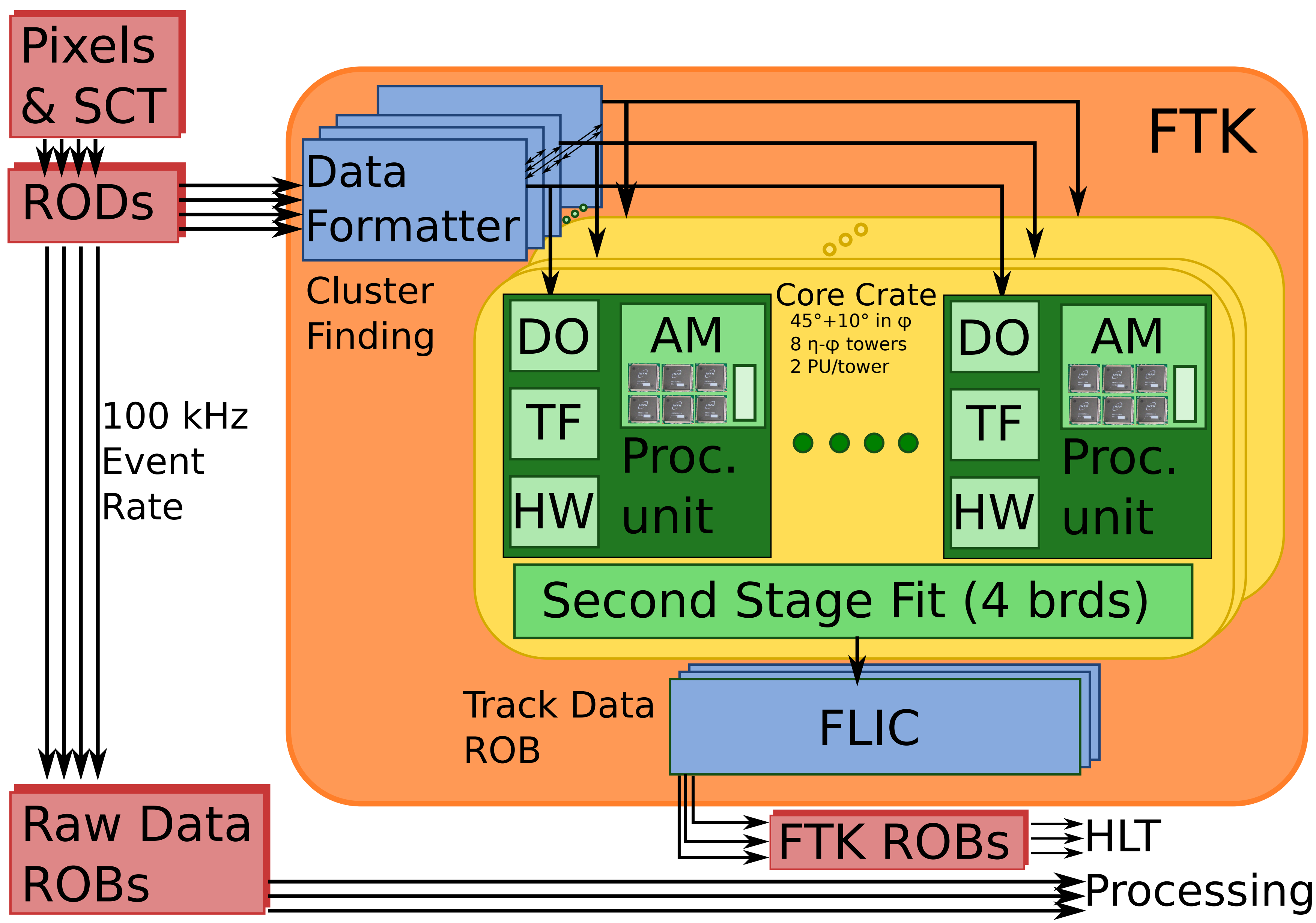
Performance: Resolutions

- Similar resolution to offline tracks at low p_T, ~2x worse at highest p_T
  - Improved with some clustering changes (not shown here)



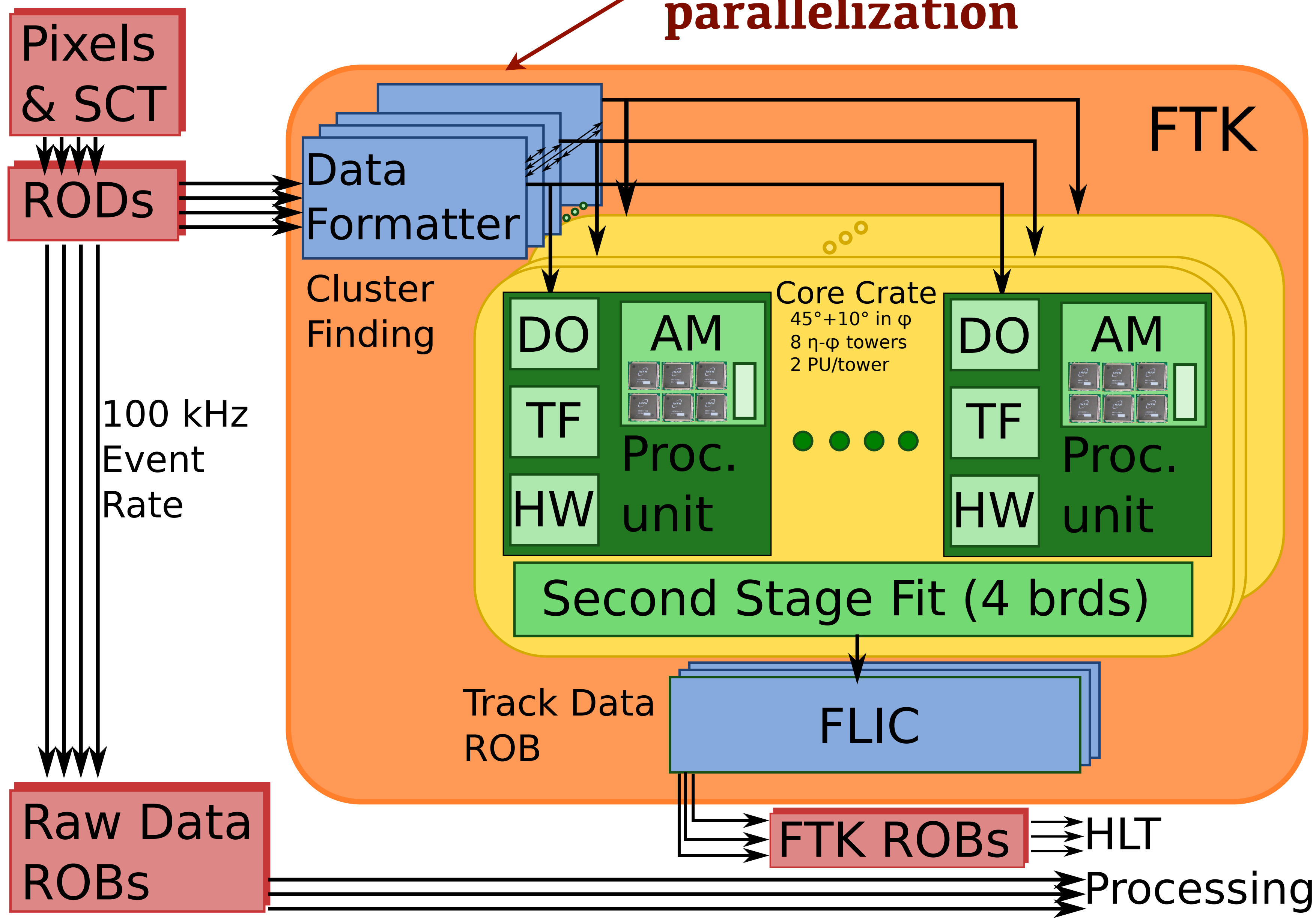


System Architecture



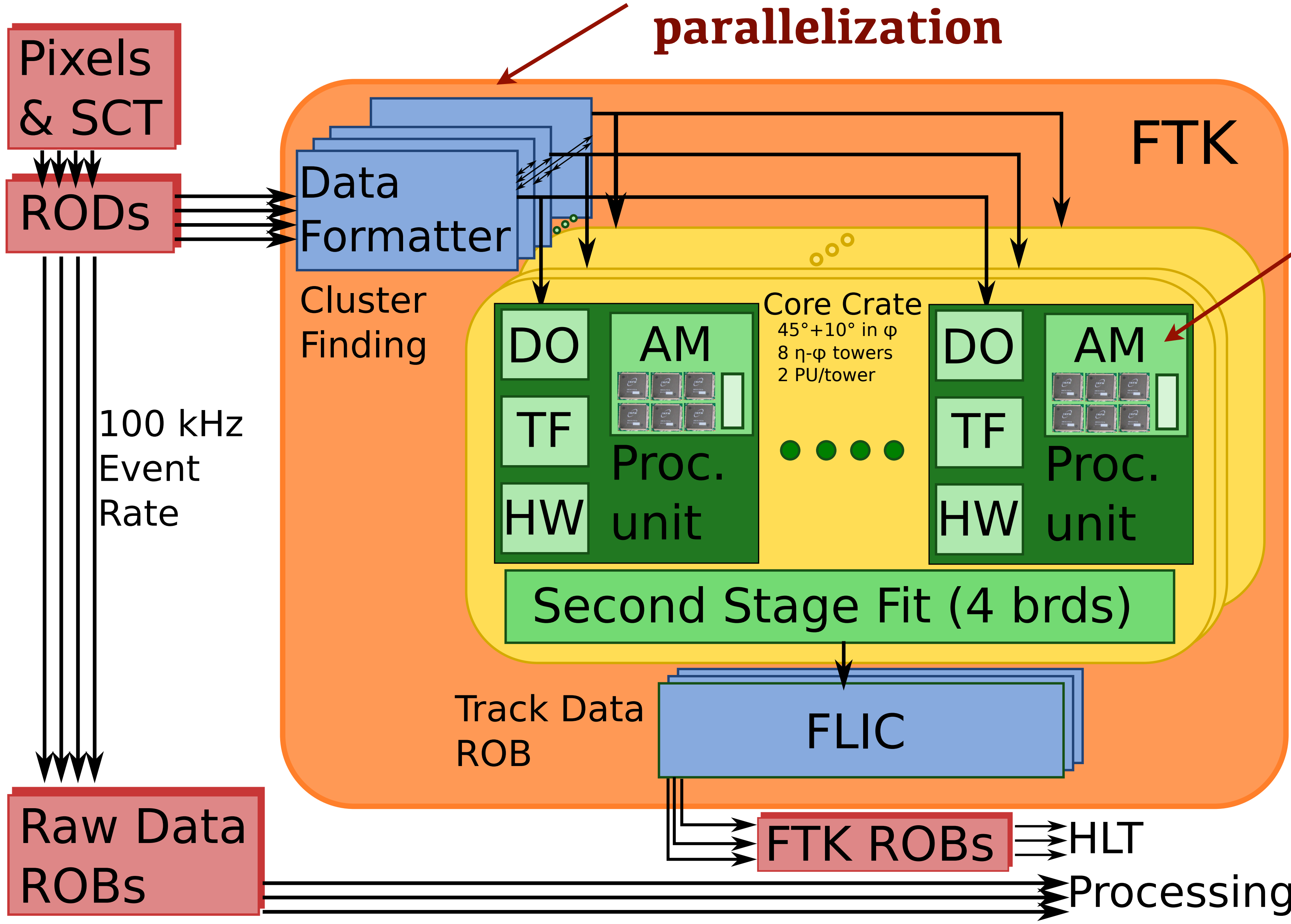
System Architecture

- **Format for parallelization**



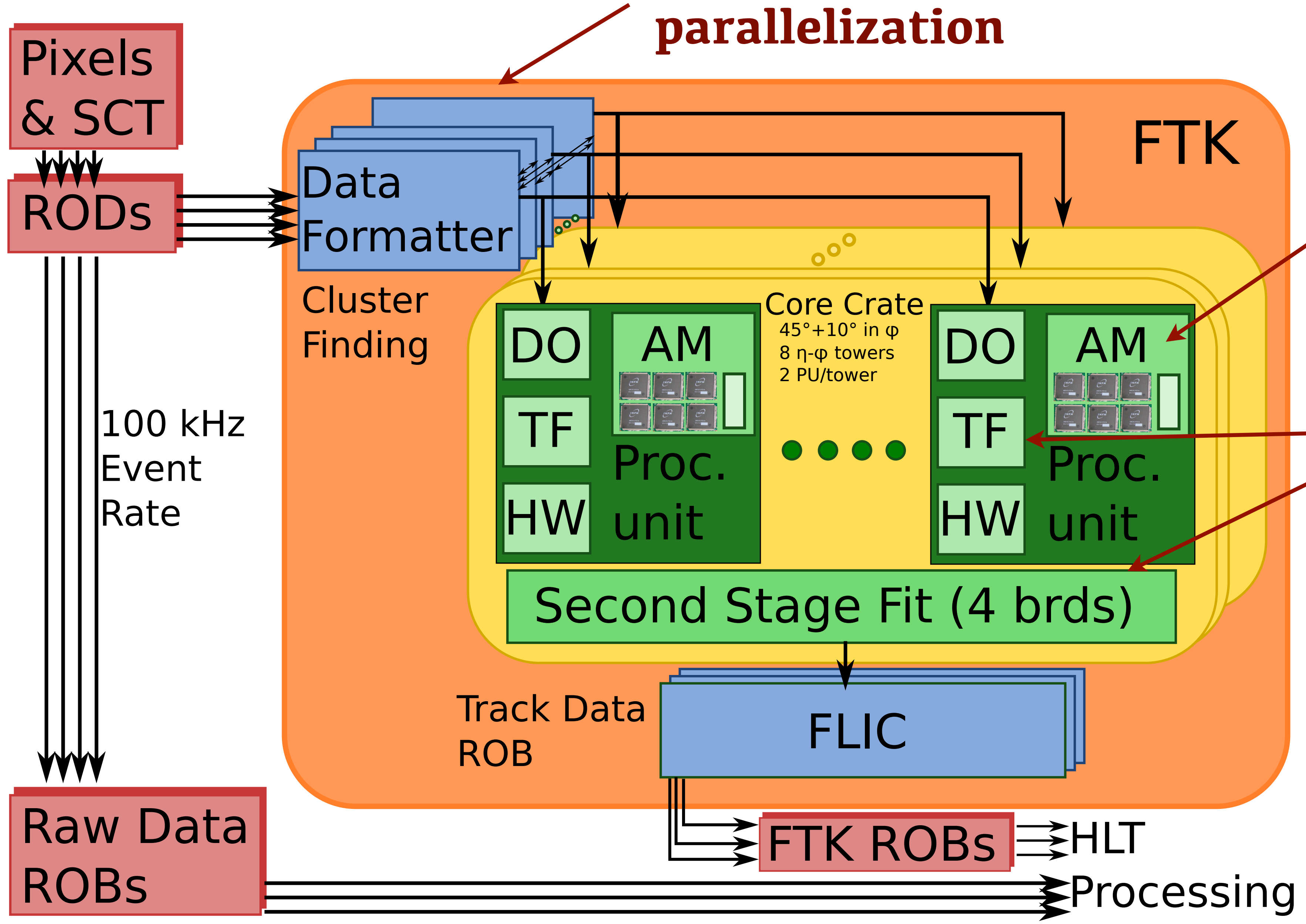
System Architecture

- **Format for parallelization**
- **Custom pattern recognition**



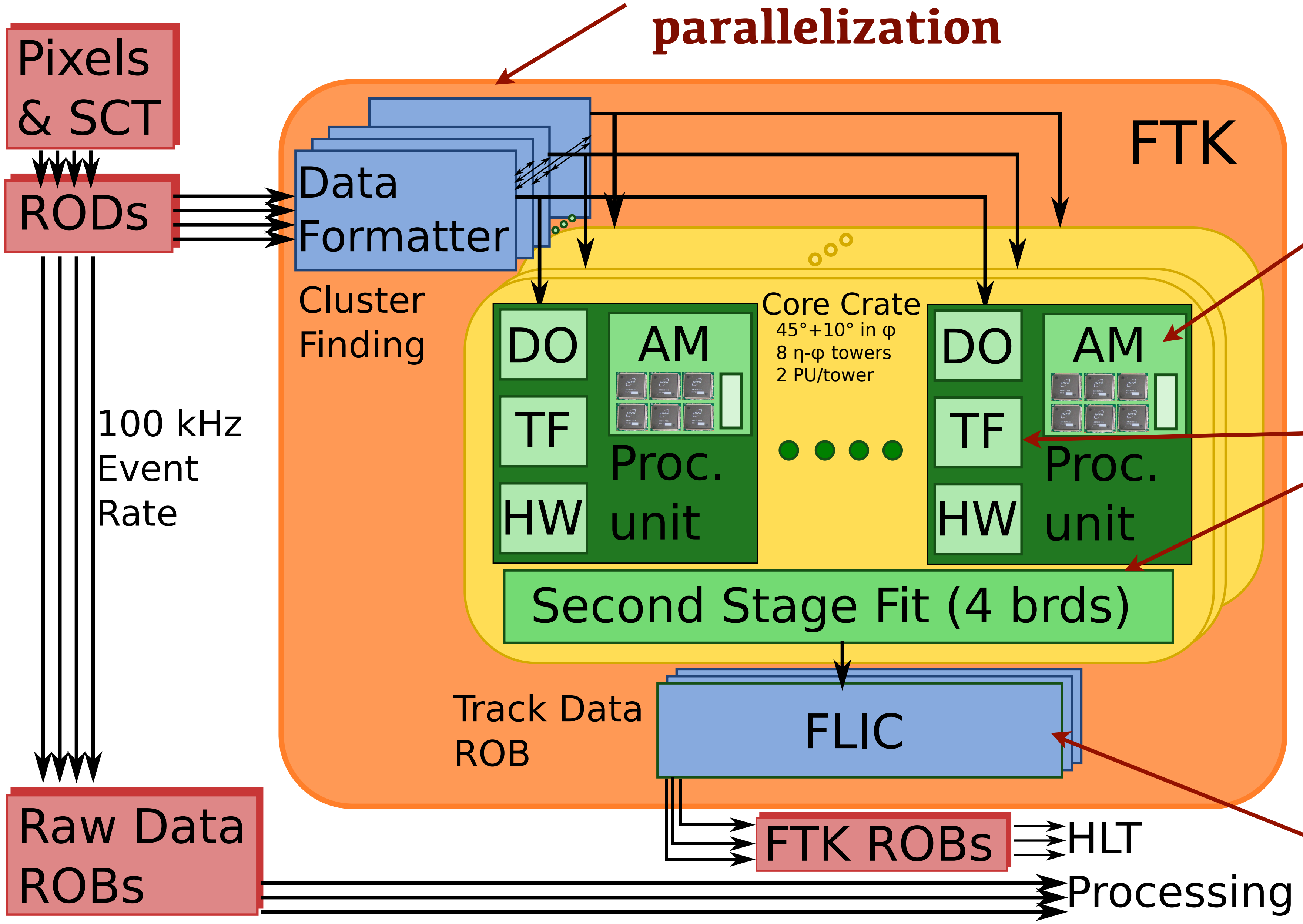
System Architecture

- **Format for parallelization**
- **Custom pattern recognition**
- **Simplified** track fitting

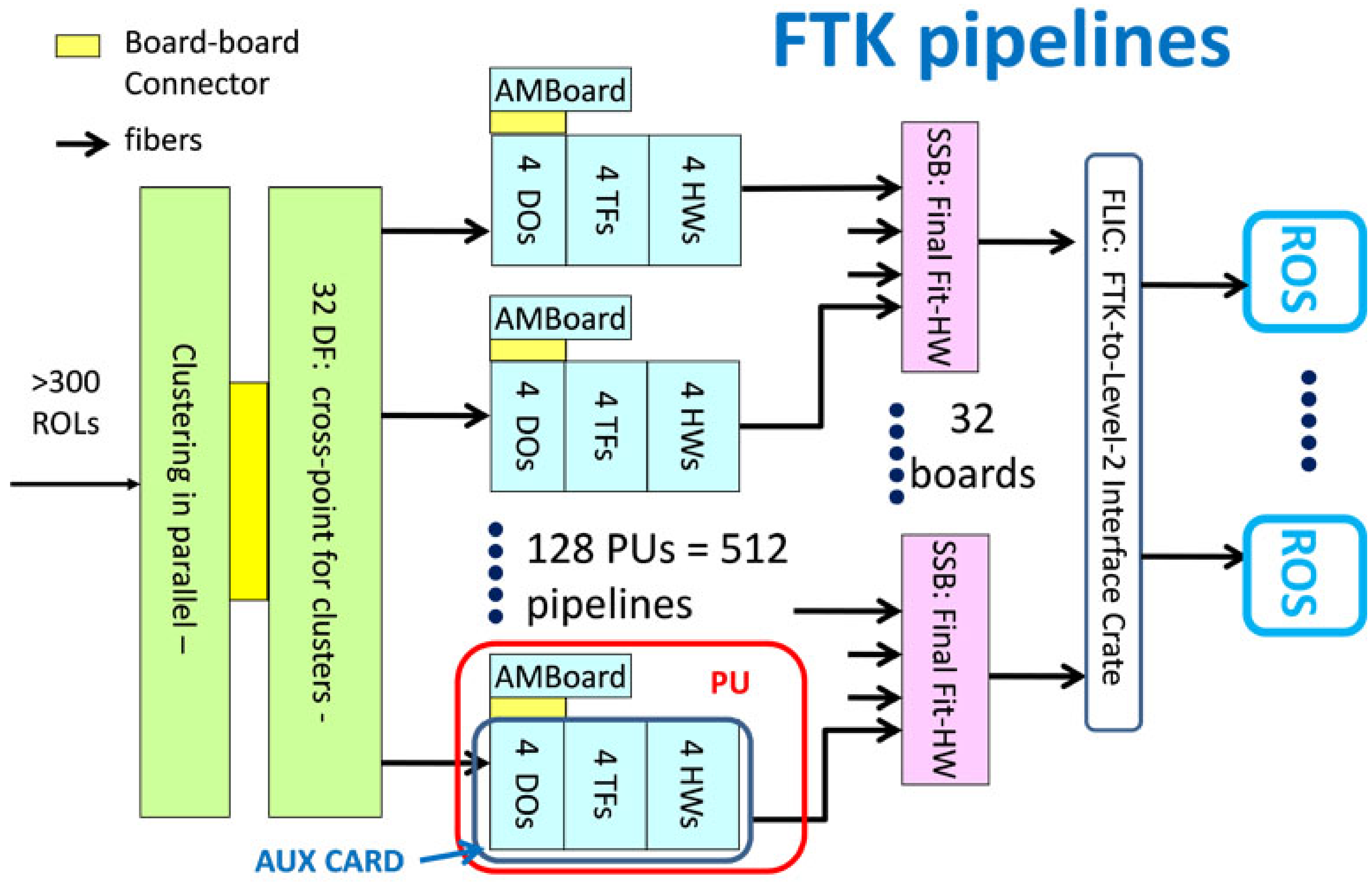


System Architecture

- **Format for parallelization**
- **Custom pattern recognition**
- **Simplified** track fitting
- Available to trigger system in O(100μs)



System Architecture



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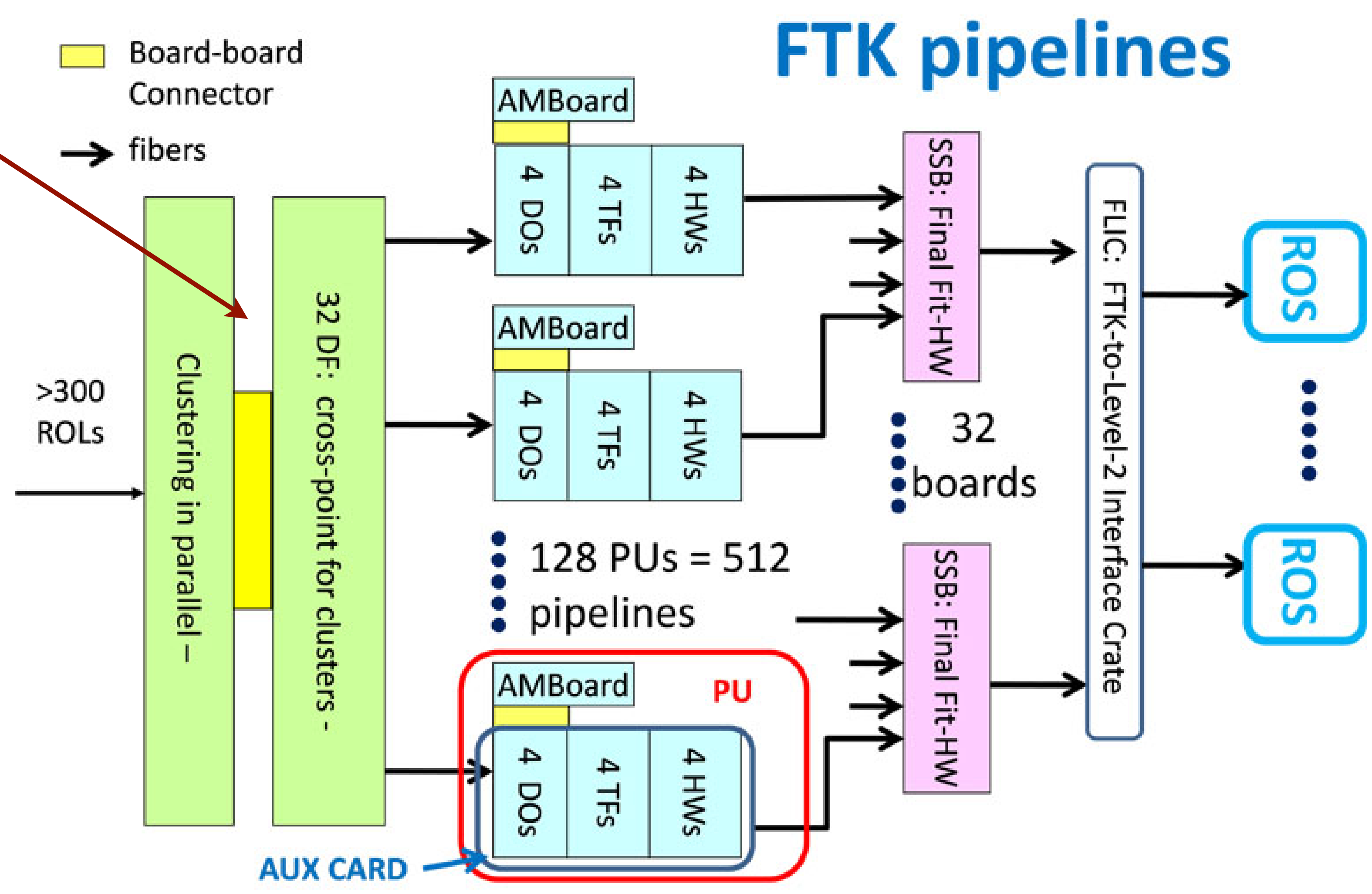

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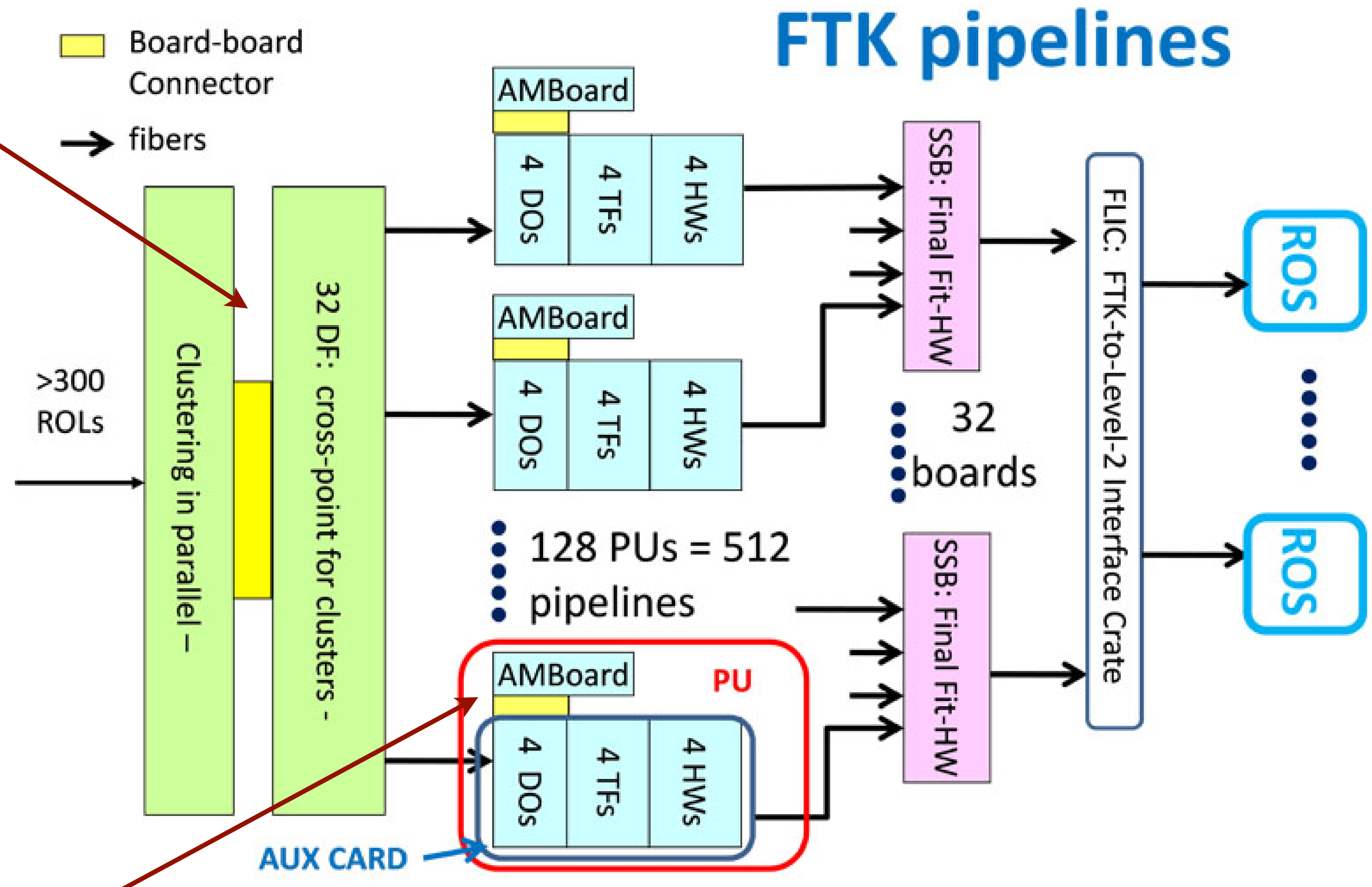
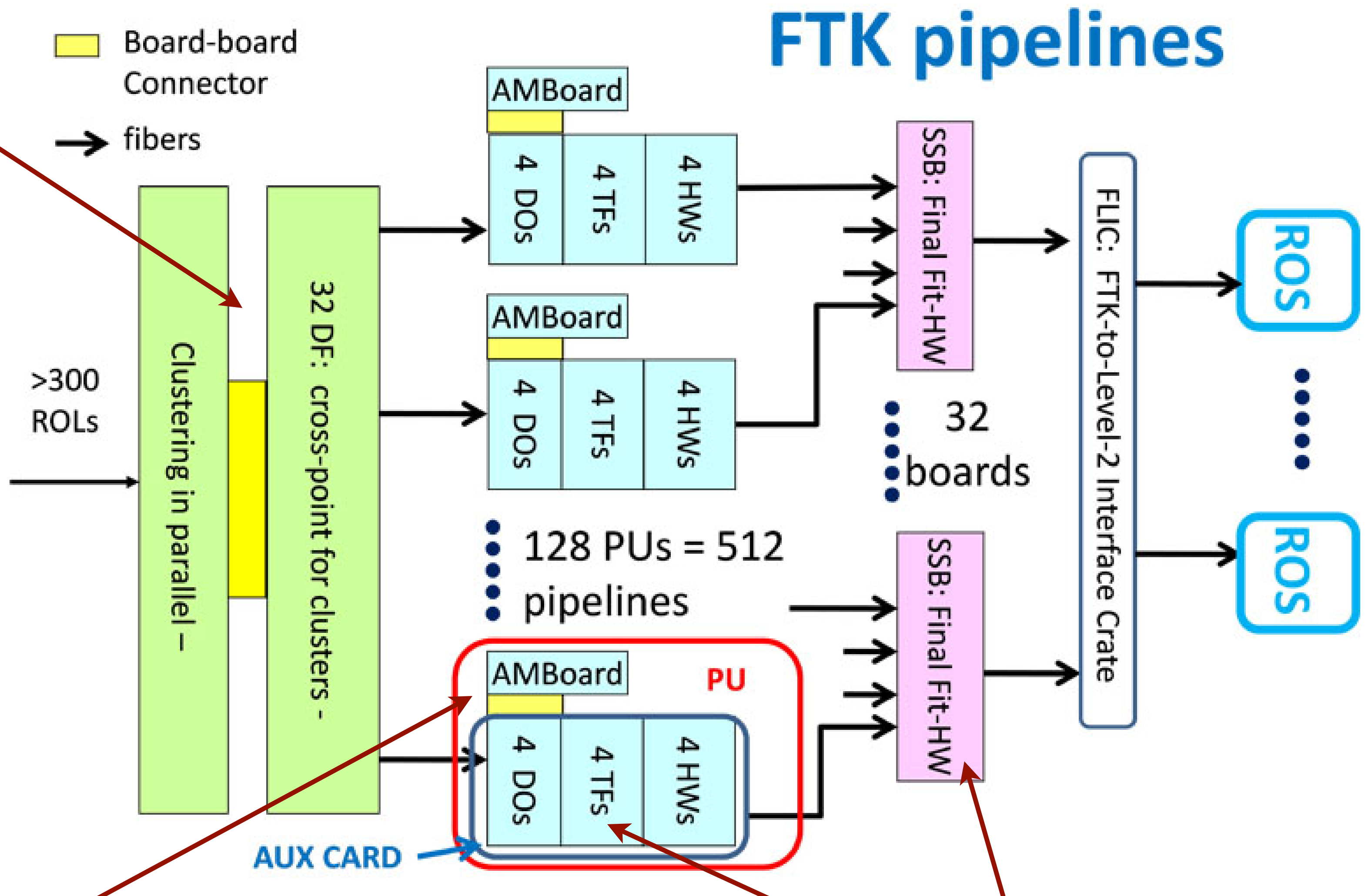


- **Custom pattern recognition**

System Architecture

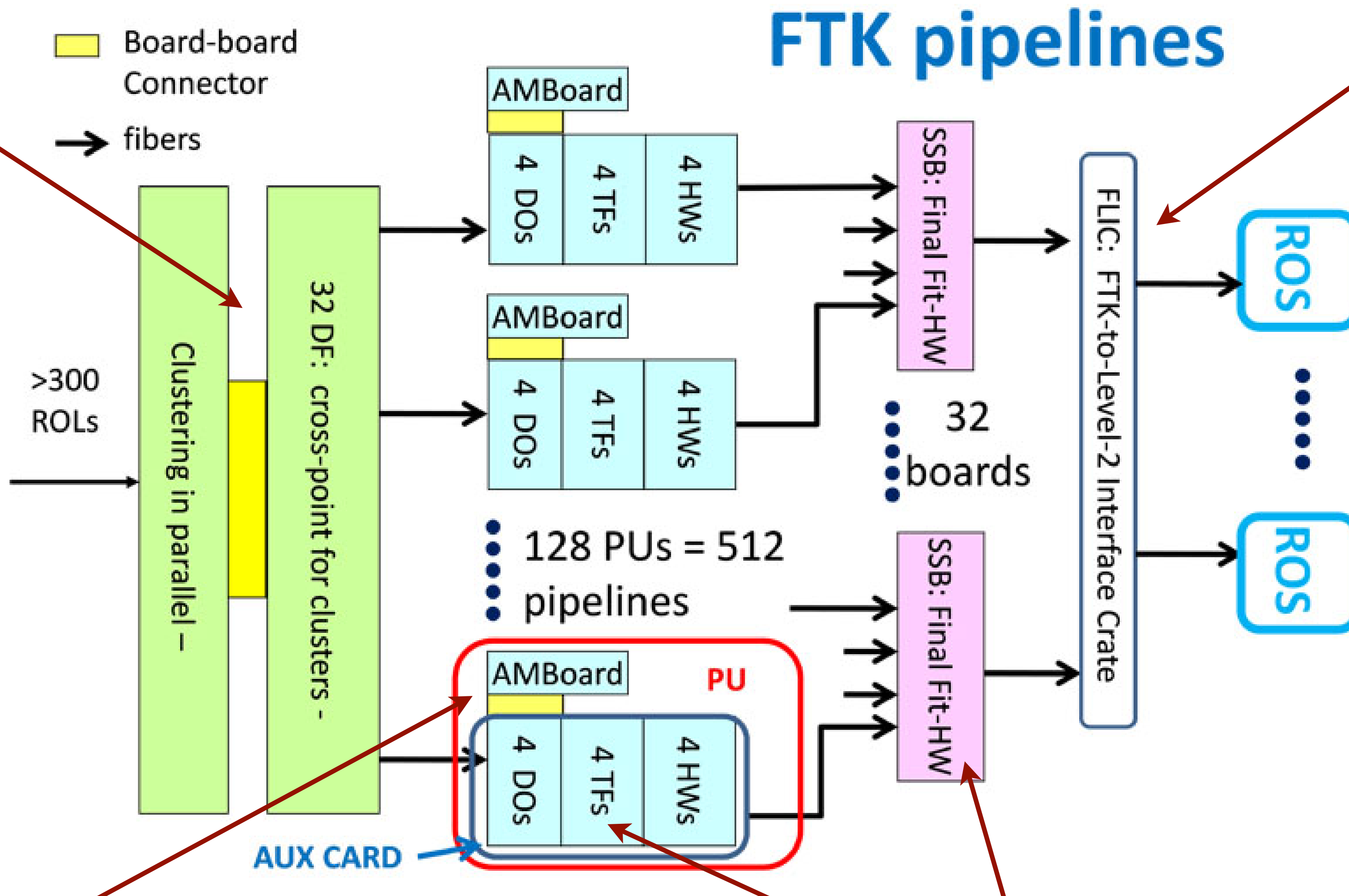
- **Format for parallelization**



- **Custom pattern recognition**
- **Simplified** track fitting

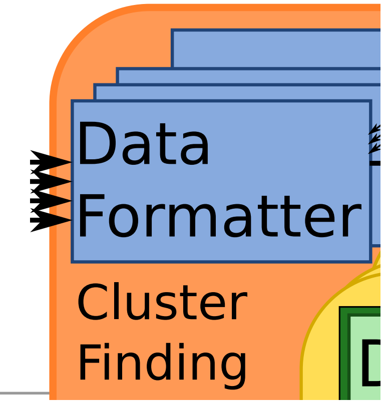
System Architecture

- **Format for parallelization**
- Available to trigger system in $O(100\mu s)$

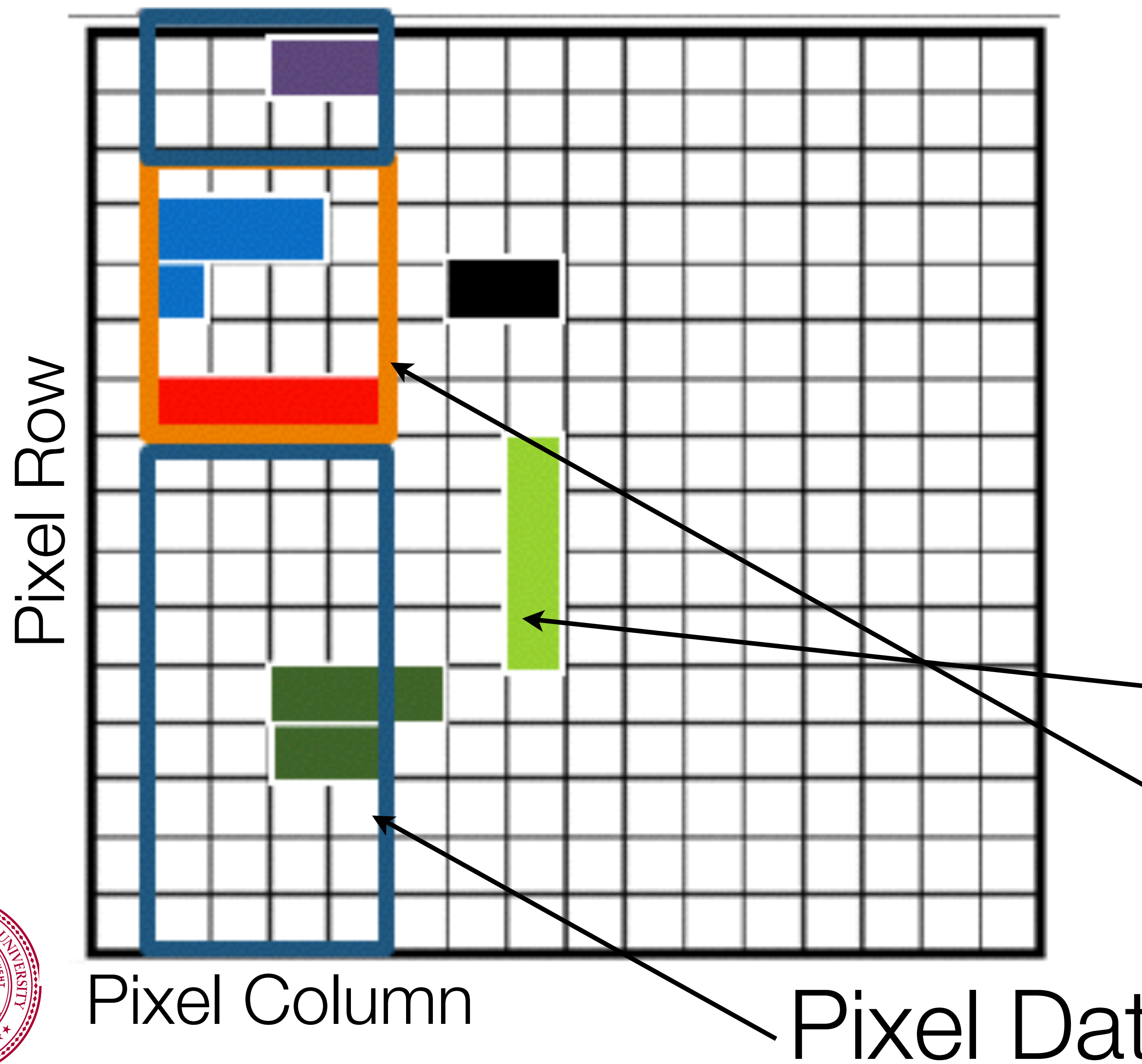


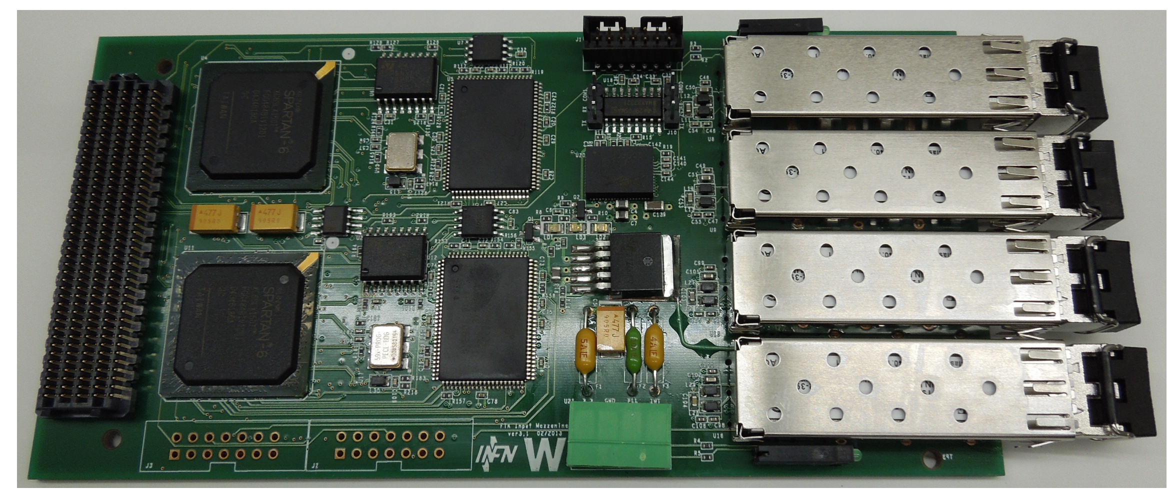
- **Custom pattern recognition**
- **Simplified** track fitting

Stage 1: Clustering



- Receive data from silicon detectors
- Cluster pixel hits using sliding window algorithm in FPGA

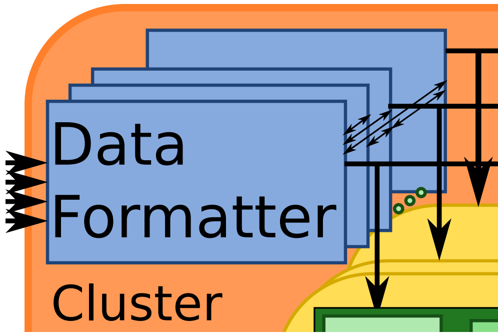




The Clustering Implementation

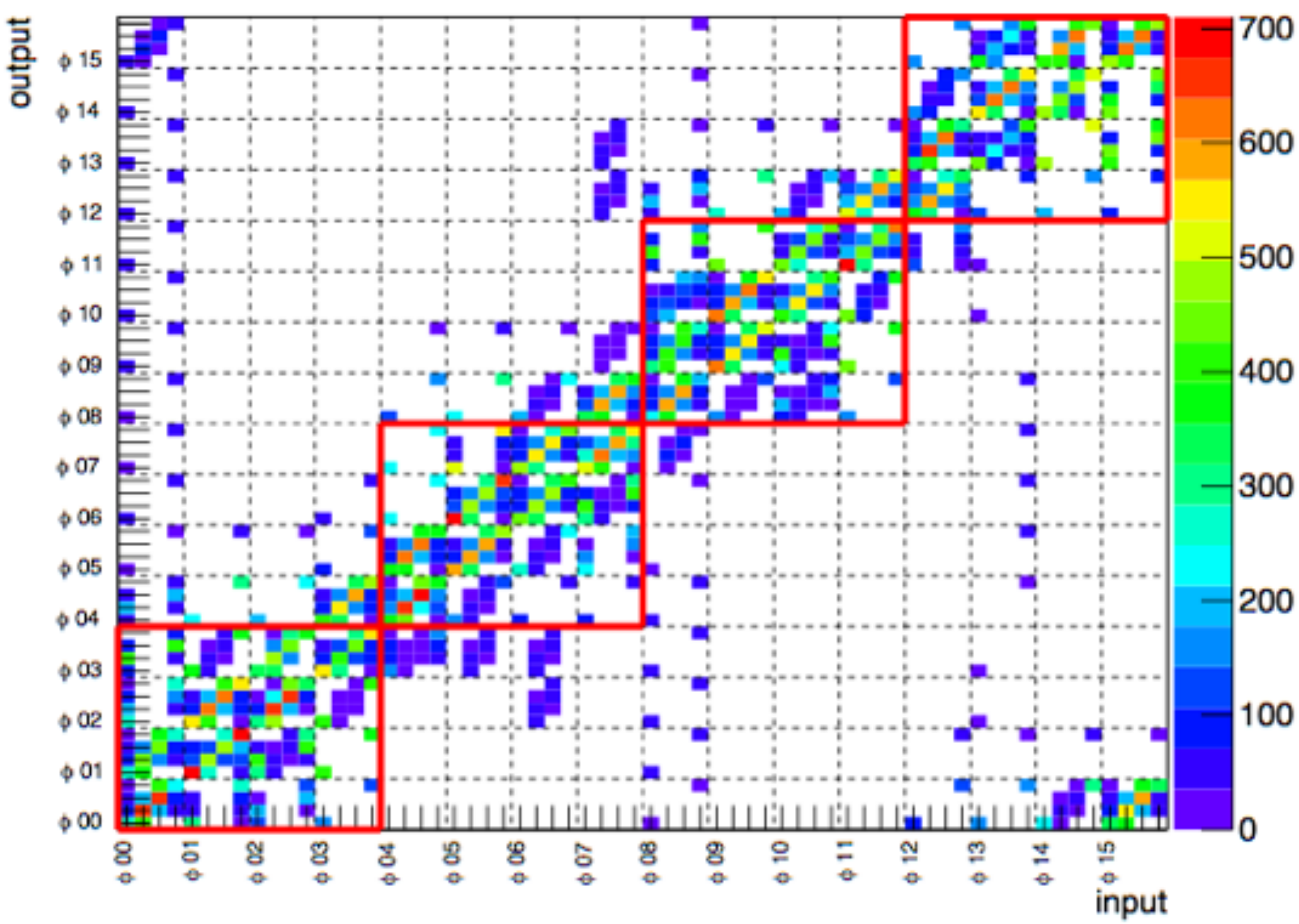
- The current implementation is an evolution of a linear algorithm with a high cost in terms of FPGA resources
- In the previous algorithm grids of 168x4 or 328x8 pixels were used. For these grid sizes the extrapolated area and clock results (for the Spartan 6-LX150T) would be:

Grid Size	Slice Registers	Slice LUTs	Clock	Frequency
21x8 (current)	696 (1%)	1950 (2%)	12ns	83Mhz
168x4	2784 (1.5%)	7800 (8.2%)	68ns	14.8Mhz
328x8	10510 (5.7%)	30457 (33%)	265ns	3.8Mhz



Stage 1: Data Formatting

- Implemented in ATCA crates with full mesh backplane
- 32 DF boards in 4 crates
- Each DF connects to 2 towers



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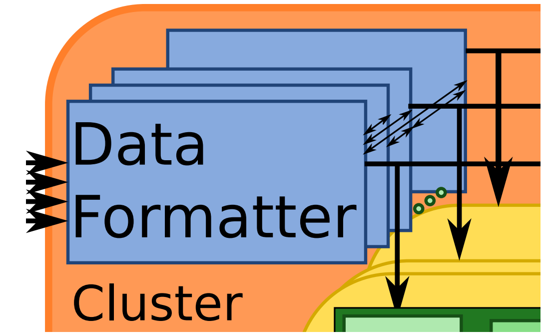

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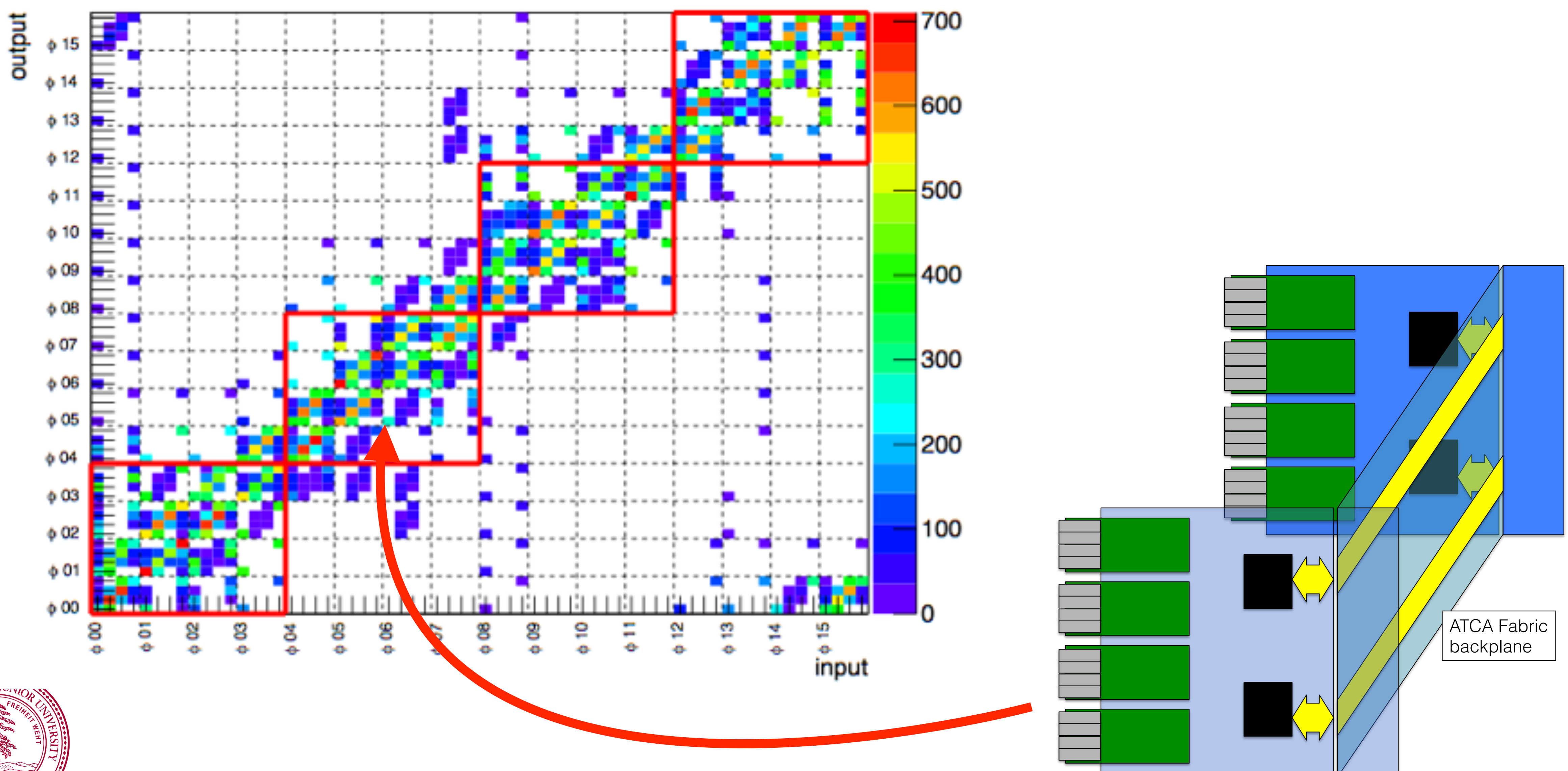

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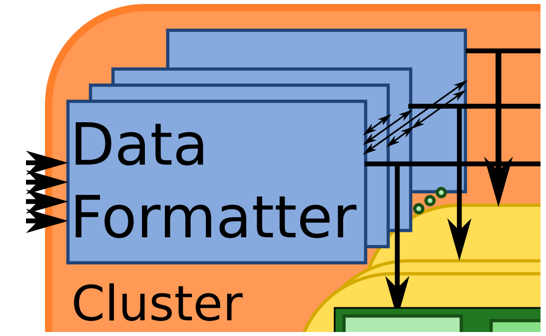

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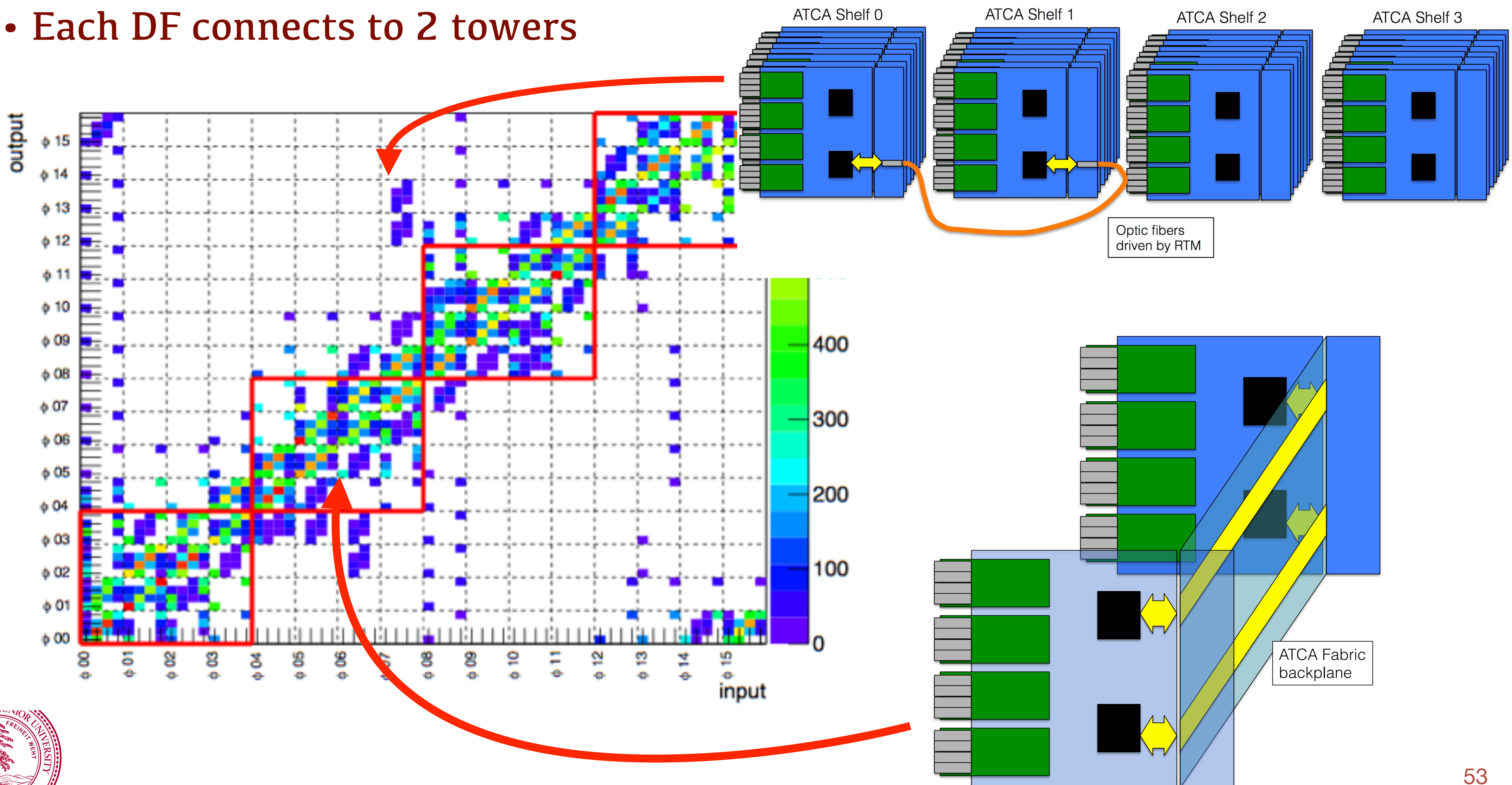
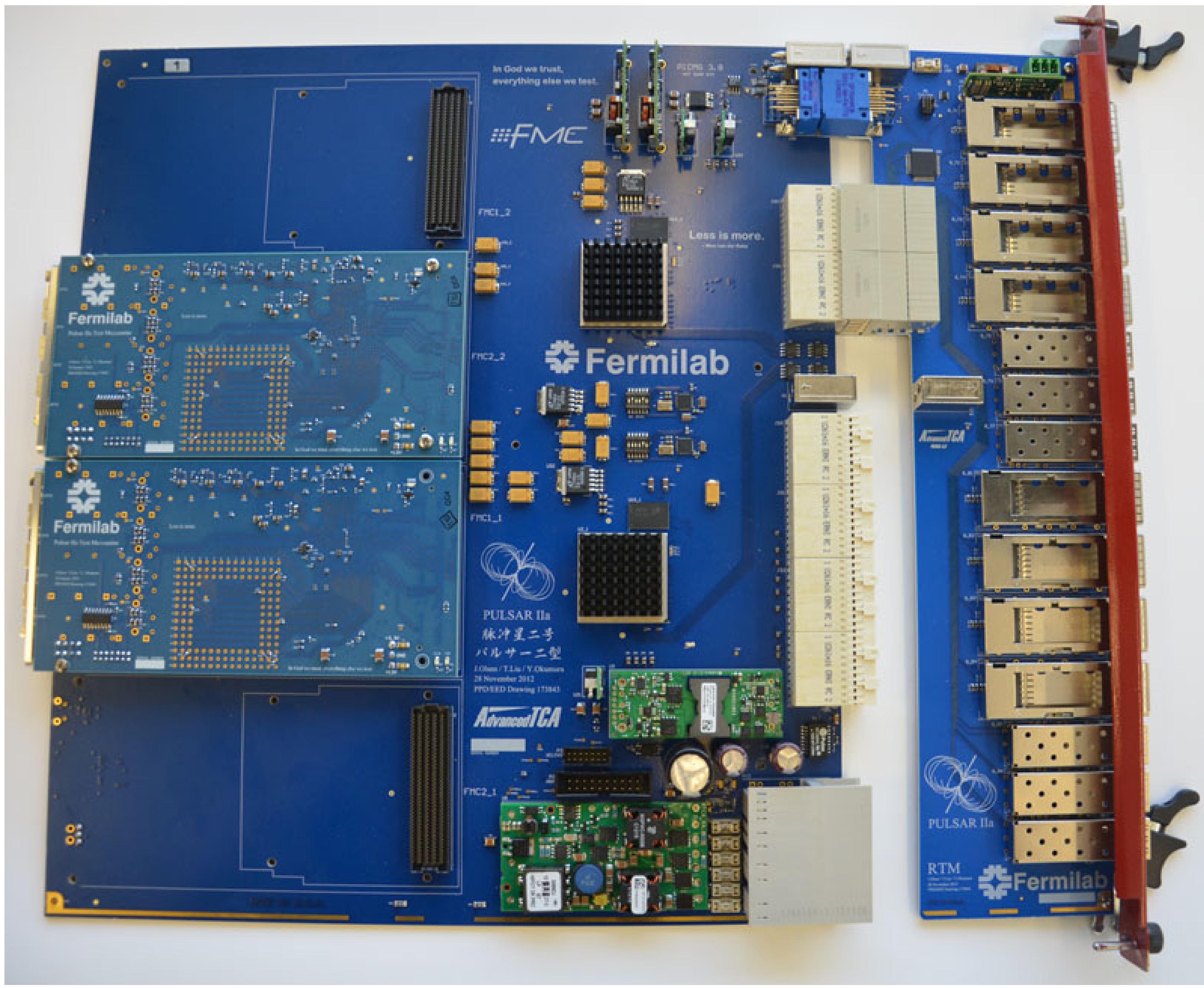


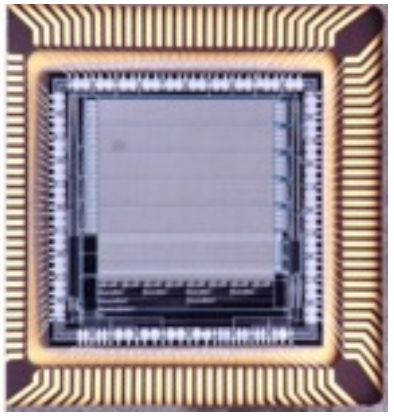
Data Formatter Prototype

Data Formatter Prototype



AM technological evolution

SVT AM chip



- (90's) **Full custom VLSI chip -** 0.7μm (INFN-Pisa)
- **128 patterns, 6x12bit words each, 30MHz**

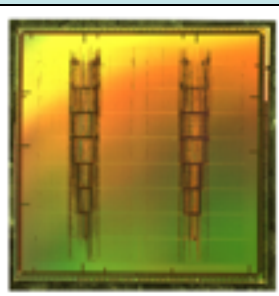
F. Morsani et al., IEEE Trans. on Nucl. Sci., vol. 39 **(1992)**

Alternative **FPGA** implementation of SVT AM chip

P. Giannetti et al., Nucl. Intsr. and Meth., vol. A413/2-3, **(1998)**

G Magazzù, 1st std cell project presented @ LHCC (1999)

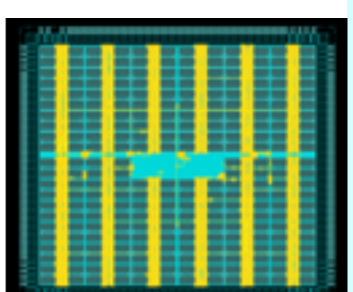
SVT upgrade



Standard Cell 0.18 μm → 5000 pattern/AM chip

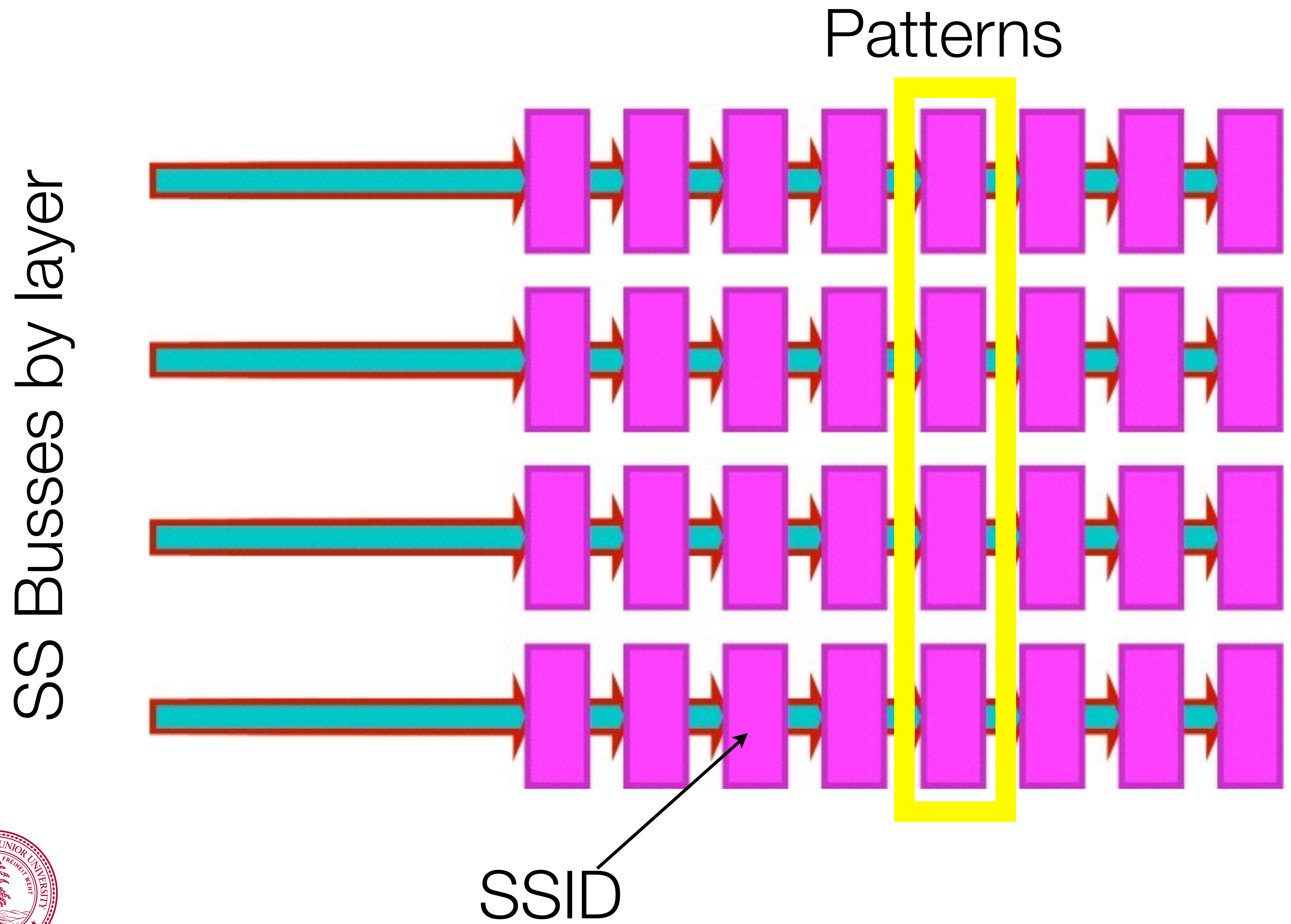
SVT upgrade total: 6M pattern, 40MHz
A. Annovi et al., **IEEE TNS**, Vol 53, Issue 4, Part 2, **2006**

FTK R&D

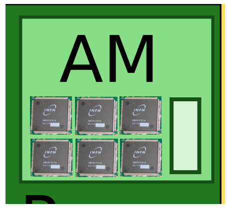


AMchip04 –65nm technology, std cell & full custom, 100MHz
Power/pattern/MHz ~30 times less. Pattern density x12.
First variable resolution implementation!
F. Alberti *et al 2013 JINST* ***8 C01040***, ***doi:***10.1088/1748-0221/8/01/C01040

Pattern Recognition Associative Memory



Pattern Recognition Associative Memory



- Allows hits arriving at different times (but same event) to be compared!

animation by Fermilab engineer Jim Hoff

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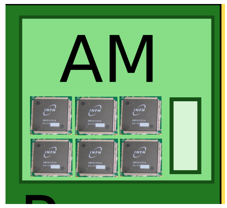

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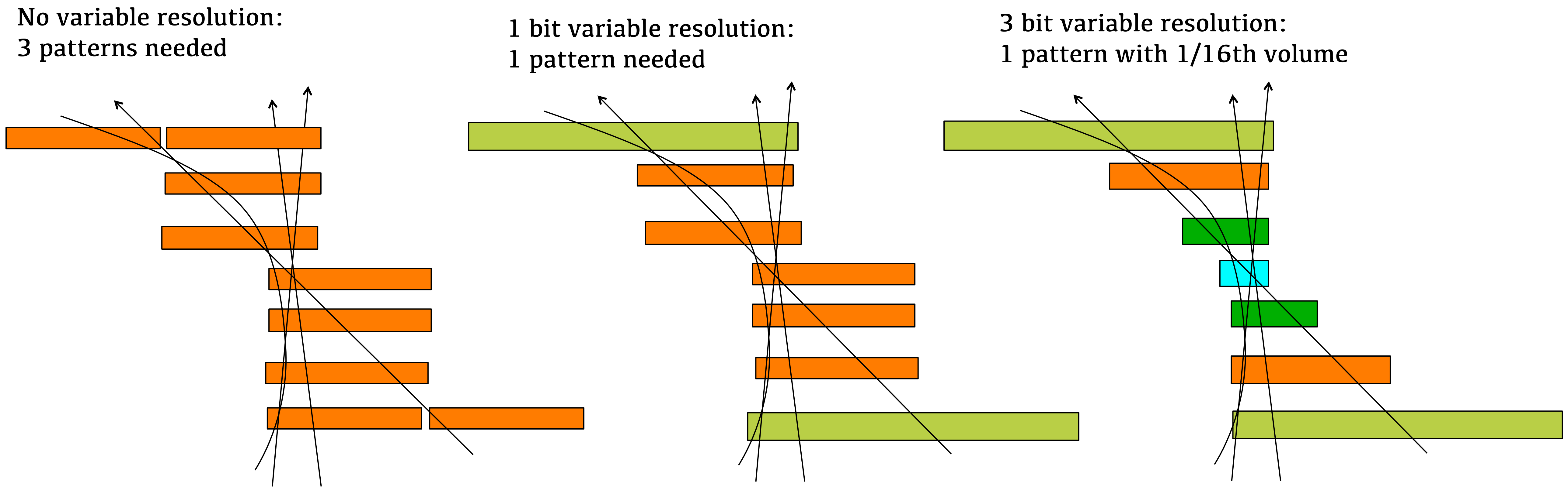
animation by Fermilab engineer Jim Hoff

Refinements

- Majority Logic: Only require N out of M layers have a match
  - Gains efficiency
- Variable Resolution Patterns (Don't Care Bits)
  - Reduces the number of patterns and fake matches



Number of don't care bits set on a layer by layer, pattern by pattern basis

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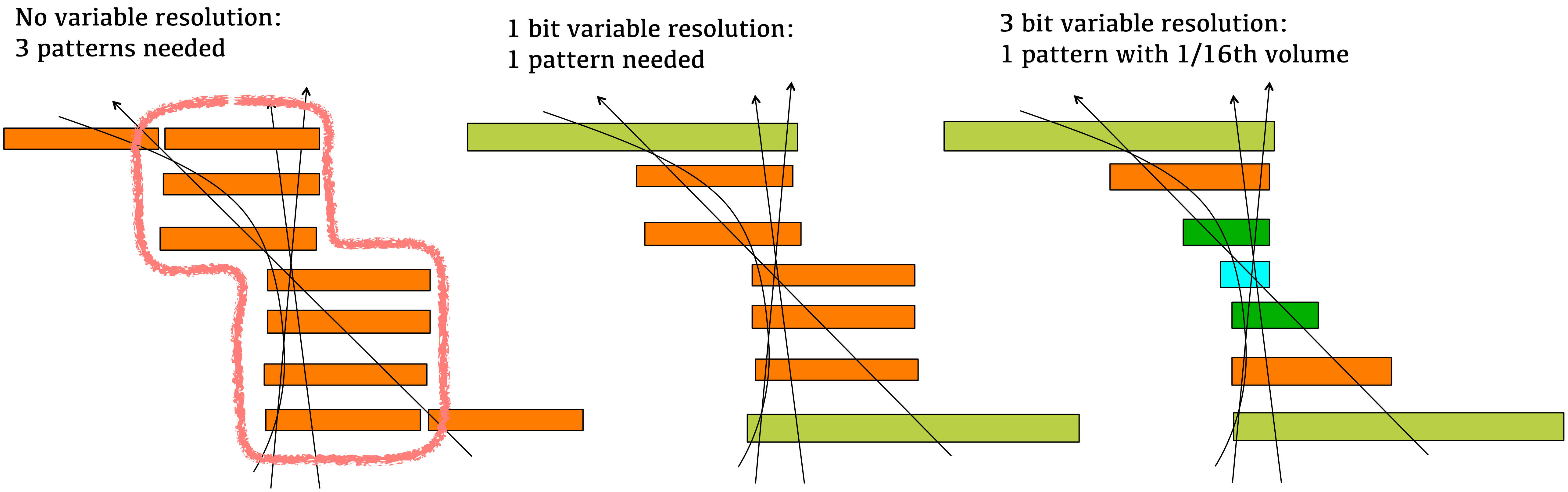

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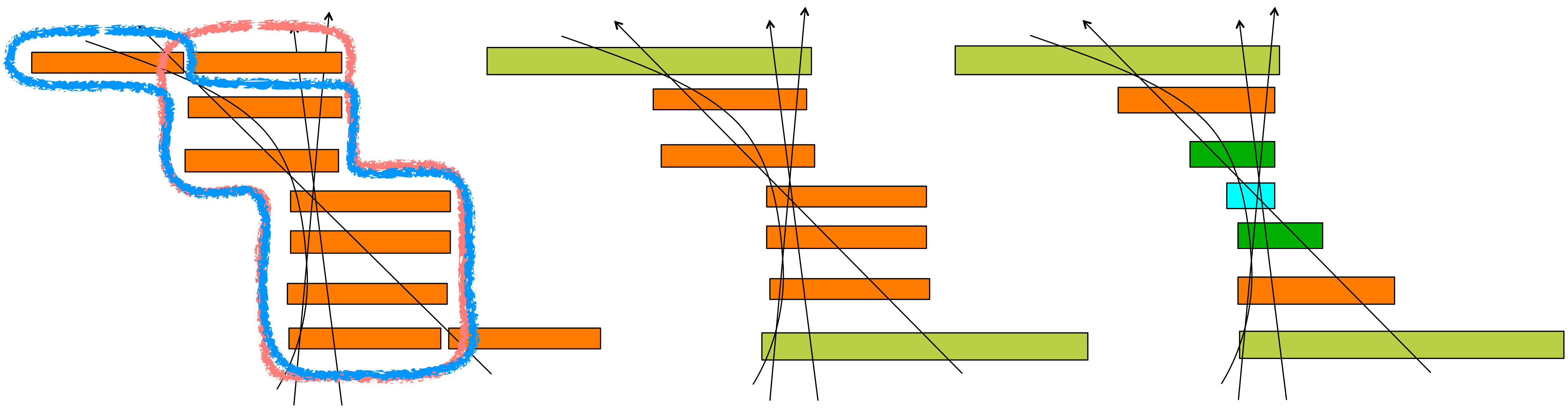
No variable resolution:
3 patterns needed

1 bit variable resolution:
1 pattern needed

3 bit variable resolution:
1 pattern with 1/16th volume



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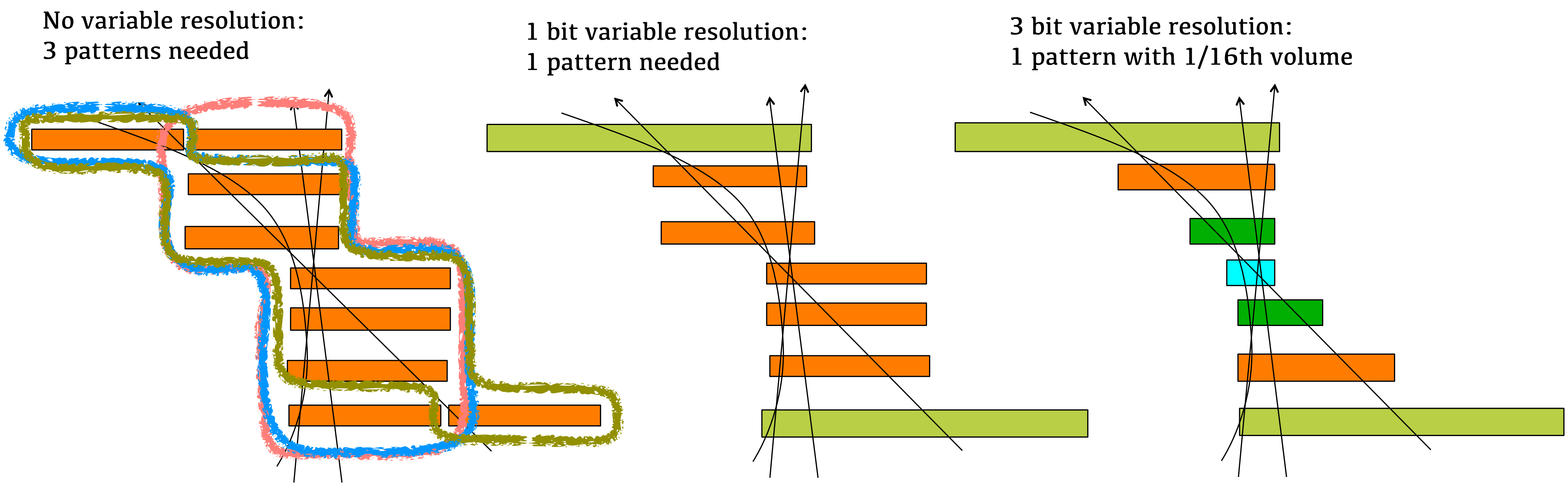

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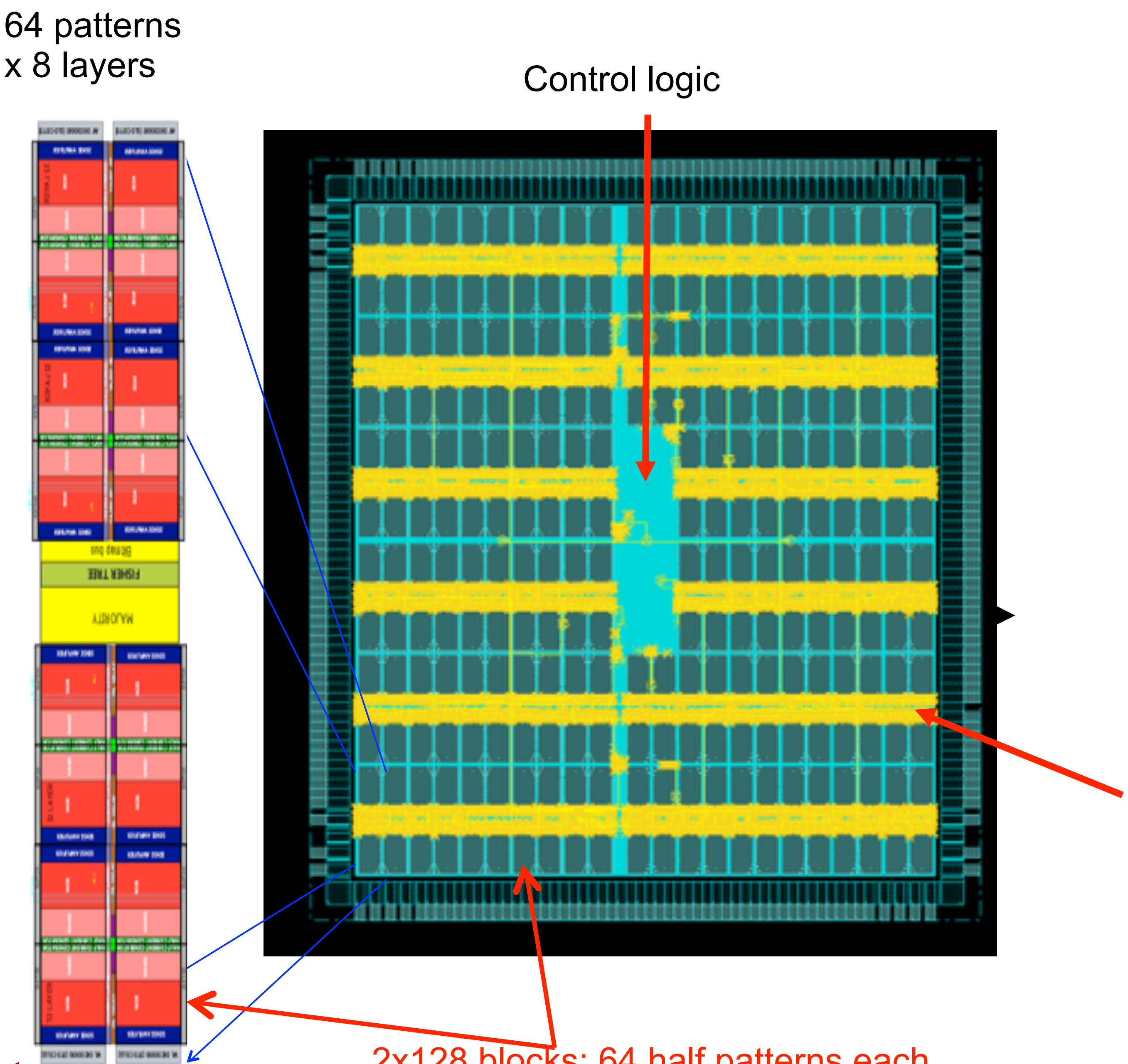
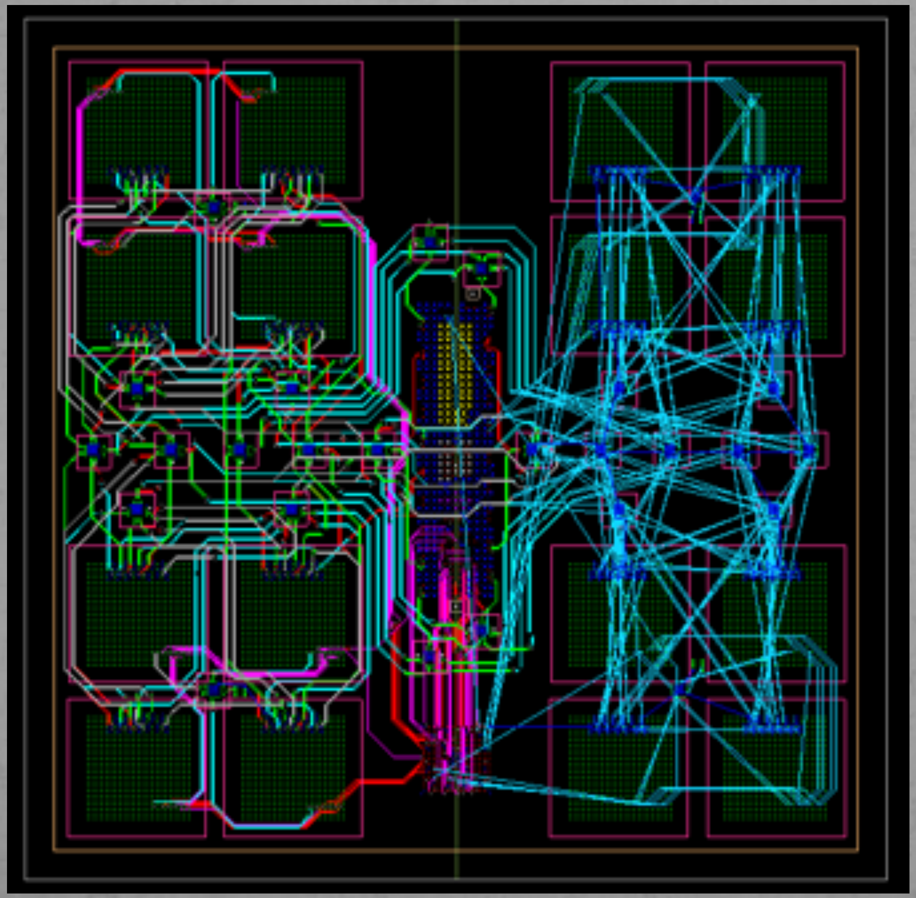
AMChips



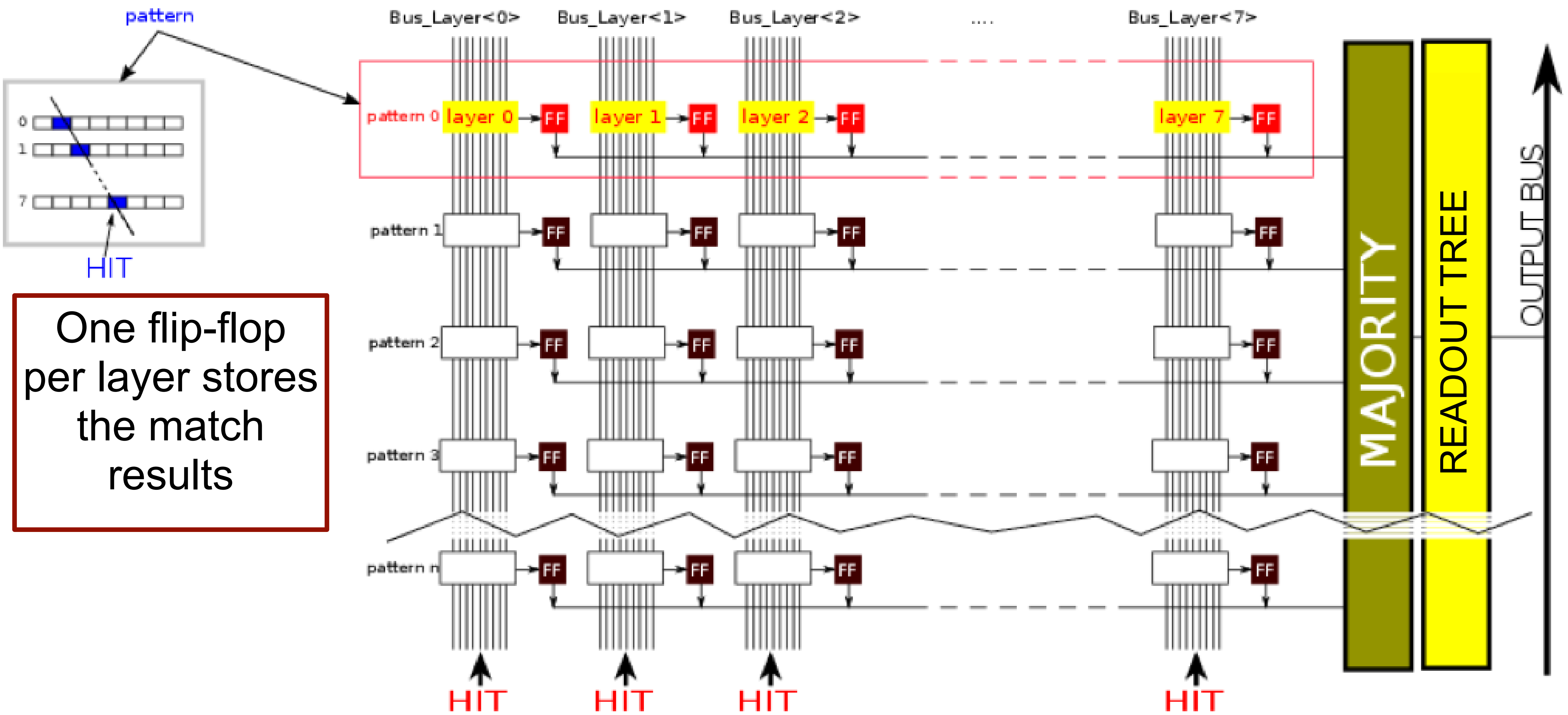
- AM Chips: 64 nm custom associative memory chips
  - **8 Layer** (3 Pix + 4 axial SCT + 1 stereo SCT) patterns
  - 3-6 bits for variable resolution patterns
  - Functionality demonstrated in small area chips (AMChip04)

F. Alberti *et al 2013 JINST* ***8 C01040,*** ***doi:***10.1088/1748-0221/8/01/C01040



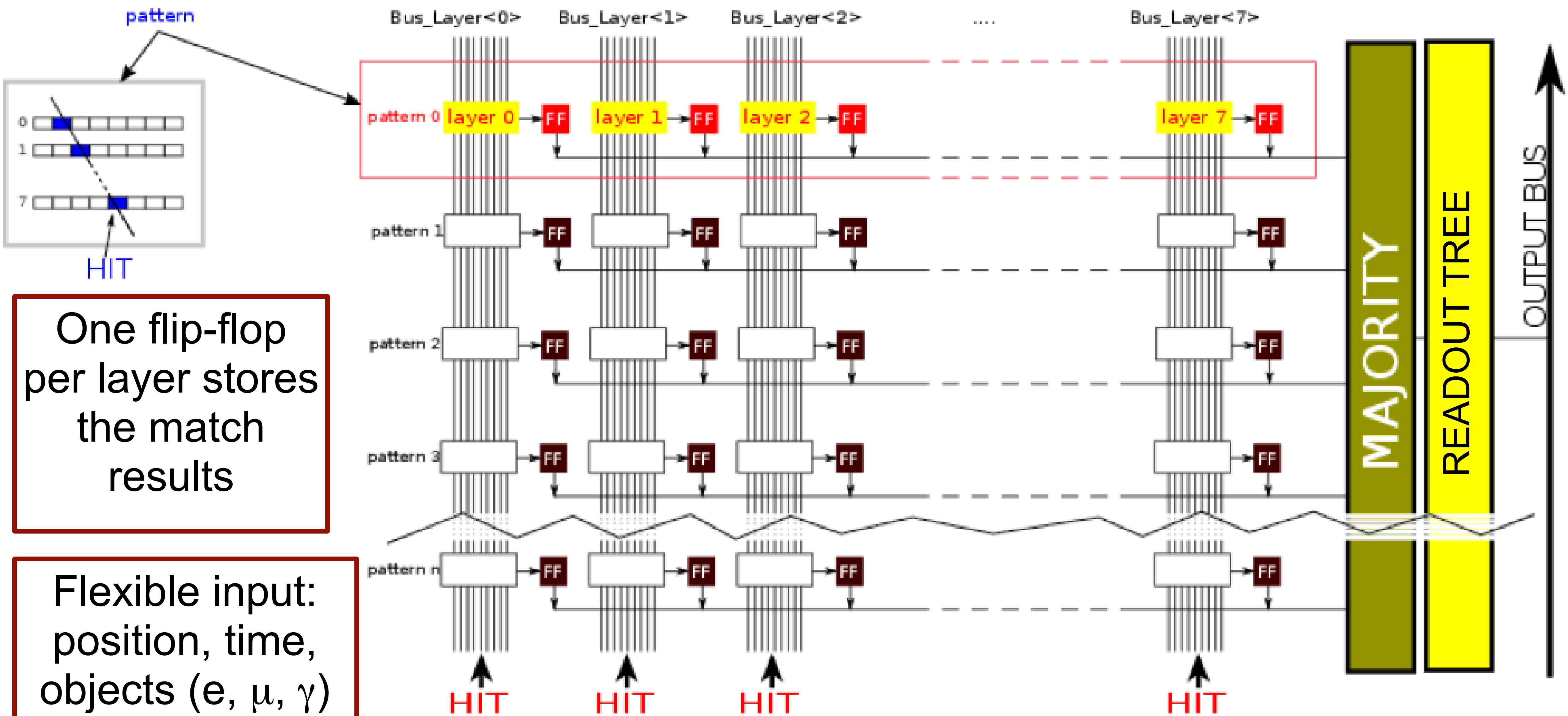
- AMBFTK is EURCARD 9U format
- Massive serial I/O
  - 2 Artix 7 FPGAs
  - Only serial communication busses
- Additional FPGAs for VME control
  - Slave for VME communication in the AUX-card
- LAMB redesigned for the newer AM-chip
  - Serial communication replaced the parallel busses
  - See M. Beretta talk on 24/09
    - https://indico.cern.ch/contributionDisplay.py?contribId=50&confId=228972
- Different voltages to be distributed
  - 3.3V for the I/O
  - 1.2V AM-chip
- High power consumption, about 200 W

AM working principle



One flip-flop per layer stores the match results

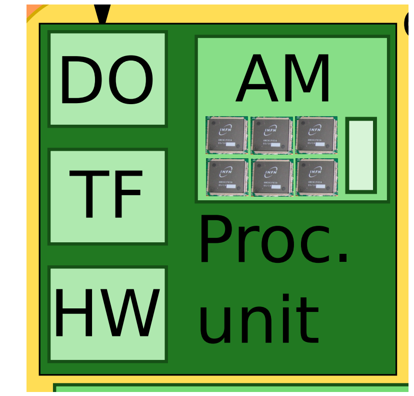
AM working principle



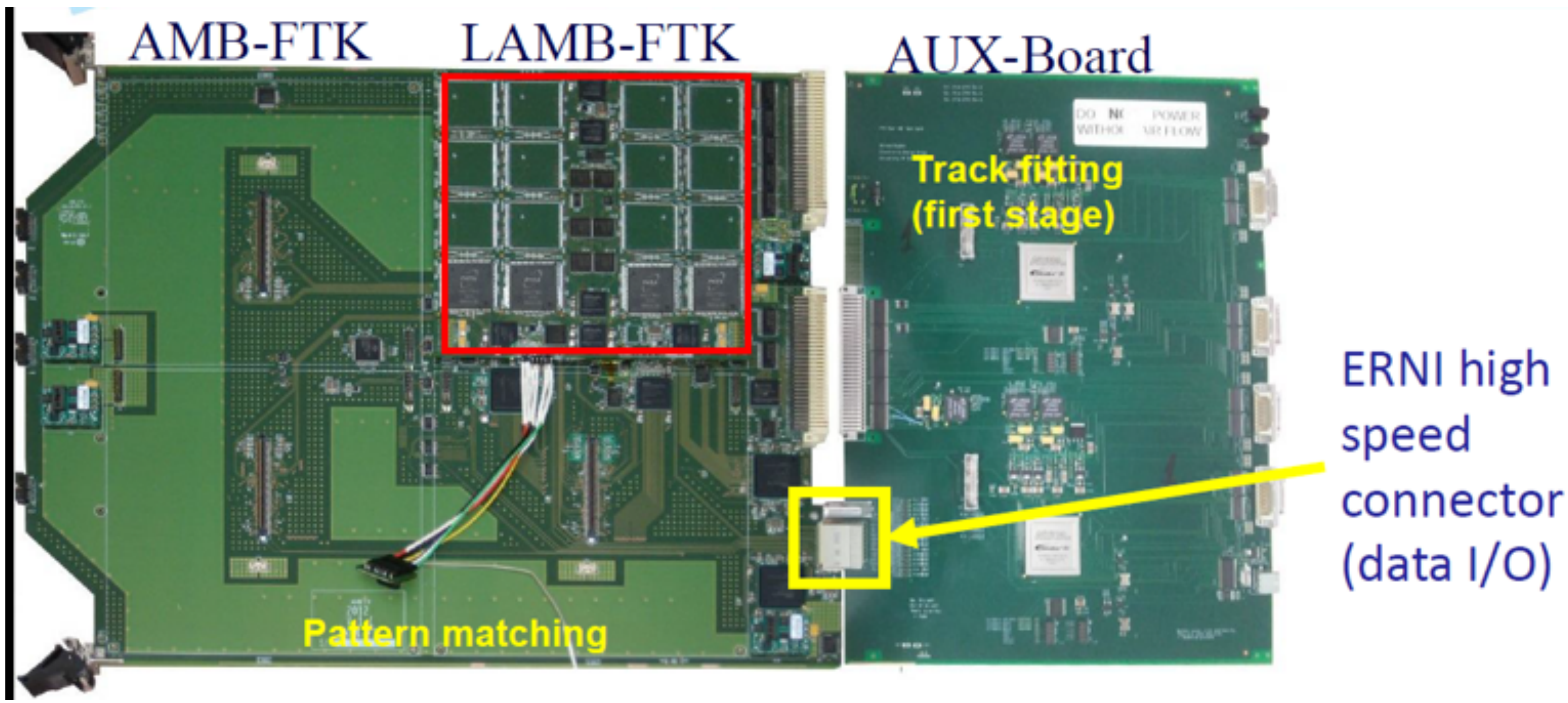
One flip-flop per layer stores the match results

Flexible input: position, time, objects (e, μ, γ)

Pattern matching is completed as soon as all hits are loaded.
Data arriving at different times is compared in parallel with all patterns.
Unique to AM chip: look for correlation of data received at different times.

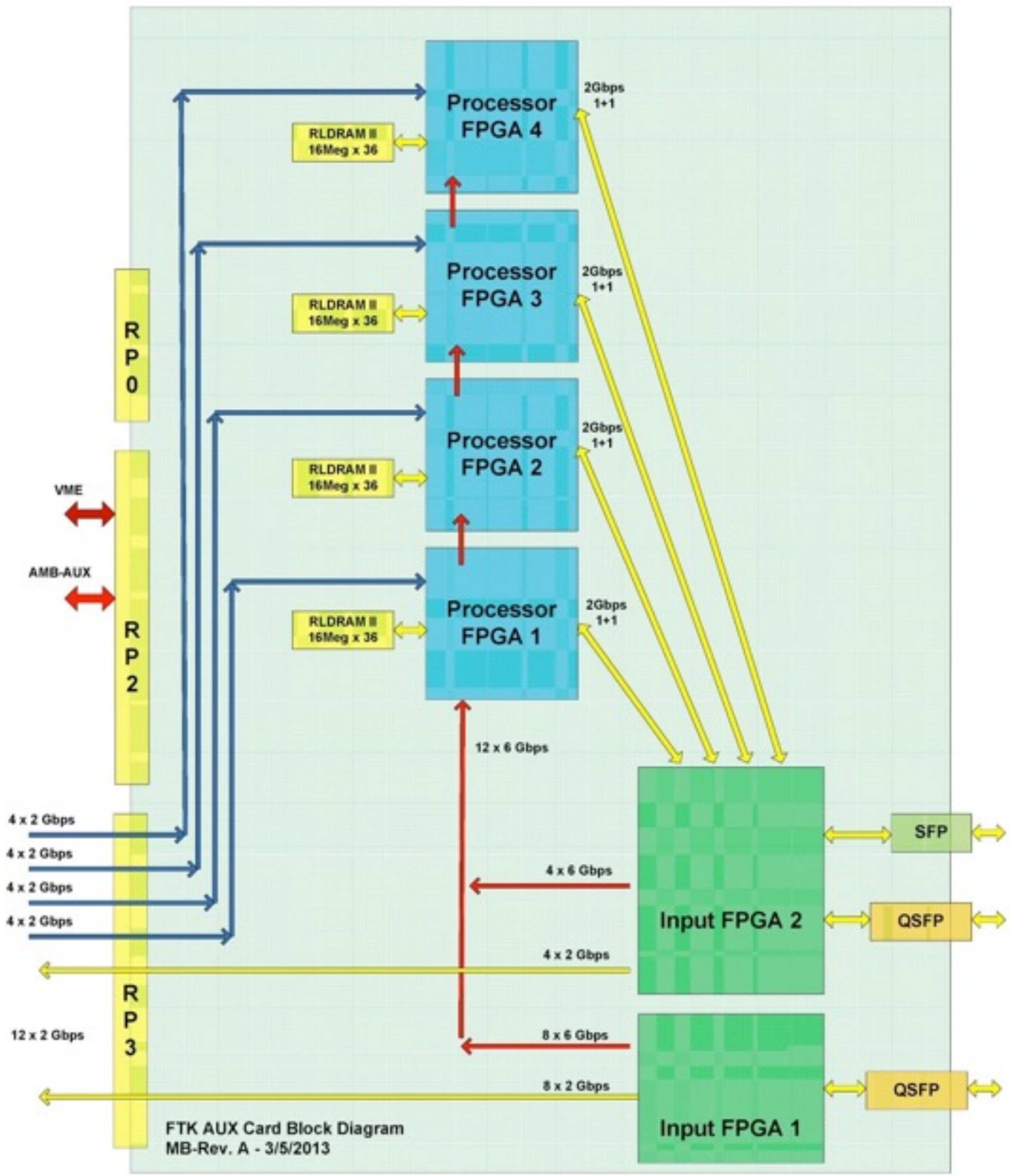


Processing Unit

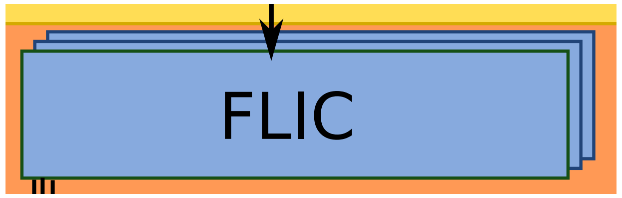


- AMChips found in Processing Unit:
  - AMboard + AUX Card
- Each AMBoard is composed of 4 LAMBs with AM chips
  - Each LAMB-FTK will contain 16 AMChips, ~10^6 patterns/LAMB
- AM Board + AUX communicate through P3 Connector
  - Successfully tested 2GBps transfer

AUX

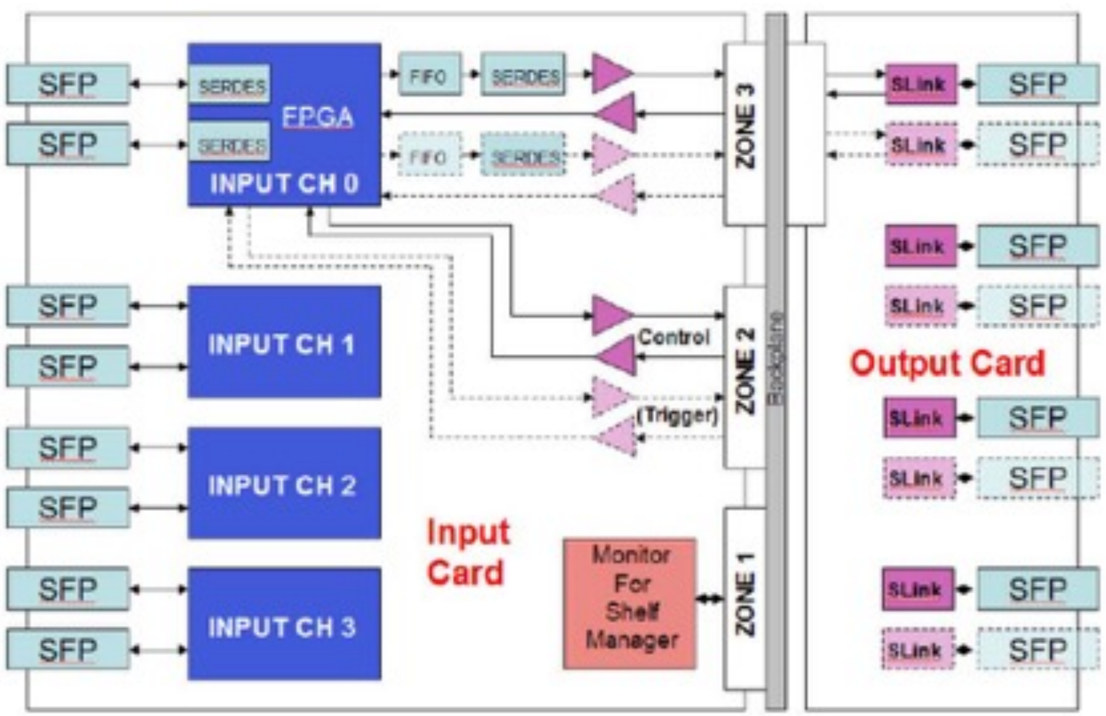


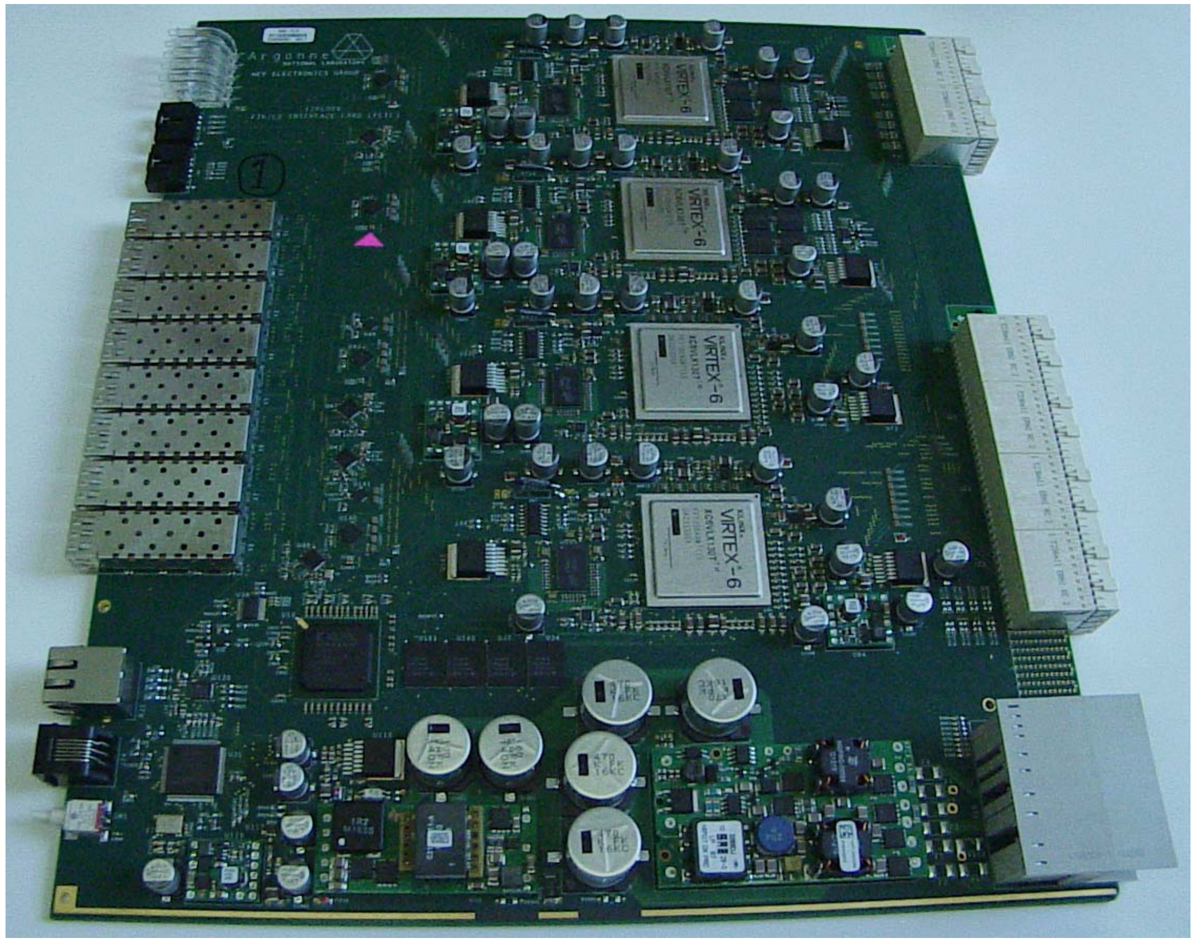
- 9U VME Rear Transition Card
  - 280mm deep!
- I/Os:
  - Fibers: to DF, SSB
    - 2 x QSFP (8 x RxTx @ 6Gbps)
    - 1 x SFP (1 x RxTx @ 2Gbps)
  - P3 Connector: Data to AMB
    - 12 x Out @ 2Gbps
    - 16 x In @ 2Gbps
  - P2 Connector: VME control, power
- Processing power: 6 Arria V FPGAs
  - 20 Mb RAM, ~1000 DSPs each



FTK to Level 2

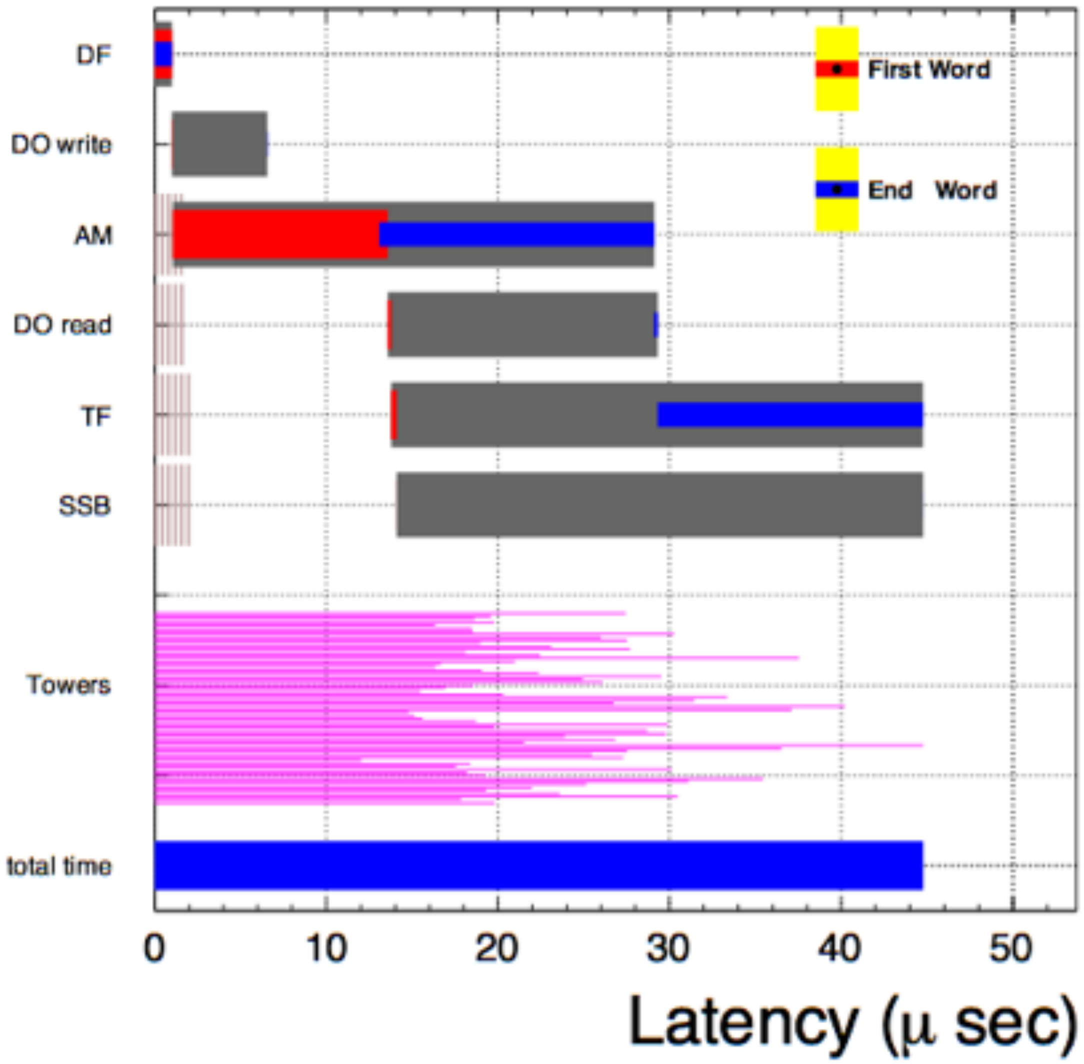
- FTK to Level 2 Interface Crate connects FTK to HLT
  - Formats data for HLT
  - Also does monitoring and control
- Uses dual-star ATCA crate
  - Will allow for local trigger processing (primary vertex finding, beamspot, MET, etc.) in the future

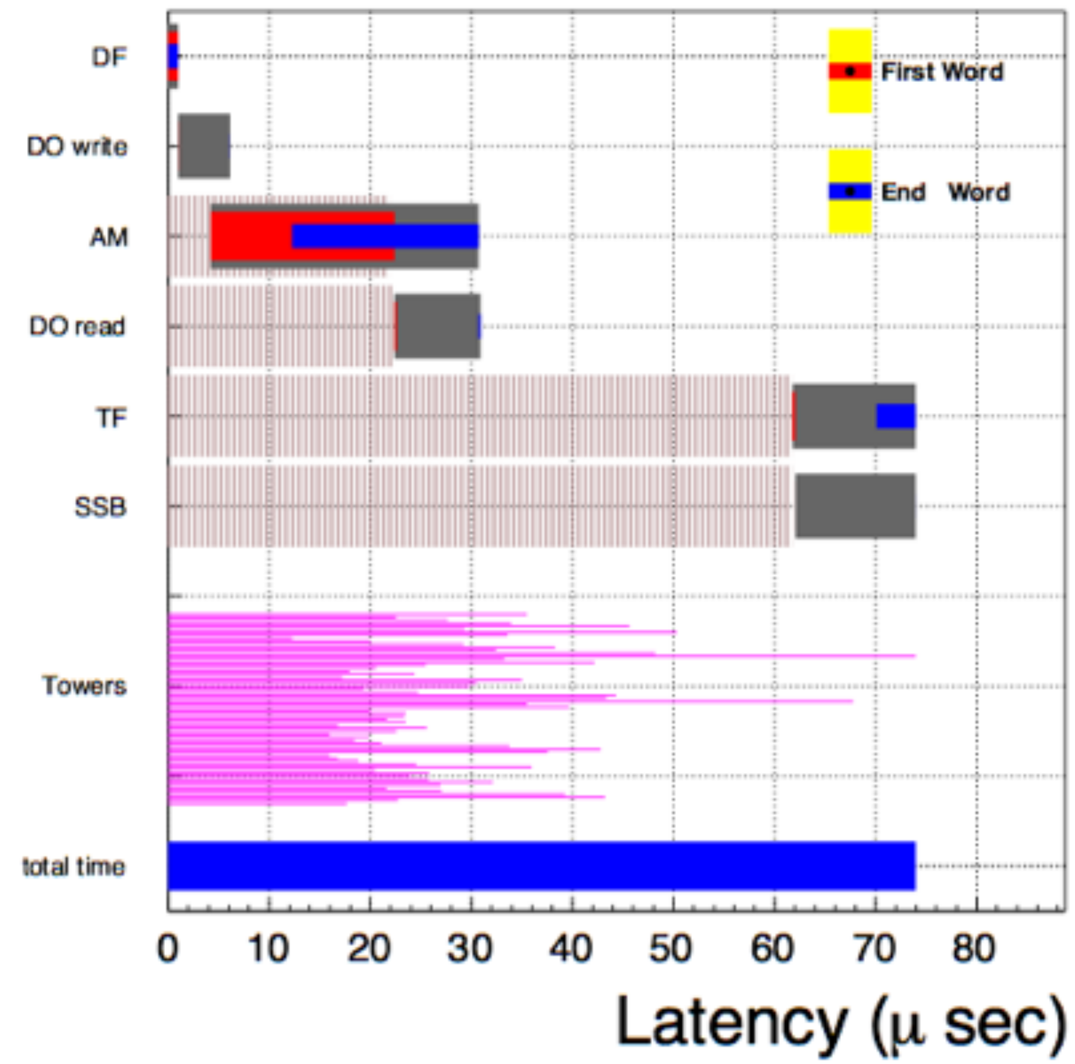




Timing Simulation

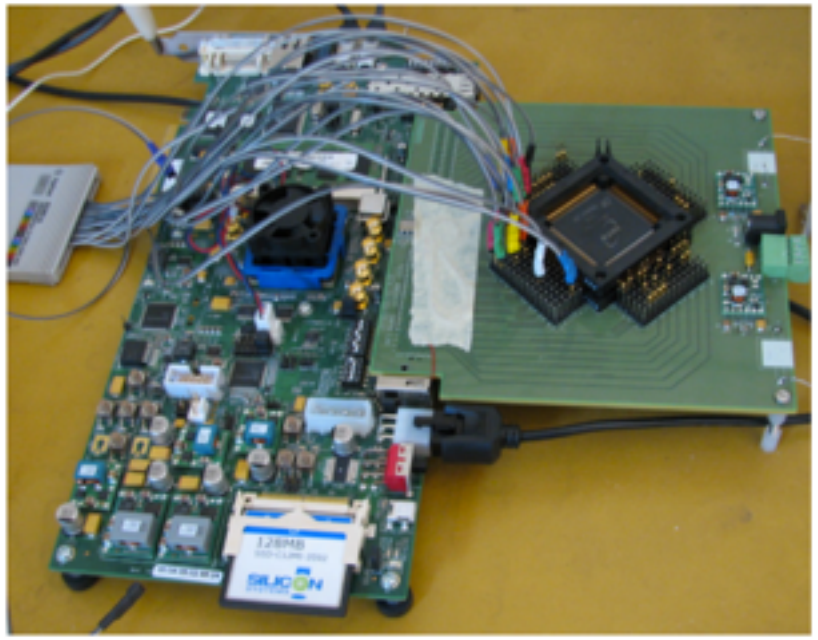
- Detailed timing studies based on per-word processing times for entire system
- 100 microsecond latency achievable at 70 interactions per crossing!

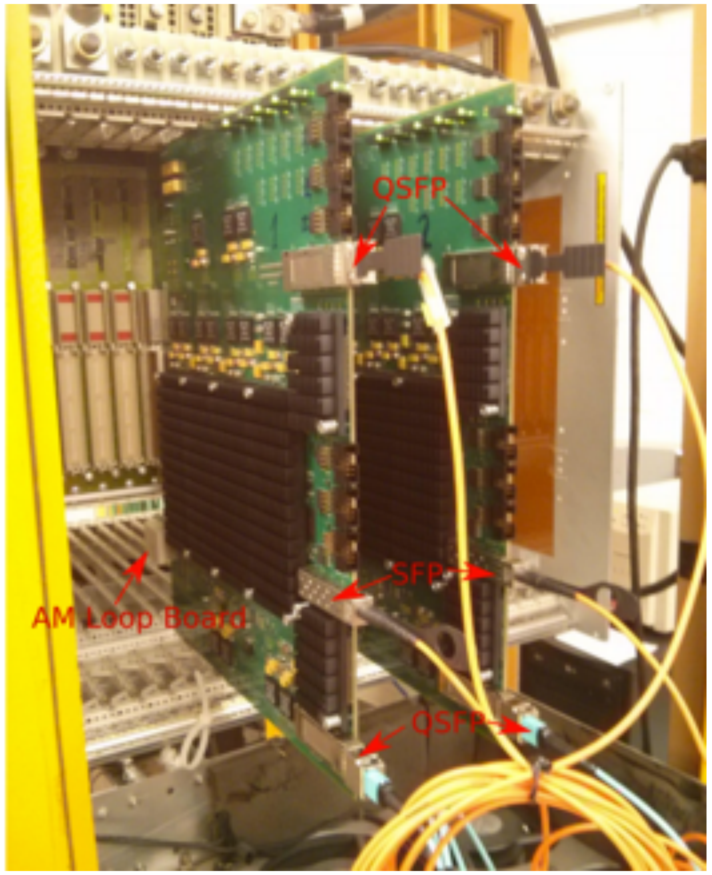




Summary of Prototype tests

- AMChips: Custom cells tested and works well!
- Processing Unit:
  - High speed communication between AUX and AMB successful
  - On board HS communication for AUX successful
  - Cooling tests for AMB underway to determine crate configuration
- Clustering Mezzanine:
  - Data transfer (SCT) tested in with collision data
  - Connection to DF through SMD connector tested
- Data Formatter:
  - Onboard and backplane data transfer tested to 10Gbps





A Andreani *et al* 2012 *JINST* **7** C08007 doi:10.1088/1748-0221/7/08/C08007

Stage 3: 12-layer Track Fitting

- Use constants precomputed from linearized constraints to guess hit coordinates

$$x_i' = \sum_{j=1}^{11} H_{ij} x_j + g_i; i = 1, \ldots, N_\chi$$

- Find matching hits
- Refit to find best χ^2 and track parameters
- Good tracks, with parameters, hits and errors are sent to final crate for formatting for the ATLAS trigger system