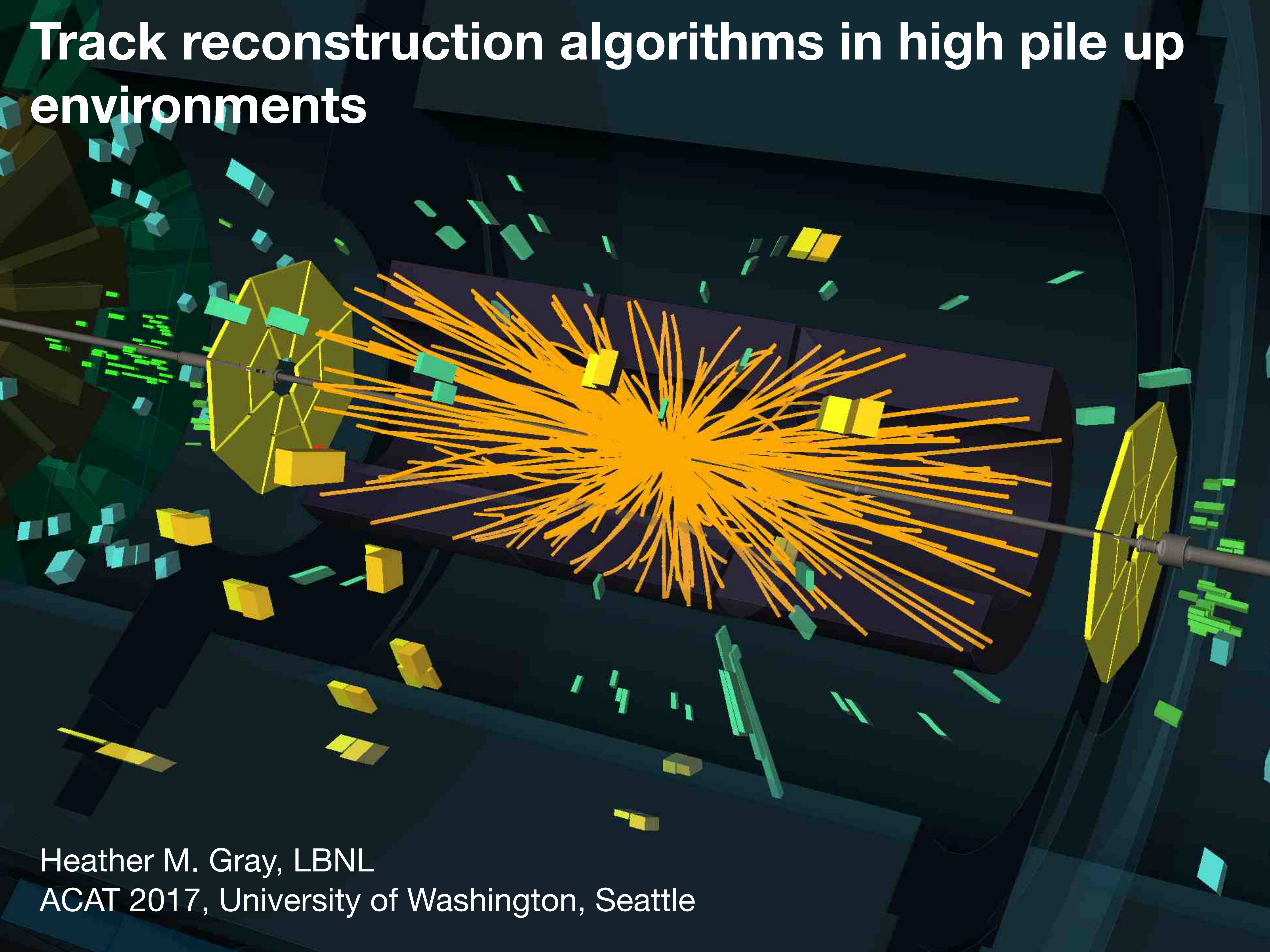
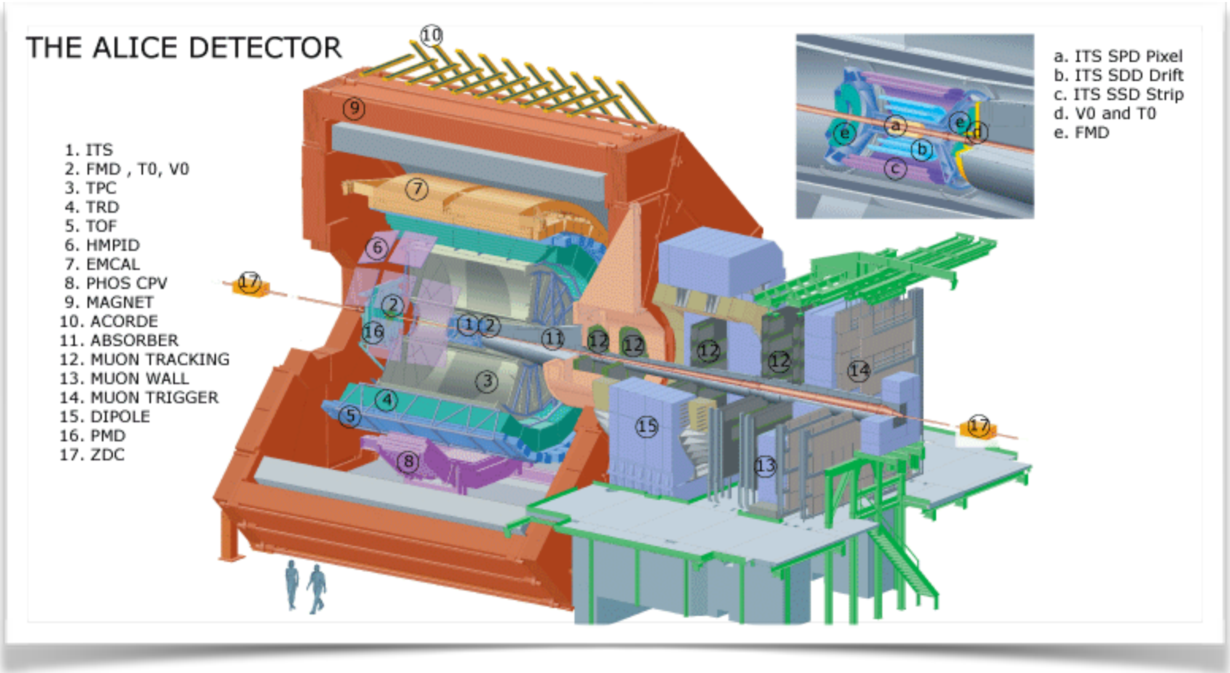
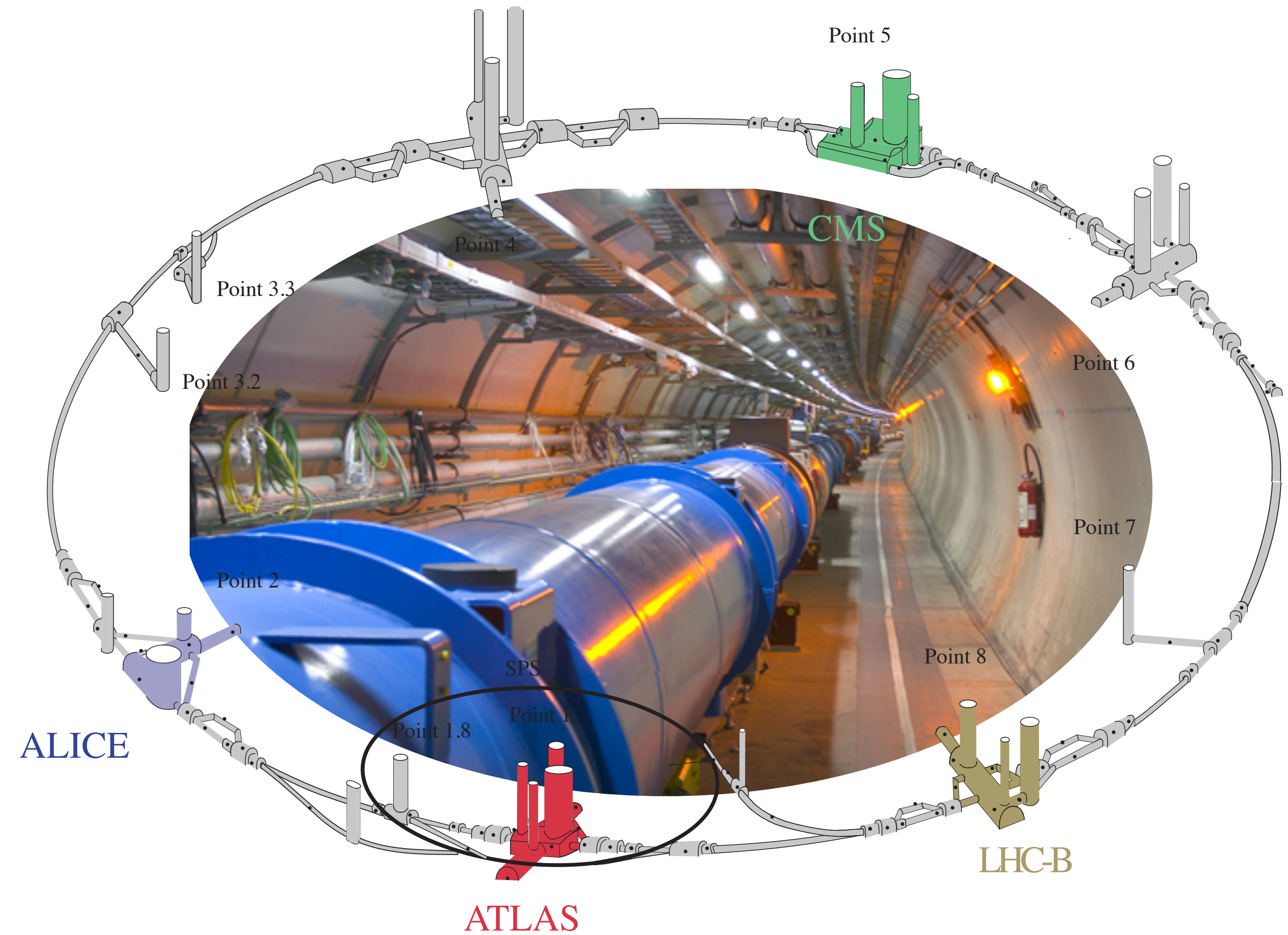
Track reconstruction algorithms in high pile up environments

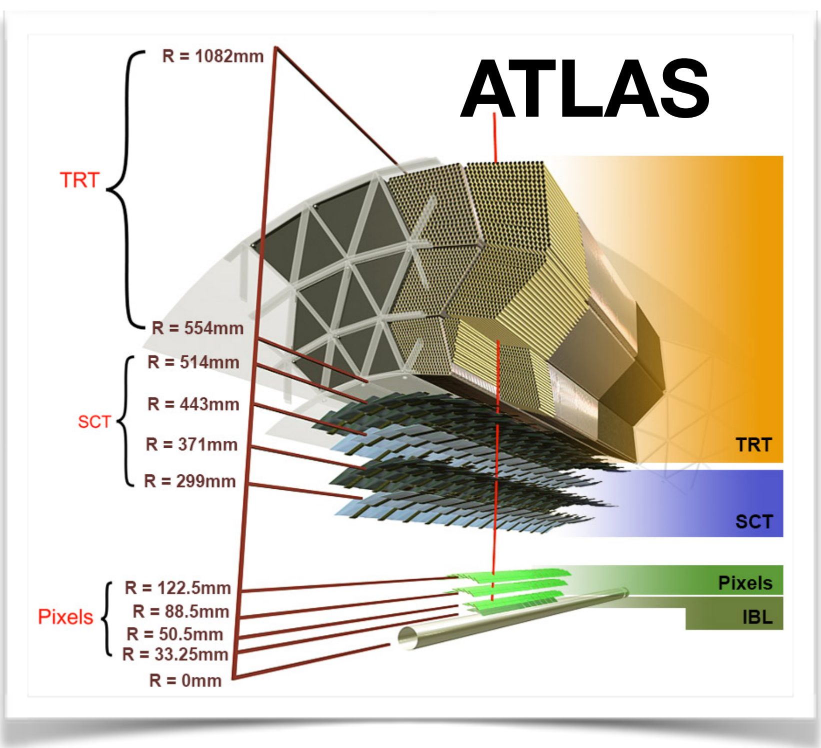


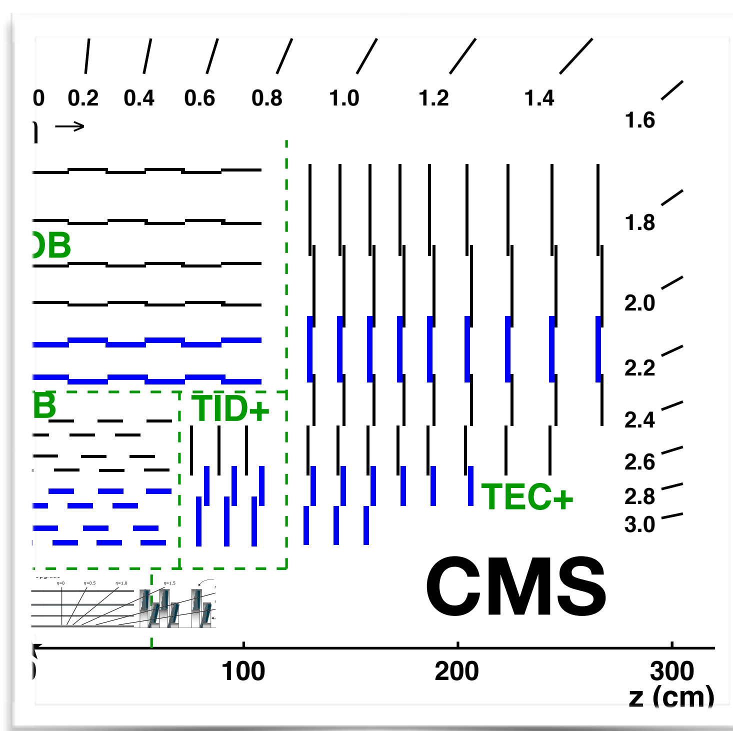
Heather M. Gray, LBNL
ACAT 2017, University of Washington, Seattle

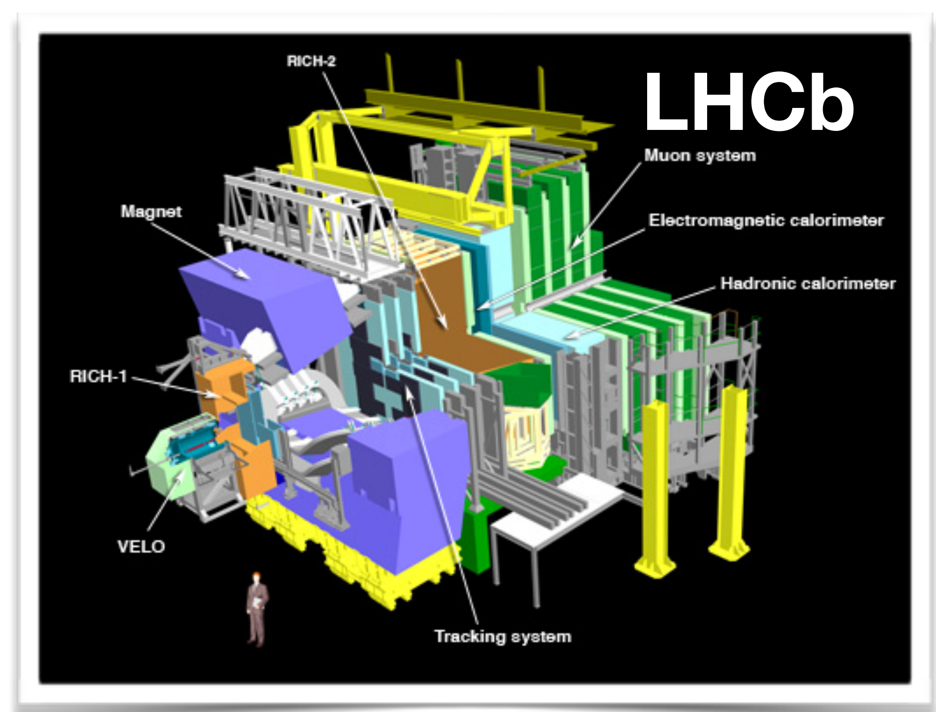
The LHC and its experiments

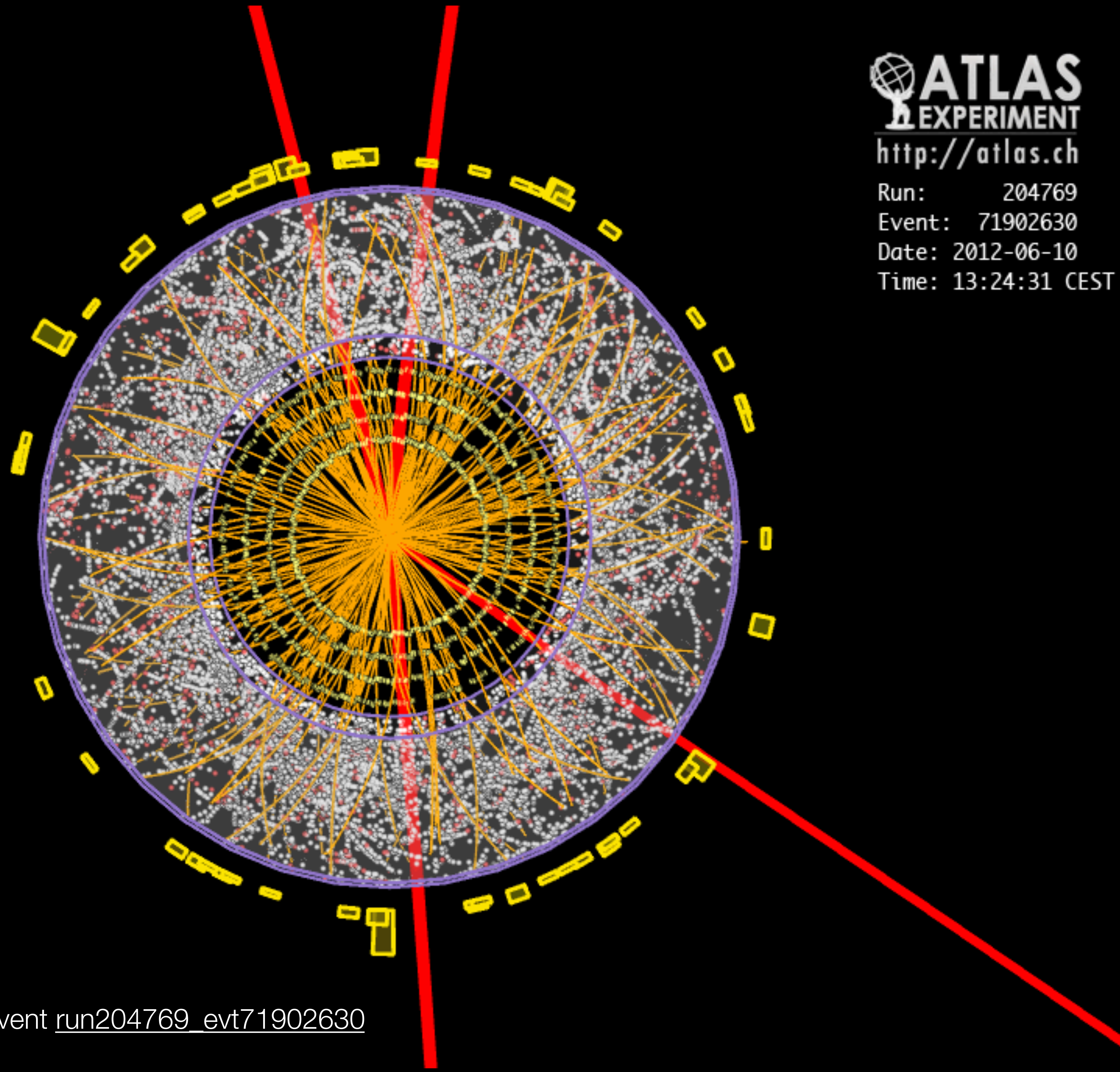












H -> ZZ candidate event run204769_evt71902630

Track Reconstruction

Image courtesy of A. Salzburger

Track reconstruction = pattern recognition + tracking fitting

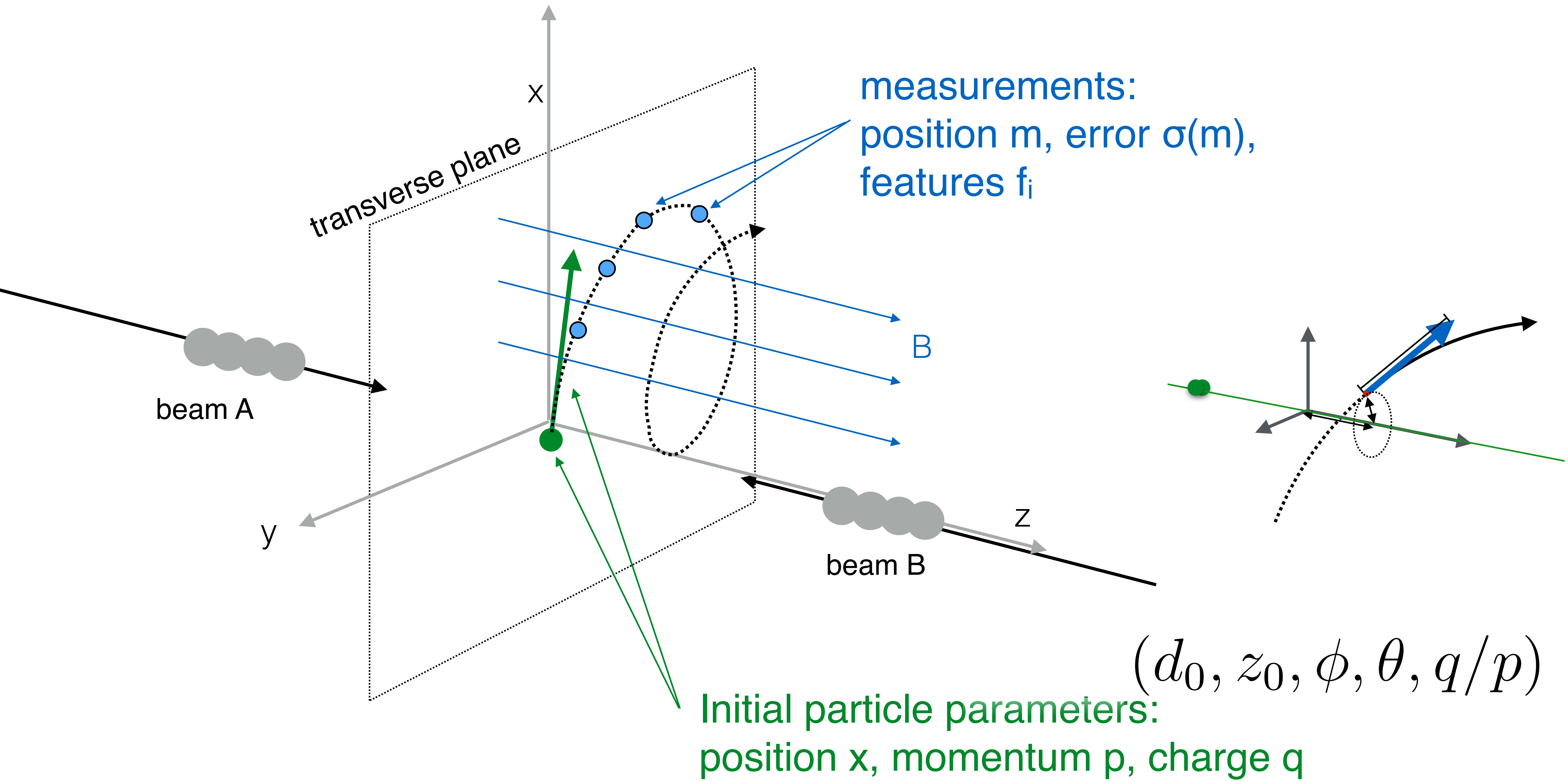
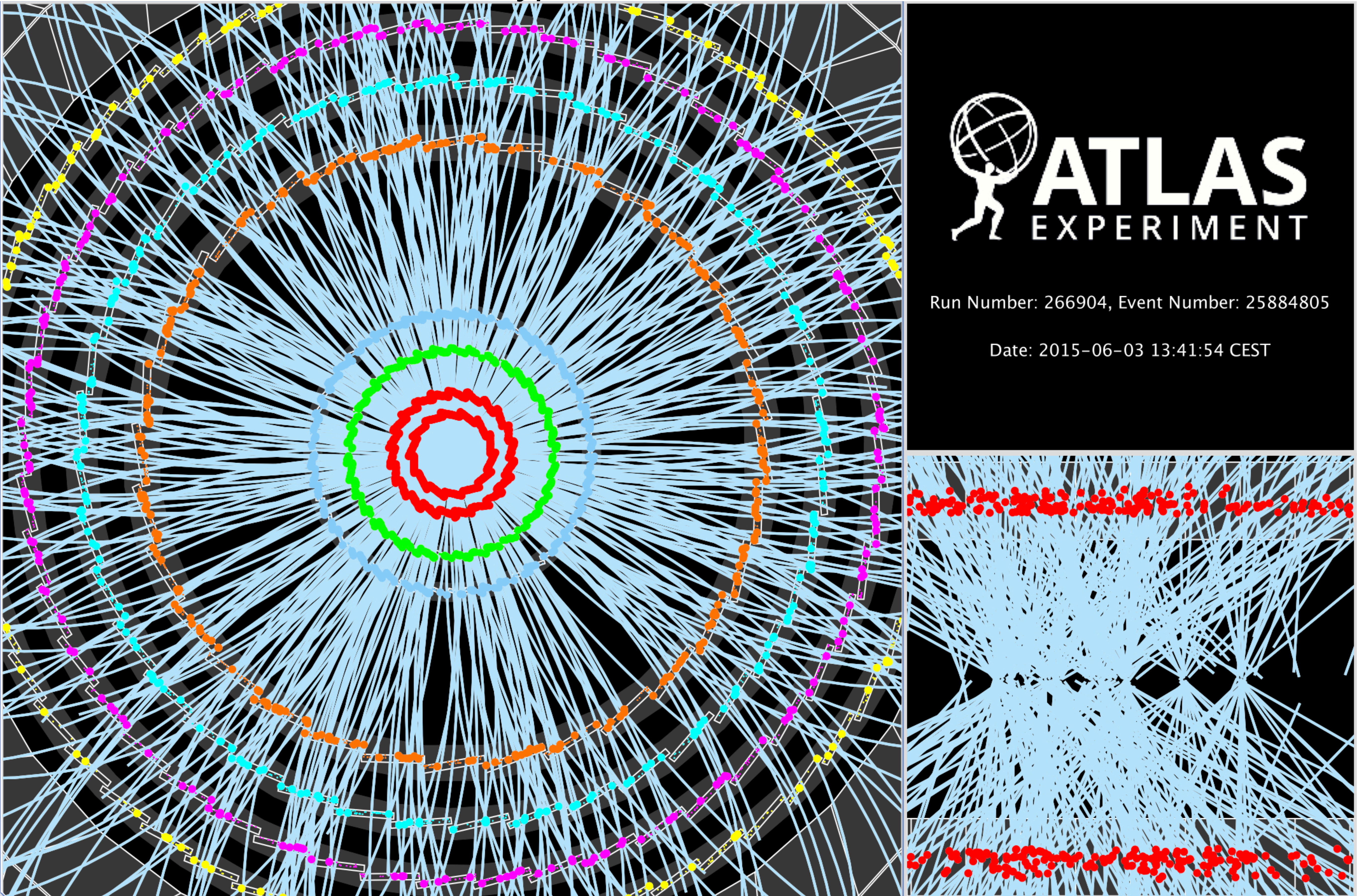
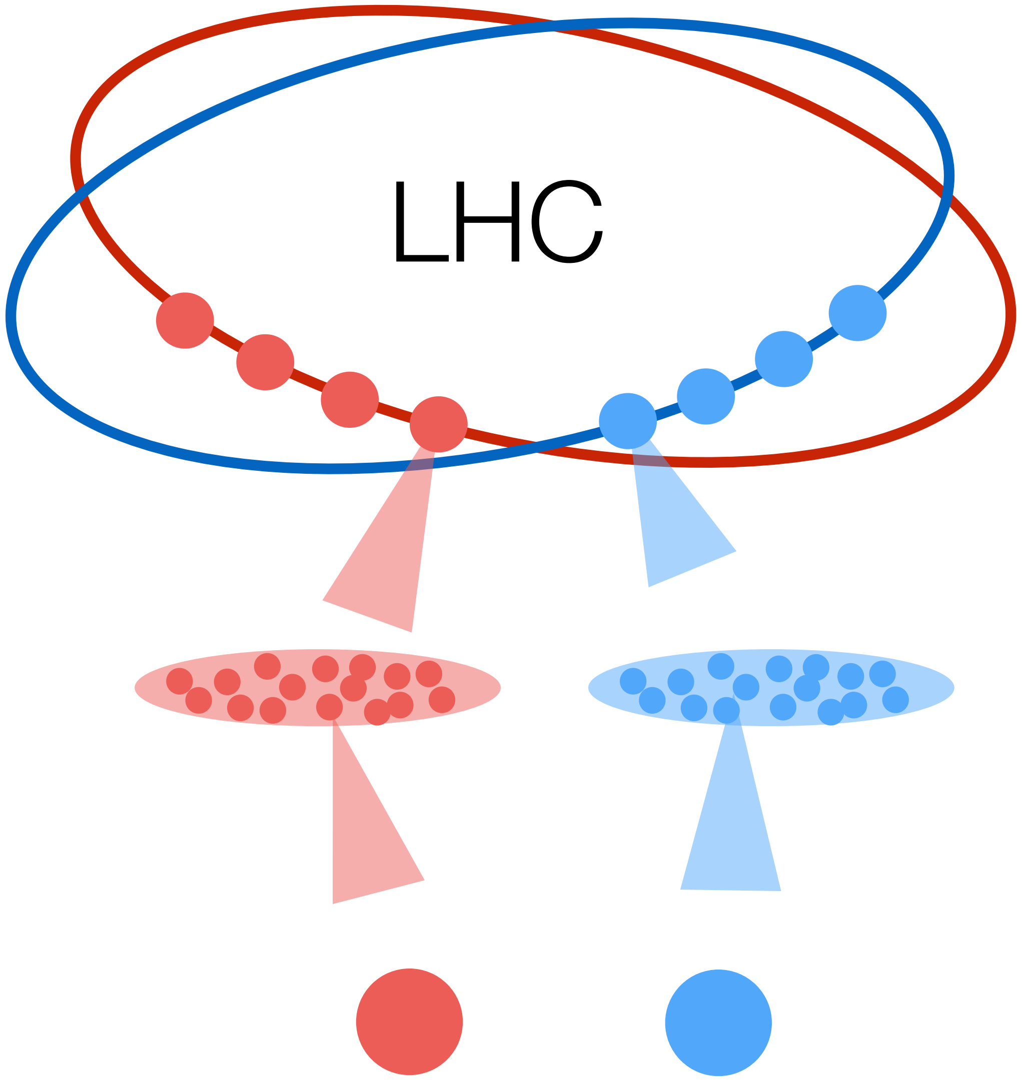


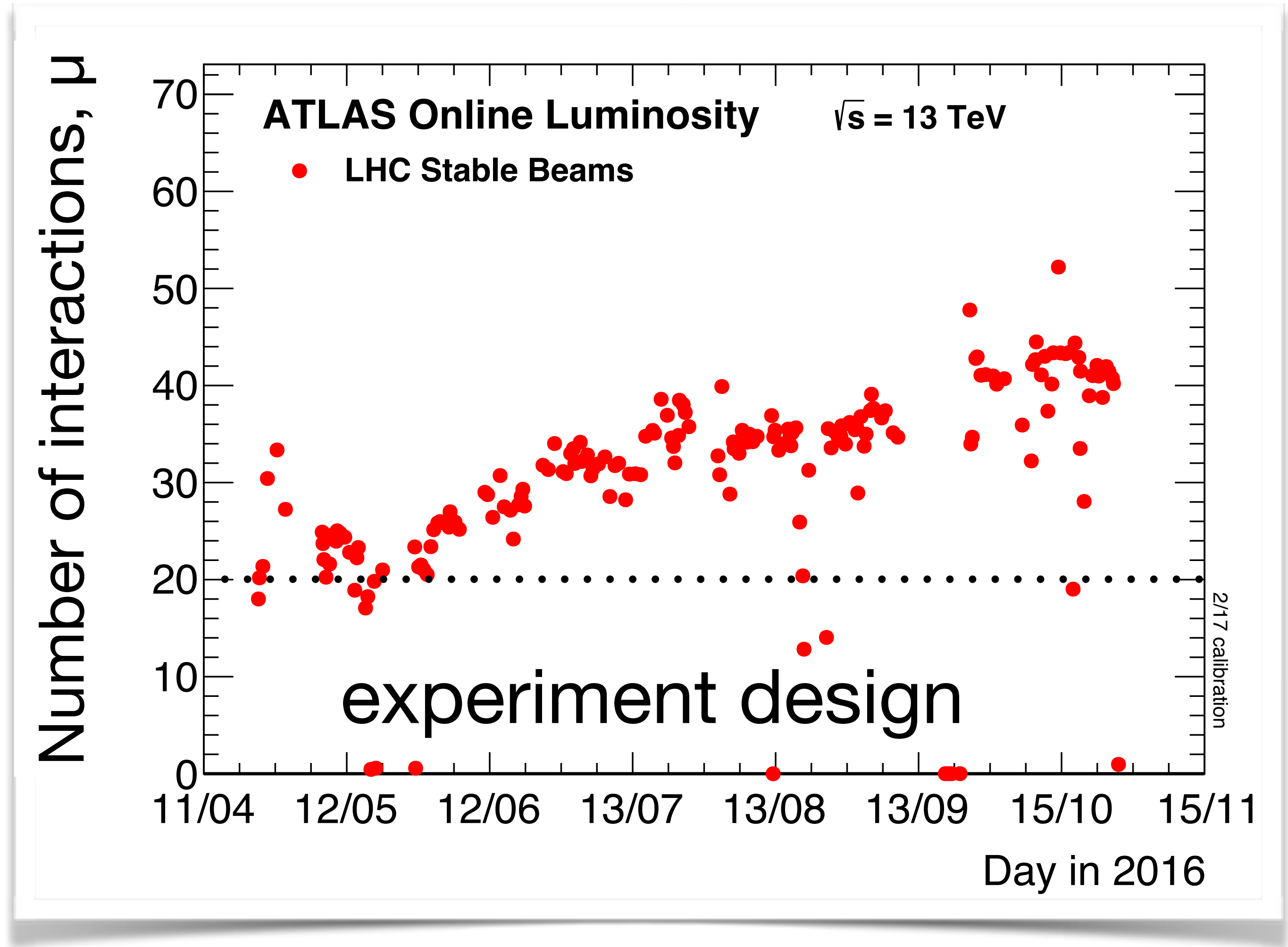
Illustration:
A schematic view of a particle in a magnetic field.

A typical 13 TeV LHC collision

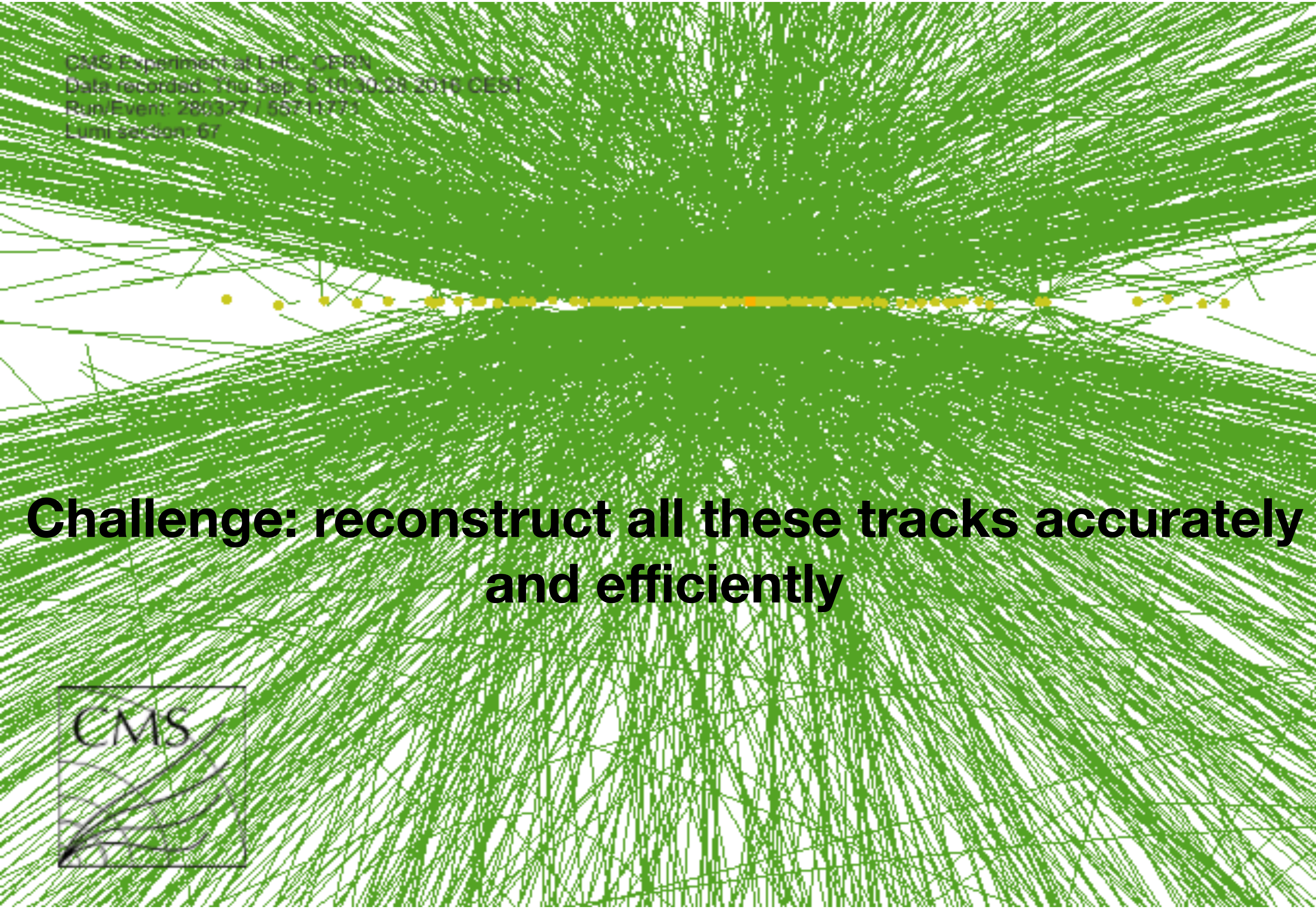


Pile up at Hadron Colliders





- ~10^{11} protons per bunch to maximise number of interactions
  - Maximise physics reach !
- But, typically more than one pair of protons collides
  - Currently, ~40 collisions per bunch crossing



Challenge: reconstruct all these tracks accurately and efficiently

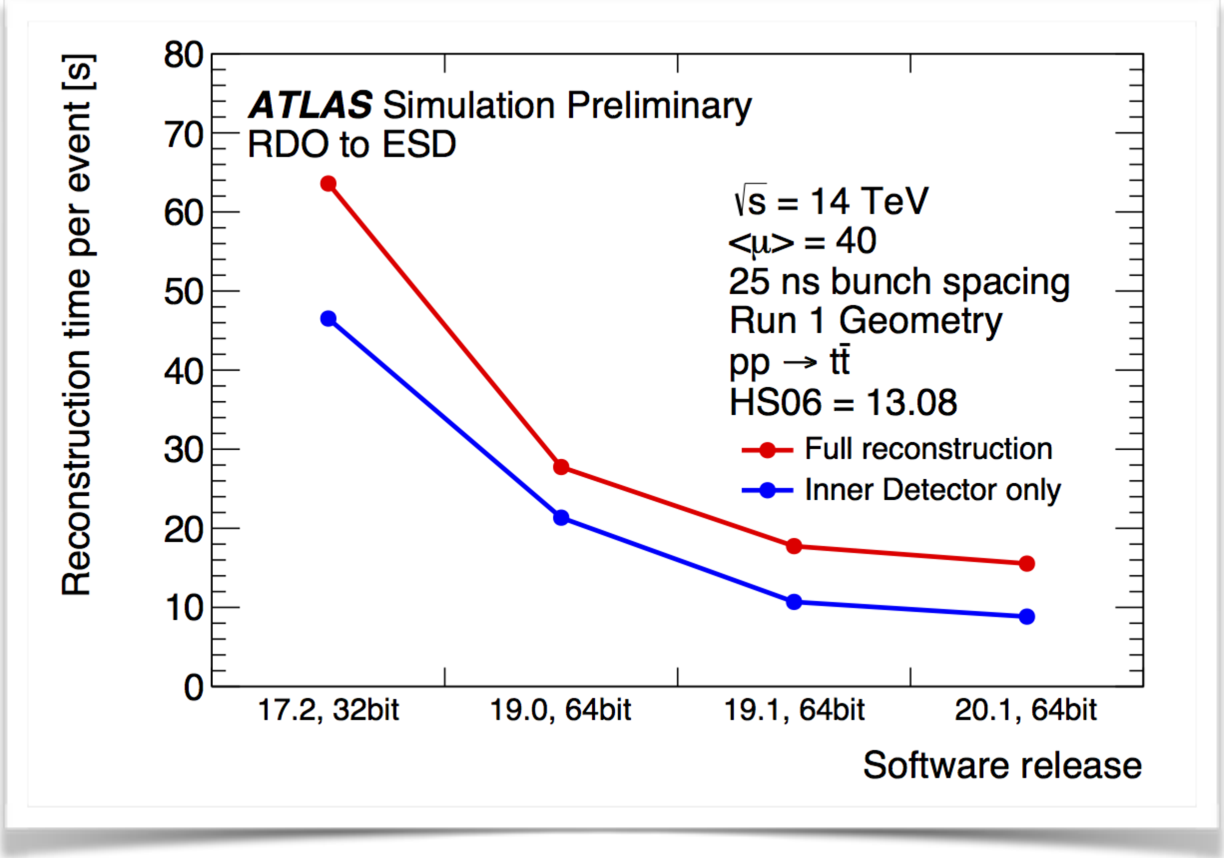
86 reconstructed vertices

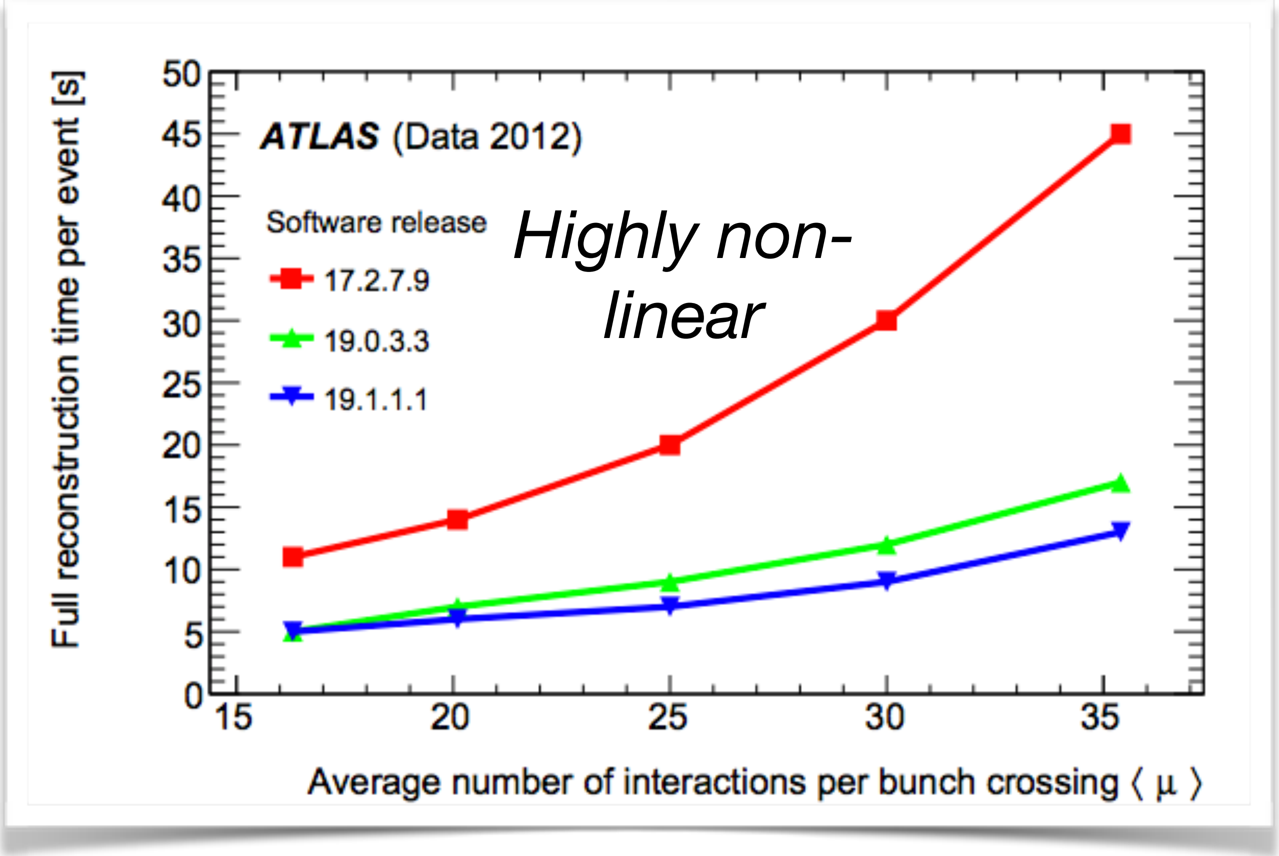
Pile up, now and in the future

	LHC Run-1 ~2010-2013	LHC Run-2 ~2015-2018	LHC Run-4 ~2026+	FCC ~2040?
μ	21	40	150-200	1000
Tracks	~280	~600	~7-10k	~100k

The Tracking Challenge

- Reconstruct charged particles **efficiently** (typically >99%) and with a **low fake rate** (typically <<1%)
- CPU time scales in ~quadrature with number of tracks or μ
- Very challenging to obtain good performance within computing resources
    - e.g. Reoptimisation to reduce CPU by factor of 4 during recent long shut-down, largely technical as opposed to algorithmic

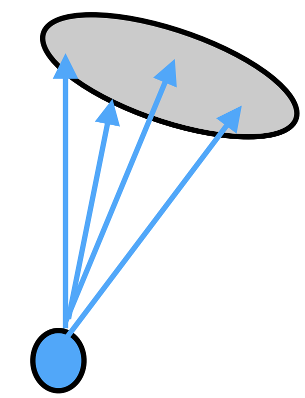




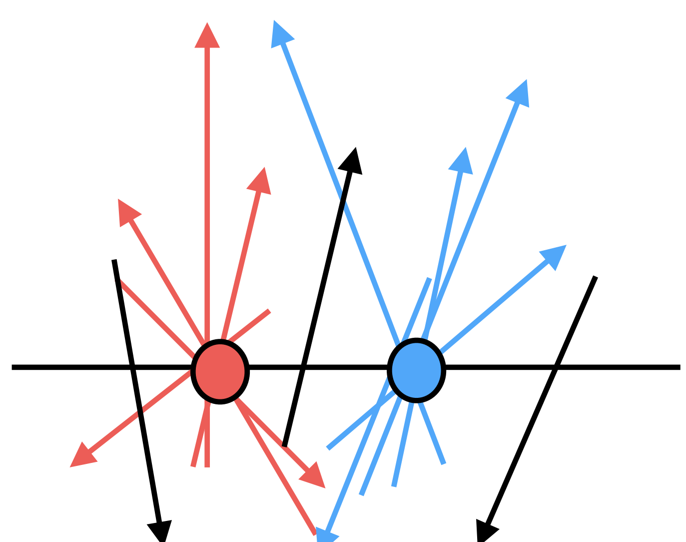
Remember: it's not only μ that is increasing, also more data with time

Not just tracking

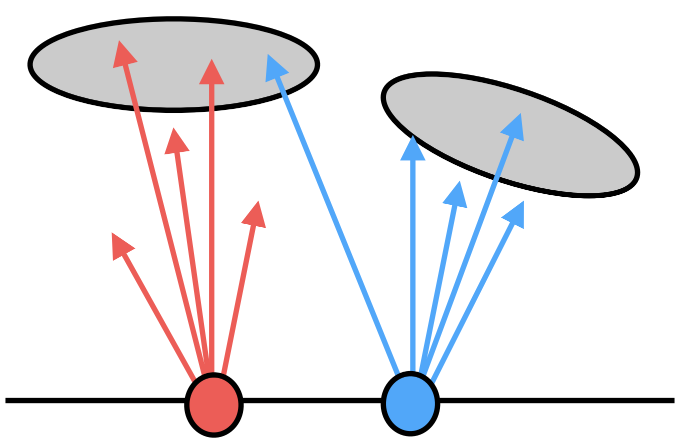
- Track reconstruction is not just about reconstructing charged particles
- Tracks are used in almost every element of reconstruction and hence physics
  - Leptons
  - Primary vertices
  - Pileup removal for jets and missing energy
  - Jet flavour tagging



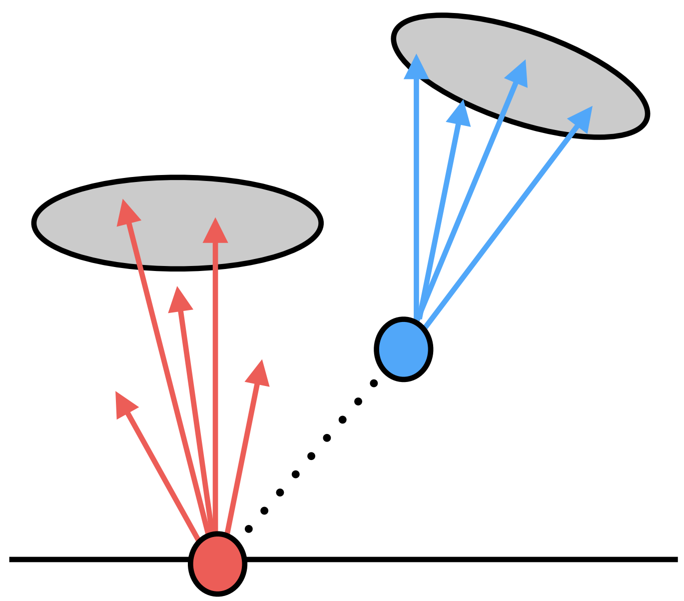
Quarks and gluons are reconstructed in the detector as jets



Vertex reconstruction



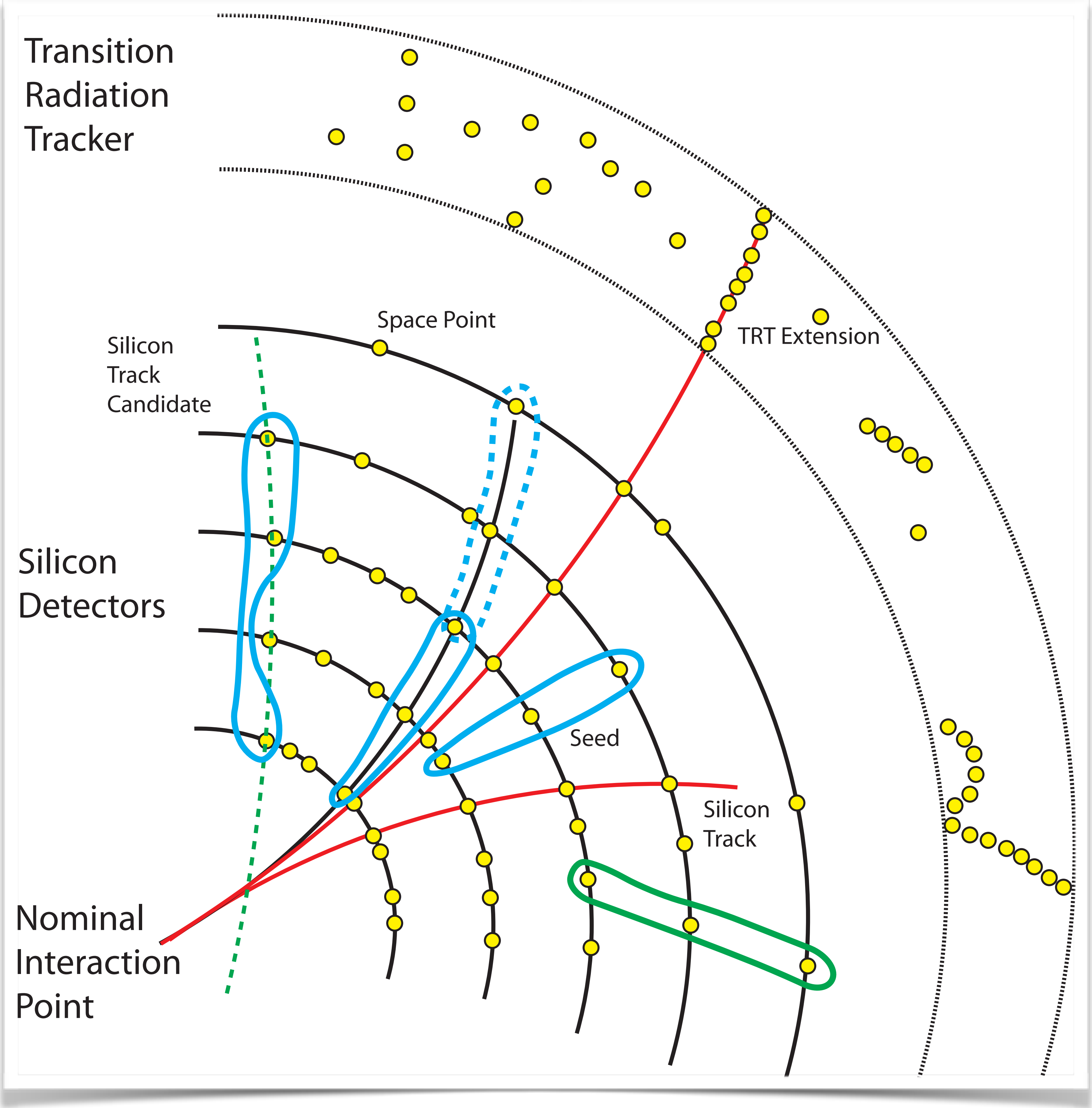
Pile up removal

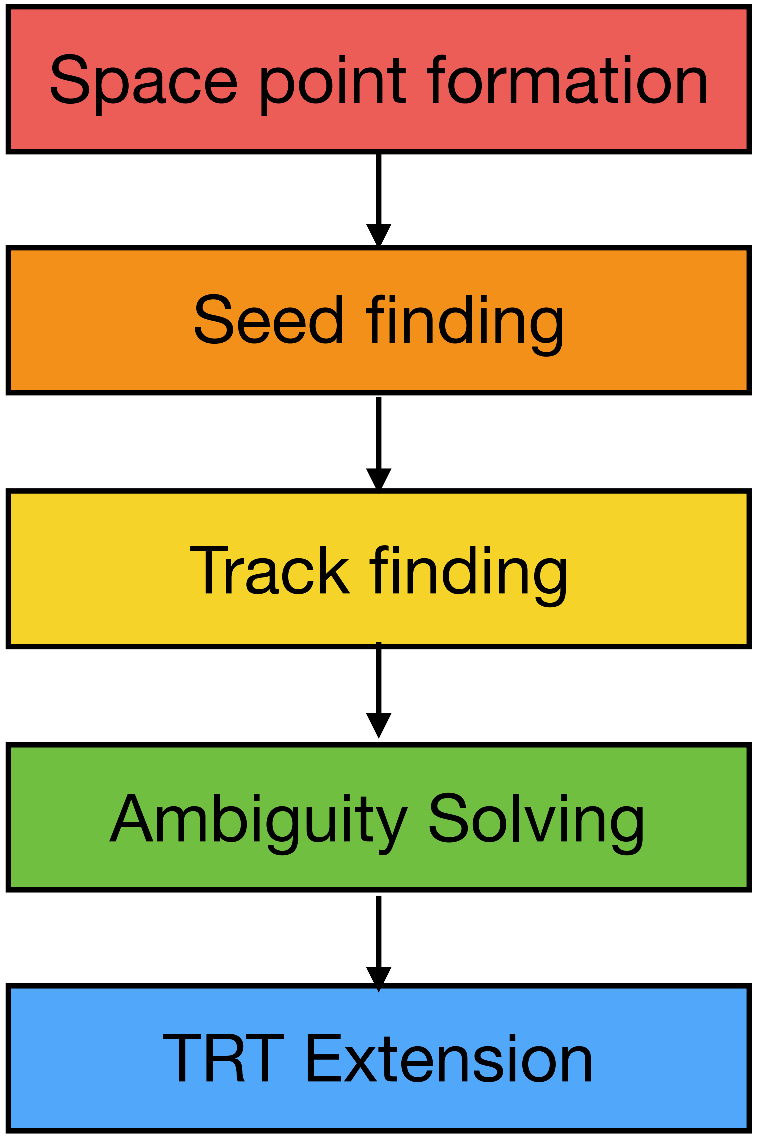


Jet flavour tagging

Tracking Algorithms

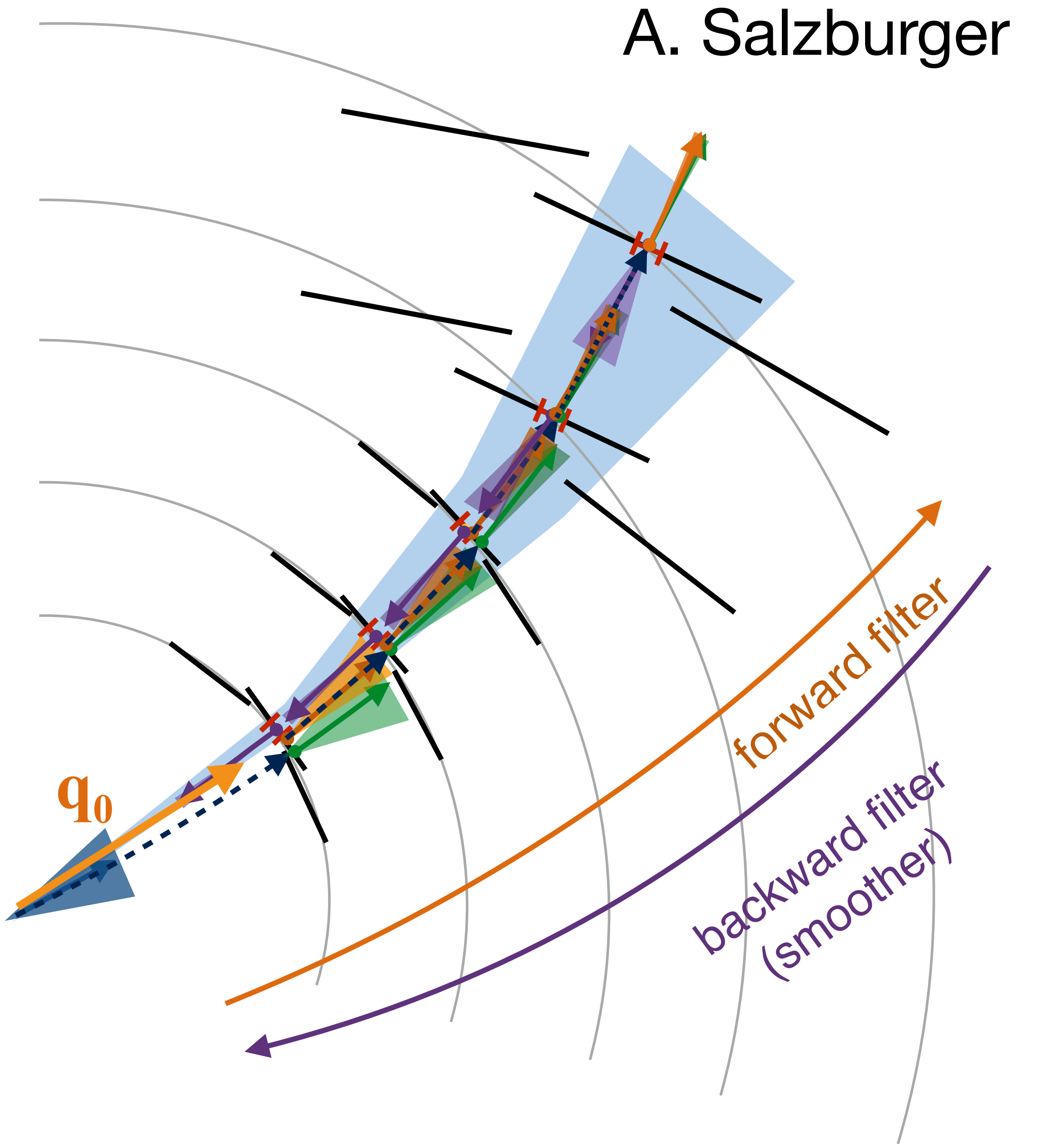
Track Reconstruction: ATLAS as an example





The Kalman Filter

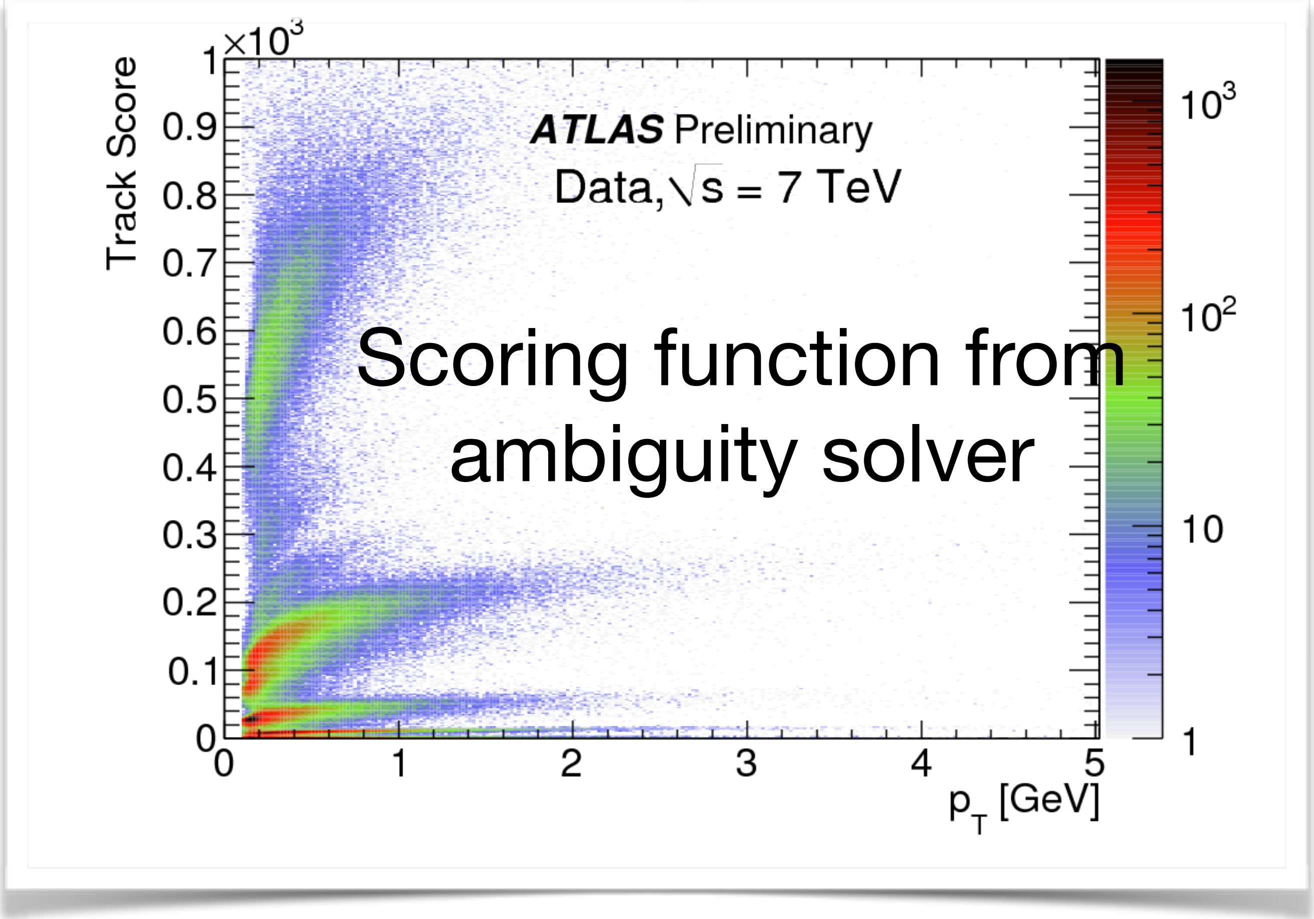
- Initially developed by R. Kalman to track missiles
- Pioneered by Billoir and R. Fruehwirth for HEP
- Progressive least square estimation
  - equivalent to a χ^2 fit (if run with a smoother)
  - start with transport of track parameters (and covariances) to measurement surface, create predicted parameters ("predicted state")
  - combine/update predicted parameters with measurement to updated parameters ("filtered state")



ATLAS Strategy: Ambiguity Solving

ATLAS-CONF-2010-072

- Strategy: Obtain high efficiency by applying loose requirements during reconstruction and find the best candidates by ambiguity solving
- Precise least-square fit to estimate track parameters
- Select best silicon-only tracks using a scoring function
  - hit content
  - holes
  - shared hits
  - fit quality



Iterative Track Reconstruction: CMS

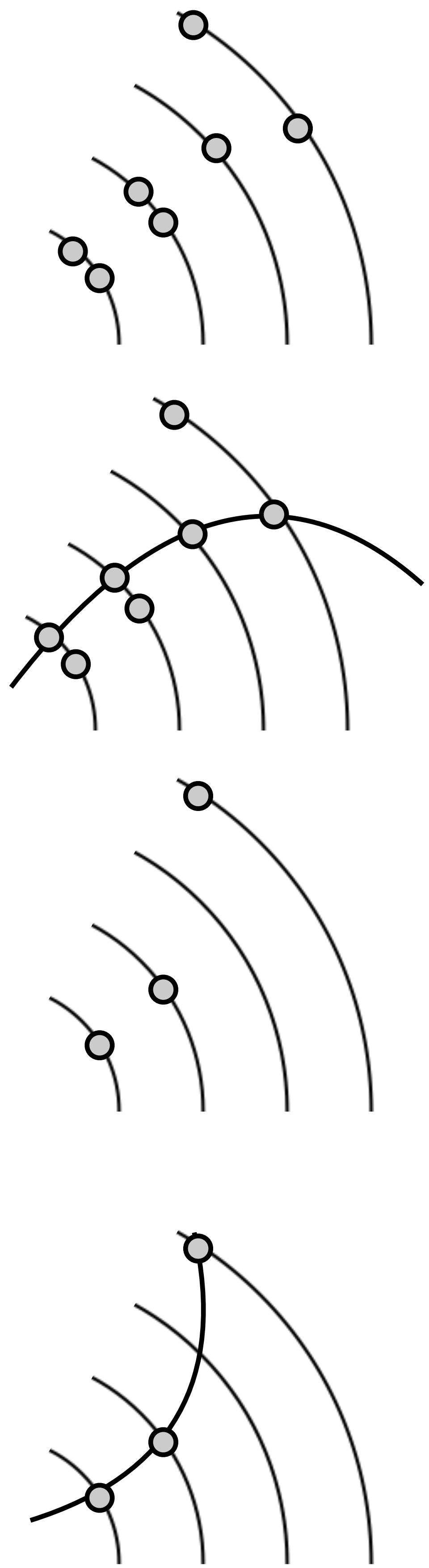
https://arxiv.org/pdf/1405.6569.pdf

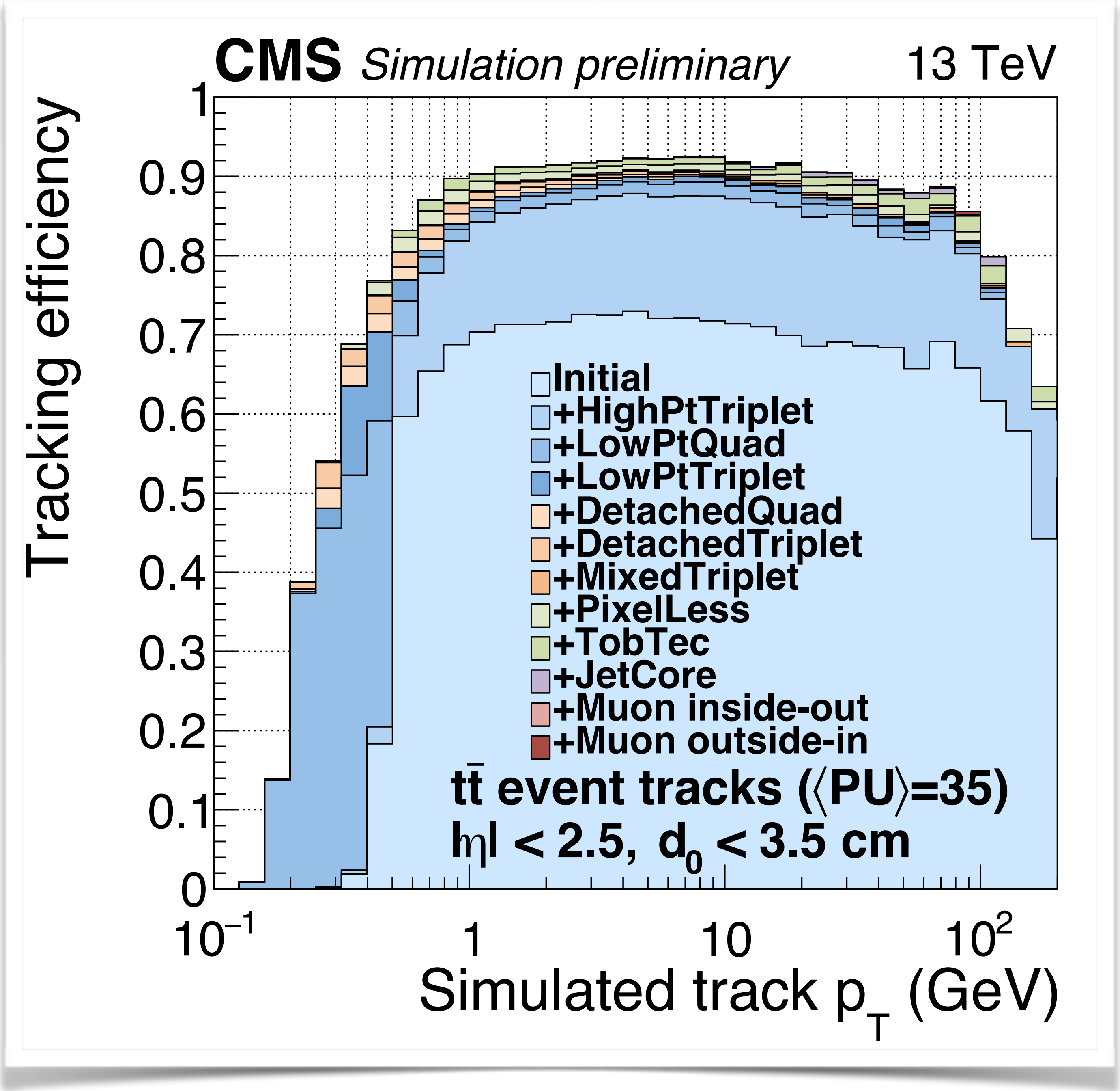
1

2

3

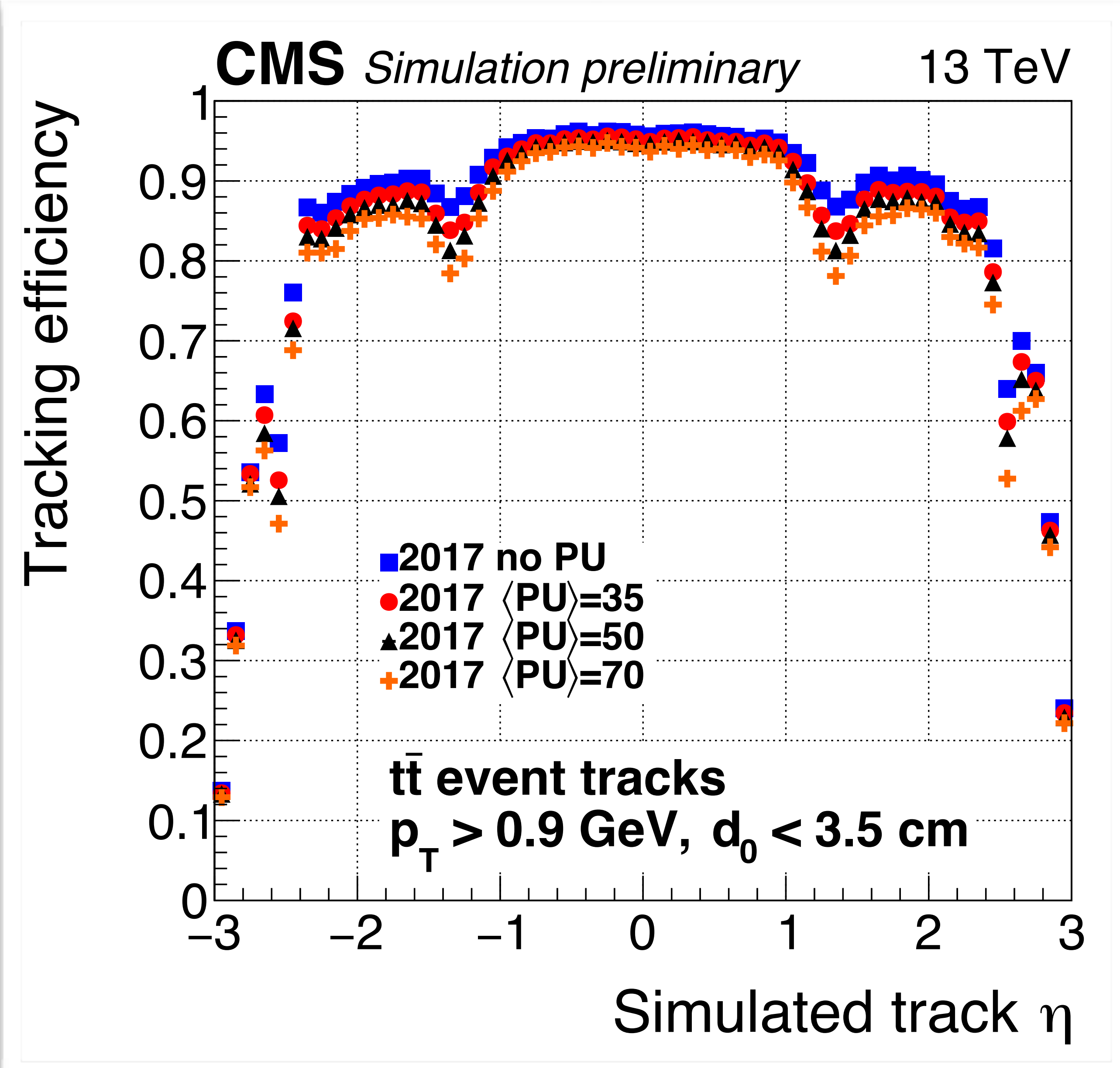
4

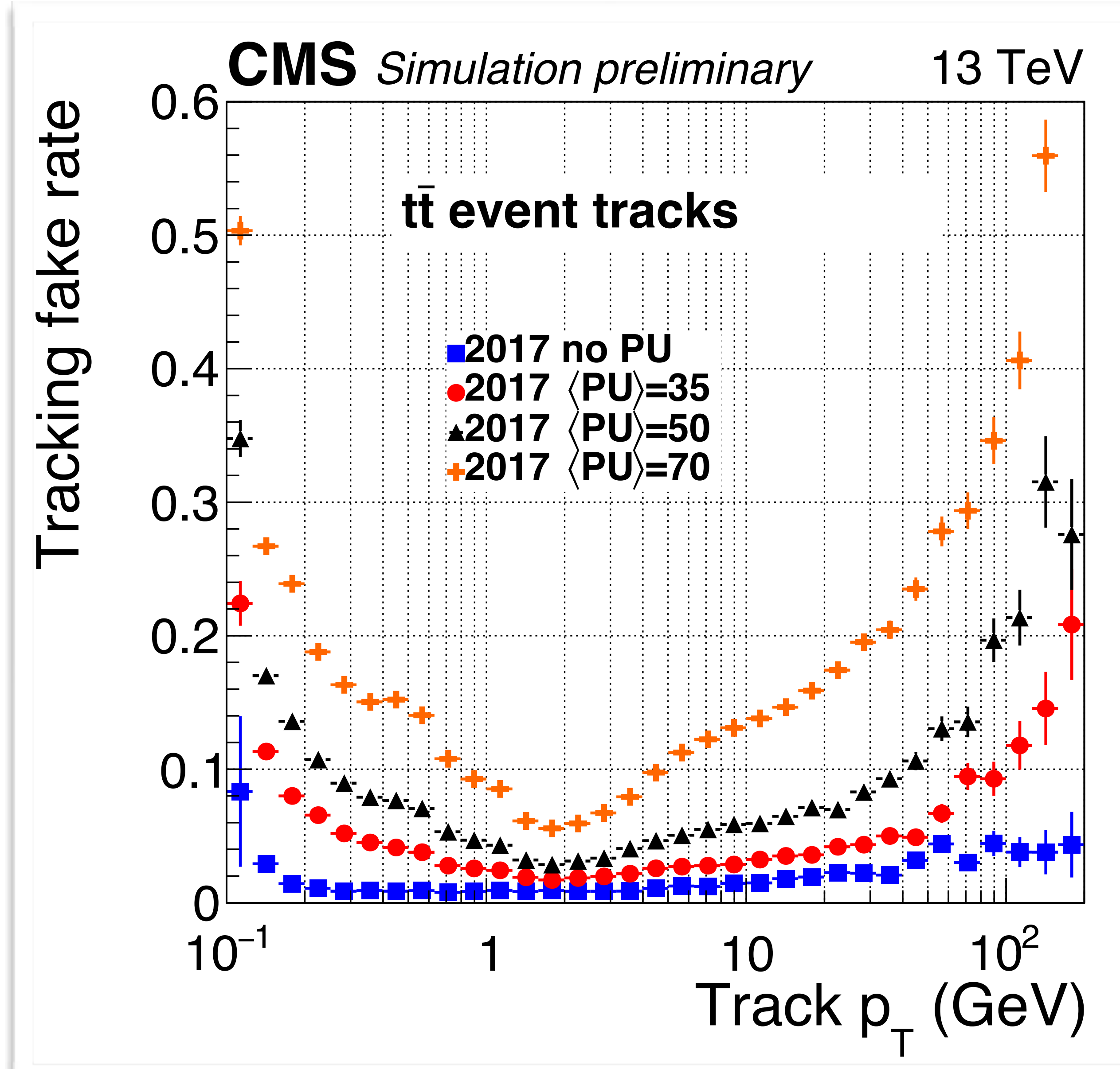




CMS example: Tracking in pile up

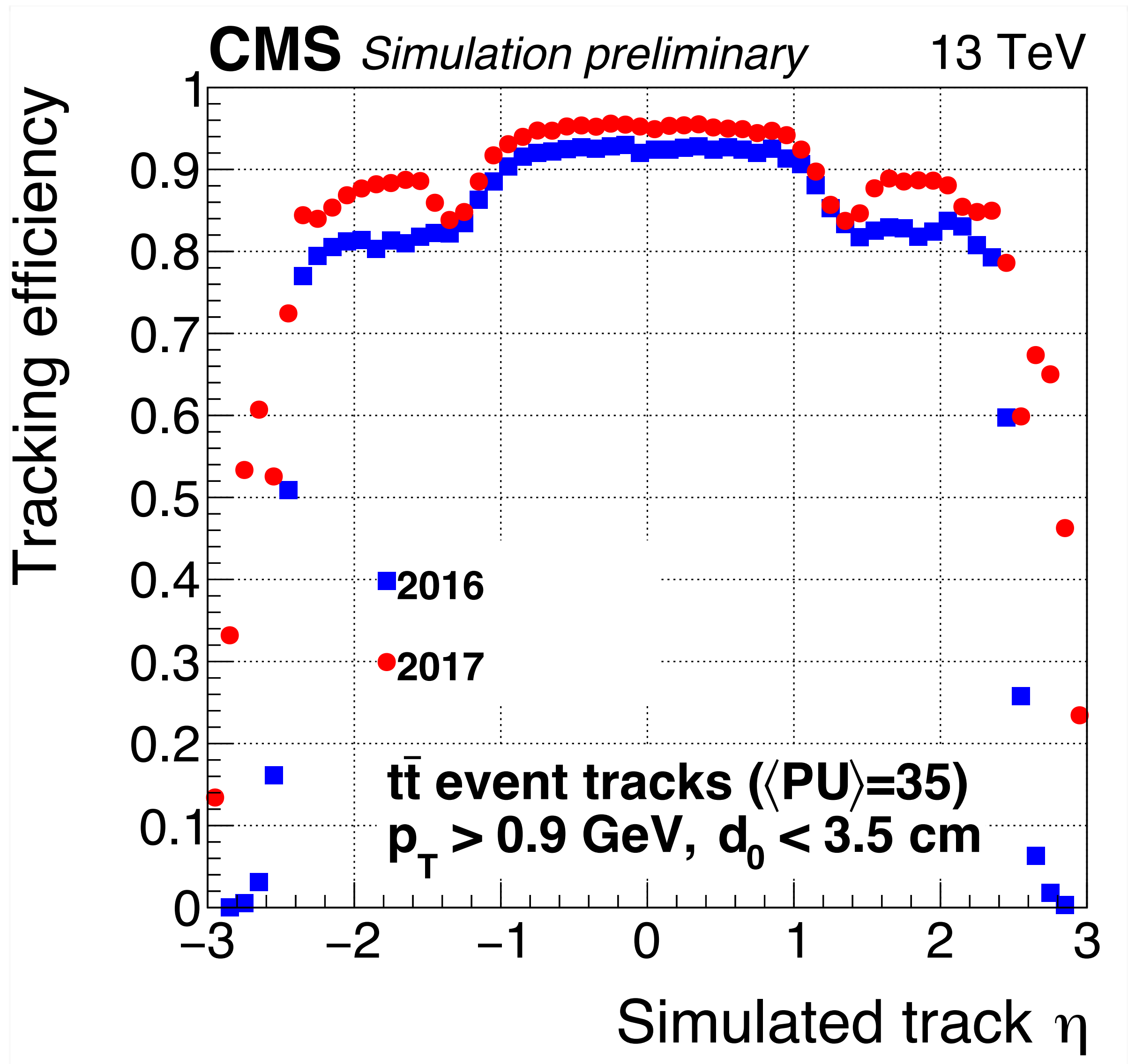
CMS twiki

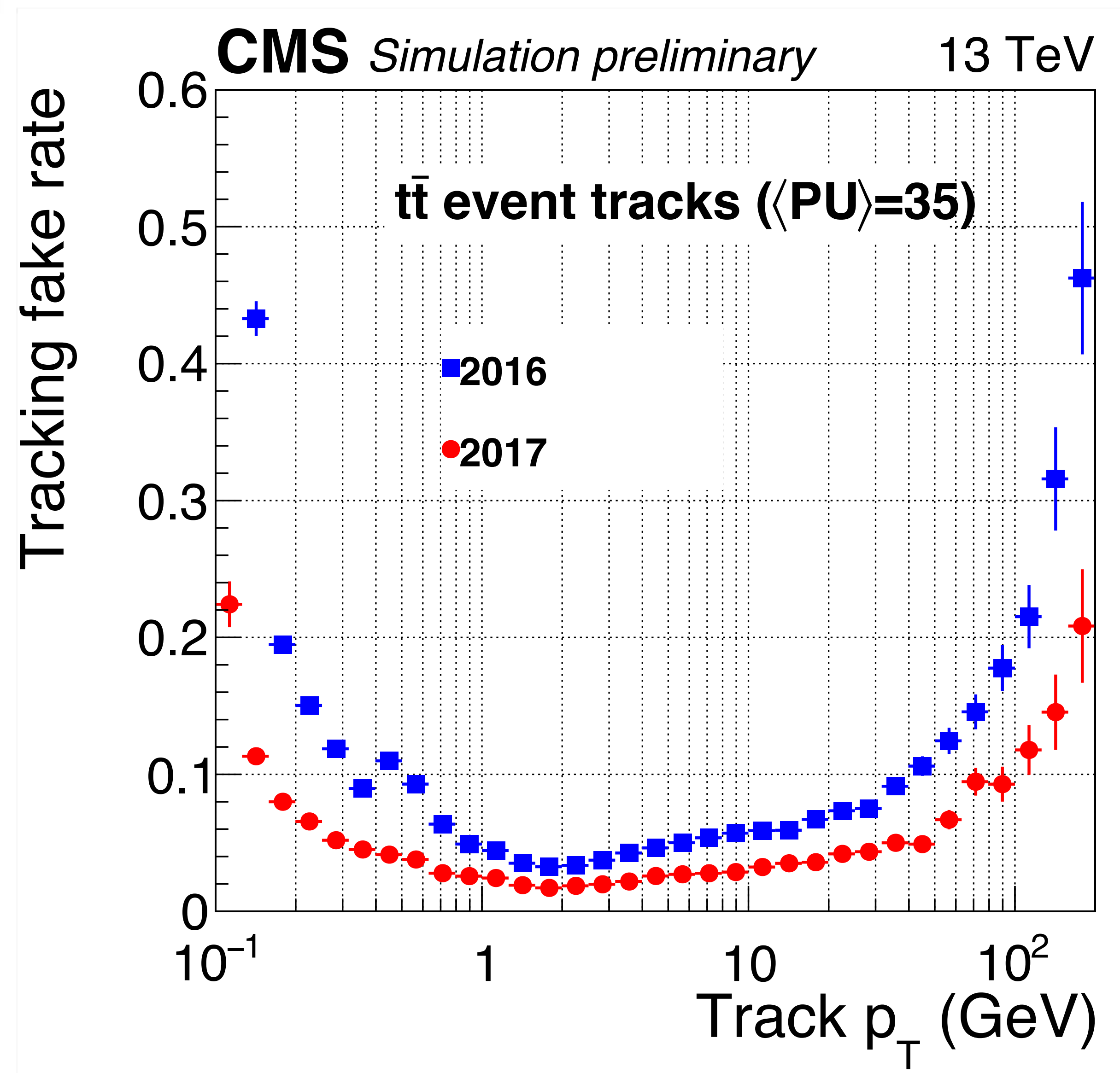




CMS: Algorithmic Improvements

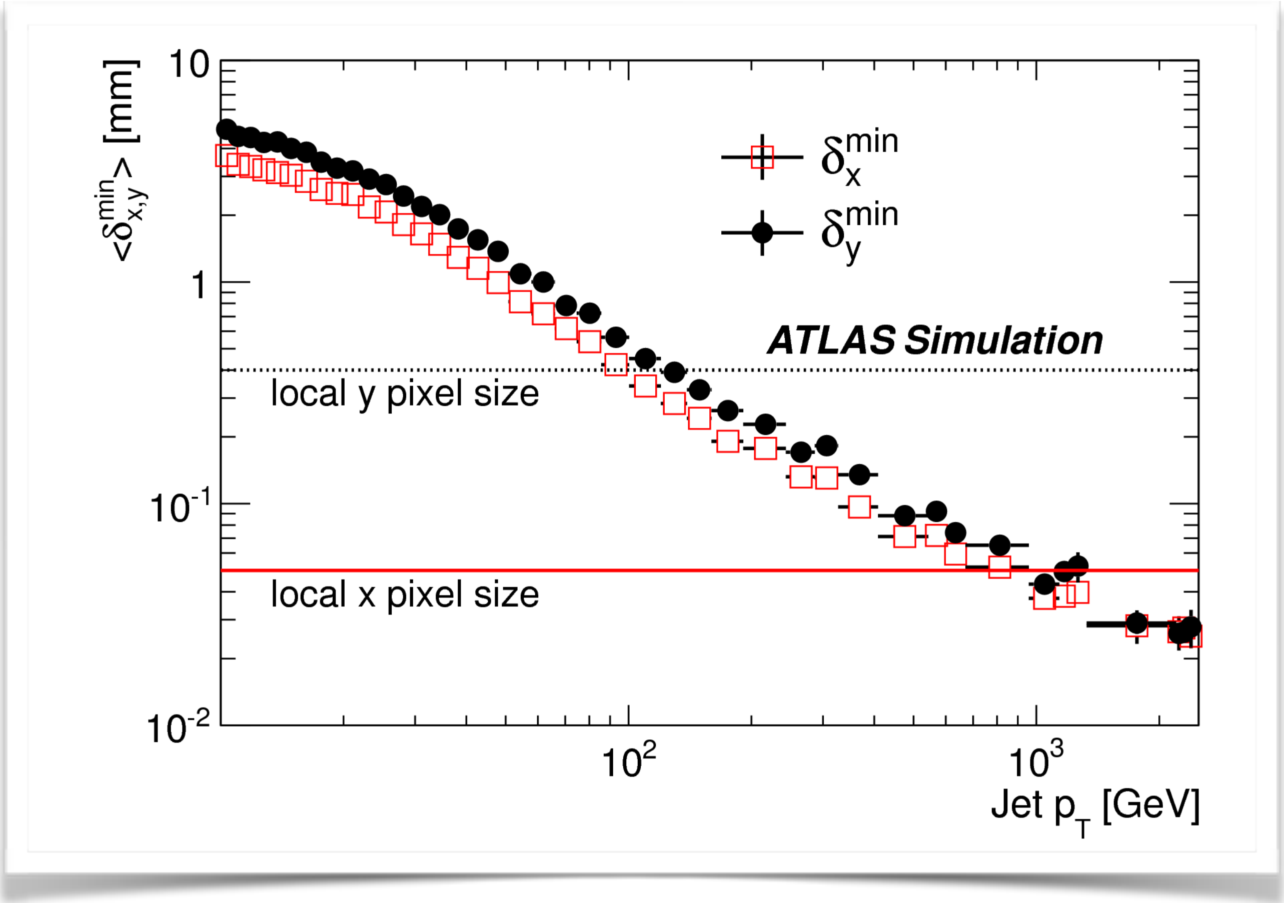
CMS twiki





Dense Environments

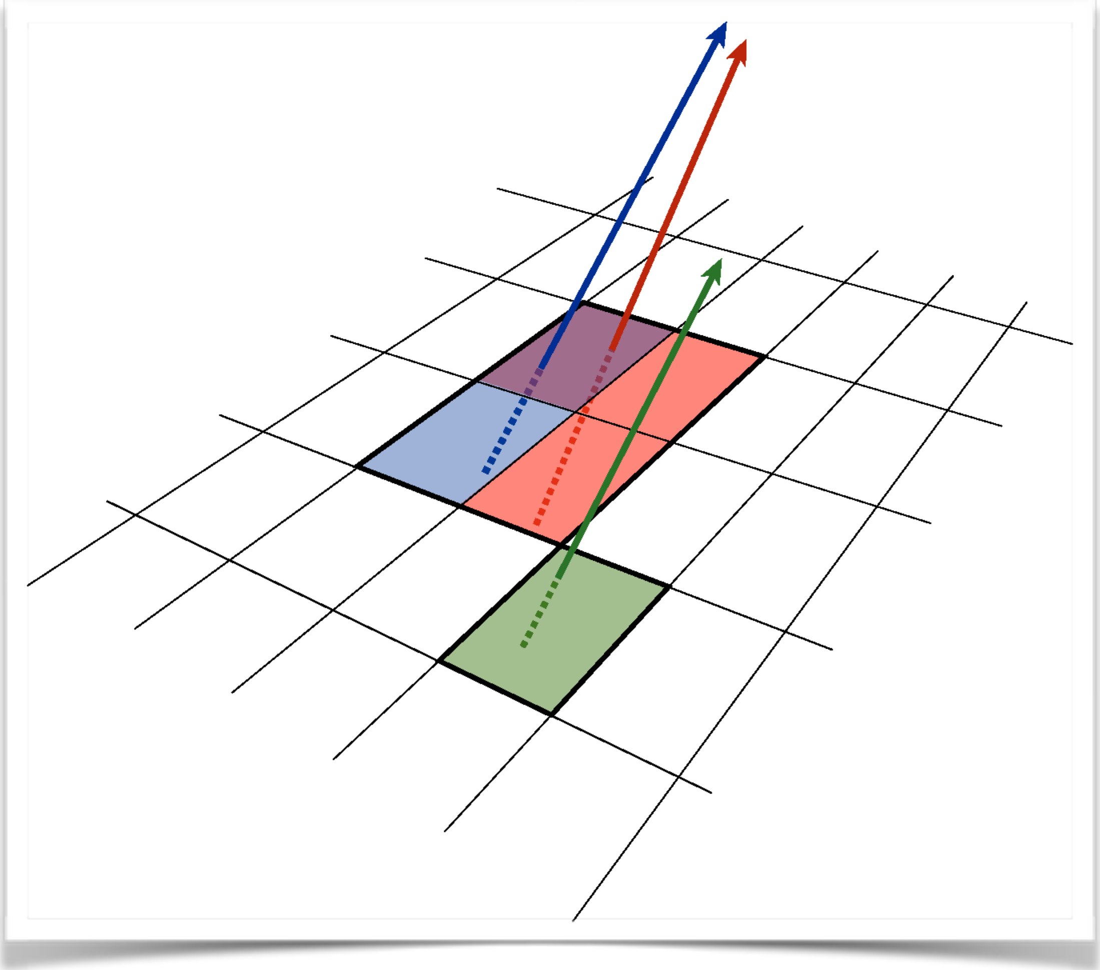
Dense Environments: Jets



The cores of jets at the LHC have higher density than from pile up

Challenge: reconstructing **overlapping tracks**

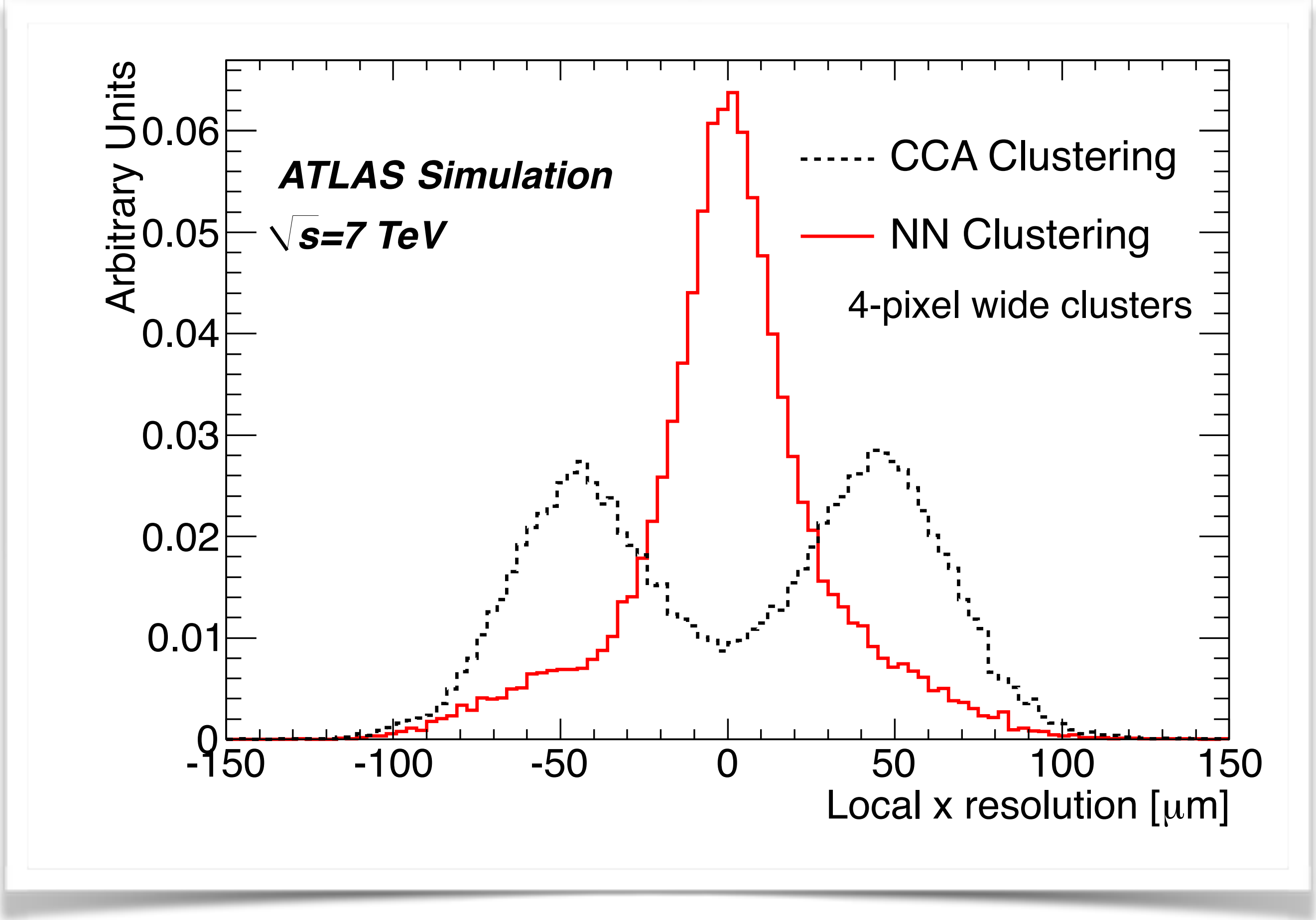
First problem is that clusters from separate tracks are no longer reconstructed as individual clusters

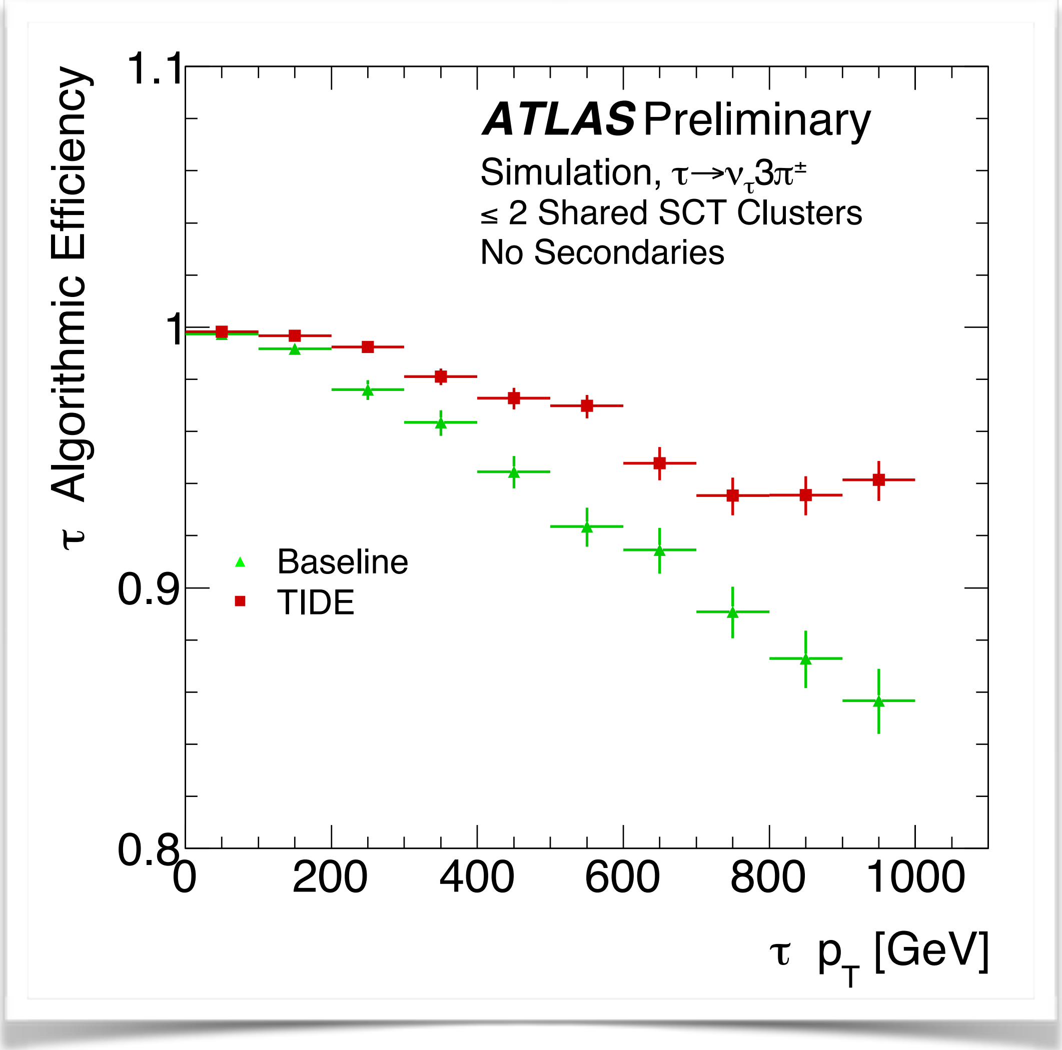


ATLAS pixel dimensions 50x400 (250) μm

Dense environments

- Efficiency improvements for overlapping particles in the cores of jets
  - 2012: multivariate technique exploiting information on cluster charge and shape
  - 2015: correlate information between layers
- Similar ideas and techniques used by CMS

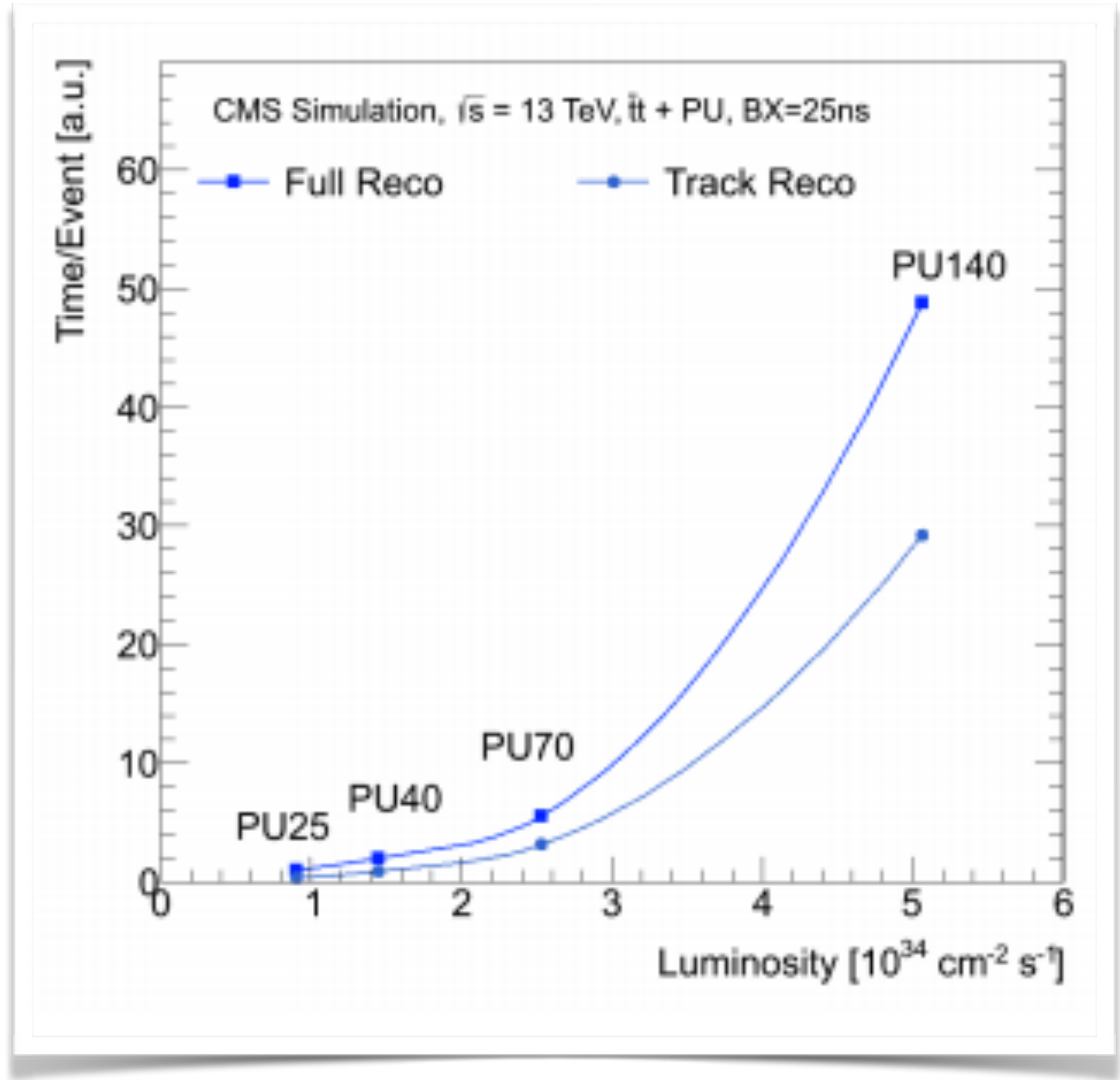




Tracking, Pile up and Computation

Pile up and the Future

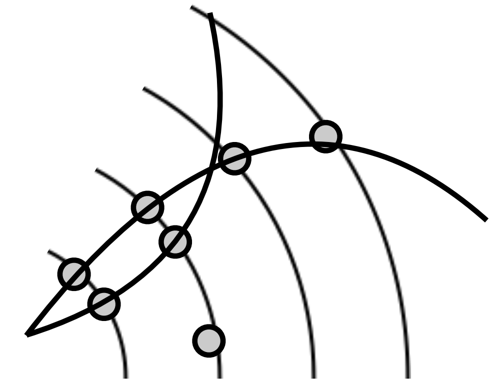
- No formal proof, but algorithms observed to scale $\propto \sim N^2$
  - Increased pile up
- Computing architectures are changing rapidly
  - Parallelism
  - Balance between CPU and memory
  - IO rate vs CPU rate
- Algorithms need to be rethought

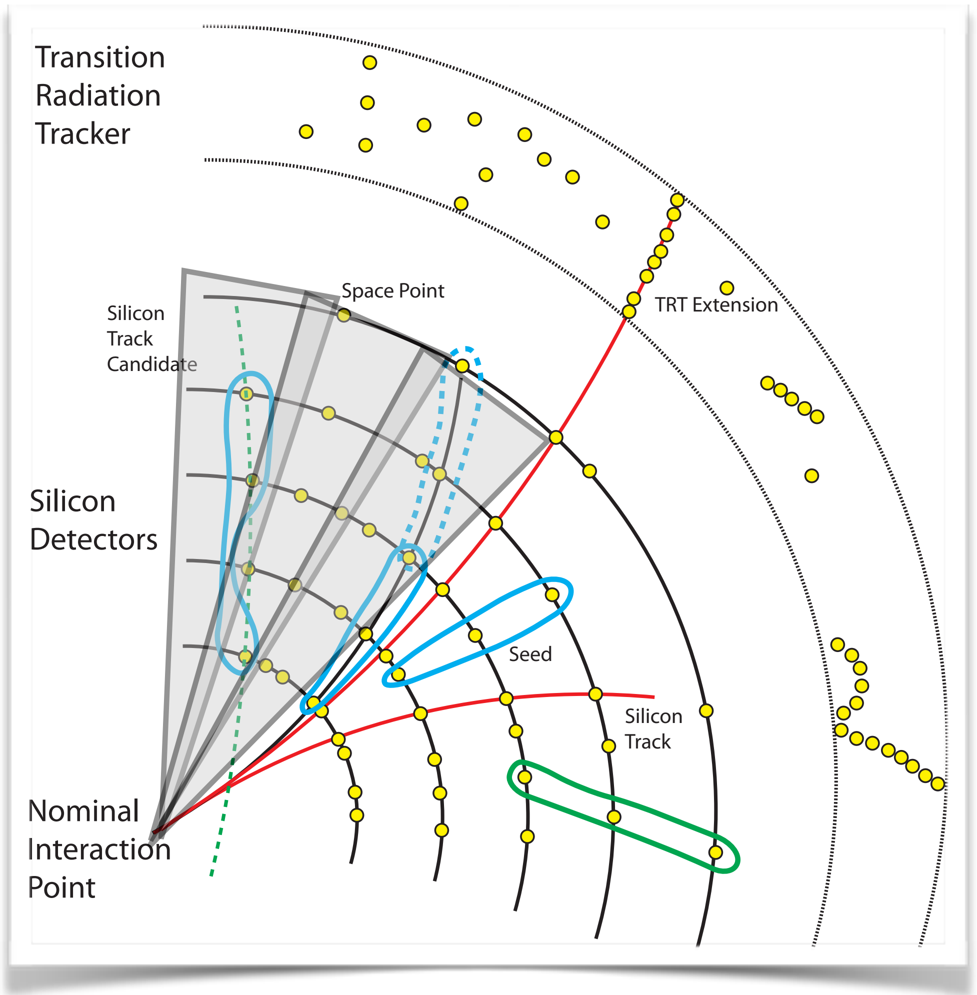


Need: new ideas and techniques

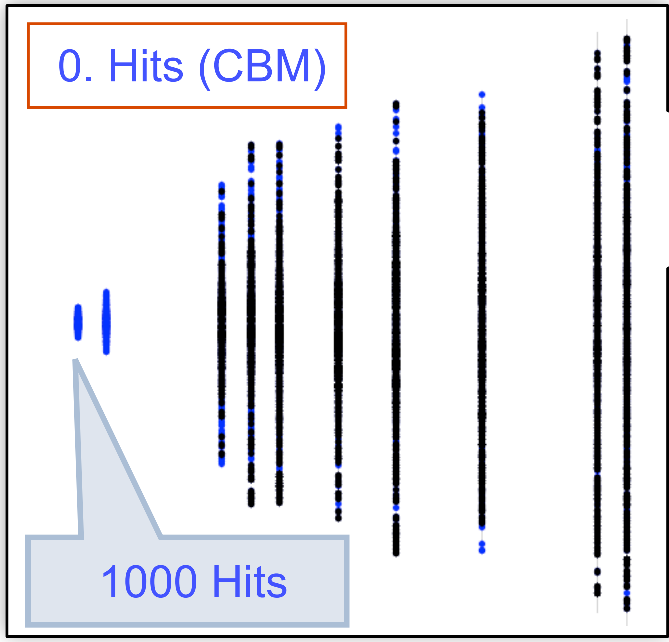
Parallelism

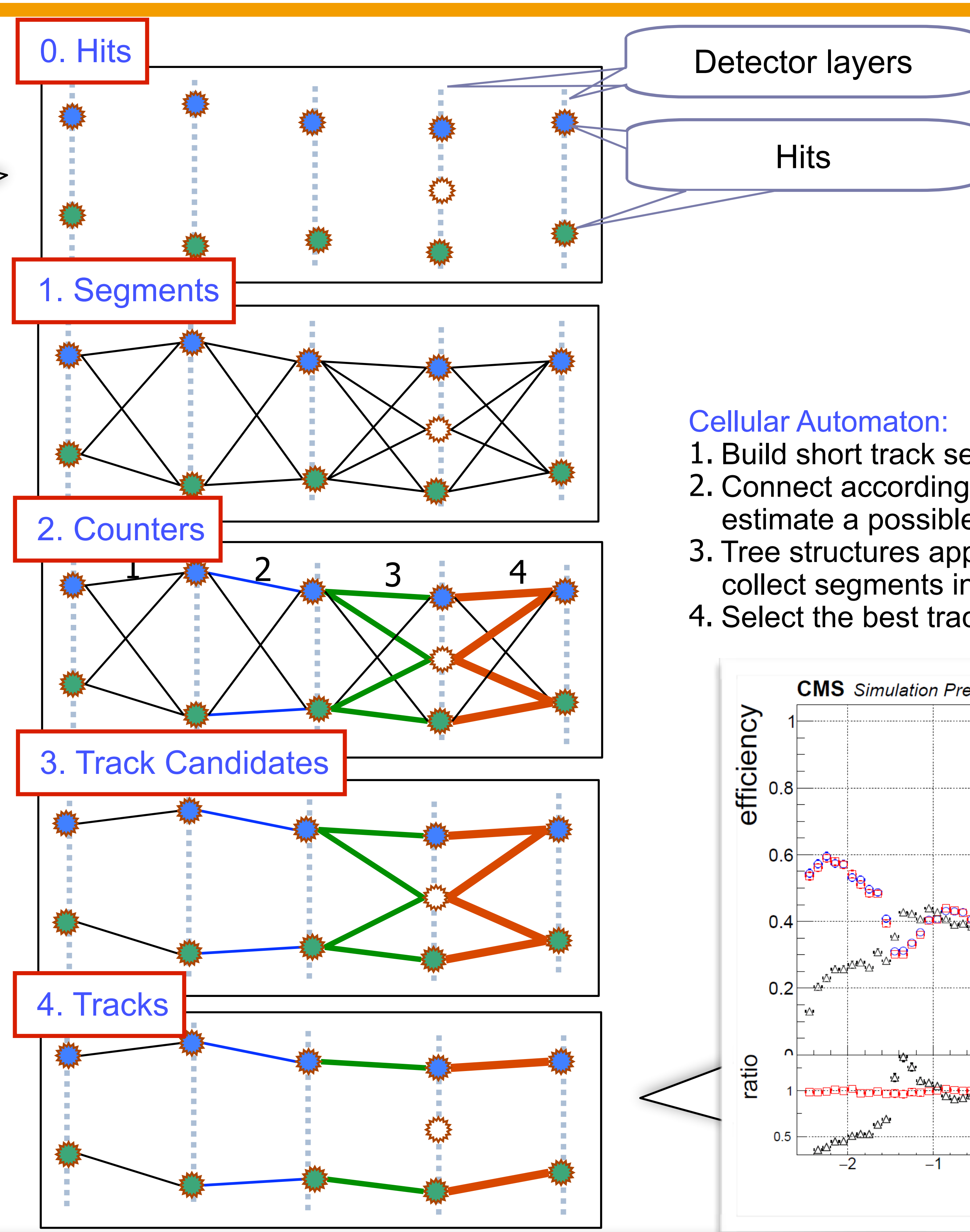
- Current algorithms cannot be ported directly to run in parallel architectures
- Optimal performance by considering the event as a whole, not individual tracks
- Challenges include
    - defining appropriate regions of interests (ROIs) without performance loss
    - thread balancing: defining an equal workload because the track density in the detector is highly non-uniform



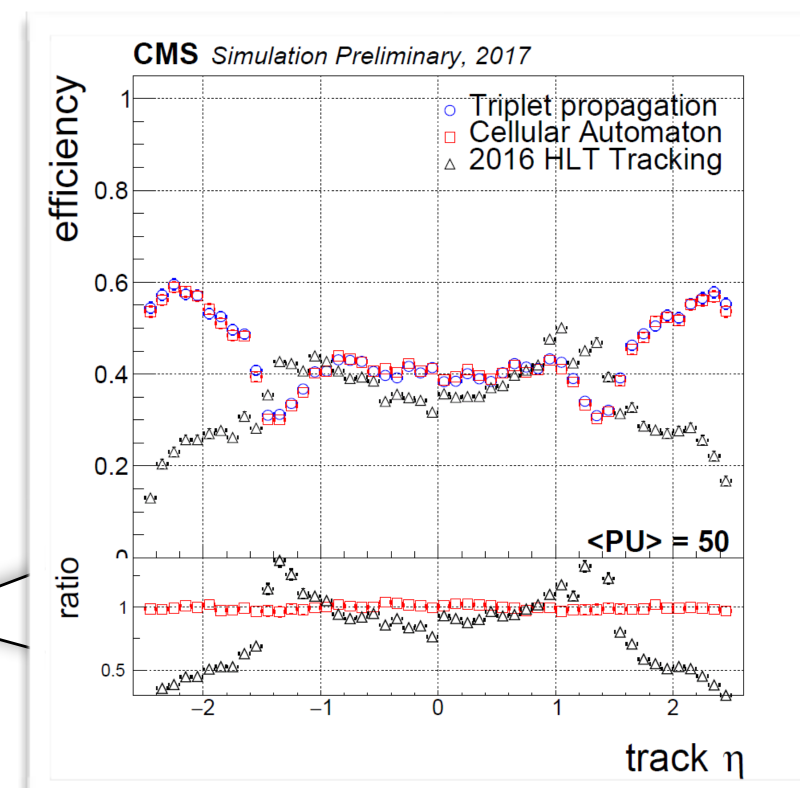


Cellular Automaton (CA) Track Finder





Cellular Automaton:
1. Build short track segments.
2. Connect according to the track model, estimate a possible position on a track.
3. Tree structures appear, collect segments into track candidates.
4. Select the best track candidates.



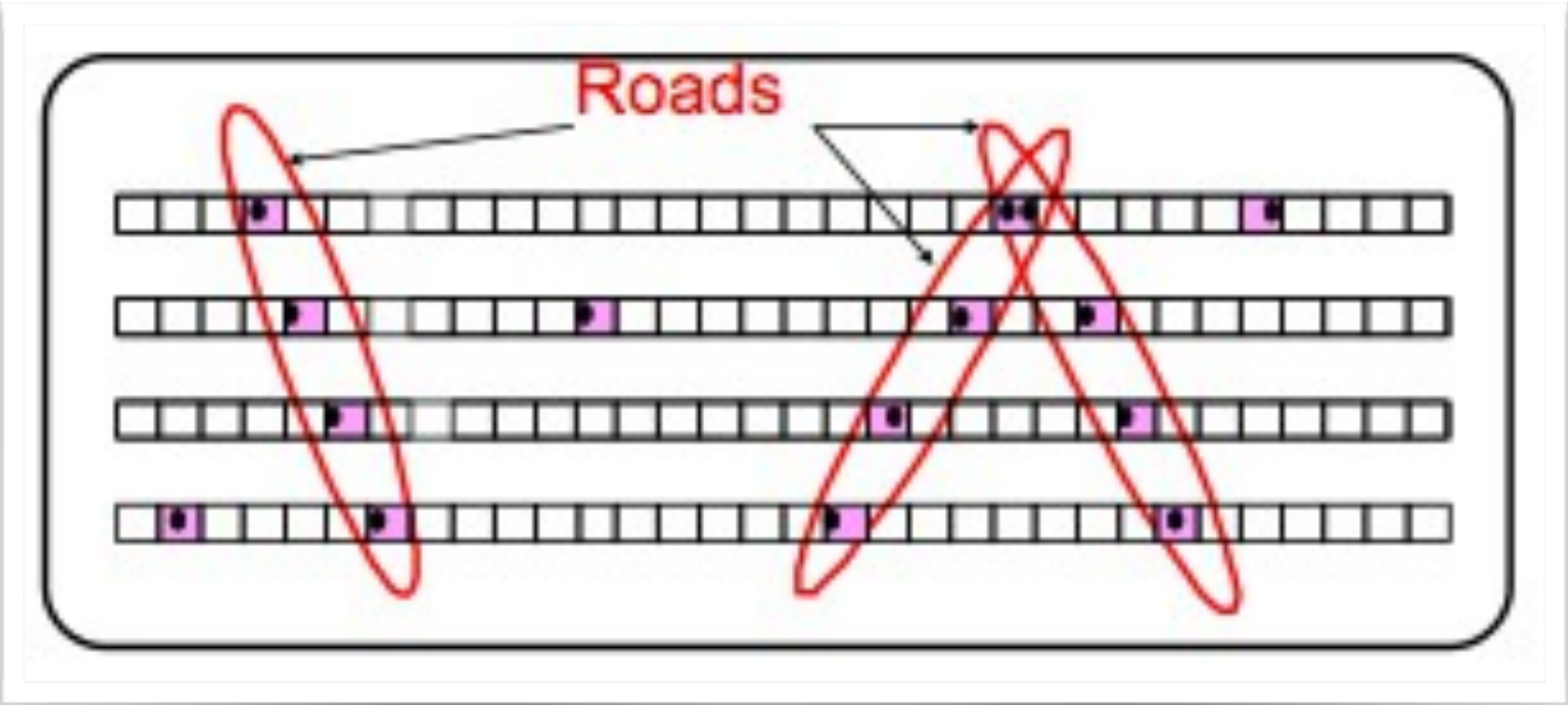
Cellular Automaton:
- local w.r.t. data
- intrinsically parallel
- extremely simple
- very fast

Perfect for many-core CPU/GPU !

Useful for complicated event topologies with large combinatorics and for parallel hardware

Associative Memory

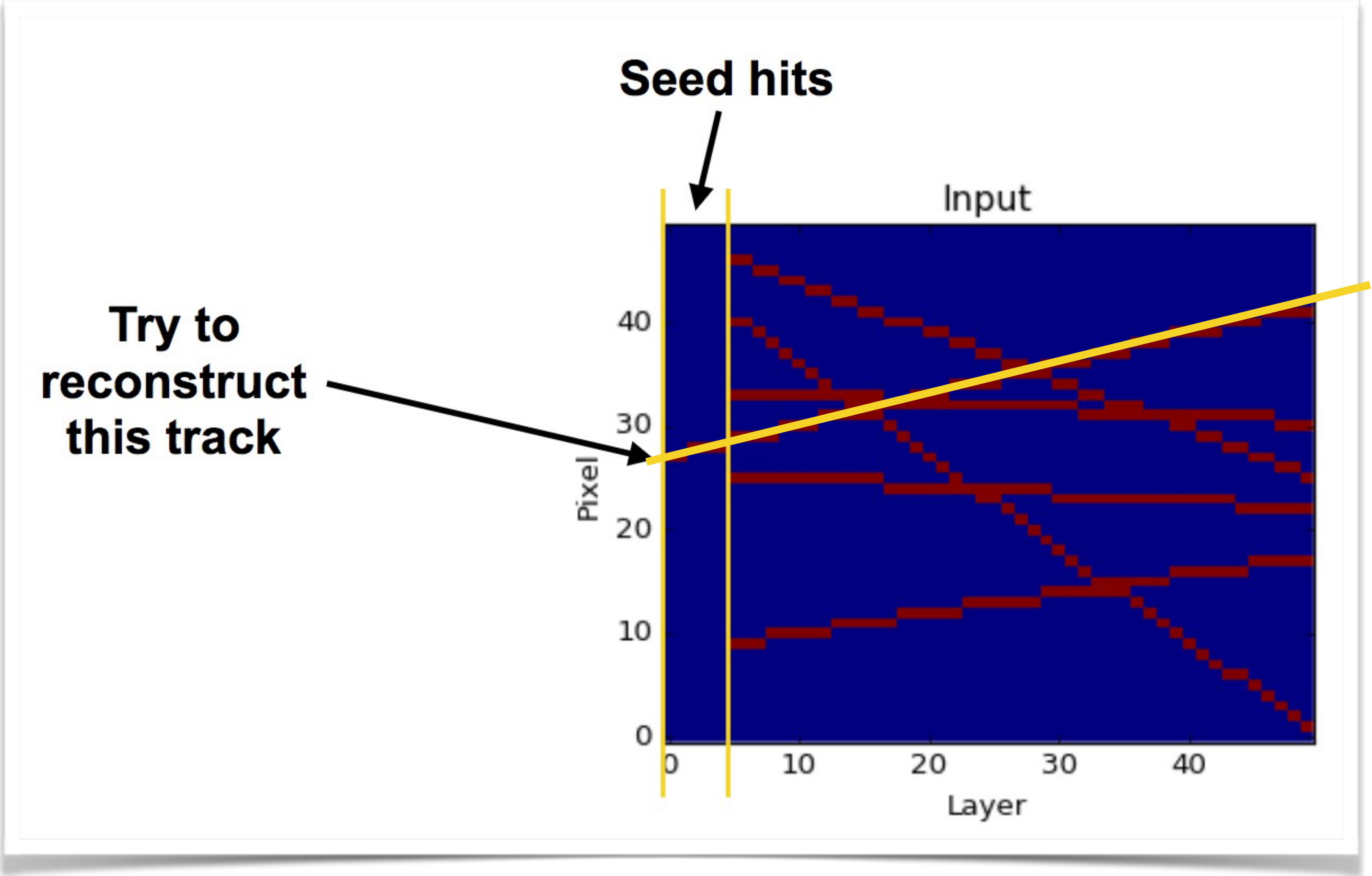
- Store possible tracks patterns directly in hardware
  - Direct mapping from hit patterns to tracks
  - Avoids scaling with combinatorics
  - Can be sensitive to changes in detector conditions
- Prototype in CDF
- Currently being installed within ATLAS as the Fast Track Trigger (FTK)
- Currently unclear if similar techniques could be used within offline algorithms



Pattern Prediction from Deep Learning

S. Farrell et al

Many techniques from machine learning are being explored in the context of track reconstruction



Predict track pattern based on seed, e.g. using LSTM , convolutional NN
Also including noise

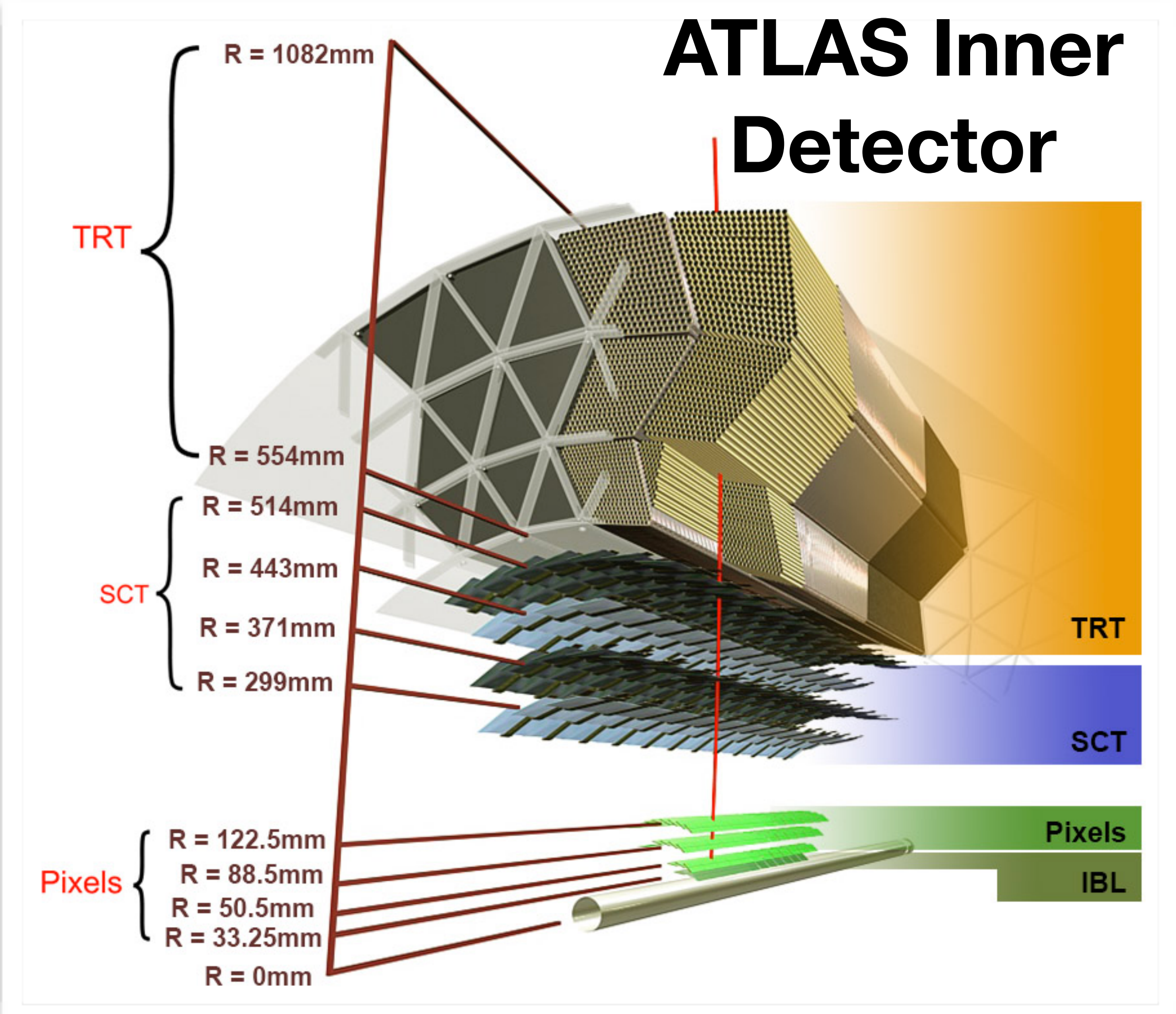
Conclusion

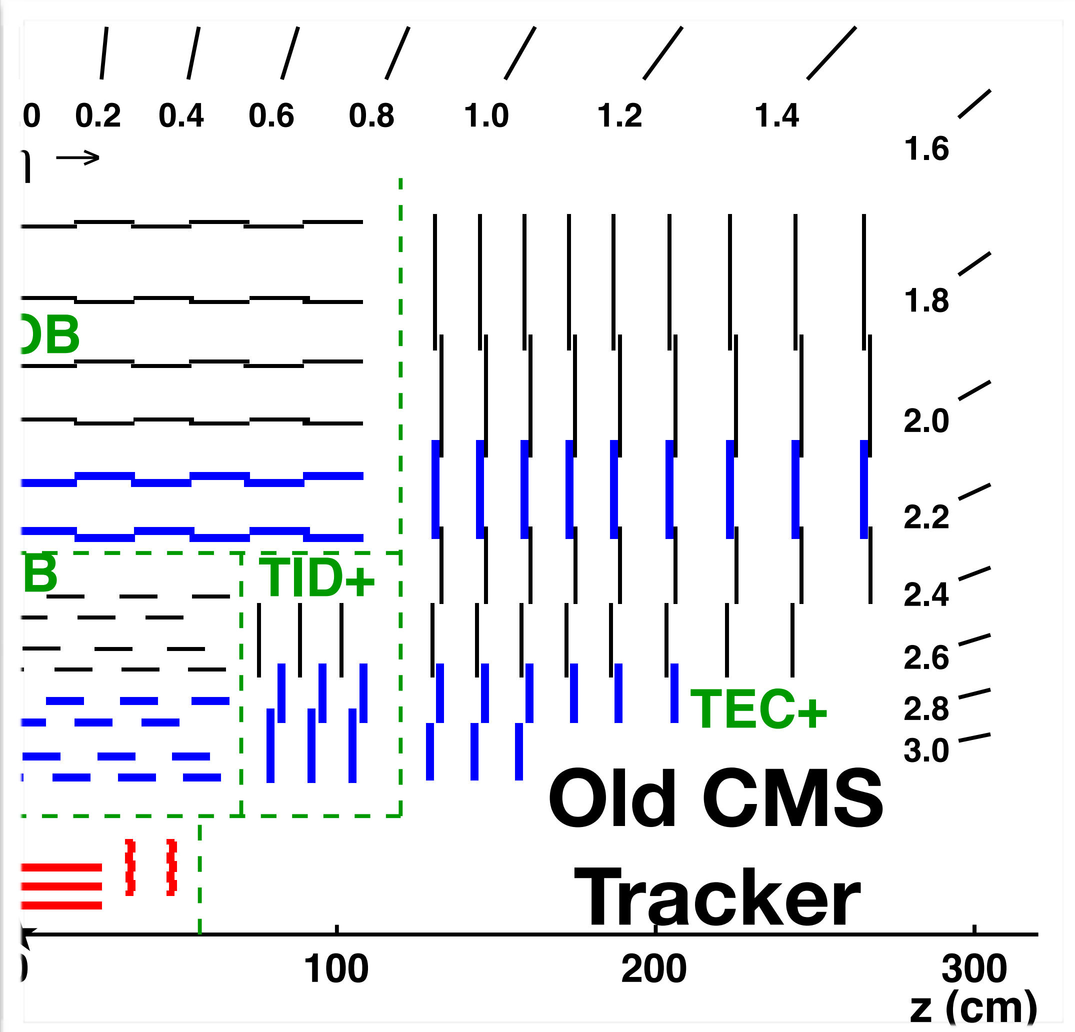
- Precise and efficient track reconstruction algorithms have been developed and used in the high pile up LHC environment
  - Play a central role in event reconstruction
  - Demand significant computing resources
- Upcoming challenges include
  - 50x more data
  - Order of magnitude increase in the number of tracks
  - Smaller increase in CPU power
- Many new ideas are being actively explored
  - Algorithms to exploit parallelisation
  - Techniques from machine learning
  - Other ideas are welcome!

Back up

Detectors for Charged Particles

ATL-PHYS-PUB-2015-009
CMS Pixel TDR





	R inner	R outer	|η| range	B field	X_0 at |η|=0	p_T resolution at 1 (100) GeV, |η|=0	d_0 resolution at 1 (100) GeV, |η|=0 [μm]
ATLAS	3.3 cm	1.1 m	2.5	2 T	0.3	1.3 (3.8)%	70 (5)
CMS	3 cm	1.1 m	2.5	4T	0.4	0.7 (1.5)%	90 (20)

Challenges in Tracking: Alignment

Precise positions of detector elements are not known a priori, determine via alignment procedure

- Minimise a X^2 matrix

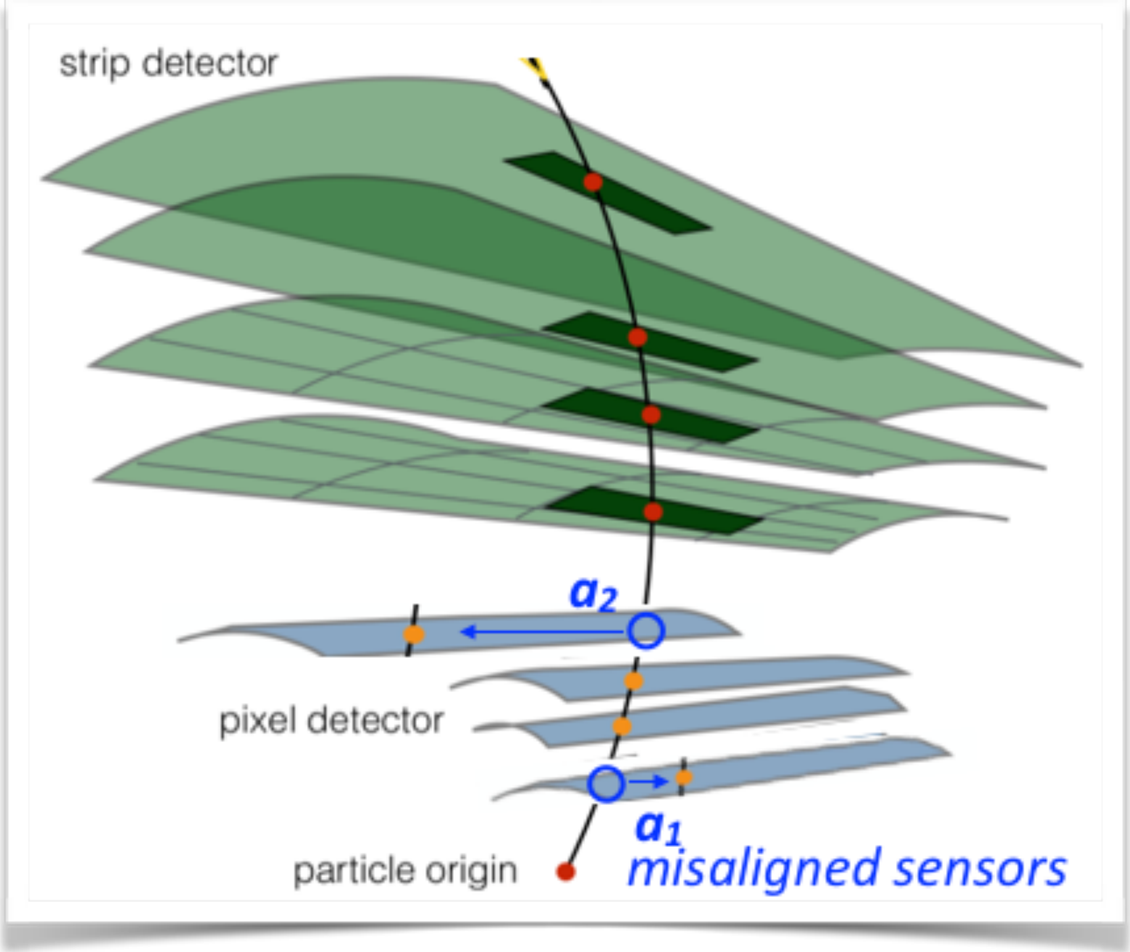
$$\chi^2 = \sum_{tracks} \mathbf{r}^T(t,a)\mathbf{V}^{-1}\mathbf{r}(t,a)$$

  - track parameters

$$t = (d_0, z_0, \eta, \phi, q/p)$$

  - alignment parameters

$$a = (T_x, T_y, T_z, R_x, R_y, R_z)$$

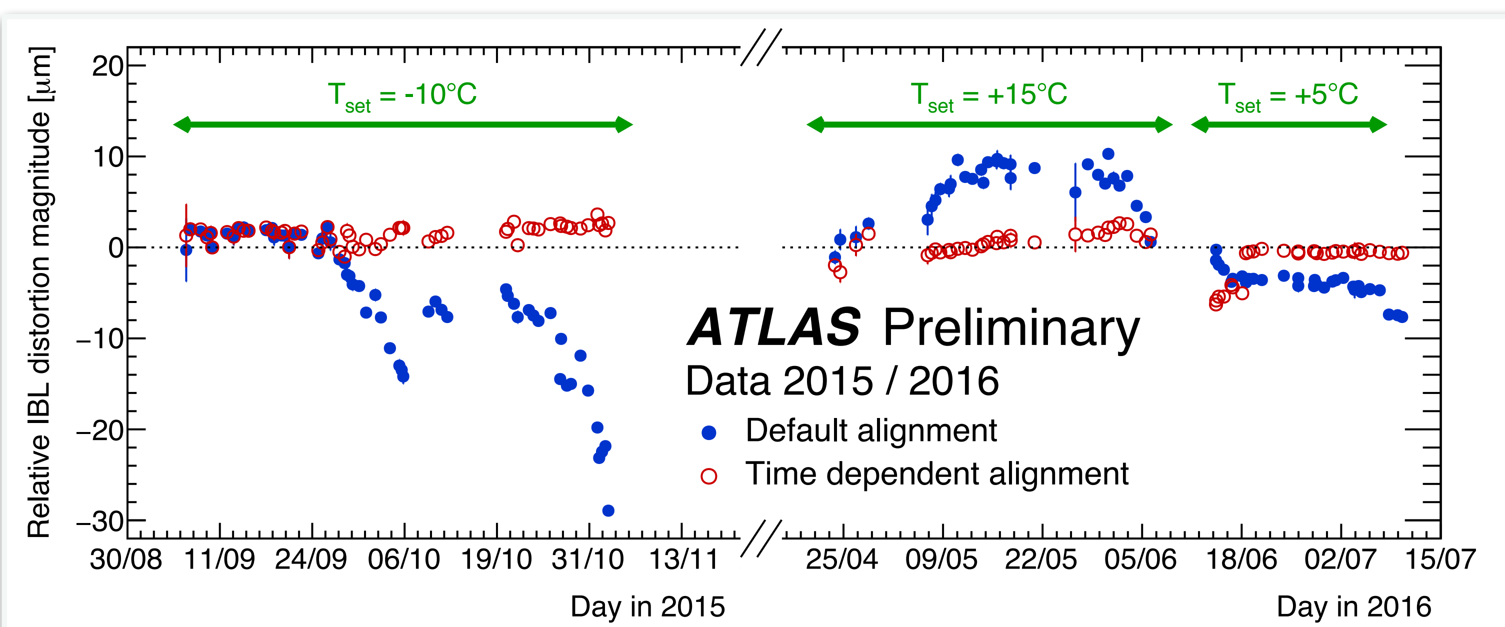


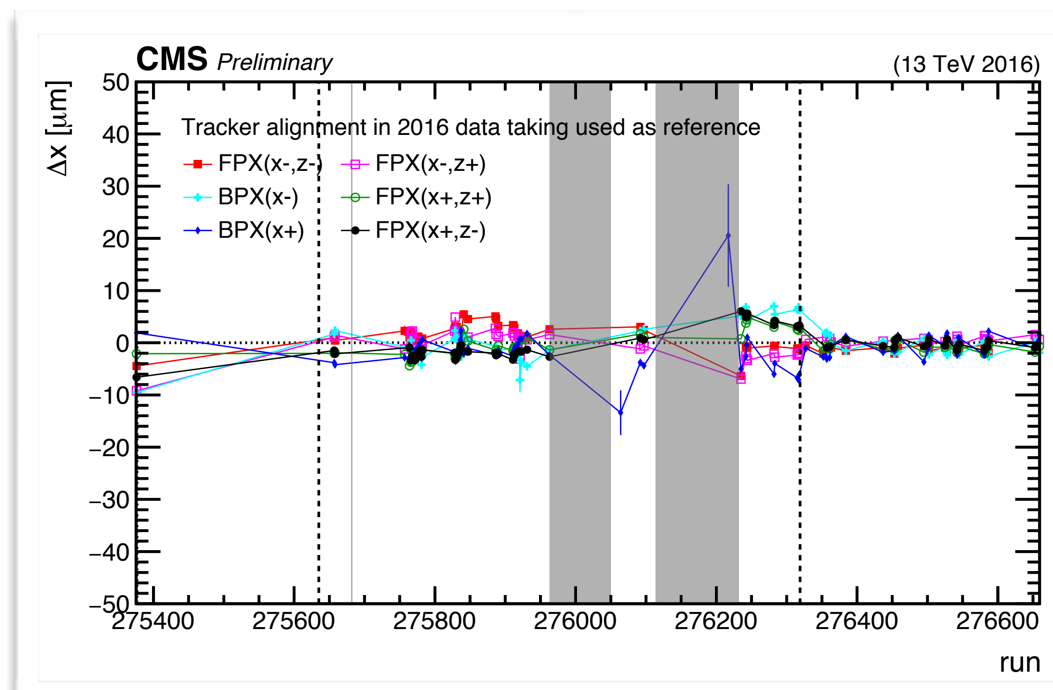
- Weak modes are geometrical distortions that leave the X^2 invariant
- Additional information via constraints to remove weak modes
  - on track parameters (e.g. beam spot, resonance inv. mass ($Z \rightarrow \mu\mu$))
  - and/or alignment parameters (e.g. assembly survey)

Challenges: Dynamic Alignment

[CMS 2016 align](#)
[IDTR-2016-005](#)

- Detector components have been observed to move e.g. due to power consumption or magnetic field changes
- ATLAS made a major upgrade to its alignment procedure to allow the alignment to be updated every ~100 minutes
- Obtained performance comparable or better than during Run-1 despite detector movements
- CMS employs an automatic procedure to monitor movements of high-level structures
  - When appropriate detector geometry is updated based on these online results





Back up

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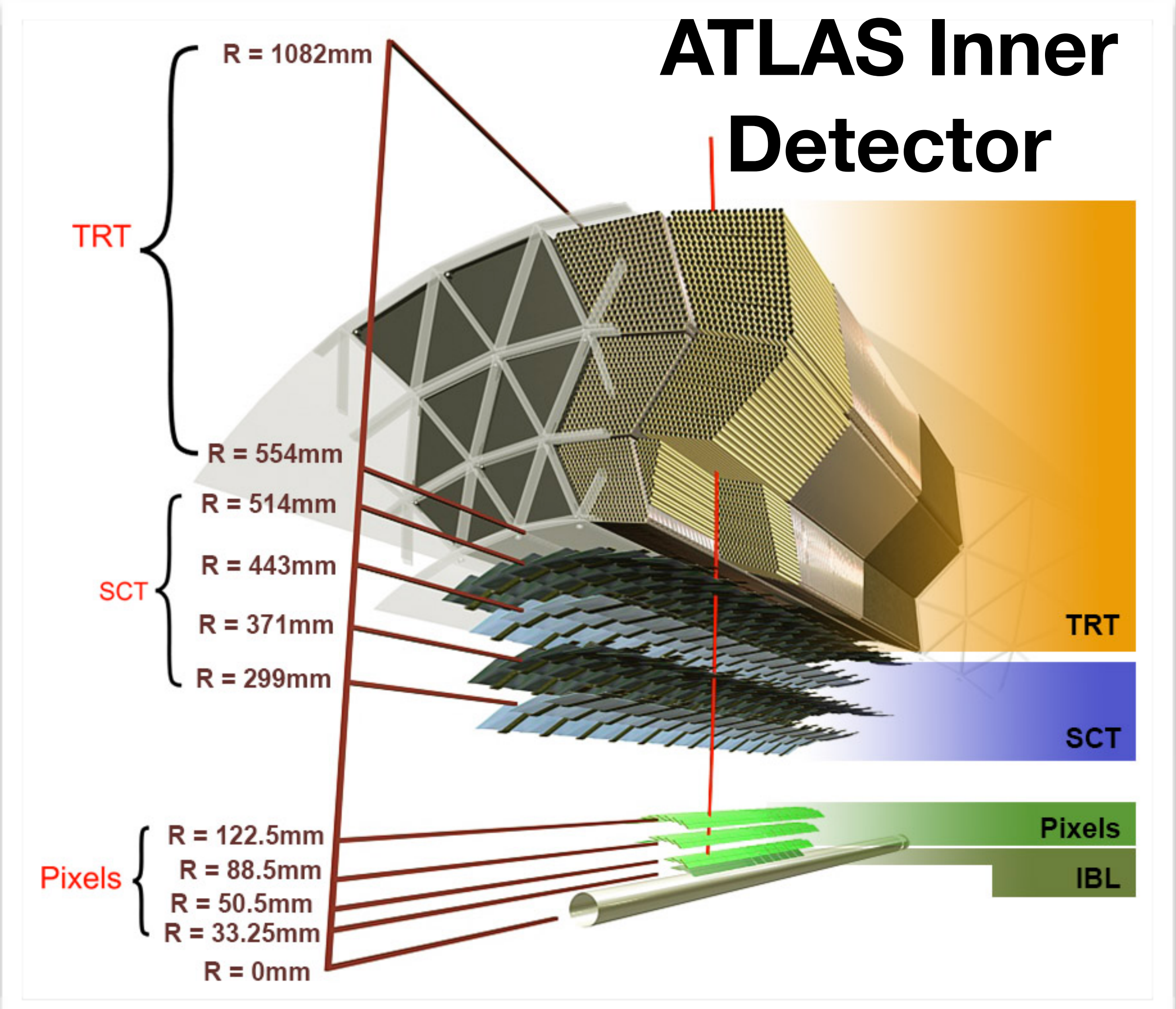

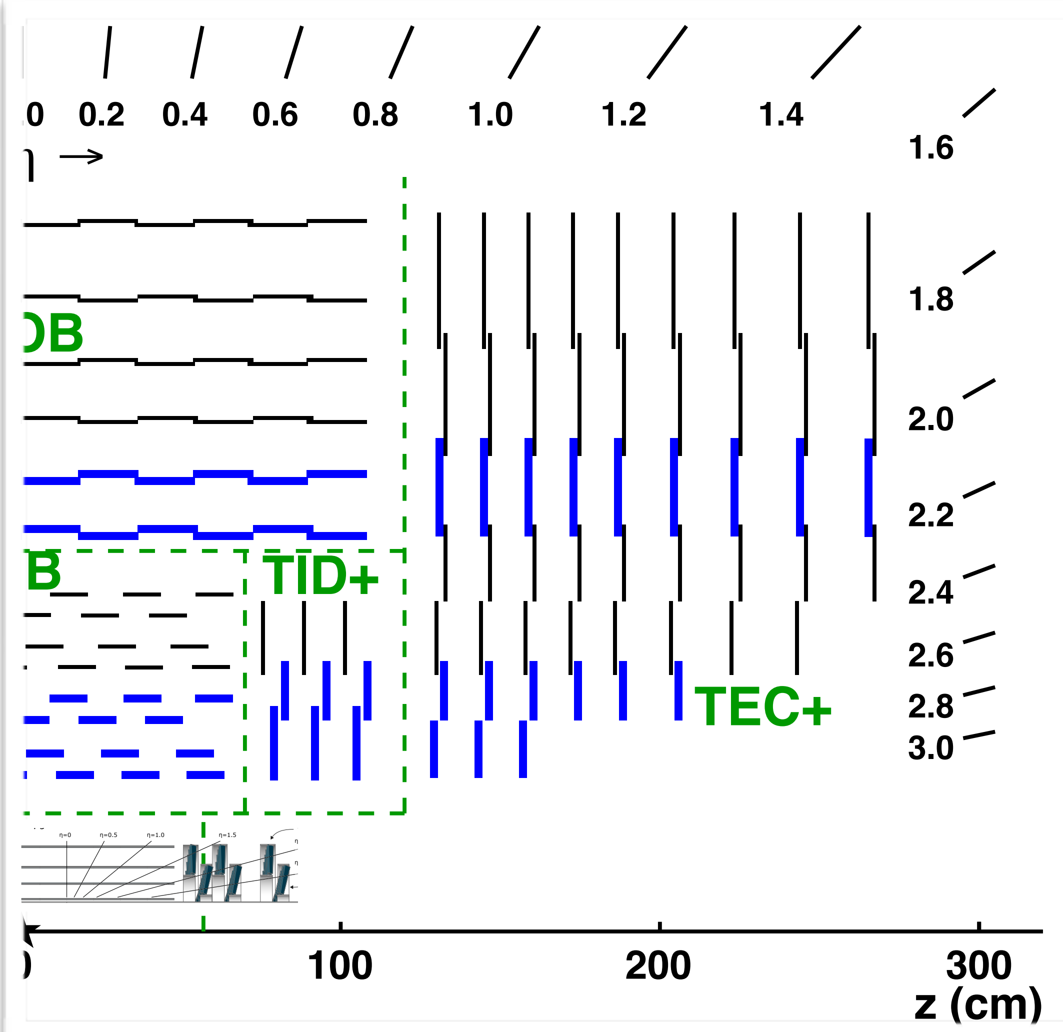

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