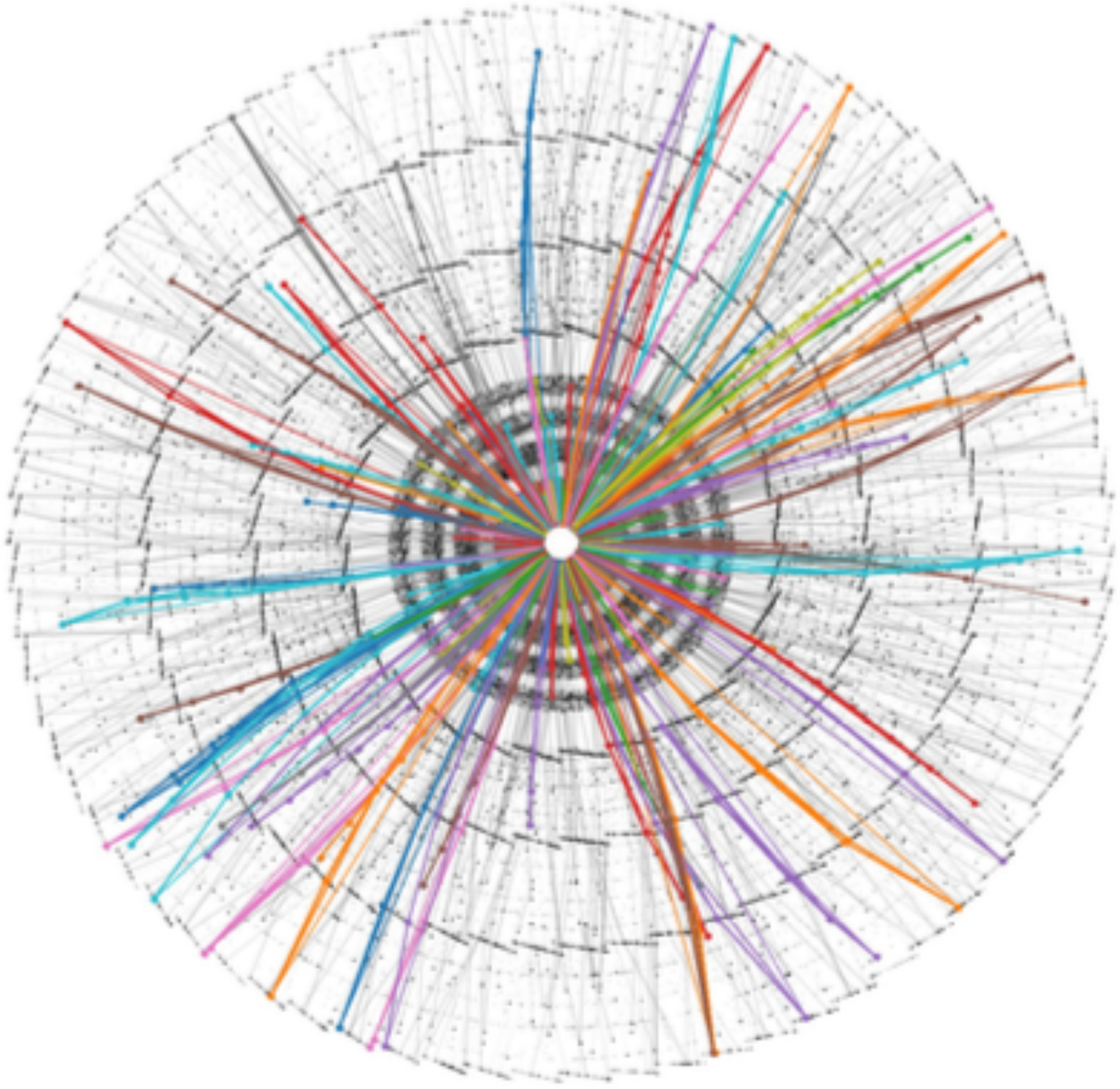


Particle Detectors*

*in my very biased point of view.

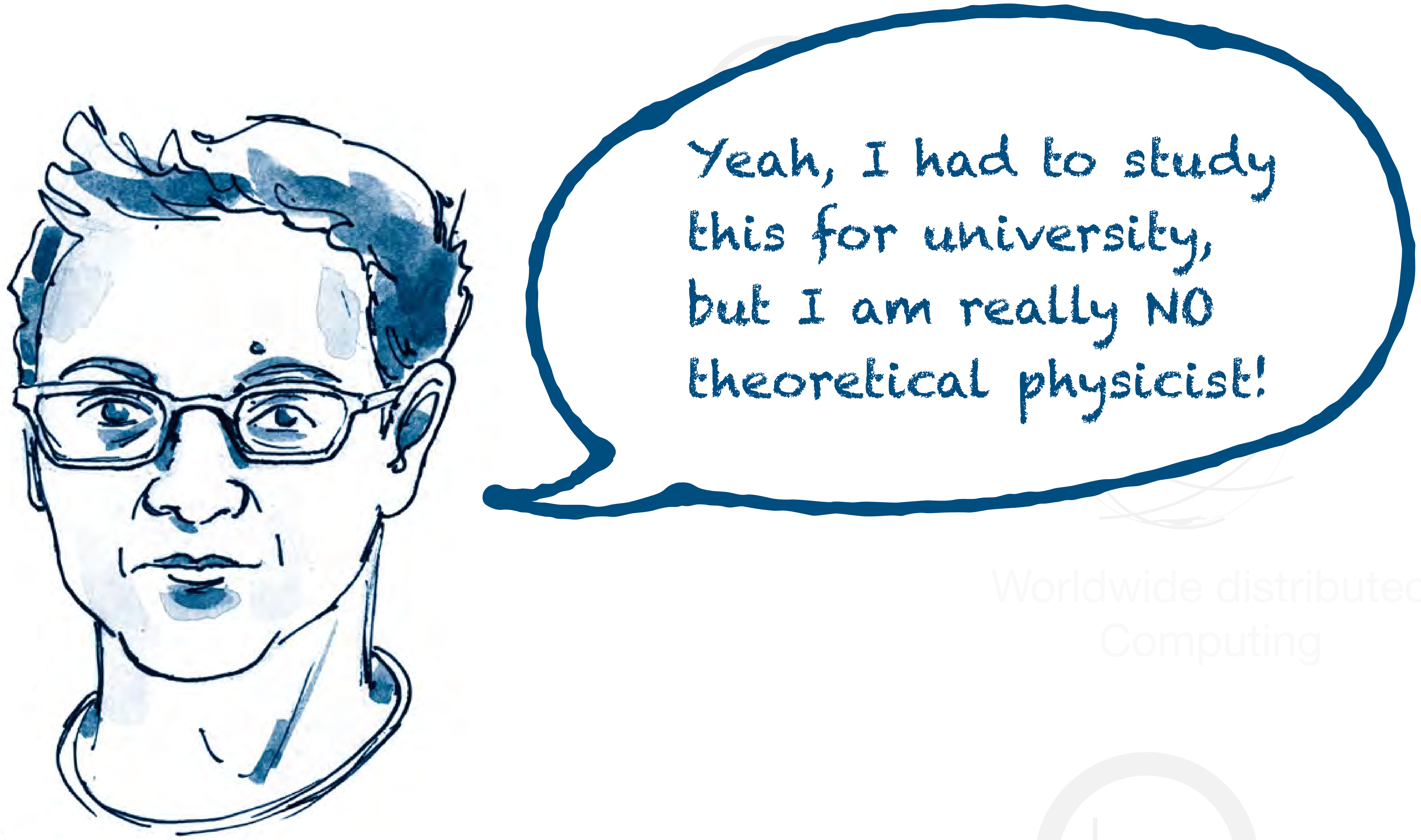
A. Salzburger (CERN)

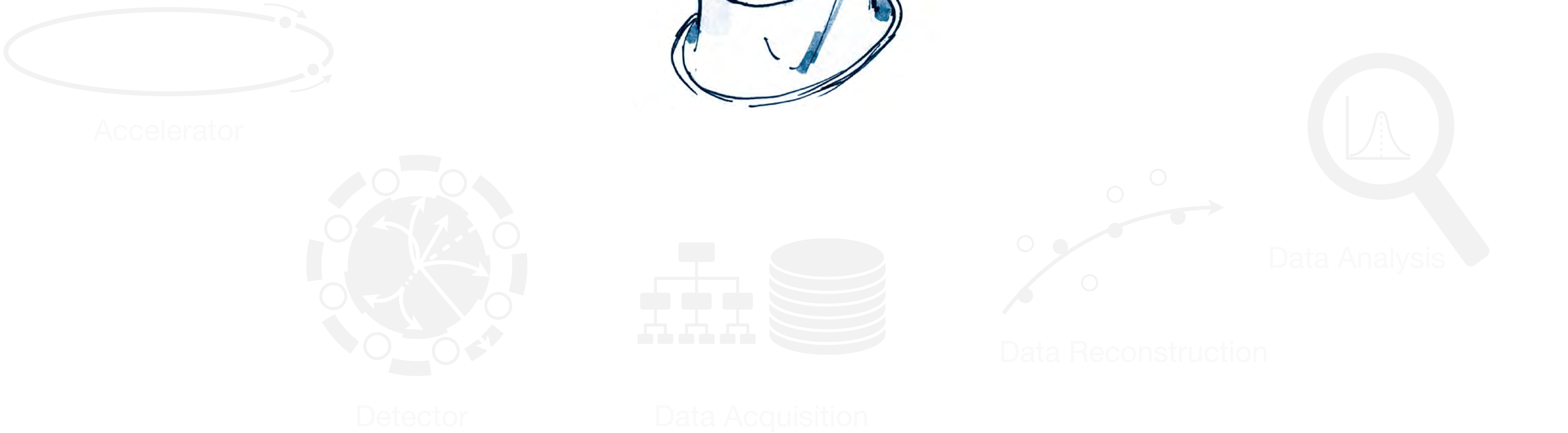
my very biased point of view.

Why biased?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

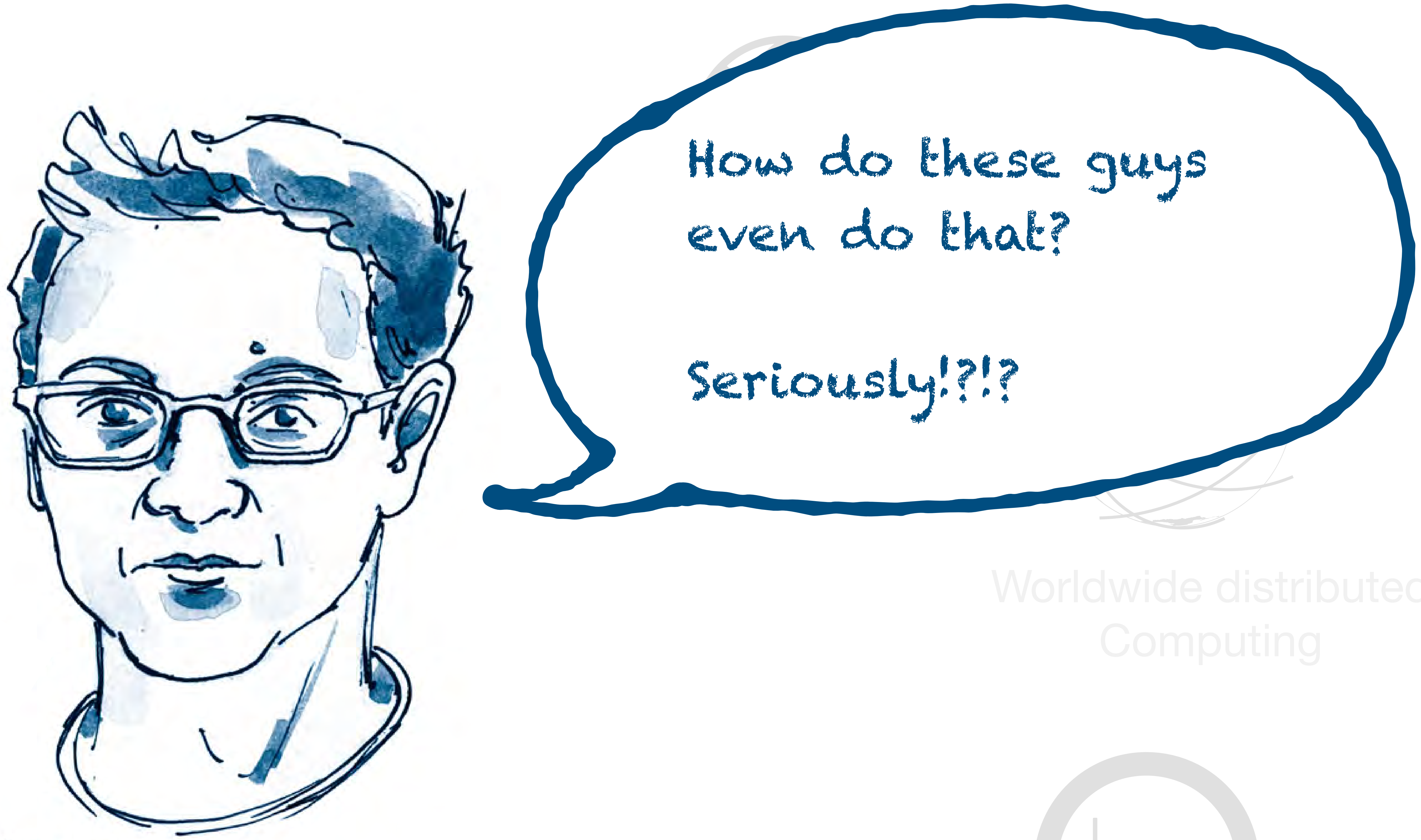
Theory



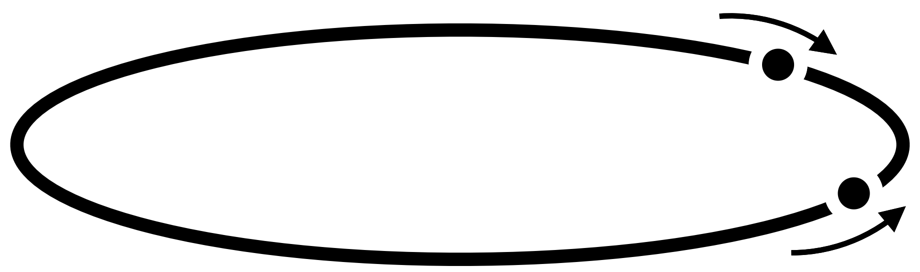


Why biased?

Theory



Worldwide distributed Computing



Accelerator

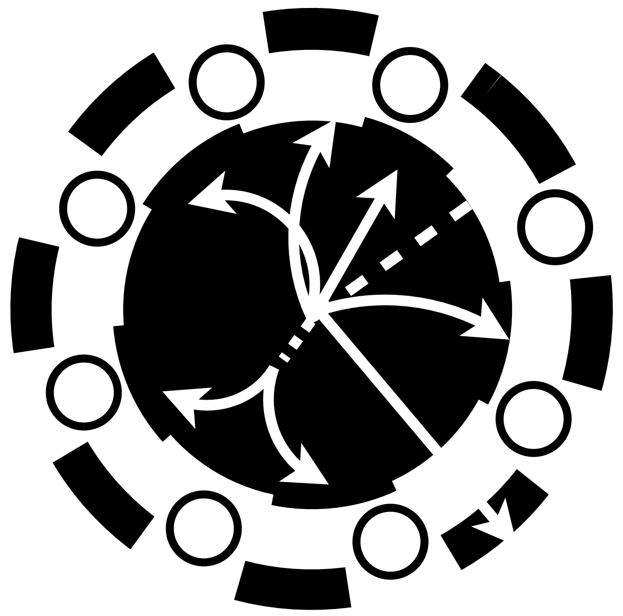
Detector

Data Acquisition

Data Reconstruction

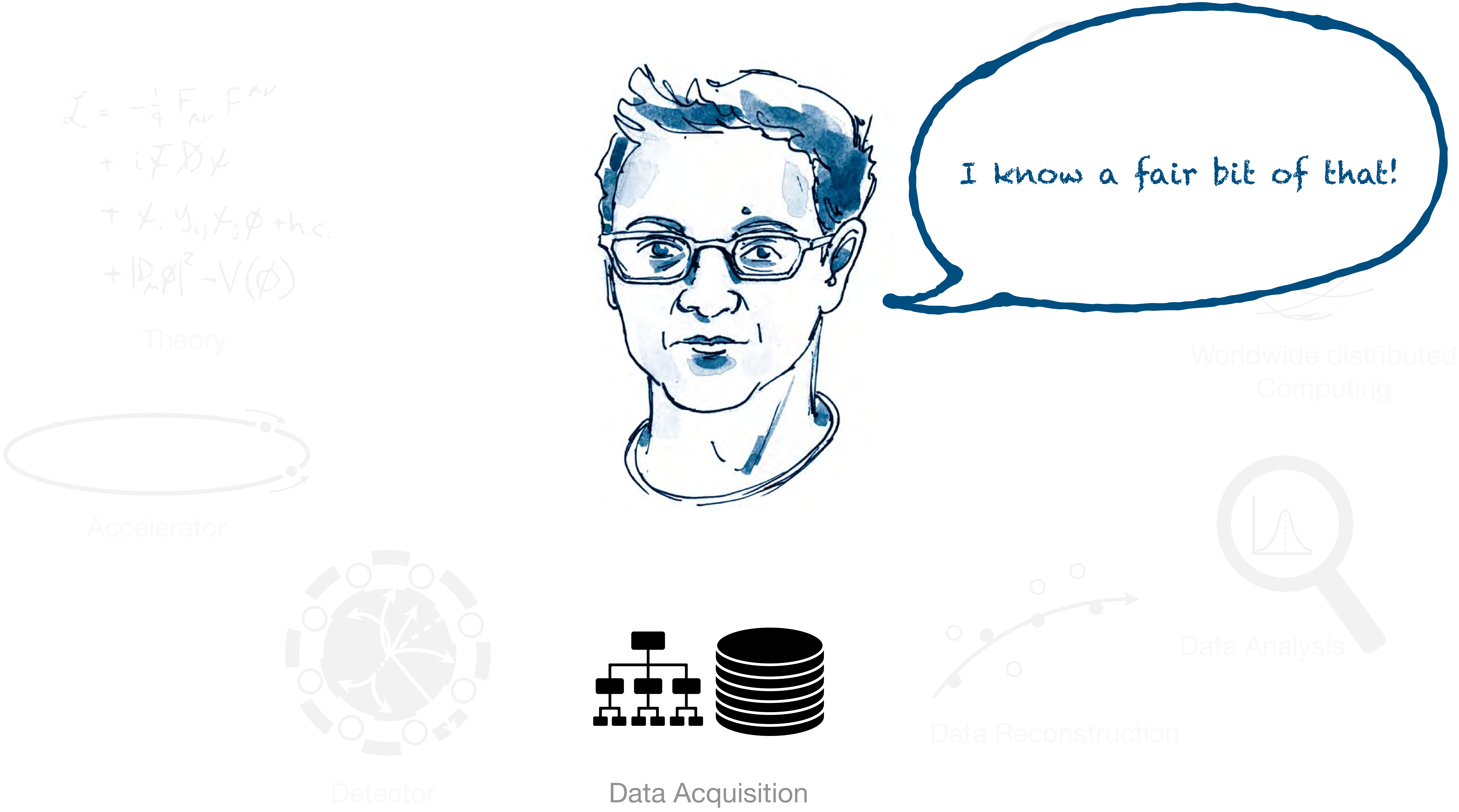
Data Analysis

Why biased?

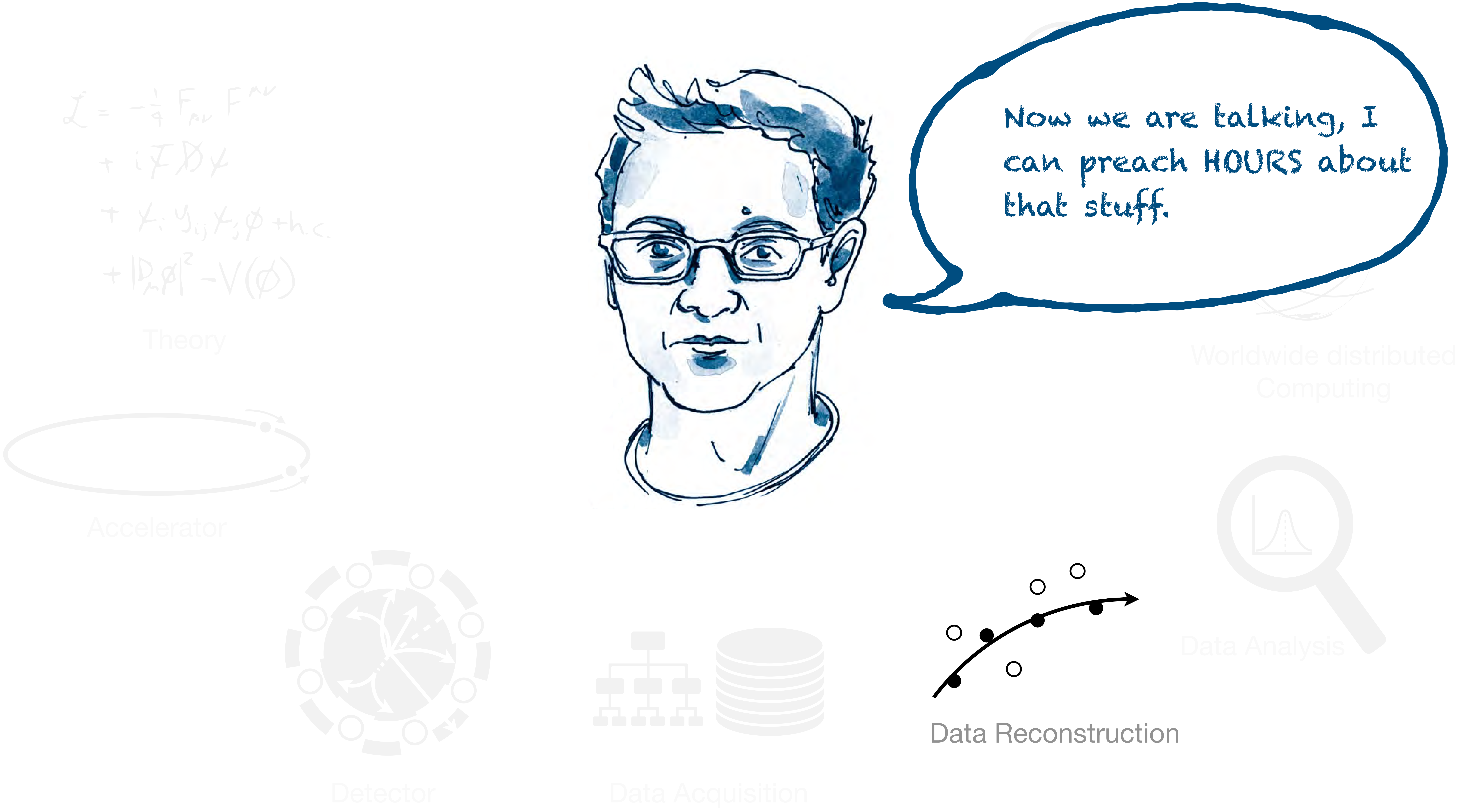


Detector

Why biased?


I know a fair bit of that!
Theory
Accelerator
Detector
Data Acquisition
Data Reconstruction
Data Analysis
Worldwide distributed Computing

Why biased?

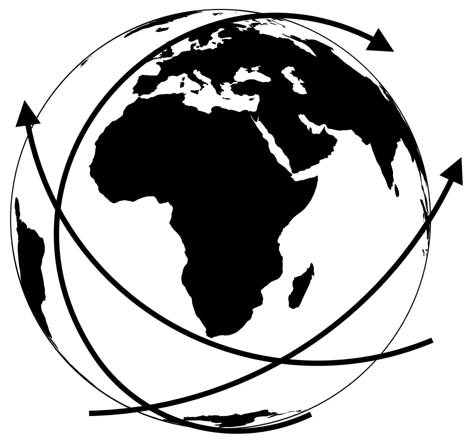


Now we are talking, I can preach HOURS about that stuff.
Theory
Accelerator
Detector
Data Acquisition
Data Reconstruction
Worldwide distributed Computing
Data Analysis

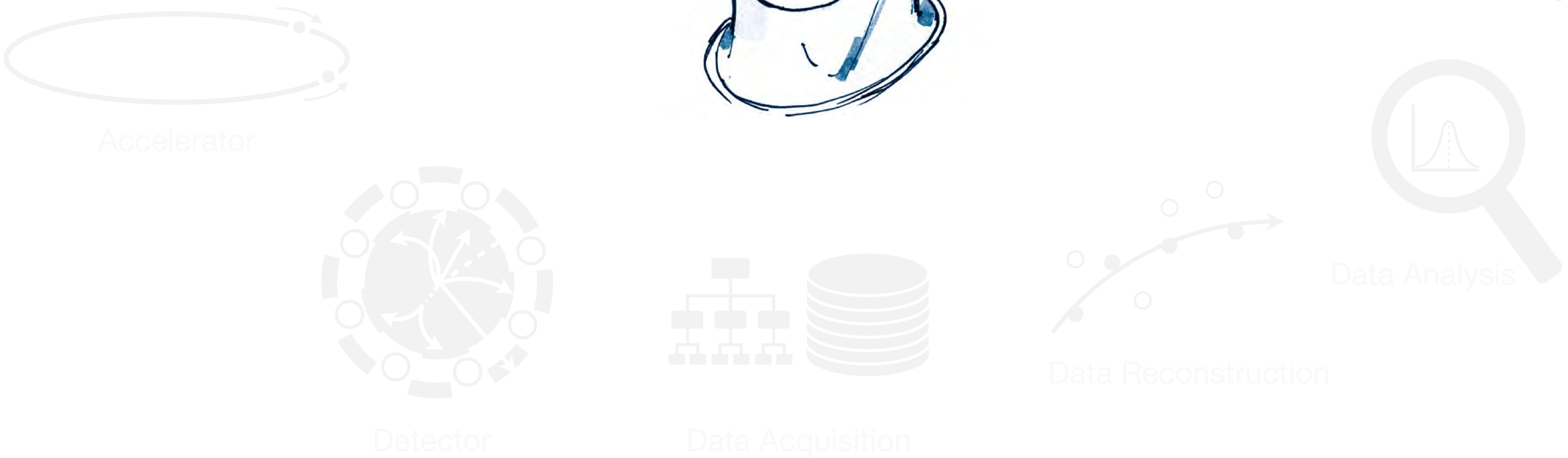
Why biased?


Theory
Accelerator
Detector
Data Acquisition
Data Reconstruction
Worldwide distributed Computing
Yup, seen that, done that.
Data Analysis

Why biased?



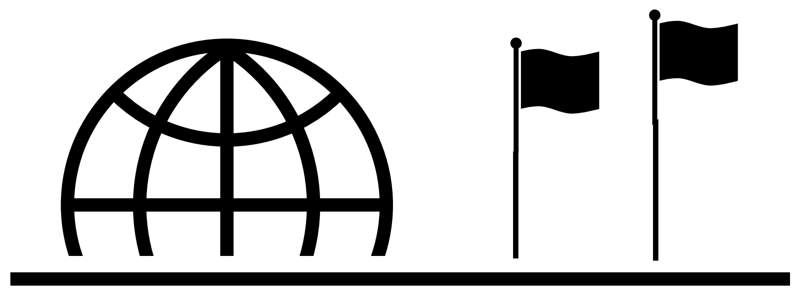
Worldwide distributed Computing



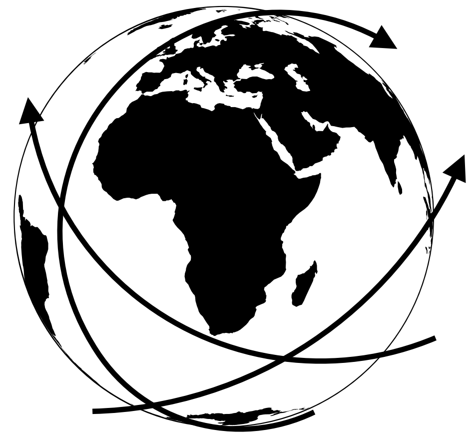
So complex!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

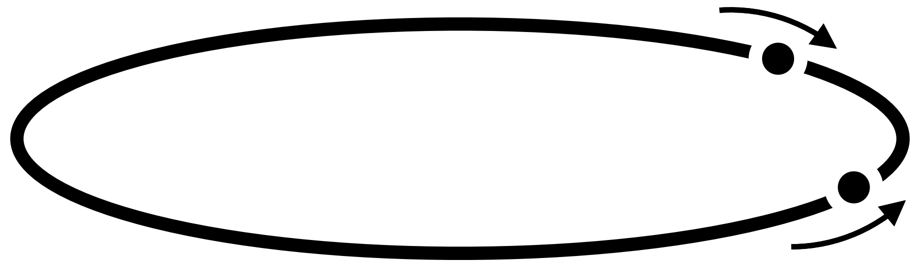
Theory



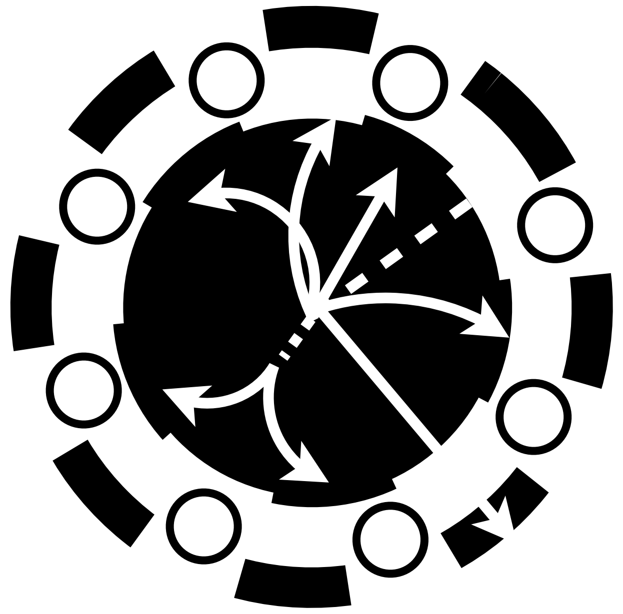
Laboratory



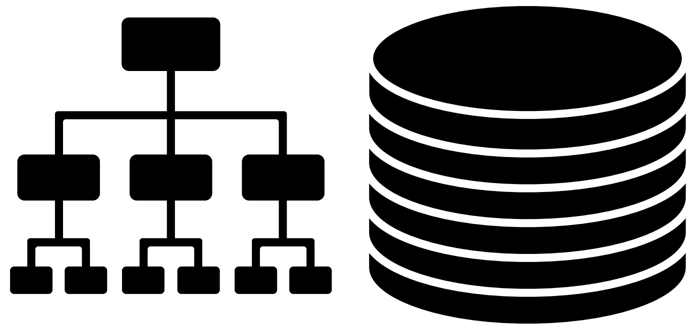
Worldwide distributed Computing



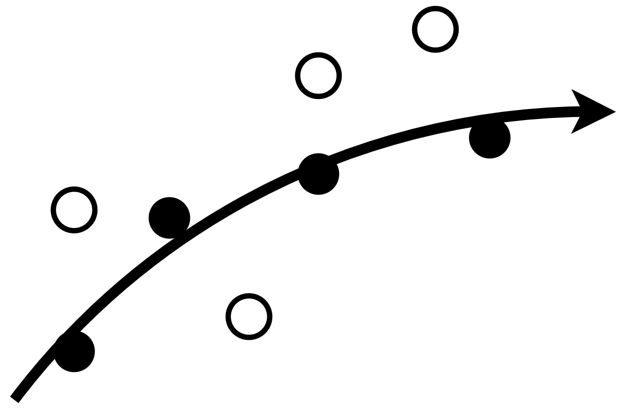
Accelerator



Detector



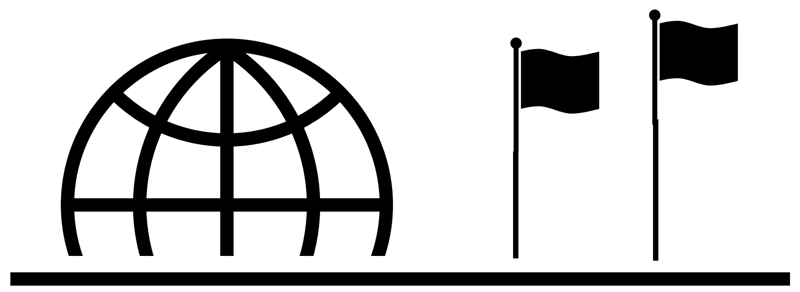
Data Acquisition



Data Reconstruction

Data Analysis

And yet …



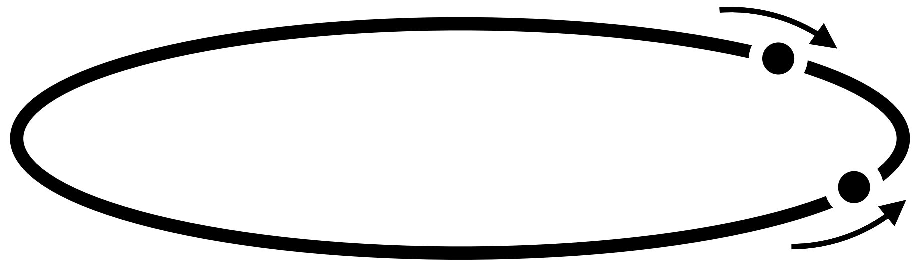
Laboratory

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Theory

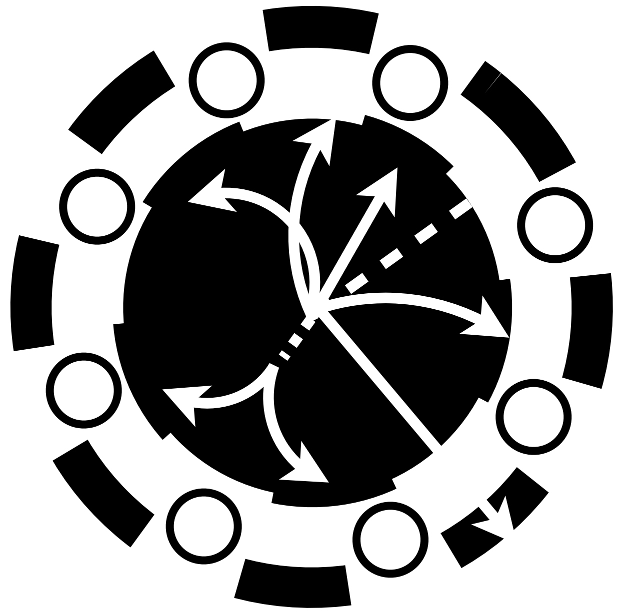
… all of that has to work together!

Worldwide distributed Computing

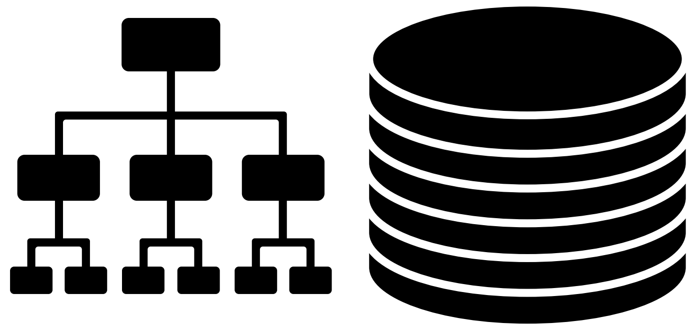


Accelerator

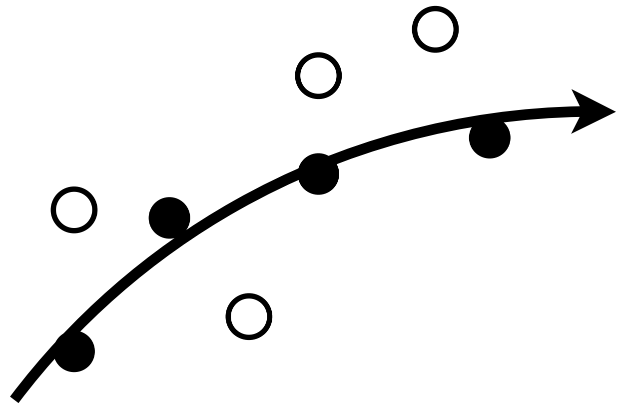
Data Analysis



Detector

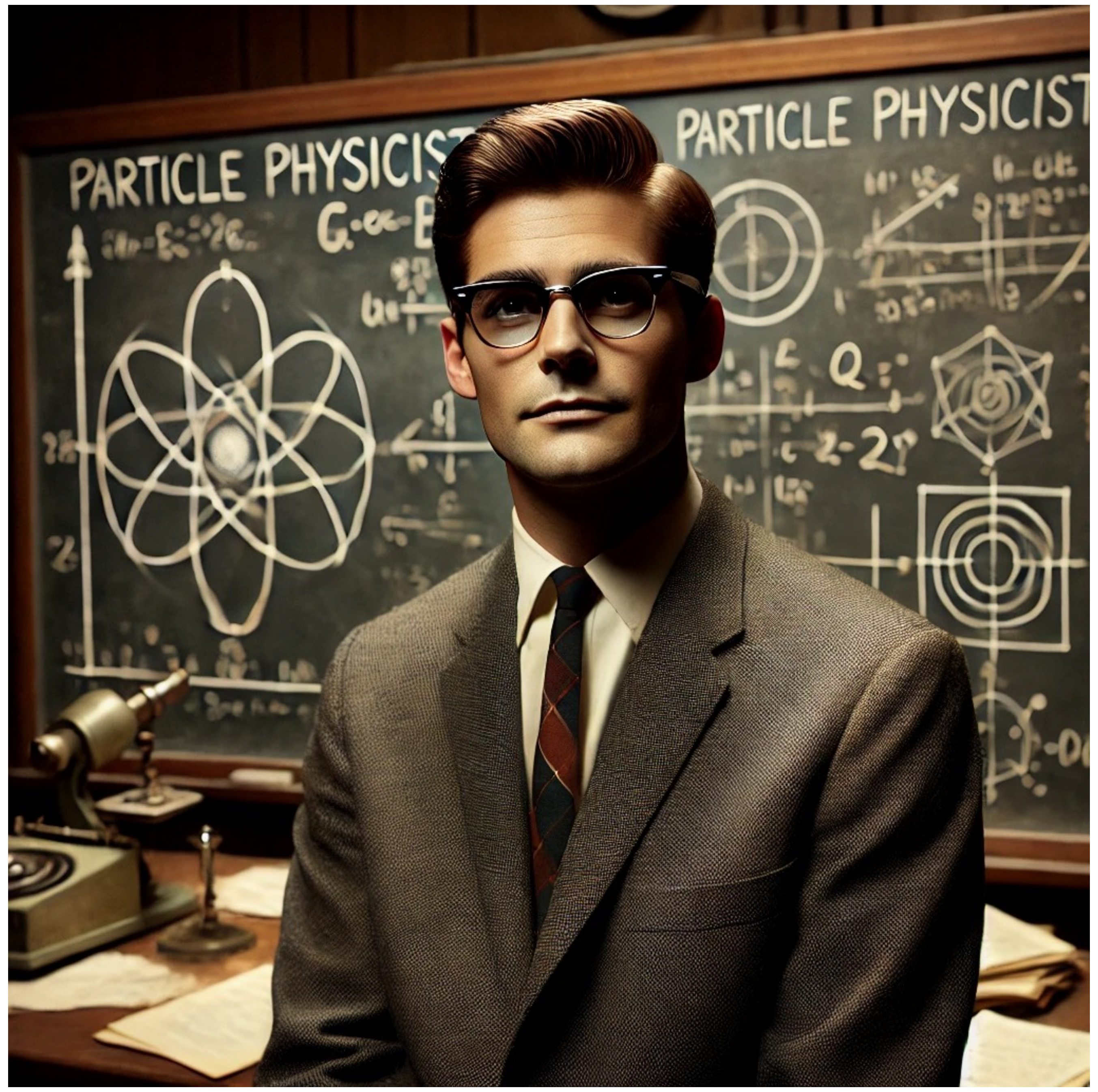


Data Acquisition

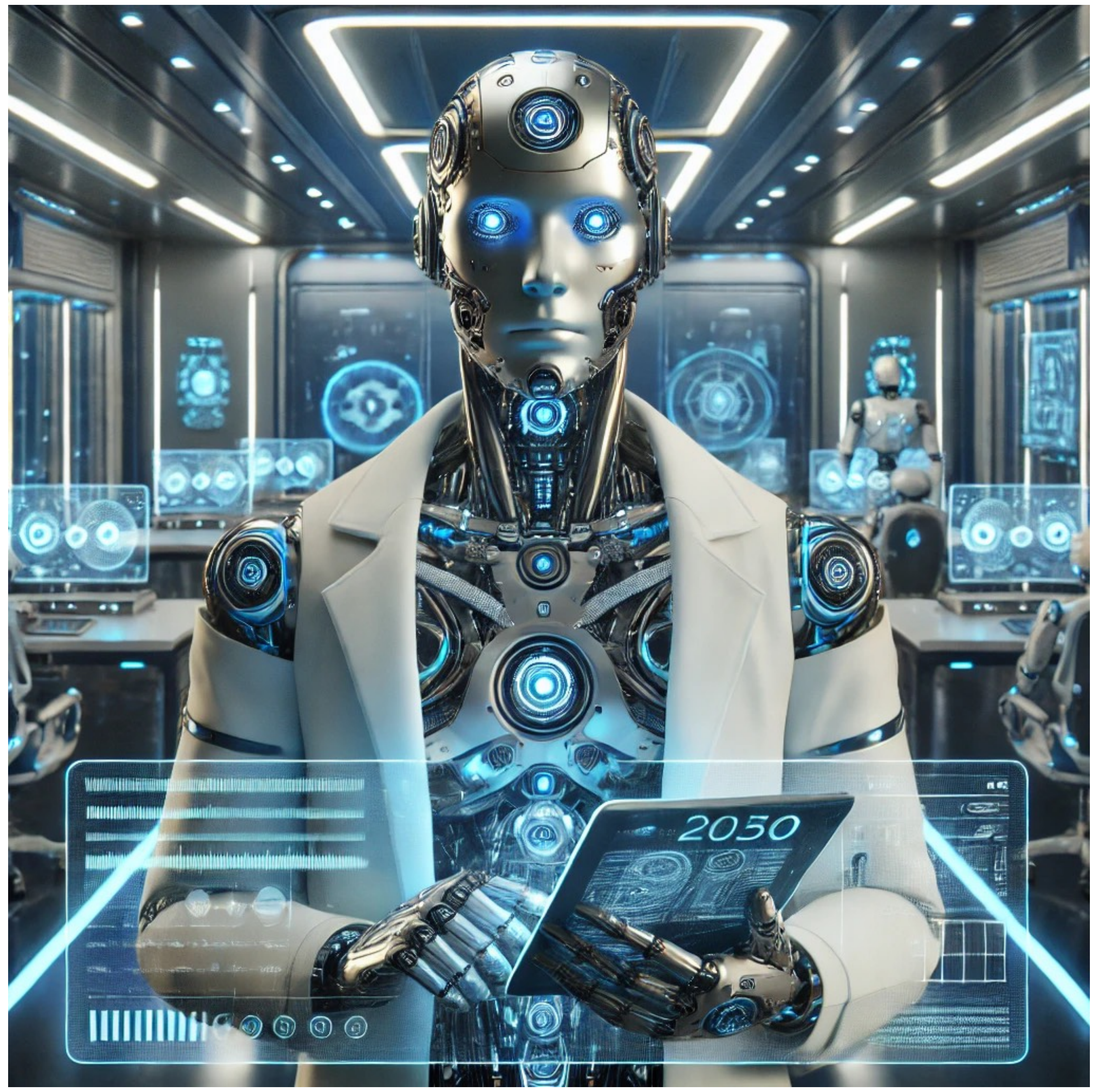


Data Reconstruction

My two assistants for today

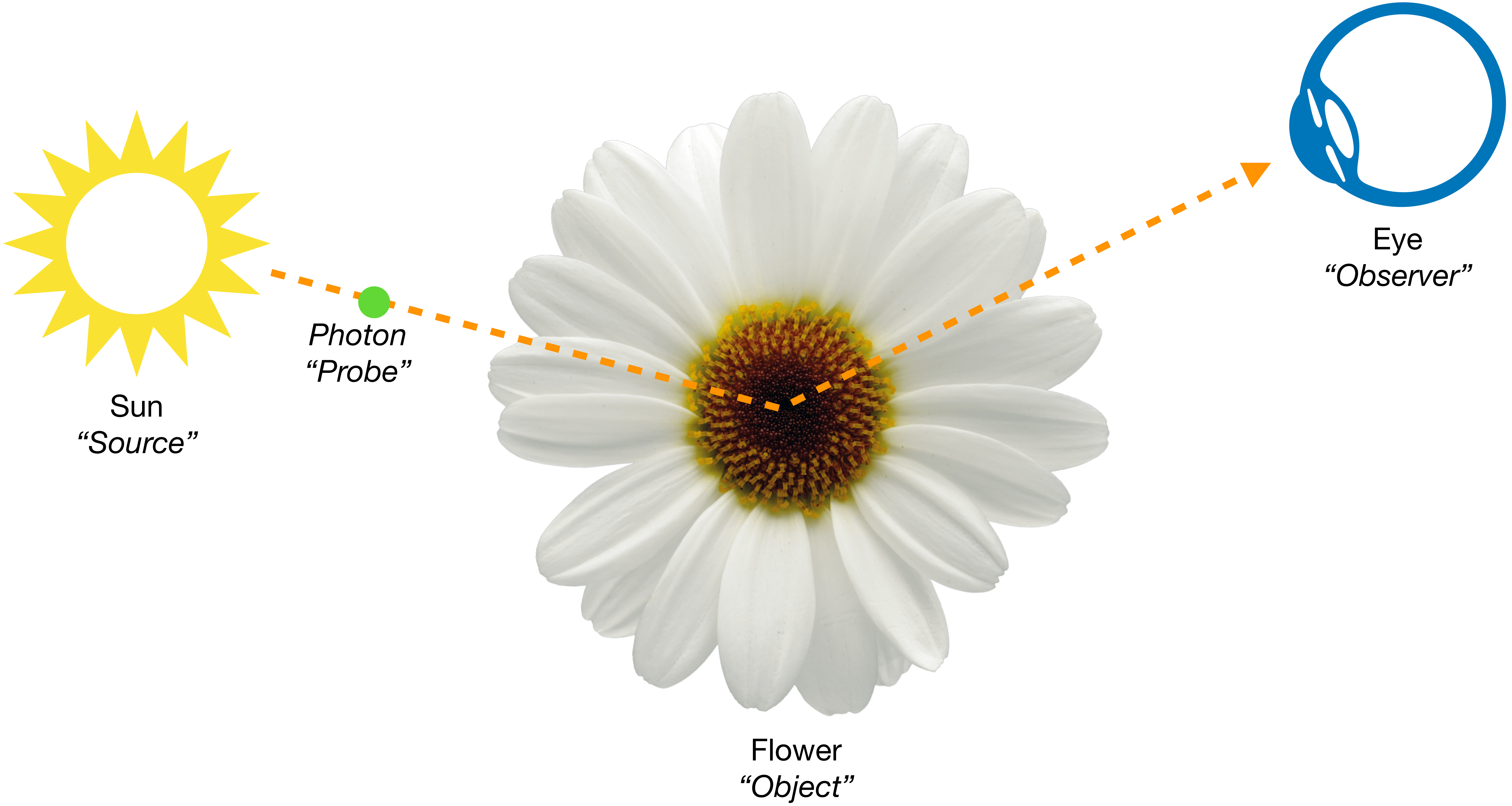


Generate a portrait of a particle physicist in the 1960s



Generate a portrait of a robot physicist in the future

A daily observation

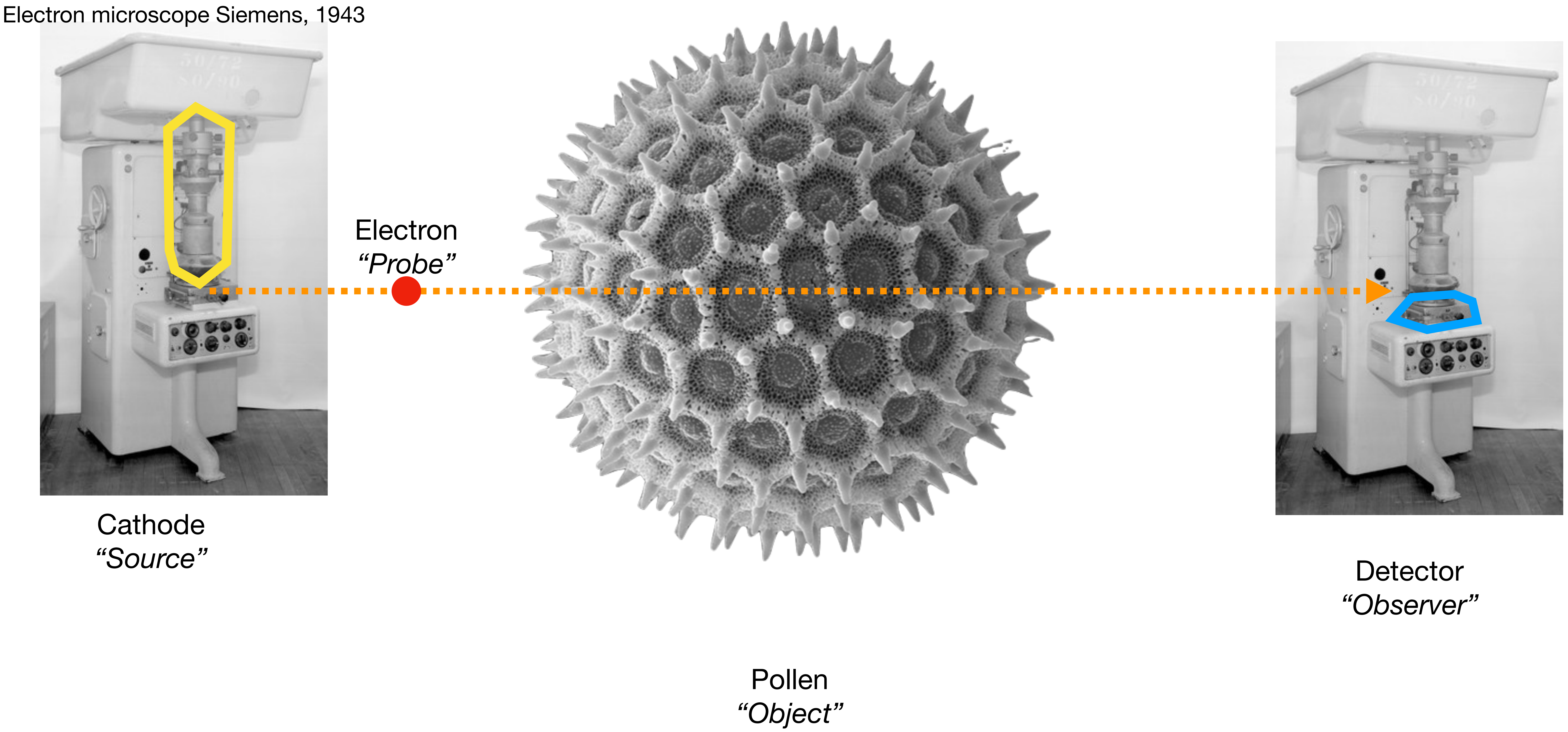


[Image source]

A good microscope

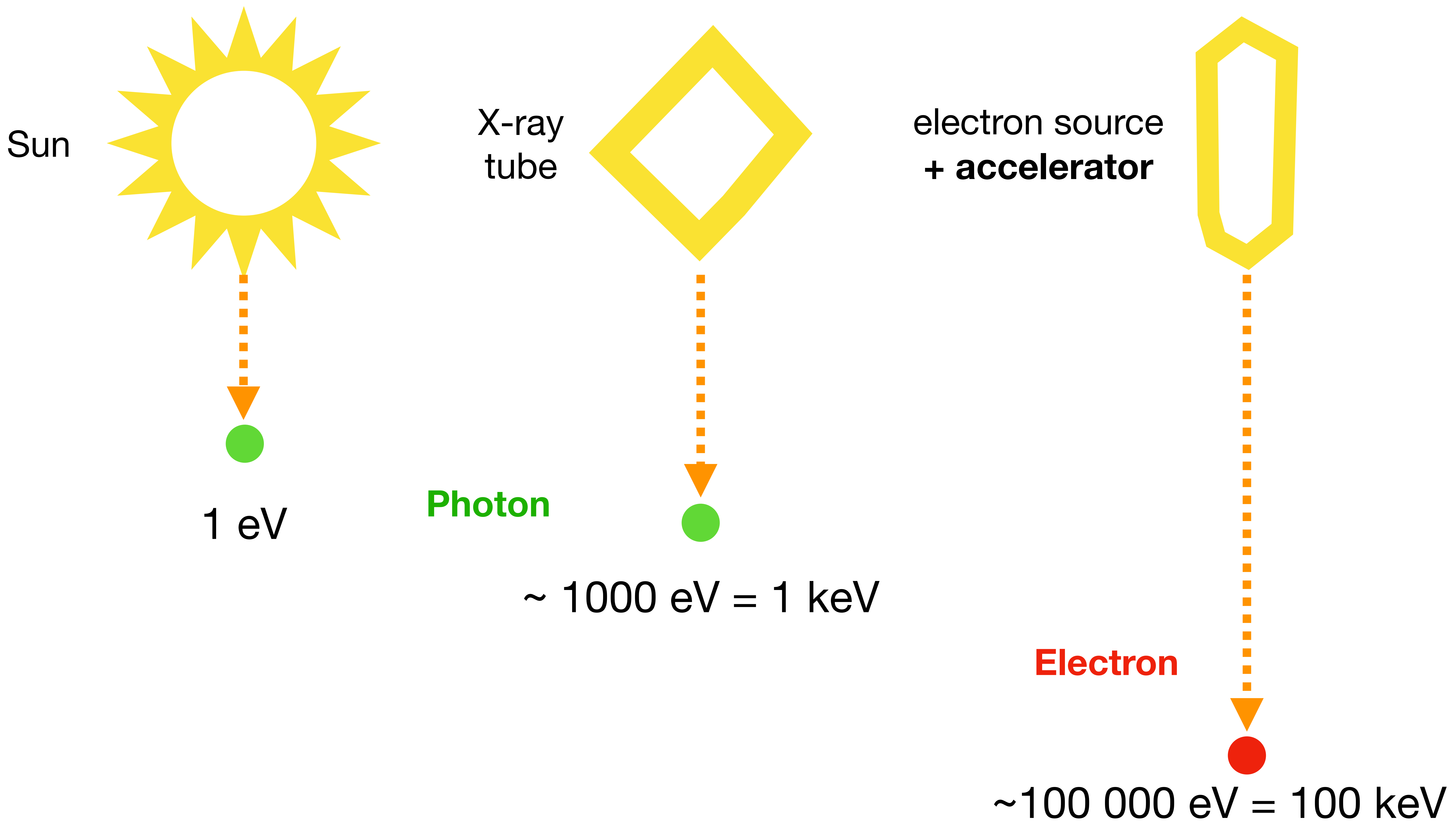
[Image Source]

A very good microscope

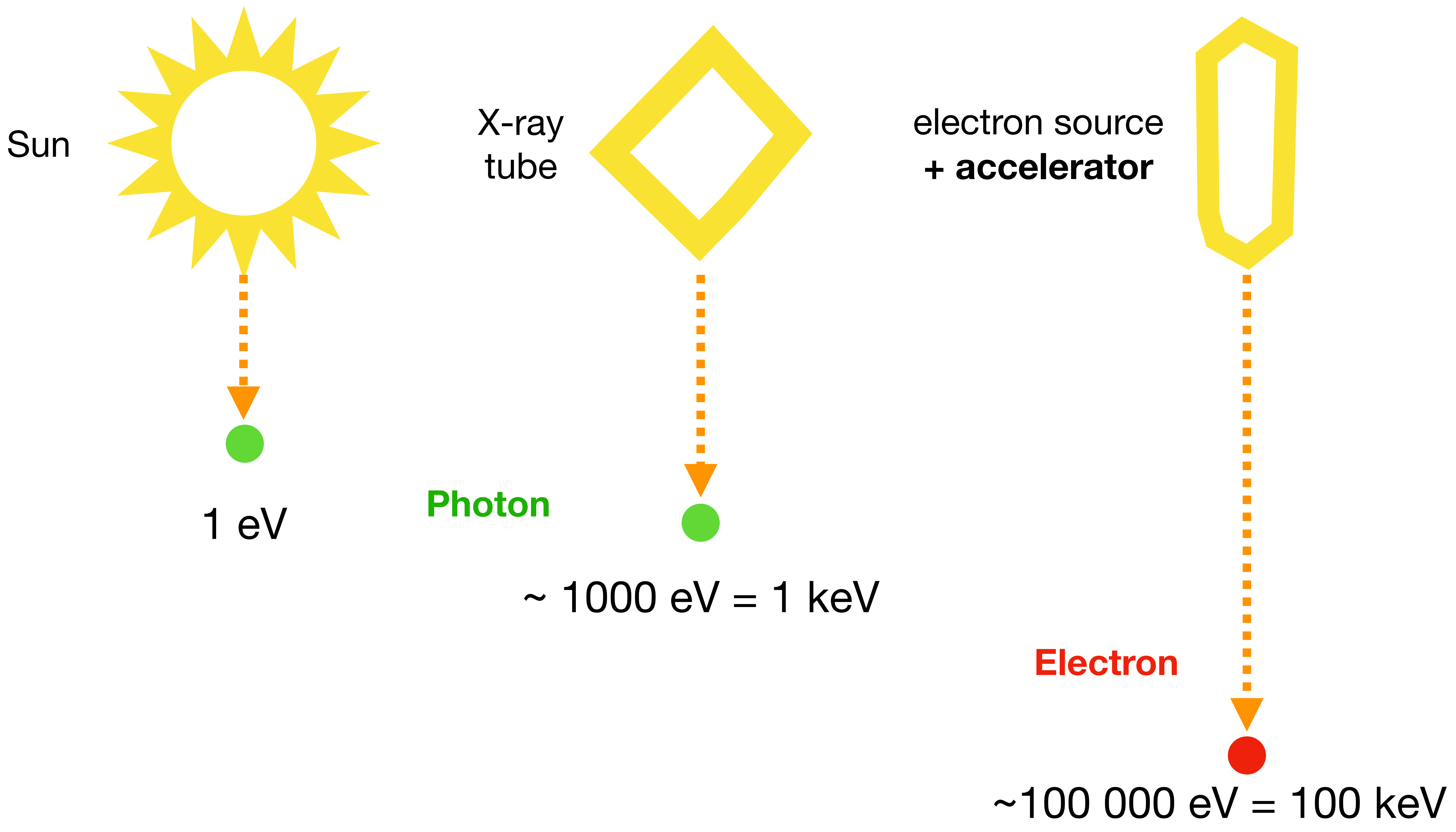


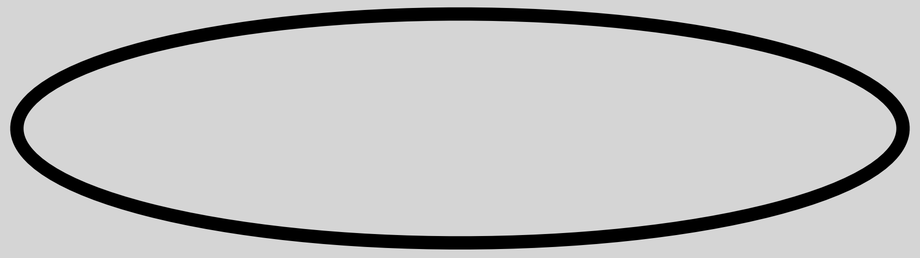
[Image source: EM]
[Image source: Pollen]

My experiments so far …



My experiments so far …

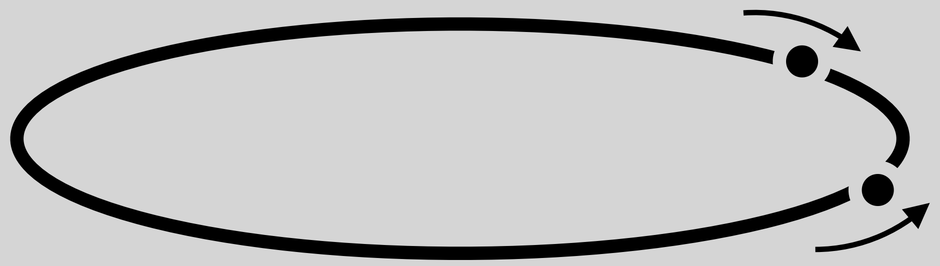




Large Hadron Collider

$\sqrt{s} =$ 14 TeV (design)

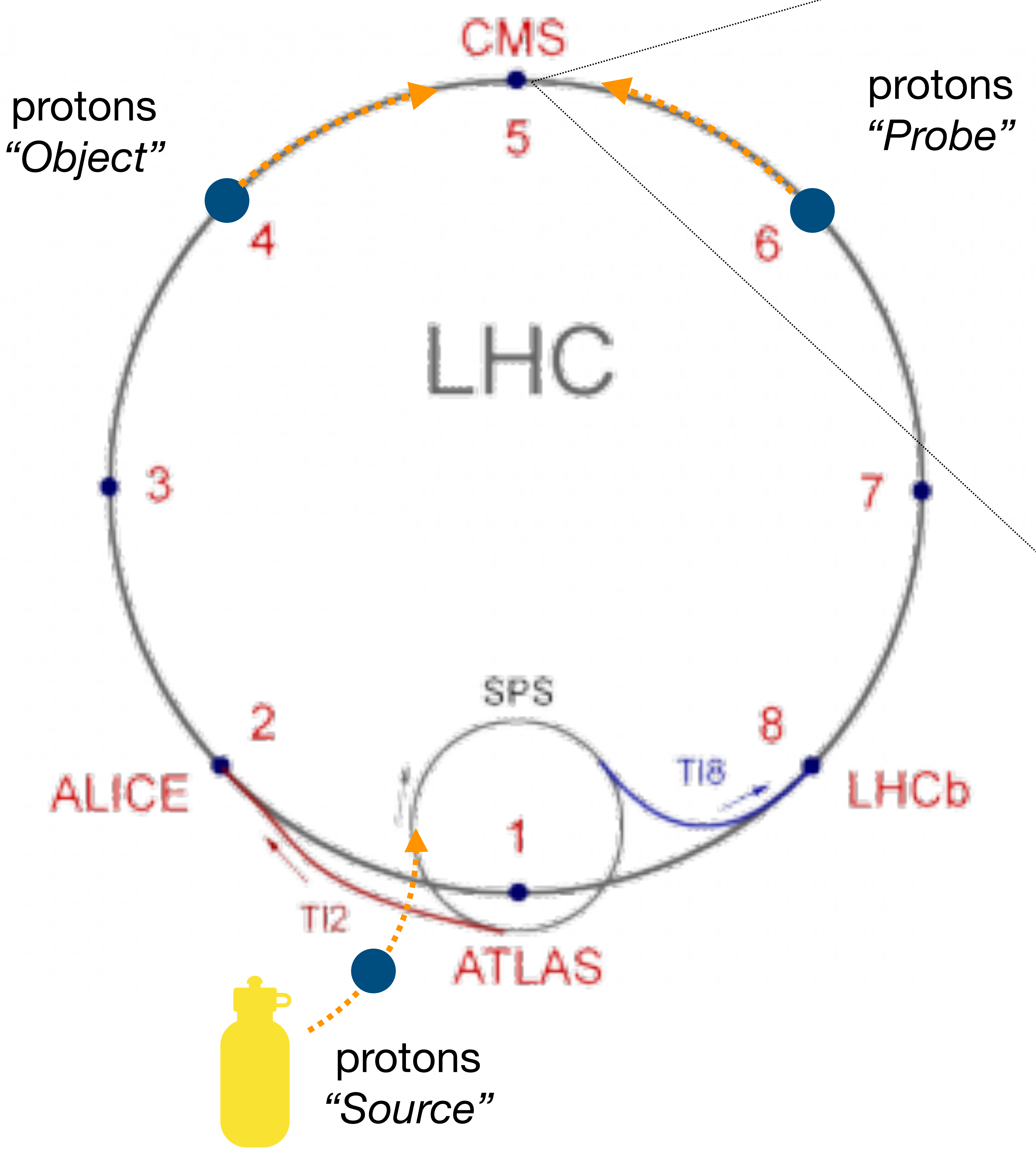
The collider

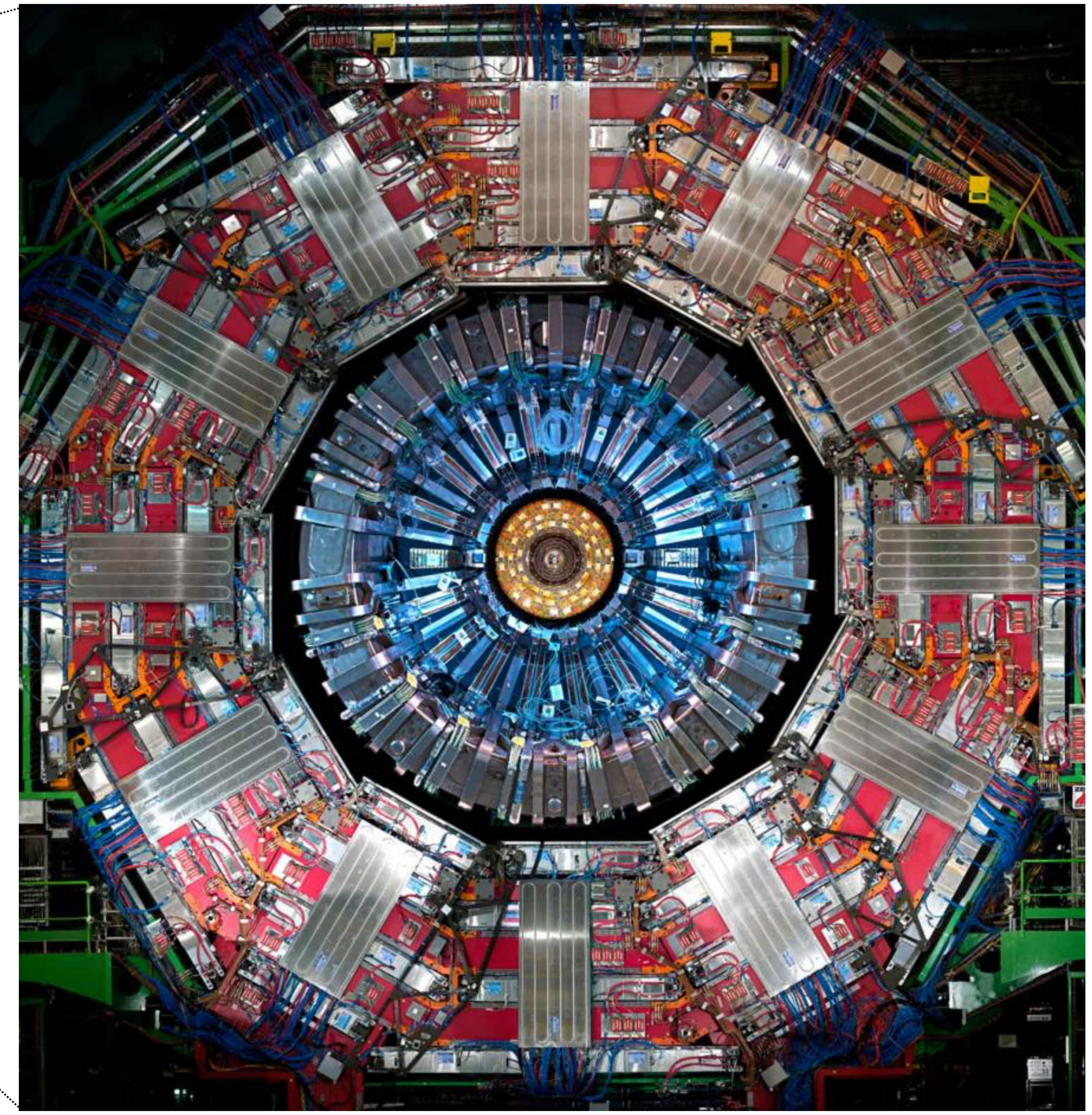


Large Hadron Collider

$\sqrt{s} = $ 14 TeV (design)

A very large microscope

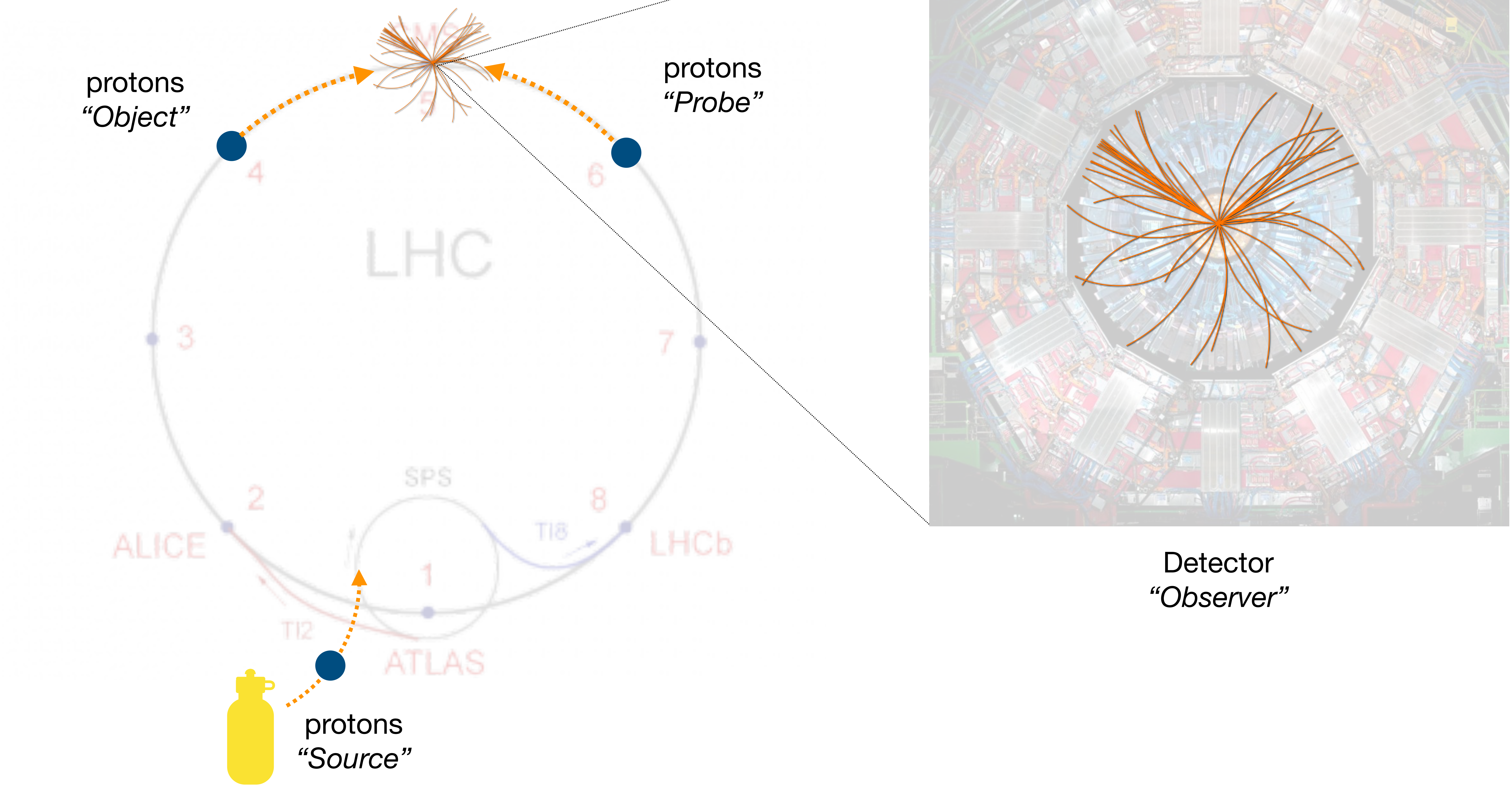




Detector
"Observer"

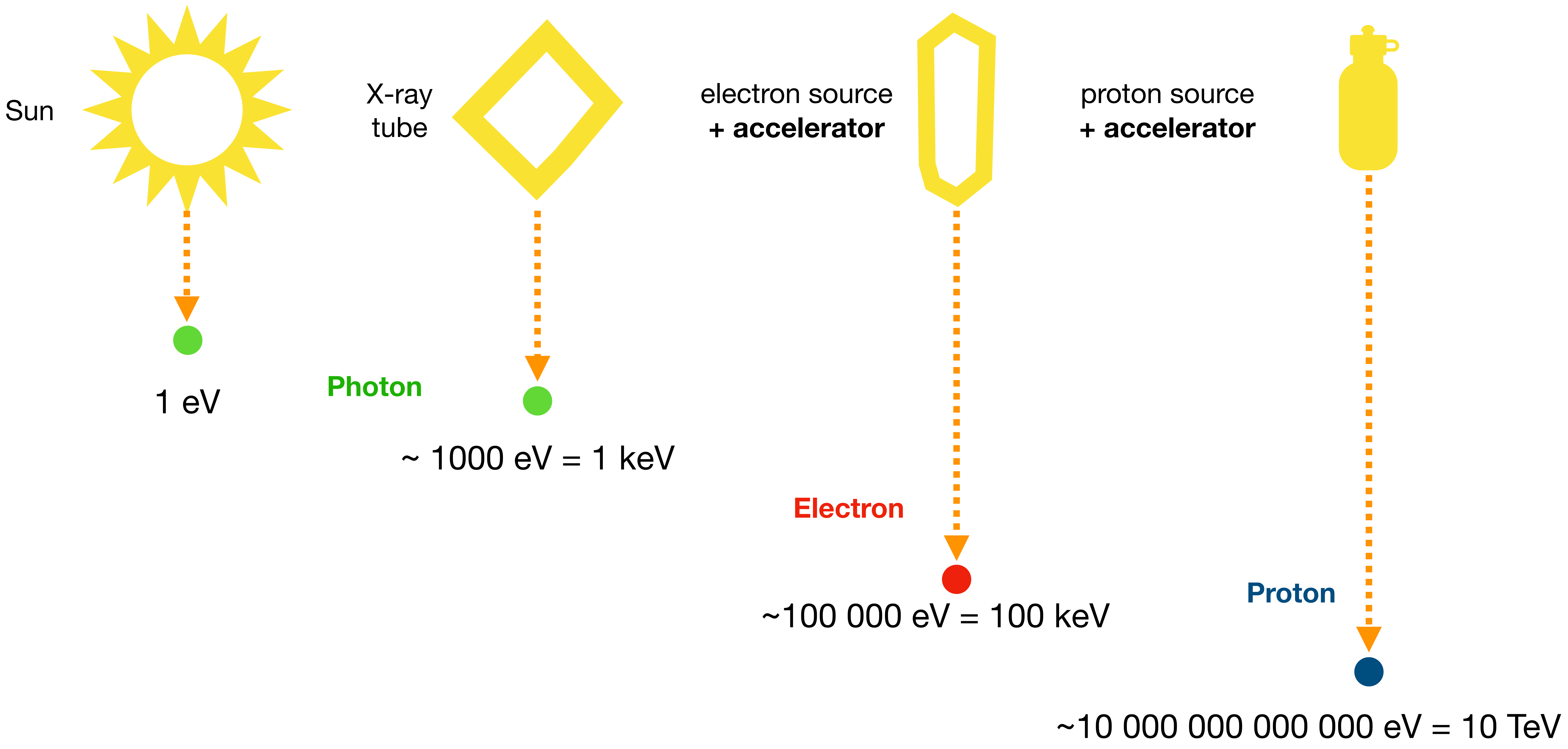
[Image source]

A very large microscope

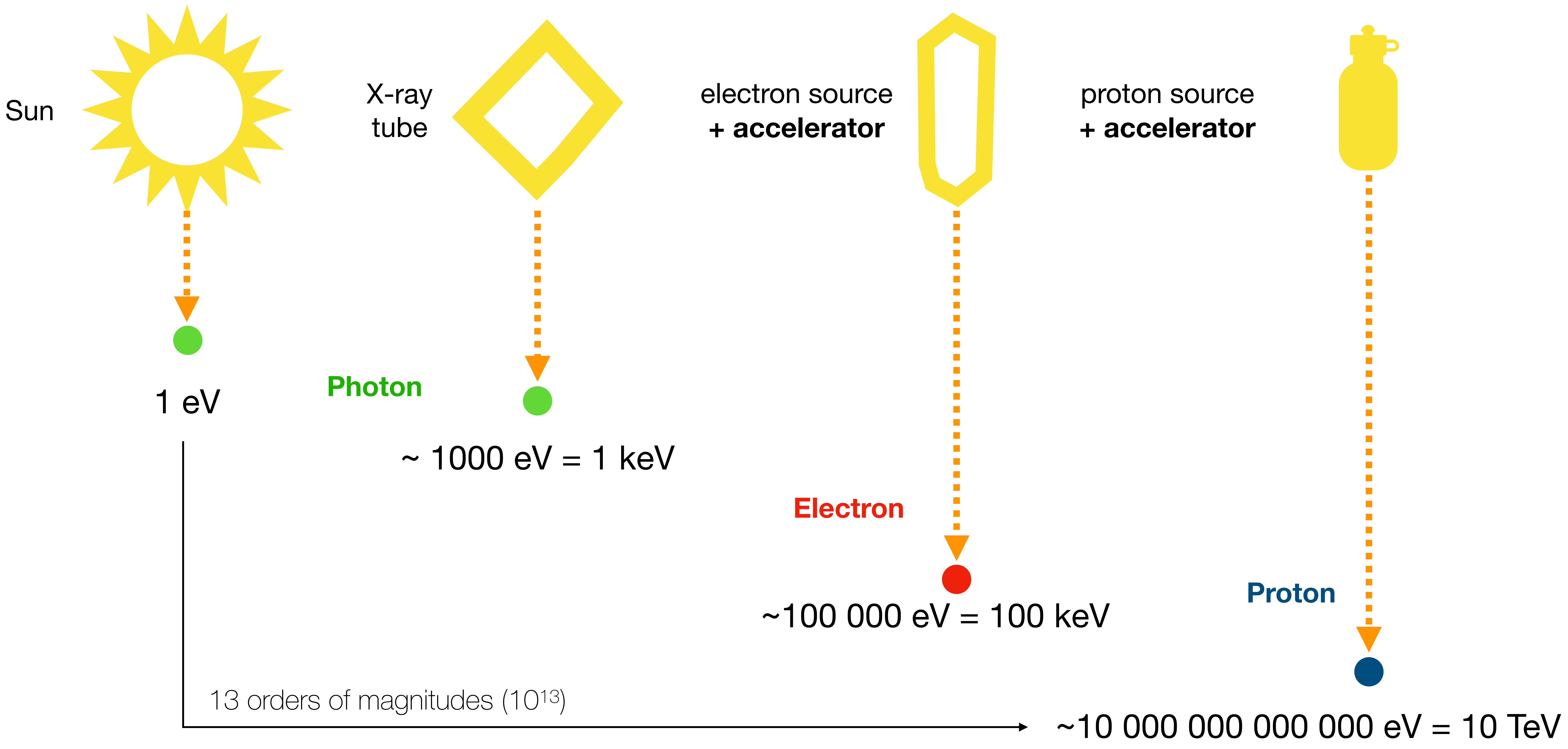


[Image source]

eV


Sun
X-ray
tube
electron source
+ accelerator
proton source
+ accelerator
1 eV
Photon
~ 1000 eV = 1 keV
Electron
~100 000 eV = 100 keV
Proton
~10 000 000 000 000 eV = 10 TeV

eV


Sun
1 eV
X-ray
tube
Photon
~ 1000 eV = 1 keV
electron source
+ accelerator
Electron
~100 000 eV = 100 keV
proton source
+ accelerator
Proton
~10 000 000 000 000 eV = 10 TeV
13 orders of magnitudes (10^13)

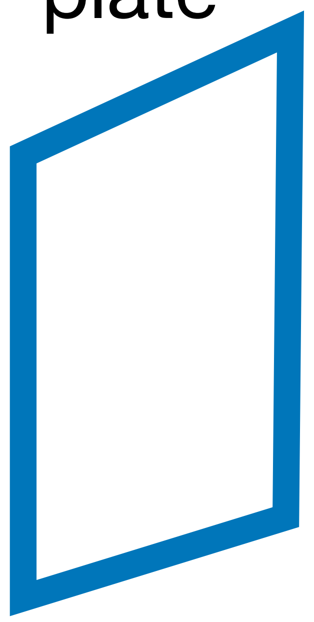
eV … and what you can see

1 eV Photon

eye

1 keV Photon

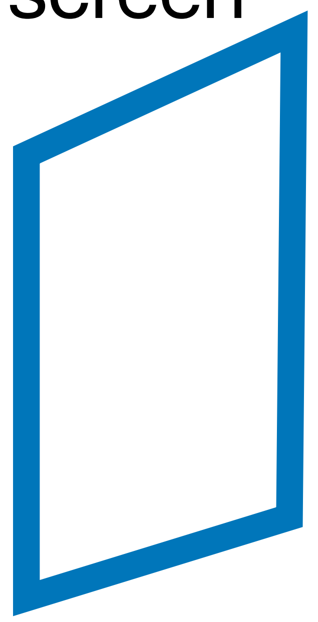
photo plate



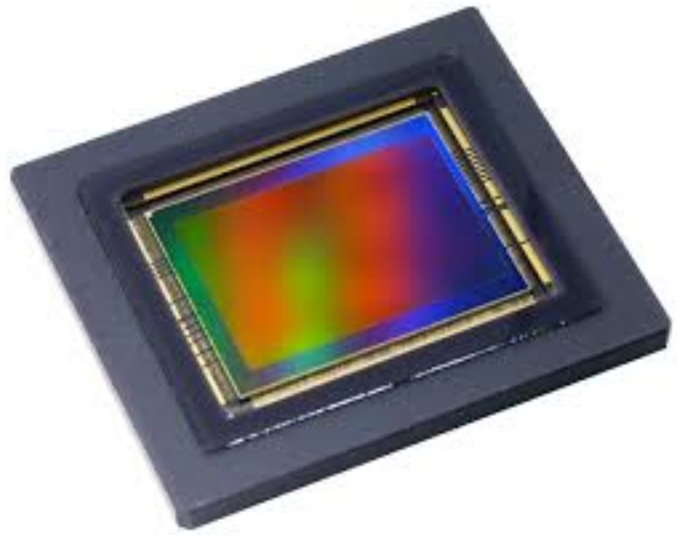
low energy sensor

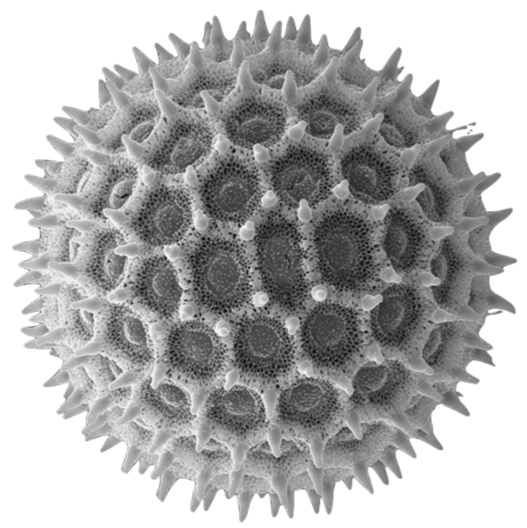
100 keV Electron

fluorescent screen



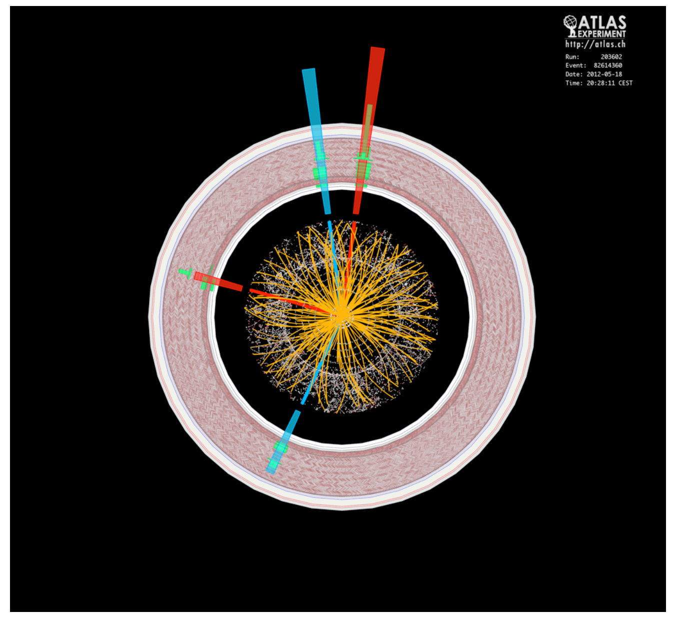
electron detector

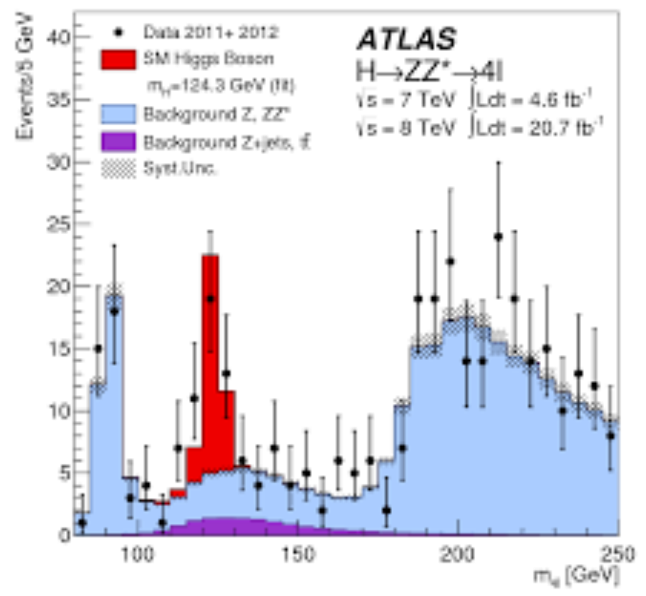




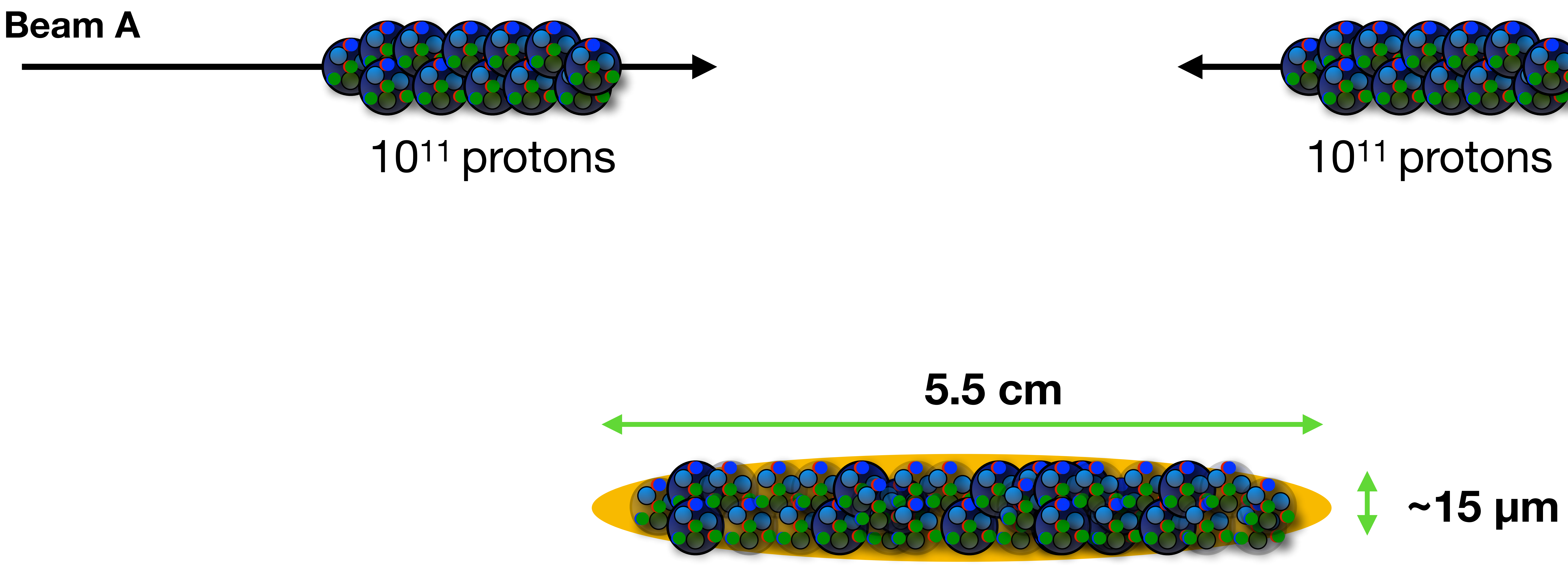
10 TeV Proton

particle detector



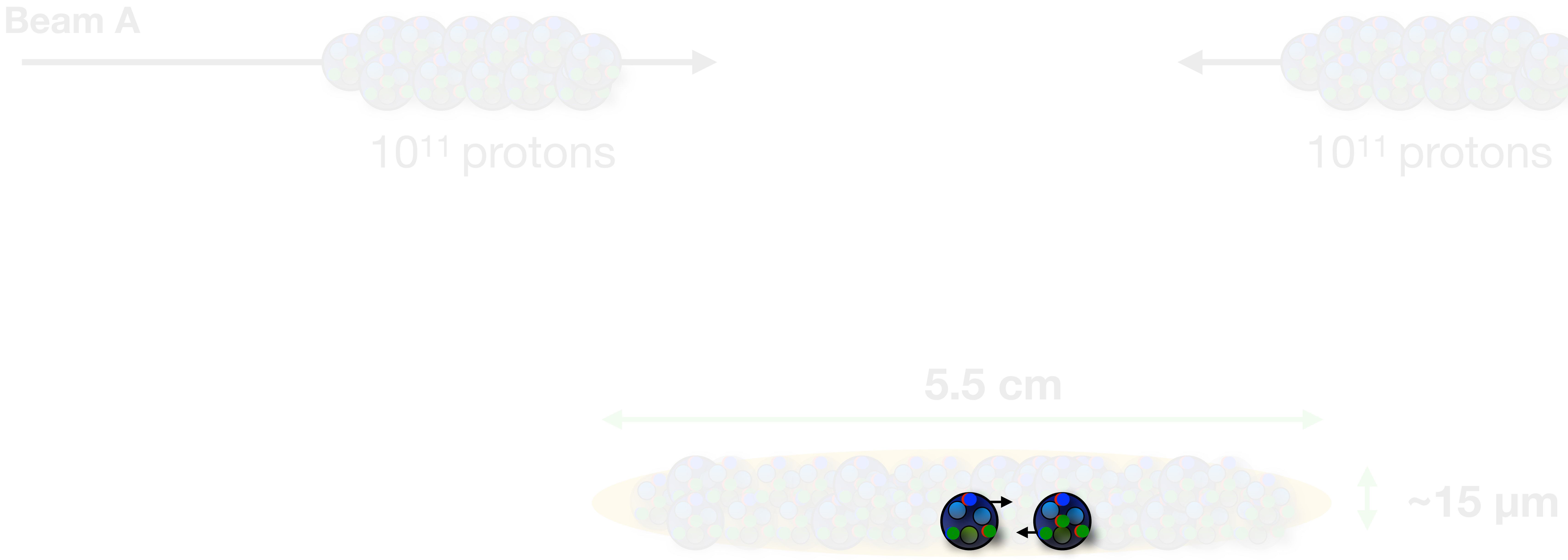


Creating the Higgs Boson



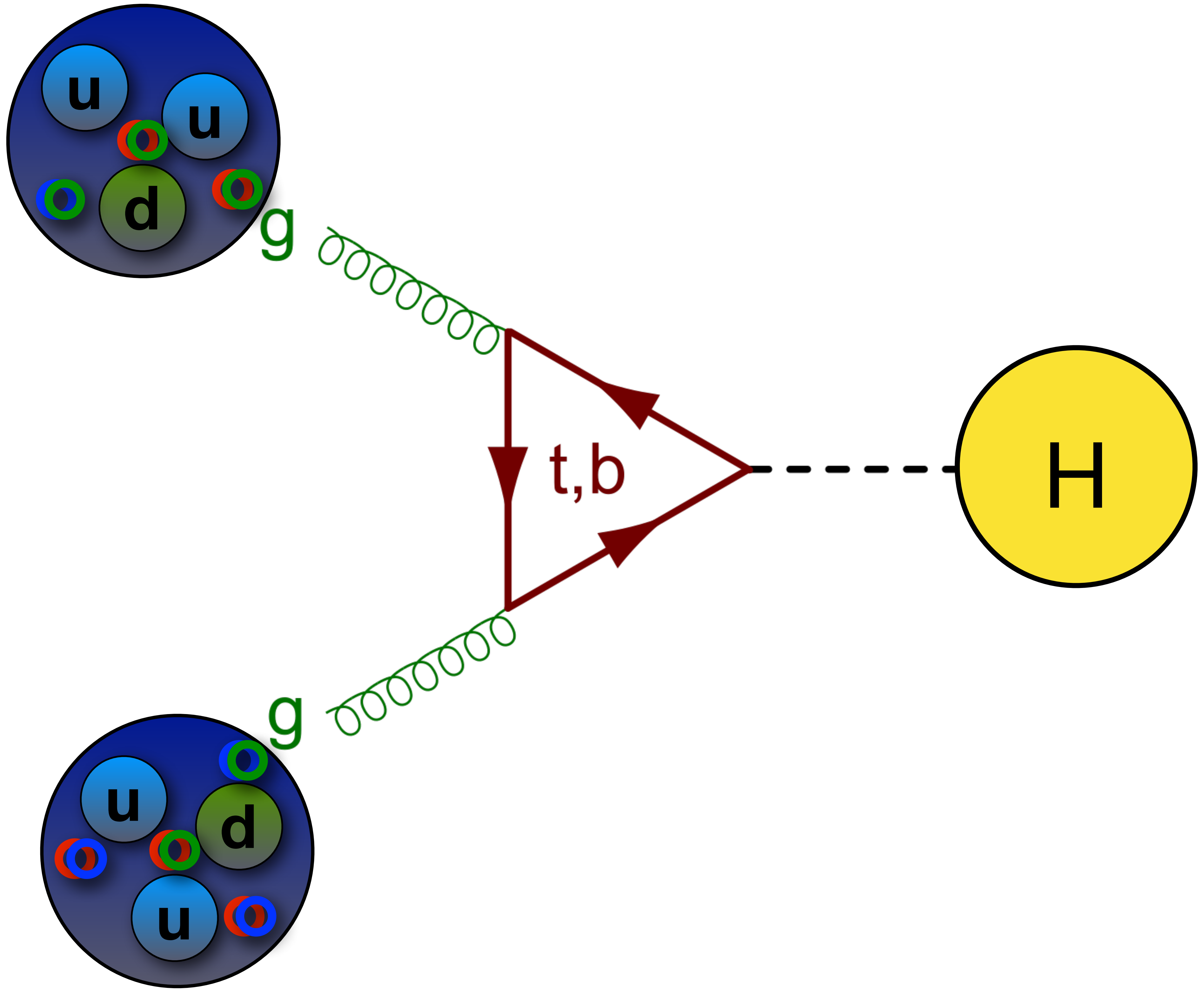
~ 60 individual proton-proton interactions

Creating the Higgs Boson



individual proton-proton interactions

Creating the Higgs Boson



Unfortunately … this does not happen often.

The boring regime:
"probability" of
any interaction

10^{10}

The exciting regime:
"probability" of
a Higgs boson
production

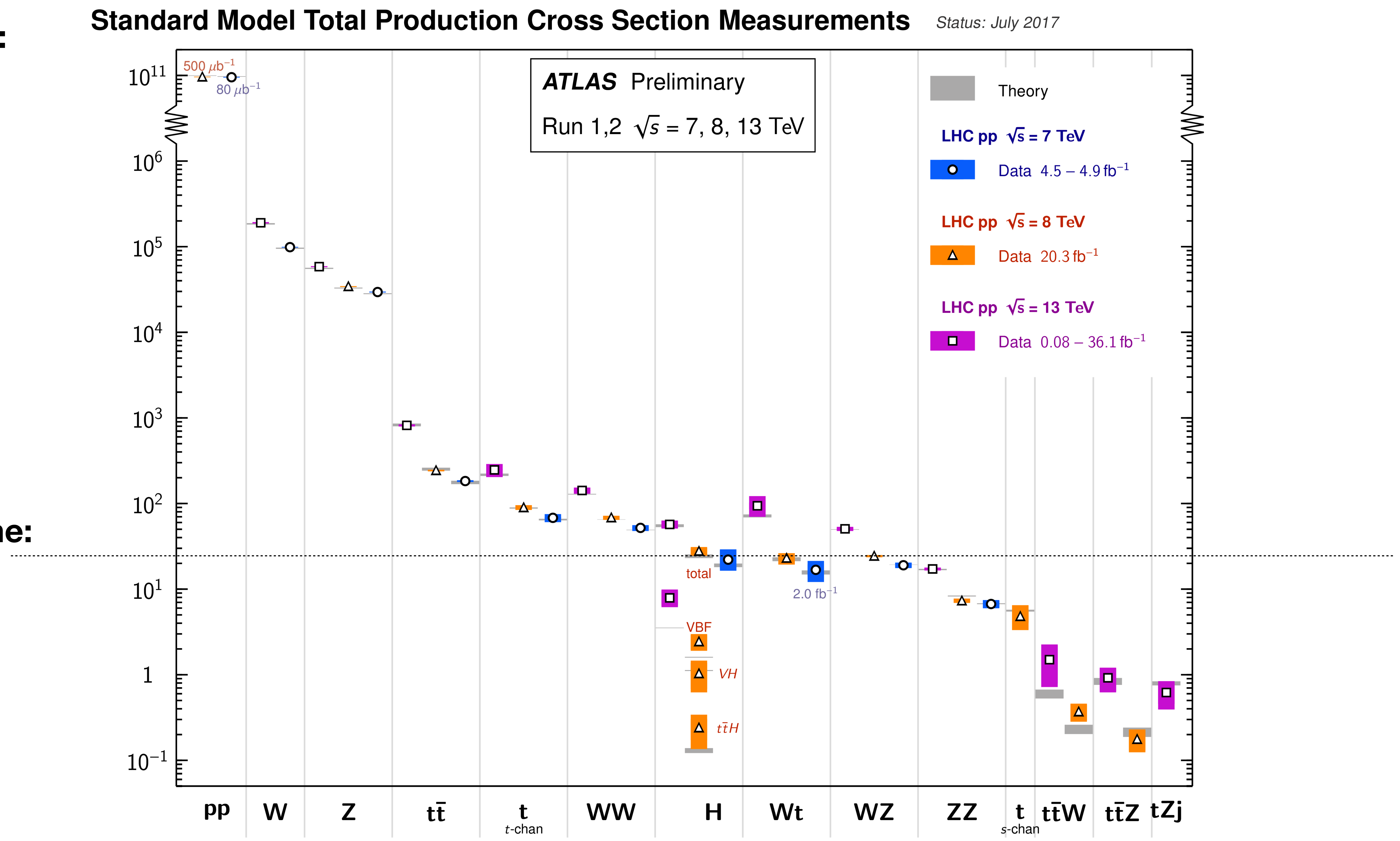
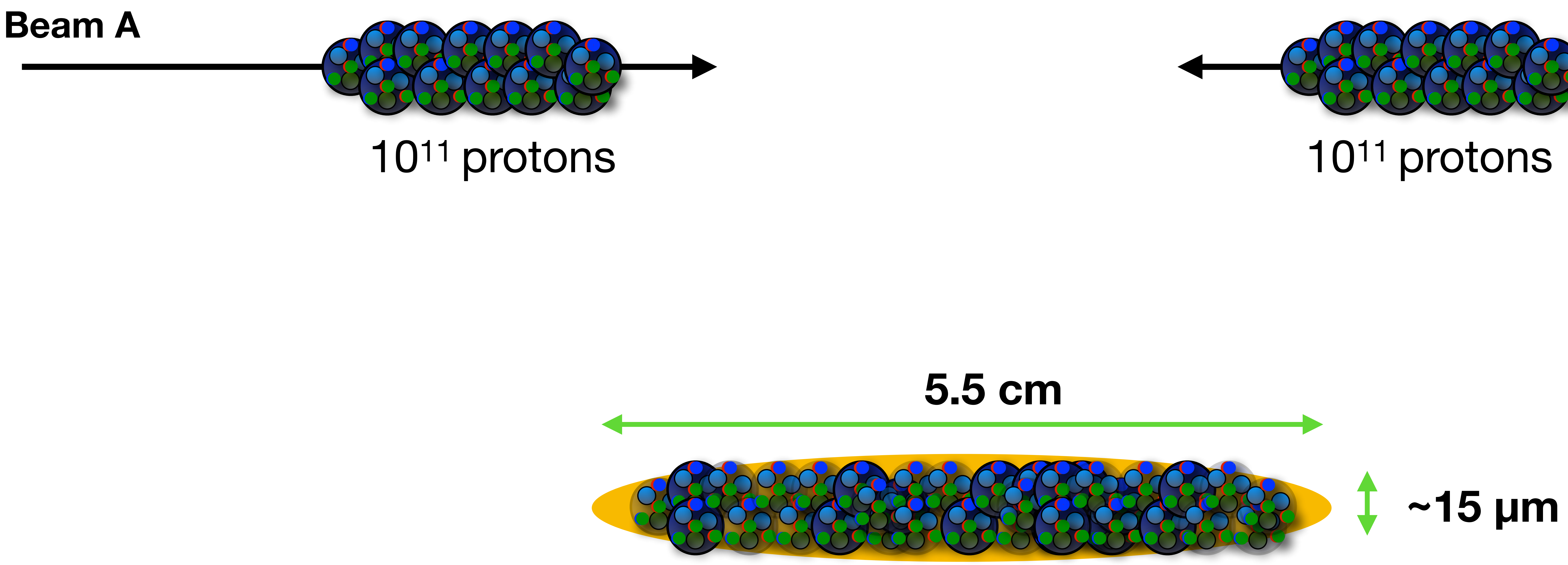


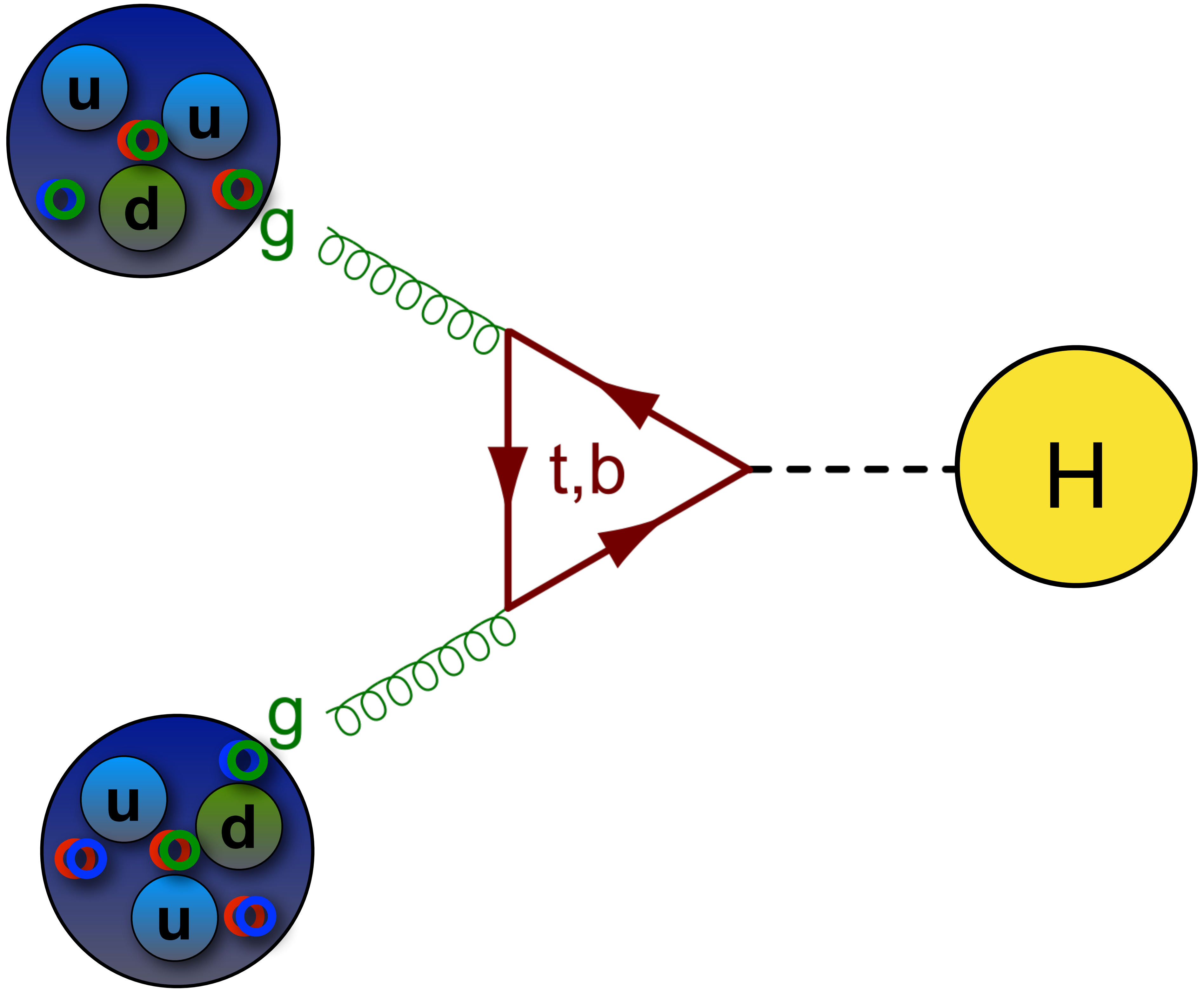
Figure:
Standard Model cross sections measured with the ATLAS experiment and compared to theoretical predictions, July 2017

This is why we do this every 25 nanoseconds!

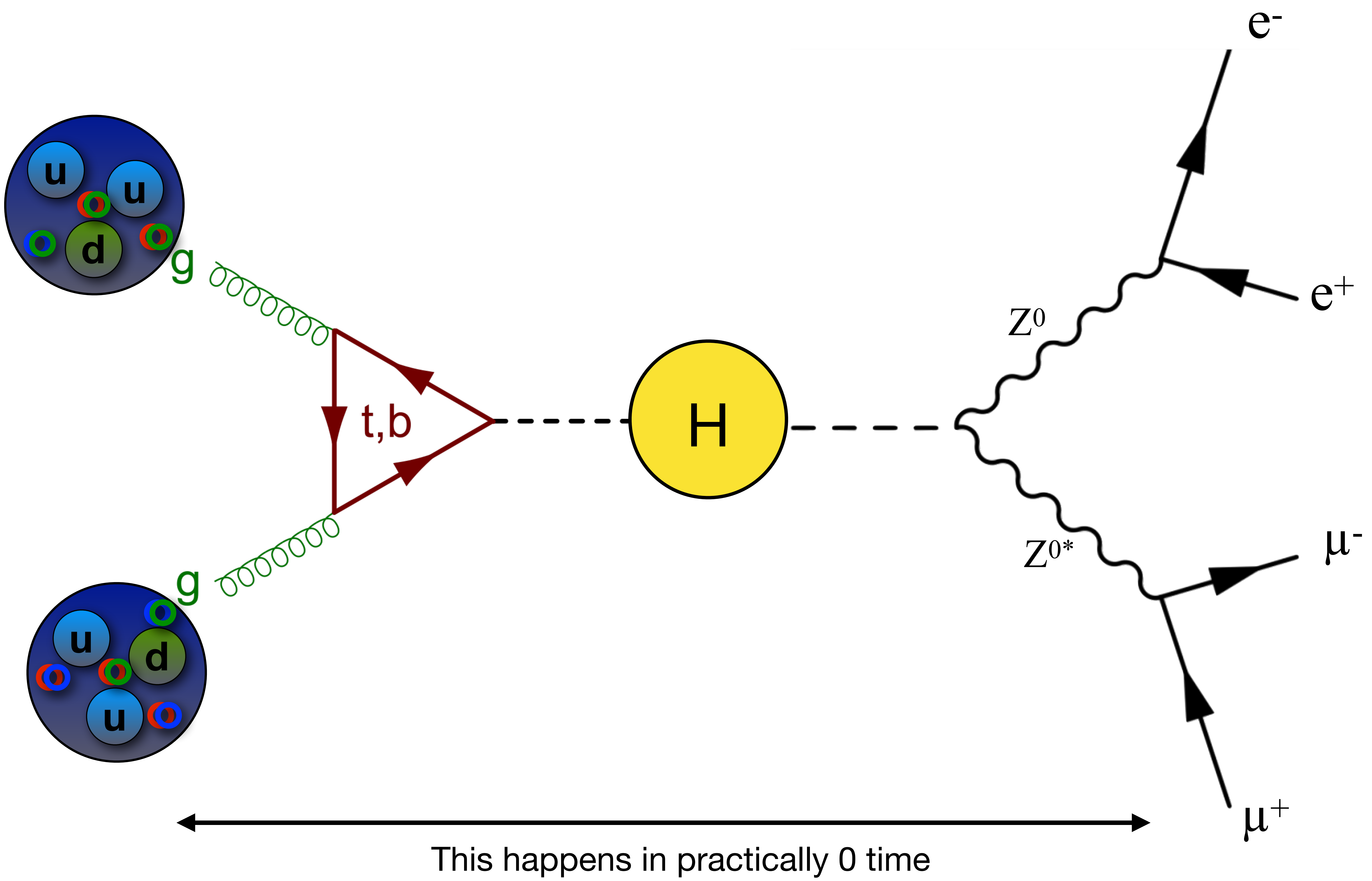


~ 60 individual proton-proton interactions

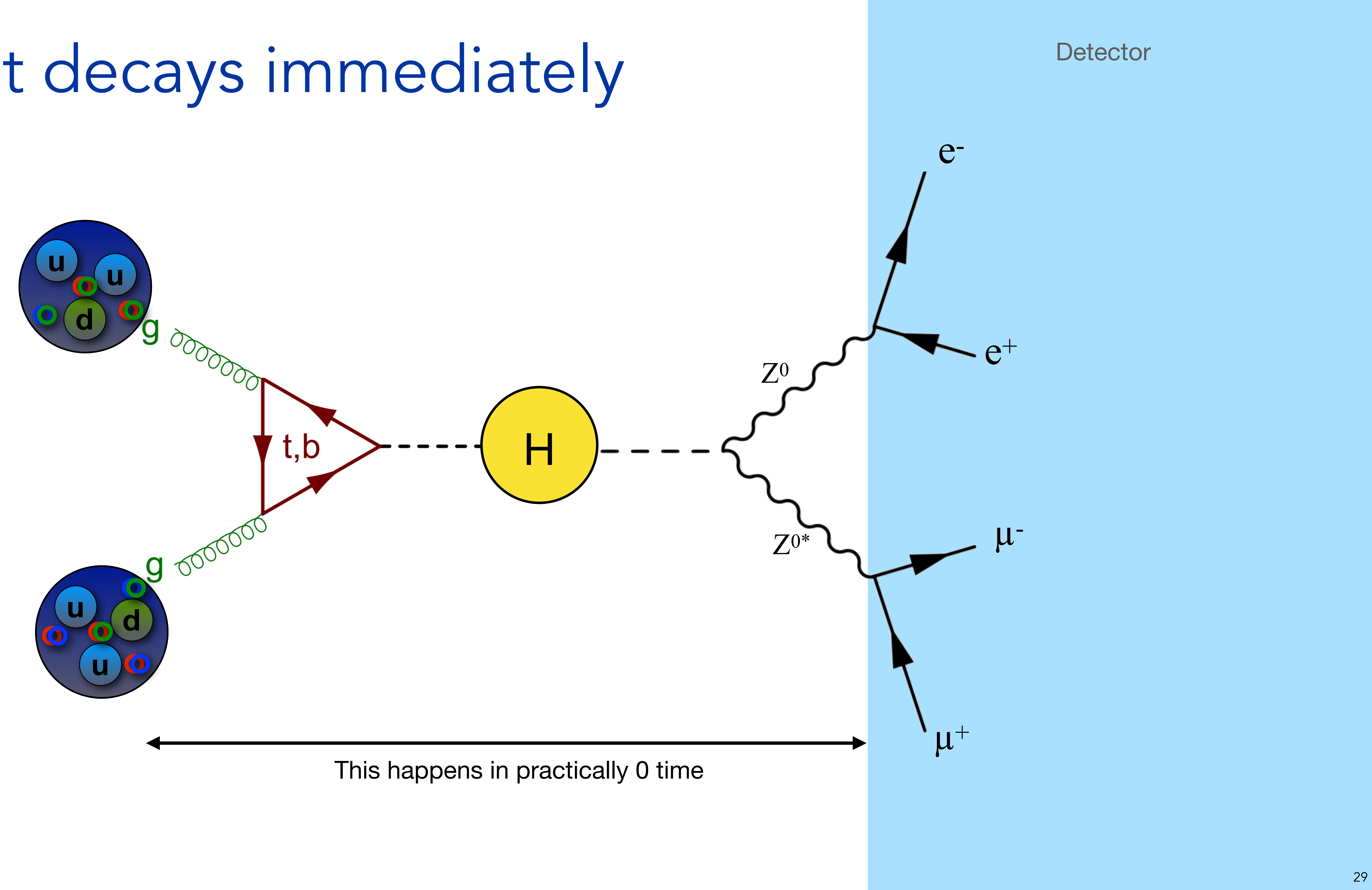
… and when it happens …



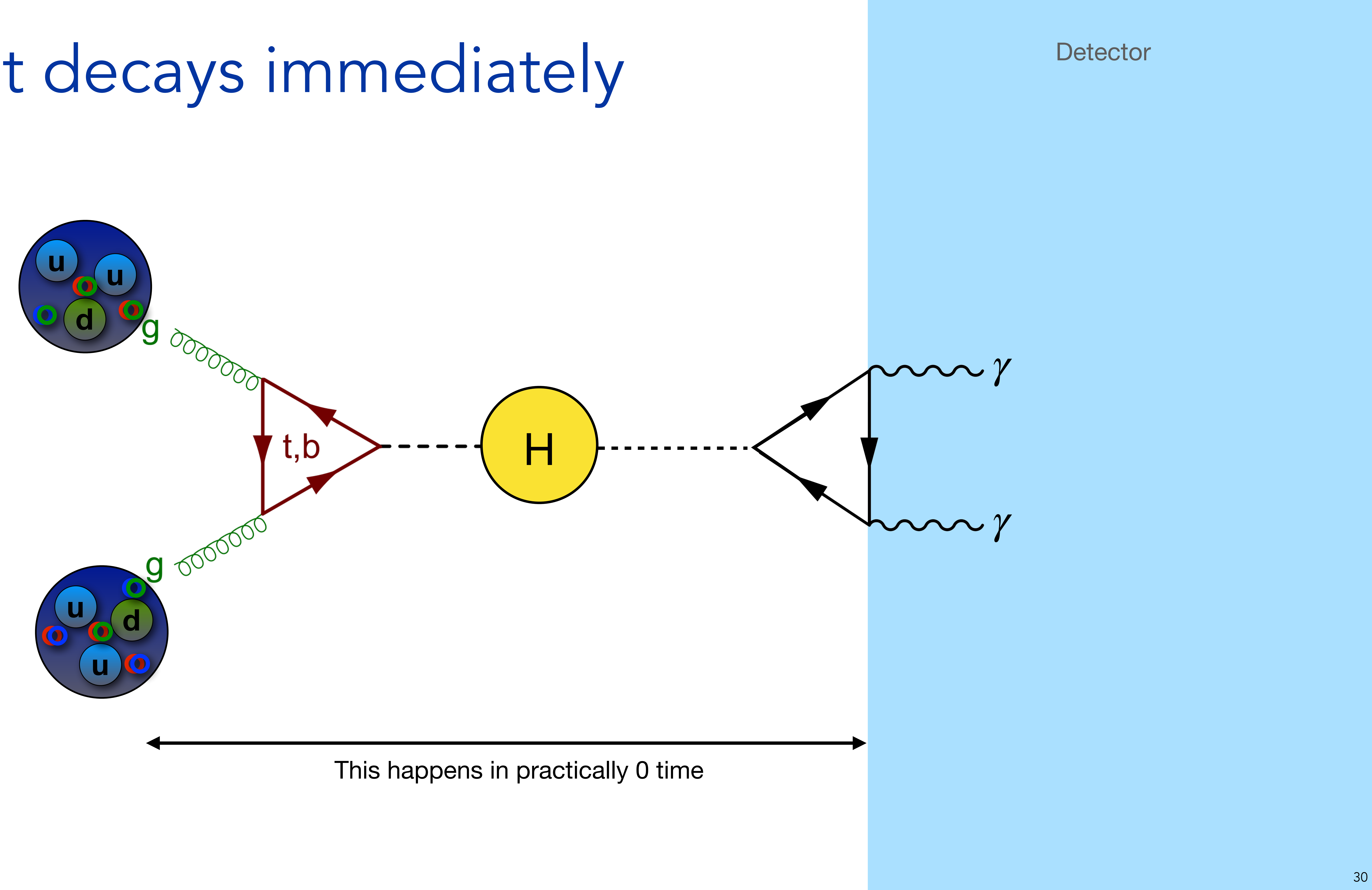
… it decays immediately



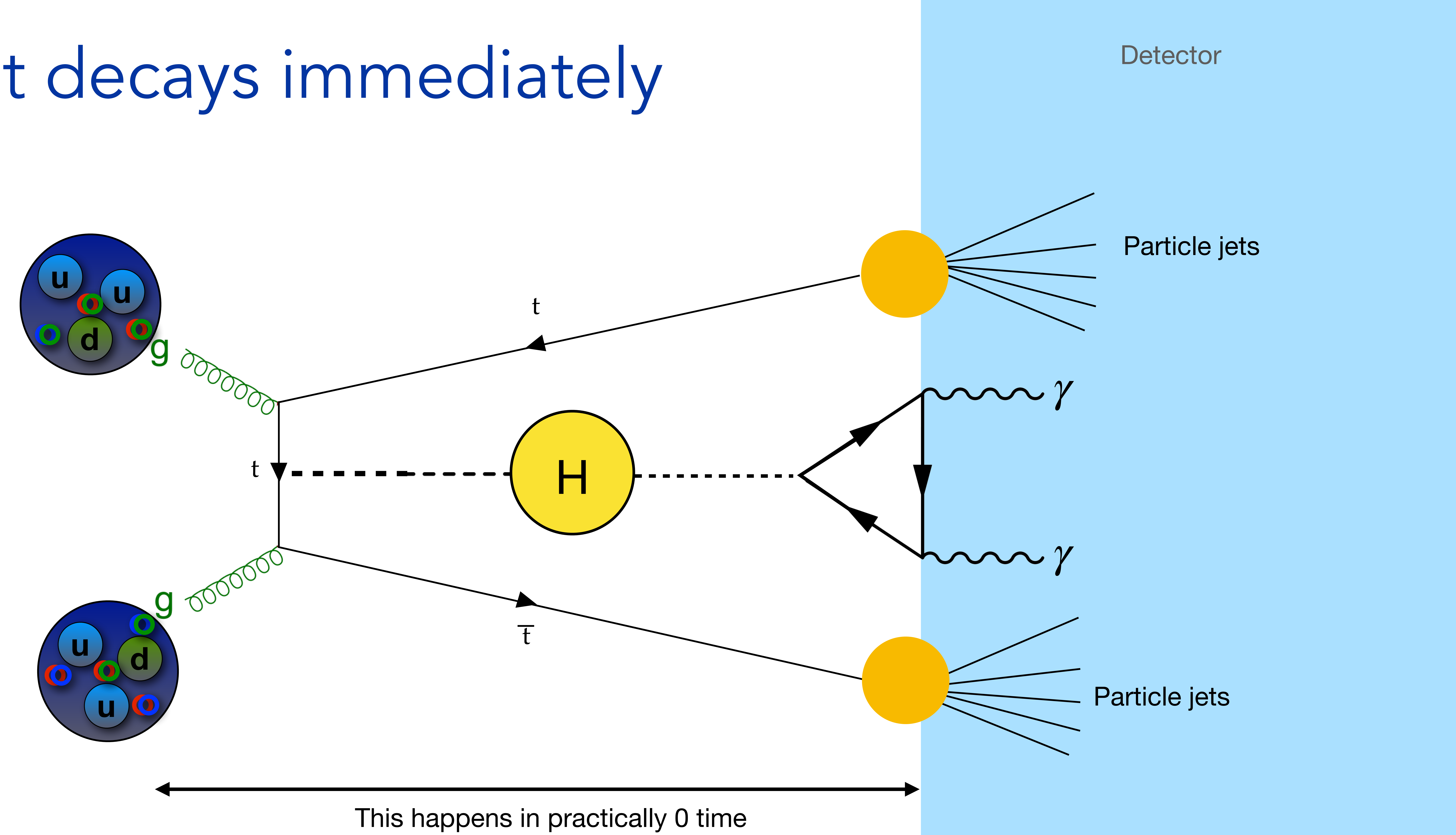
… it decays immediately



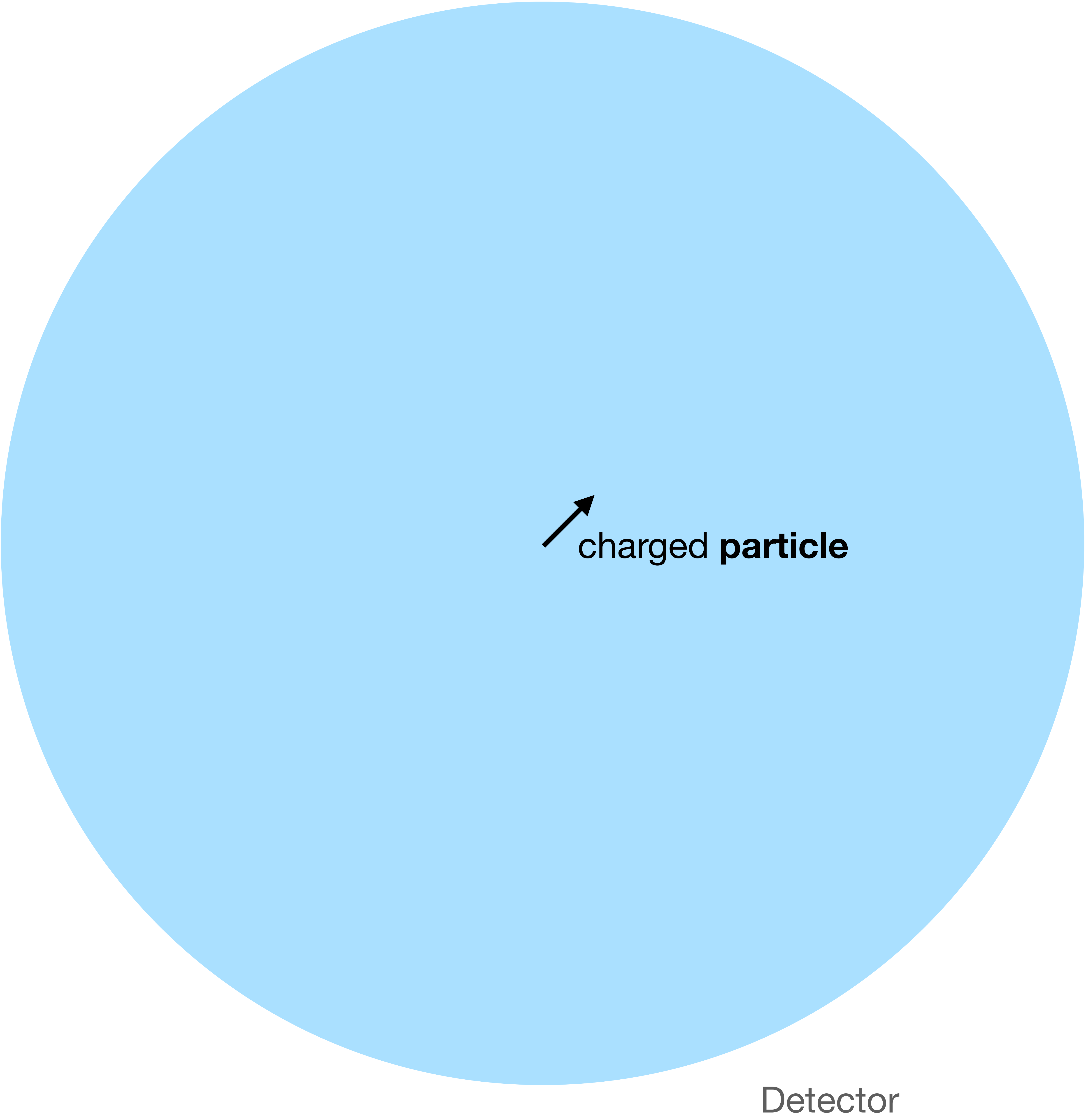
… it decays immediately

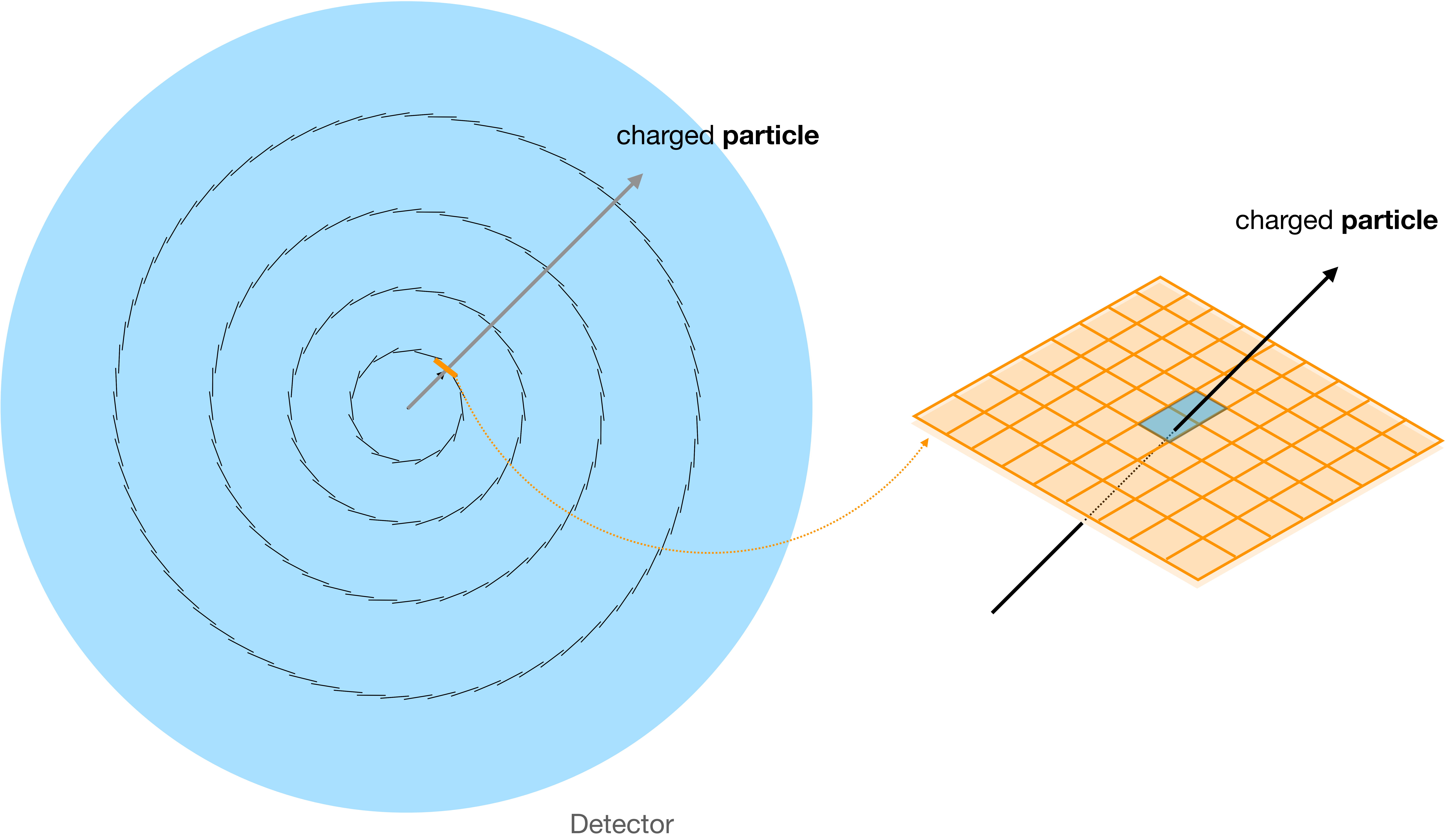


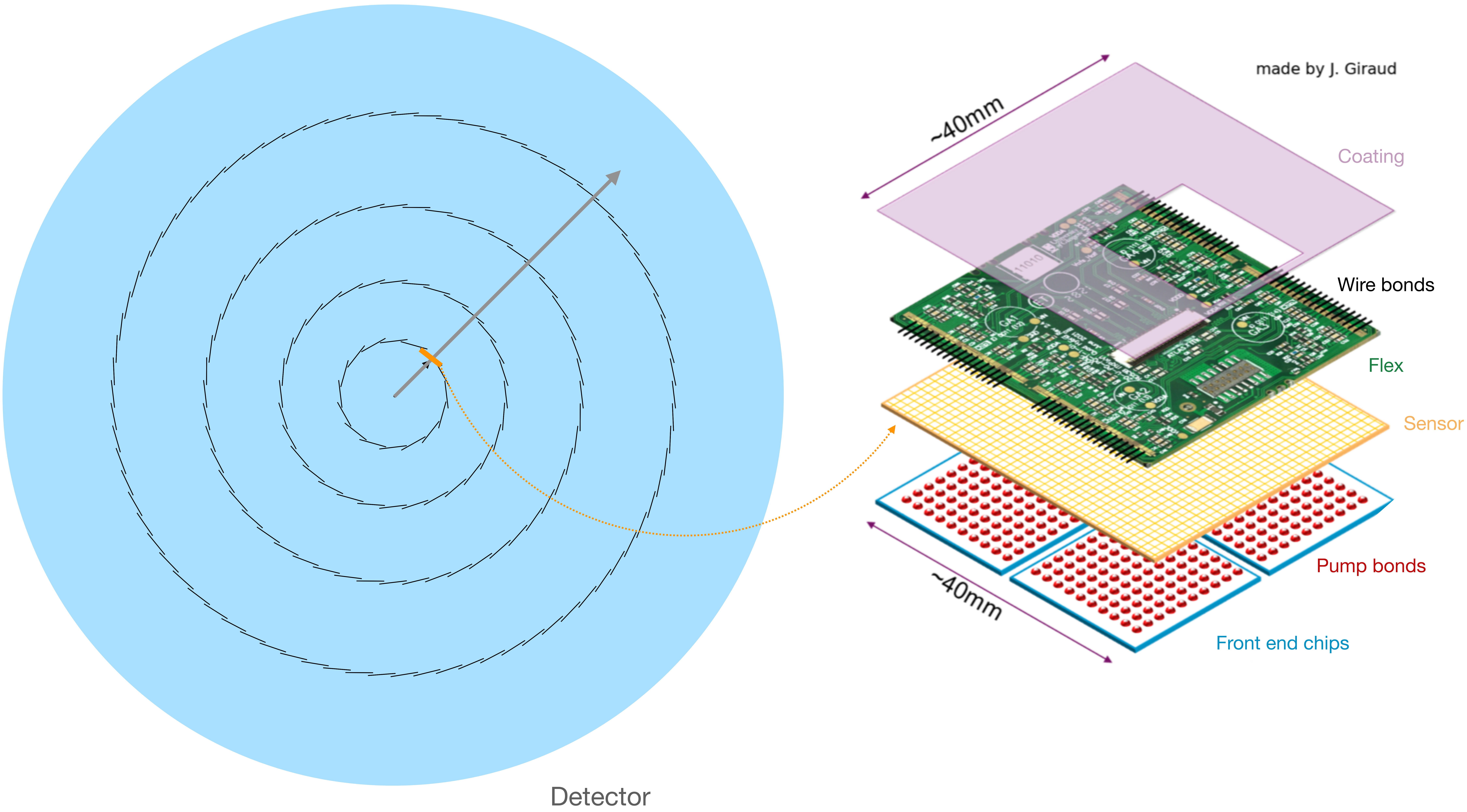
… it decays immediately

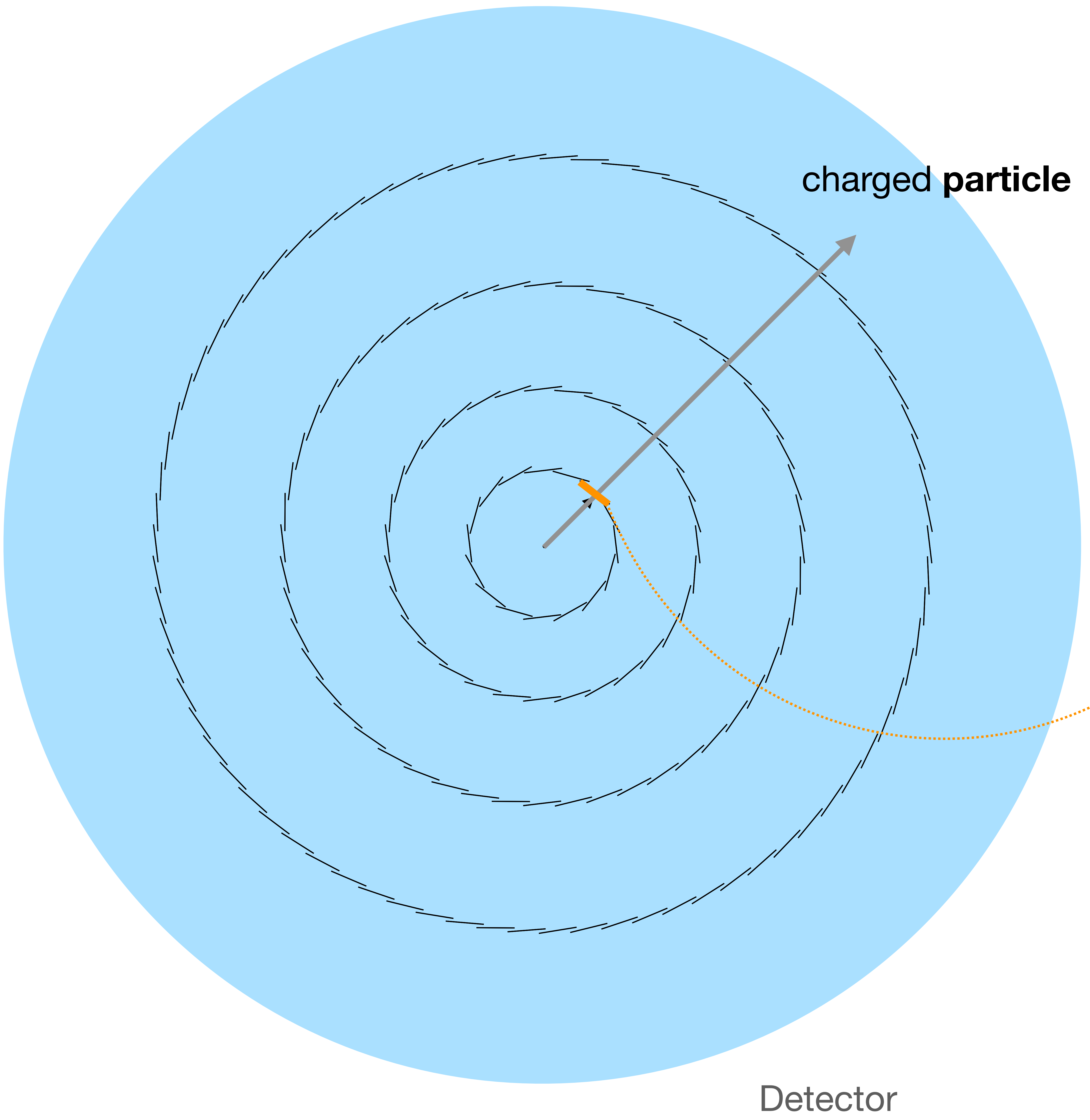


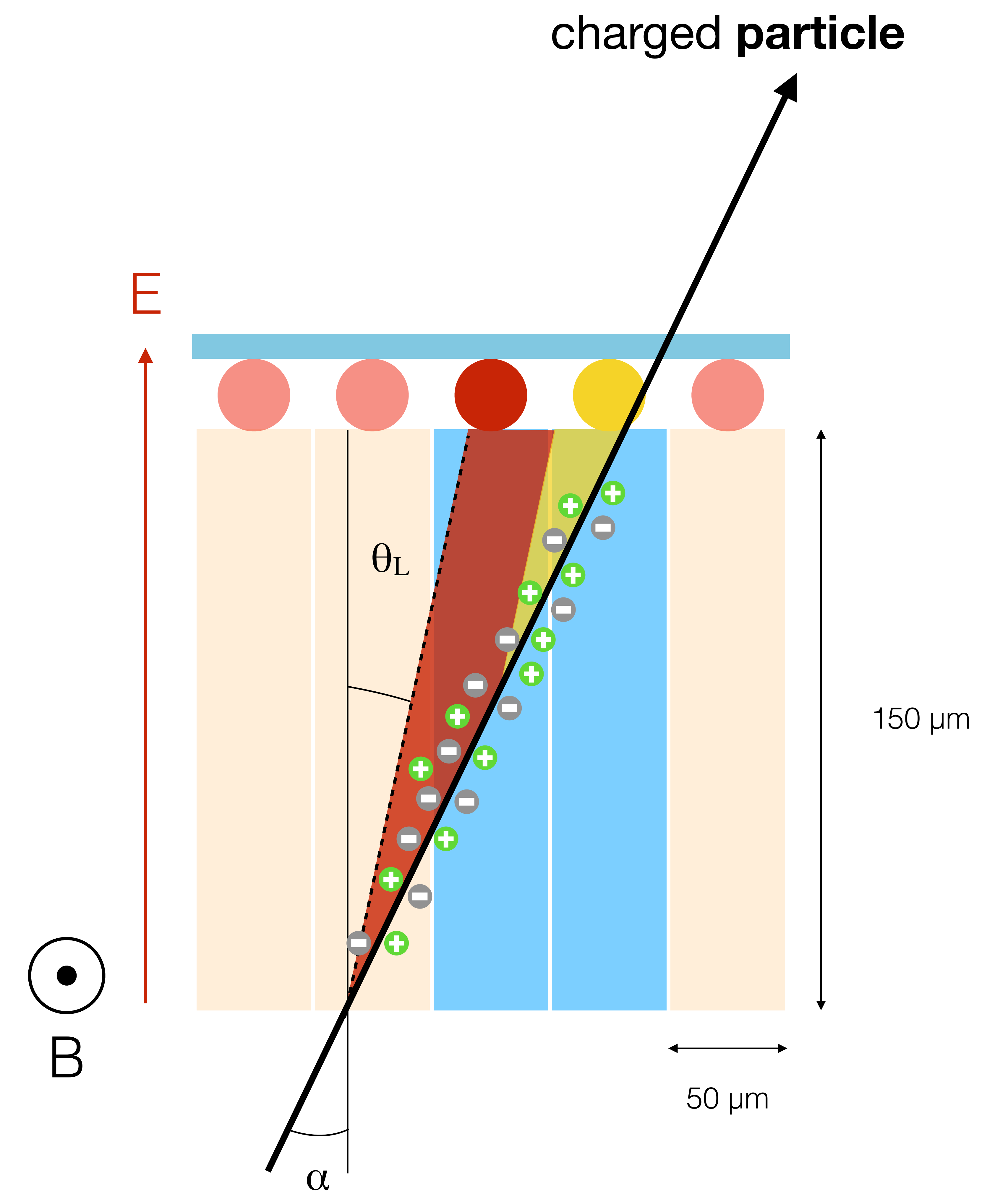
… let's build a detector



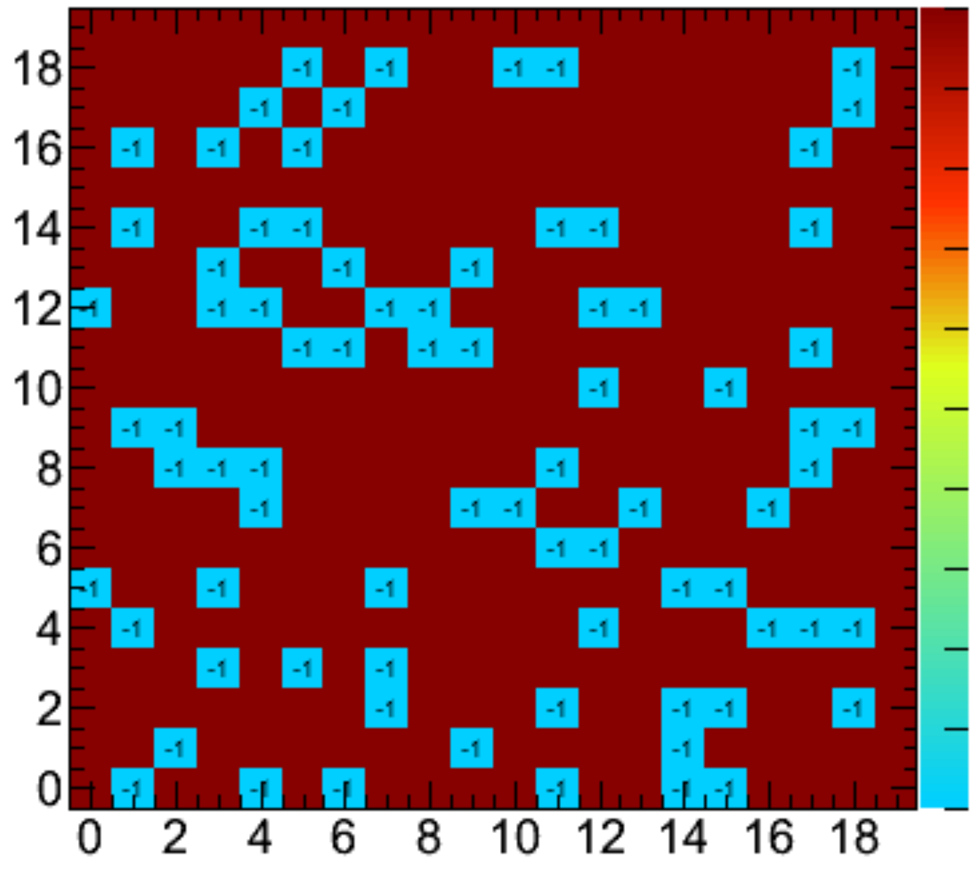

charged **particle**
charged **particle**
Detector

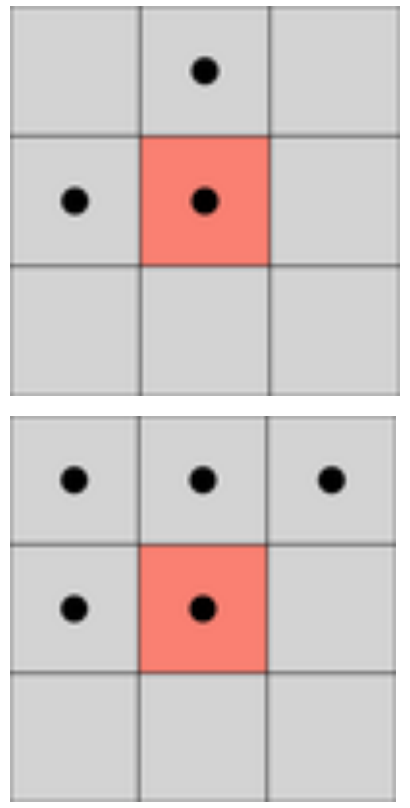

made by J. Giraud
~40mm
Coating
Wire bonds
Flex
Sensor
Pump bonds
~40mm
Front end chips
Detector

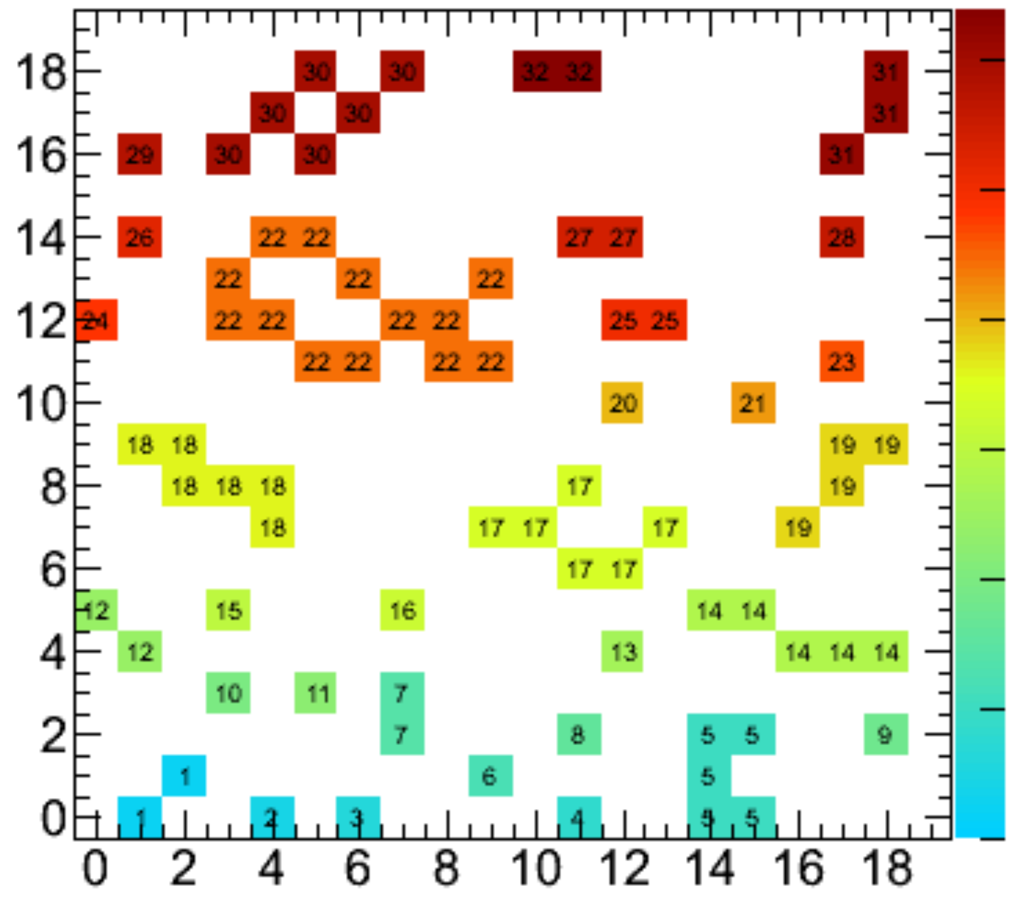

charged **particle**
Detector


charged **particle**
E
θL
150 μm
50 μm
B
α

First stage of local reconstruction

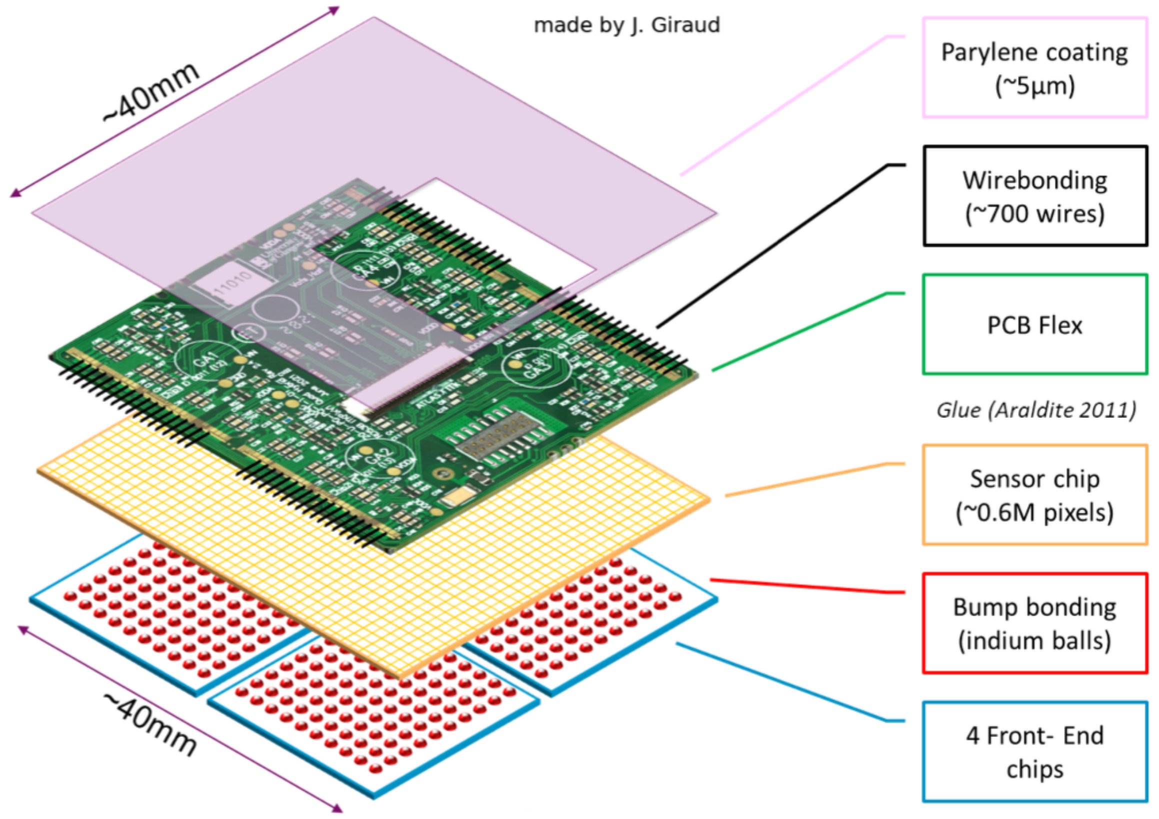






Connected component labelling finds adjacent cells.

Modern detectors can do this
on the readout chip!



First systematic description in the 19th century trying to understand the

$$\underset{\mathbf{S}}{\arg\min} \sum_{i=1}^{k} \sum_{\mathbf{x} \in S_i} \|\mathbf{x} - \boldsymbol{\mu}_i\|^2 = \underset{\mathbf{S}}{\arg\min} \sum_{i=1}^{k} |S_i| \operatorname{Var} S_i$$

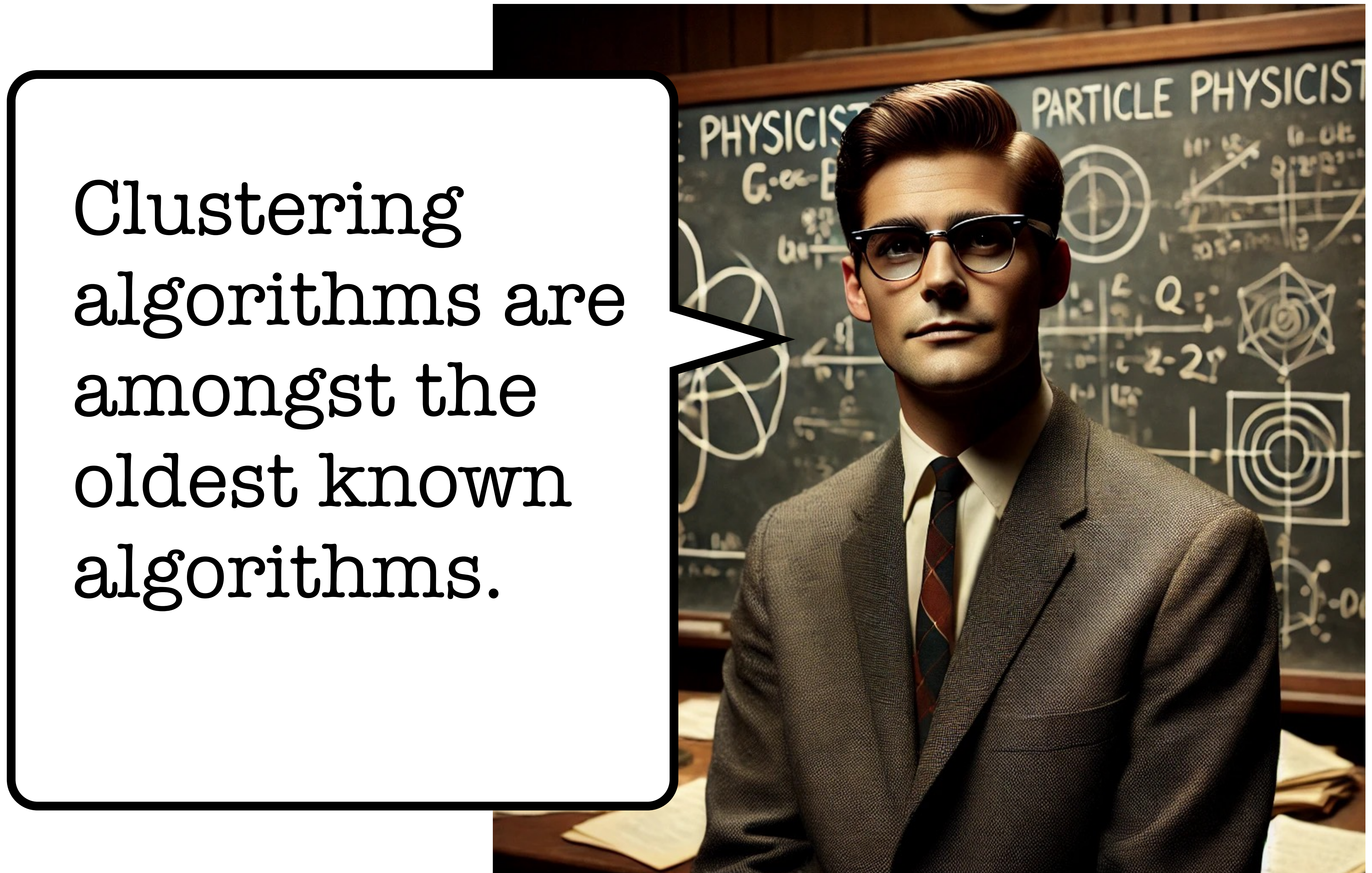
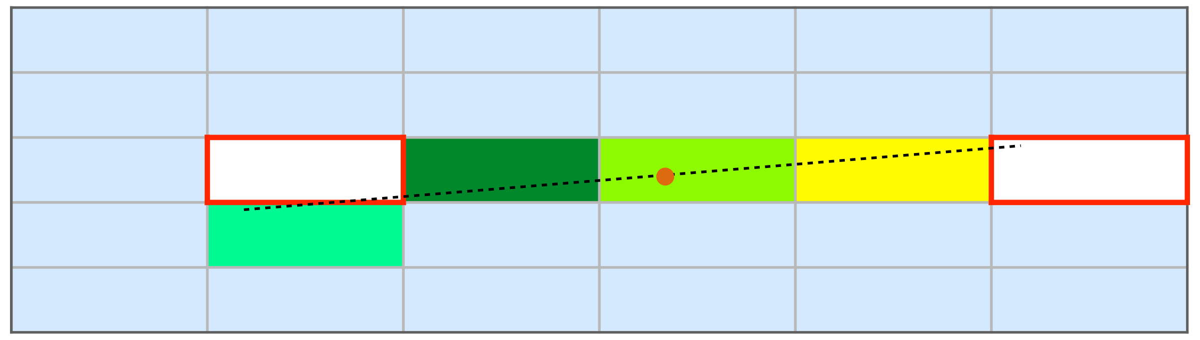
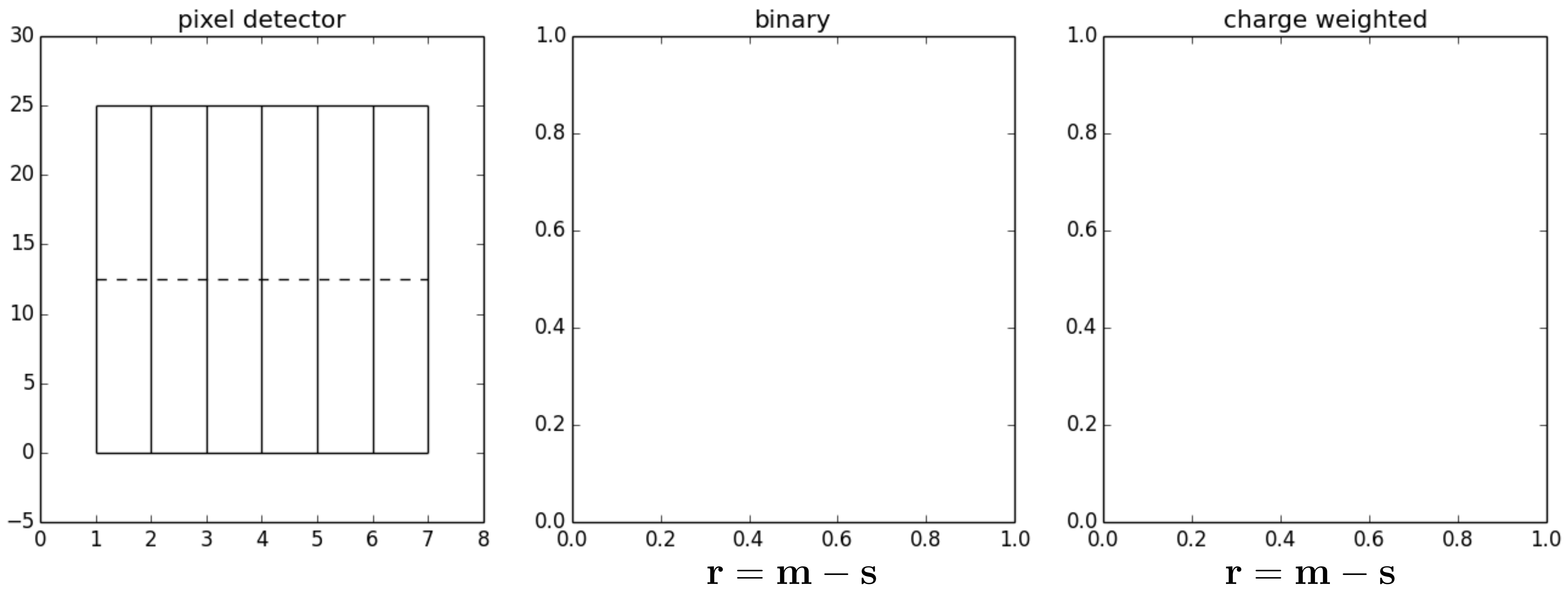
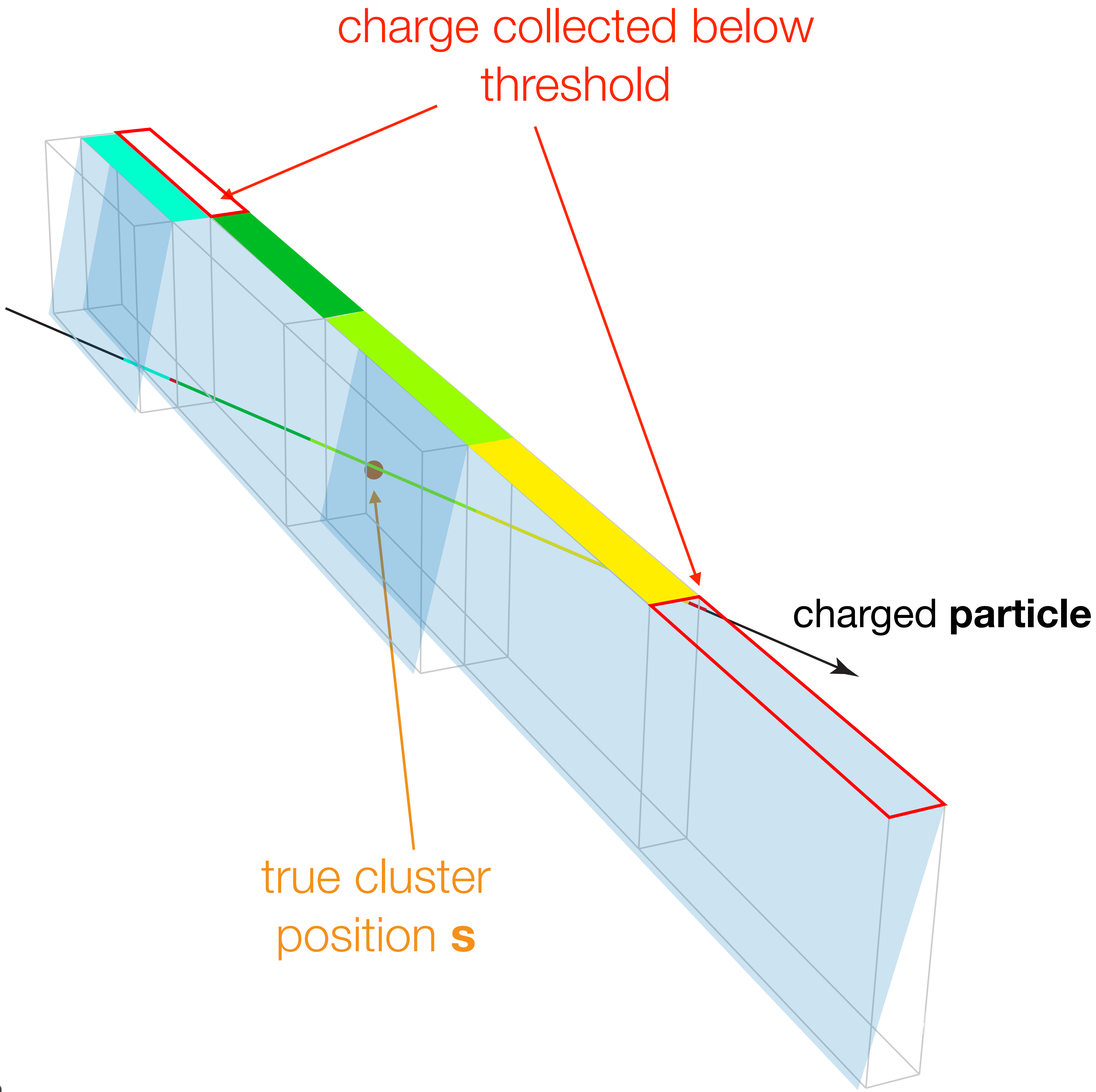


Illustration:
Parts of the map of the 1854 cholera outbreak in London's Soho district by **Dr. John Snow**.

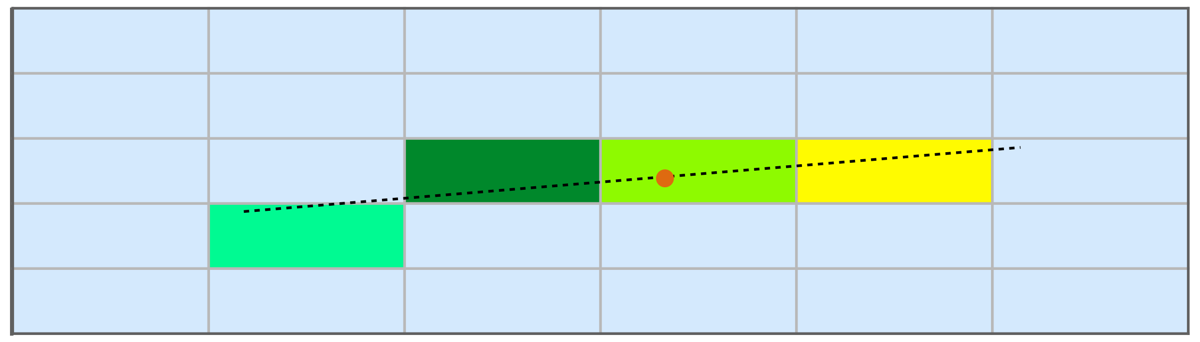
Measurement precision

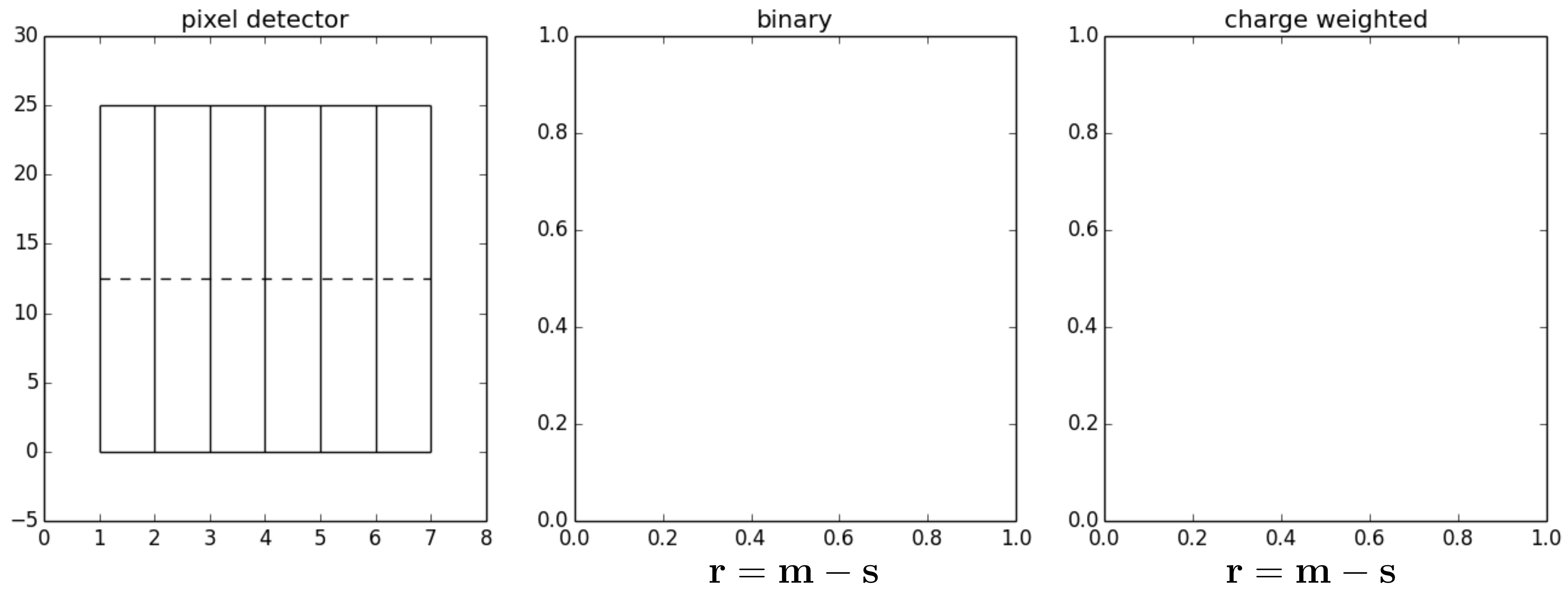


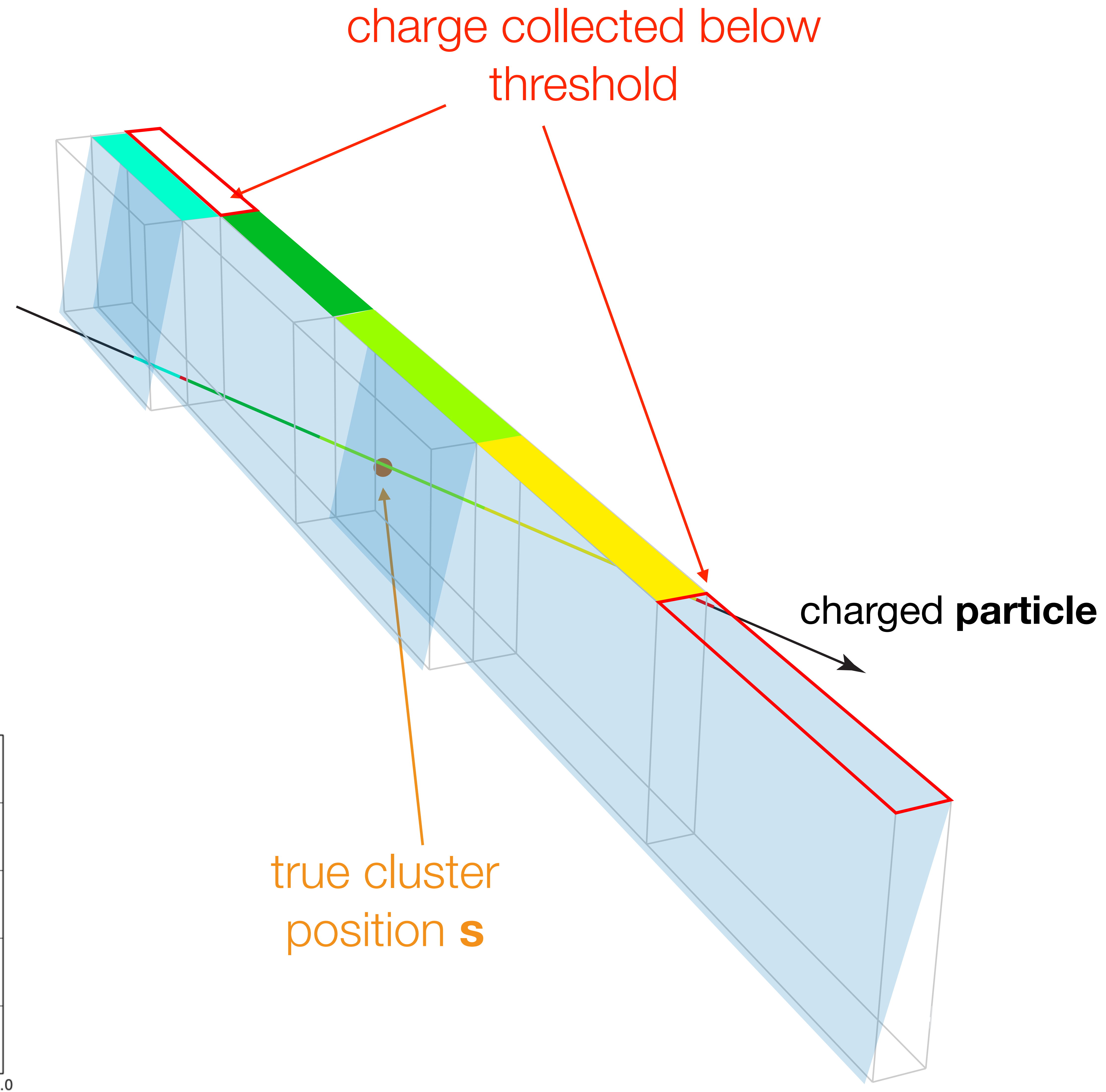




Measurement precision





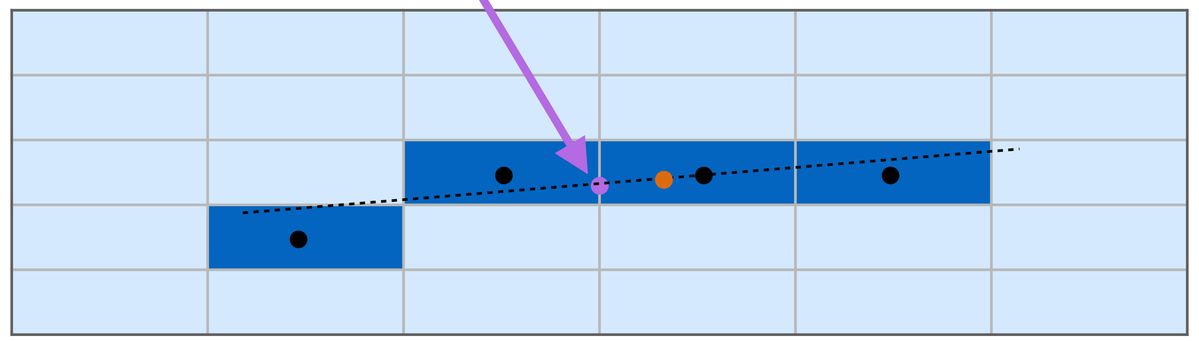


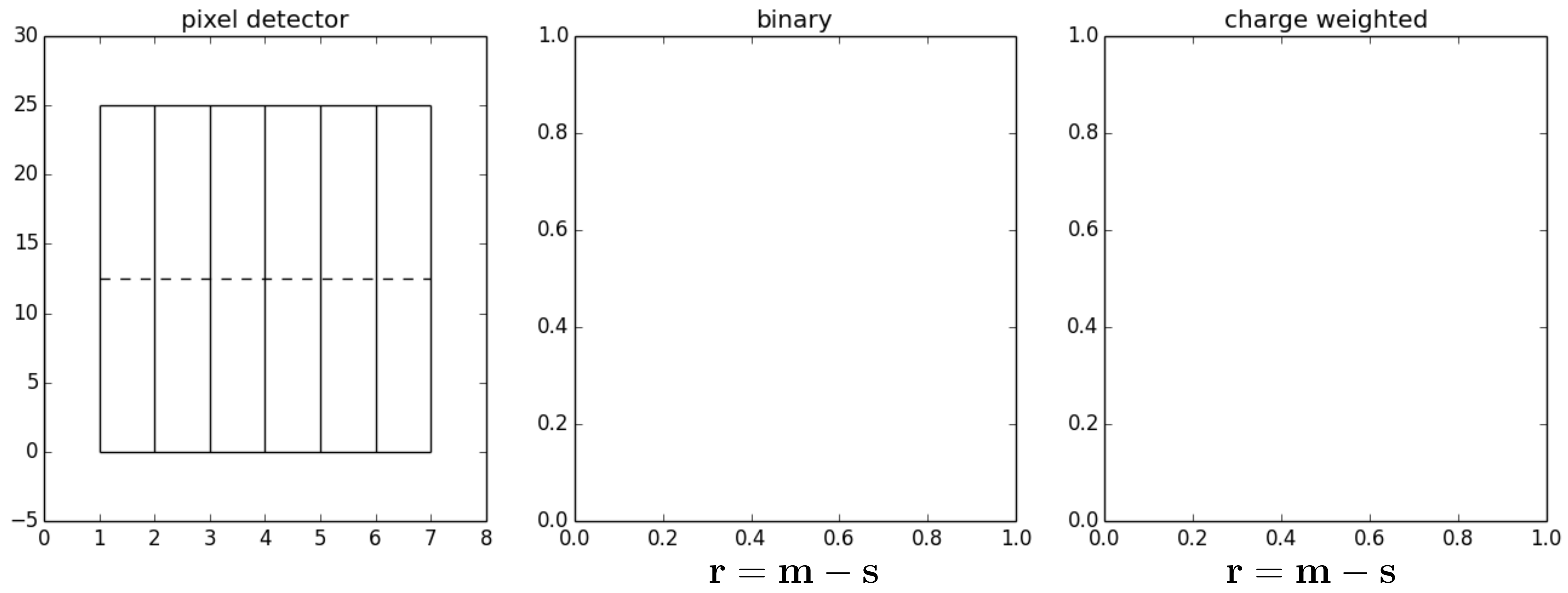
Measurement precision

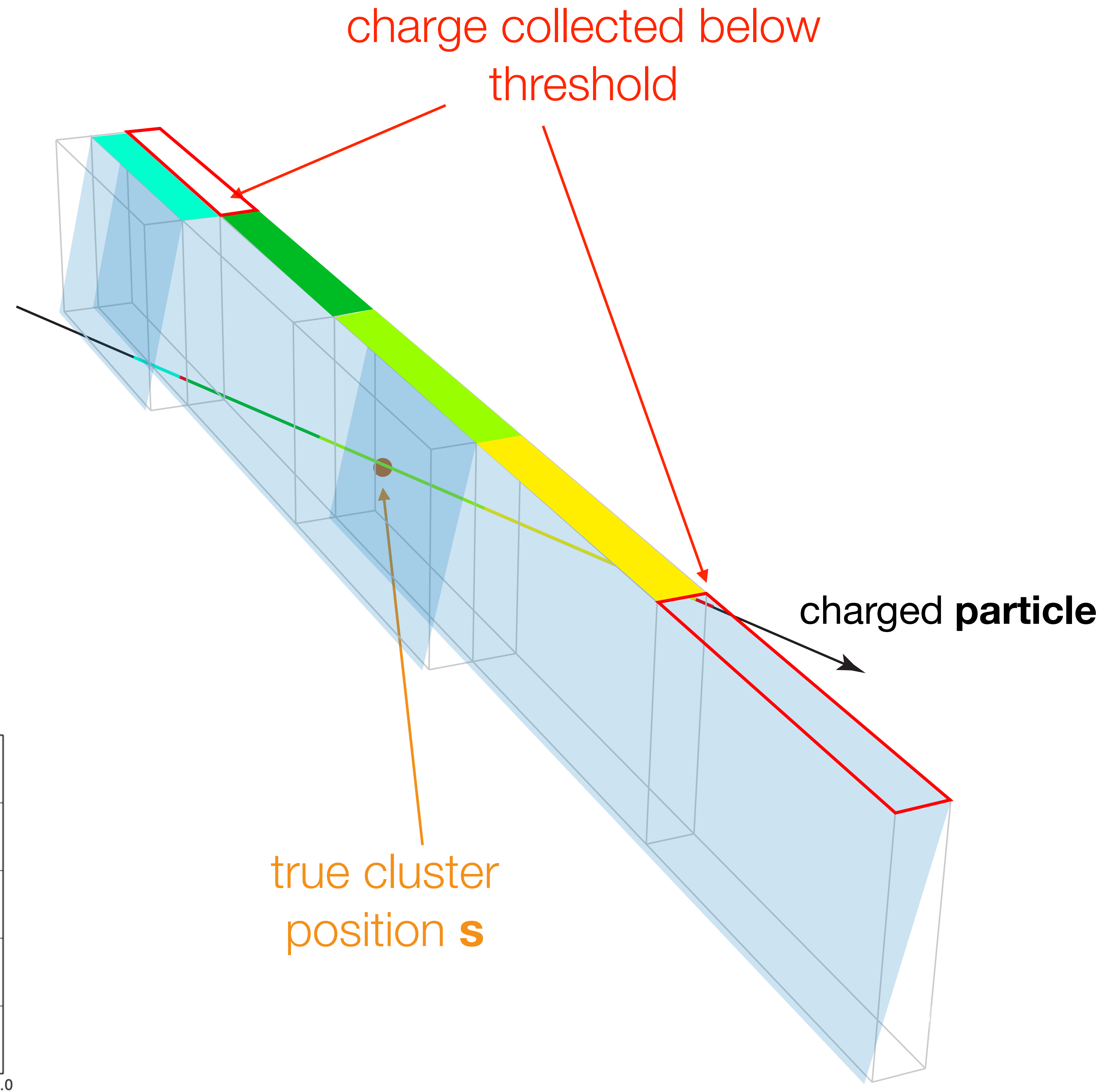
the binary approach:

i-th pixel position

measurement $\mathbf{m} = \frac{1}{N} \sum_{i=1,N} l_i$





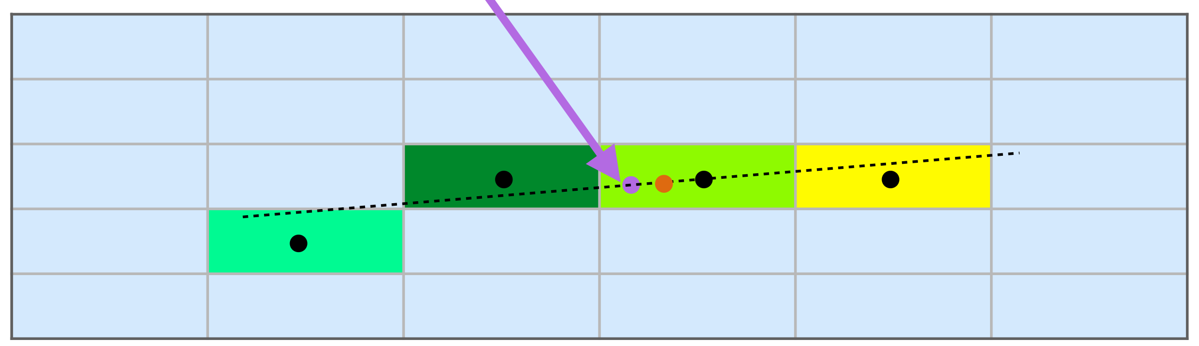


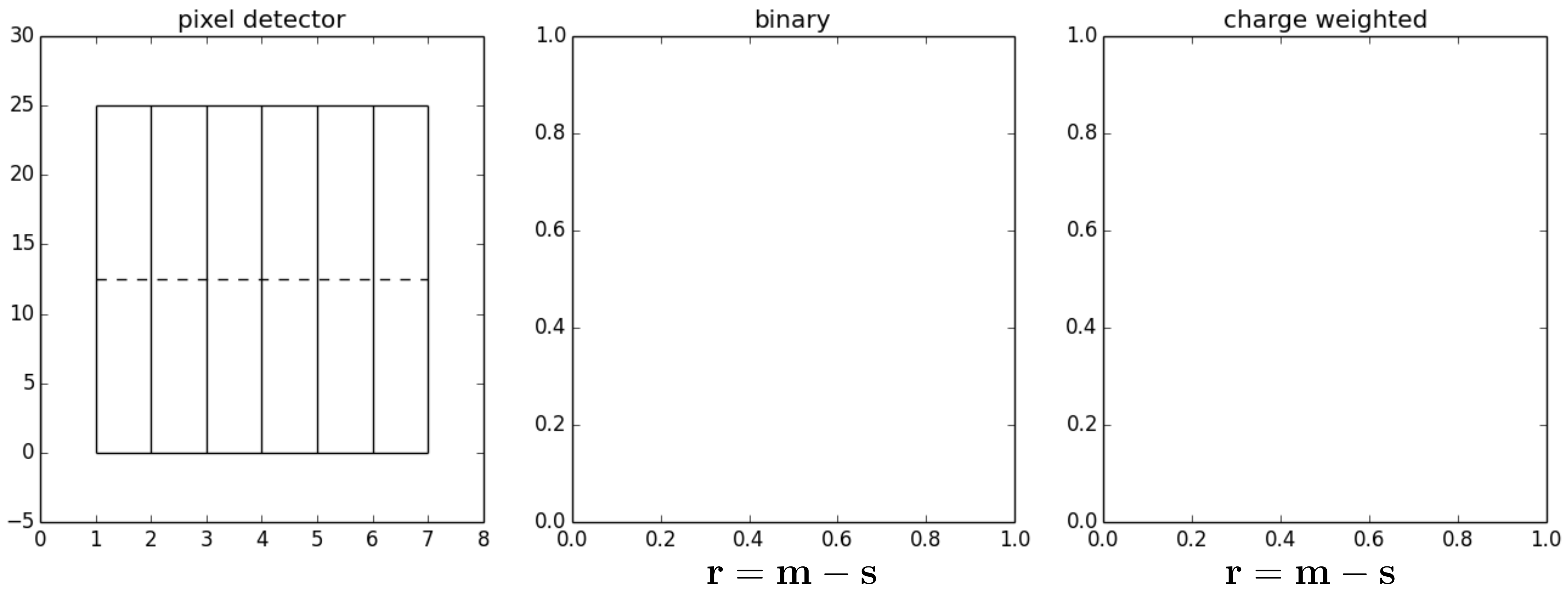
Measurement precision

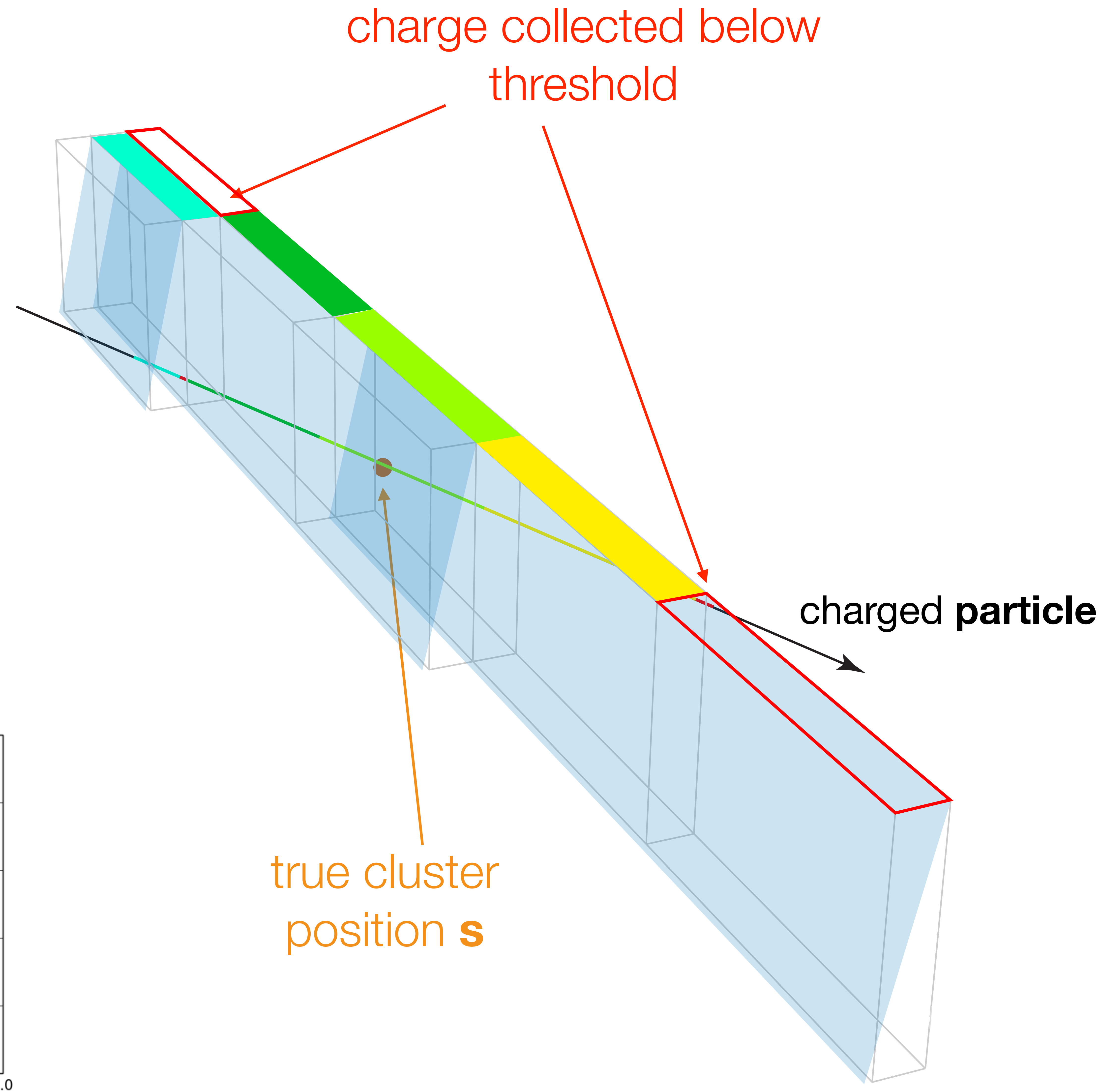
the charge-weighted approach :

$$\mathbf{m} = \frac{1}{\sum_{i=1,N} q_i} \sum_{i=1,N} q_i l_i$$

charge collected in cell i







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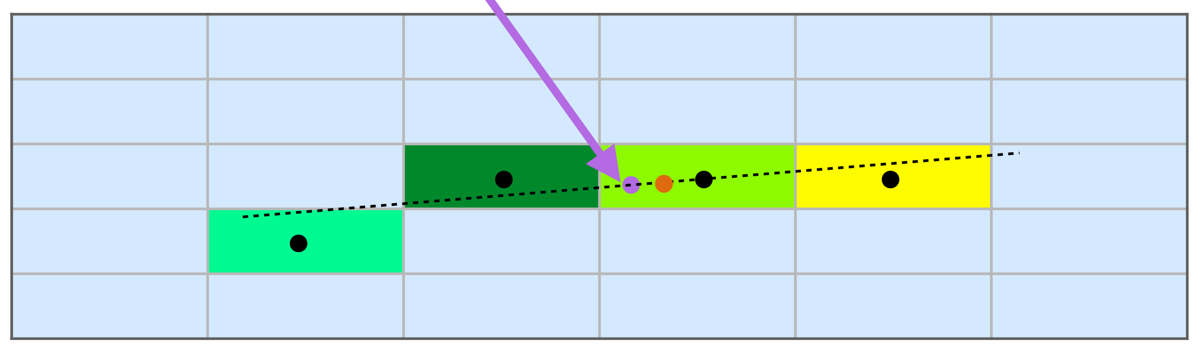
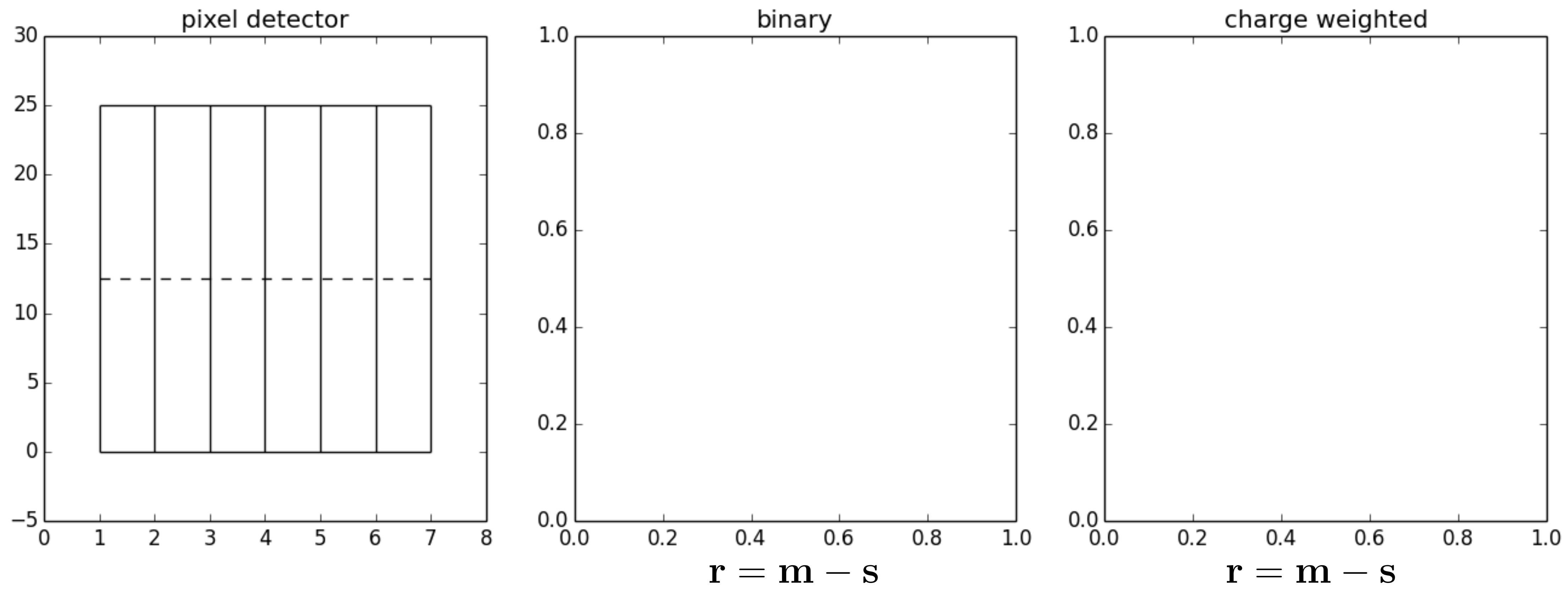
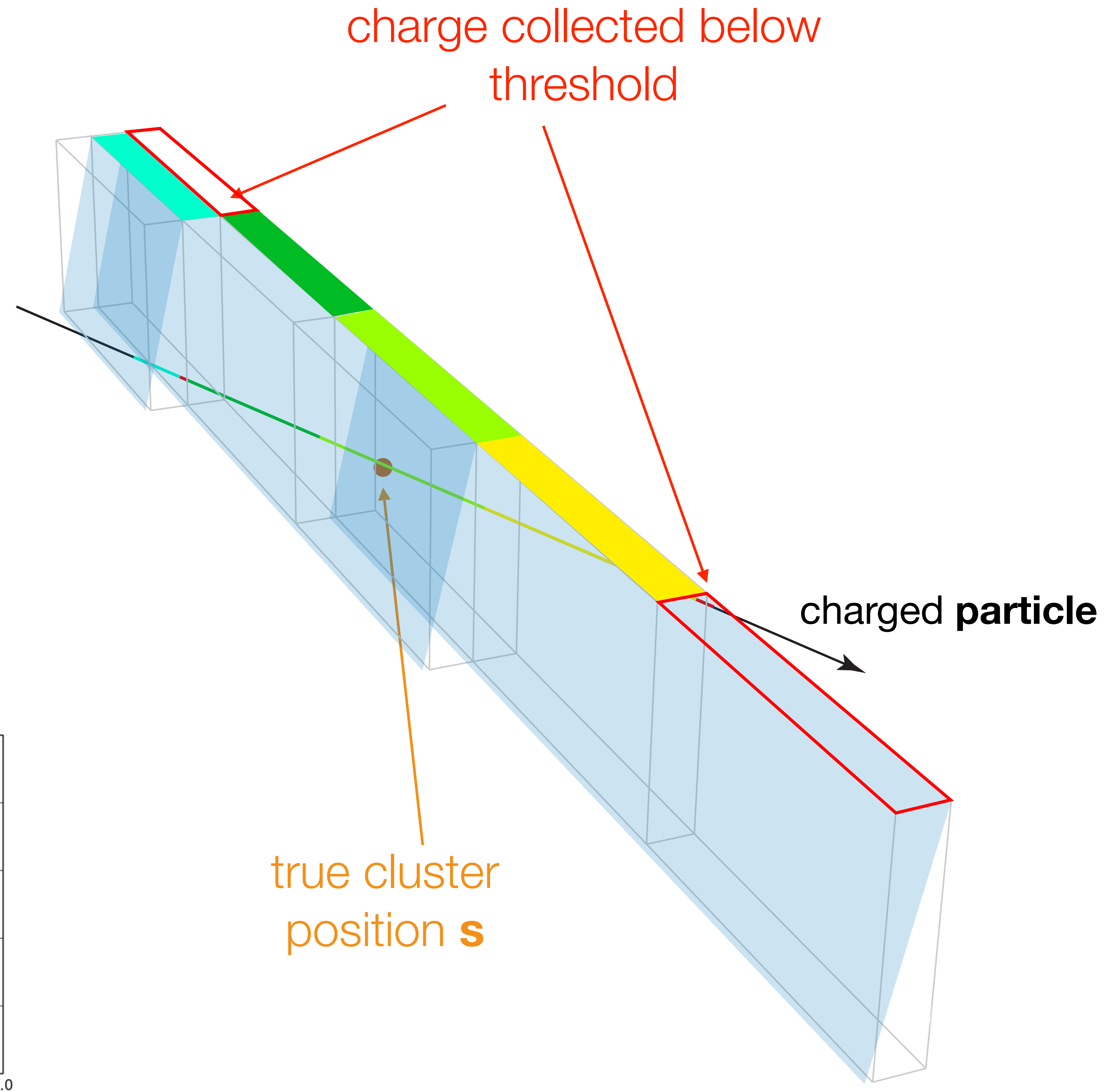


which one is better ?

let's measure it using the residuum

$$\mathbf{r} = \mathbf{m} - \mathbf{s}$$





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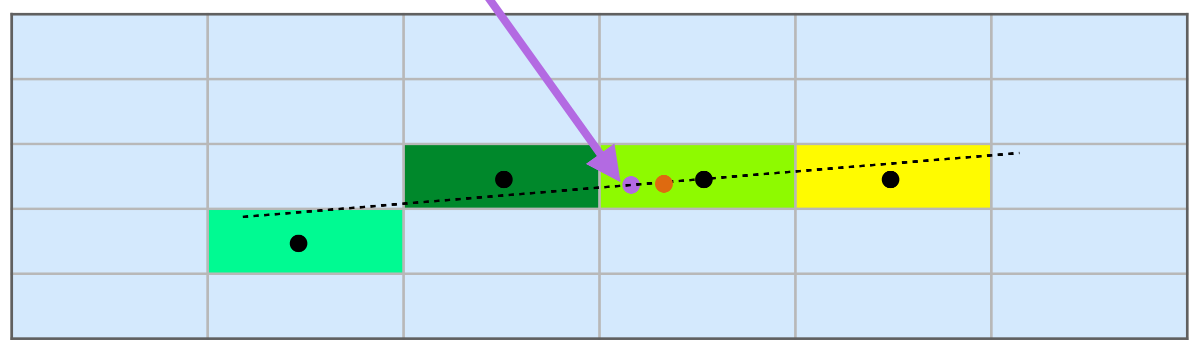

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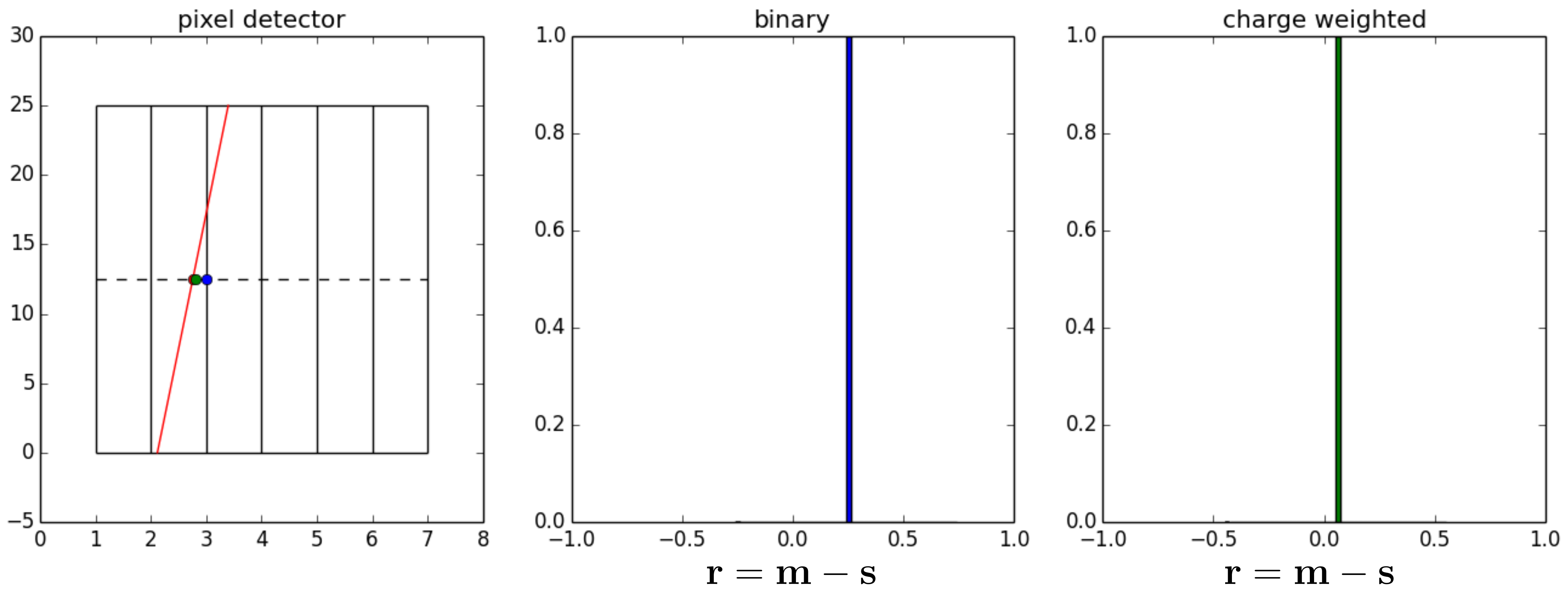

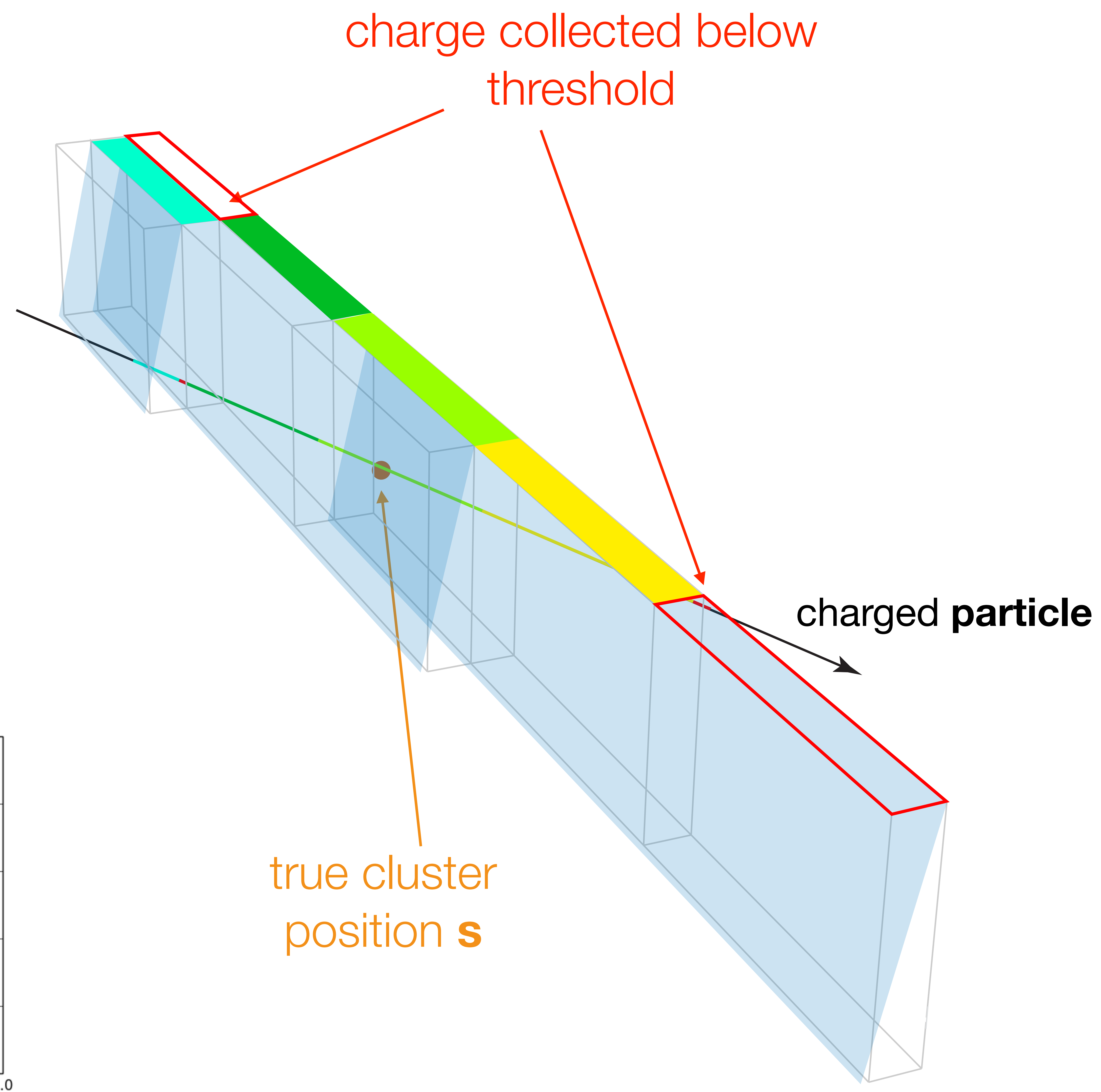

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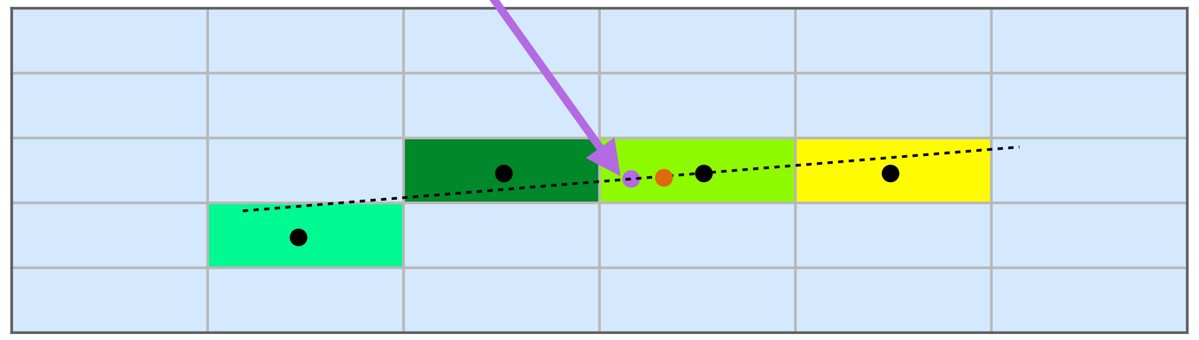

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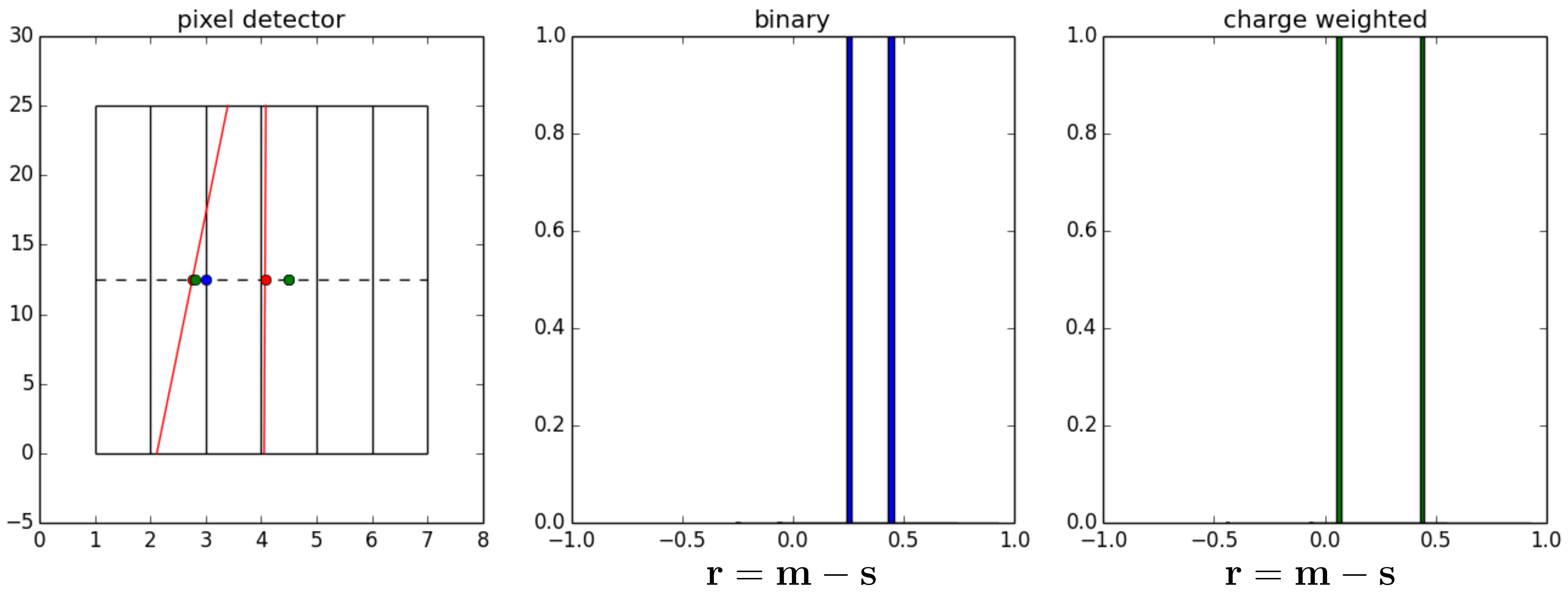

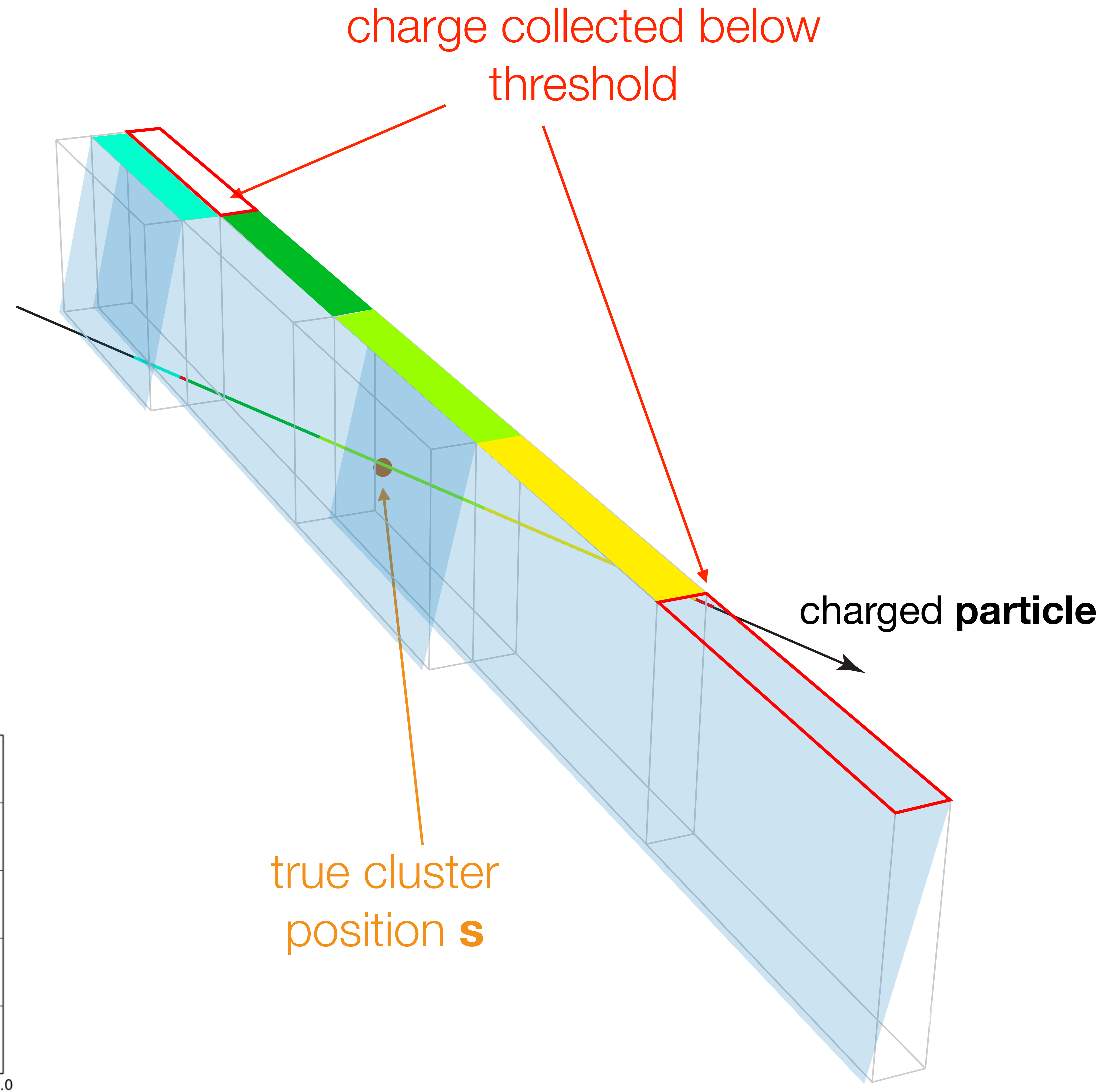

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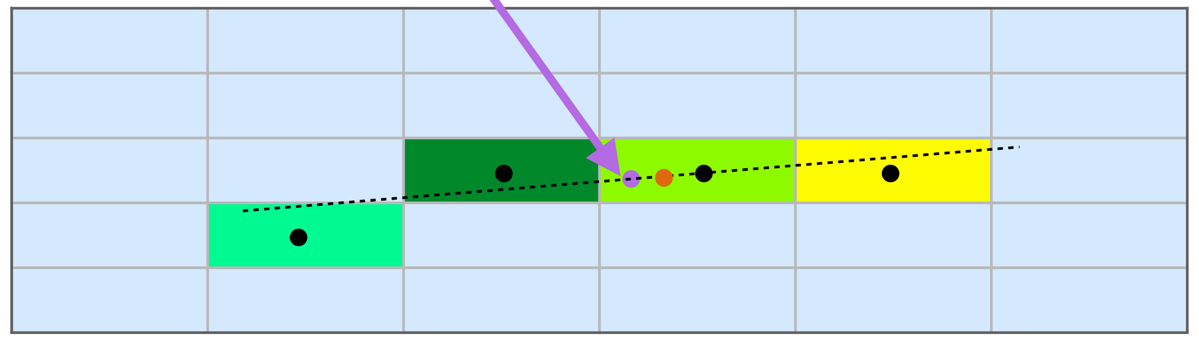

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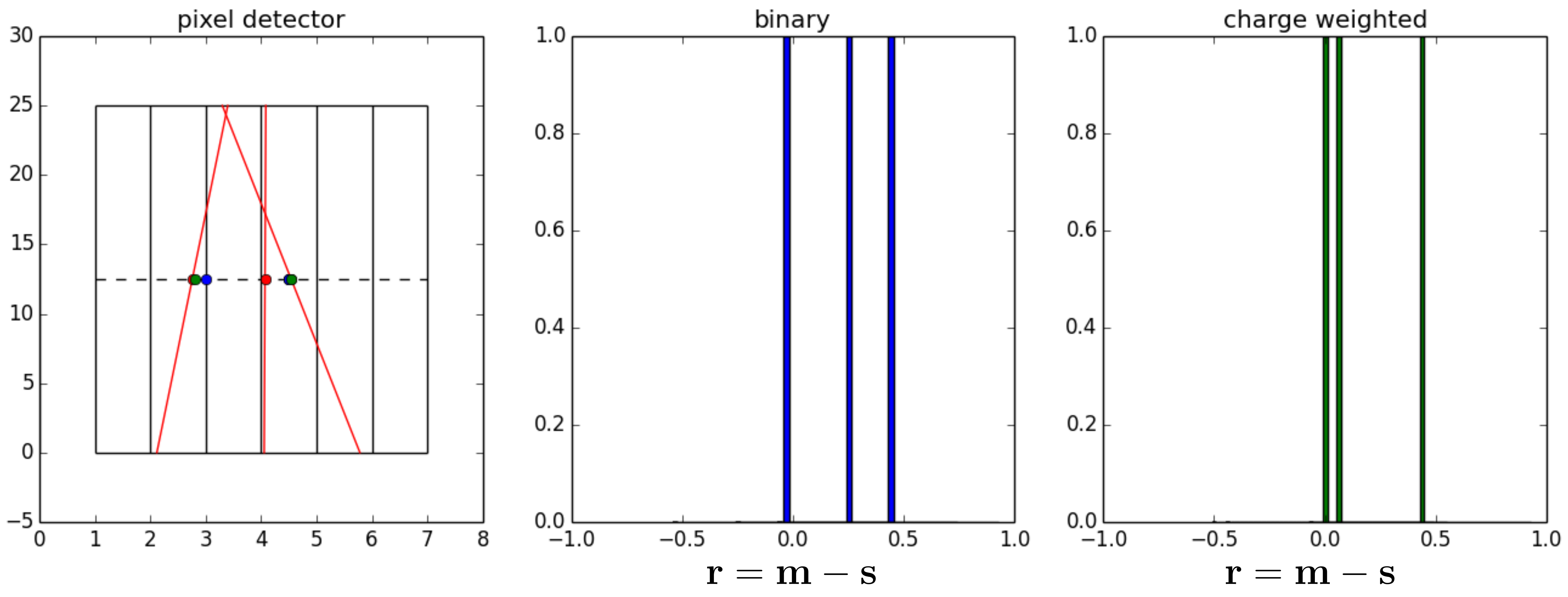

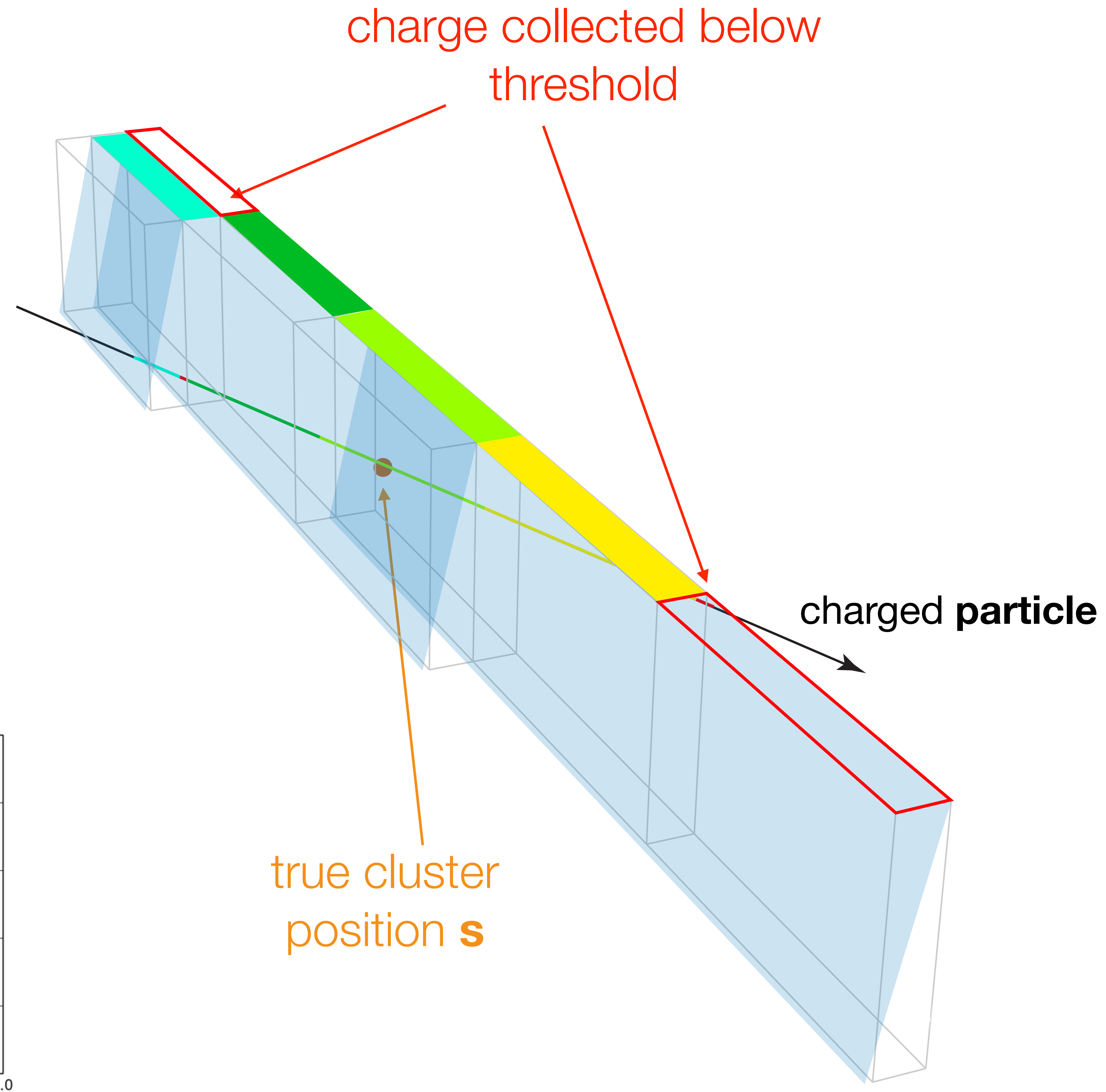

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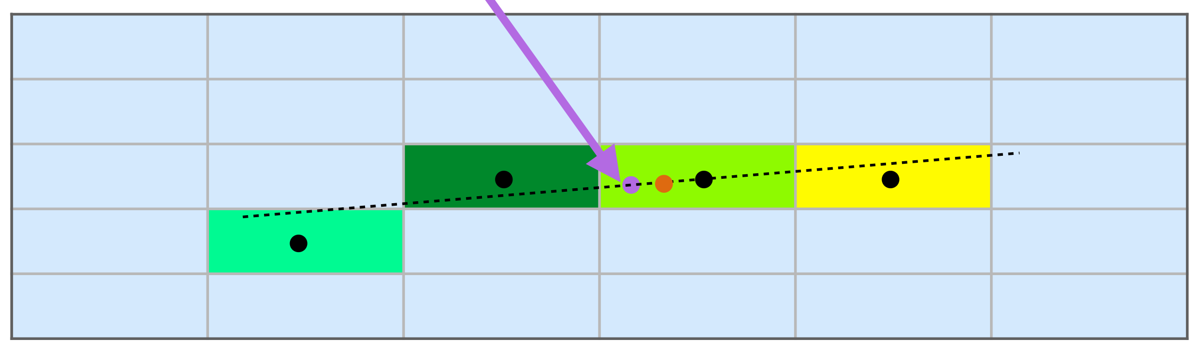

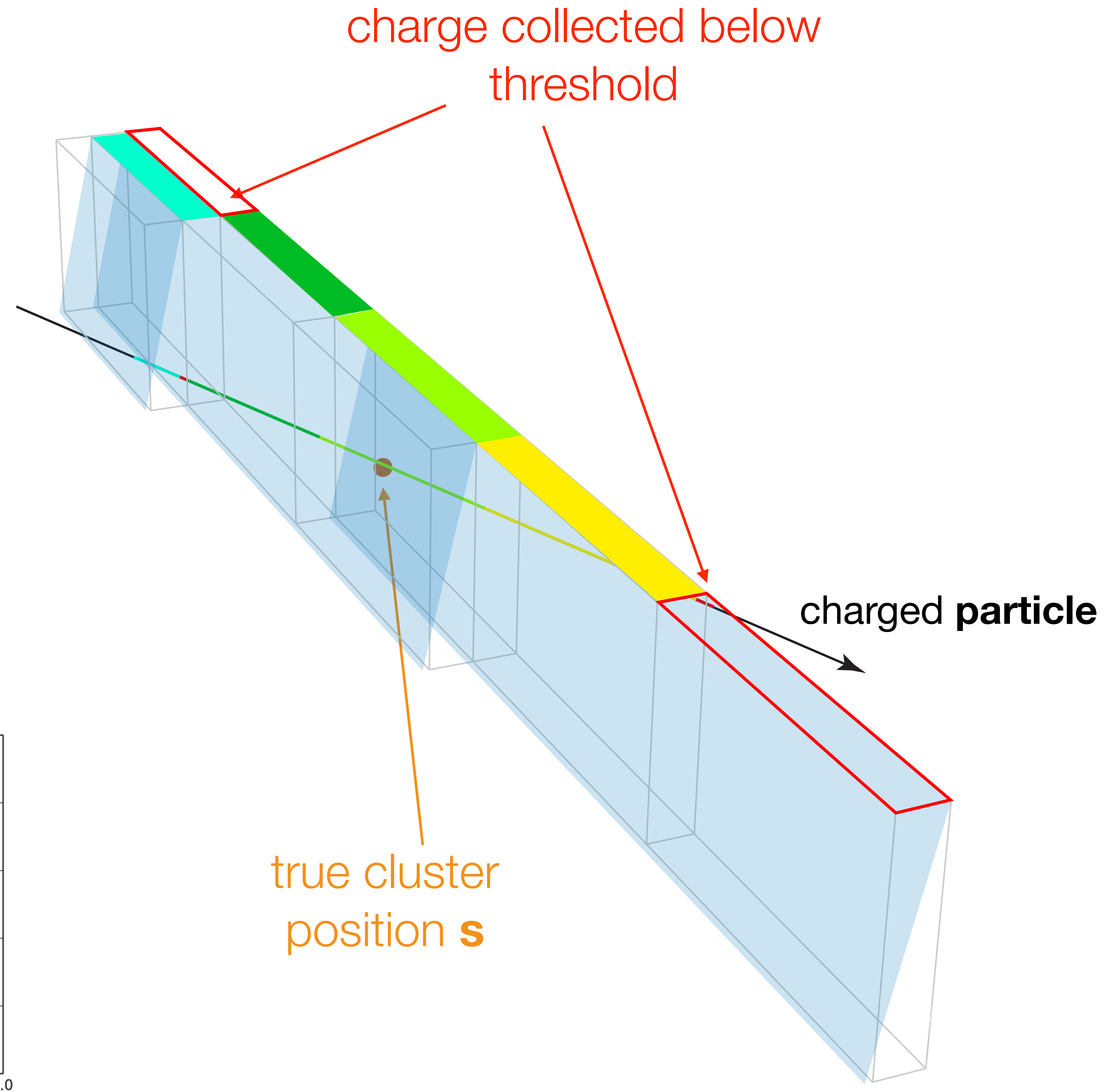

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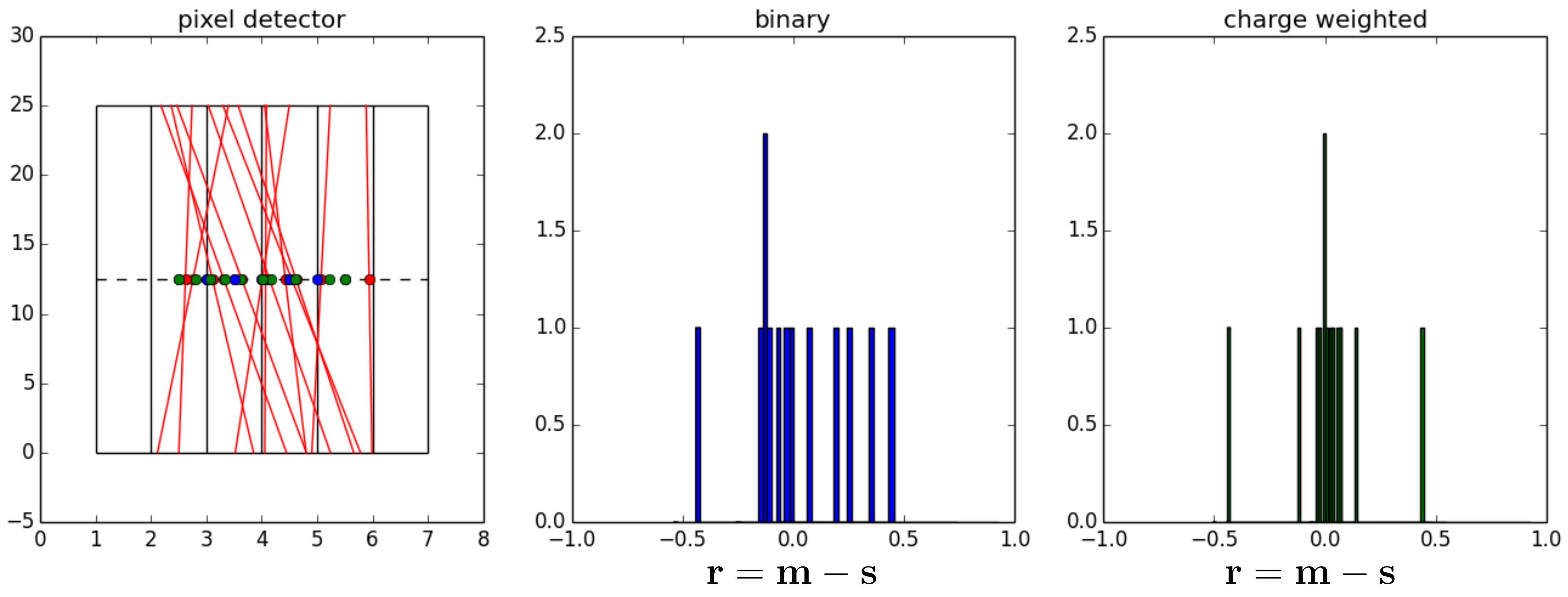

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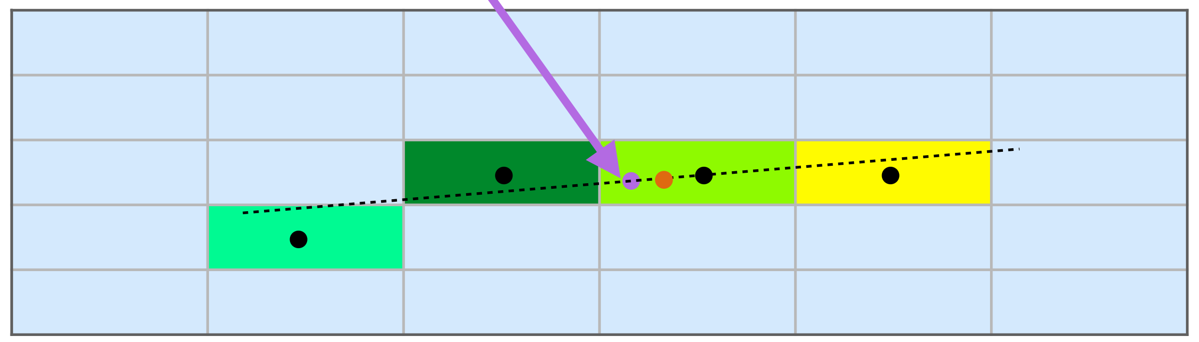

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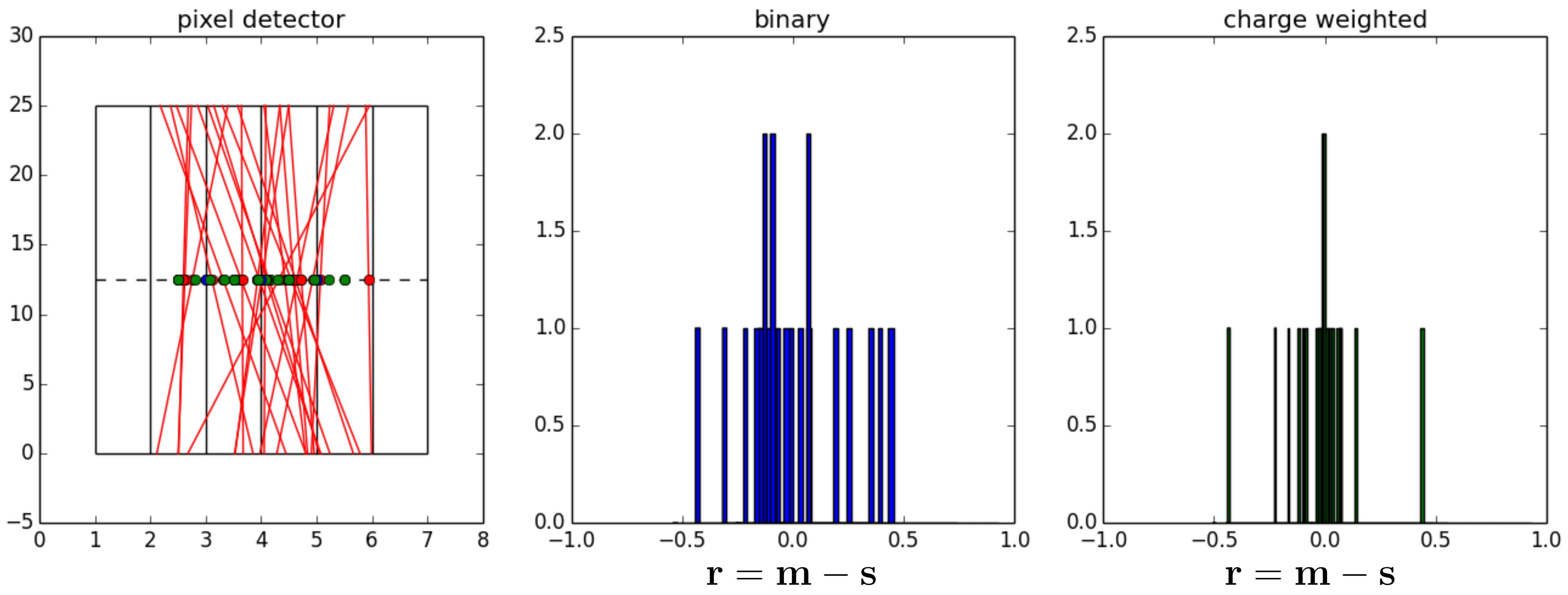

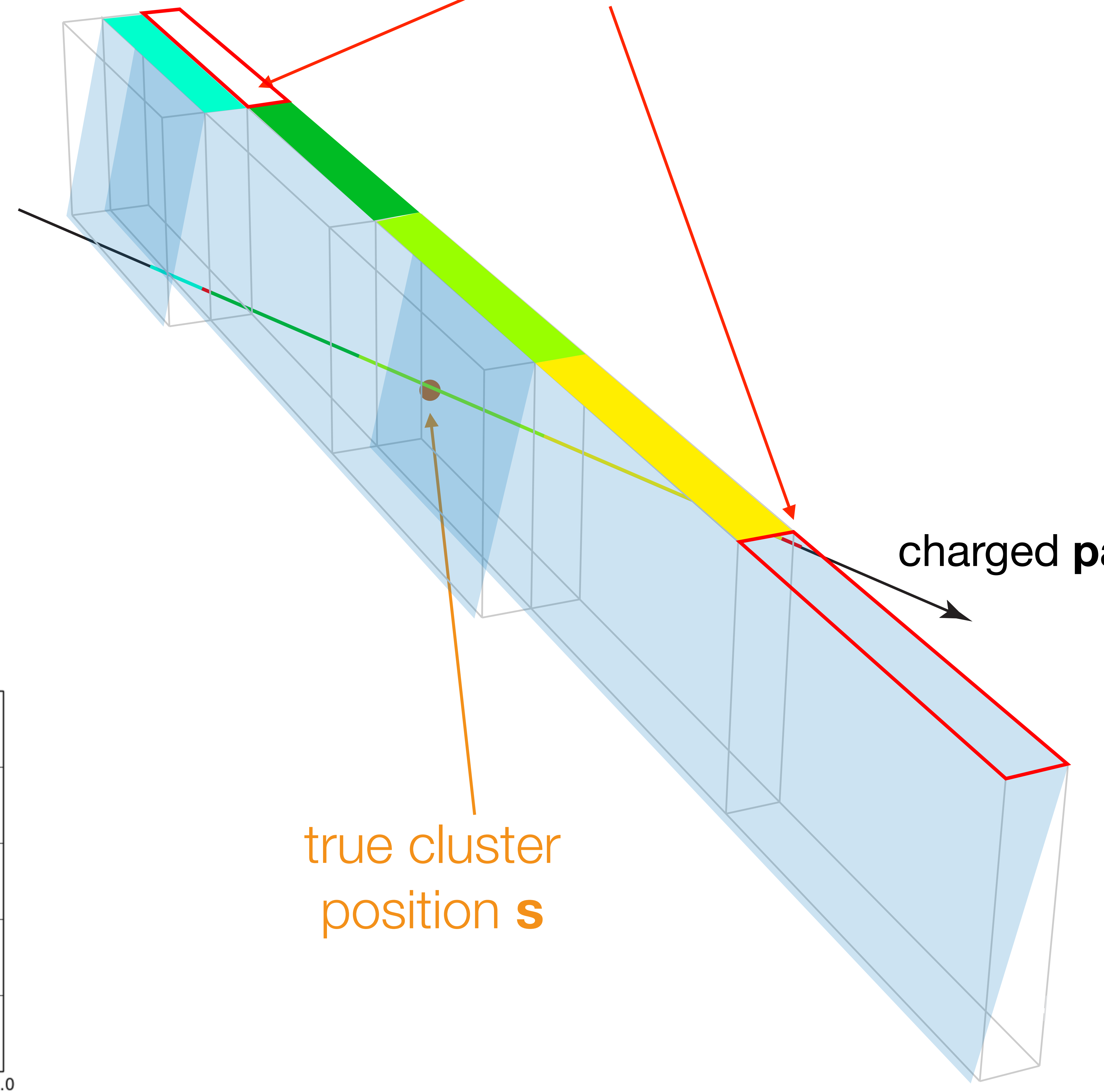

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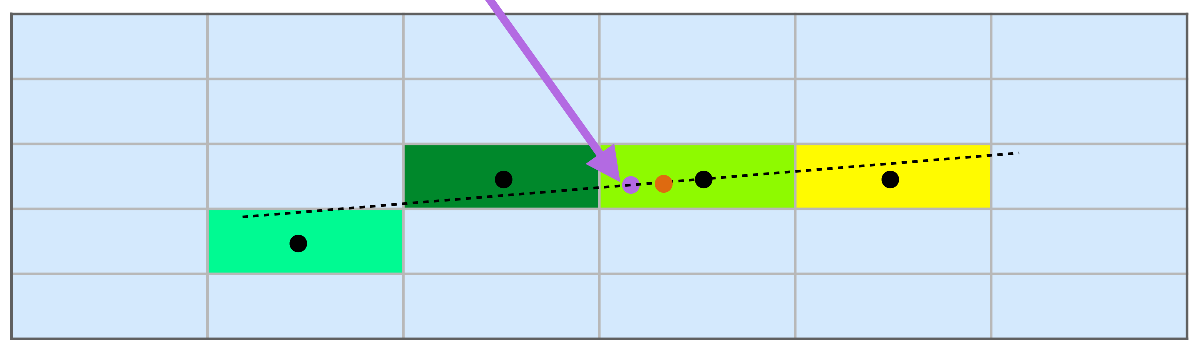

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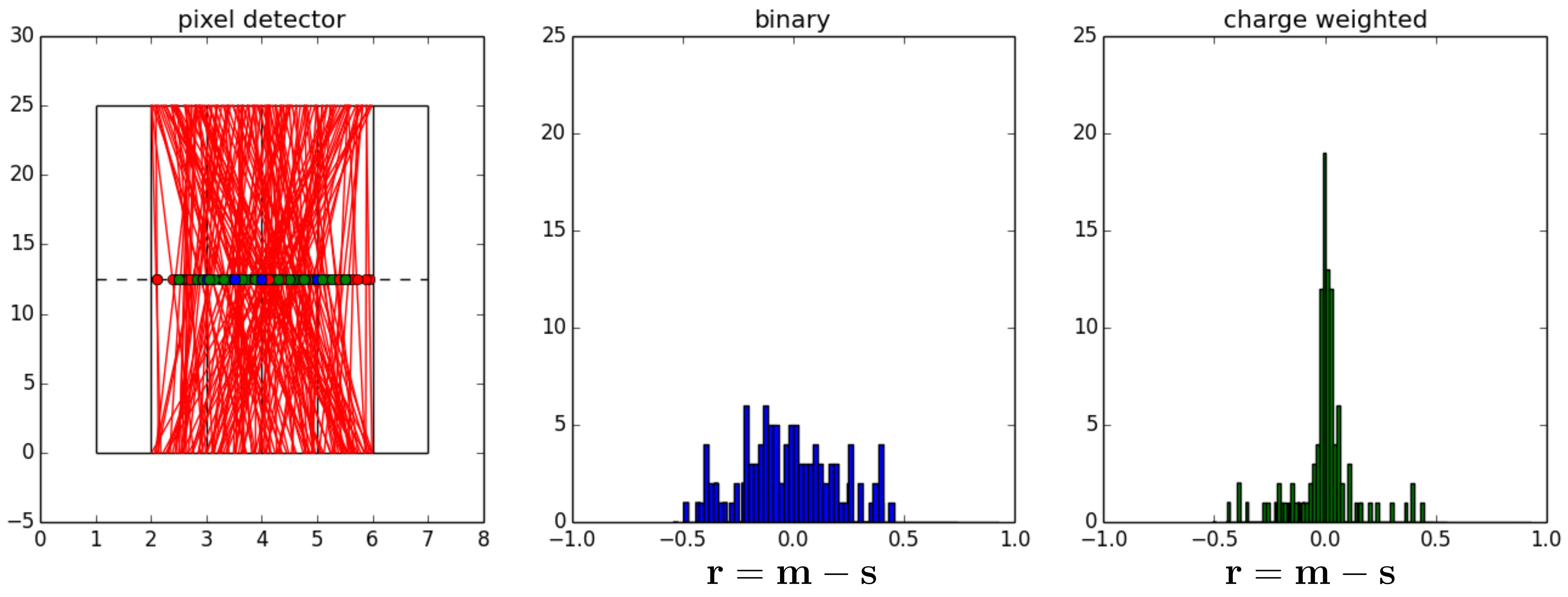

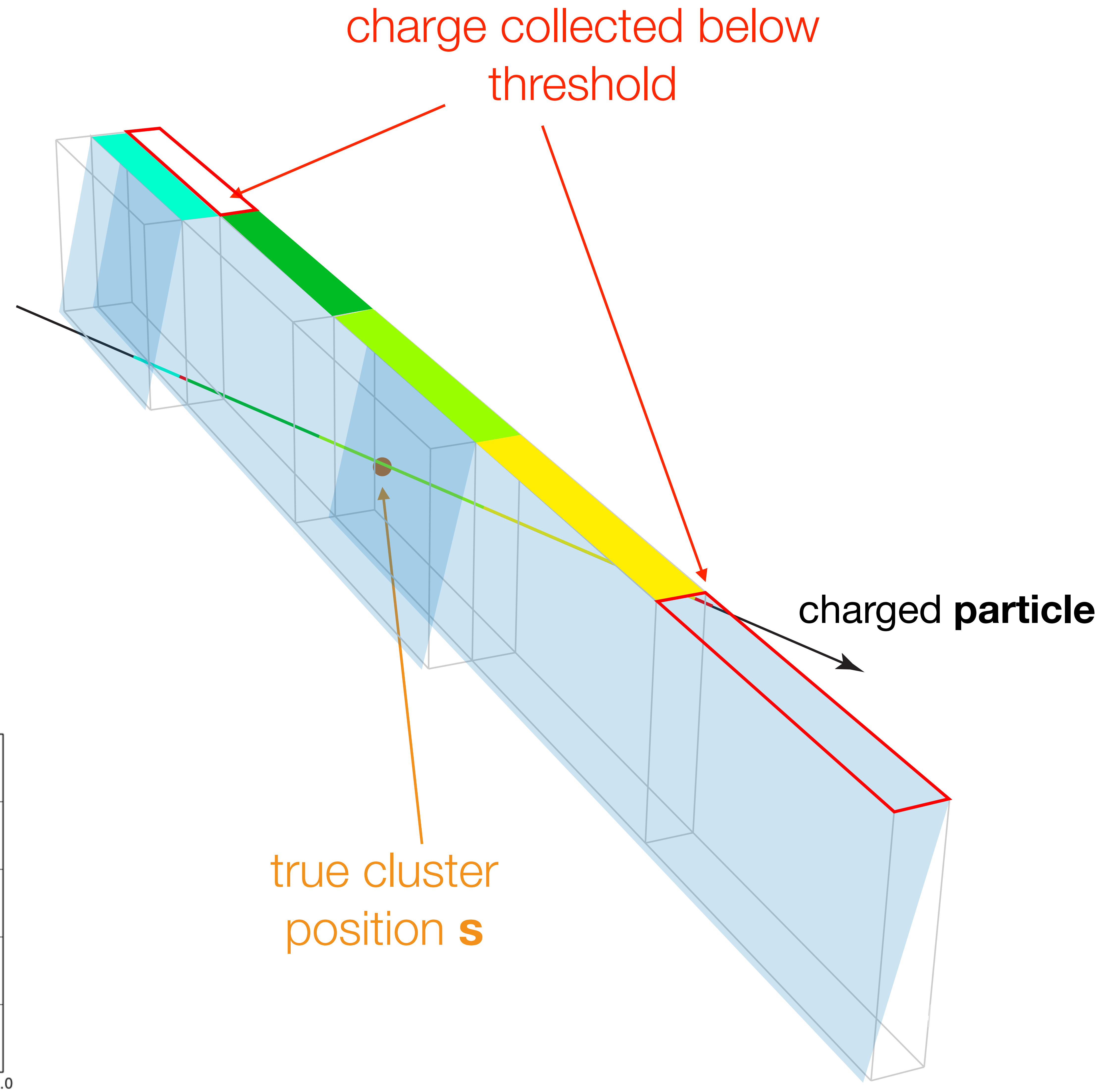

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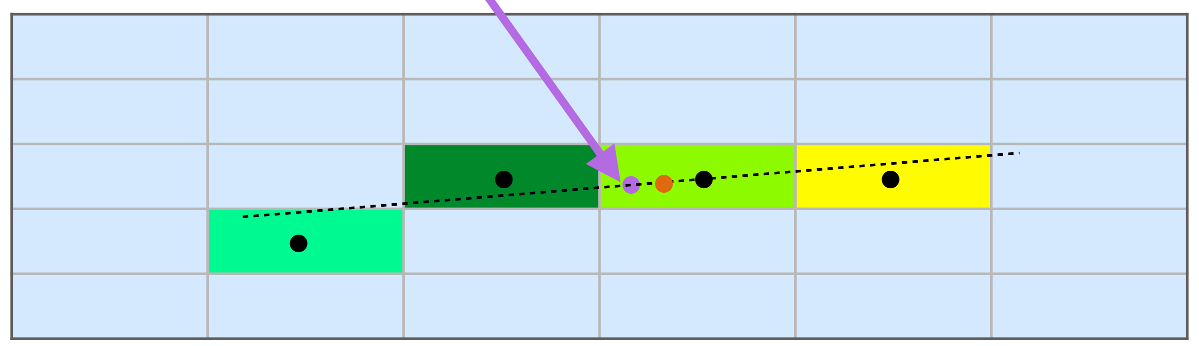

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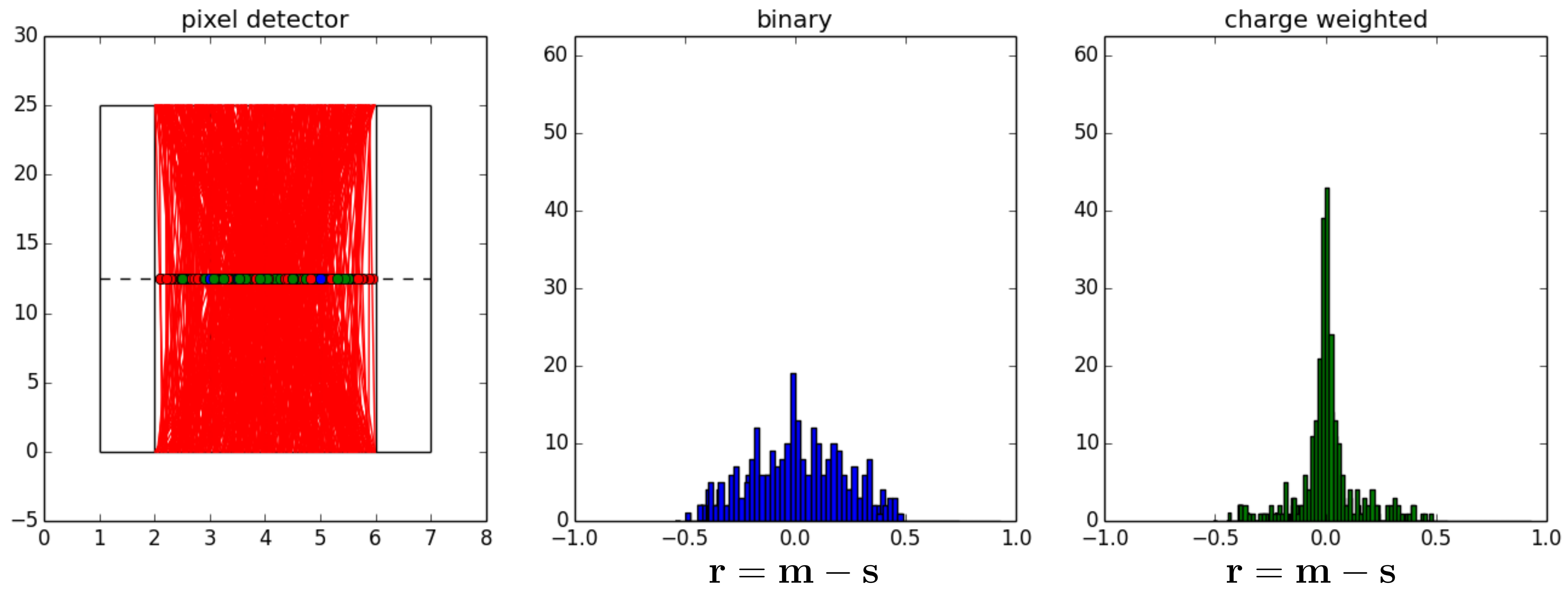

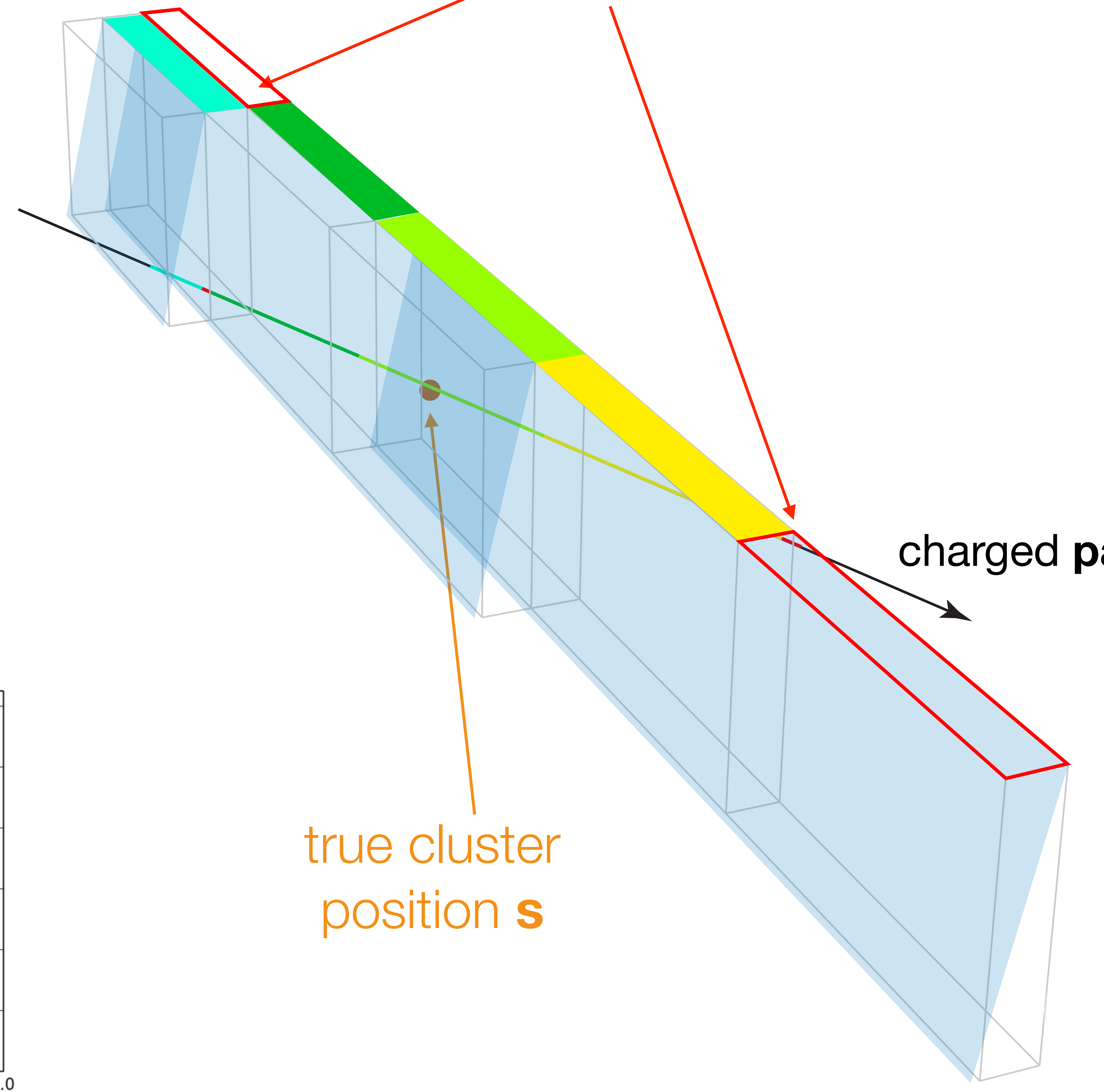

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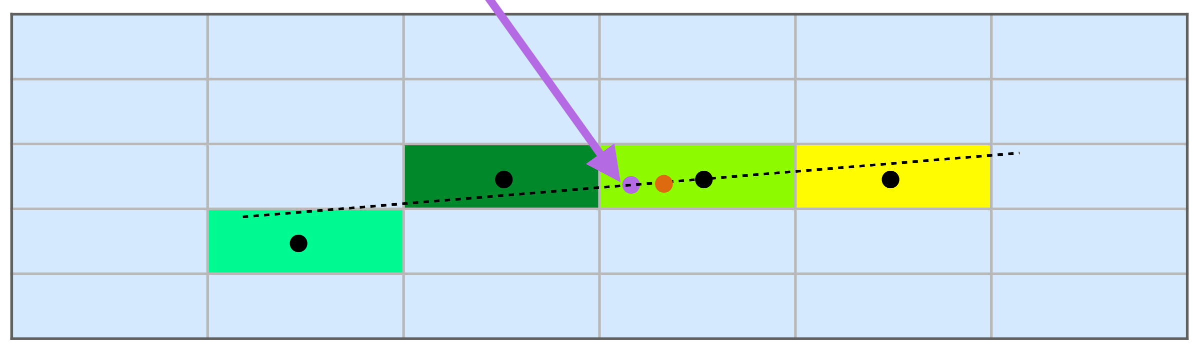

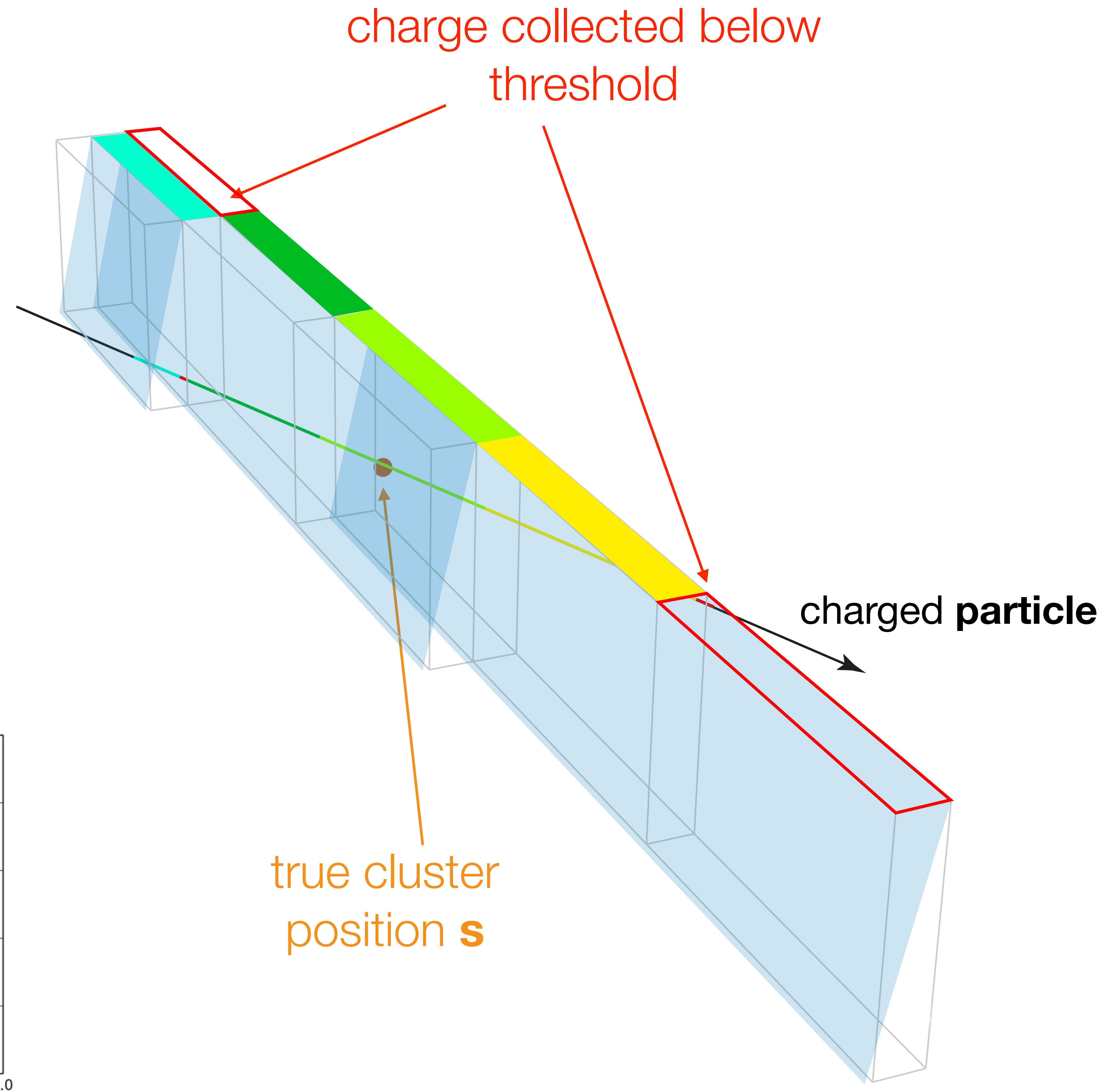

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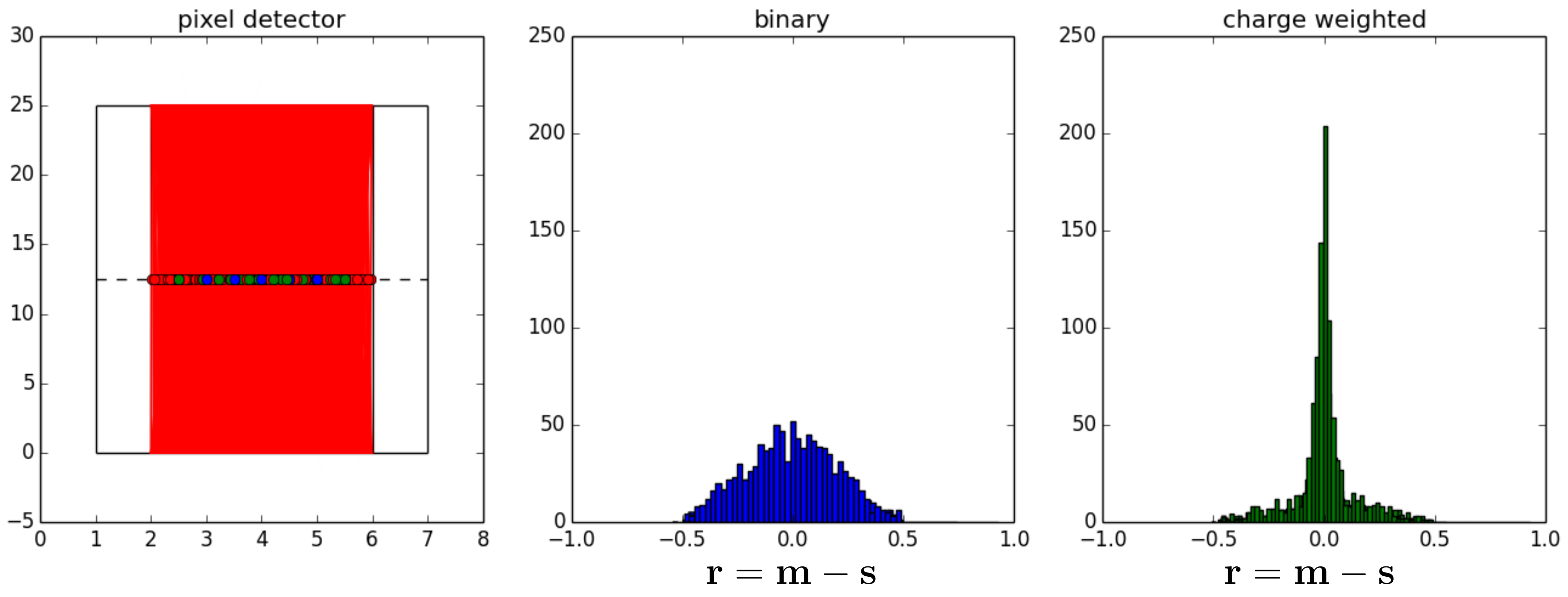

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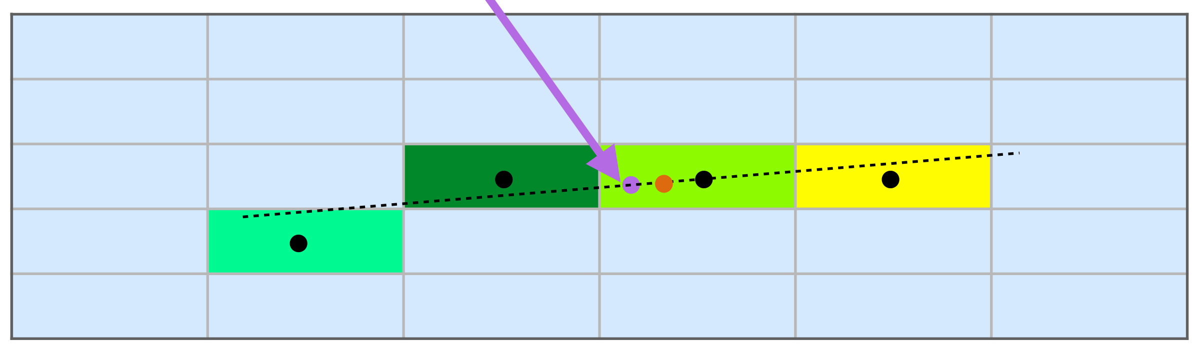

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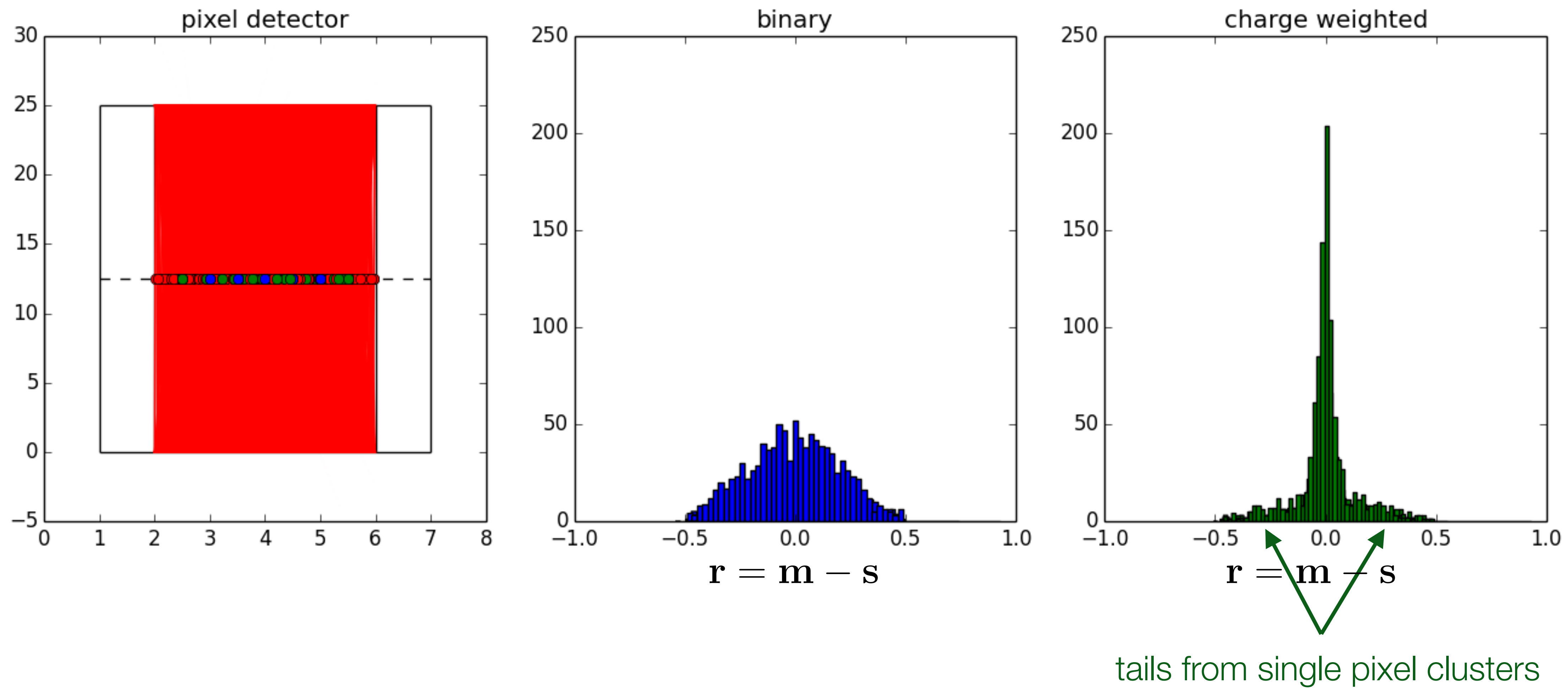
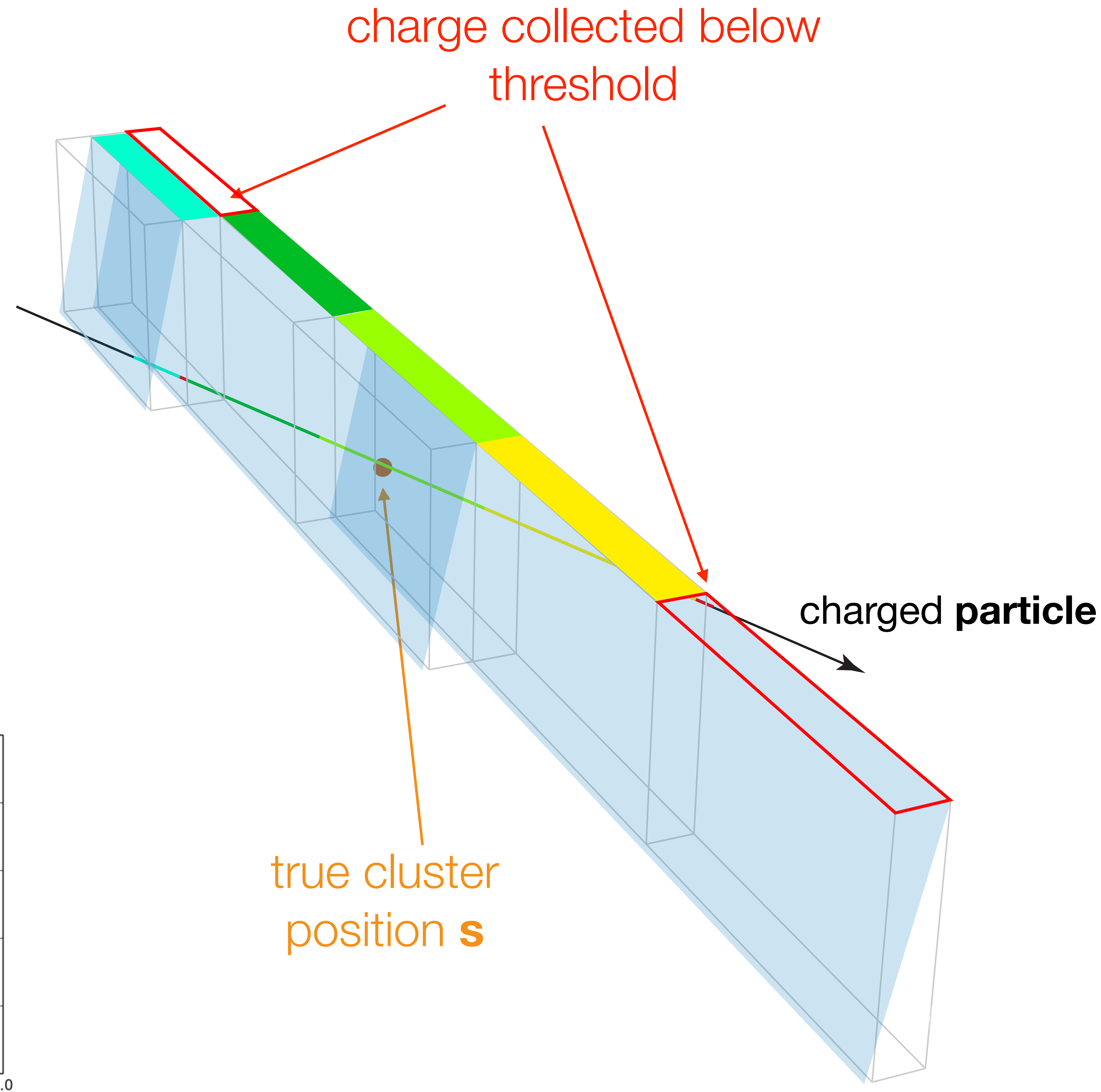
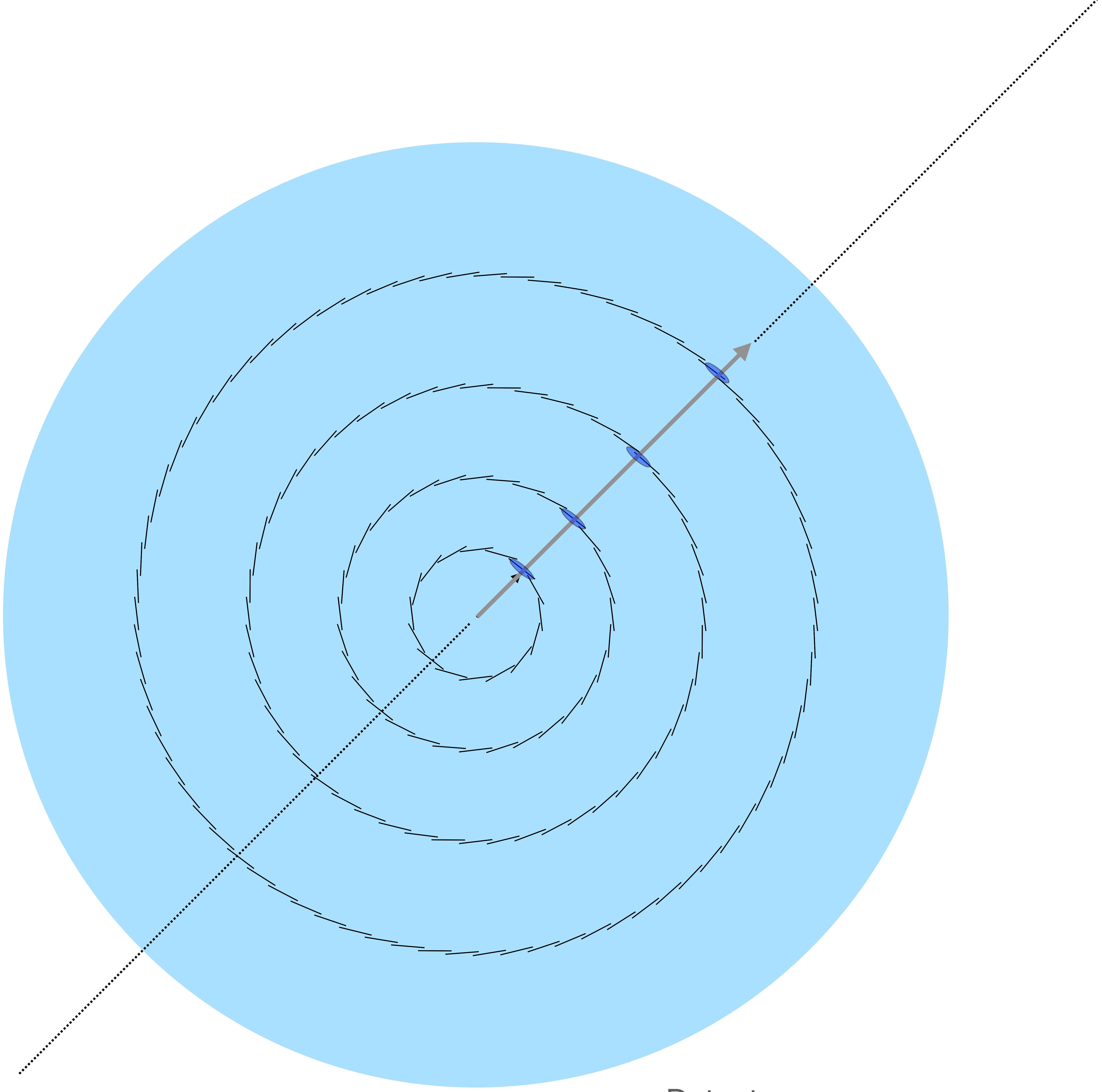
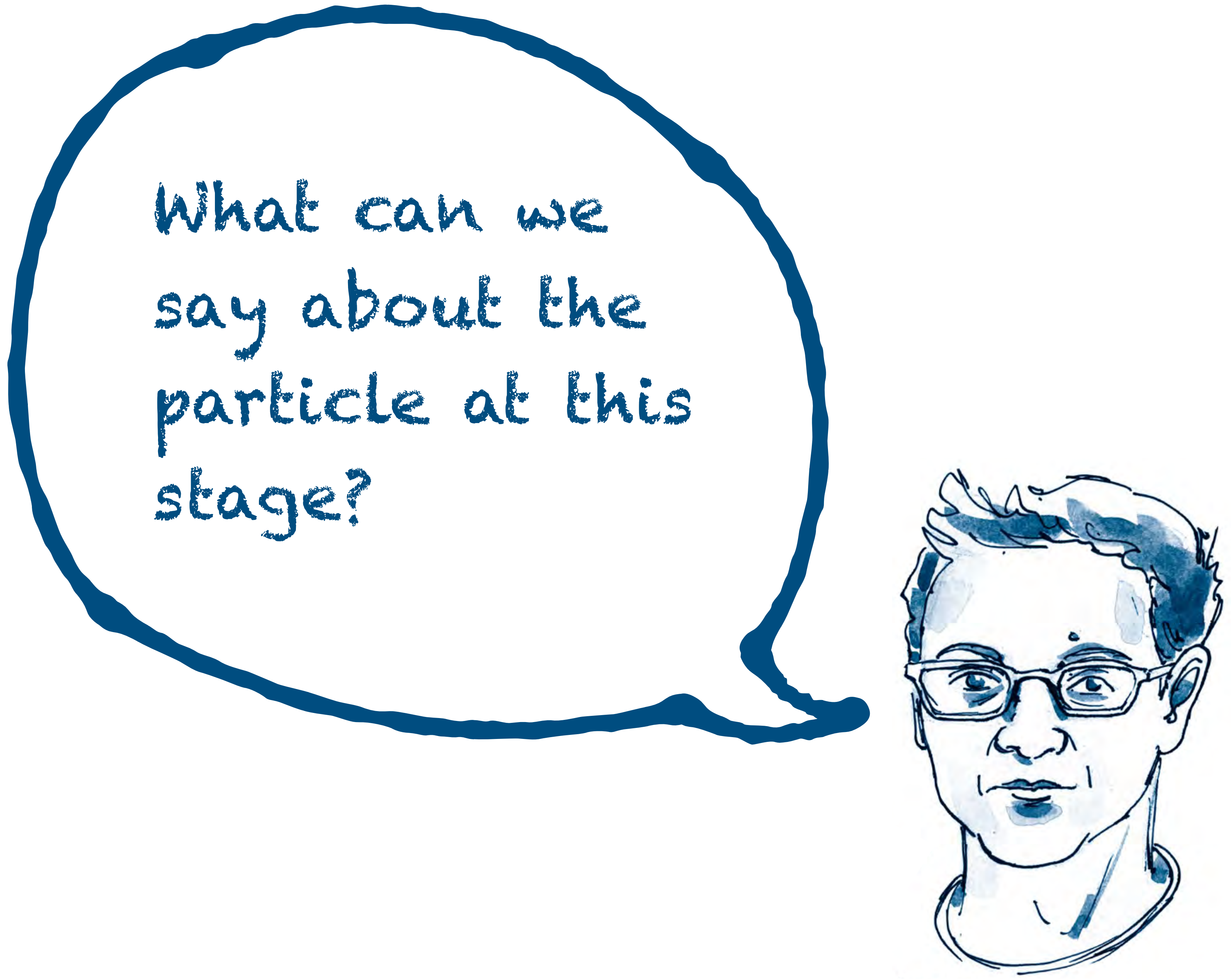
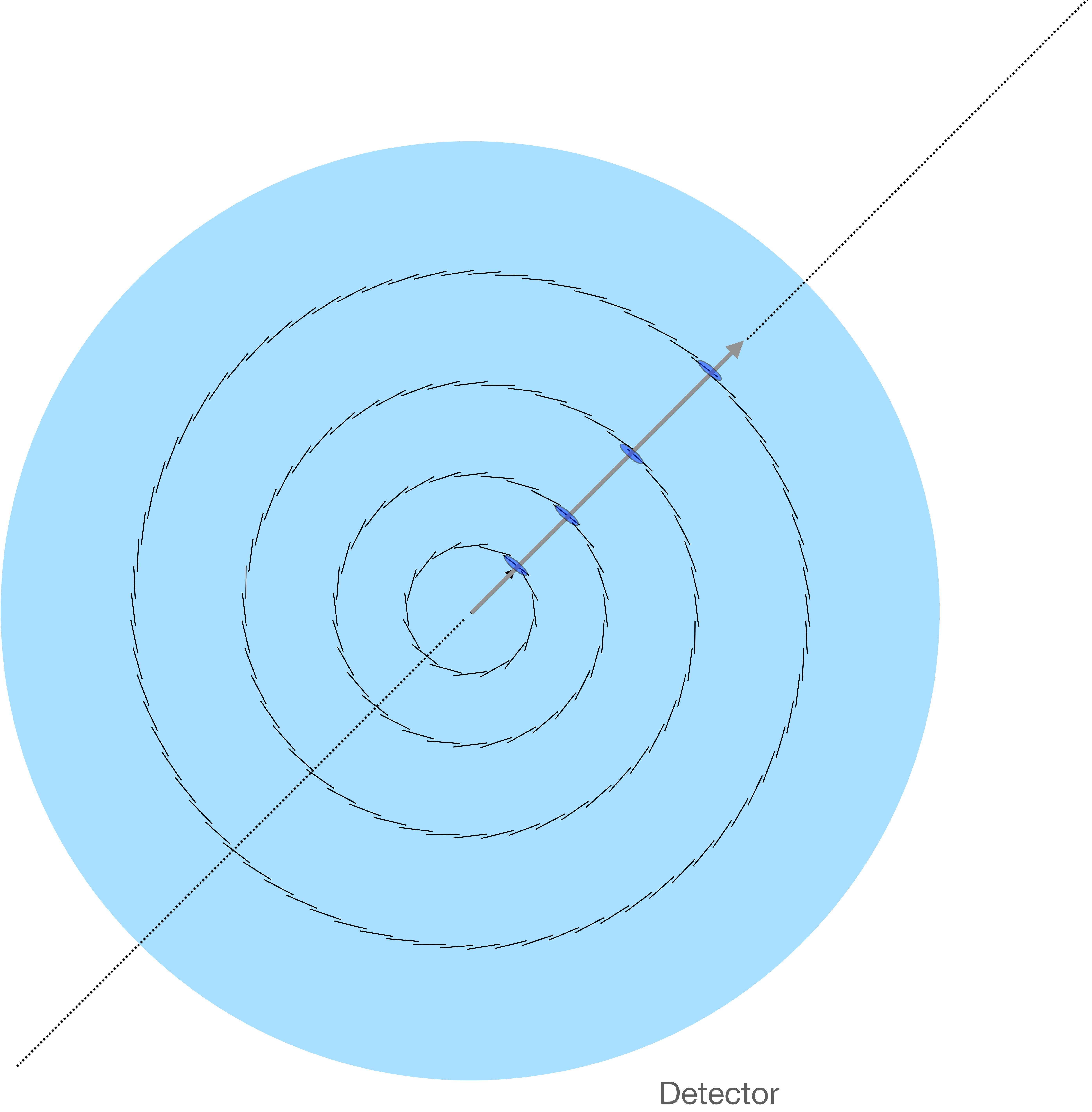




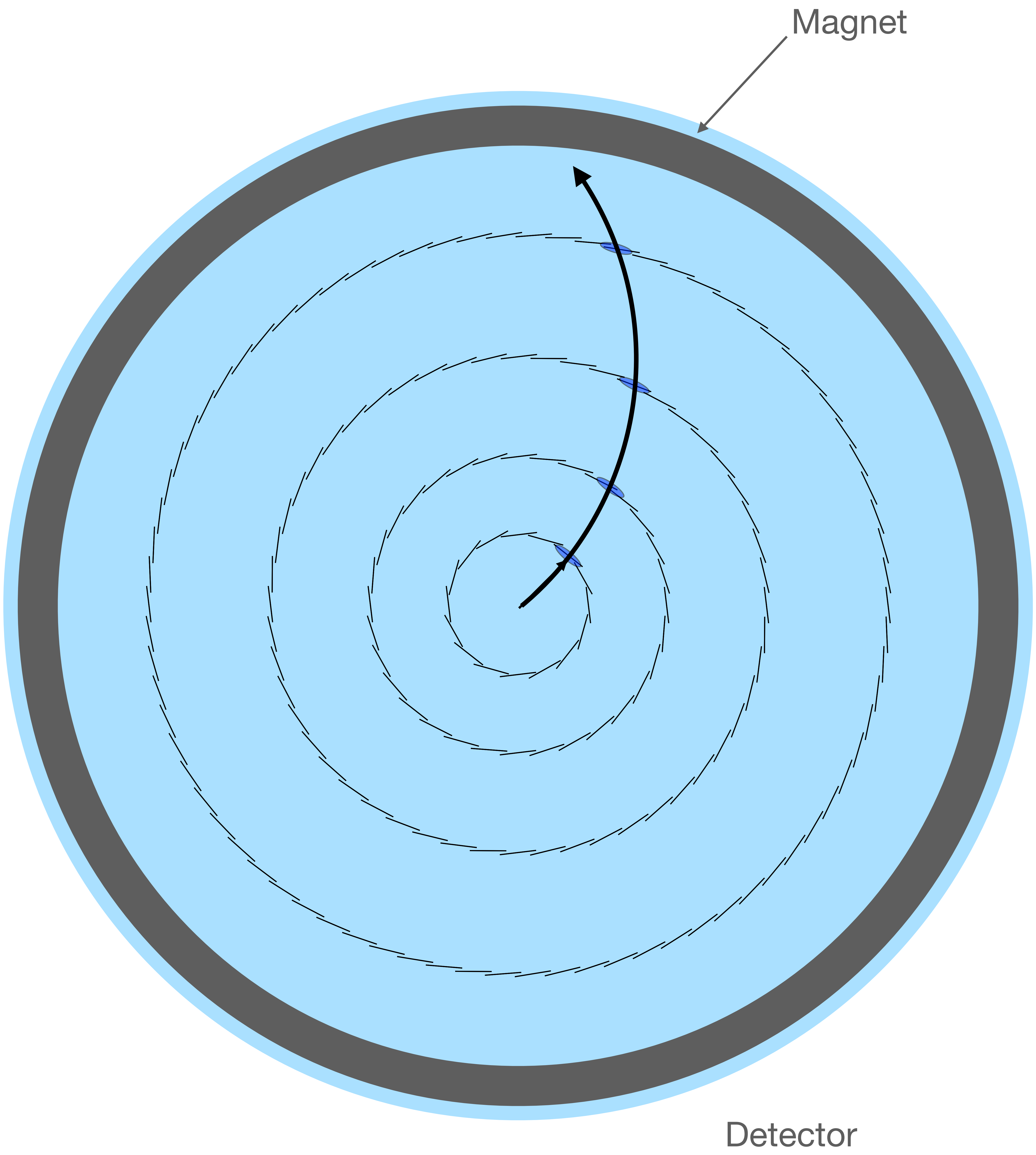


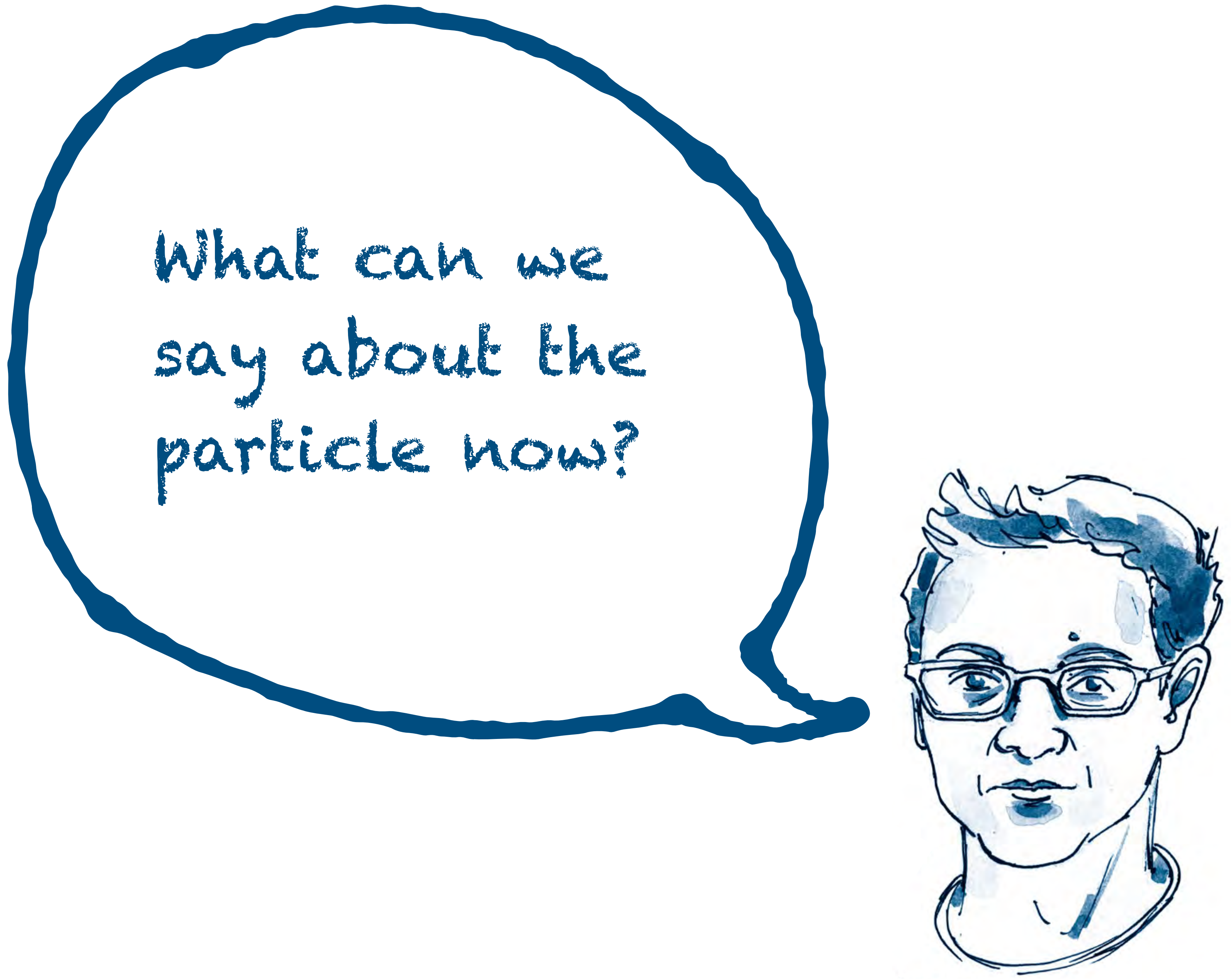
Detector



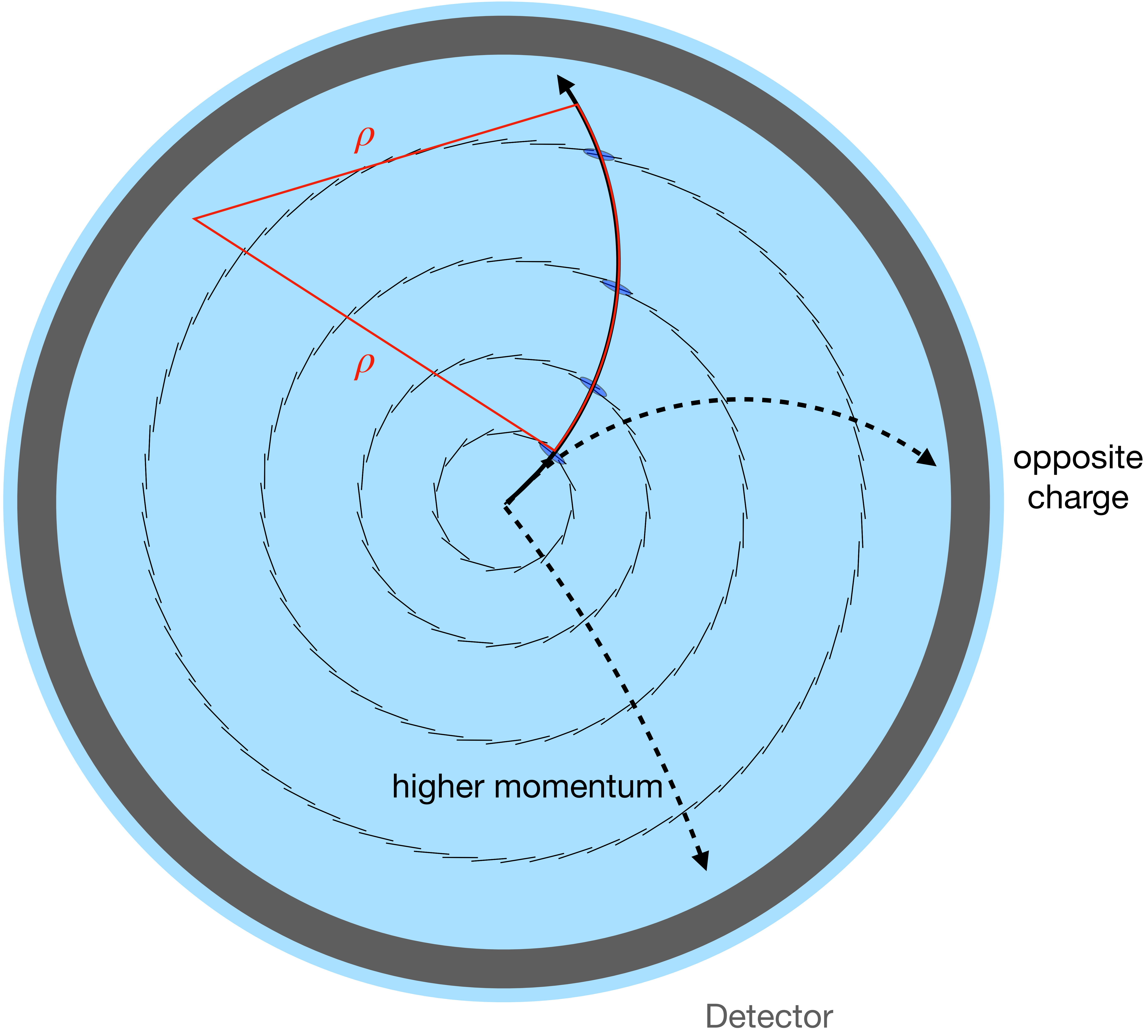


✅ it's charged
🚫 type/strength of charge
🚫 momentum of particle
🚫 origin
🚫 type of particle


Magnet
Detector


What can we say about the particle now?

Tracking detector

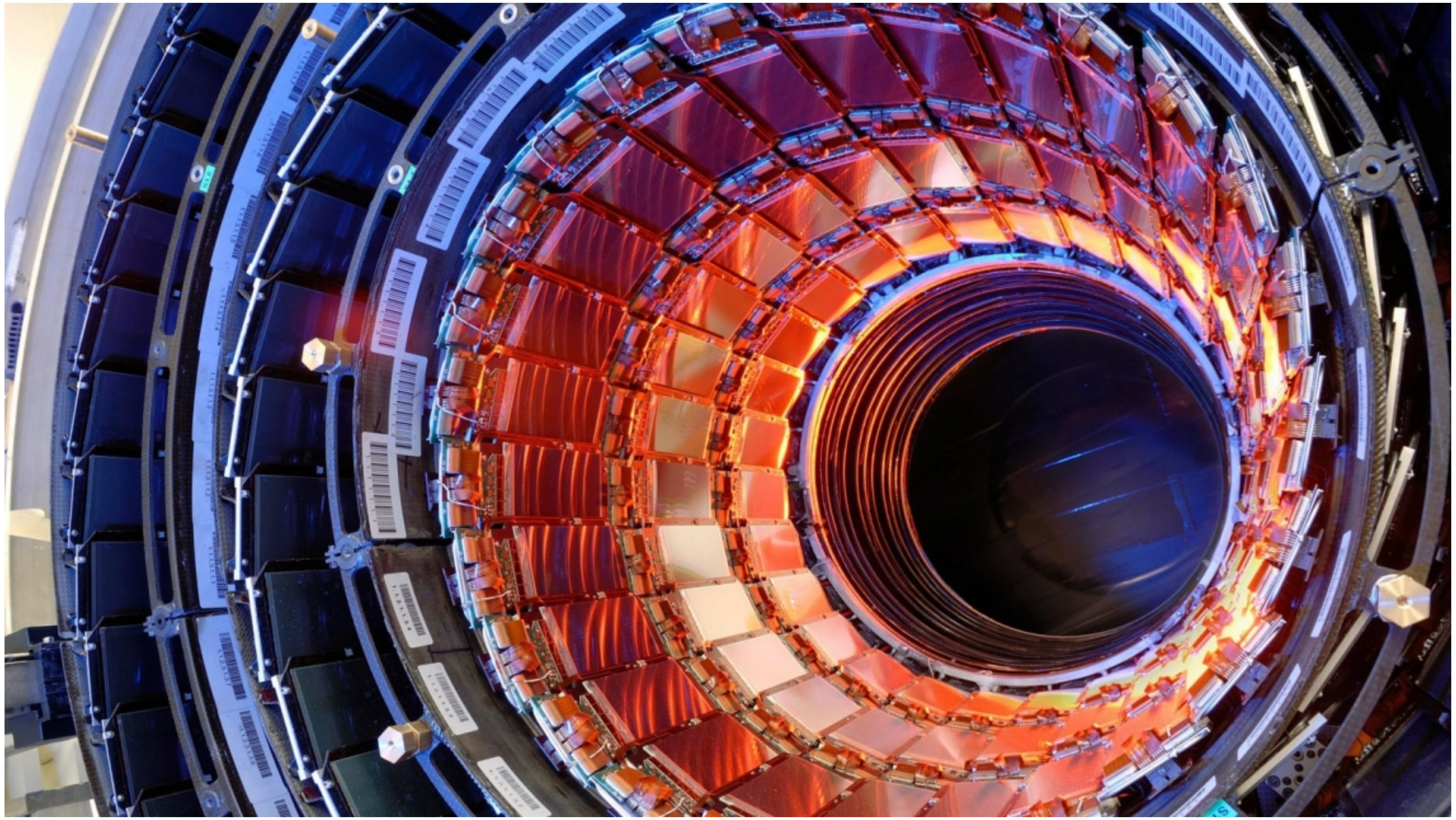


$$\rho \sim \kappa \cdot q/p_T$$

charge → q
transverse momentum → p_T

- ✅ it's charged
- 🟠 type/strength of charge
- ✅ momentum of particle
- 🚫 origin
- 🚫 type of particle

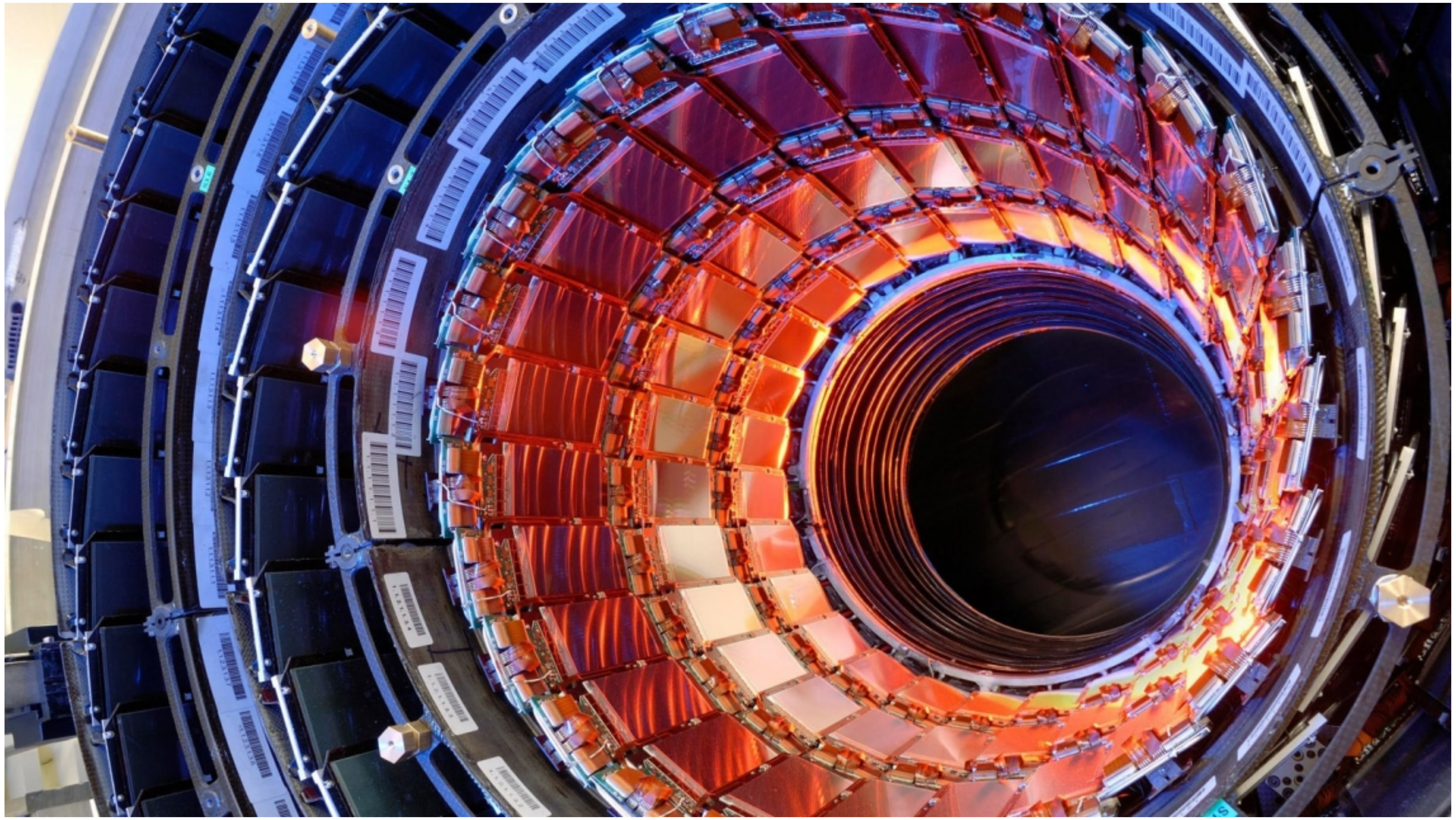
Tracking detector



CMS Tracking detector during installation.

The detector influences the measurement!

Tracking detector



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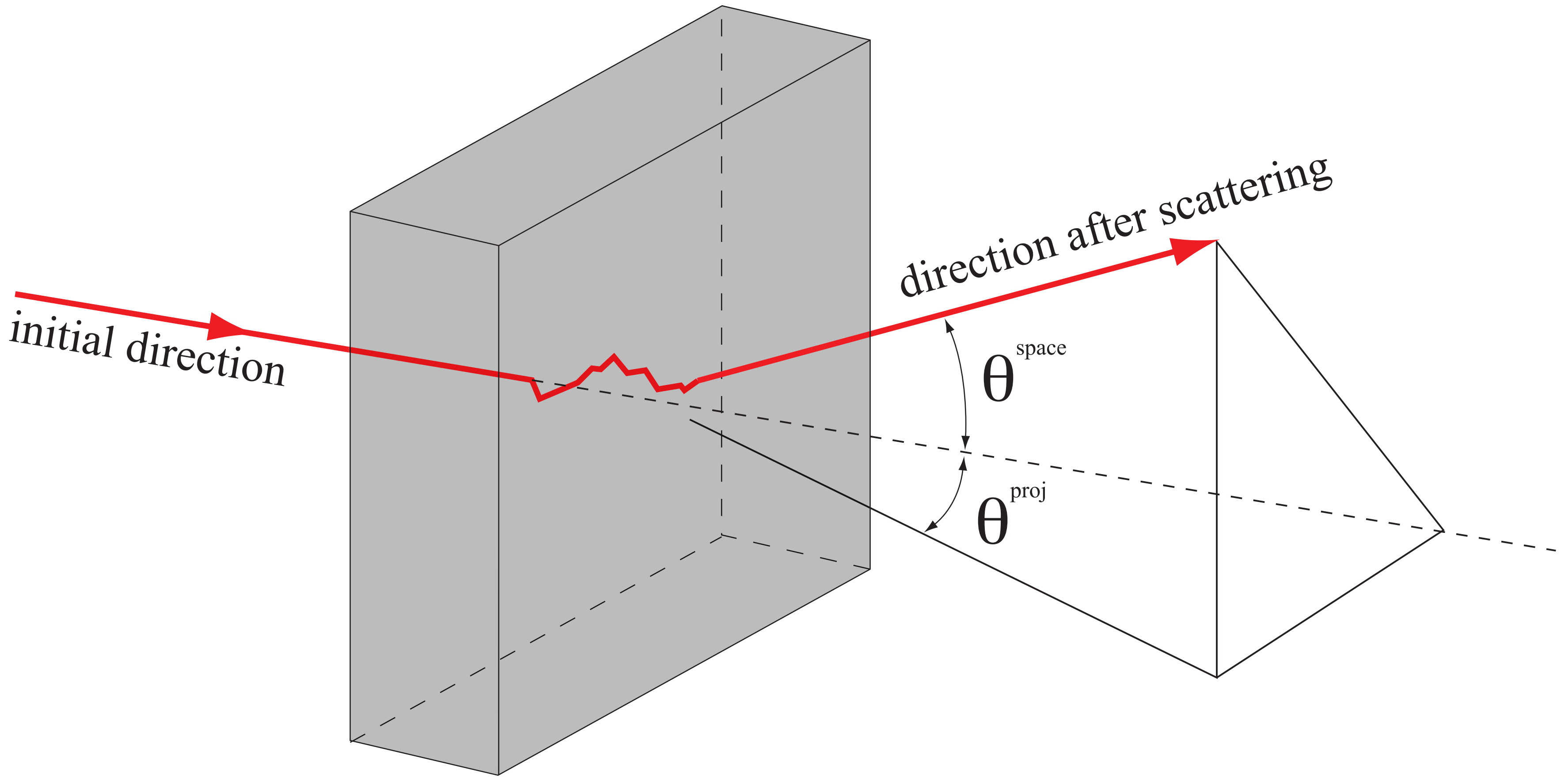
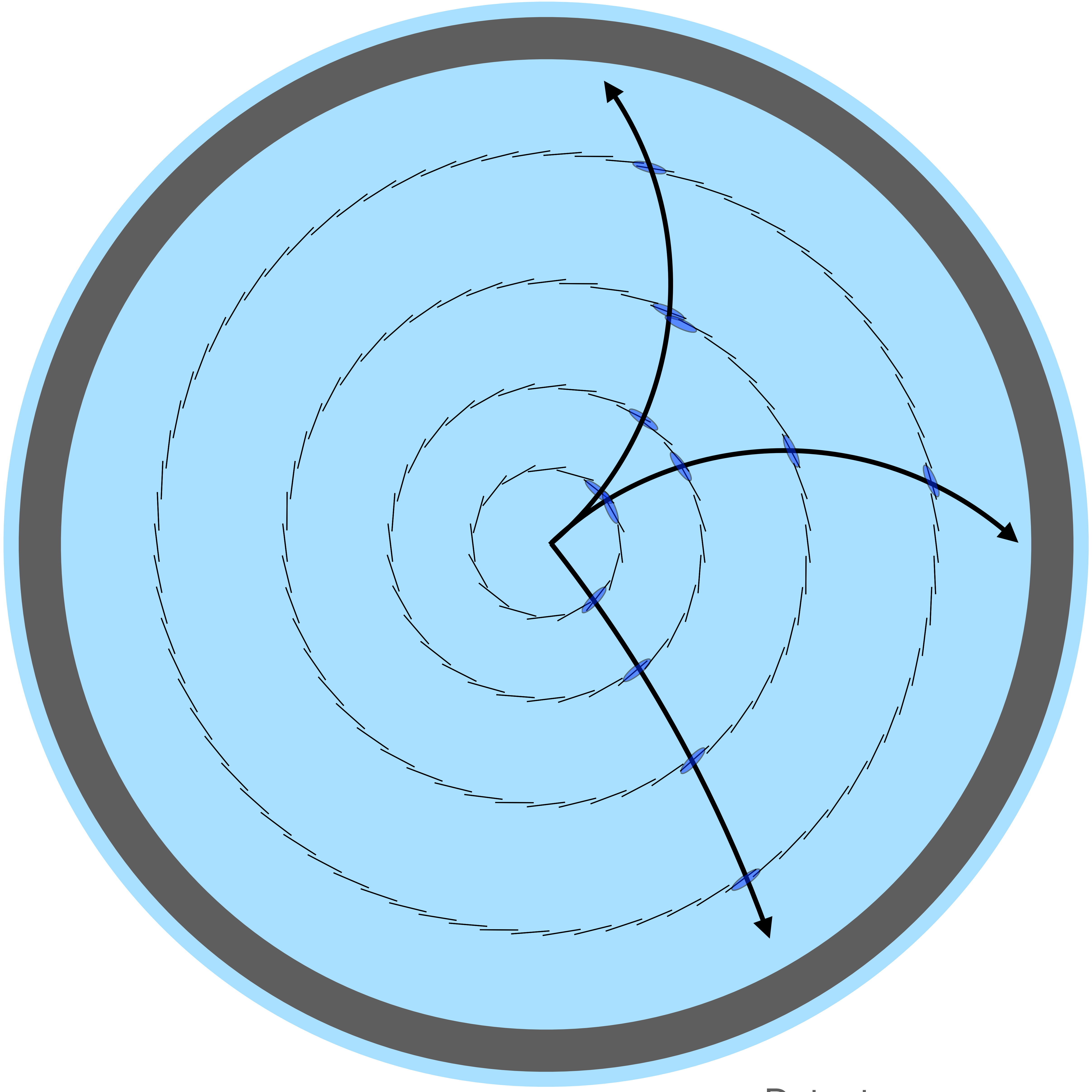
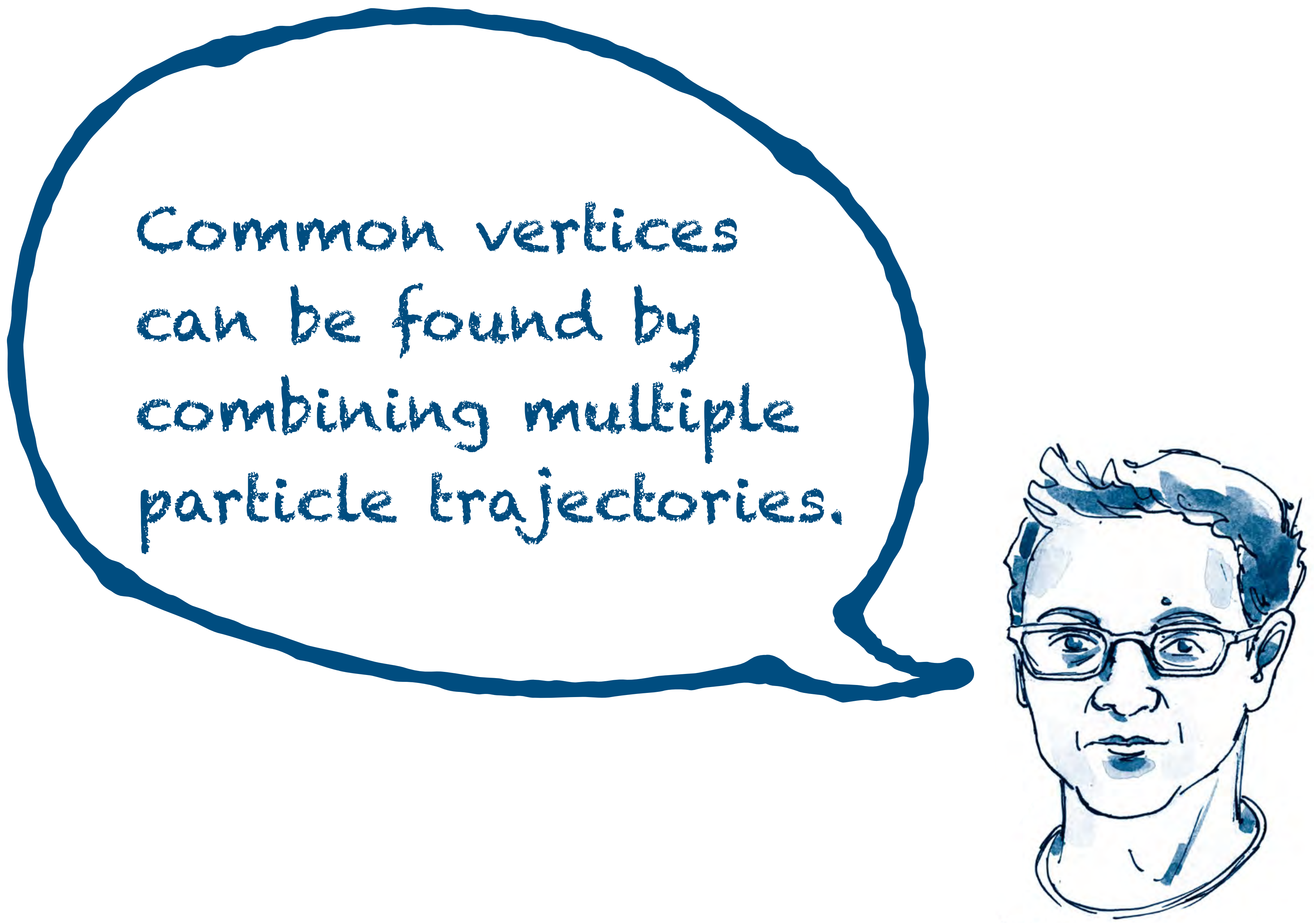


$$\sigma_{ms}^{proj} = \frac{13.6\ \text{MeV}}{\beta c p} Z \sqrt{t/X_0}\left[1 + 0.038 \ln\left(t/X_0\right)\right]$$

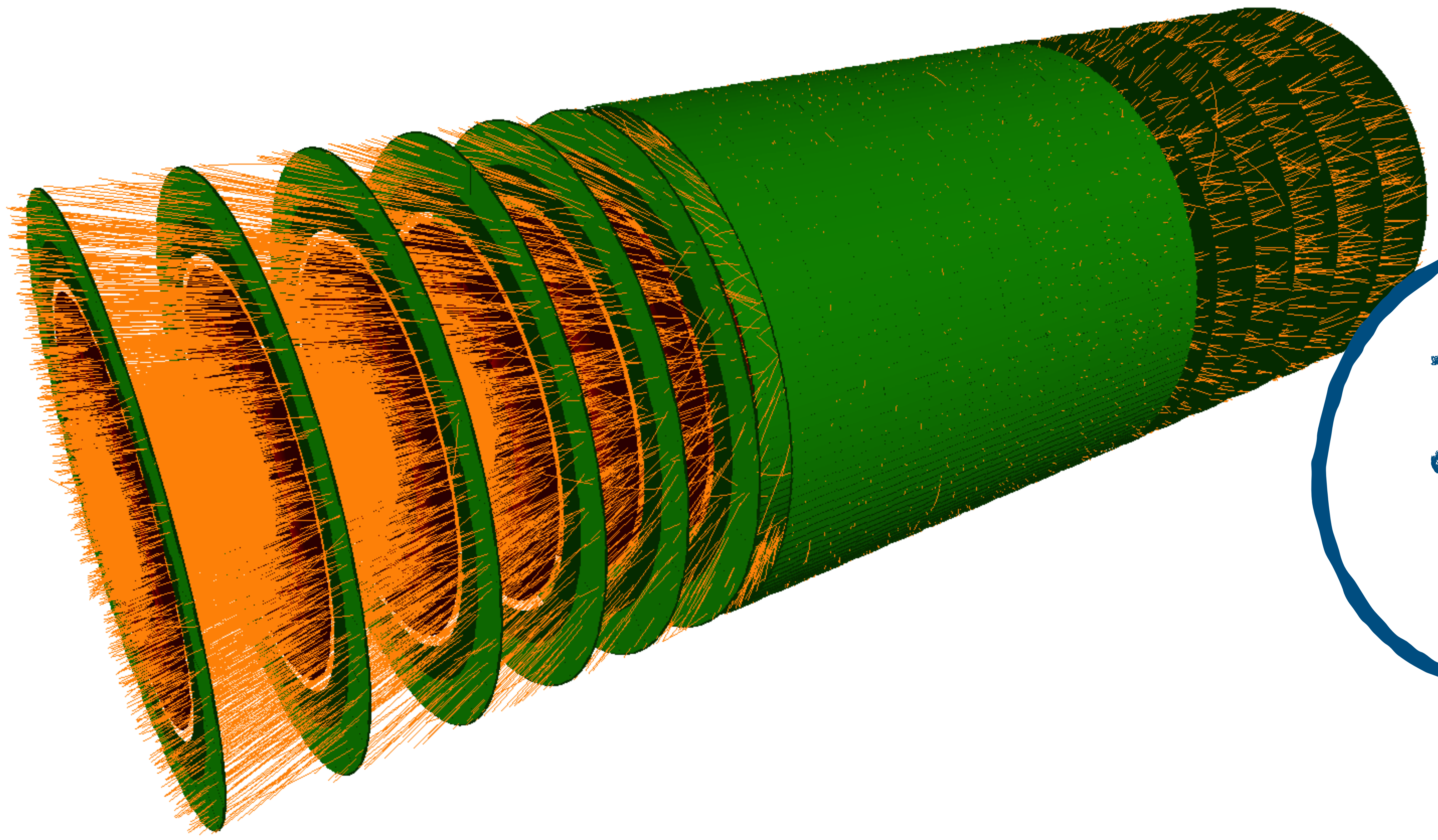
Tracking detector

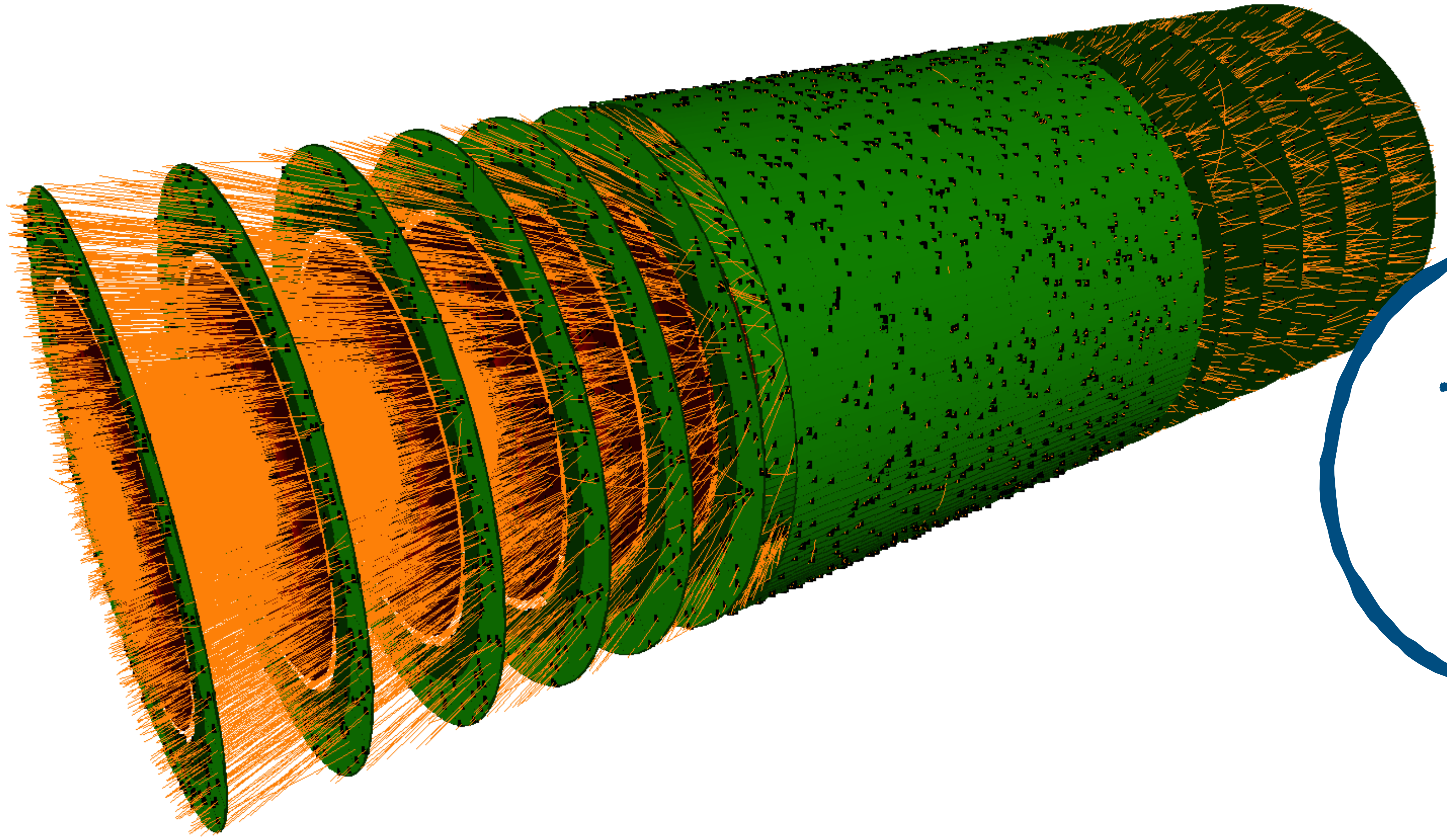


Detector

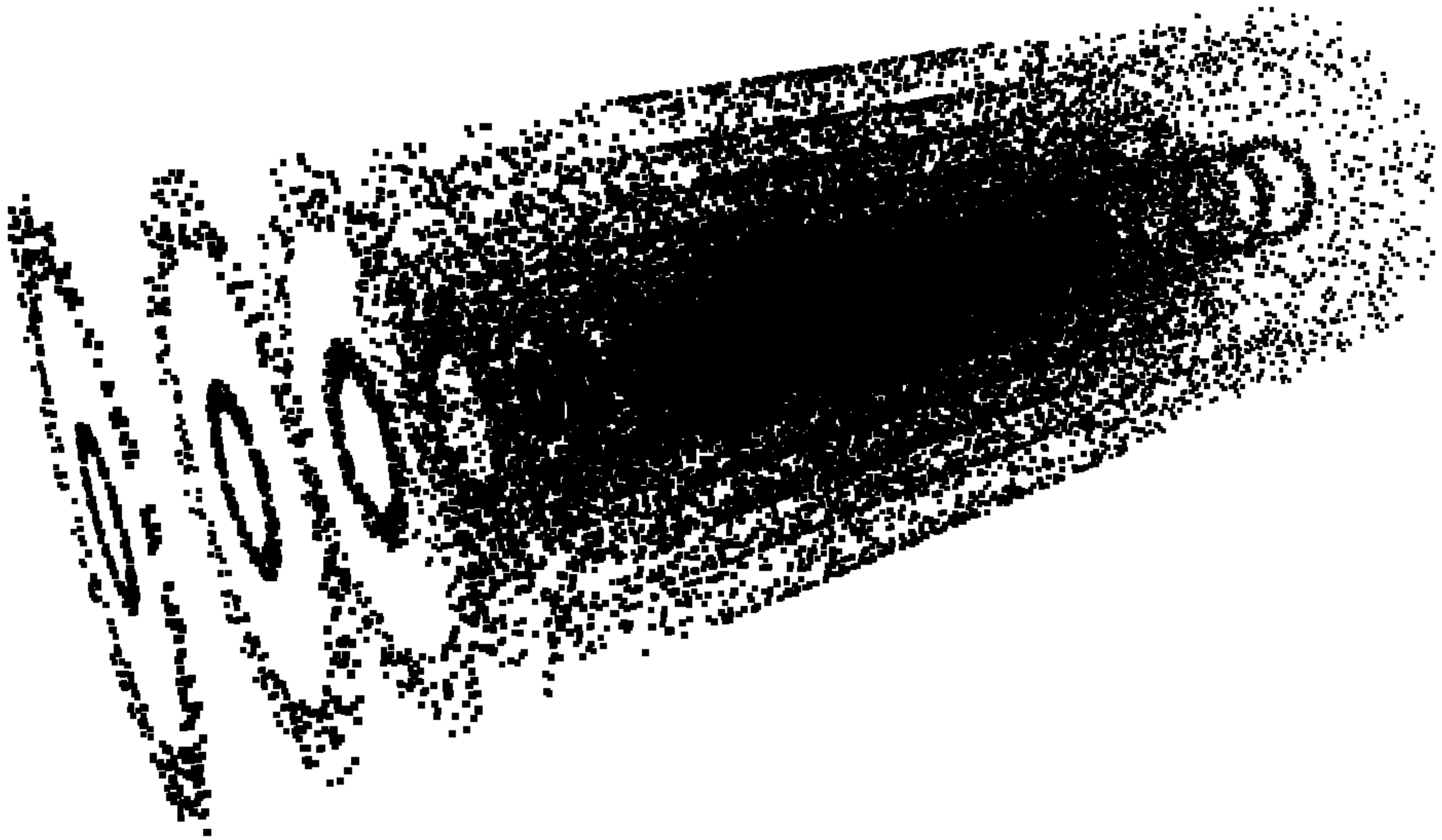


Reconstruct trajectories

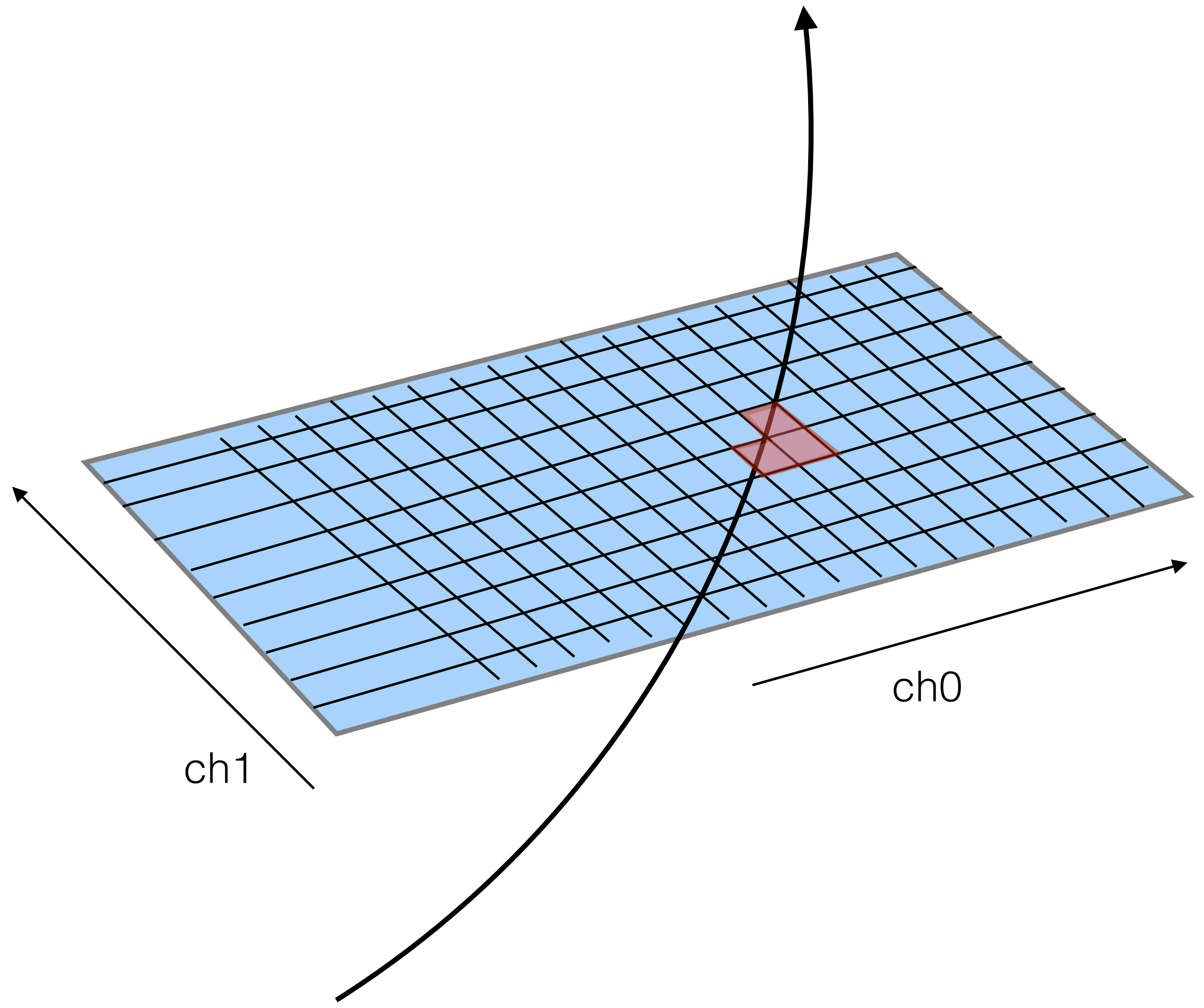


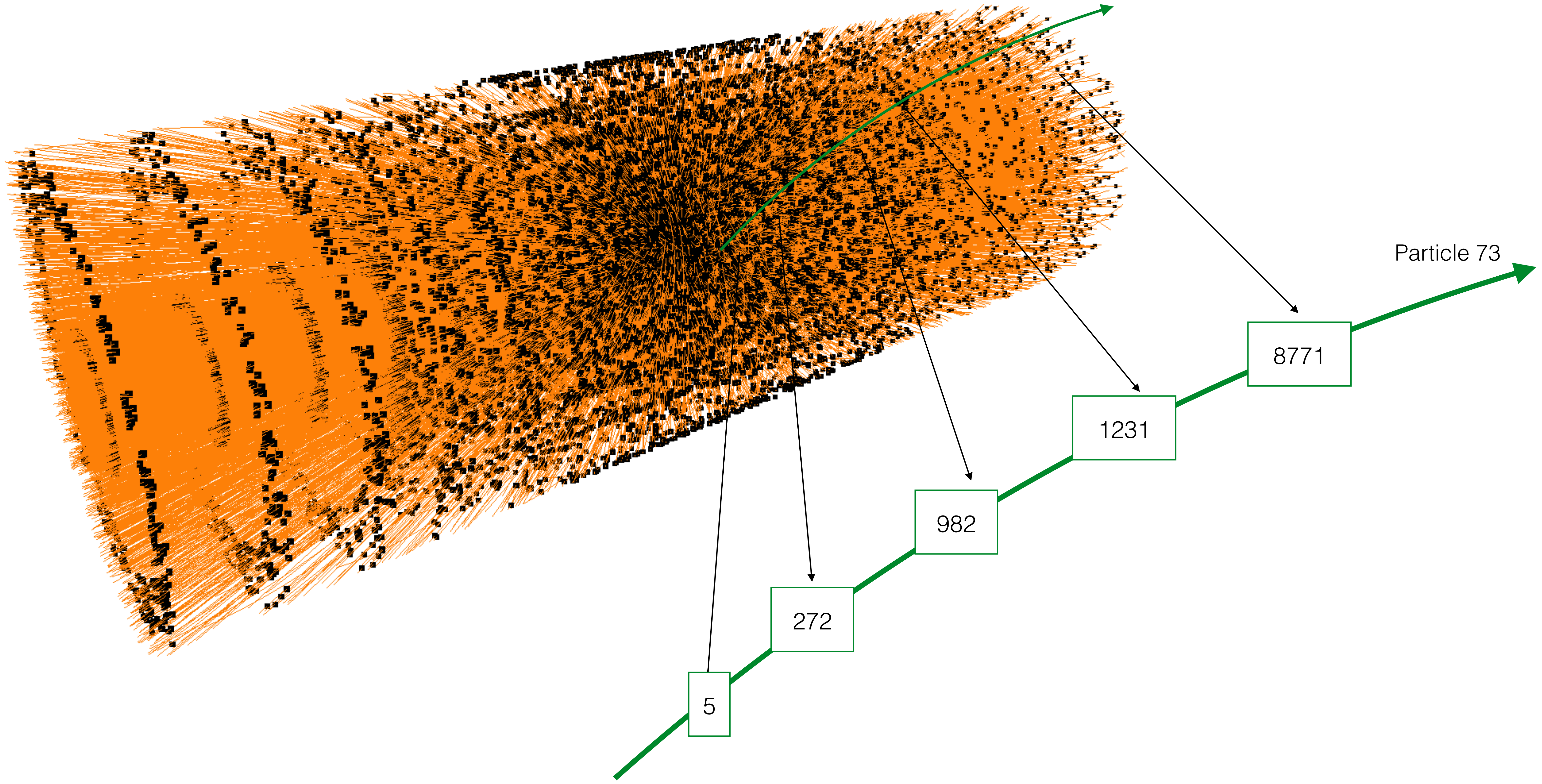


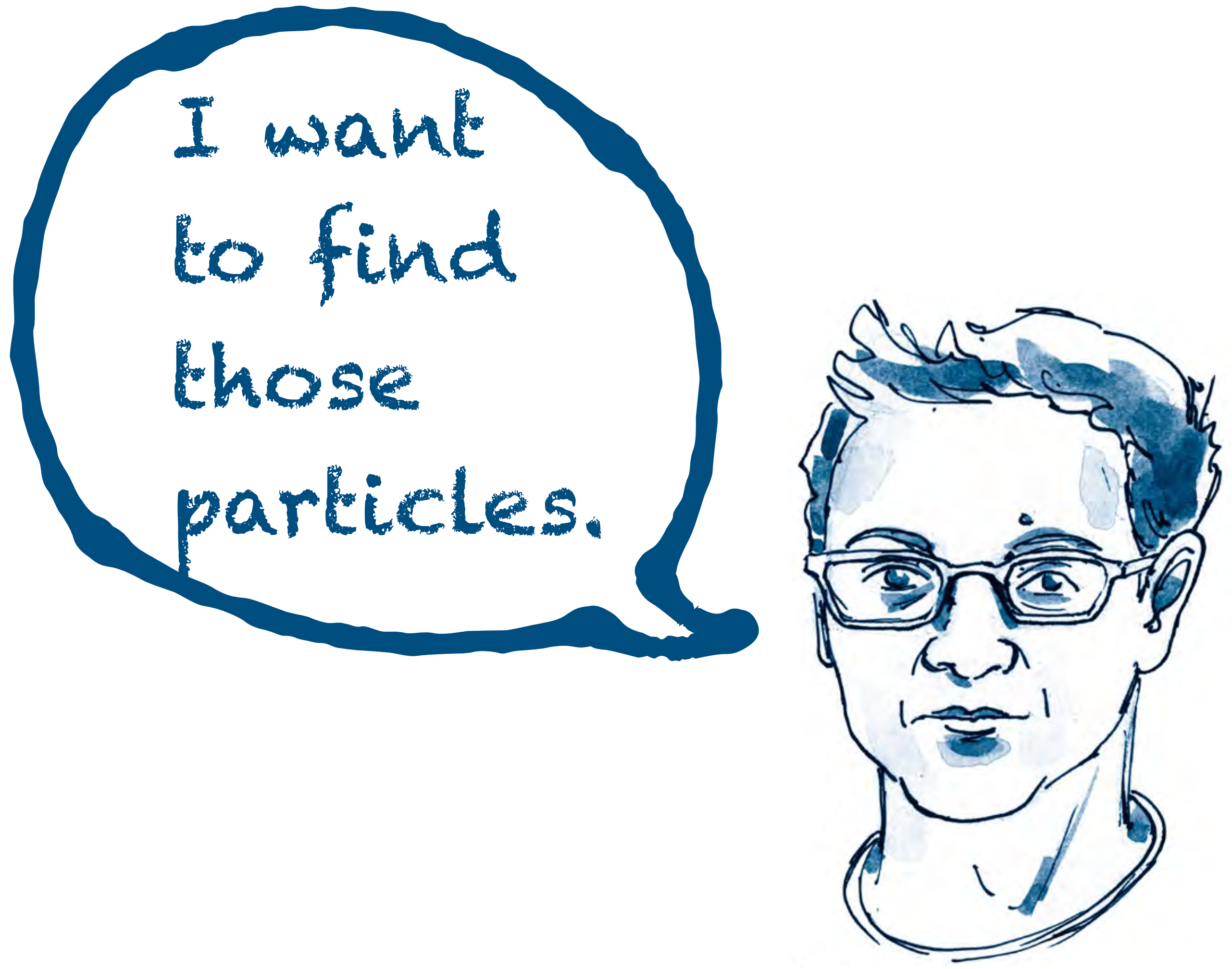

... neither is that ...

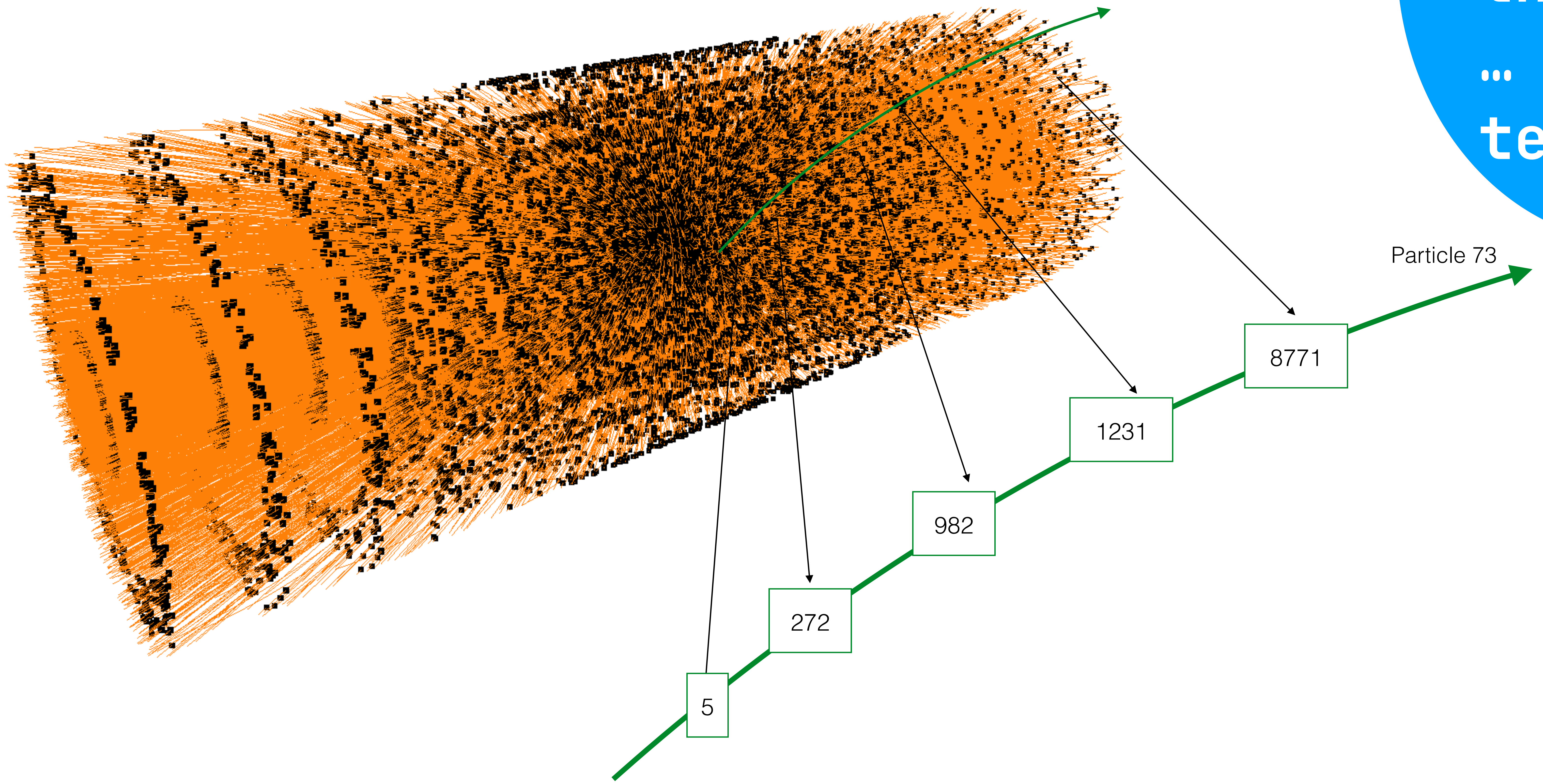


Detection **devices** measure the particle with a given resolution.

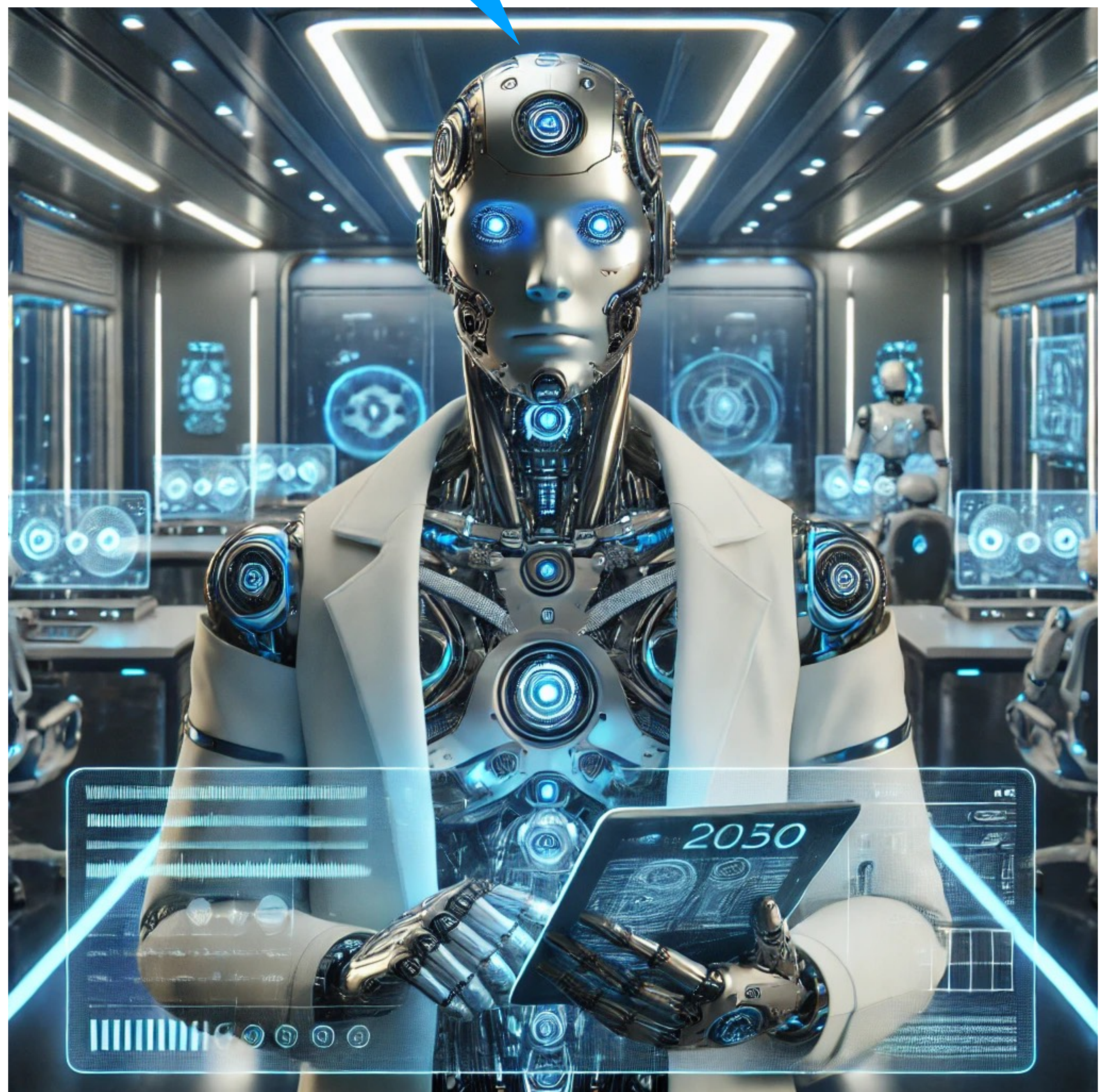



Particle 73
8771
1231
982
272
5

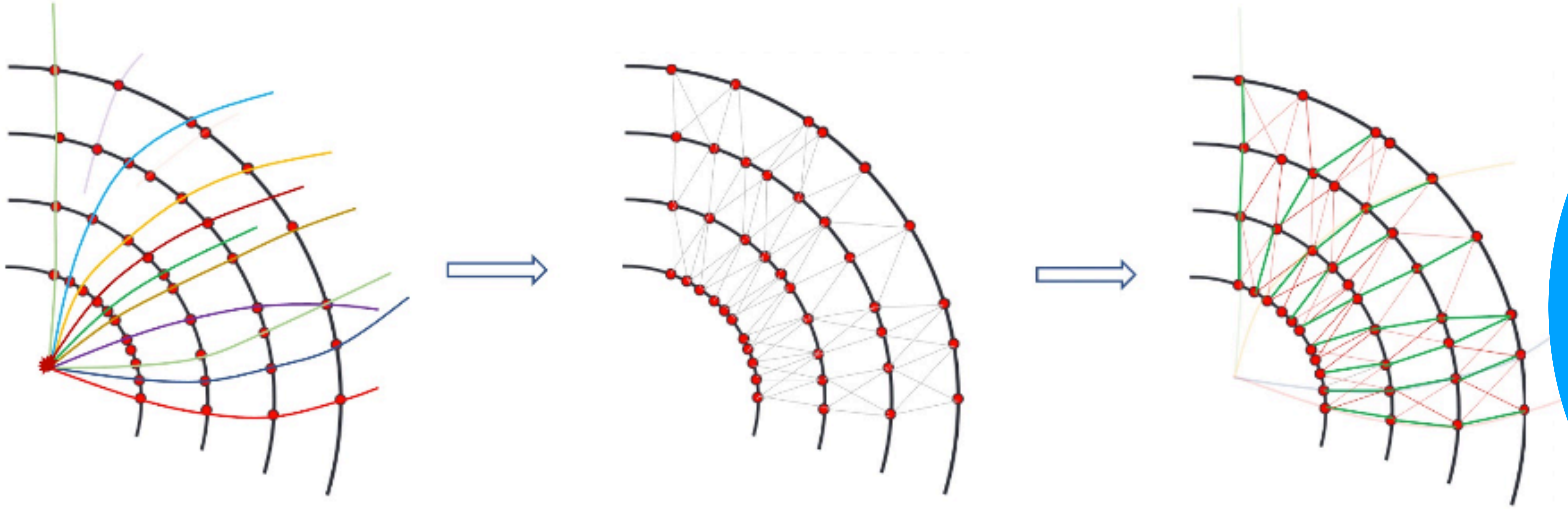

I want to find those particles.

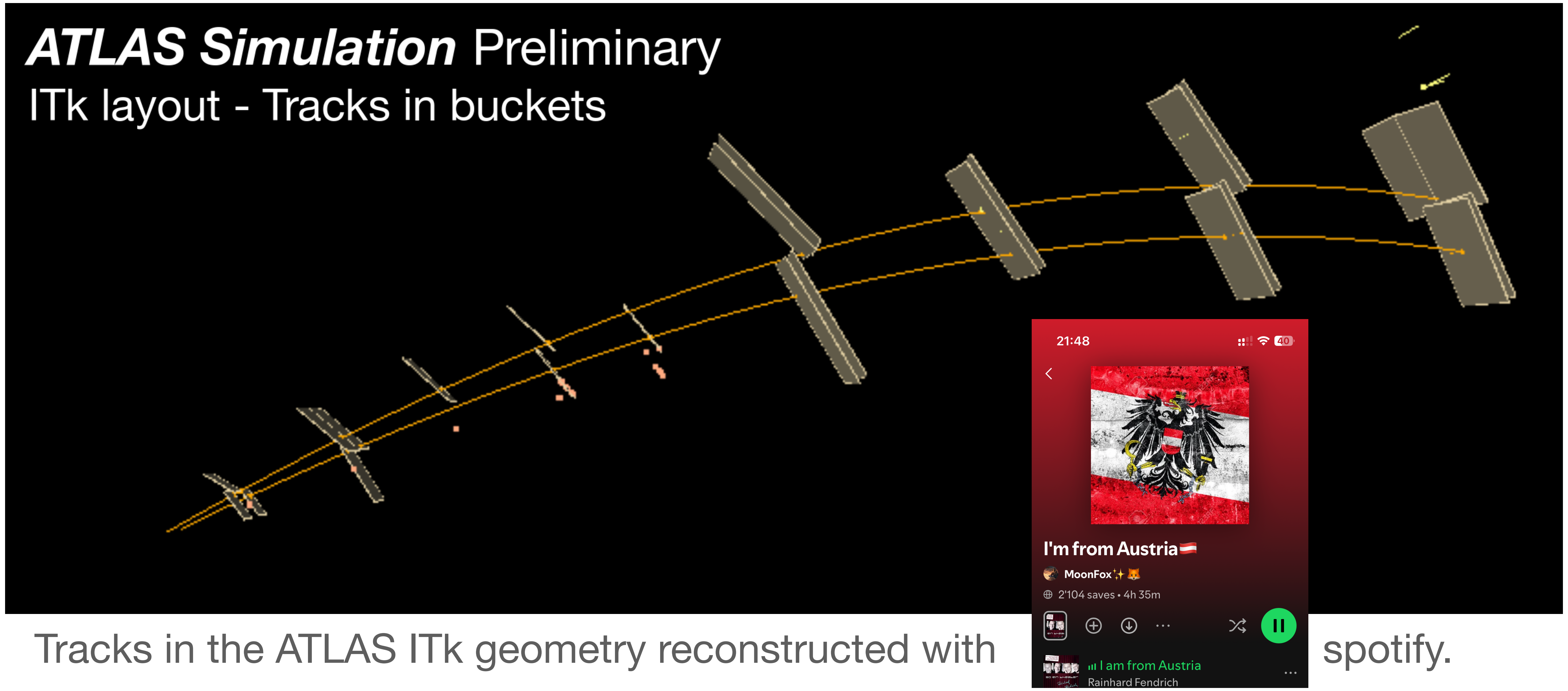


I can help you with that …
… if you teach me.



Graph Neural Network based track finding





Tracks in the ATLAS ITk geometry reconstructed with spotify.

I can help you with that …
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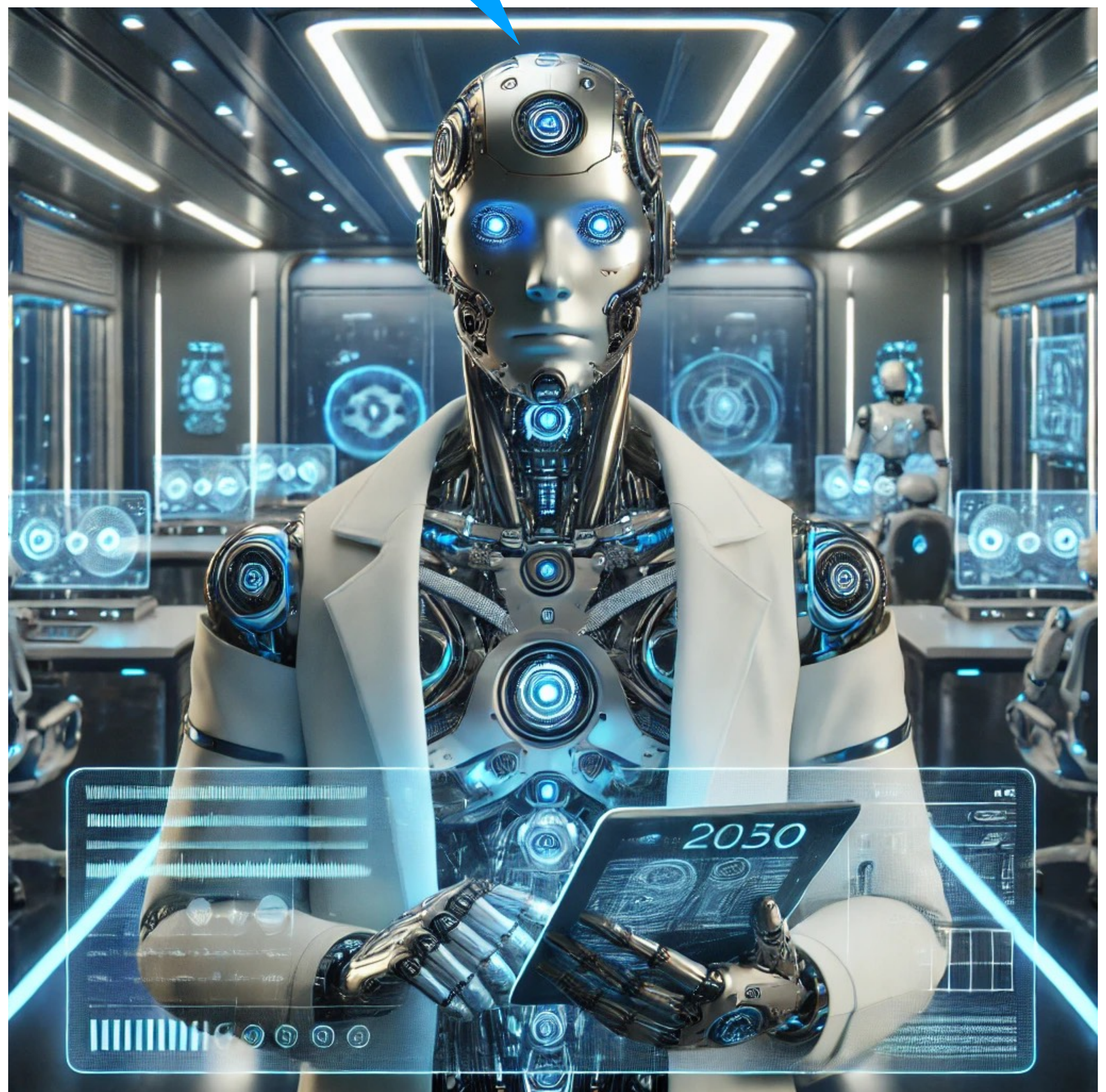
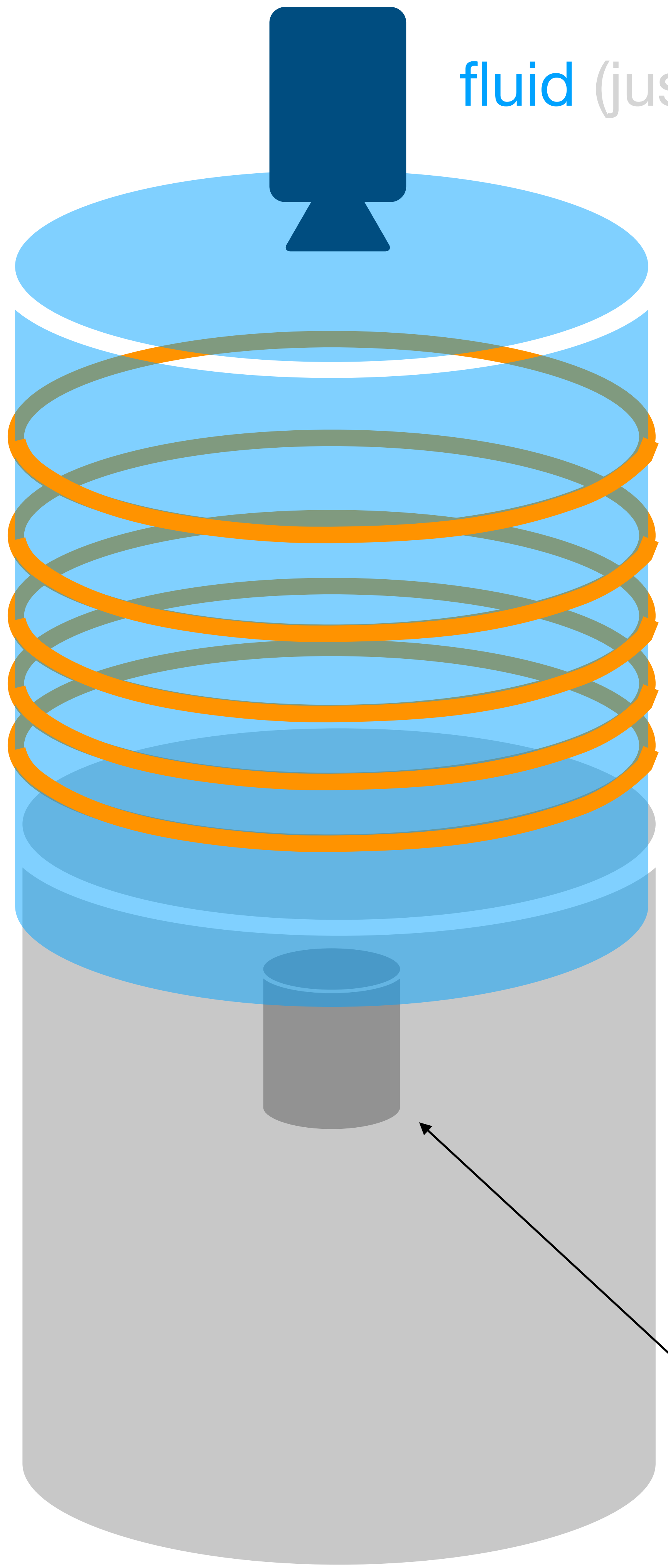
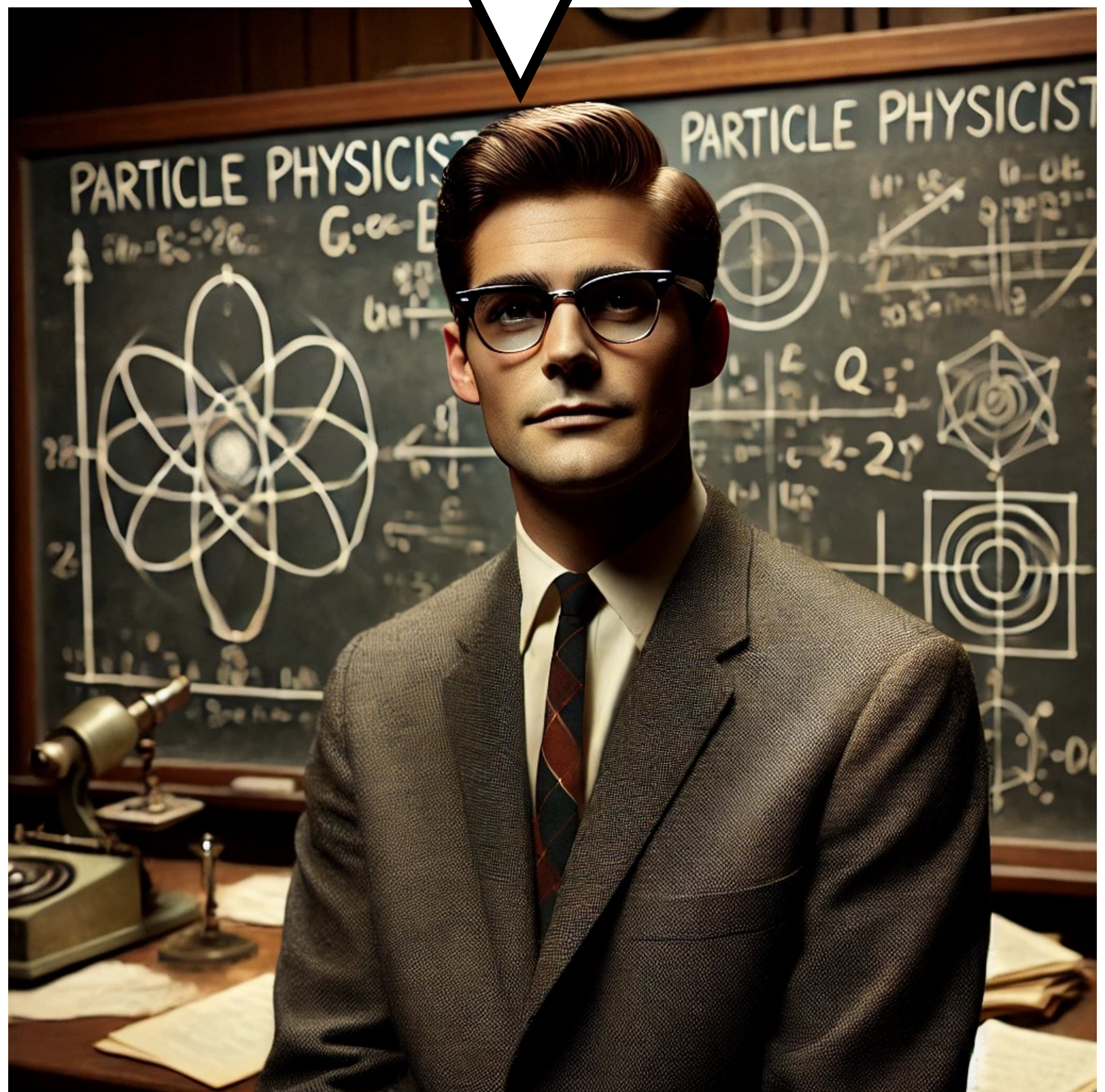
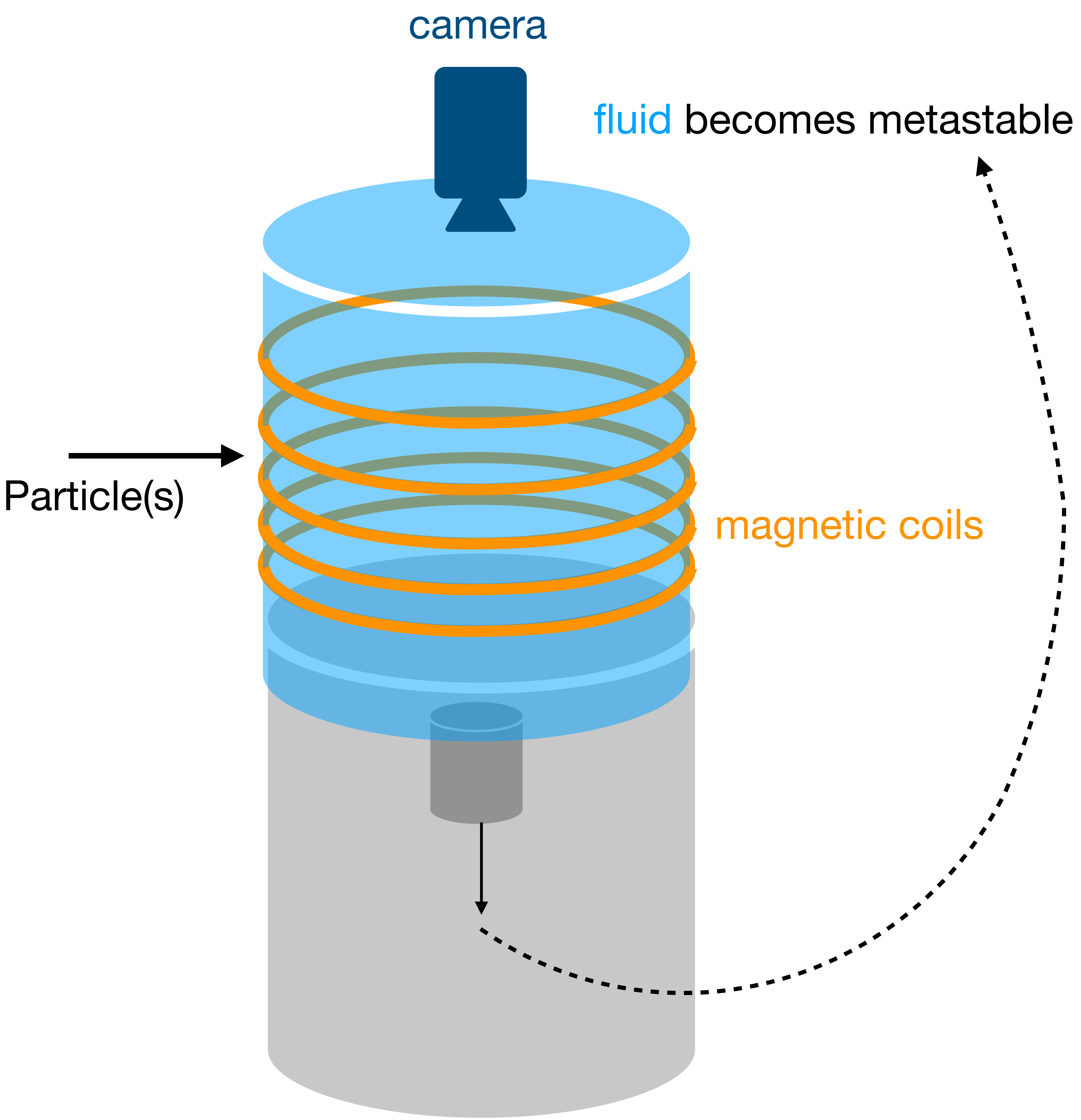




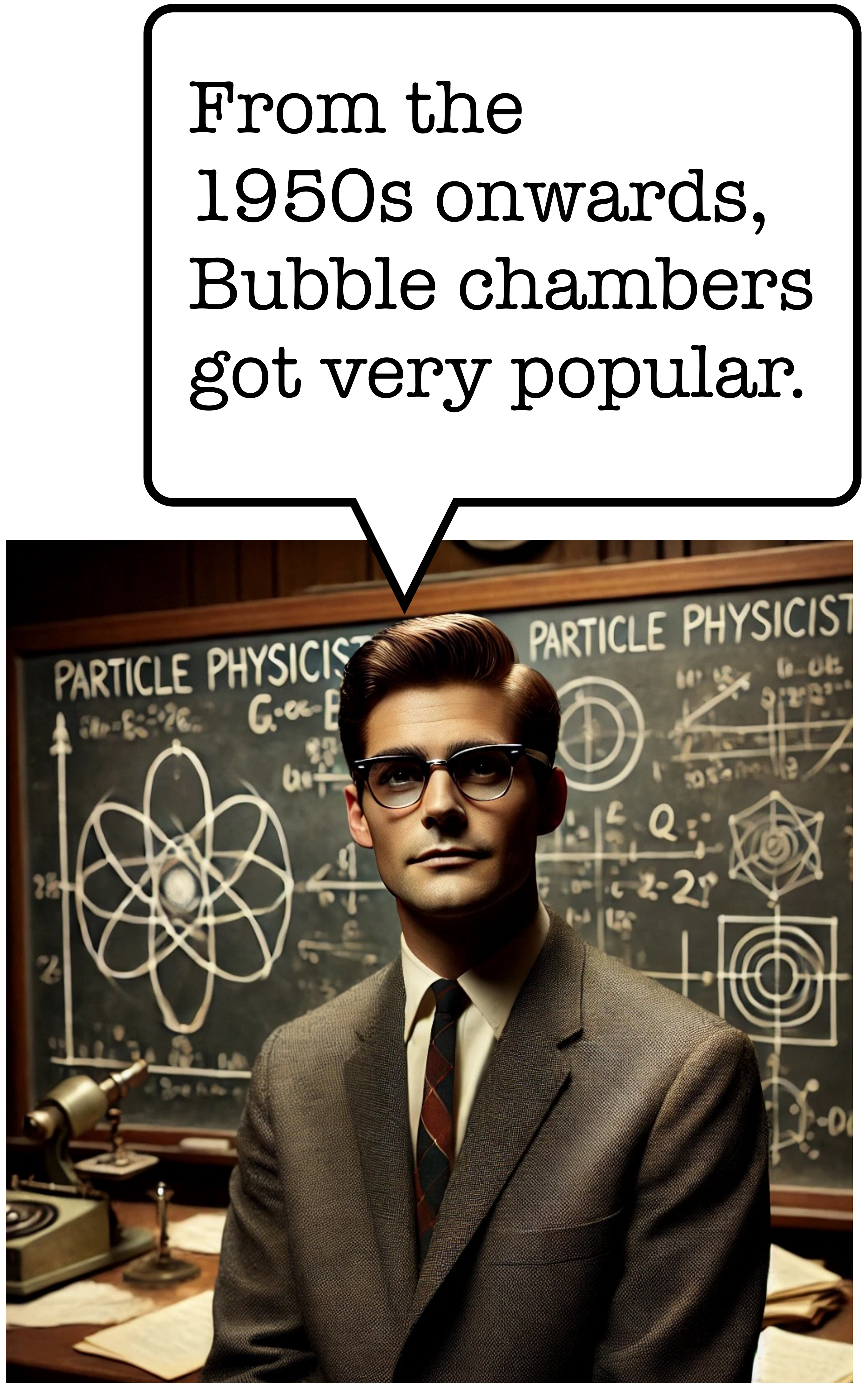
Bubble chamber invented 1954 by A. Glaser

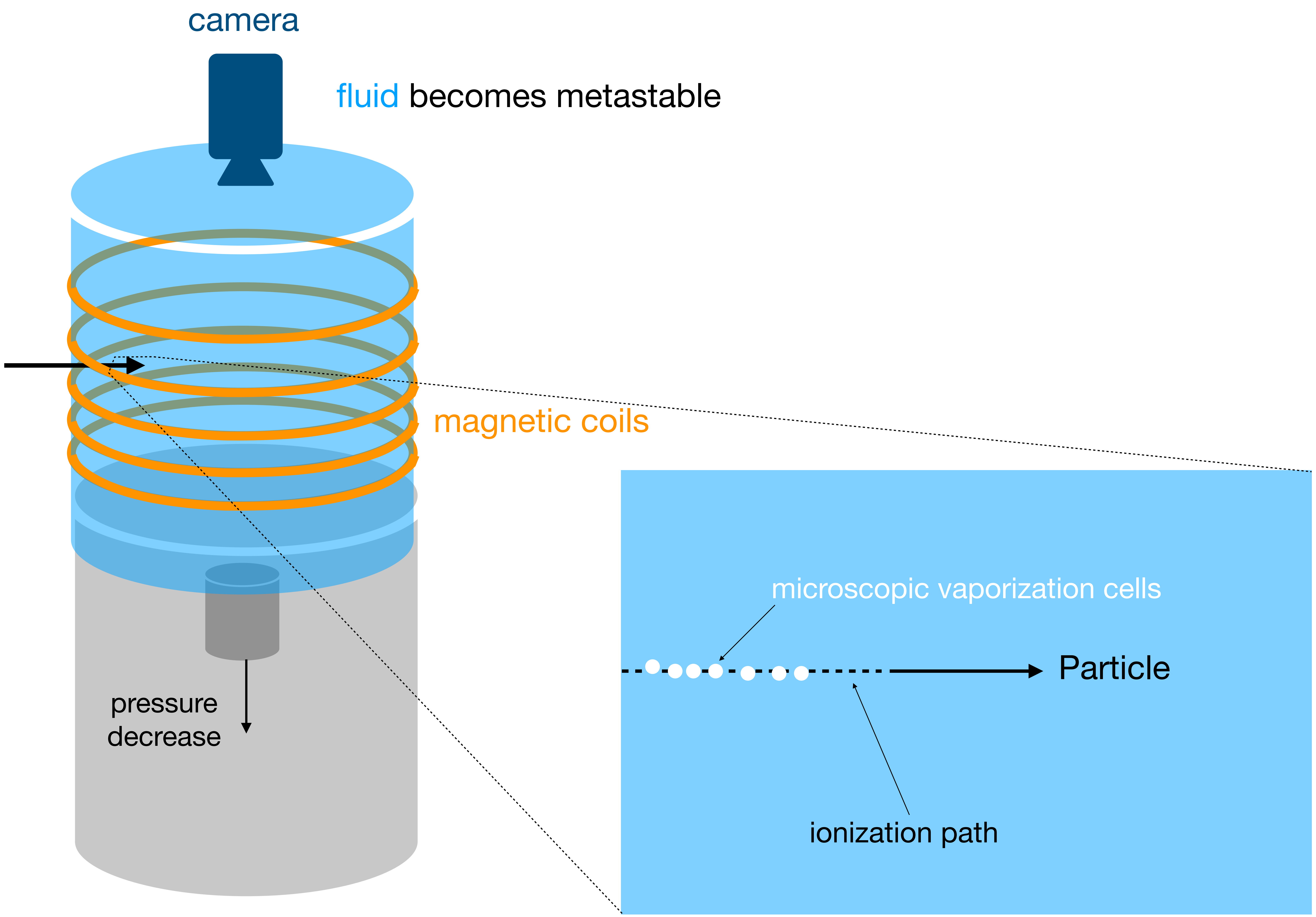
From the 1950s onwards, Bubble chambers got very popular.

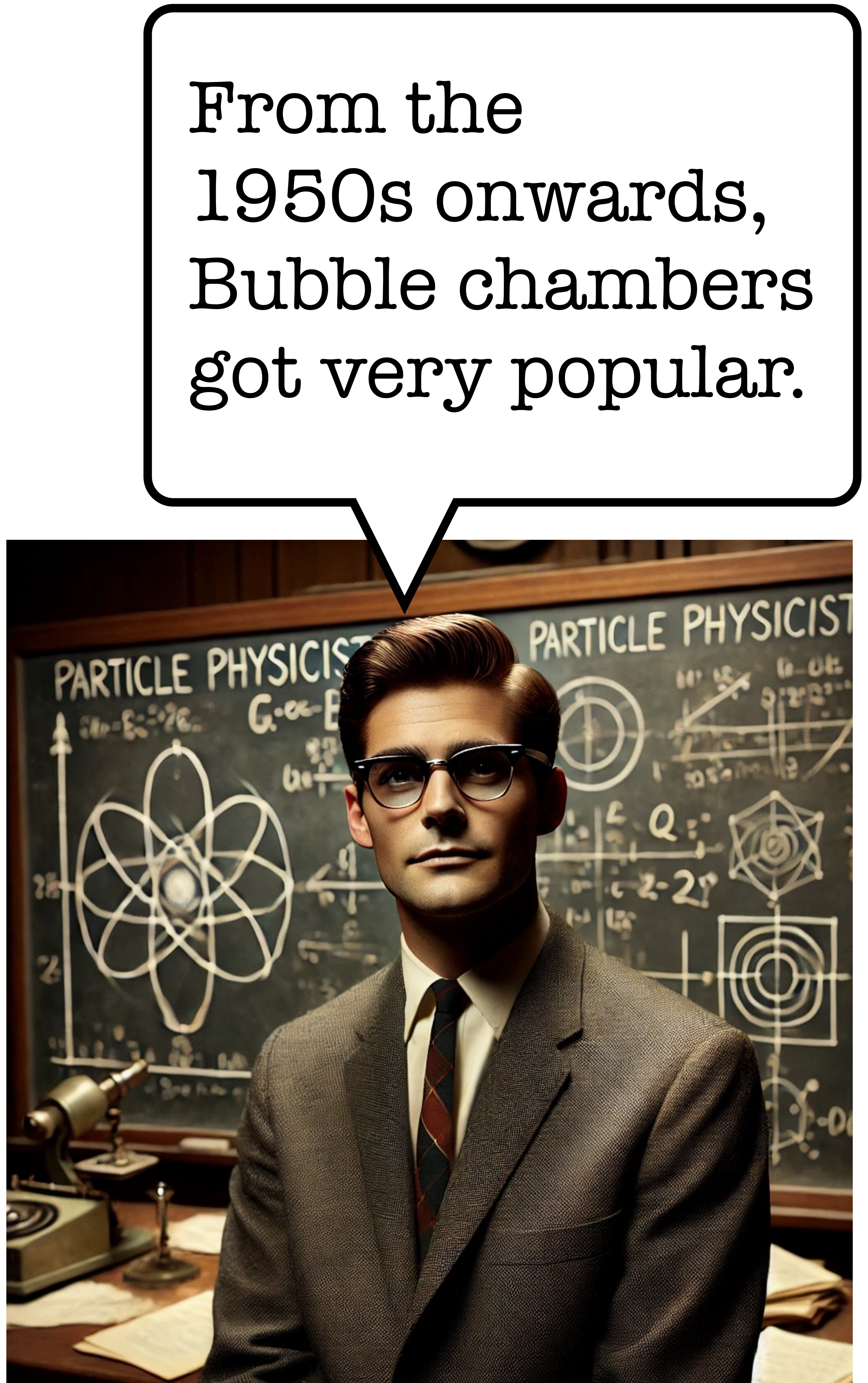




Bubble chamber invented 1954 by A. Glaser







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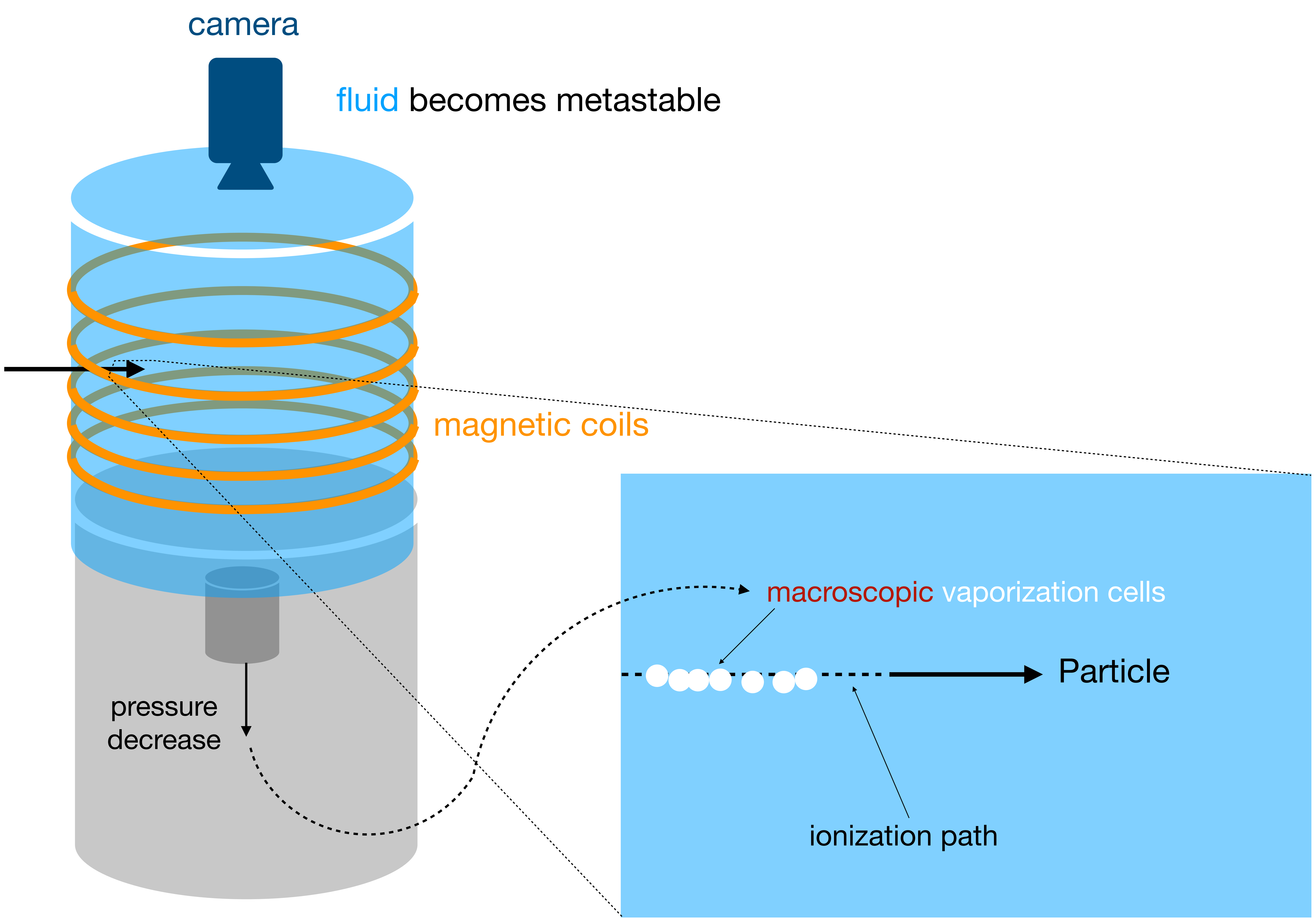
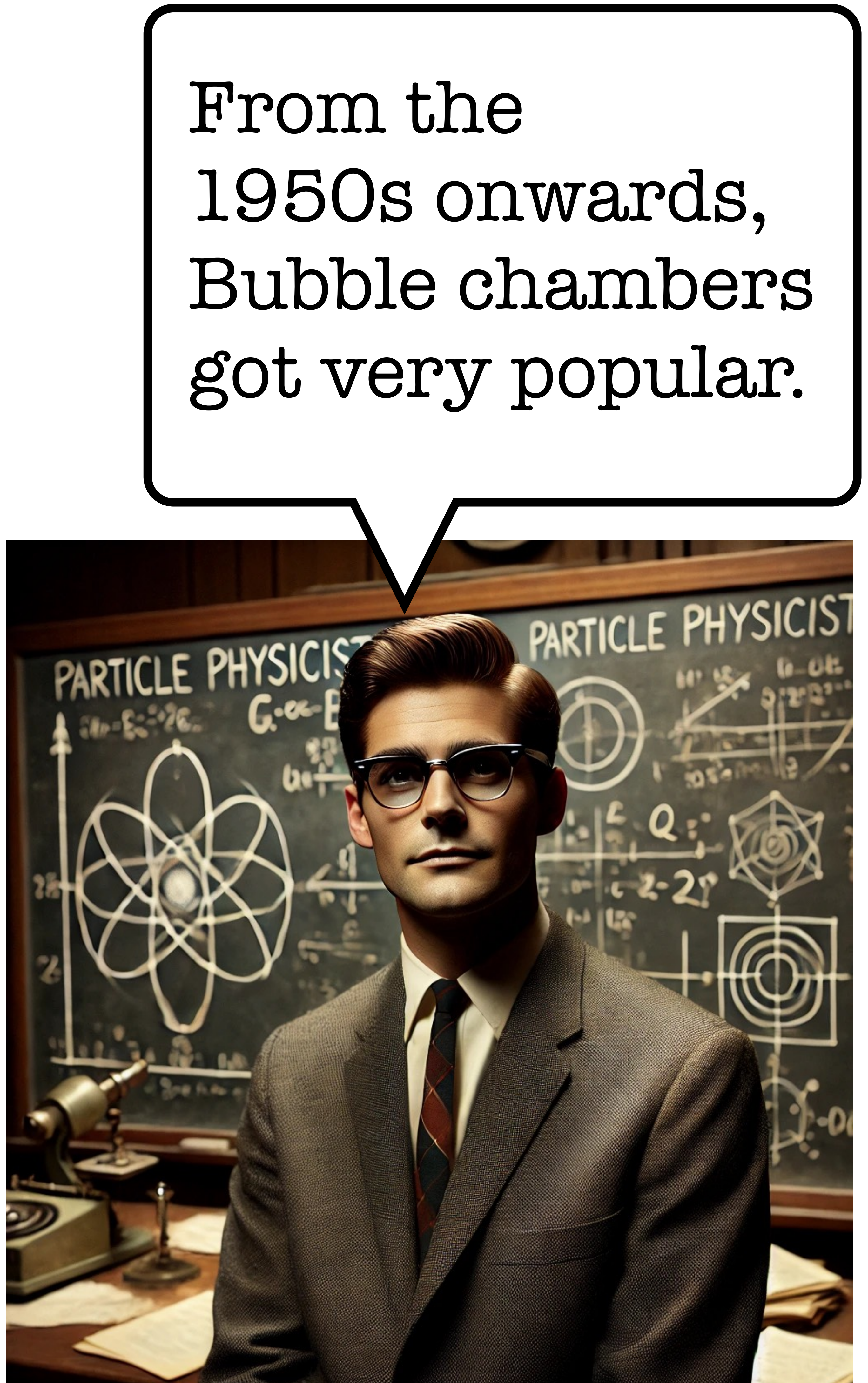
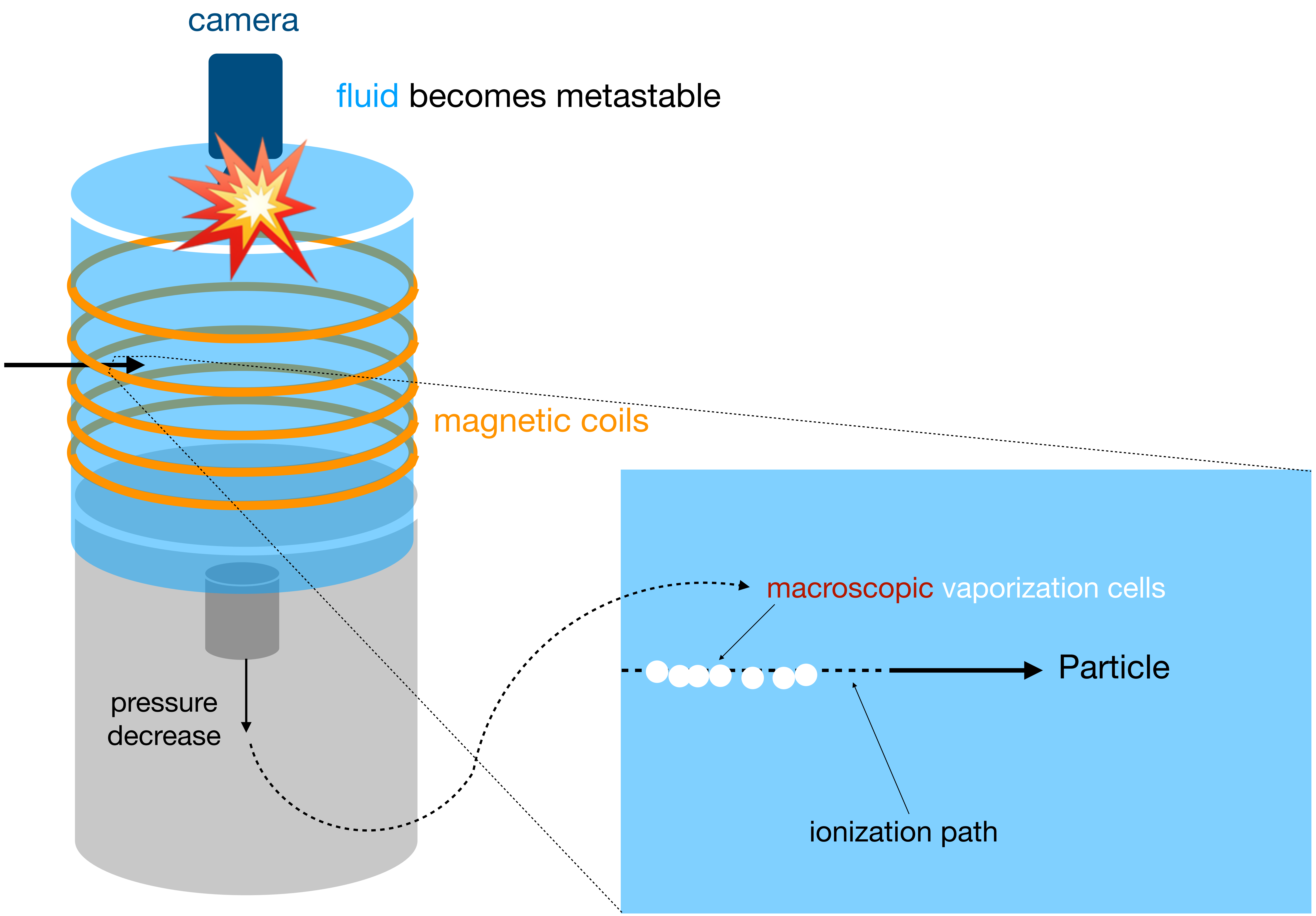
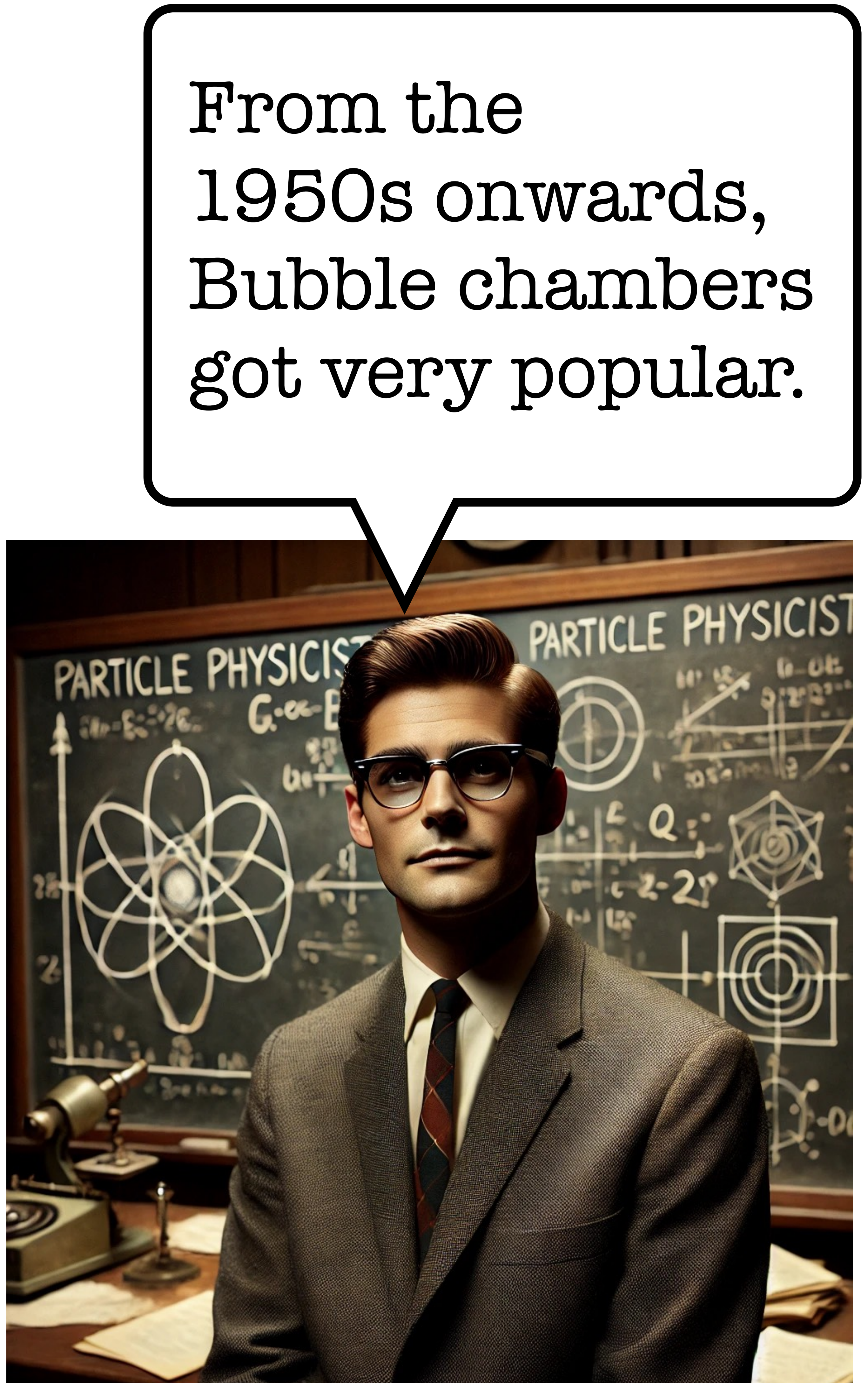


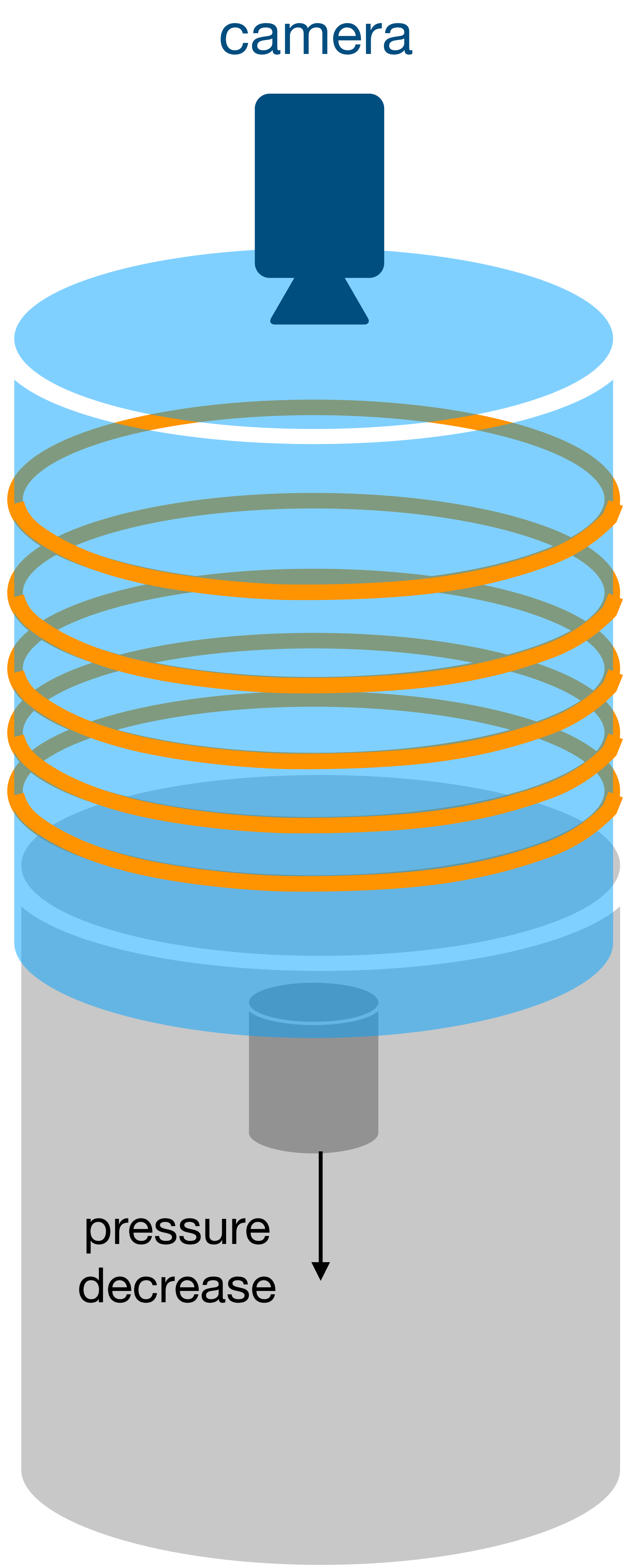


Bubble chamber invented 1954 by A. Glaser

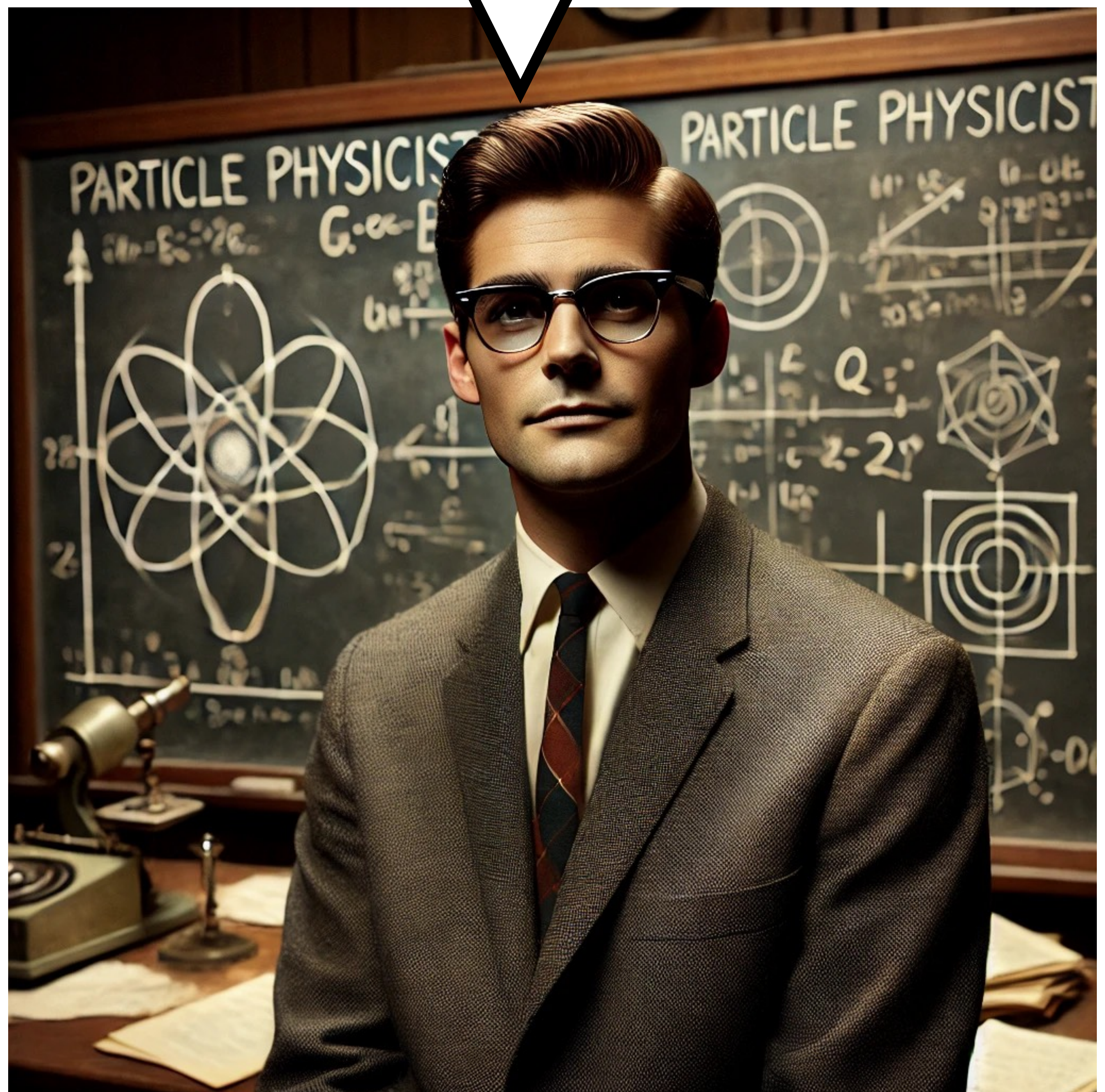


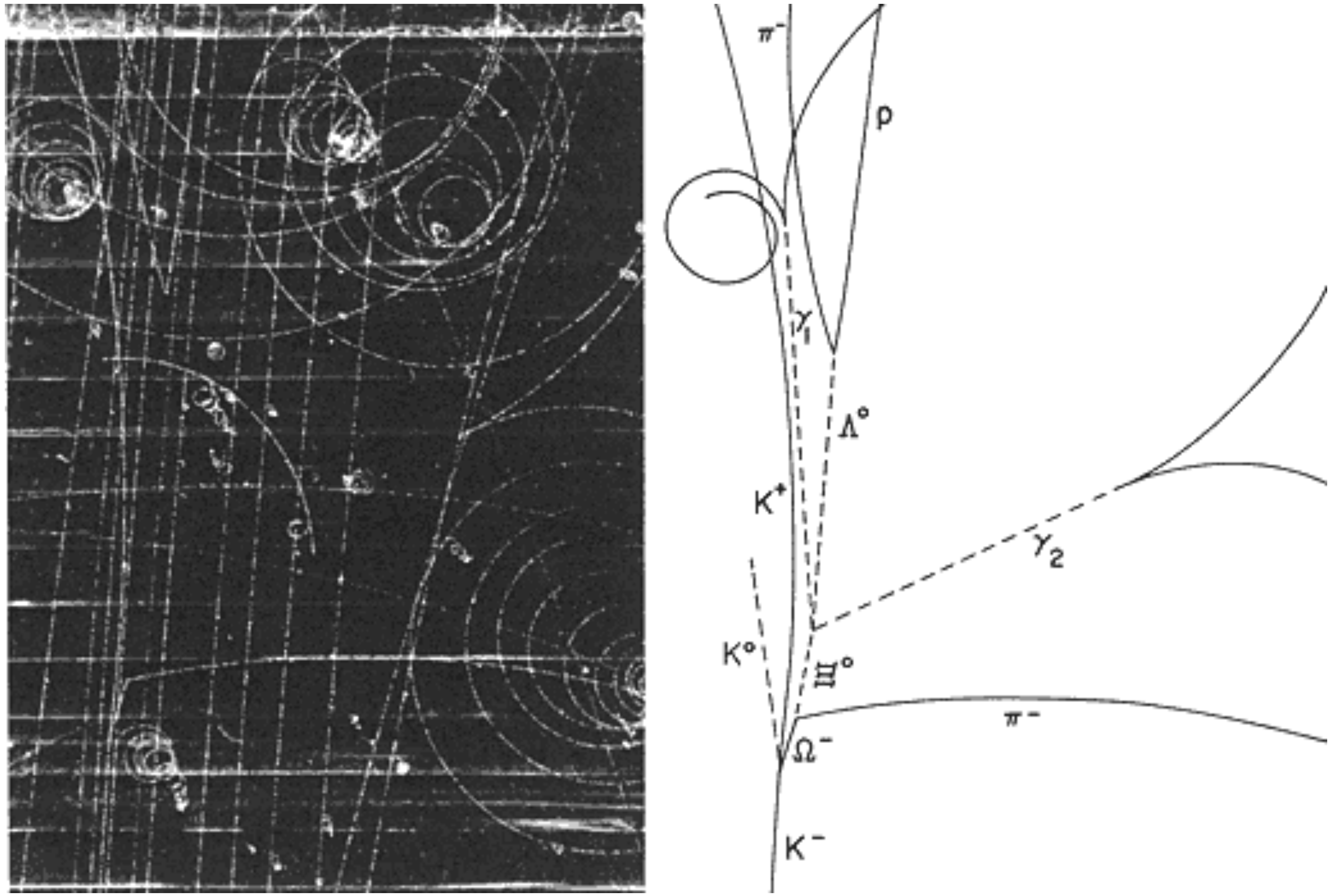


Bubble chamber invented 1954 by A. Glaser



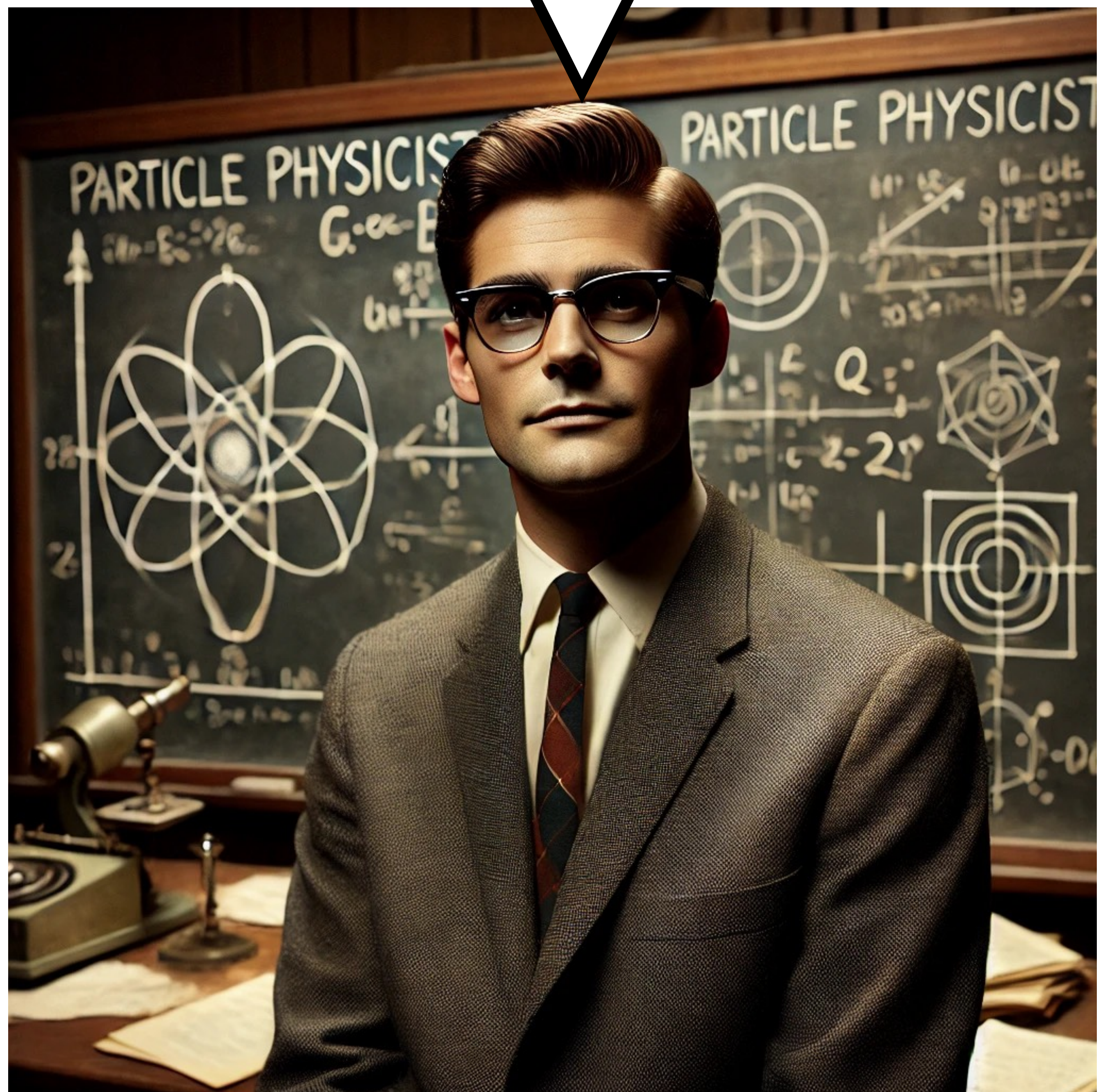
From the 1950s onwards, Bubble chambers got very popular.



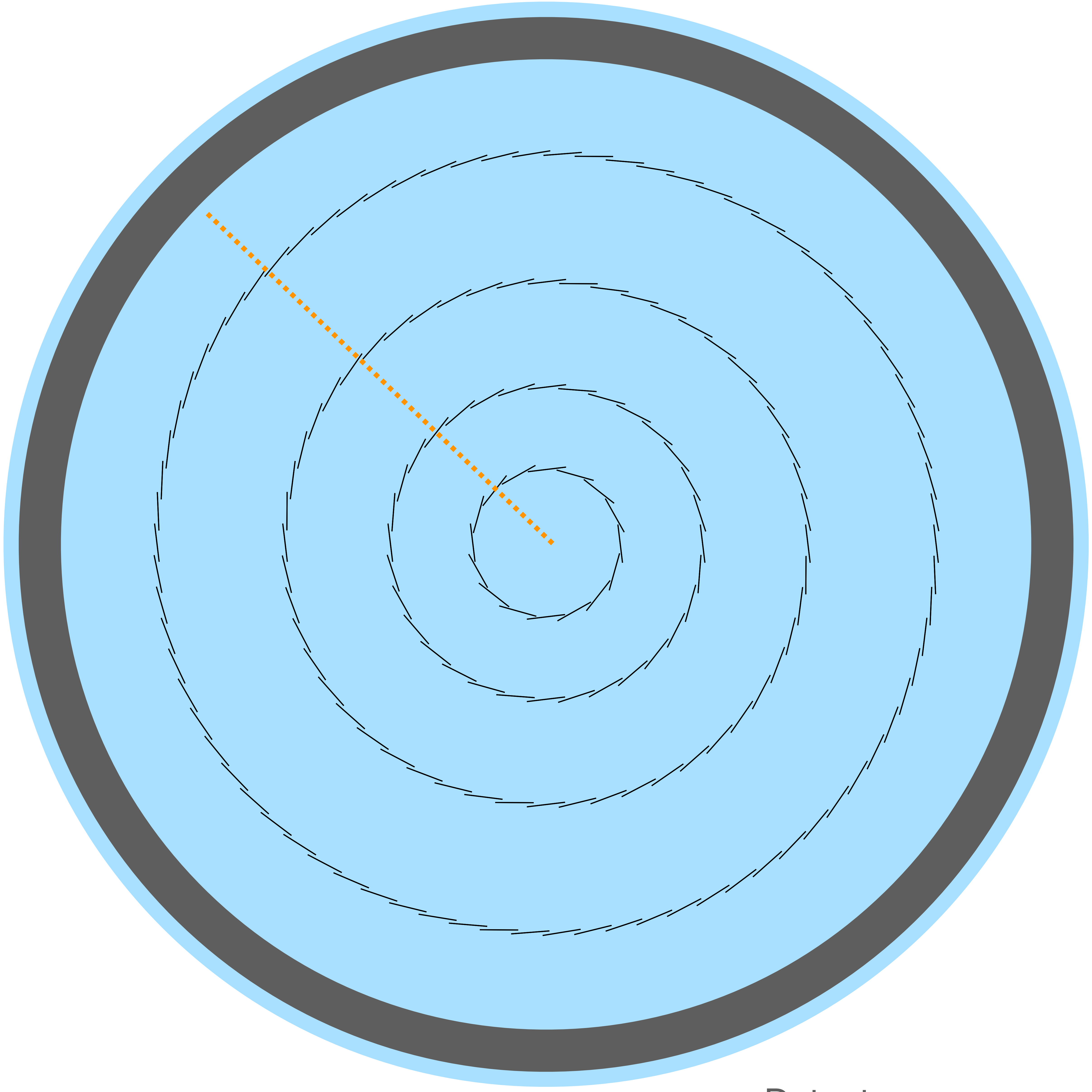


Discovery of the Ω^- in 1964

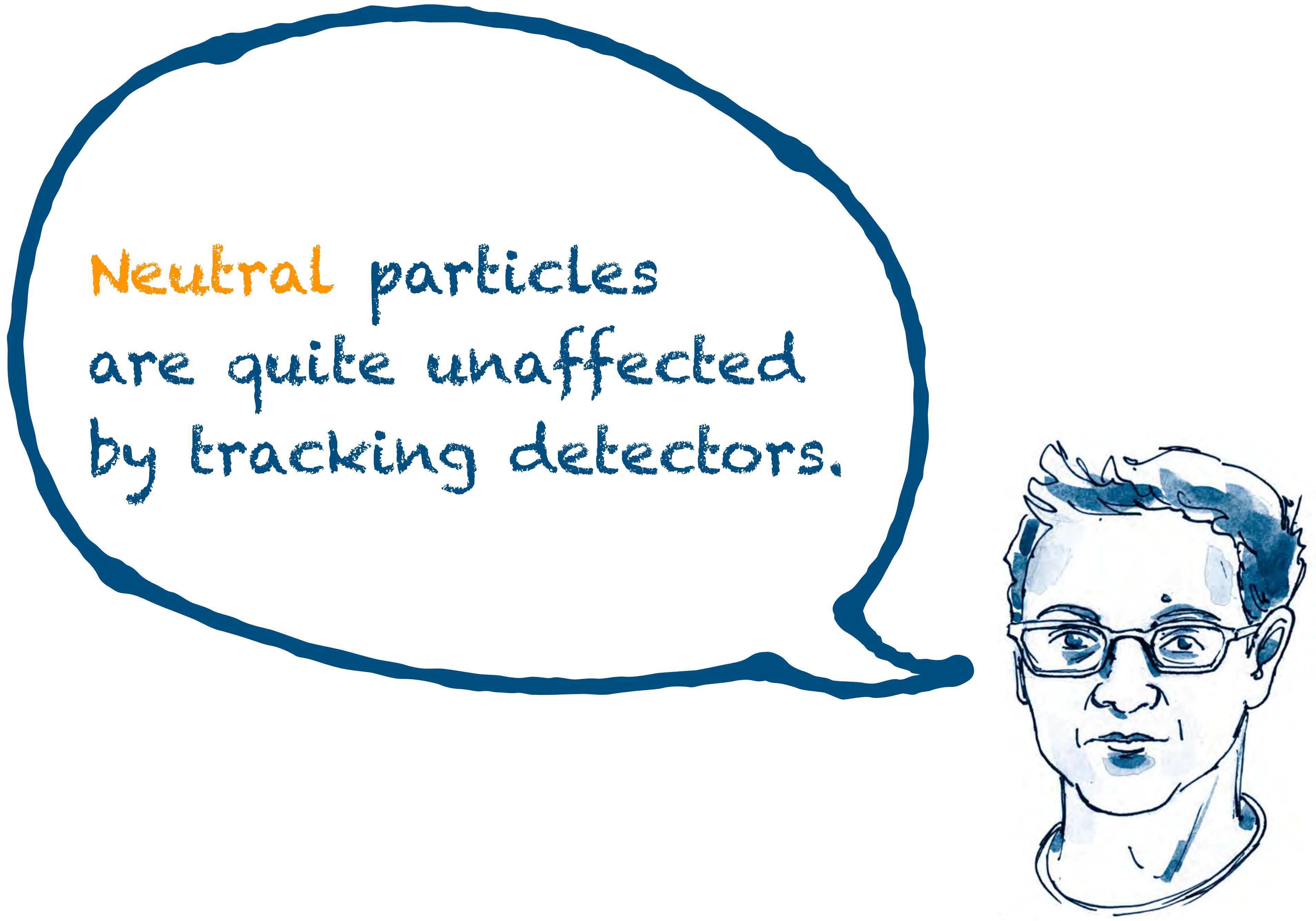
Analyzers hat to scan through thousands of those photo-graphs.



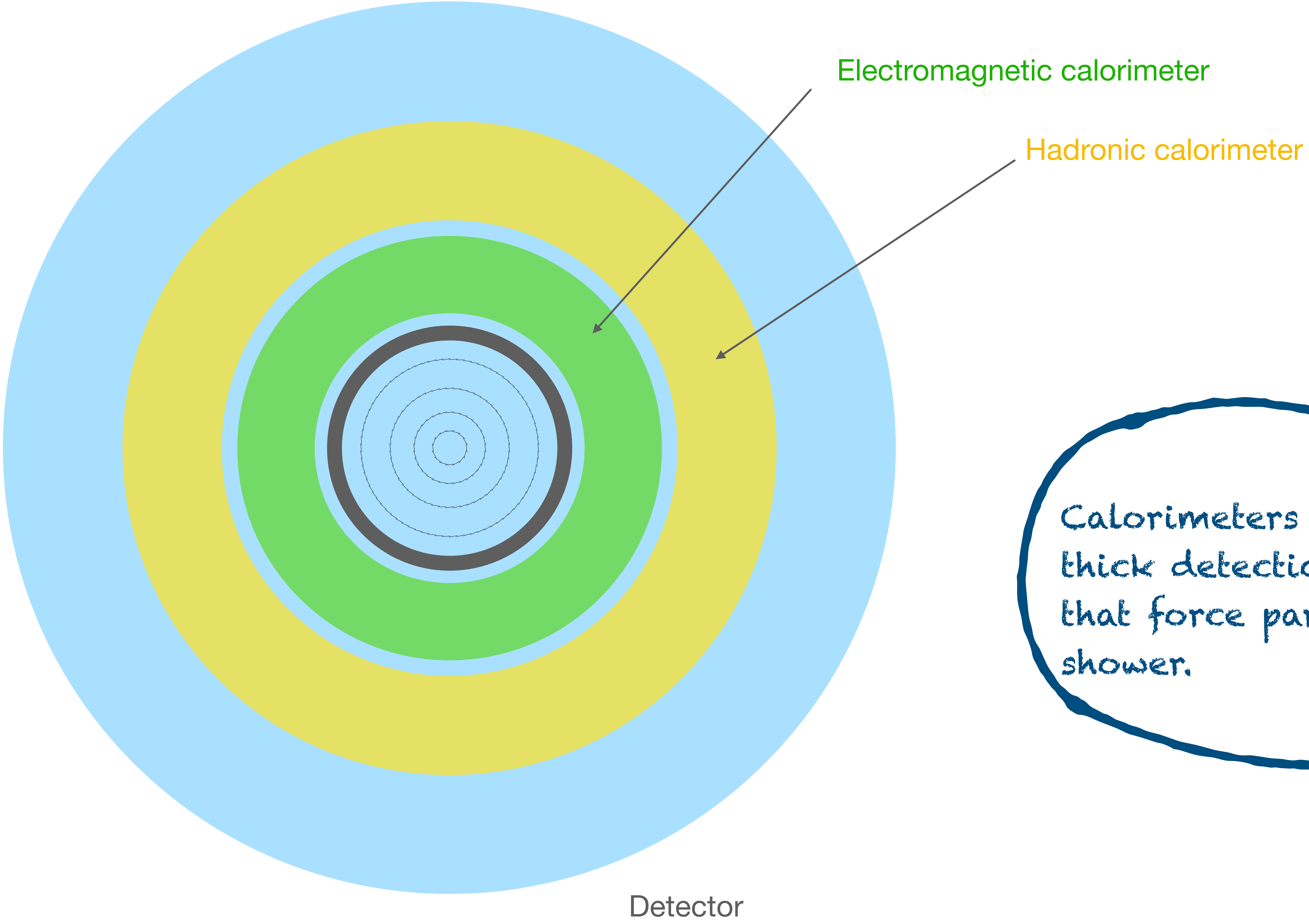
Tracking detector

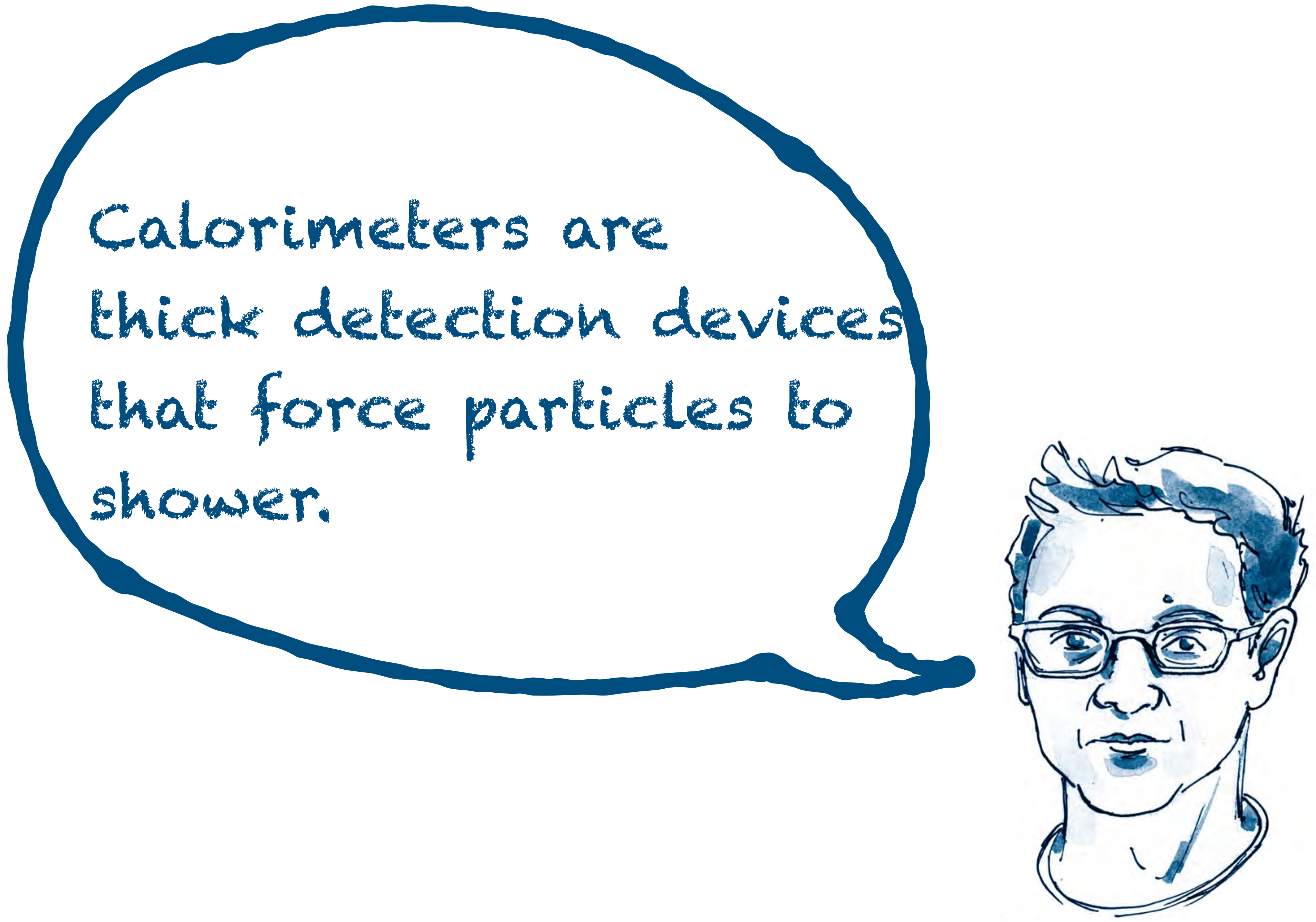


Detector

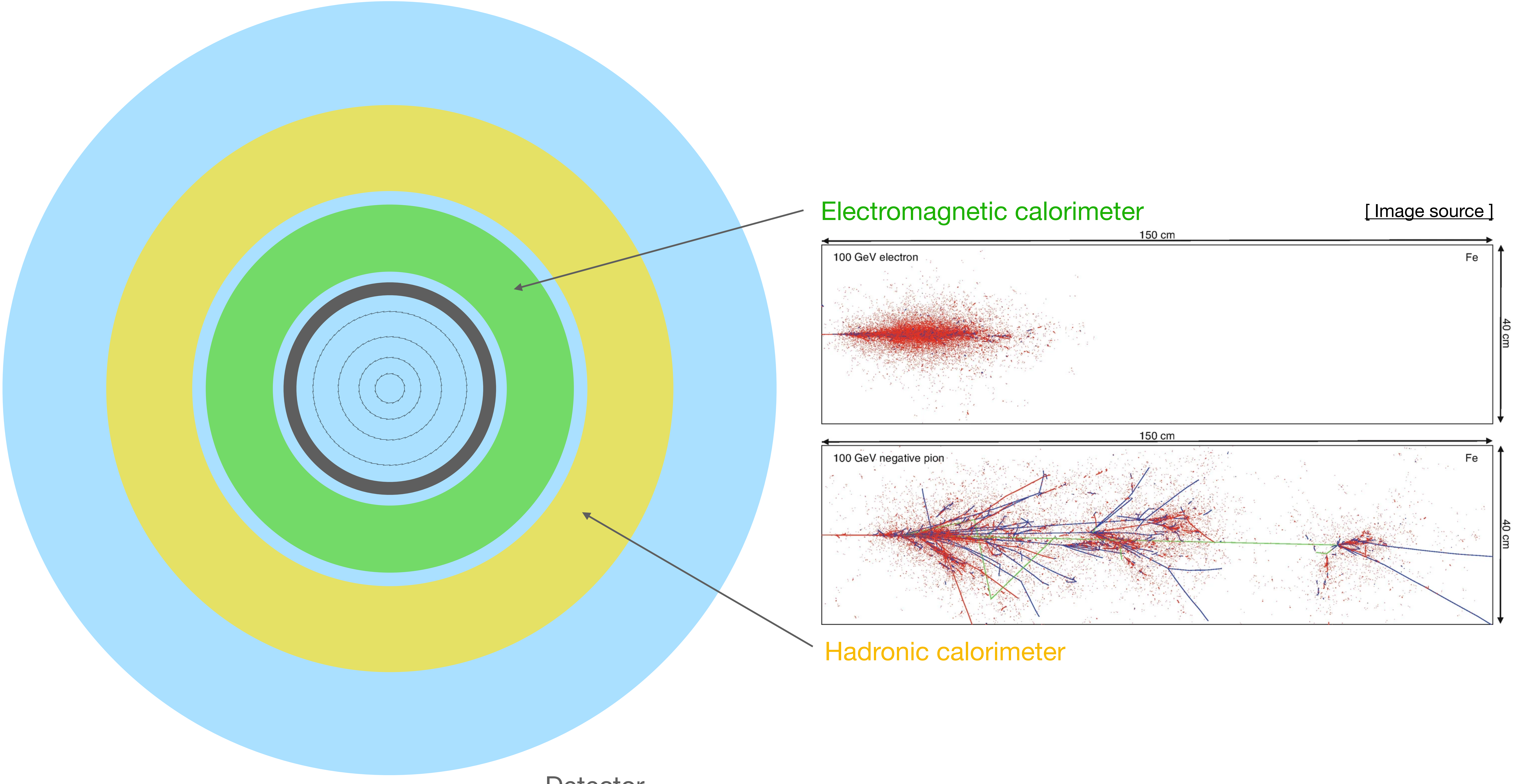


Calorimeters

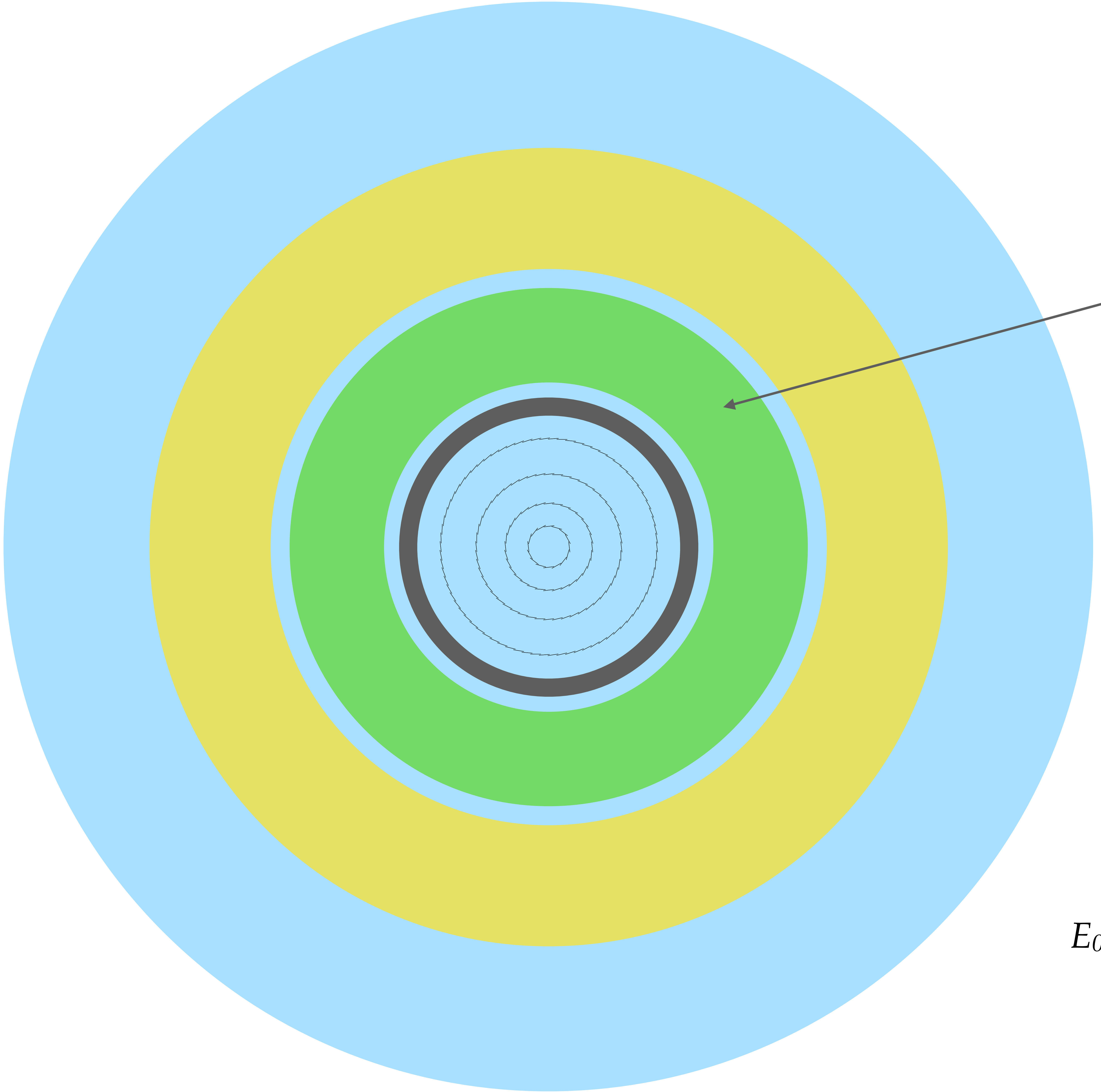




Calorimeters



Calorimeters

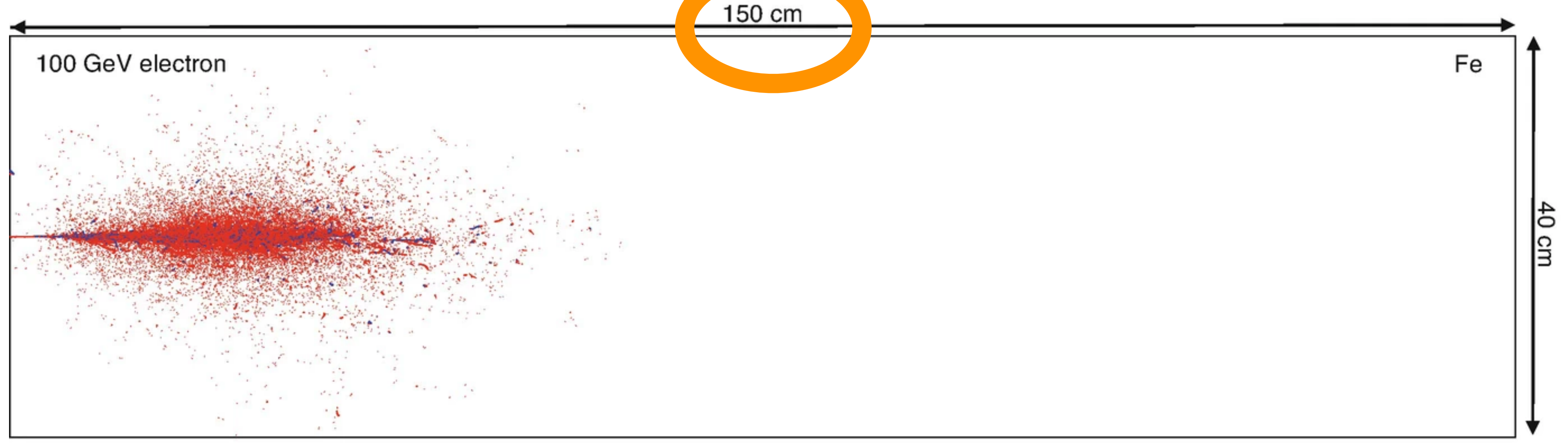


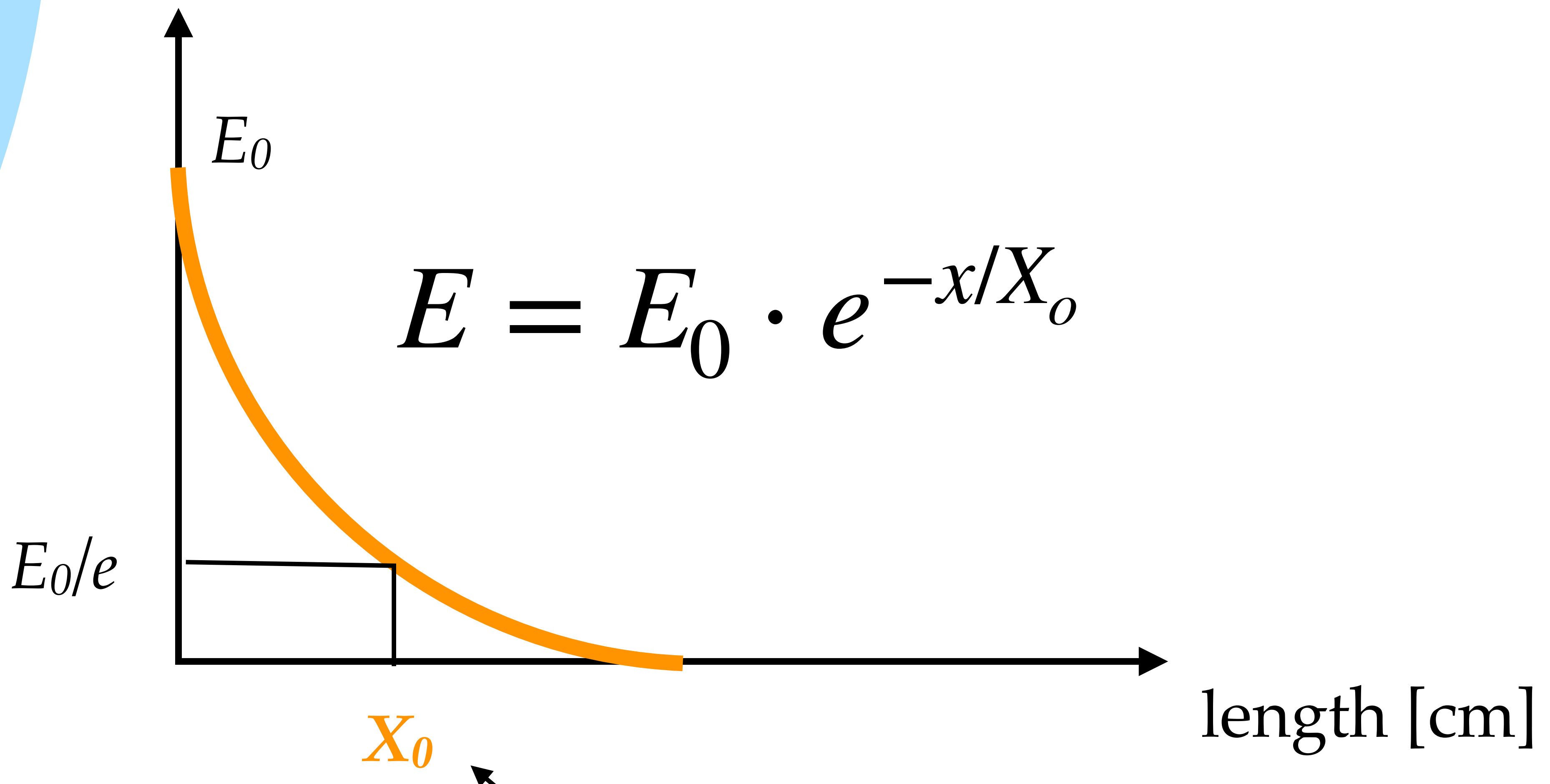
Detector

Electromagnetic calorimeter

How thick ?

[Image source]

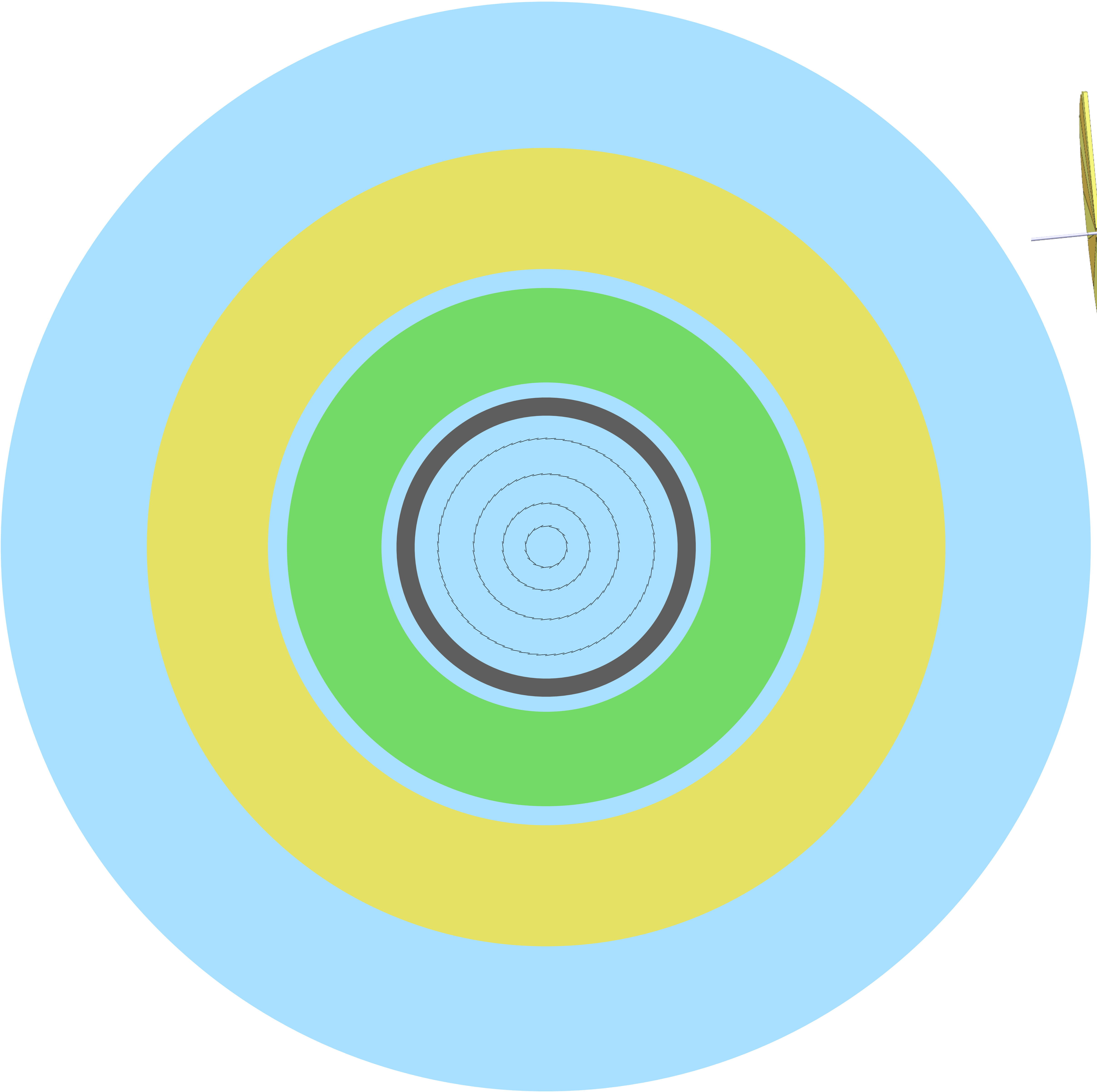


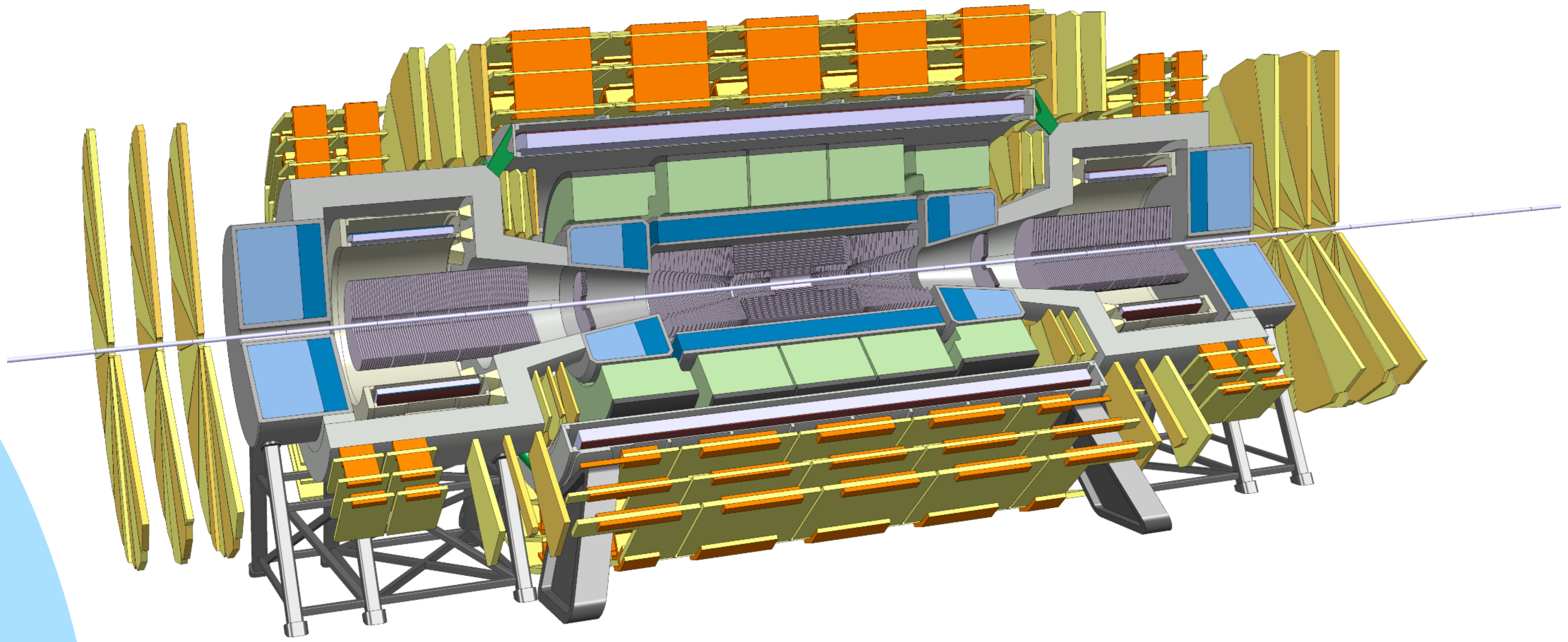


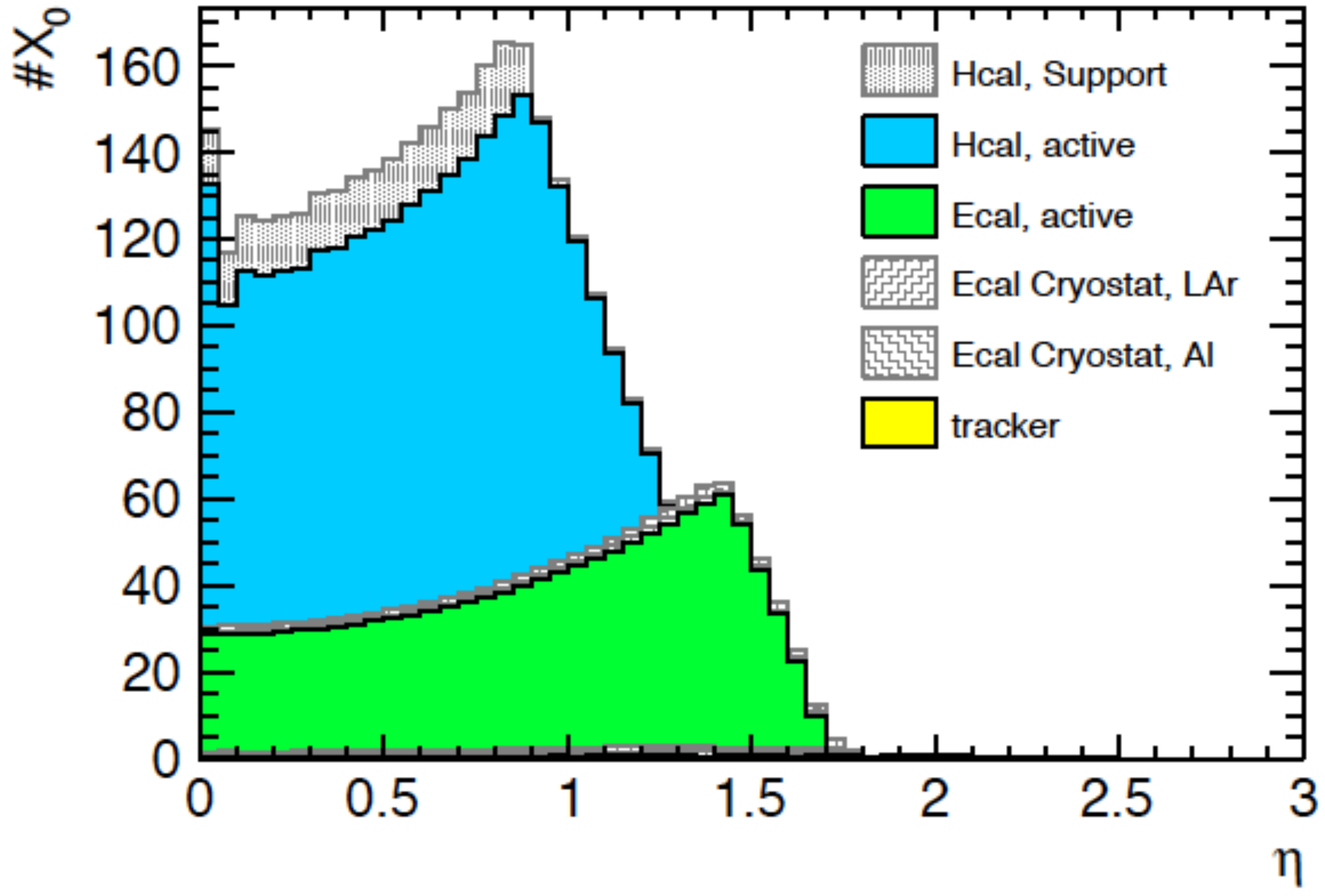
Radiation length

Calorimeters

FCC-hh detector design study

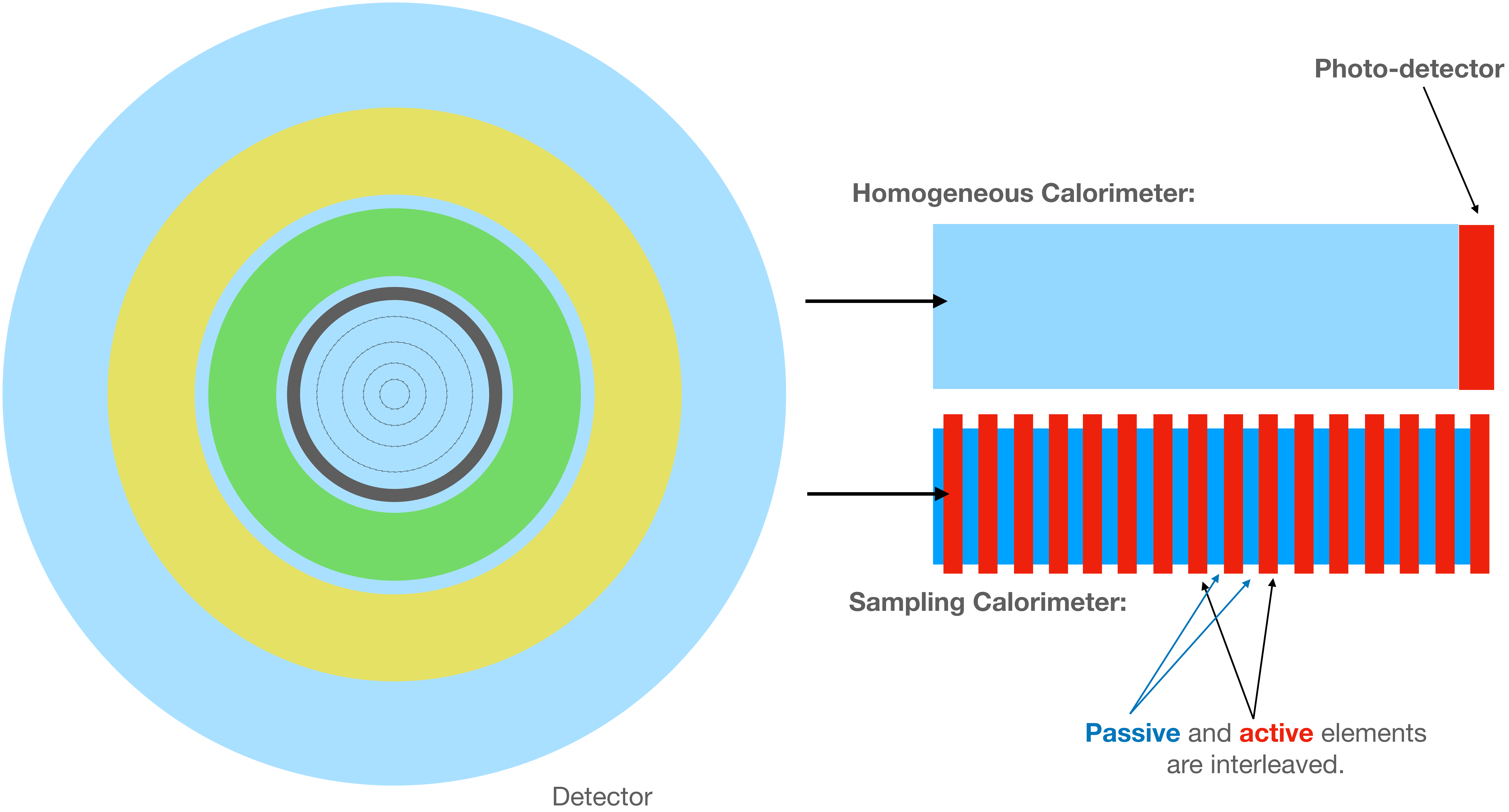




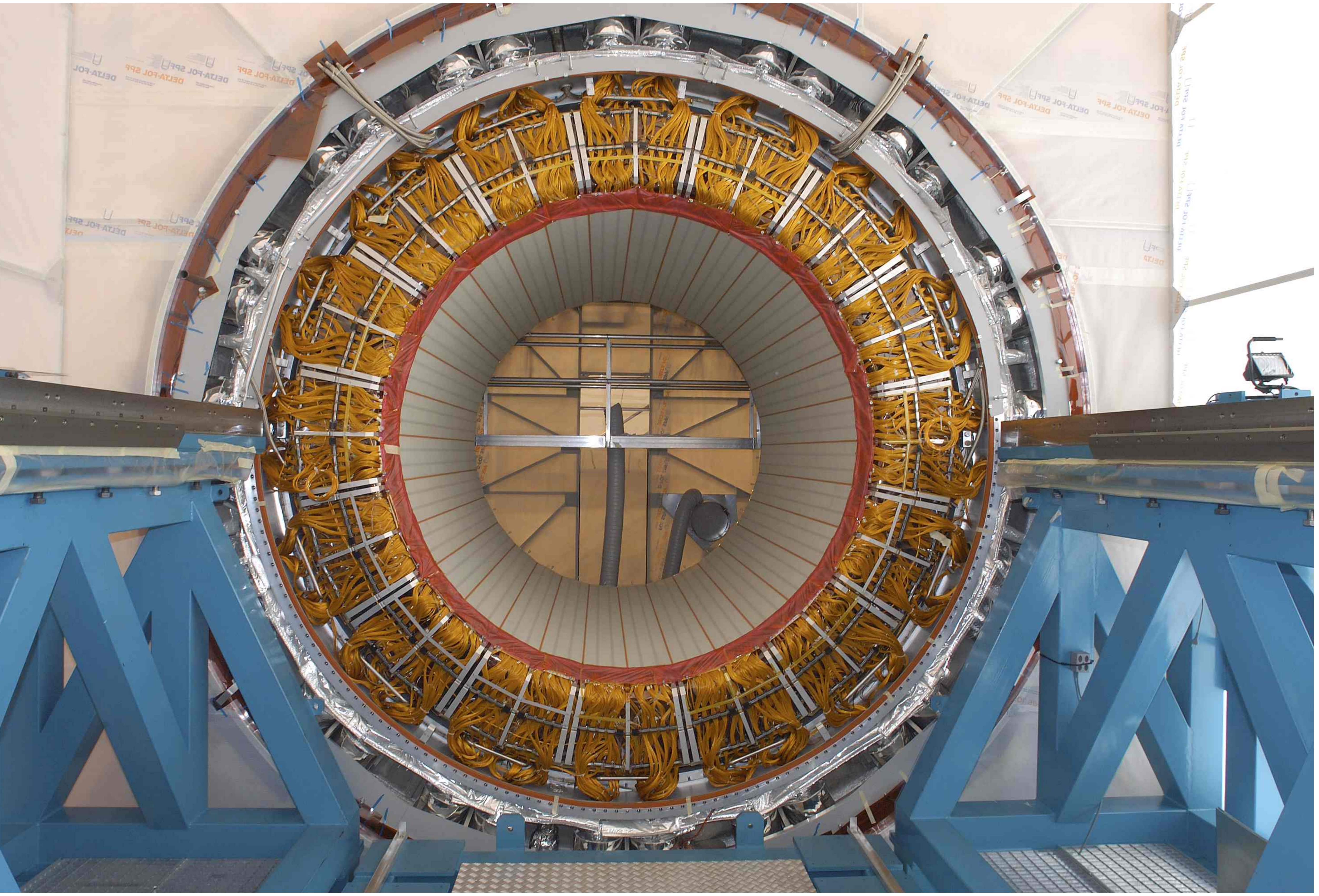


Detector

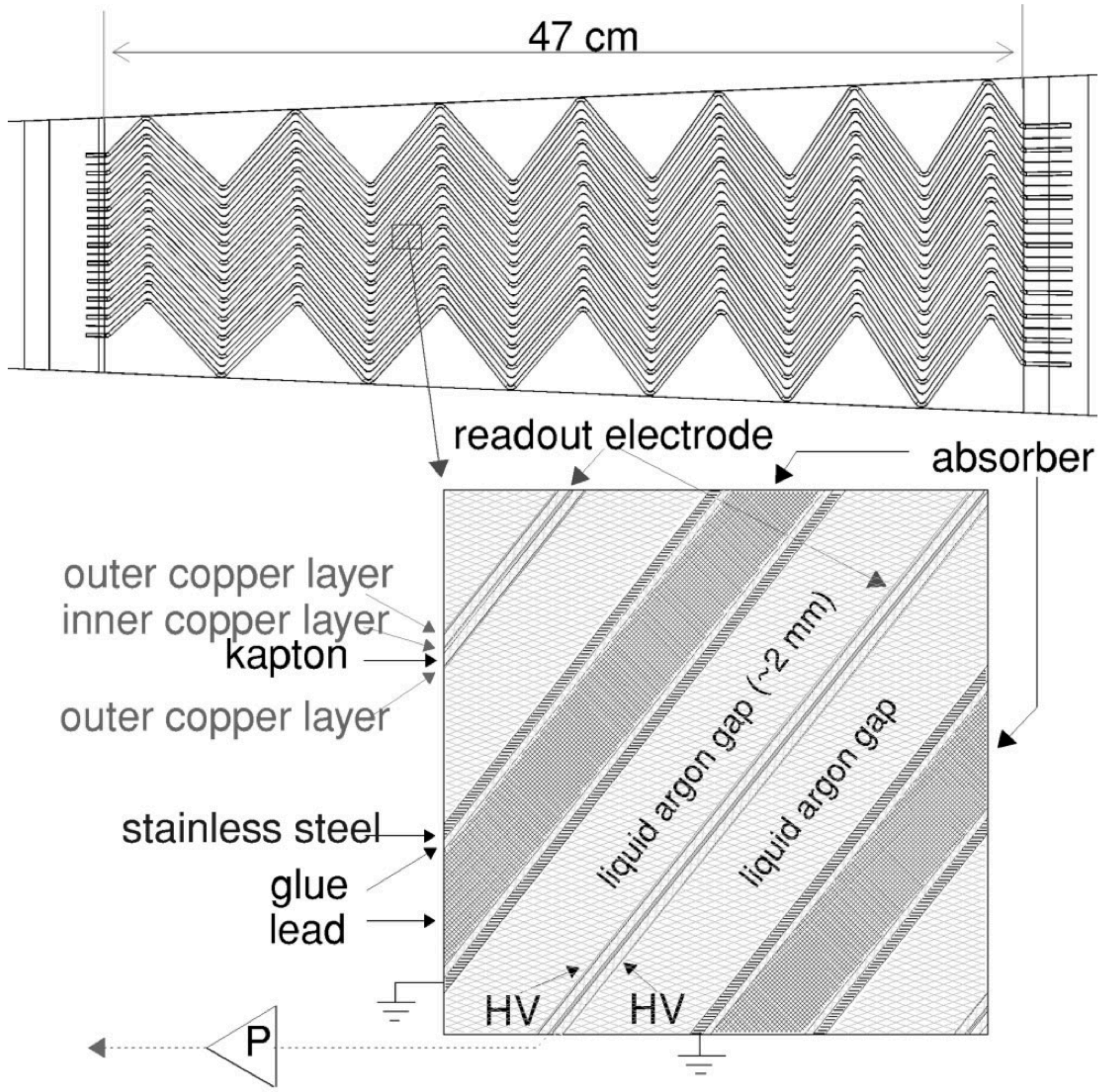
Calorimeters

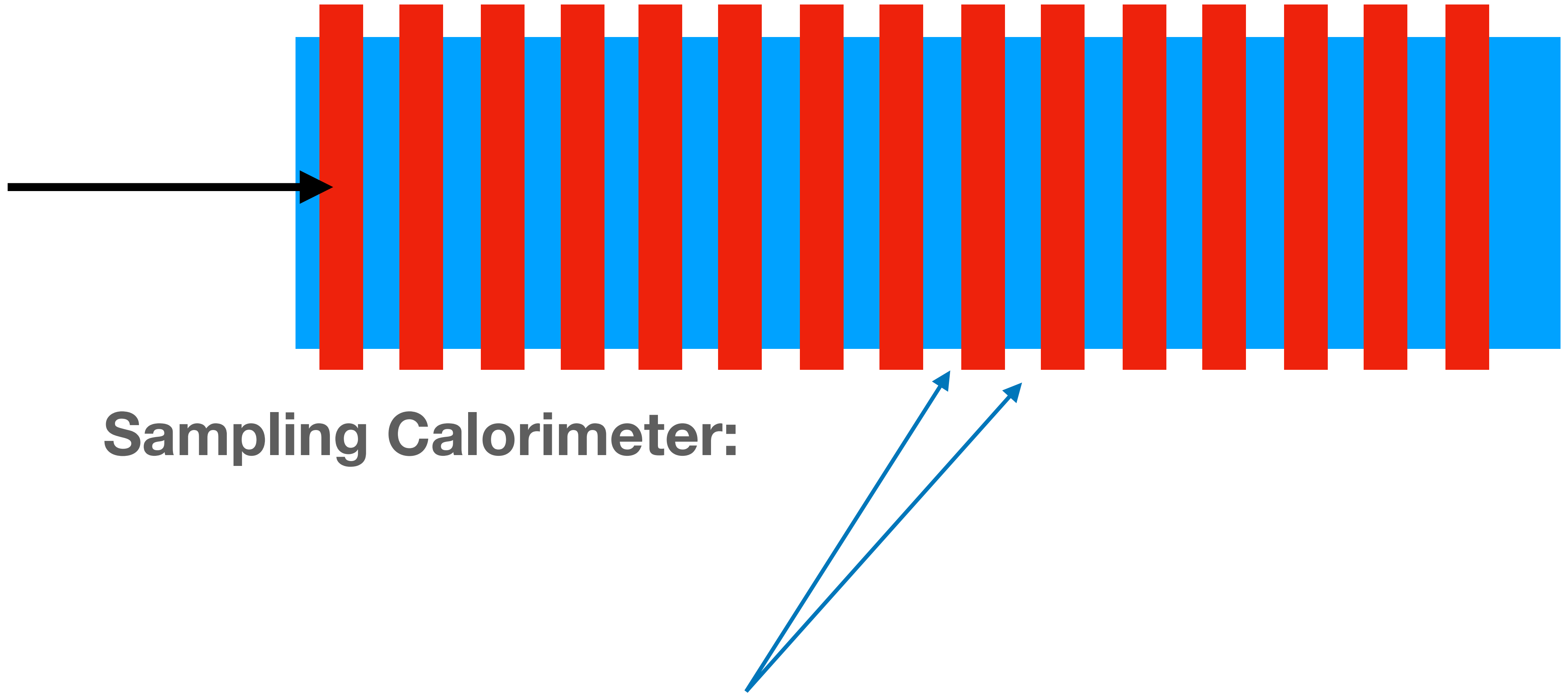


Calorimeters



ATLAS Liquid Argon Sampling calorimeter (EM)

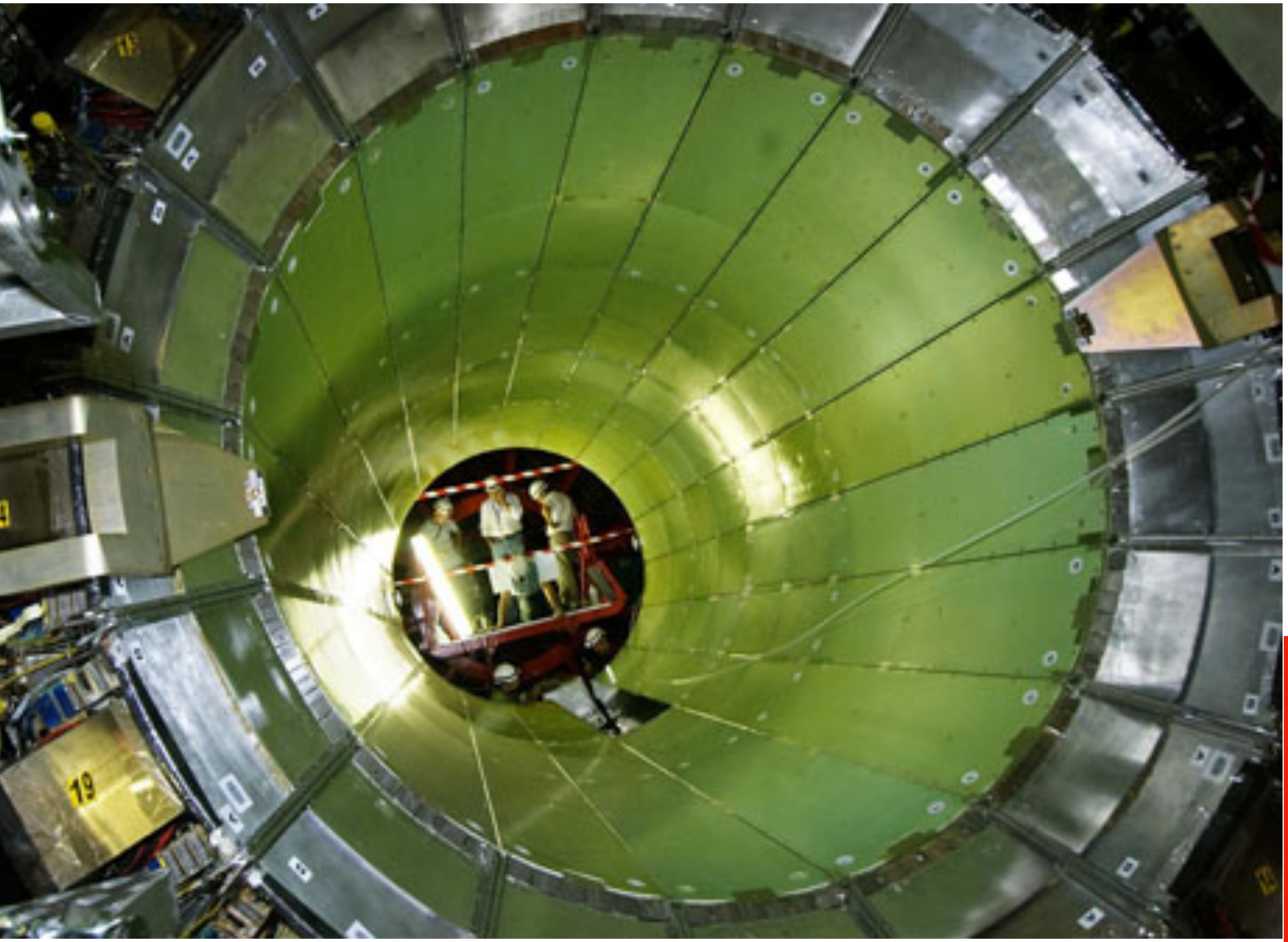




Sampling Calorimeter:

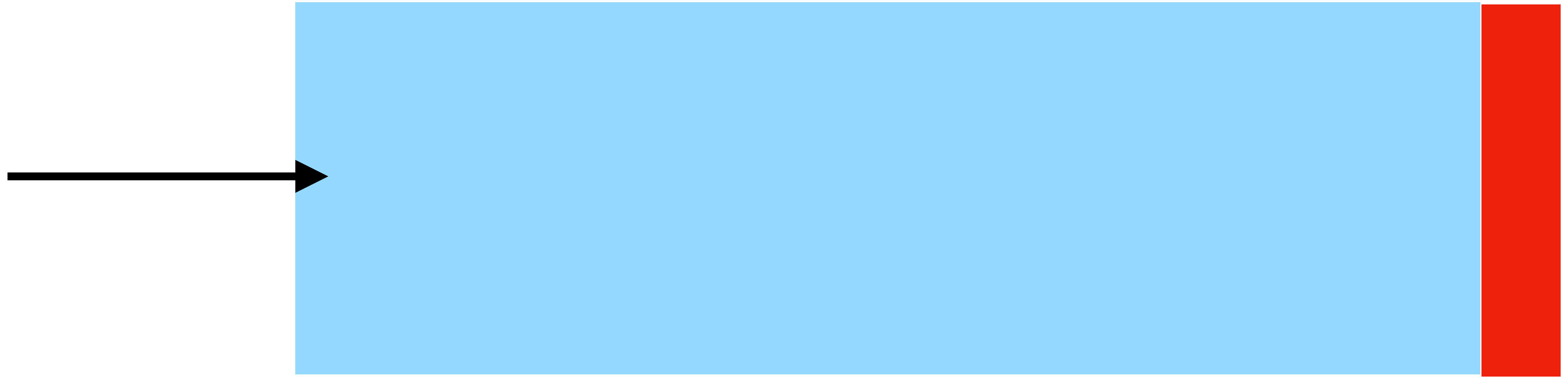
Passive and **active** elements
are interleaved.

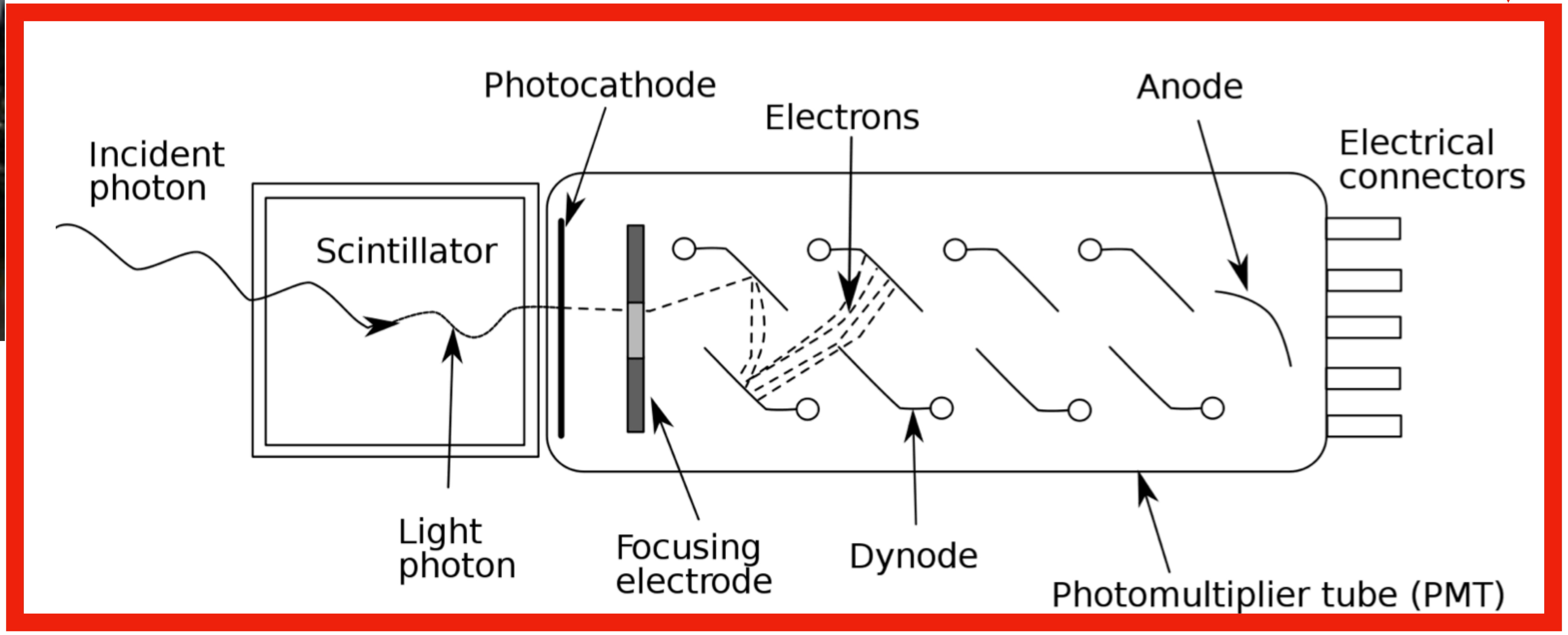
Calorimeters



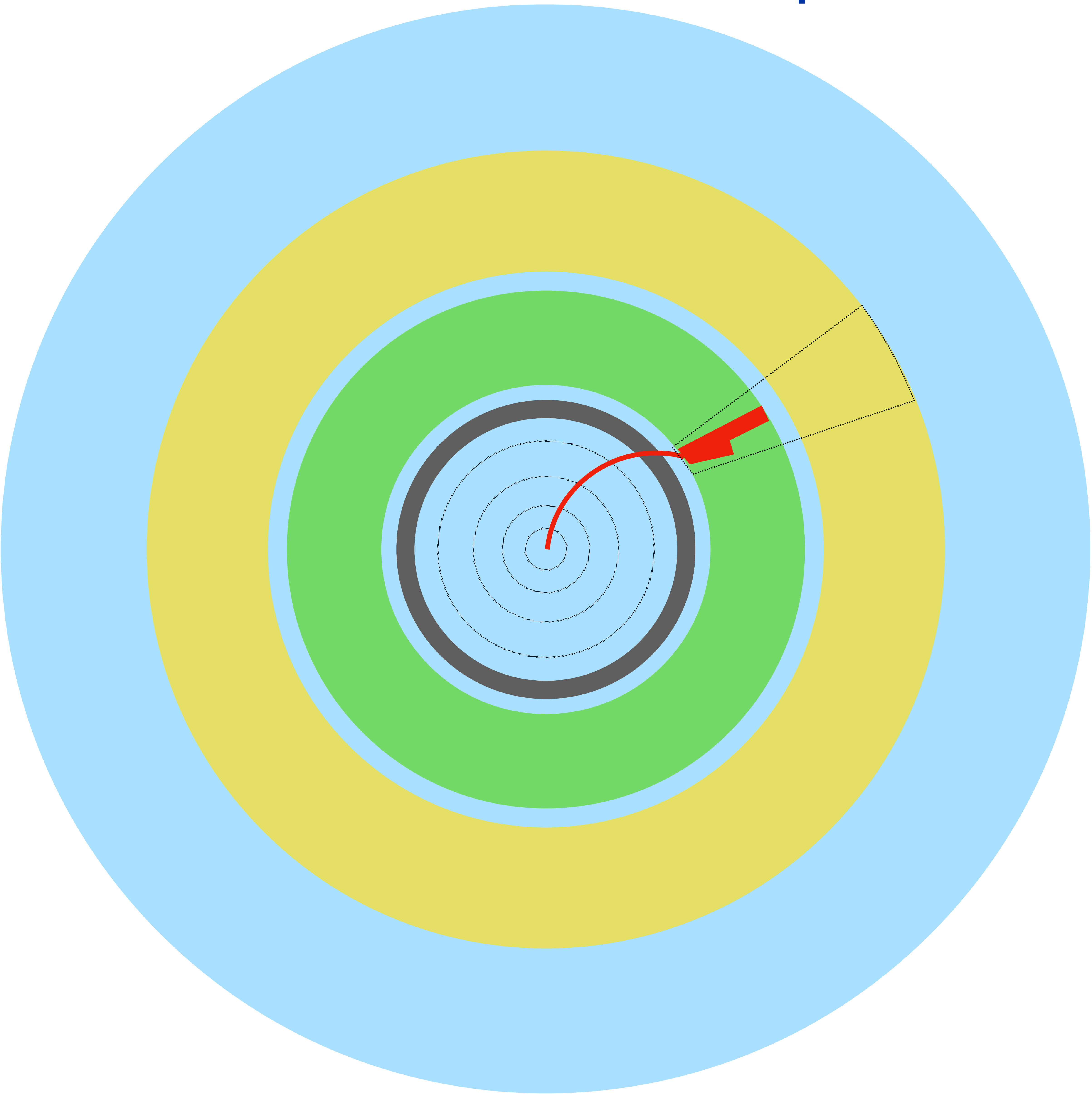
CMS Lead Tungsten Crystal EM calorimeter

Homogeneous Calorimeter:



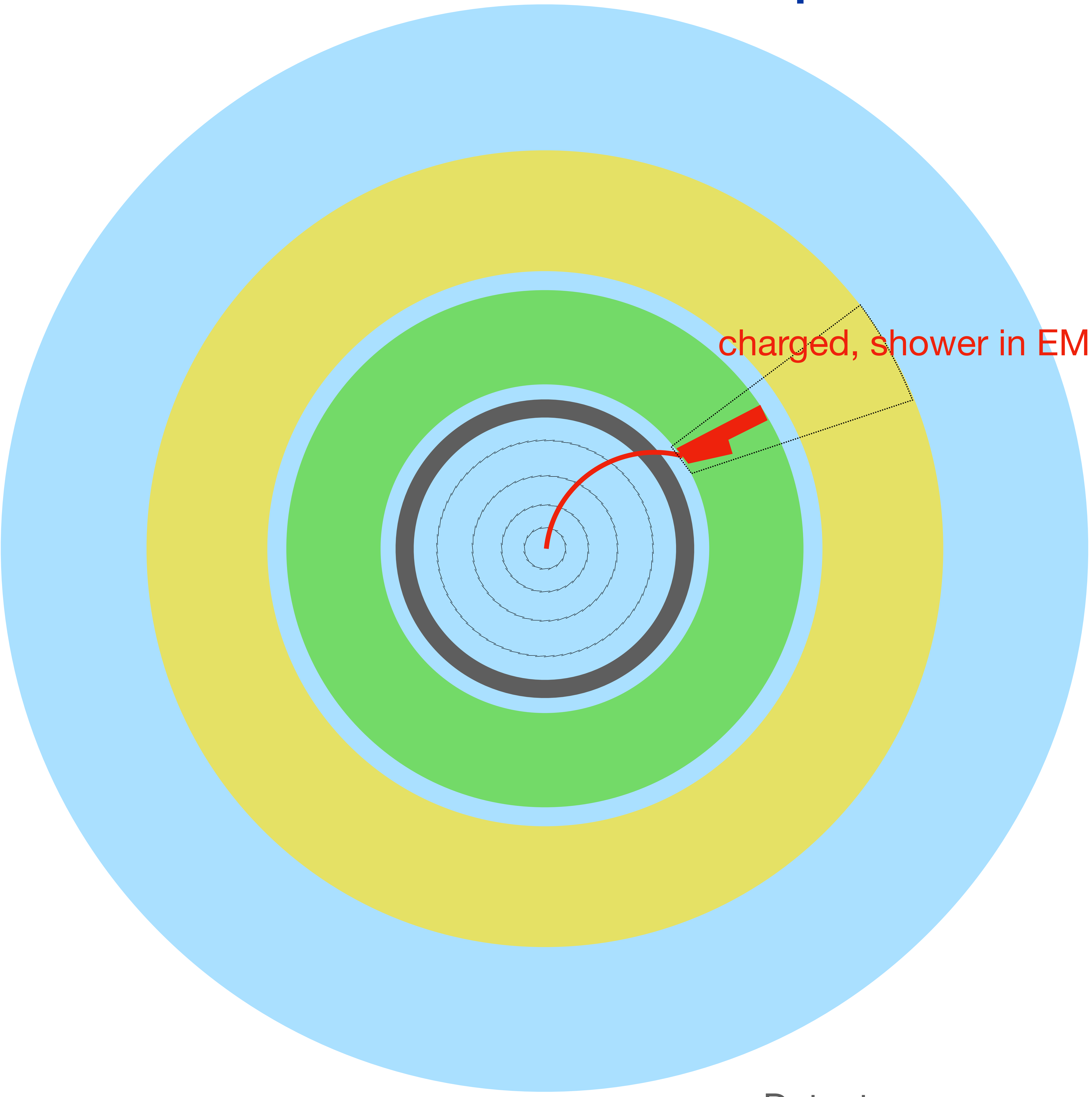


A little detection quiz



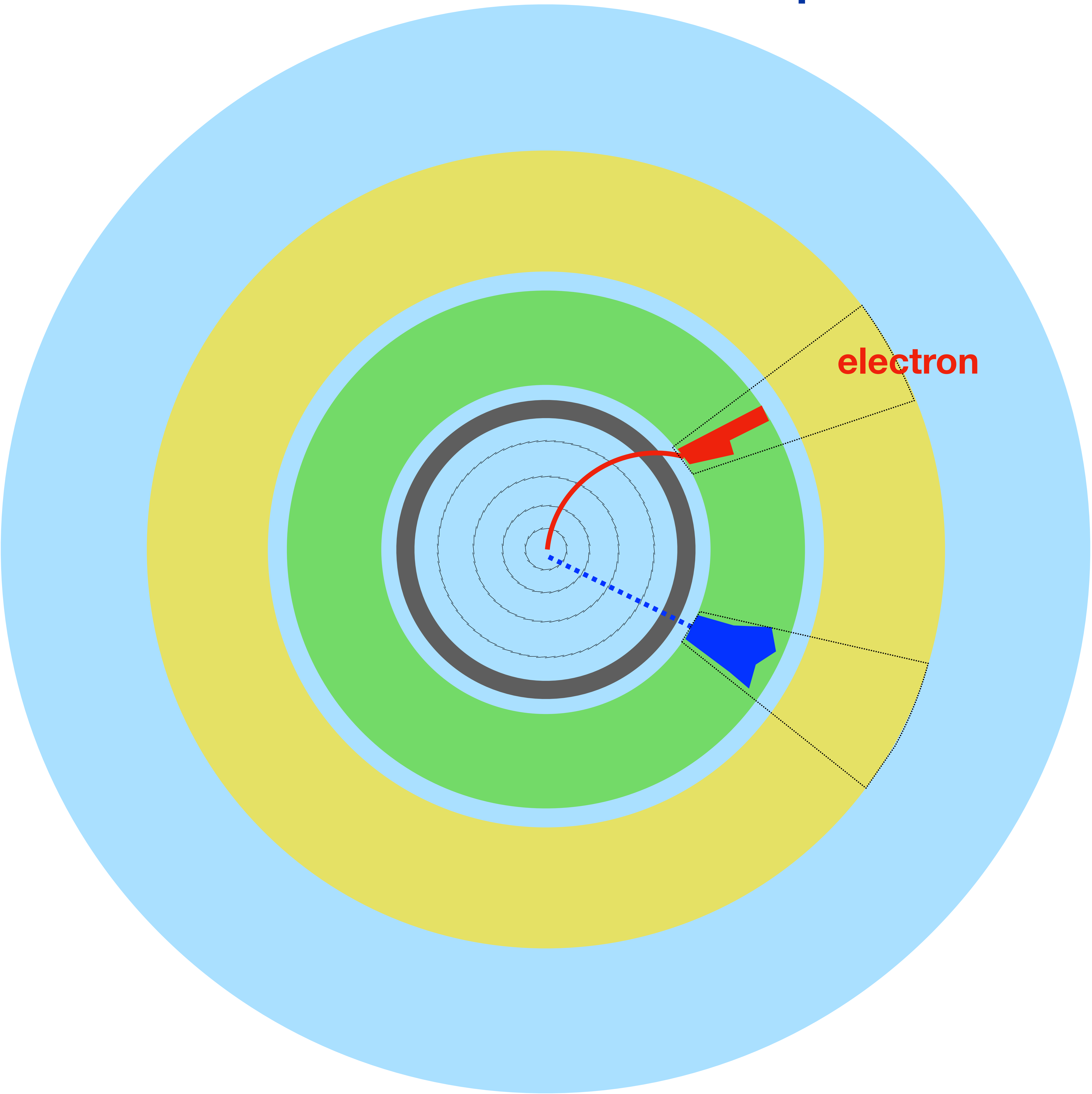
Detector

A little detection quiz



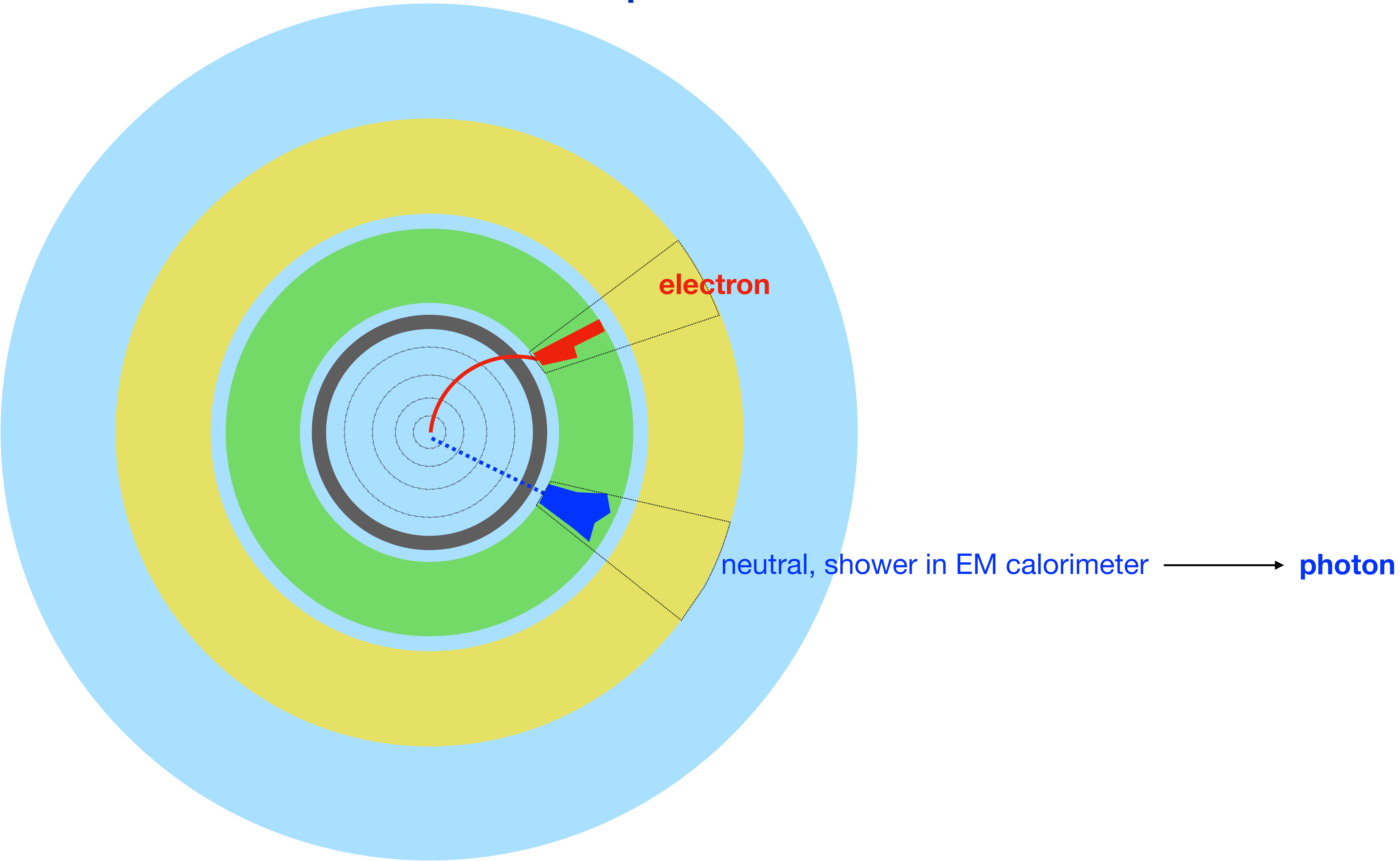
Detector

A little detection quiz



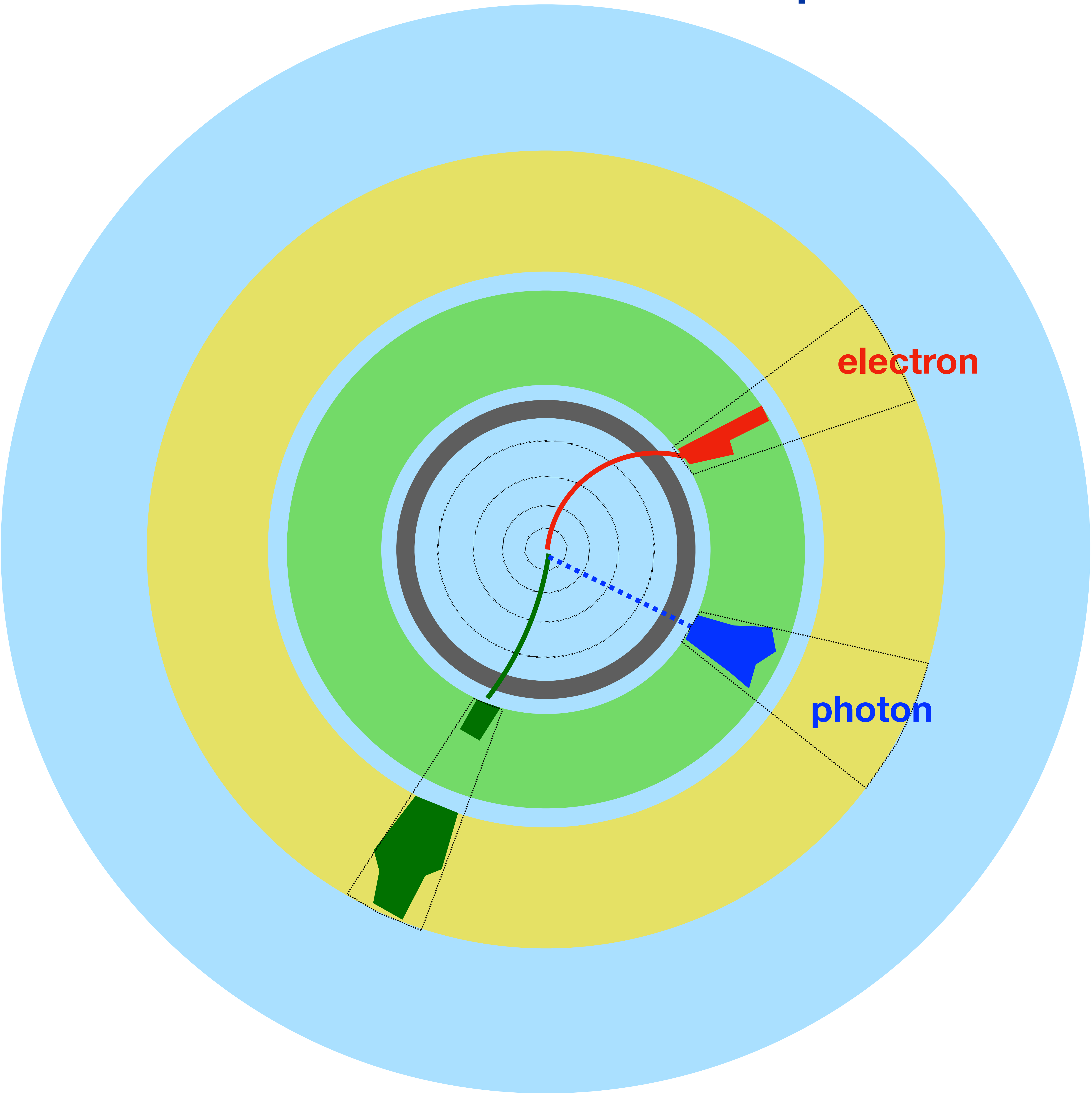
Detector

A little detection quiz



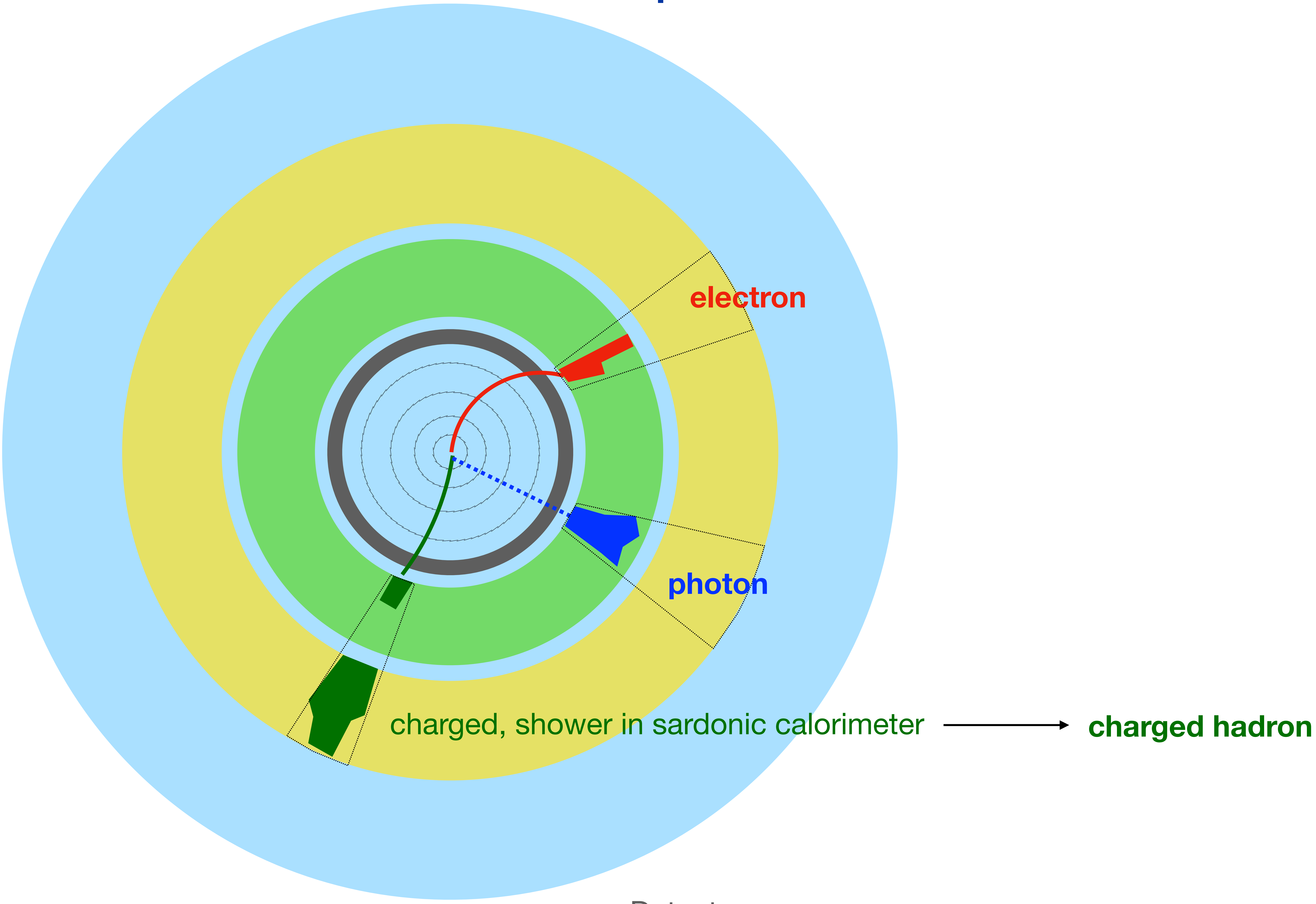
Detector

A little detection quiz



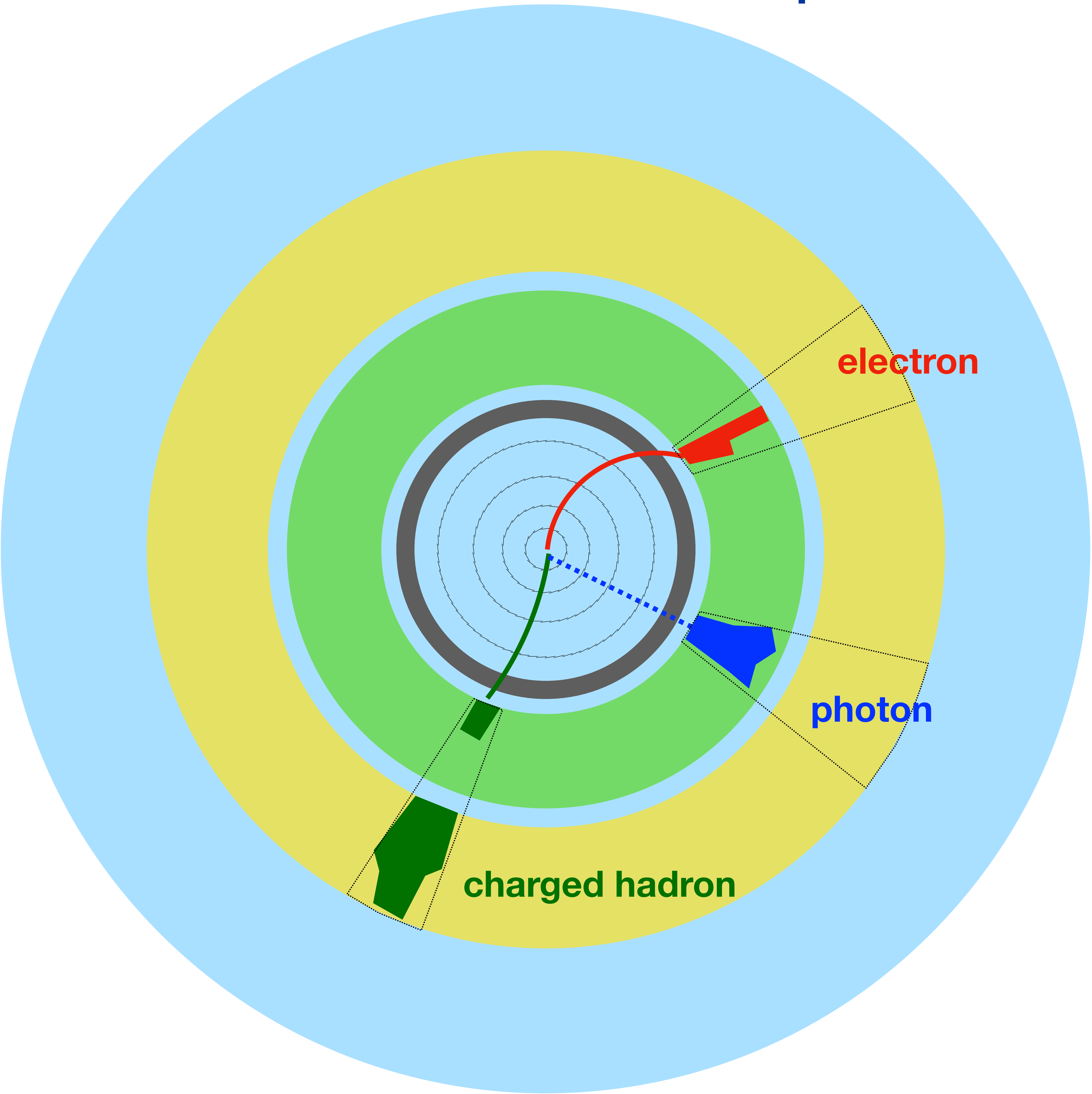
Detector

A little detection quiz



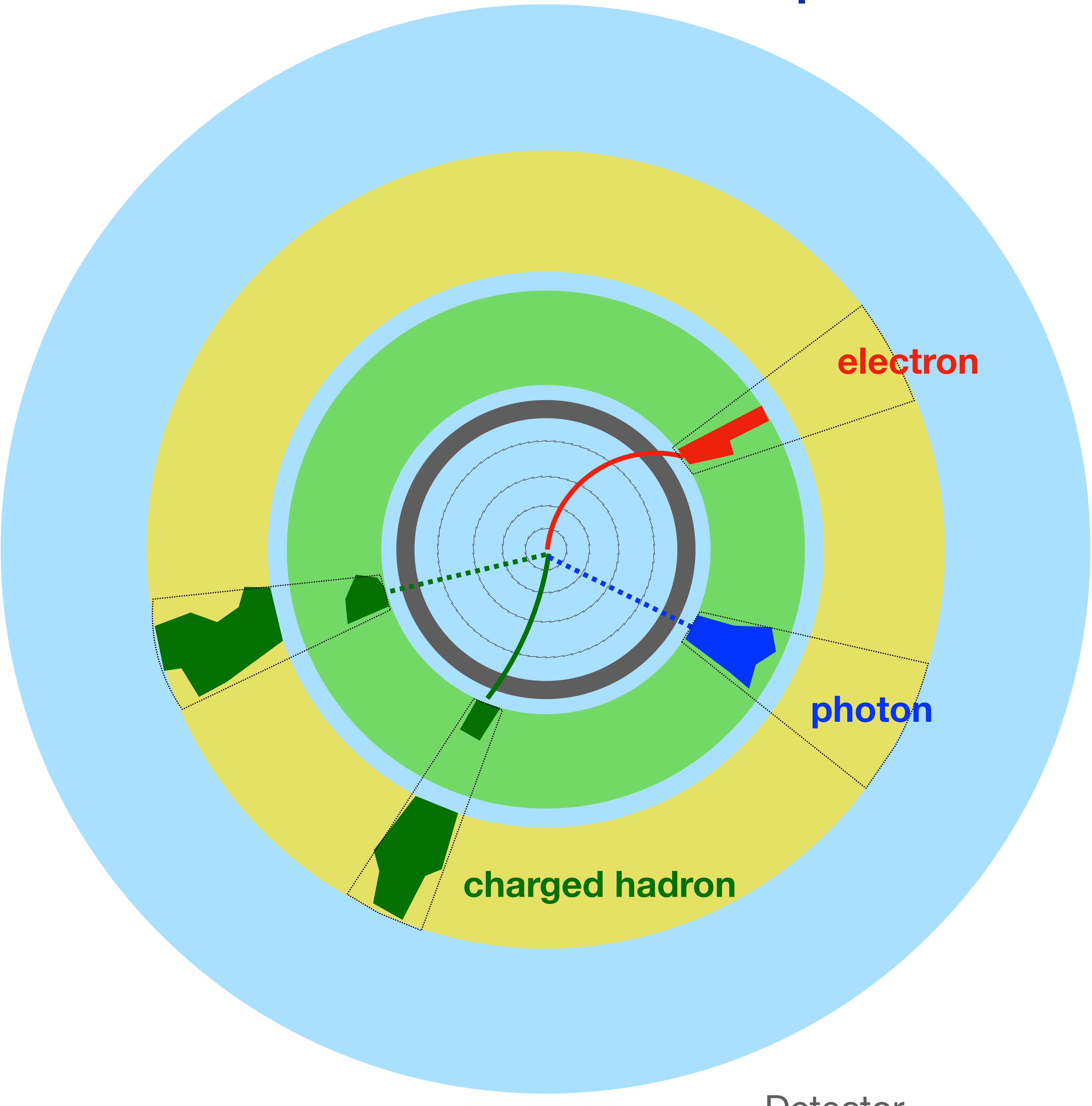
Detector

A little detection quiz

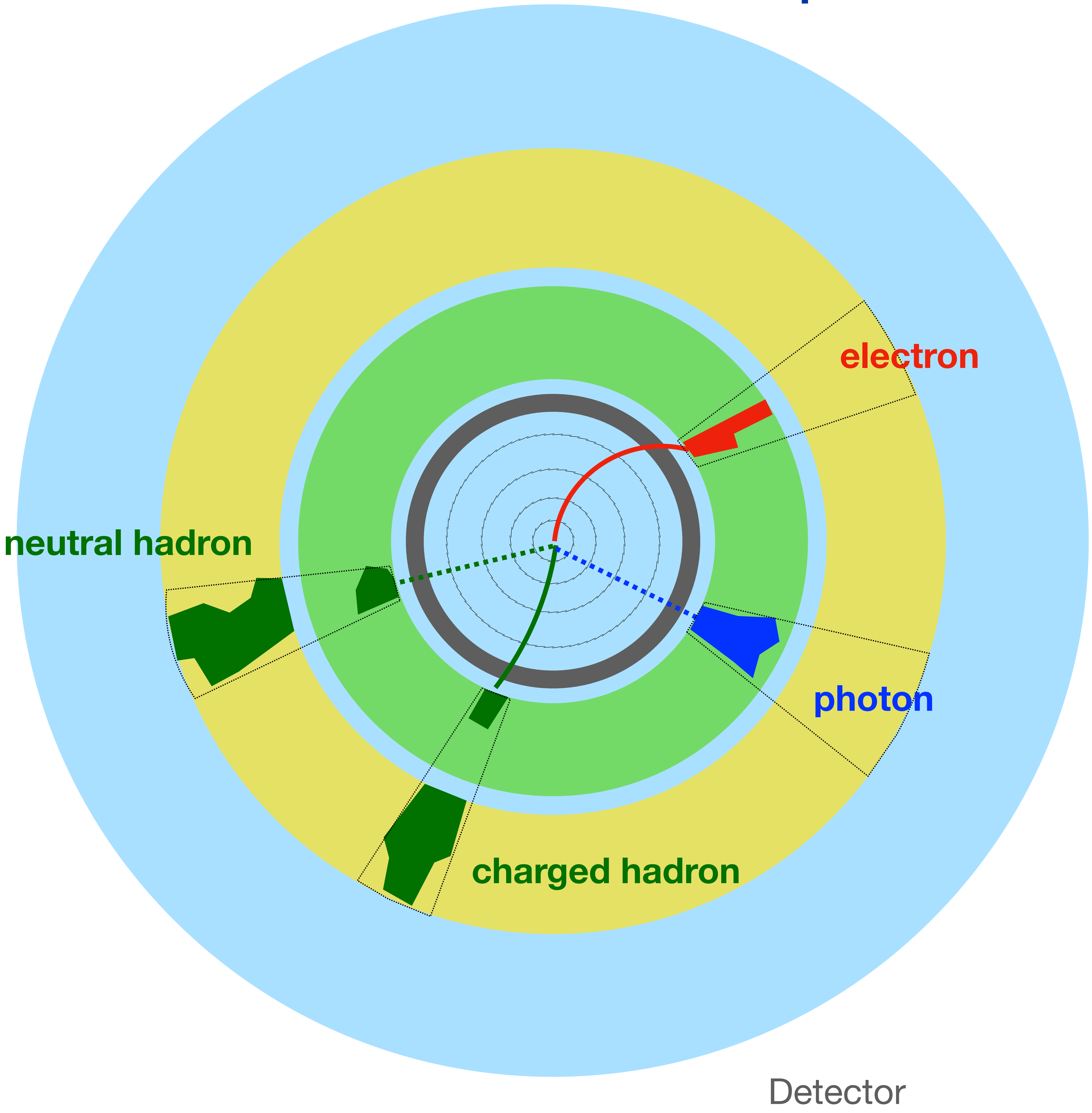


Detector

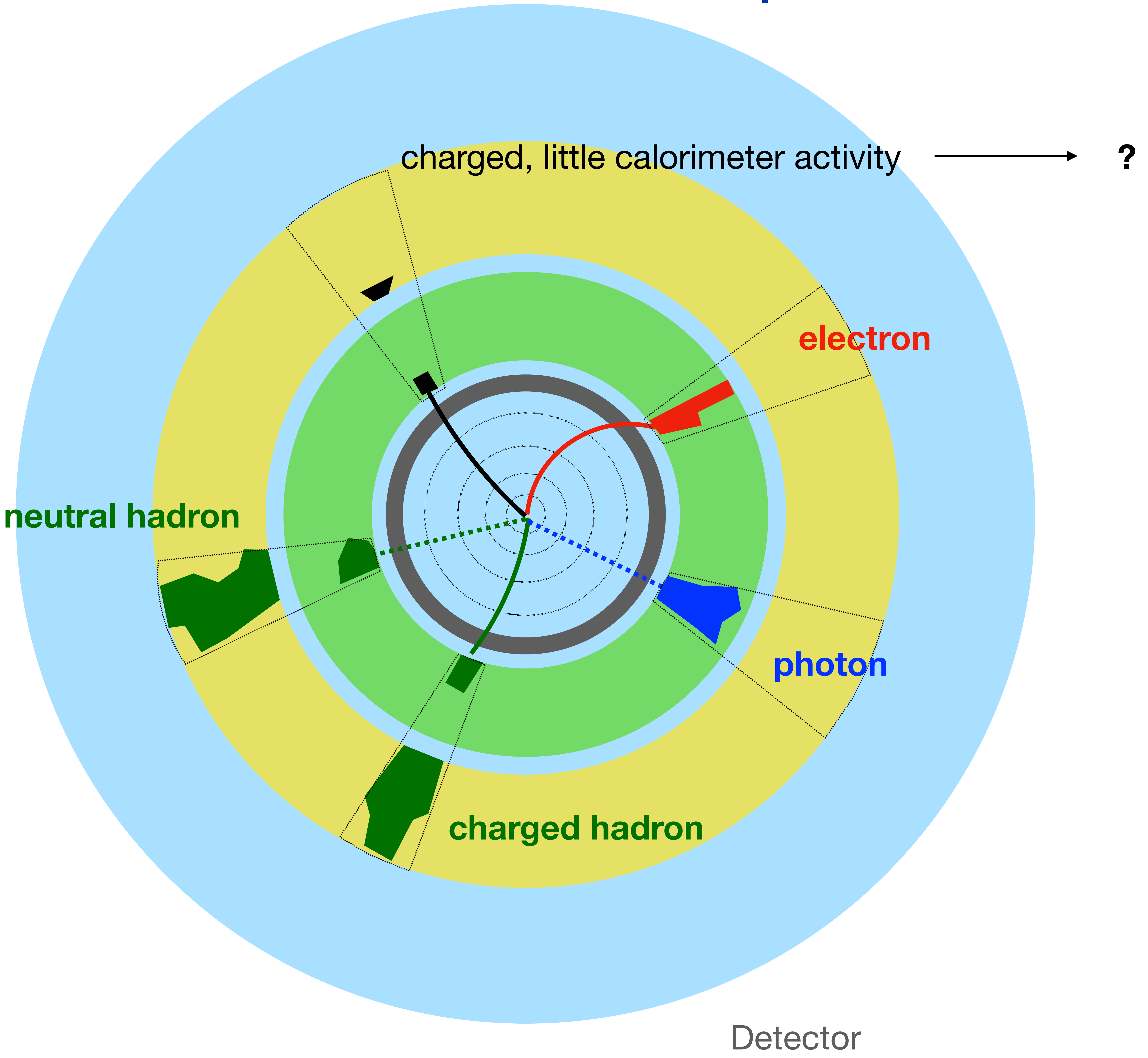
A little detection quiz



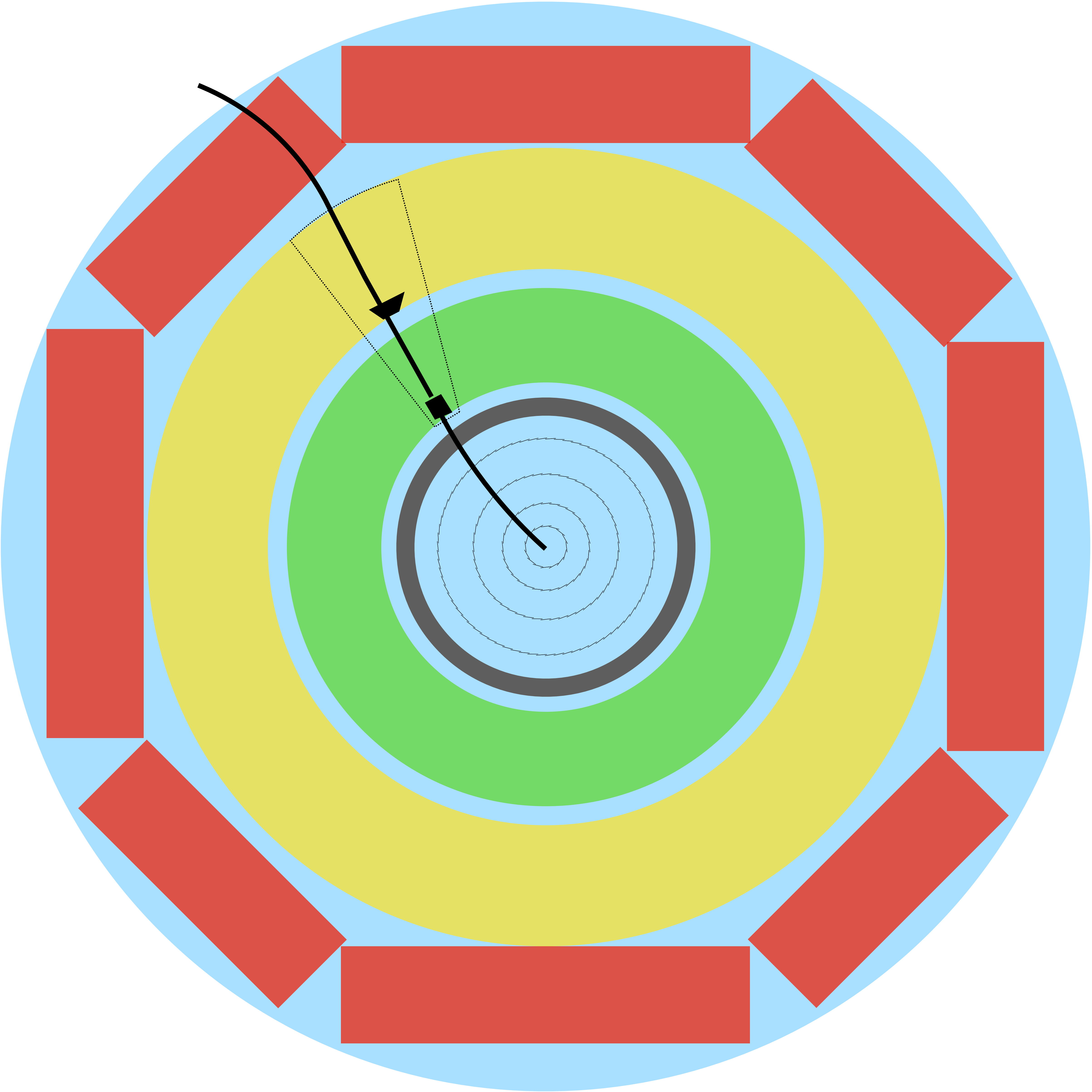
A little detection quiz



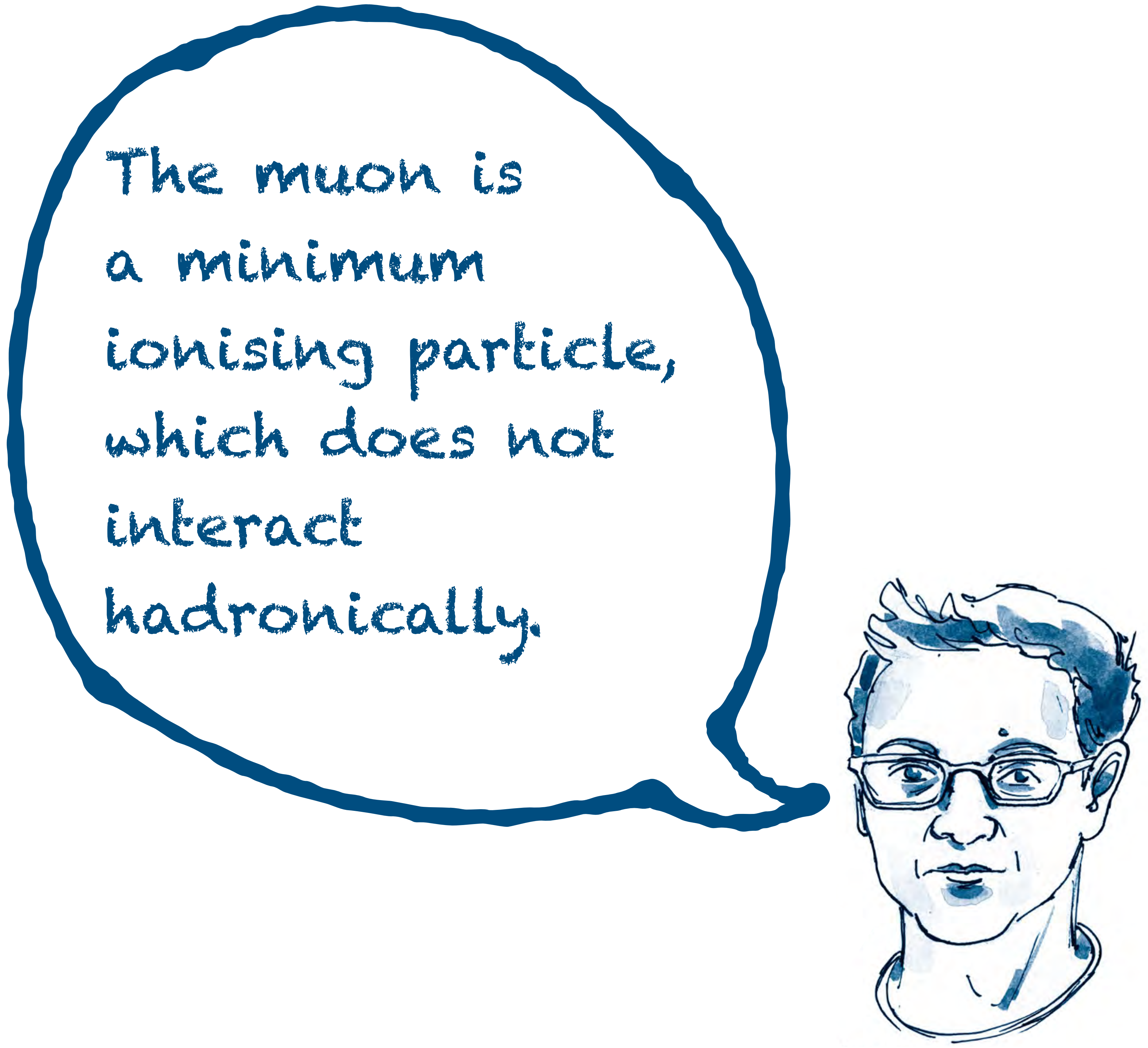
A little detection quiz

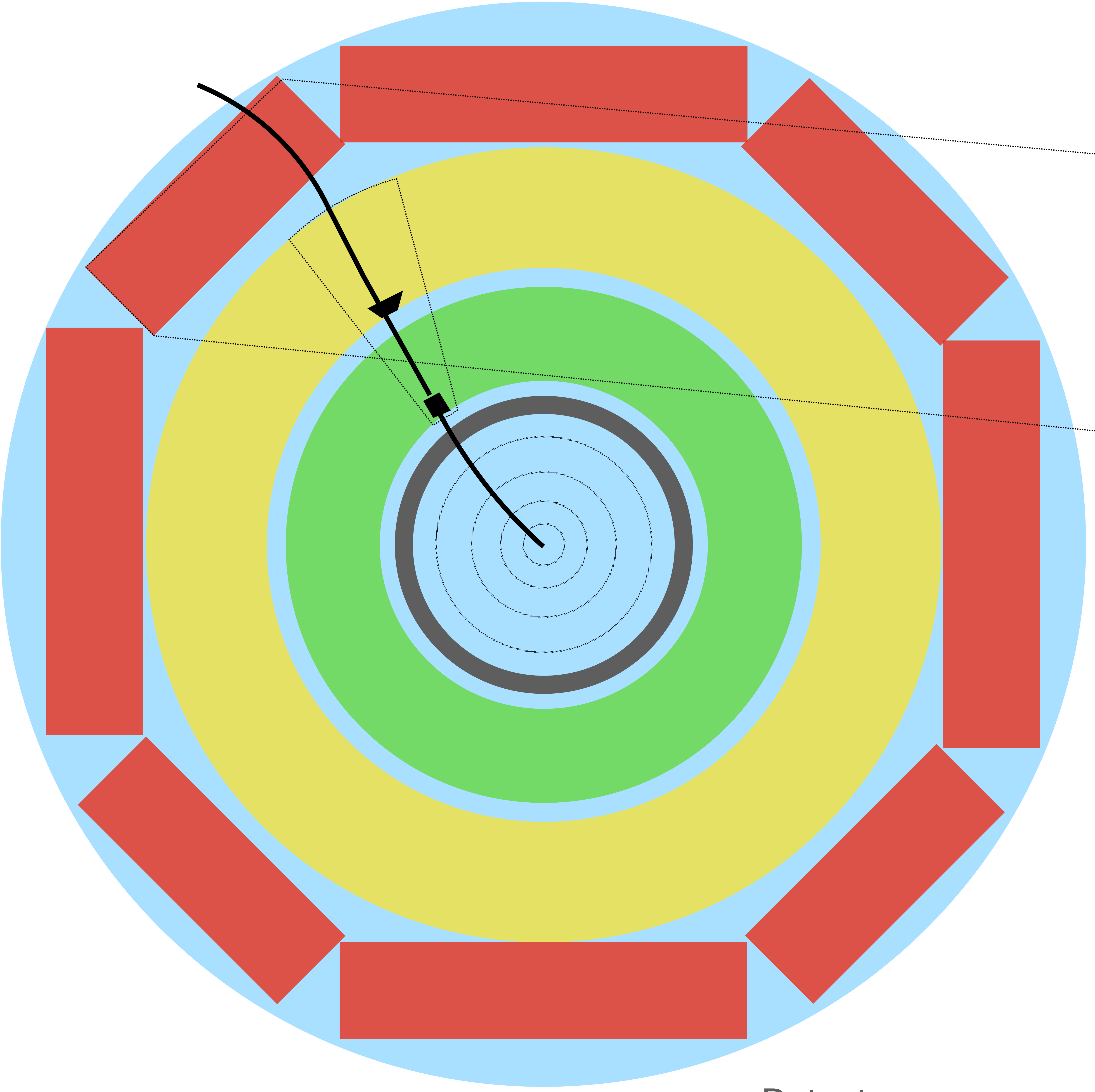


Muon System

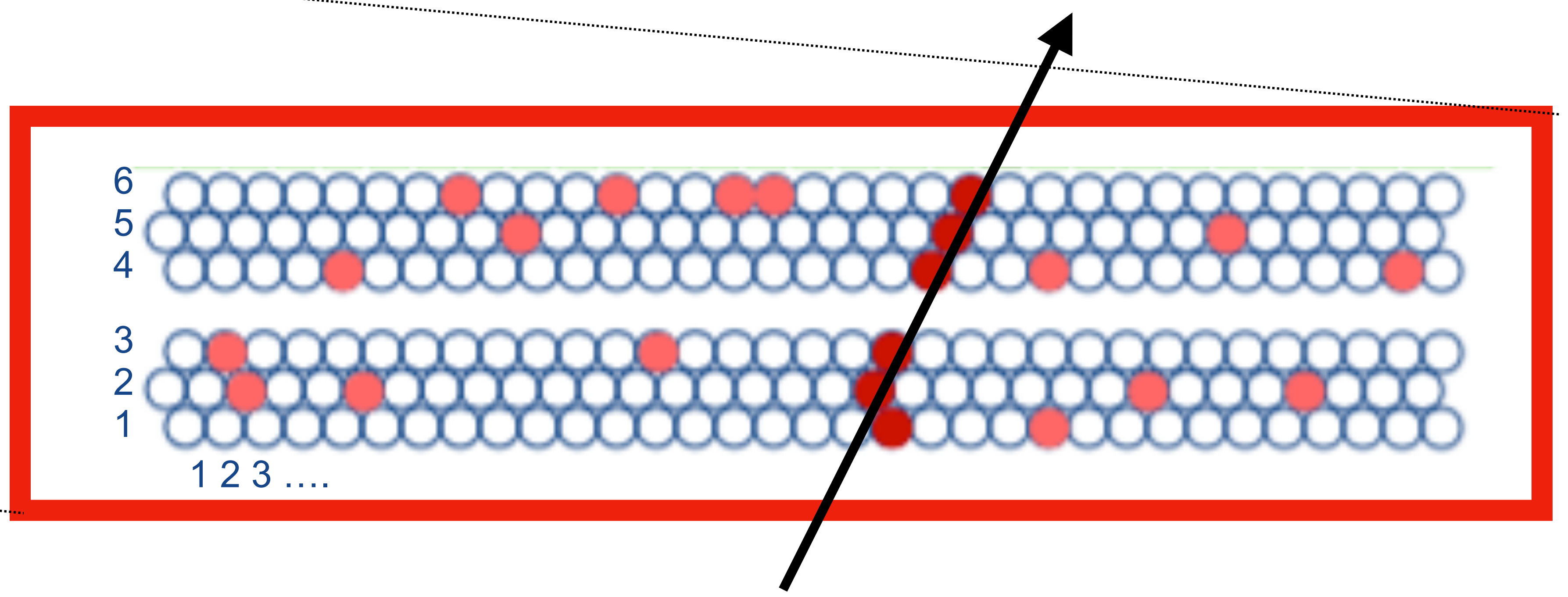


Detector

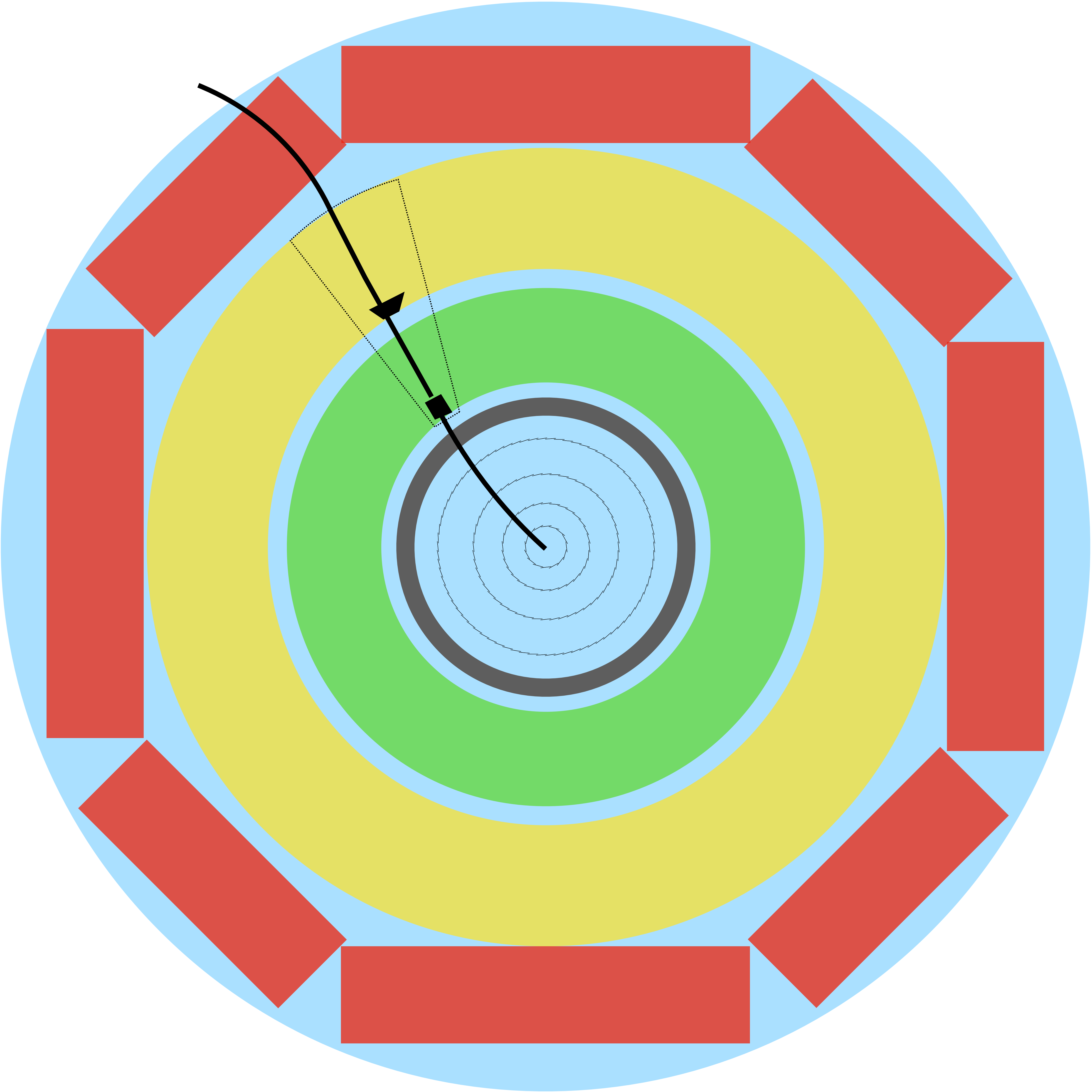


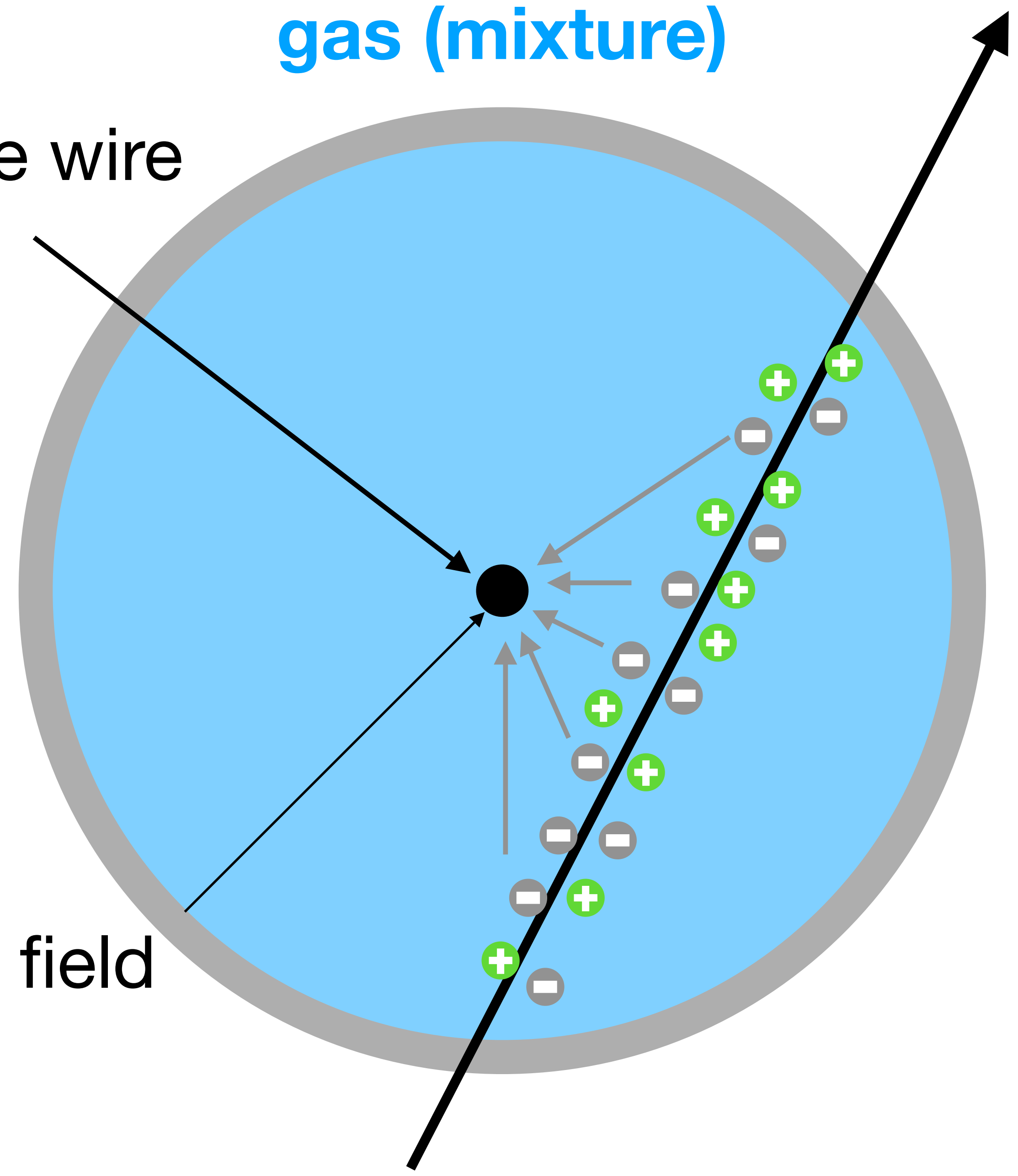


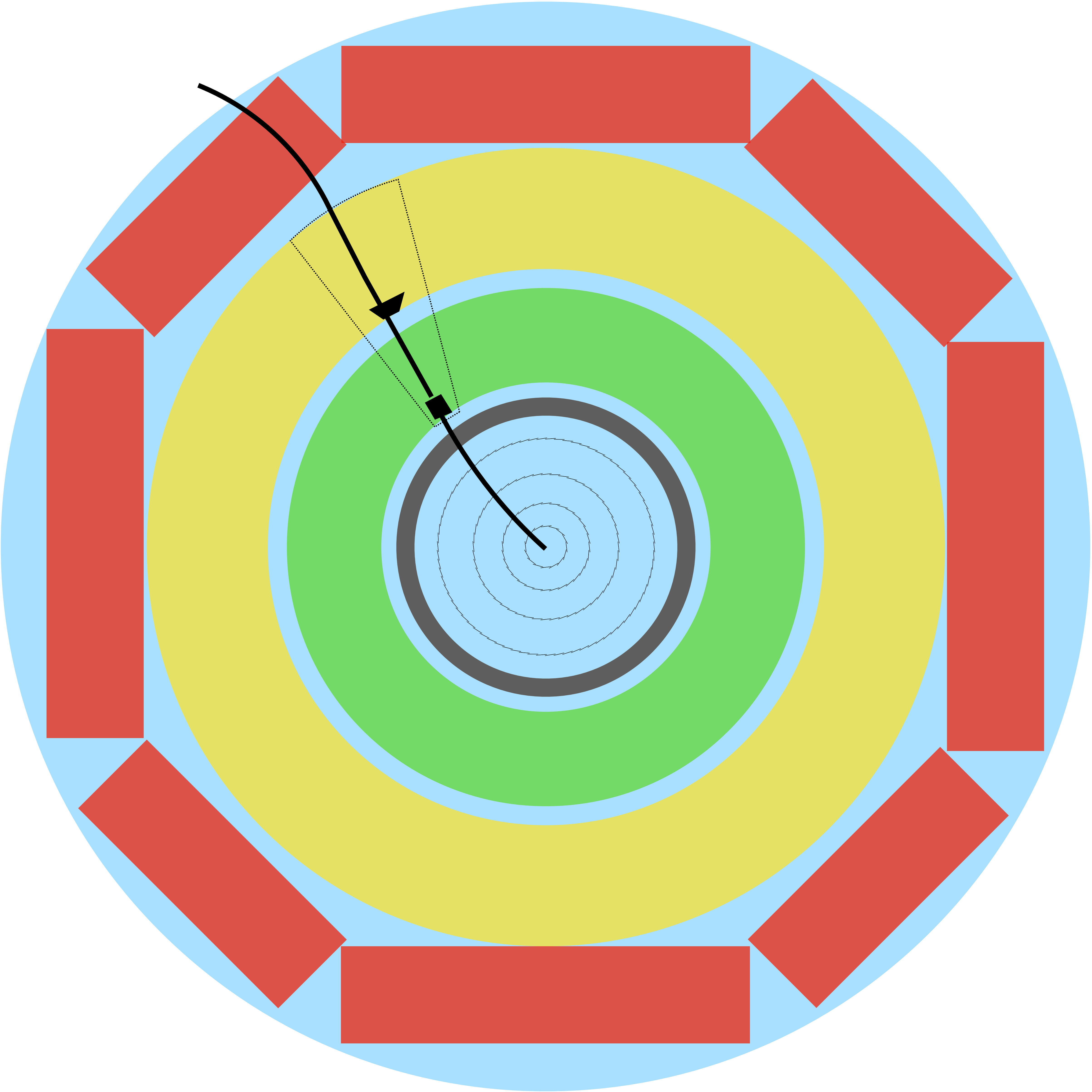
Detector

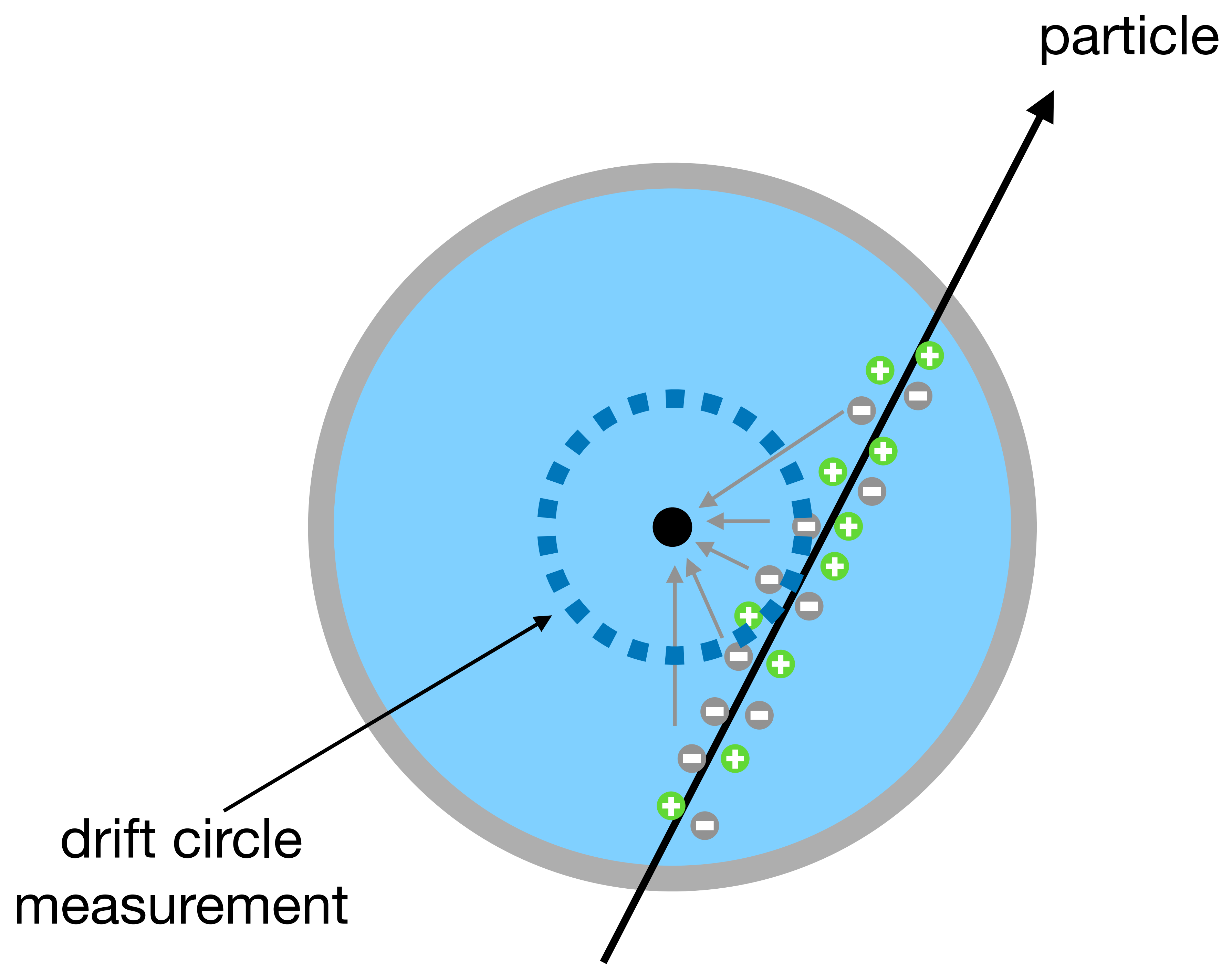


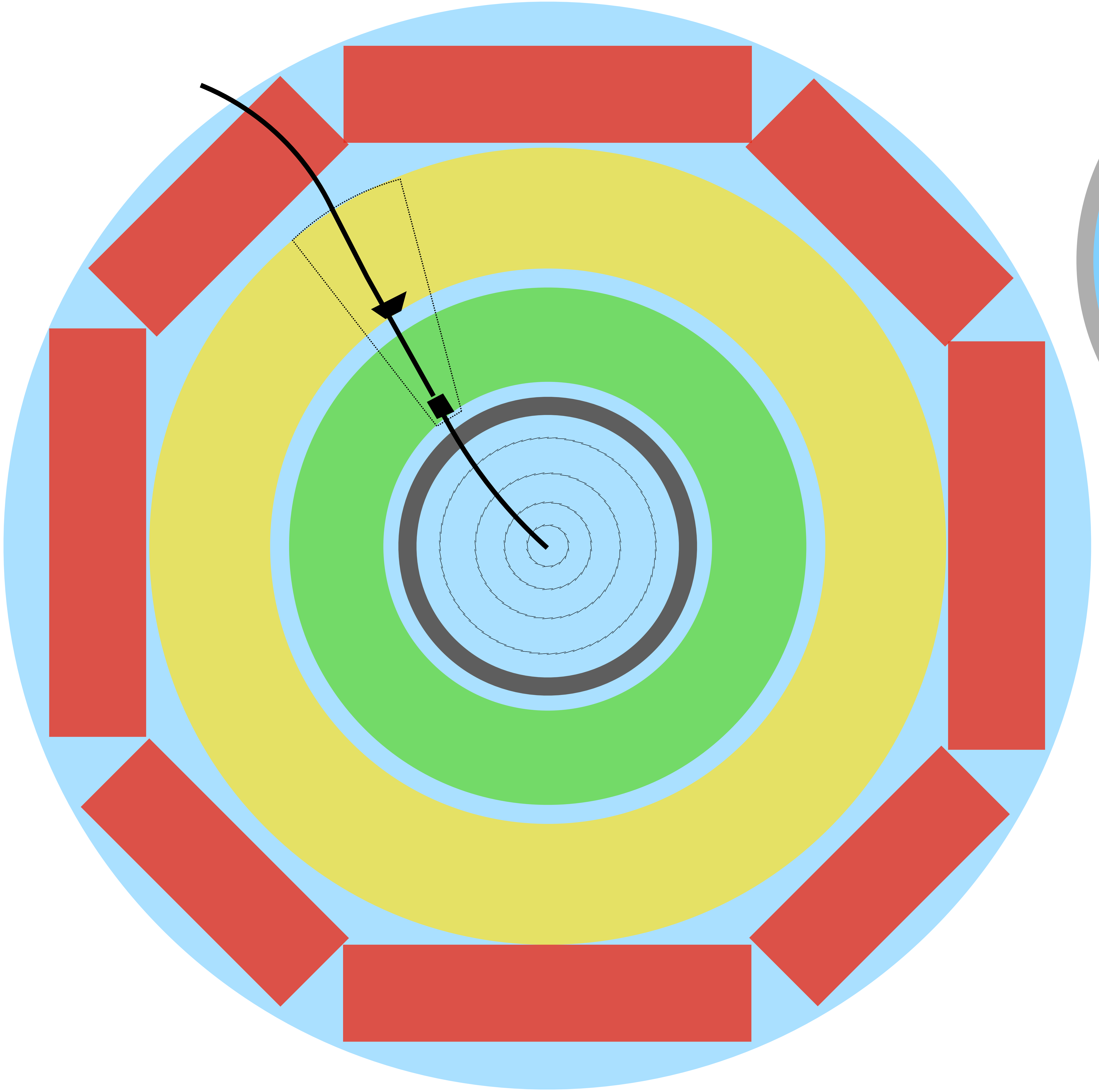
Possible technology:
drift detectors

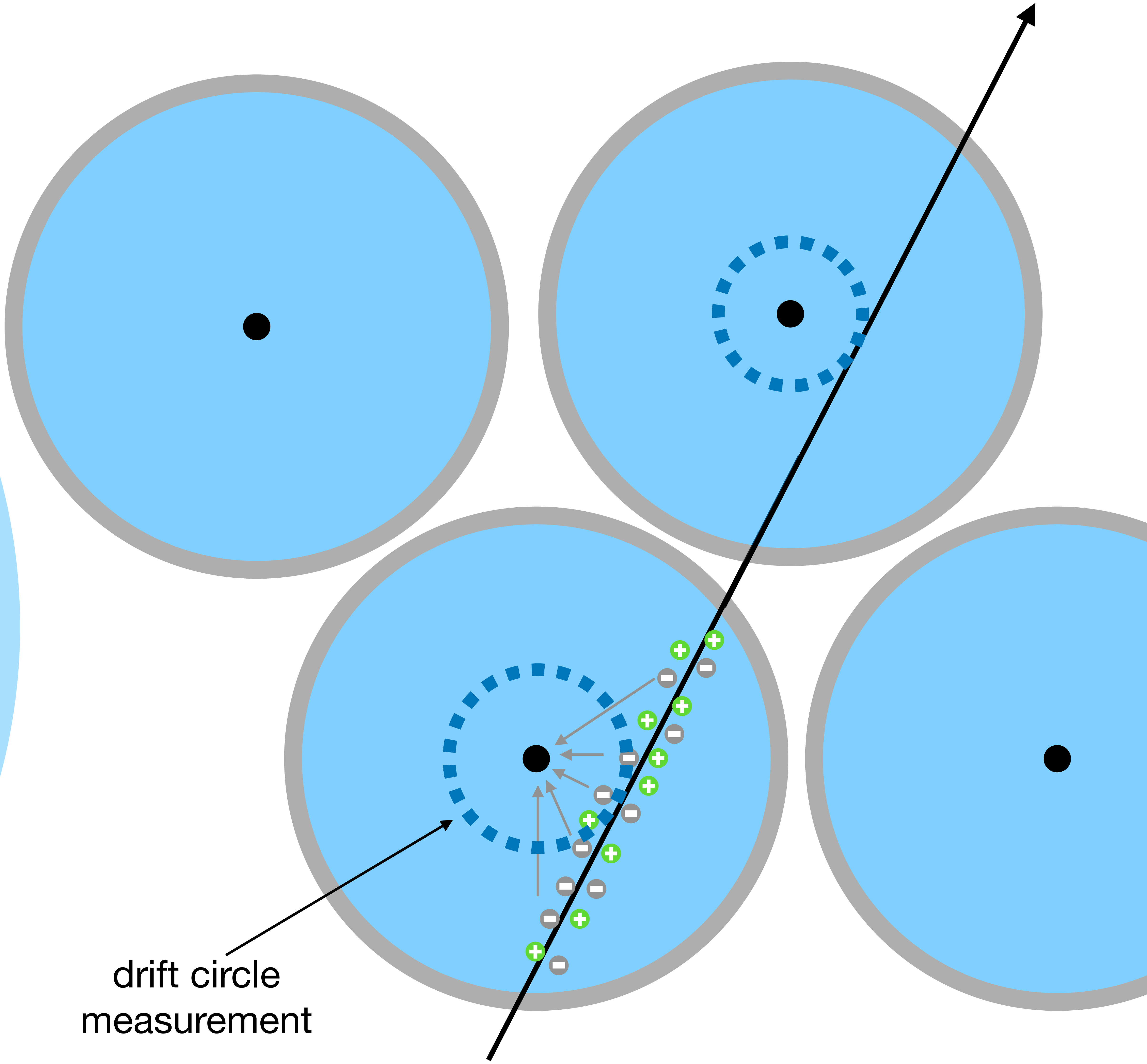



particle
gas (mixture)
anode wire
electric field

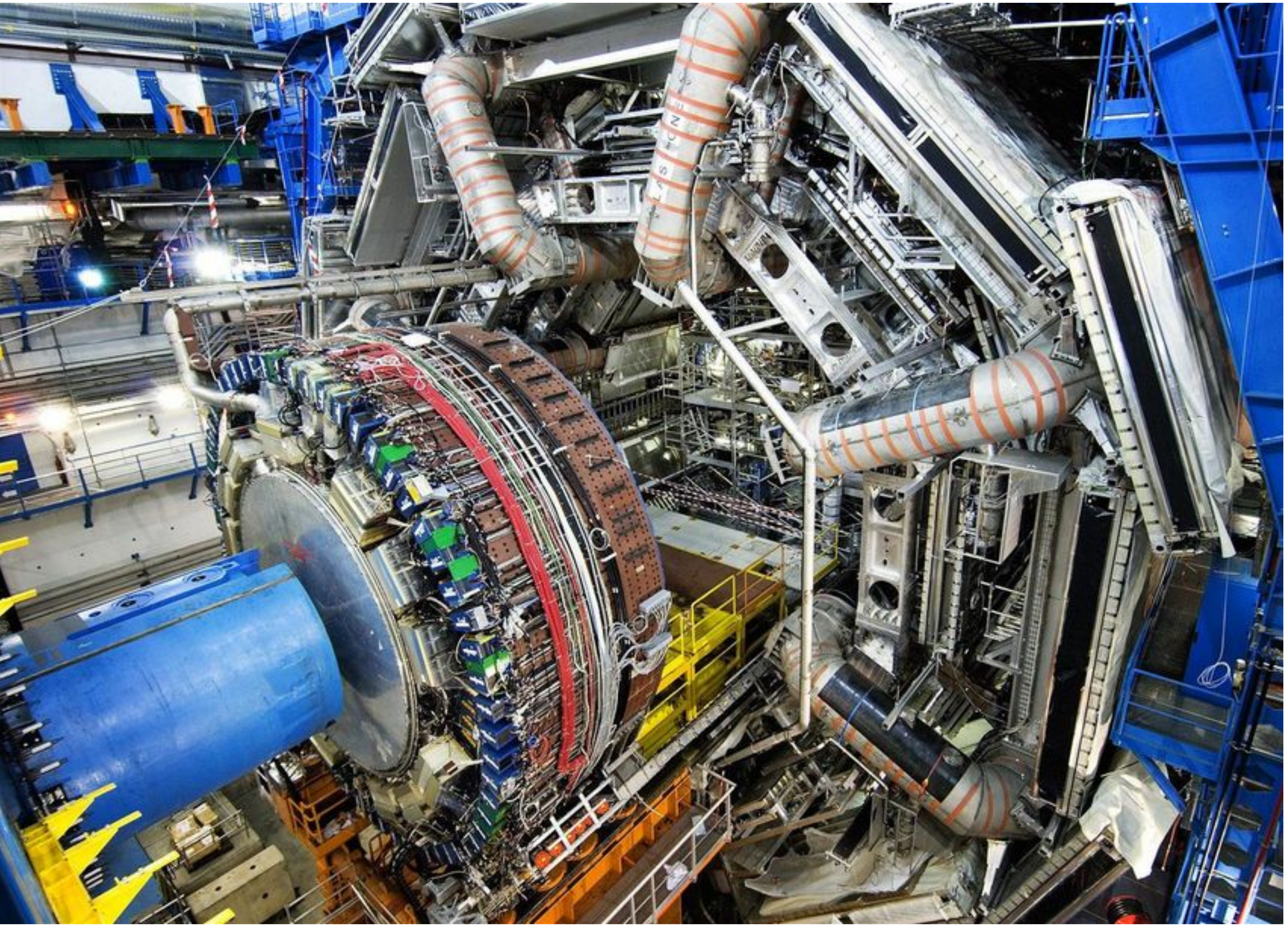



particle
drift circle
measurement

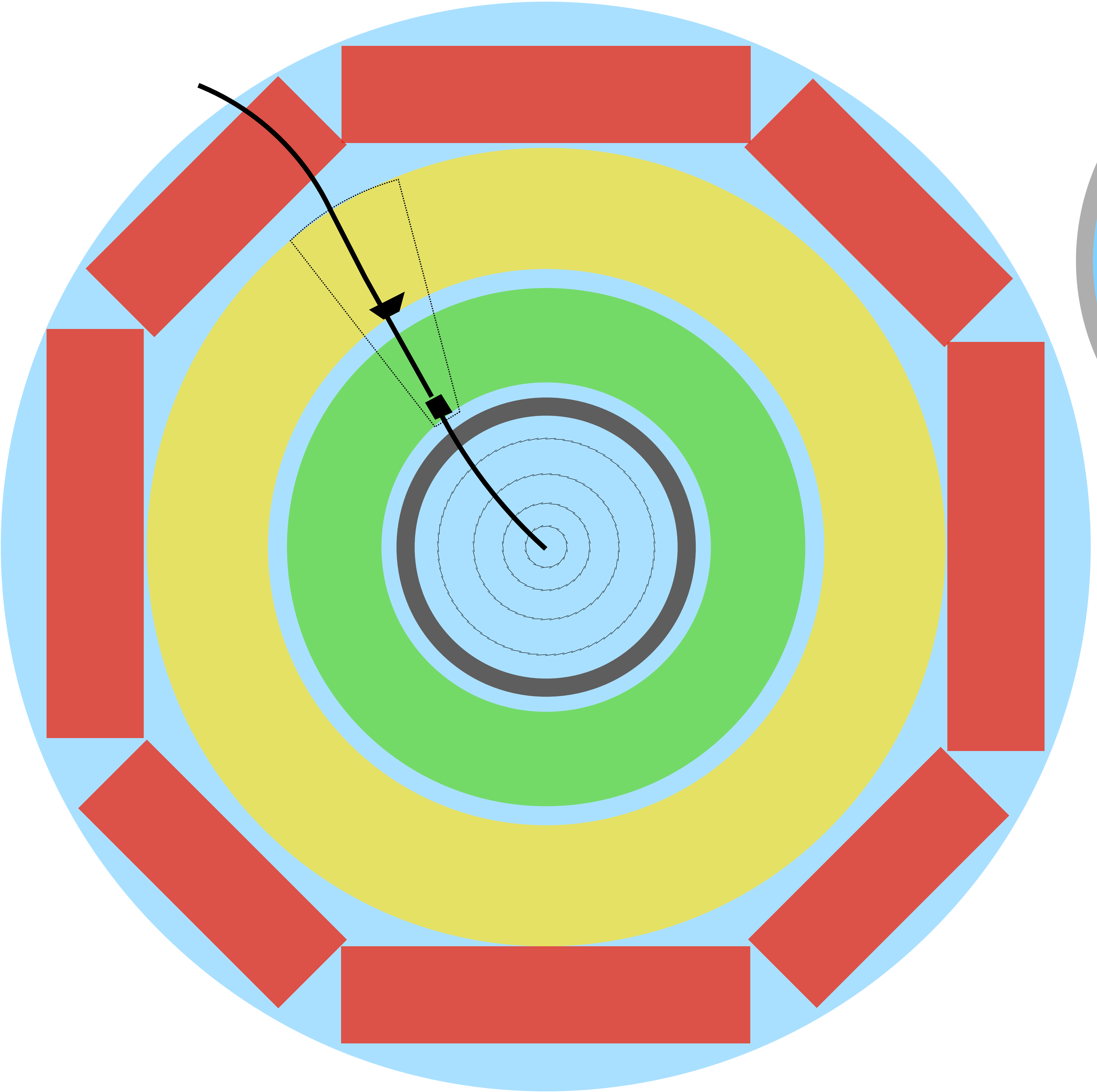


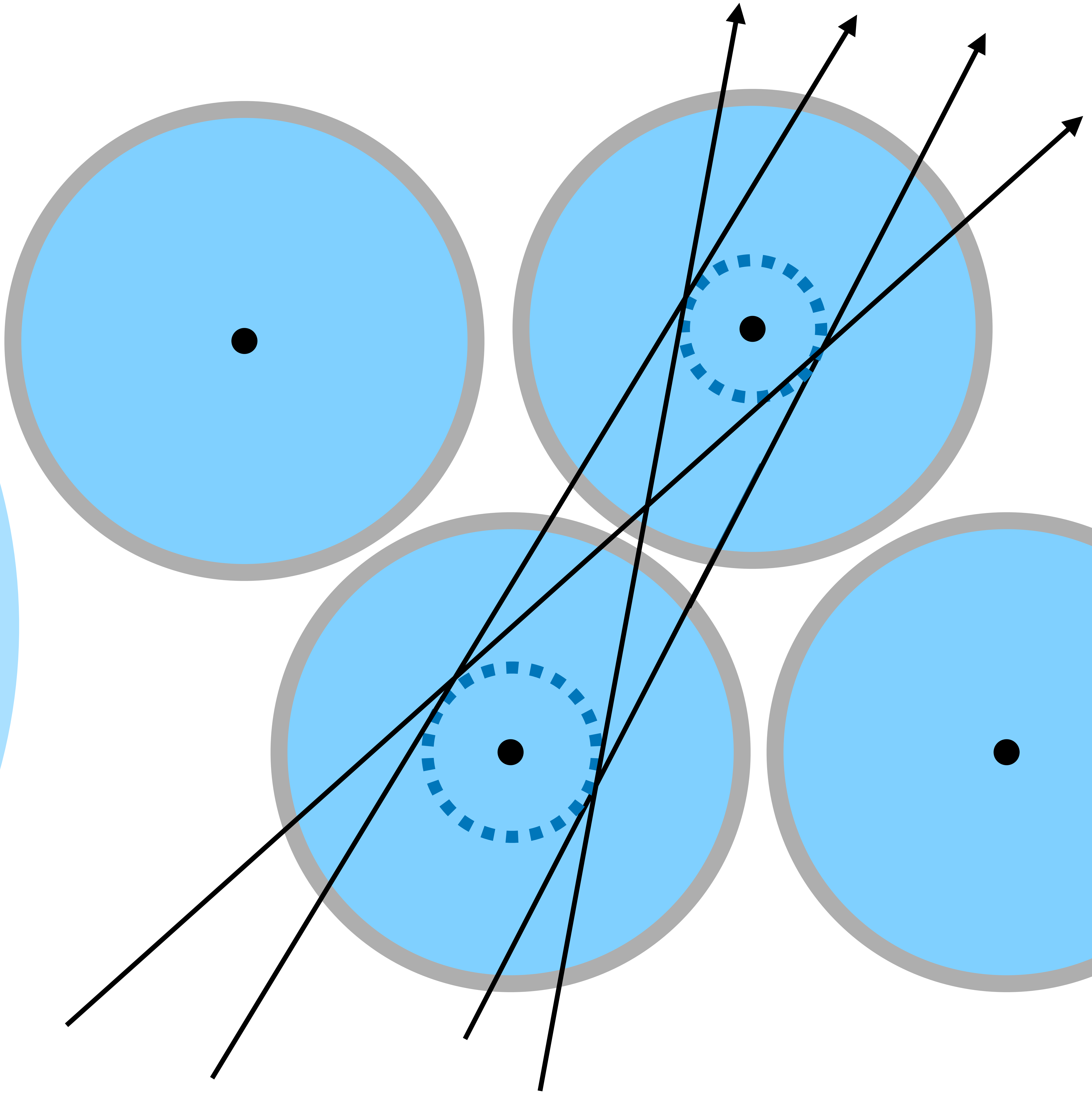

drift circle
measurement

Muon System

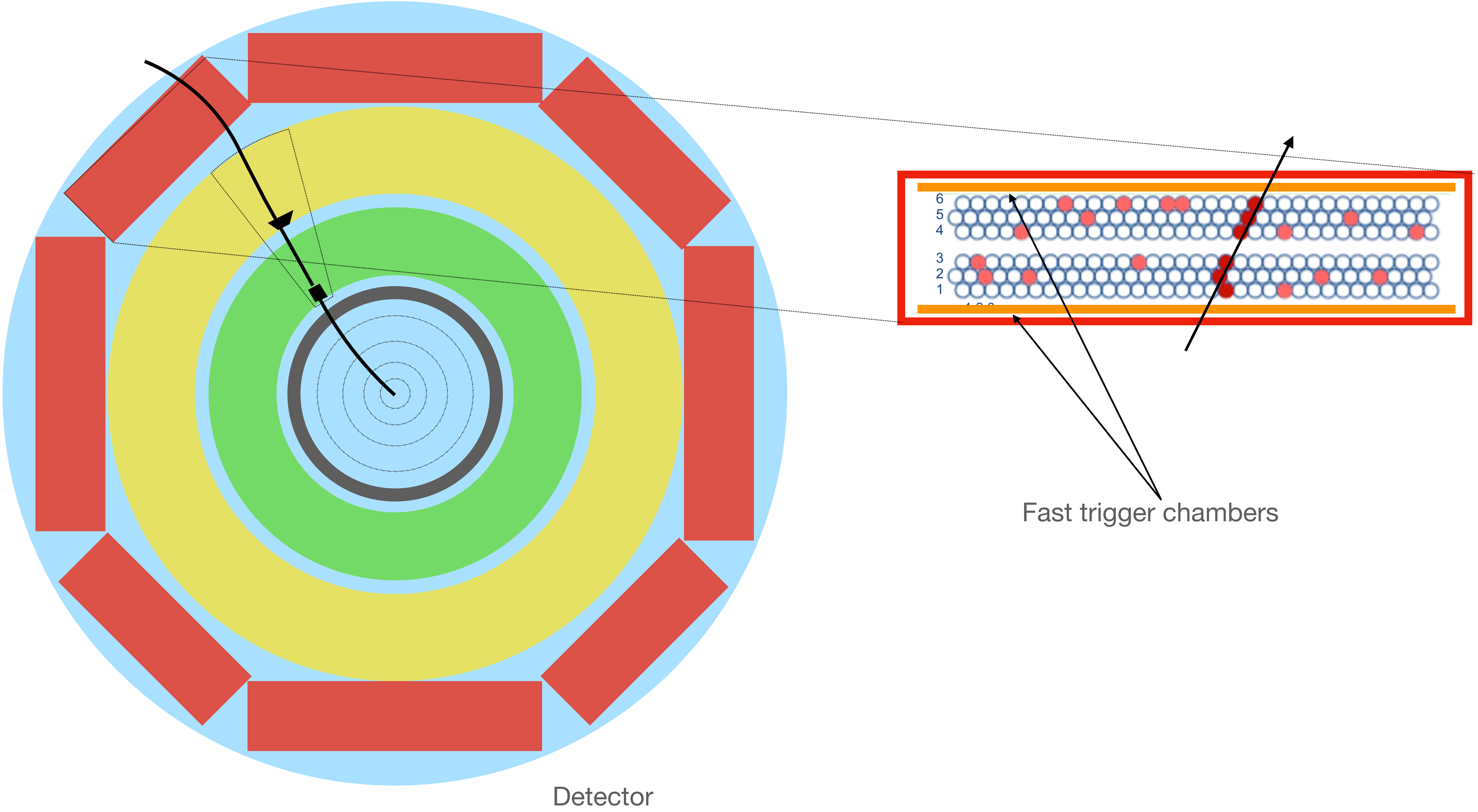


ATLAS Muon Spectrometer





Which is the right one?



6
5
4
3
2
1
Fast trigger chambers
Detector

Let's skip back one step …

Unfortunately … this does not happen often.

The boring regime:
"probability" of
any interaction

10^{10}

The exciting regime:
"probability" of
a Higgs boson
production

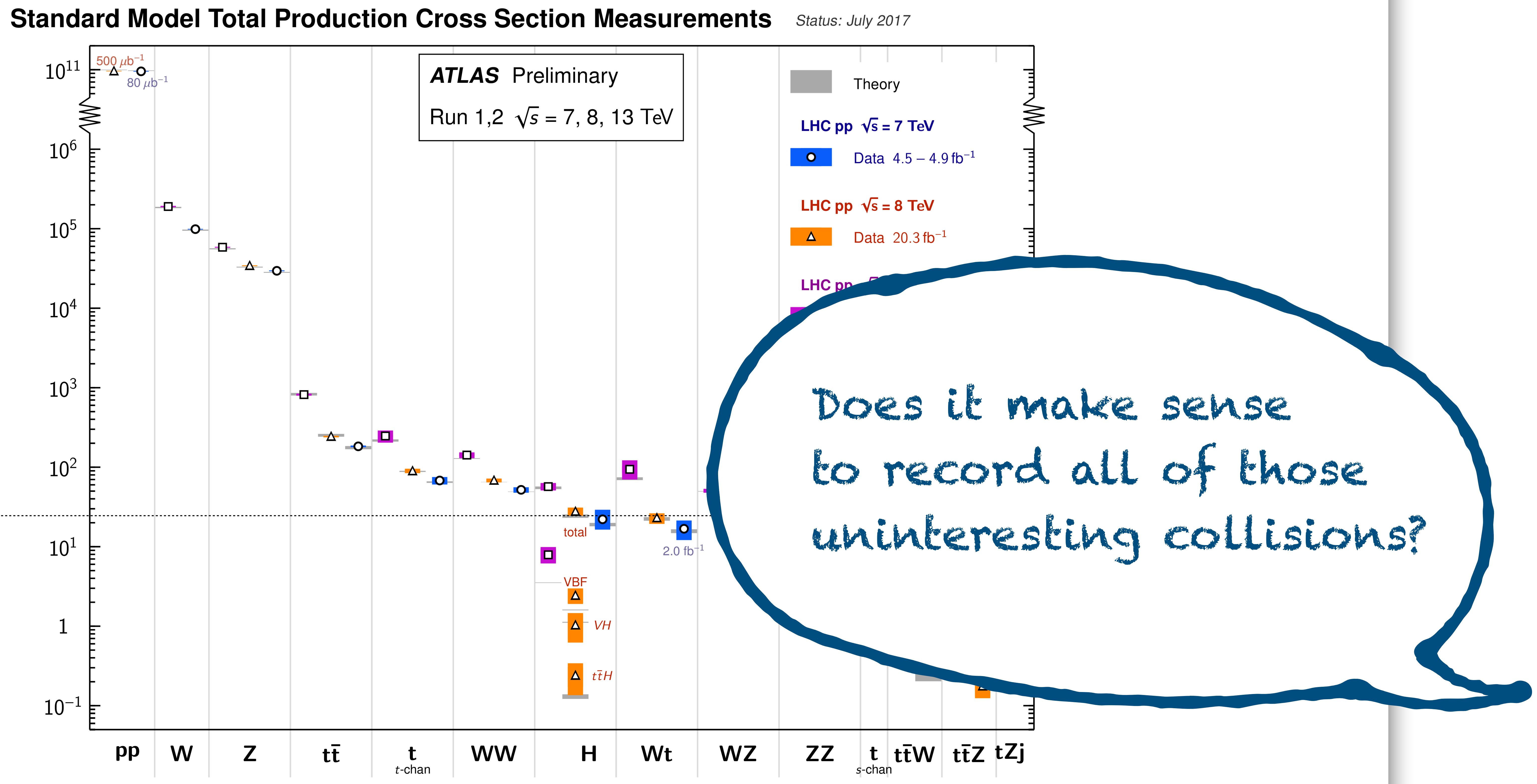
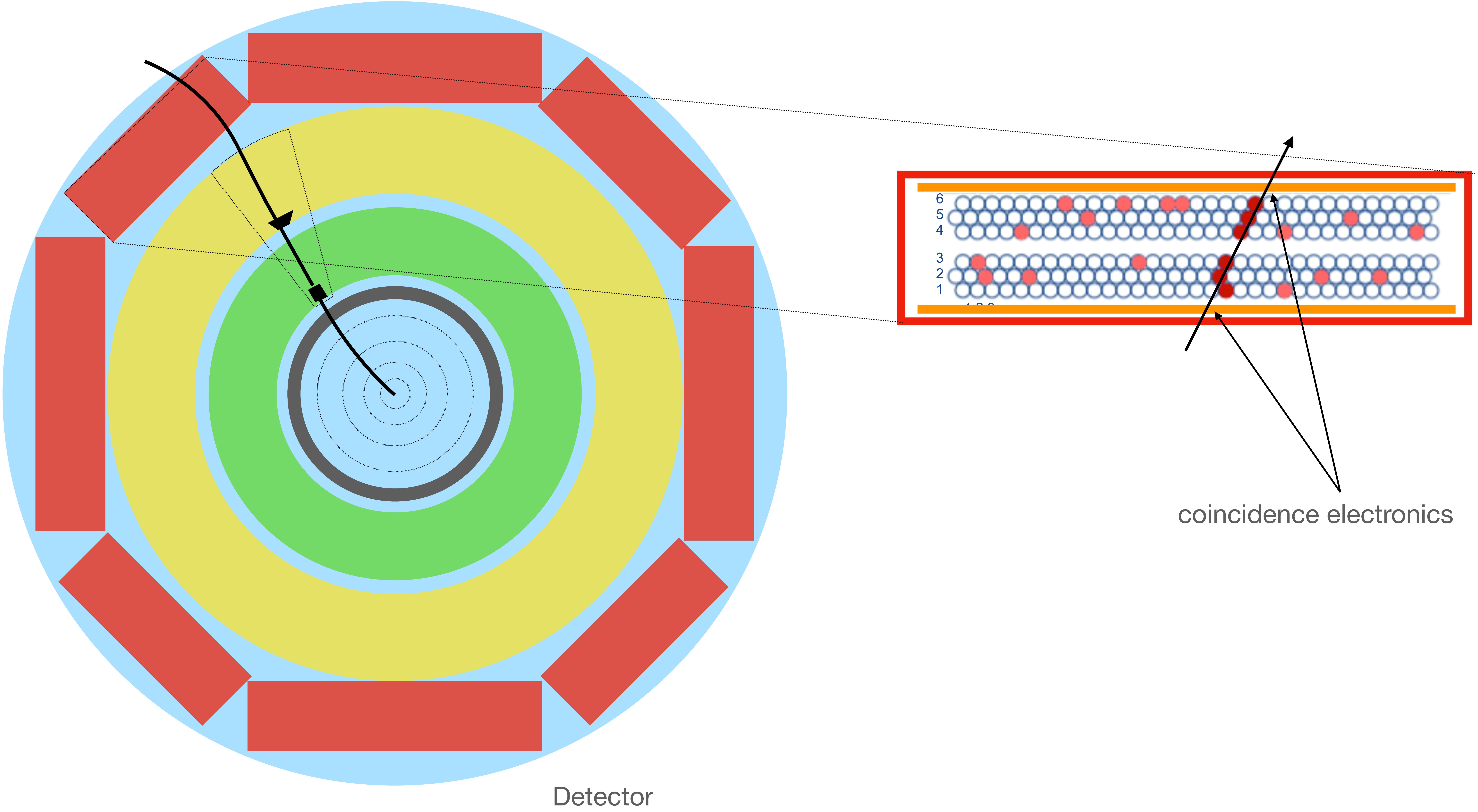
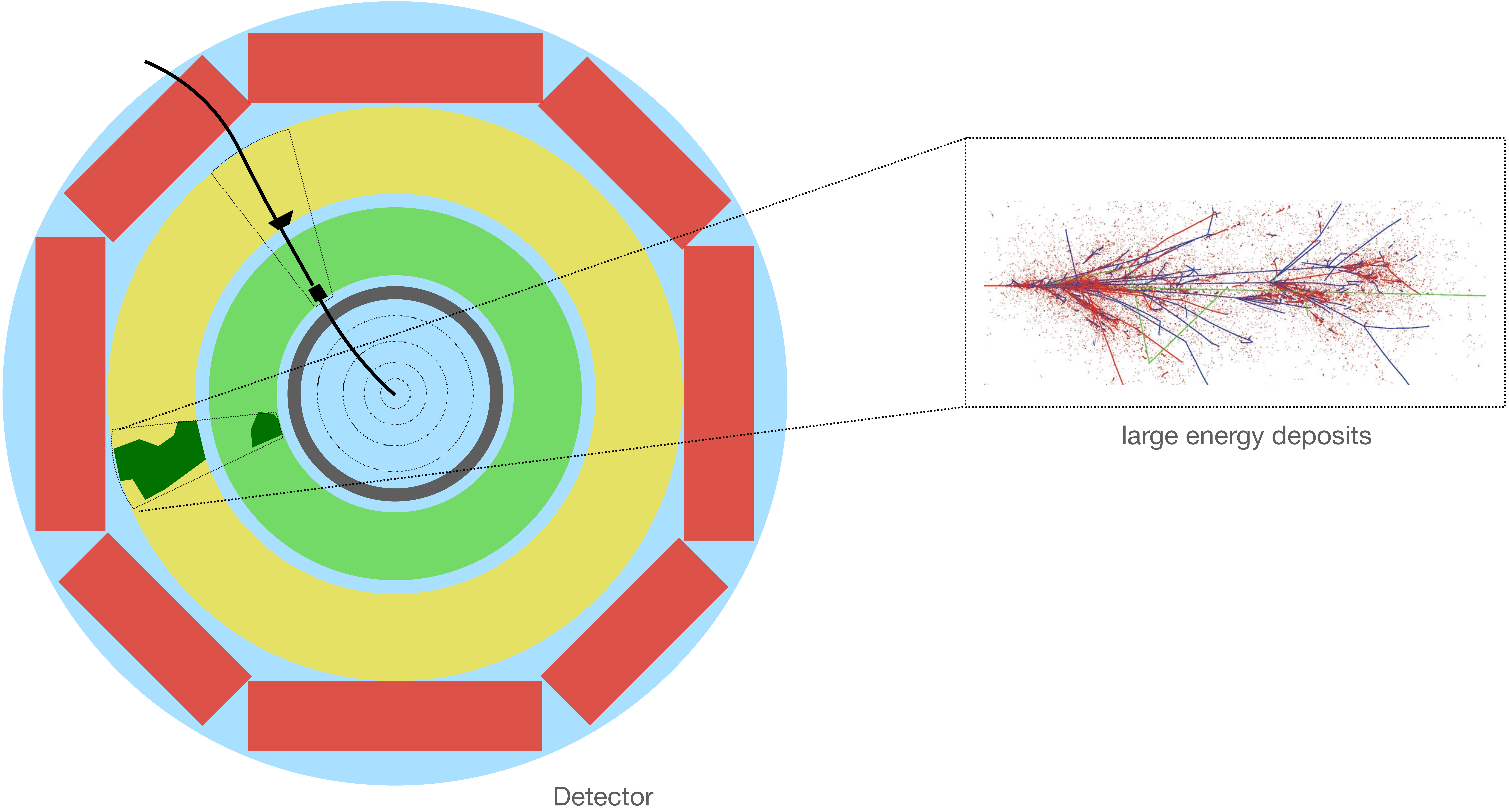


Figure:
Standard Model cross sections measured with the ATLAS experiment
and compared to theoretical predictions, July 2017

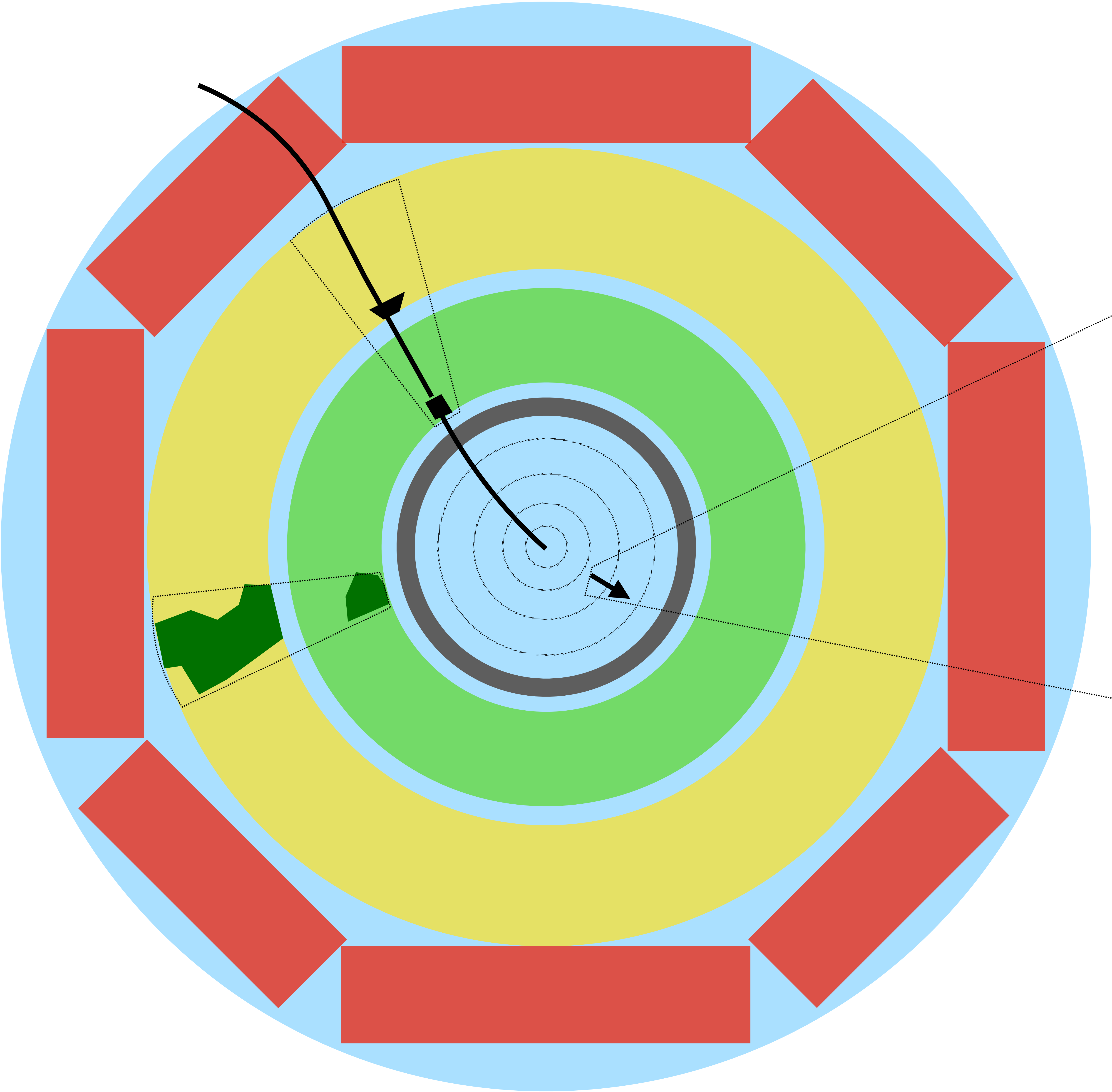
Triggers



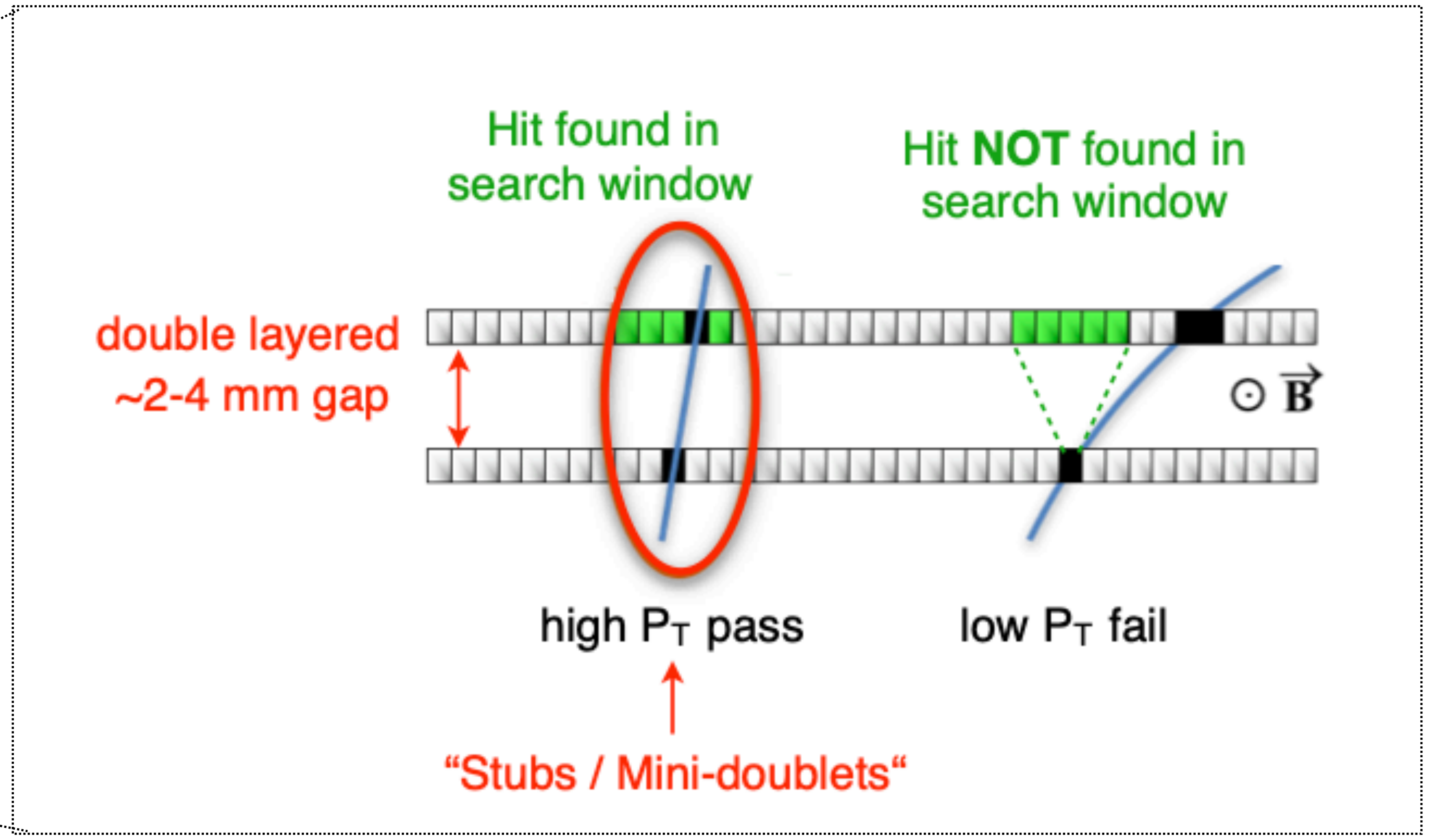
Triggers



Triggers

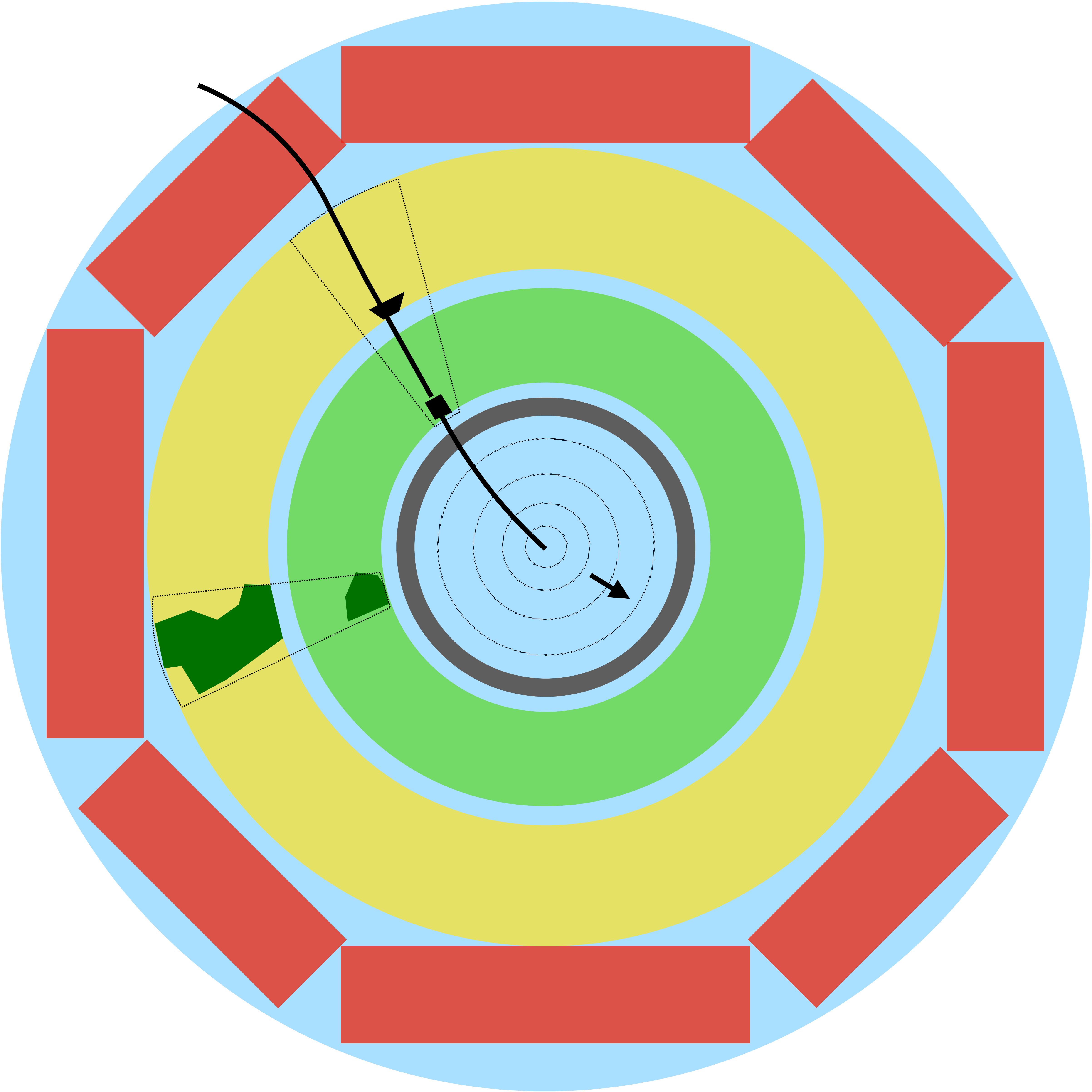


Detector



compatible tracklets

Triggers



Detector

Collision rate: 40 MHz

Dedicated readout

coincidence electronics

large energy deposits

compatible trackless

ASICS/FPGAs

simple algorithms

GPUs

fast algorithms

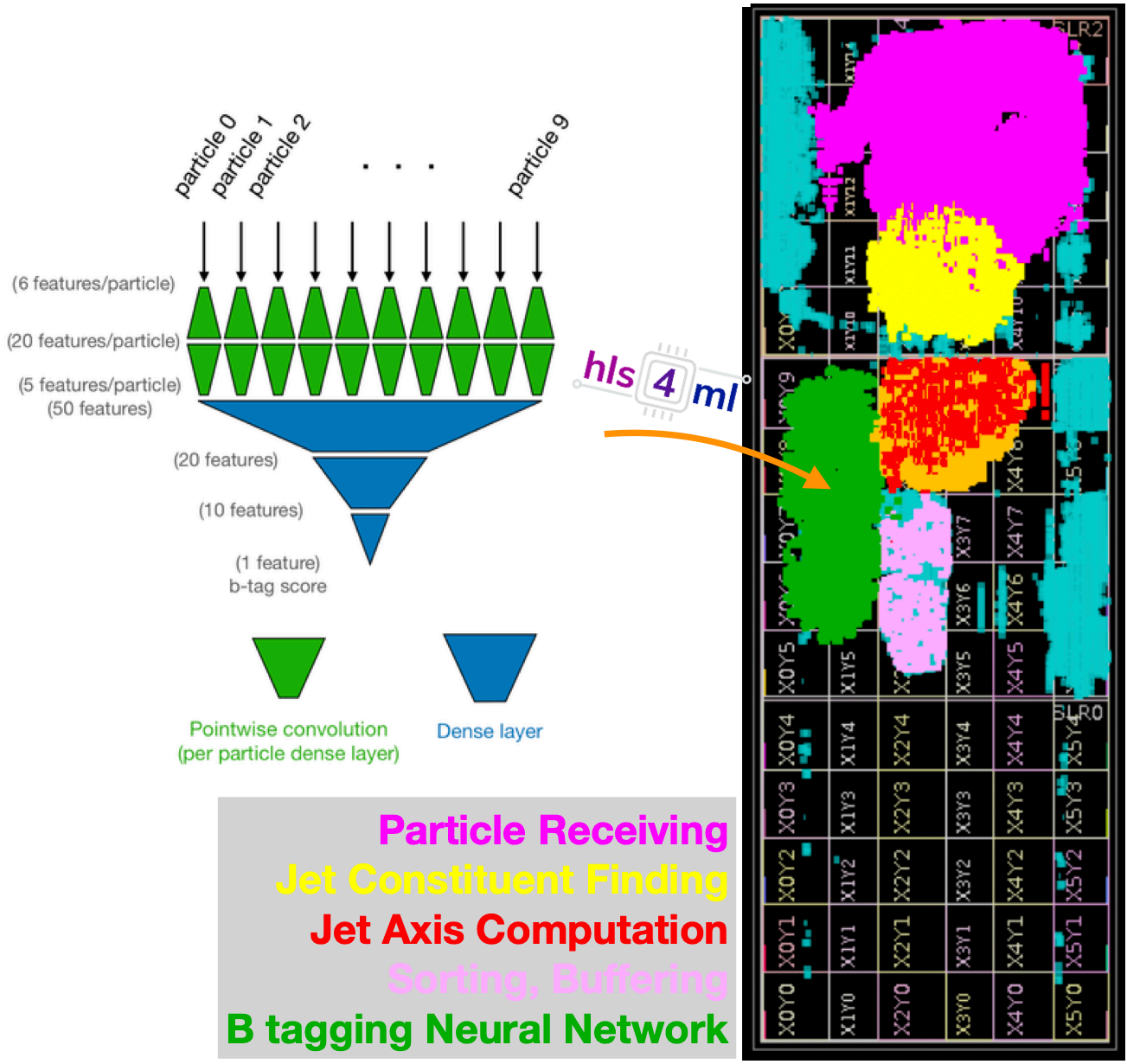
CPUs

Compute intense algorithms

Writing rate to disk: ~ 1-5 kHz

Triggers

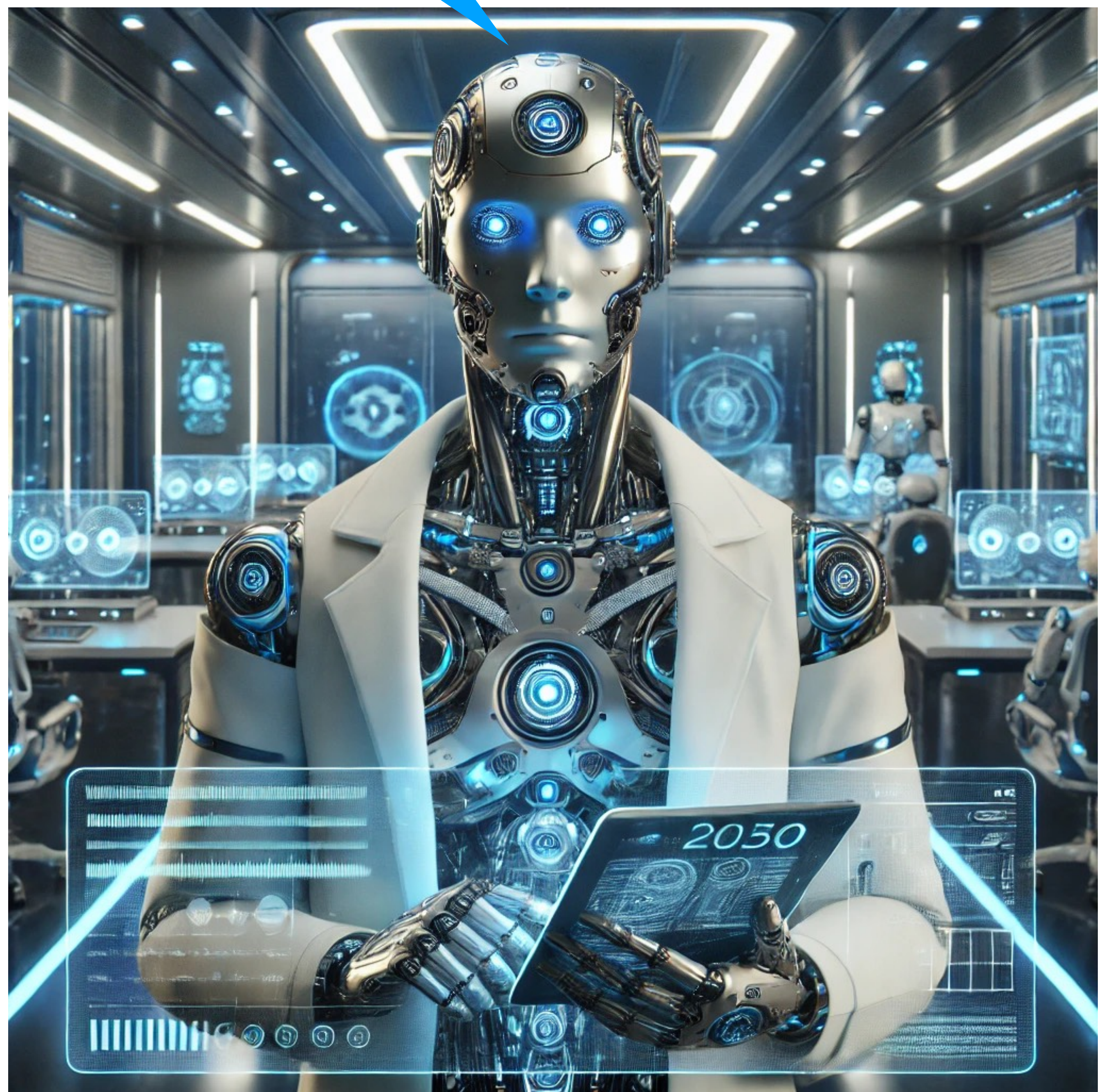
[Source]



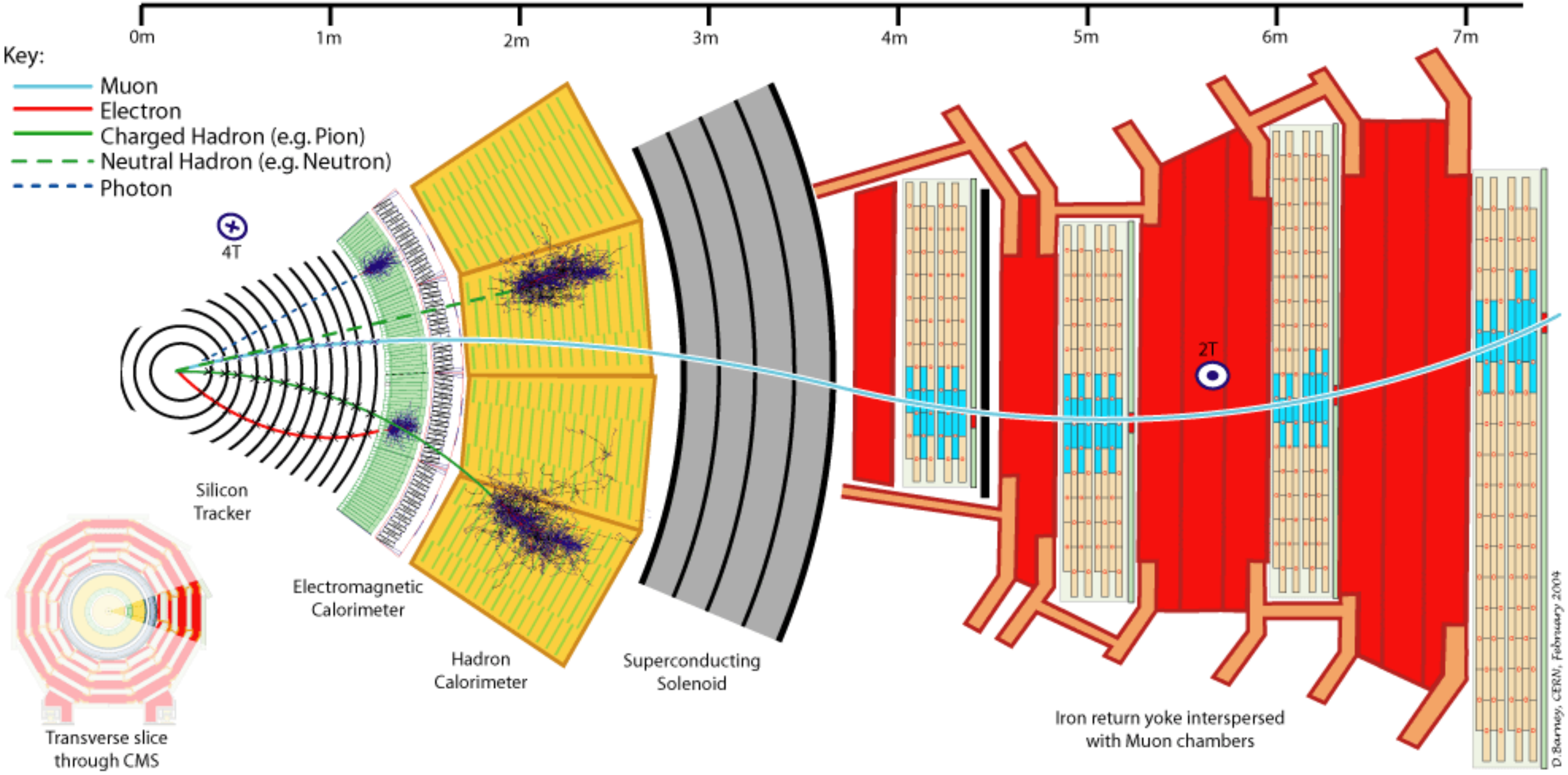
AMD VU9P

Jet tagging network for triggers in CMS executed on an FPGA.

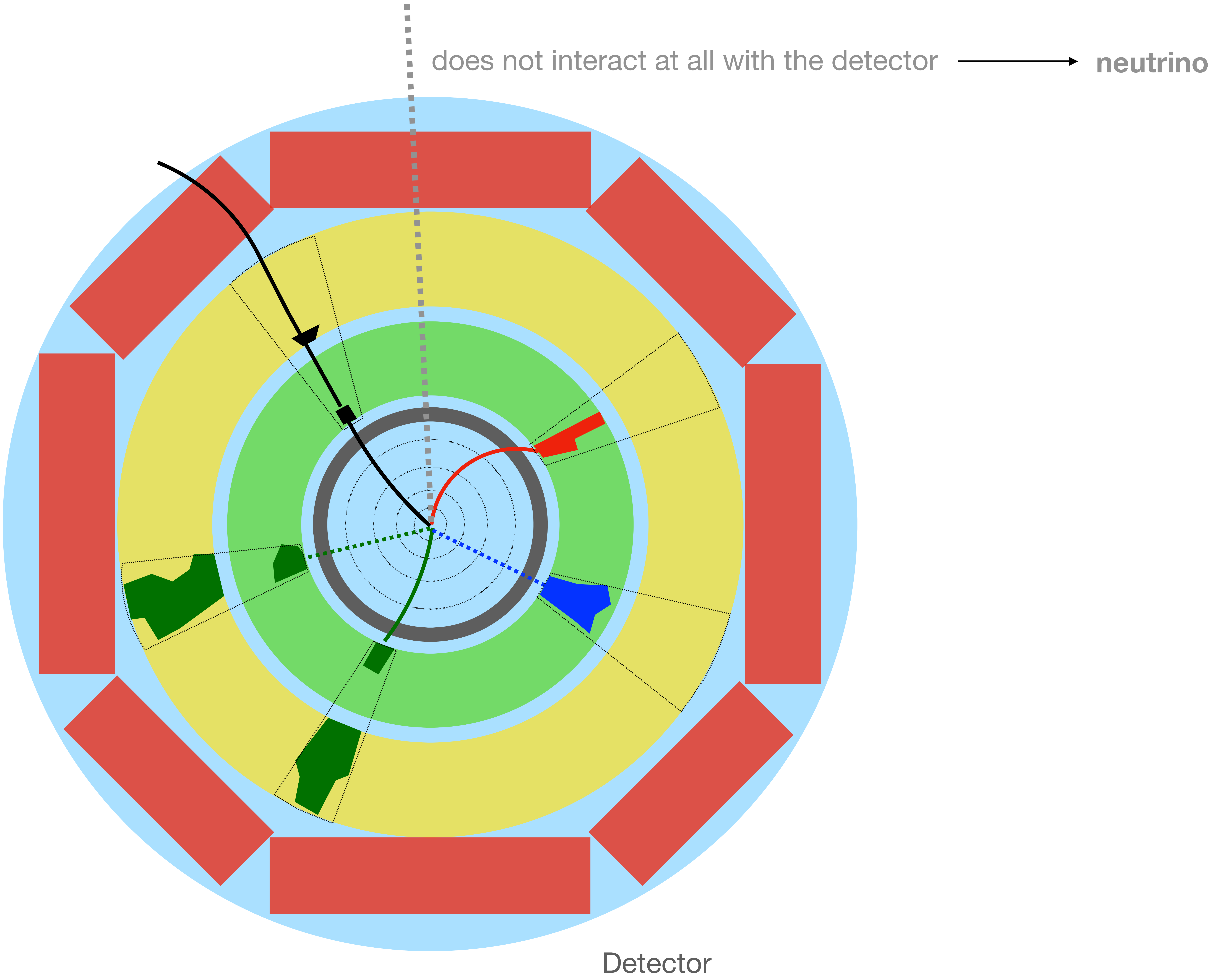
Artificial Intelligence for Triggering is a very active research field.

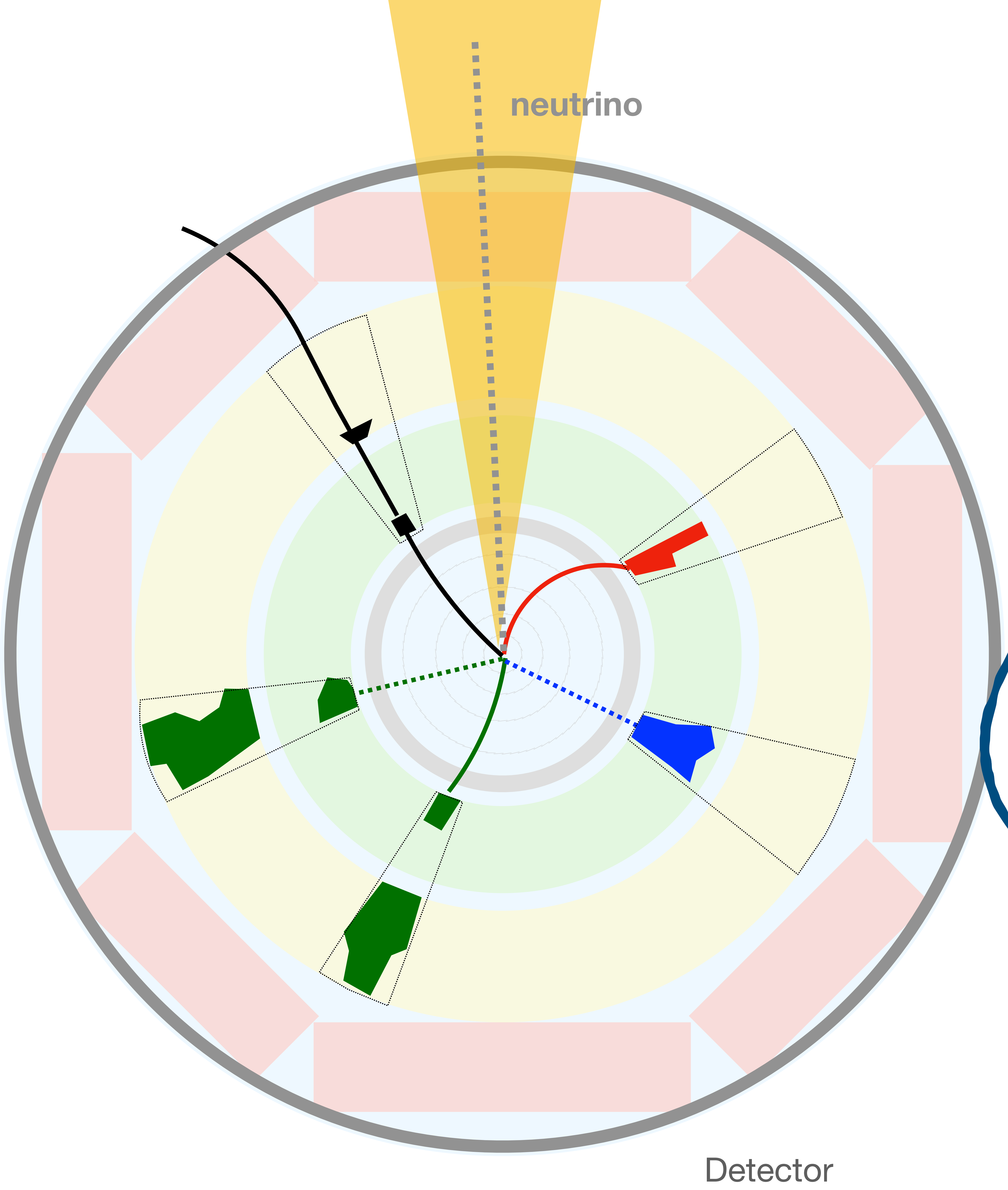


Summary



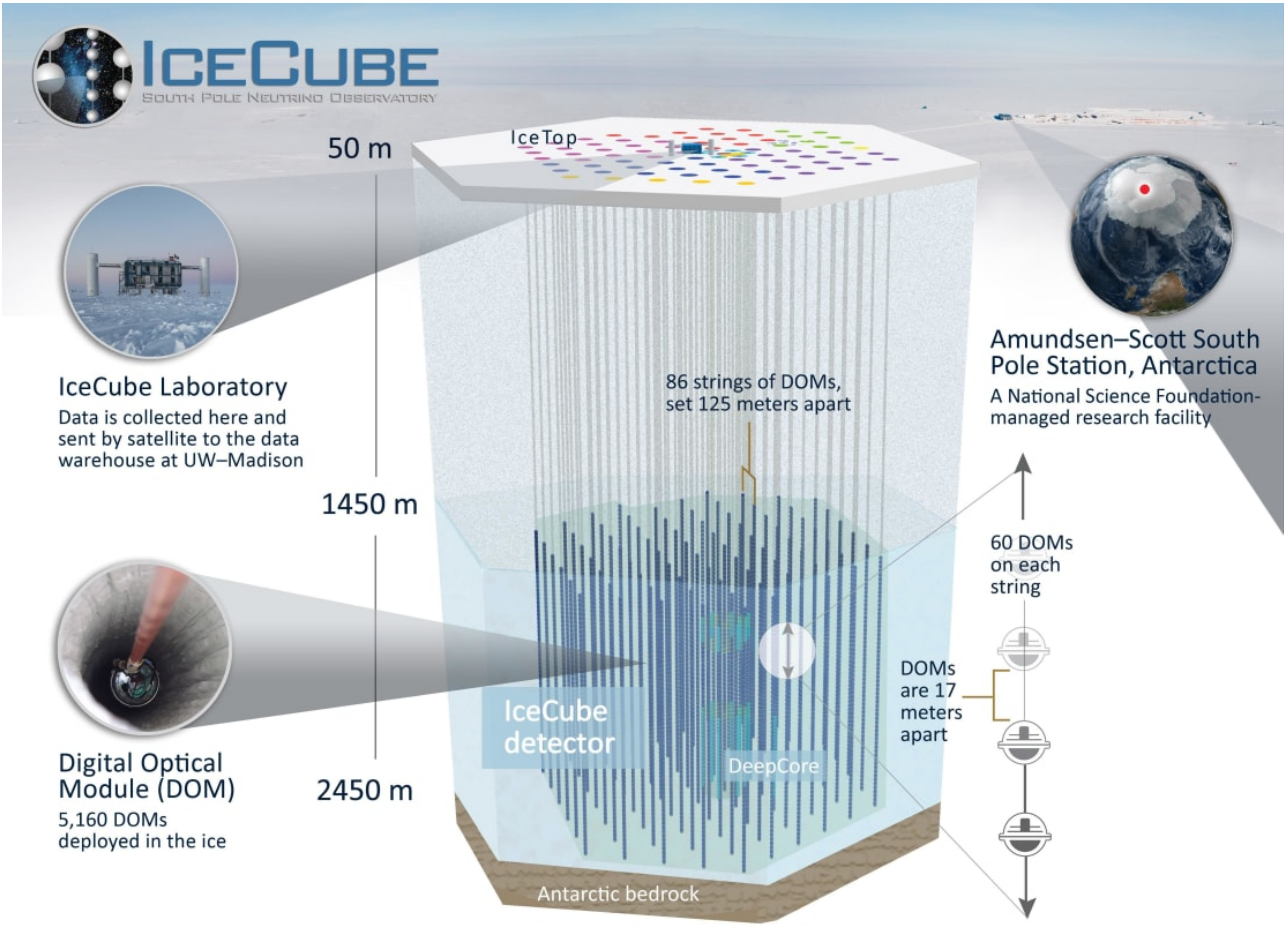
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

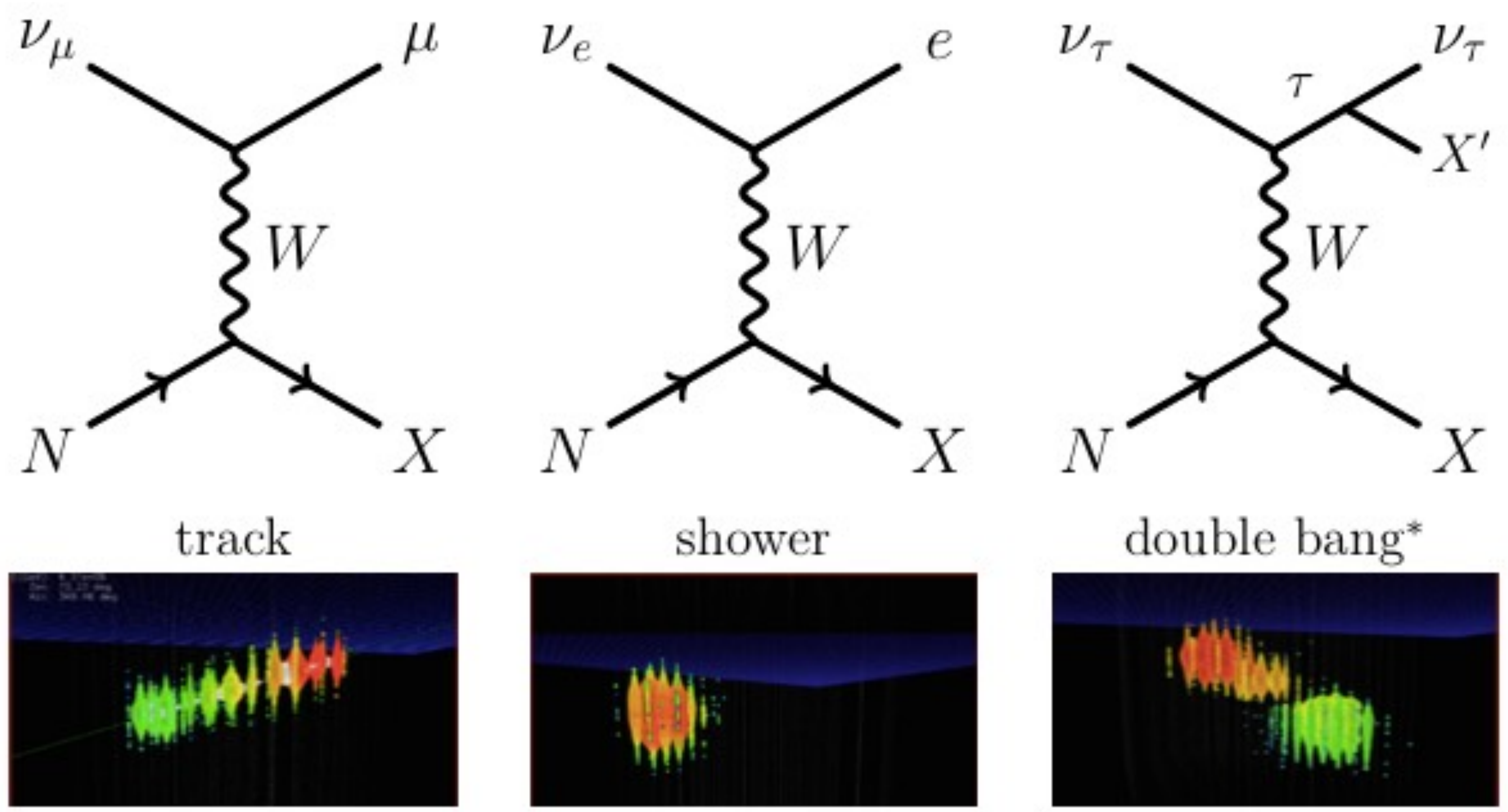

does not interact at all with the detector
neutrino
Detector


neutrino
Detector

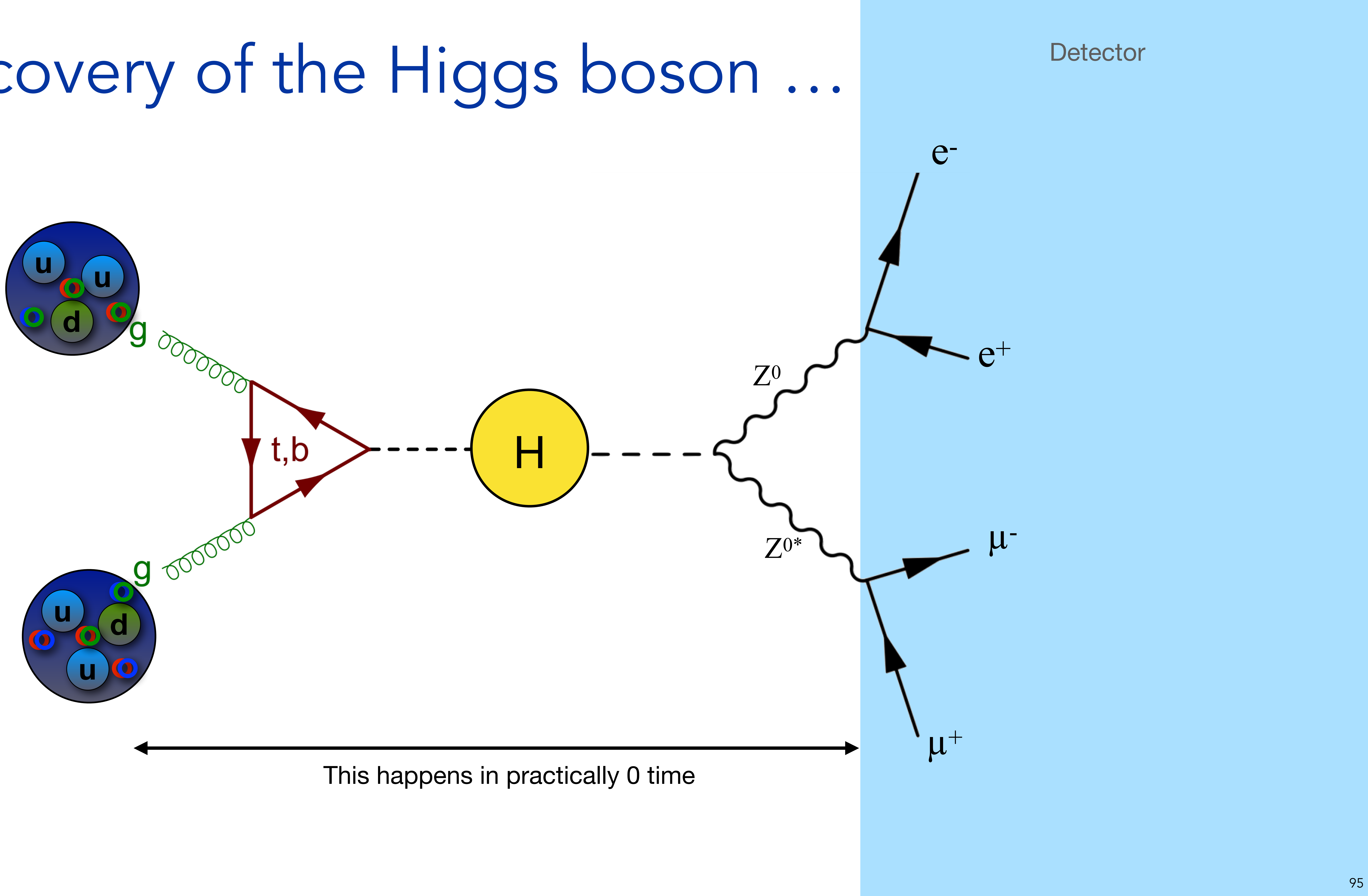

Neutrinos (or their missing energy) are estimated using momentum and energy conservation laws.

Neutrino Detectors



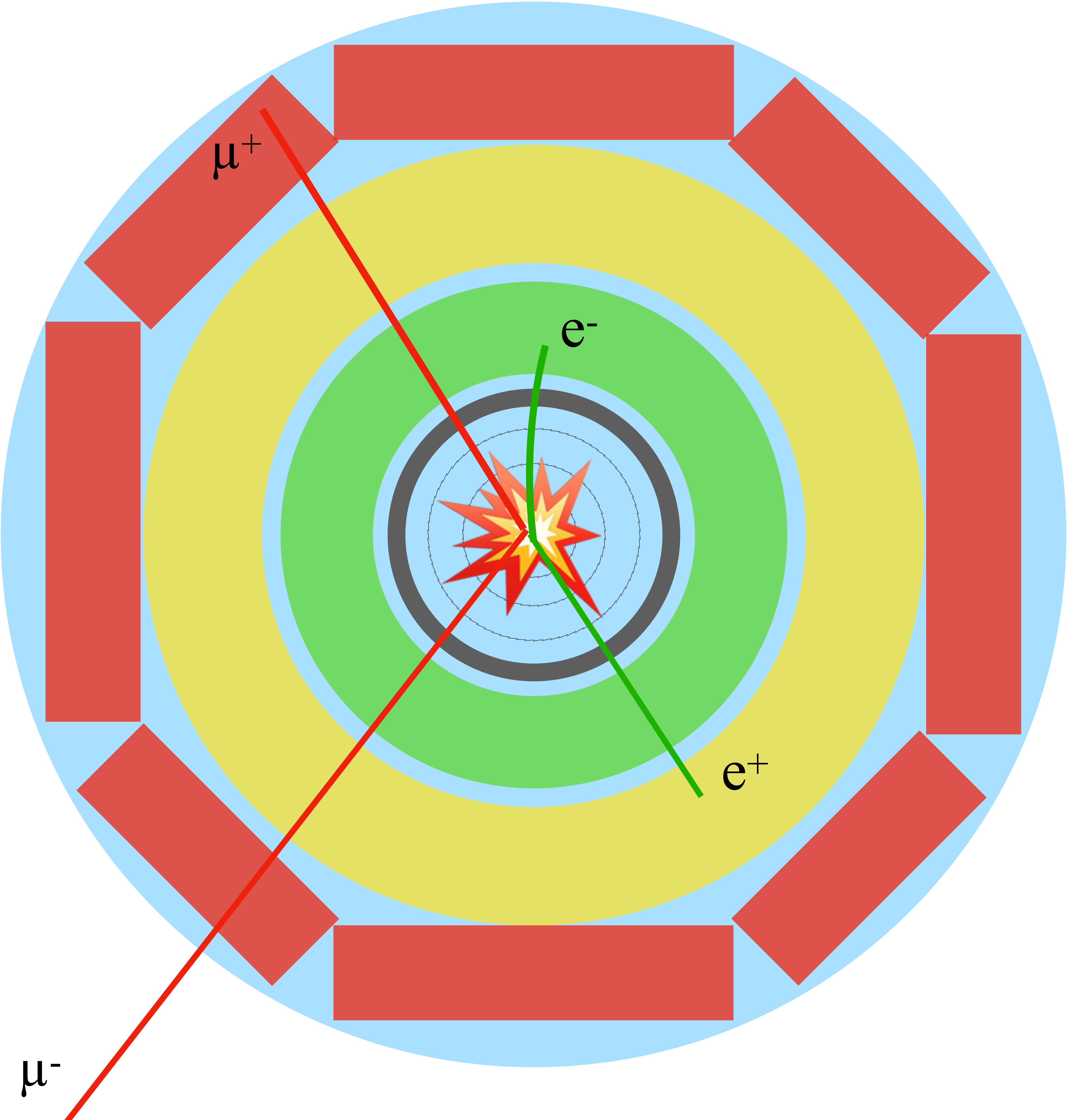


Discovery of the Higgs boson …

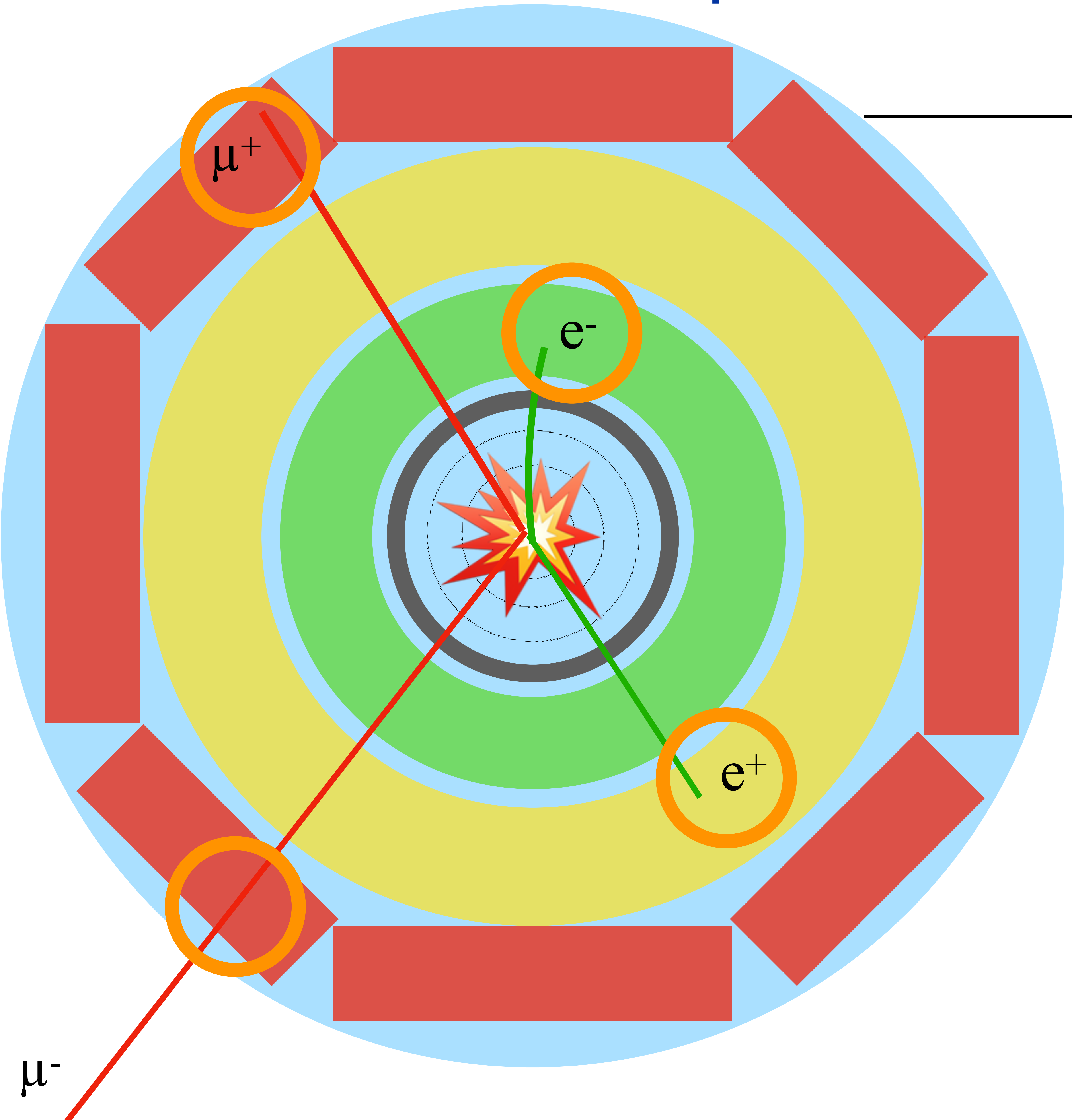


This happens in practically 0 time

… in our detector



Let us run the experiment



Level 1 Trigger to 100 kHz
detector electronics

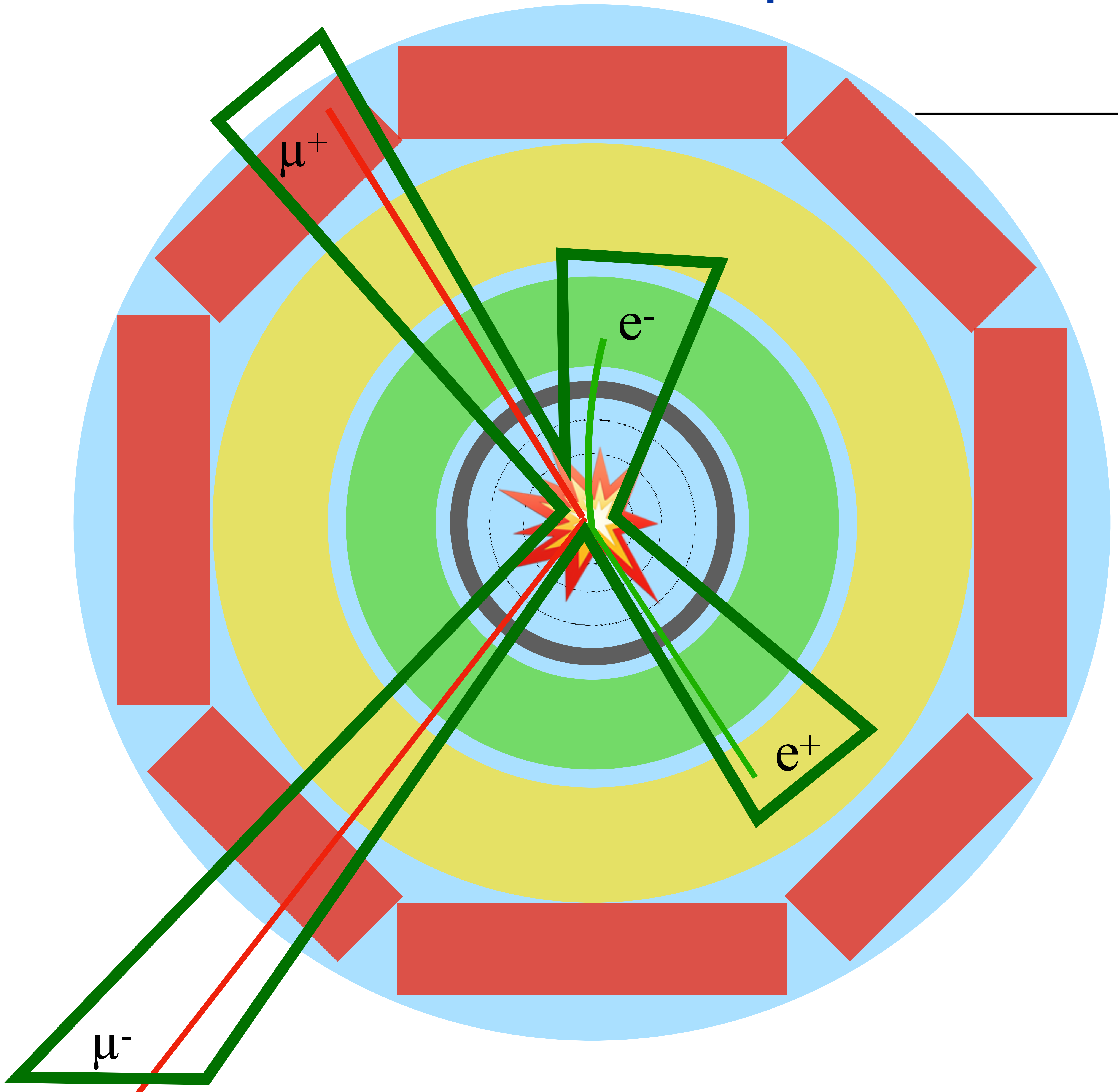
4 lepton signals

High level trigger ~1kHz
close-by computer farm

Full processing of events
1000 events/second

Data Analysis & publication

Let us run the experiment



Level 1 Trigger to 100 kHz
detector electronics

4 lepton signals

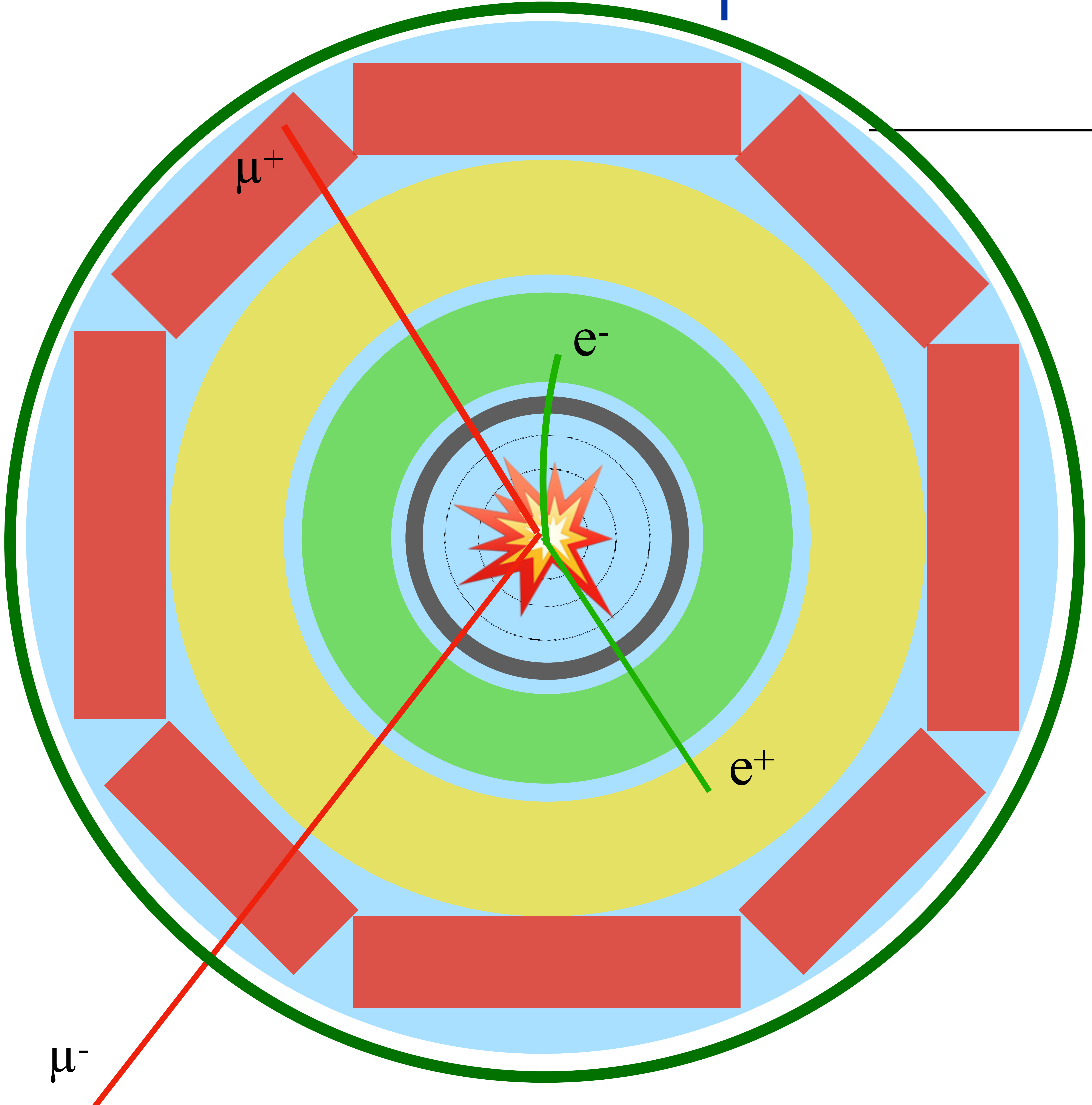
High level trigger ~1kHz
close-by computer farm

4 lepton signals confirmed

Full processing of events
1000 events/second

Data Analysis & publication

Let us run the experiment



Level 1 Trigger to 100 kHz
detector electronics

4 lepton signals

High level trigger ~1kHz
close-by computer farm

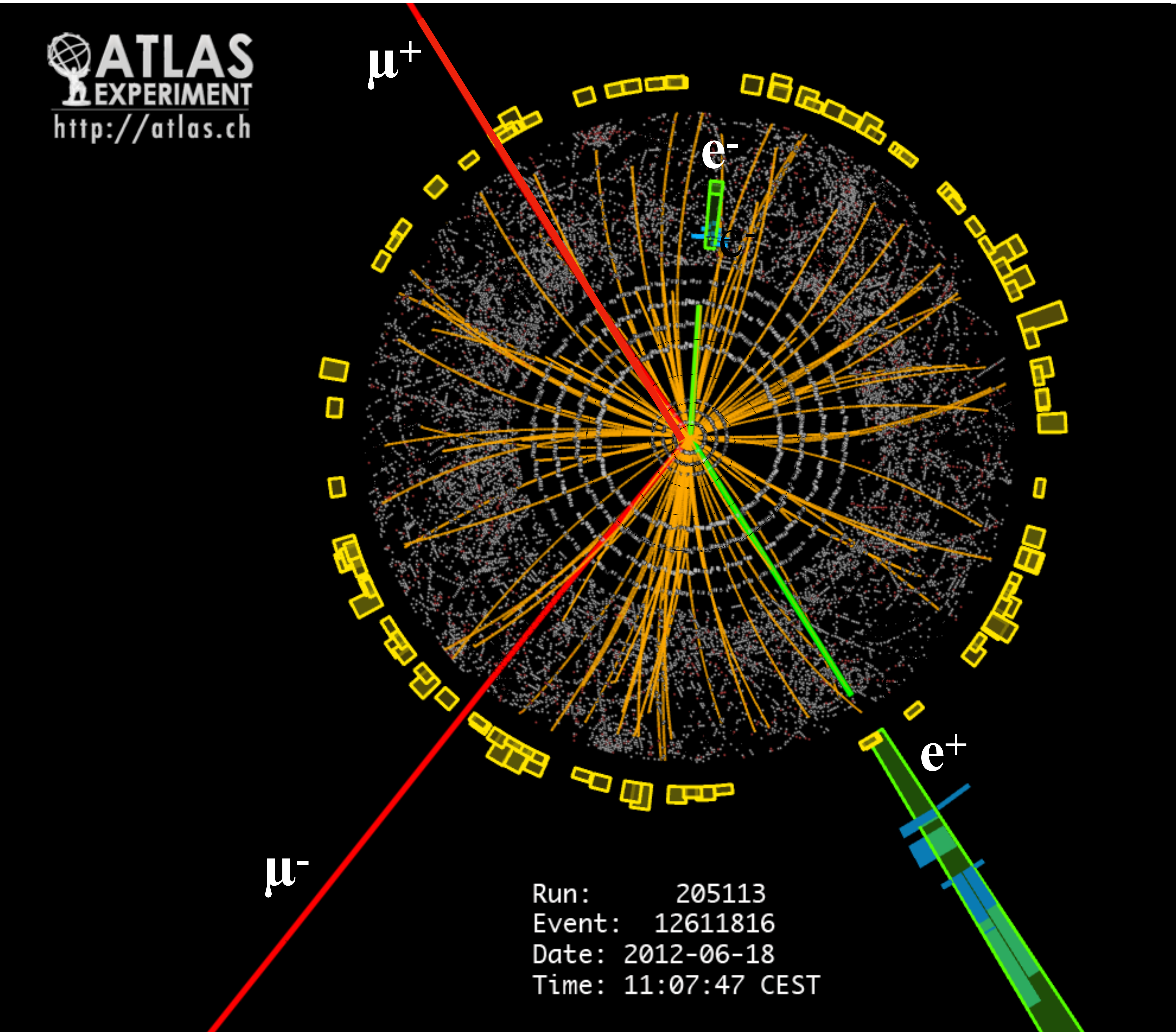
4 lepton signals confirmed

Full processing of events
1000 events/second

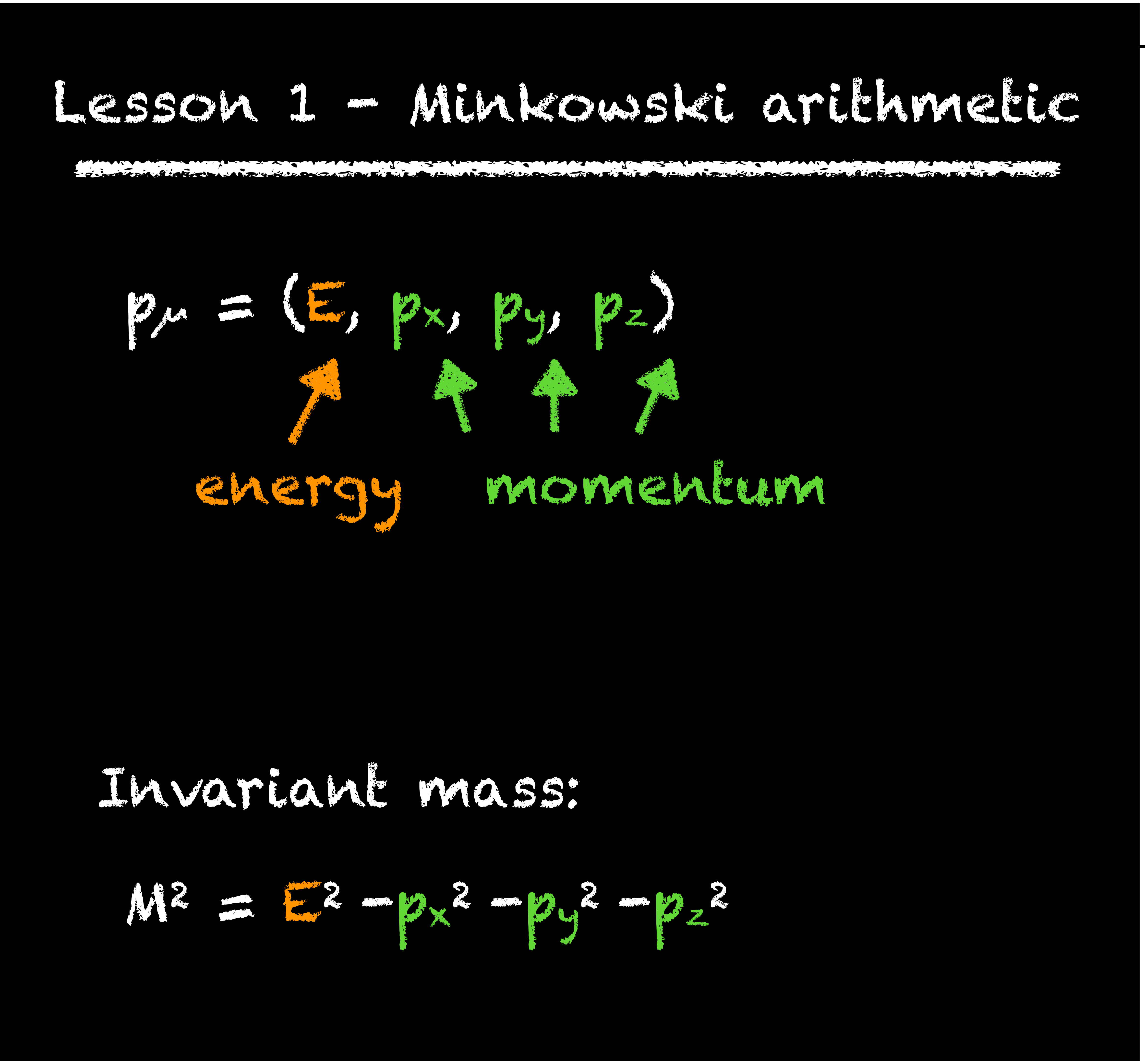
2 opp. charged muons
2 opp. charged electors

Data Analysis & publication

… in real: ATLAS experiment.



Data analysis



Level 1 Trigger to 100 kHz
on detector electronics

4 lepton signals

High level trigger ~1kHz
close-by computer farm

4 lepton signals confirmed

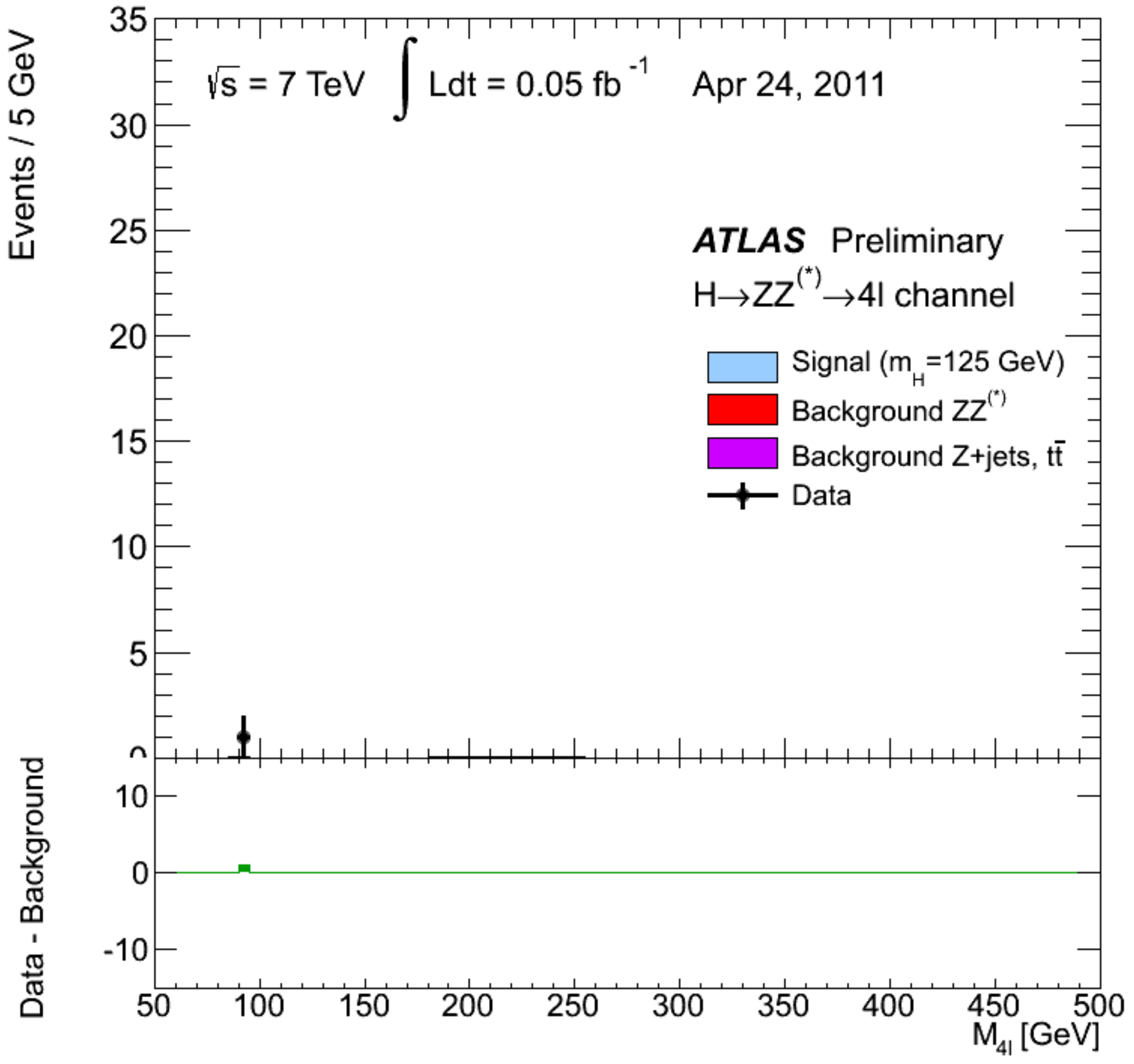
Full processing of events
1000 events/second

2 positive leptons
2 negative leptons
and measured

Data Analysis & publication

Nobel prize

Let us run the experiment … for real



[Animation source]

Level 1 Trigger to 100 kHz
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Full processing of events
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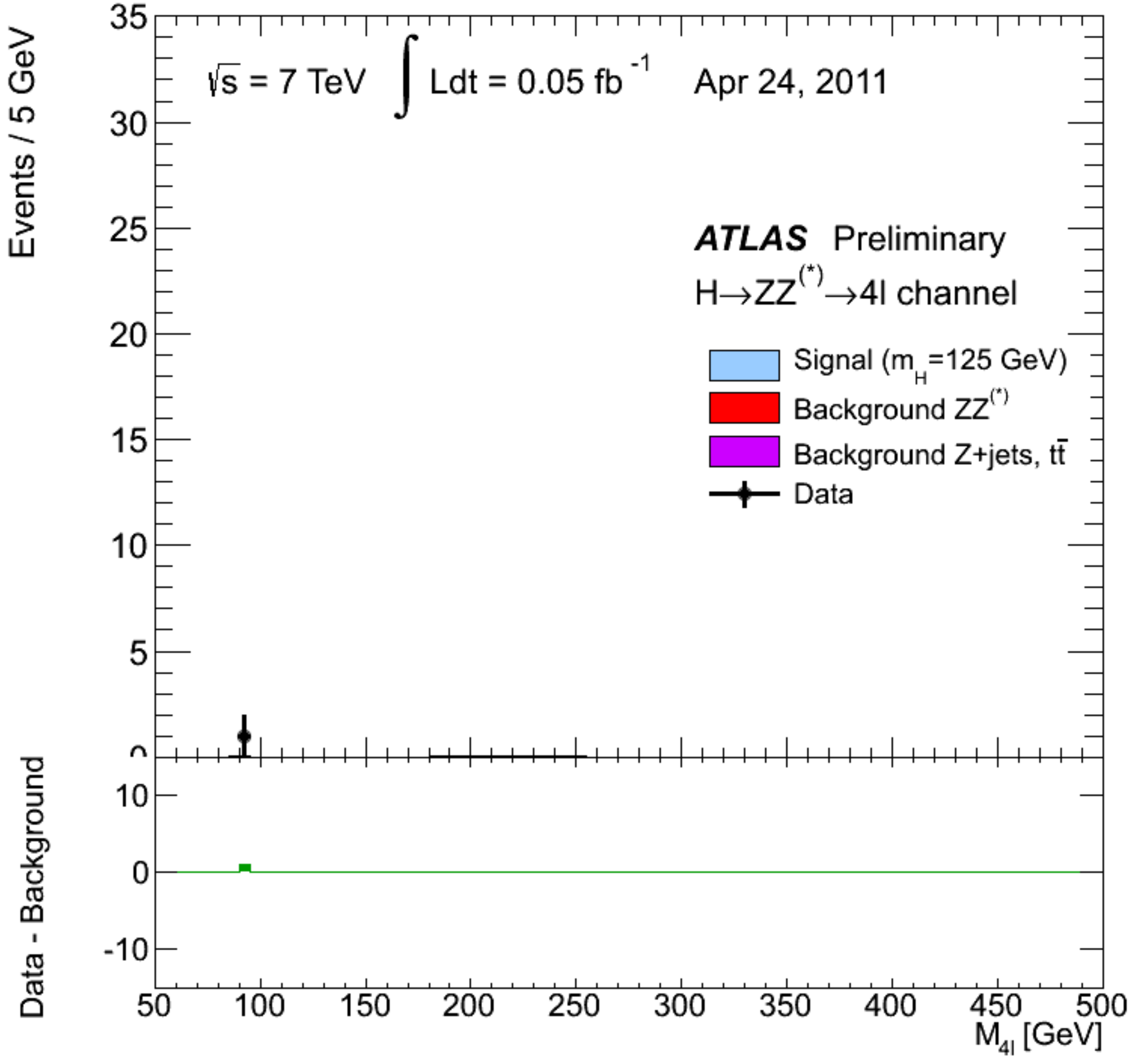
Data Analysis & publication

Nobel prize

Let us run the experiment … for real



Level 1 Trigger to 100 kHz
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Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

[Animation source]

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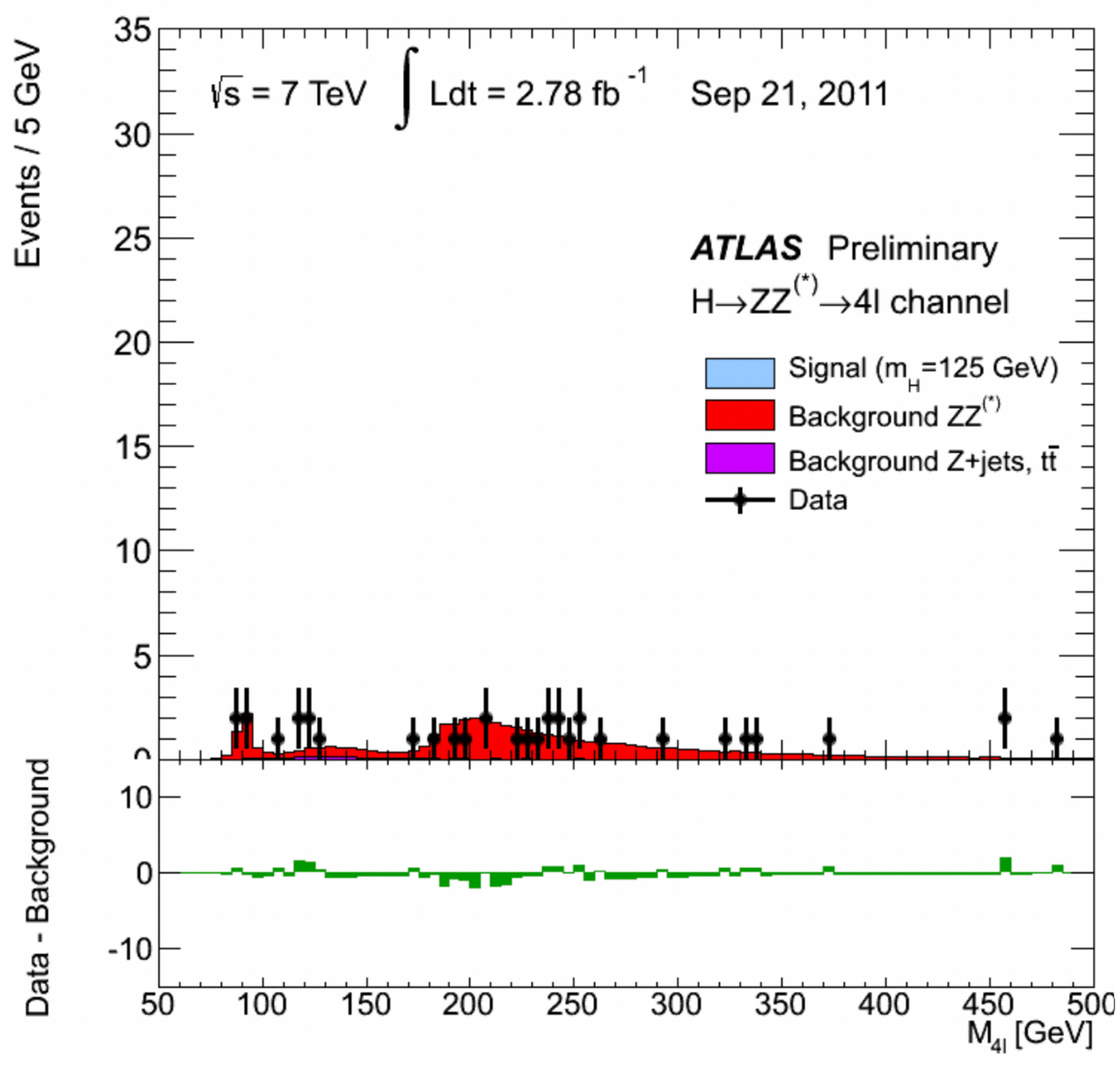

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Full processing of events
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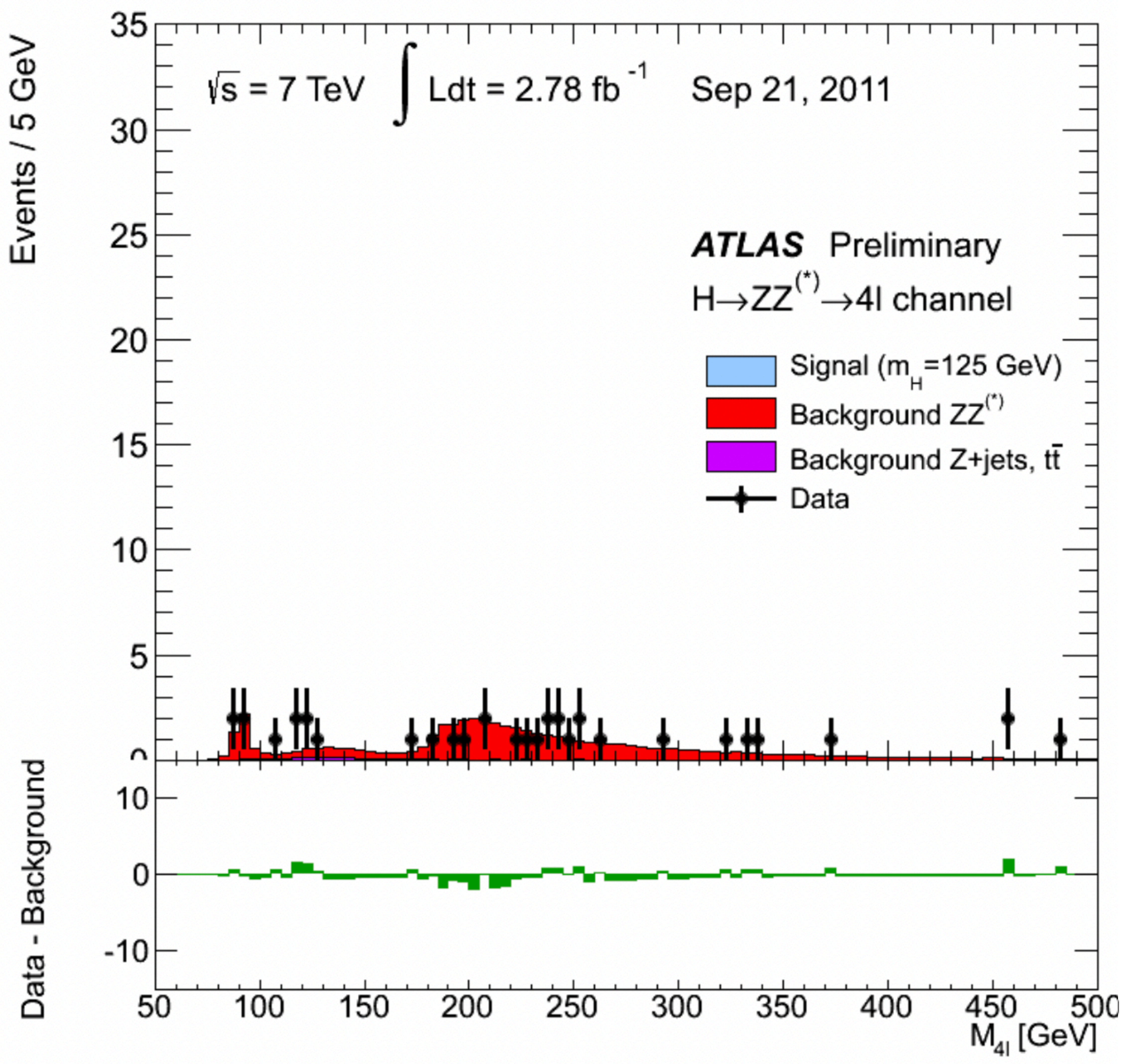
Data Analysis & publication

Nobel prize

[Animation source]

Let us run the experiment … for real



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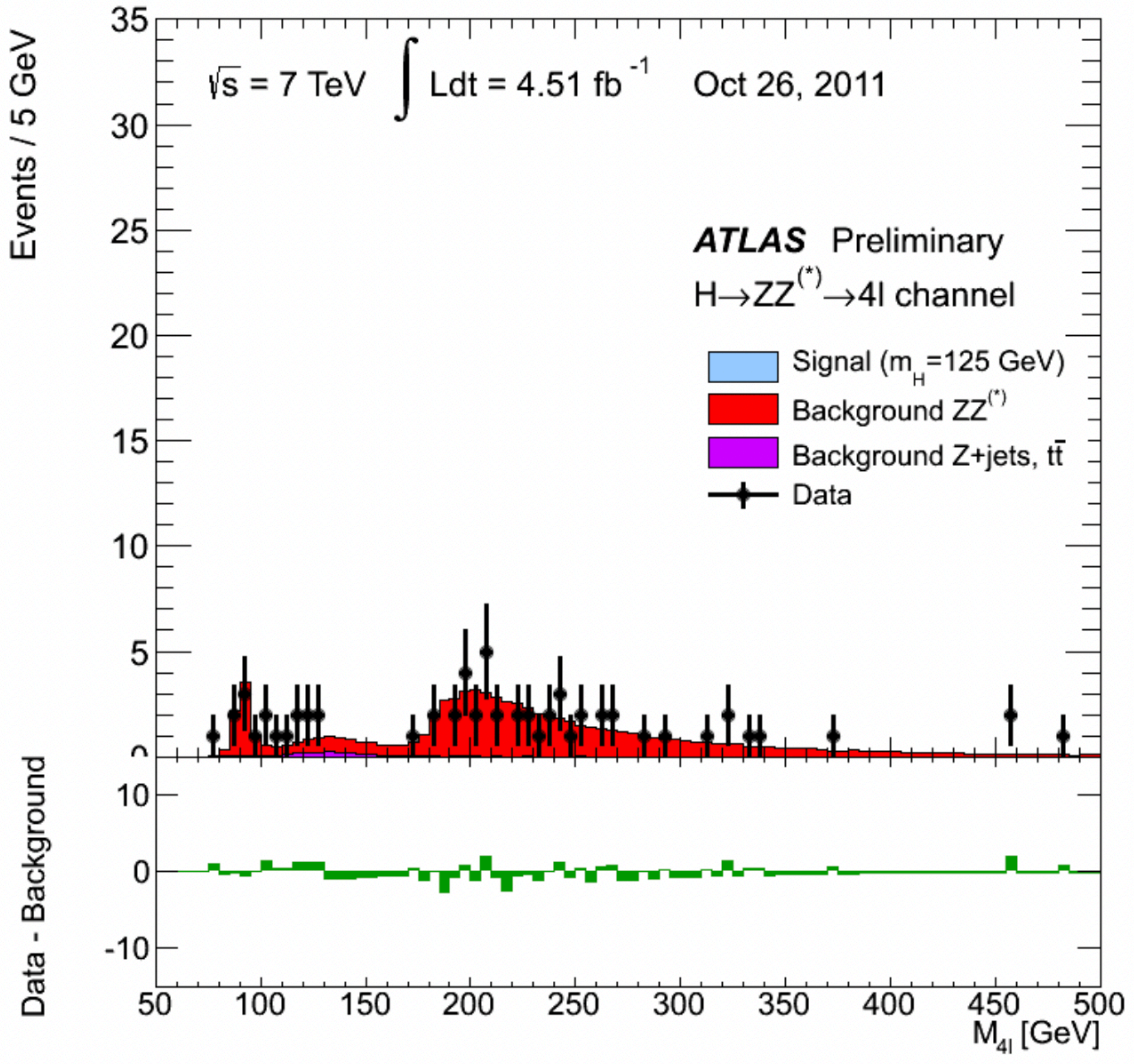
Data Analysis & publication

Nobel prize

[Animation source]

Let us run the experiment … for real



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Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

[Animation source]

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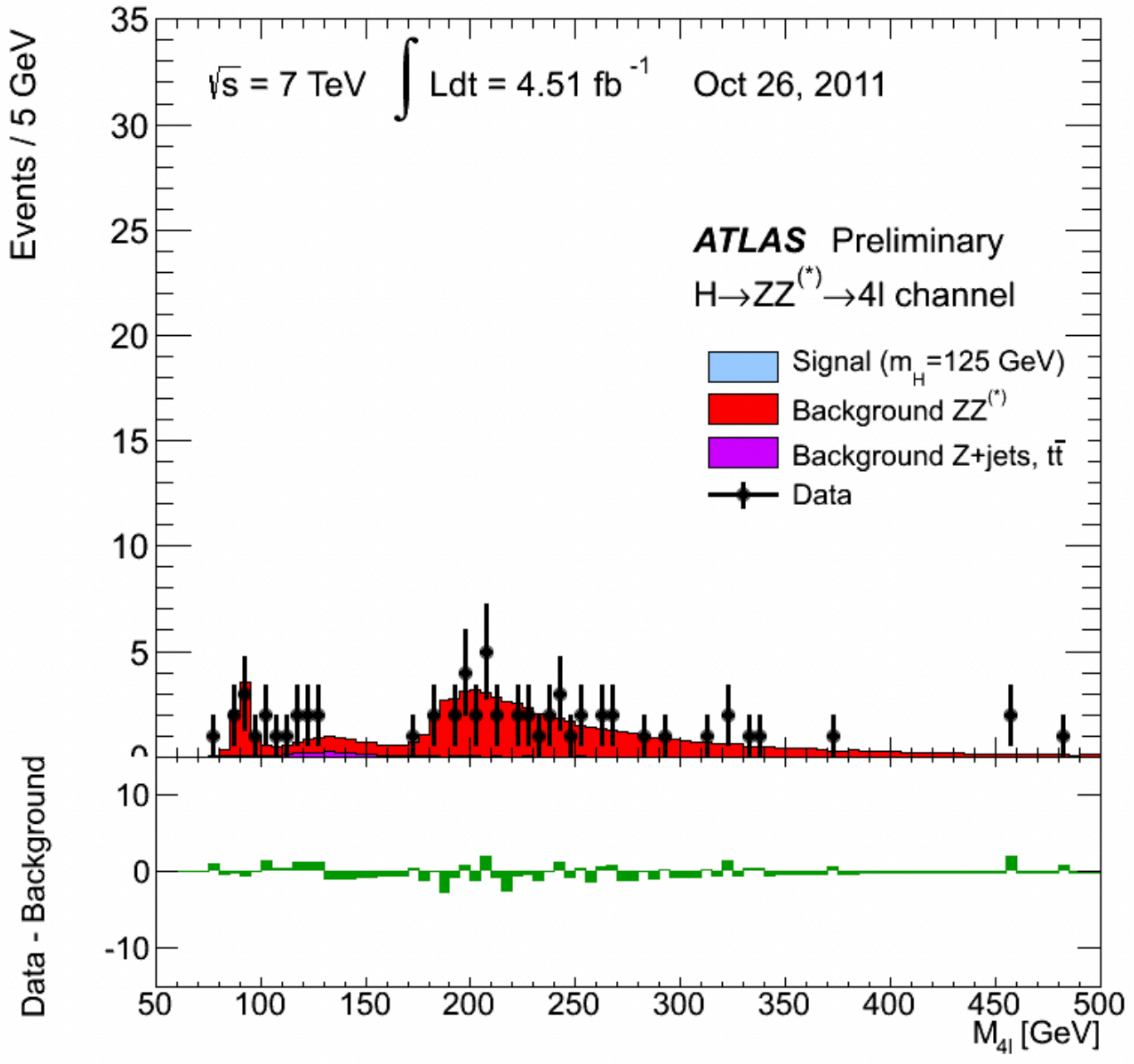

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Data Analysis & publication

Nobel prize

[Animation source]

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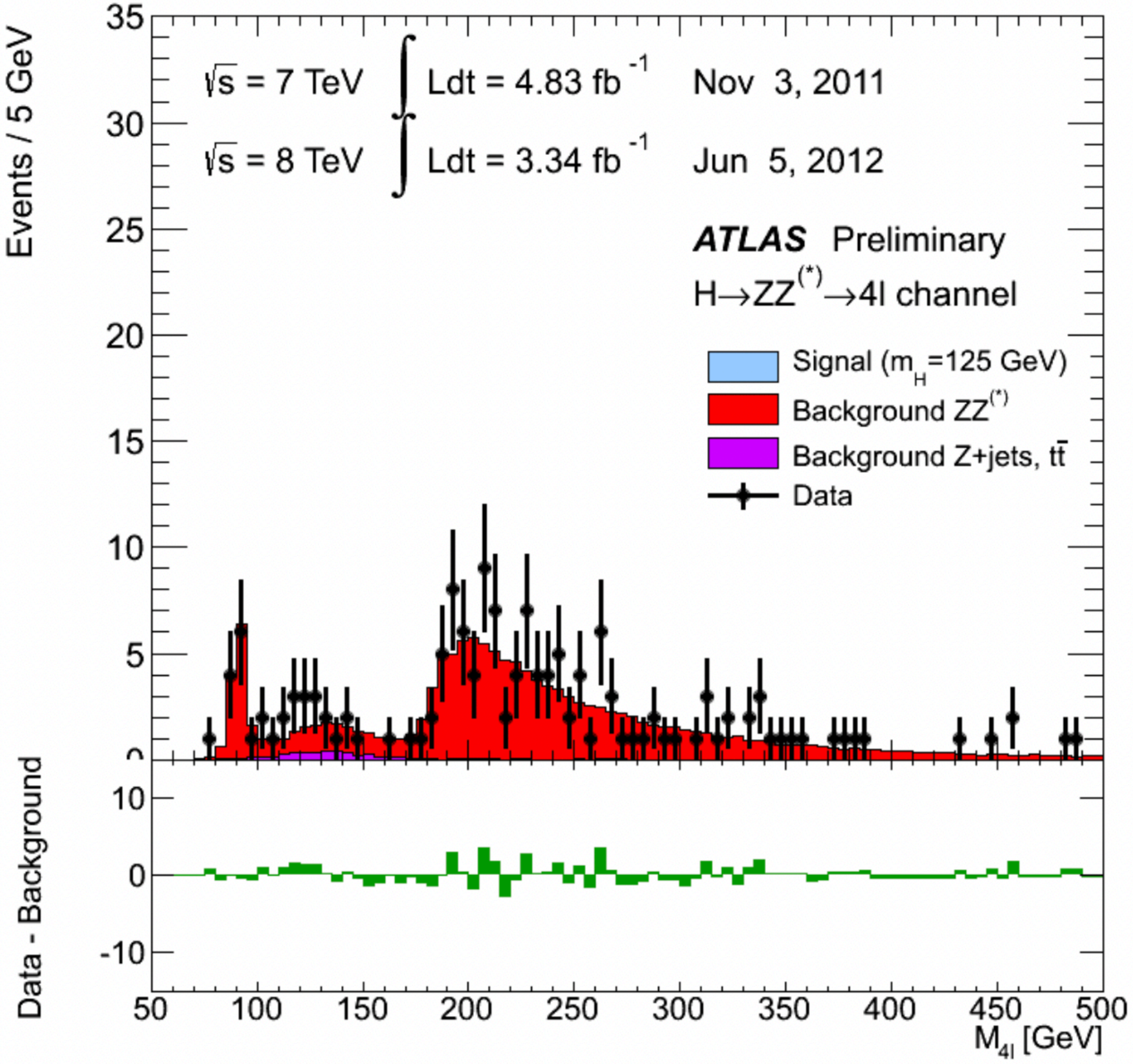

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Data Analysis & publication

Nobel prize

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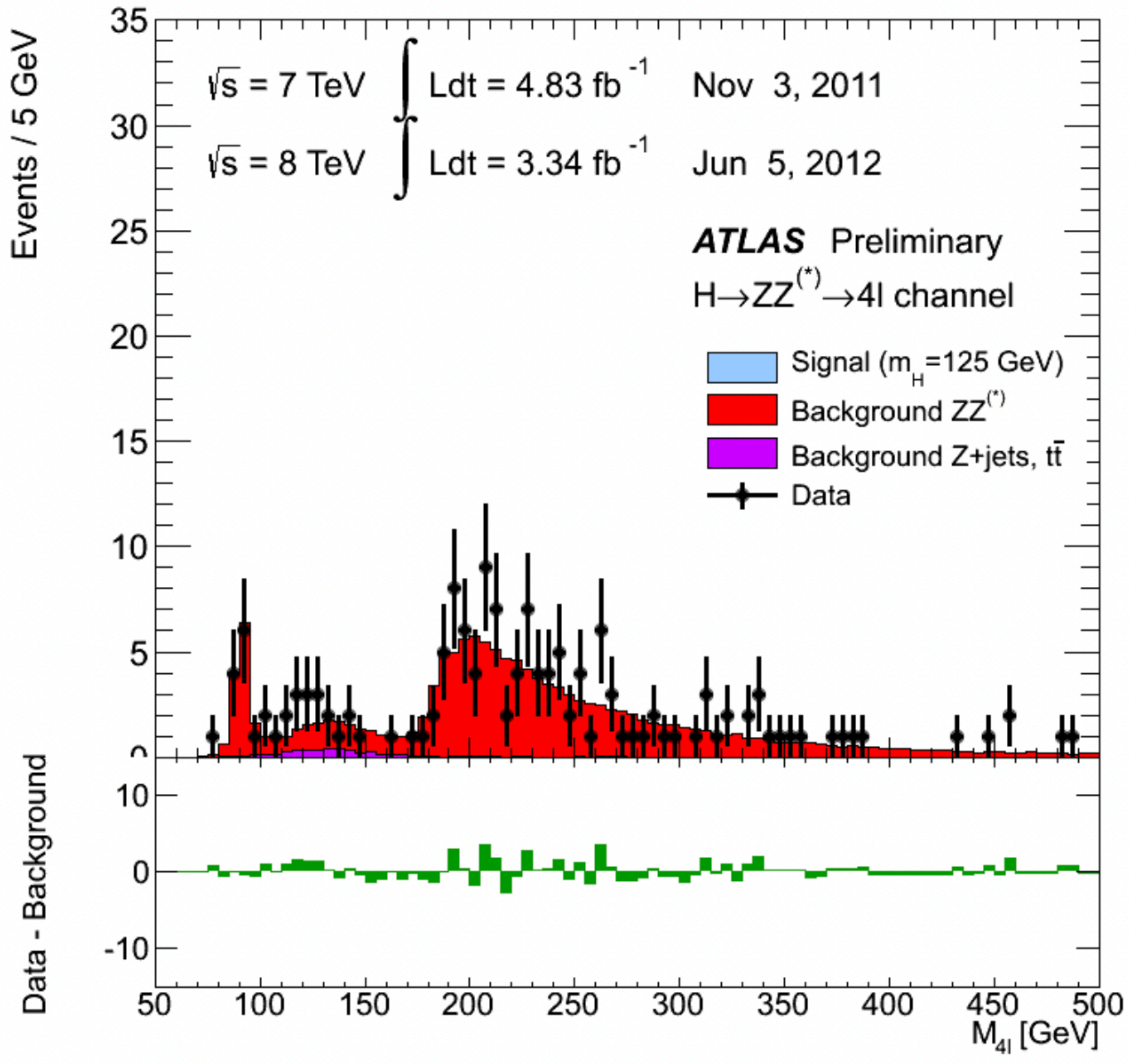

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Nobel prize

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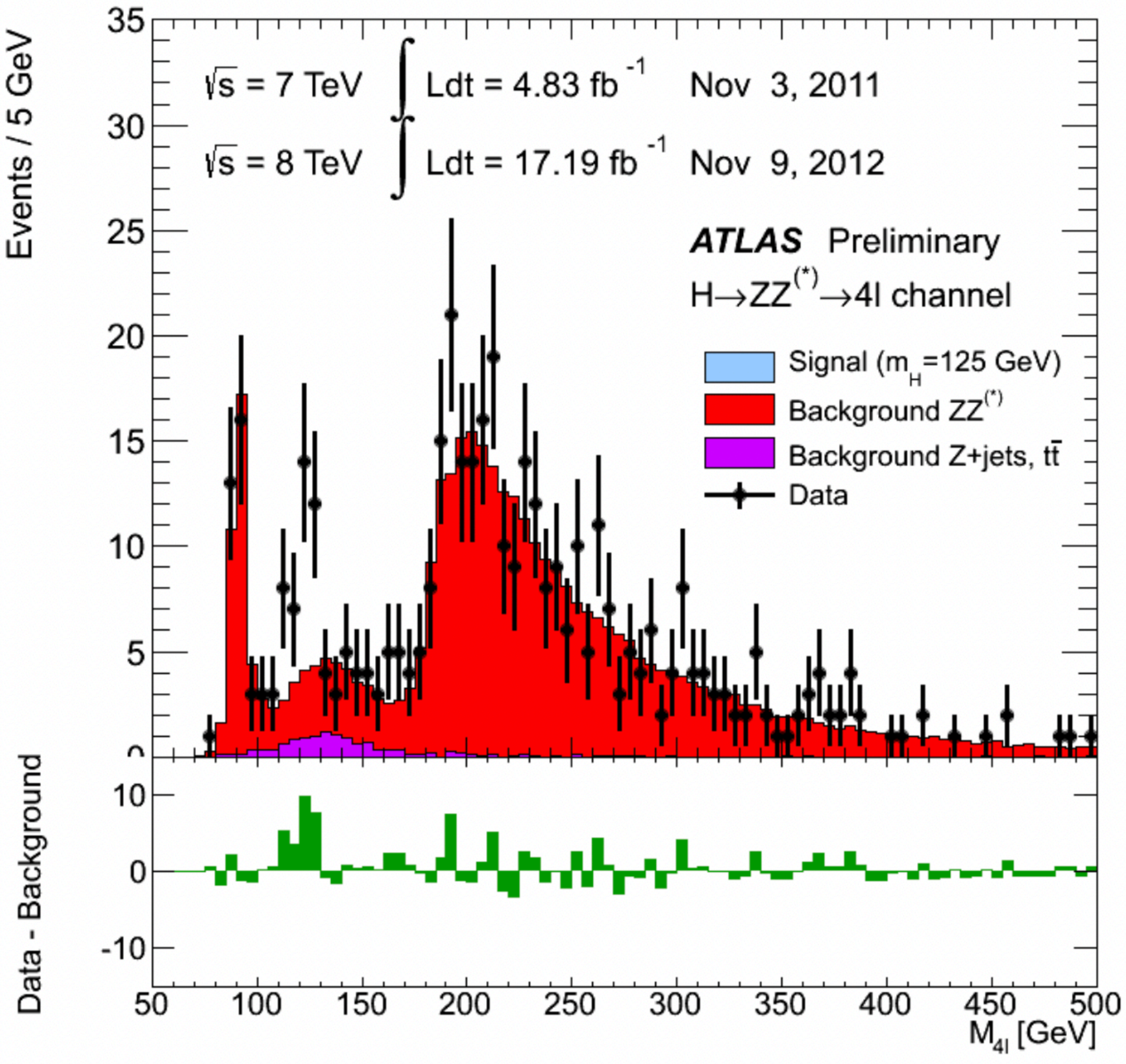

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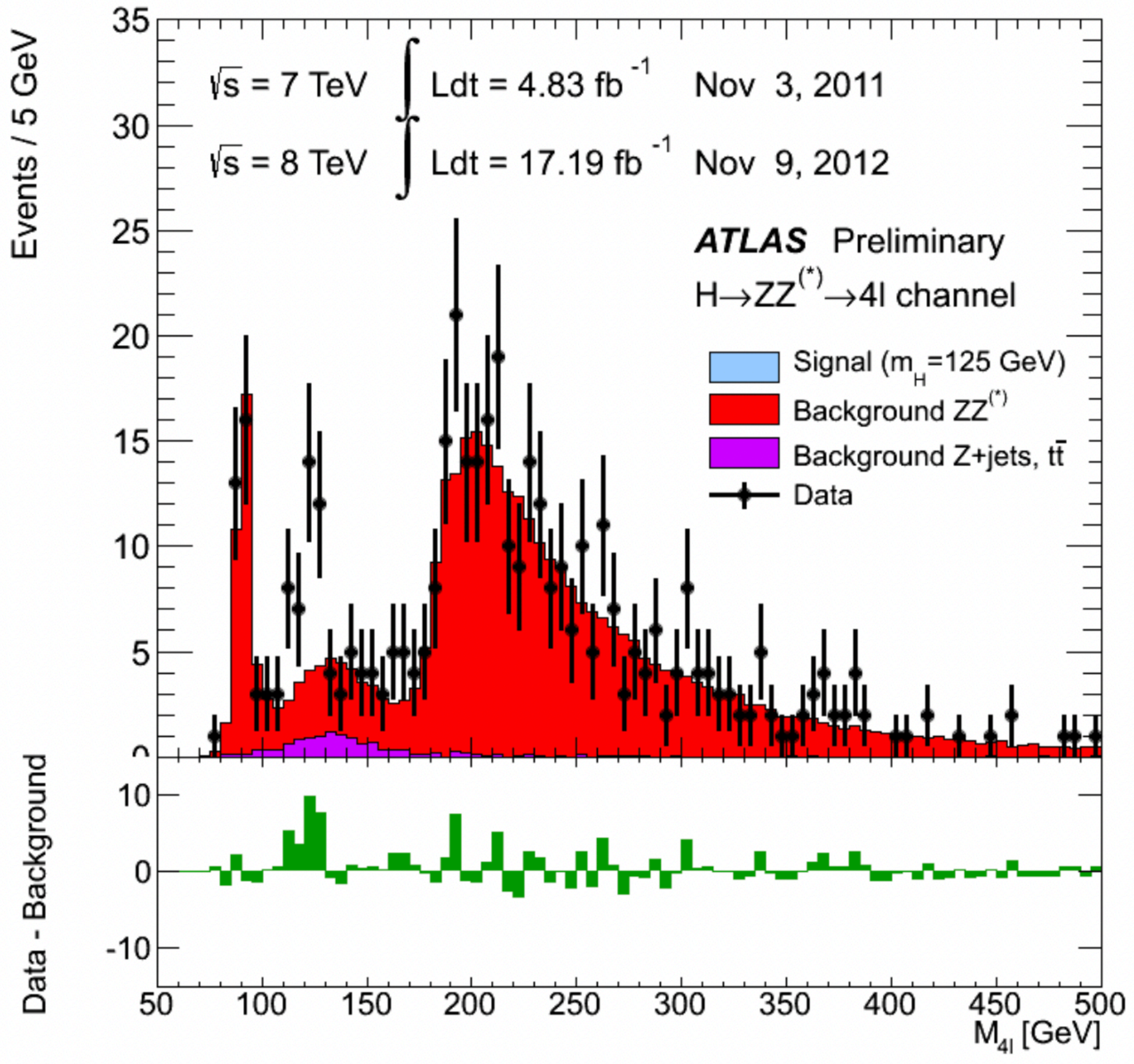

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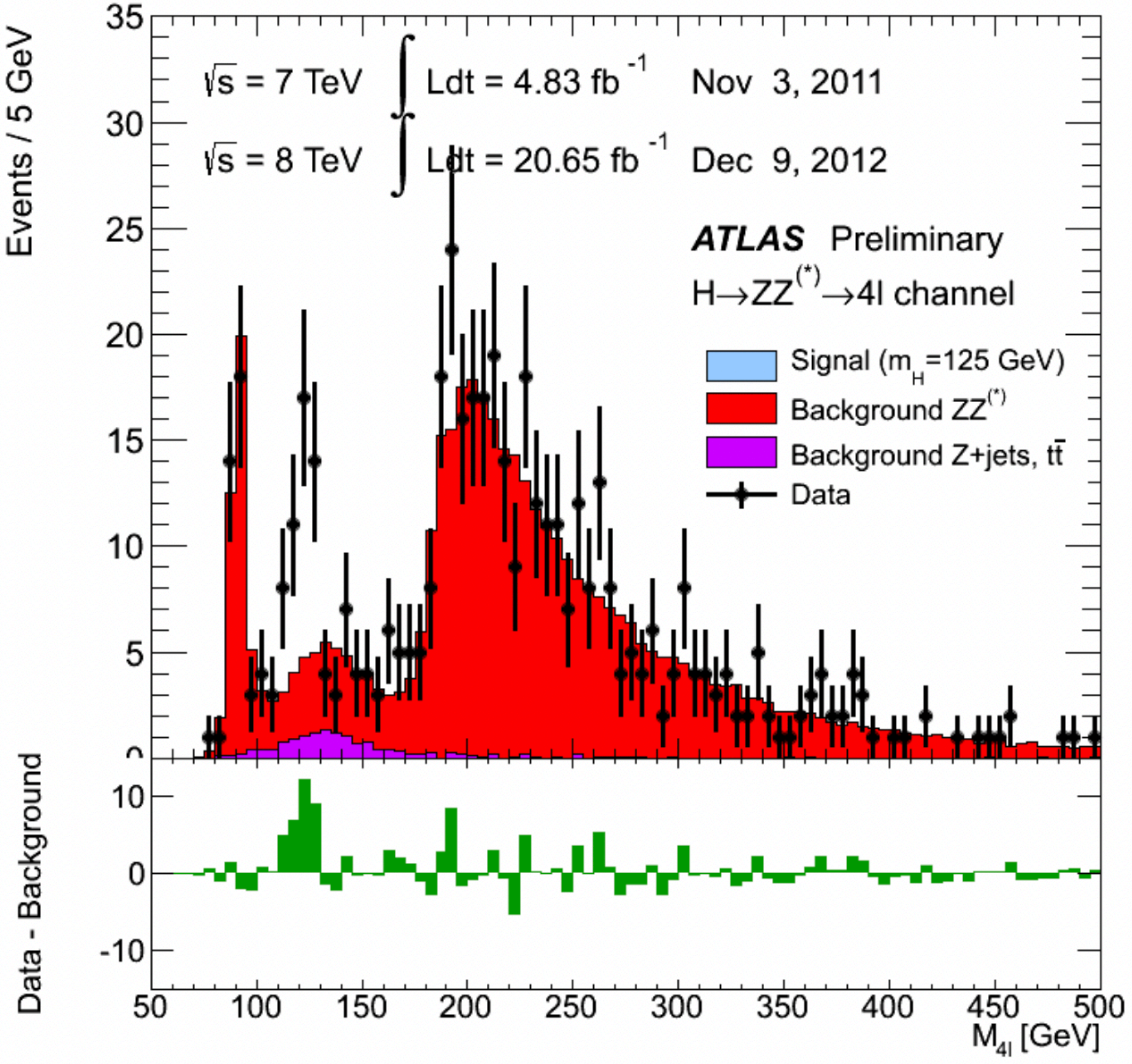

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Data Analysis & publication

Nobel prize

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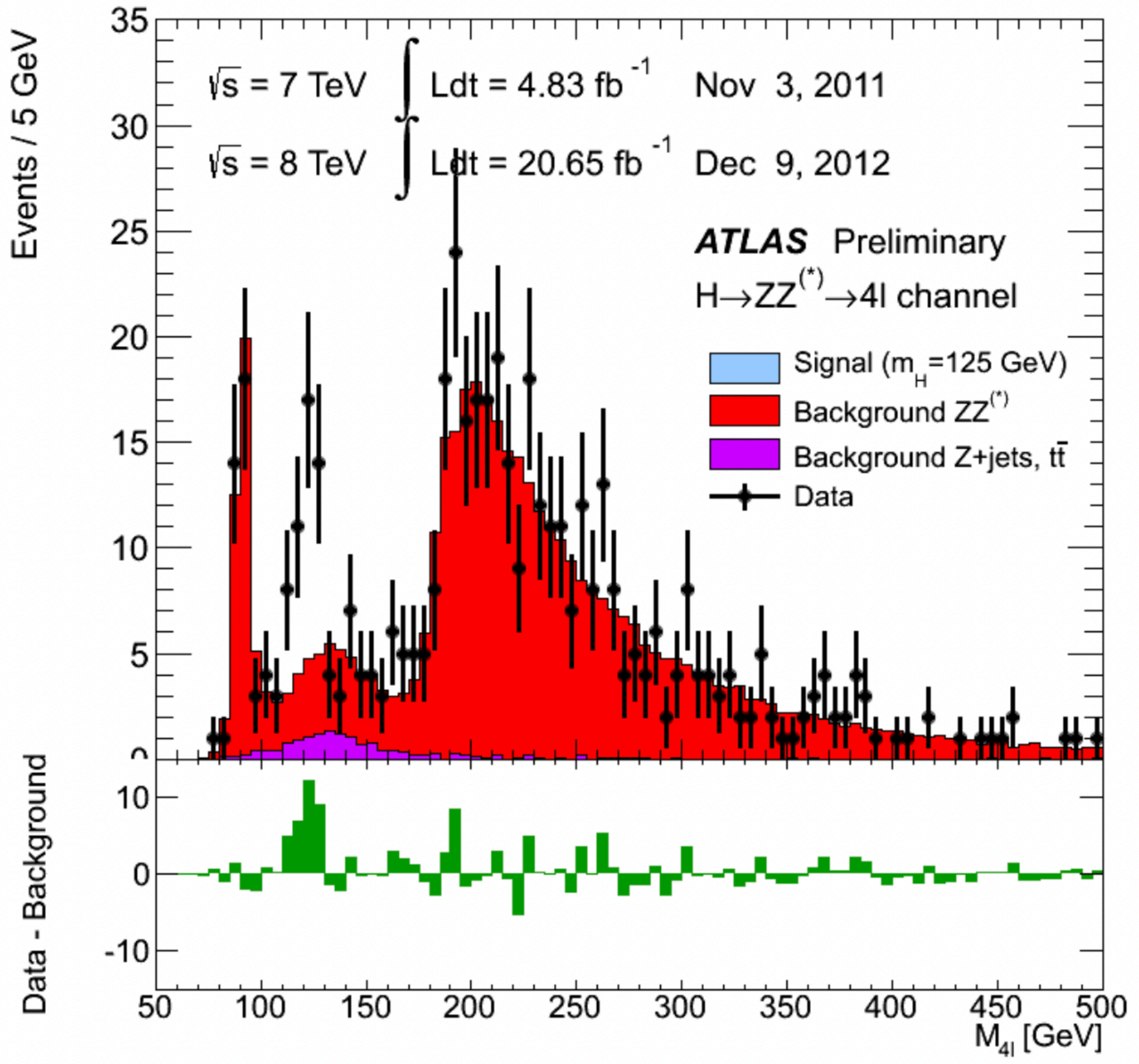

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Data Analysis & publication

Nobel prize

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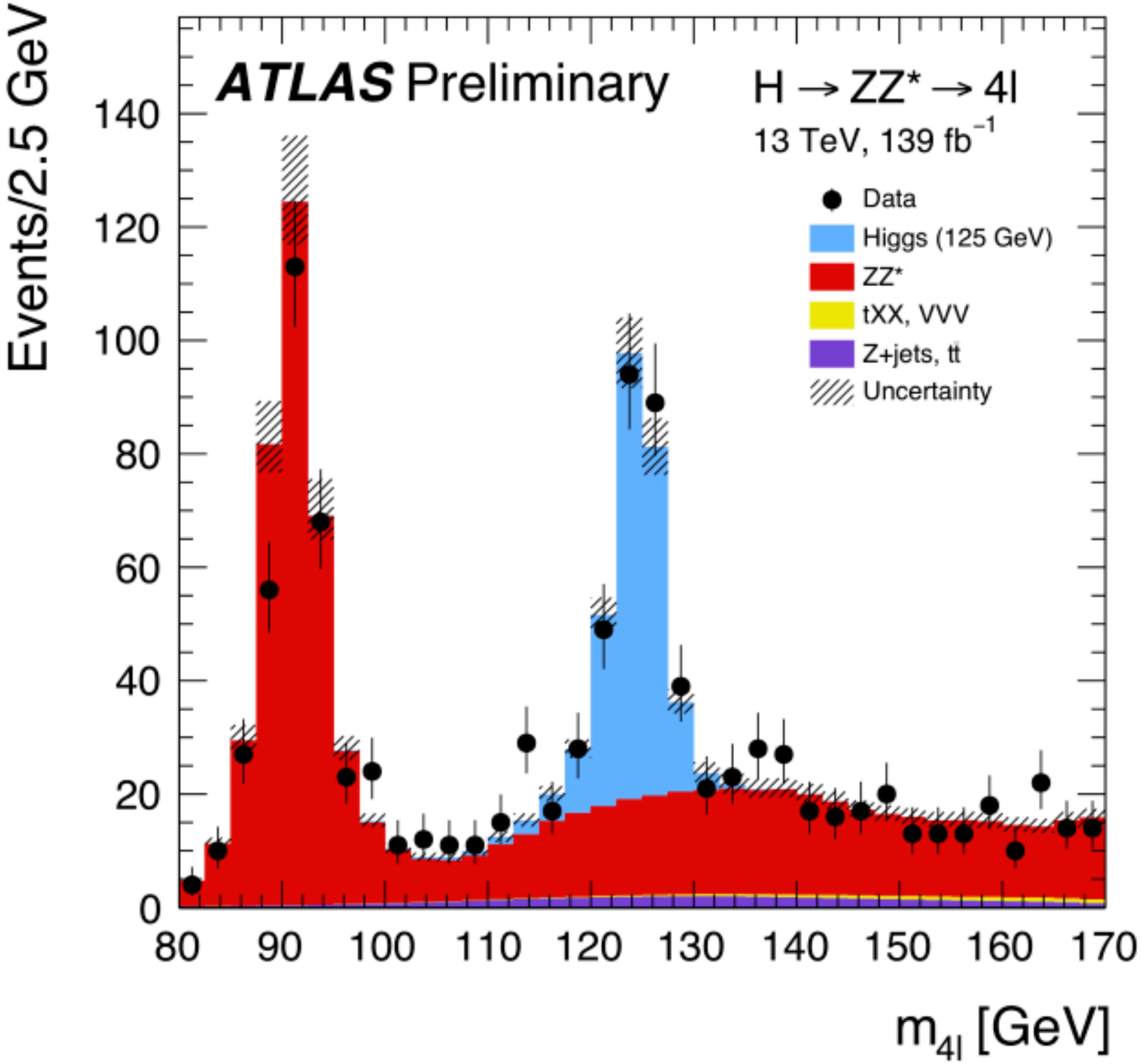

Level 1 Trigger to 100 kHz
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High level trigger ~1kHz
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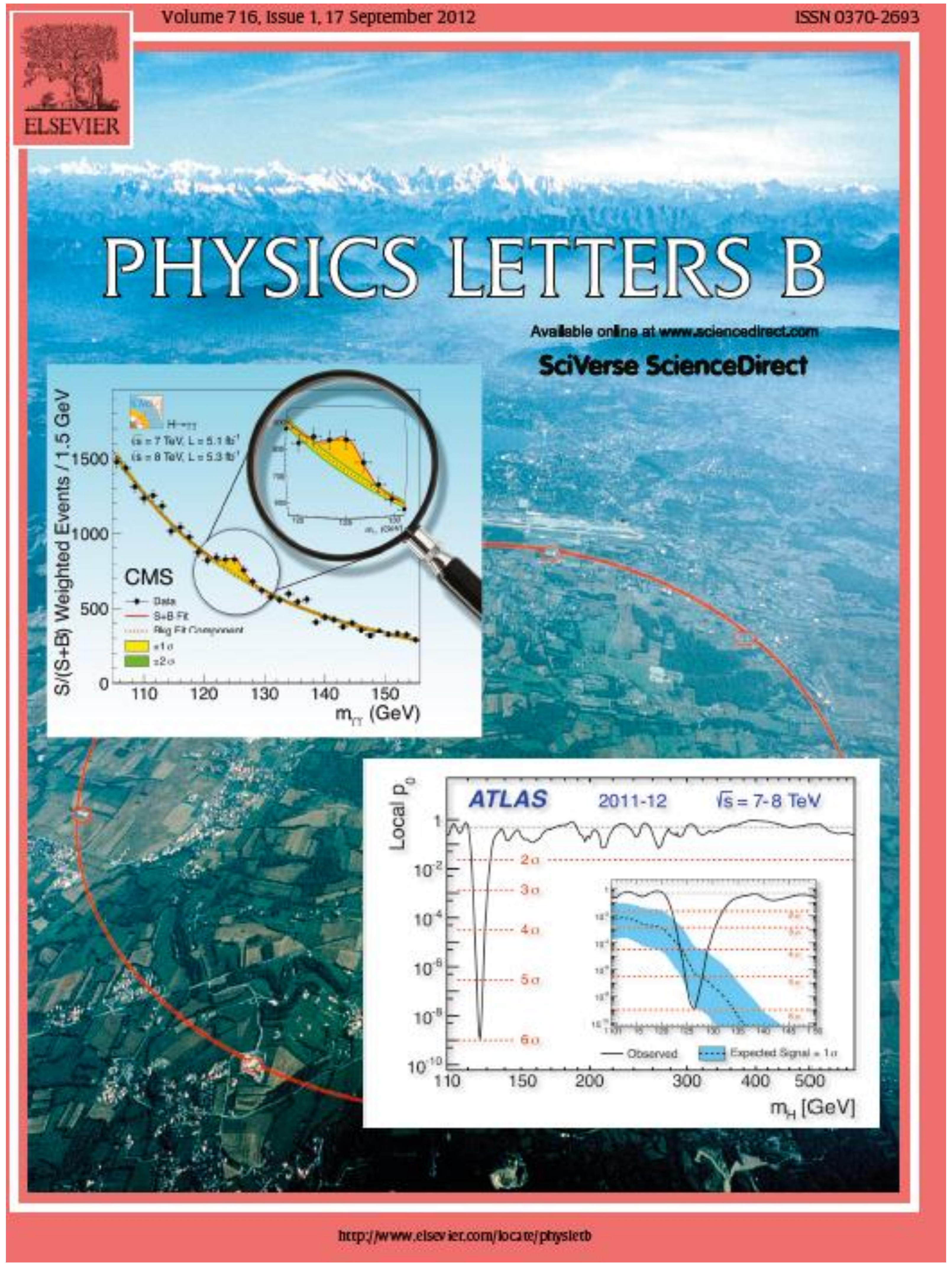
Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

[Animation source]

And so it went …



Level 1 Trigger to 100 kHz
on detector electronics

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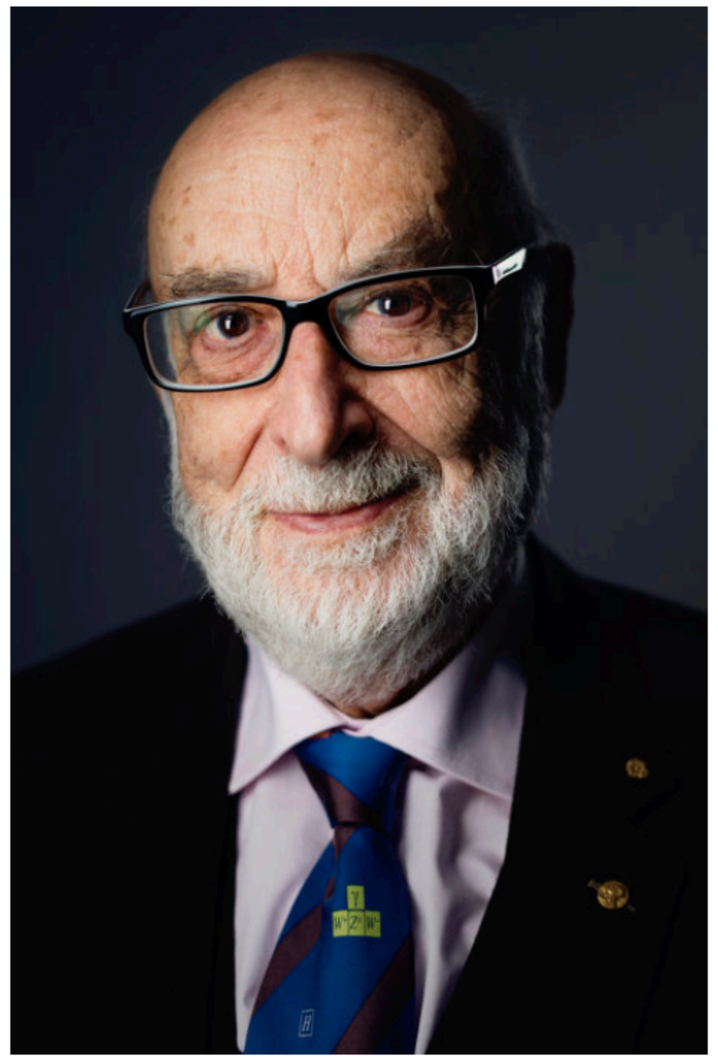
close-by computer farm

Full processing of events
1000 events/second

Data Analysis & publication

… and of course the right guys got it.

The Nobel Prize in Physics 2013



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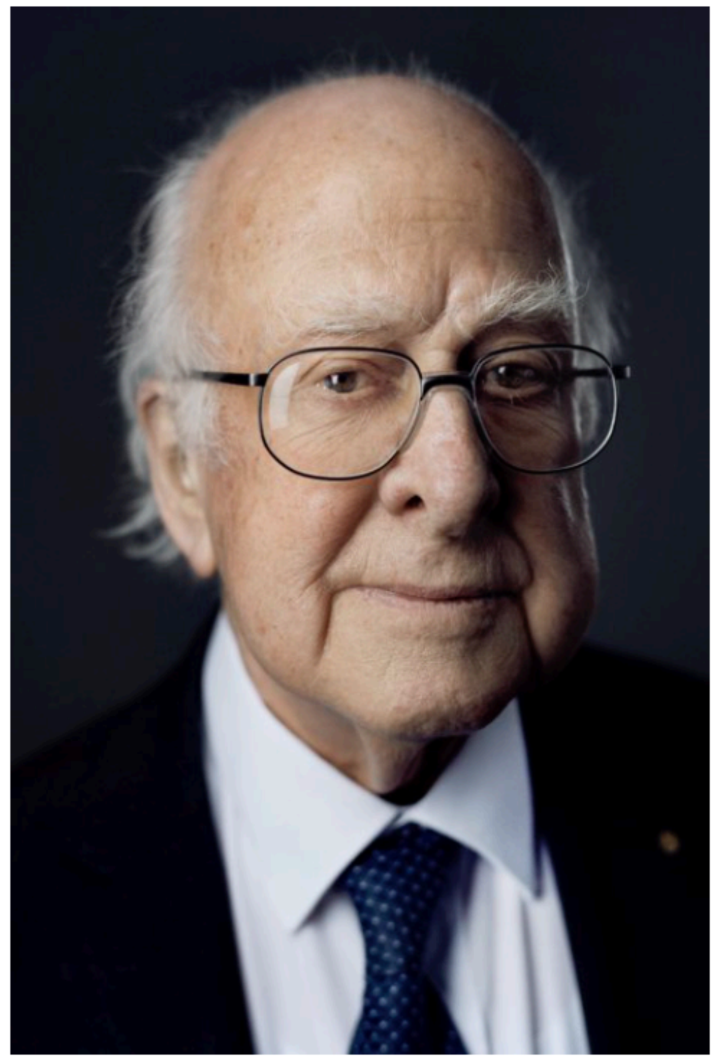
François Englert

Prize share: 1/2



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Peter W. Higgs

Prize share: 1/2

Level 1 Trigger to 100 kHz
on detector electronics

↓

High level trigger ~1kHz
close-by computer farm

↓

Full processing of events
1000 events/second

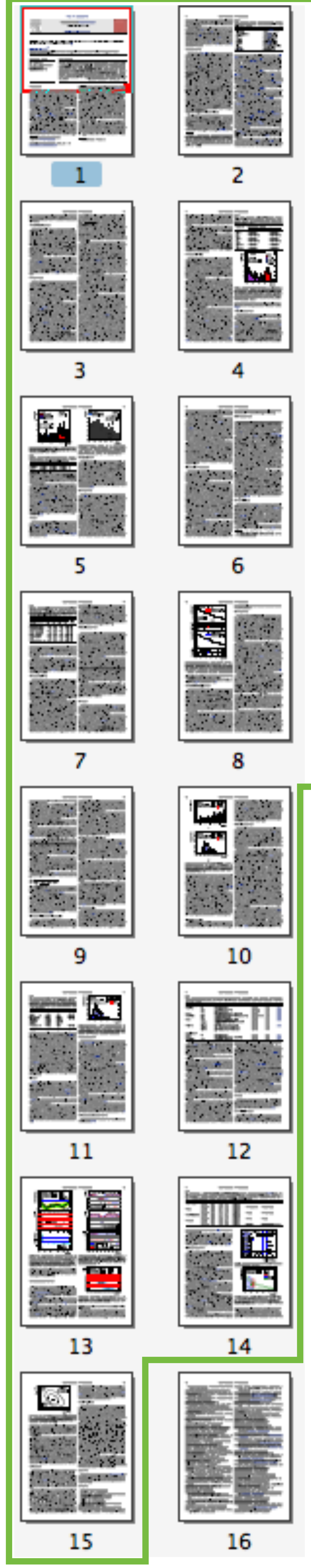
↓

Data Analysis & publication

→

Nobel prize

[Animation source]



scientific information

Physics Letters B 716 (2012) 1–29

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Physics Letters B

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Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

A R T I C L E I N F O

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A B S T R A C T

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}=7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}=8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

15 pages scientific context

~ 3000 authors

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ATLAS Collaboration *

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ABSTRACT

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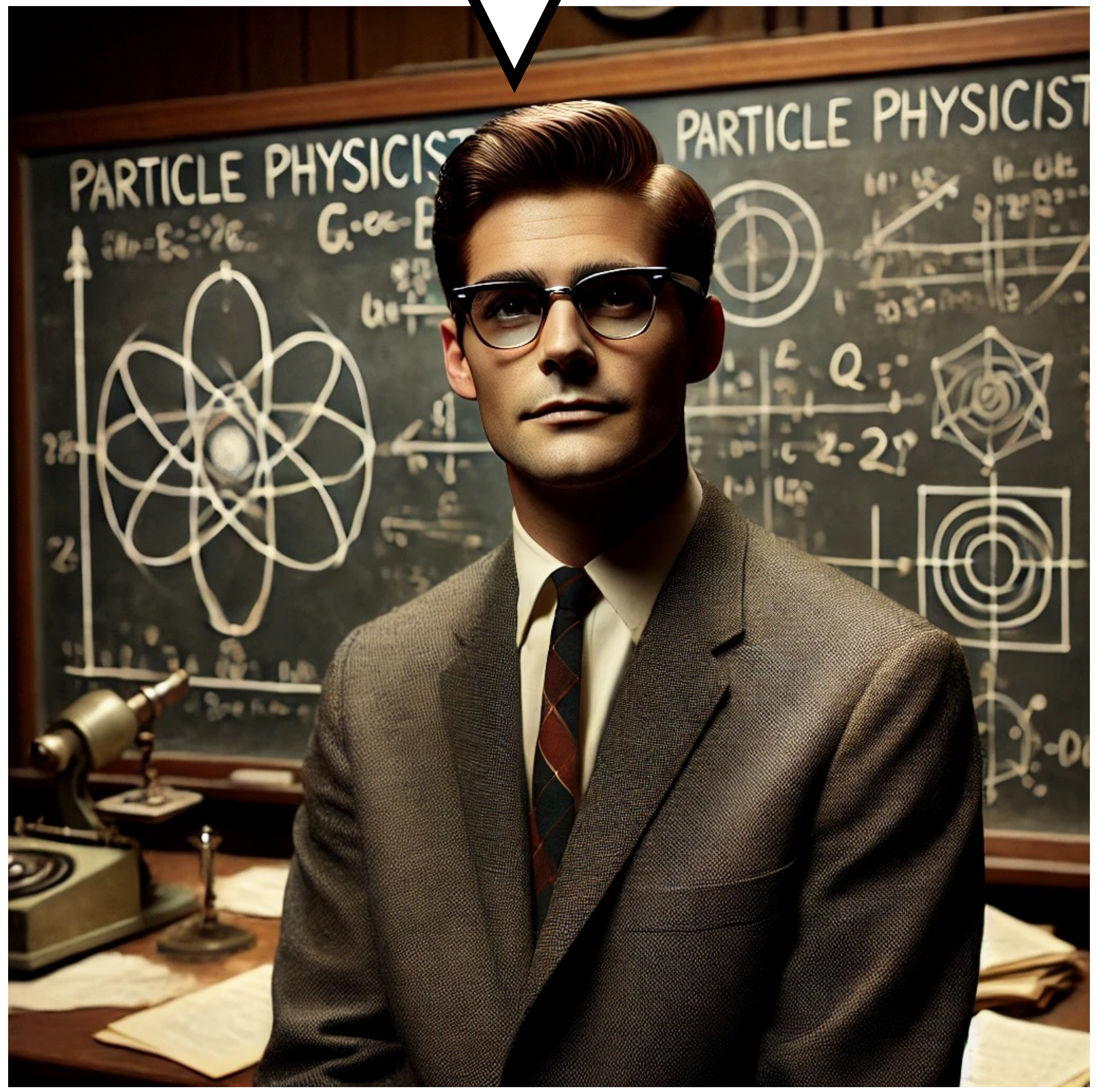
L. Rumyantsev [64], Z. Rurikova [48], N.A. Rusakovich [64], J.P. Rutherfoord [7], P. Ruzicka [125], Y.F. Ryabov [121], M. Rybar [126], G. Rybkin [115], N.C. Ryder [118], A.F. Saavedra [150], I. Sadeh [153], H.F.-W. Sadrozinski [137], R. Sadykov [64], F. Safai Tehrani [132a], H. Sakamoto [155], G. Salamanna [75], A. Salamon [133a], M. Saleem [111], D. Salek [30], D. Salihagic [99], A. Salnikov [143], J. Salt [167], B.M. Salvachua Ferrando [6], D. Salvatore [37a,37b], F. Salvatore [149], A. Salvucci [104], A. Salzburger [30], D. Sampsonidis [154], B.H. Samset [117], A. Sanchez [102a,102b], V. Sanchez Martinez [167], H. Sandaker [14], H.G. Sander [81], M.P. Sanders [98], M. Sandhoff [175], T. Sandoval [28], C. Sandoval [162], R. Sandstroem [99], D.P.C. Sankey [129], A. Sansoni [47], C. Santamarina Rios [85], C. Santoni [34], R. Santonico [133a,133b], H. Santos [124a], J.G. Saraiva [124a], T. Sarangi [173], E. Sarkisyan-Grinbaum [8], F. Sarri [122a,122b], G. Sartisohn [175], O. Sasaki [65], Y. Sasaki [155], N. Sasao [67], I. Satsounkevitch [90], G. Sauvage [5,*], E. Sauvan [5], J.B. Sauvan [115], P. Savard [158,d], V. Savinov [123], D.O. Savu [30], L. Sawyer [25,m], D.H. Saxon [53], J. Saxon [120], C. Sbarra [20a], A. Sbrizzi [20a,20b], D.A. Scannicchio [163], M. Scarcella [150], J. Schaarschmidt [115], P. Schacht [99], D. Schaefer [120], U. Schäfer [81], A. Schaelicke [46], S. Schaepe [21], S. Schaetzel [58b], A.C. Schaffer [115], D. Schaile [98], R.D. Schamberger [148], A.G. Schamov [107], V. Scharf [58a], V.A. Schegelsky [121], D. Scheirich [87], M. Schernau [163], M.I. Scherzer [35], C. Schiavi [50a,50b], J. Schieck [98], M. Schioppa [37a,37b], S. Schlenker [30], P. Schmid [30], E. Schmidt [48], K. Schmieden [21], C. Schmitt [81], S. Schmitt [58b], M. Schmitz [21], B. Schneider [17], U. Schnoor [44], L. Schoeffel [136], A. Schoening [58b], A.L.S. Schorlemmer [54], M. Schott [30], D. Schouten [159a], J. Schovancova [125], M. Schram [85], C. Schroeder [81], N. Schroer [58c], M.J. Schultens [21], J. Schultes [175], H.-C. Schultz-Coulon [58a], H. Schulz [16], M. Schumacher [48], B.A. Schumm [137], Ph. Schune [136], C. Schwanenberger [82], A. Schwartzman [143], Ph. Schwegler [99],

15 pages scientific context

~ 3000 authors

In summary

Particle detectors
are at the forefront
of technology.



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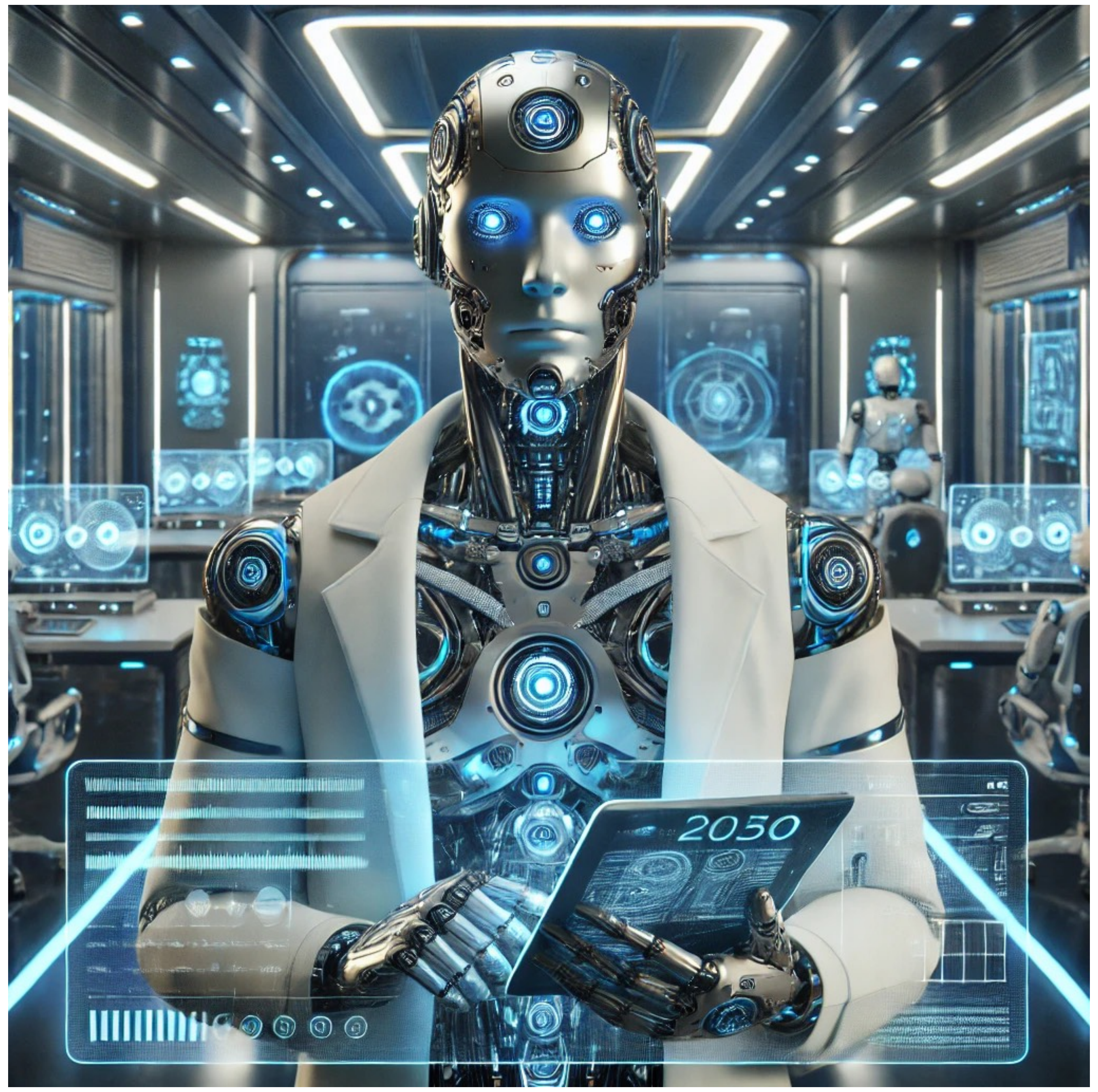
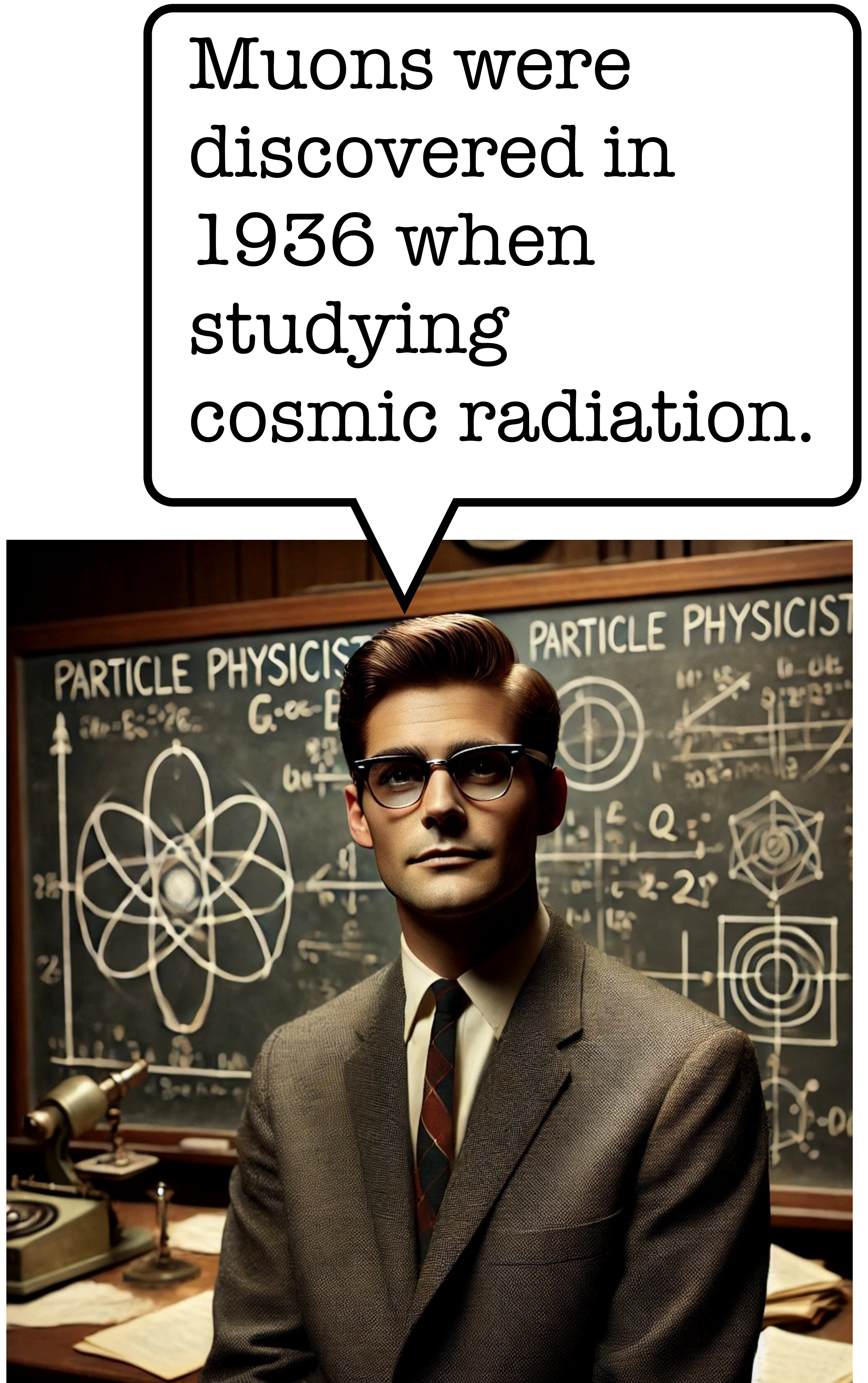


Andreas.Salzburger@cern.ch

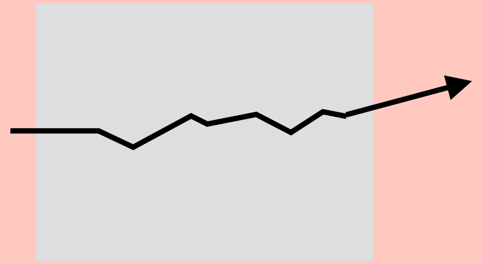
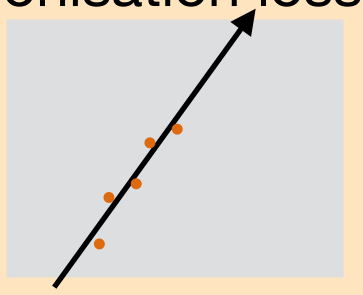
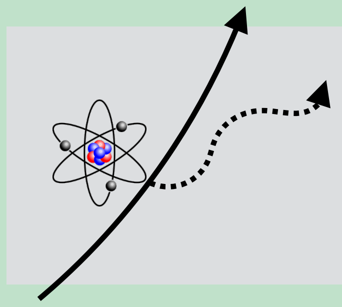
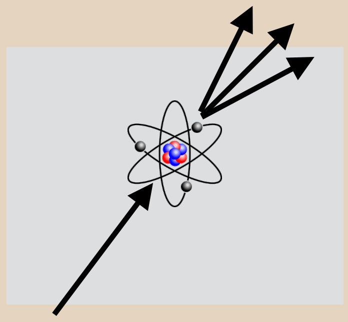
Backup section

[Image source]



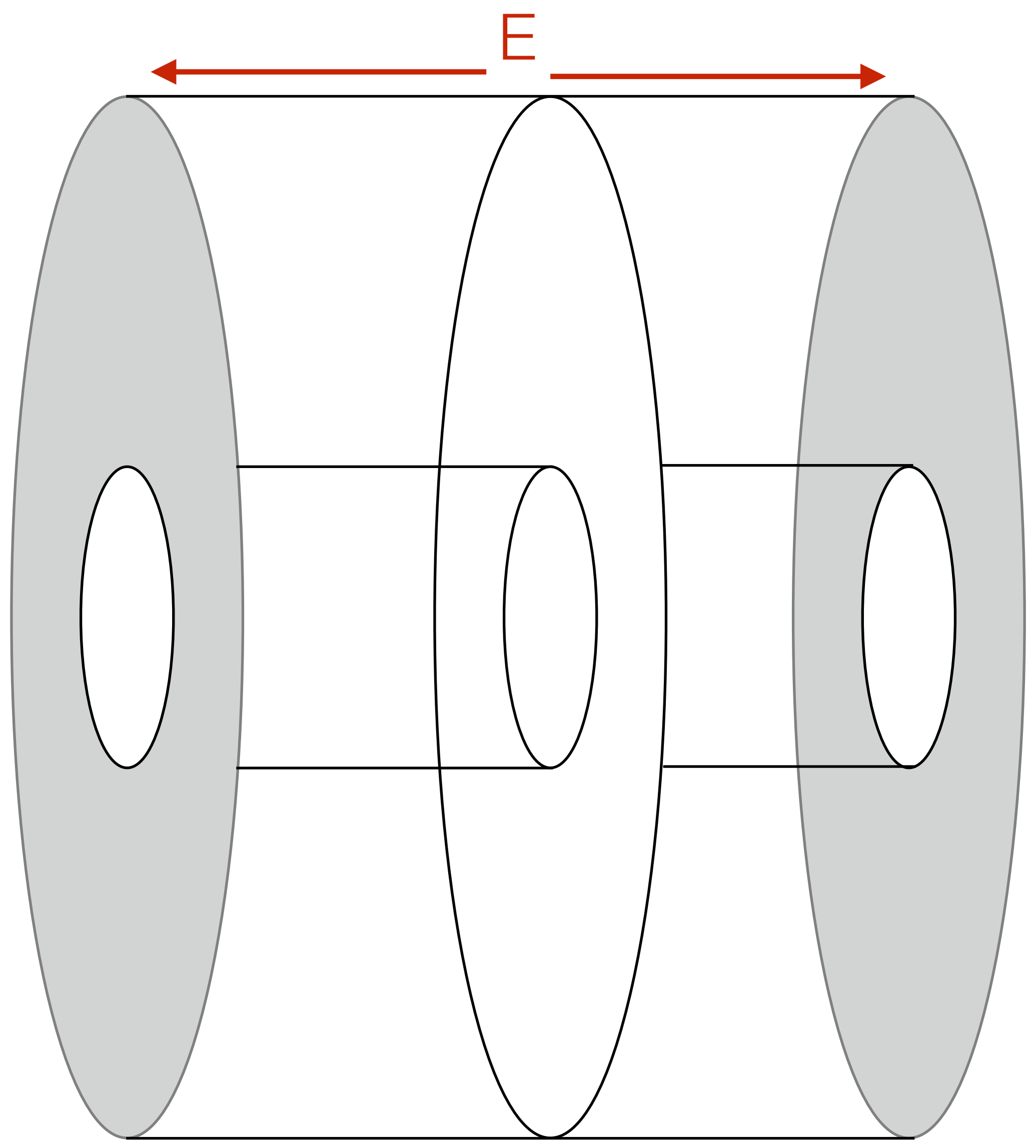
1912 discovery of cosmic ray radiation by **Victor Franz Hess**
1936 first evidence as part of cosmic rays by **Carl D. Anderson** and **Seth Neddermeyer** at Caltech
1937 by **J. C. Street a**nd **E. C. Stevenson's cloud** chamber

Interaction with detector material

Type	particles	fund. parameter	characteristics	effect
Multiple Scattering 	all charged particle	radiation length X_0	almost gaussian average effect 0 depends ~ $1/p$	deflects particles, increases measurement uncertainty
Ionisation loss 	all charged particle	effective density $A/Z * \rho$	small effect in tracker, small dependence on p	increases momentum uncertainty
Bremsstrahlung 	all charged particle, dominant for e	radiation length X_0	highly non-gaussian, depends ~ $1/m^2$	introduces measurement bias
Hadronic Int. 	all hadronic particles	nuclear interaction length Λ_0	destroys particle, rather constant effect in p	main source of track reconstruction inefficiency

Time projection chamber

- TPCs allow to build huge tracking devices to relative moderate cost
  - precise track reconstruction

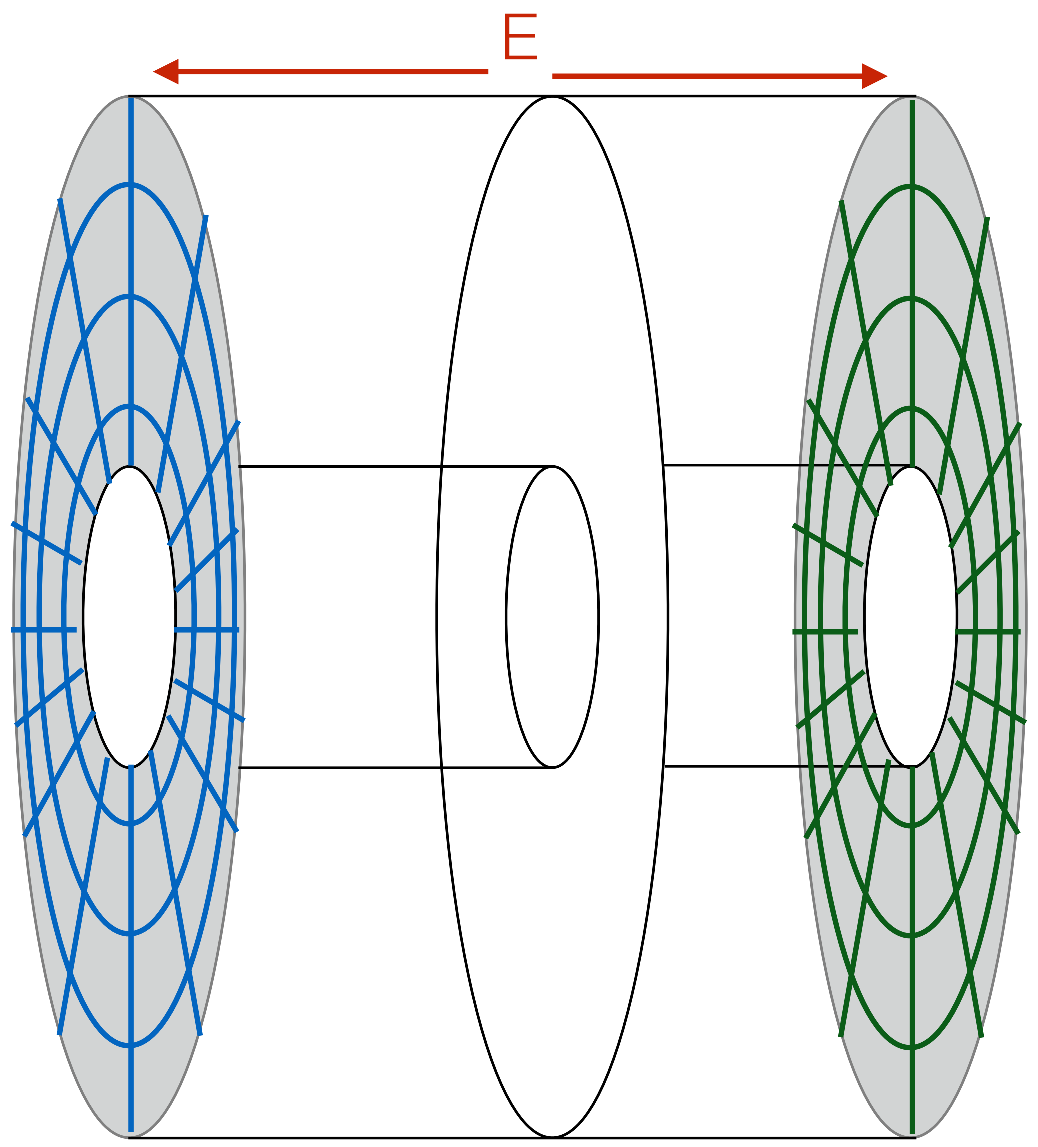


a gas filled vessel (ionisable)

electric field for the charge drift

Time projection chamber

- TPCs allow to build huge tracking devices to relative moderate cost
  - precise track reconstruction



a gas filled vessel (ionisable)

electric field for the charge drift

segmented readout chambers
(different technologies possible)

Time projection chamber

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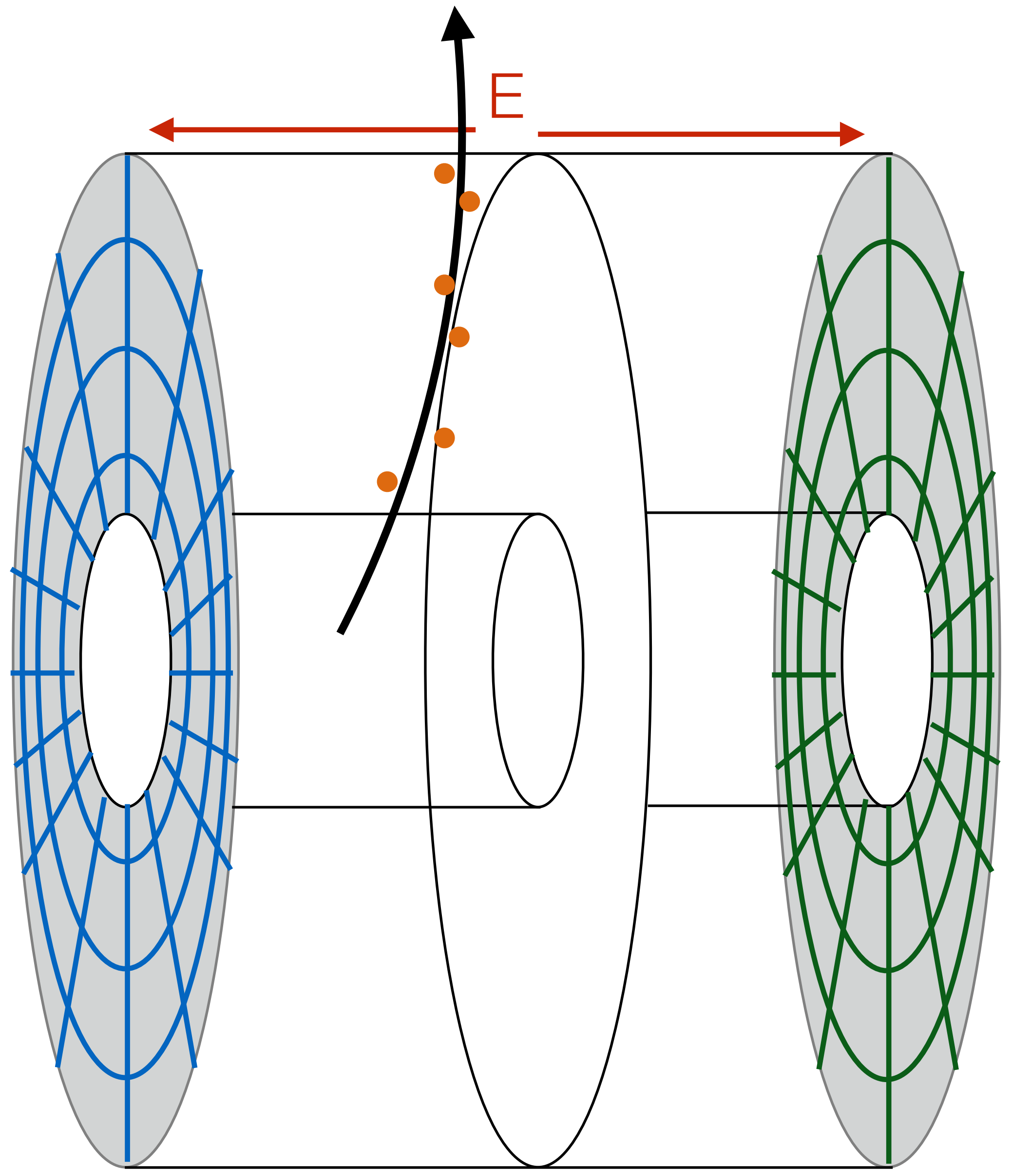

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track ionises the gas

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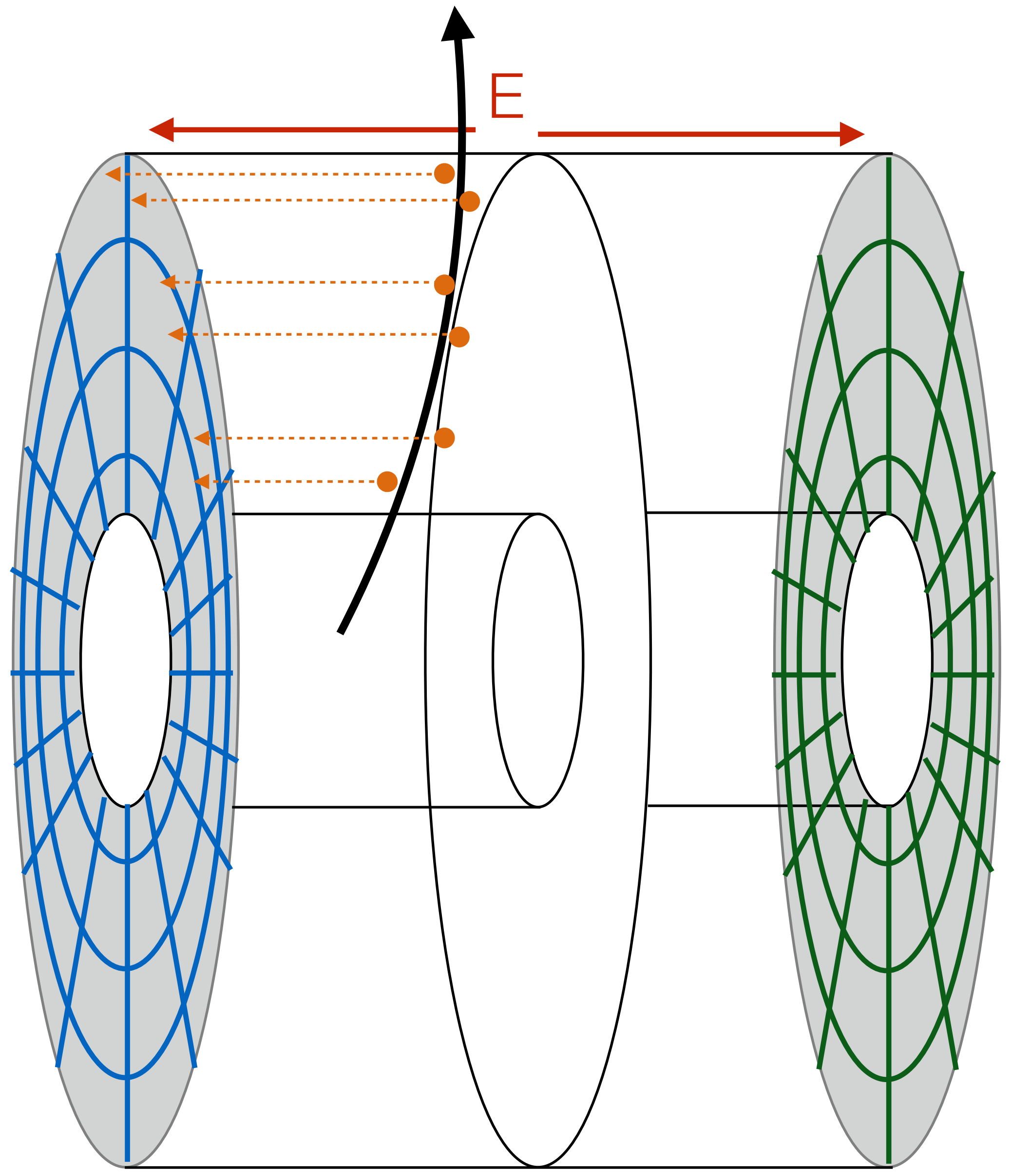

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track ionises the gas

charge drift to the readout chambers

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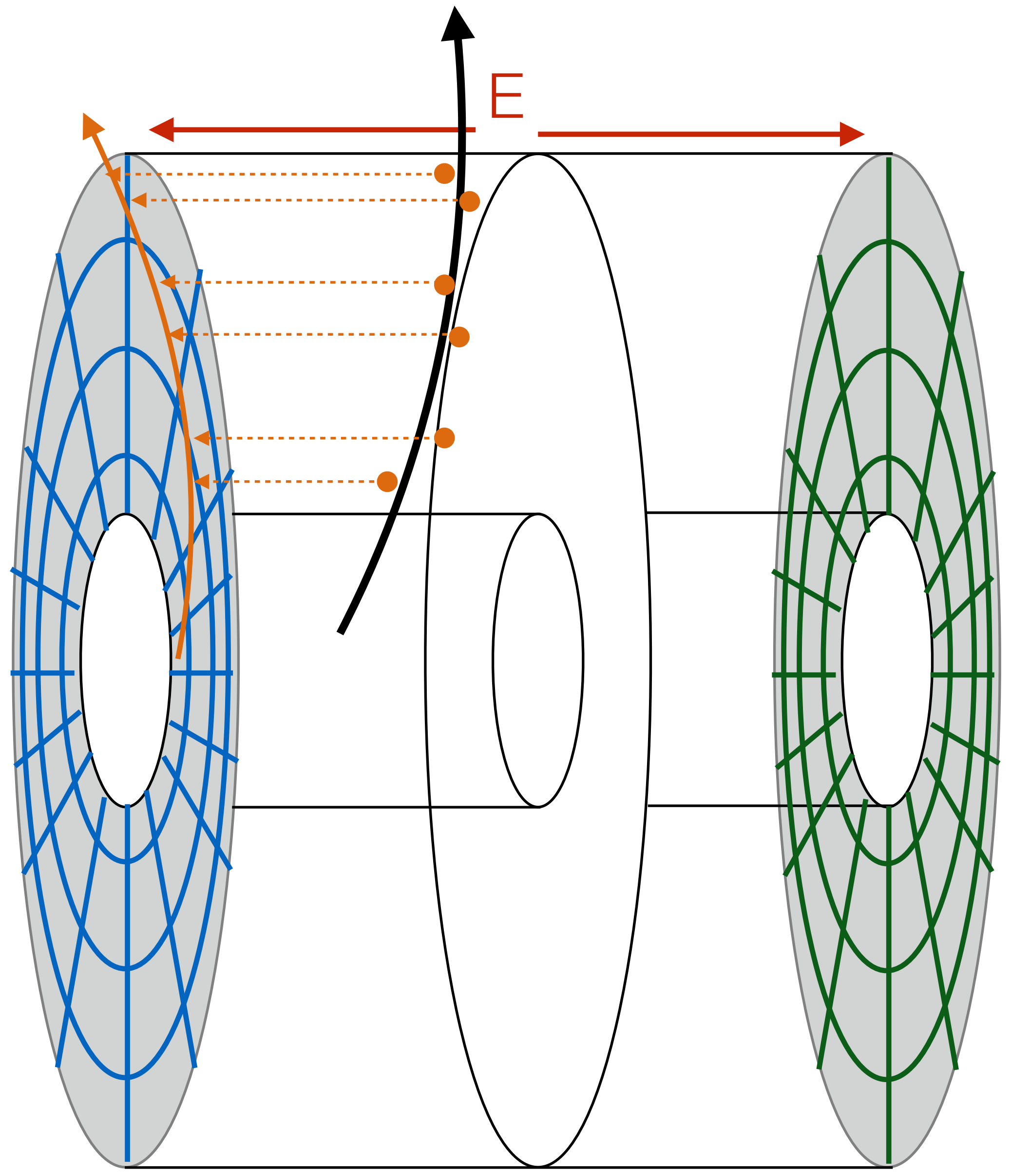

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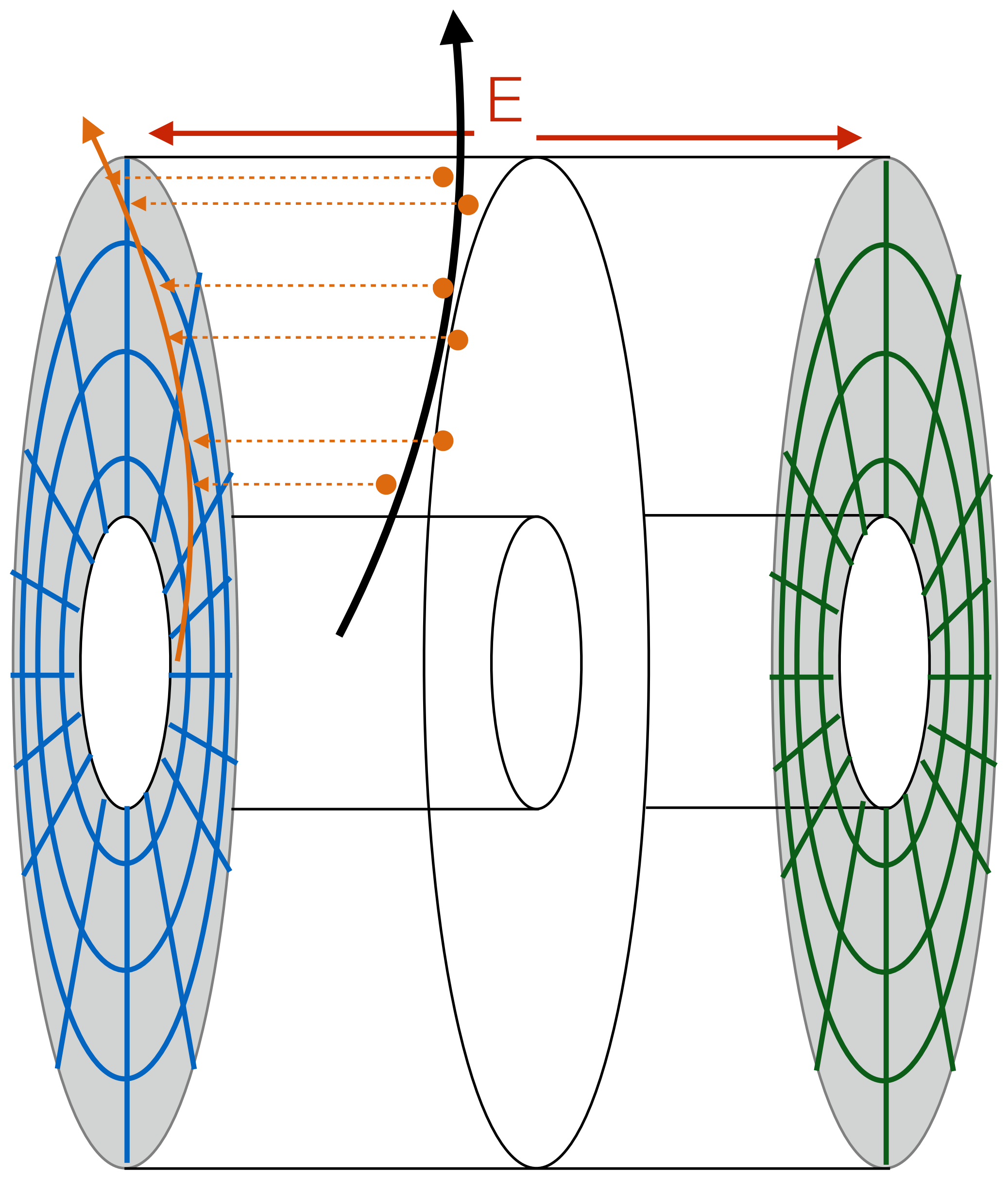


a gas filled vessel (ionisable)

electric field for the charge drift

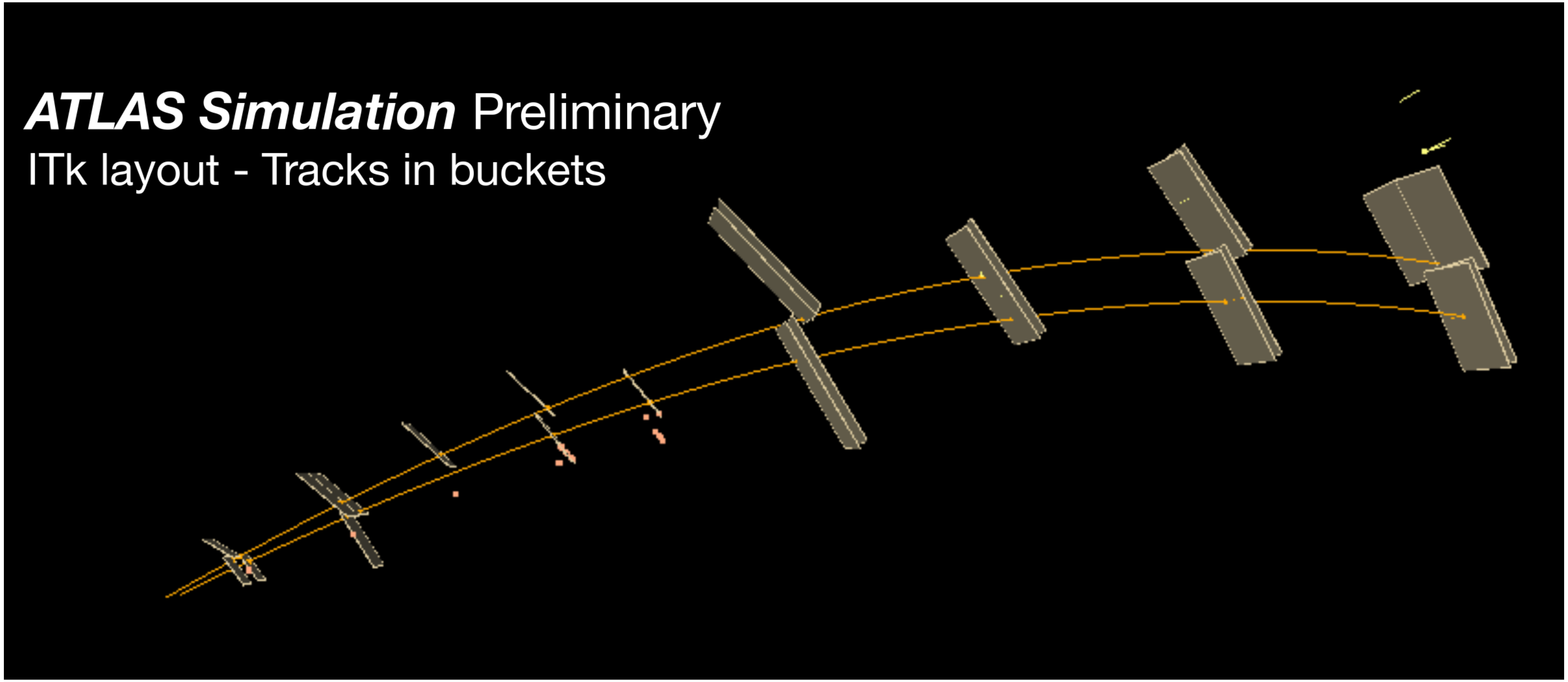
segmented readout chambers
(different technologies possible)

track ionises the gas

charge drift to the readout chambers

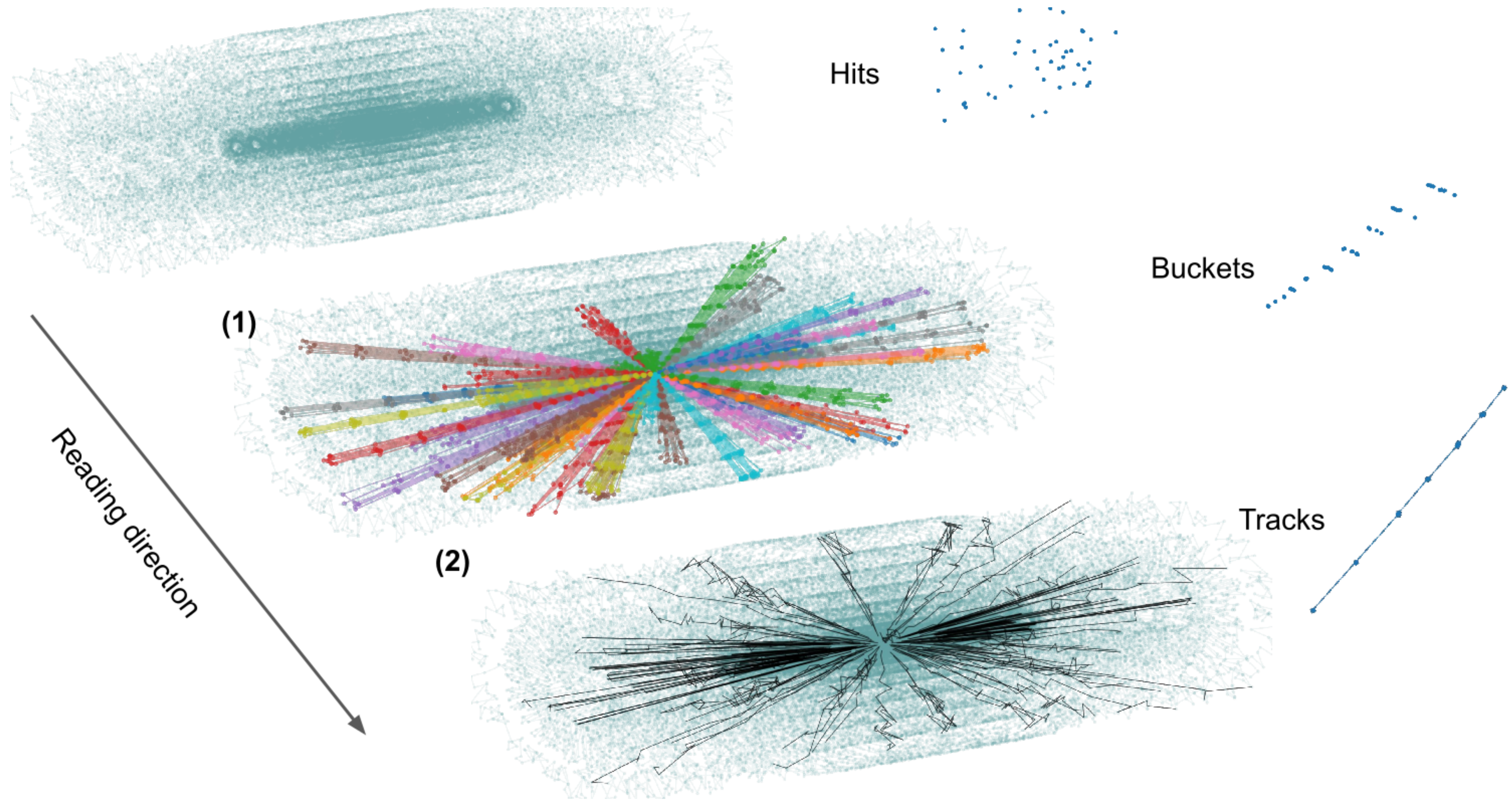
measurements:
(x,y) from readout segmentation
(z) from drift time

Labelling: Music Neighbours



Trajectories from simulated particles in the ATLAS upgrade tracker, **found** with (the help of) **Spotify**

Labelling: Music Neighbours



[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

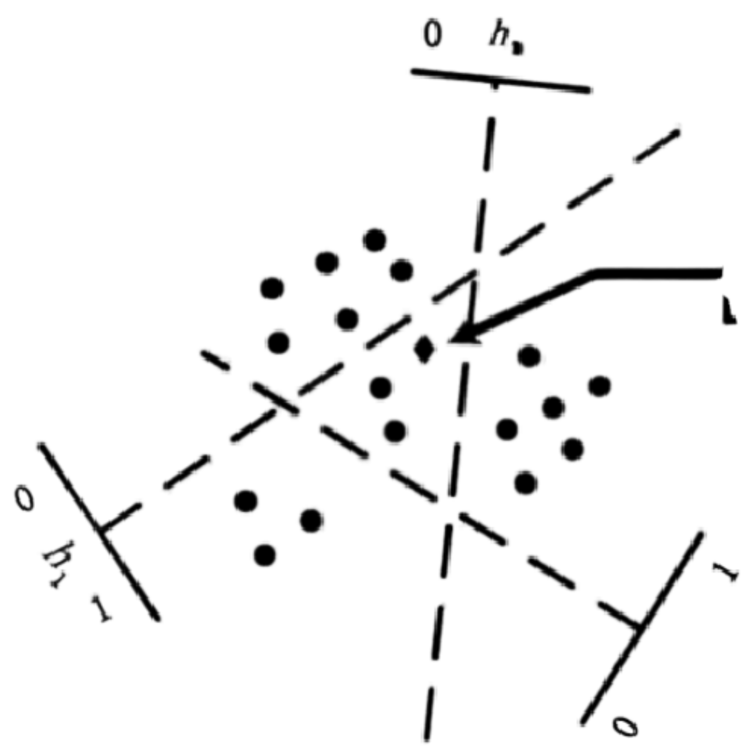
Labelling: Music Neighbours

Perfect hash function would solve the tracking problem

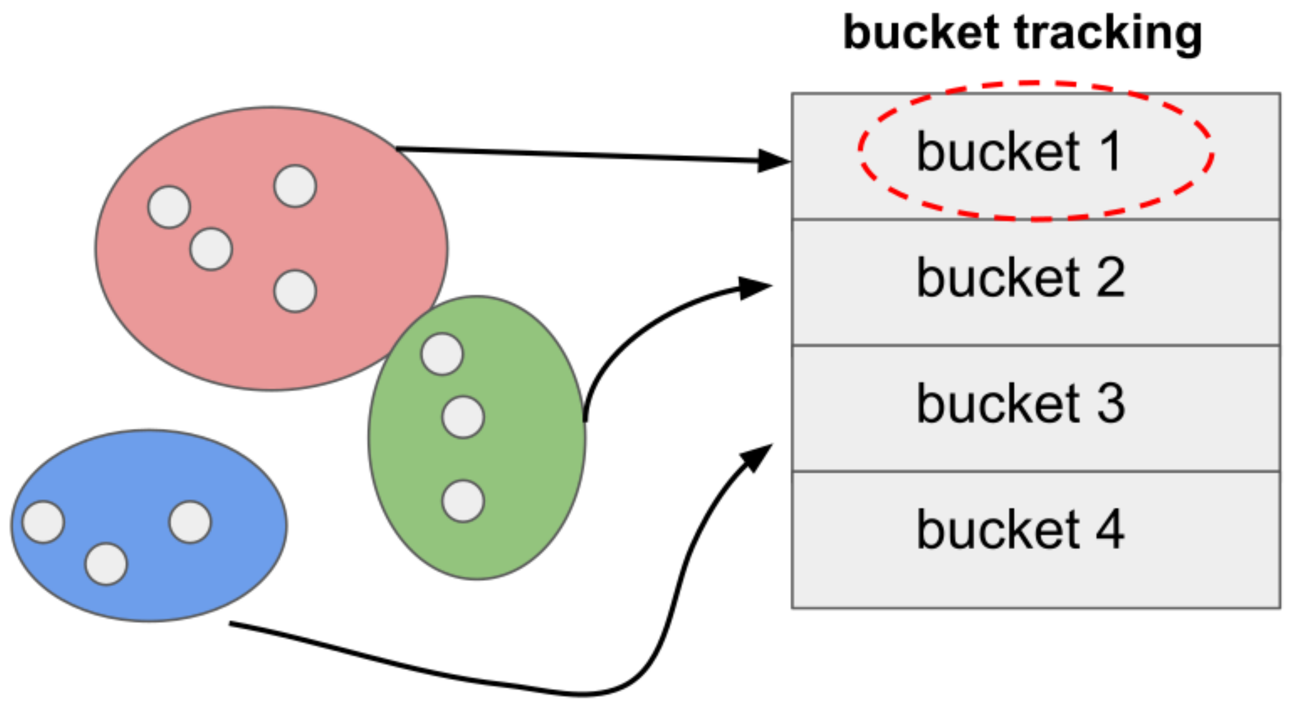
```
h(hit) = track number
```

Approximate hashing, however, can be done

```
h(track 1, hit 0) = group x
h(track 1, hit 1) = group x
h(track 0, hit 1) = group x
```



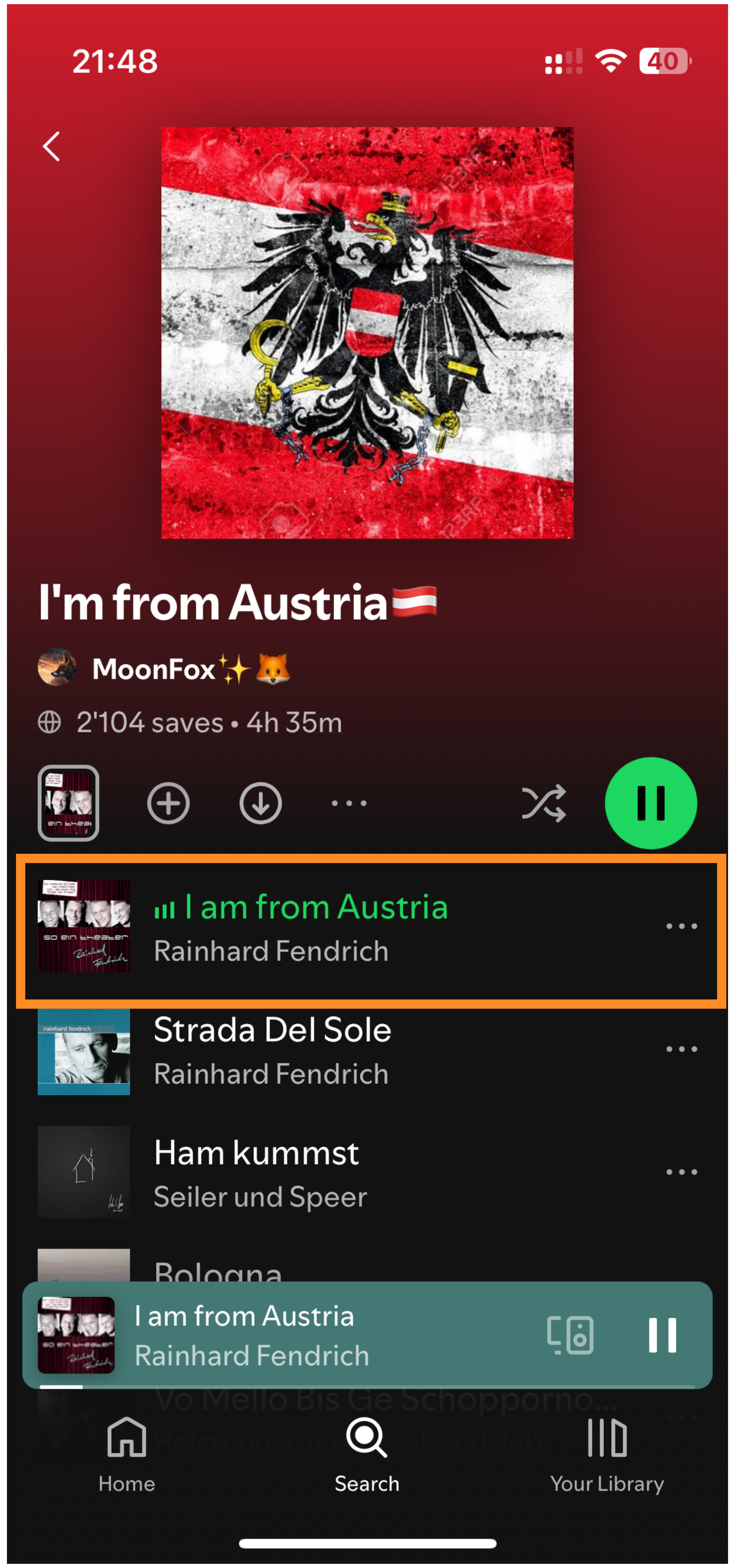
RADNOM PROJECTIONS



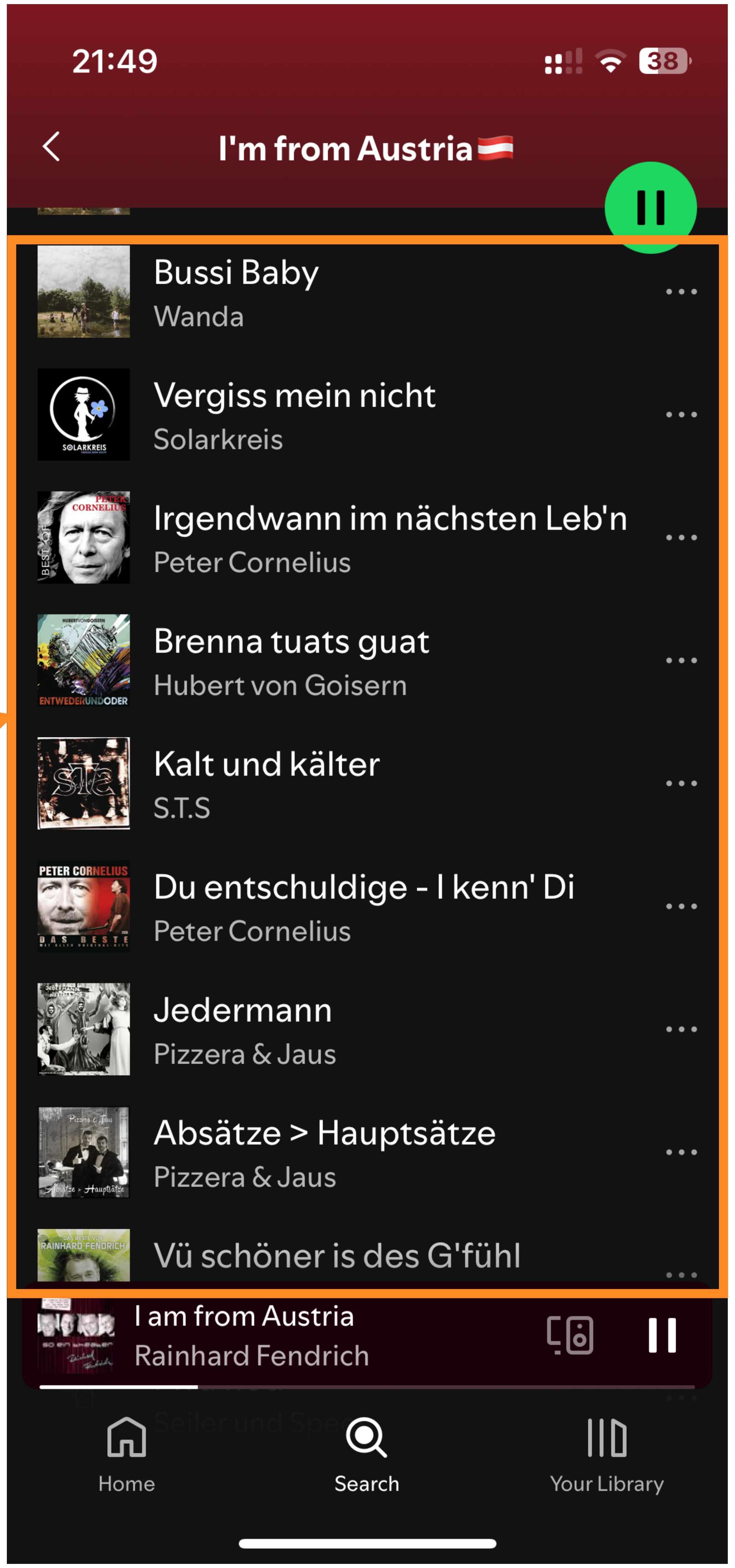
APPROXIMATE NEAREST NEIGHBOURS

[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

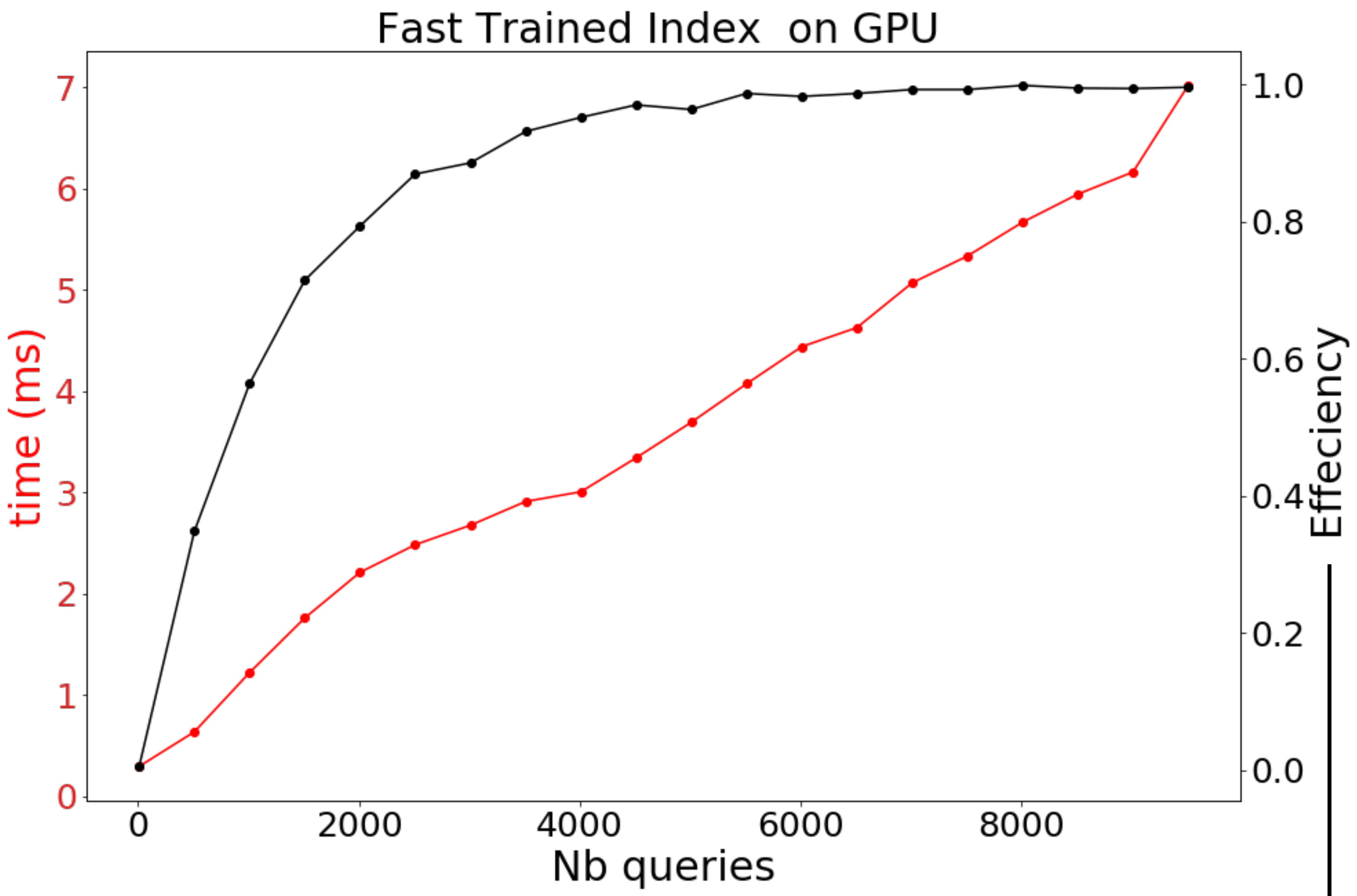
Labelling: Music Neighbours



Spotify's approximate nearest neighbourhood library: [ANNOY]



Industry/open source libraries offer quite some **potential** also for science applications



To find a bucket with at least 4/hits of the track contained (good enough for track seeding)

[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

Labelling: Music Neighbours

Industry/open source libraries offer quite some **potential** also for science applications, **but …**


Add items without copying #389

Closed msmk0 opened this issue on May 24, 2019 · 1 comment

msmk0 commented on May 24, 2019

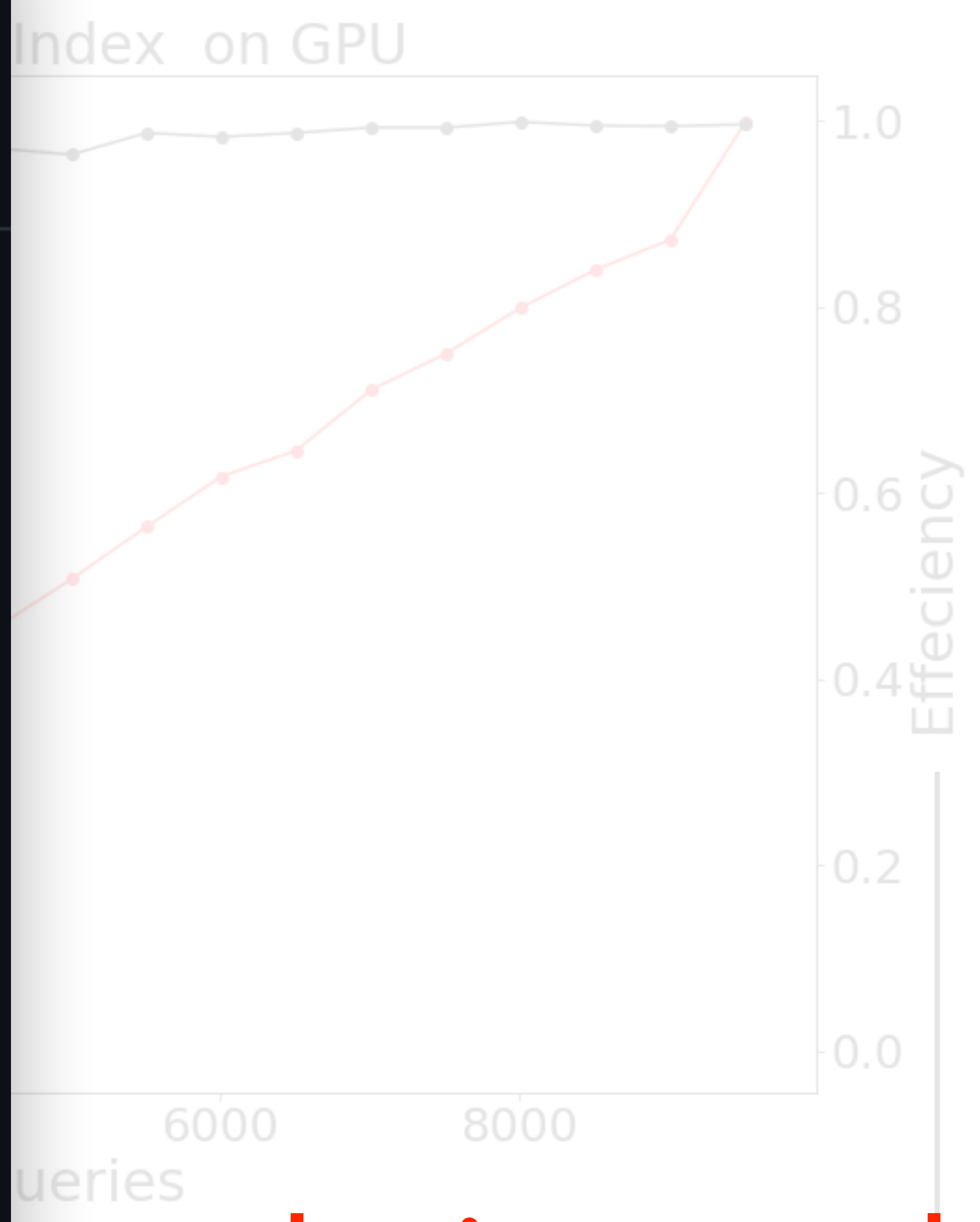
This is more of a question than an issue and relates to the C++ implementation.

From my understanding of the code, item elements/weights are copied when using `.add_item(...)`. In our application we already have all items stored in memory. Would it be possible to avoid the copy and use the elements directly by reference/pointer? If so, where in the library would this change have to be implemented?

erikbern commented on May 25, 2019 — Collaborator

I think that would be somewhat hard to implement given the memory layout of Annoy indexes, unfortunately!

erikbern closed this as completed on May 25, 2019



.. no business model!

(In other words)

[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]