Calorimetry and Tracking - Day 2

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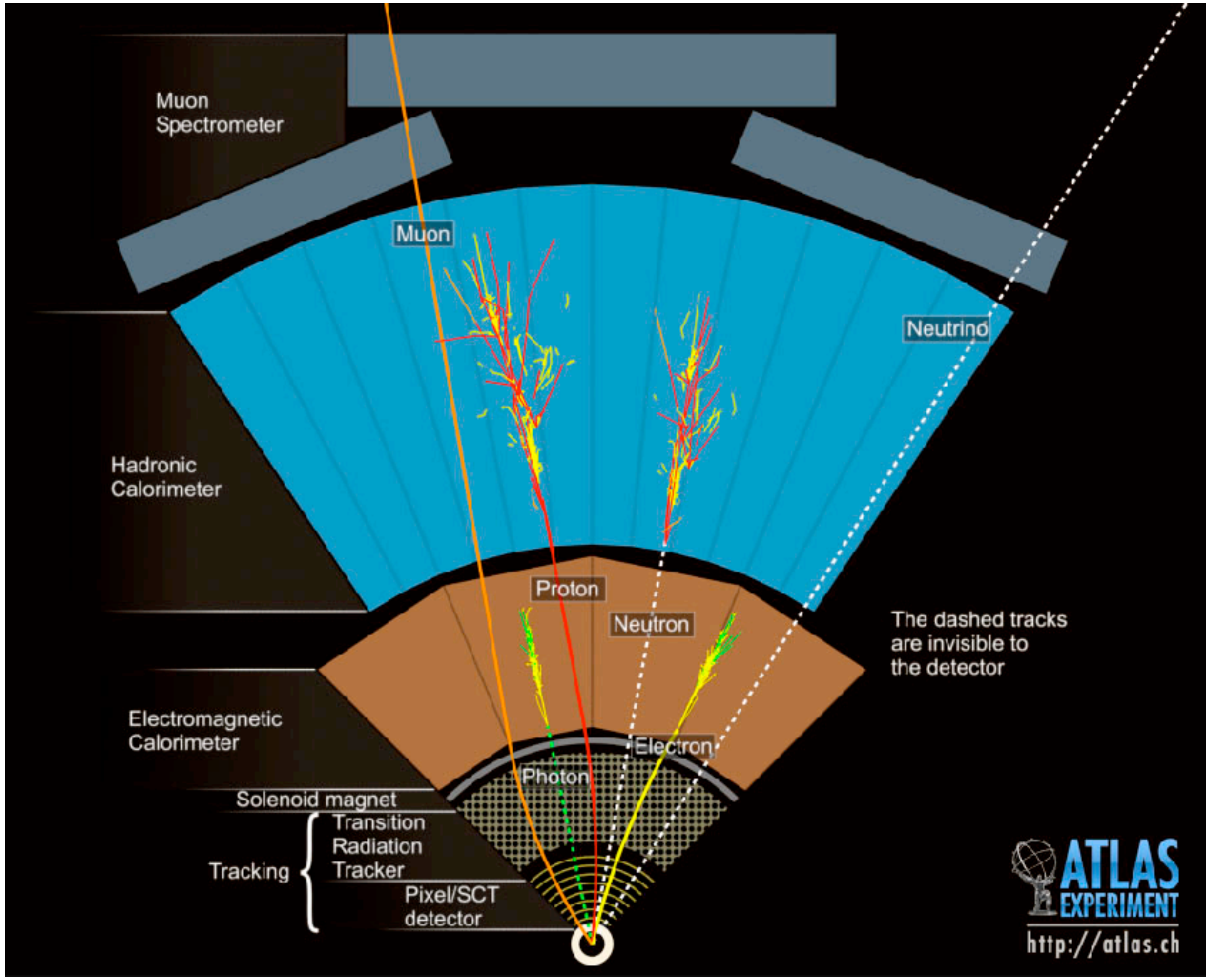
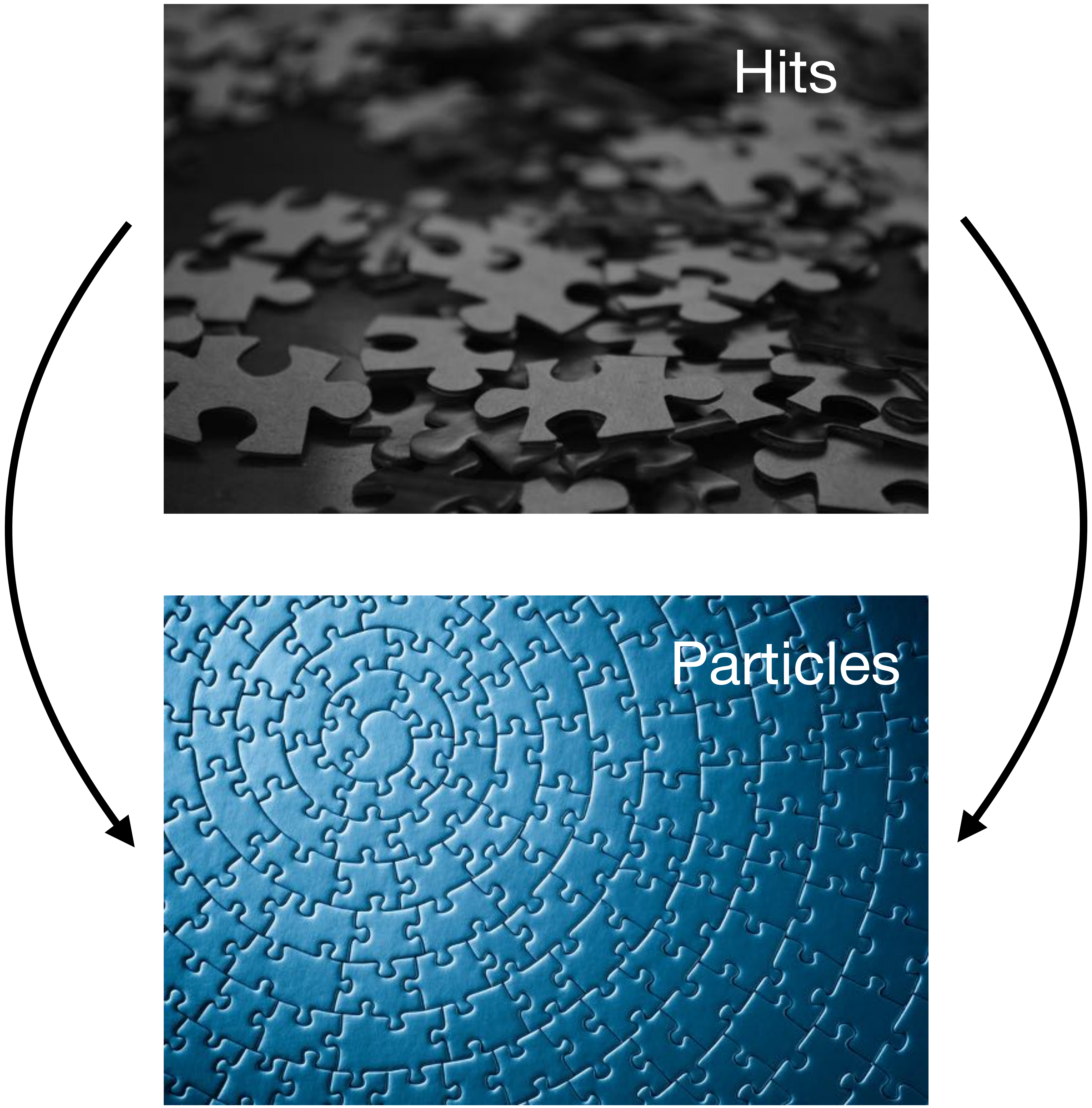
Review

- Tracking - small material detectors to measure signals where particles traverse. Use the signals to determine the particle trajectory in magnetic field
    - Measures 3 momentum, charge, and position of track
- Calorimetry - Dense material detectors to stop particles. Use signals to determine particle energy
    - Measures charged and neutral energy deposited by particles

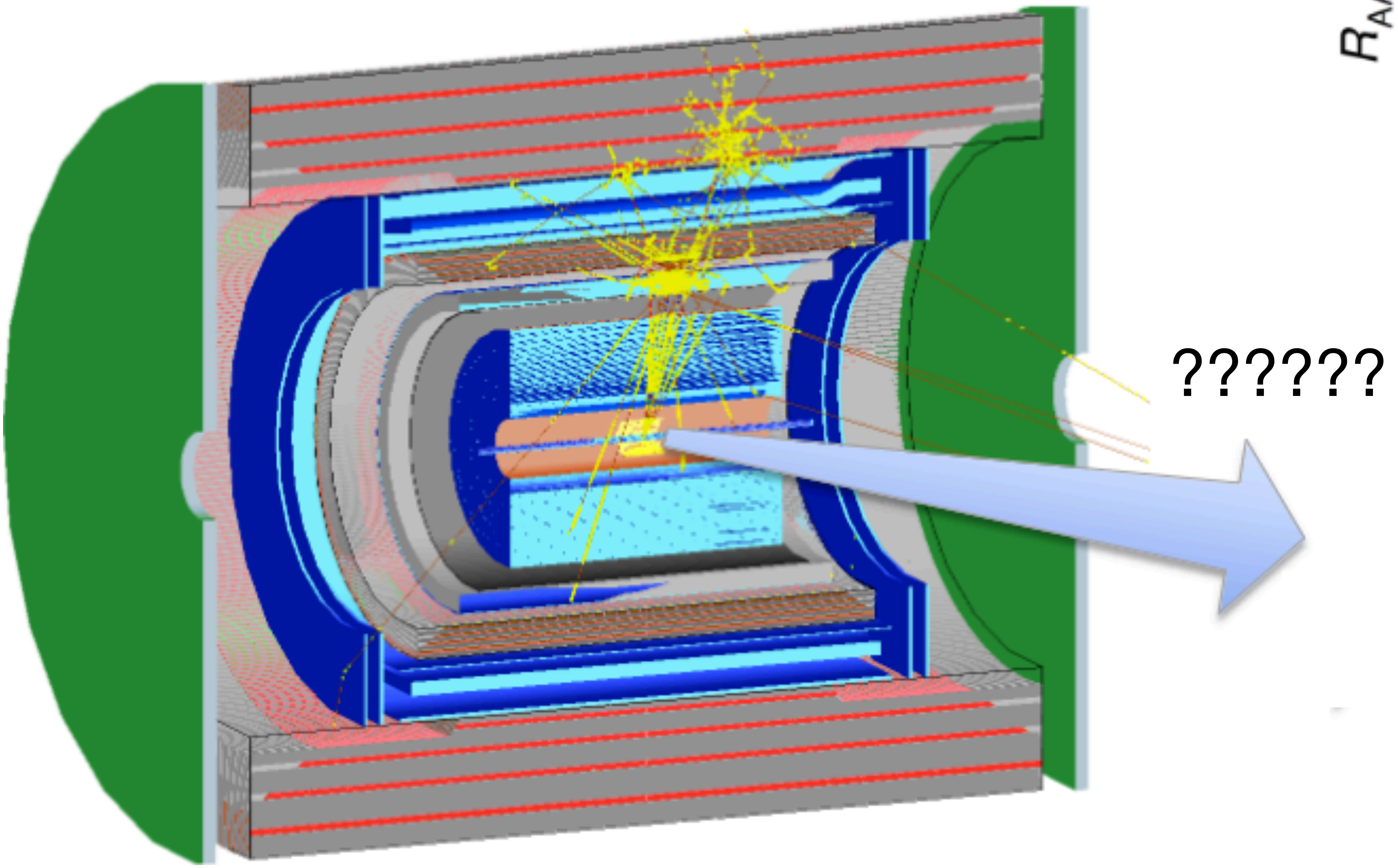


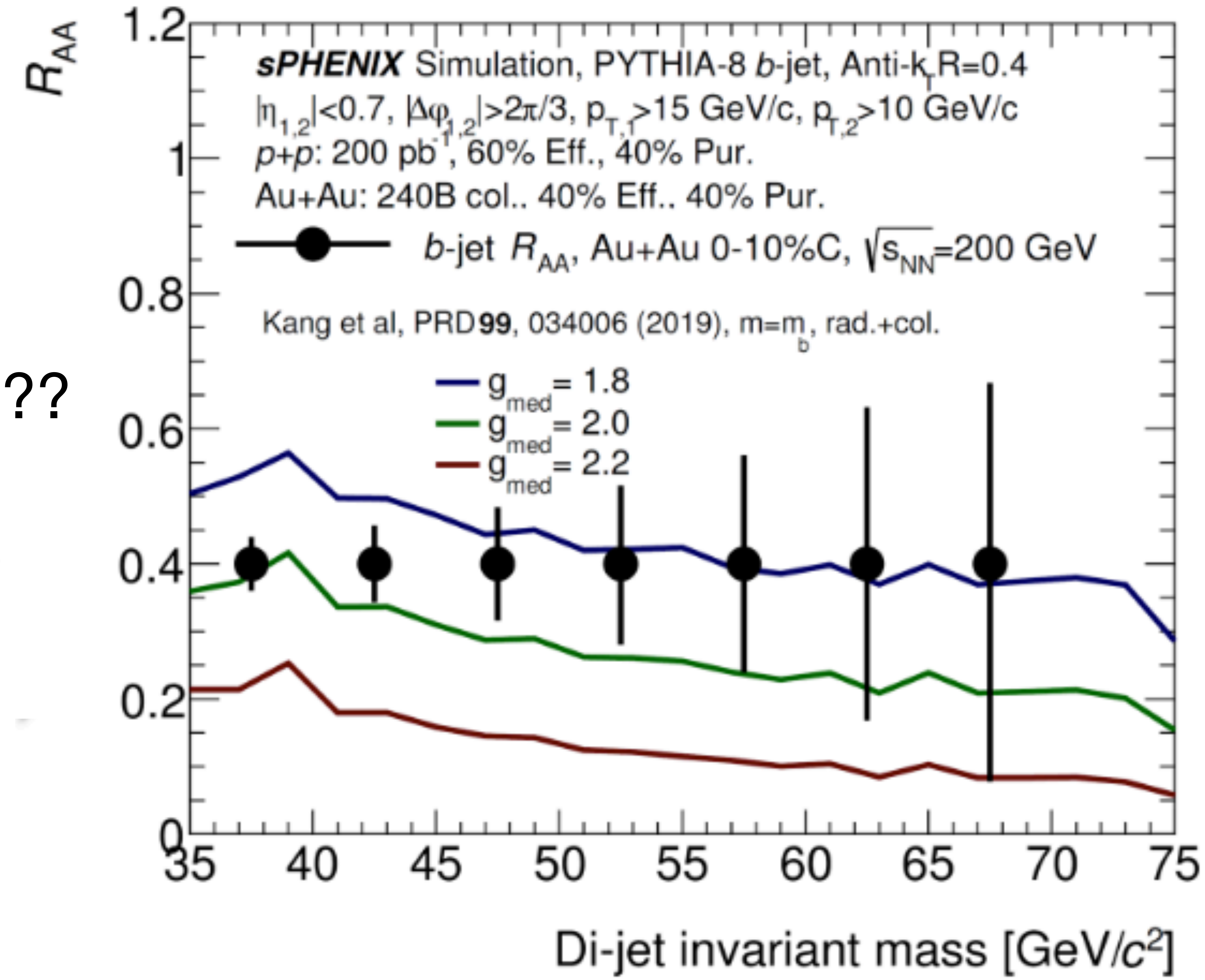
Now What?

- Detectors each register a pulse or signal (typically called a “hit”)
- This does not tell us anything about the particle itself!
- Necessary to reconstruct the data
    - Event reconstruction - putting all the pieces together



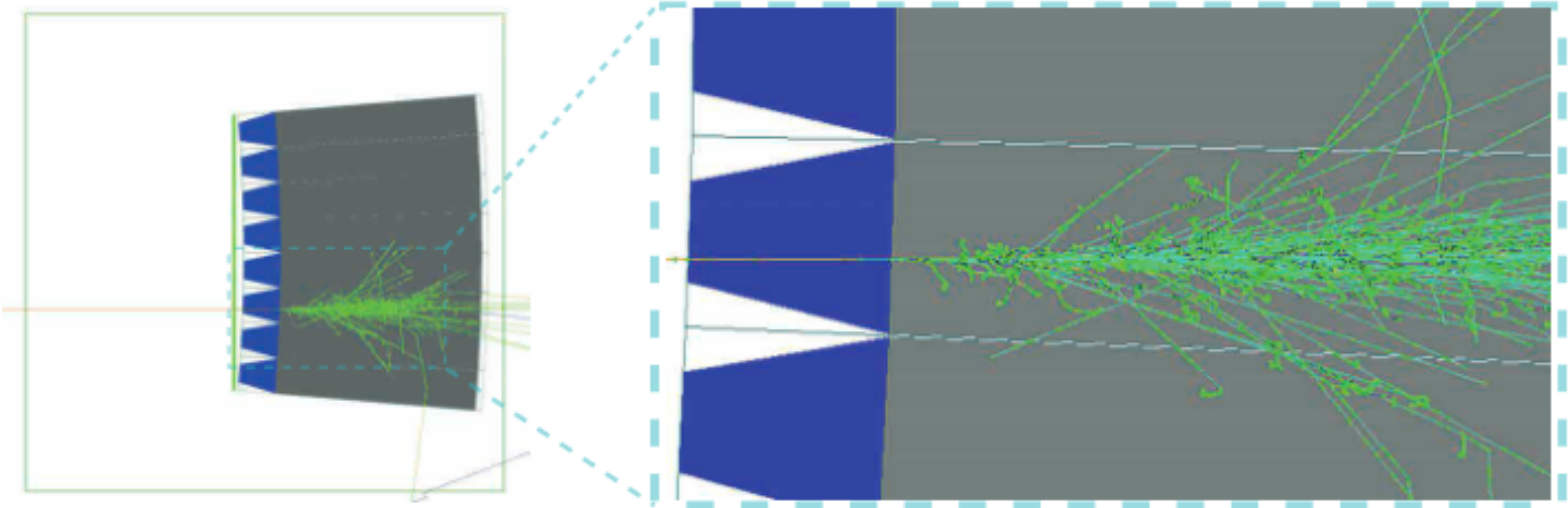
Reconstruction





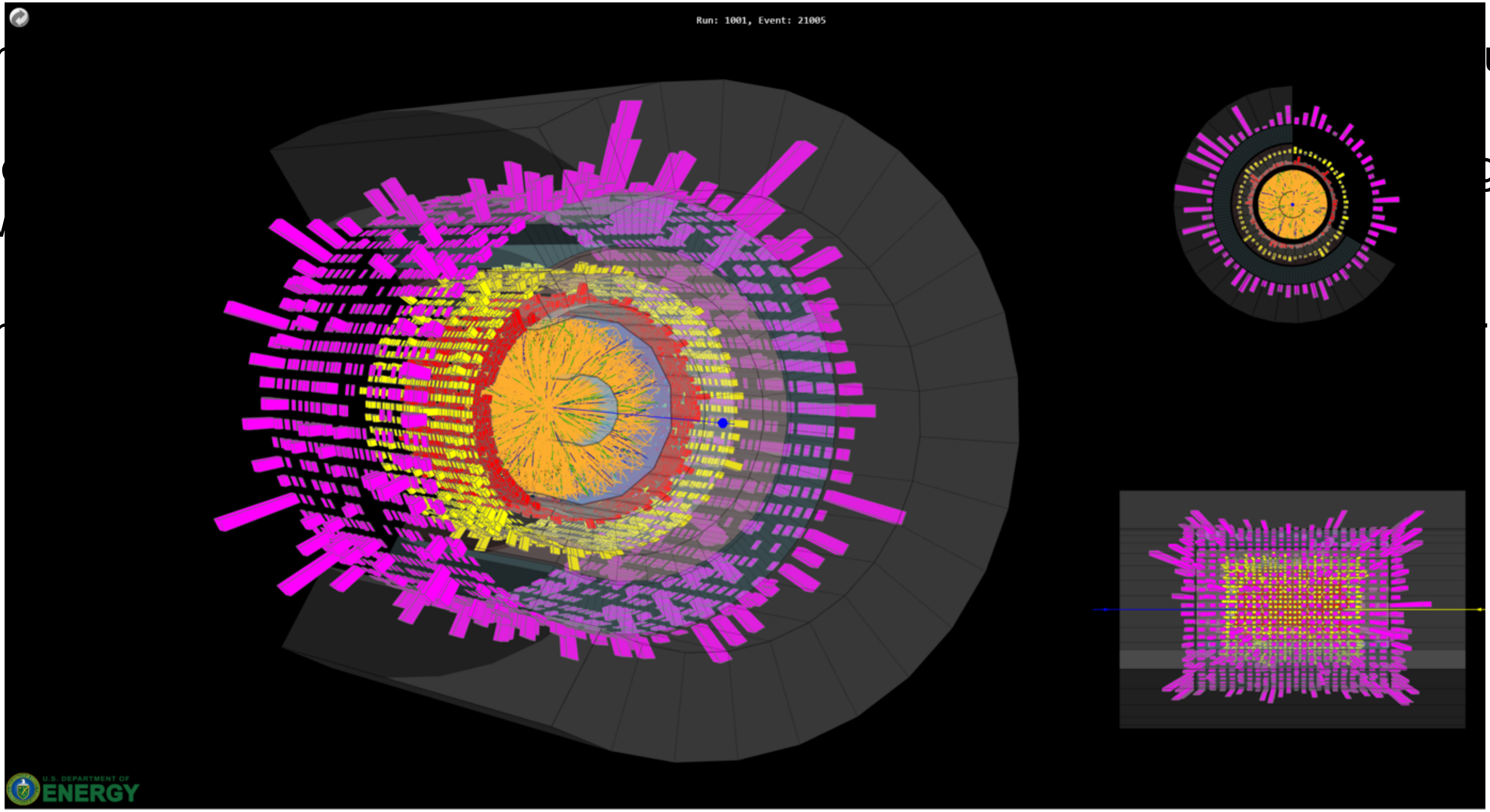
Clustering

- We have implicitly assumed that one particle deposits charge into one readout unit
- Generally not the case - particles may enter active detector volume at an angle, shower may develop broadly, etc…
- Example - Single 8 GeV electron enters (middle and normal to!) EMCal tower



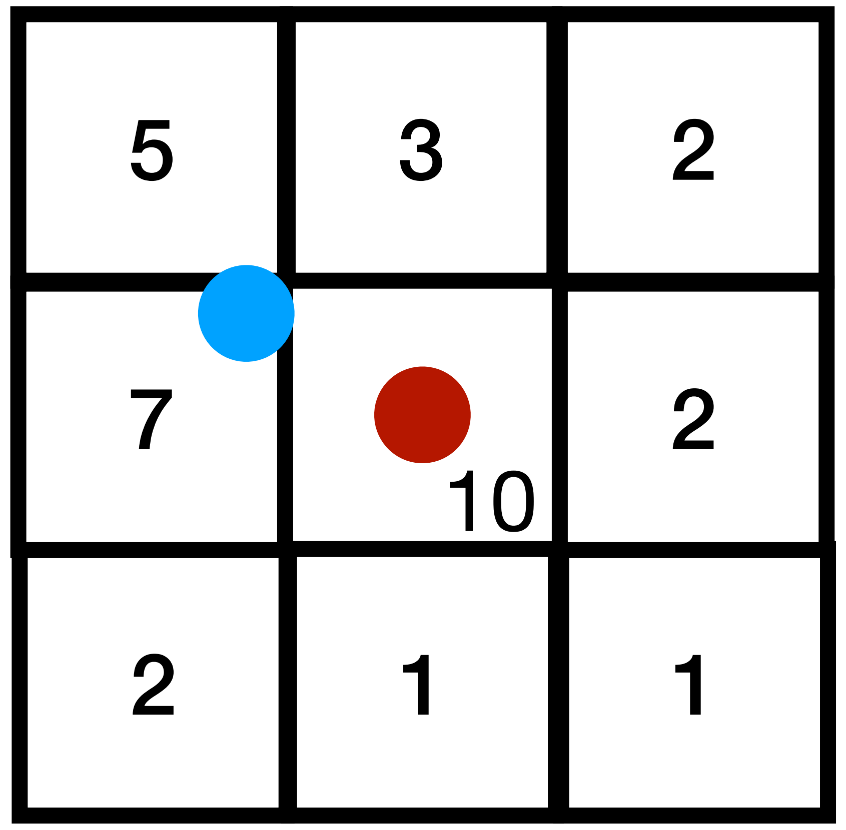
Clustering

- We h ut unit
- Gen gle, show
- Exar

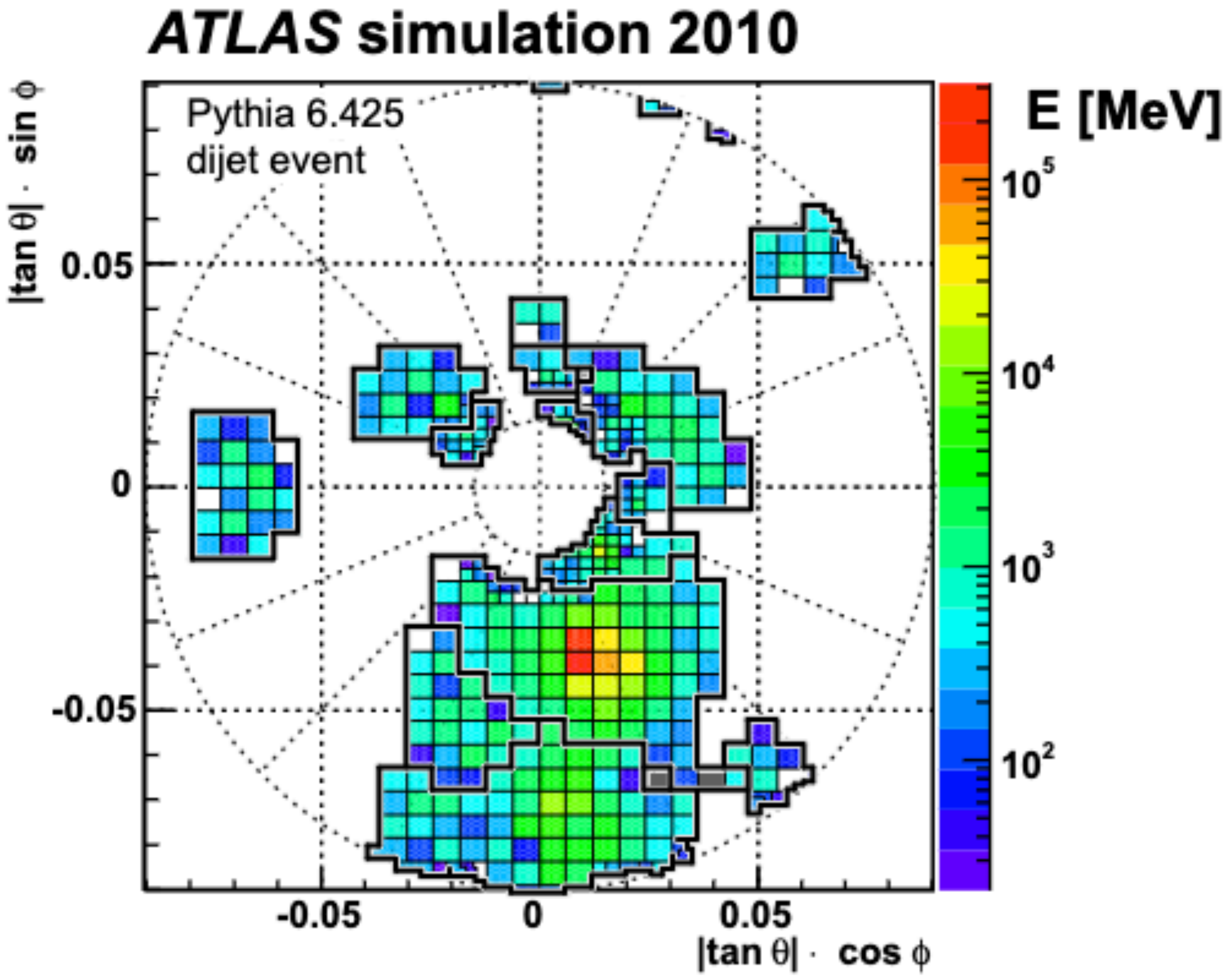


Clustering Algorithms

- Many clustering algorithms have been developed, all have pros and cons for different use cases
- Simple example - 3x3 tower sum around max tower energy
- Complex example - island clustering or topological clustering



Energy weighted 3x3 sum
Single max tower

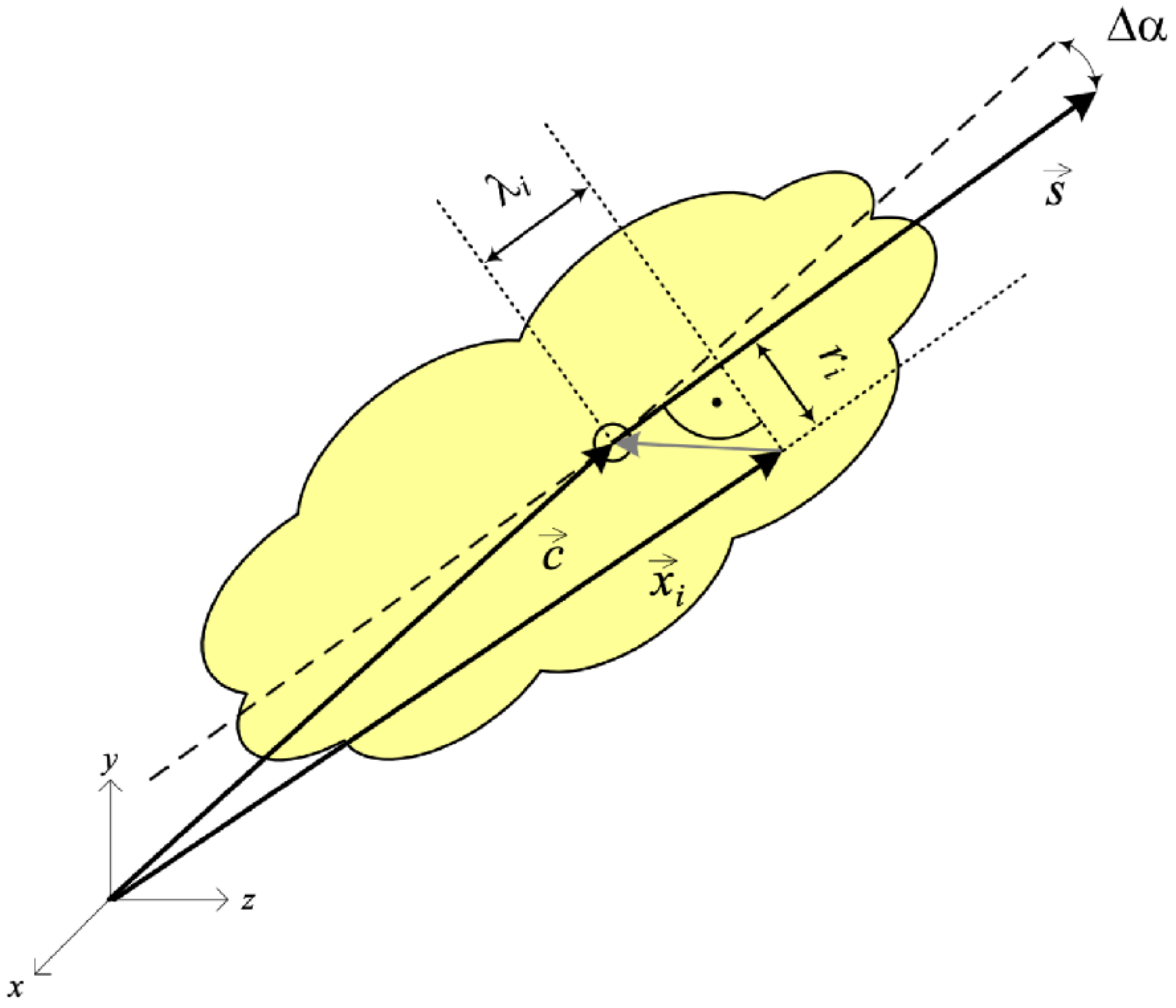


EPJC 77, 490 (2017)

Calo Clustering Algorithms

- What does a good clustering algorithm do?
  - Determines best position and energy resolution possible, limited only by inherent detector resolution
  - Properly assigns neighboring towers or energy deposits to appropriate cluster (gets the cluster shape correct)
  - Mitigates effects from detector noise, beam pile up, other backgrounds
  - (Potentially) connects clusters from adjacent calorimeters (e.g. EMCal+HCal)

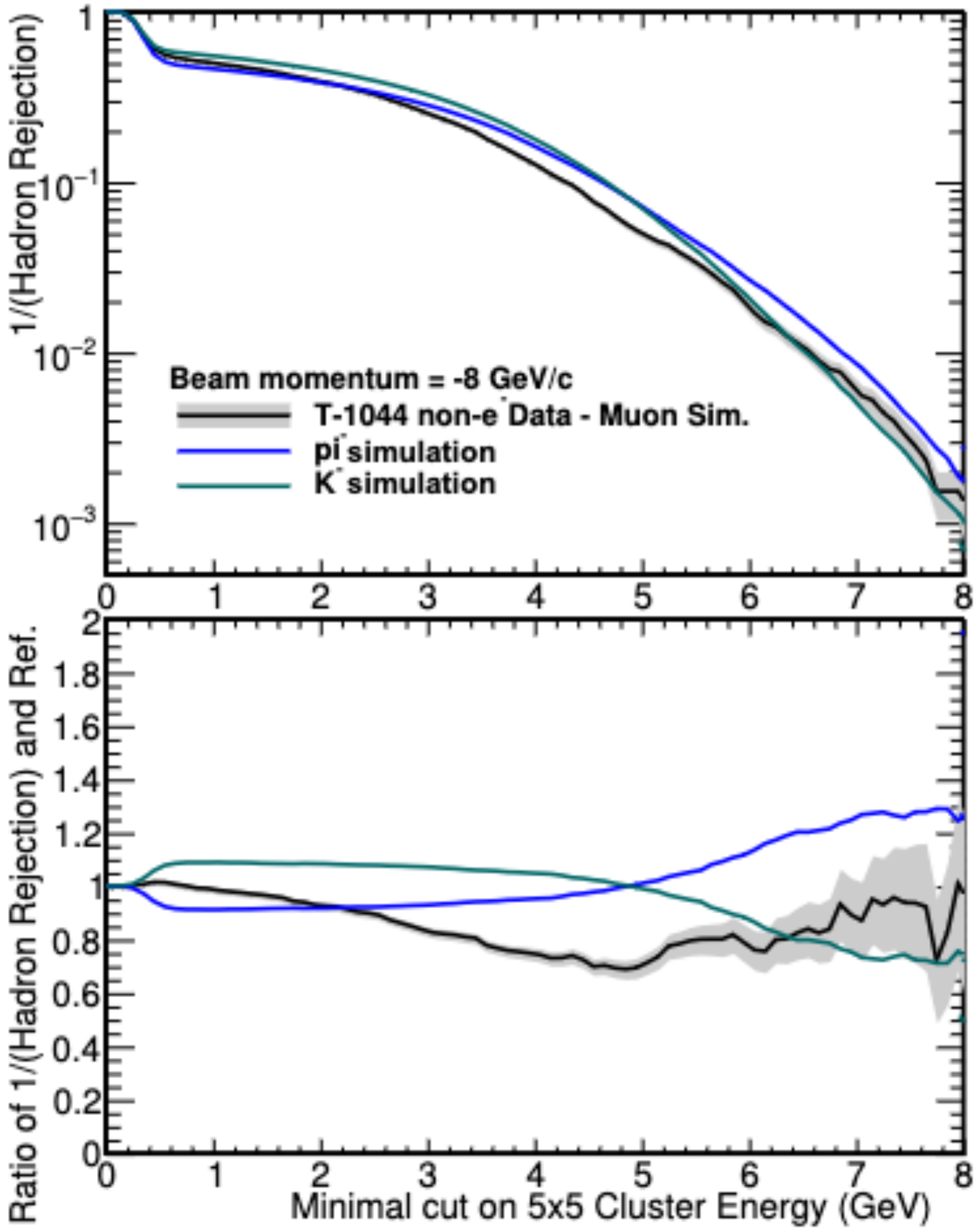
Calo Clustering



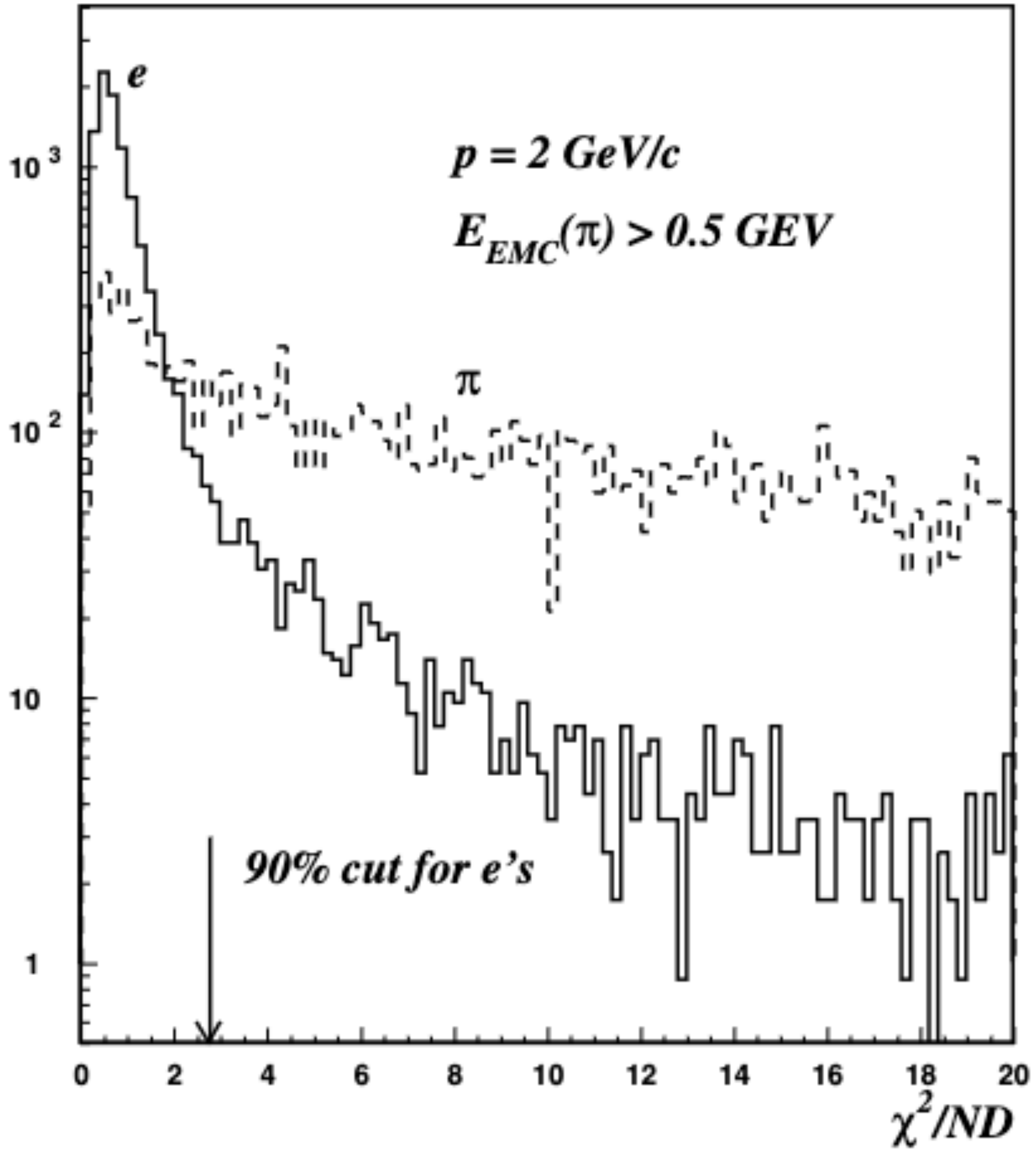
- $\vec{c}$ — *centre of gravity of cluster, measured from the nominal vertex* $(x = 0, y = 0, z = 0)$ *in ATLAS*
- $\vec{x}_i$ — *geometrical centre of a calorimeter cell in the cluster, measured from the nominal detector centre of ATLAS*
- $\vec{s}$ — *particle direction of flight (shower axis)*
- $\Delta\alpha$ — *angular distance* $\Delta\alpha = \angle(\vec{c}, \vec{s})$ *between cluster centre of gravity and shower axis* $\vec{s}$
- λ_i — *distance of cell at* $\vec{x}_i$ *from the cluster centre of gravity measured along shower axis* $\vec{s}$ $(\lambda_i < 0$ *is possible)*
- r_i — *radial (shortest) distance of cell at* $\vec{x}_i$ *from shower axis* $\vec{s}$ $(r_i \geq 0)$

Cluster Shower Shapes

- Can use information from clustering to help with particle ID
- Example - development of pion vs. electron shower is different in EMCal!
- Can optimize signal —> background accordingly



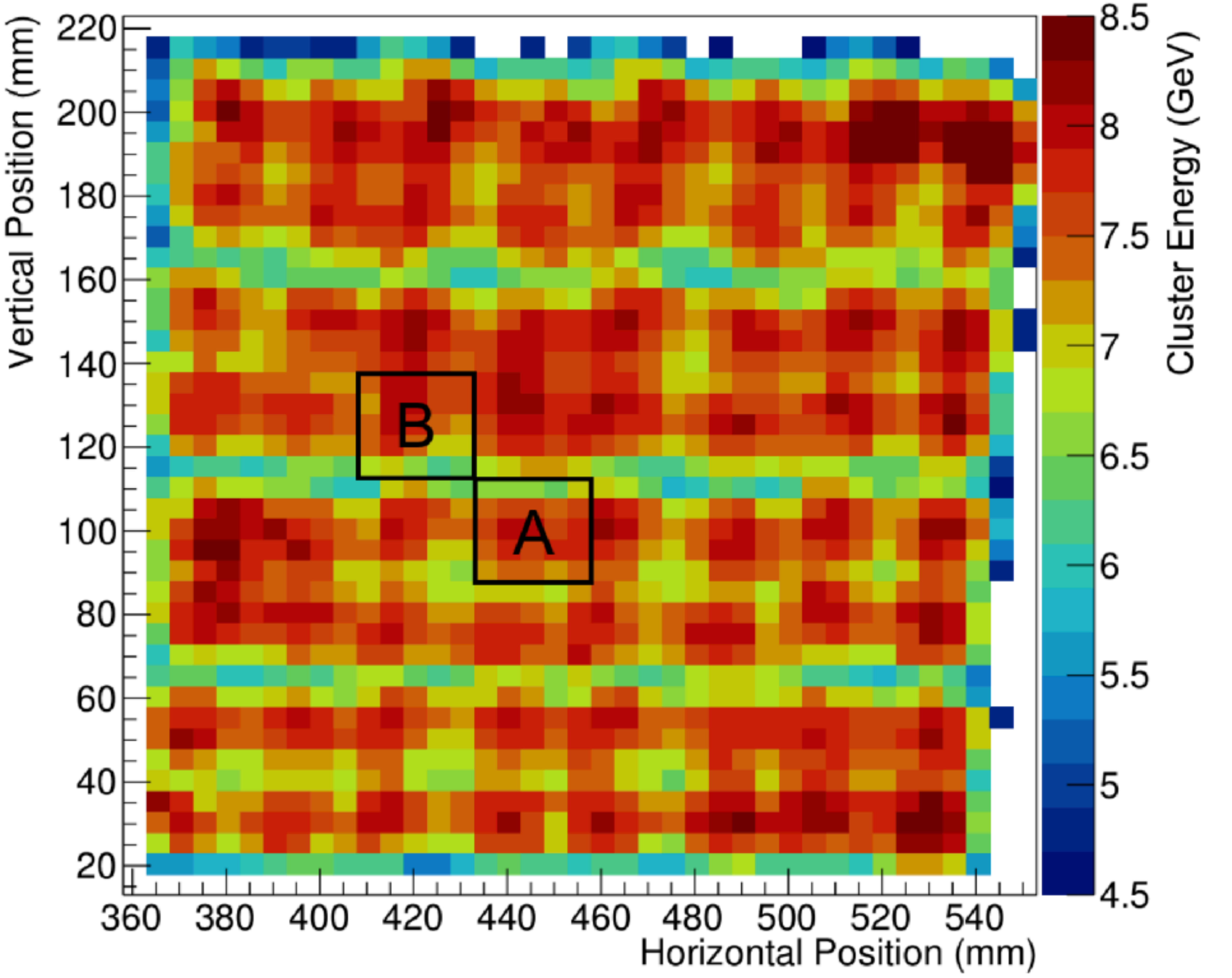
IEEE TNS 65 (2018) 12, 2901



NIMA 499, 521 (2003)

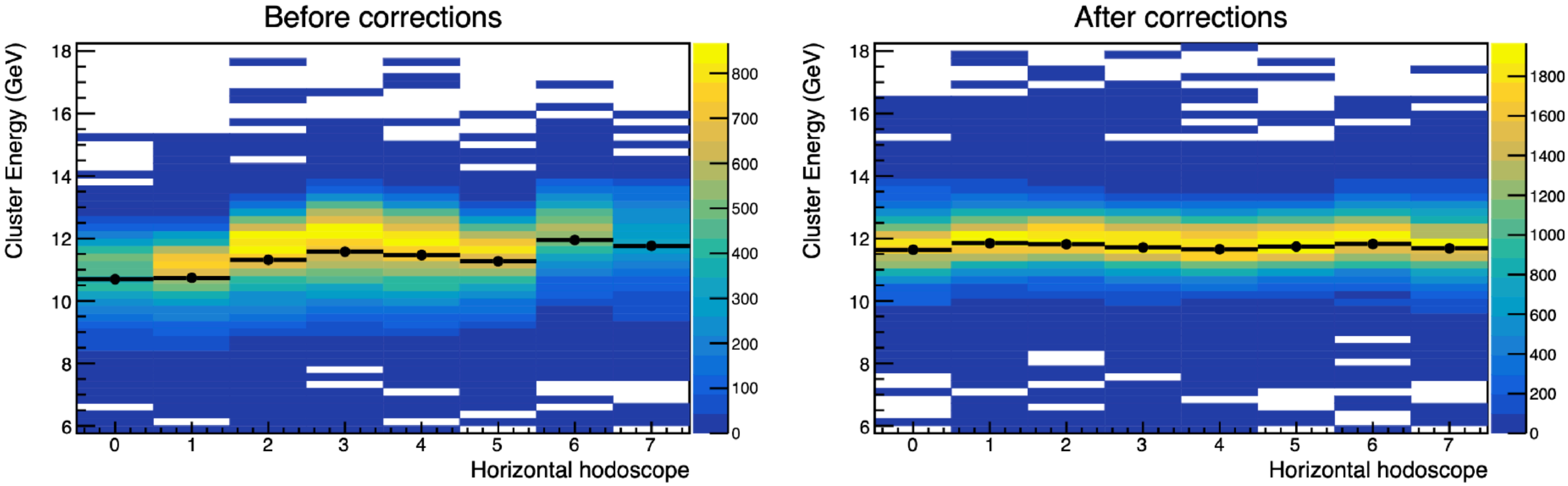
Cluster Corrections

- Calorimeters are not perfect - some energy escapes detection or is lost completely due to mechanical constraints
- Example - sPHENIX EMCal block boundaries
- Reconstructed cluster energy for 8 GeV electron has large position dependence



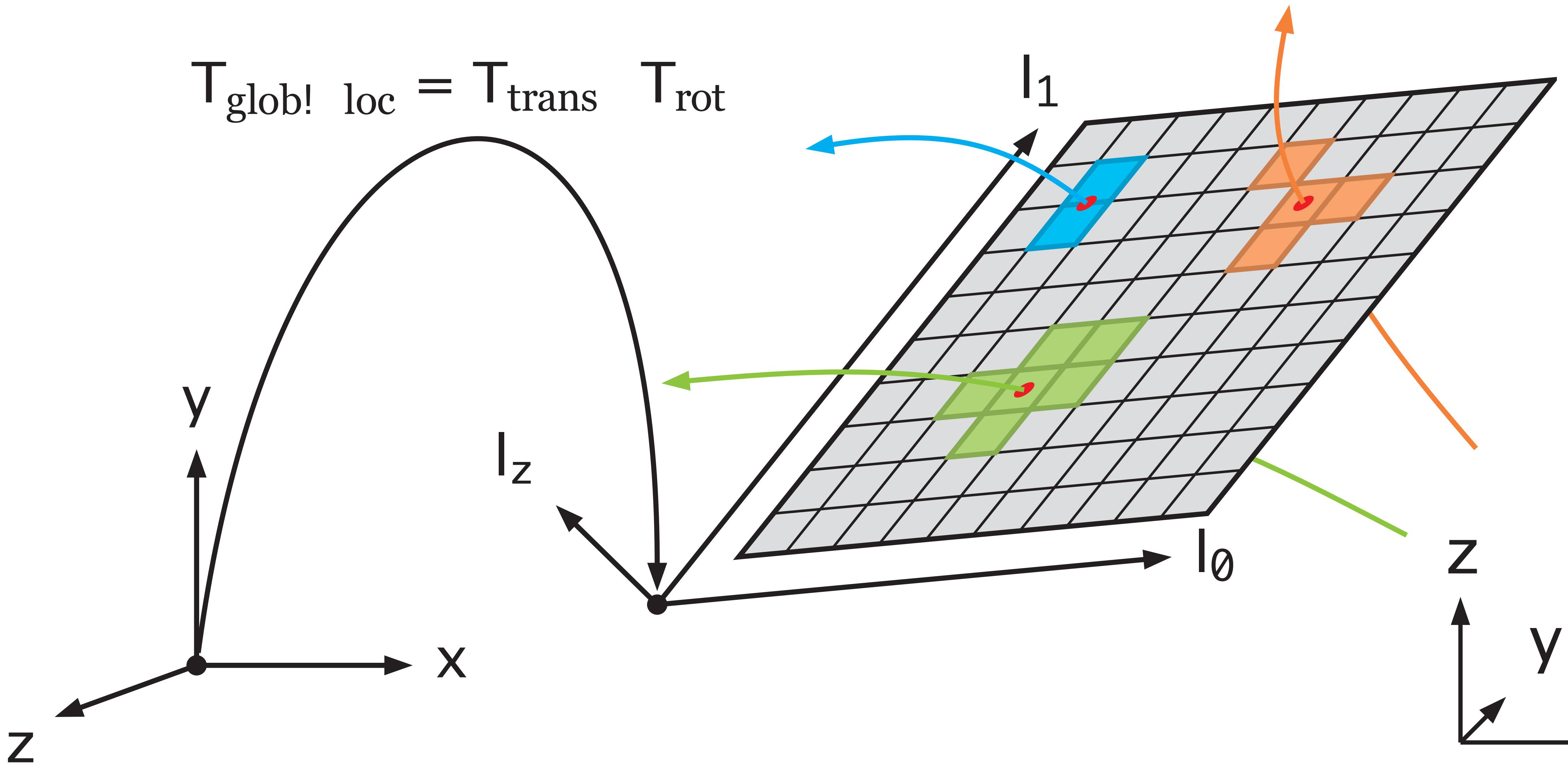
IEEE TNS 68 (2021) 2, 173-181

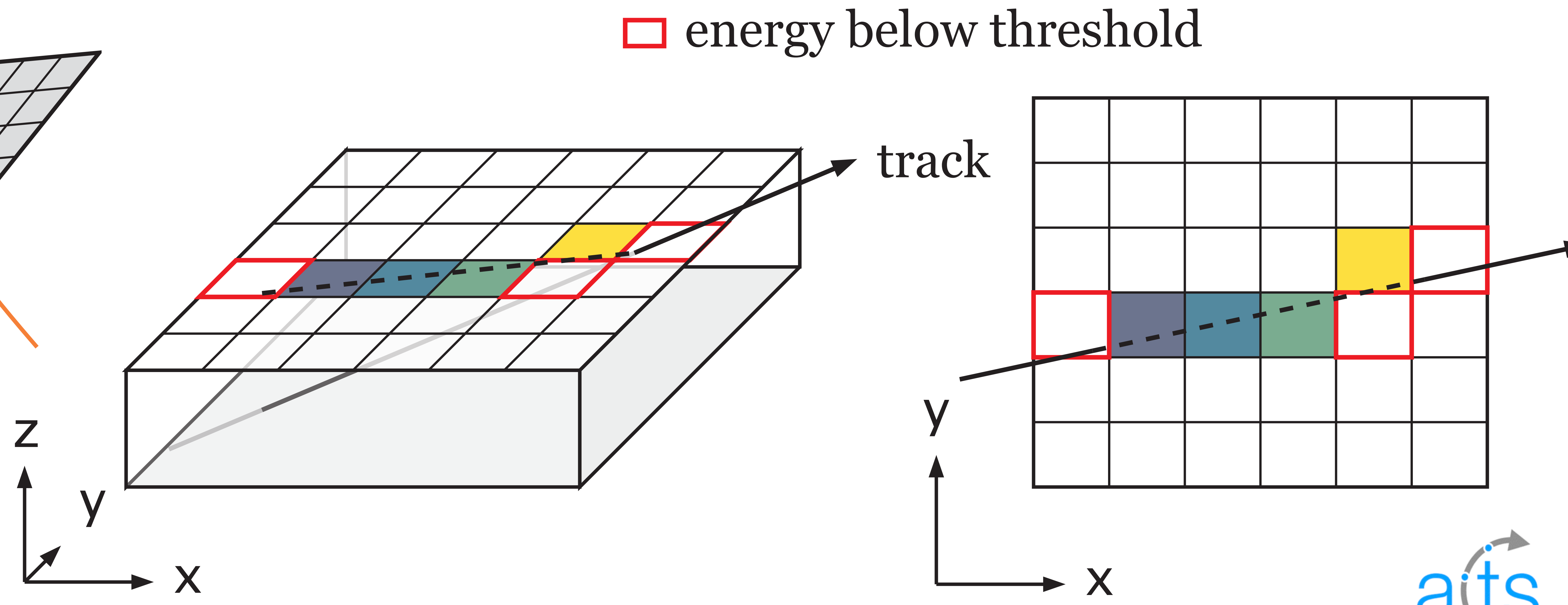
Cluster Calibration



- Can calibrate cluster energies based on position dependence
- May depend on electron or photon signal (electrons bend!)

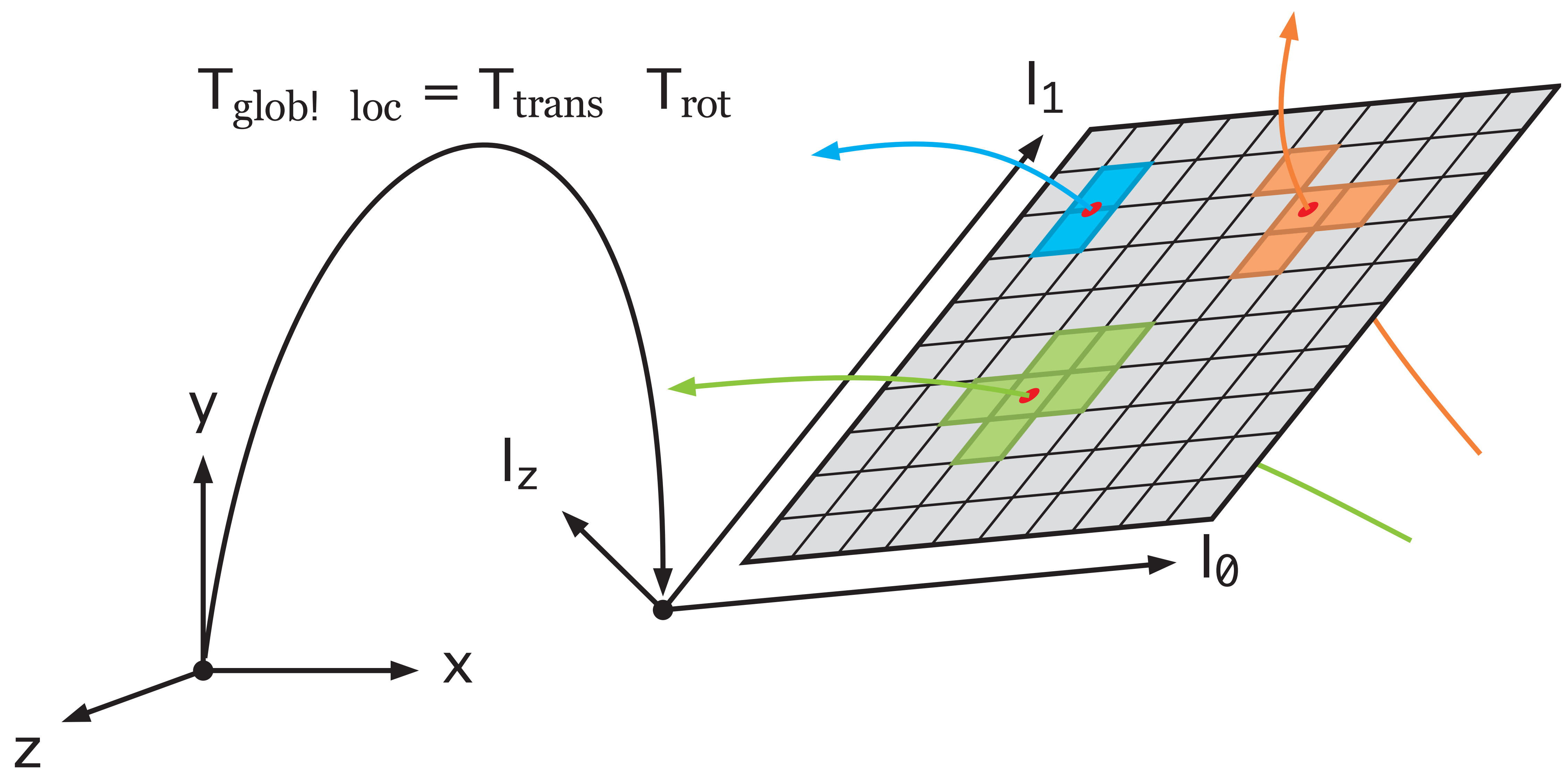
Clustering - Tracking

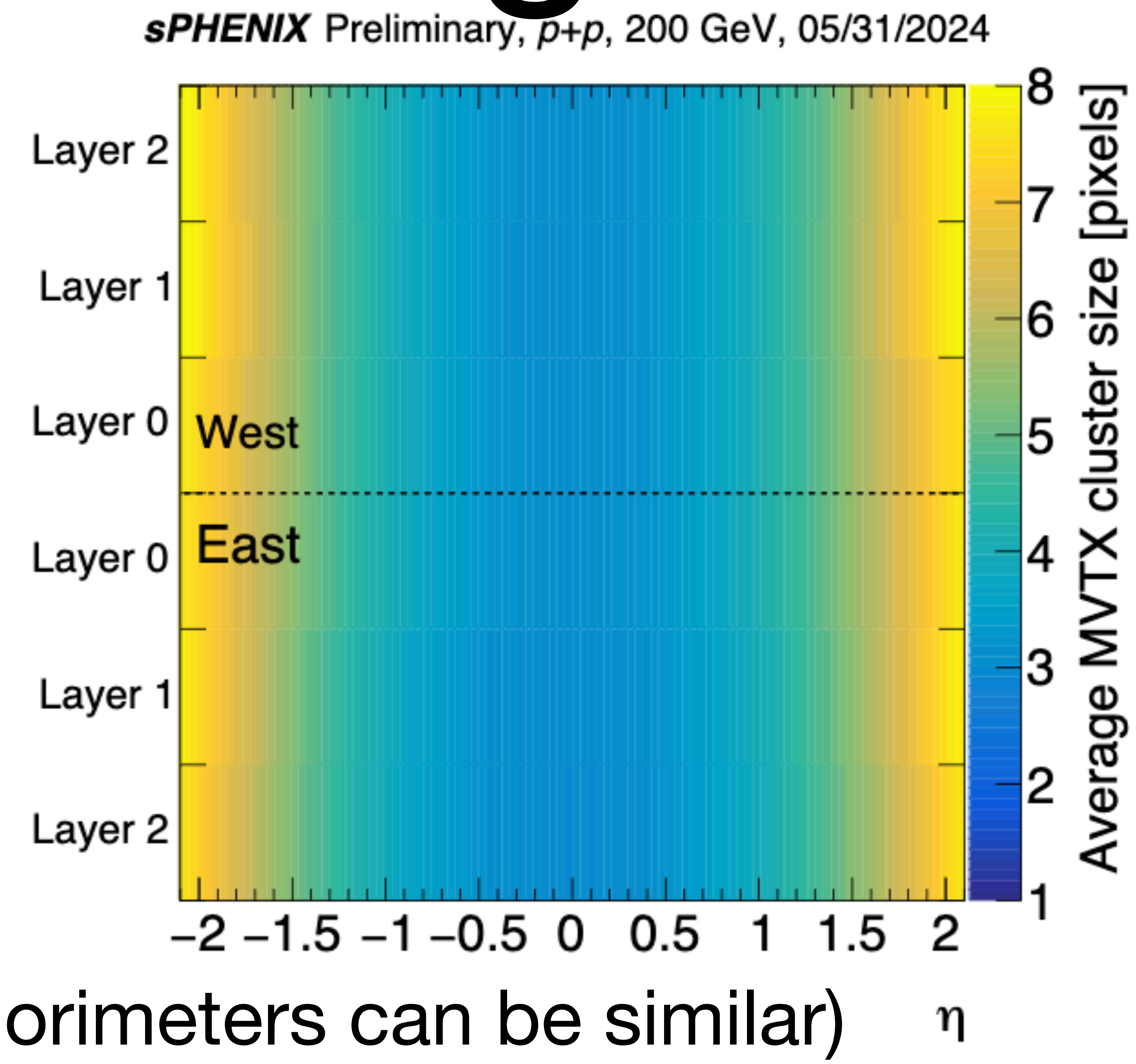




- Clustering often performed in local coordinates (calorimeters can be similar)
- Cluster position in global coordinates is determined by applying sensor transformation (affine translation+rotation)
- Cluster size is important for precise position determination!

Clustering - Tracking





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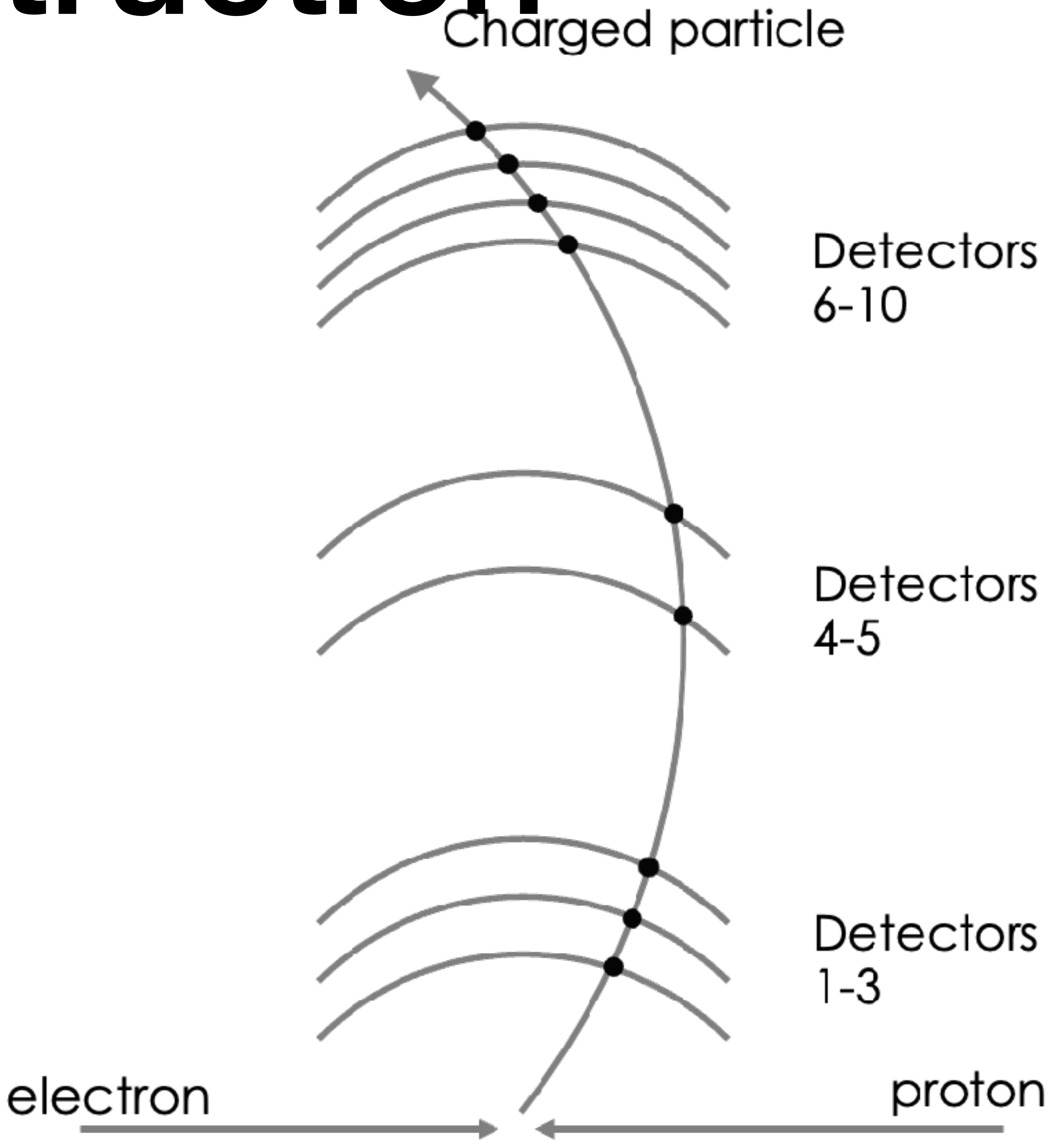
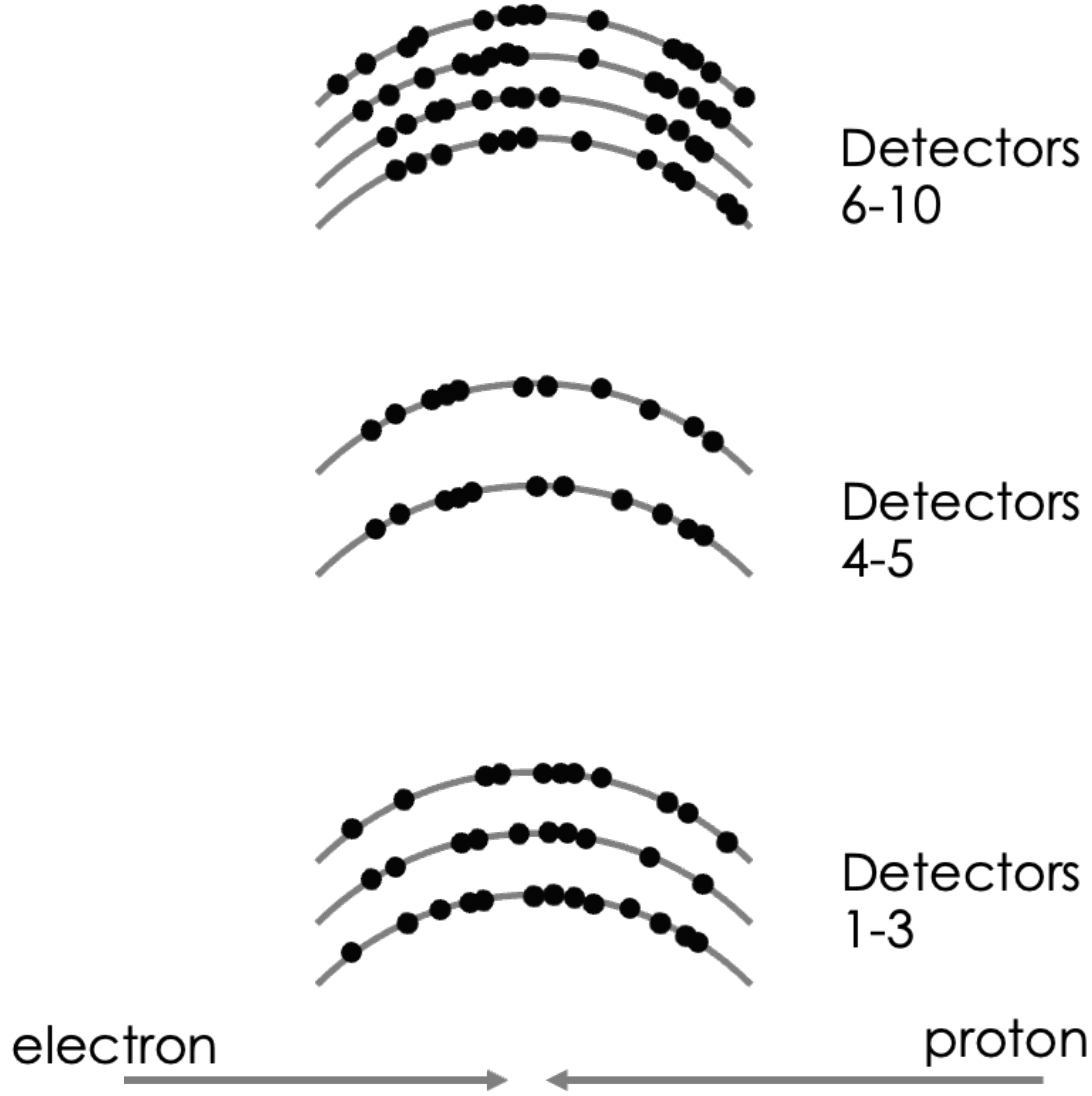
Track Reconstruction

- Track reconstruction requires correlating clusters across detectors
- For a single track, one could easily pick out the clusters that belong to it
- Straightforward enough to write an algorithm to do this



Track Reconstruction

- What if you have 20 particles?
- What if you have 10,000 particles, leaving O(100,000) clusters in your tracking layers?
- What if your detector has hot/dead areas that add/miss clusters?
- What if many of the clusters are from background sources not associated with the physics event?
- …



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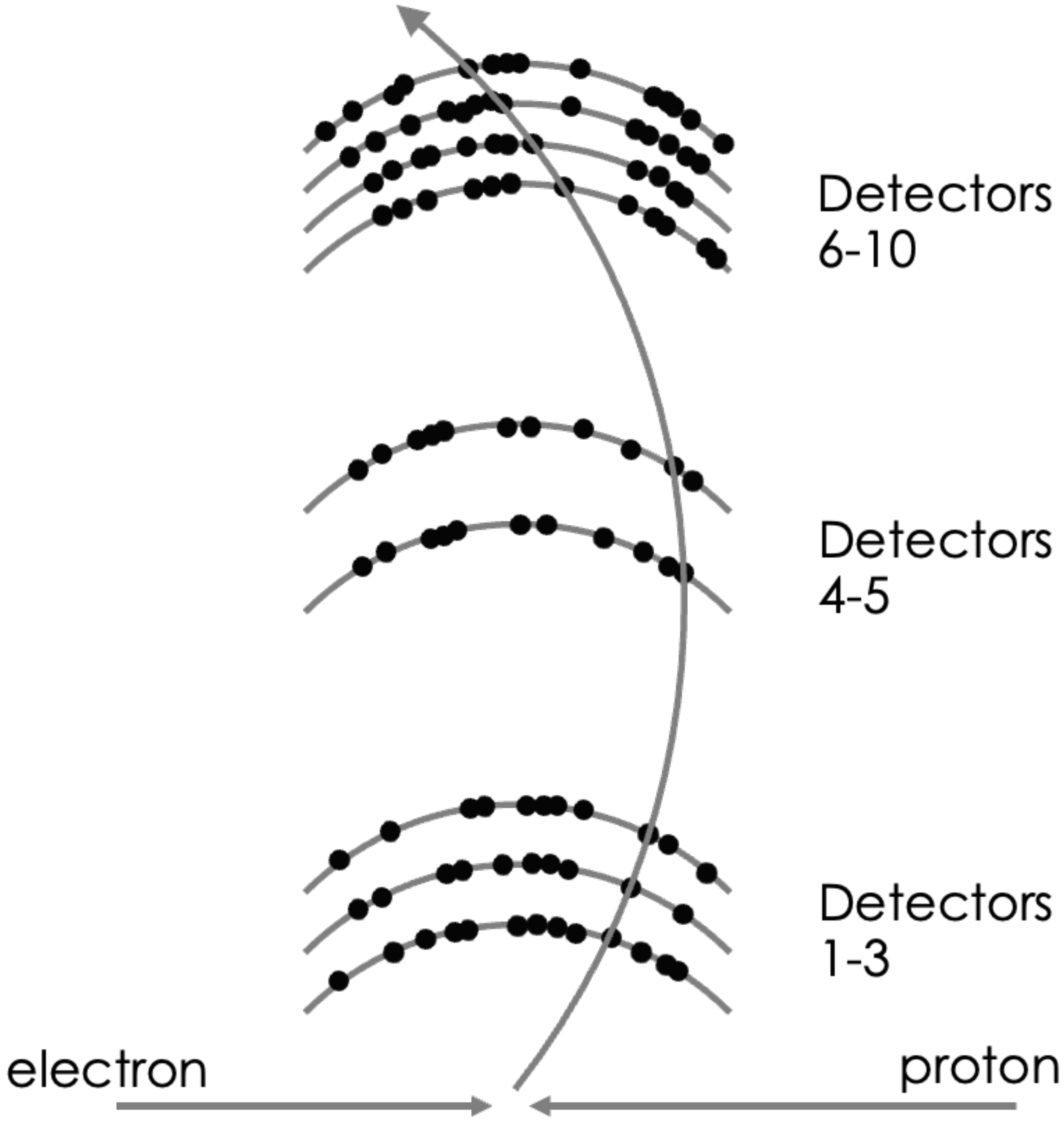
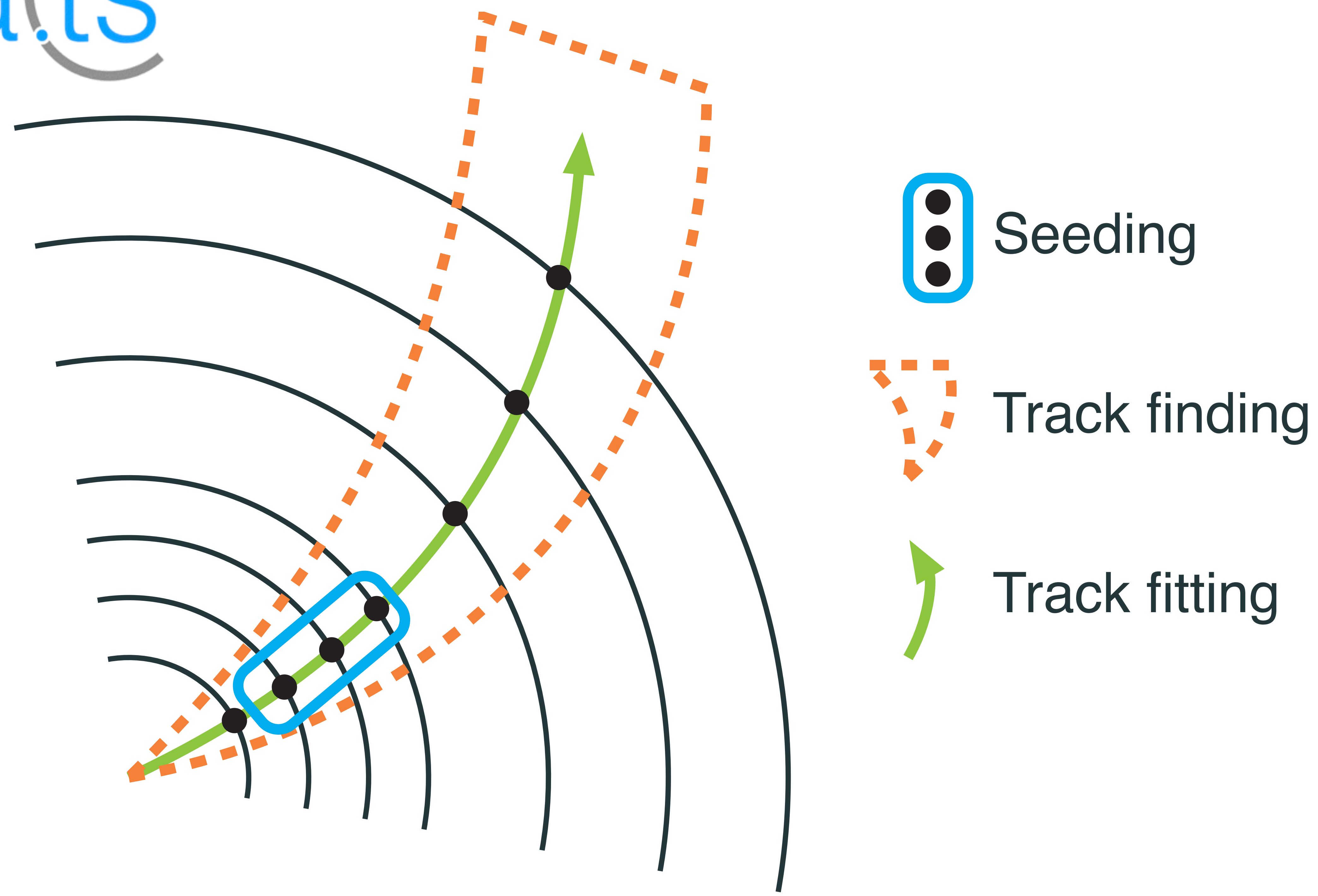


Track Reconstruction



$$\vec{x} = (l_0, l_1, \phi, \theta, q/p)$$

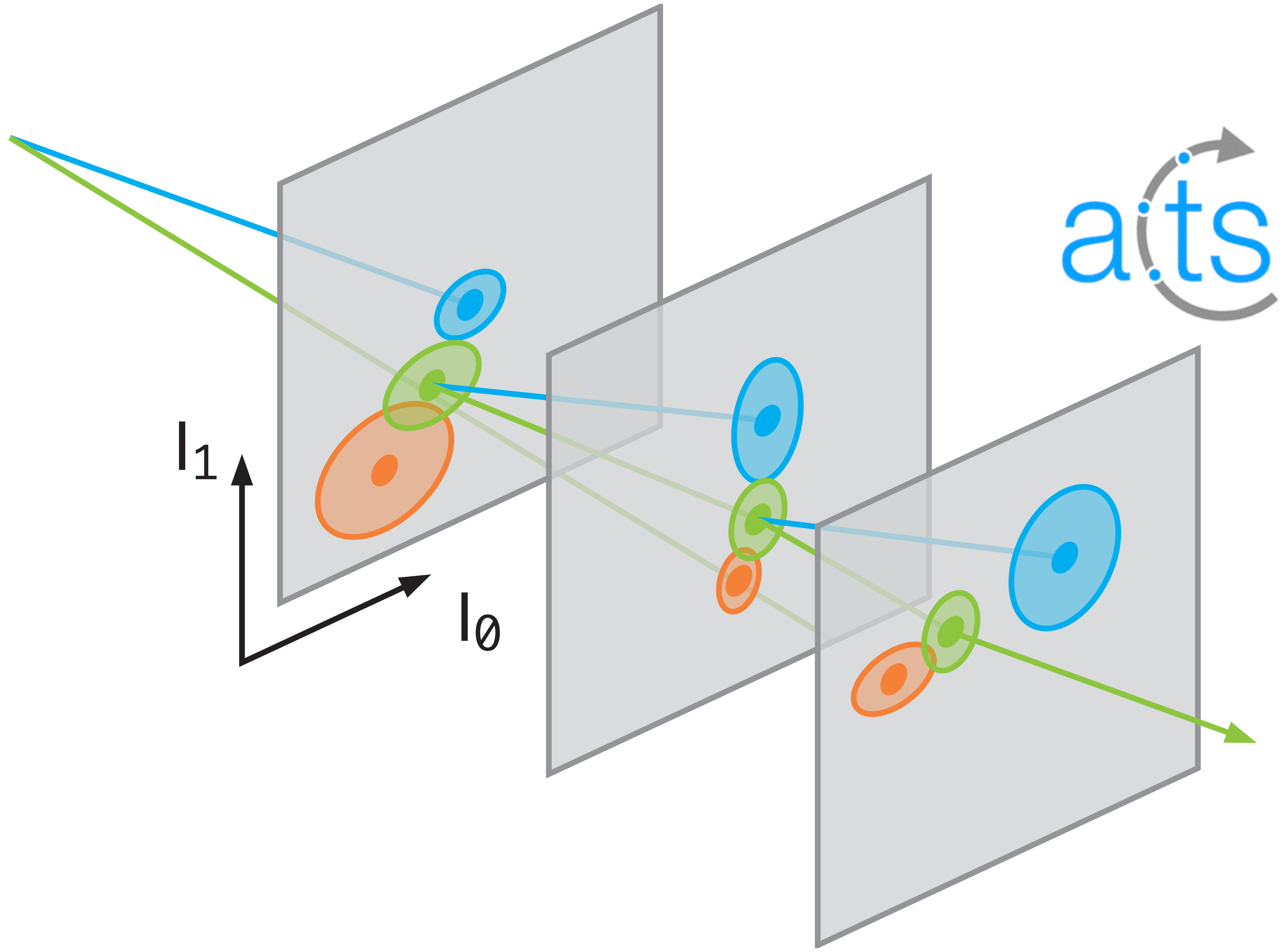
- Three stages of track reconstruction
  - Seeding - obtaining initial guess for the track
  - Finding - adding additional clusters to the track
  - Fitting - determine final track parameters precisely

Track Fitting

- Kalman Filter - powerful algorithm that uses measurements as a function of time to produce estimates of unknown variables

    - Examples - navigation of vehicles, signal processing, robotic motion, trajectory optimization…

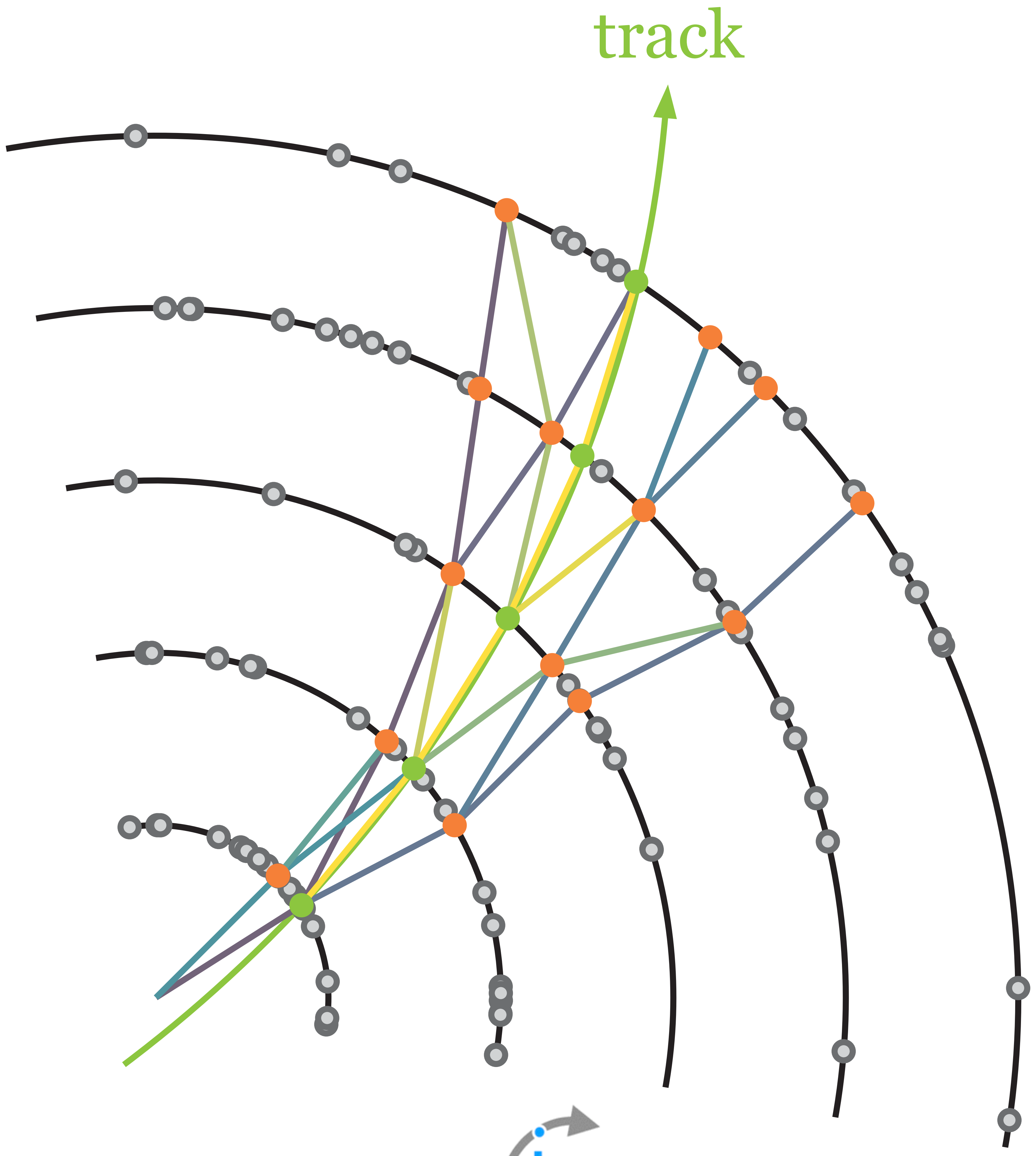
- In NHEP, Kalman Filters are used to precisely determine the track parameters



Prediction
Filter
Measurement

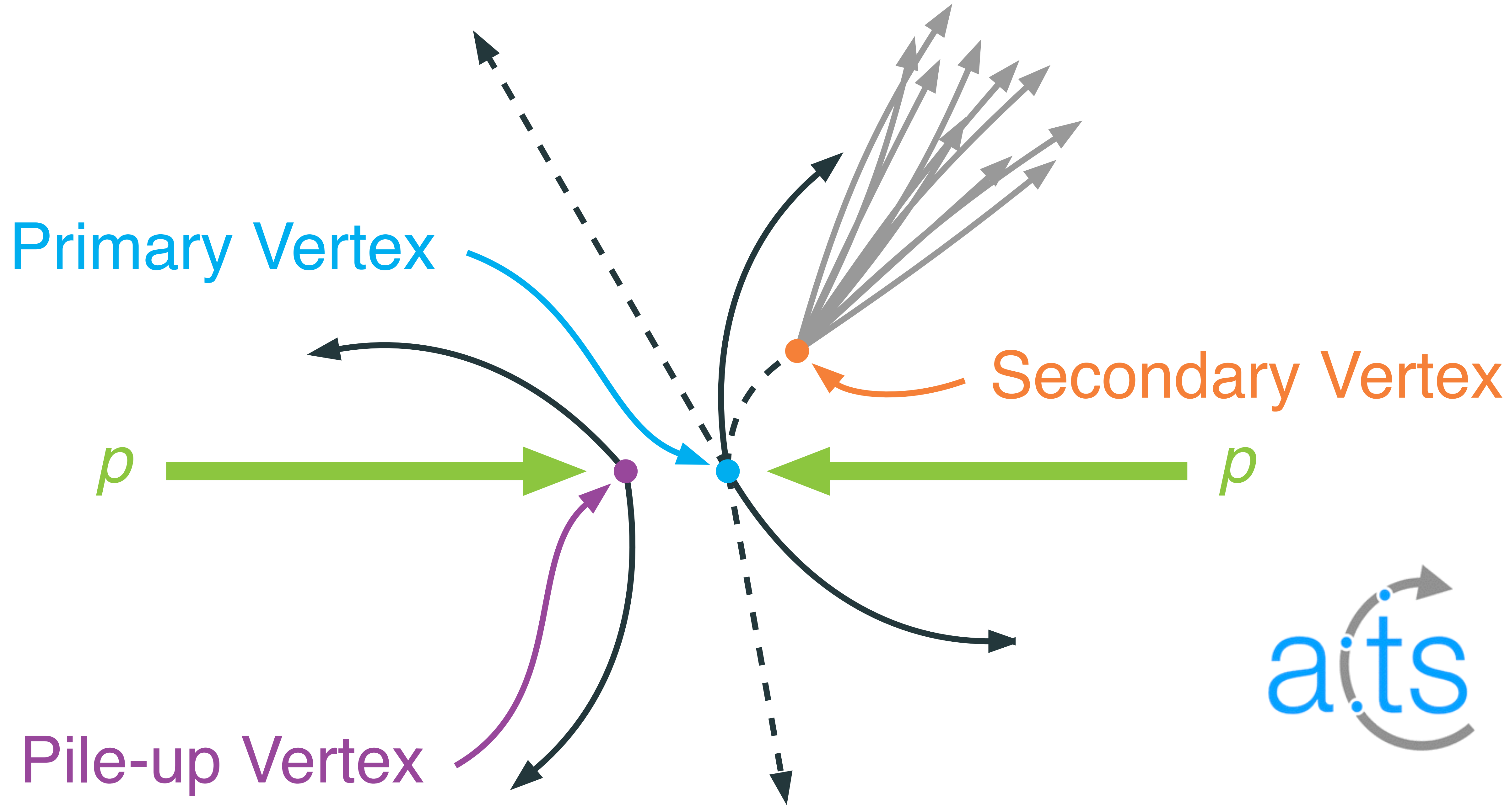
Combinatorial Kalman Filter

- The Combinatorial Kalman Filter (CKF) combines track finding and fitting
- Produces branches of possible track candidates from initial seed estimates
- Requires tuning of allowed measurements via χ^2 and ambiguity resolution

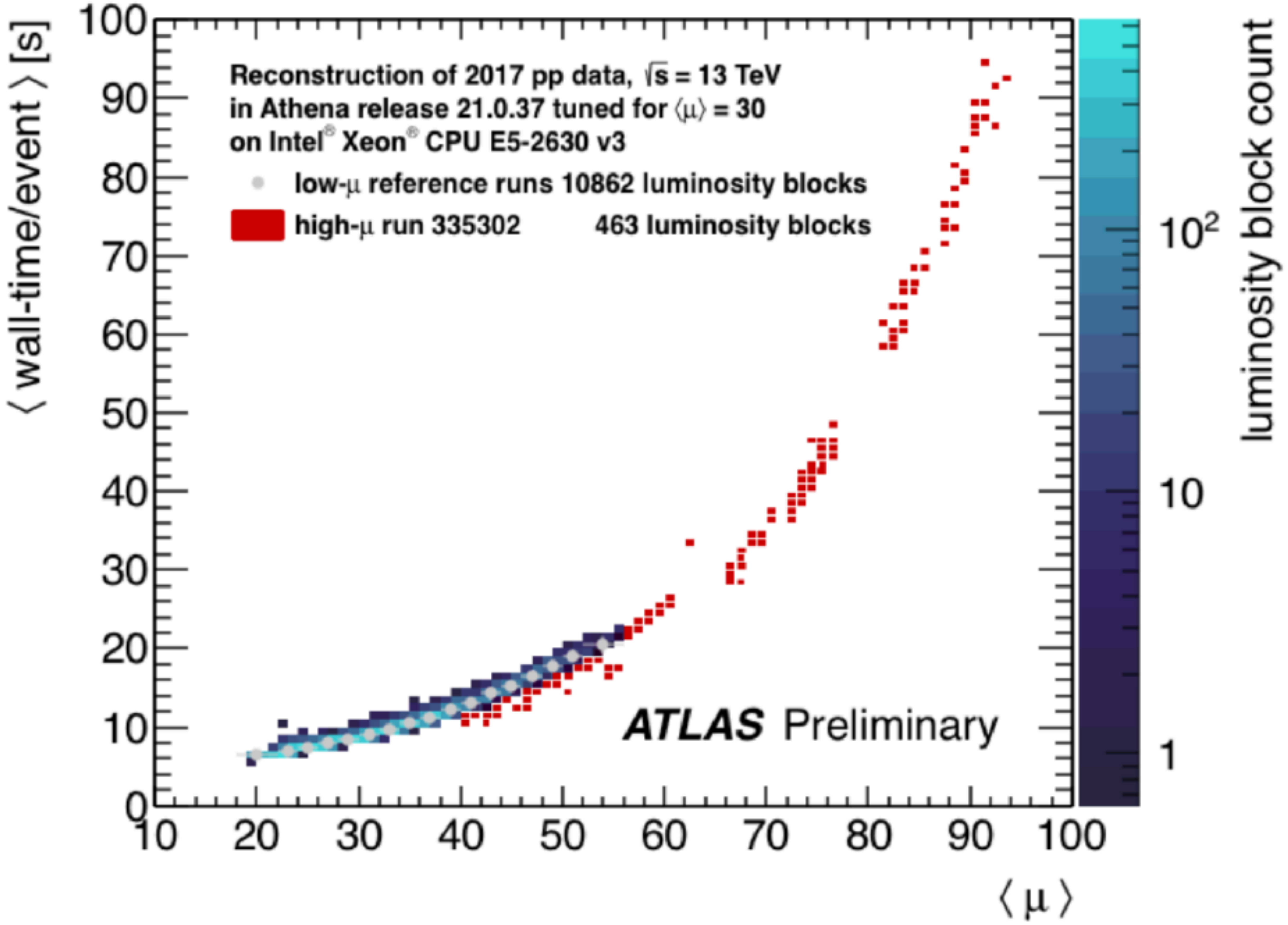


Vertex Reconstruction

- With reconstructed tracks, can propagate back to a common origin to determine collision vertex
  - Vertex finders/fitters operate similarly to tracking finding/fitting
- Important to differentiate between primary, secondary, and pile up vertices!



Track Reconstruction Challenges



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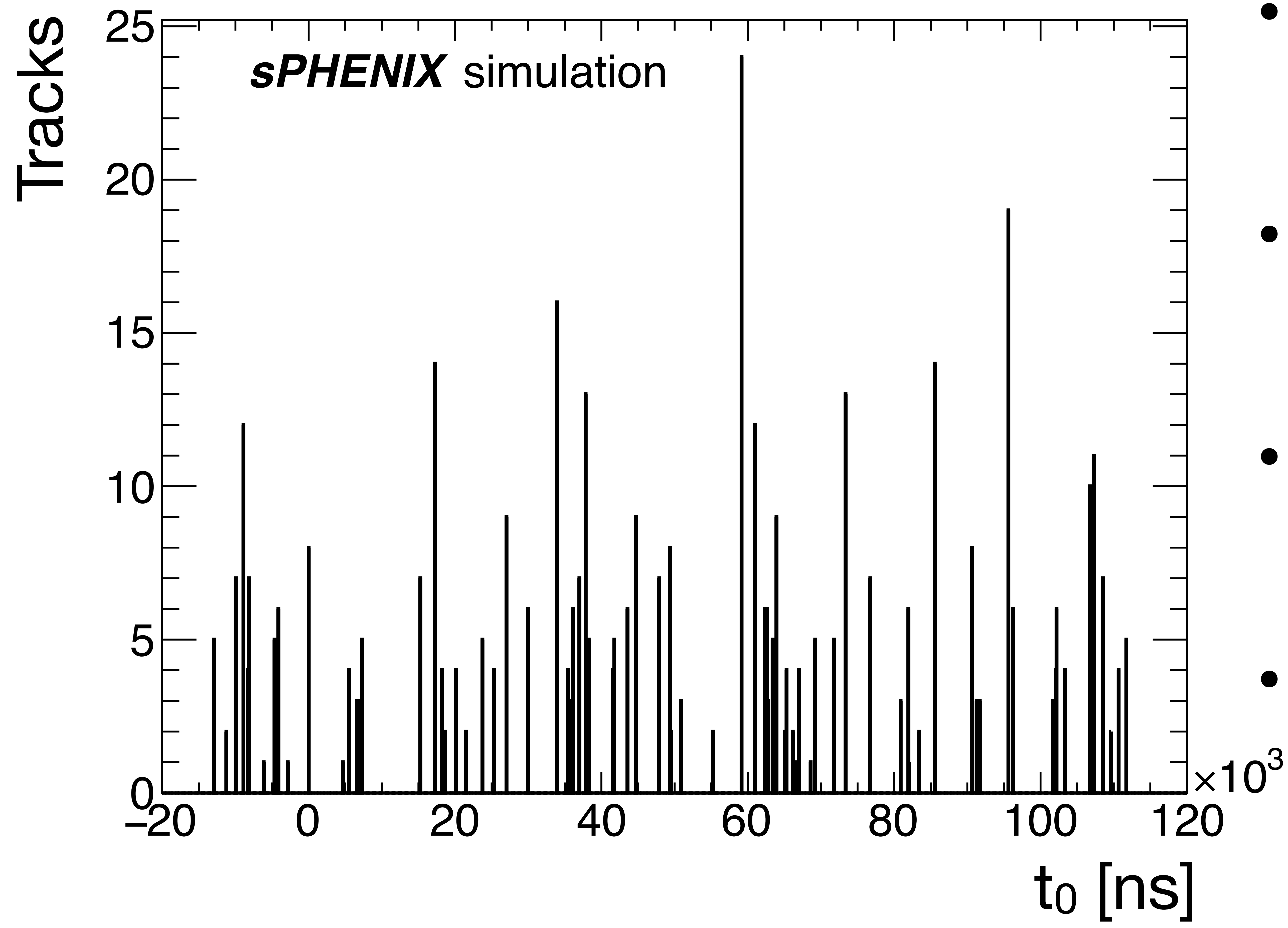
- Computationally expensive
  - Scales quadratically with the number of clusters in the event
  - Scales linearly with the number of track seeds created
- Track reconstruction needs to have high efficiency and purity to maximize physics and CPU resources

EIC Tracking Challenges

	EIC	RHIC	LHC → HL-LHC
Collision species	$\vec{e}+\vec{p}, \vec{e}+A$	$\vec{p}+\vec{p}/A, A+A$	$p+p/A, A+A$
Top x-N C.M. energy	140 GeV	510 GeV	13 TeV
Bunch spacing	10 ns	100 ns	25 ns
Peak x-N luminosity	10^{34} cm^{-2} s^{-1}	10^{32} cm^{-2} s^{-1}	$10^{34} \rightarrow 10^{35}$ cm^{-2} s^{-1}
x-N cross section	**50 μb**	**40 mb**	**80 mb**
Top collision rate	500 kHz	10 MHz	1-6 GHz
$dN_{ch}/d\eta$ in p+p/e+p	0.1-Few	~3	~6
Charged particle rate	**4M N_{ch}/s**	**60M N_{ch}/s**	**30G+ N_{ch}/s**

- EIC has low physics collision rate, despite high luminosity (~α_{EM}^2)
- Events have diverse topology —> stream 100% of the data rather than trigger on events
- Large background rate compared to physics collision rate

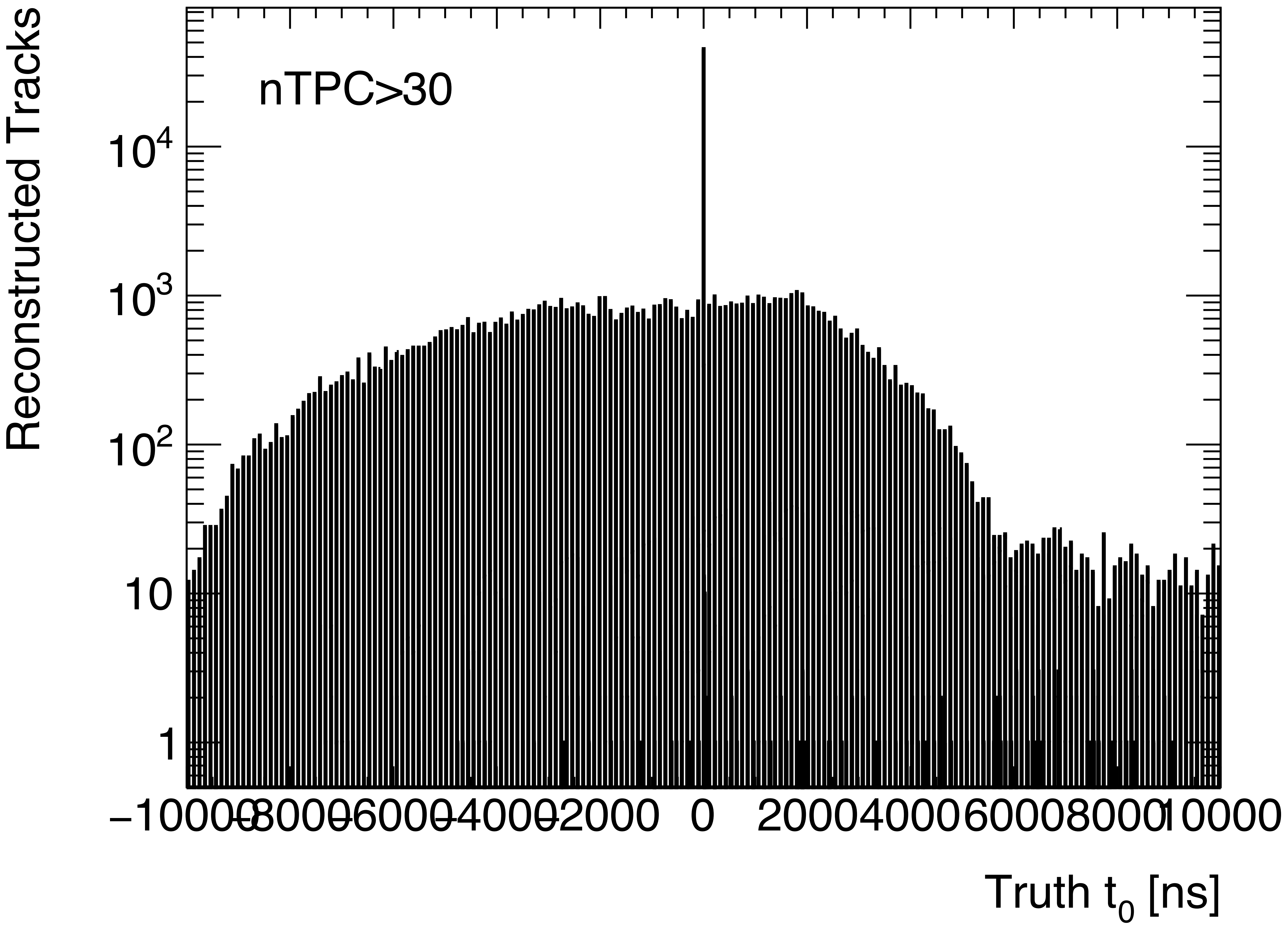
Event Reconstruction



- In a streaming system, the "event unit" is a time frame
- Reconstruction must operate in a time frame, identifying real physics events
- Collision of interest may have out of time pile up or hits embedded in it!
- Track and calorimeter reconstruction moving towards 4 and 5 dimensional (e.g. HGHCal, CALICE, ePIC forward HCal insert, tracking at sPHENIX, ePIC, LHC…)

4D Track Reconstruction

- Example - TPC has readout time of ~13 μs, while RHIC collides at ~100 ns
    - TPC sensitive to entire RHIC bunch structure!
- Requiring MVTX clusters on track (5 μs readout) greatly reduces out of time pileup
- Requiring INTT clusters on track almost entirely eliminates pileup



4D Track Reconstruction

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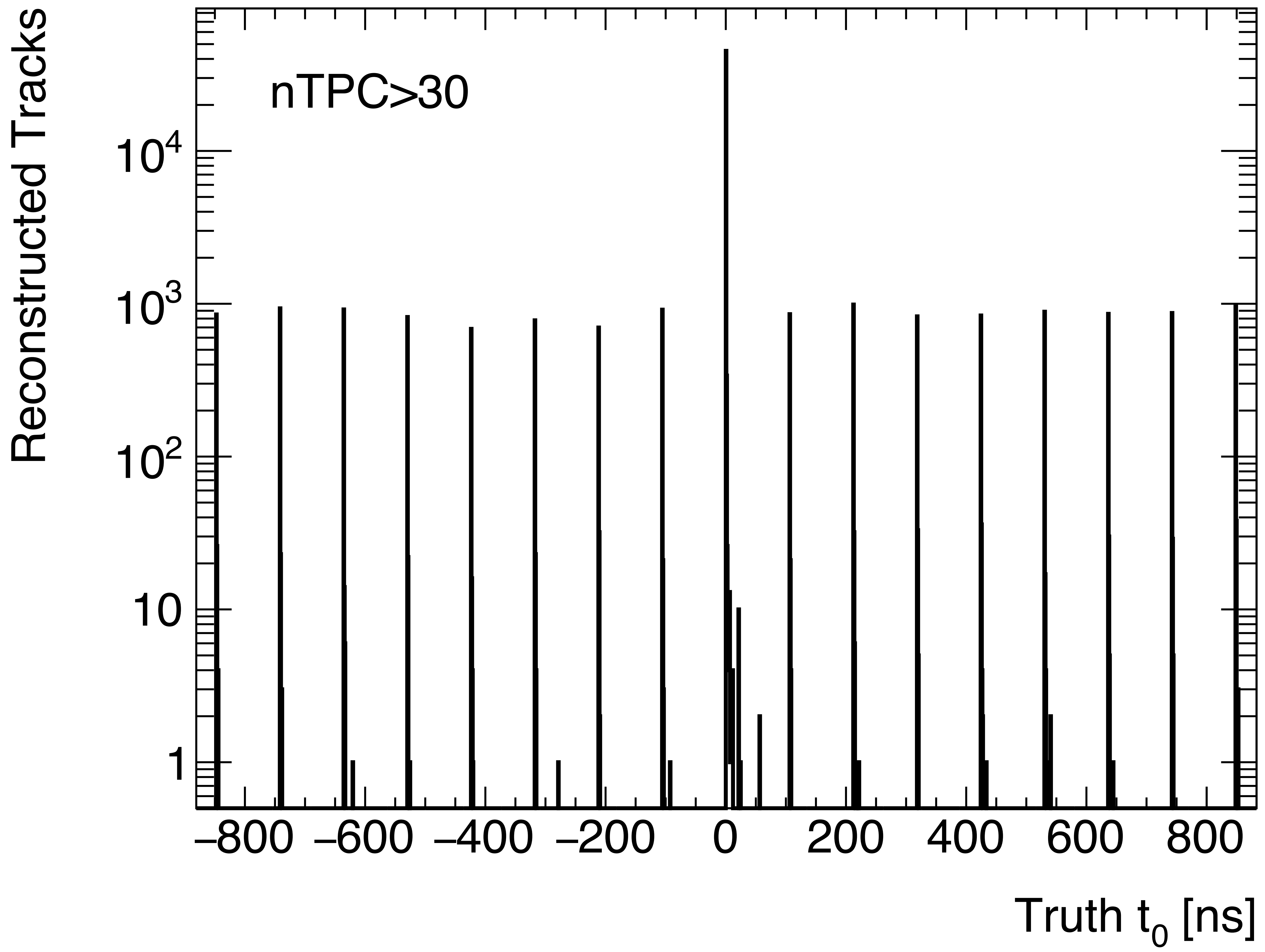

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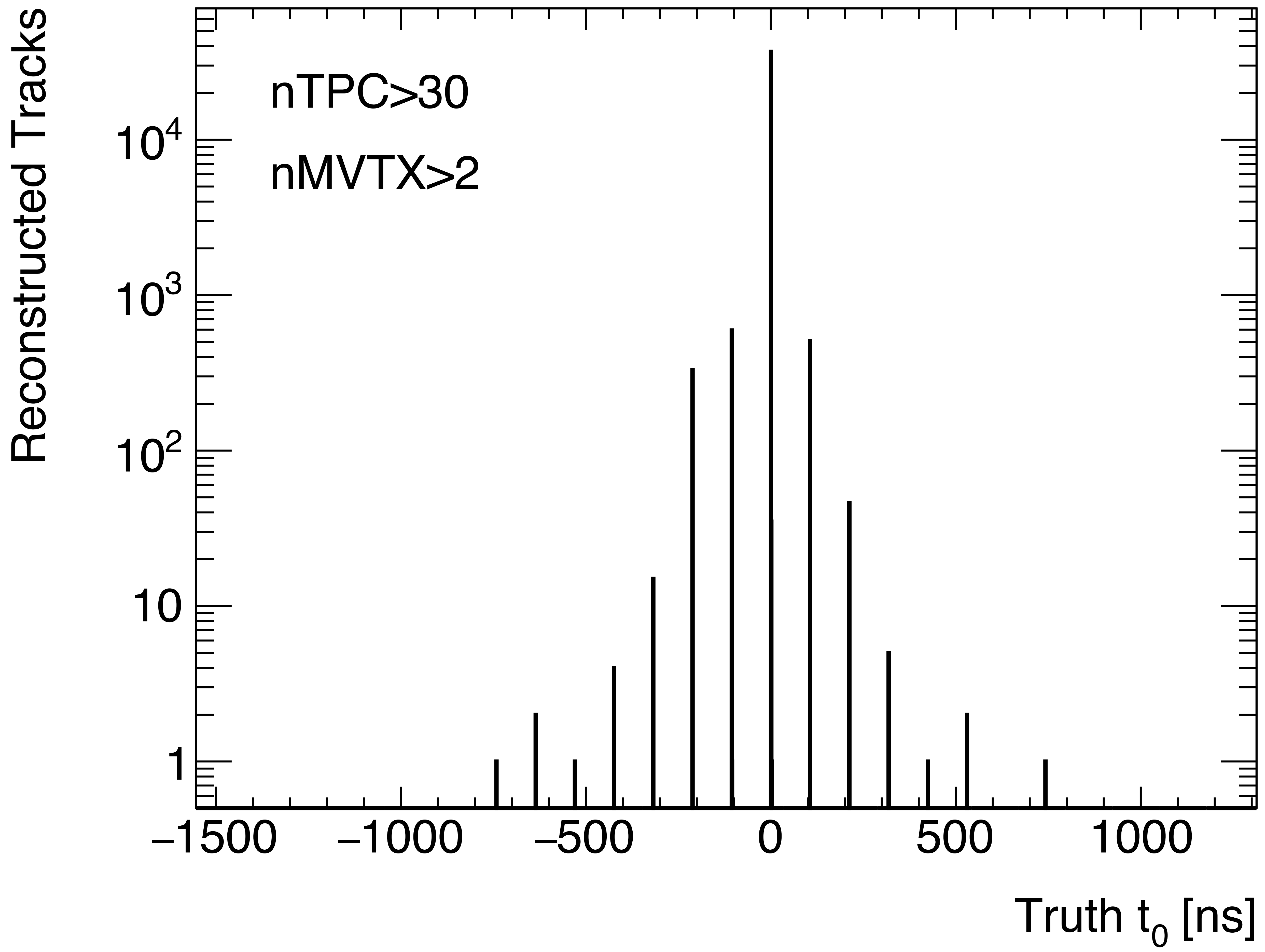

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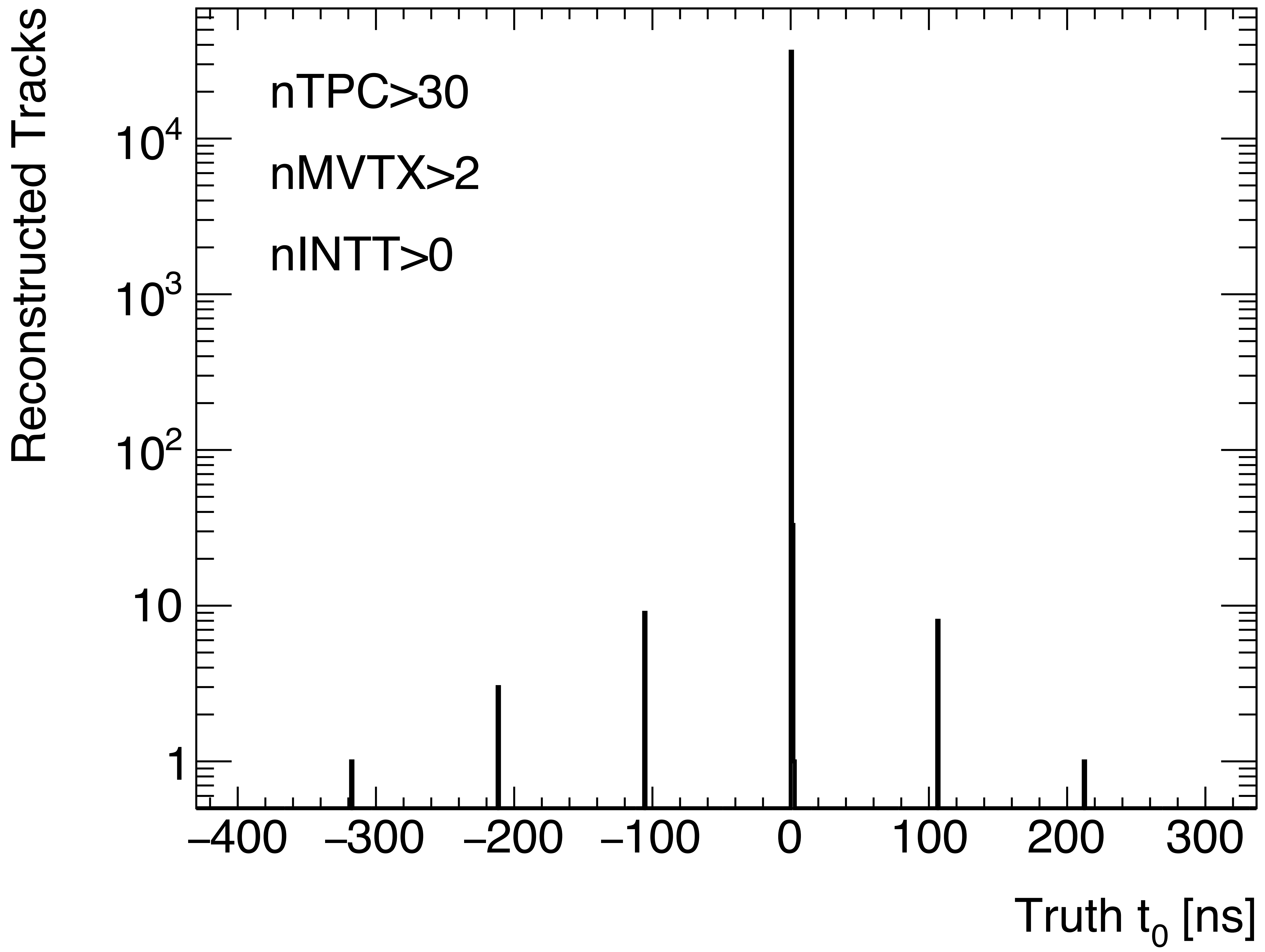
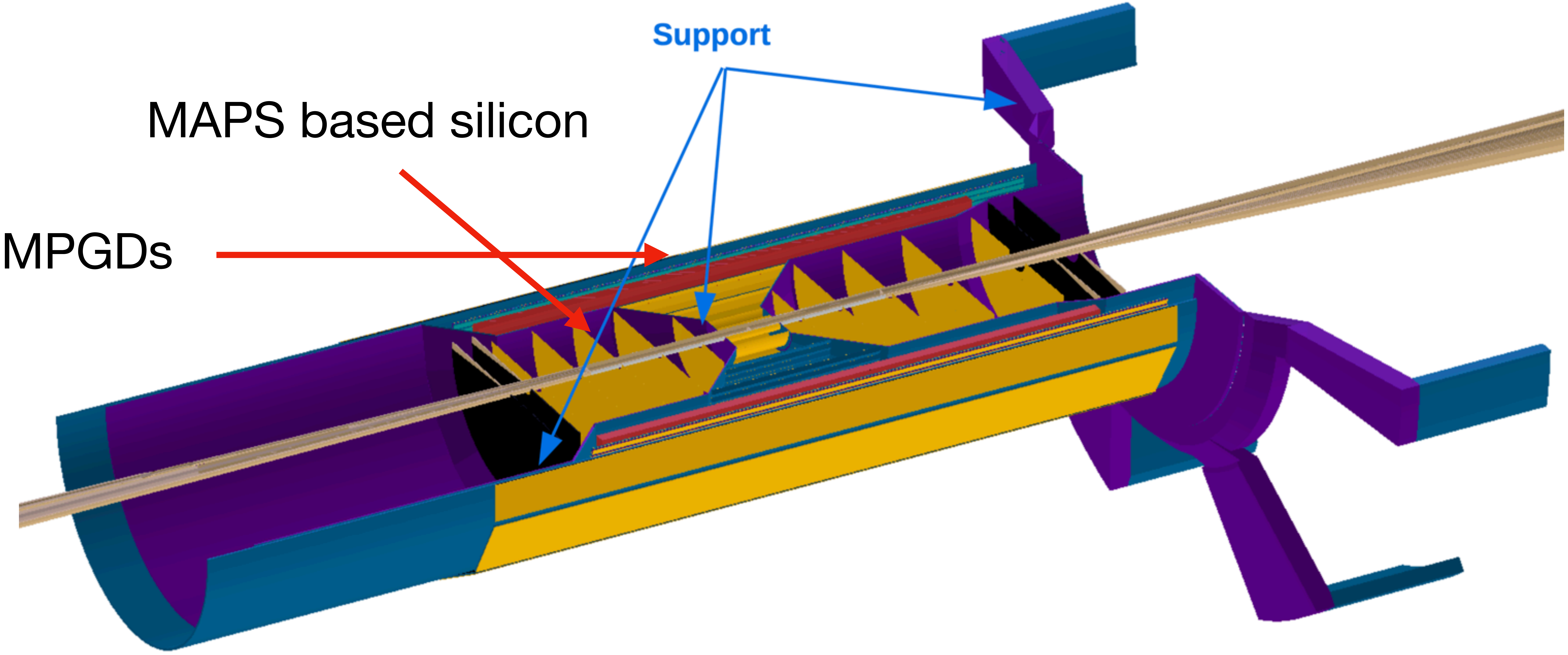


4D Track Reconstruction

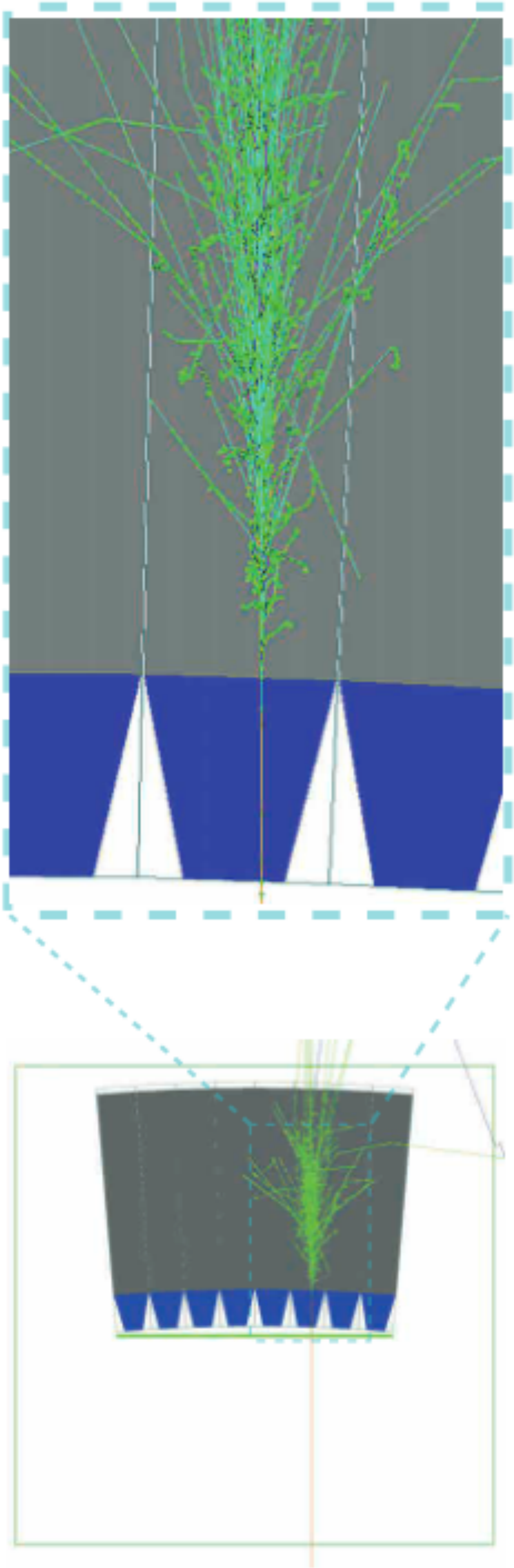


- Similar concept at ePIC - silicon slow (5 μs) and MPGD fast (~10s ns)
- Silicon sensitive to O(500) bunch crossings!

Reminder

- We started out saying we wanted to know all particles
  - 4 momentum and position of origin (position of closest approach to vertex)
  - Charge
  - Particle type (need PID, but we can use some tricks with tracking and calorimetry)
- We have this information from tracks + calorimeter clusters. Can we combine them?

Particle Flow

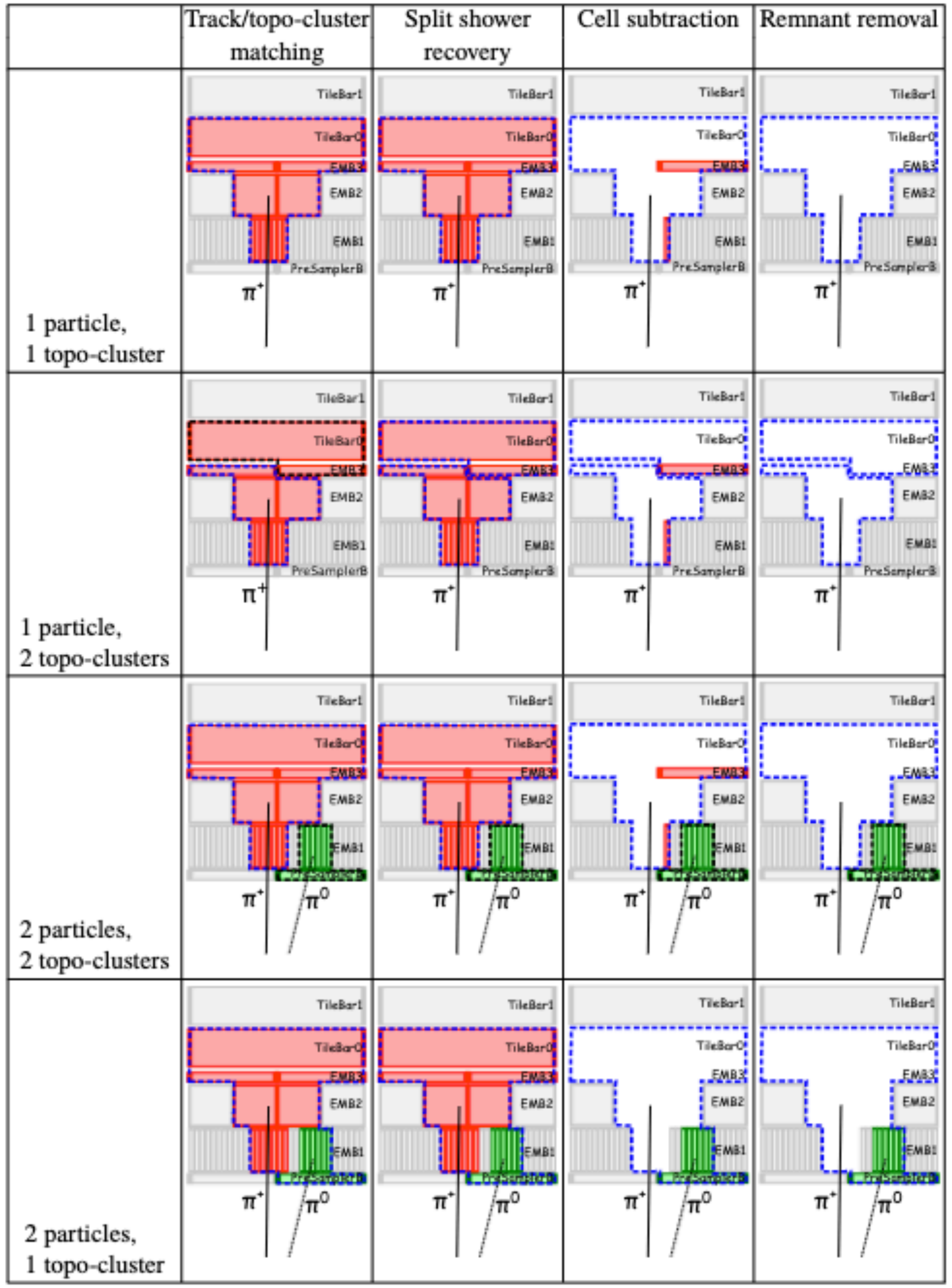


- Connecting tracks to calorimeter clusters is the basis for particle flow algorithms to create real particles with 4 momenta

- In principle - easy

- In practice - very complex as there are many different situations the algorithm needs to consider

Particle Flow



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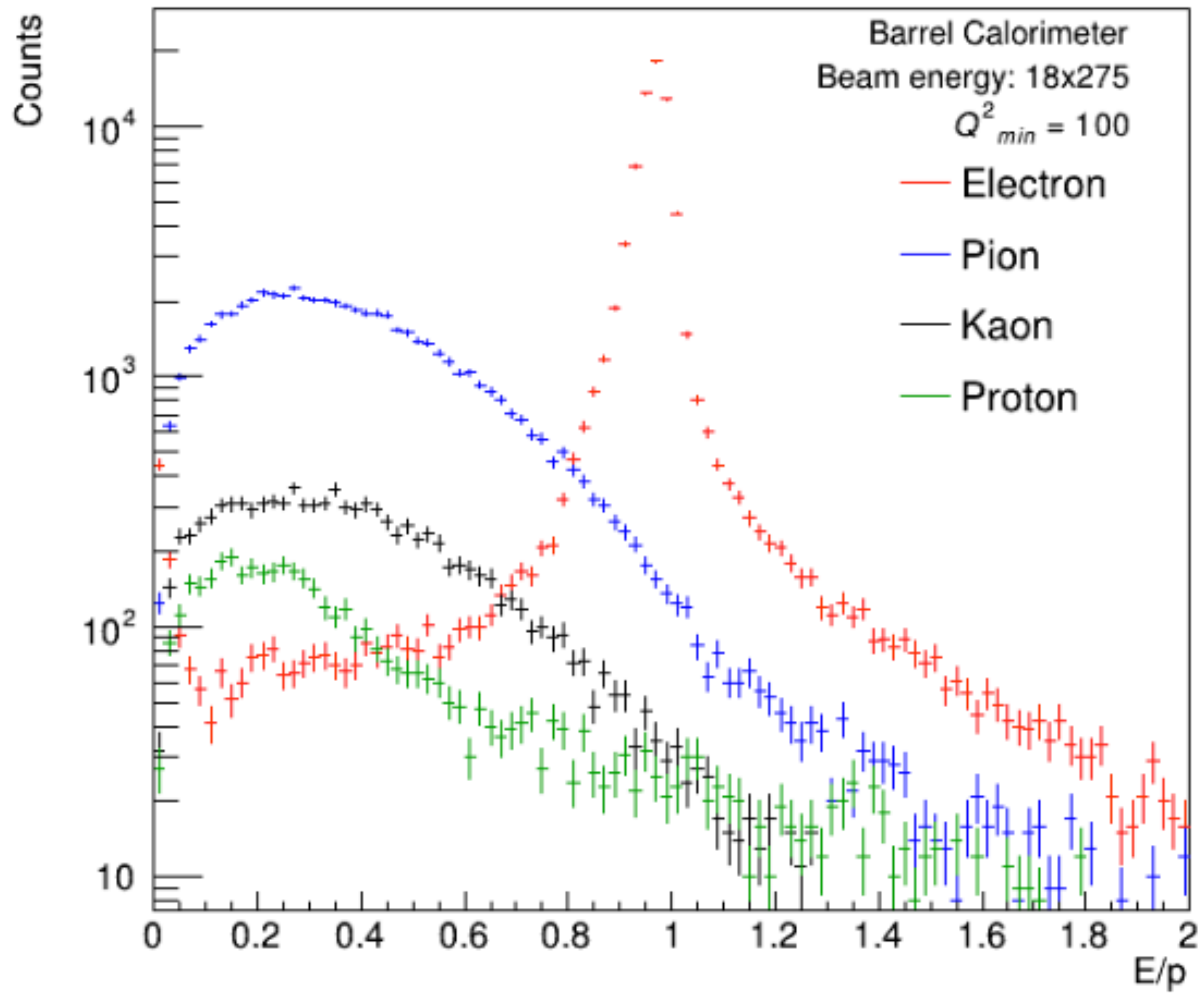
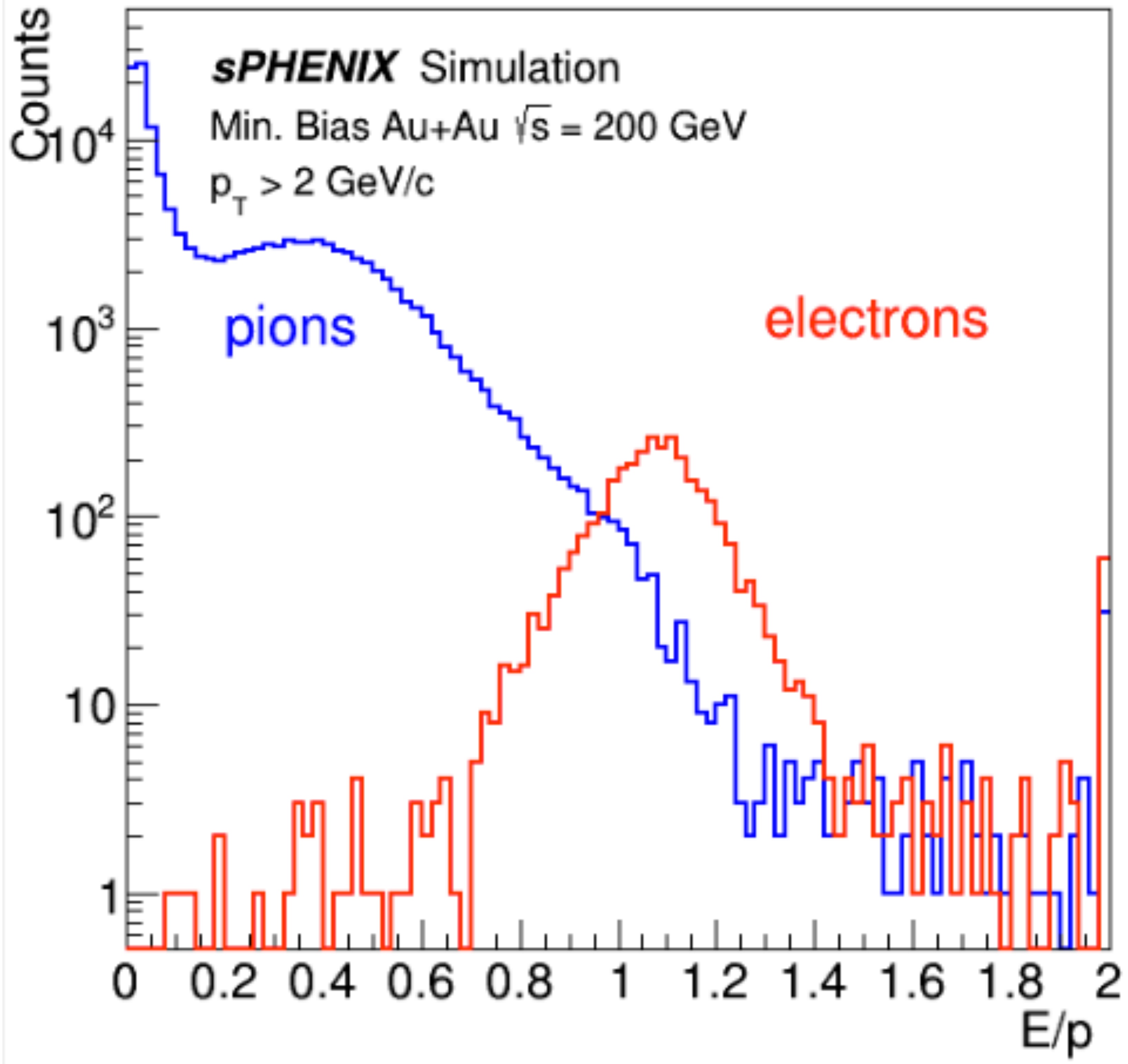
EPJC 77, 466 (2017)

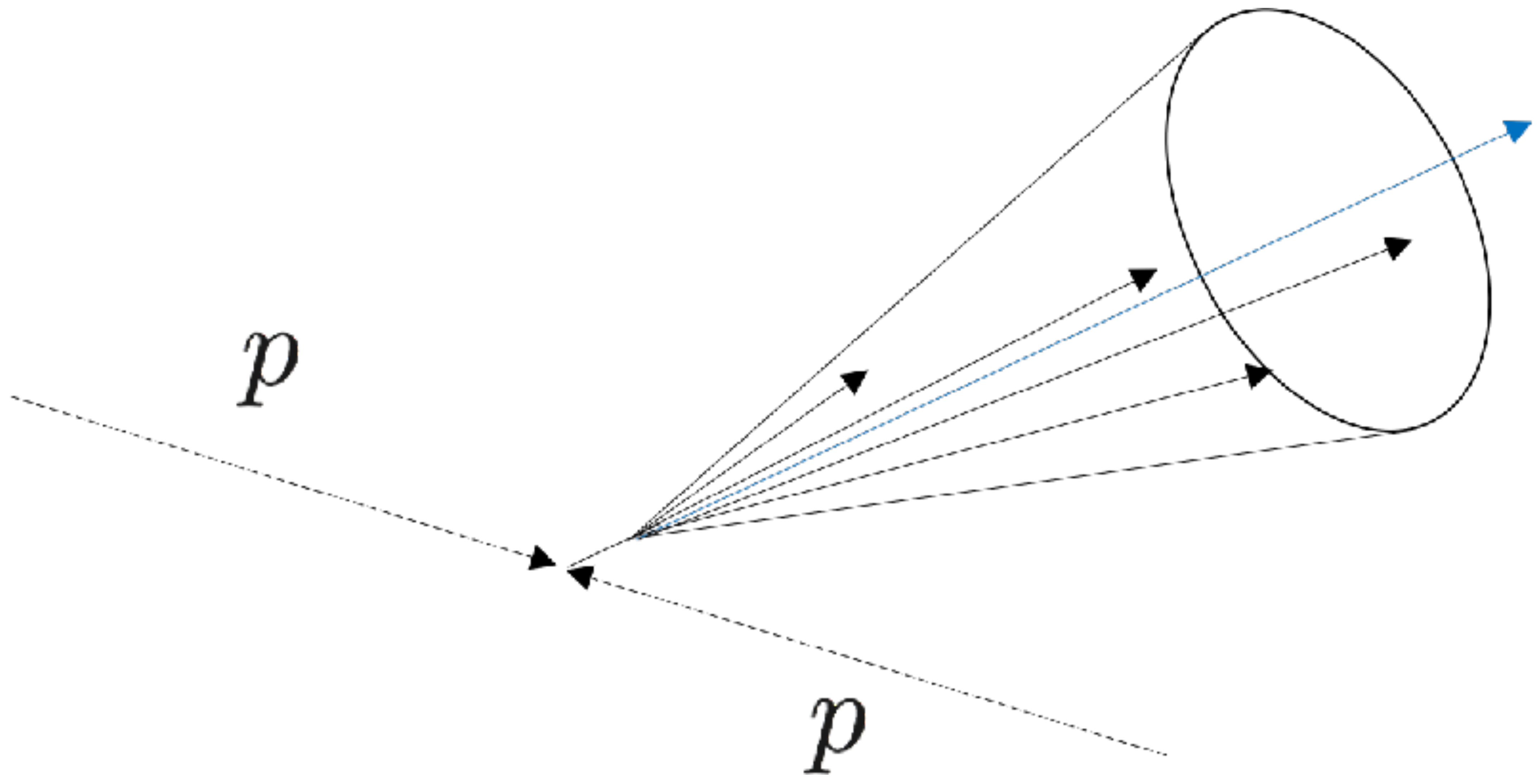
Electron Finding





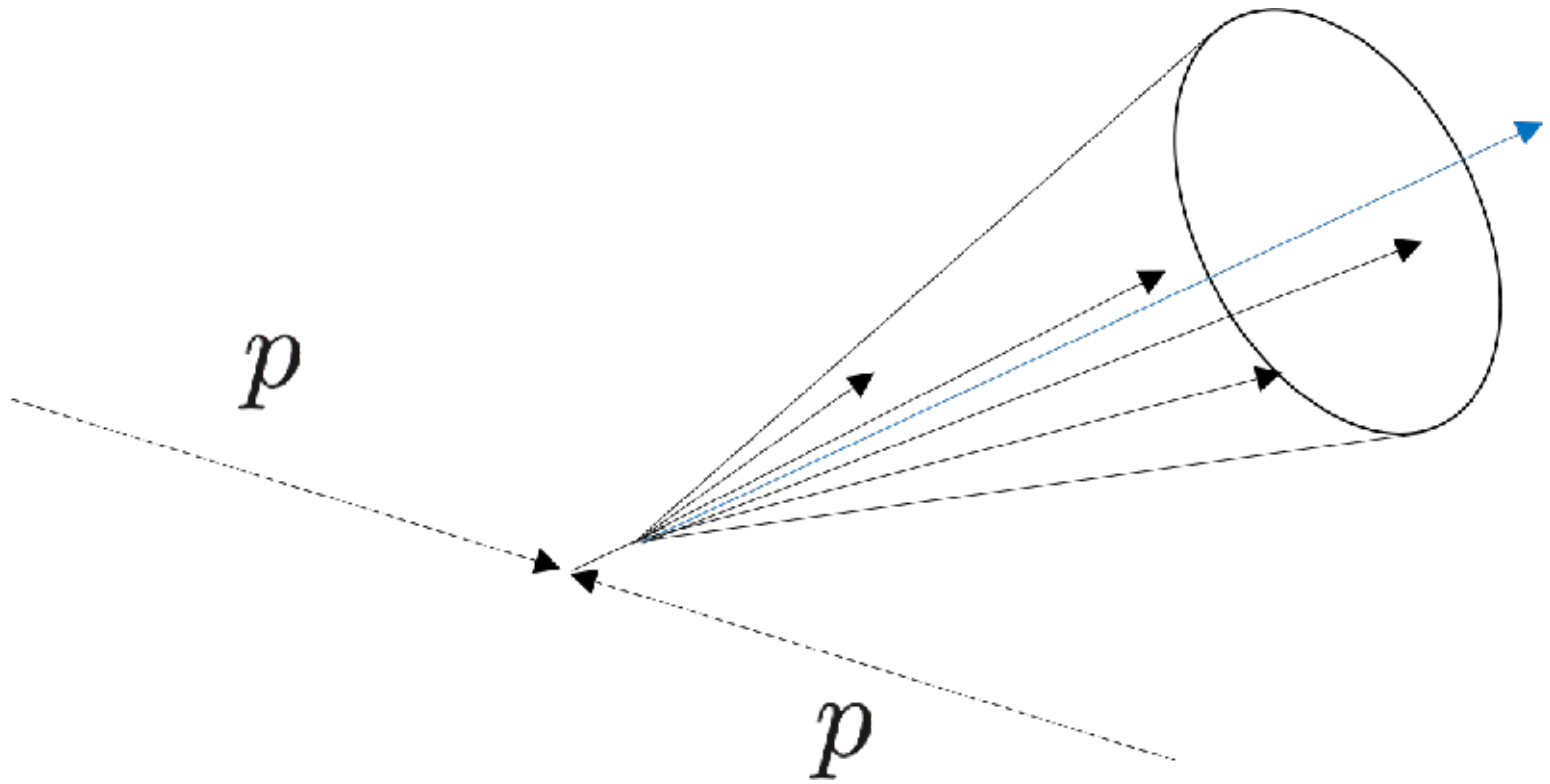
- Electron finding is made easier since electromagnetic showers are more contained than hadronic showers
- Can match tracks to calorimeter clusters and make strong energy/momentum cuts
  - Electrons deposit nearly all energy into EMCal, hadrons should not

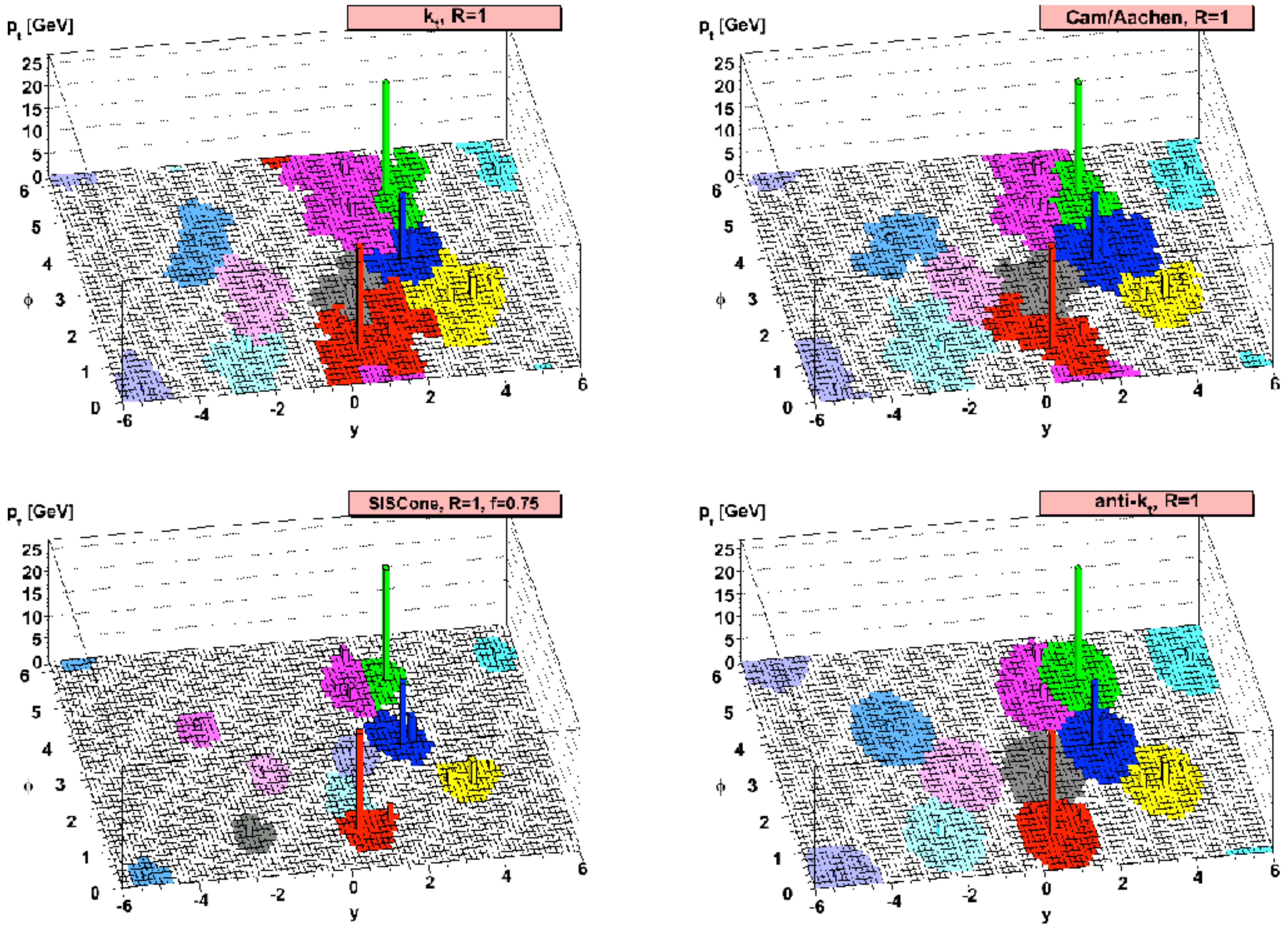
Jet Finding



- Physics definition of a jet - spray of particles resulting from a high energy parton
- Experimental definition - what a jet reconstruction algorithm determines
- Could find jets with calo clusters, tracks, particle flow objects…

Jet Finding





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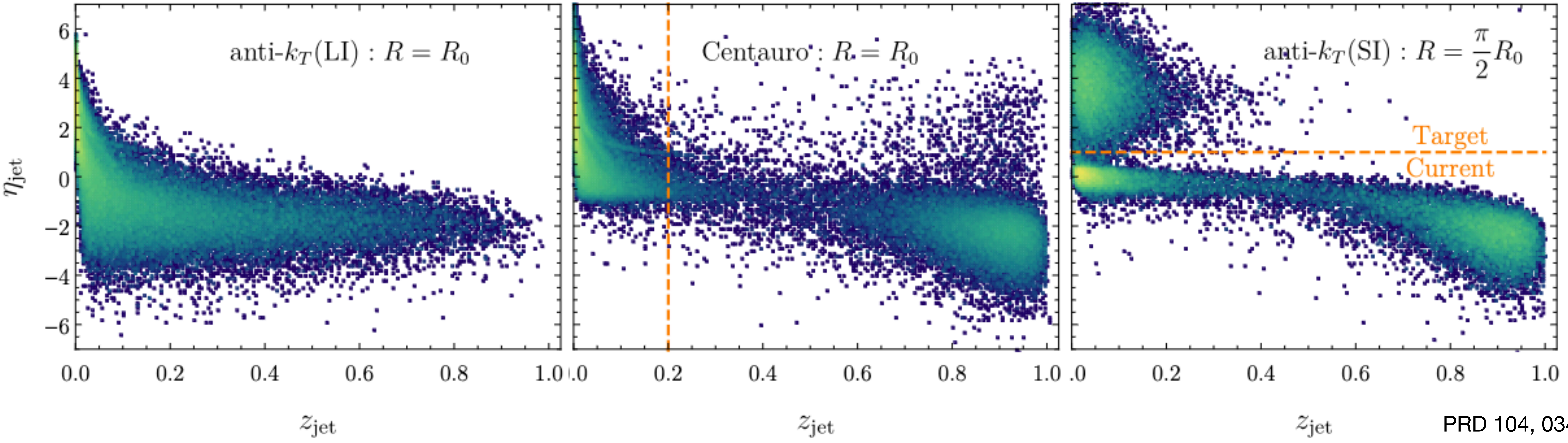
JHEP 04, 063 (2008)

Jet Finding



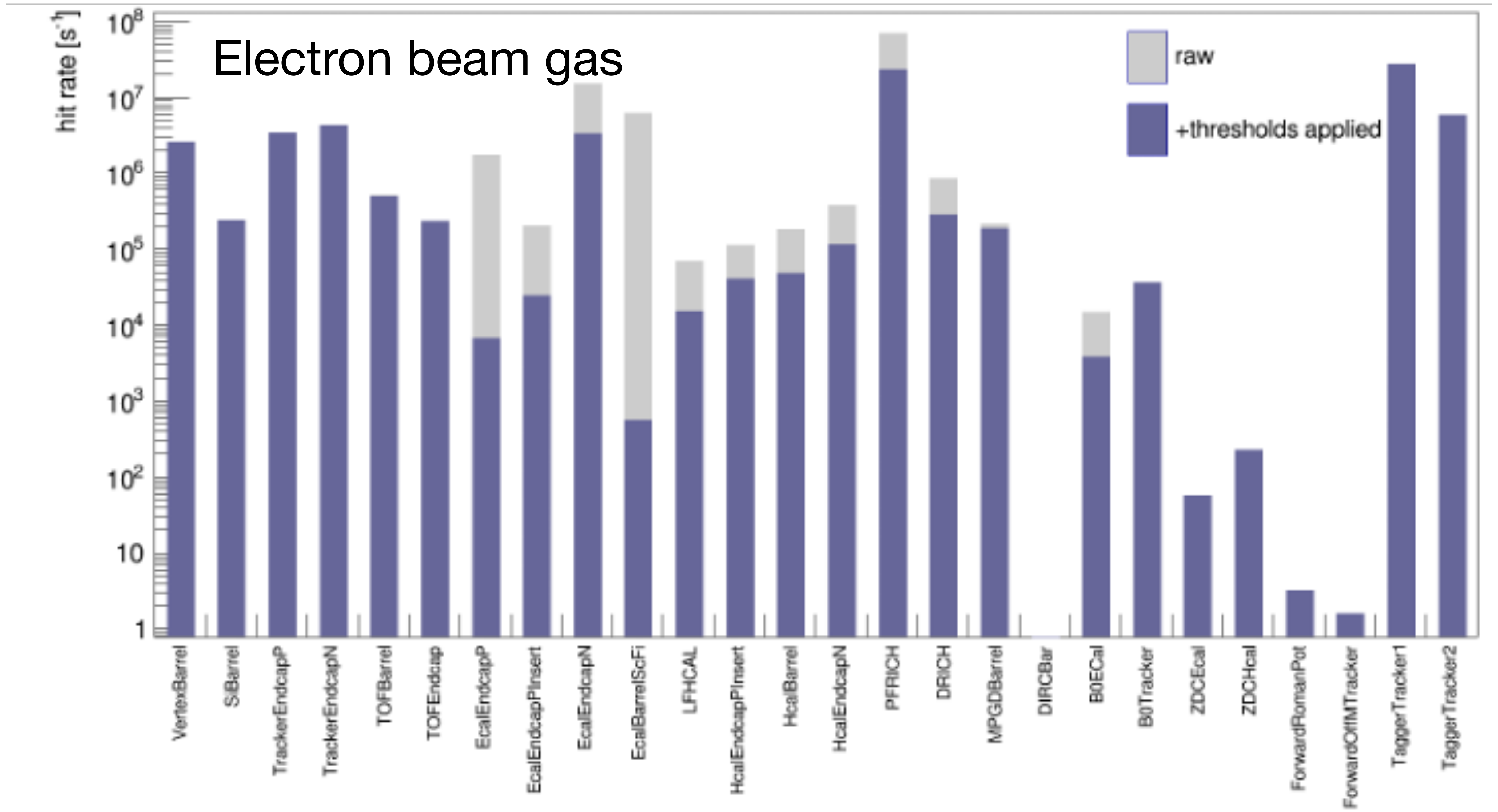
PRD 104, 034005 (2020)

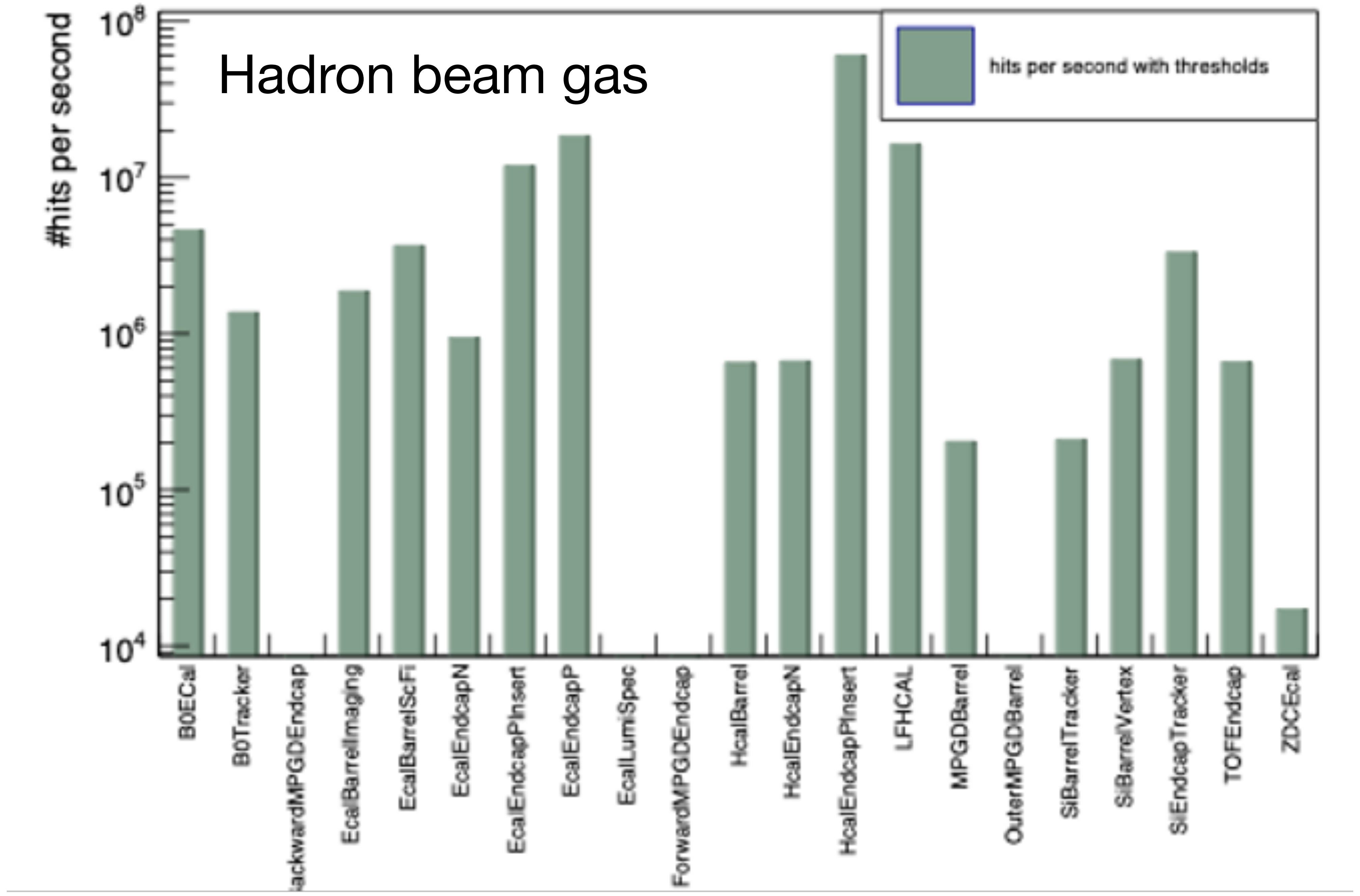
- Most common jet algorithm at hadron colliders is anti-k_T
- However, new algorithms can be defined that better suit DIS kinematics

Backgrounds

- Event reconstruction is significantly simpler in the single physics event simulation world
- Real life has contributions from many different background sources
    - Synchrotron radiation, electron/proton beam gas background, beam pipe effects…
- Even reconstruction has to handle these contributions

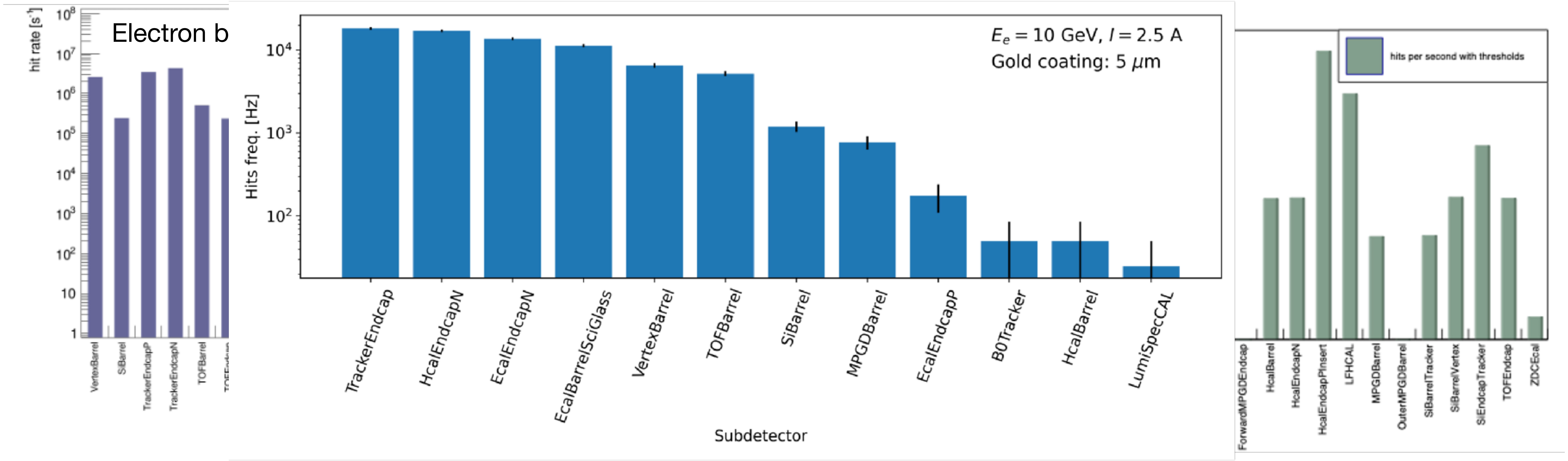
Backgrounds - Examples





- Example - electron and hadron beam gas backgrounds currently expected to provide millions of additional hits per second in detectors!
- Synchrotron radiation backgrounds need to be understood too

Backgrounds - Examples



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(Some) Conclusions

- Modern particle physics experiments are an incredibly complex system of hardware, computing, engineering, and science
    - Things I didn't cover in the detail they deserve
        - Interplay between DAQ, streaming readout, and reconstruction
        - Calibrations - energy calibrations, tracker alignment…
        - Analysis techniques - unfolding, efficiencies, resolutions…
        - Many hardware/software R&D efforts
        - …
- 2 hours only scratching the surface - new detector R&D and algorithmic/computational R&D are pushing the field forward
- EIC has a long but exciting road ahead!