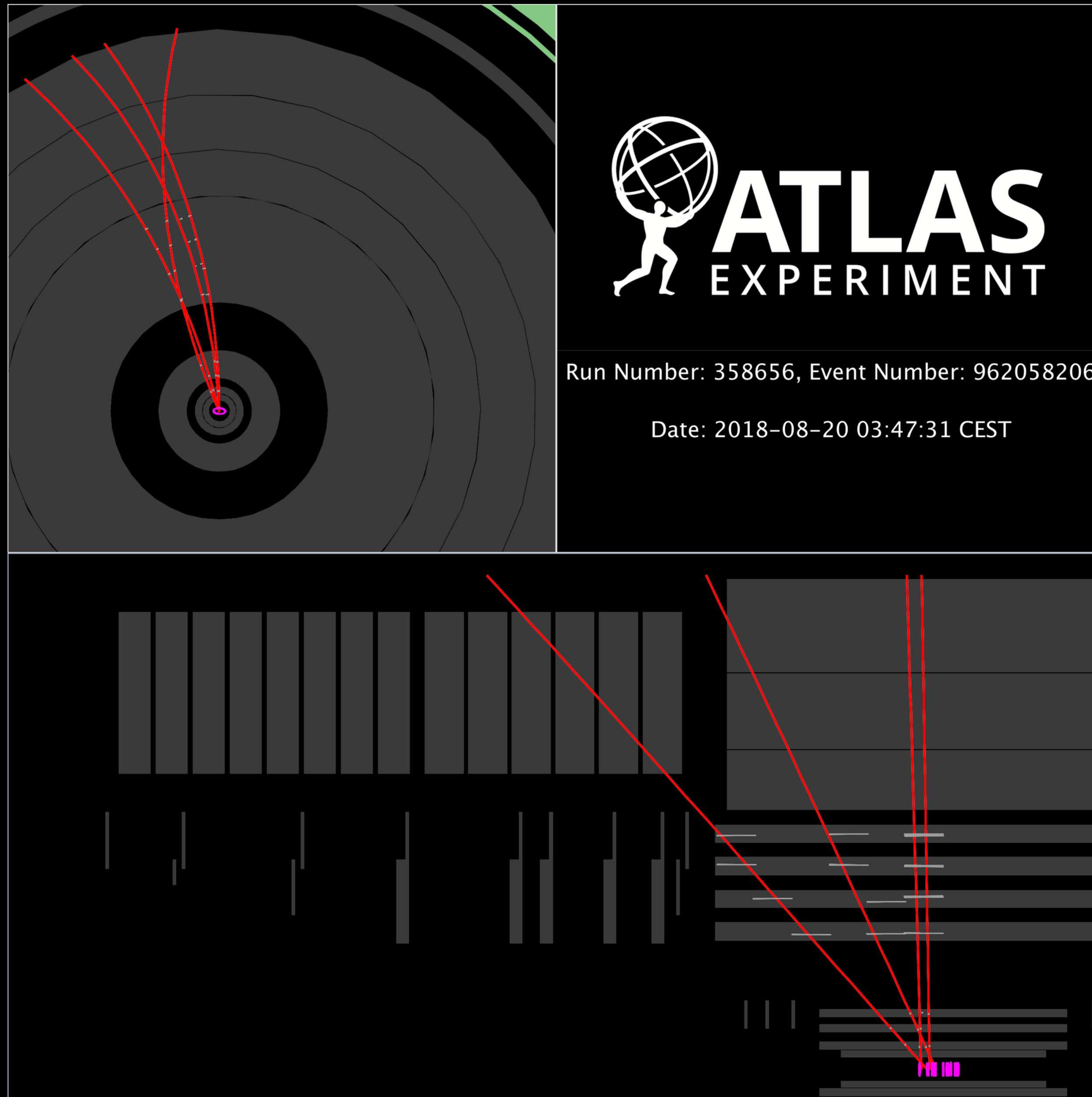
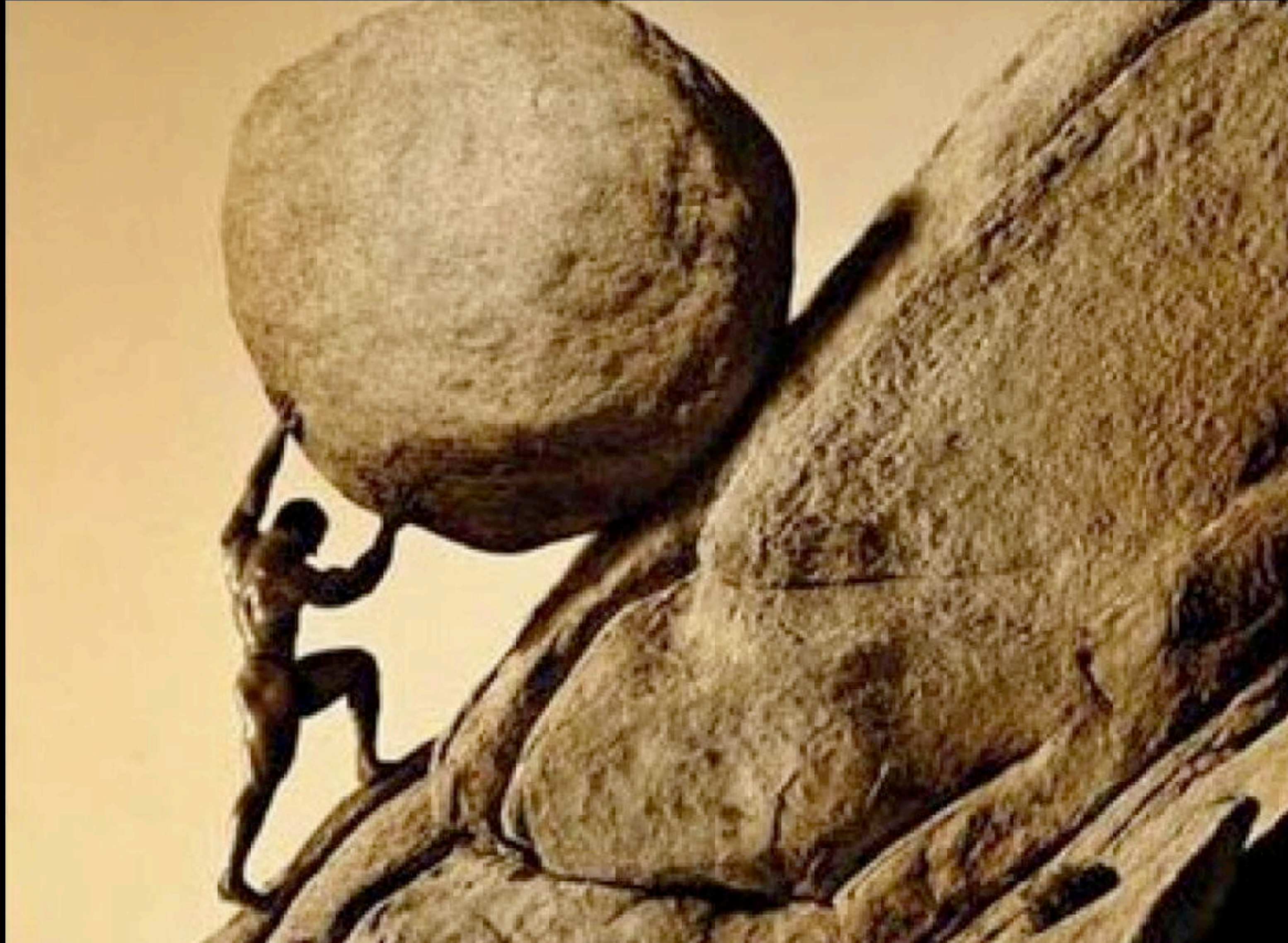


# TRACK TRIGGERS IN ATLAS





# TRACK TRIGGERS IN ATLAS





# THE FTK STORY





# THE FTK STORY



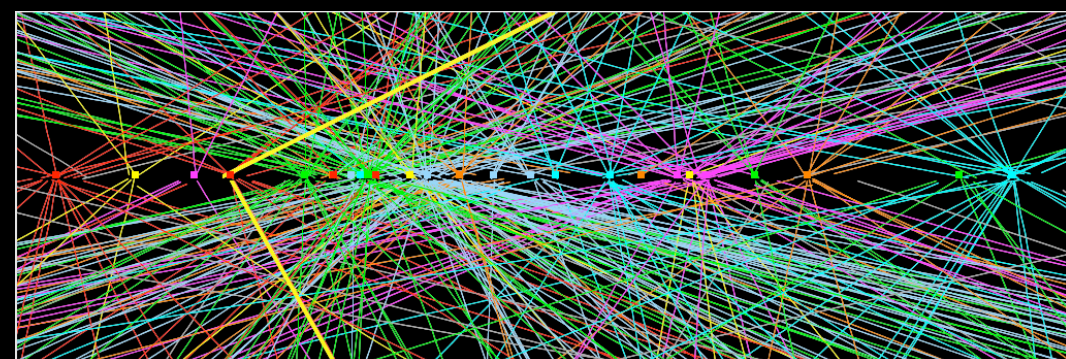
+ more I have missed!



# WHAT WAS FTK?



# WHAT WAS FTK?

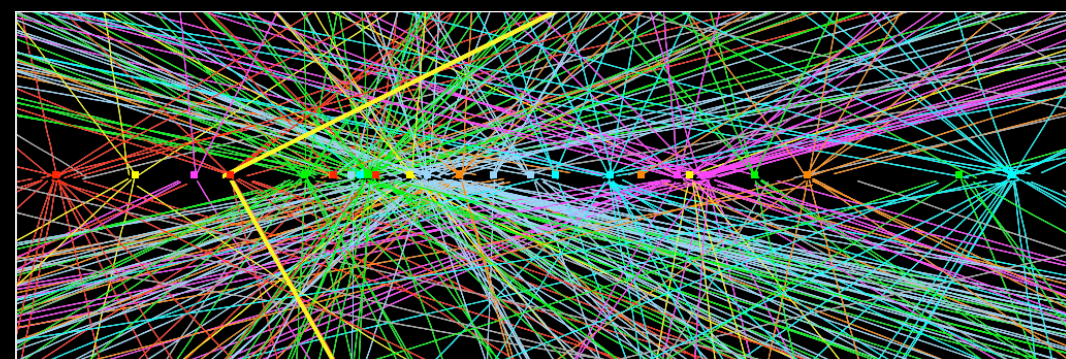
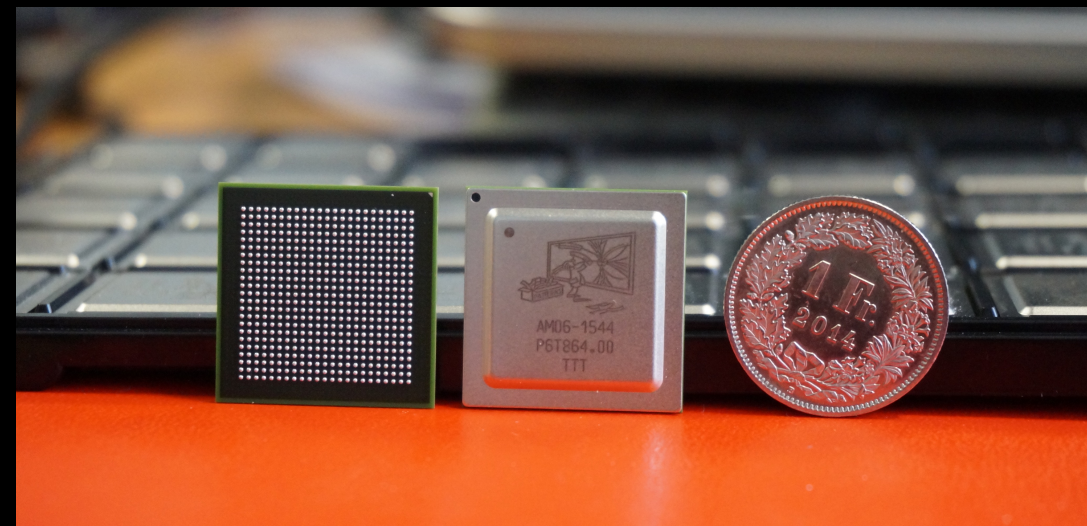




# WHAT WAS FTK?



100,000 x second

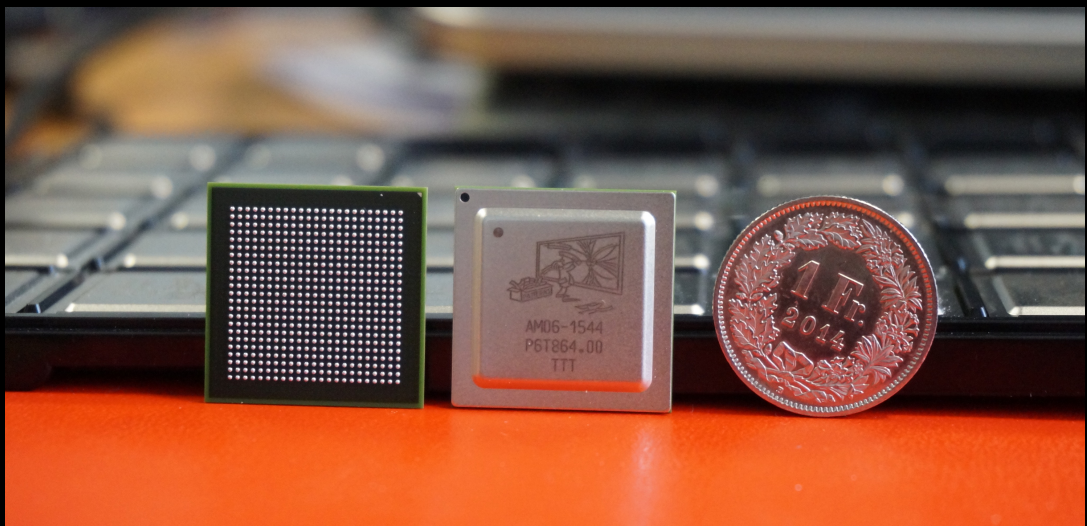
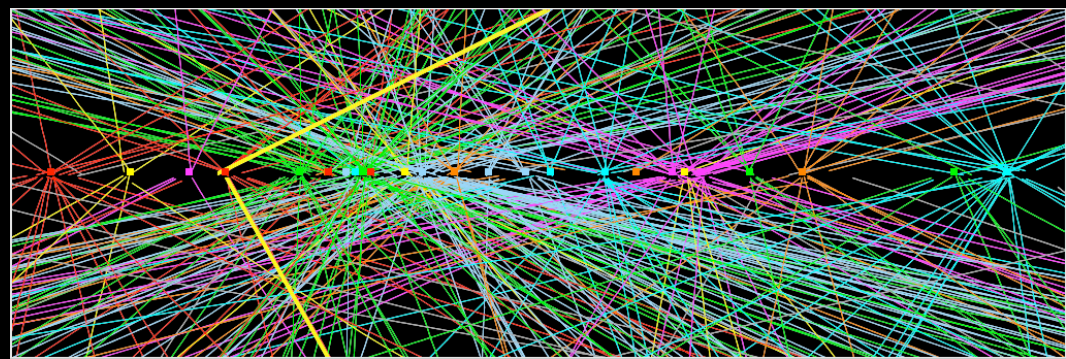





# WHAT WAS FTK?



100,000 x second



Award Abstract # 1126275  
MRI: Development of Ultrafast Tracking Electronics for the ATLAS Trigger

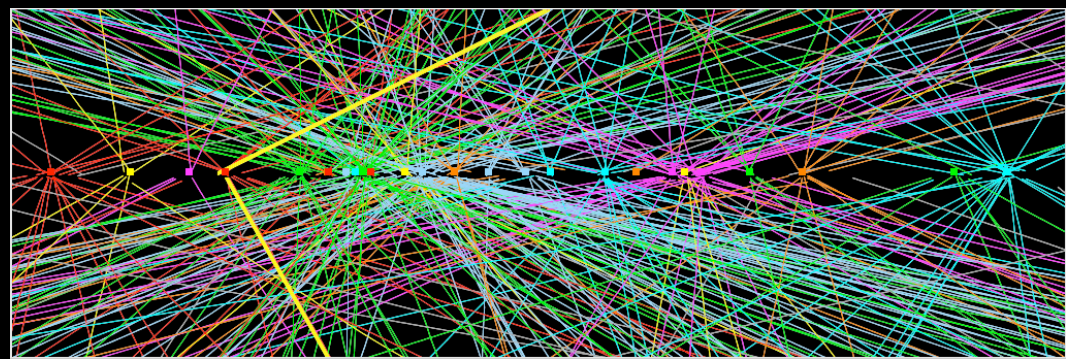
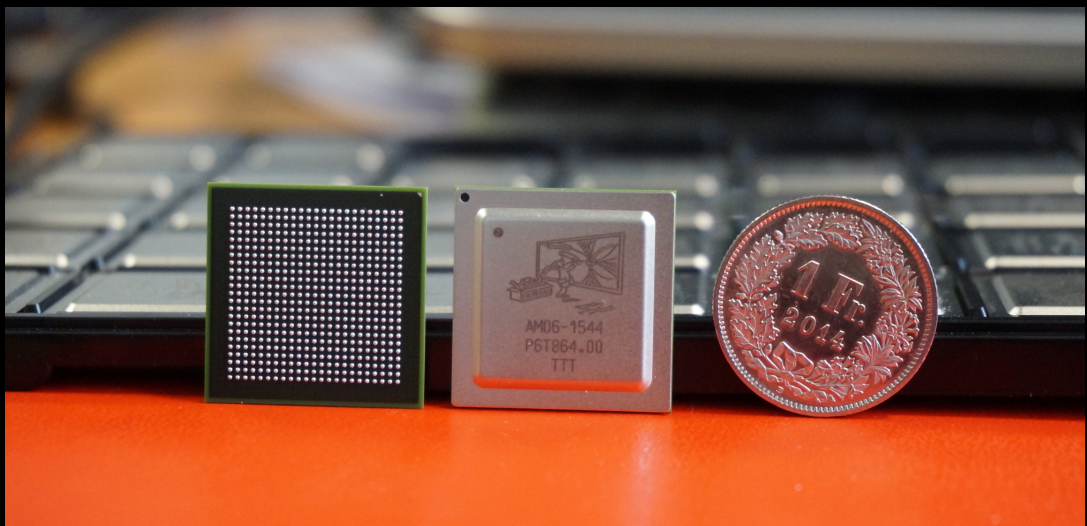
NSF Org:	<a href="#">PHY</a> <a href="#">Division Of Physics</a>	 National Science Foundation
Recipient:	UNIVERSITY OF CHICAGO	
Initial Amendment Date:	September 13, 2011	




# WHAT WAS FTK?



100,000 x second



Award Abstract # 1126275  
MRI: Development of Ultrafast Tracking Electronics for the ATLAS Trigger

NSF Org:	<a href="#">PHY</a> <a href="#">Division Of Physics</a>	 National Science Foundation
Recipient:	UNIVERSITY OF CHICAGO	
Initial Amendment Date:	September 13, 2011	

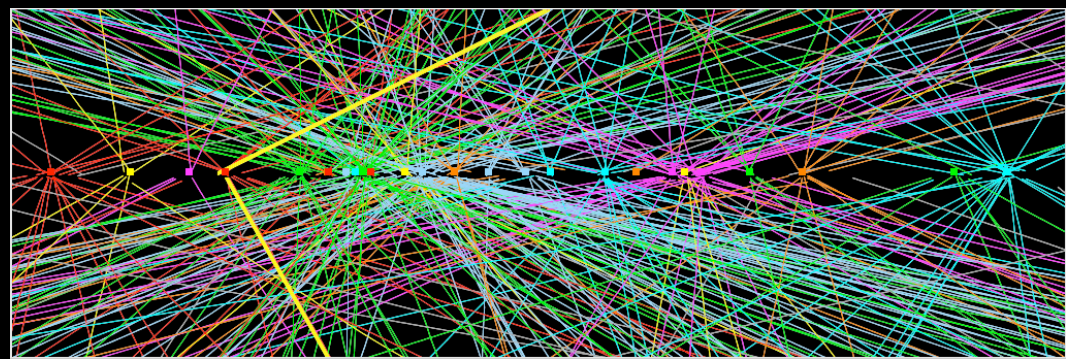
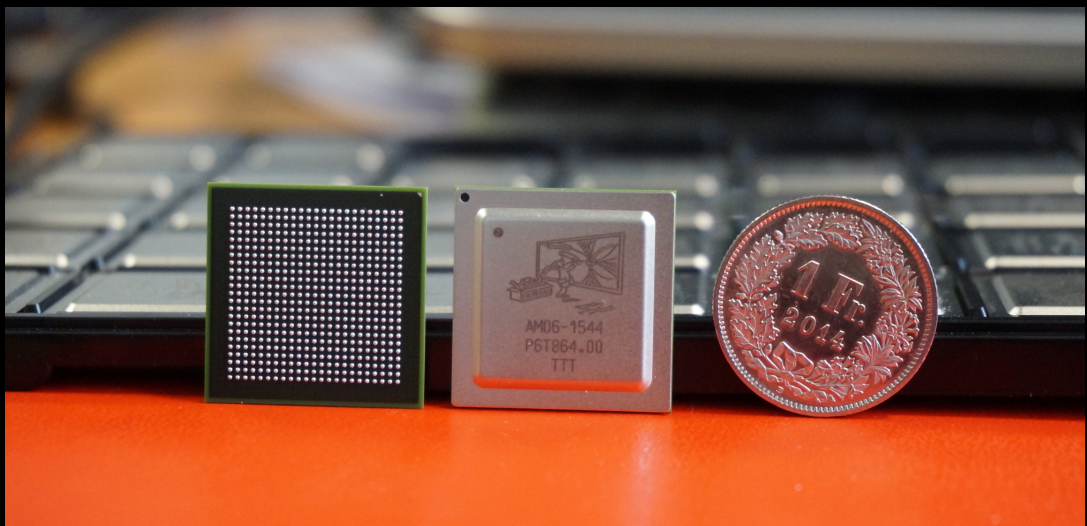




# WHAT WAS FTK?

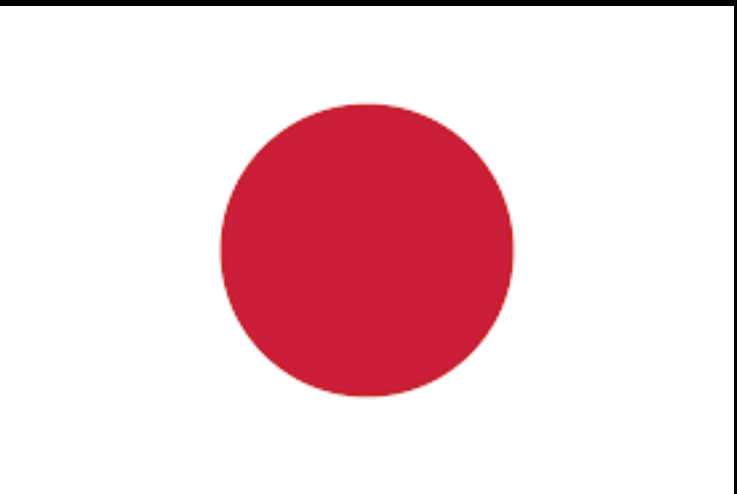


100,000 x second



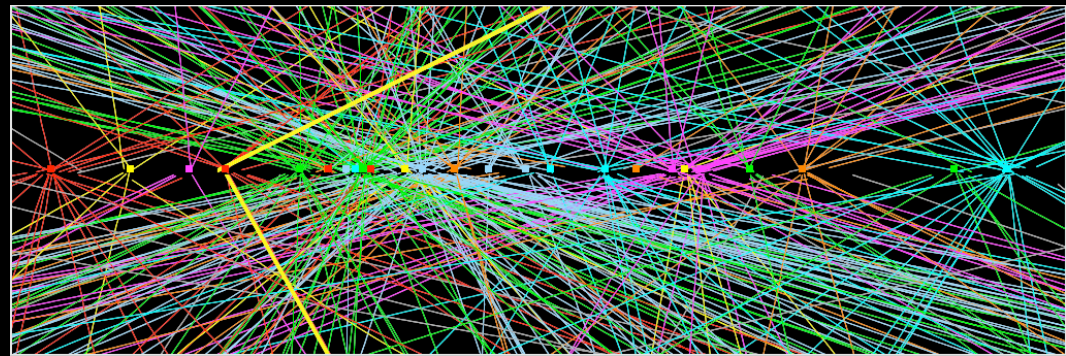
Award Abstract # 1126275  
MRI: Development of Ultrafast Tracking Electronics for the ATLAS Trigger

NSF Org:	<a href="#">PHY</a> <a href="#">Division Of Physics</a>	 National Science Foundation
Recipient:	UNIVERSITY OF CHICAGO	
Initial Amendment Date:	September 13, 2011	

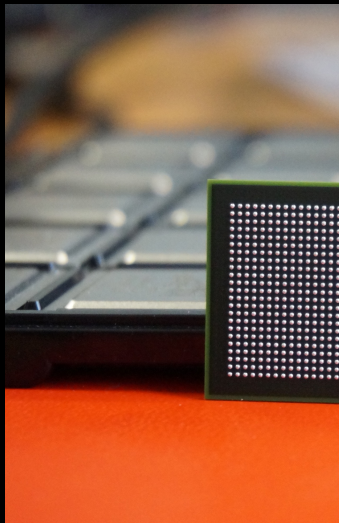





# WHAT WAS FTK?

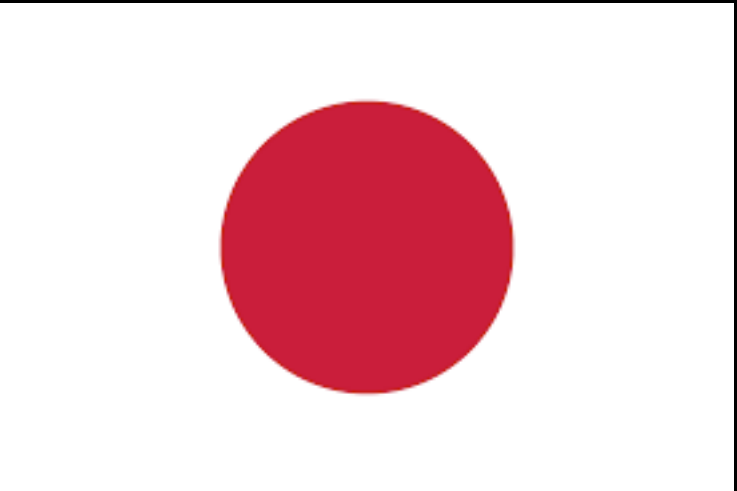


100,0



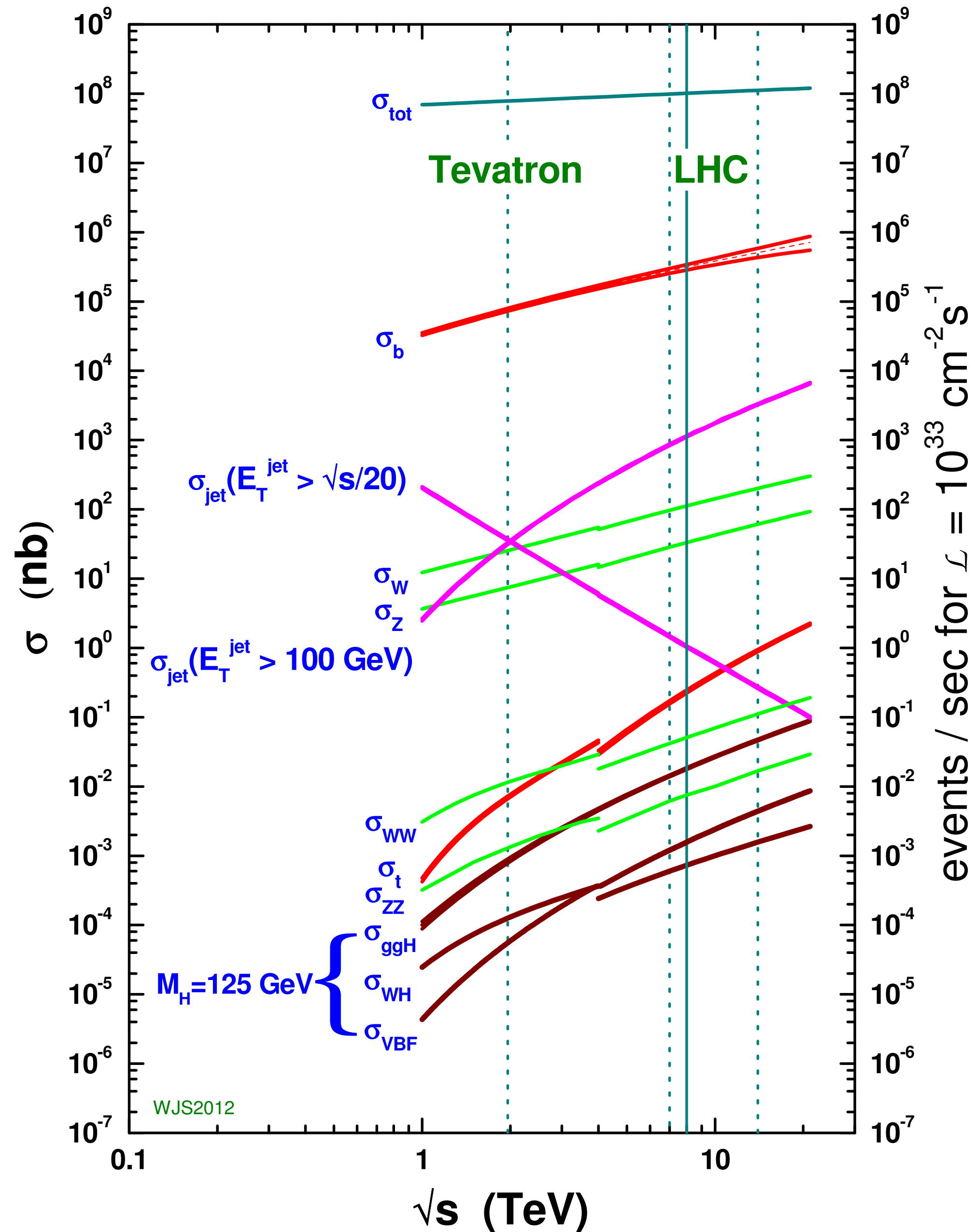
Award Abstract # 1126275  
MRI: Development of Ultrafast Tracking Electronics for the ATLAS Trigger

NSF Org:	<a href="#">PHY</a> <a href="#">Division Of Physics</a>	 National Science Foundation
Recipient:	UNIVERSITY OF CHICAGO	
Initial Amendment Date:	September 13, 2011	



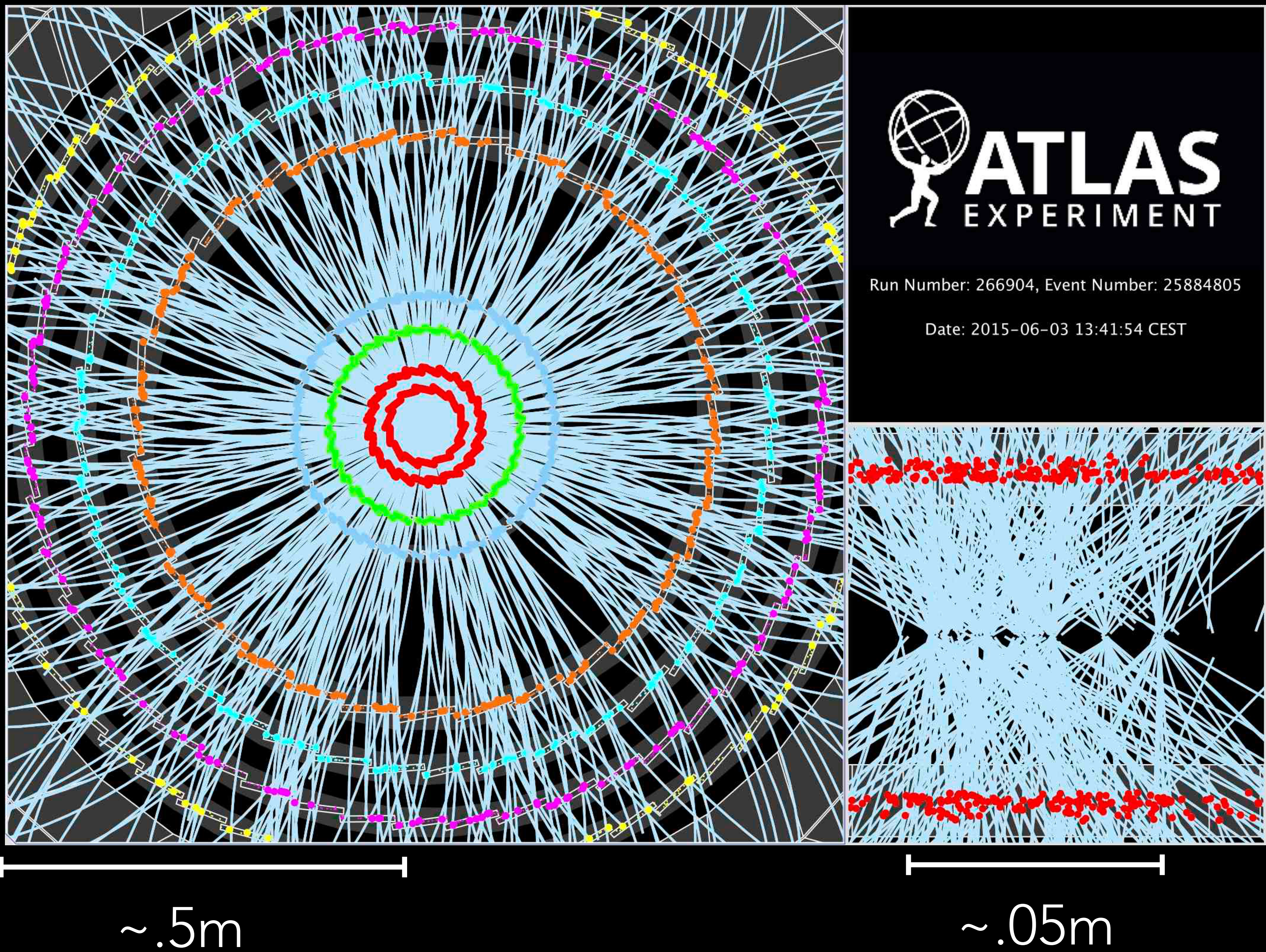


# proton - (anti)proton cross sections

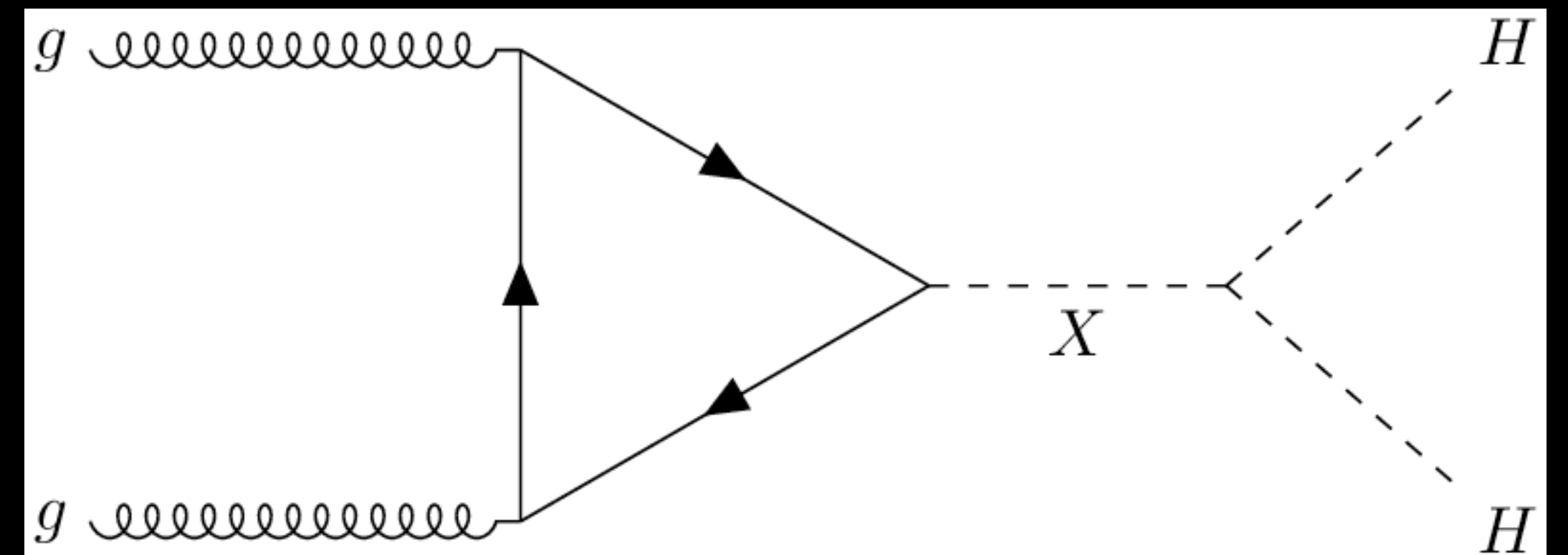
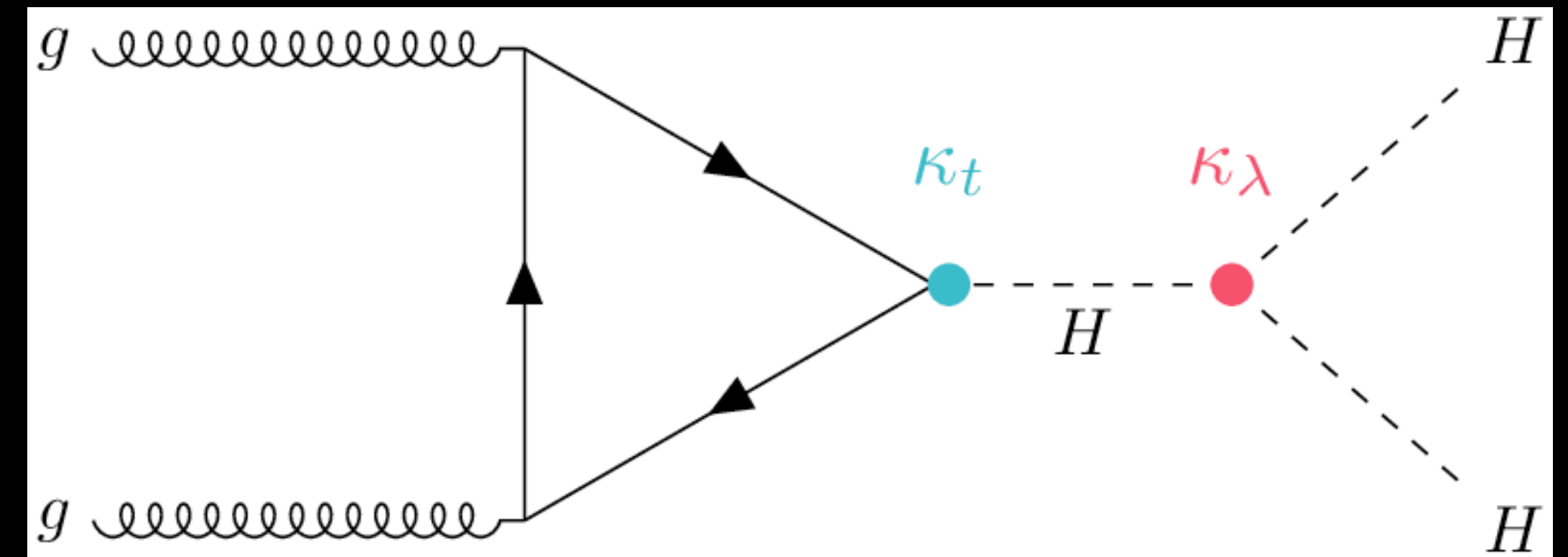
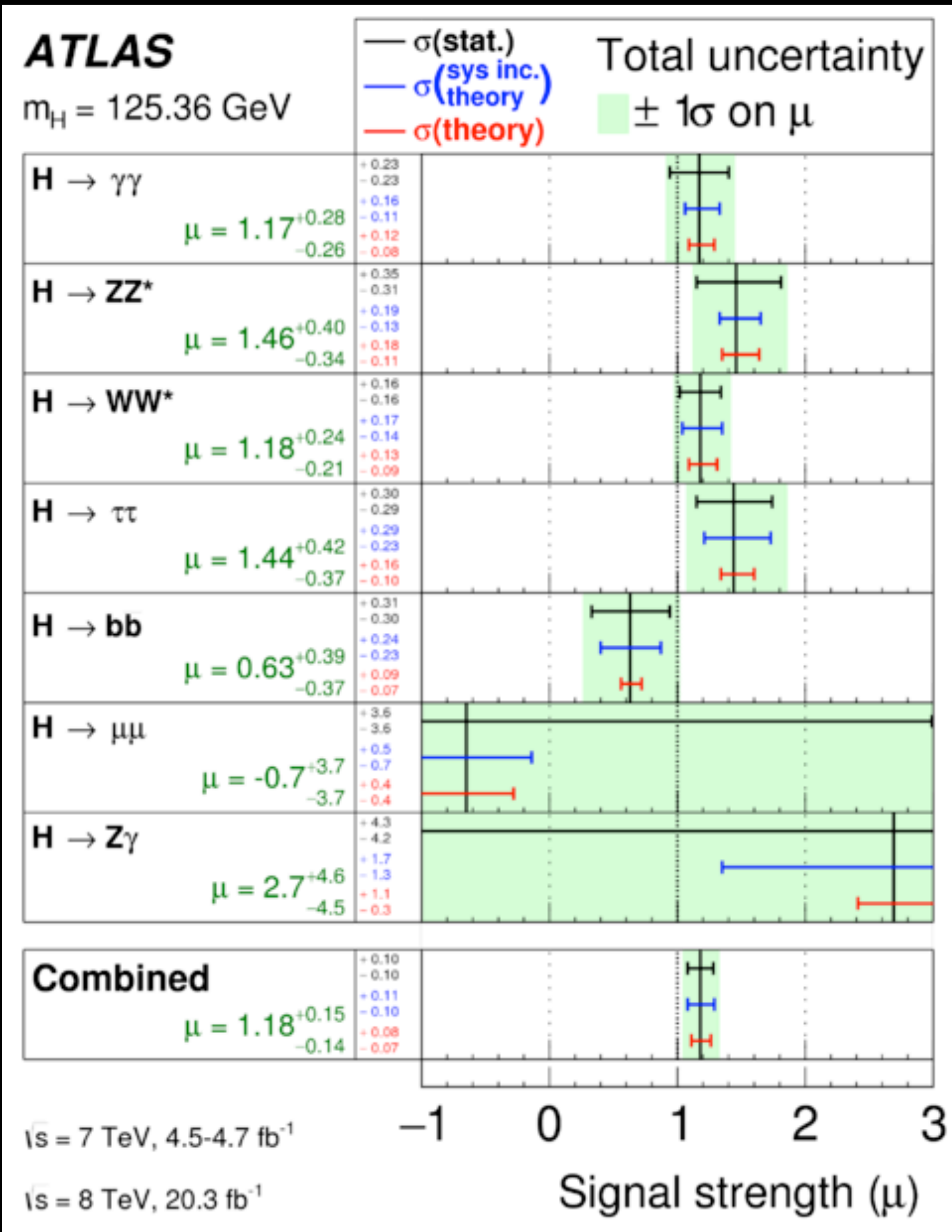


- Initial LHC design luminosity was  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  (23 simultaneous pp collisions)
- But LHC quickly surpassed that and Run II saw up to 60 simultaneous collisions. The experiments were told to prepare for  $\sim 80$ .



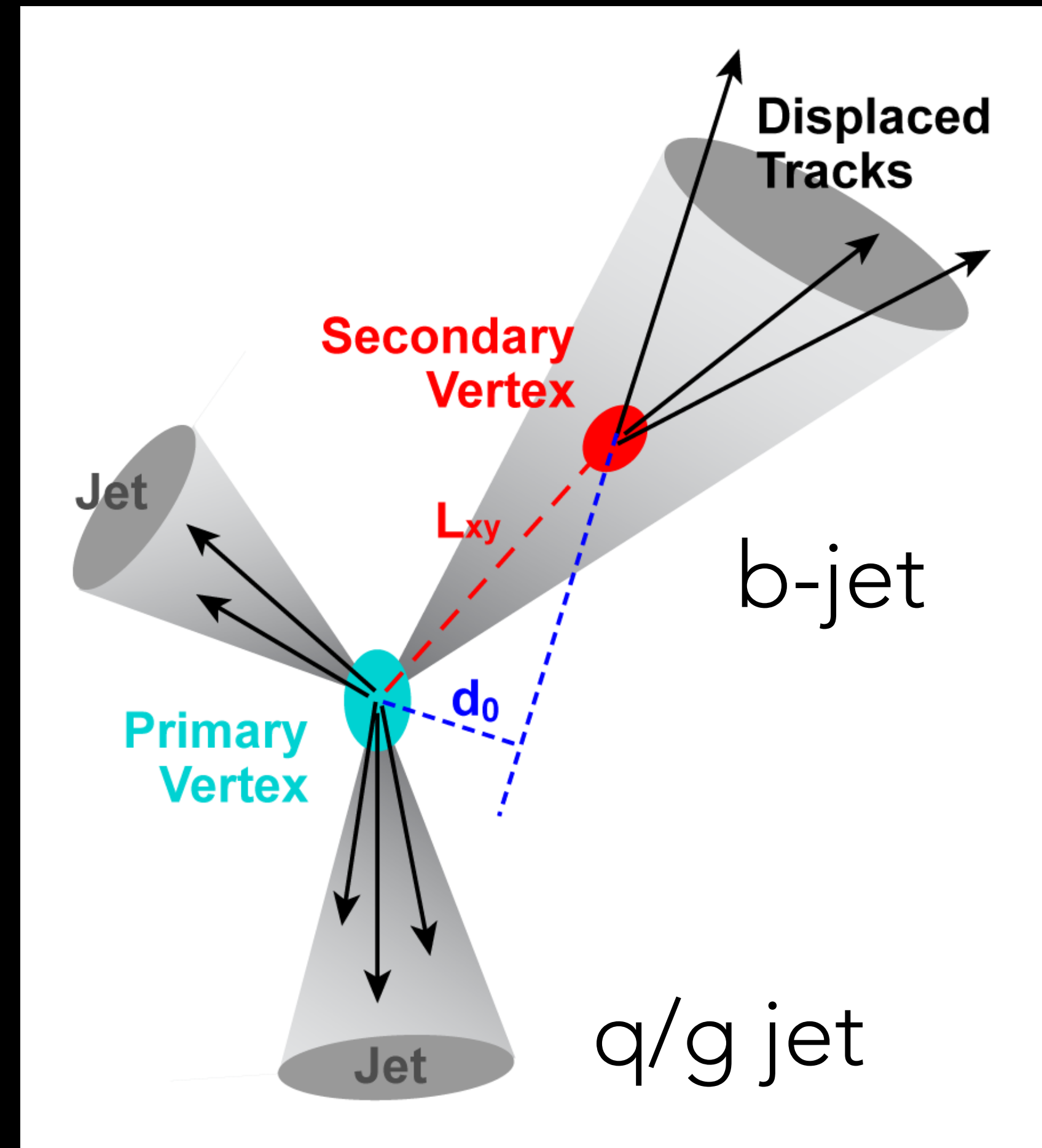
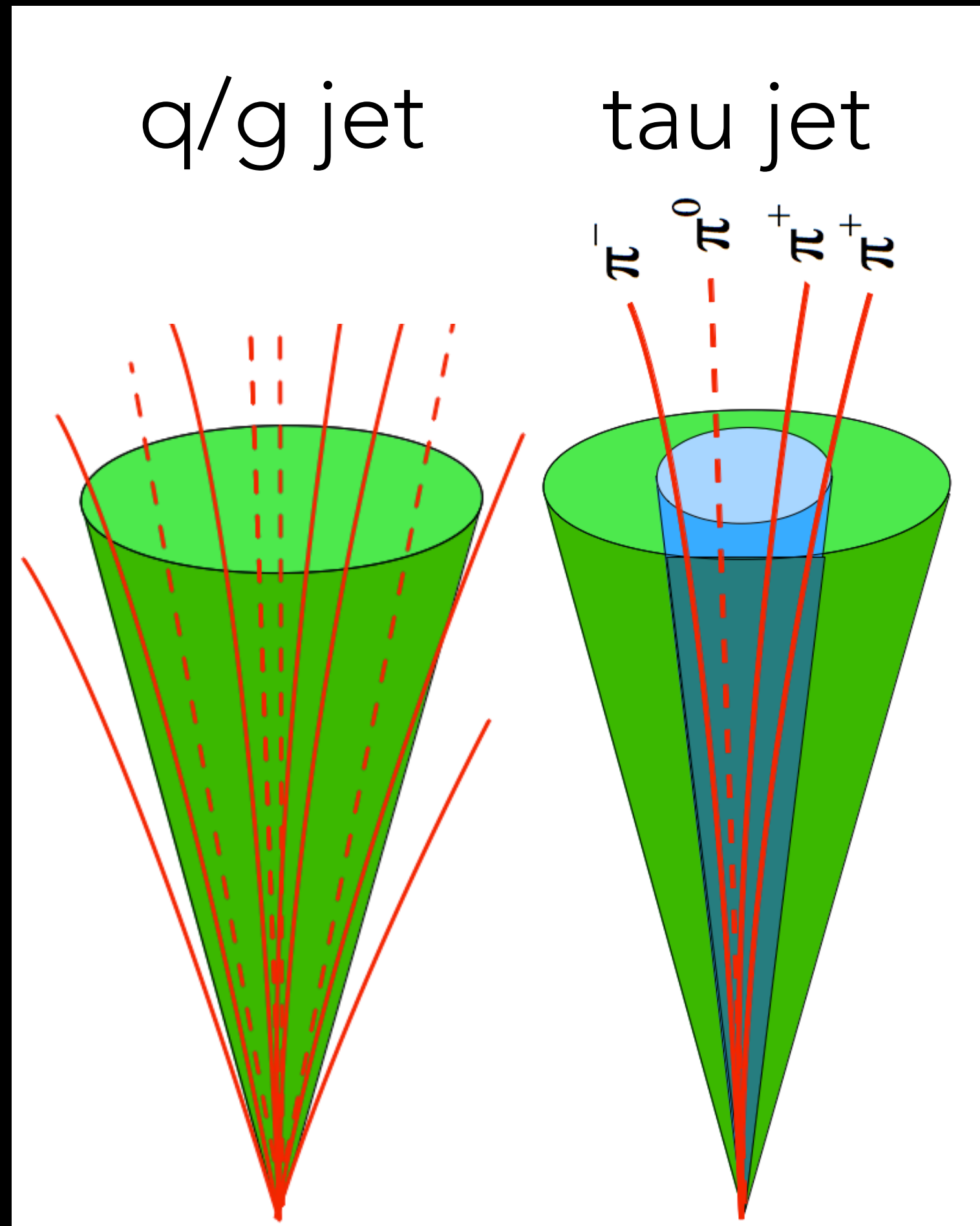









# TRACKING CRITICAL INPUT





			
<b>Proposal to prepare a technical design report for FTK, a hardware track finder upgrade to the ATLAS trigger</b>			
<i>ATLAS Upgrade Document No:</i>	<i>Institute Document No.</i>	<i>Created:</i> <b>28/06/2007</b>	<i>Page:</i> <b>1 of 11</b>
		<i>Modified:</i> <b>05/12/2007</b>	<i>Rev. No.:</i> <b>2.00</b>

2007

Abstract

We propose to build a hardware track finder (FTK) as an upgrade to the ATLAS trigger. It will provide global reconstruction of tracks above 1 GeV/c in the silicon detectors, with high quality helix parameters, by the beginning of level-2 trigger processing. FTK can have broad applications and be particularly important for the selection of 3<sup>rd</sup>-generation fermions (*b* and *τ*). These have enormous background from QCD jets, which can be quickly rejected in level-2 if reconstructed tracks are available early. This R&D proposal is aimed at producing a full technical design report for FTK in the next year.

Contact Person: (with e-mail address)

Mel Shochet ([shochet@hep.uchicago.edu](mailto:shochet@hep.uchicago.edu))  
Paola Giannetti ([paola.giannetti@pi.infn.it](mailto:paola.giannetti@pi.infn.it))

<i>Prepared by:</i> <b>M. Shochet (University of Chicago)</b>	<i>Checked by:</i> <b>ATLAS High Luminosity Upgrade Steering Group</b>	<i>Approved by:</i>
--	---	---------------------



Paola Gianetti

### 1 Introduction

Experience at high luminosity hadron collider experiments shows that controlling trigger rates can be extremely challenging as the luminosity increases, physics goals change in response to new discoveries, and the detector ages. It is thus essential that the trigger system be flexible and robust, and have redundancy and significant operating margin. Providing high quality track reconstruction over the full ATLAS detector by the start of processing in the level-2 computer farm can be an important element in achieving these goals. This has certainly been the case in the CDF experiment where the Silicon Vertex Trigger<sup>1,2</sup>(SVT) has significantly extended the experiment’s physics capability. The figures below give a few recent examples. Figure 1 shows the  $Z \rightarrow b\bar{b}$  signal for 630  $pb^{-1}$  of data, which determines the jet-energy scale to  $\pm 2\%$ . This is important both for the top-quark mass and the Higgs mass if a discovery is made in the  $b\bar{b}$  final state. Figure 2 shows the precision measurement of the terahertz  $B_s^0 - \bar{B}_s^0$  oscillation frequency. In both cases, all events were selected in the level-2 trigger by the presence of SVT tracks with large impact parameter relative to the beamline.

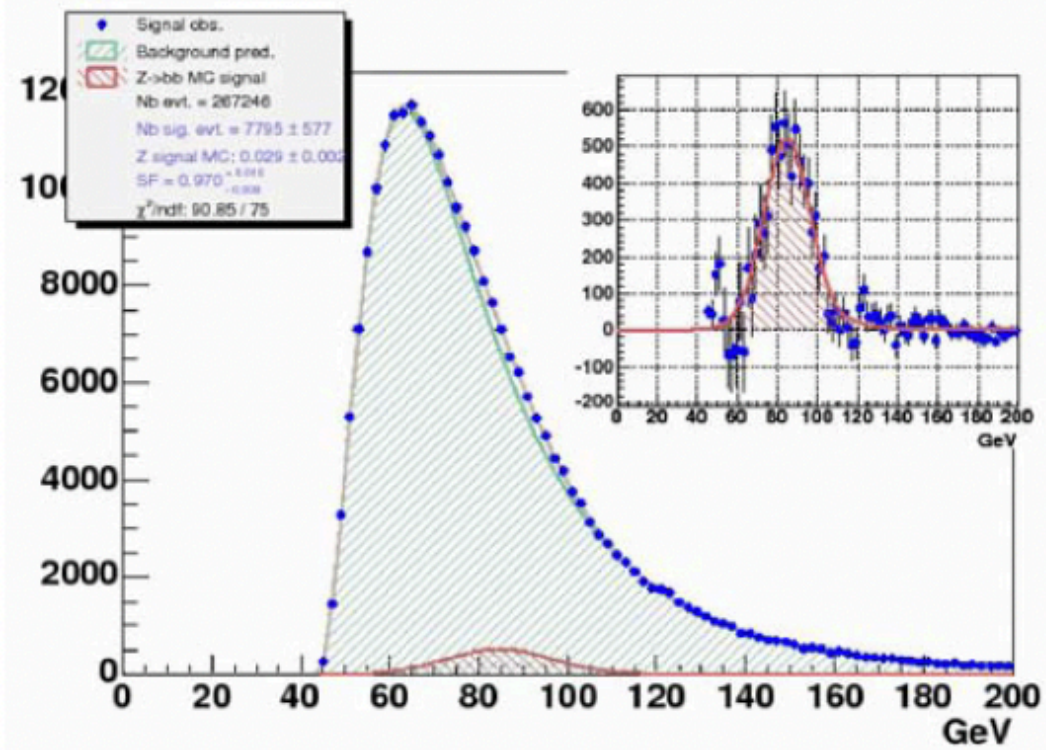


Figure 1: The CDF dijet mass distribution for *b*-jet pairs. The inset shows the  $Z^0$  signal after background subtraction.

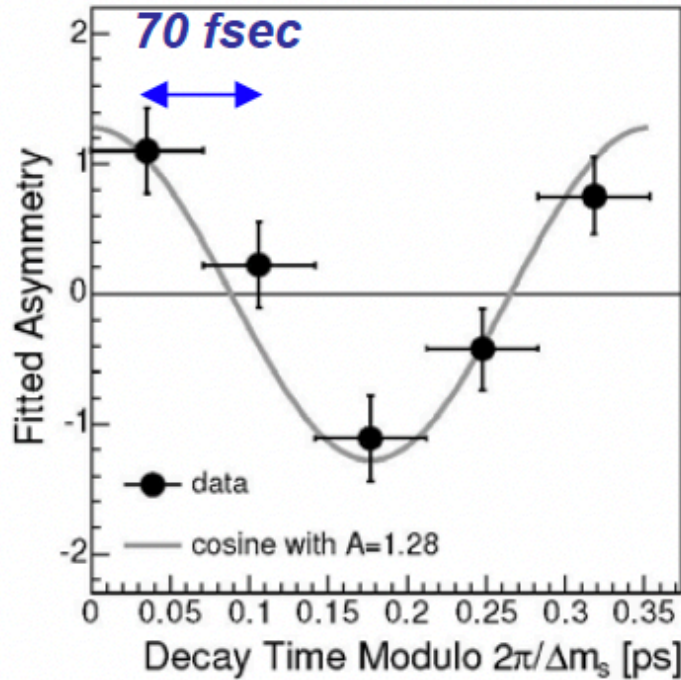
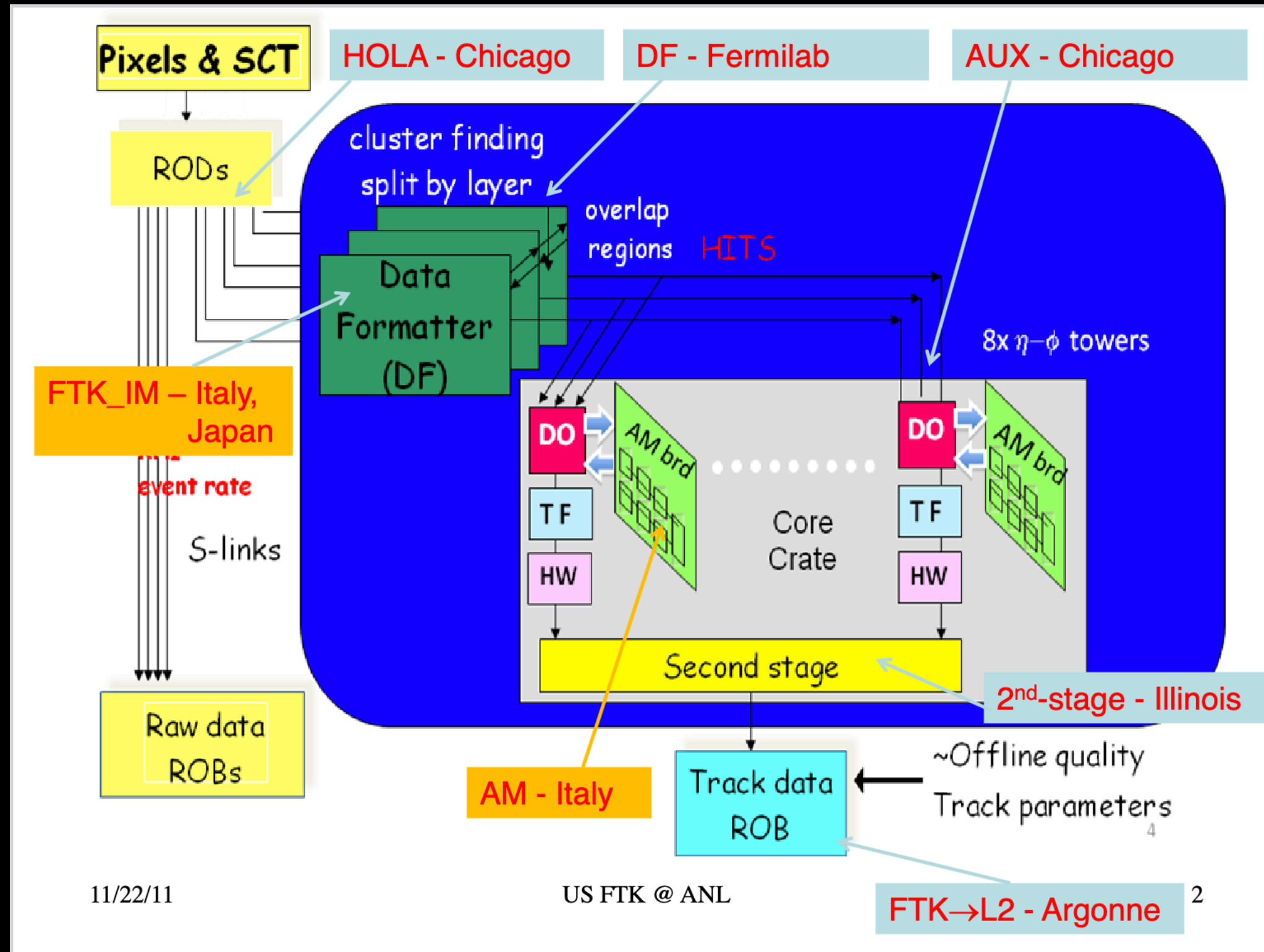


Figure 2: The CDF  $B_s^0 - \bar{B}_s^0$  oscillation data.



# THE TEAM



- In addition:
- IM: Thessoloniki ; DF: Stanford; SSB: SMU;
- FTKSim: DESY, Heidelberg, Pisa
- Online software: Pavia, Heidelberg
- + others...



+ others!



# 1<sup>st</sup> US FTK Face-to-Face Meeting

**M. Shochet**

11/22/11

US FTK @ ANL

1



# 1<sup>st</sup> US FTK Face-to-Face Meeting

M. Shochet

## How we got here

- Early studies and prototypes – **early in the last decade largely in Italy, then with US involvement starting in ~2002**
- Technical Proposal – **January 2010**
- TDAQ approval – **April, 2010**
- ATLAS design and management review – **December, 2010**
- ATLAS Collaboration Board approval – **June, 2011**
- Submit NSF MRI proposal – **January, 2011**
- MRI approval – **September, 2011**

**NOW WE HAVE TO BUILD IT & MAKE IT WORK!**

11/22/11

US FTK

11/22/11

US FTK @ ANL

4



# 1<sup>st</sup> US FTK Face-to-Face Meeting

M. Shochet

## How we got here

- Early studies and prototypes – **early in the last decade largely in Italy, then with US involvement starting in ~2002**
- Technical Proposal – **January 2010**
- TDAQ approval – **April, 2010**
- ATLAS design and management review – **December, 2010**
- ATLAS Collaboration Board approval – **June, 2011**
- Submit NSF MRI proposal – **January, 2011**
- MRI approval – **September, 2011**

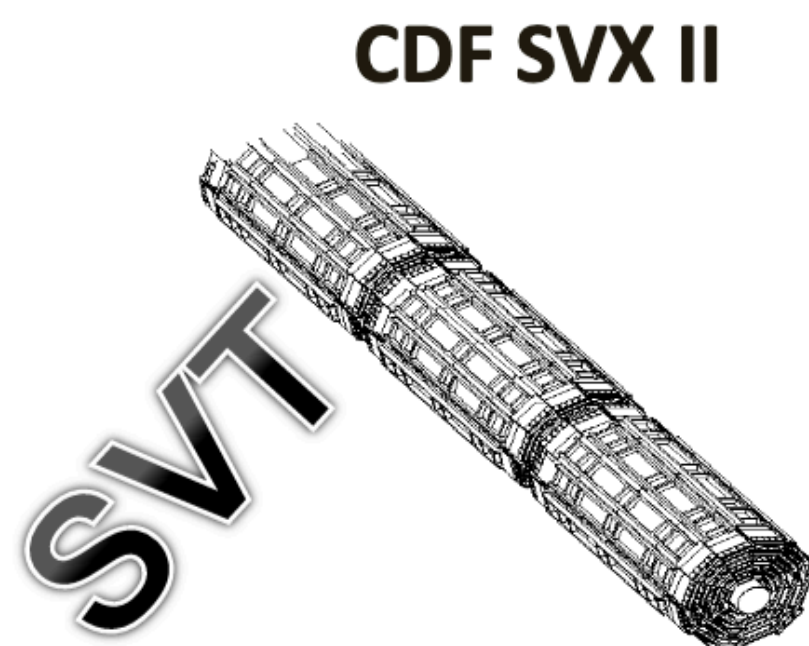
**NOW WE HAVE TO BUILD IT & MAKE IT WORK!**

## The Challenges

- Handling enormous data rates
  - **$2 \times 10^{10}$  hits per second**
  - **$10^{11}$  reads per second**
  - **60 gigabits per second from one DO to its TF**demands highly parallel system – hardware, data paths, and firmware.  
**Reducing execution time by  $10^3$ - $10^4$  is never easy!**
- Creating a system that is reliable, constantly monitored, maintainable. Ex.
  - **Spy buffers**
  - **Online software for efficiencies, read occupancy, resolution**
  - **Fast production of patterns & constants when the beam moves significantly.**
- Future expandability: phase-II, additional functions

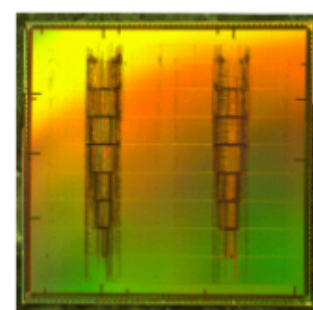


# From a Previous Success to a New Challenge



Channels used for SVT  
~ 0.2 millions

Pattern stored ~400K

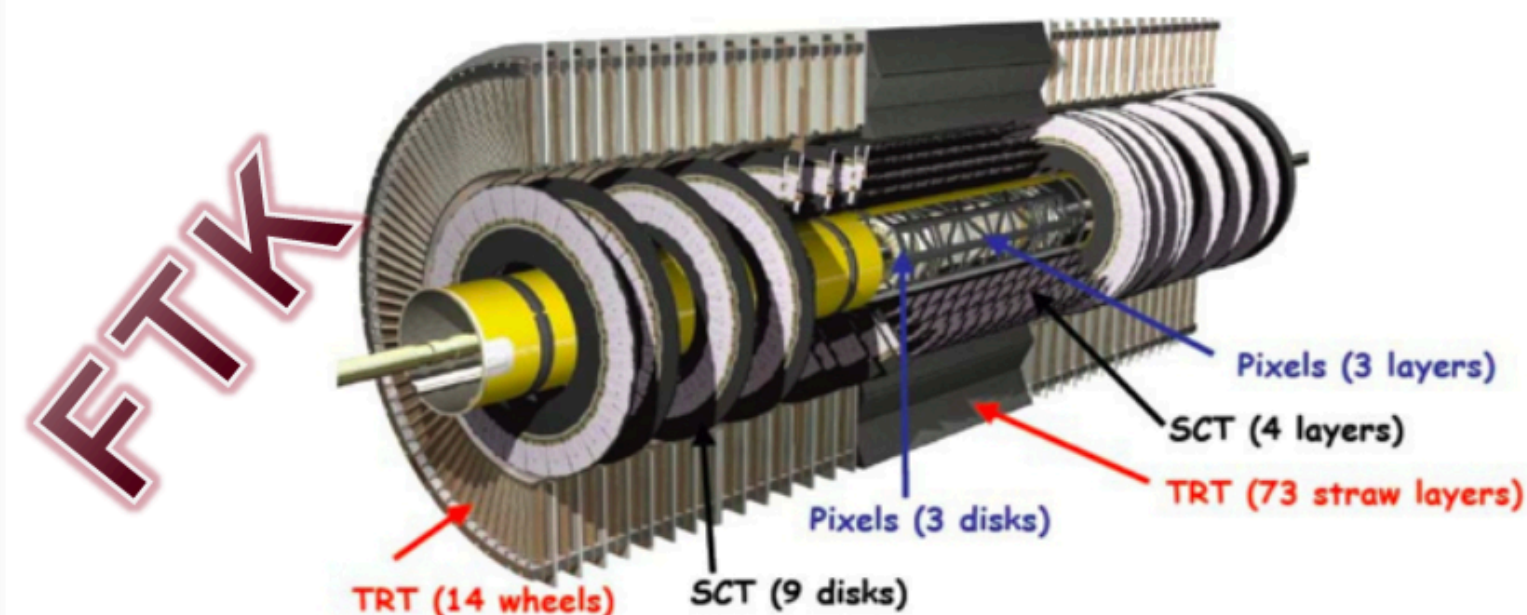


AMchip03  
180 nm  
3.7K pattern

## Parallelism

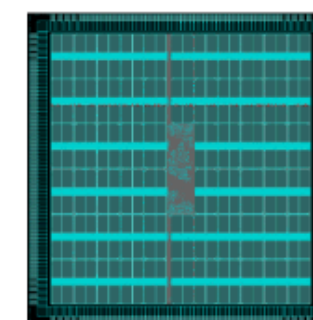
- 64  $\eta$ - $\phi$  towers
- Each tower with two processing units
- Overlaps to maintain high efficiency

## ATLAS Inner Detector



PIXEL 80 million channels  
SCT 6 million channels

Pattern stored ~ $10^9$



AMchip06  
65 nm  
128K pattern

## Two stage architecture

- PIX 3 (B or IBL)+SCT 4 axial, 2<sup>nd</sup> stereo
- Other layer extrapolation & 12-layer fit



May 28, 2013

Jinlong Zhang

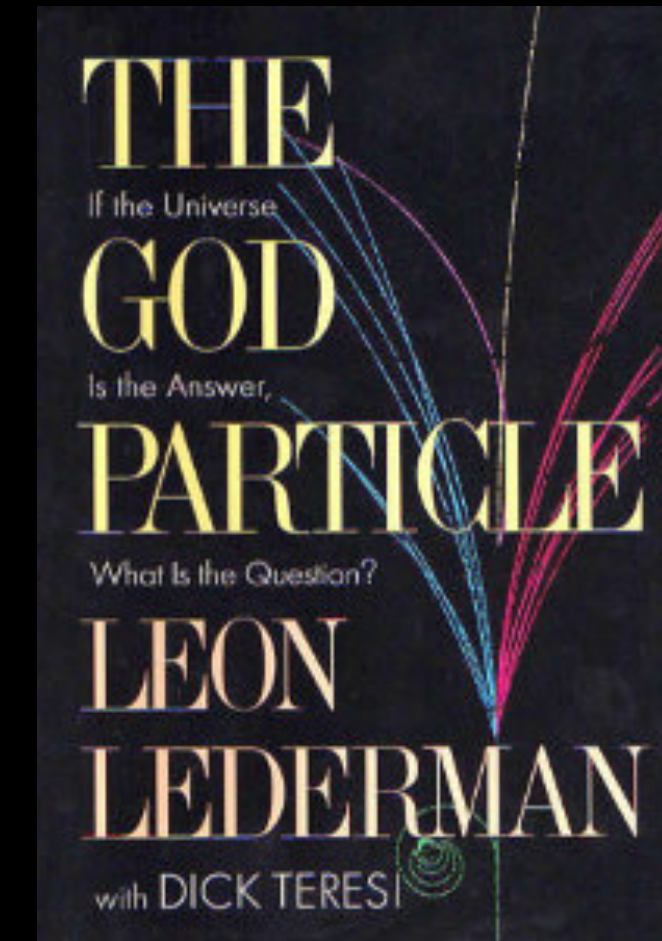


# ATLAS DATA DELUGE



# ATLAS DATA DELUGE

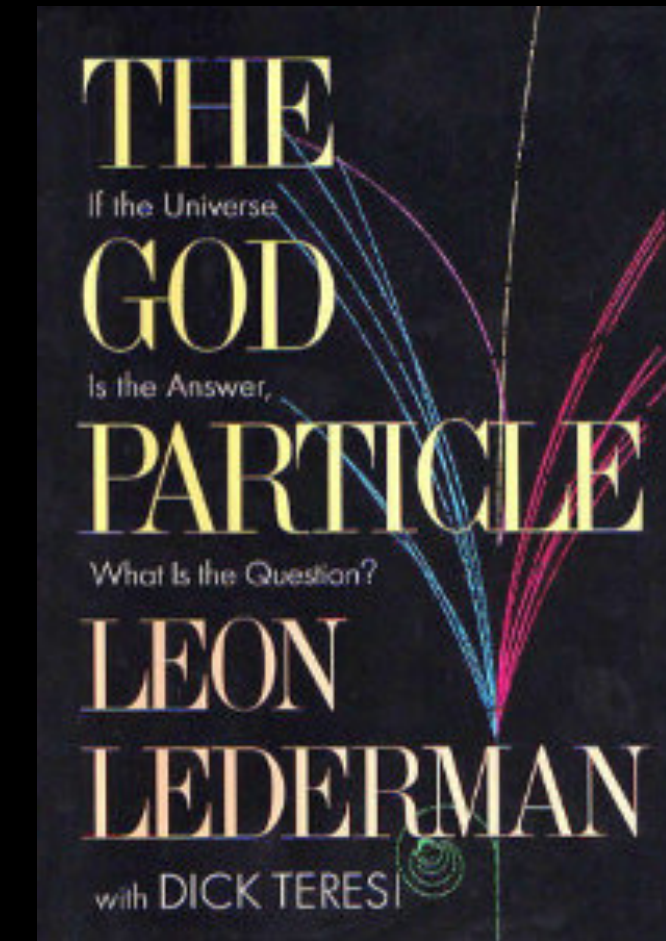
- Each event is ~ 1.25 MB
  - 1MB ~ 500 page book
  - Human genome = 800MB
  - 40 million events per second = 50 TB/second
    - 5x library of congress's printed collection!
  - ~100000s Trillions of collisions in Run II (2015-2018)!





# ATLAS DATA DELUGE

- Each event is ~ 1.25 MB
  - 1MB ~ 500 page book
  - Human genome = 800MB
- 40 million events per second = 50 TB/second
  - 5x library of congress's printed collection!
- ~100000s Trillions of collisions in Run II (2015-2018)!

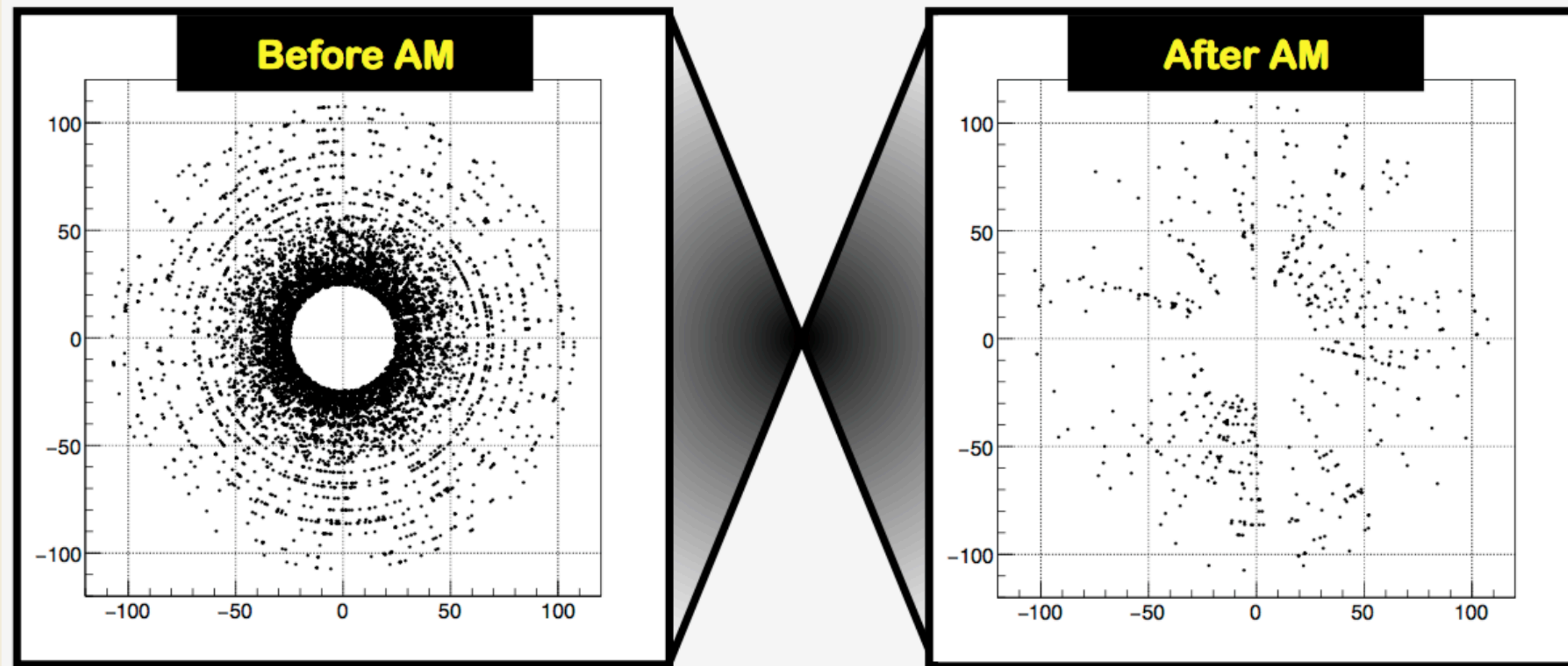


WAY TOO MUCH!



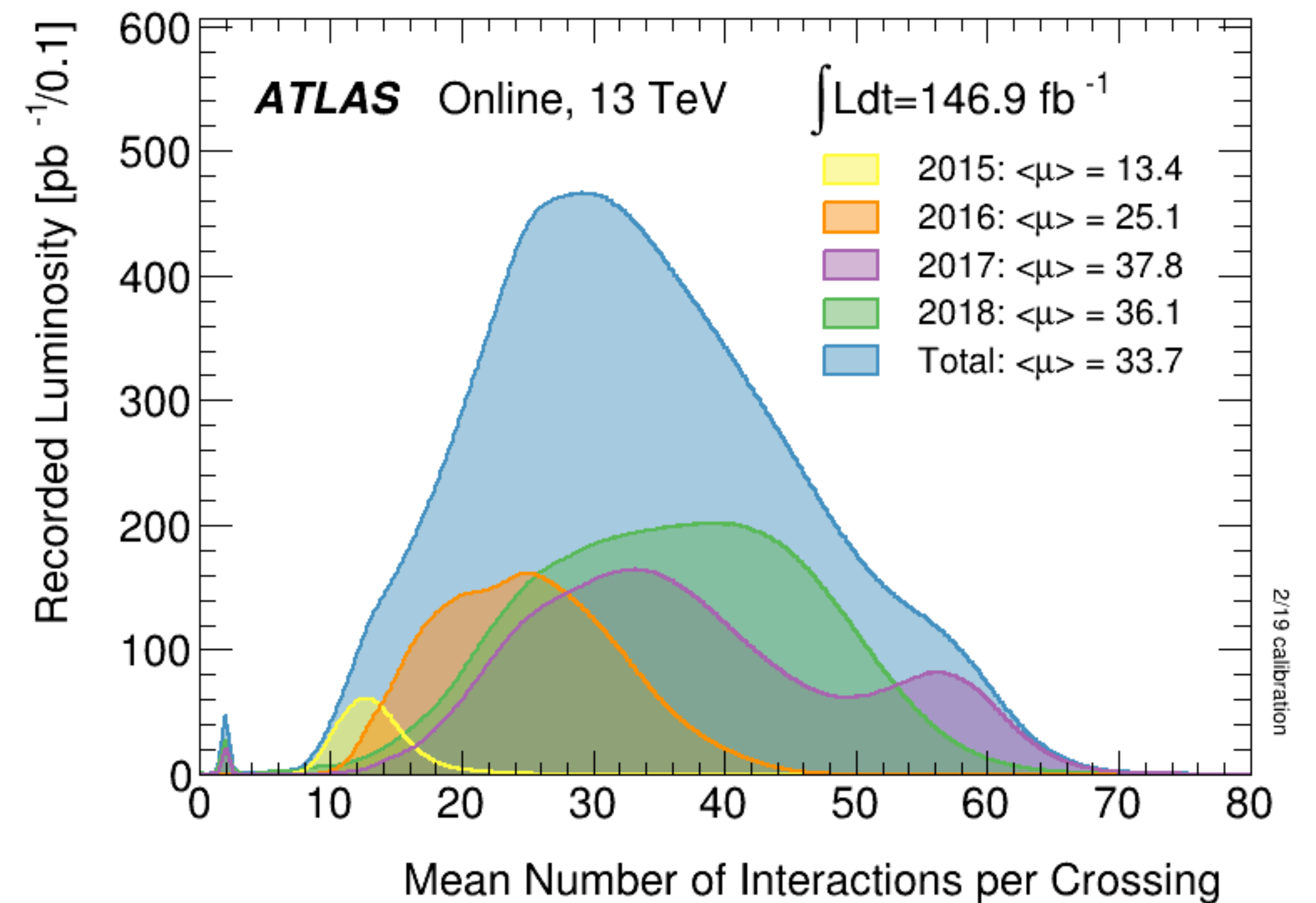
Luciano Ristori - October 19, 2016

## The Associative Memory does a lot in a very short time



Simulated beam crossing at the HL-LHC  
(drawing courtesy of Seb Viret)

26



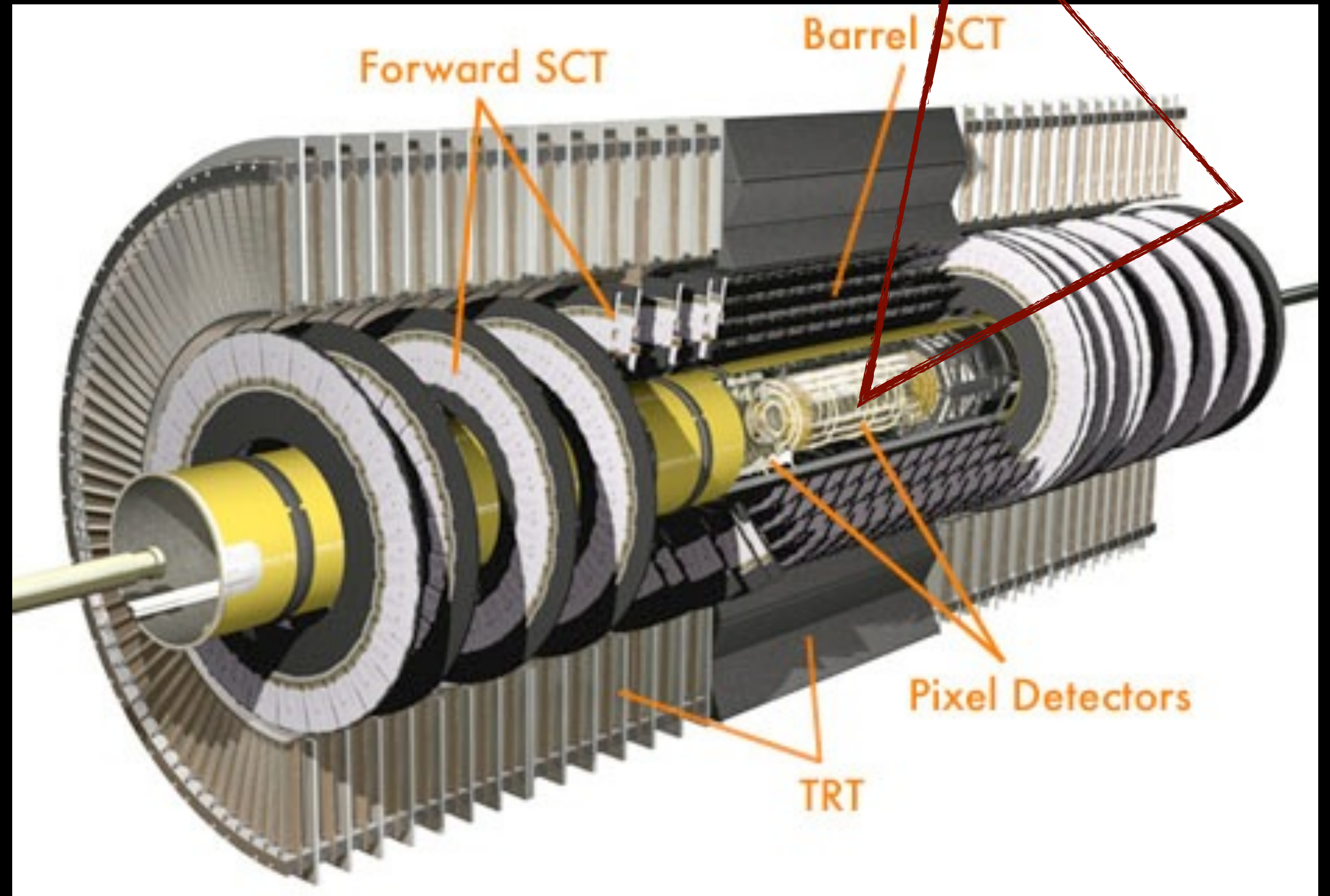


HOW WAS IT DONE?



# STAGE 1: DATA FORMATTING

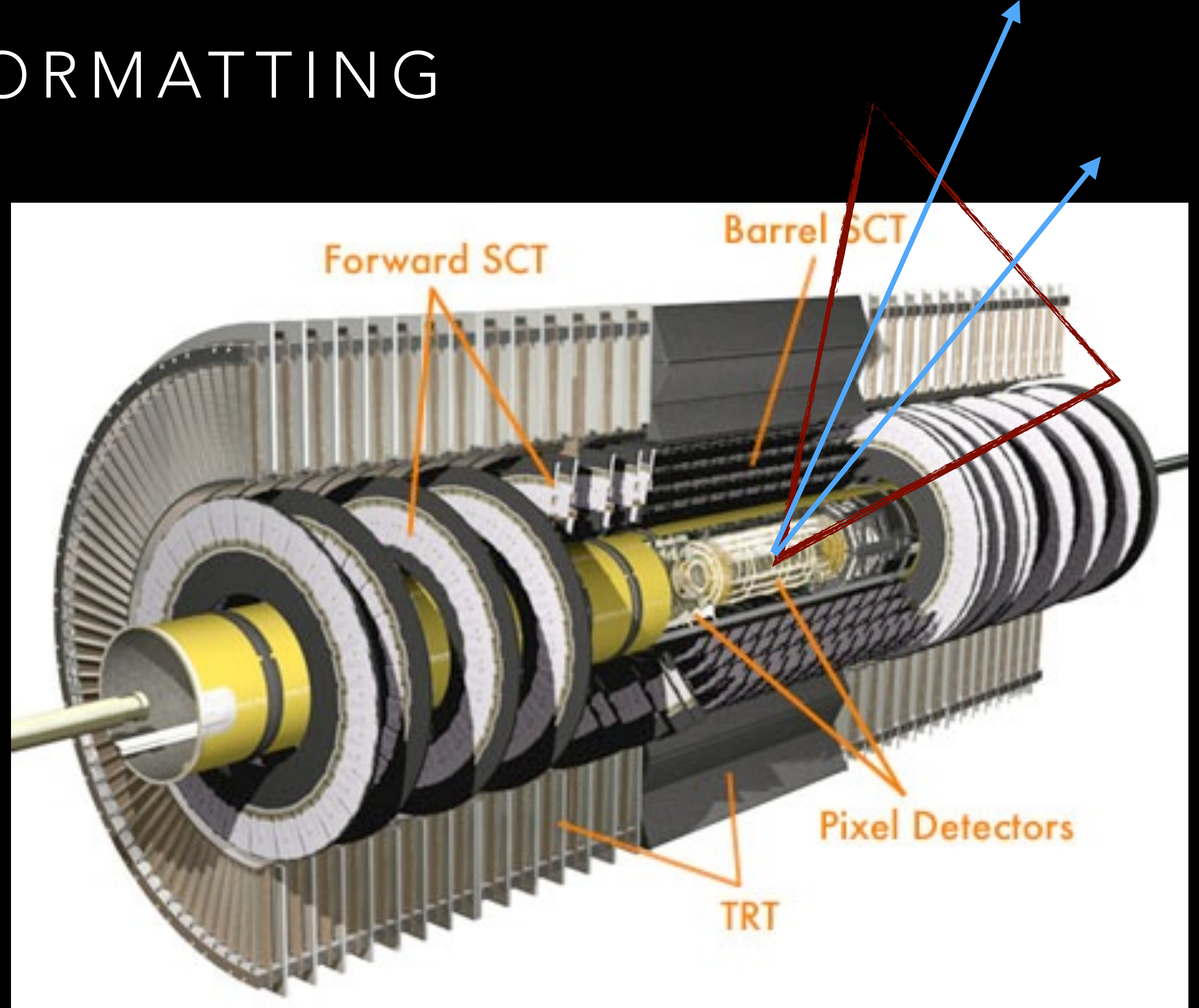
- Clustering, data cleaning, event synchronization
- Route clusters to FTK eta-phi towers





# STAGE 1: DATA FORMATTING

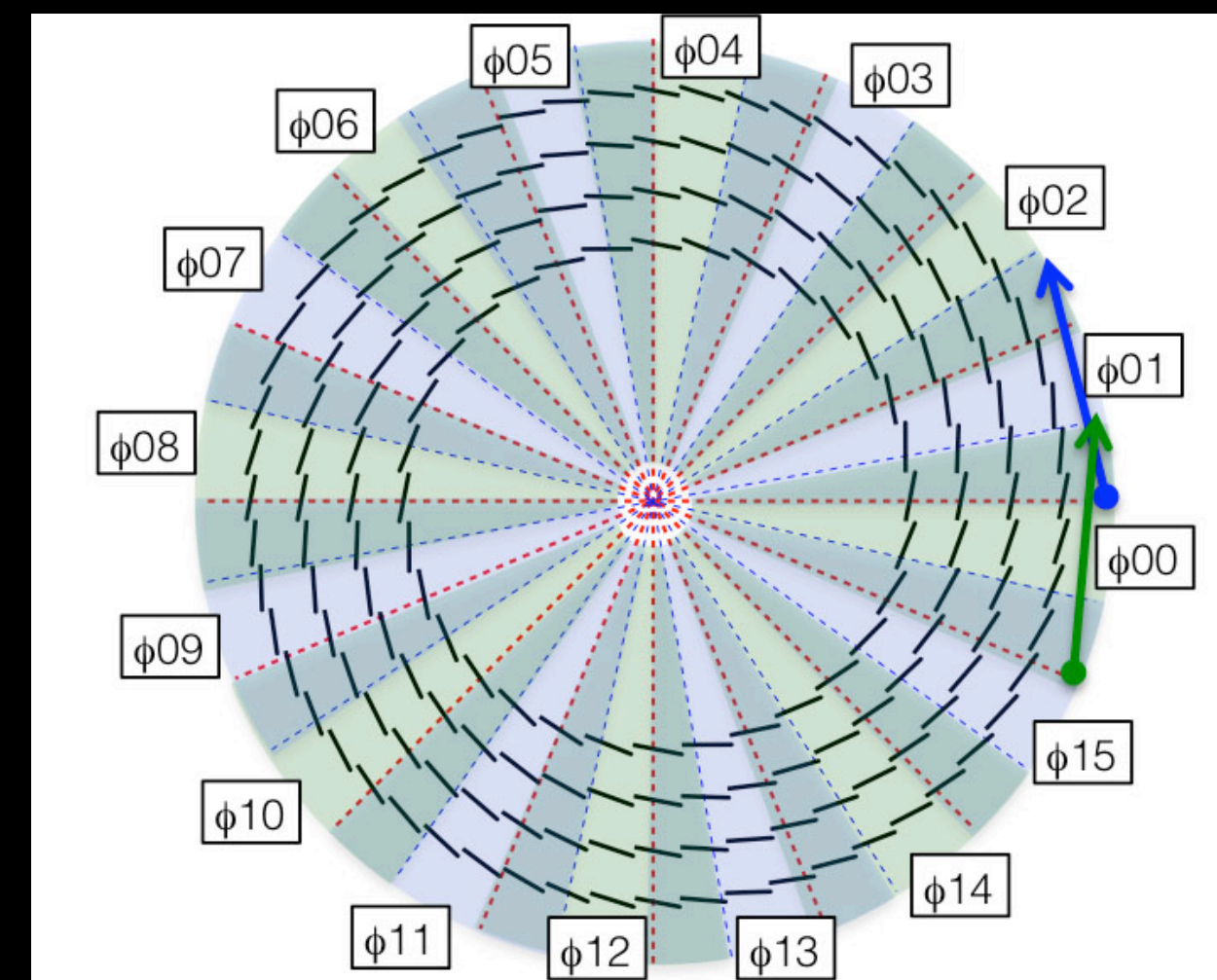
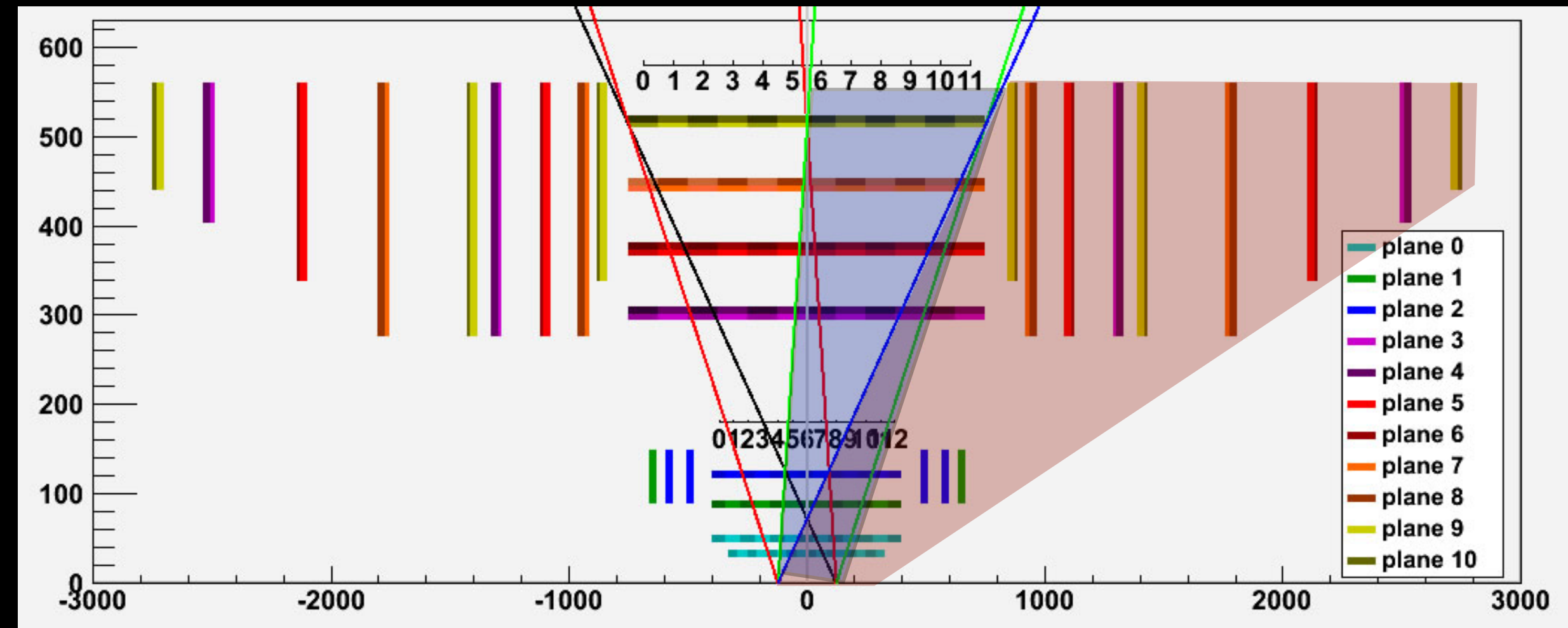
- Clustering, data cleaning, event synchronization
- Route clusters to FTK eta-phi towers





# STAGE 1: DATA FORMATTING

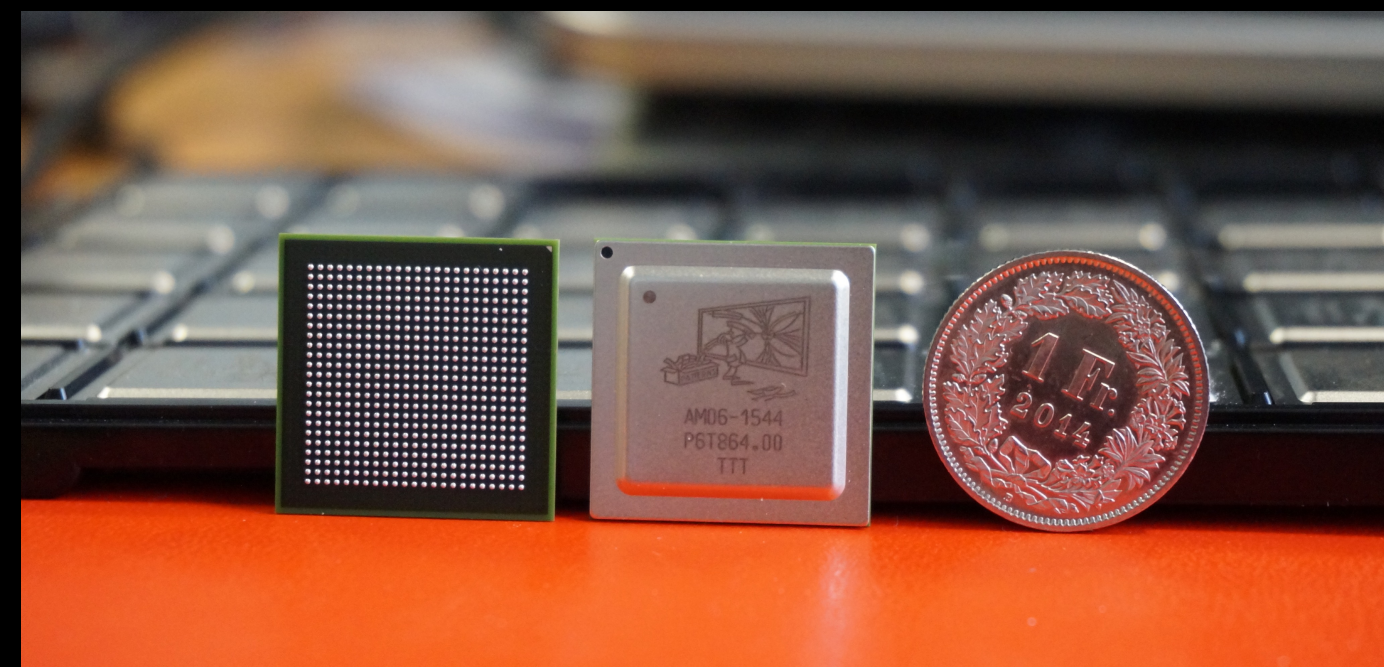
- Clustering, data cleaning, event synchronization
- Route clusters to FTK eta-phi towers





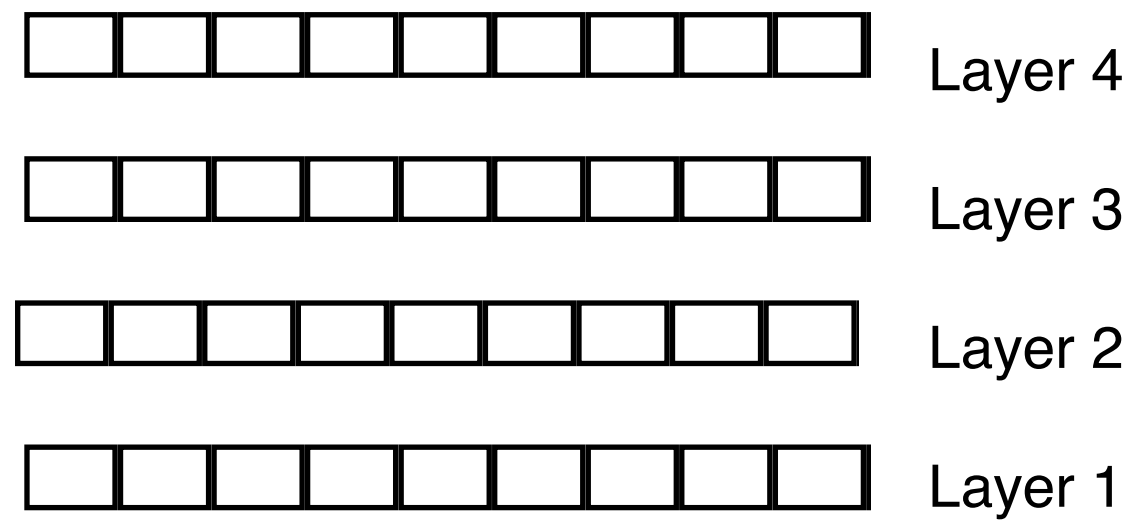
# NEXT STEP: BINGO!

- Hits are ganged together into coarse resolution hits

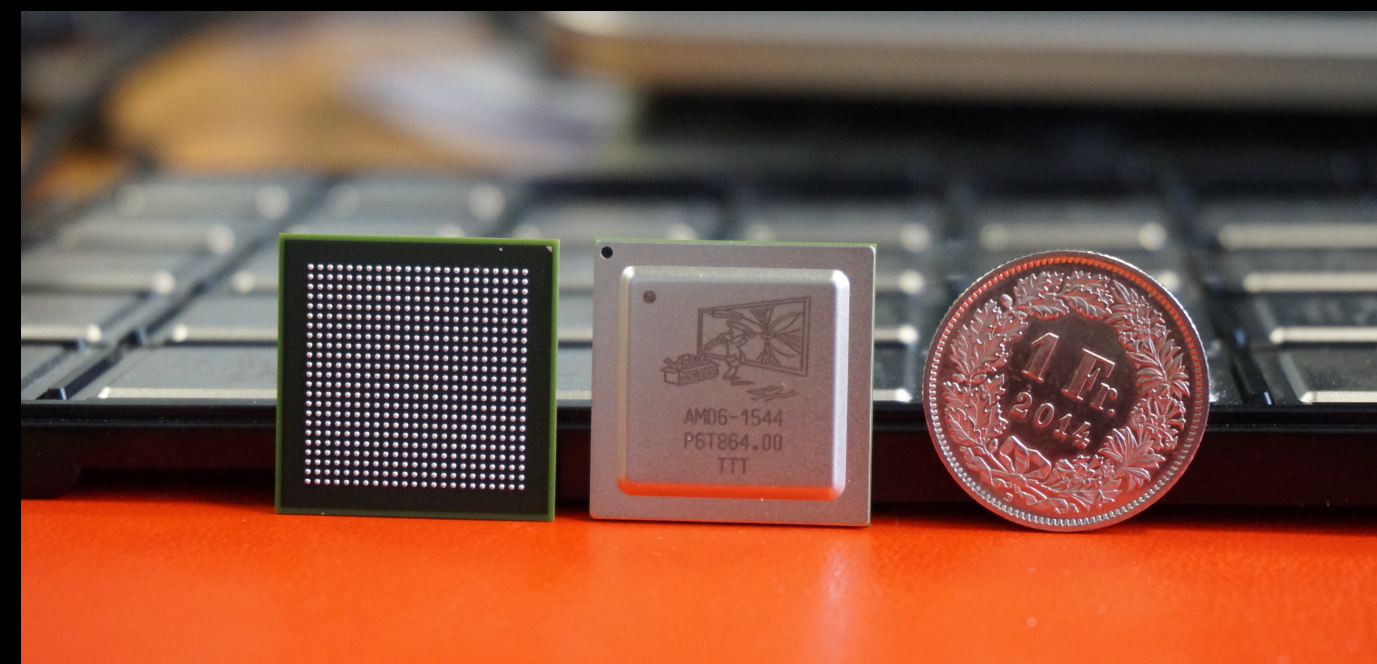




# NEXT STEP: BINGO!

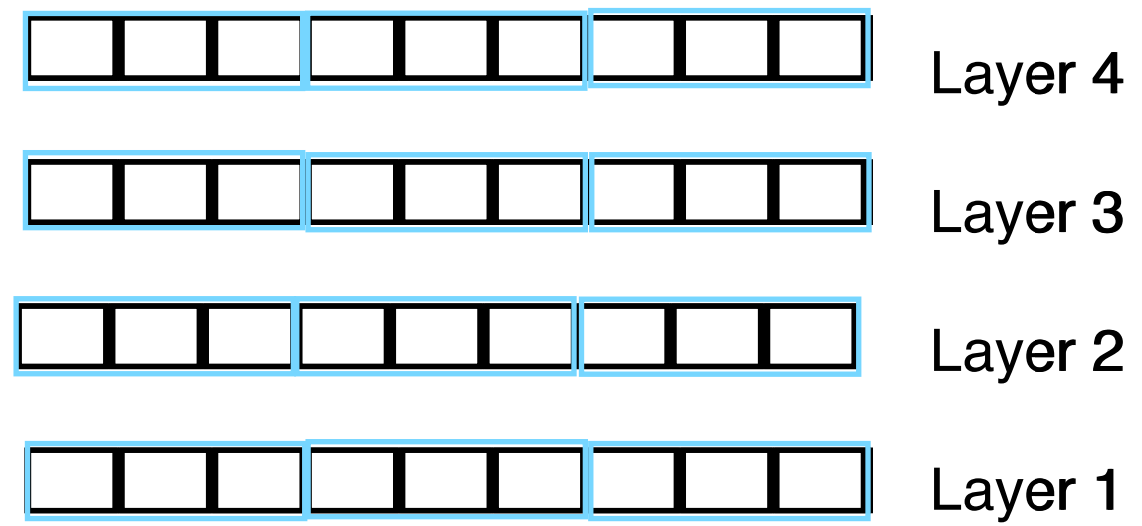


- Hits are ganged together into coarse resolution hits

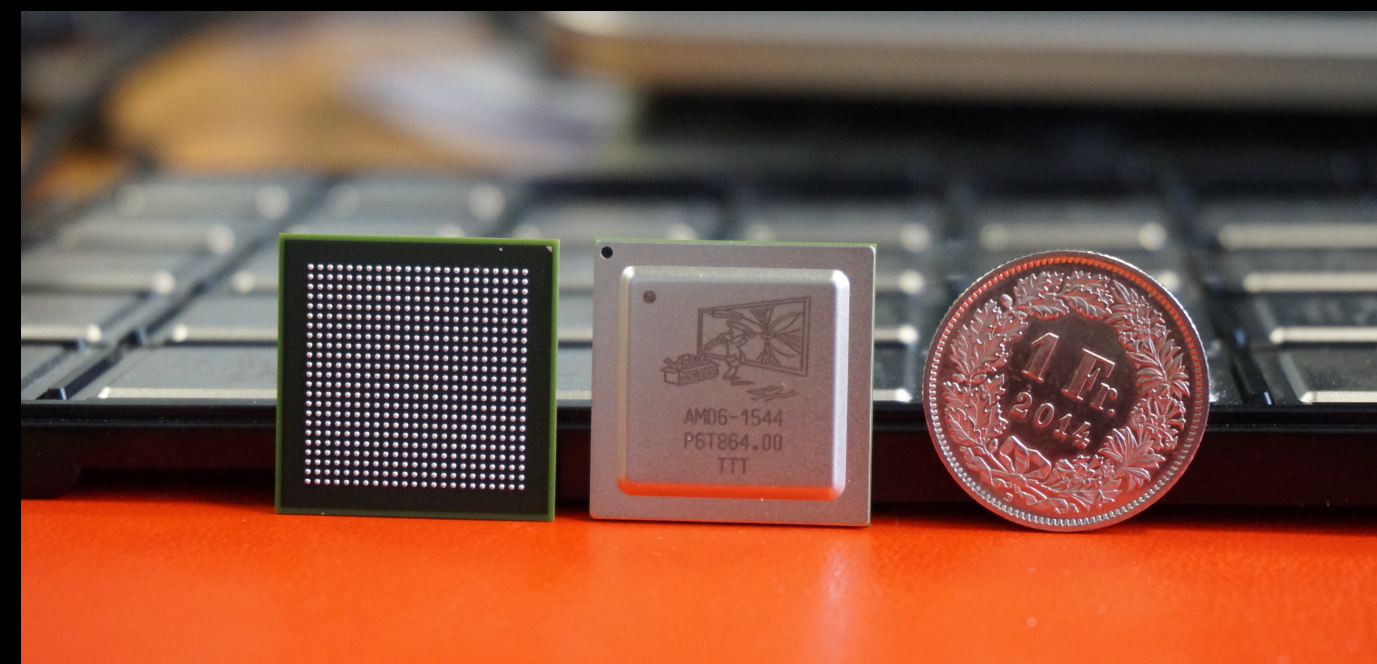




# NEXT STEP: BINGO!

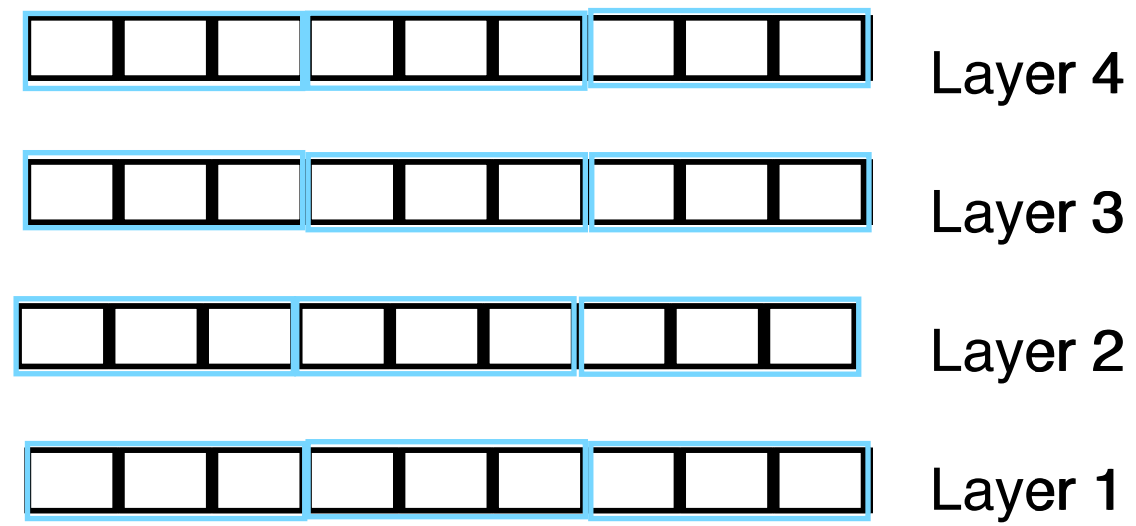


- Hits are ganged together into coarse resolution hits

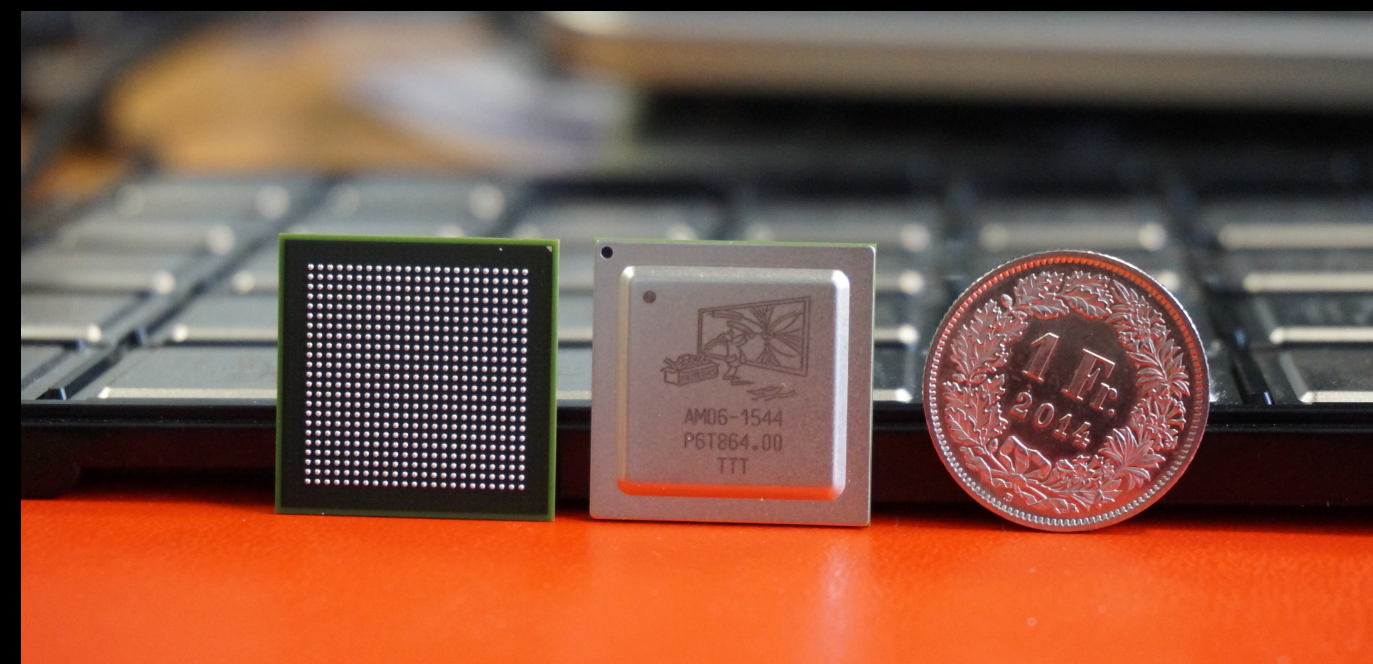




# NEXT STEP: BINGO!

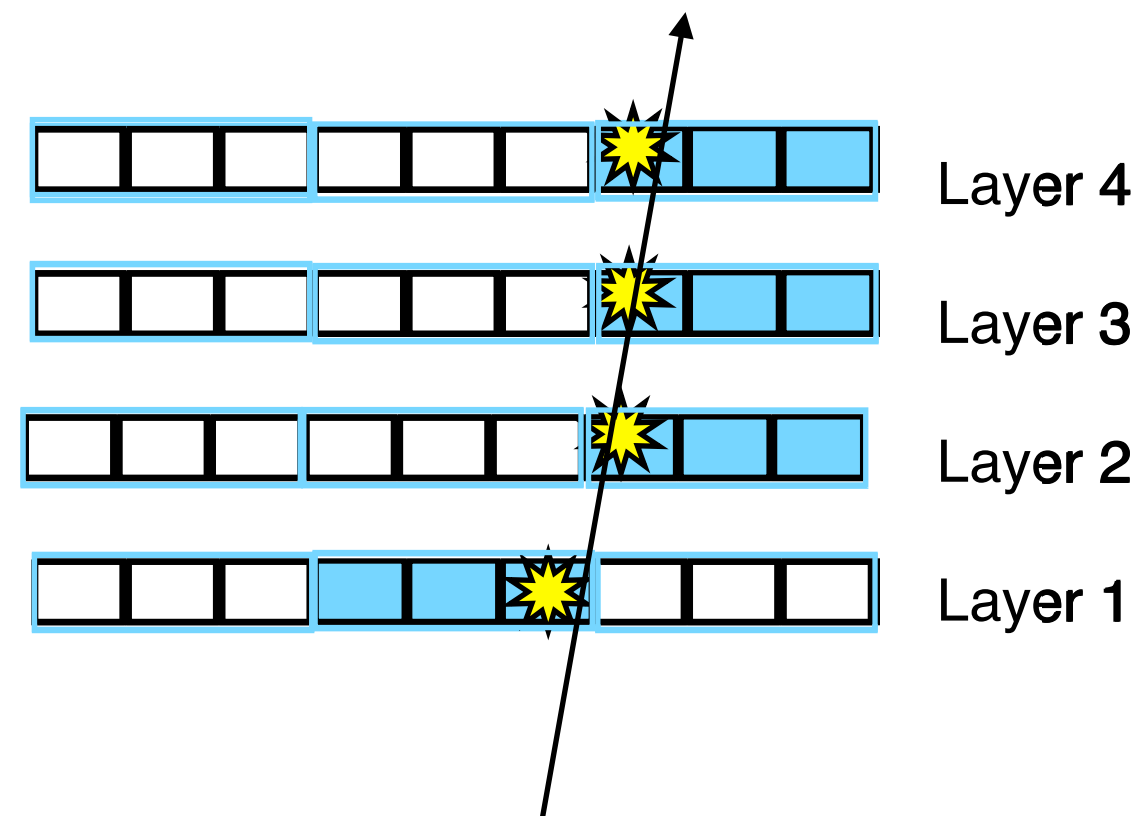


- Hits are ganged together into coarse resolution hits
- All possible patterns of coarse resolution hits determined from simulation

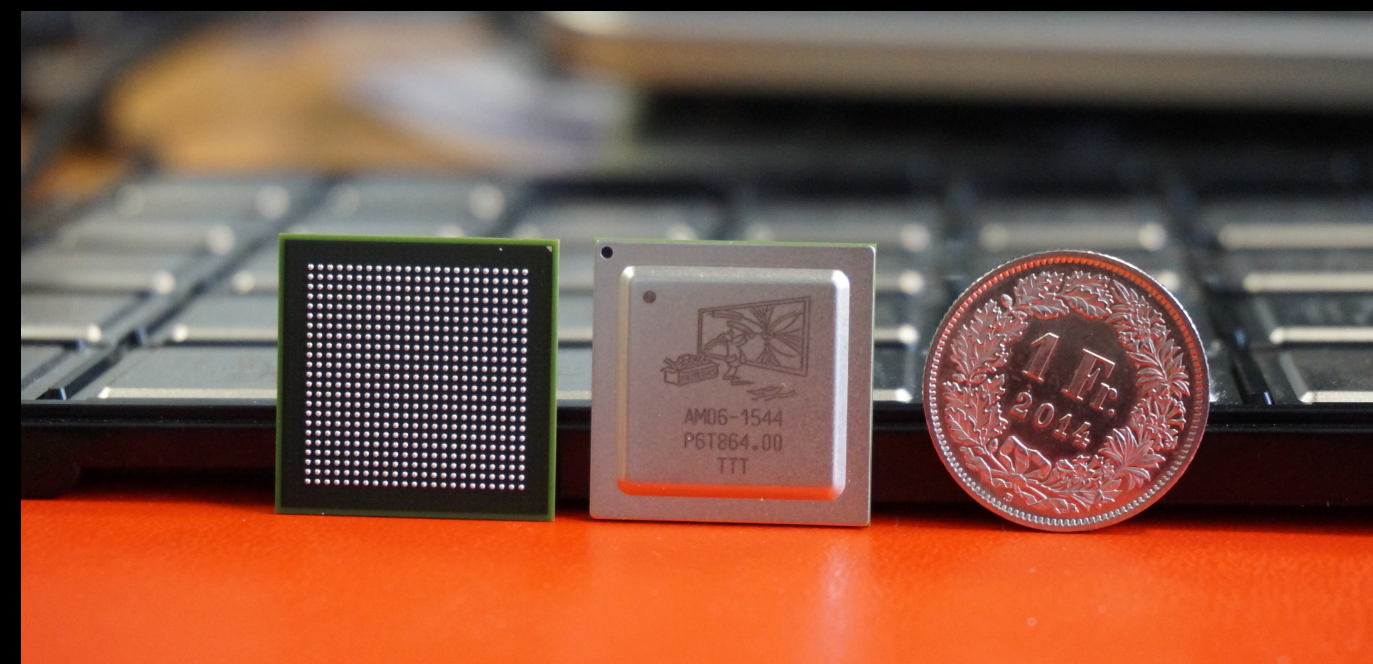




# NEXT STEP: BINGO!

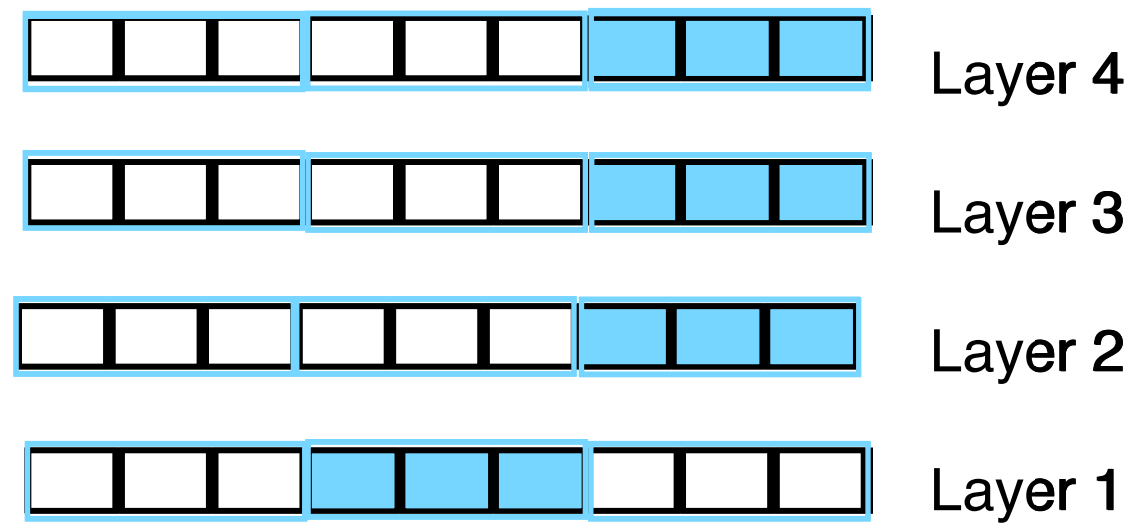


- Hits are ganged together into coarse resolution hits
- All possible patterns of coarse resolution hits determined from simulation

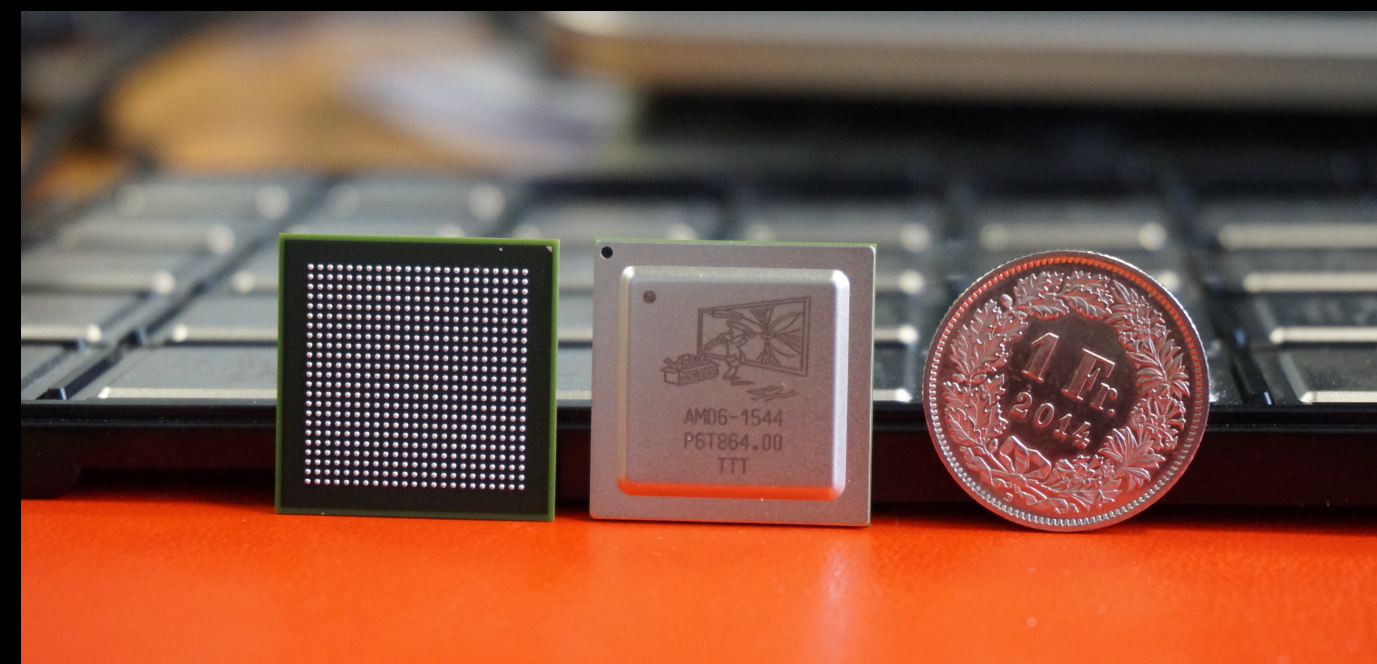




# NEXT STEP: BINGO!

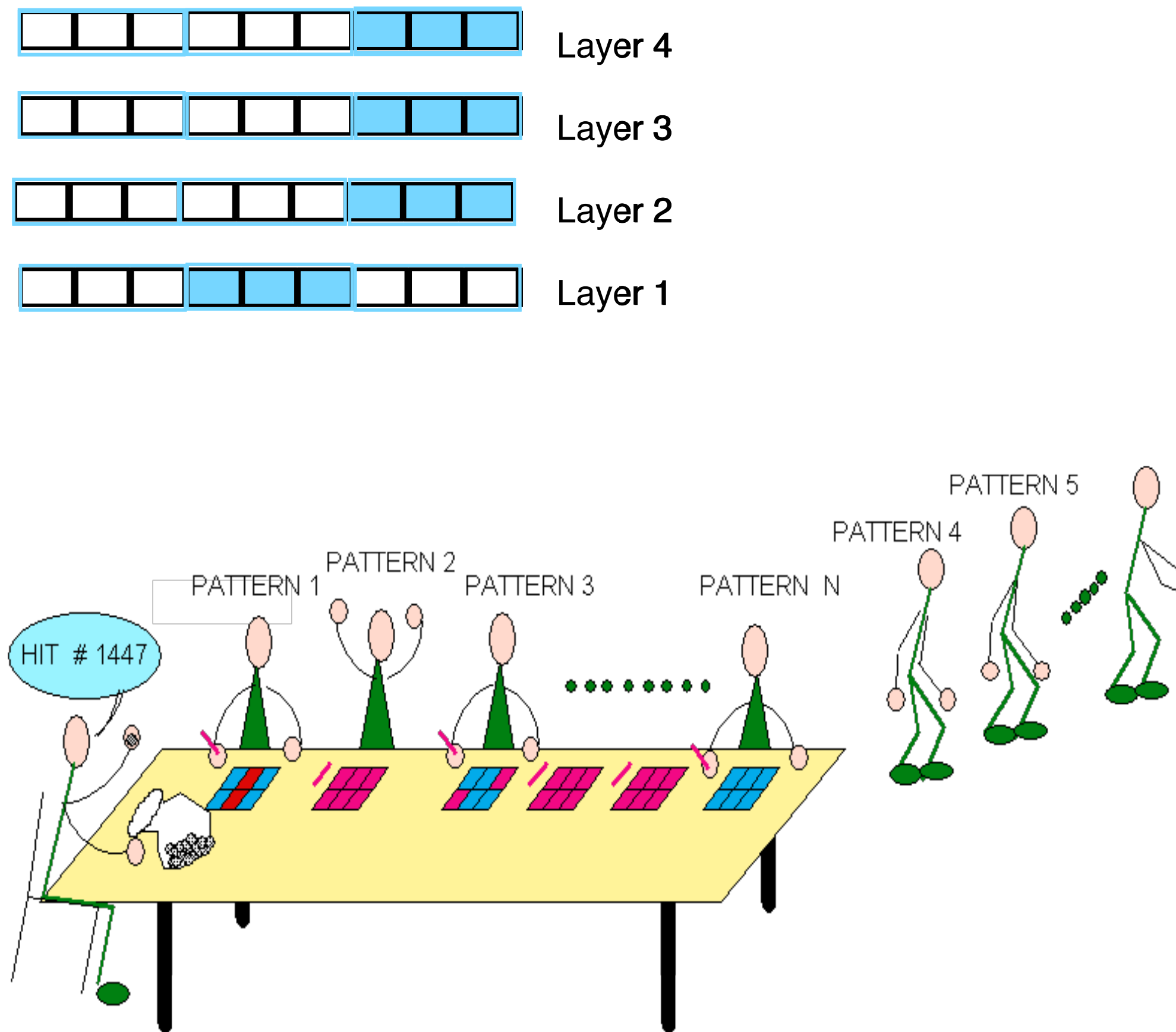


- Hits are ganged together into coarse resolution hits
- All possible patterns of coarse resolution hits determined from simulation

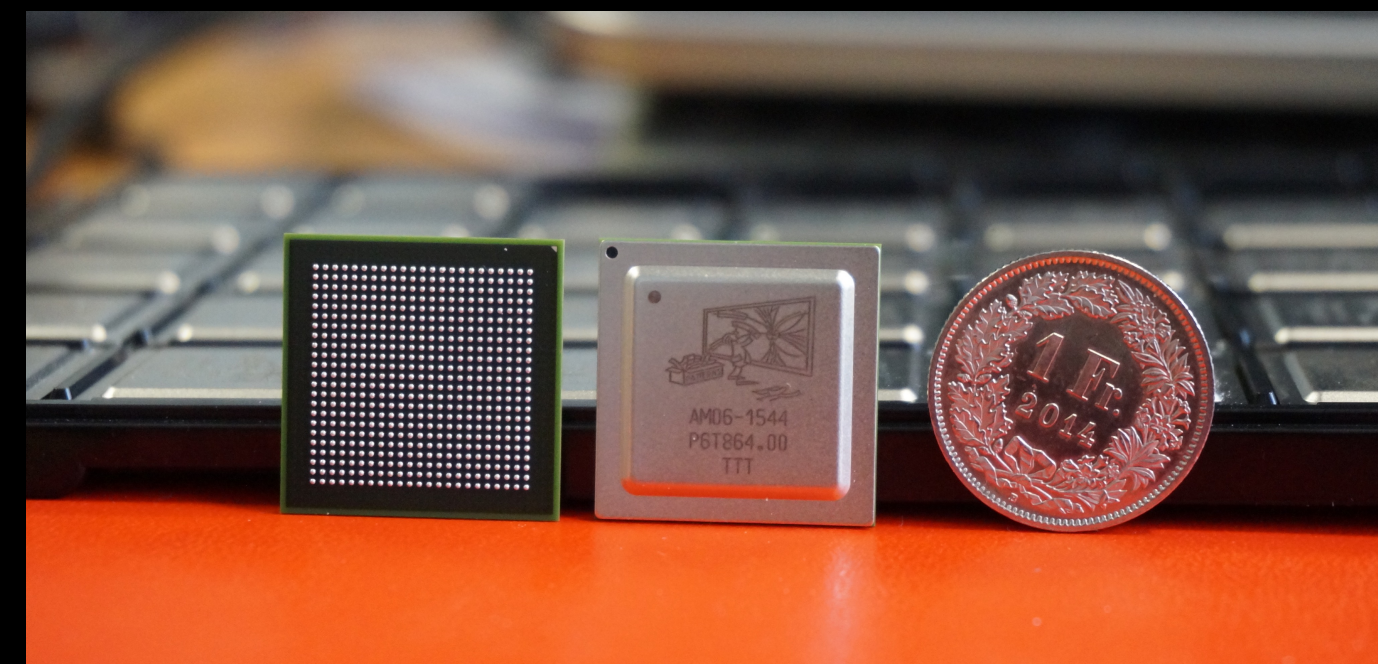




# NEXT STEP: BINGO!



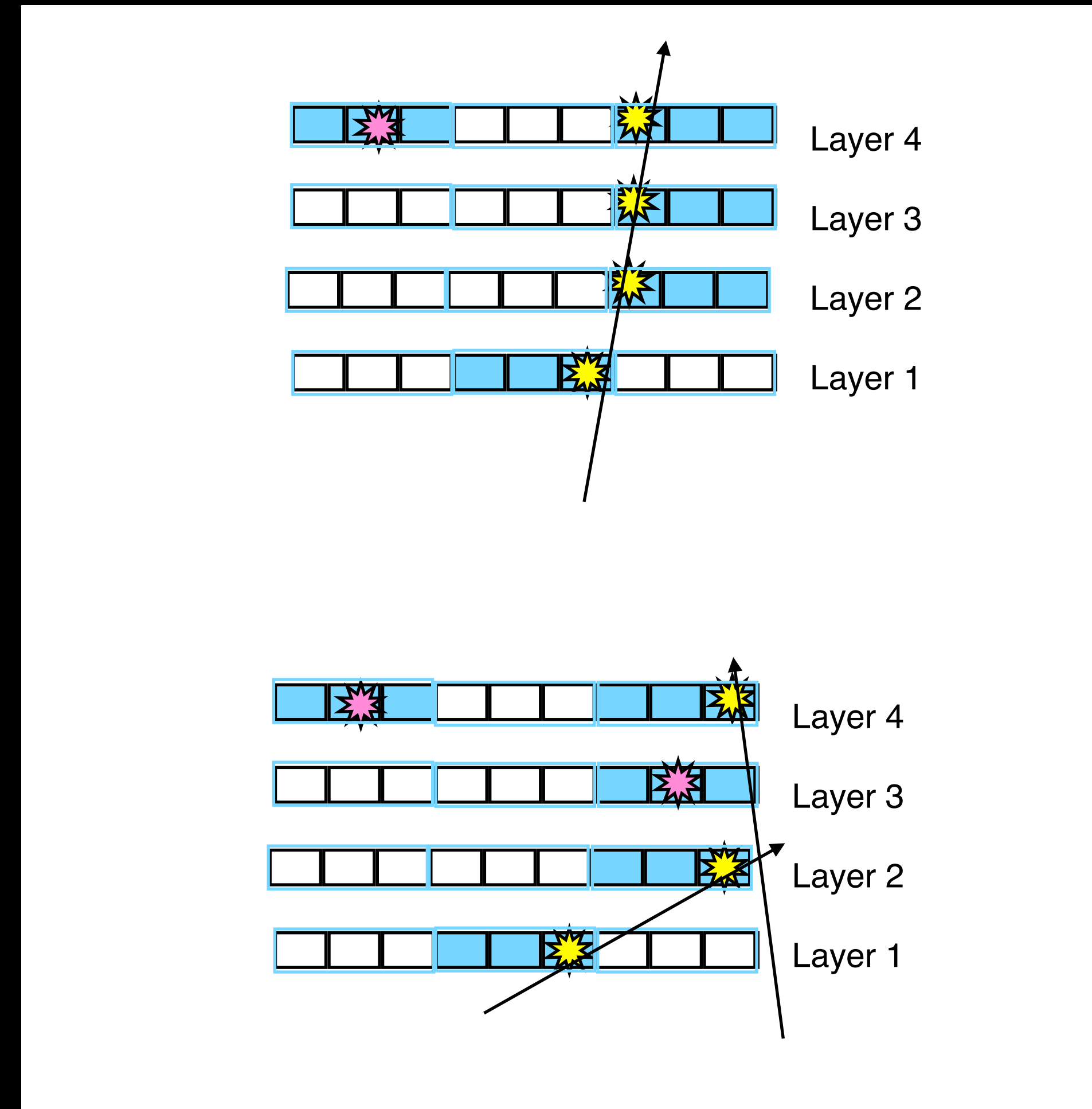
- Hits are ganged together into coarse resolution hits
- All possible patterns of coarse resolution hits determined from simulation





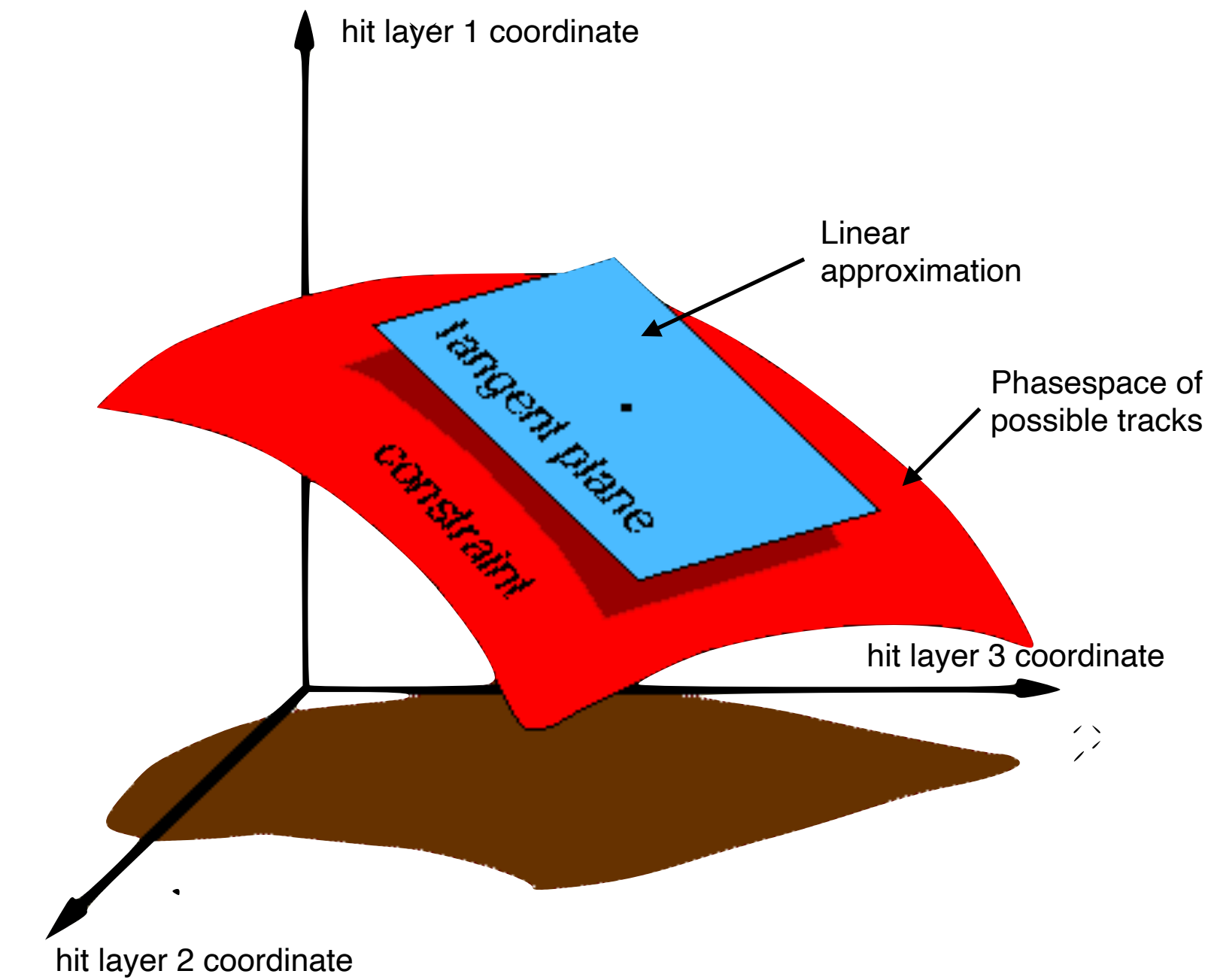
# TRACK FITTING

- 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





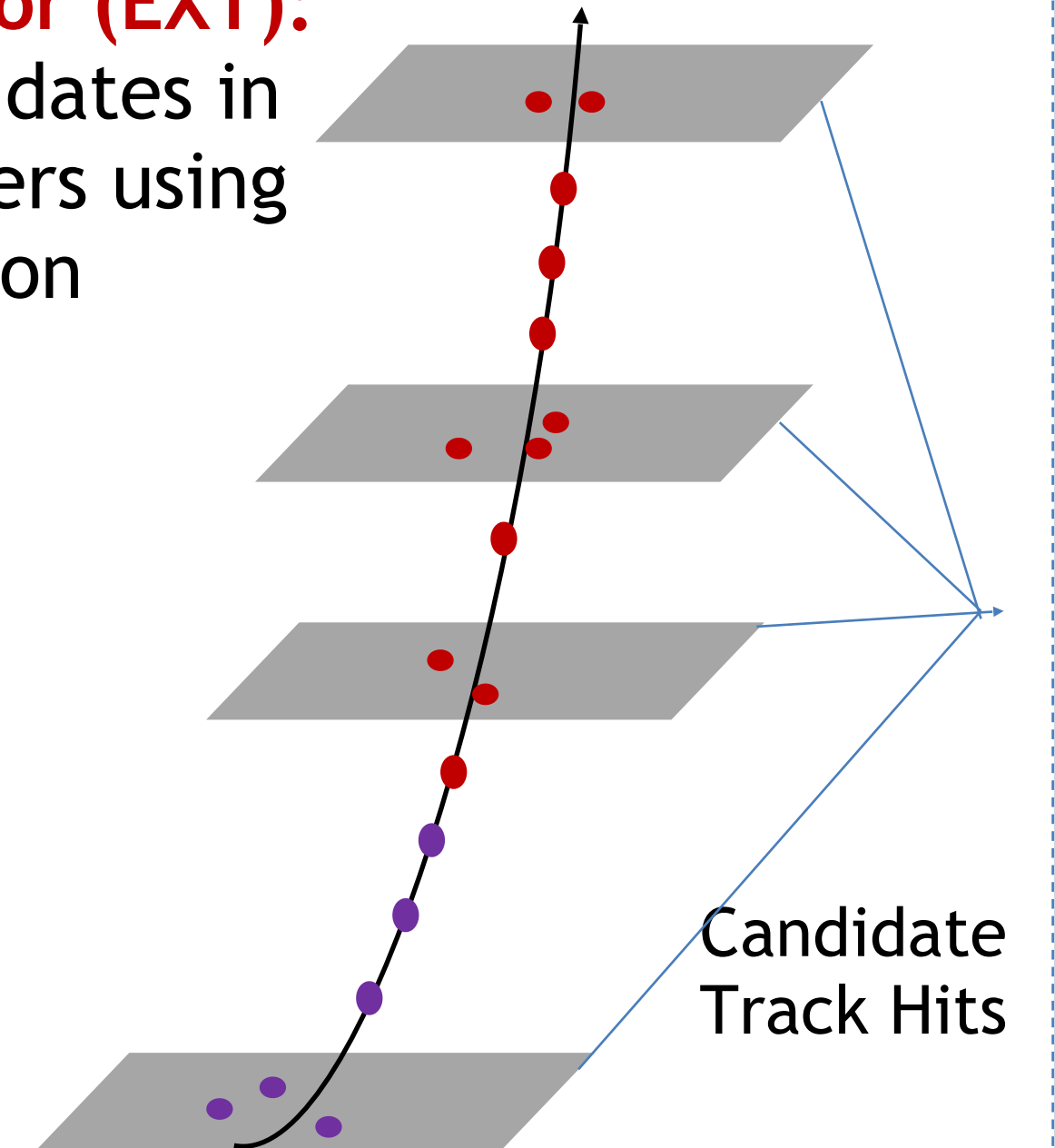
# 5 PICOSECOND TRACK FITTING



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

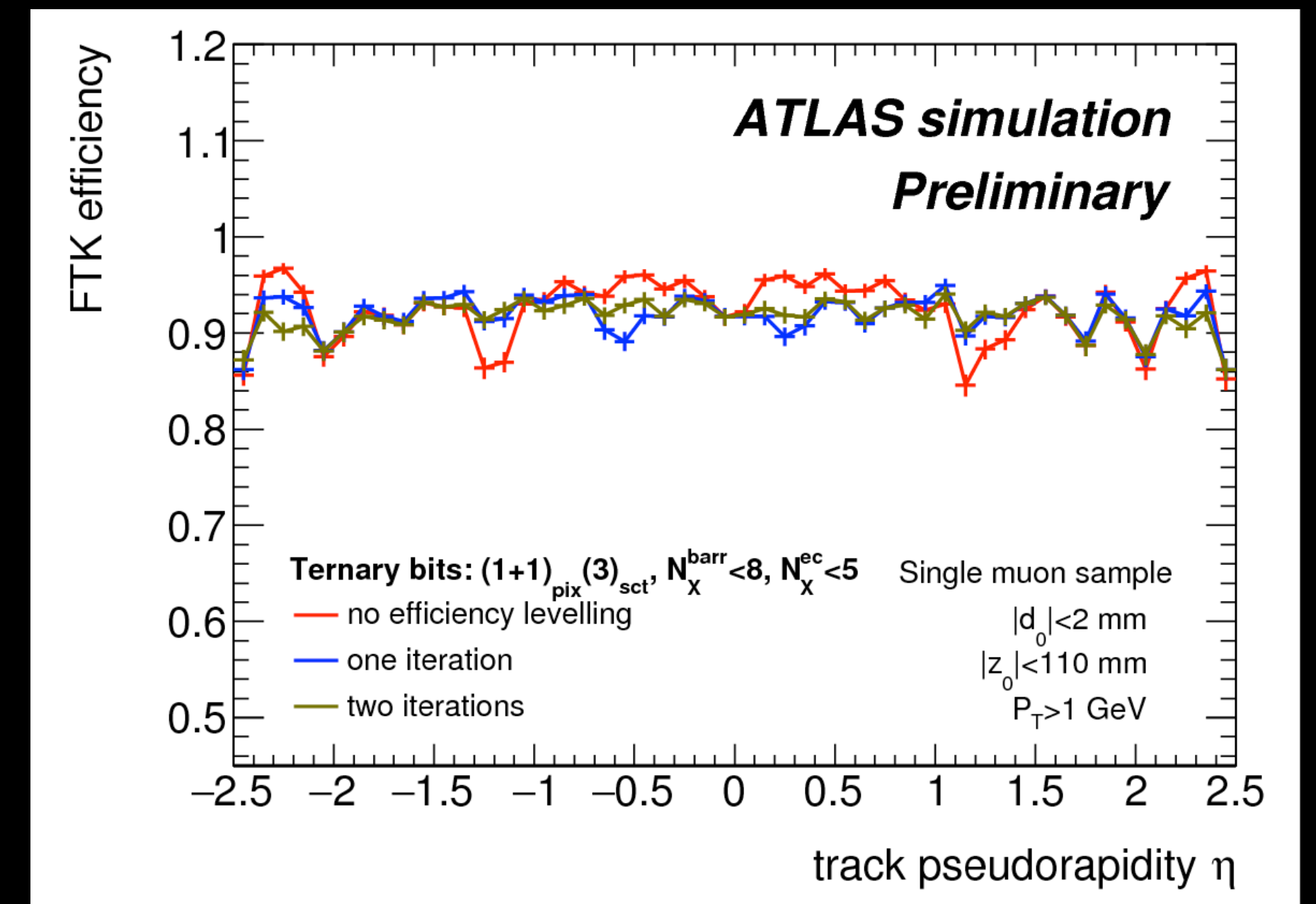
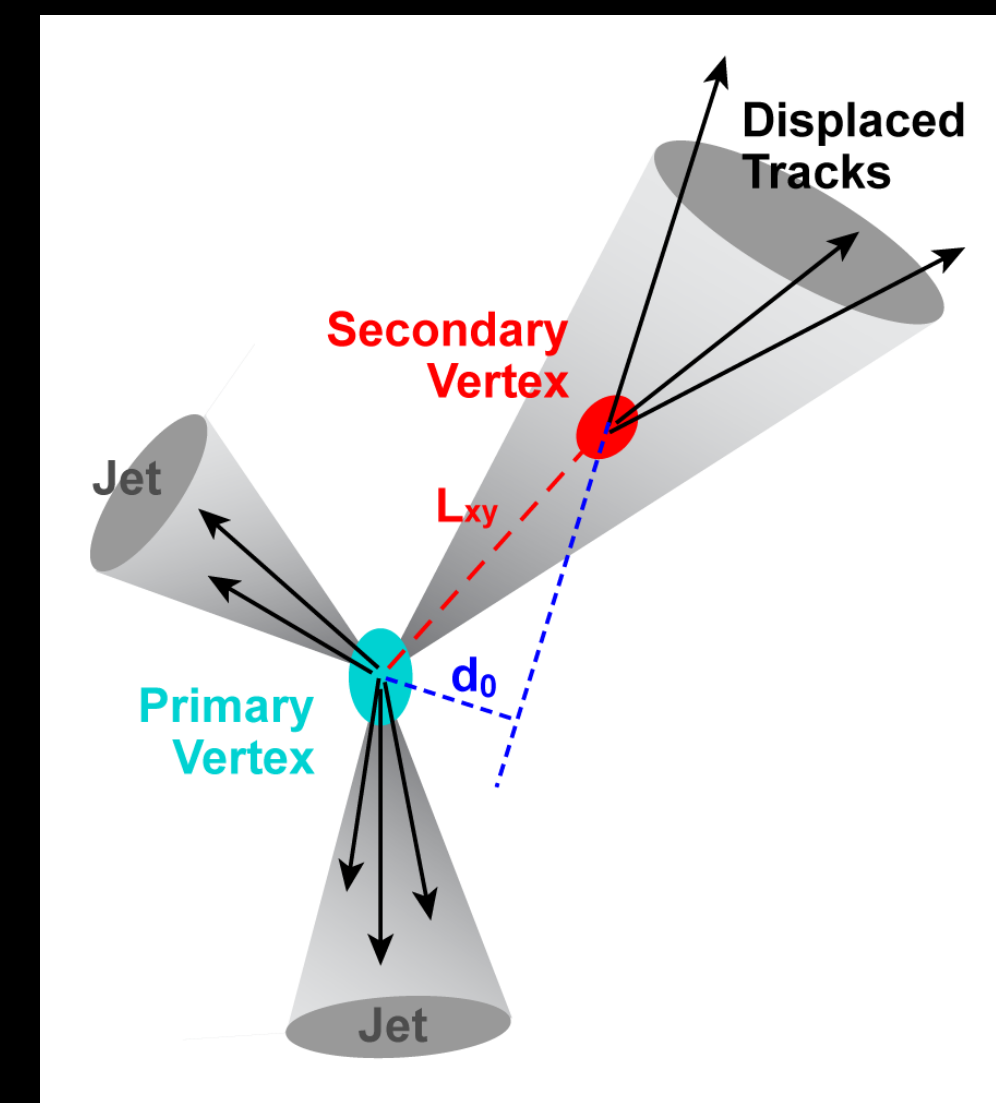
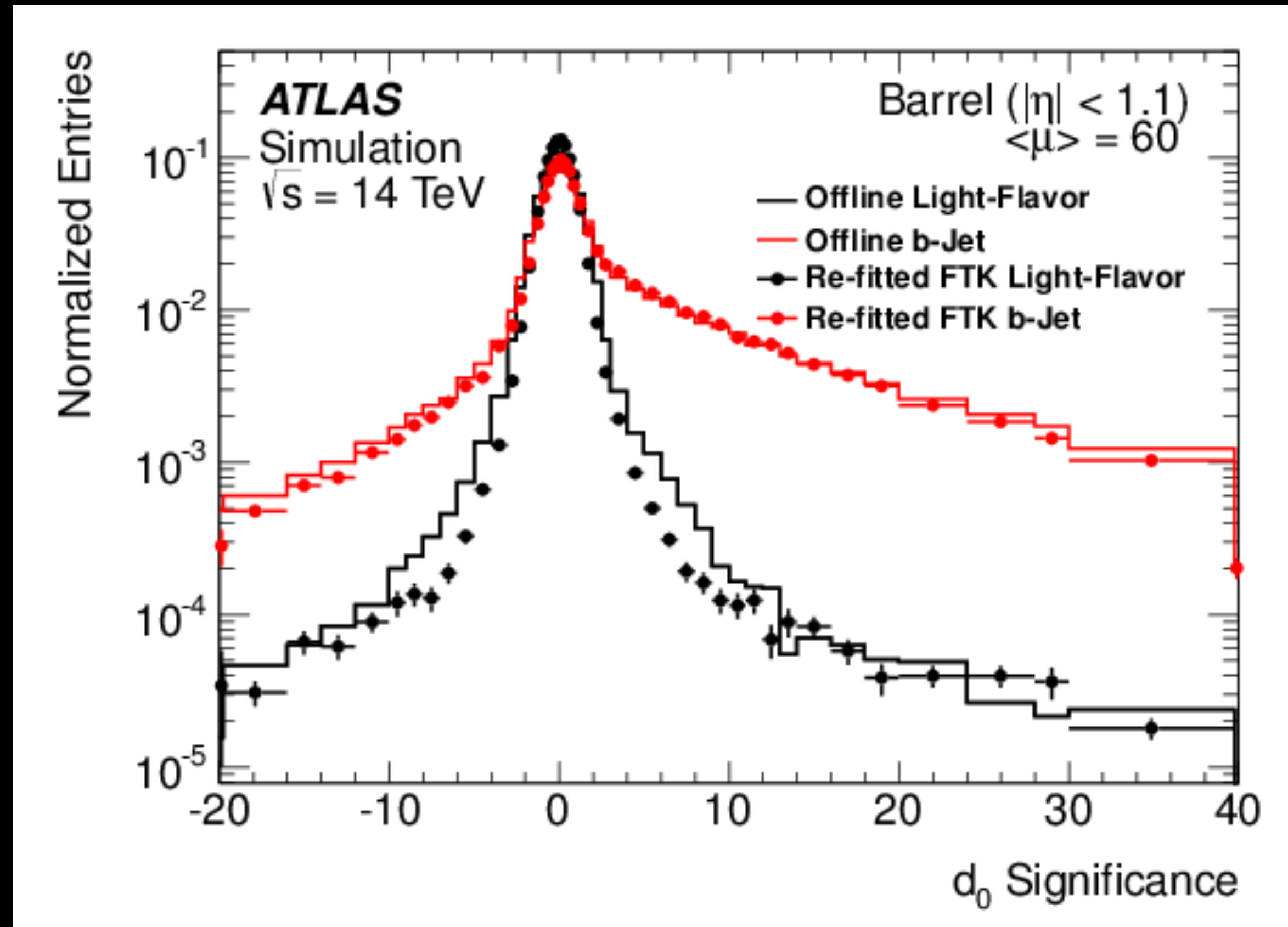
8 → 12 layer tracks

**Extrapolator (EXT):**  
Finds candidates in  
unused layers using  
extrapolation  
constants



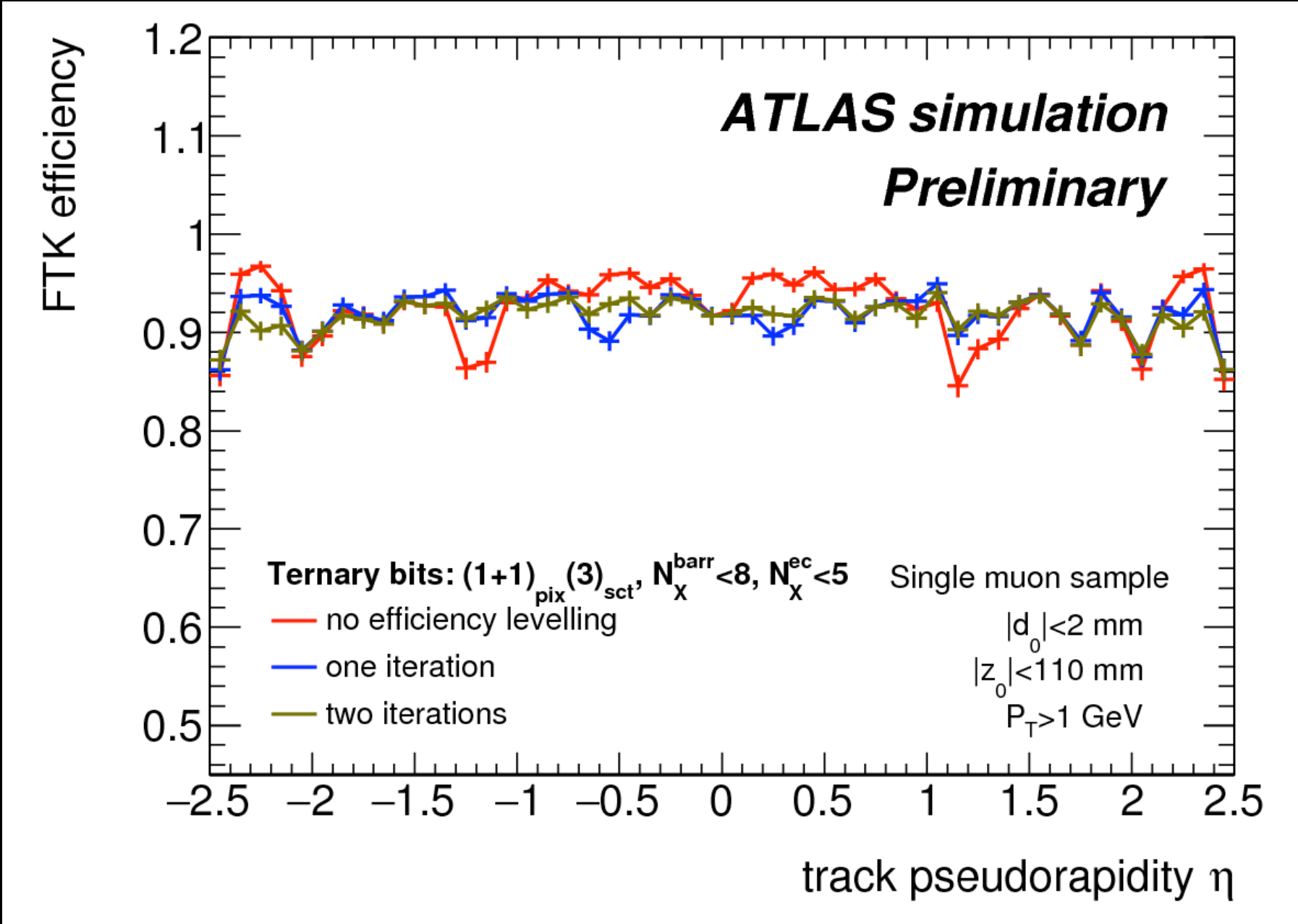
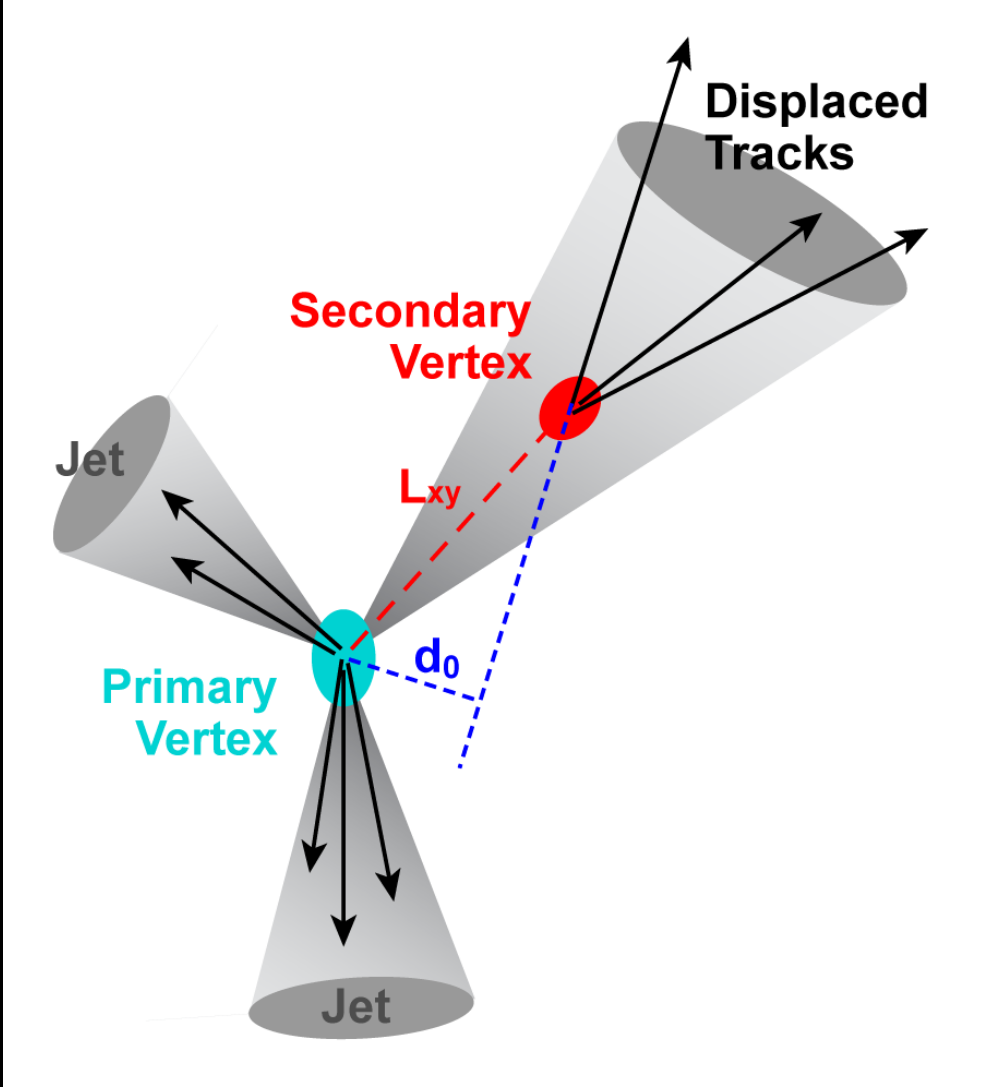
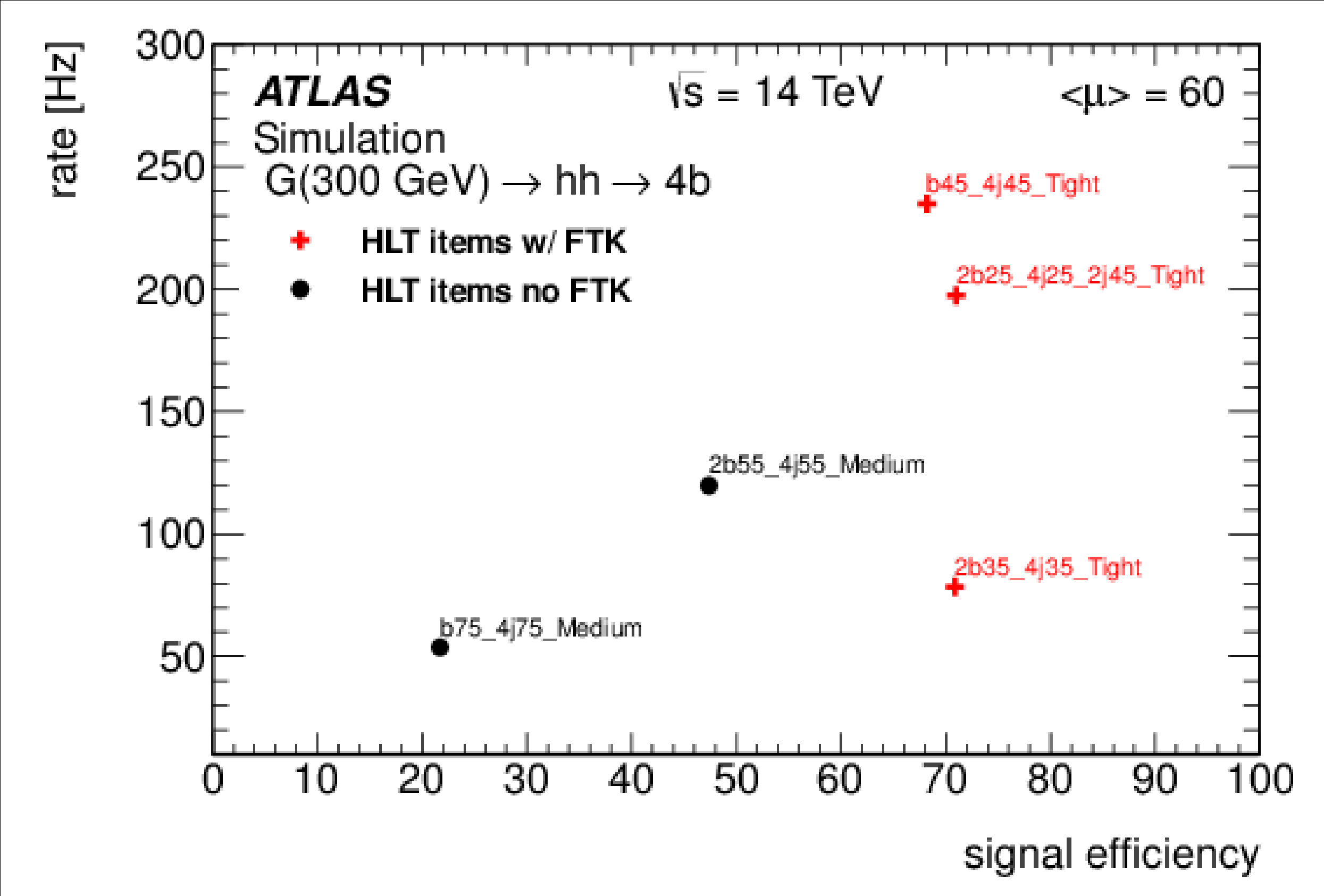


# EXAMPLE USES: B-JETS



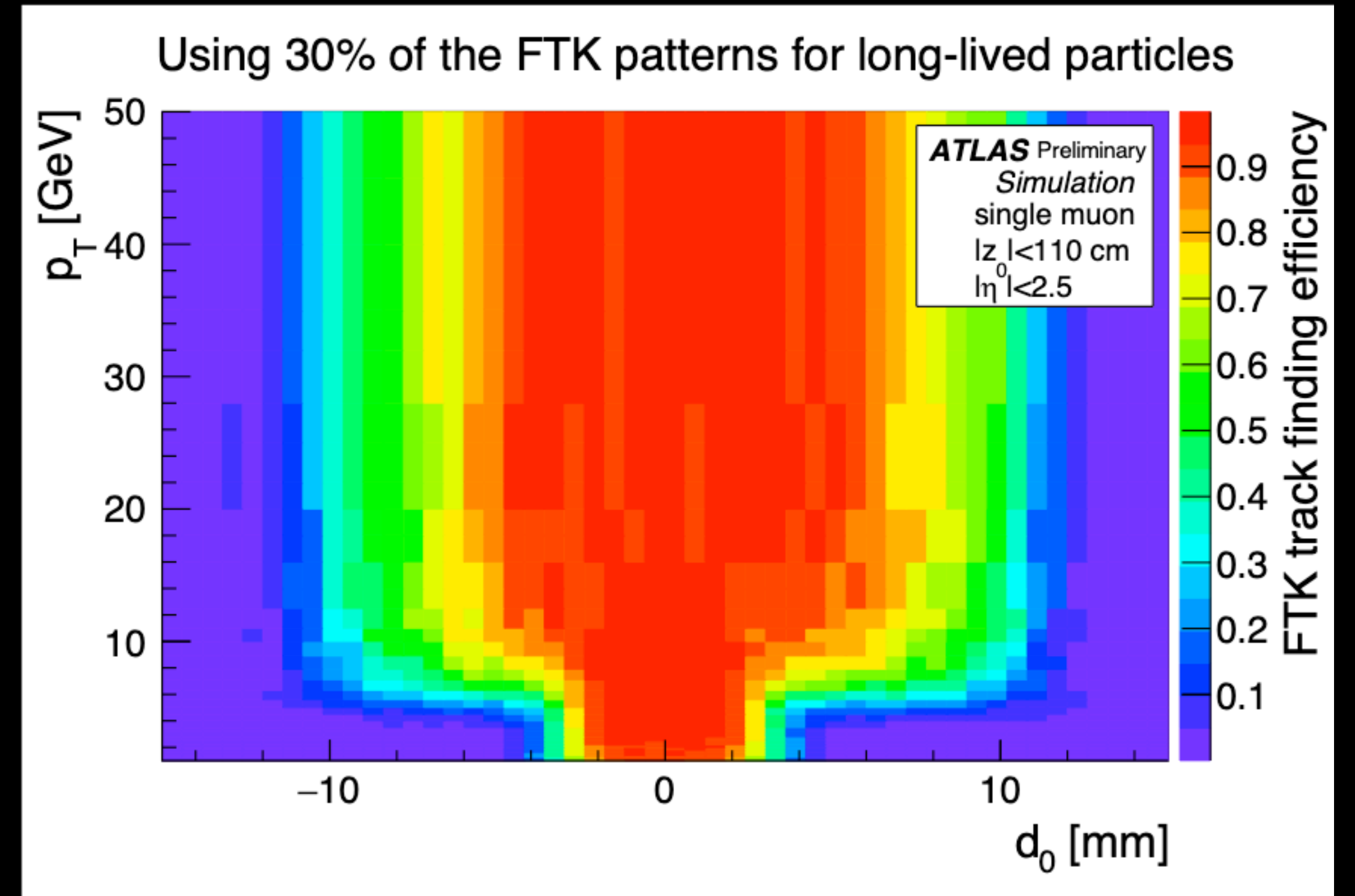
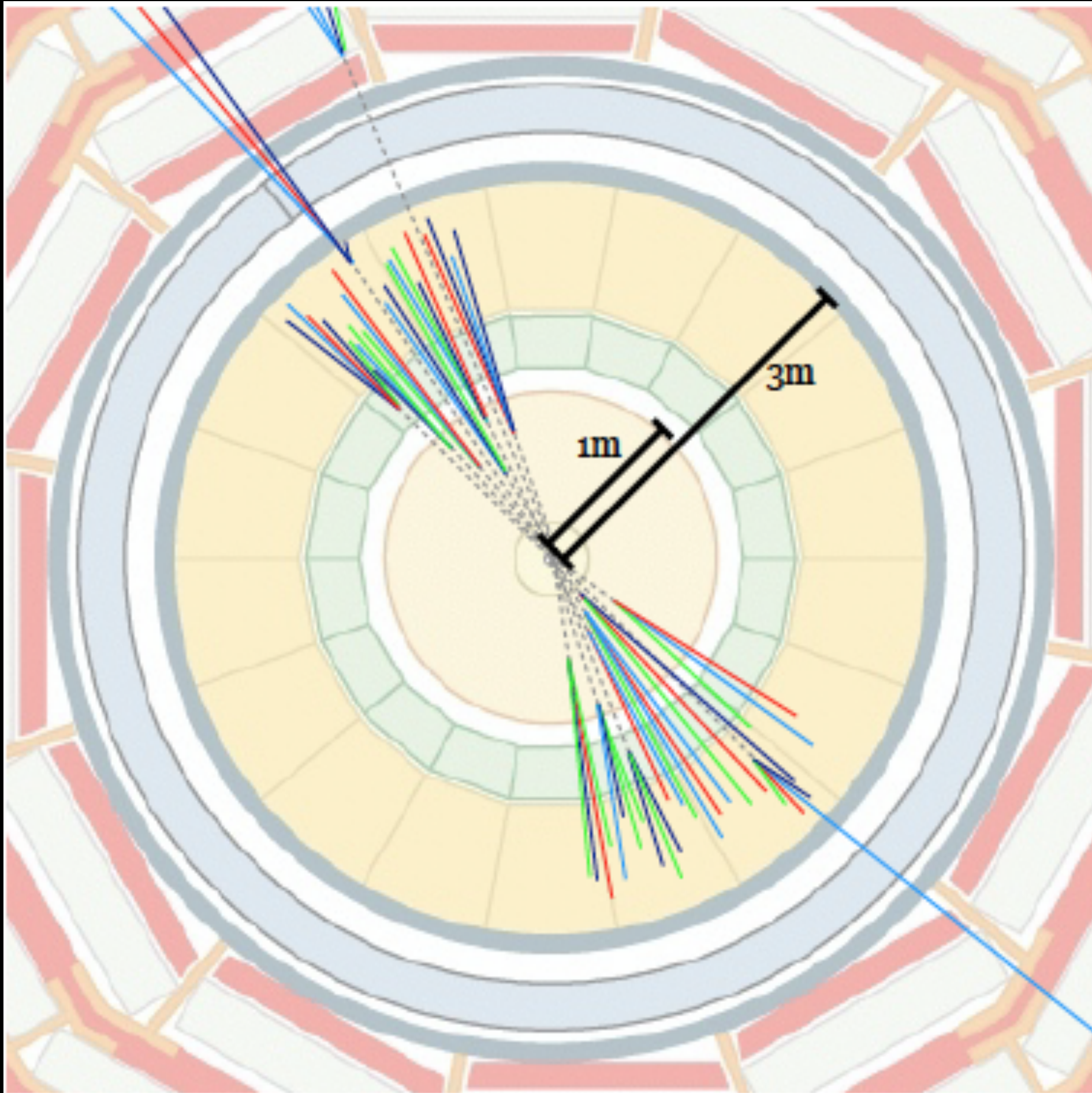


# EXAMPLE USES: B-JETS





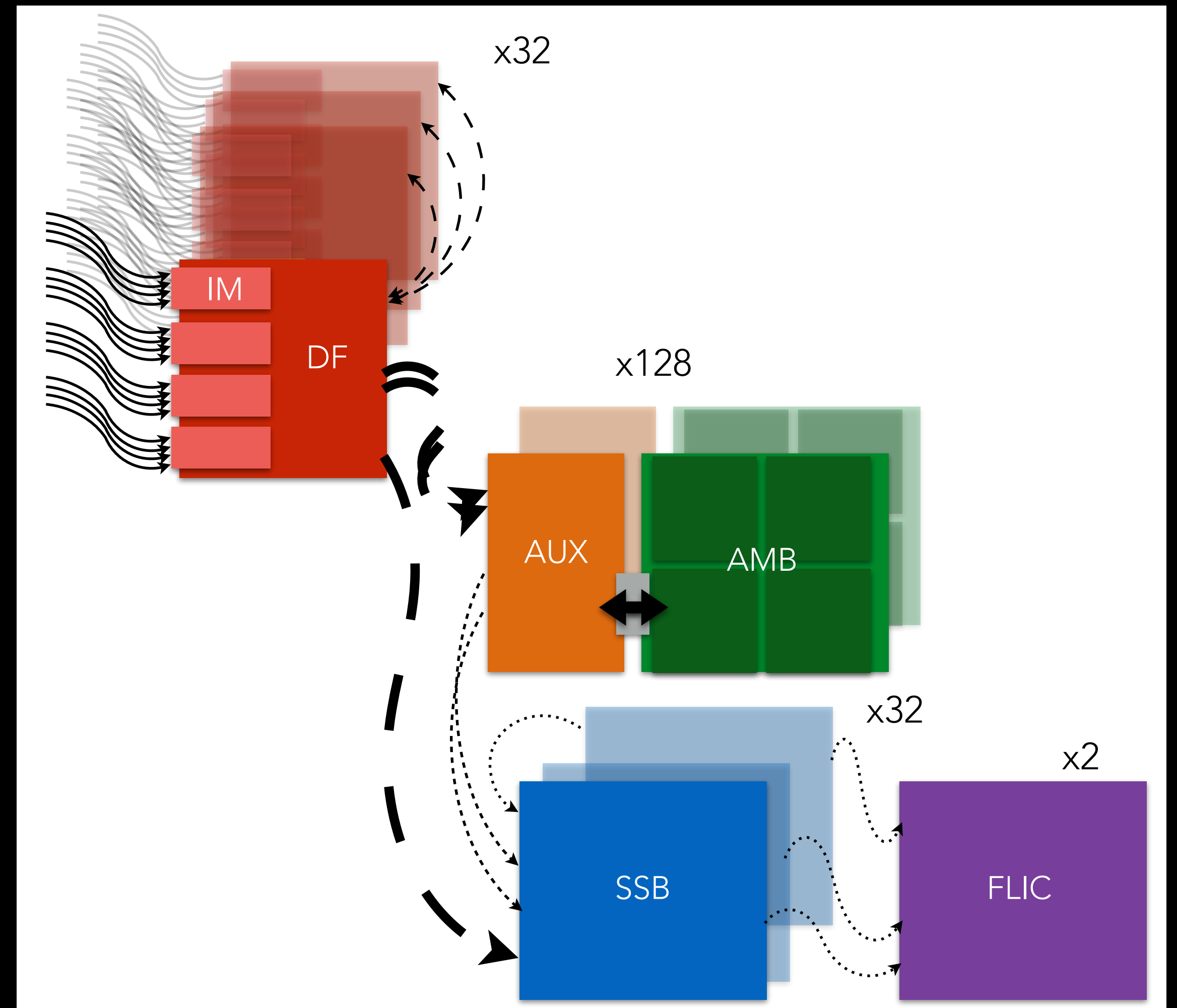
# GOING BEYOND





# DETECTOR CHALLENGES

- Large system: 9 separate components, ~1000 PCBs, thousands of FPGAs





# DETECTOR CHALLENGES

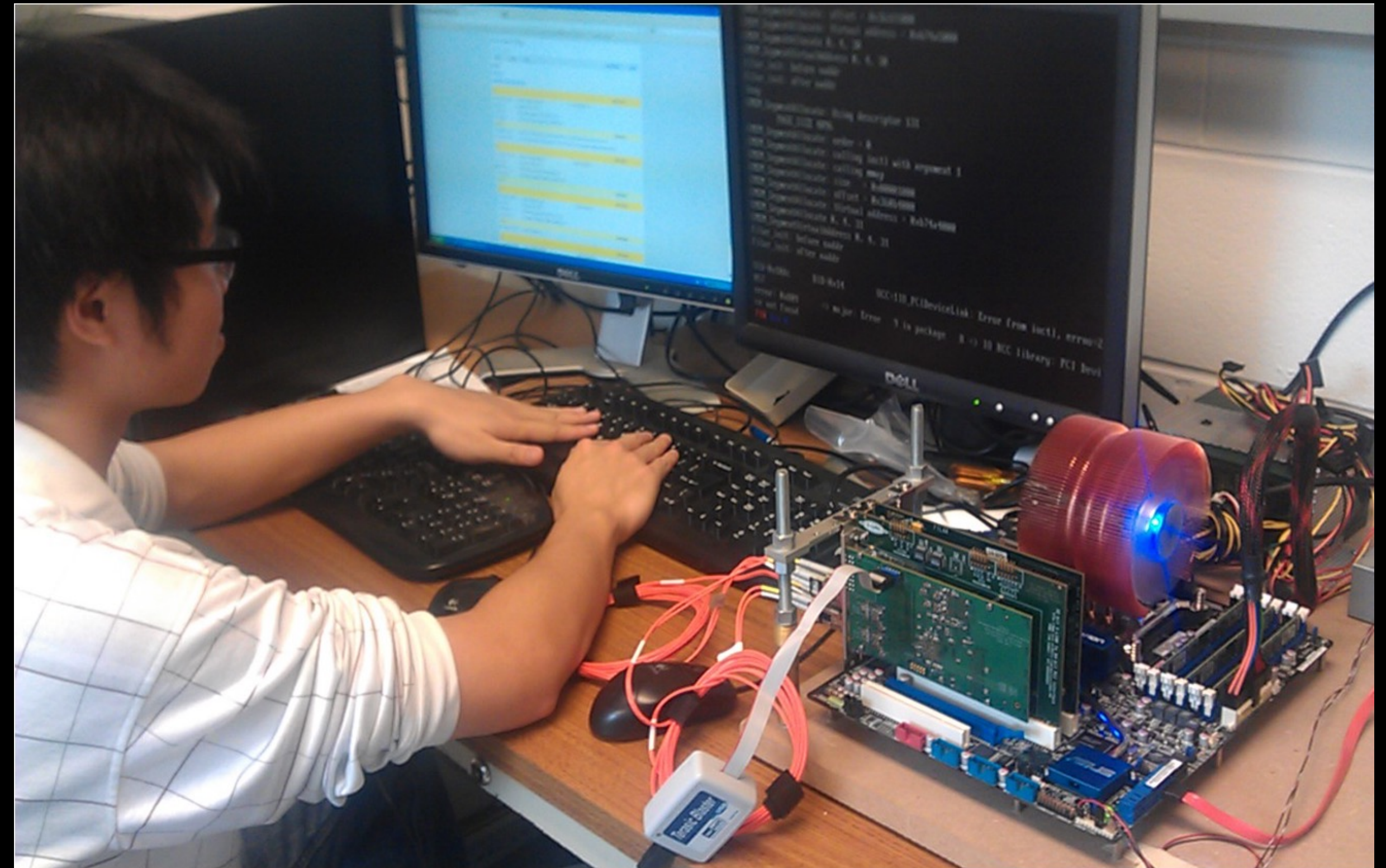
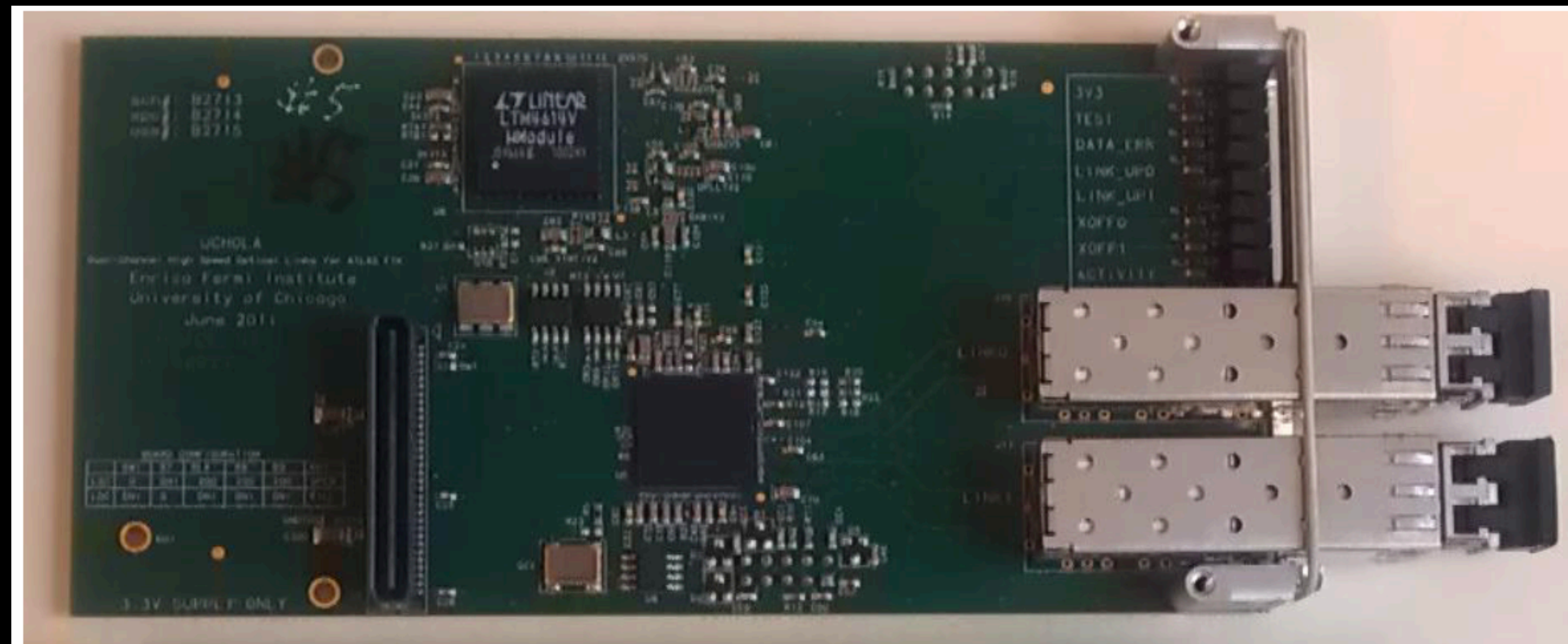
- Large system: 9 separate components, ~1000 PCBs, thousands of FPGAs



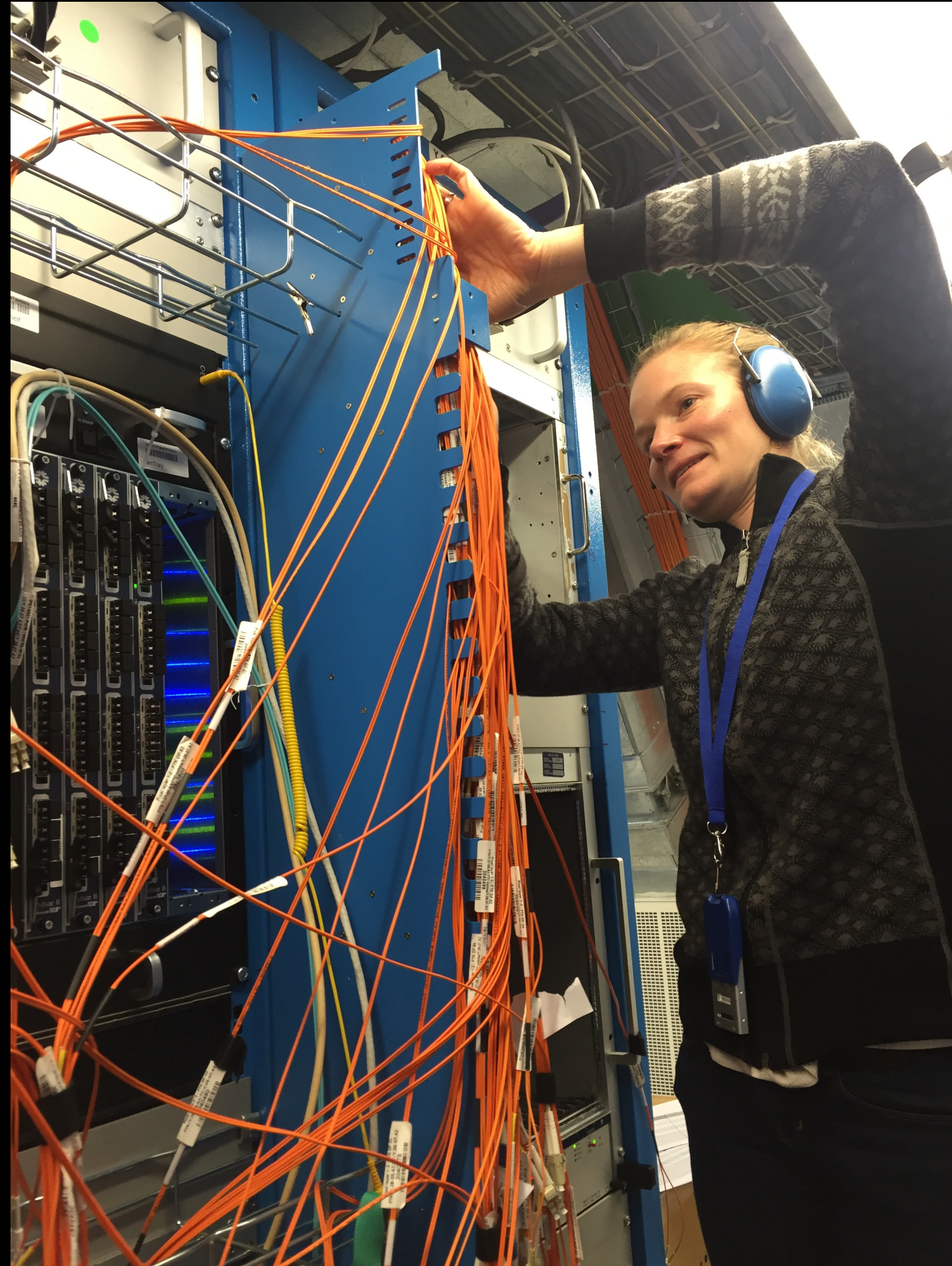


# FULLY INSTALLED: DUAL OUTPUT HOLAS

- First part of FTK fully installed and operational (2012)
- Created copy of pixel & SCT data for FTK use



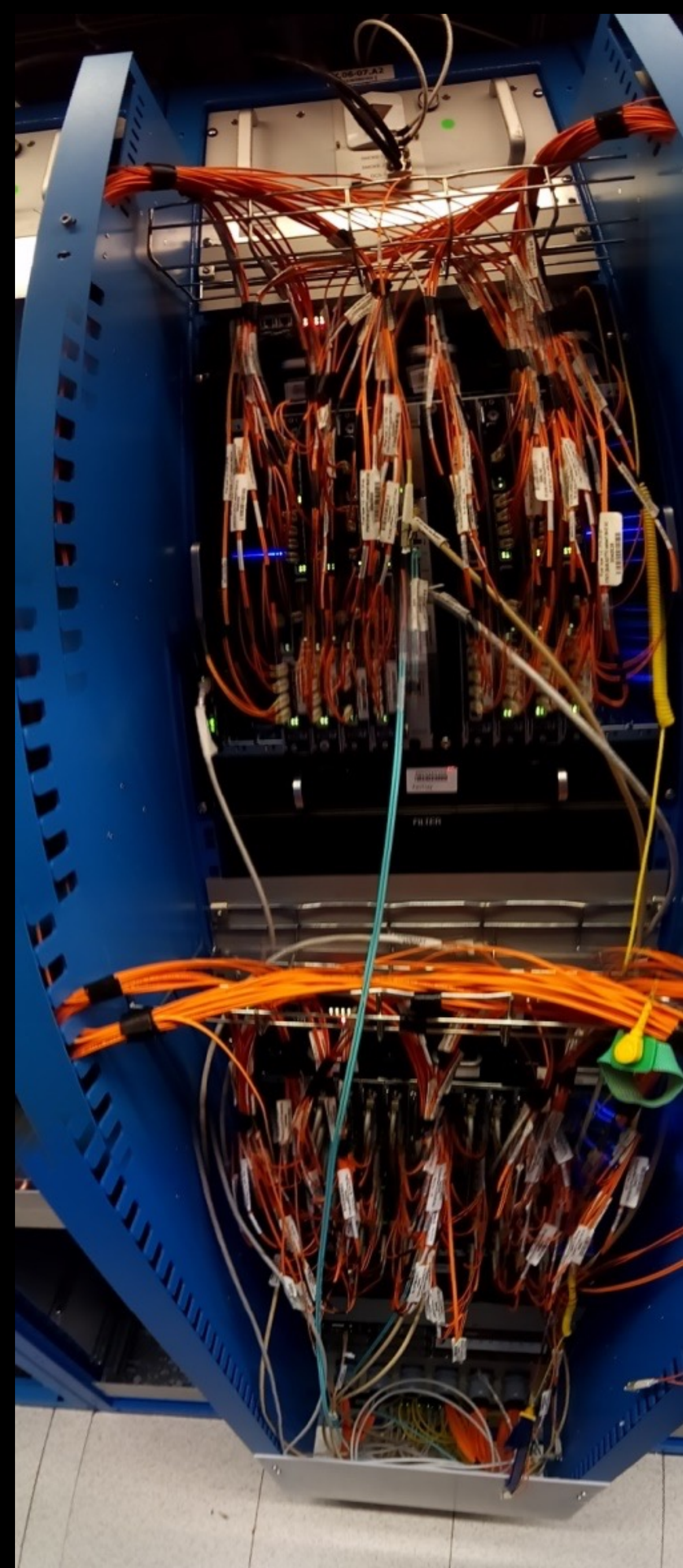
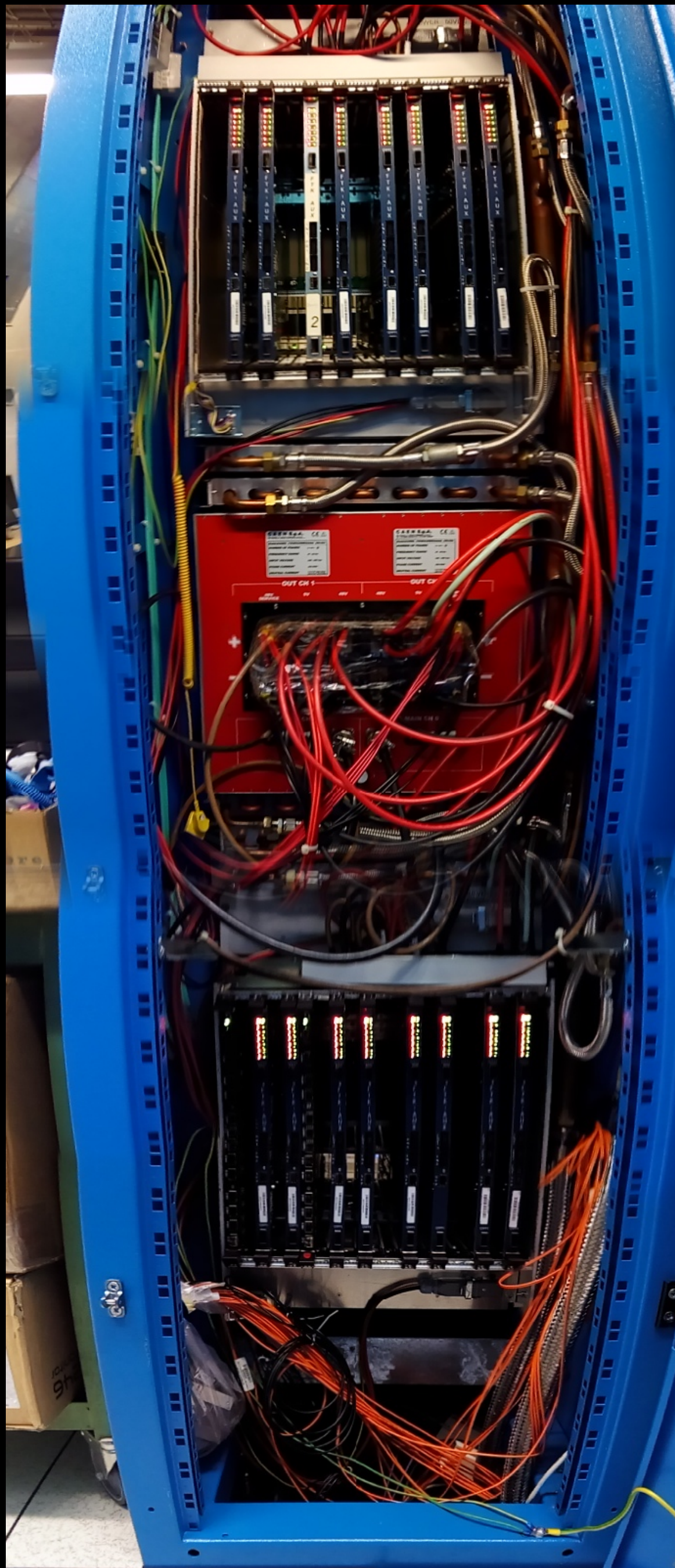




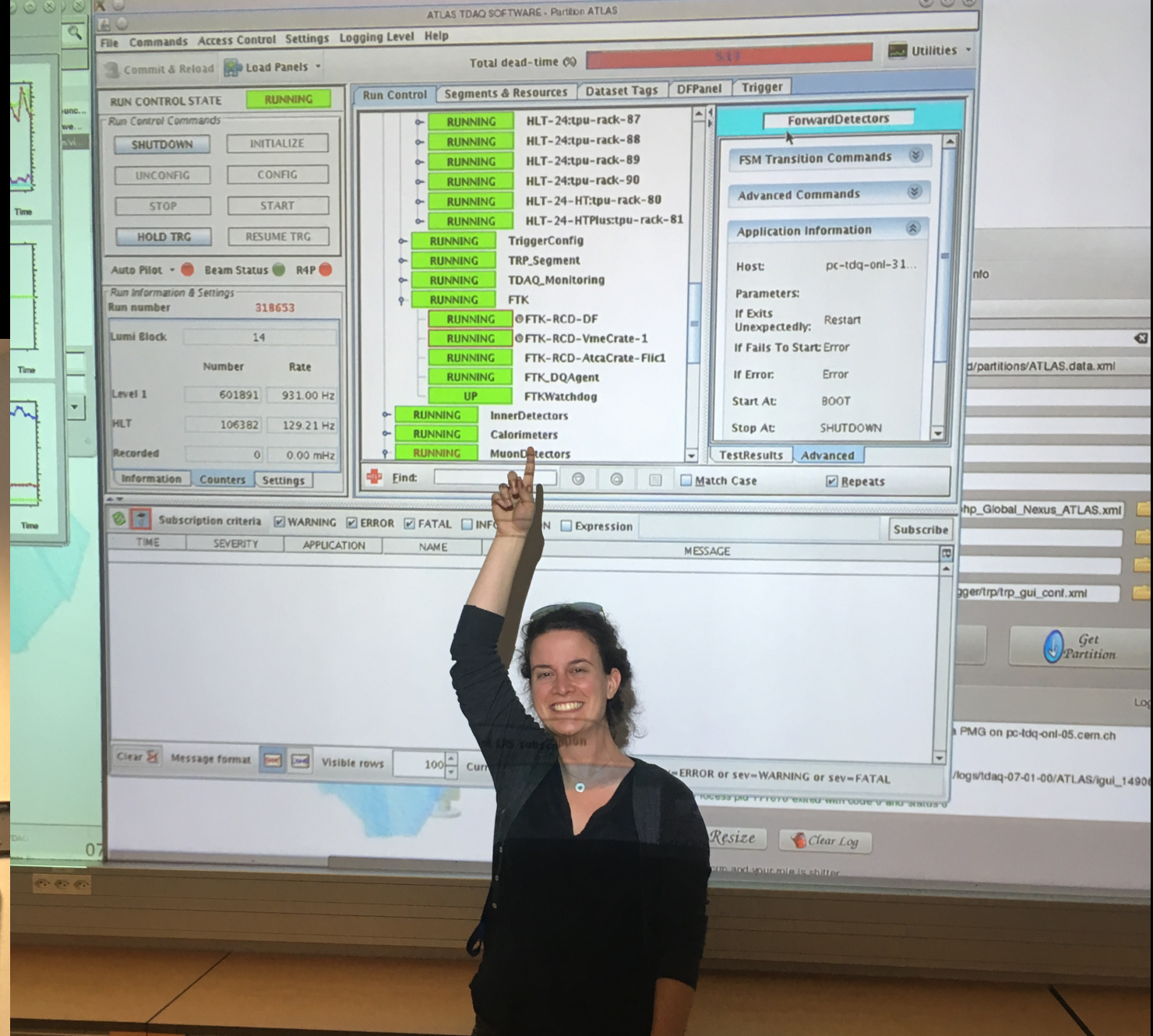




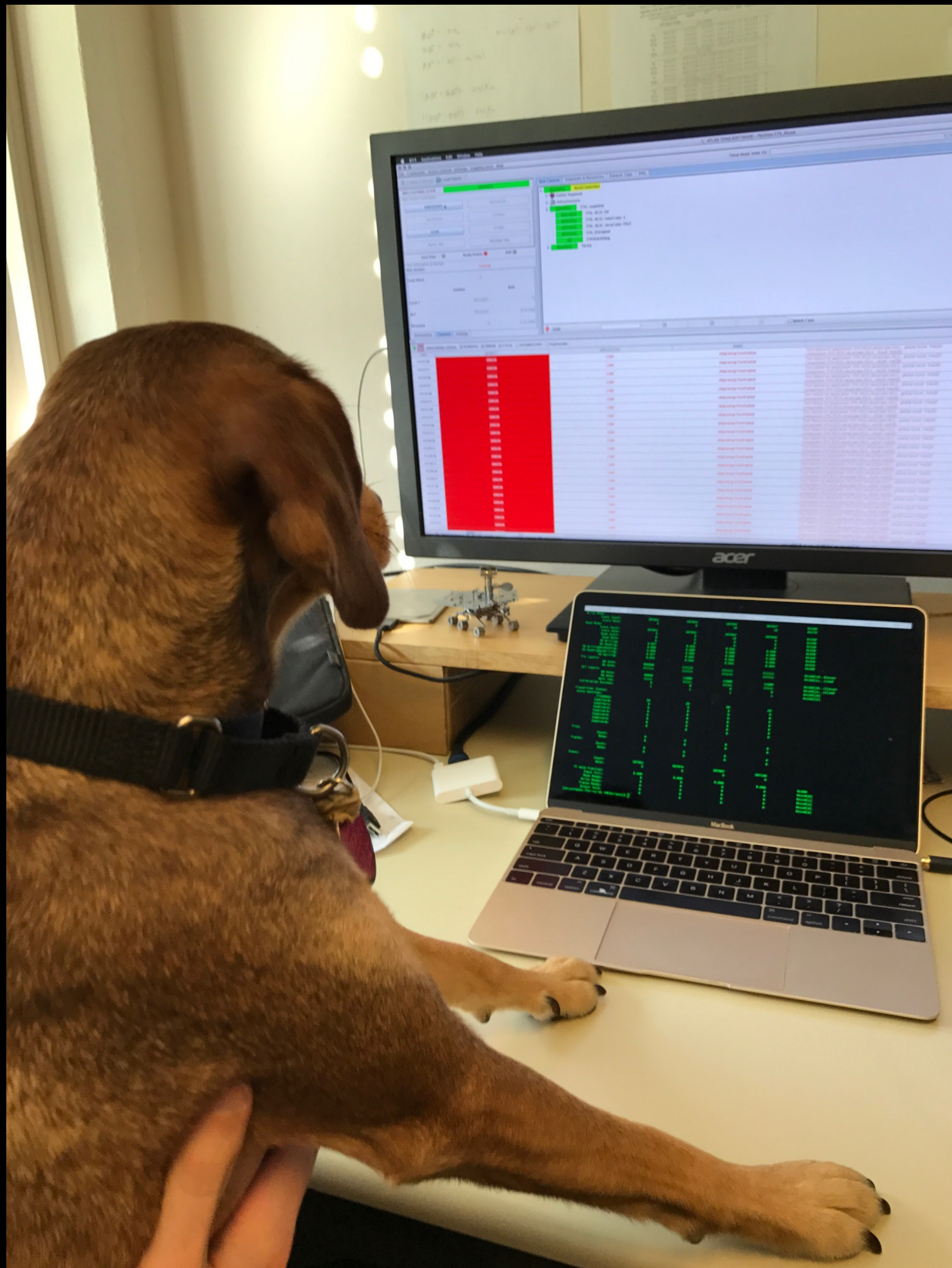
























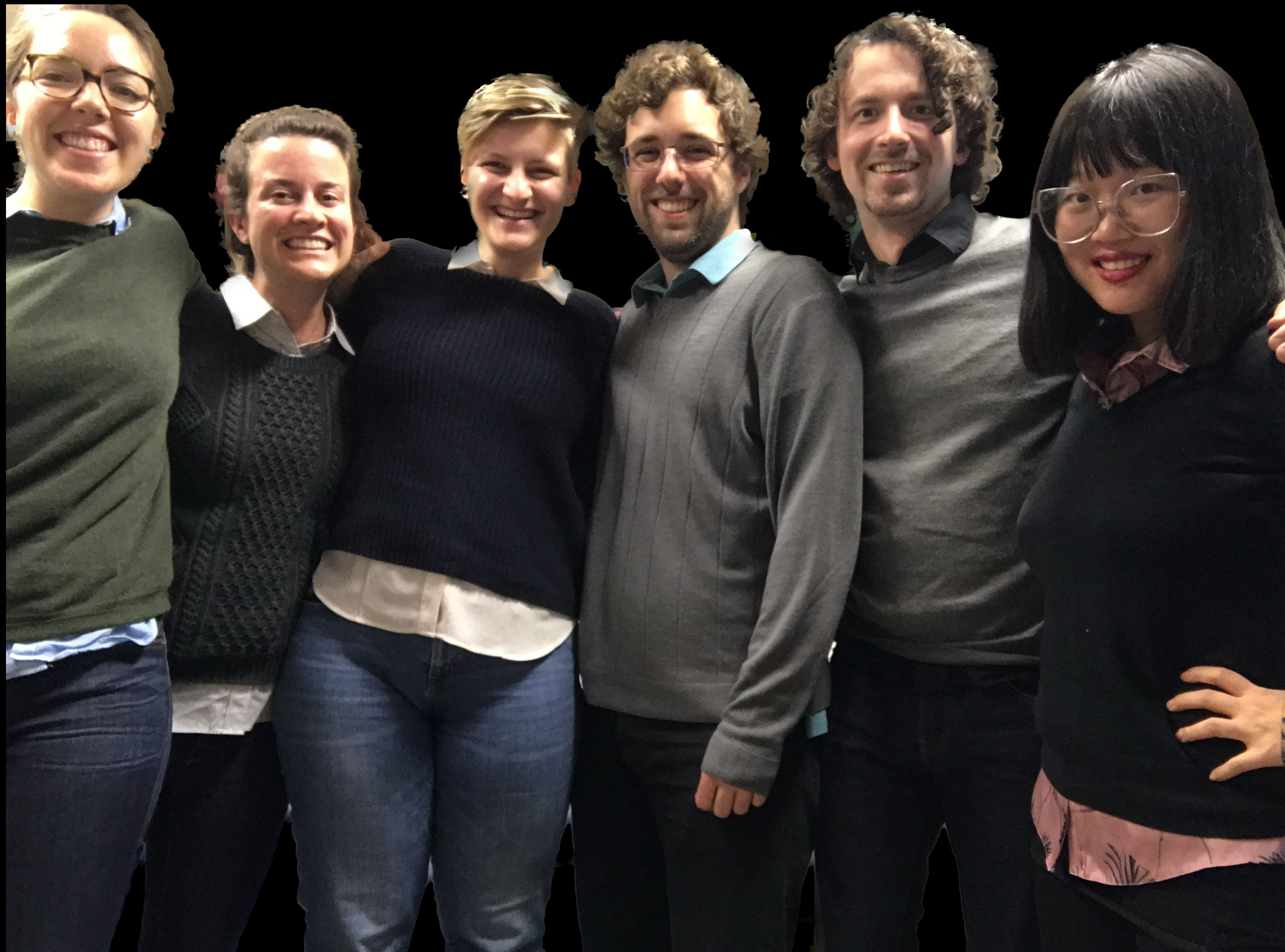




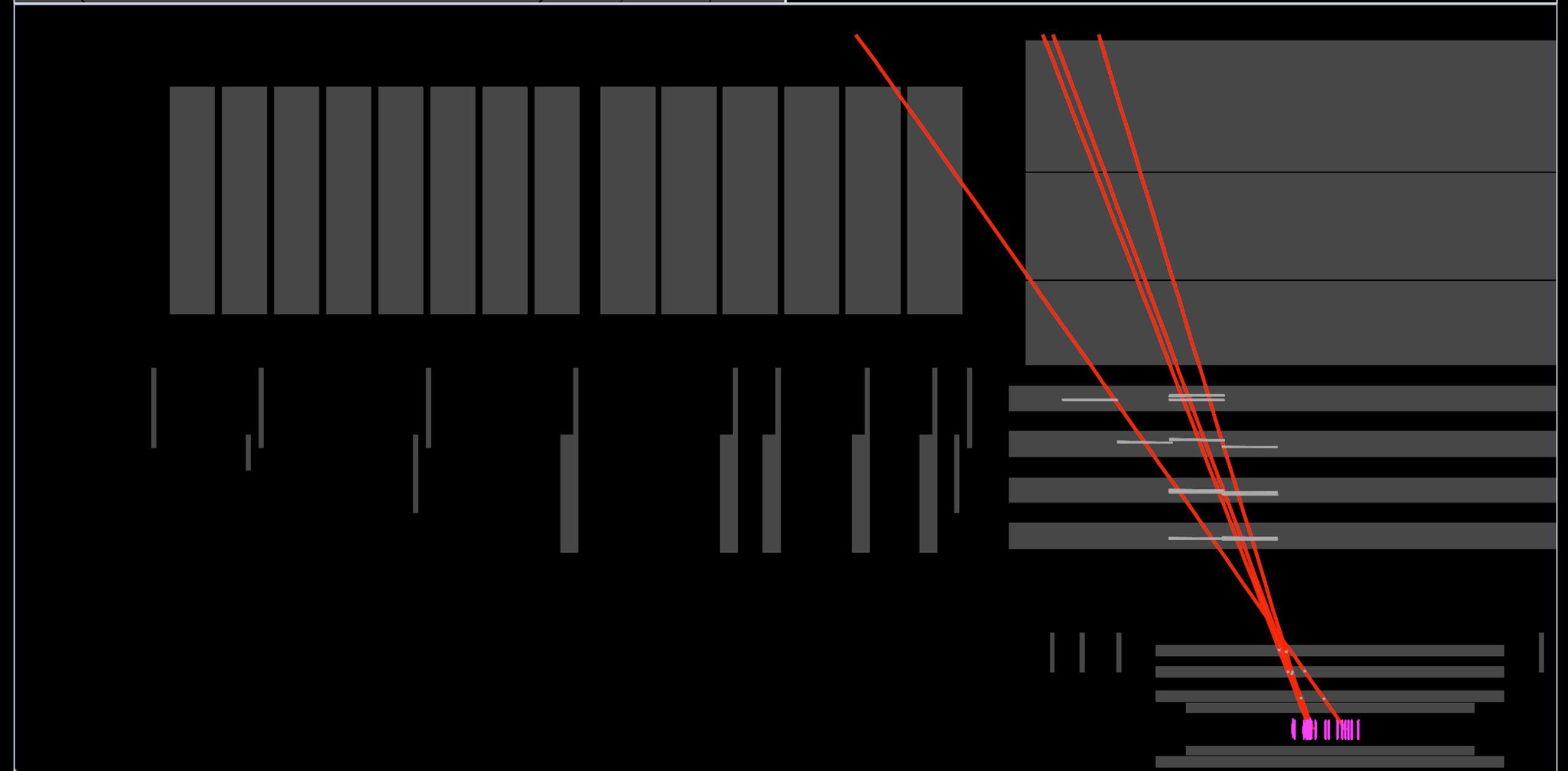
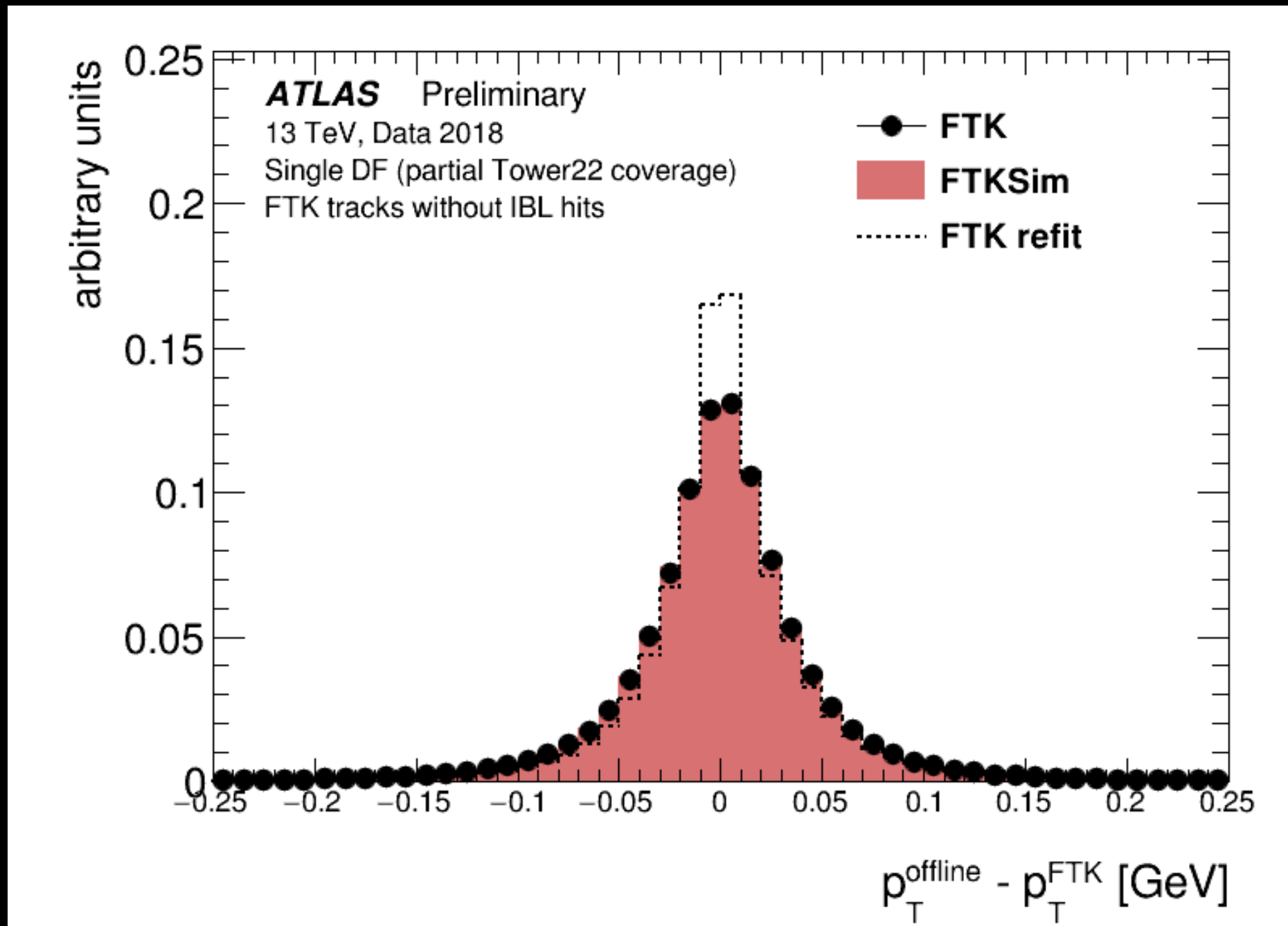
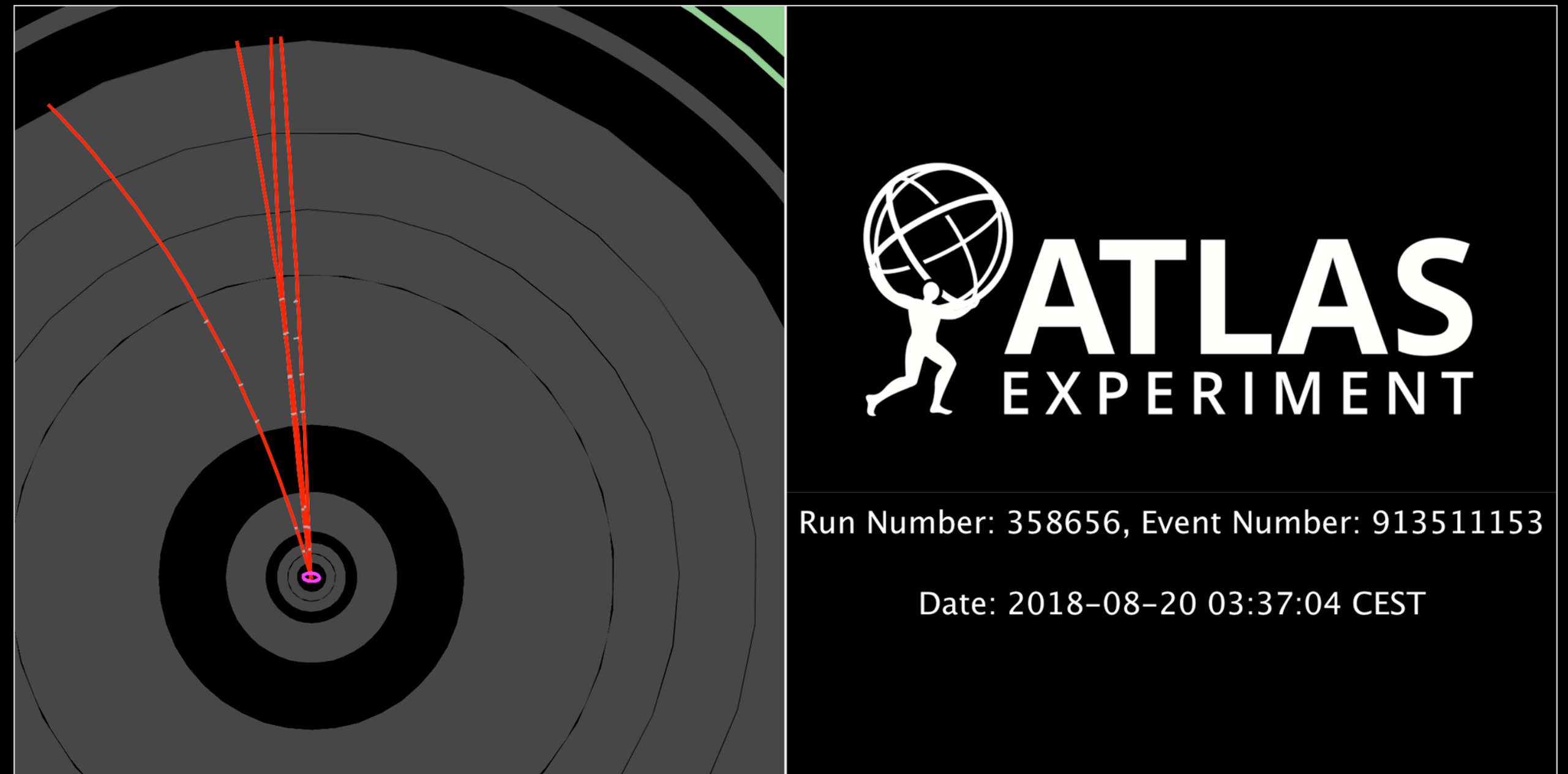
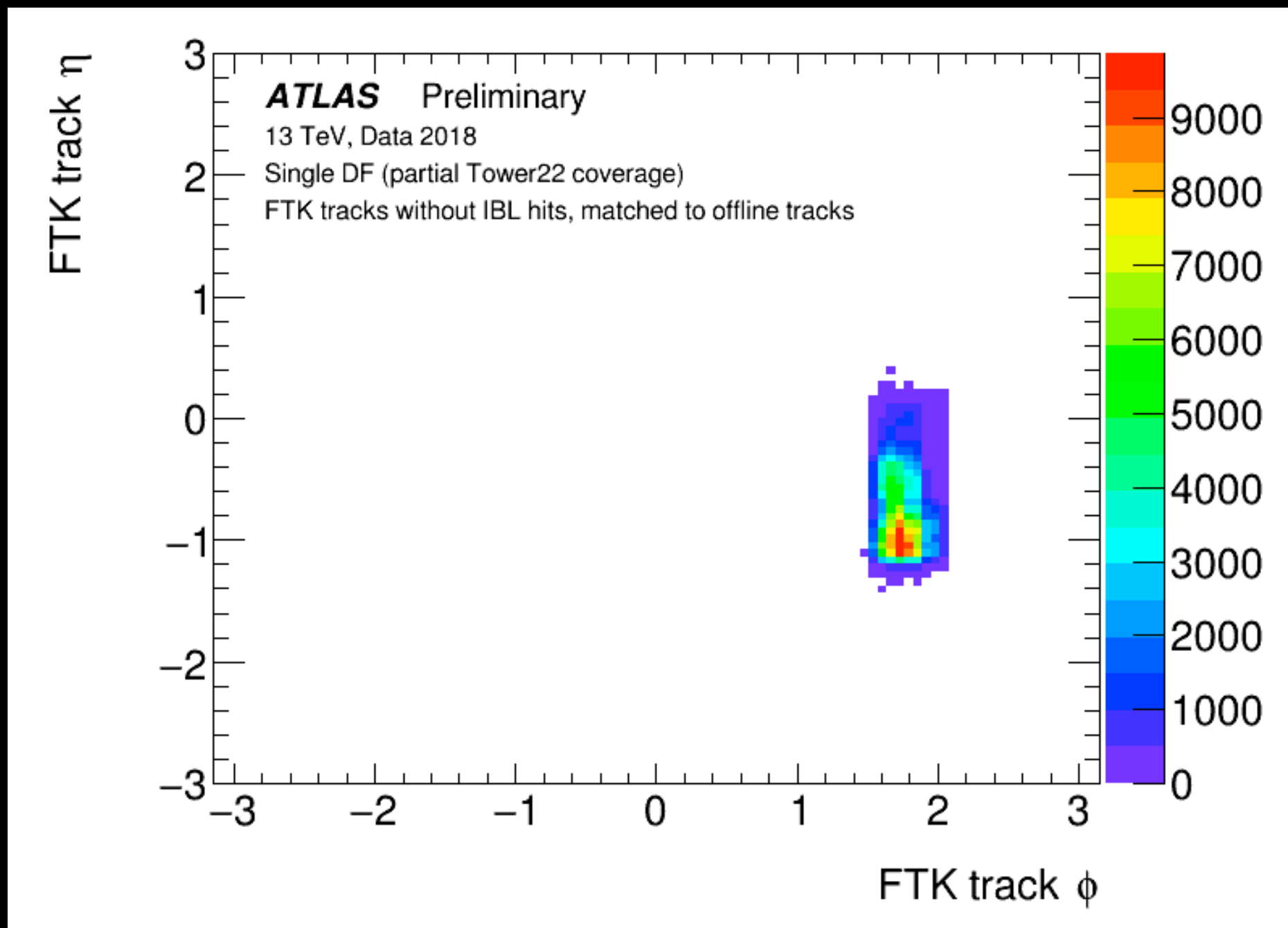














# FTK'S SUCCESSES

- First project pushing for ATLAS upgrades, including first to look at high pile-up simulation
- First demonstration of heterogenous computing
- Pushed the HLT tracking to get better
- Inspired work ongoing for the HL-LHC Upgrades
- MOST IMPORTANTLY: Culture in which people, particularly young people, felt like they could innovate, have with their work, and enjoy the people they work with.



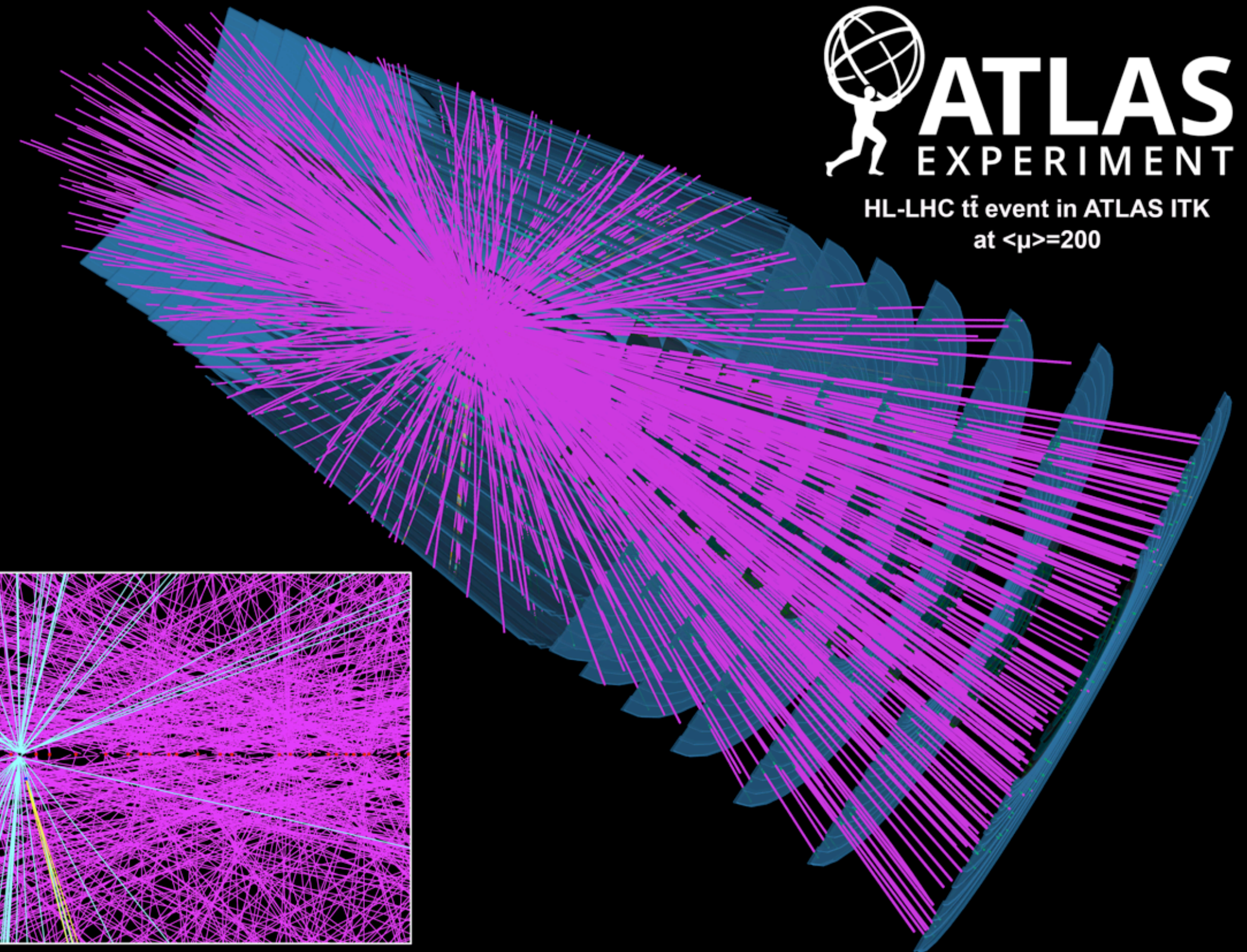
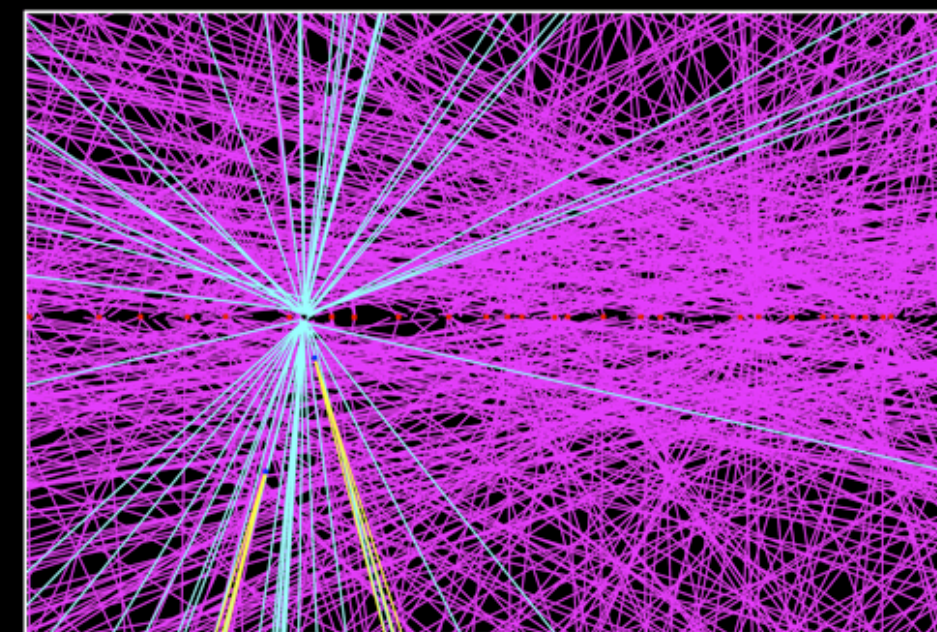
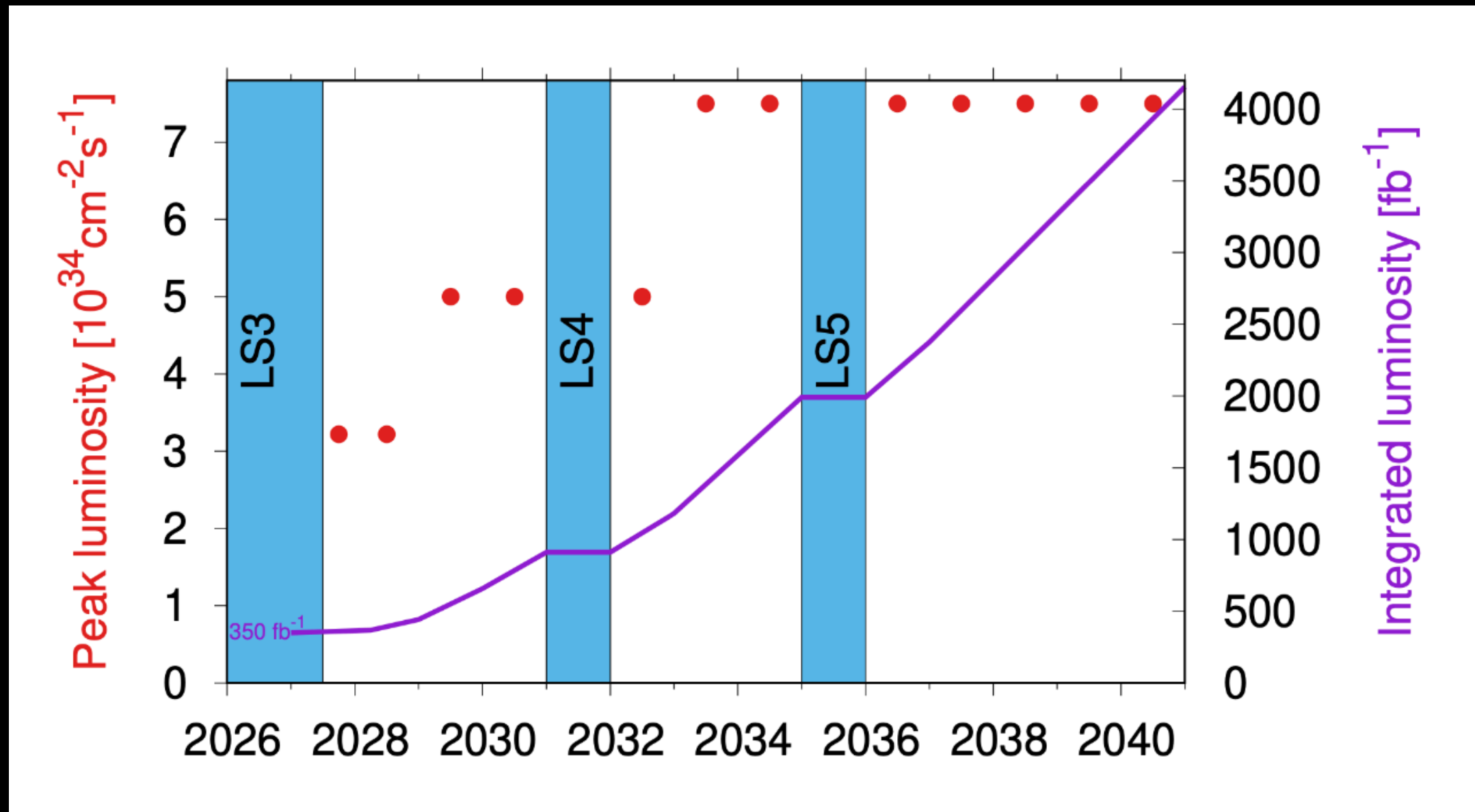
# FTK'S SUCCESSES

- First project pushing for ATLAS upgrades, including first to look at high pile-up simulation
- First demonstration of heterogenous computing
- Pushed the HLT tracking to get better
- Inspired work ongoing for the HL-LHC Upgrades
- MOST IMPORTANTLY: Culture in which people, particularly young people, felt like they could innovate, have with their work, and enjoy the people they work with.

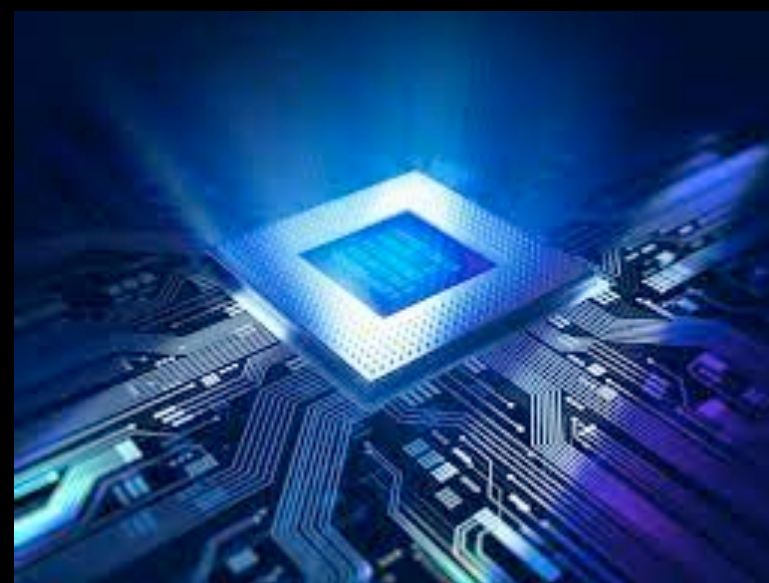
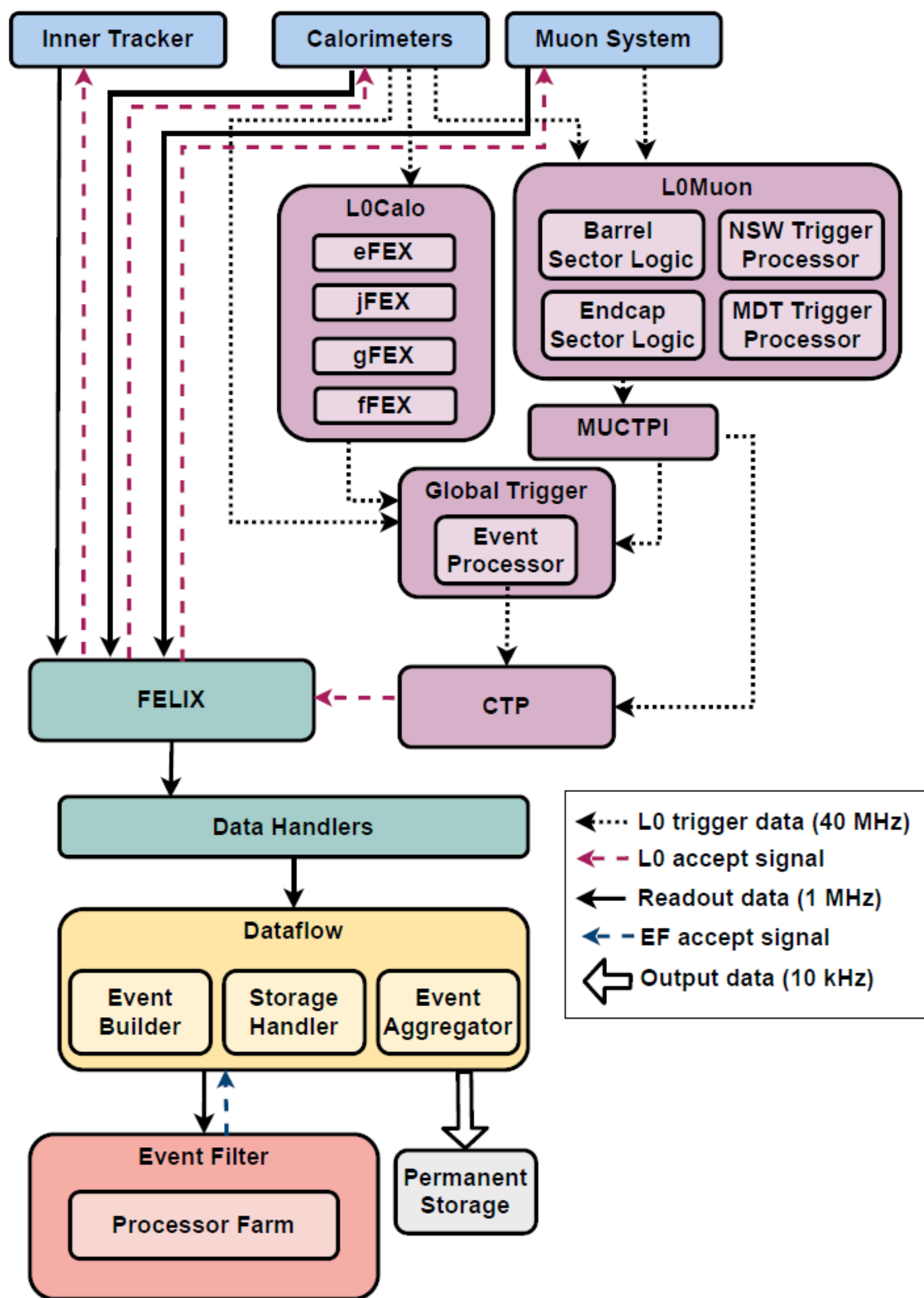




# THE FUTURE



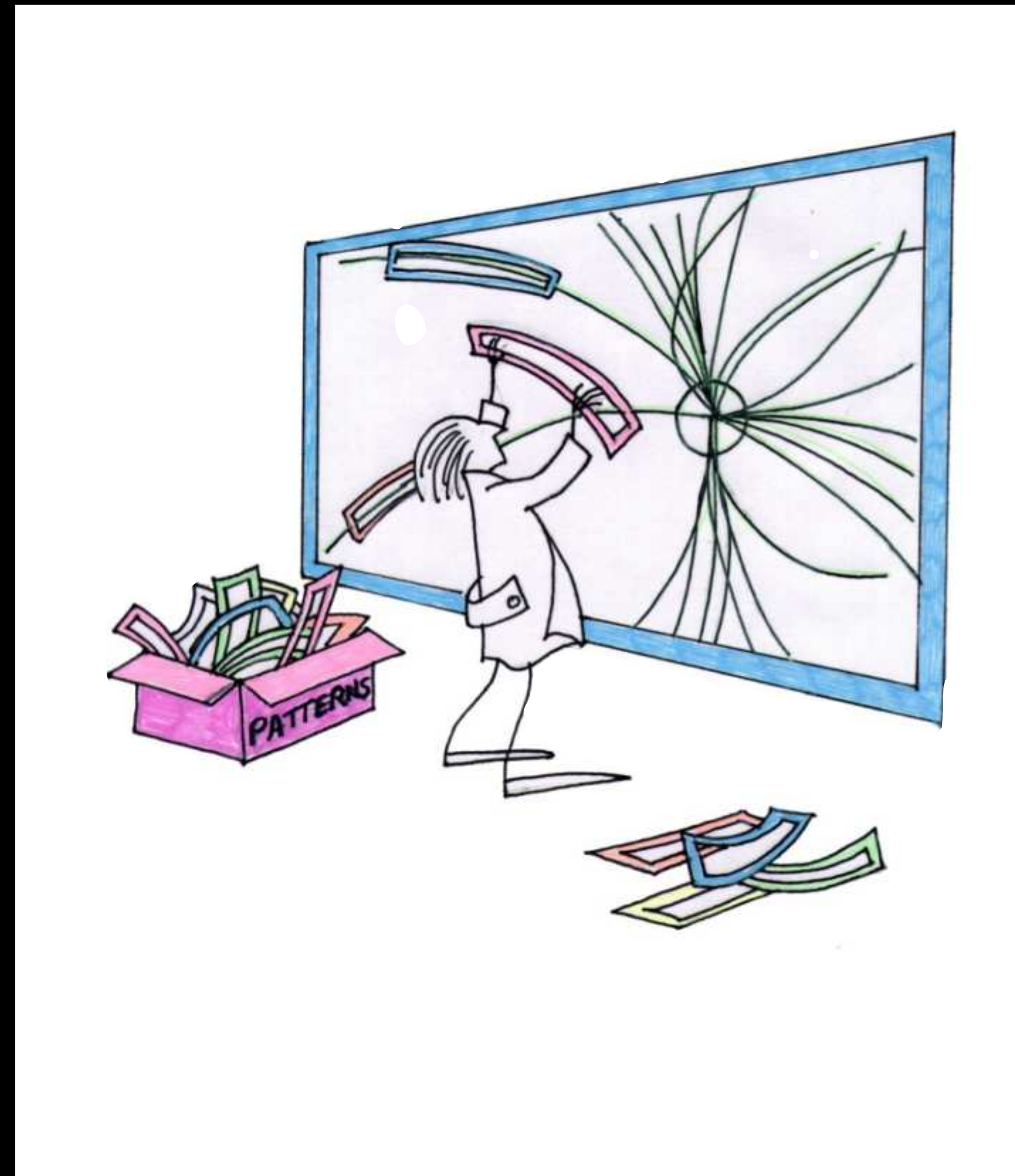






# CONCLUSIONS

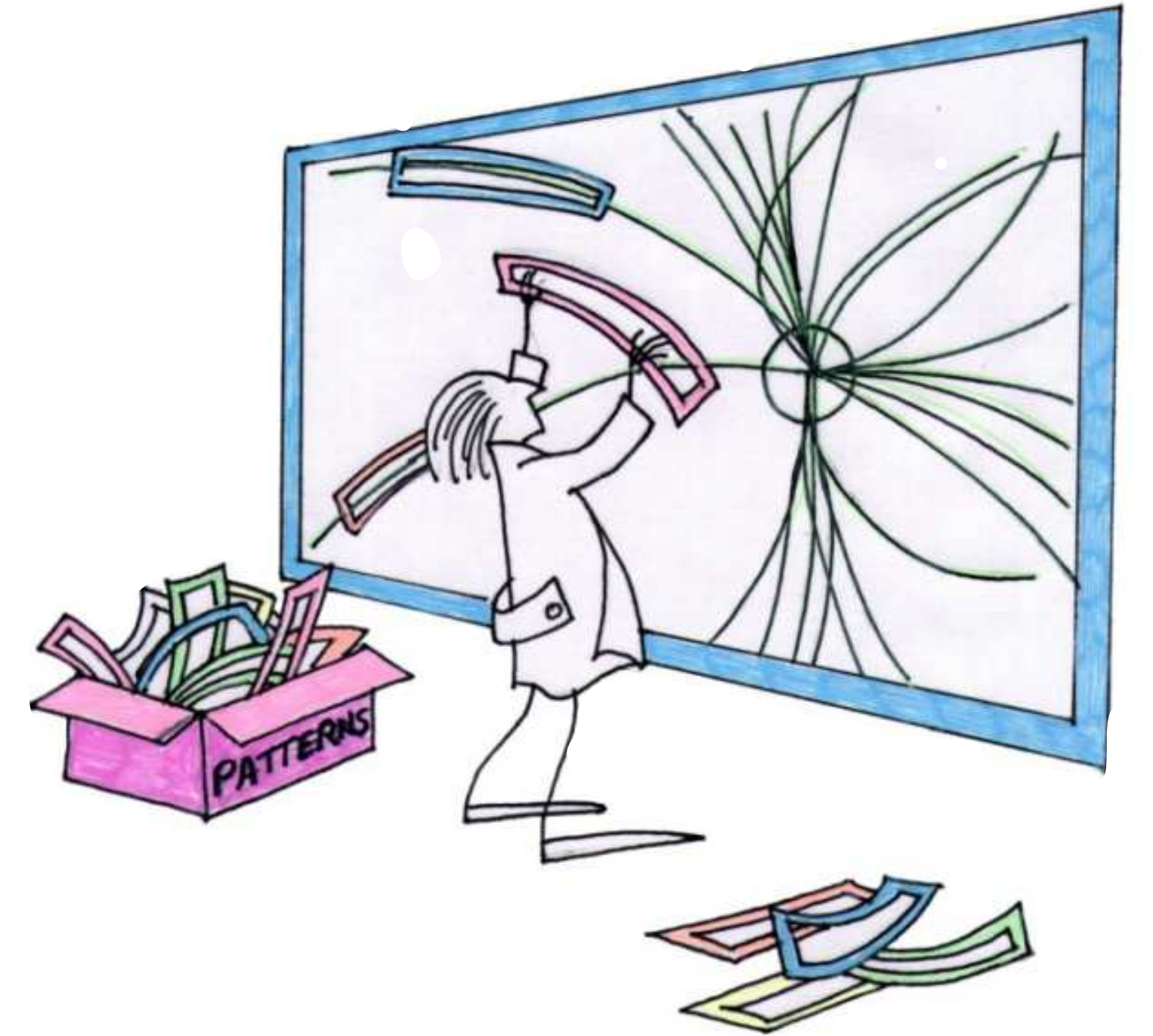
- Mel led an ambitious program to demonstrate track triggering at the LHC
- He provided support for generations of young physicists who are now thriving





# CONCLUSIONS

- Mel led an ambitious program to demonstrate track triggering at the LHC
- He provided support for generations of young physicists who are now thriving





# CONCLUSIONS

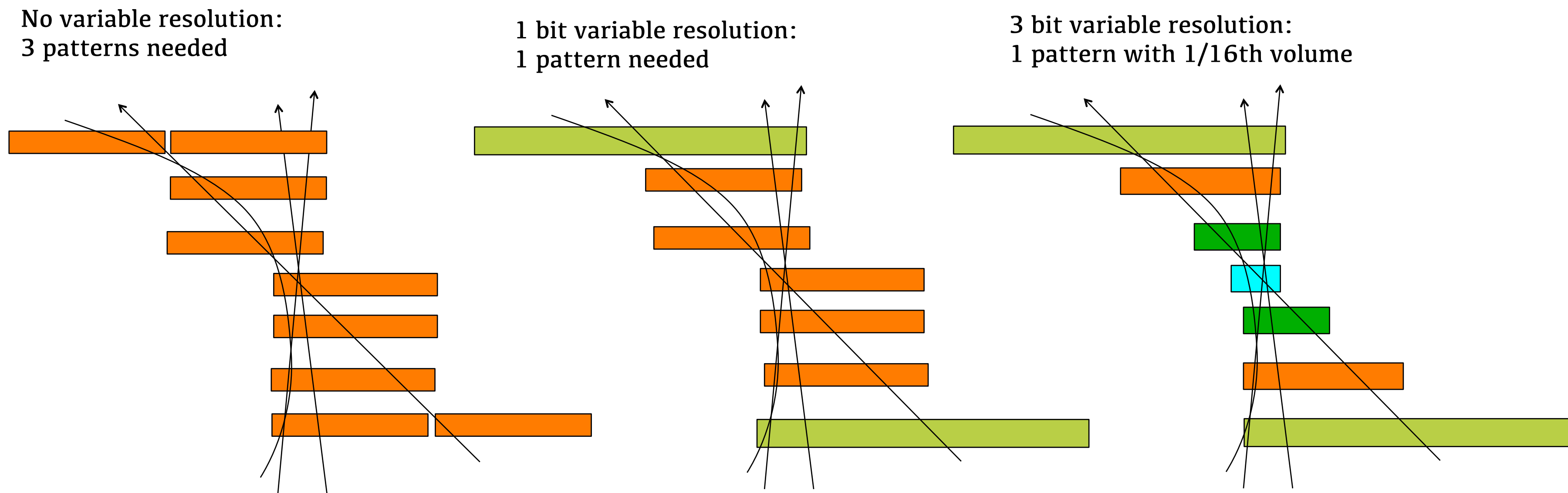
- Mel led an ambitious program to demonstrate track triggering at the LHC
- He provided support for generations of young physicists who are now thriving





# 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

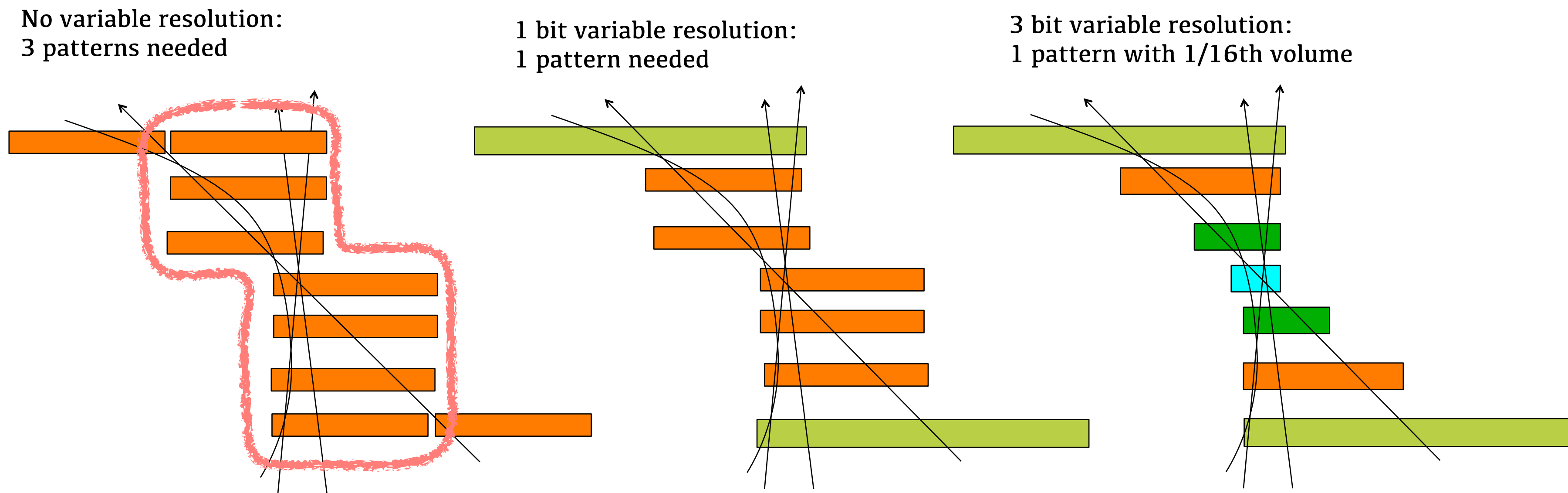


- Number of don't care bits set on a layer by layer, pattern by pattern basis



# 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

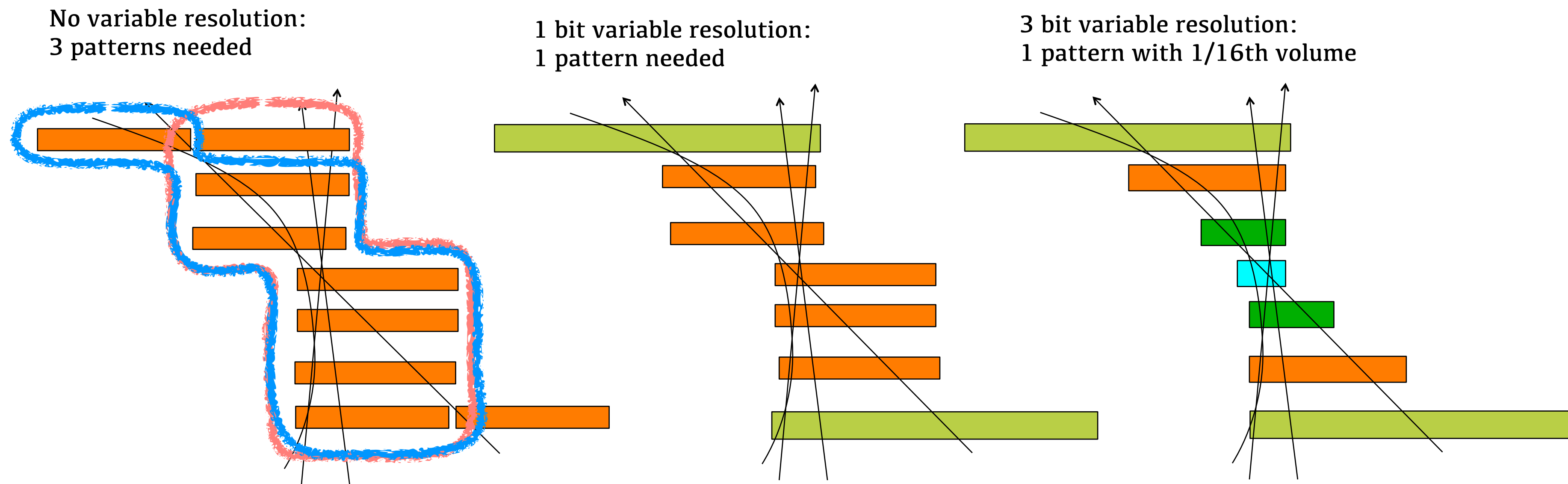


- Number of don't care bits set on a layer by layer, pattern by pattern basis



# 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

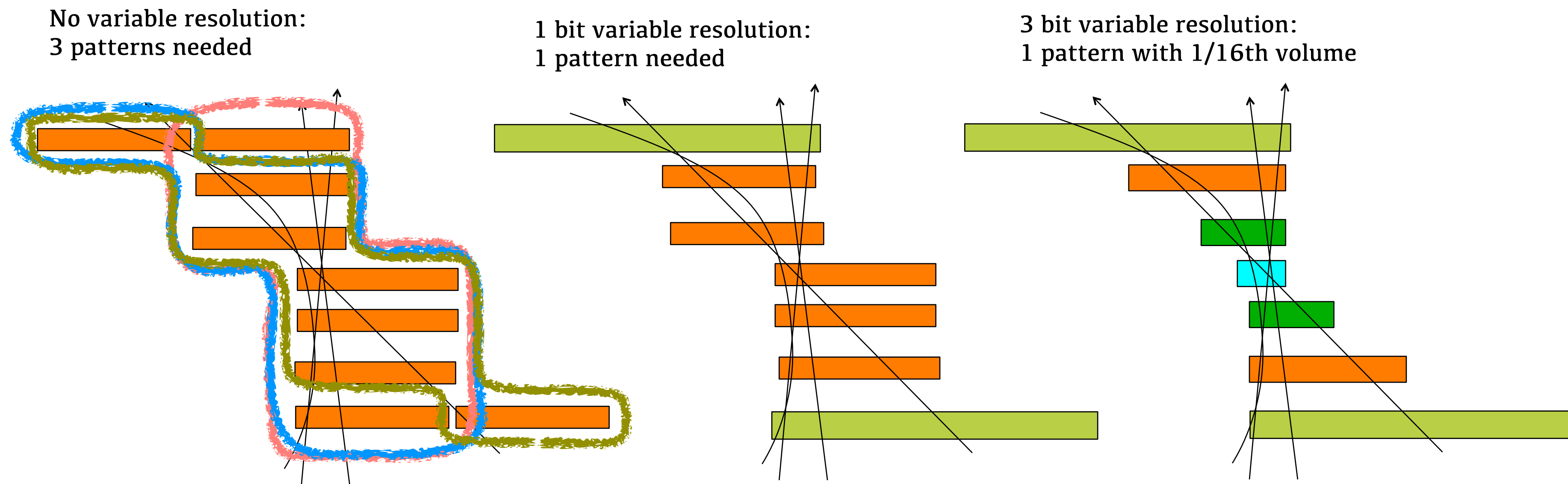


- Number of don't care bits set on a layer by layer, pattern by pattern basis



# 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