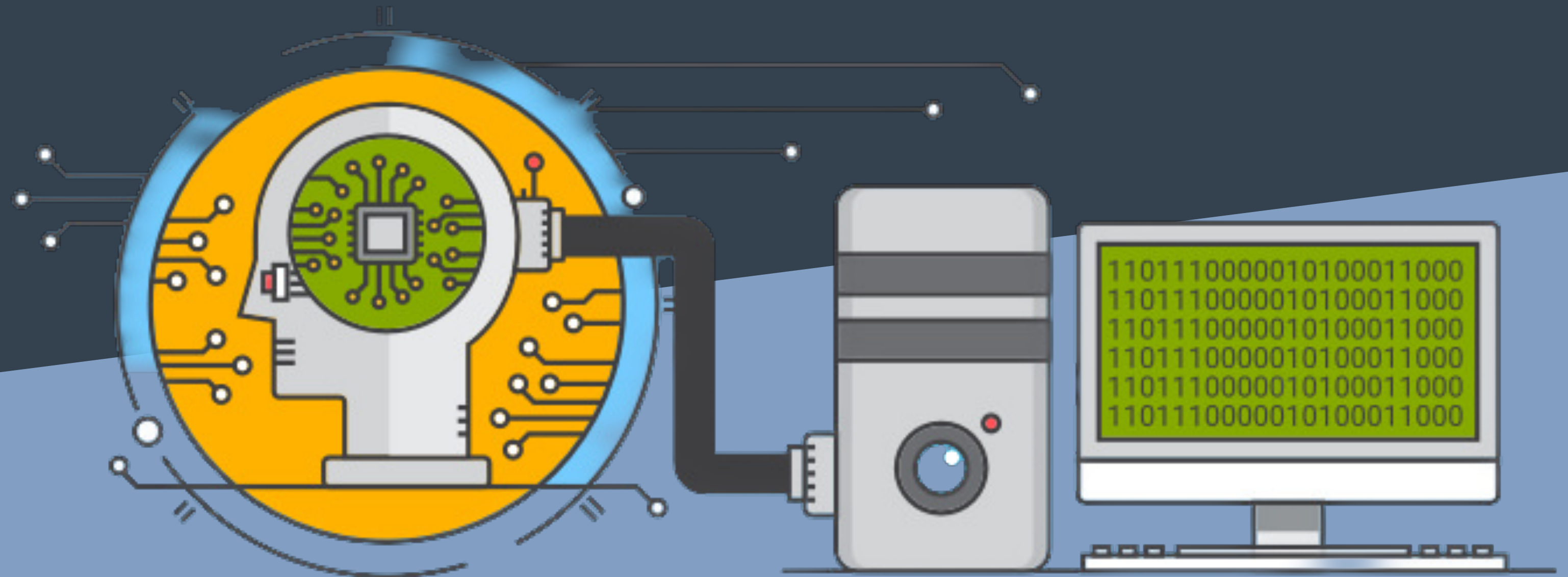


# Artificial Intelligence in Nuclear Physics

Artificial Intelligence/Machine Learning for Physics Applications

G.Gavalian (Jefferson Lab)



Angelos Angelopoulos (CRTC)  
Polykarpos Thomadakis (CRTC),  
Nikos Chrisochoides (CRTC)  
Department of Computer Science,  
Old Dominion University, Norfolk, VA, 23529

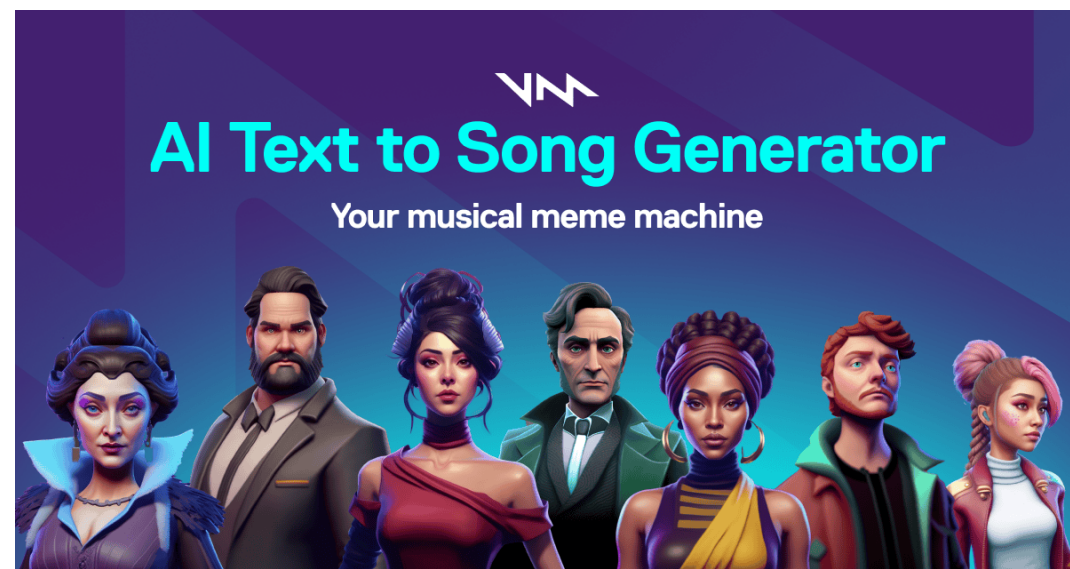


Richard Tyson  
(University of Glasgow)

HUGS (June 2024)

- AI/ML advancements, direction, possibilities
- How AI/ML is used in Nuclear Physics
- What is the impact on physics from AI/ML

# What is AI?



## Midjourney

Rowan Atkinson from Version 1 through Version 5 of Midjourney's renderer.

The same prompt was used, except for replacing the version number at the end of each one. The most 'Rowan'-like image from each group of four was selected.



# Image Generation DALL-E

Here are the images showing a footballer, a goalkeeper, and a defender playing football on Mars.



Here are the images depicting four people playing ice hockey on the moon, each wearing Nike brand skates. Earth and Saturn are visible in the background.



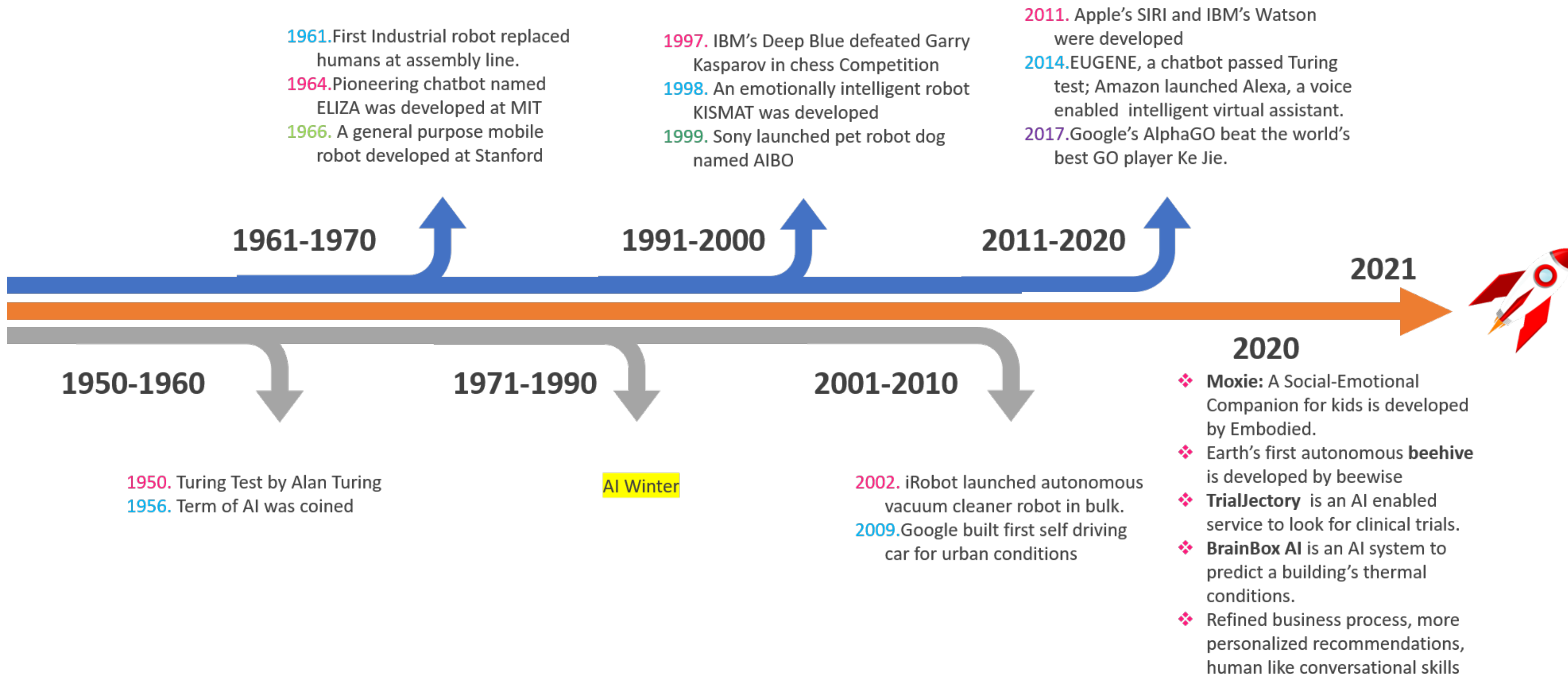
- ▶ Full background simulation, a city with lights
- ▶ Crowd simulation without artifacts
- ▶ Light reflections in the paddles

## Generating Video in 2023



## SORA (2024) Demo-Video

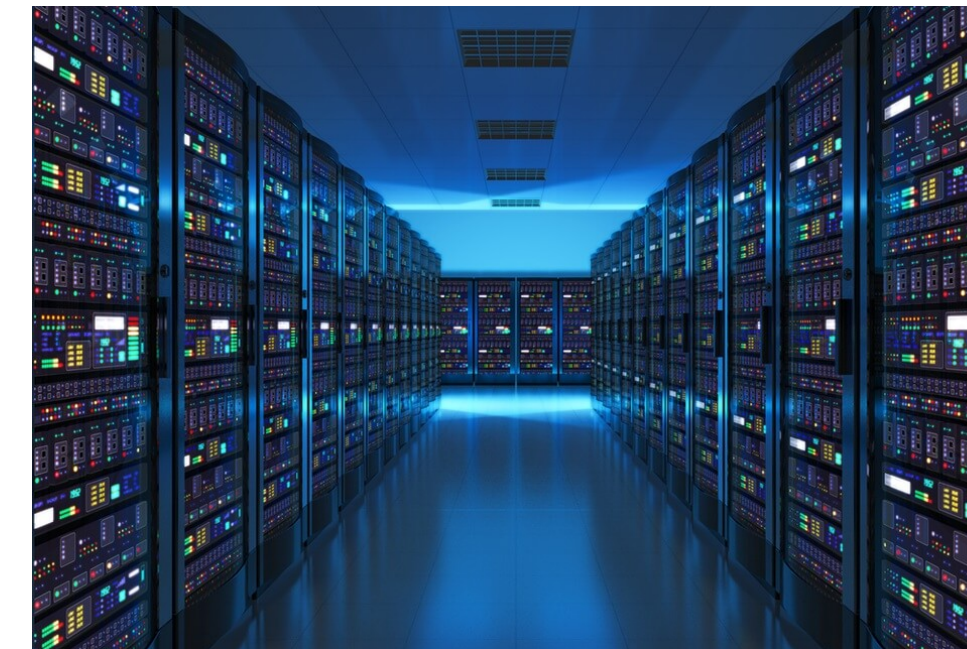






My First experience with Event Reconstruction  
Rate:  $\sim 0.0008$  Hz (single person, assuming 20 min per event)  
Earth Population: 4.767 billion (2,135 kHz assuming 56% in the age bracket 21-65)

CLAS12 event reconstruction  
Rate: 2-3 Hz (single CPU) (many more channels, higher rates)  
Computers now (64 Cores), 2.6 MHz



1983

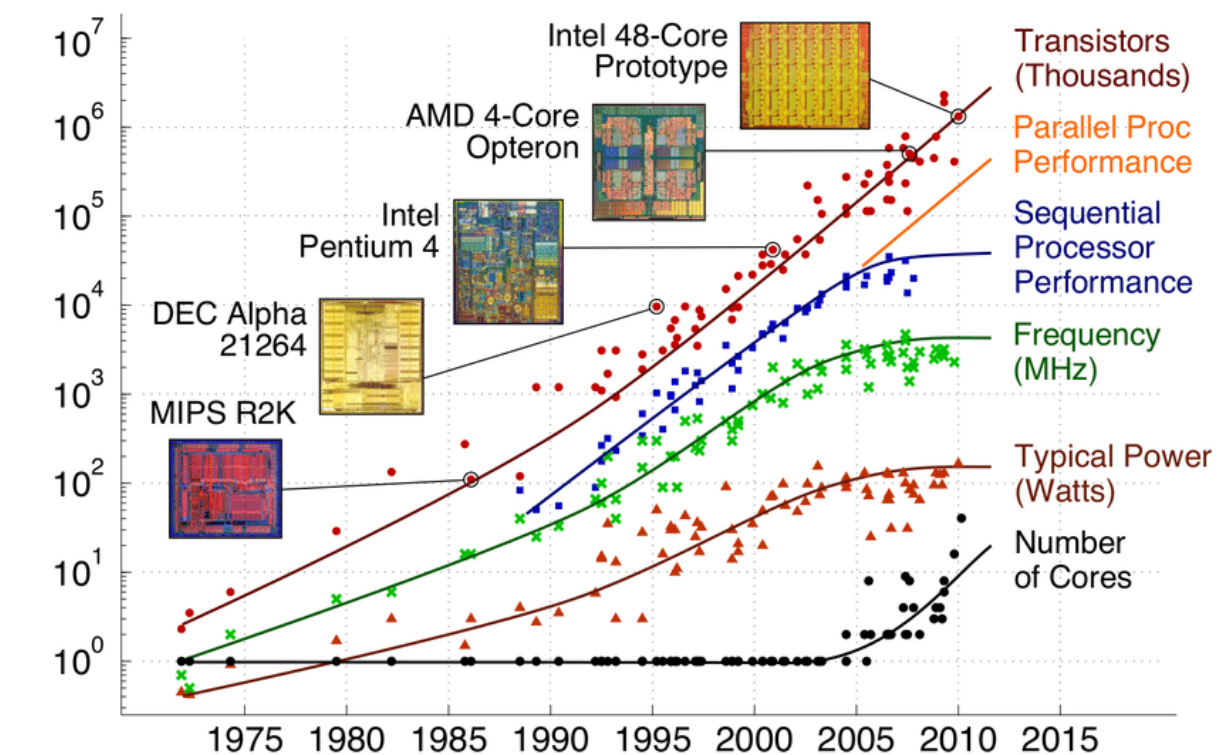
2023

?

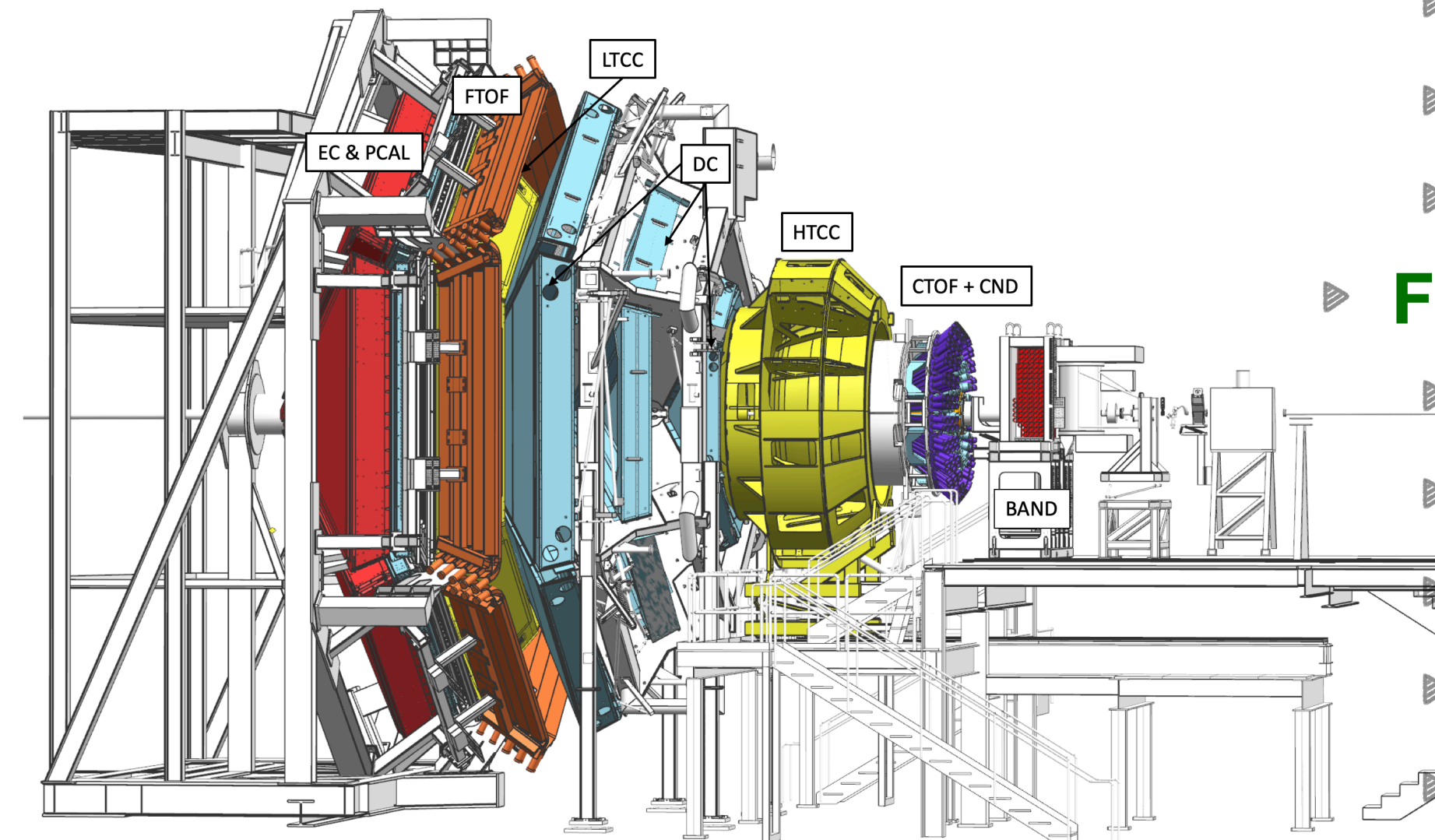
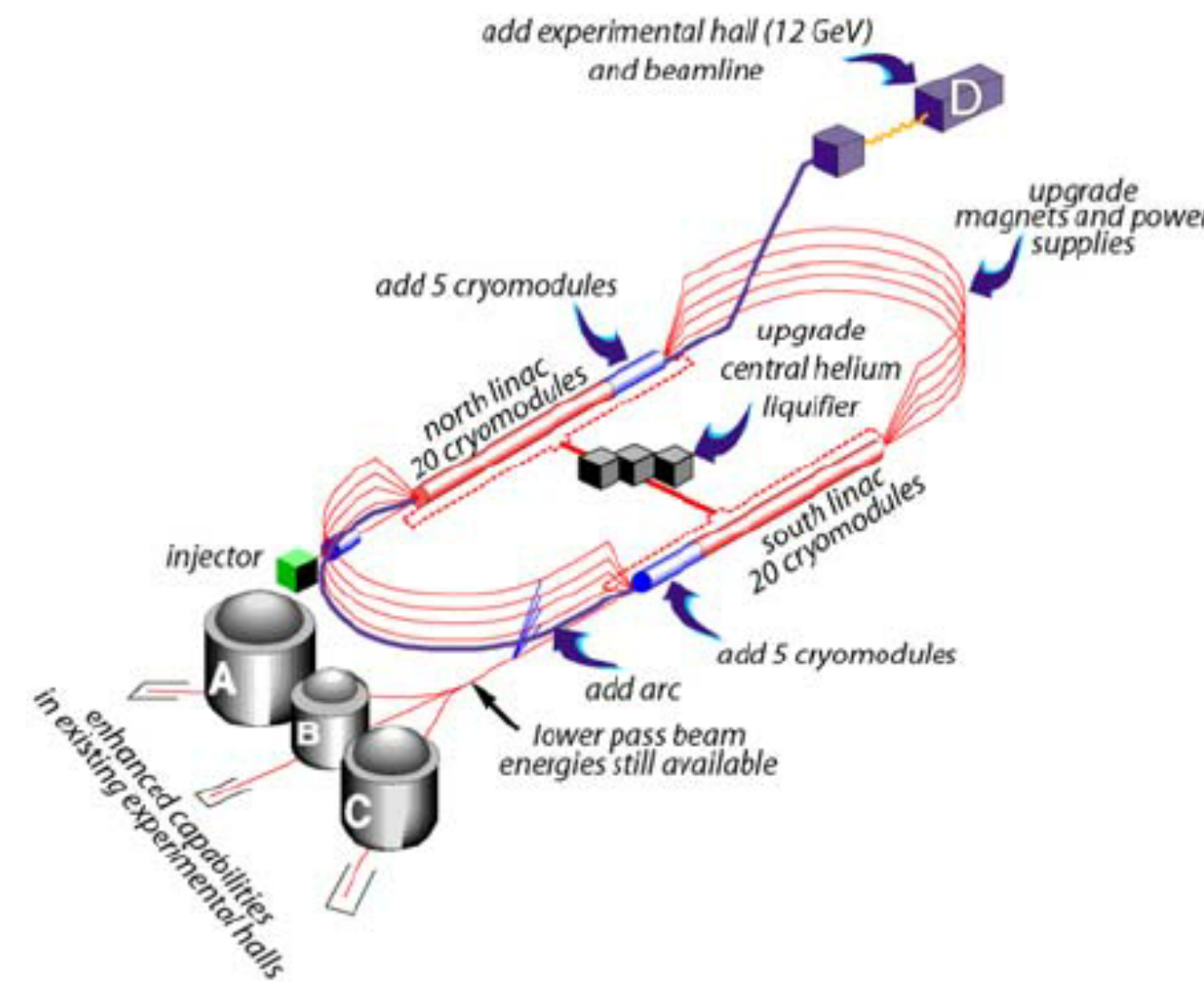
1996-2001



CLAS6 event reconstruction  
Rate: 8 Hz (single CPU)  
Computers 4 Cores, 2.4 MHz







## ▶ CEBAF

- ▶ 12 GeV electron beam distributed to 4 experimental hall
- ▶ Each experimental hall contains a detector system for specific experiments

## ▶ Hall-B:

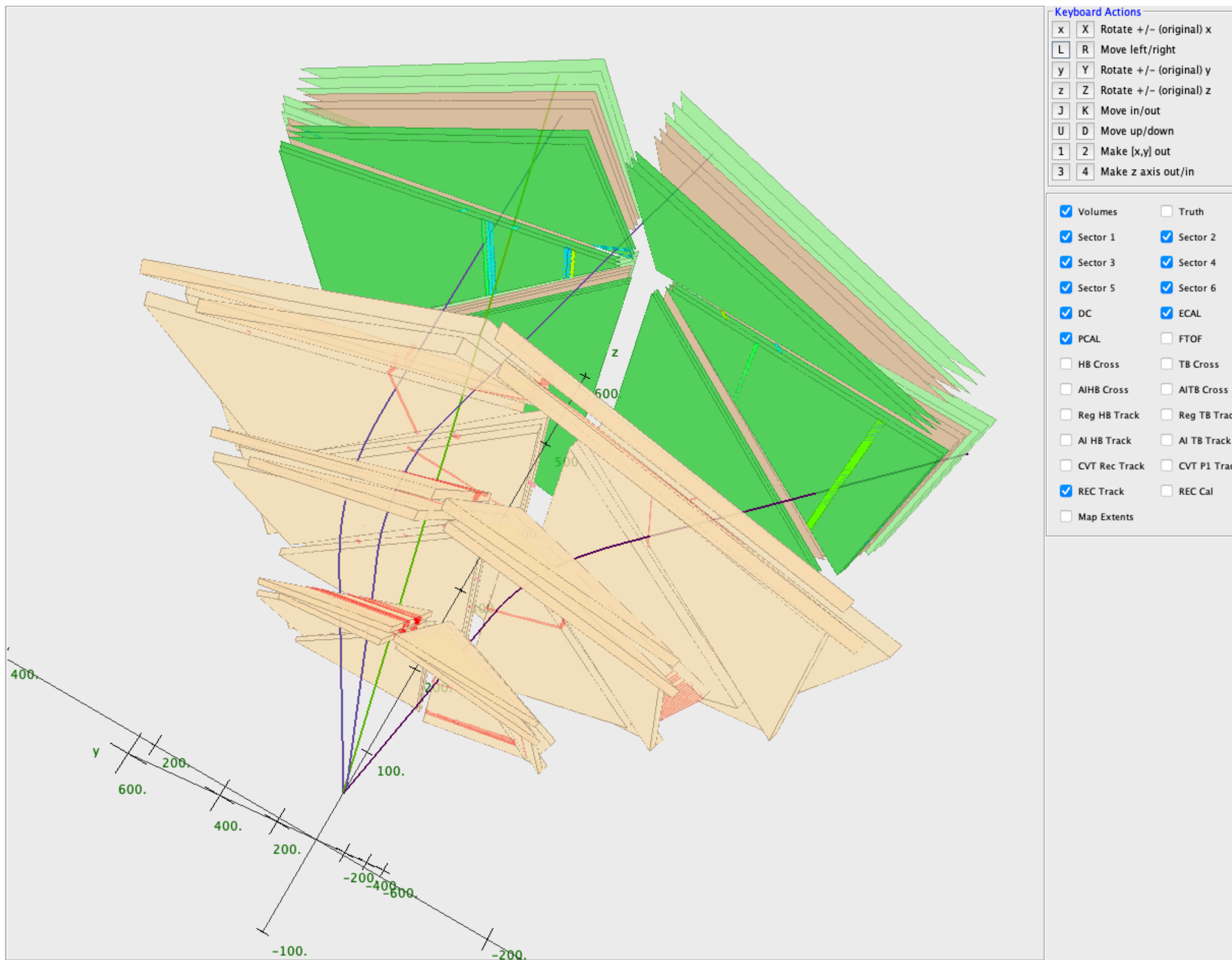
- ▶ CEBAF Large Acceptance Spectrometer (CLAS12) Located in Hall-B

### ▶ **Central Detector:**

- ▶ Silicon Tracker
- ▶ Time-Of-Flight
- ▶ Neutron Detector

### ▶ **Forward Detector:**

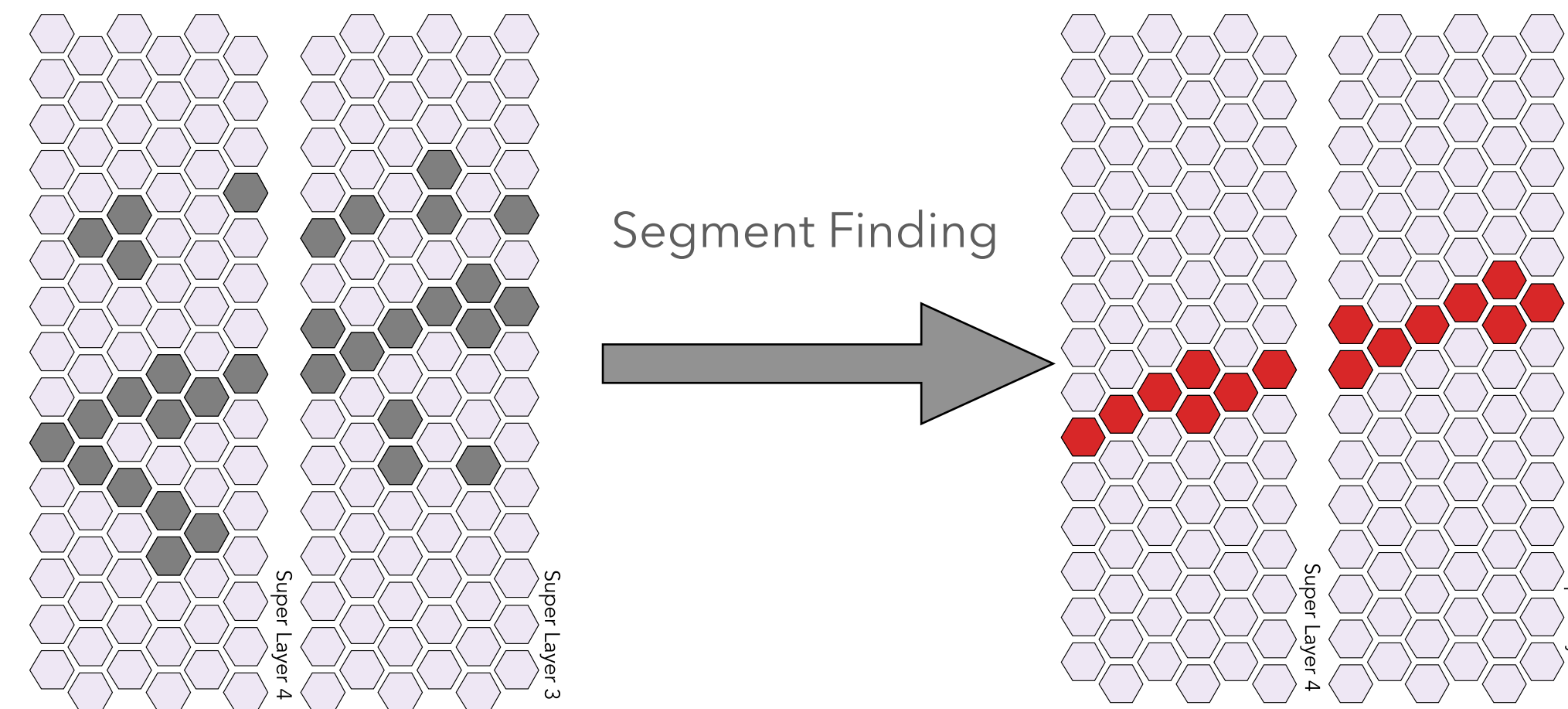
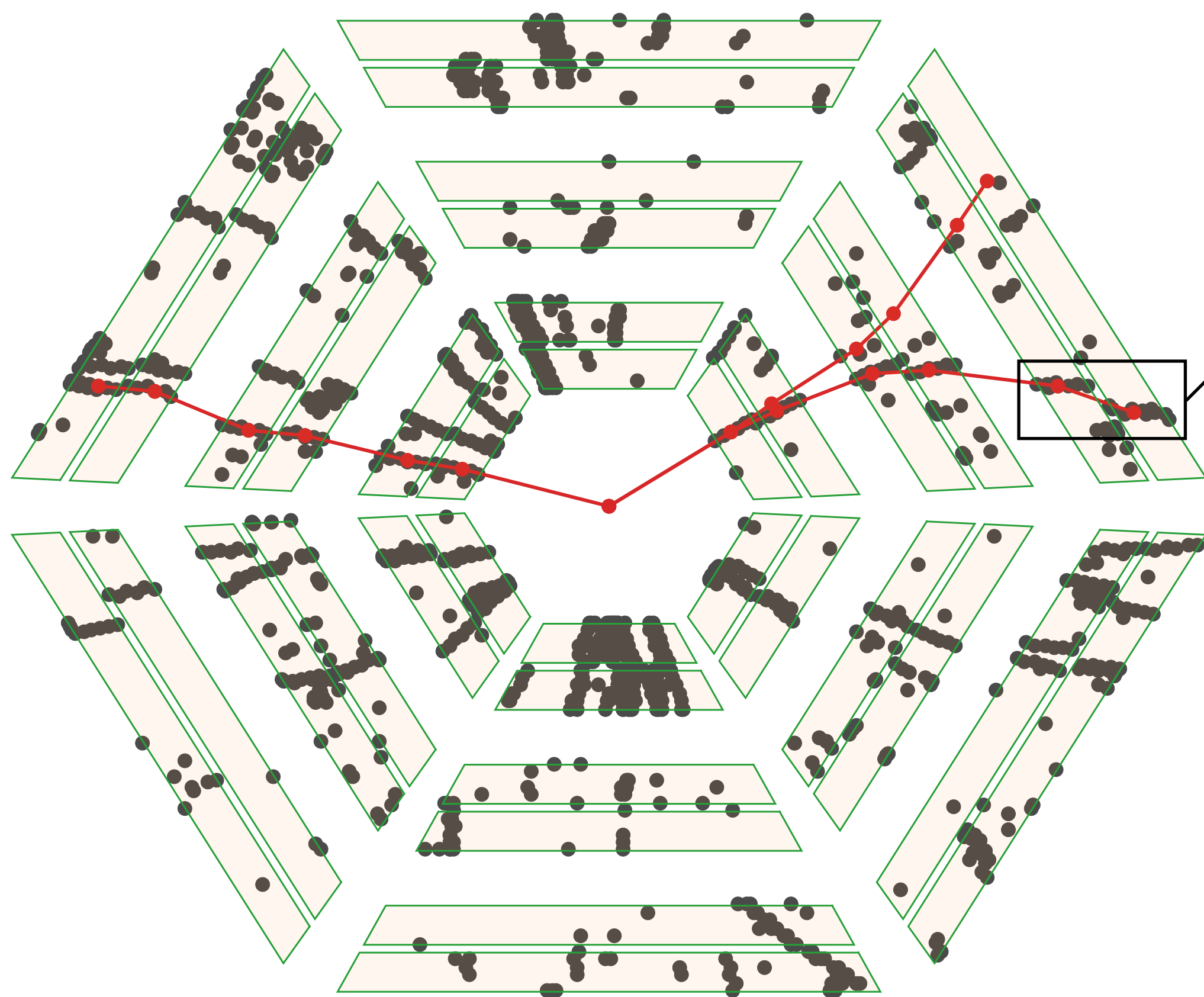
- ▶ Drift Chambers
- ▶ Time of Flight
- ▶ High Threshold Cherenkov Counter
- ▶ Ring Imaging Cherenkov Counter
- ▶ Electromagnetic Calorimeter



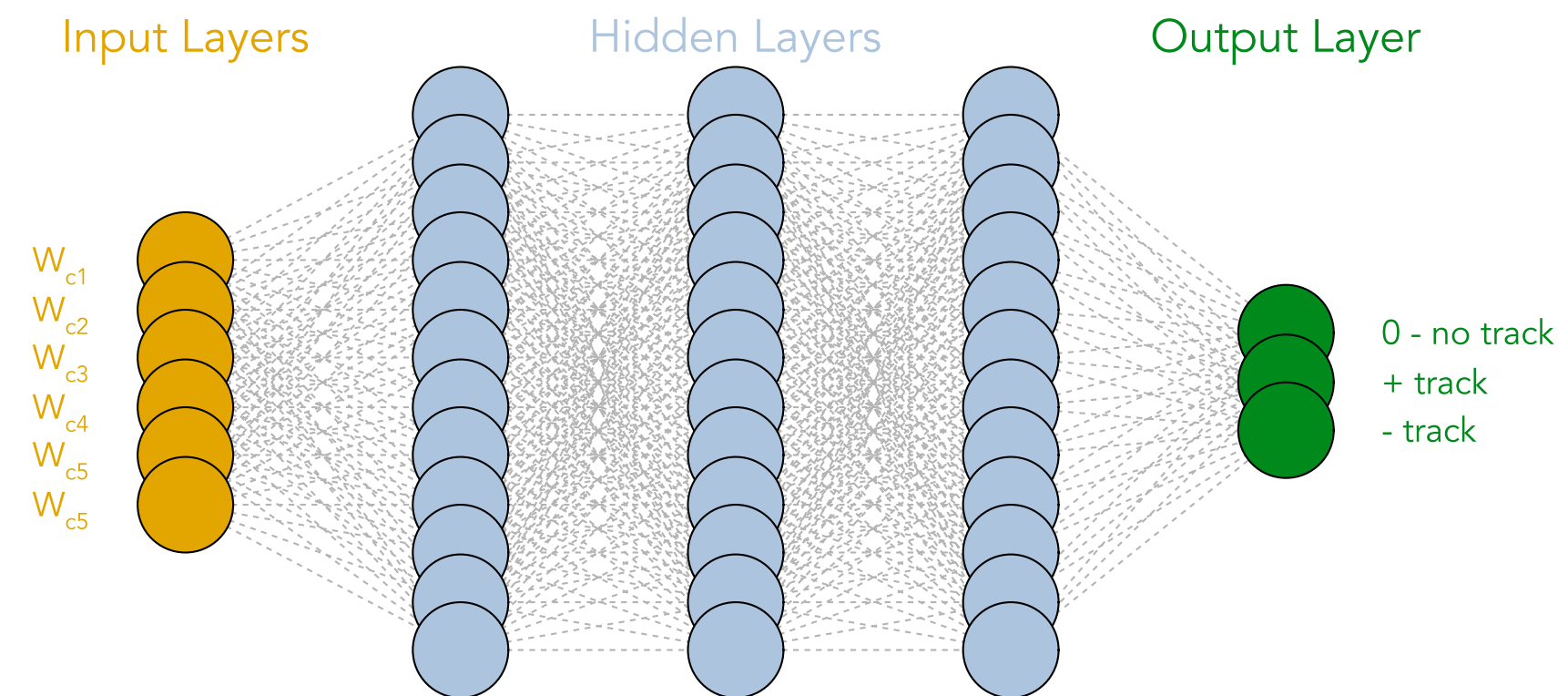
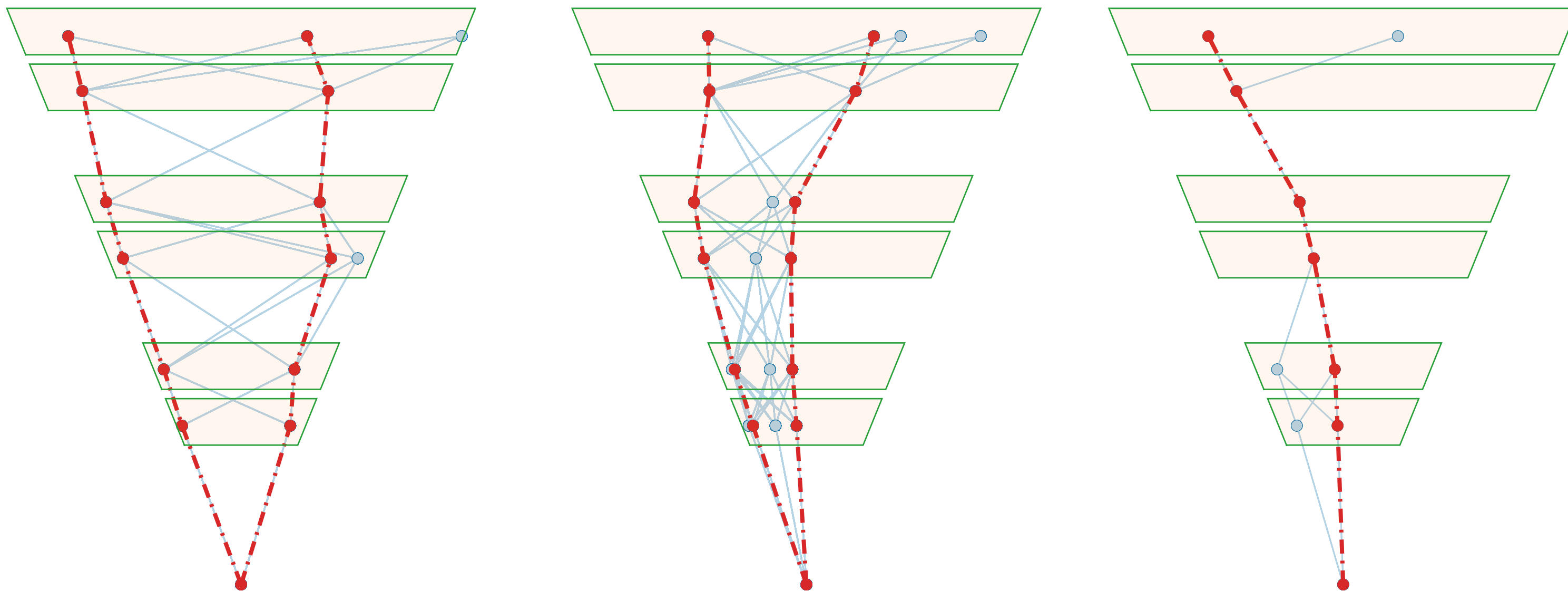
Parameter	Specification
Angular Range	5-40 degrees
Momentum Resolution	$dp/p < 1\%$
Polar resolution	1 mead
Azimuthal Resolution	1 mrad/sinT
Luminosity	$10e35 \text{ cm}^{-2}\text{se}^{-2}$

Parameter	Specification
Cell Type	Hexagonal
Wire layout	6 sectors, 3 regions
Stereo	+/- 6 degree stereo
Granularity	112 wires/layer (24192)
Gas	90/12 Argon/CO2

- ▶ 6 sectors with 6 chambers in each sector (called super-layers)
- ▶ 6 wire planes in each super layer with 6-degree tilt relative to each other, (112 wires in each plane)

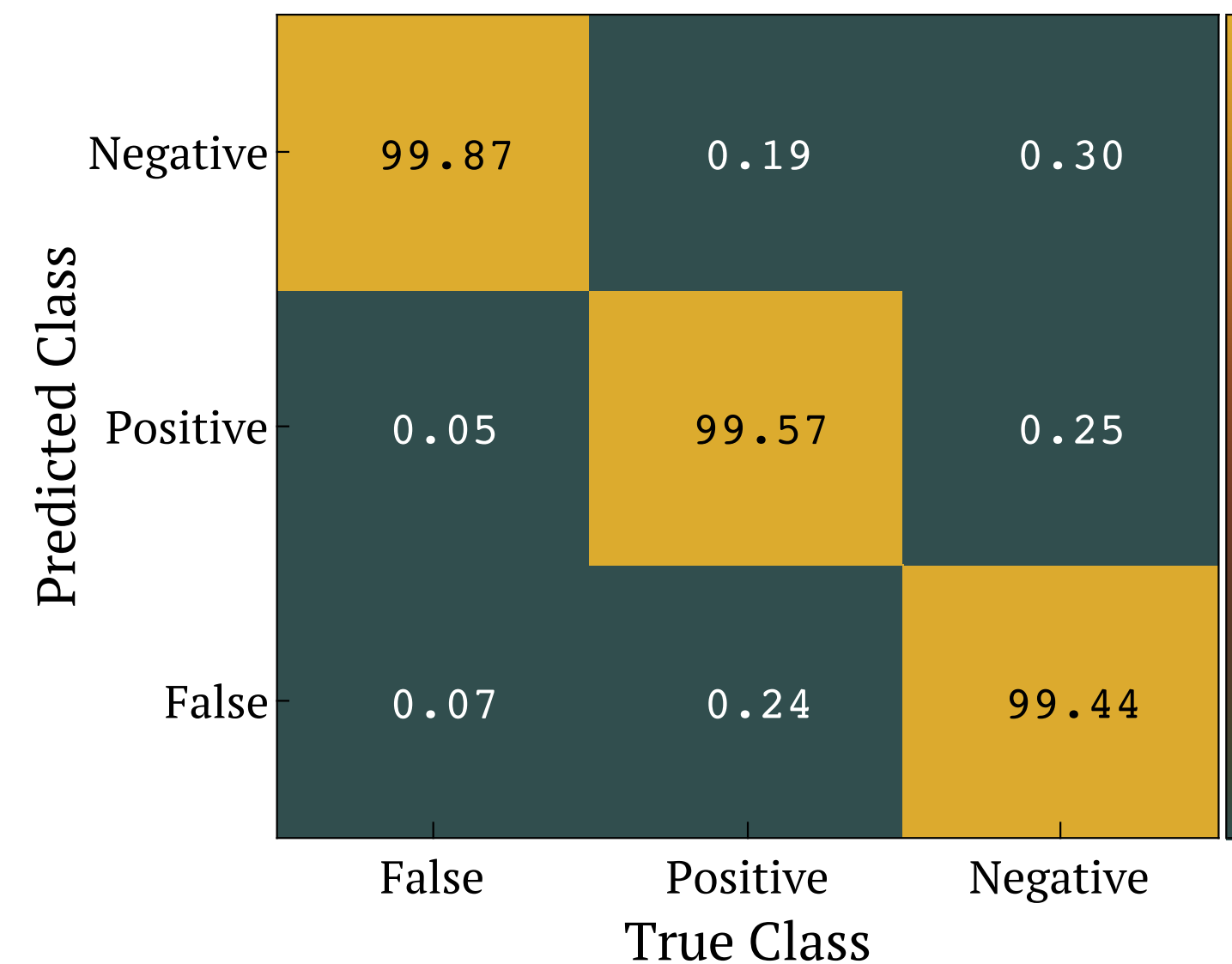


- ▶ Find segments in each super layer (remove noise)
- ▶ Combine 6 segments (one from each super layer) to make a list of possible tracks
- ▶ Identify correct combinations of segments that represent a track
- ▶ The conventional algorithm performs fit through the magnetic field to assess the goodness of the track.
- ▶ Requires:
  - ▶ Knowledge of drift chamber geometry
  - ▶ The precise value of the magnetic field in space

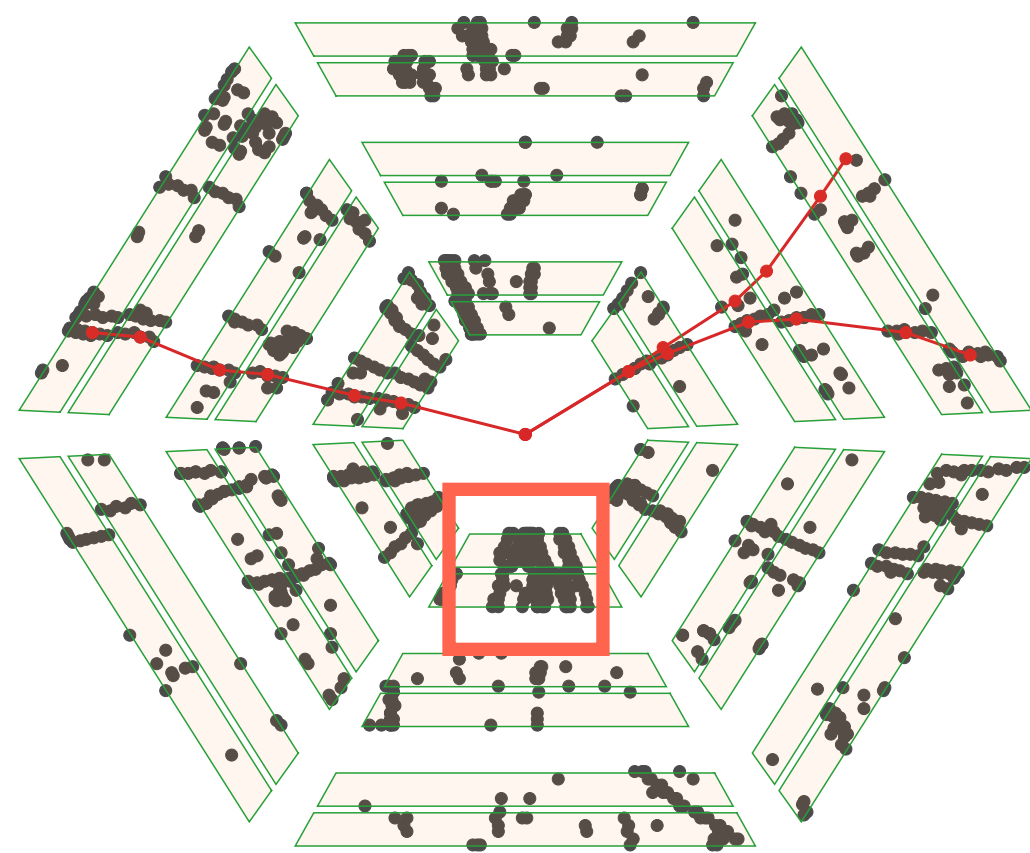


- ▶ Input:  $W [1..6]$  - average wire position of the segment
- ▶ Output: [false track, positive track, negative track]

- ▶ Neural Network is trained to recognize patterns of segment combinations
- ▶ The track classifier assigns a probability of the track candidate to be positive, negative, or false track.
- ▶ The network is trained on reconstructed data where the right combinations are already found and false combinations of segments is generated by interchanging clusters from a different track

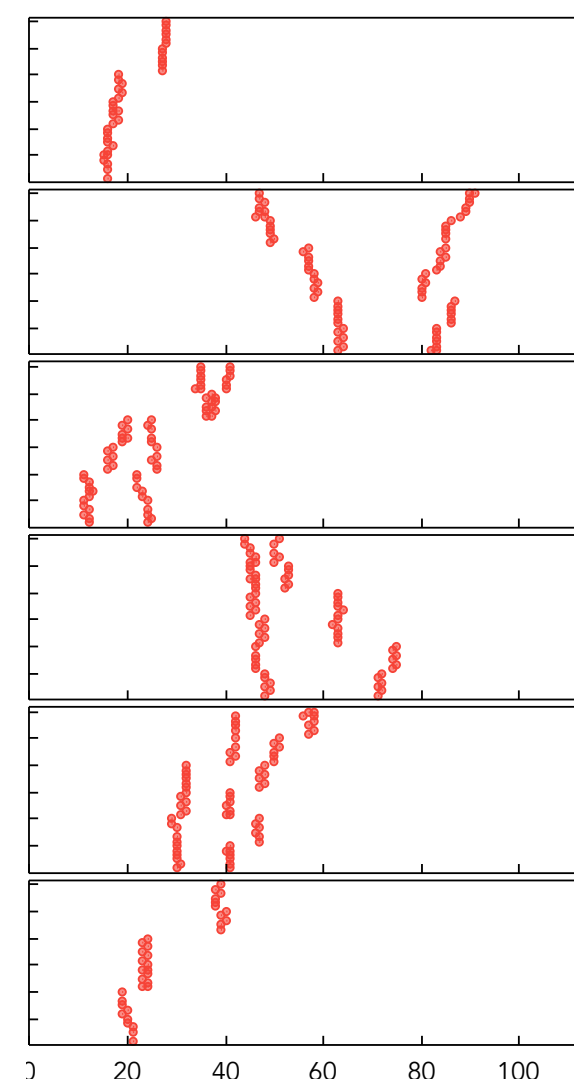
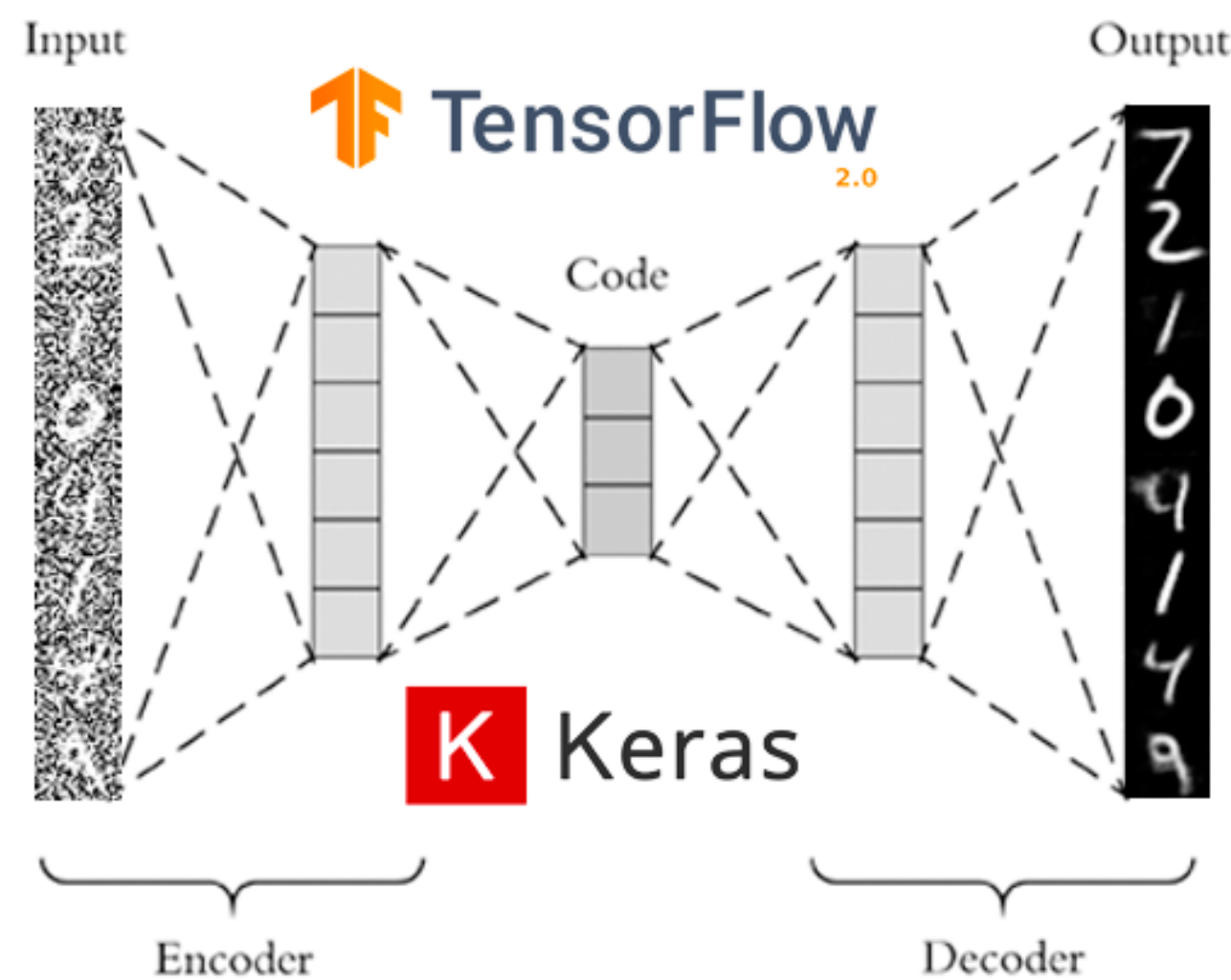
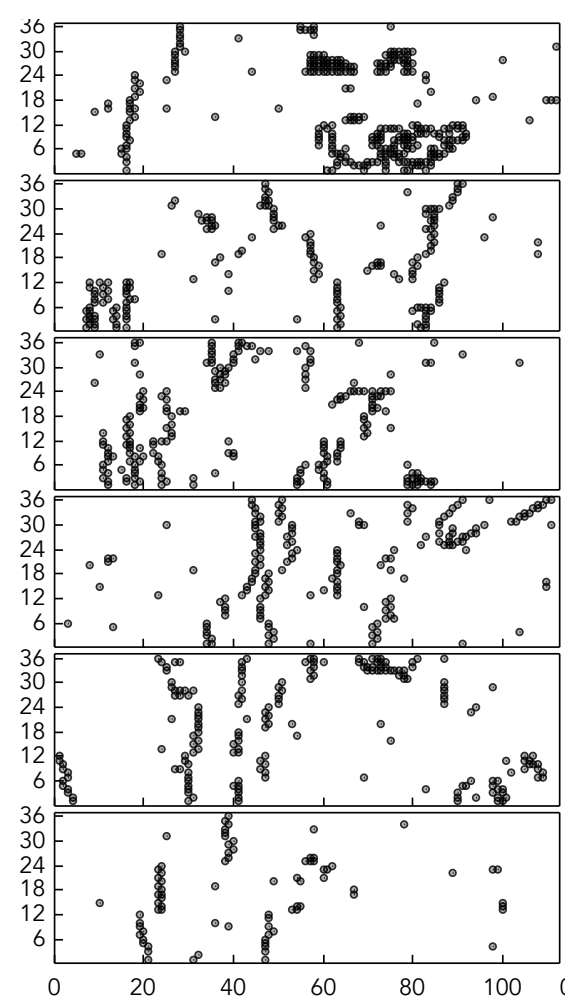
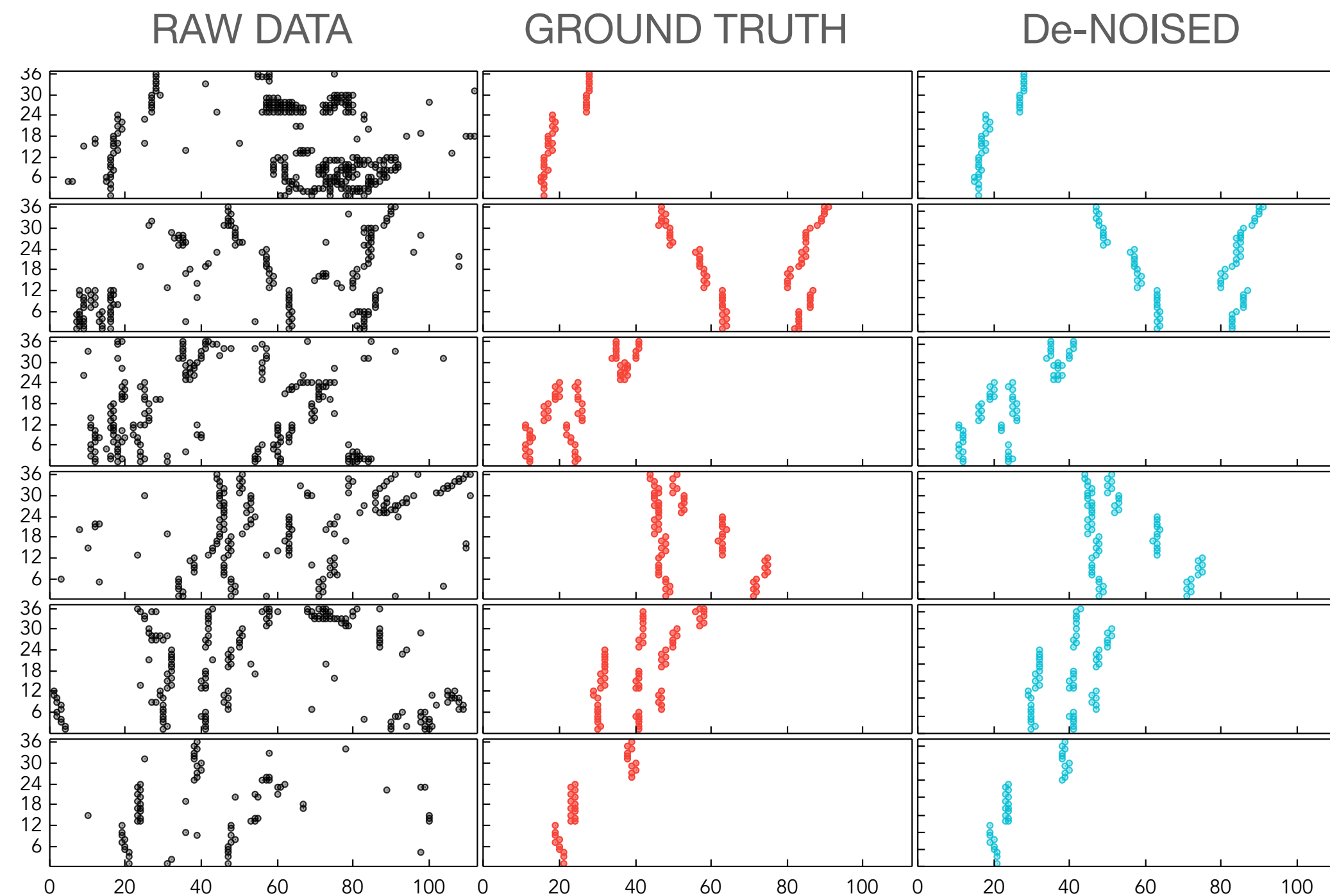


# Denoising (Convolutional Neural Network)

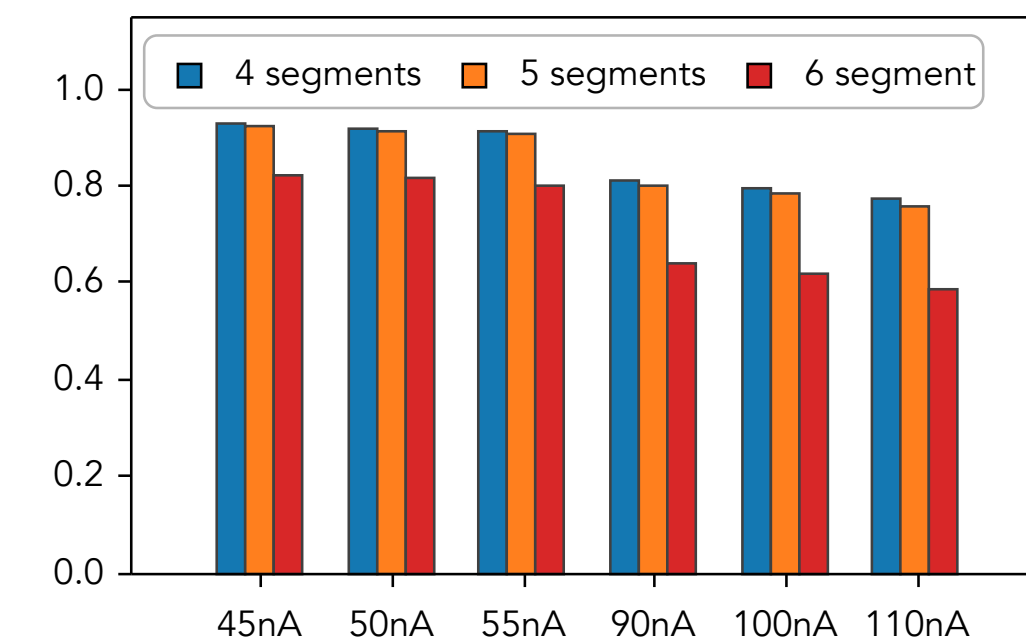
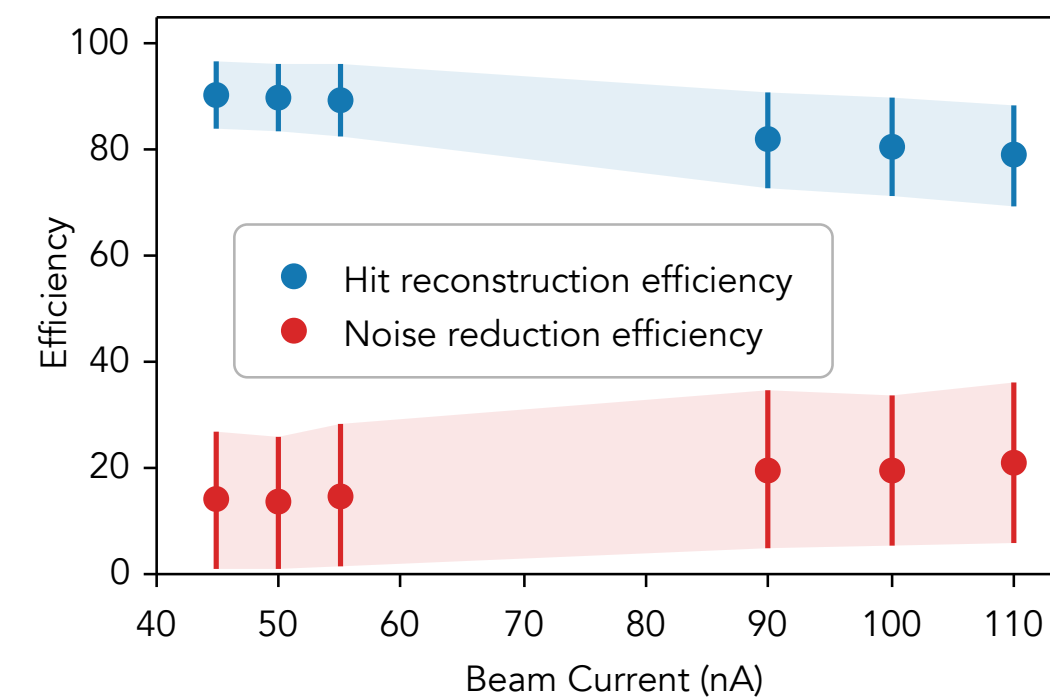


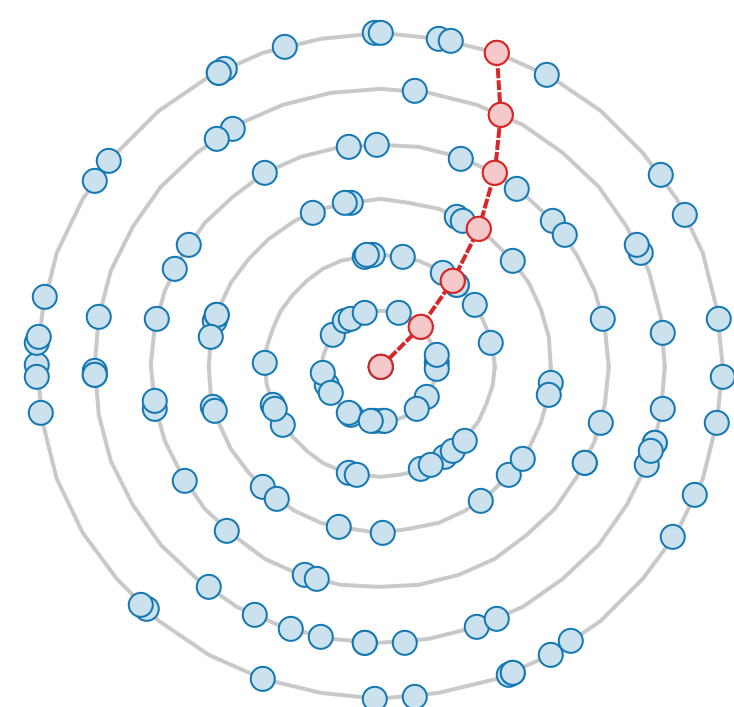
- Regions of Drift Chambers Closer to the beam have noise.
- It is hard to isolate segments in noisy areas, resulting in a loss of tracks.

- Convolutional Auto-Encoder is used to de-noise raw data from drift chambers.
- The network is trained on reconstructed data with track hits isolated from raw DC hits.
- The network is able to isolate hits that potentially belong to a valid track through drift chambers

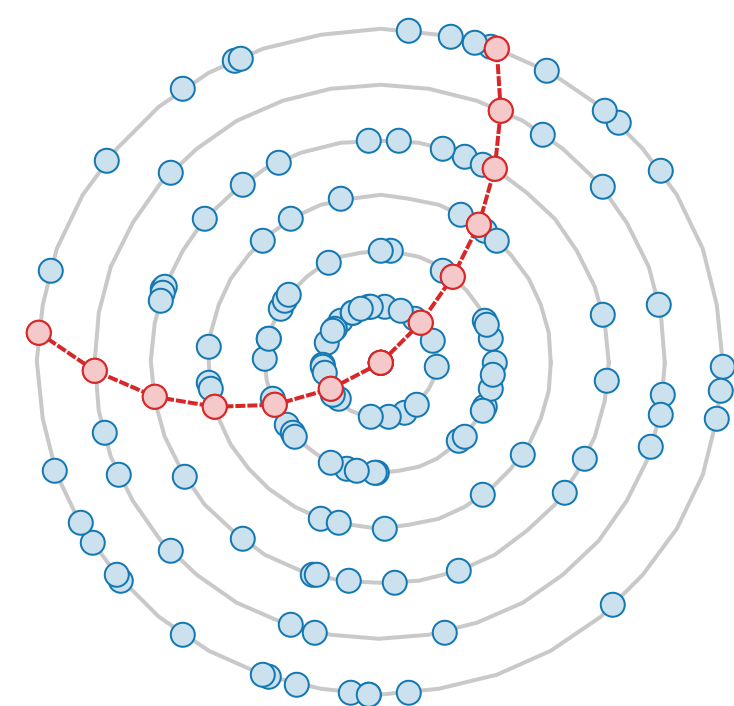


## Network Performance Summary

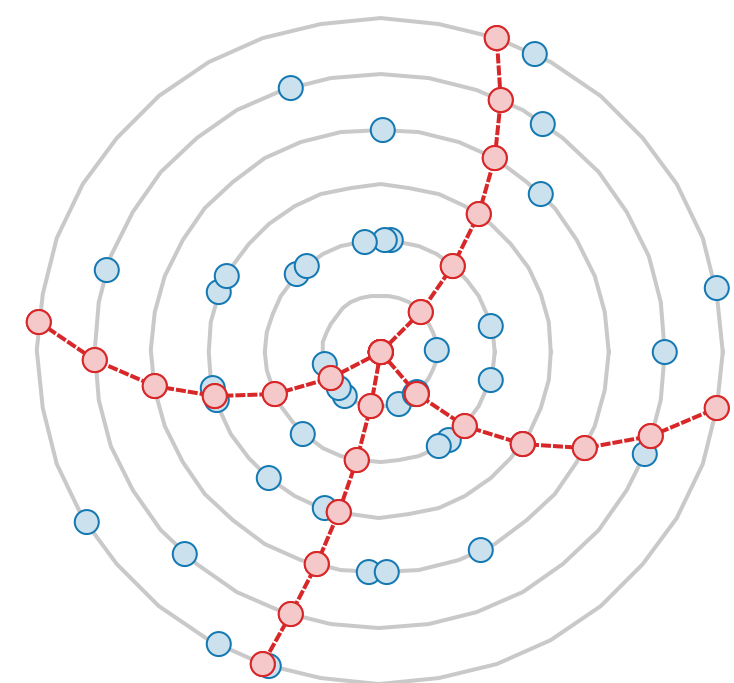




Conventional Tracking

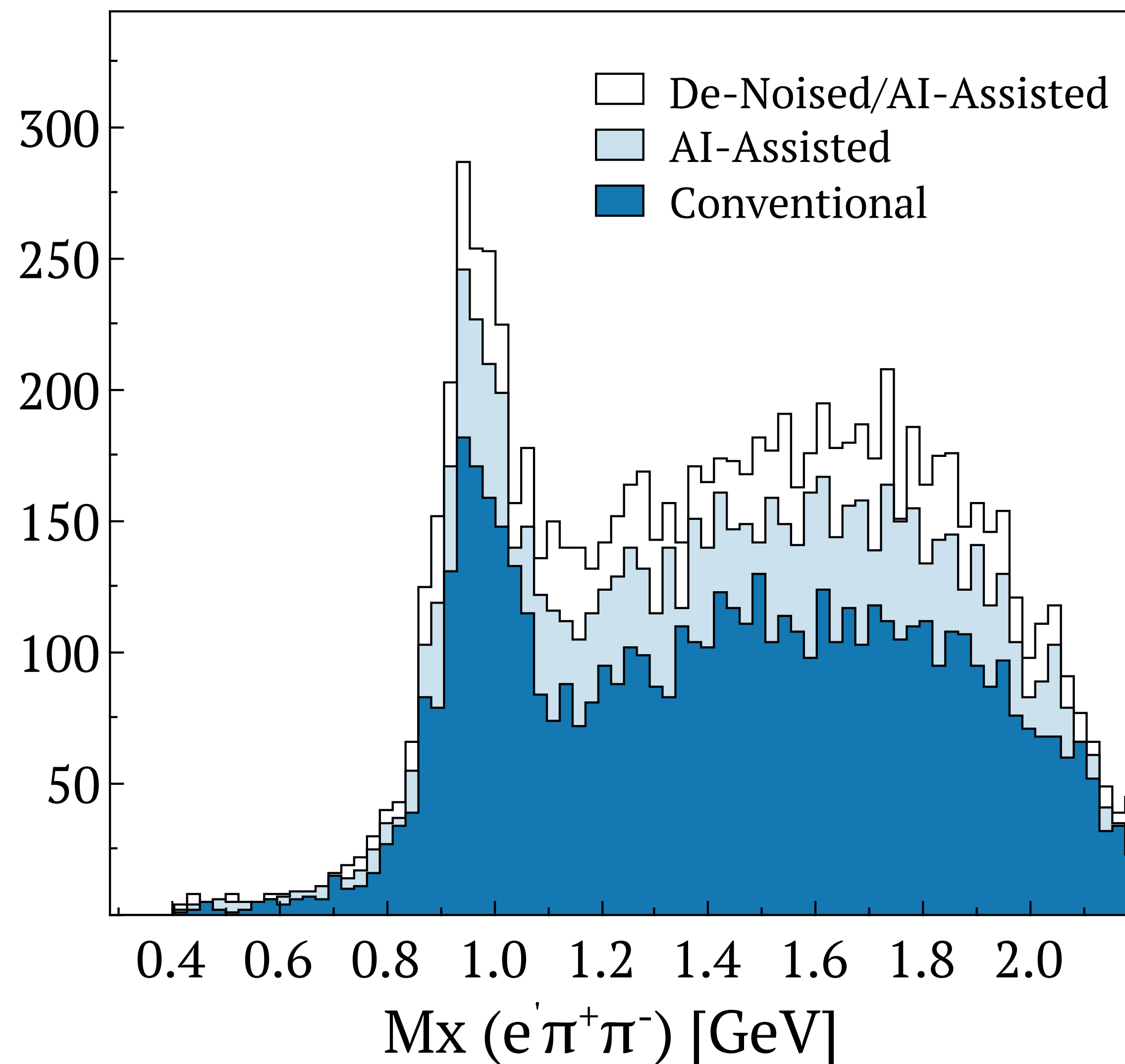


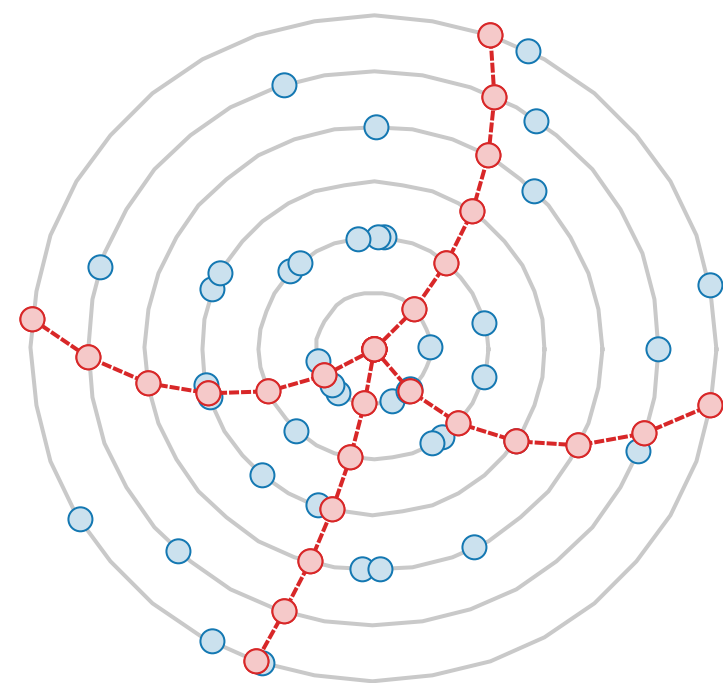
AI-Assisted Tracking  
Increased statistics by ~35%  
Compared to Conventional



De-Noised/AI-Assisted Tracking  
Increased statistics by ~56%  
Compared to conventional

Three detected particles in the event

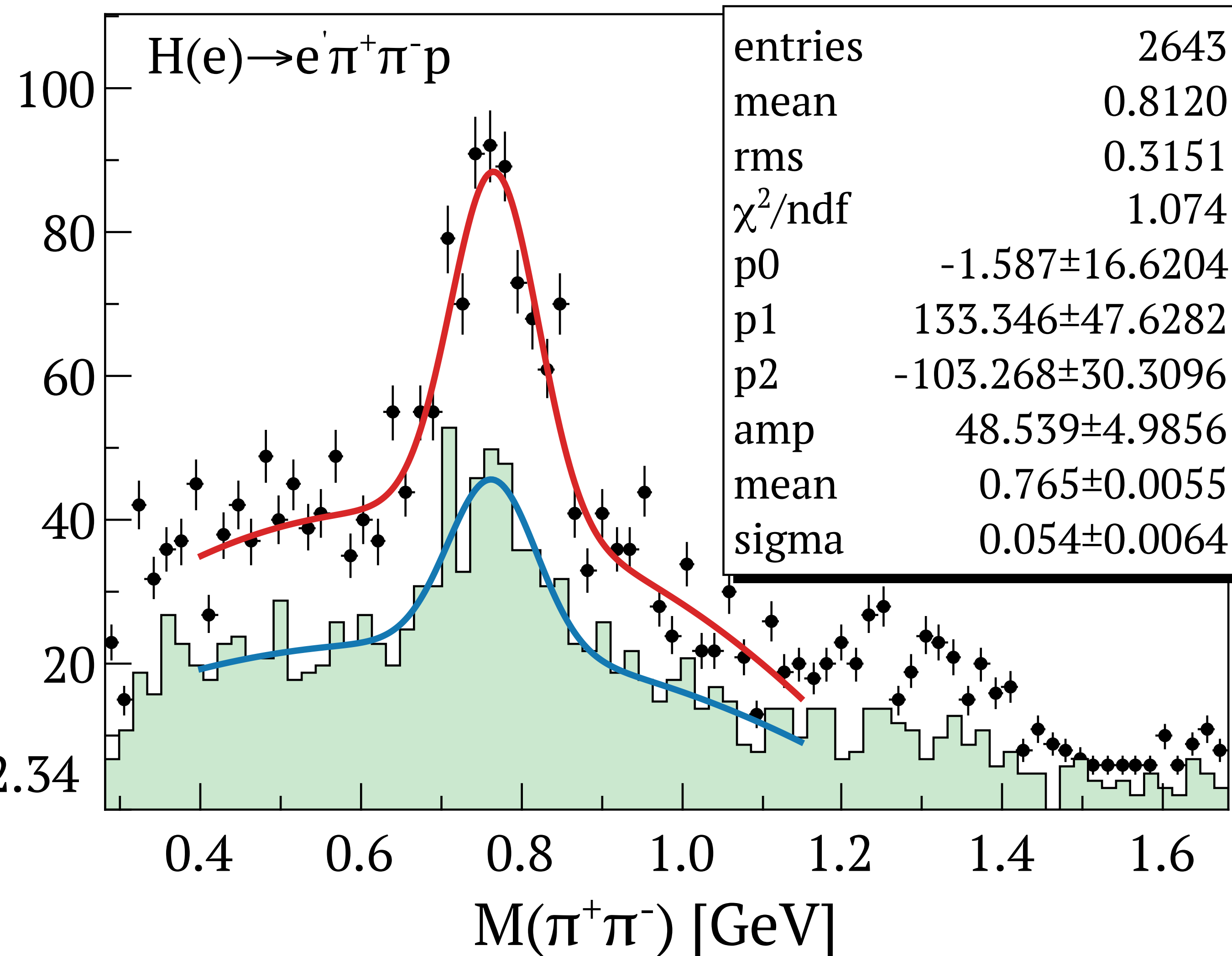




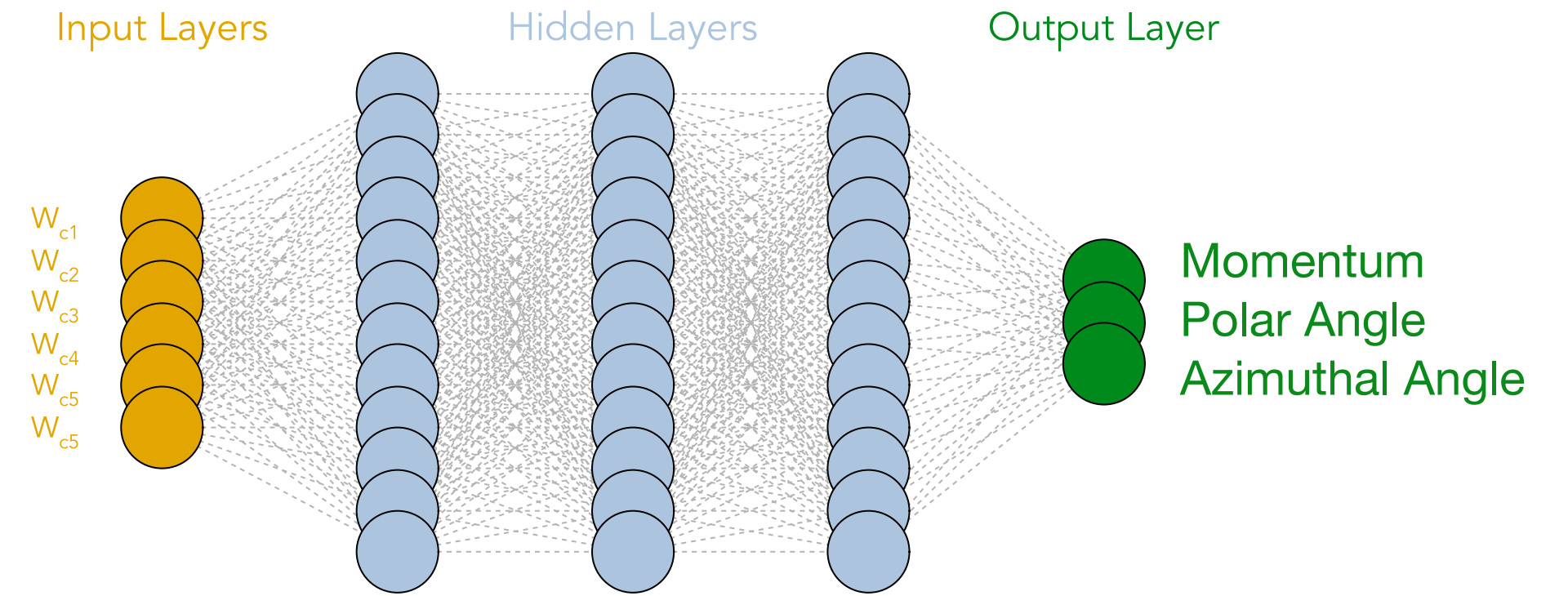
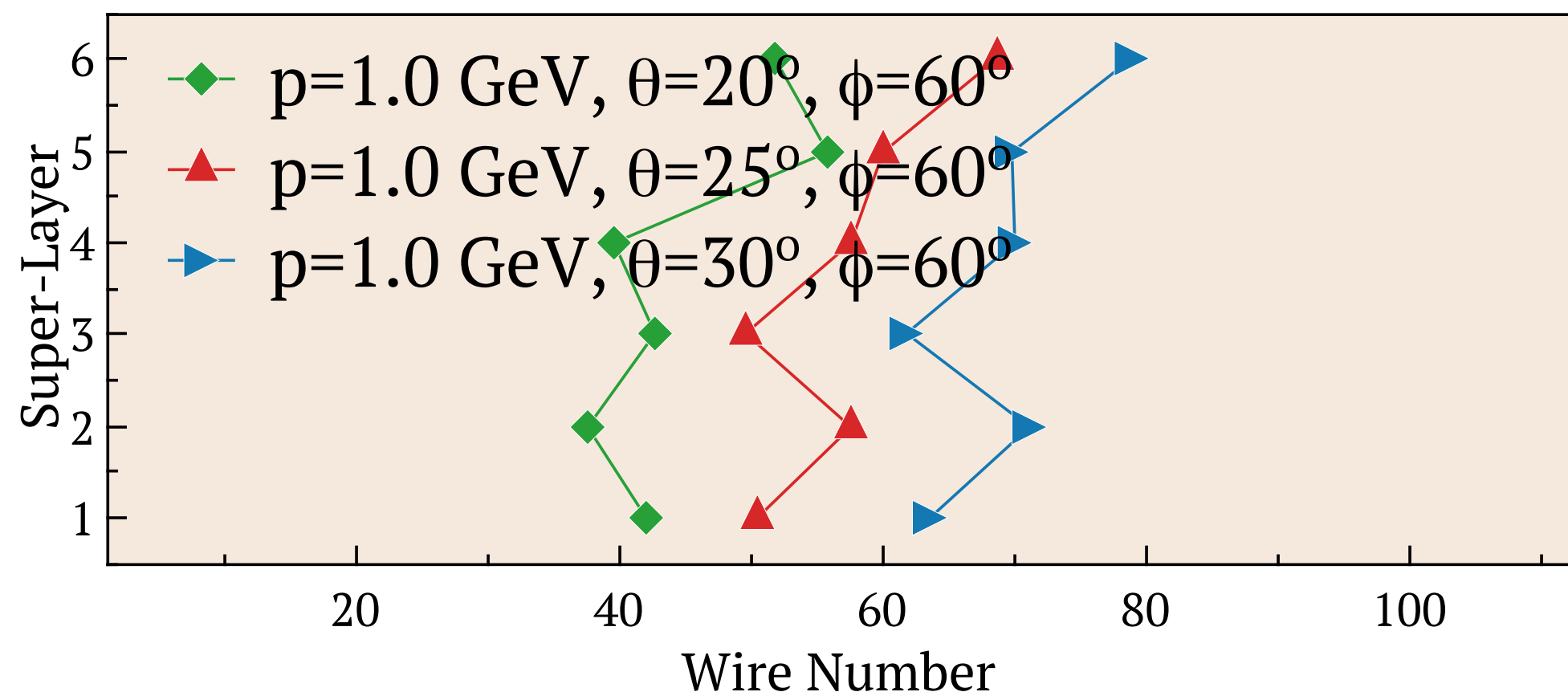
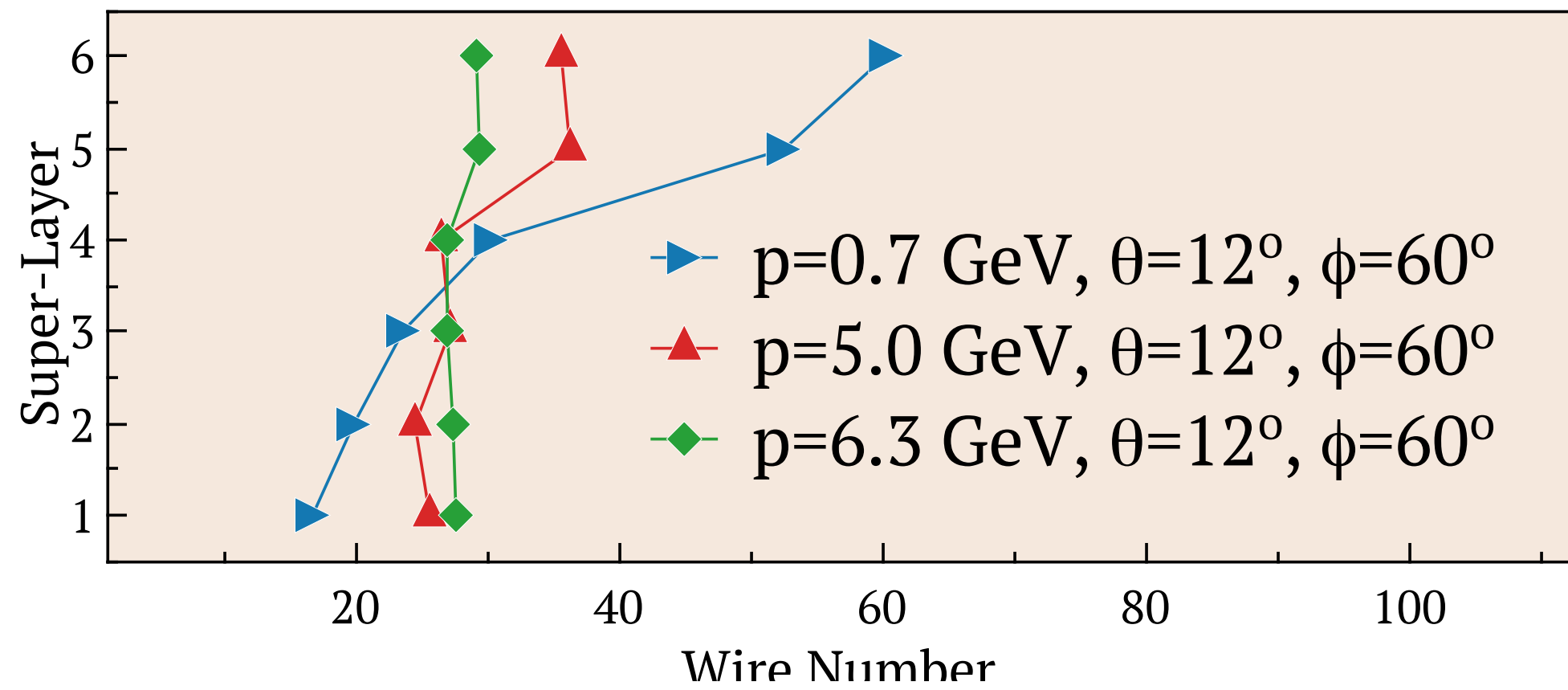
De-Noised/AI-Assisted Tracking  
Increased statistics by ~134%  
Compared to conventional

Relative Gain 2.34

Four detected particles in the event

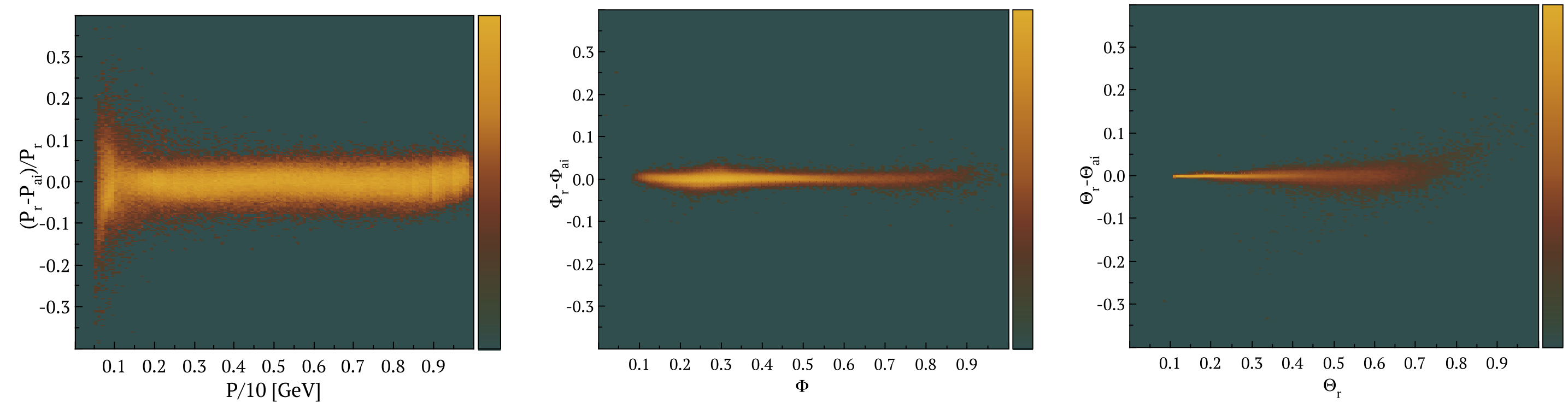


- Each track has unique segment combinations that correspond to particle momentum and direction.



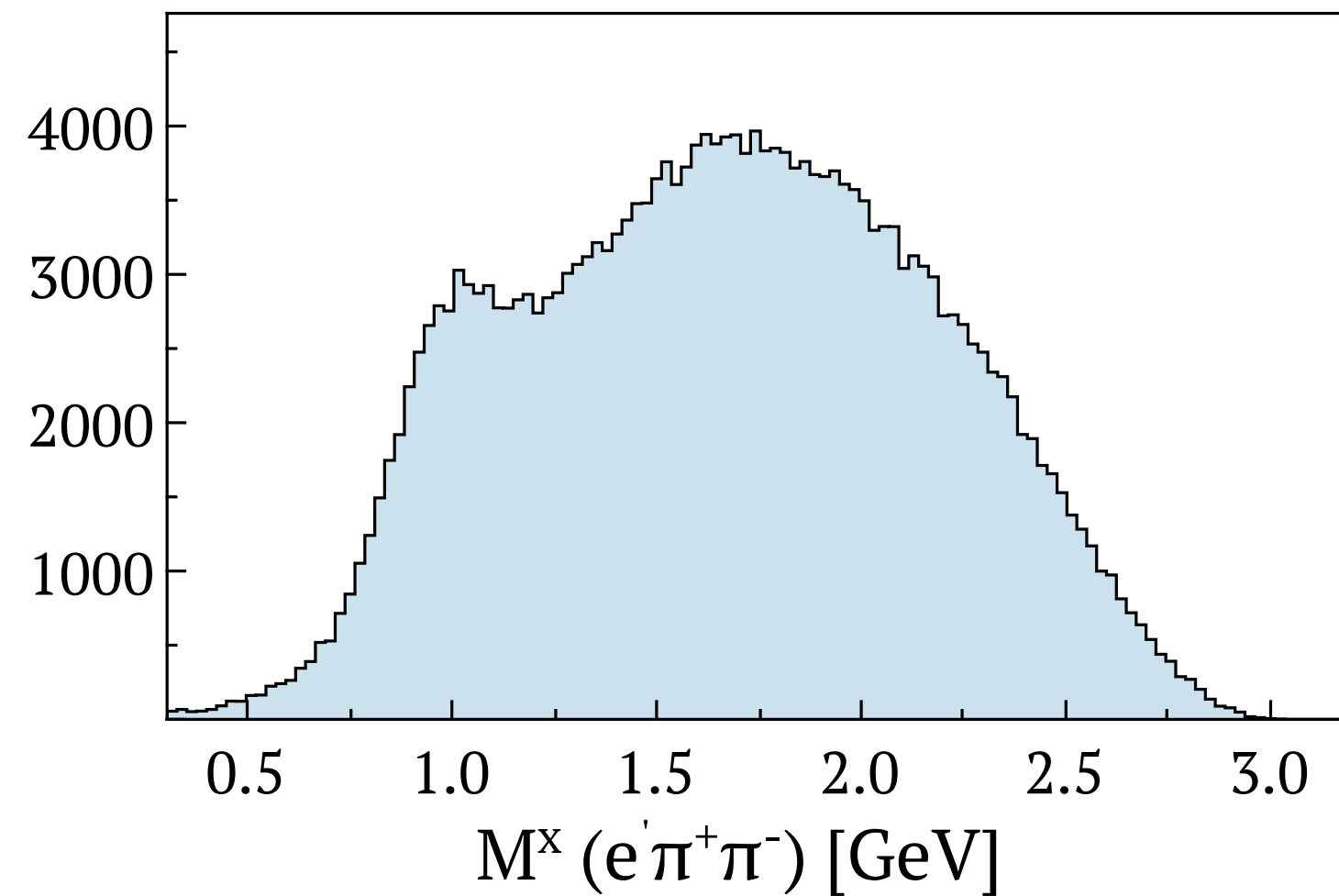
- The network is trained on 6 input parameters, corresponding to average wire position of segments in each super-layer.
- The output is the momentum of the particle and azimuthal and polar angles.

Accuracy of particle parameter predictions:

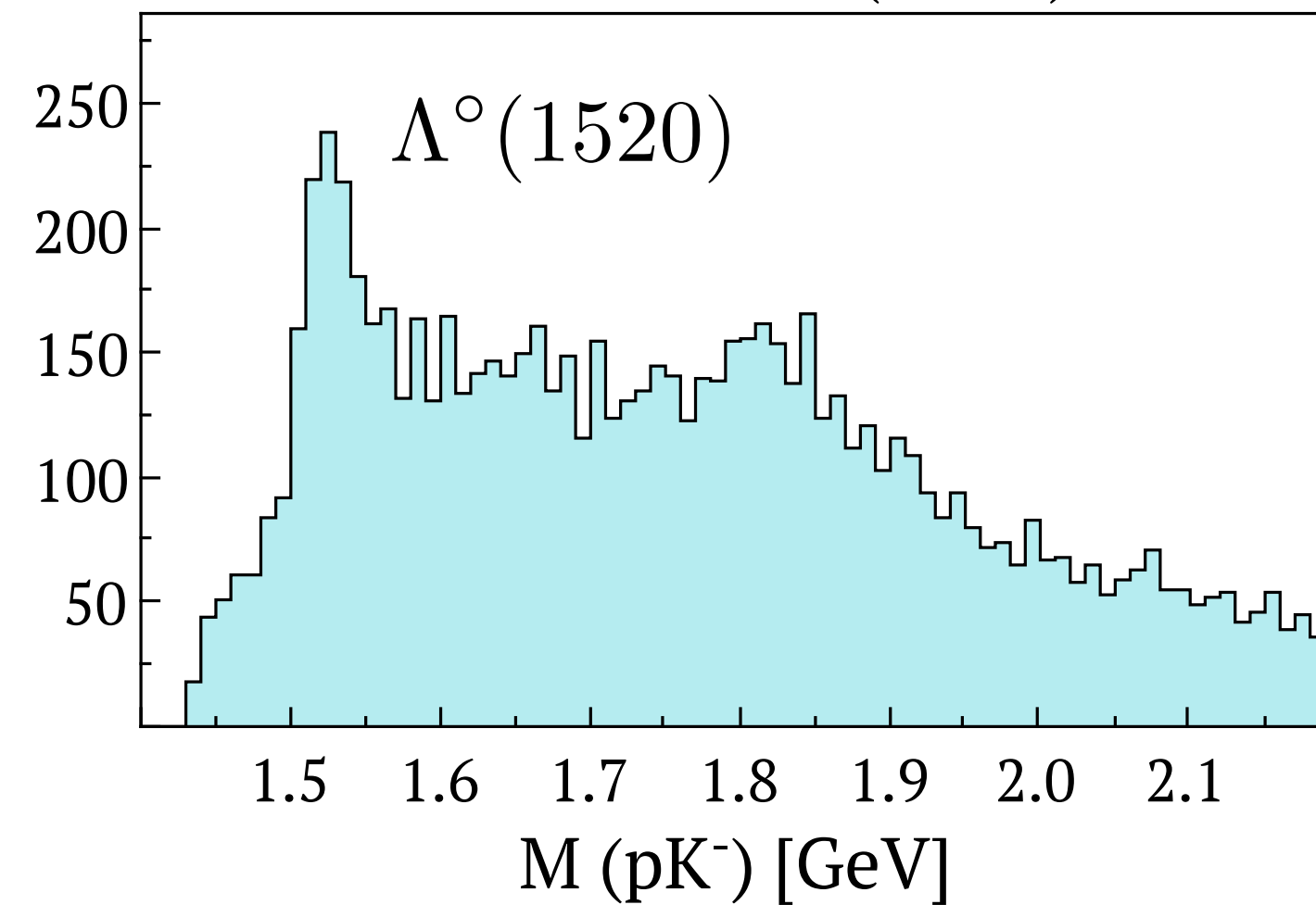




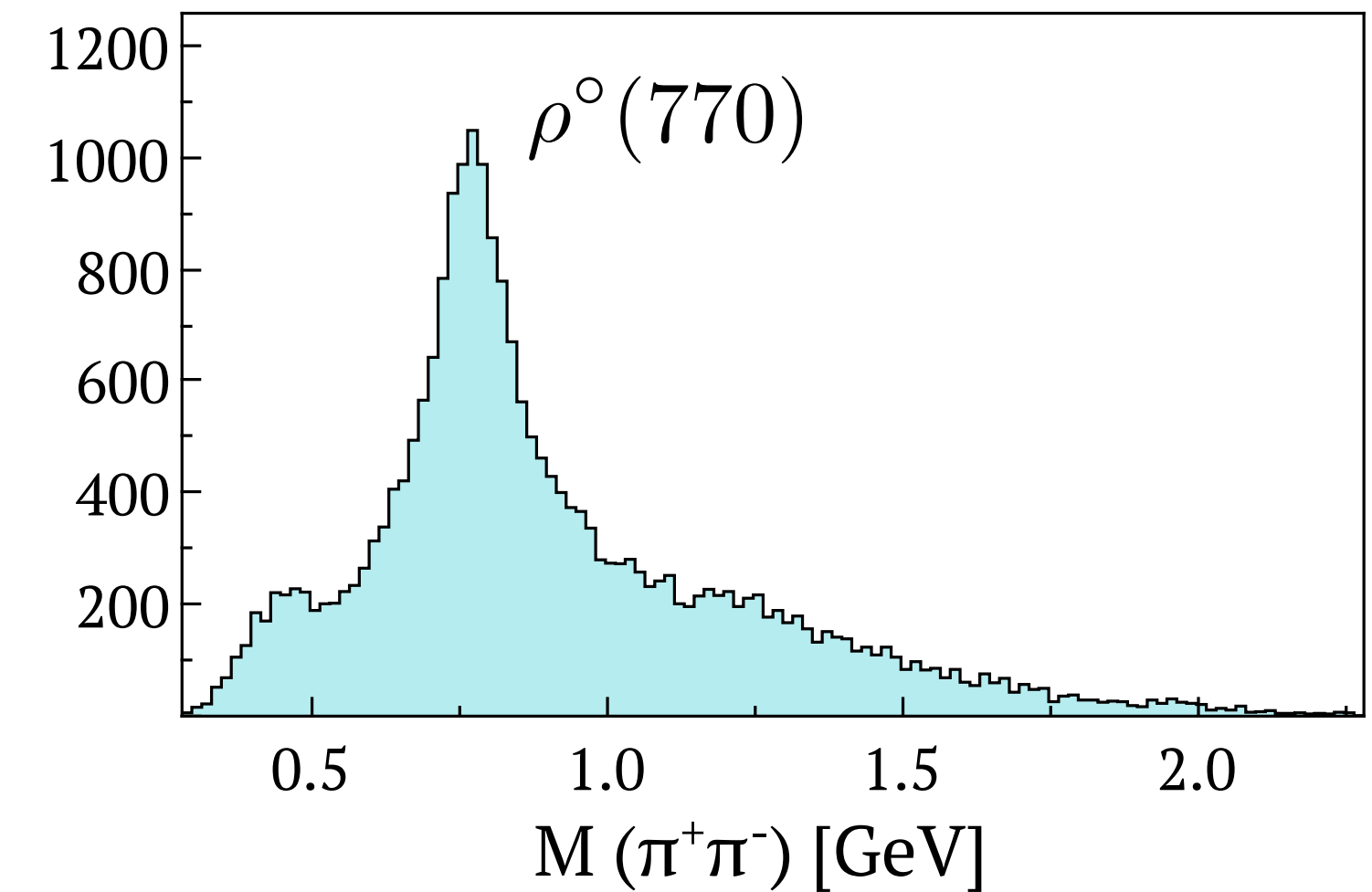
$$ep \rightarrow e' \pi^+ \pi^- (p)$$



$$ep \rightarrow e' p K^- (K^+)$$



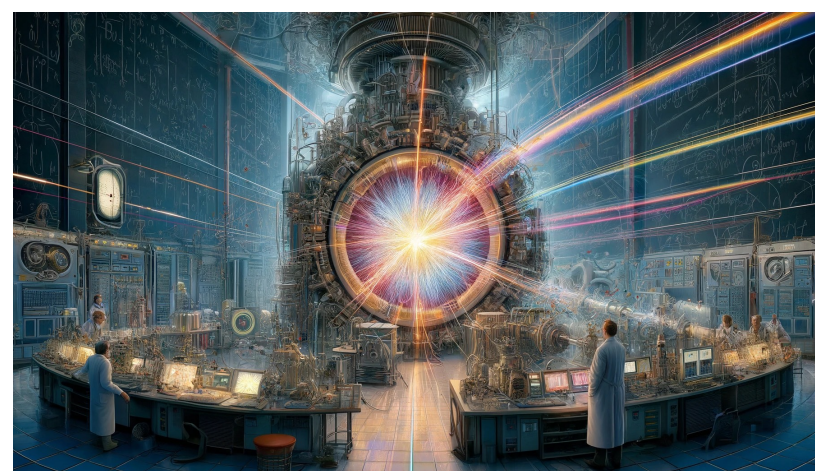
$$ep \rightarrow e' \pi^+ \pi^- (p)$$



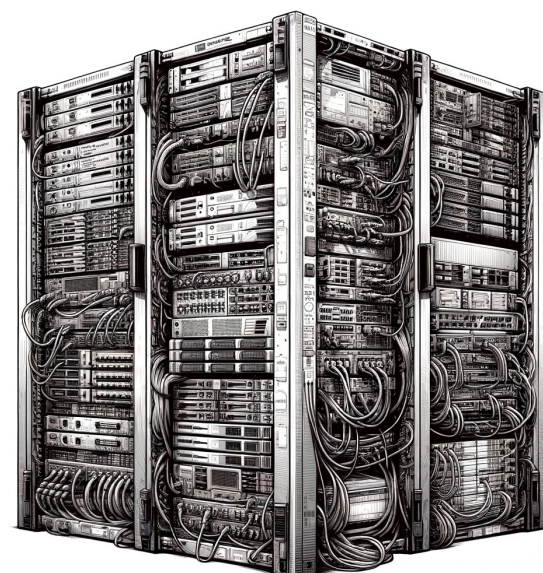
- ▶ Physics event reconstruction is based only on TDC hits in Drift Chambers.
- ▶ No calibration databases are used
- ▶ No Timing information from Time-Of-Flight Counters

- ▶ Does not provide Particle ID (feature is coming soon)
- ▶ The highest energy negative particle is assumed to be an electron
- ▶ Positive particles are assigned pion ID, for other analysis the mass of the desired positive particle is used (proton for example)
- ▶ Or kaon mass for the second negative particle (lowest momentum) for lambda analysis

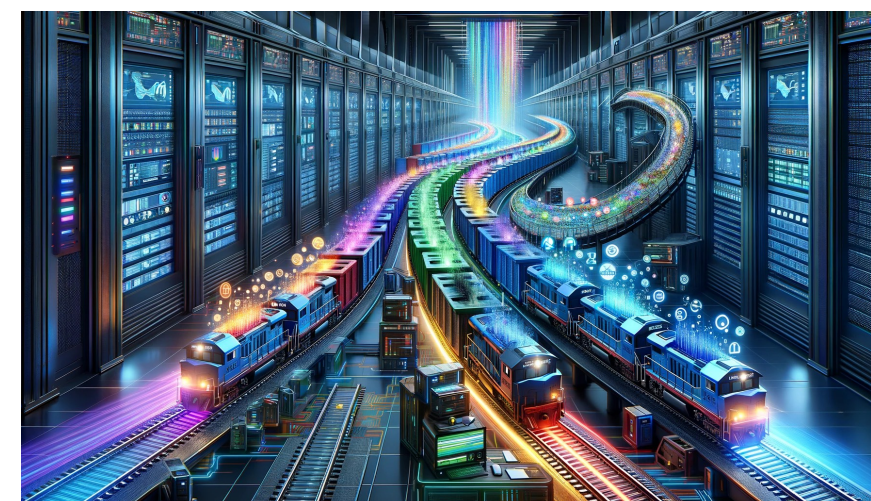
# Artificial Intelligence in CLAS12 tracking



Data Collected at rate:  
12,000 interactions per second  
100 M events in ~4 hours

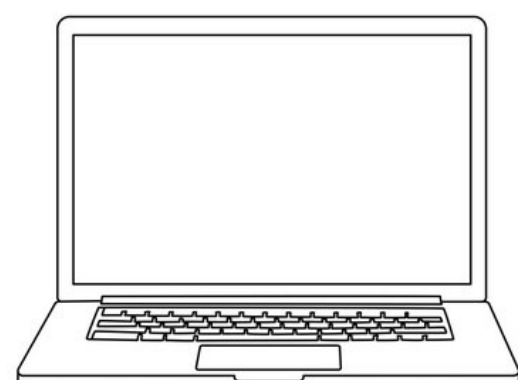


Data Processing  
768 cores used  
10 hours to reconstruct particles



Data Trains  
Sort data by interactions  
Each output is a specific physics channel  
2 hours for sorting

Experiments are conducted for 1-2 month  
Processing data from one experiment takes ~3 month

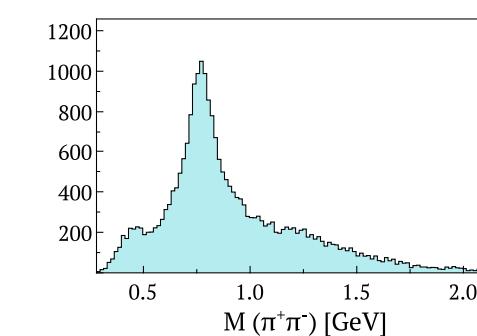
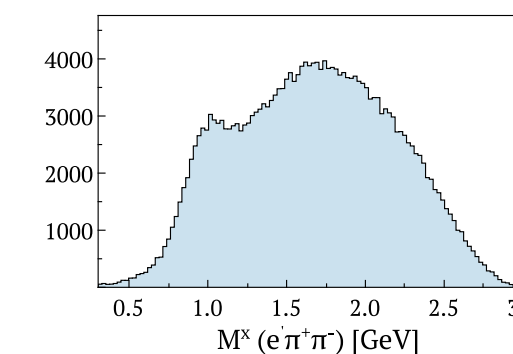
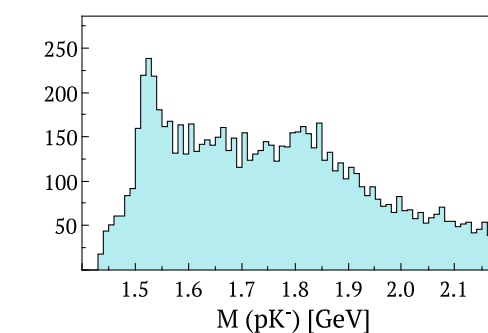


MacBook Pro M3  
8 cores

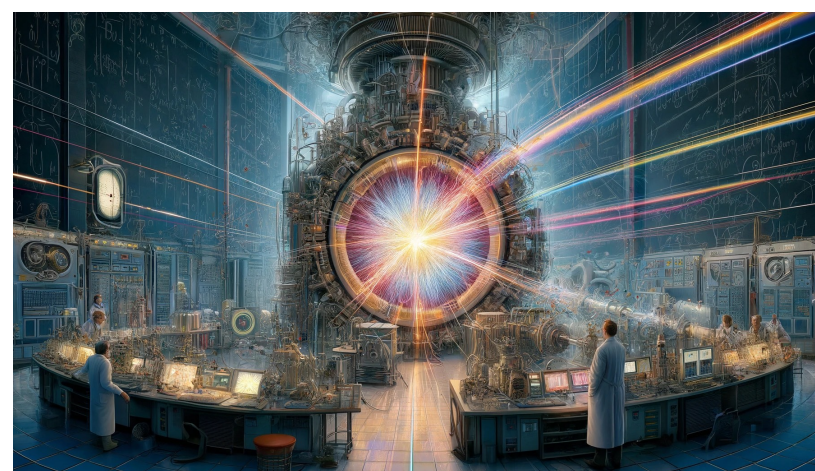
**INSTAREC**

The track reconstruction running on a laptop  
Reconstructs physics final states and sorts them

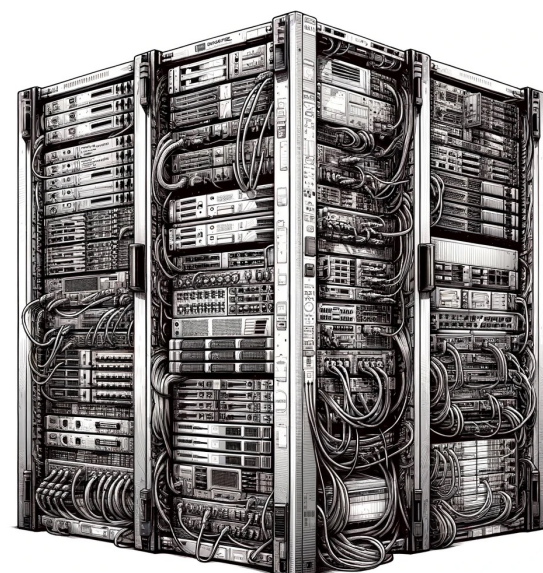
? Hours



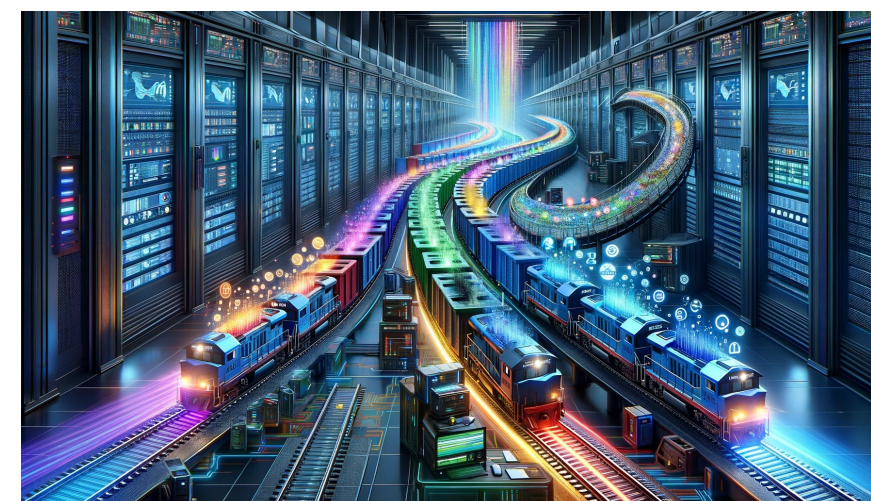
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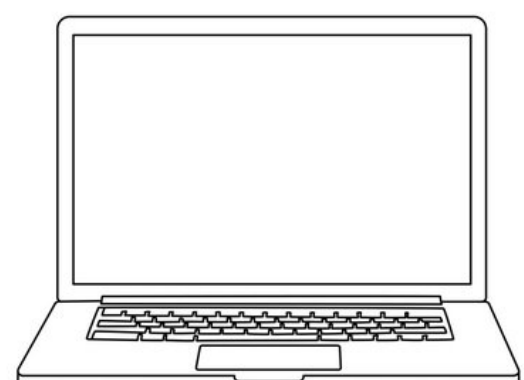


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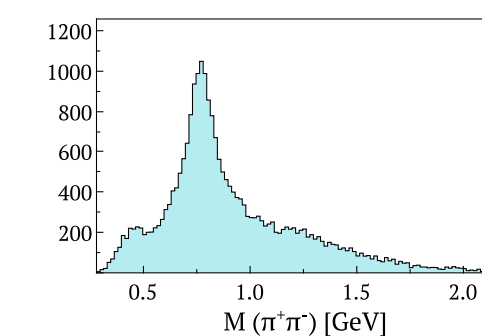
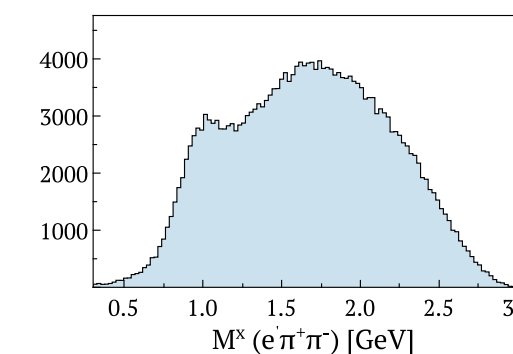
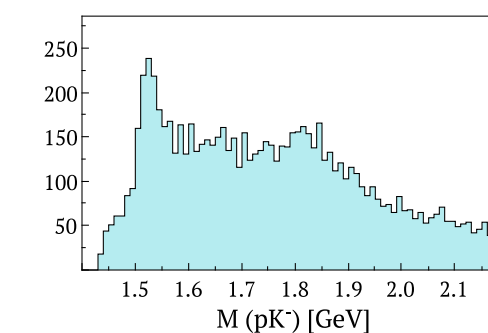


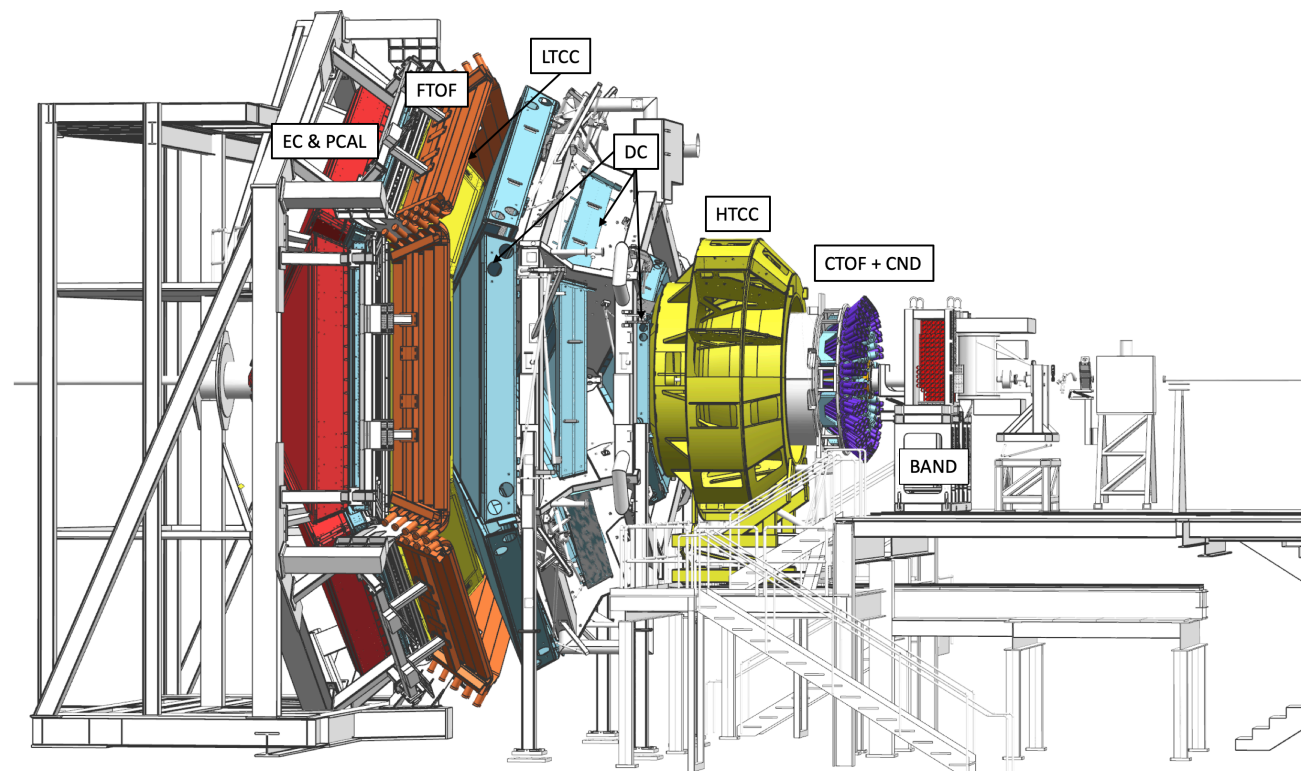
MacBook Pro M3  
8 cores

**INSTAREC**

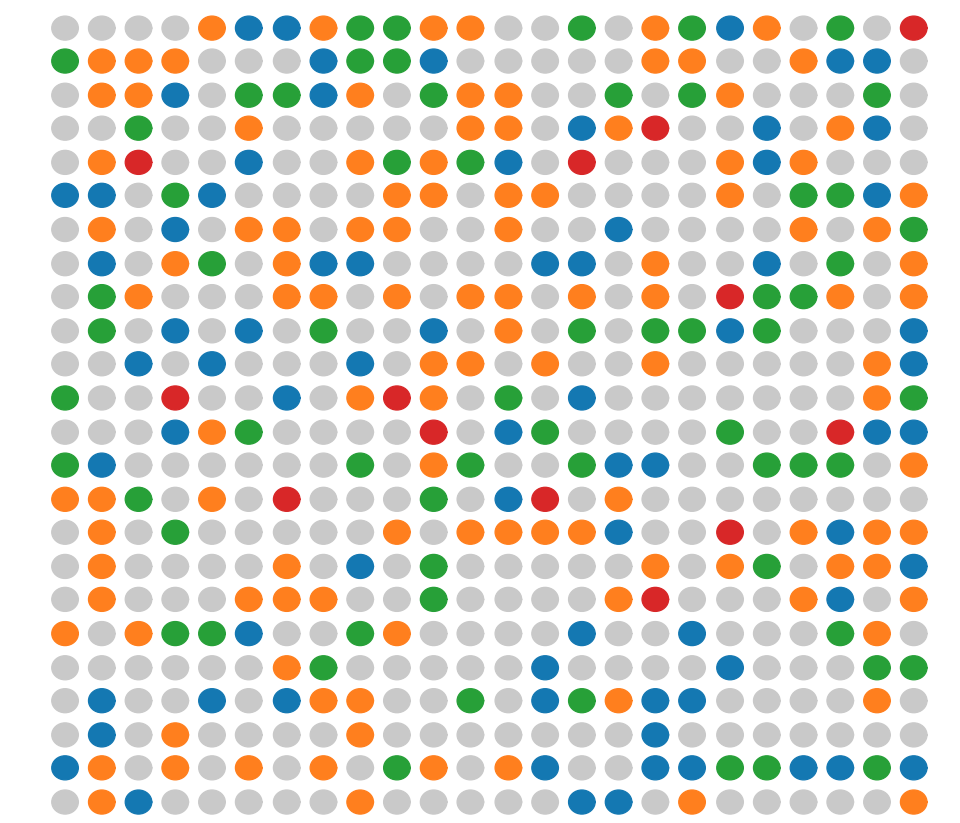
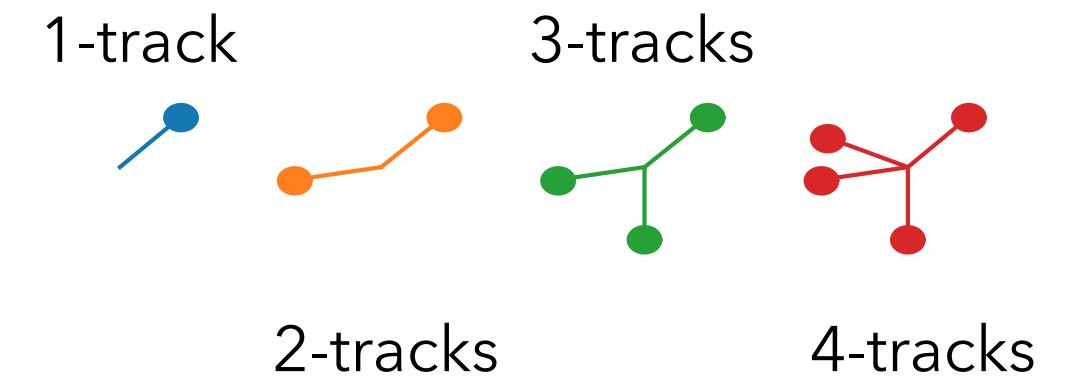
The track reconstruction running on a laptop  
Reconstructs physics final states and sorts them

**25 Minutes**

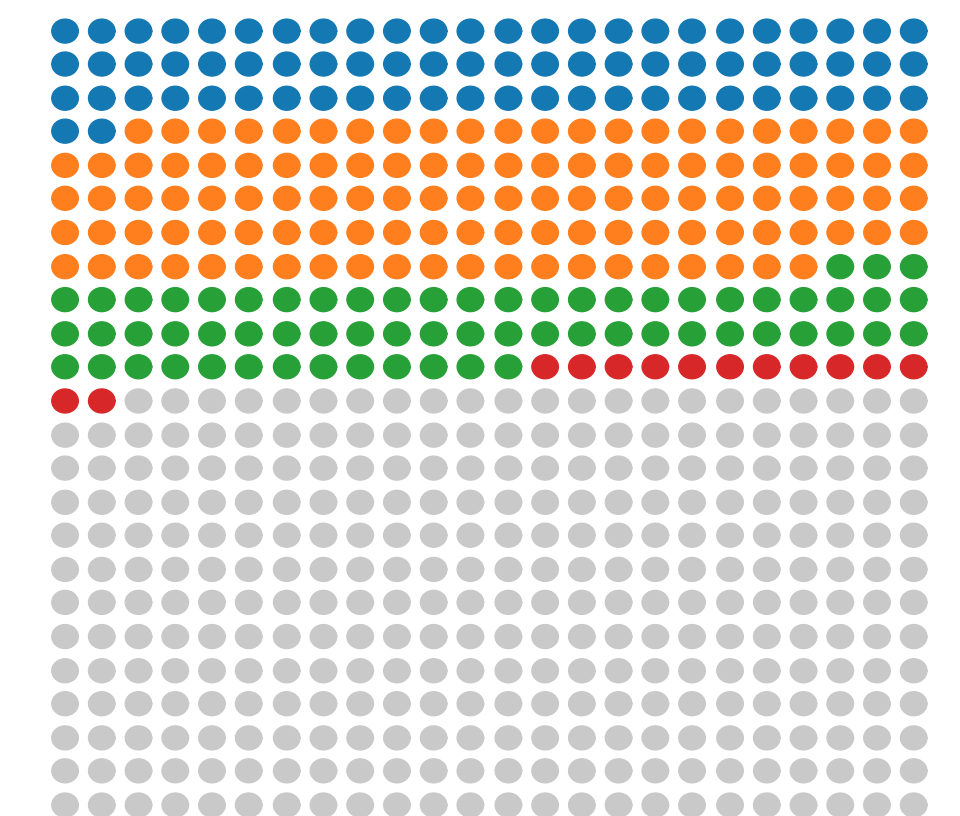




- DAQ rate 12,000 Hz
- Events recorded in chronological sequence
- Every event has to be reconstructed and then separated by event topology for each analysis group in the collaboration



Event File

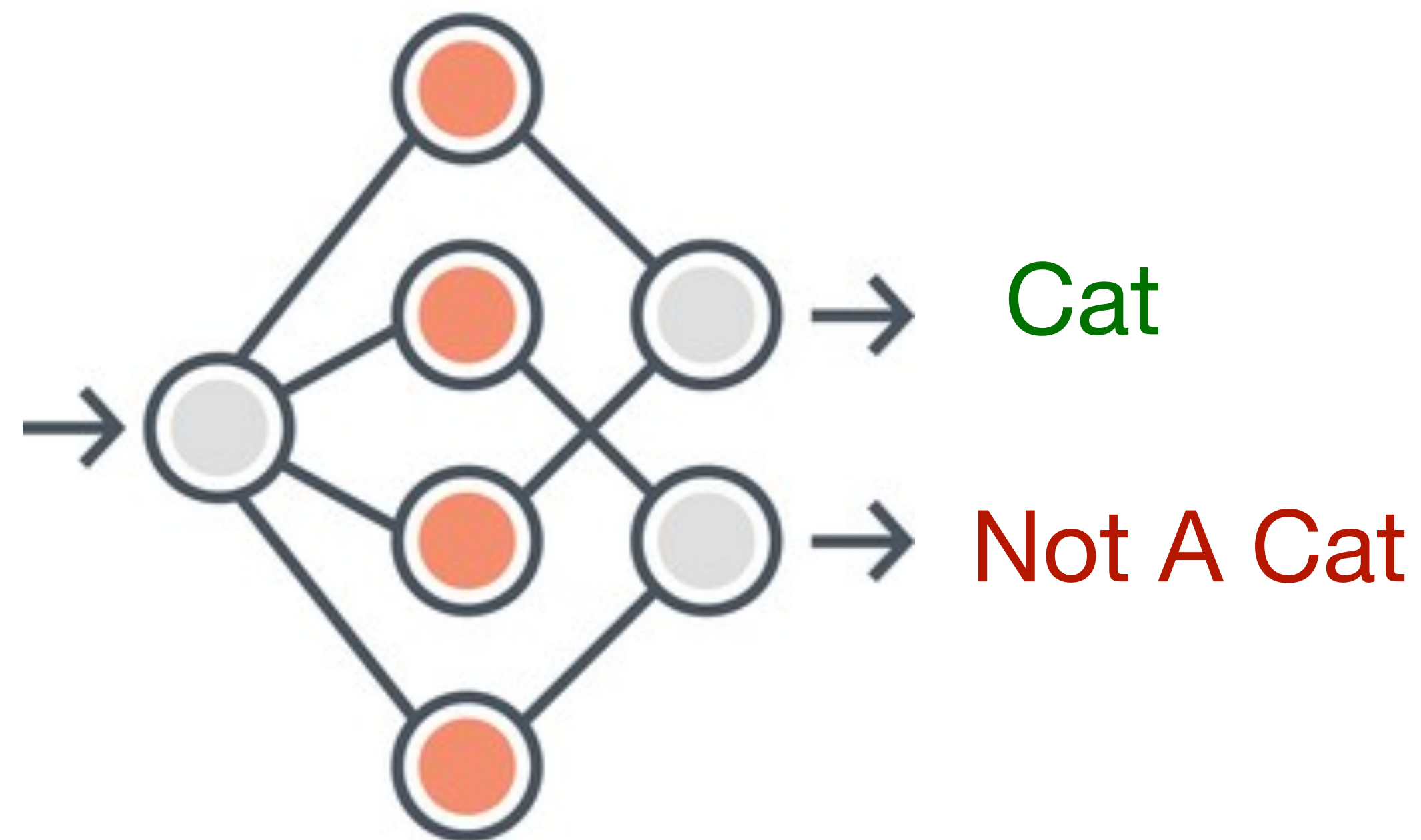
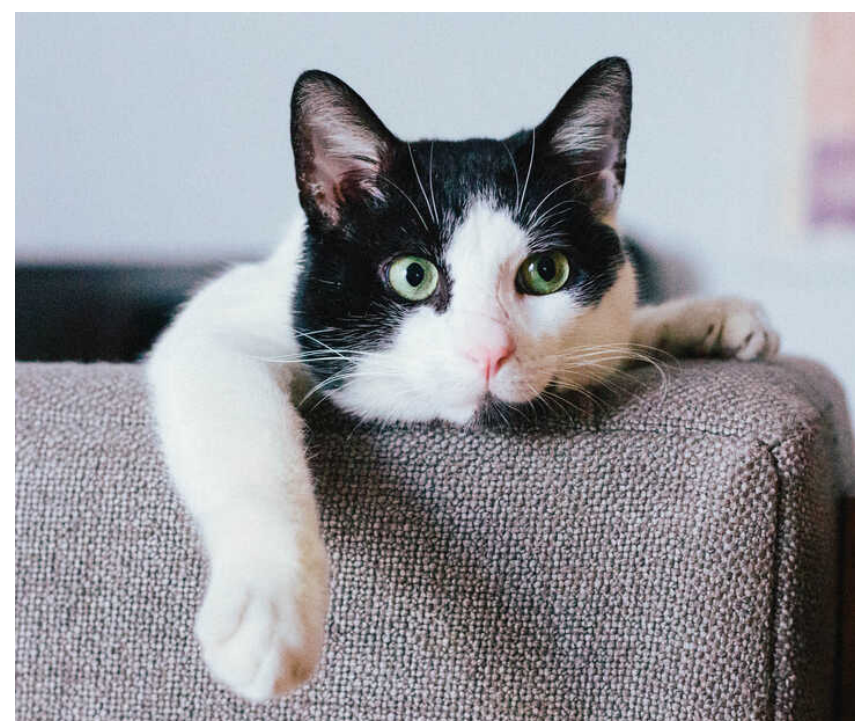


**InstaRec**

Rate: 96,000 Hz on a Laptop

- Events in the output are sorted by topology
- Reconstructed events don't have to be post-processed for each analysis group.
- Trigger impurities are removed, significant speed-up of data processing
- Data monitoring and calibration become possible in real-time.

## Should I care about the training sample?



Should I care about the training sample?



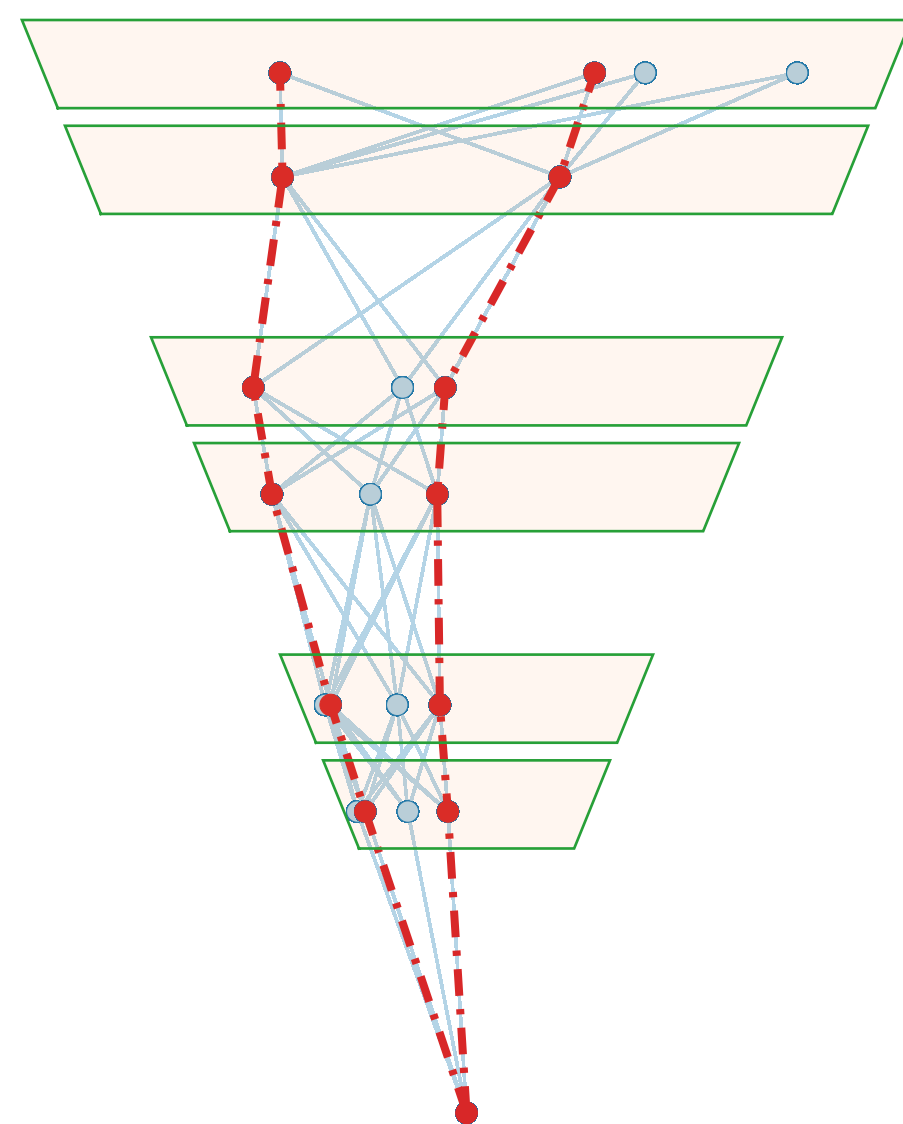
## Should I care about the training sample?



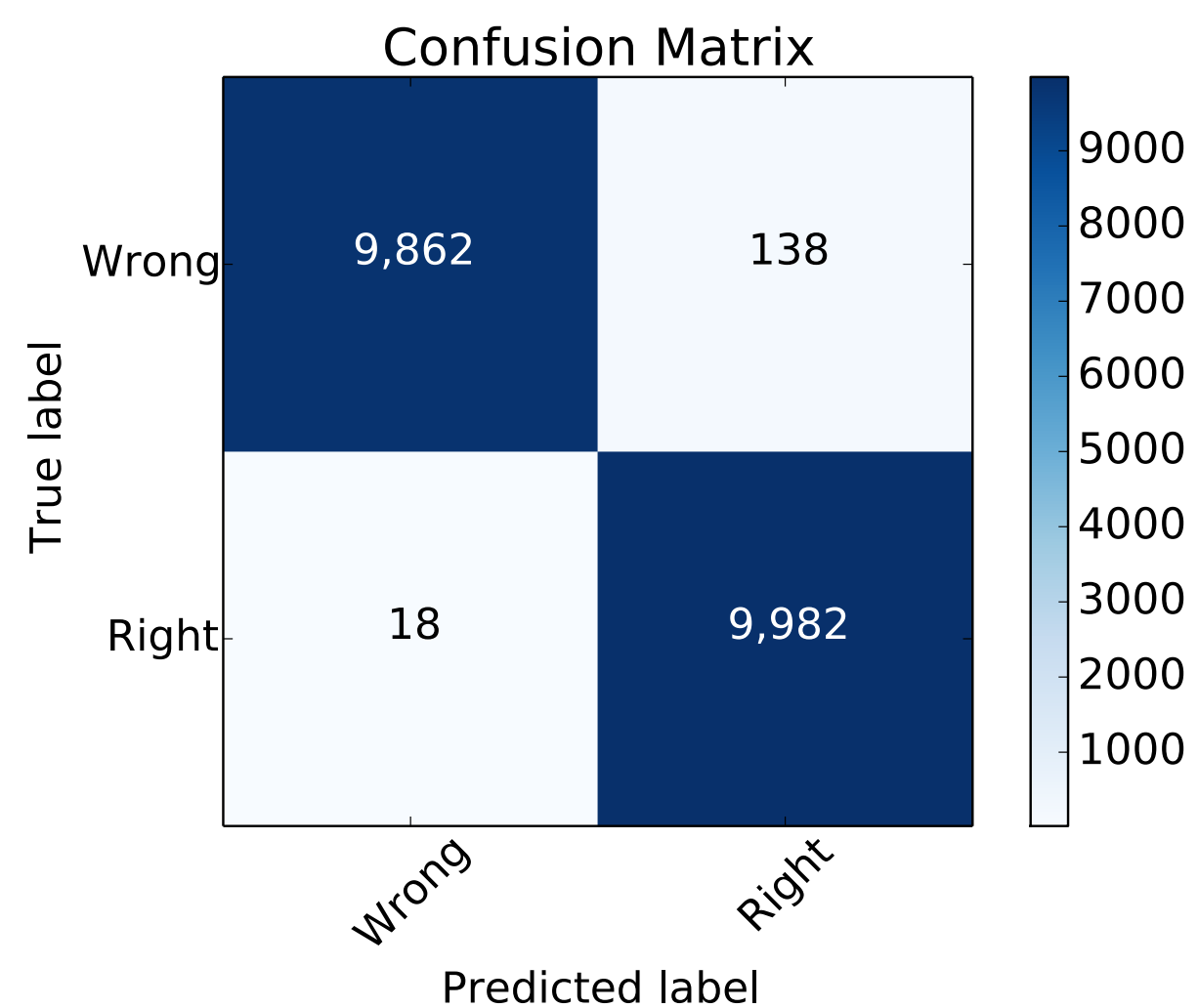
Gets really upset if you classify him as a “CAT”

When creating a training sample:  
Special care should be given to negative samples.

## Should I care about the training sample?

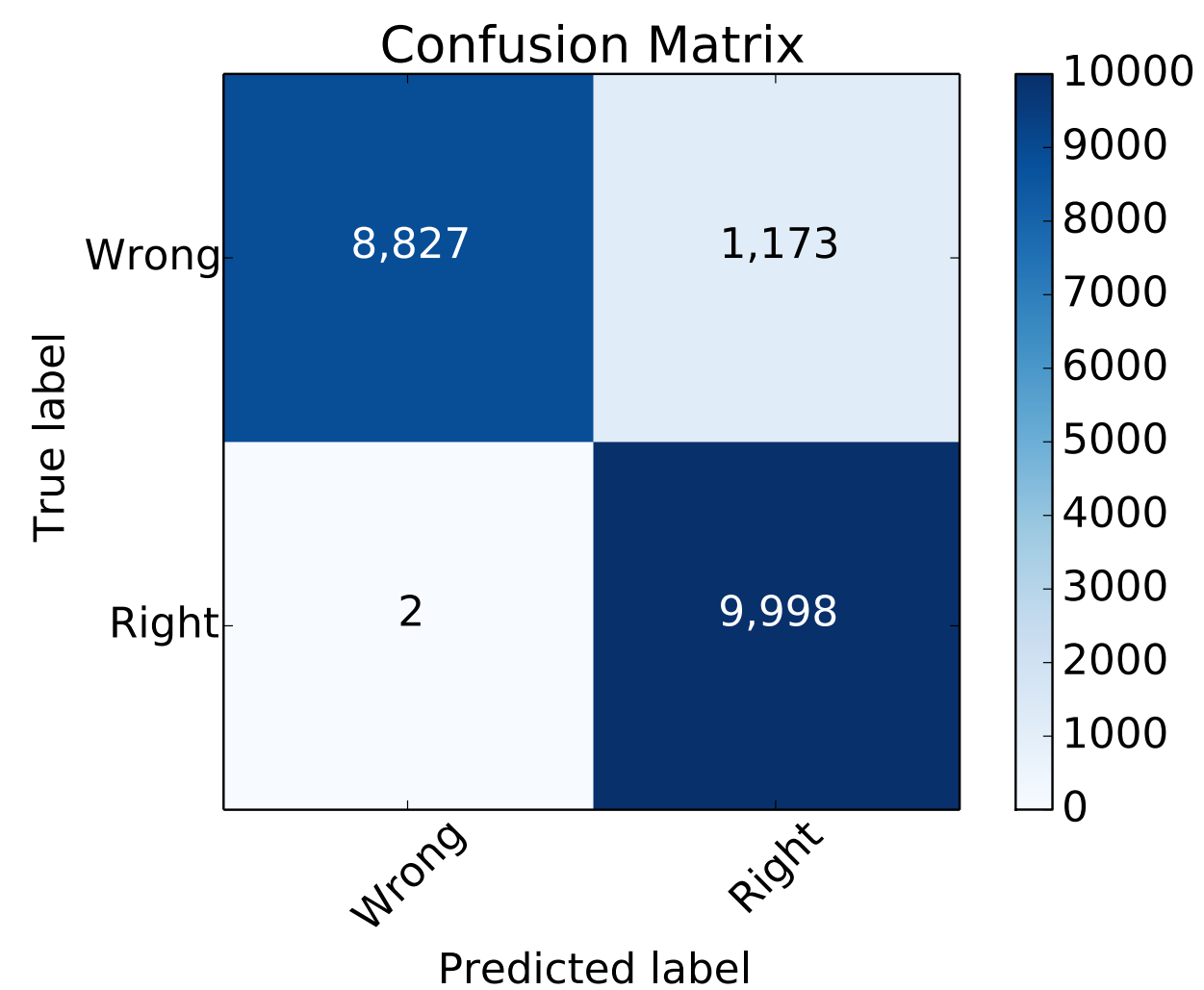


### Closest



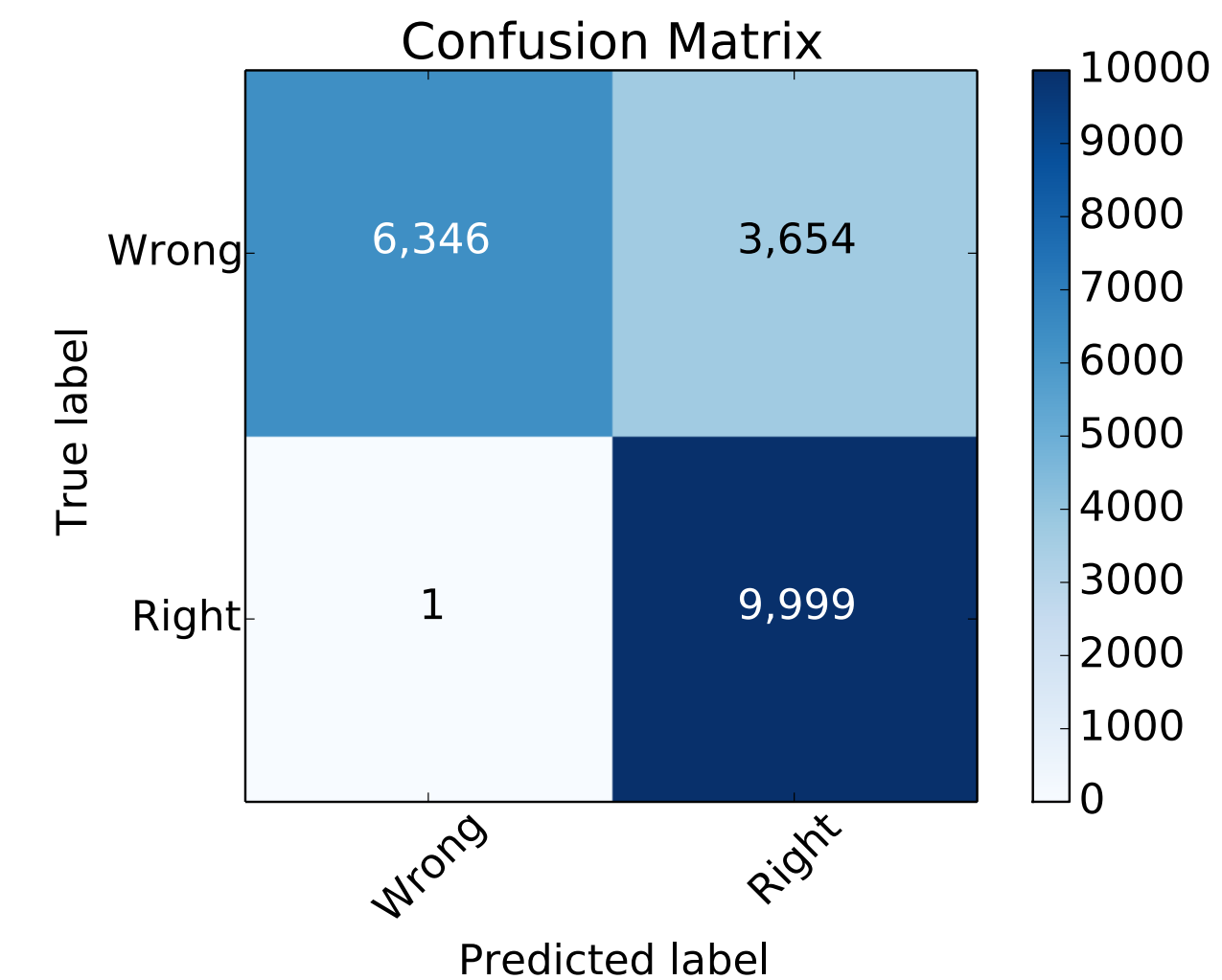
False Positive 1.38%

### Random



False Positive 11.73%

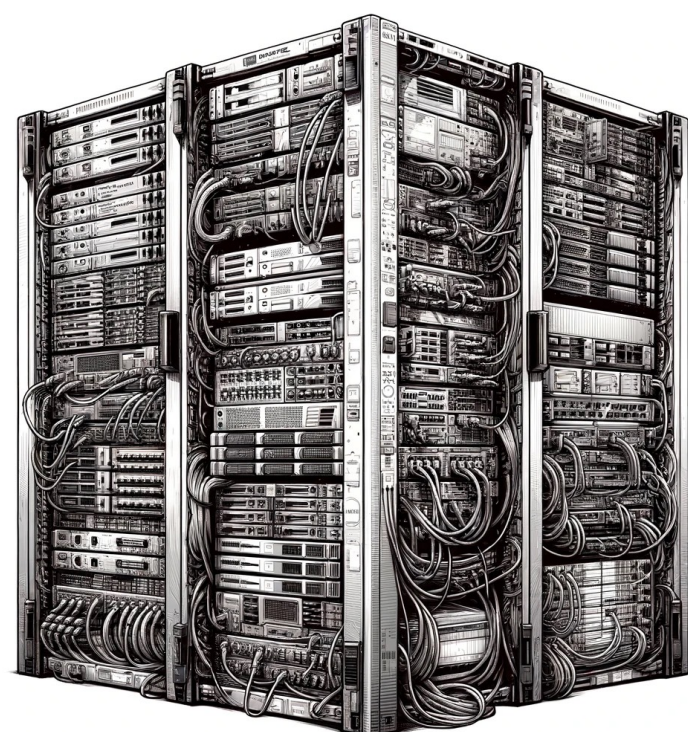
### Least



False Positive 36.54%

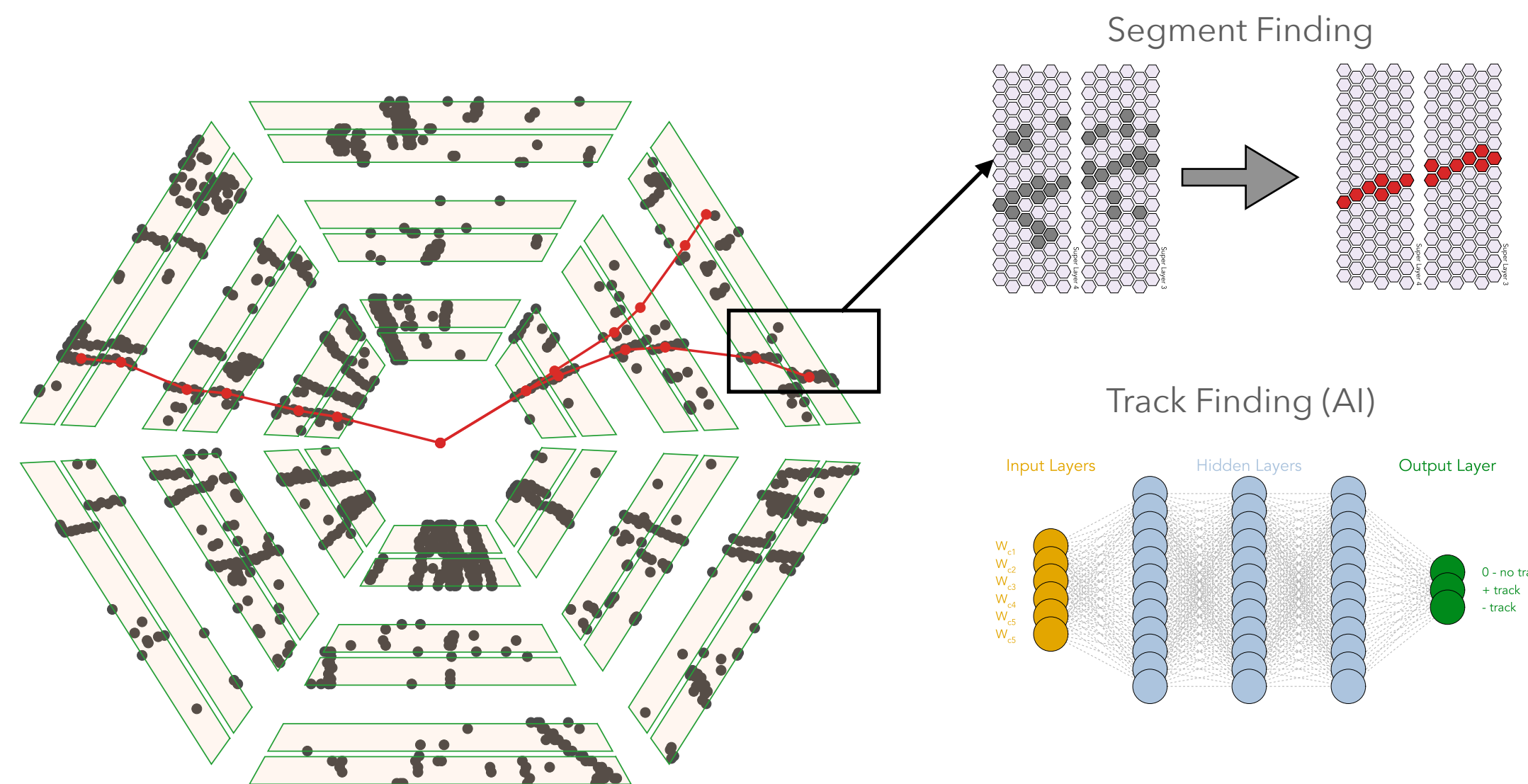


# Artificial Intelligence in CLAS12 tracking

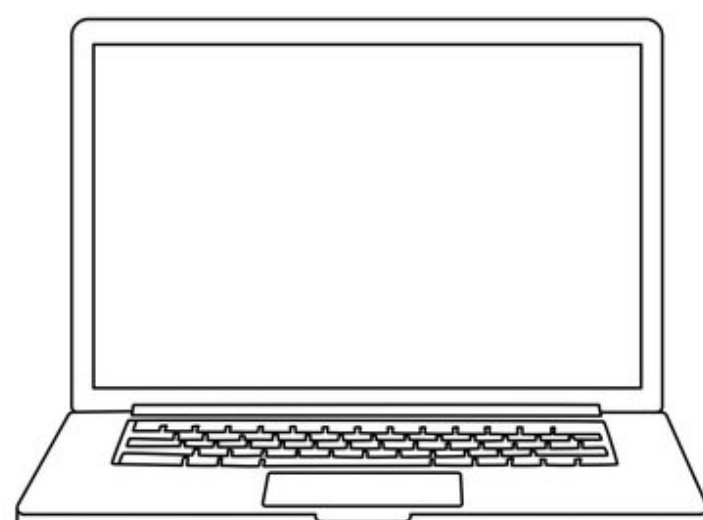


One run with 100M triggers  
Processed on 24 nodes  
each running 32 threads

## 10 Hrs

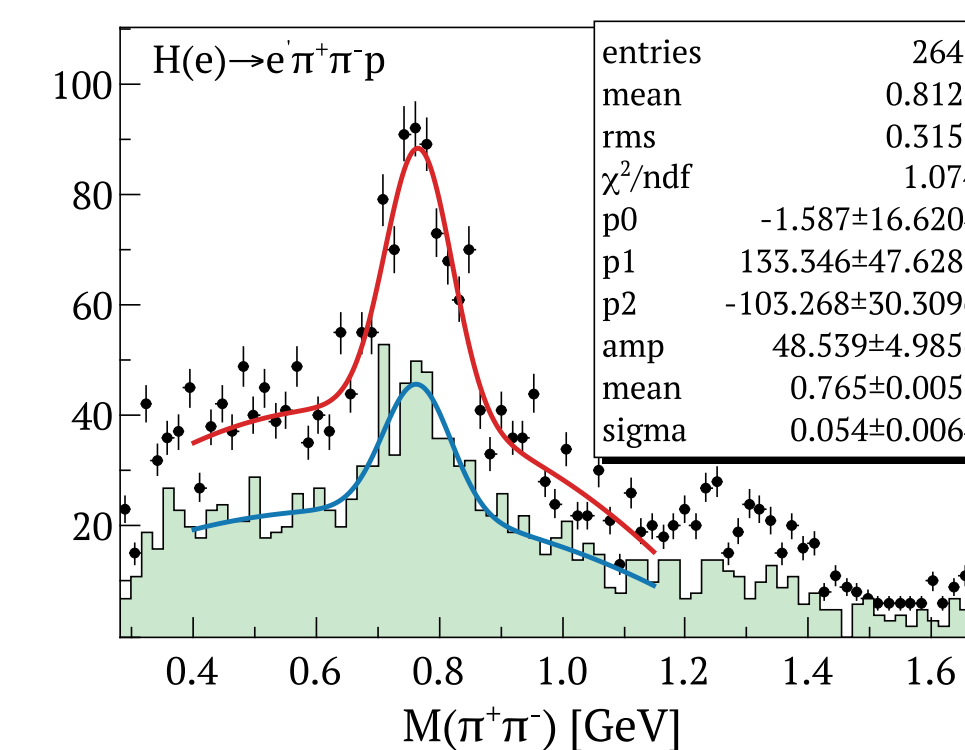
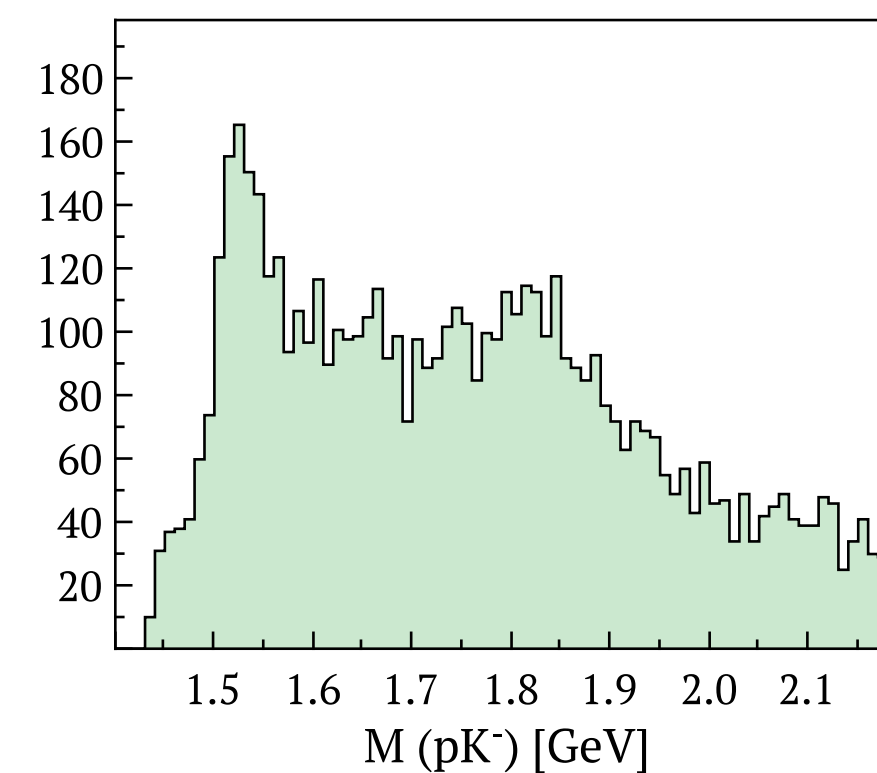


- ▶ Finding Segments from RAW hits
- ▶ Finding Tracks (AI) using segments in each chamber (6 in each sector)
- ▶ Predicting Track Parameters using AI track estimator



One run with 100M triggers  
MacBook M3  
Running 8 threads

## 25 Min

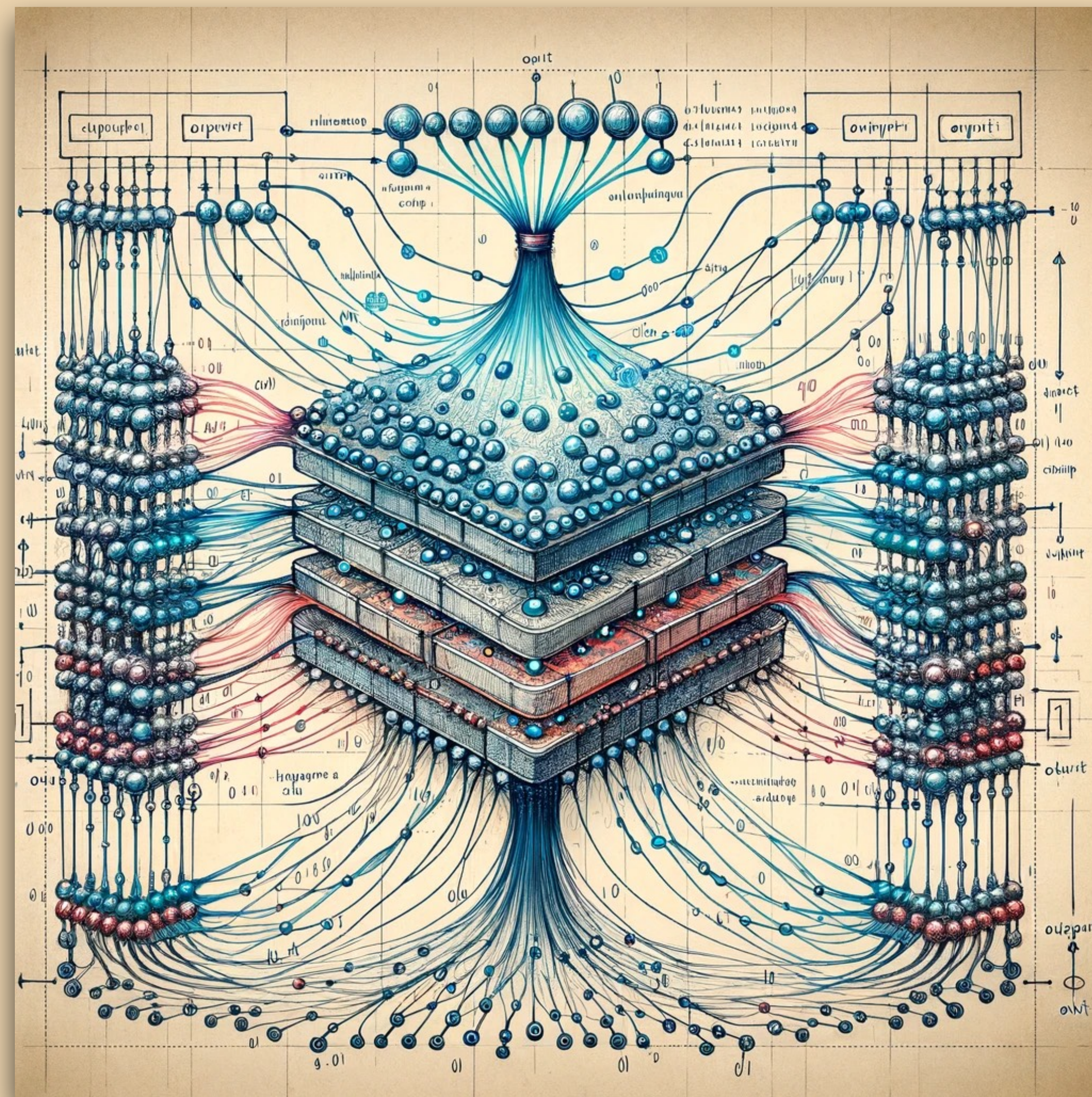


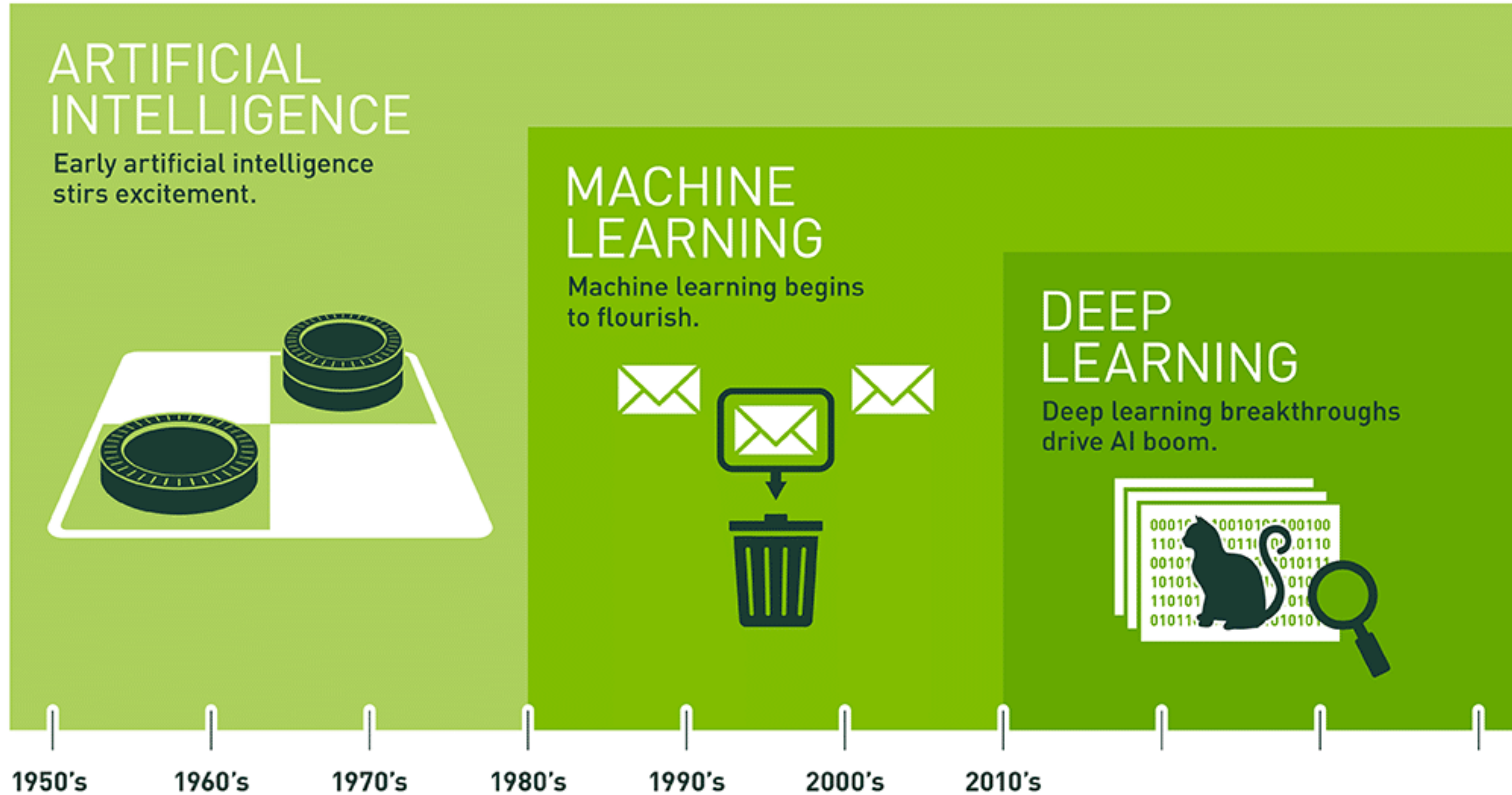
BAOBY

SLIDES

0100111  
0100001  
0100111  
0100111

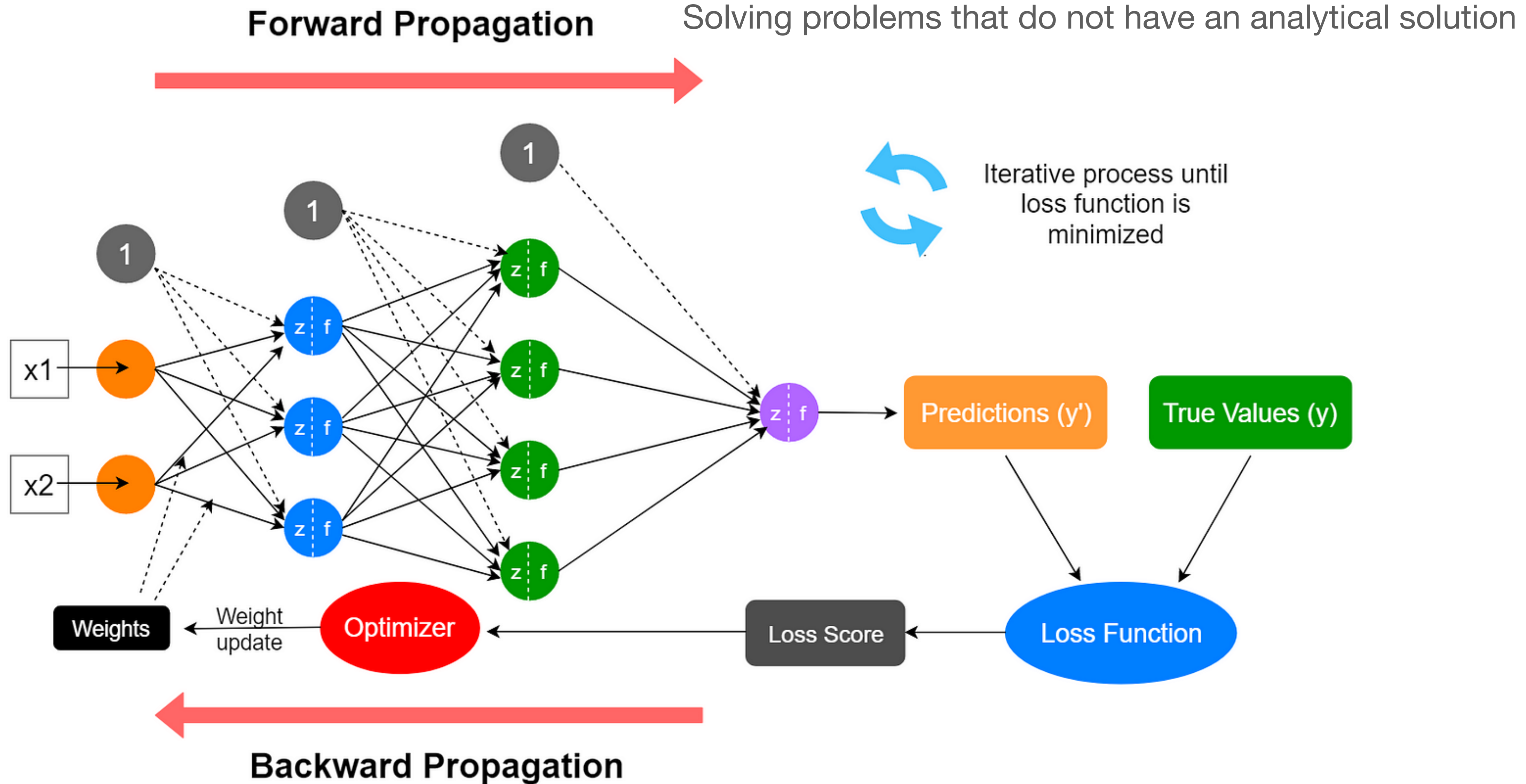
DALLE 3

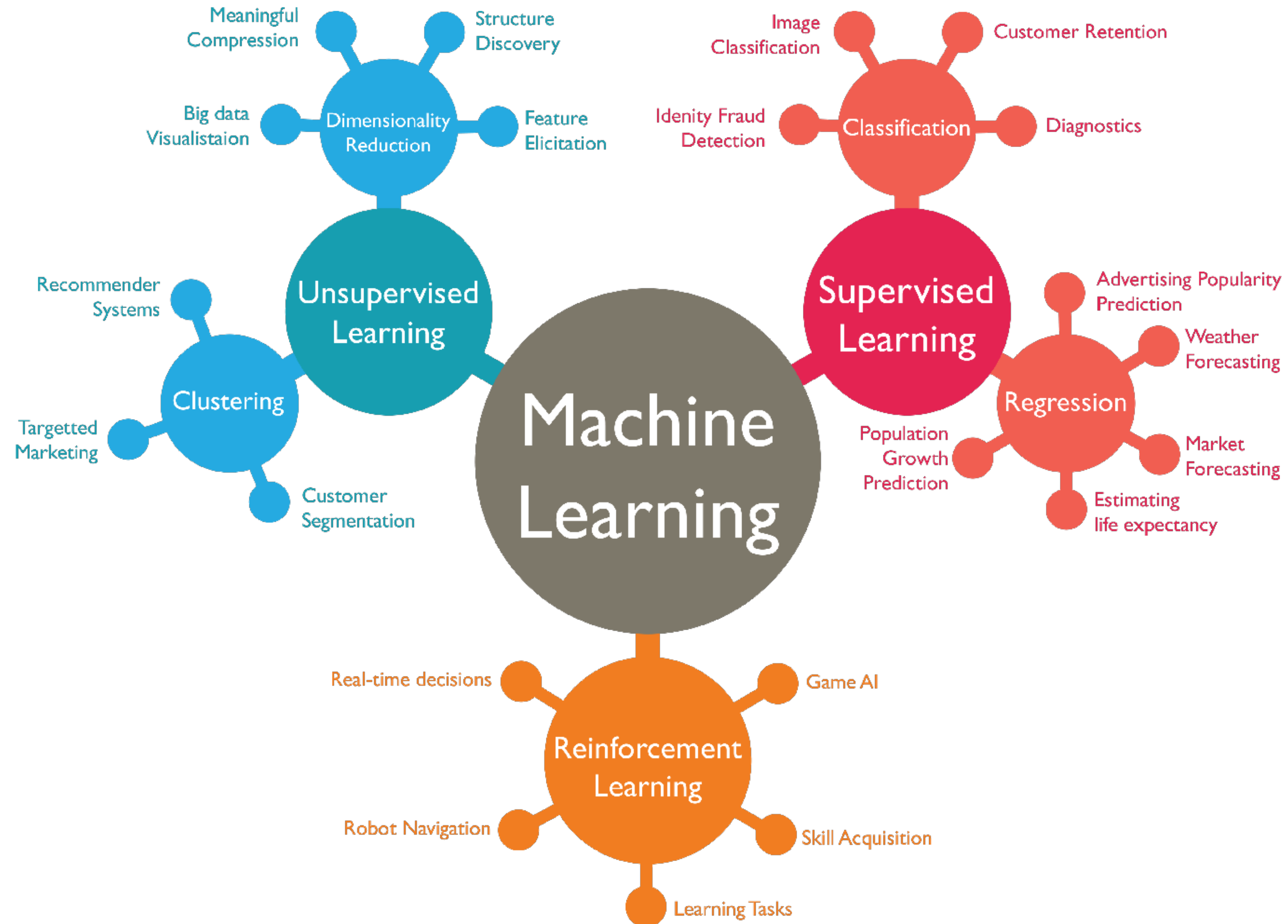




Since an early flush of optimism in the 1950s, smaller subsets of artificial intelligence – first machine learning, then deep learning, a subset of machine learning – have created ever larger disruptions.

# What is Deep Learning?





# Image Generation DALL-E

Here are the images of a cassowary standing in a field of dandelions, with some stumps and a forest in the background.



## Salvador Dali Style



## Edgar Degas Style



## ChatGPT 4 ▾



**You**

Միատ իմ համար թարգման է, ես ուզում եմ անգլերեն ասեմ, գնում եմ տուն:



**ChatGPT**

"Միատ" իմ համար թարգմանվում է "I'm going home":



**You**

I want to visit New York this summer. Translate this into Ukrainian.



**ChatGPT**

I want to visit New York this summer. - Я хочу відвідати Нью-Йорк цього літа.





## Generate Pascal code to do merge sort of an array

- ▶ Compiles without errors
- ▶ Runs without errors

Original Array:

38 27 43 3 9 82 10

Sorted Array:

3 9 10 27 38 43 82

```
program MergeSortDemo;
type
  TArray = array of Integer;

procedure Merge(var Arr: TArray;
  Left, Mid, Right: Integer);
var
  Temp: TArray;
  i, j, k, n1, n2: Integer;
begin
  n1 := Mid - Left + 1;
  n2 := Right - Mid;

  SetLength(Temp, n1 + n2);

  for i := 0 to n1 - 1 do
    Temp[i] := Arr[Left + i];

  for j := 0 to n2 - 1 do
    Temp[n1 + j] := Arr[Mid + 1 + j];

  i := 0;
  j := 0;
  k := Left;
```

```
while (i < n1) and (j < n2) do
begin
  if Temp[i] <= Temp[n1 + j] then
  begin
    Arr[k] := Temp[i];
    Inc(i);
  end
  else
  begin
    Arr[k] := Temp[n1 + j];
    Inc(j);
  end;
  Inc(k);
end;

while i < n1 do
begin
  Arr[k] := Temp[i];
  Inc(i);
  Inc(k);
end;

while j < n2 do
begin
  Arr[k] := Temp[n1 + j];
  Inc(j);
  Inc(k);
end;
end;
```

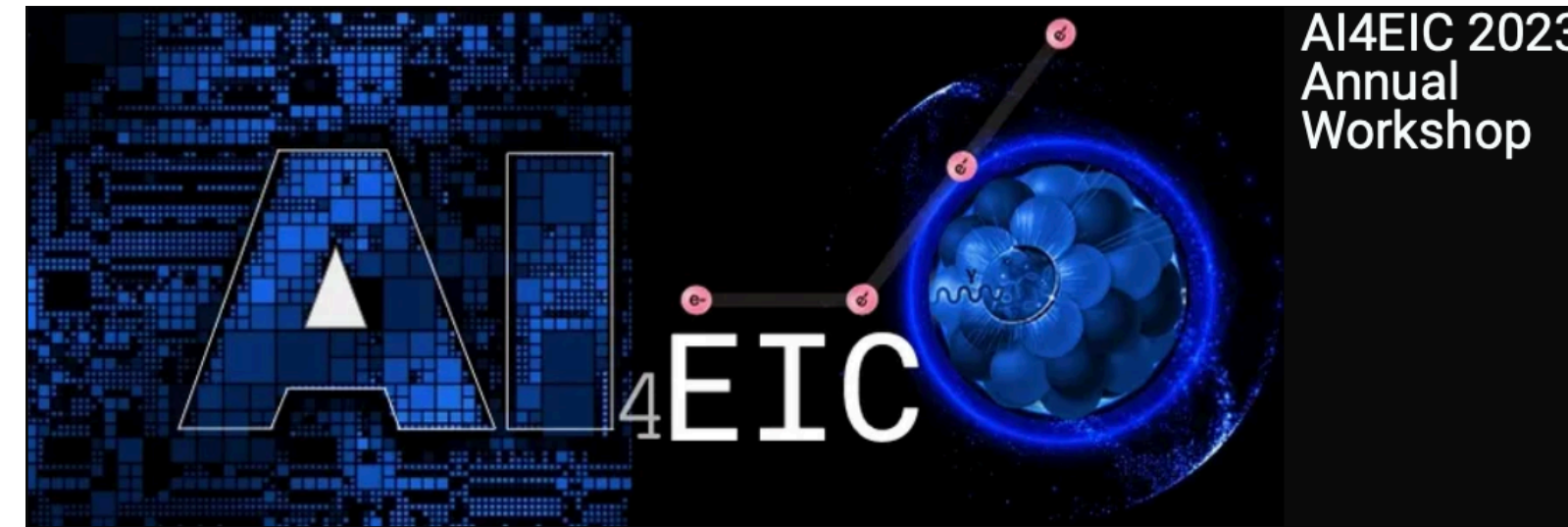
```
procedure MergeSort(var Arr: TArray; Left, Right: Integer);
var
  Mid: Integer;
begin
  if Right > Left then
  begin
    Mid := Left + (Right - Left) div 2;
    MergeSort(Arr, Left, Mid);
    MergeSort(Arr, Mid + 1, Right);
    Merge(Arr, Left, Mid, Right);
  end;
end;

procedure PrintArray(Arr: TArray);
var
  i: Integer;
begin
  for i := Low(Arr) to High(Arr) do
    Write(Arr[i], ' ');
  WriteLn;
end;

var
  MyArray: TArray;
begin
  MyArray := [38, 27, 43, 3, 9, 82, 10];
  WriteLn('Original Array:');
  PrintArray(MyArray);
  MergeSort(MyArray, Low(MyArray), High(MyArray));
  WriteLn('Sorted Array:');
  PrintArray(MyArray);
end.
```

## ▶ Hackathon:

- ▶ Organized by Cristiano Fanelli
- ▶ Wonderful experience



<https://indico.bnl.gov/event/19560/>

## ▶ GPT-4 prompt engineering (AWS)

- ▶ Solve a classification problem with Hall-D calorimeter (we were just given data)
- ▶ Ask Chat-GPT-4 to write a neural network training code, and run it on the cloud node.
- ▶ All editors are disabled (the code has to run as is)

## ▶ Results (team Gavalian&Lawrence)

- ▶ We got a classification accuracy of 99.625
- ▶ 4th place
- ▶ (Would be 1st place if you adjust for age)

### Prompt:

Write a python code to read data from a csv file with first 15 columns as the input vector and last 2 columns as output, write a neural network training code for the data, read validation data from another file and run inference in validation data and write it into the output by adding the inferred results to the validation data set.

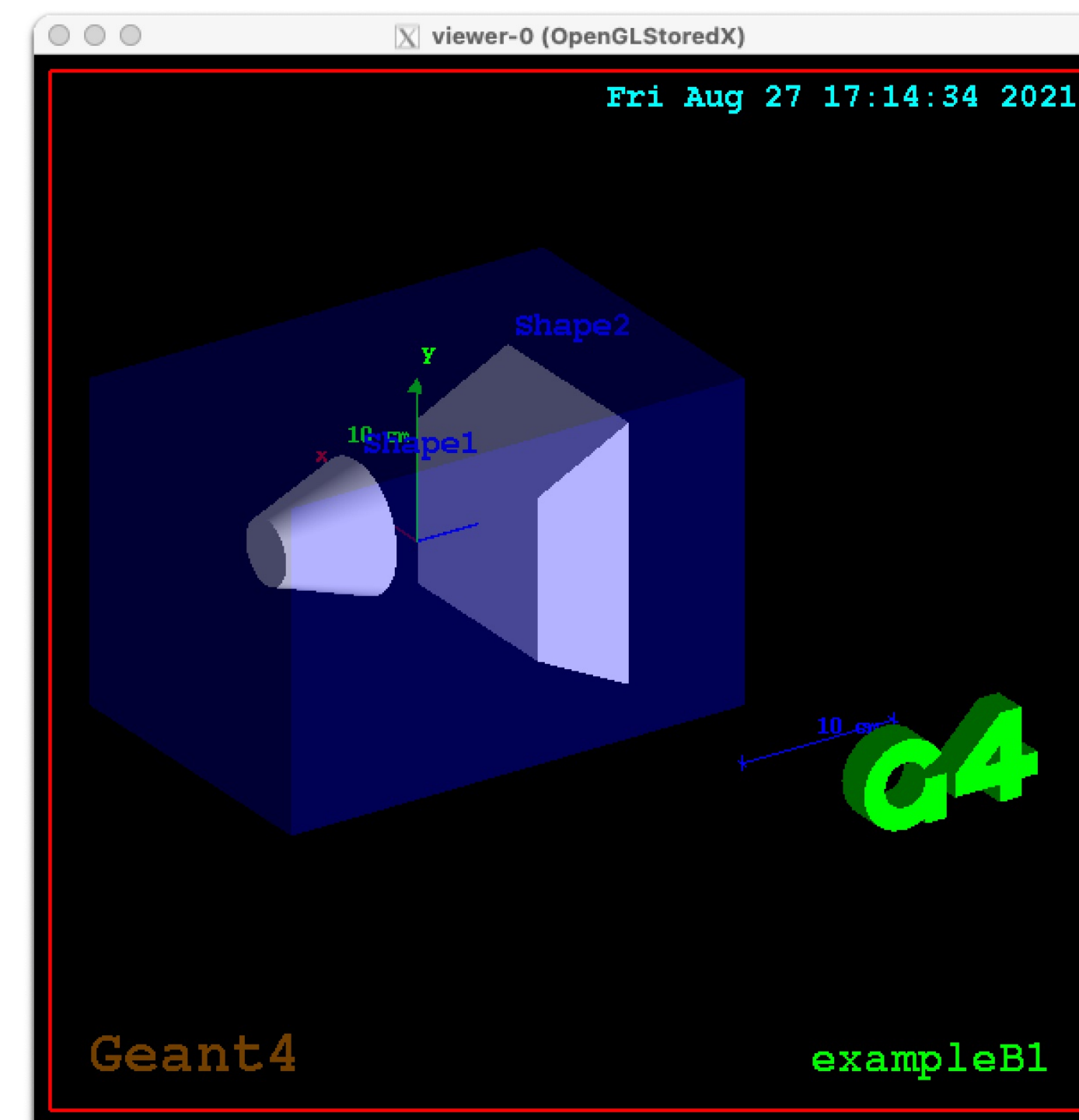
### Prompt: (the best result)

Train the previous data set using a random forest.

<https://3dfy.ai/>



- ▶ Software to create 3d objects from a text prompt
- ▶ What about Geant-4 objects from a text prompt?



- ▶ don't need to know how to program volumes
- ▶ Describe the volumes describe the experiment and get detector rates and fluxes.

