Particle Detection and Belle II

2025 Belle II International masterclass

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Bonn

INTERNATIONAL MASTERCLASSES hands on particle physics
International Particle Physics Outreach Group
UNIVERSITÄT BONN
BLUB
Belle II

Why studying the Standard Model?

Macroscopically there are effects which CAN NOT be explained with the Standard Model

↓

something missing!

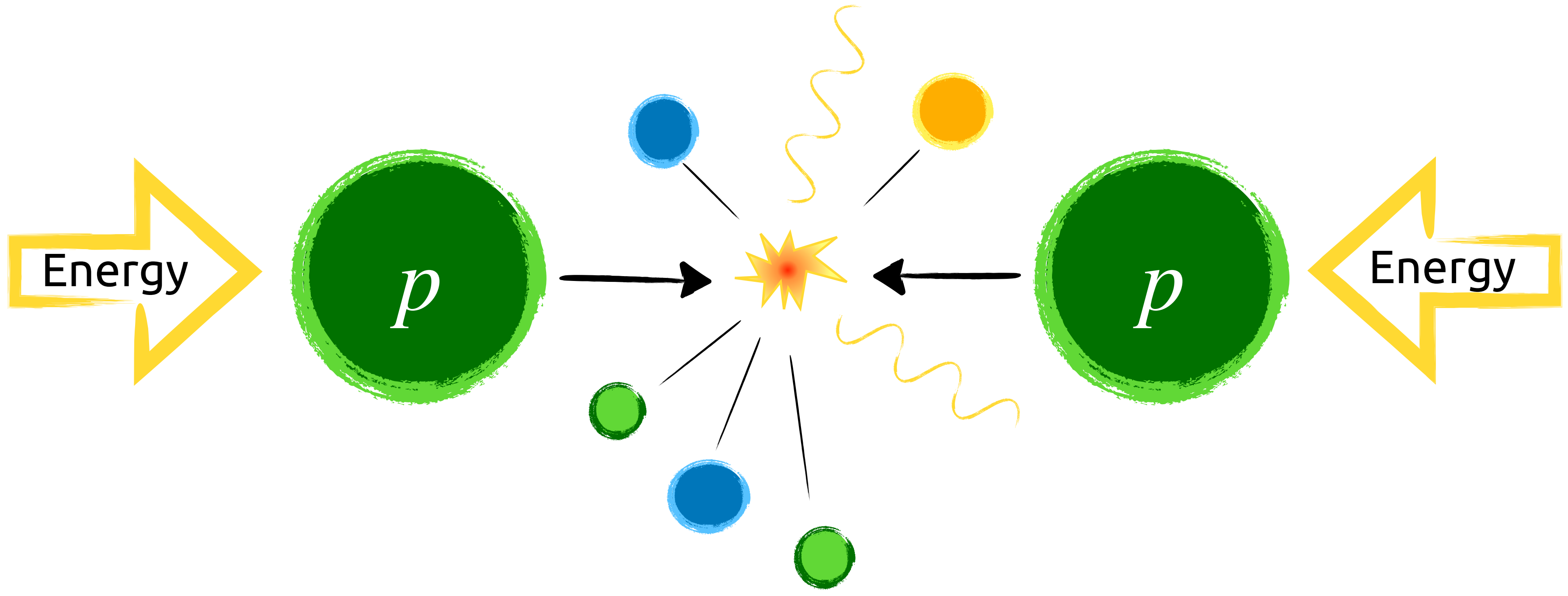
- **(about)1967-2012**: Theoretical development and experimental confirmation of the Standard Model
- **2012-???** : Search of New Physics beyond the Standard Model

↓

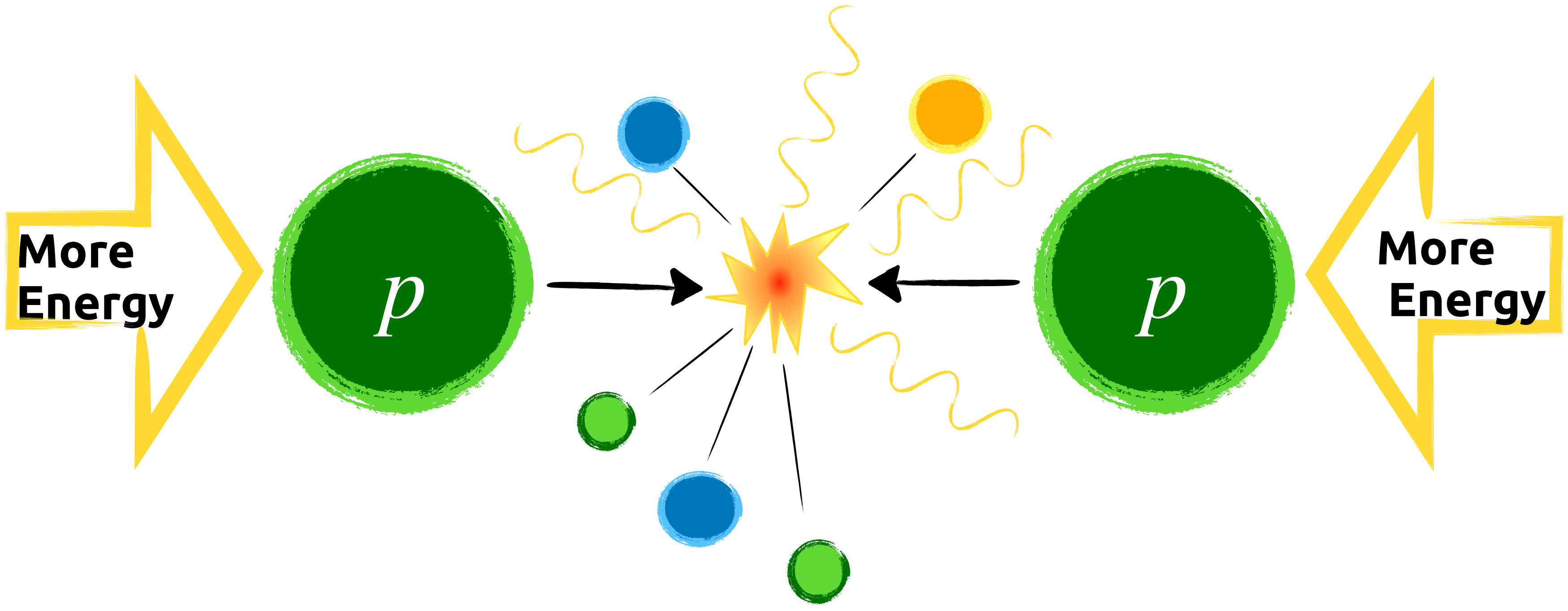
We are pushing the limits of the Standard Model to try to observe, in laboratory, where is not working anymore. We are pursuing two approaches:

- **Higher energies** --> looking for "smaller and smaller" things: **Energy frontier**
- **Better precision** --> searching for discrepancies from the Standard Model: **Intensity frontier**

Energy frontier



Energy frontier



More energy in!

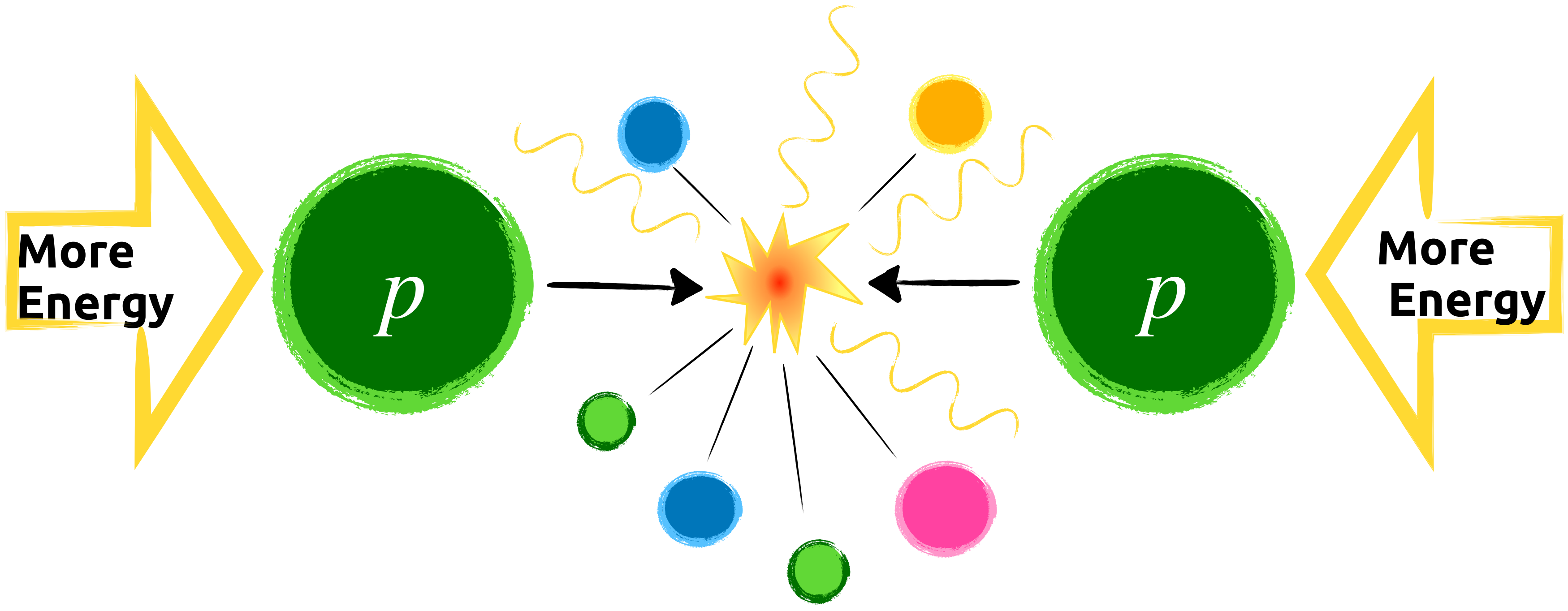
↓

More energy out

↓

We can create additional particles

Energy frontier



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Maybe something **unexpected** will pop up!

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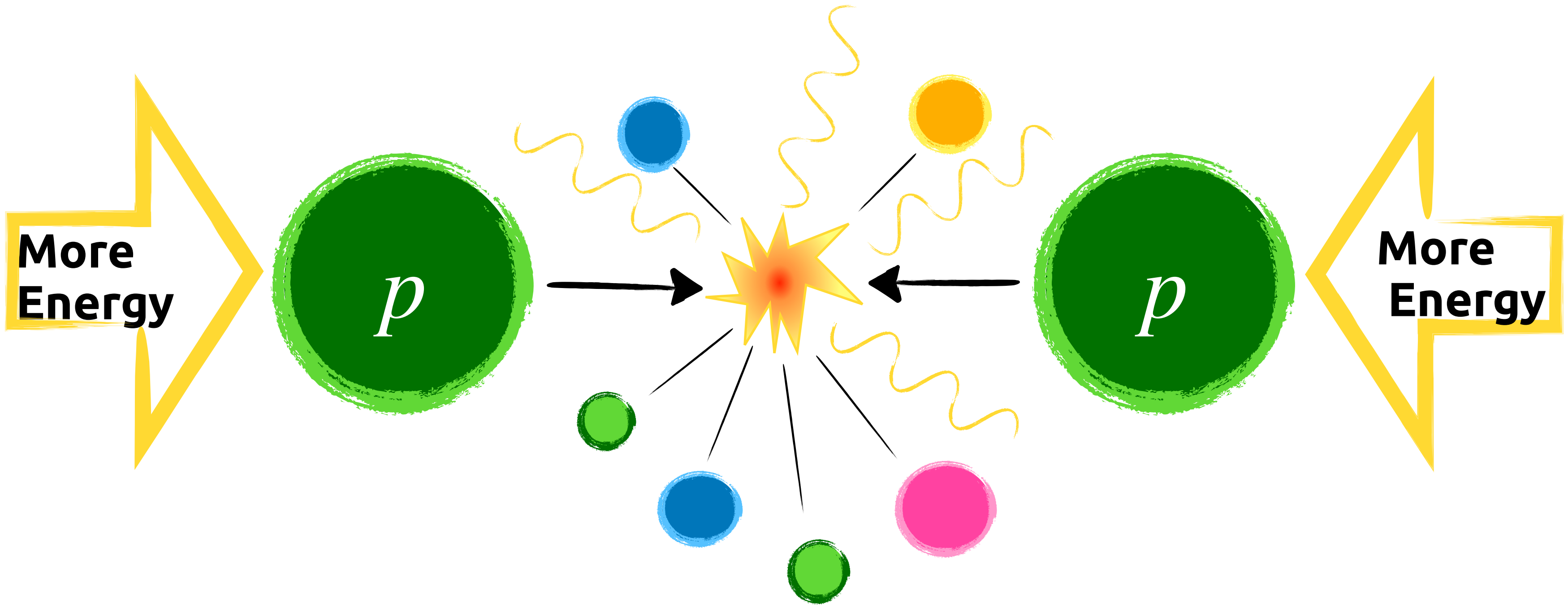

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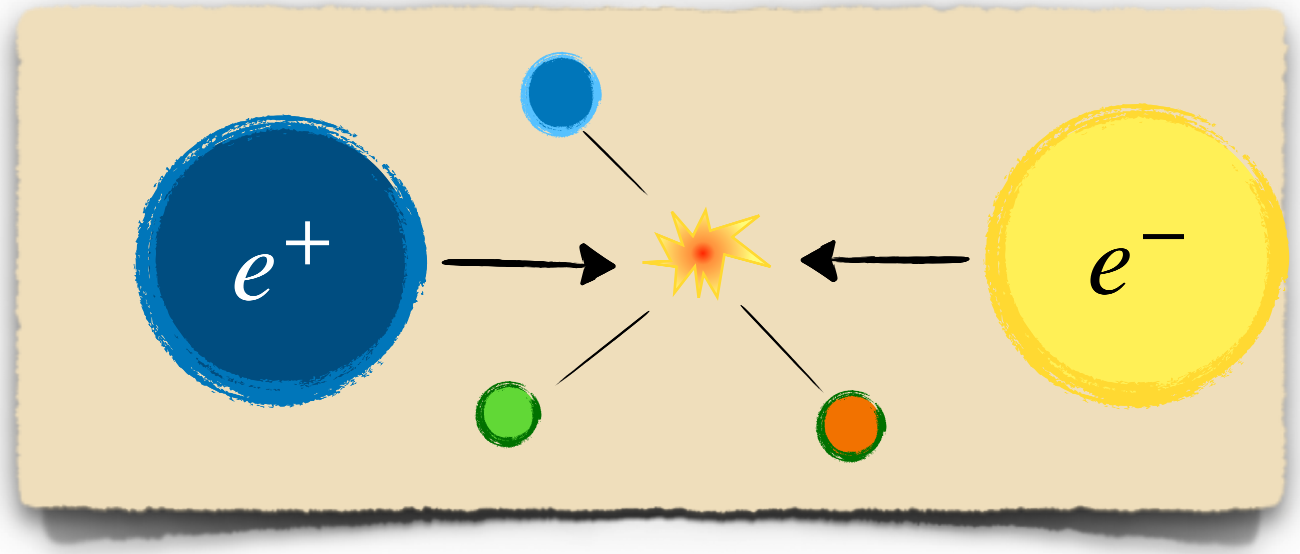
Intensity frontier

SM Probability: $\mathcal{P}$(● ● → ● ● ●) = X%



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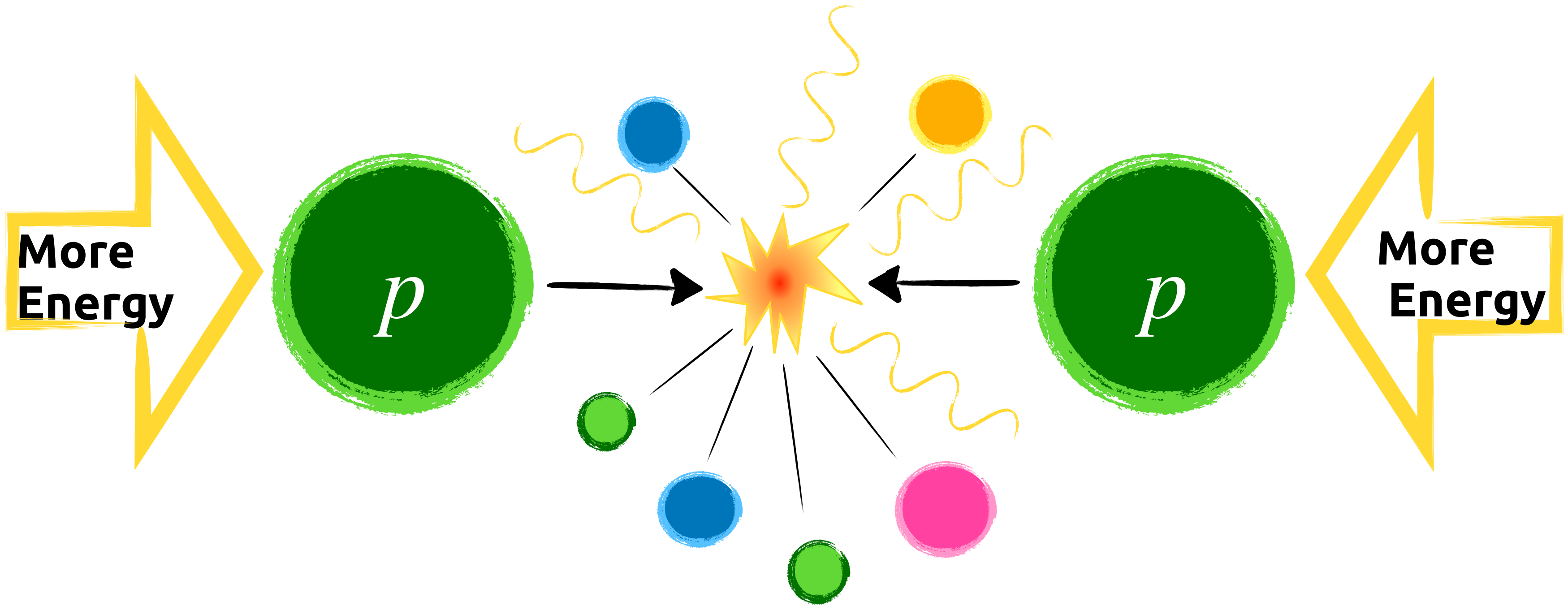

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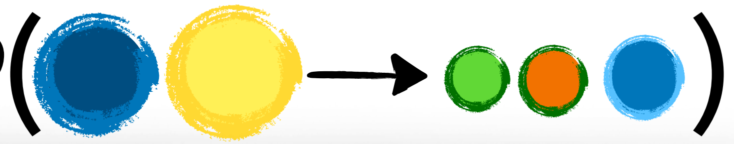
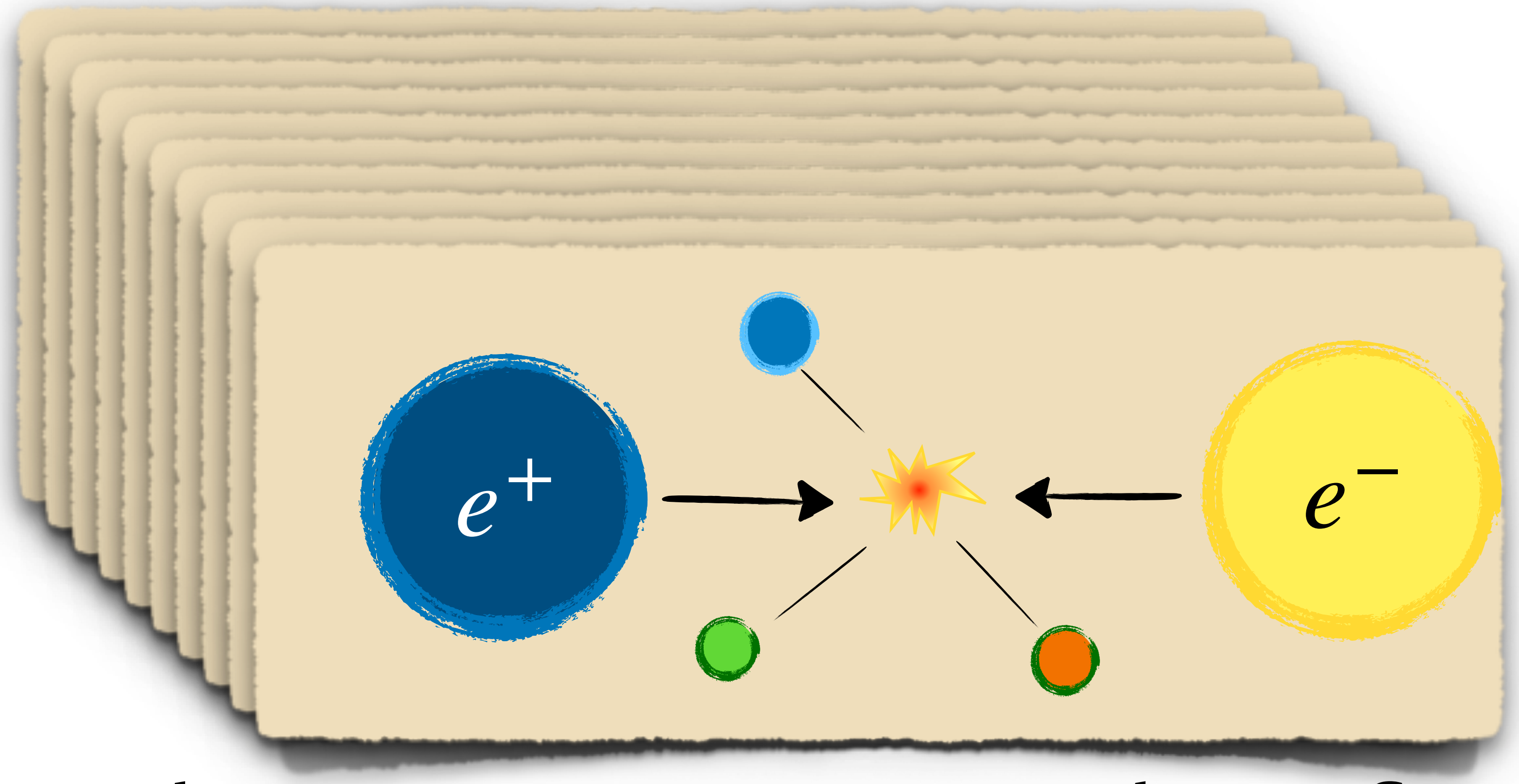
SM Probability: $\mathcal{P}$() = X%

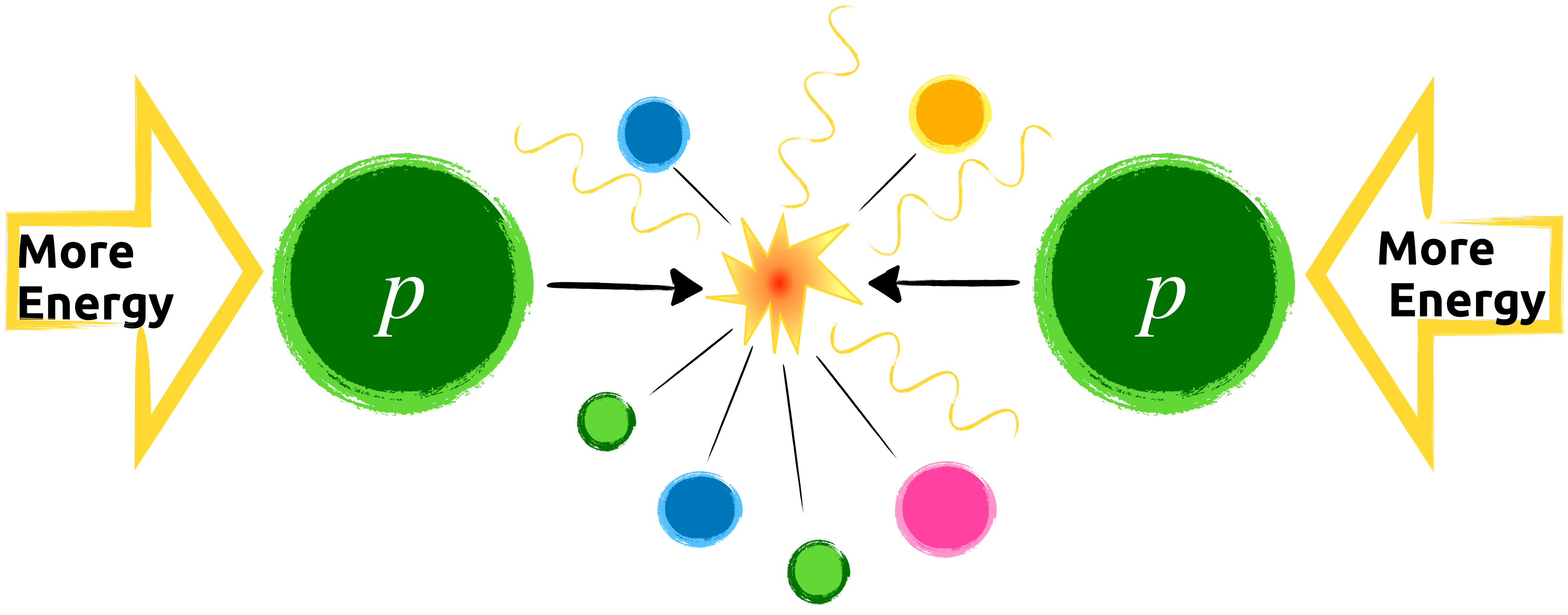


Repeat the measurement a lot of times
--> very precise measurement of $\mathcal{P}$

↓

Are we finding exactly what we expect from SM?

Energy frontier



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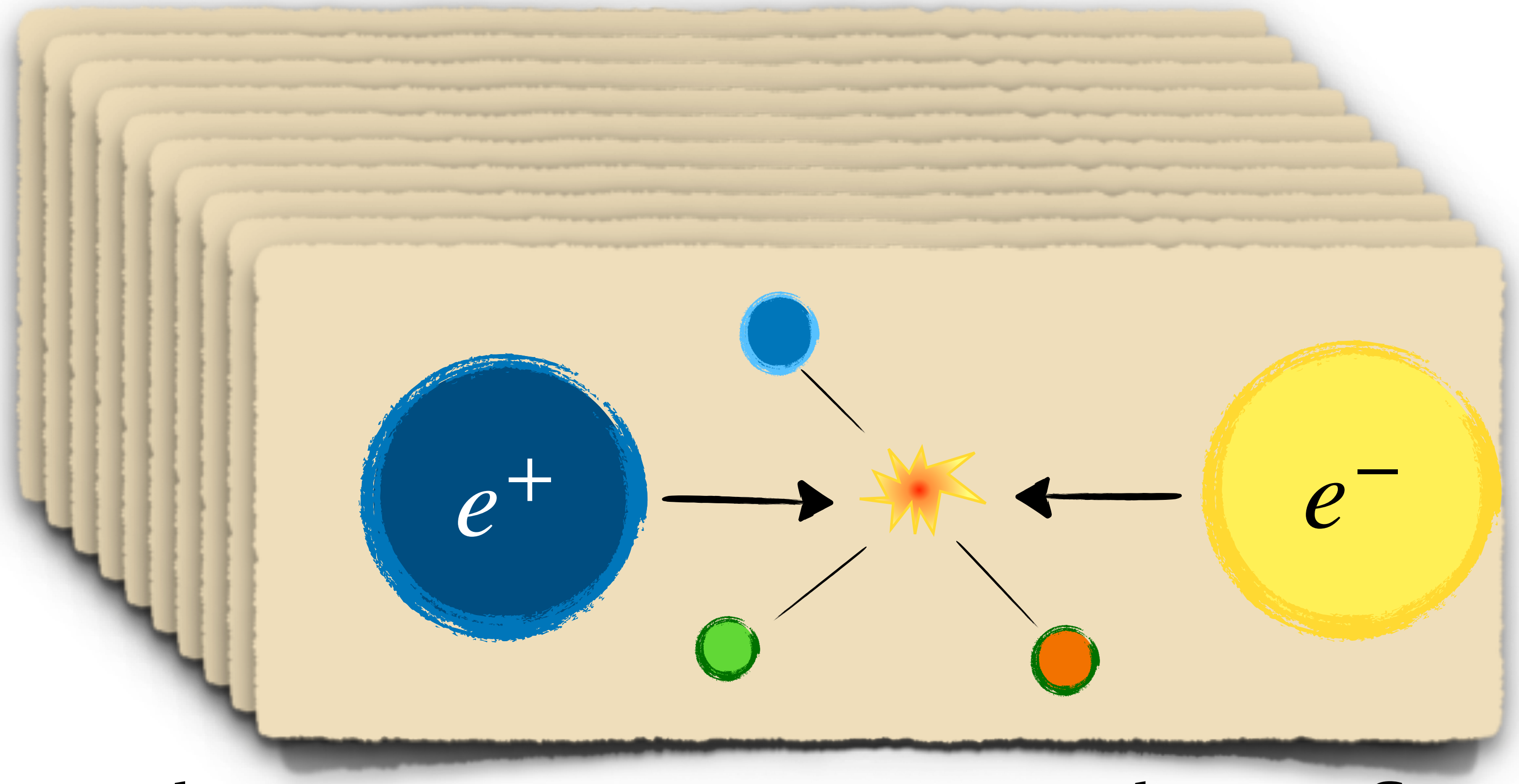

Repeat the measurement a lot of times
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Are we finding exactly what we expect from SM?

yes

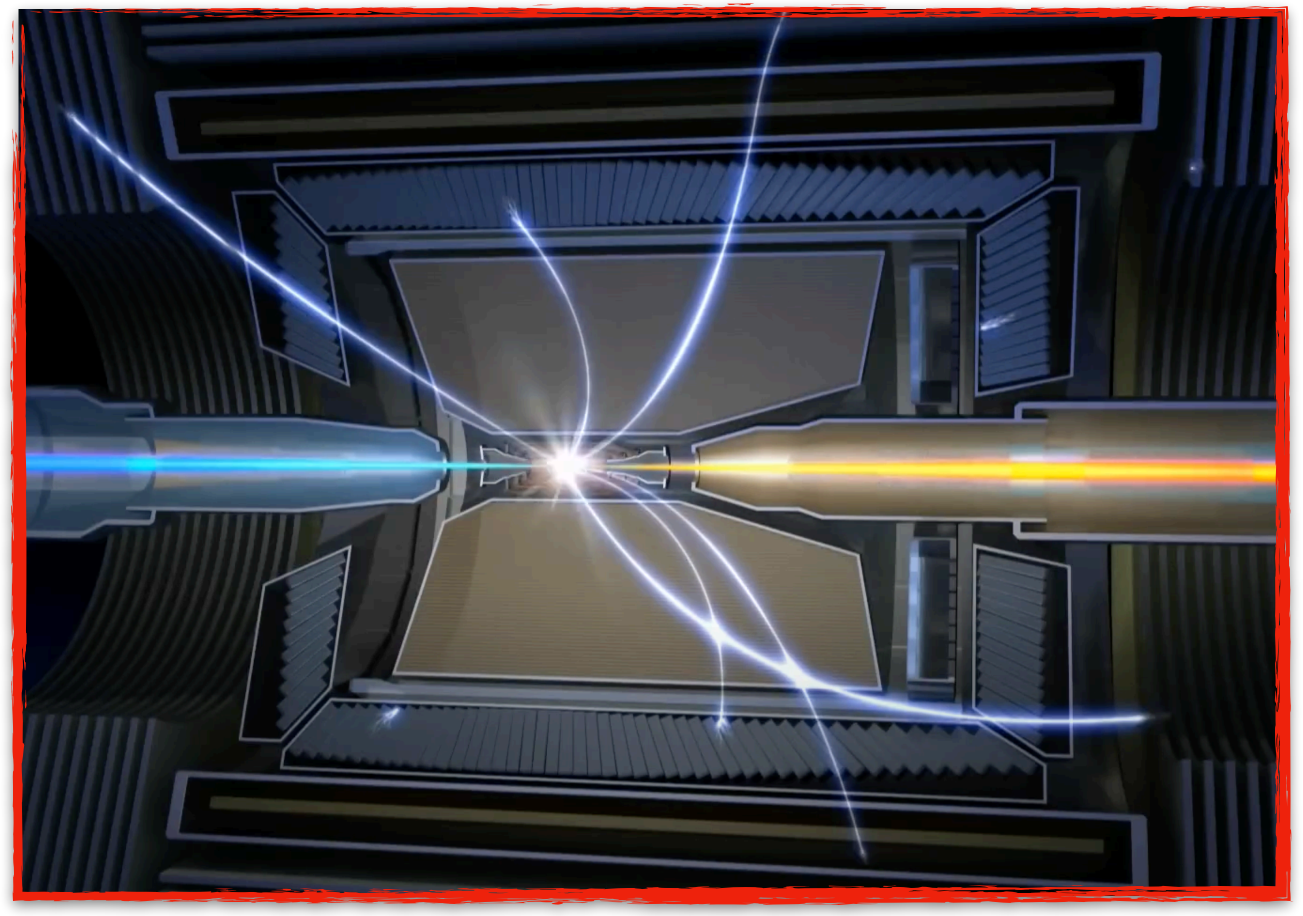
No New Physics today

no

We broke the SM!

How to

Accelerate particles and make them **collide**



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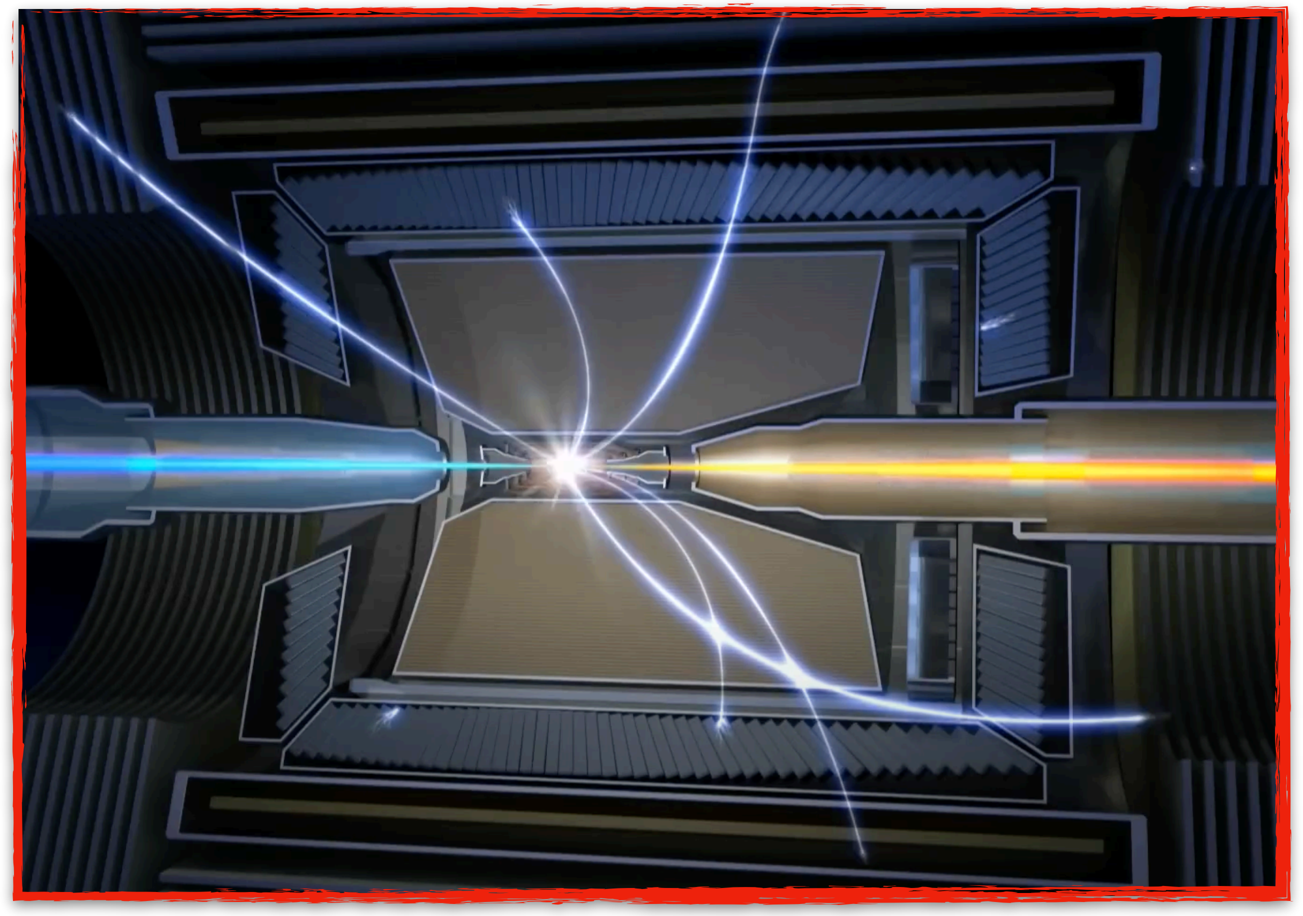
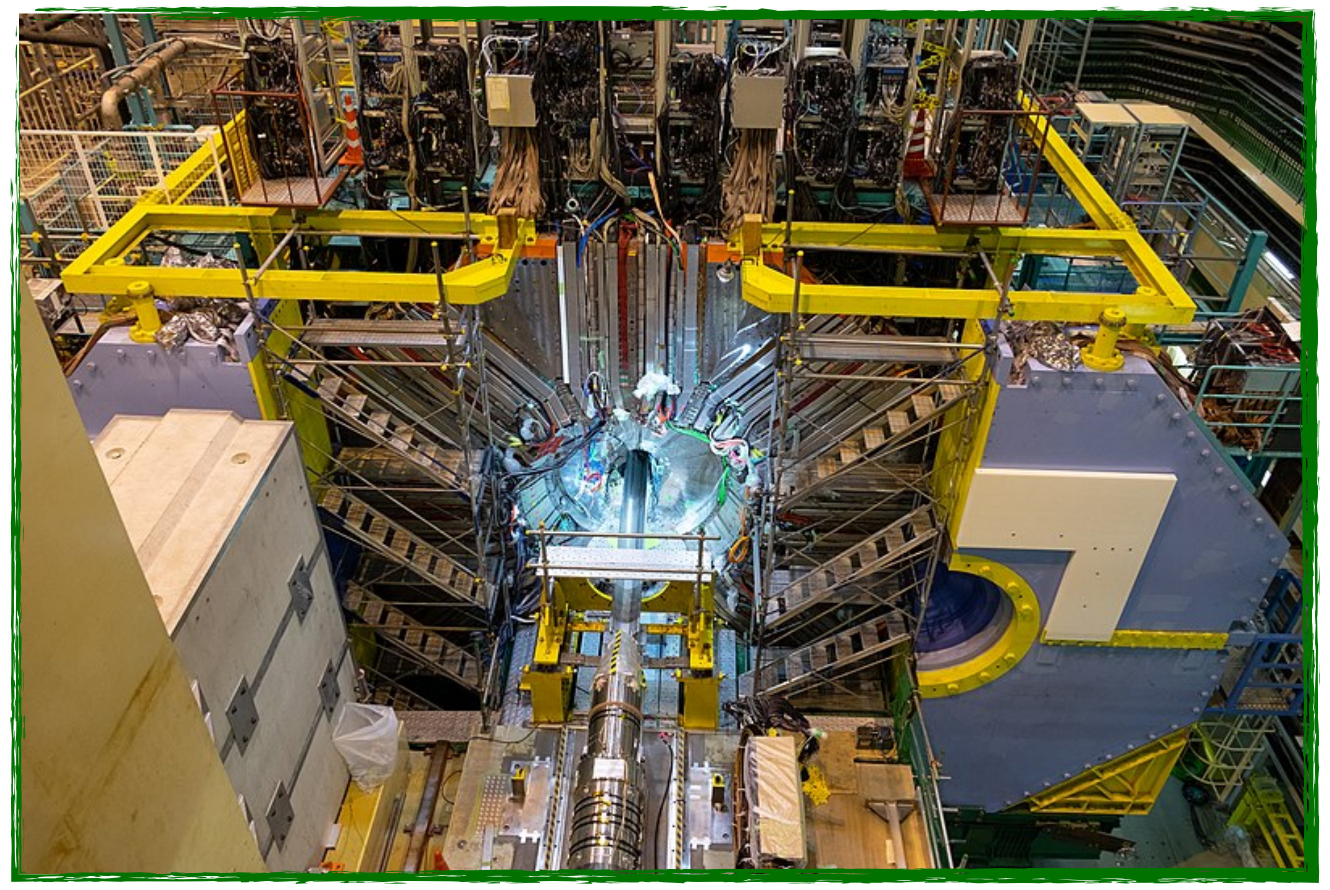
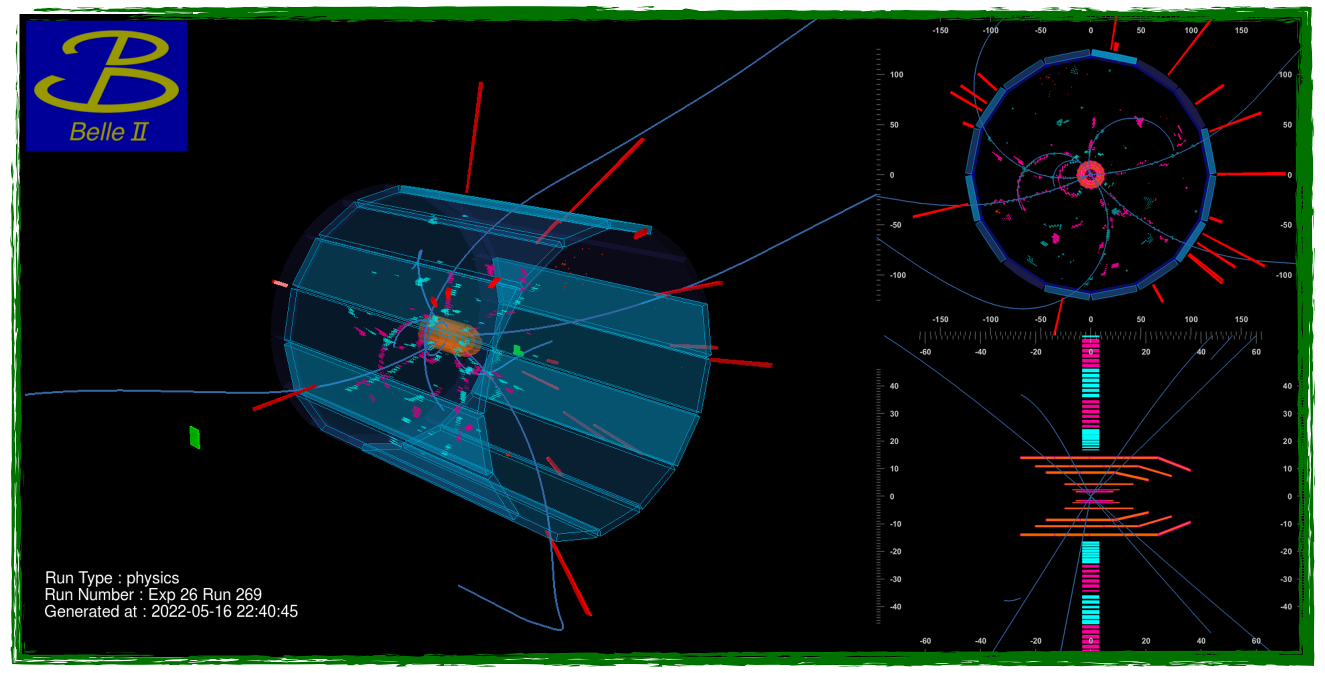


Detect the particles
resulting from the collision
and measure their properties





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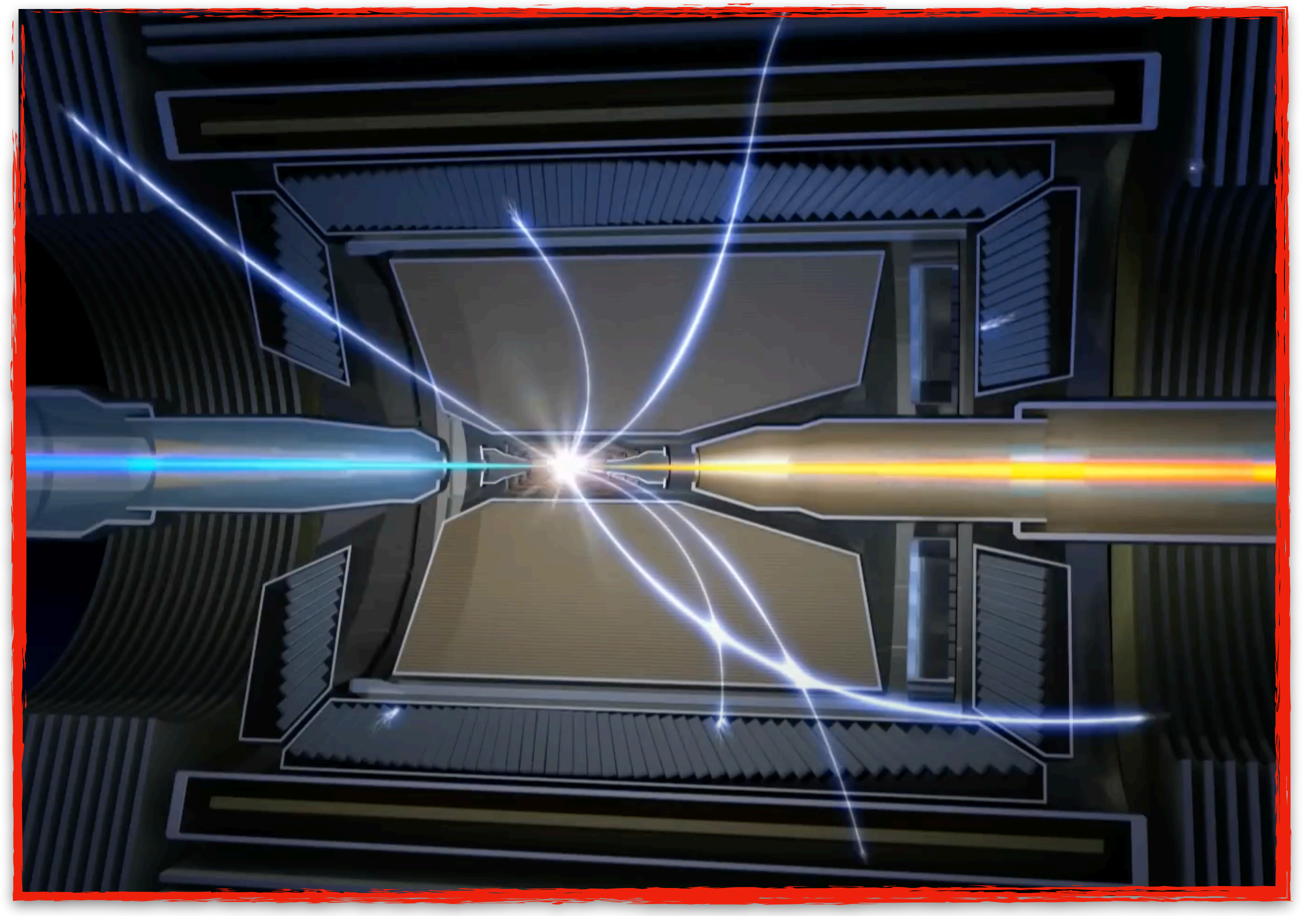

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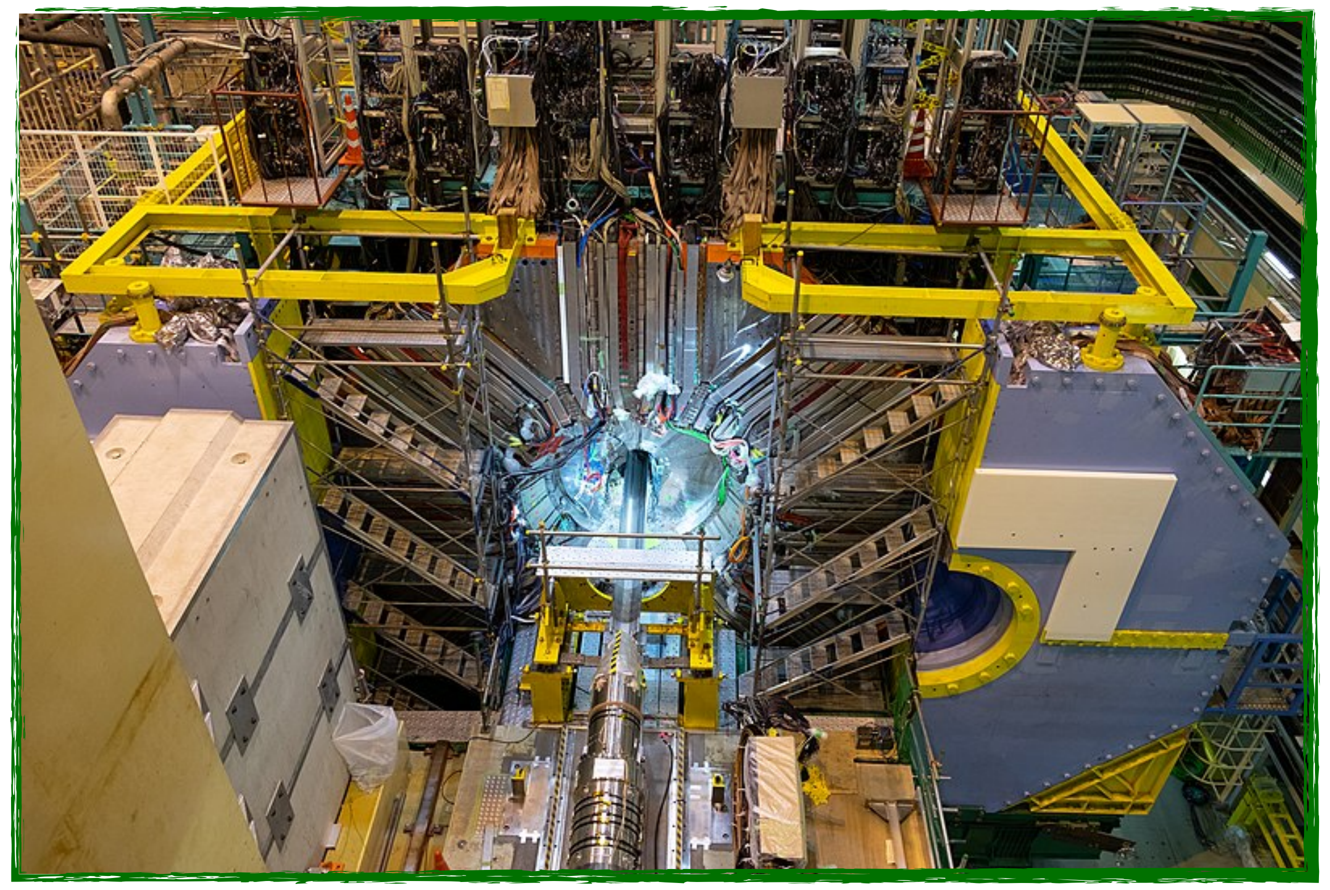
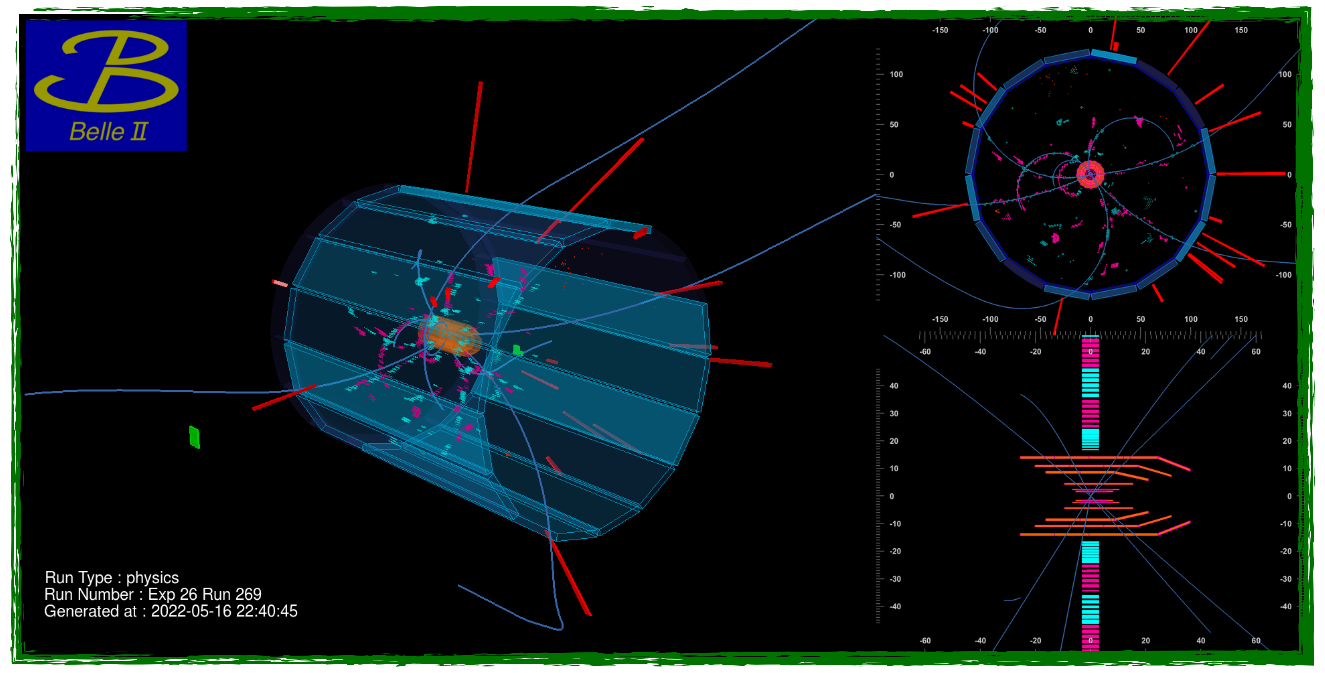
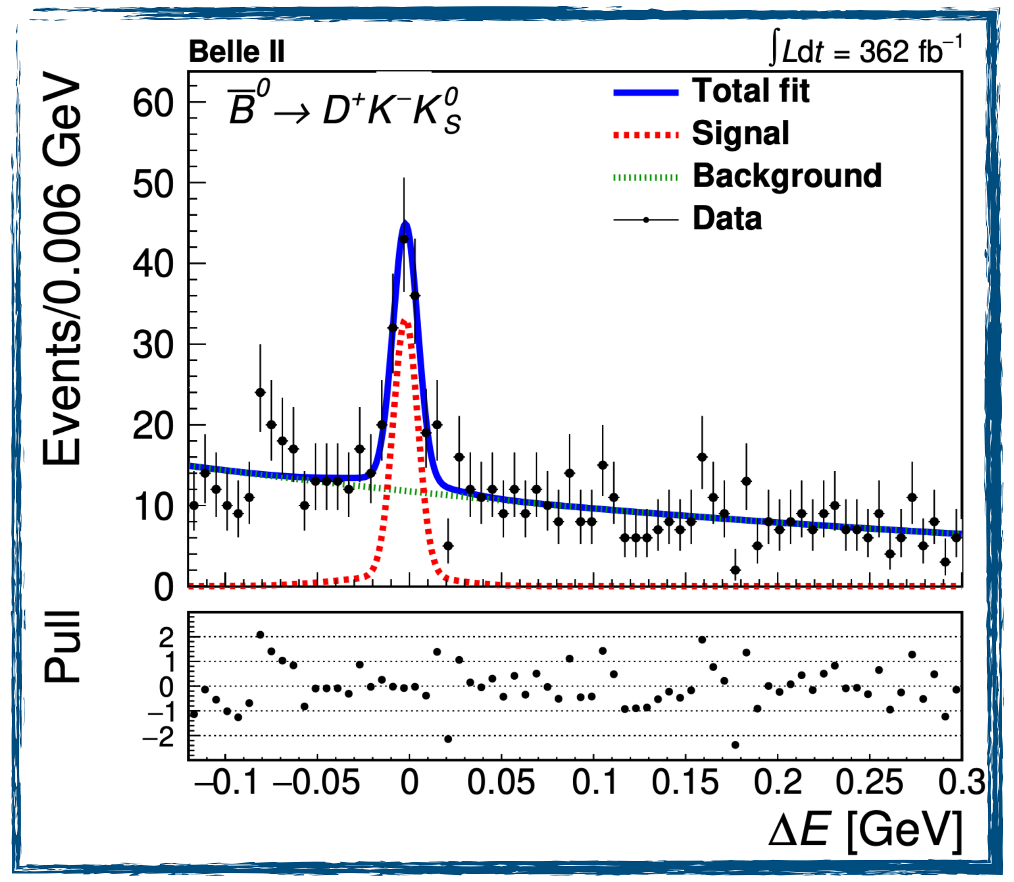




Analyze data coming from billions of collisions



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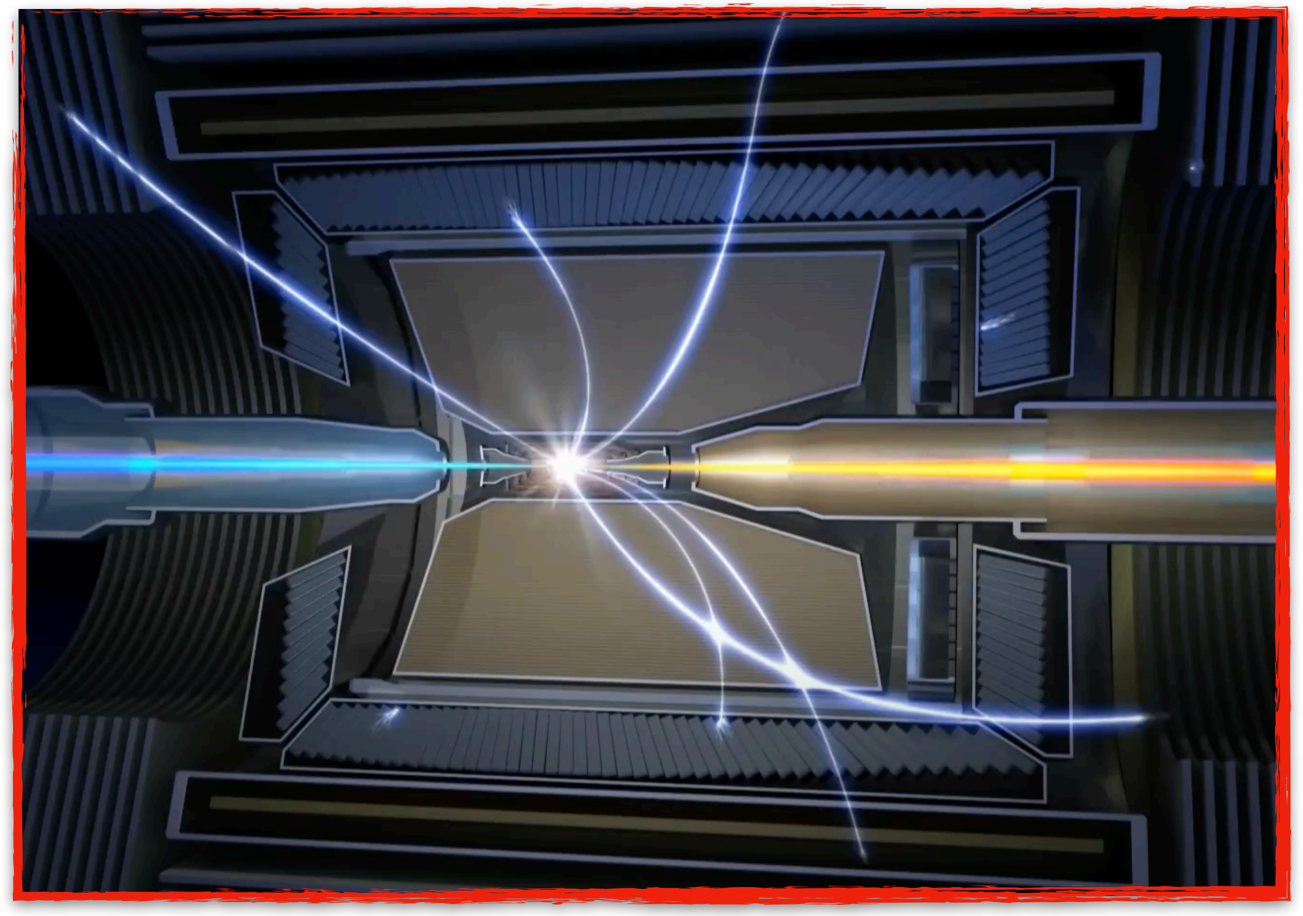

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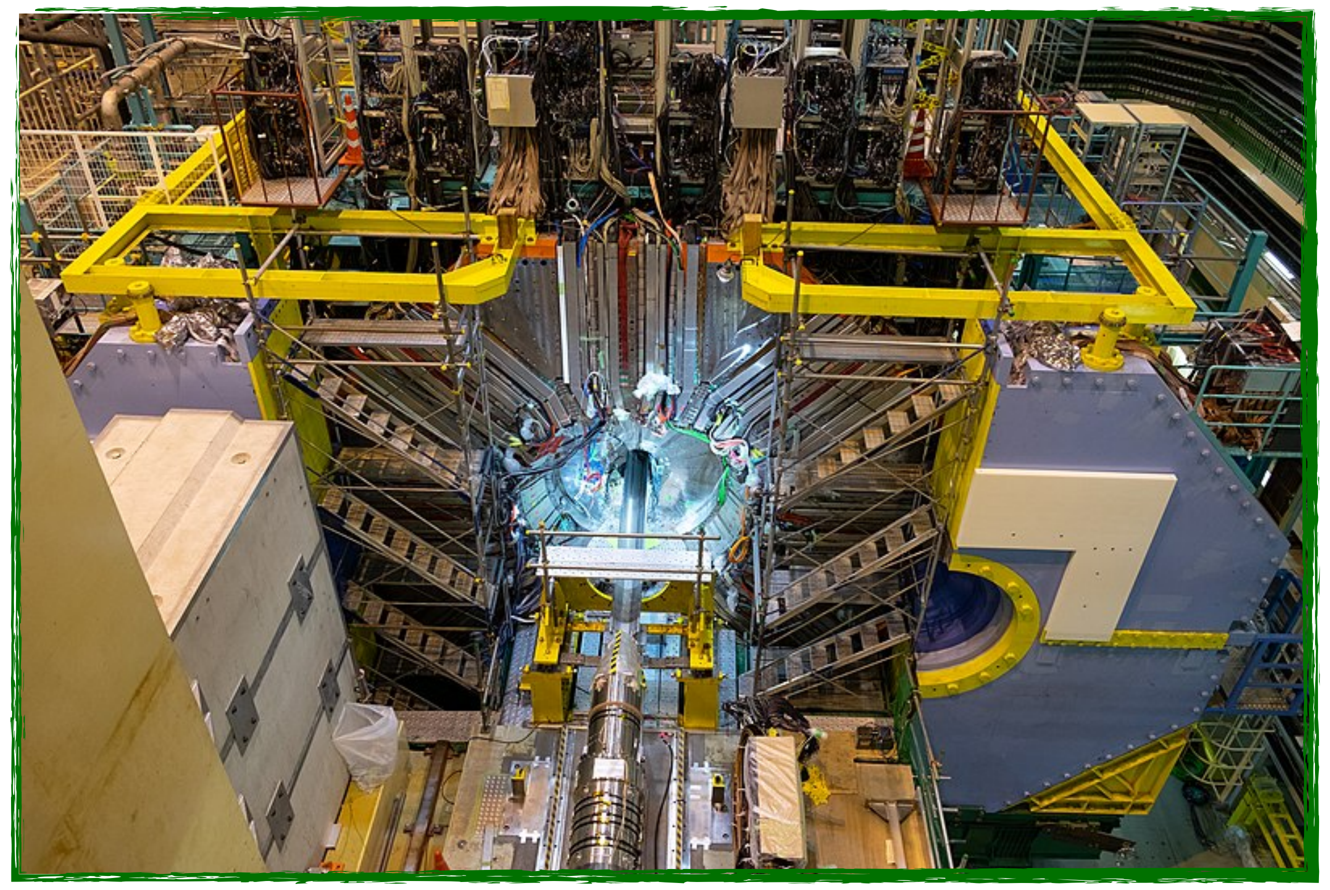

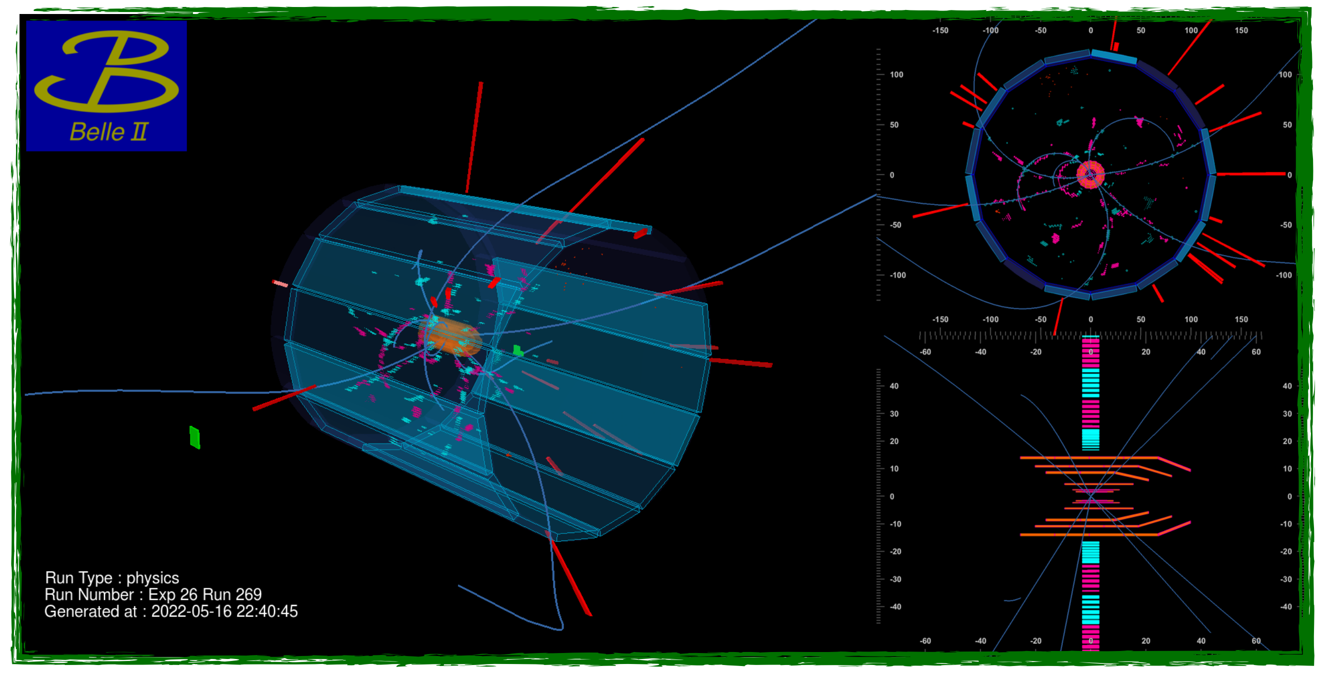

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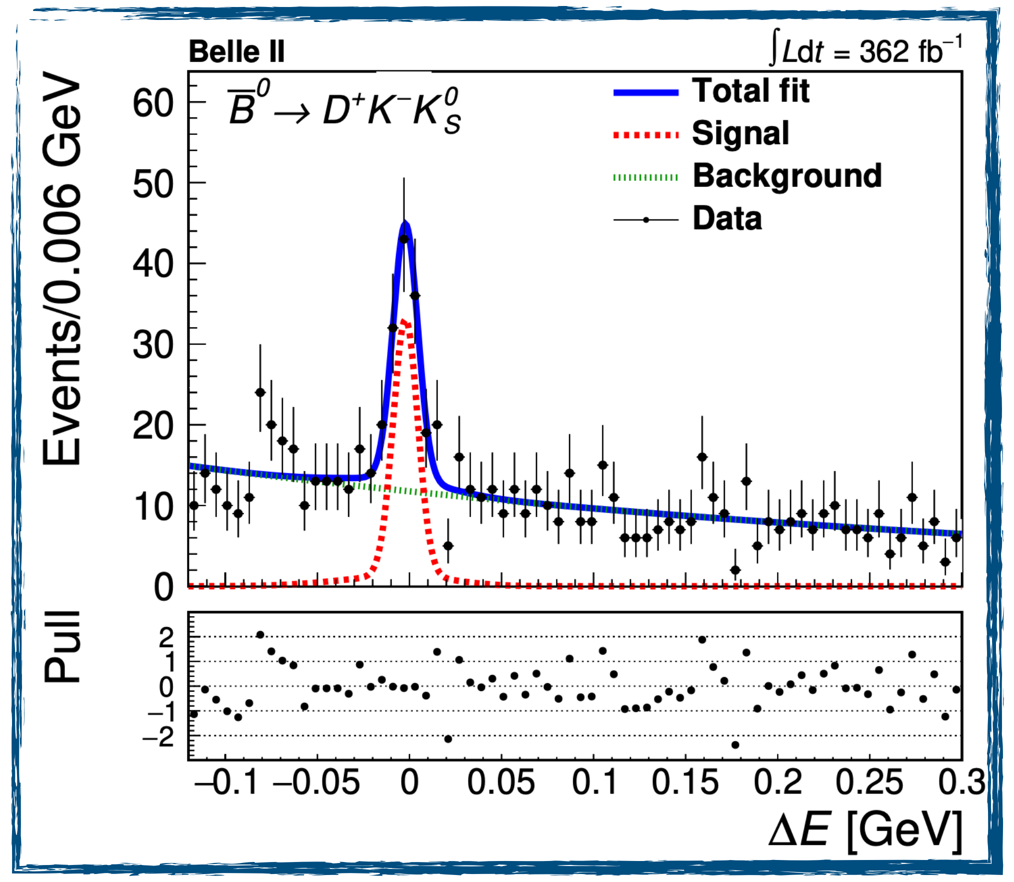


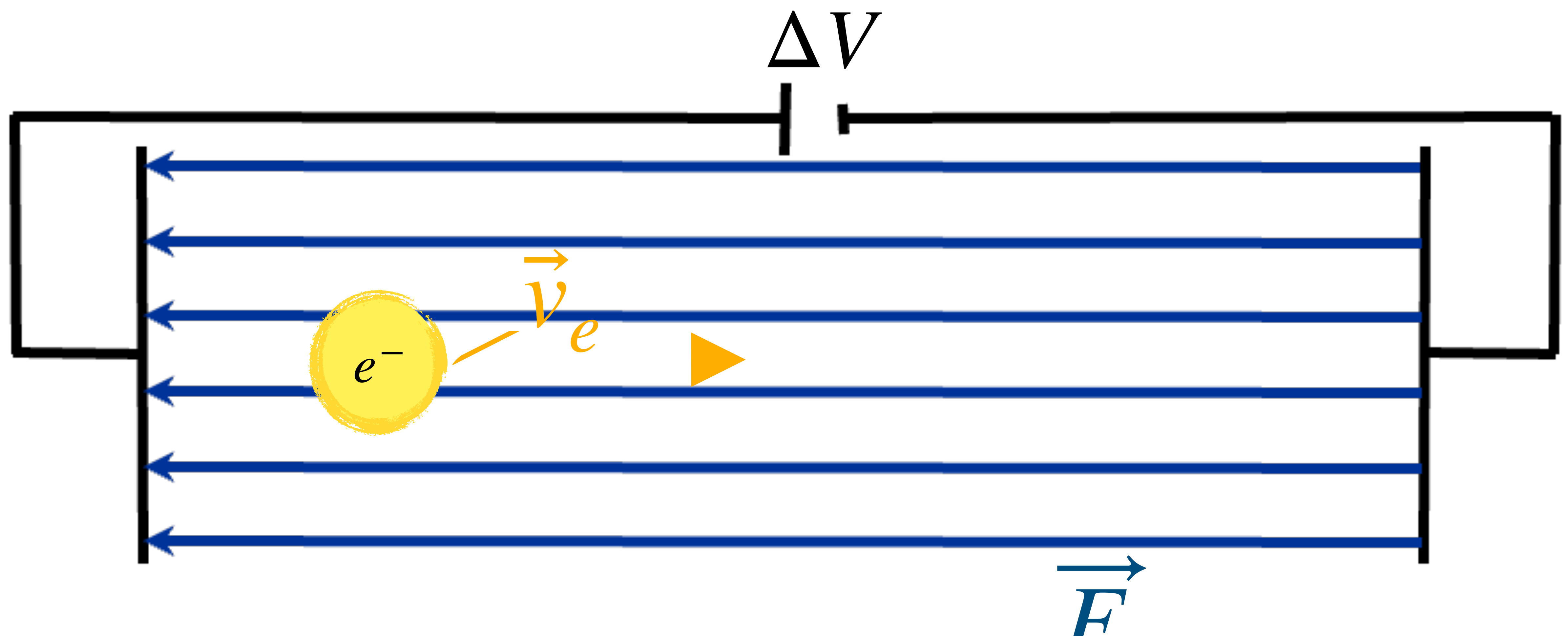
Publish the results


PHYSICAL REVIEW D 109, 112006 (2024)

Evidence for $B^+ \to K^+ \nu \bar{\nu}$ decays

Particle acceleration

- Generate an electric field $\overrightarrow{E}$
- The e^- will be accelerated with $\overrightarrow{F} = q\overrightarrow{E}$, gaining an energy: $E = q\Delta V$



Particle acceleration

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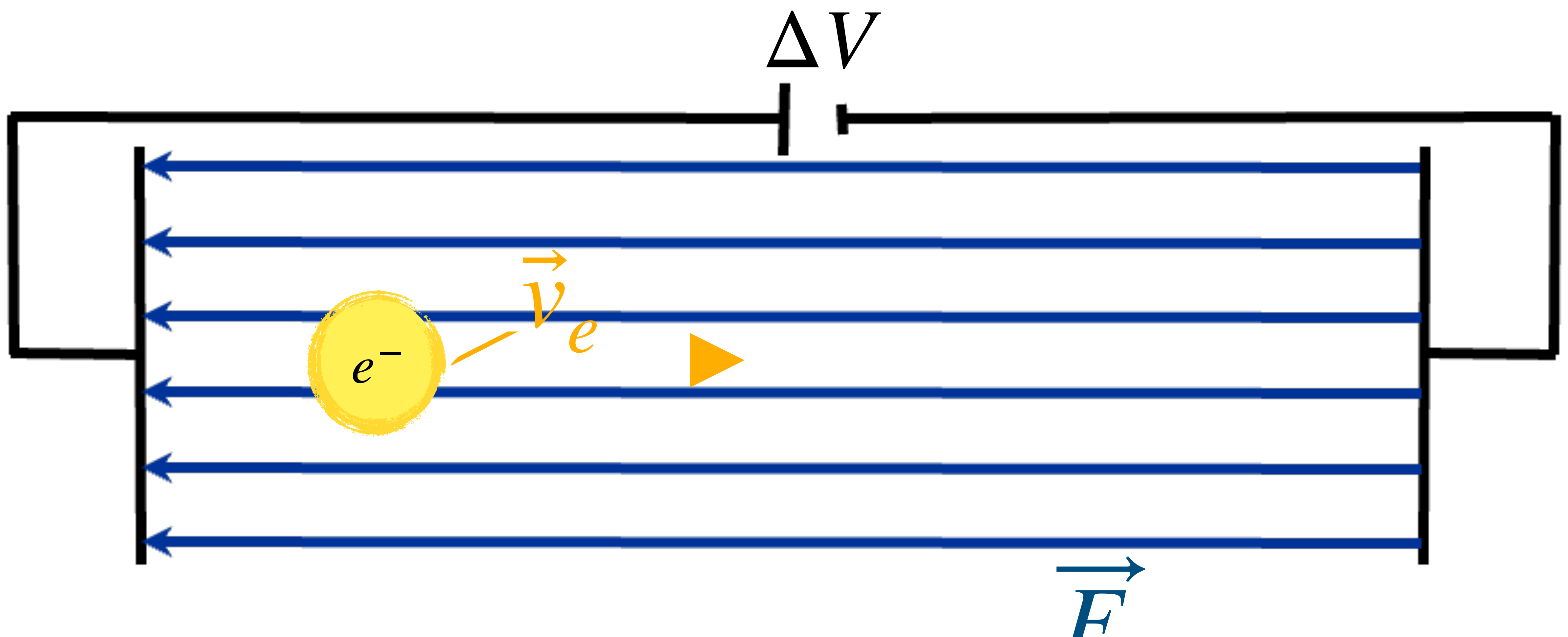
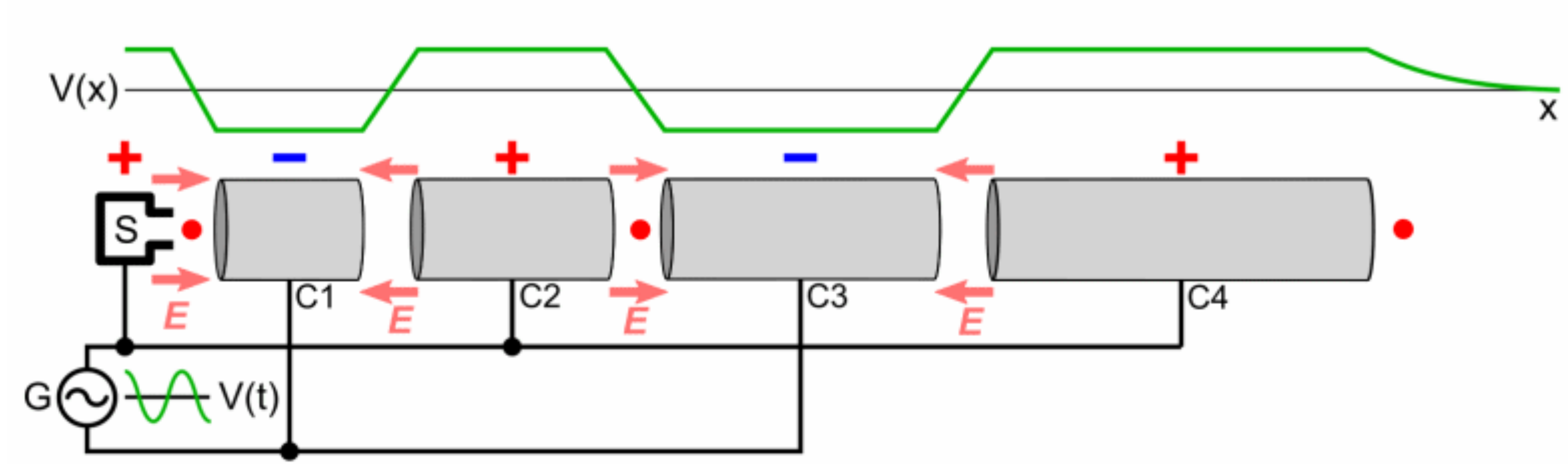
- Some numbers:
  - if $\Delta V = 1\ \mathrm{V} \Rightarrow E = 1\ \mathrm{eV}$
  - if $\Delta V = 100\ \mathrm{kV} \Rightarrow E = 100\ \mathrm{keV}$ ... we can't go much further with a single element



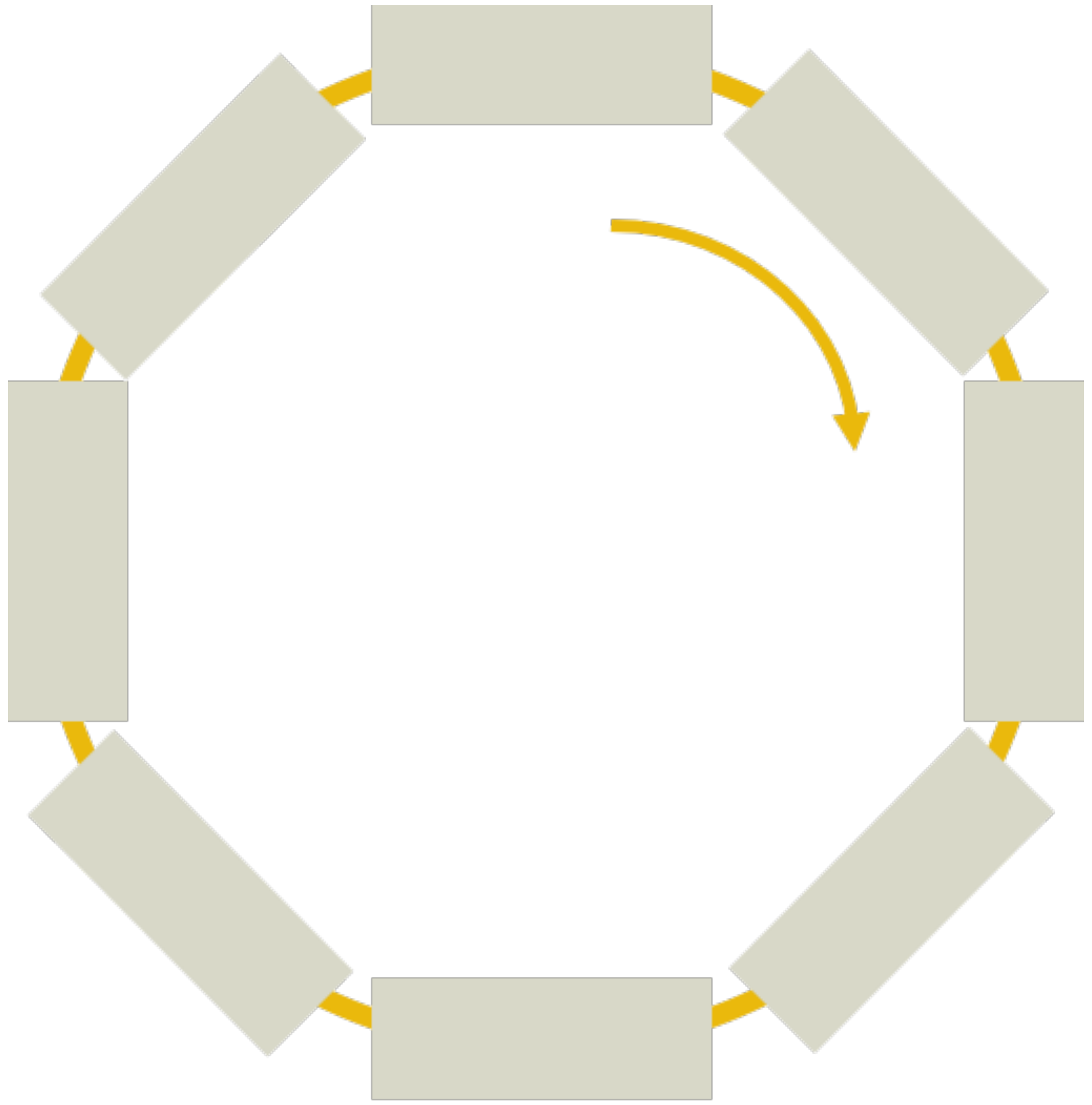
Particle acceleration

- So the solution use multiple element in series and an alternating field
- The electron always feels the force in one direction!
- However in this way we need a veeery long accelerator



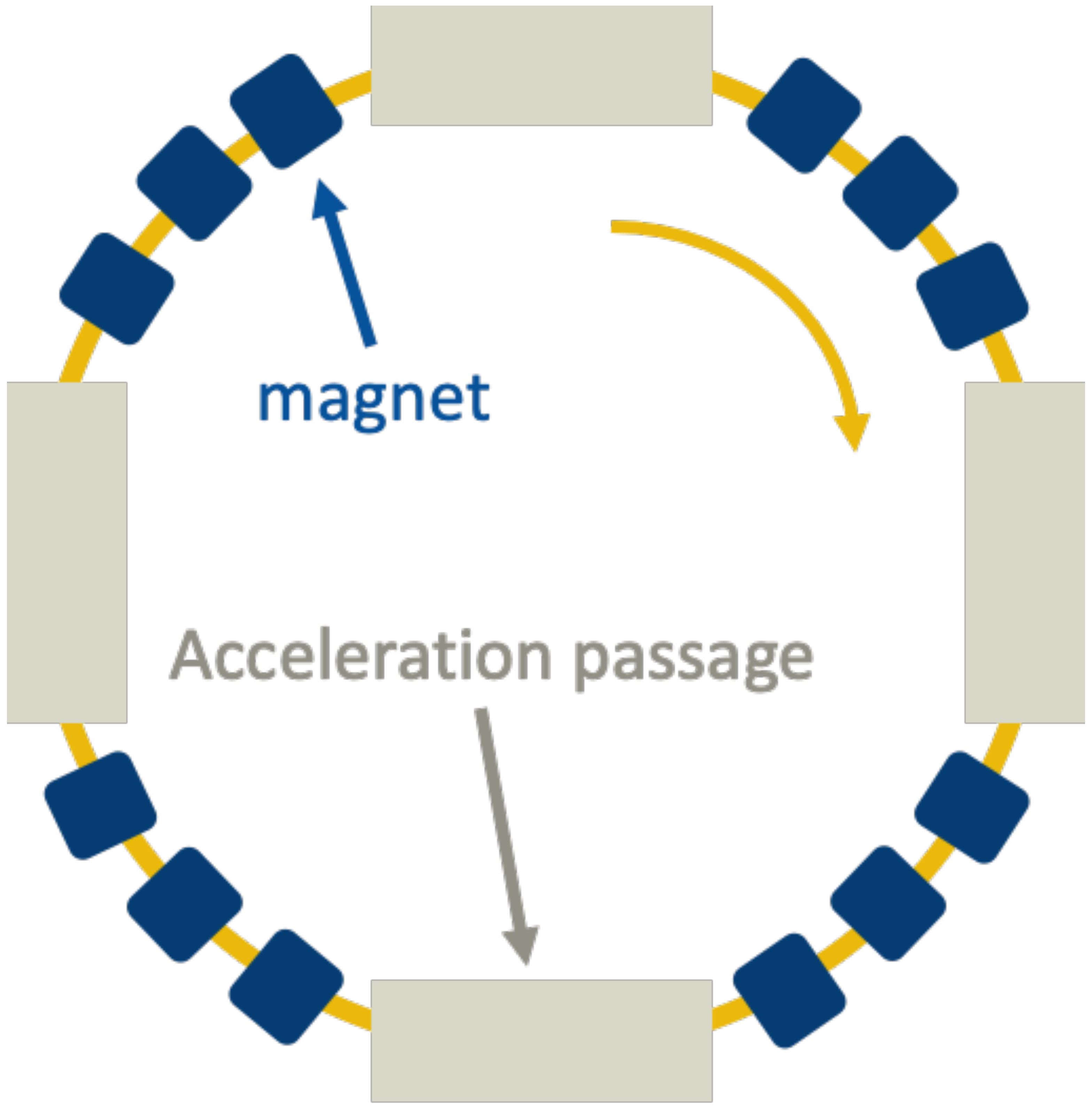
Particle acceleration

- The solution is bending!
- We can arrange the single element in a **circle** and make e^- **pass multiple times** by the accelerating elements
- How to bend?



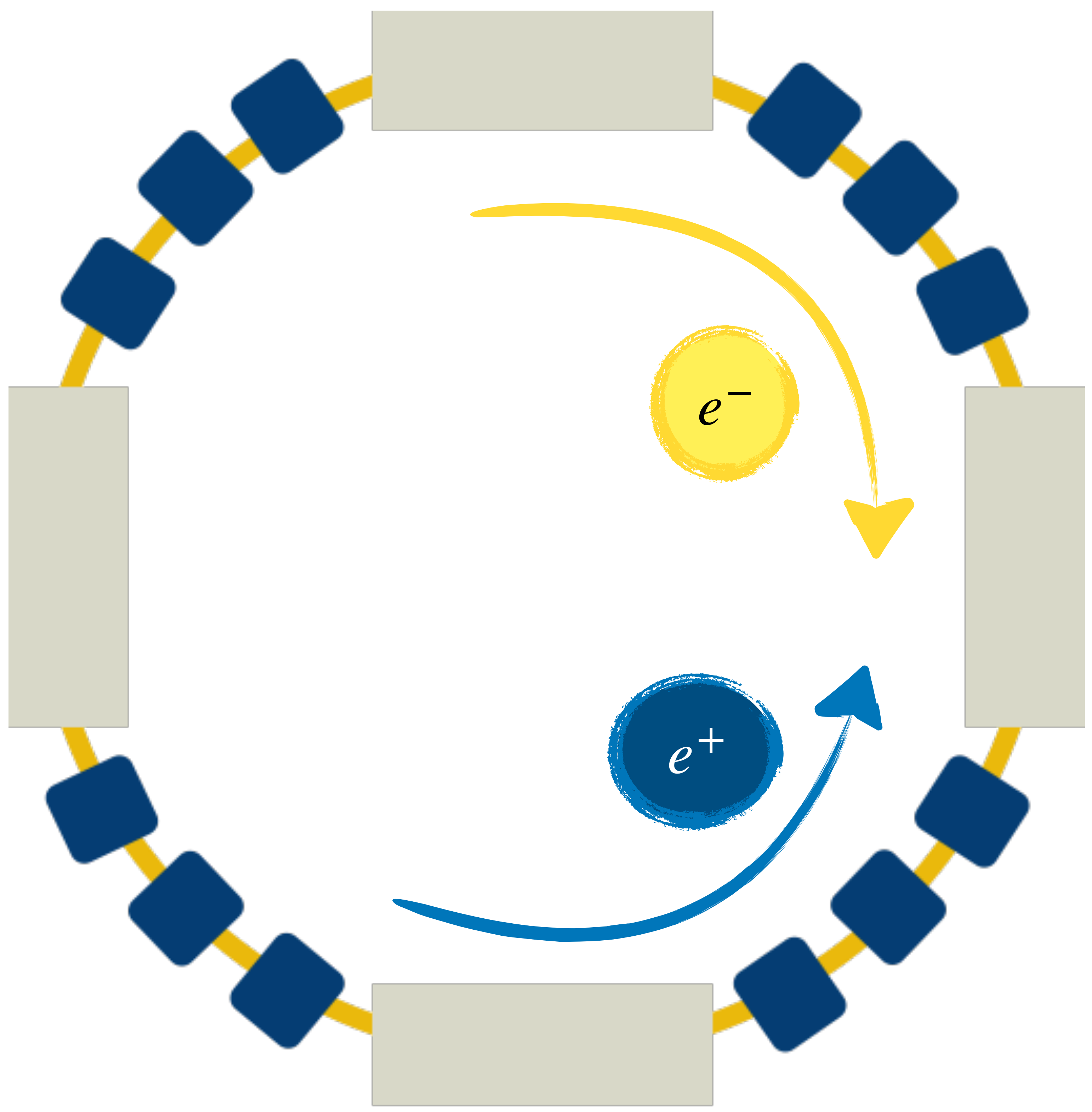
Particle acceleration

- The solution is bending!
- We can arrange the single element in a **circle** and make e^- **pass multiple times** by the accelerating elements
- How to bend? adding a **magnetic field** $\overrightarrow{B}$:
  $\overrightarrow{F} = q(\overrightarrow{E} + \vec{v} \times \overrightarrow{B})$



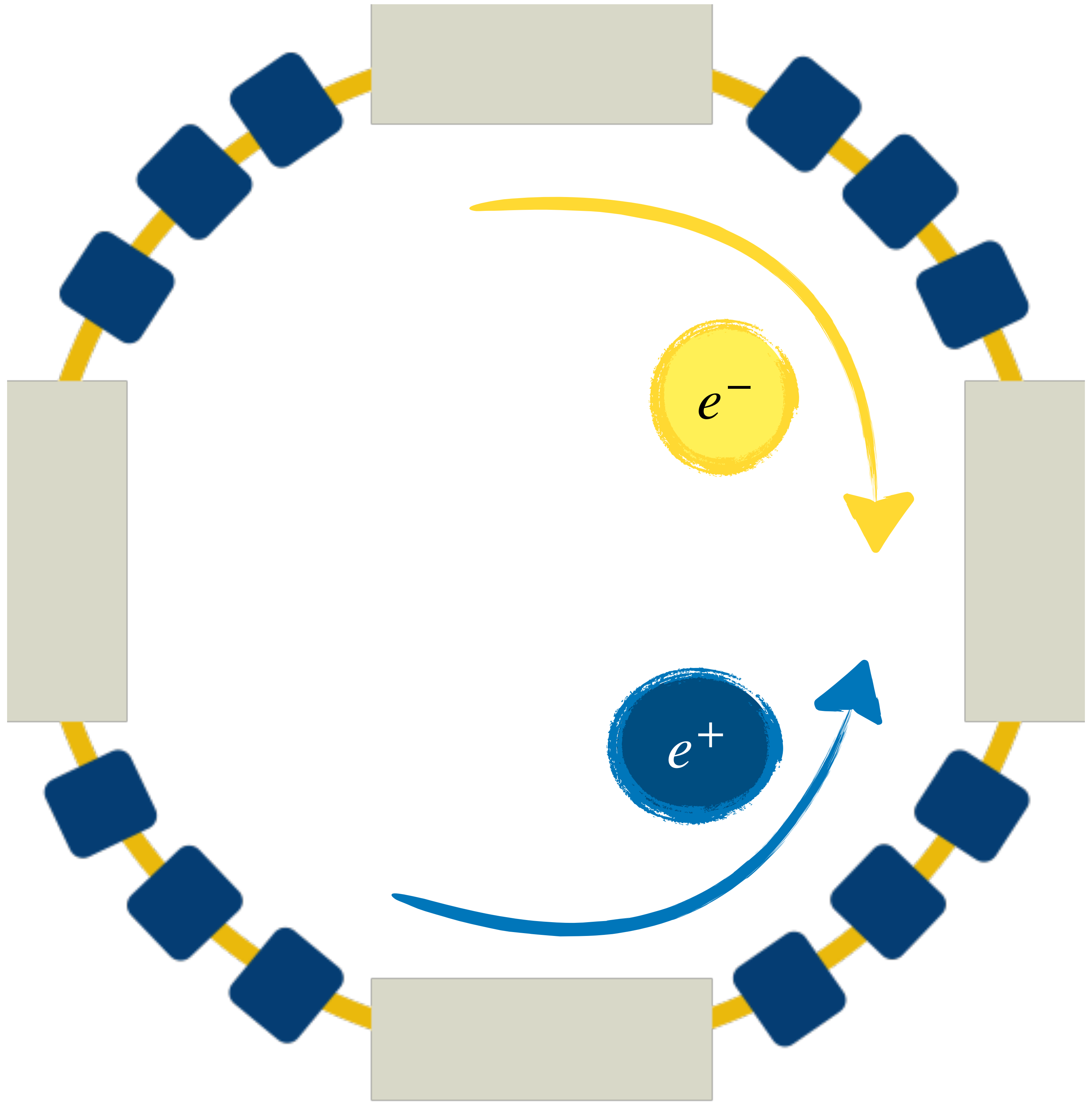
Particle acceleration + collision

- Now we can inject e^+ and e^- : they will be accelerated in opposite direction
- After reaching the desired energy we can make them collide



Particle acceleration + collision

- Now we can inject e^+ and e^- : they will be accelerated in opposite direction
- After reaching the desired energy we can make them collide
- $E = mc^2$, where m is the invariant mass of all the particles we can produce, and E the energy of the electron and the positron ($E \simeq 2\sqrt{E_{e^+}E_{e^-}}$)



Belle II collaboration

over **1100 physicists and engineers** from **122 institutions** in **27 countries**

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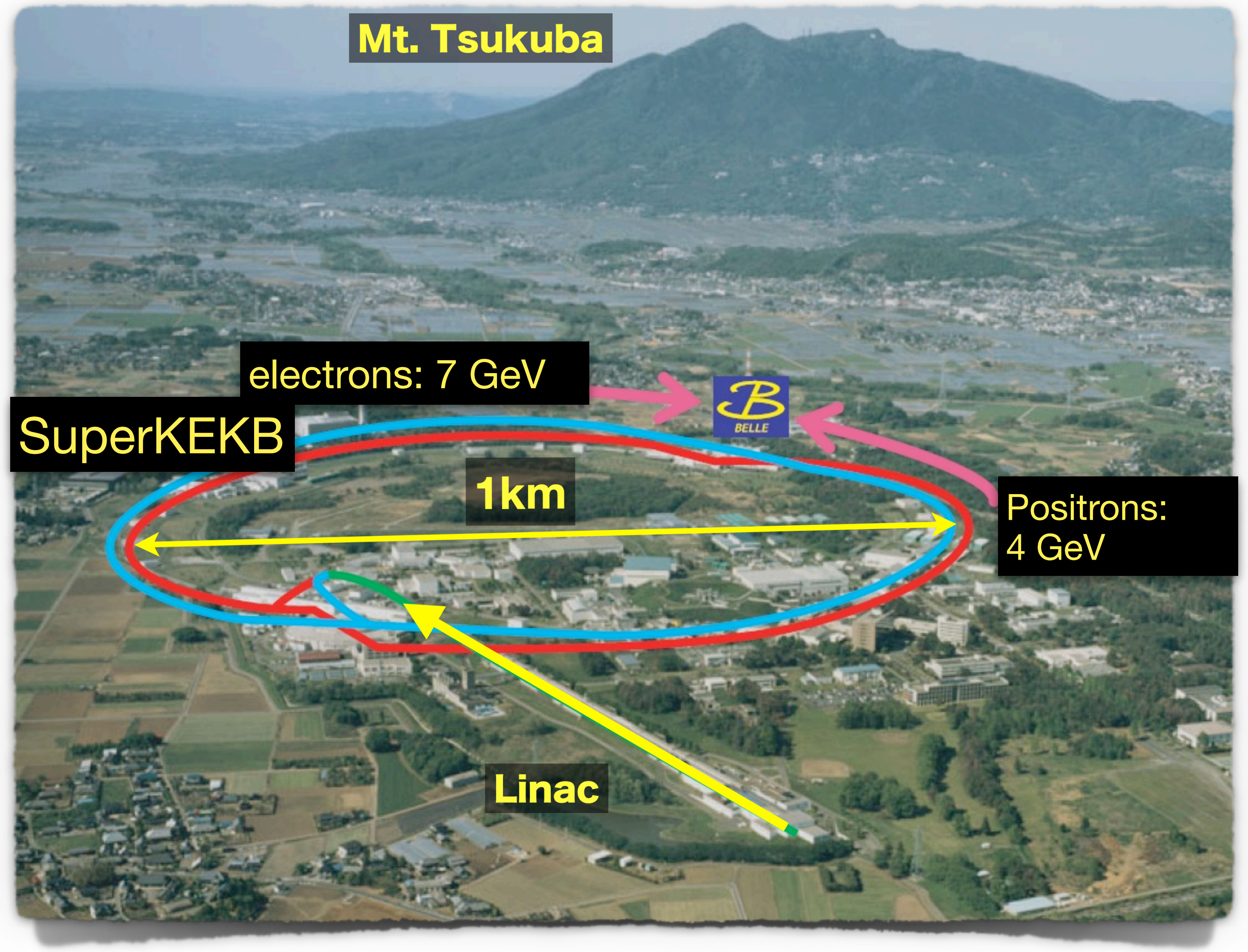
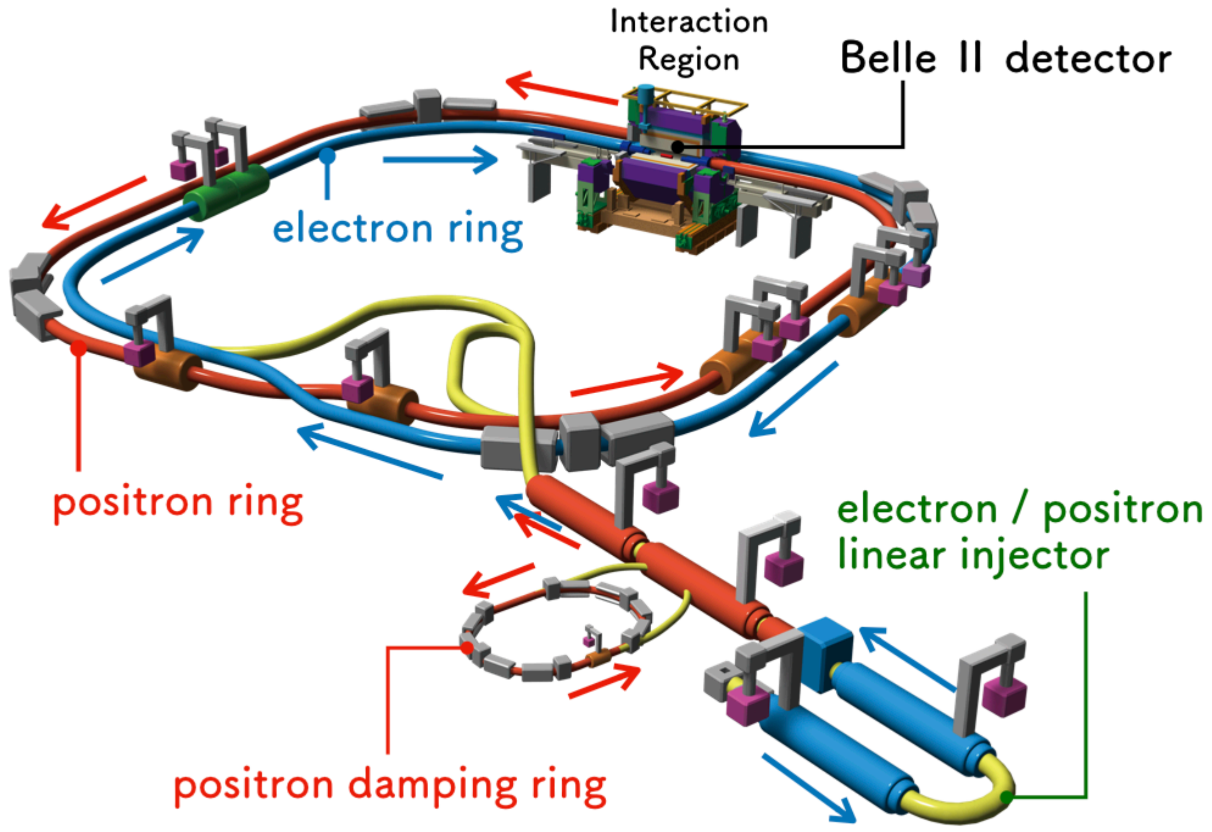
KEK Laboratory and SuperKEKB collider

In Tsukuba, about 60 Km from Tokyo

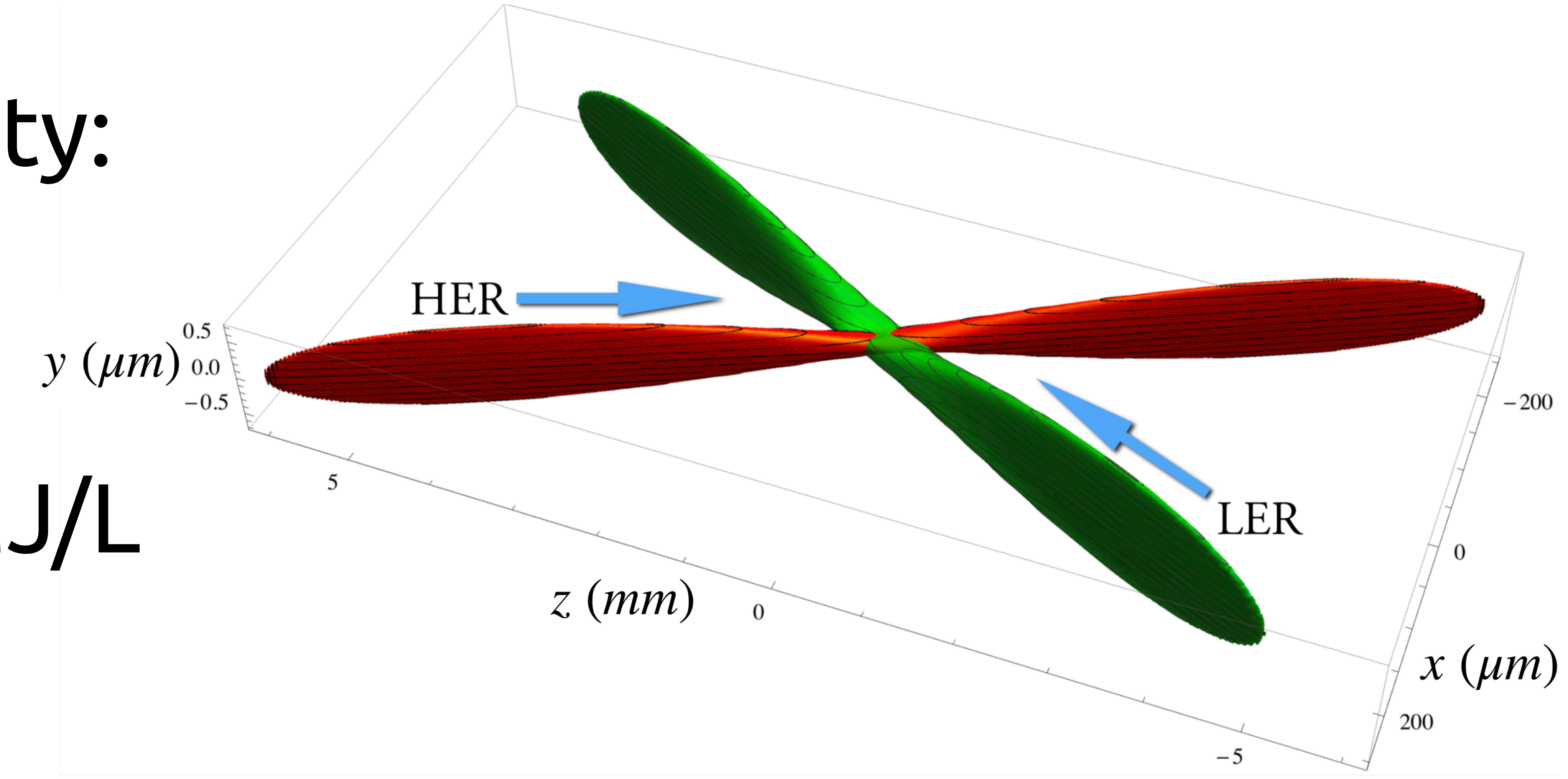




- **SuperKEKB** is a electron-positron collider
- The collision energy $E = 10.58\ \text{GeV} = 2m_B$ where B is called "B meson"... this is why this accelerator is called **B-factory**

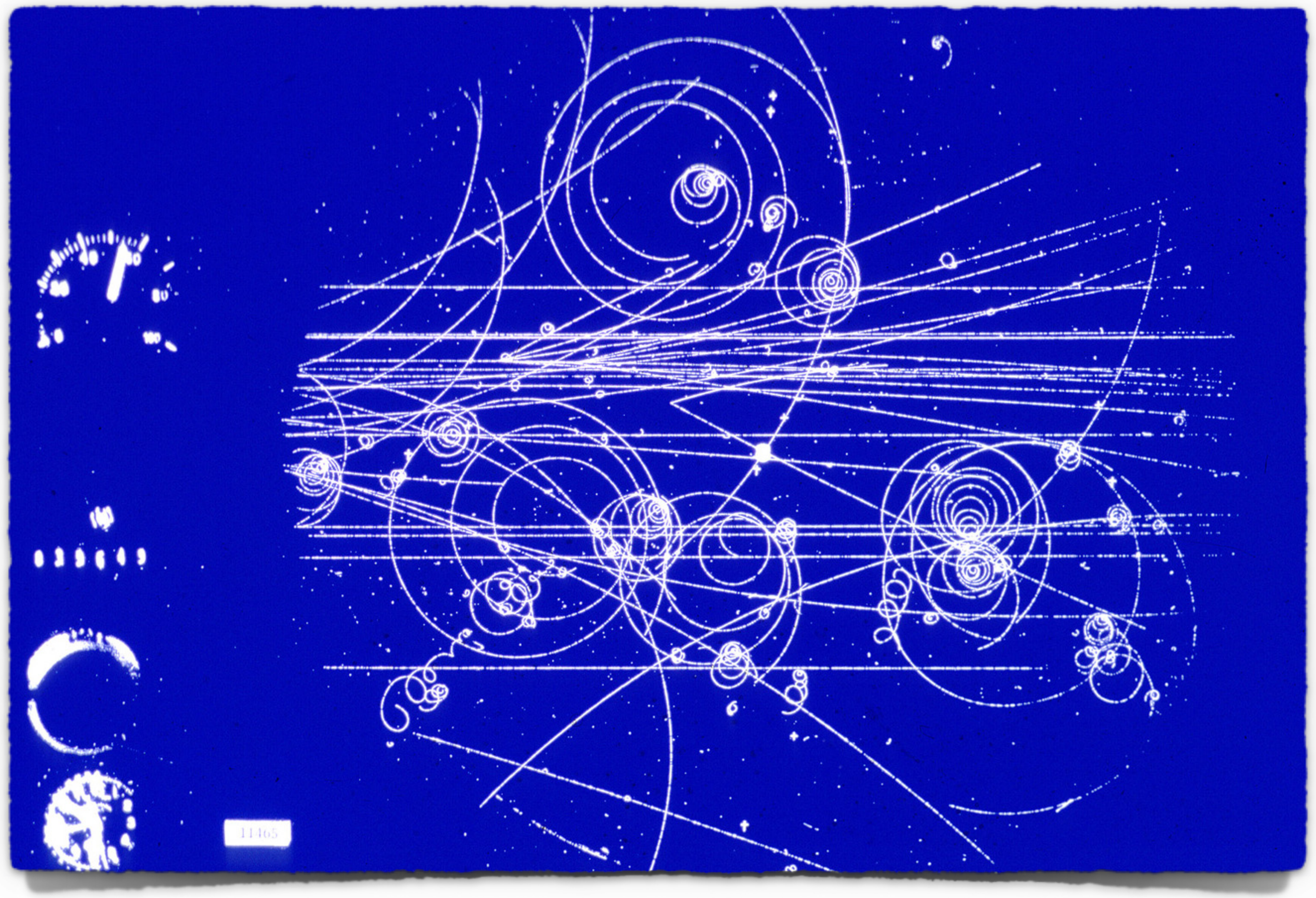
10 GeV?

- How much energy in real life? Not much considering one single electron
- But this is the energy of every single electron in the beam:
  - the two beams are made of 2500 bunch of about $6 \cdot 10^{10}$ electrons each
- The total energy is about 0.2 MJ --> the energy of a car at 70 km/h
- But the "big number" is actually the energy density:
  - burning car oil: 34.6 MJ/L
  - bunch of SuperKEB during a collision: 70 000 MJ/L

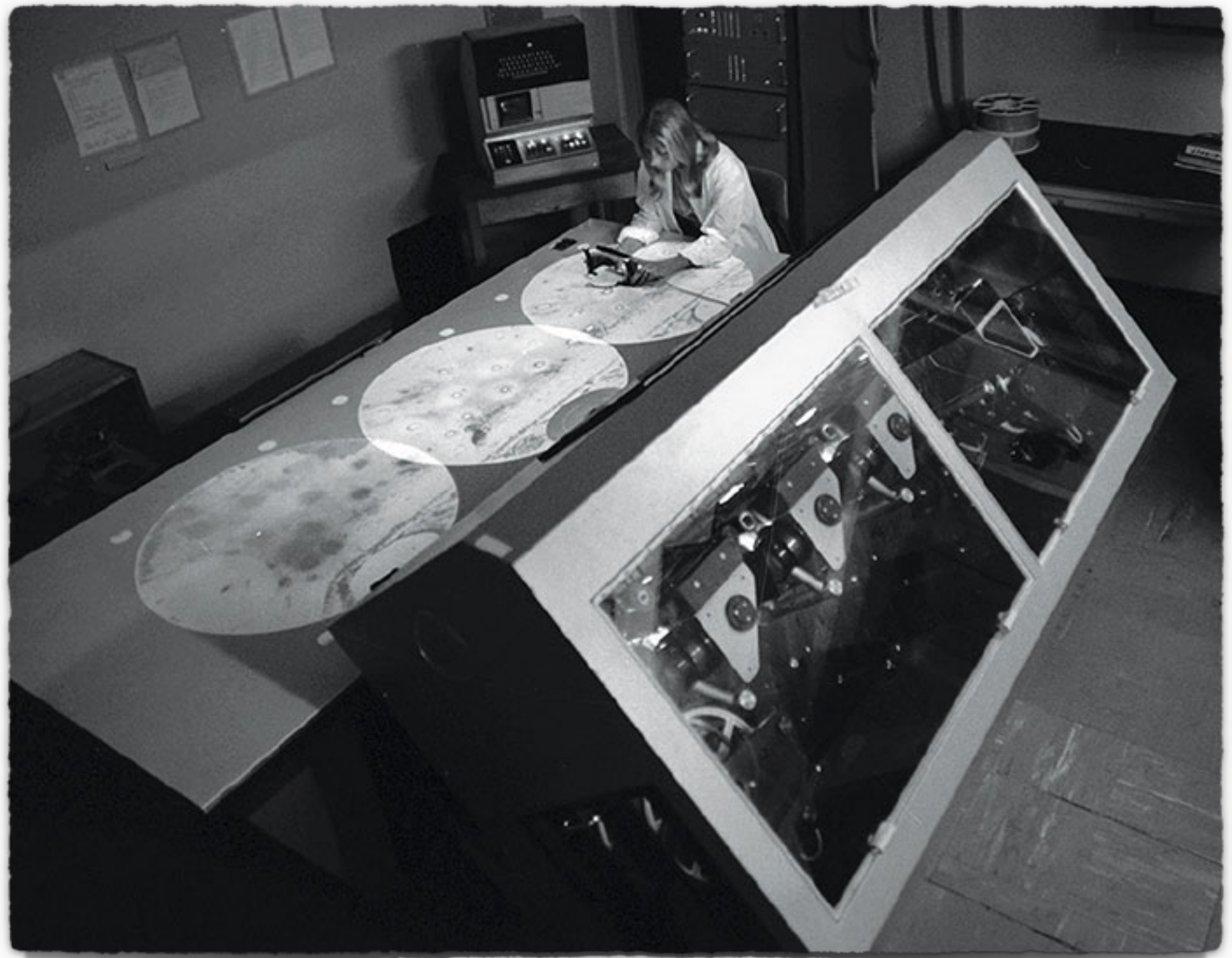


Data taking, example from the past

Bubble chamber



[CERN-EX-11465 , https://cds.cern.ch/record/39474]



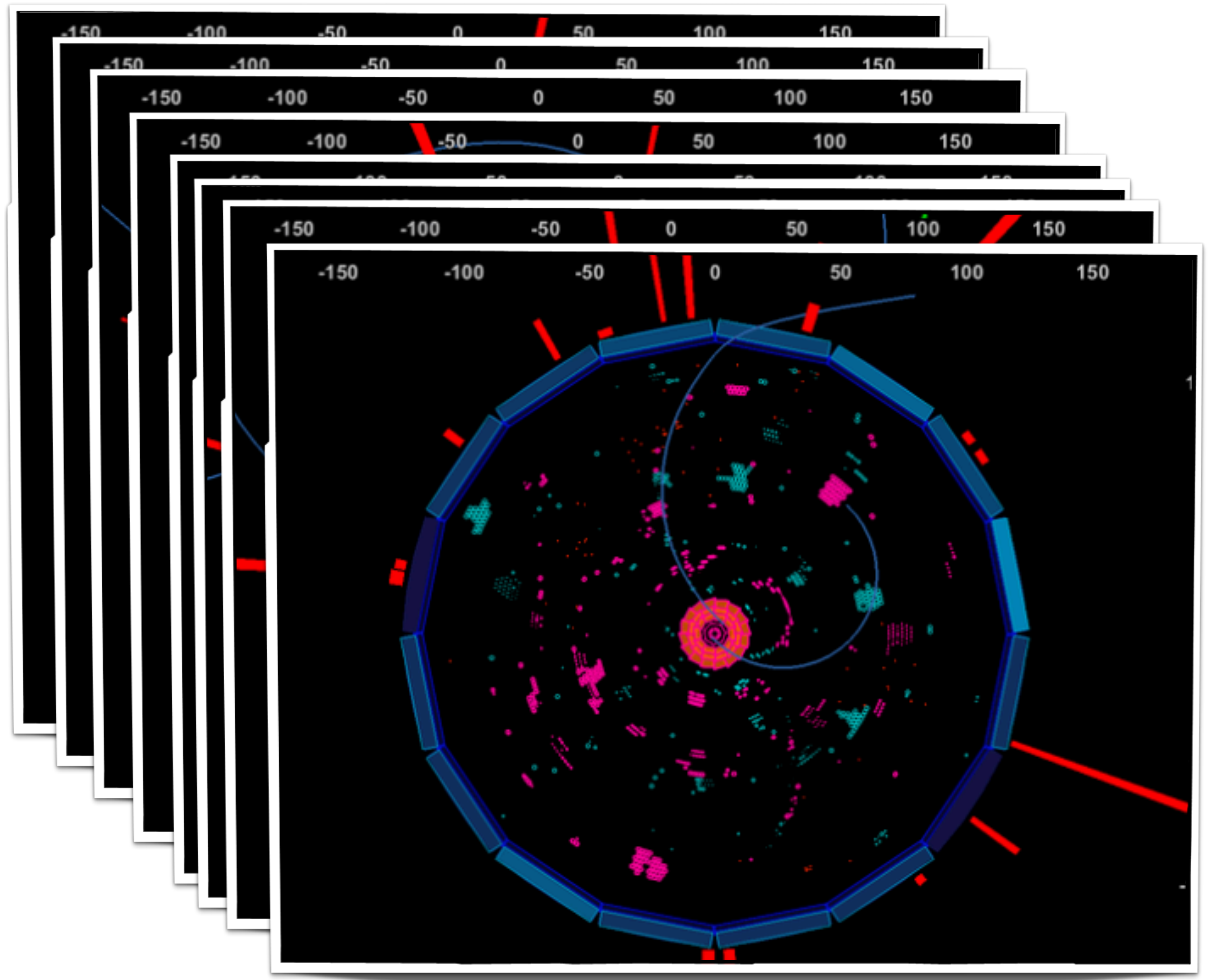
[CERN Courier, June 1973 – Esperimento Gargamelle]

Problem: collect and analyze these data is **slow**

- statistic limited --> precise/rare measurement impossible

Data taking at SuperKEKB

- An event is e^+e^- collision
- There are 250 Million collisions per second, for about 100 days per year
- We need to "take a picture" of each collision, choose which one must be recored permanently, and analyze the interesting ones



[DESY, grid computing centre Tier 2, Hamburg]

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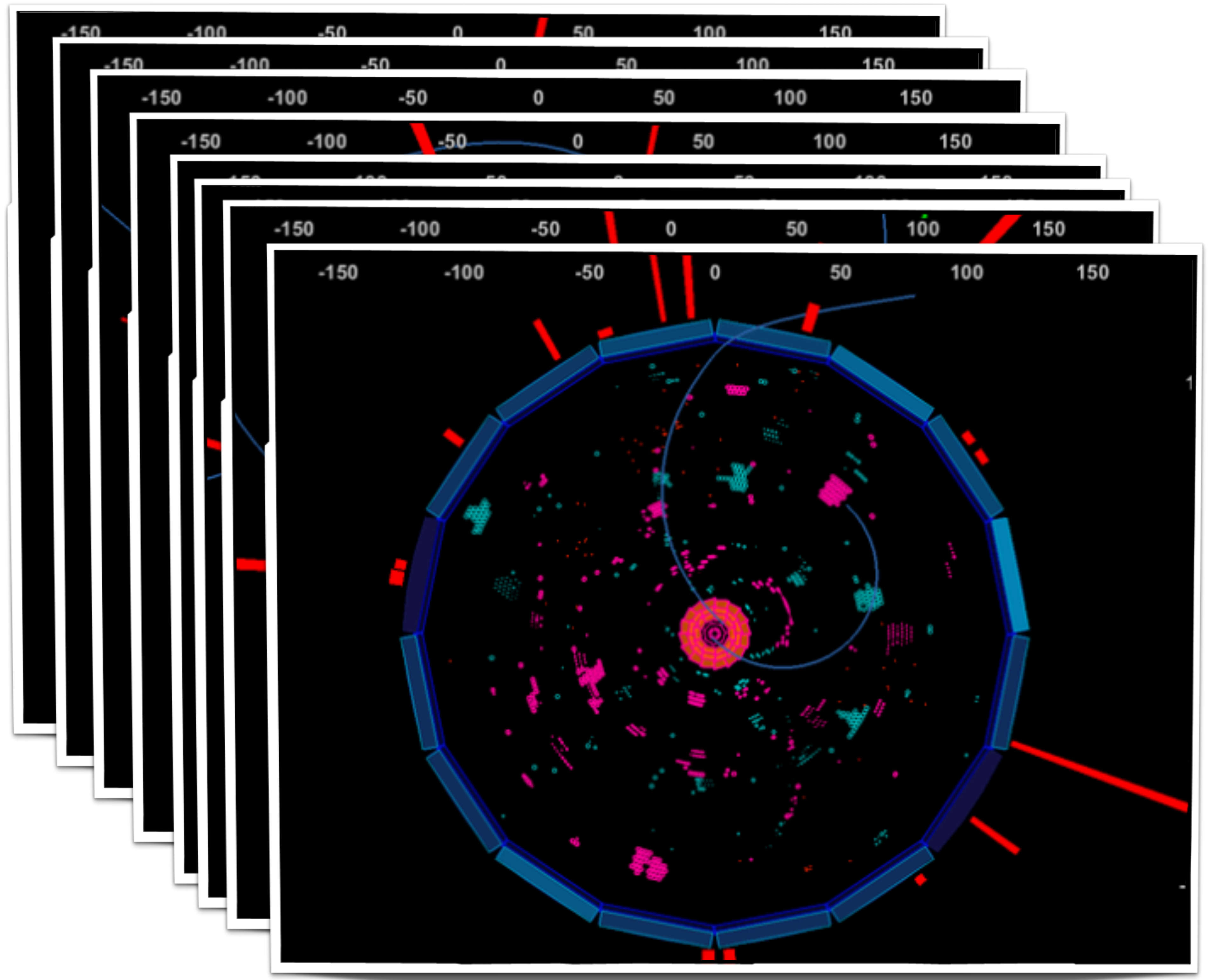

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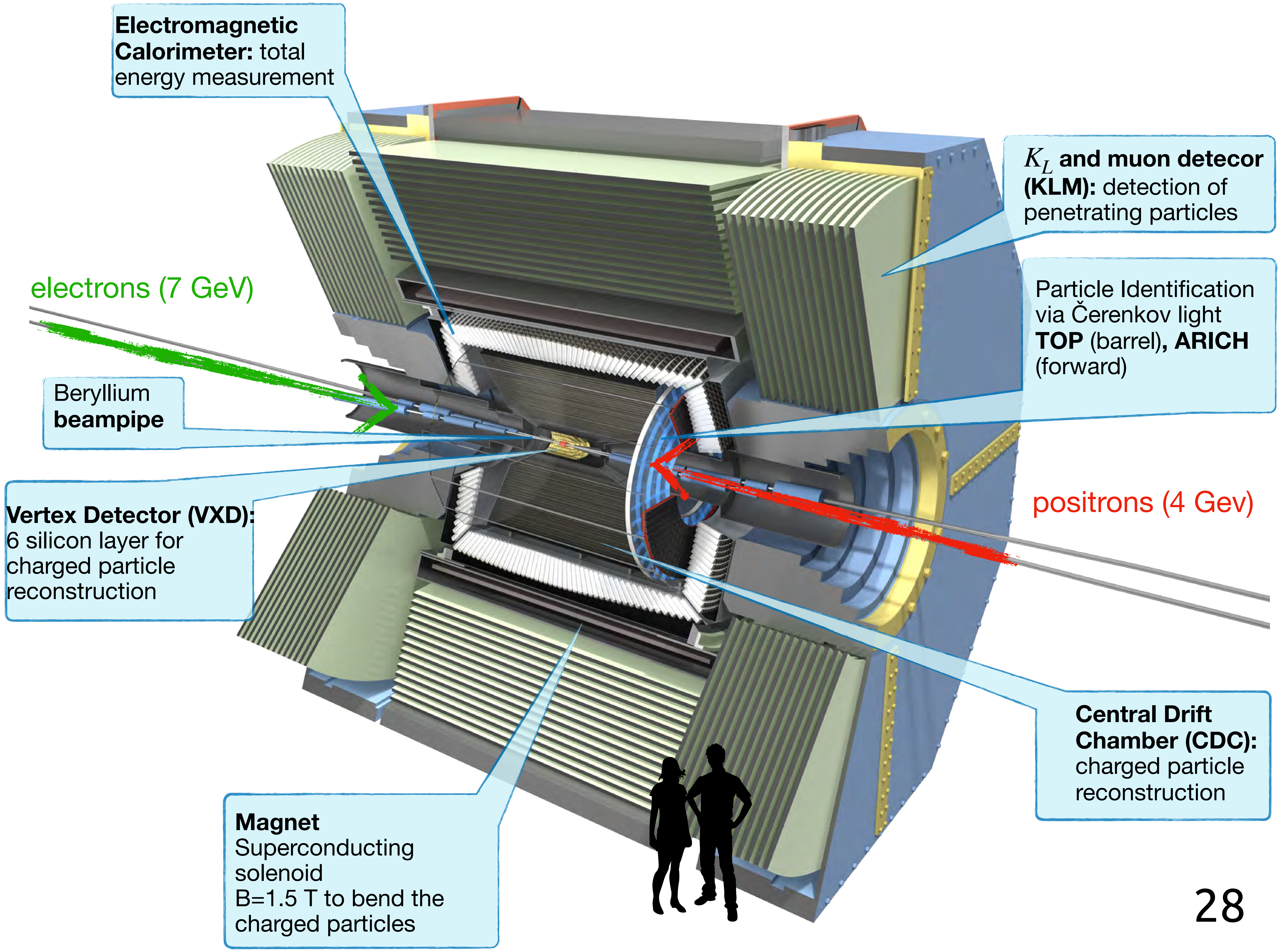
Belle II

Belle II detector

- Build **around the collision point**
  - we want to see all the particles which are appearing from the e^+e^- collision
  - Ideally spherical, practically cylindrical
- The **onion** shape: detector with multiple **layers**. Every layer has a **precise task** to collect one precise information:
  - Or without modify the particle
  - Or destroying it (stopping it)
- Collect the information:
  - The particles **interact** with the matter of the detector
  - The detector is realized to produce an **electrical signal** when the interaction happen
  - The electrical signal is **recorded to be interpreted** later on combining the information of all the layers
- After the collection of the electrical signal we use a **event reconstruction software** to give a physical interpretation of the event

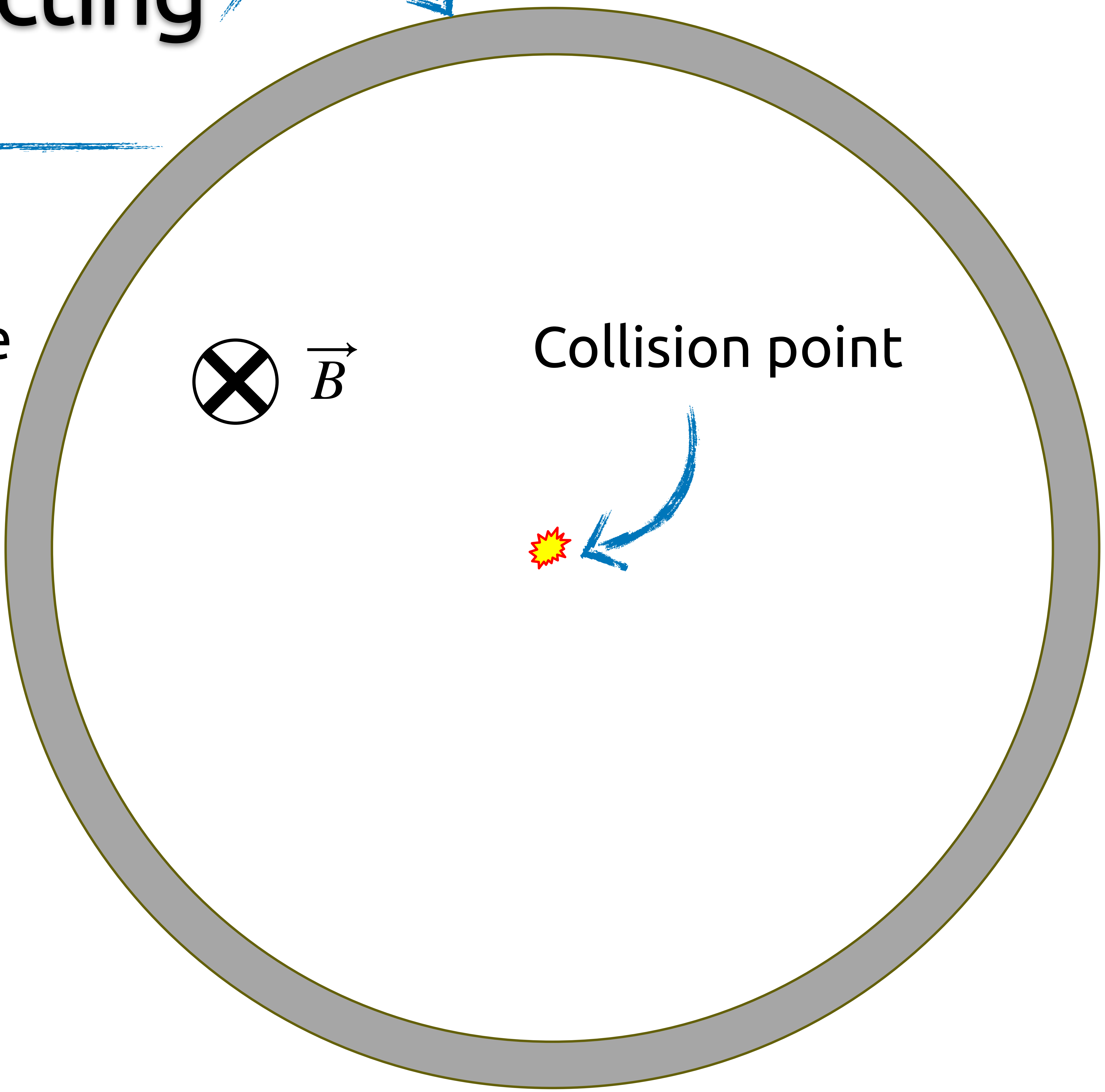


Superconducting solenoid

- Produces a uniform magnetic field inside

$$p_T[\mathrm{GeV}] = 0.3qB[\mathrm{T}]R[\mathrm{m}]$$

- The magnetic field makes the particles **bend**



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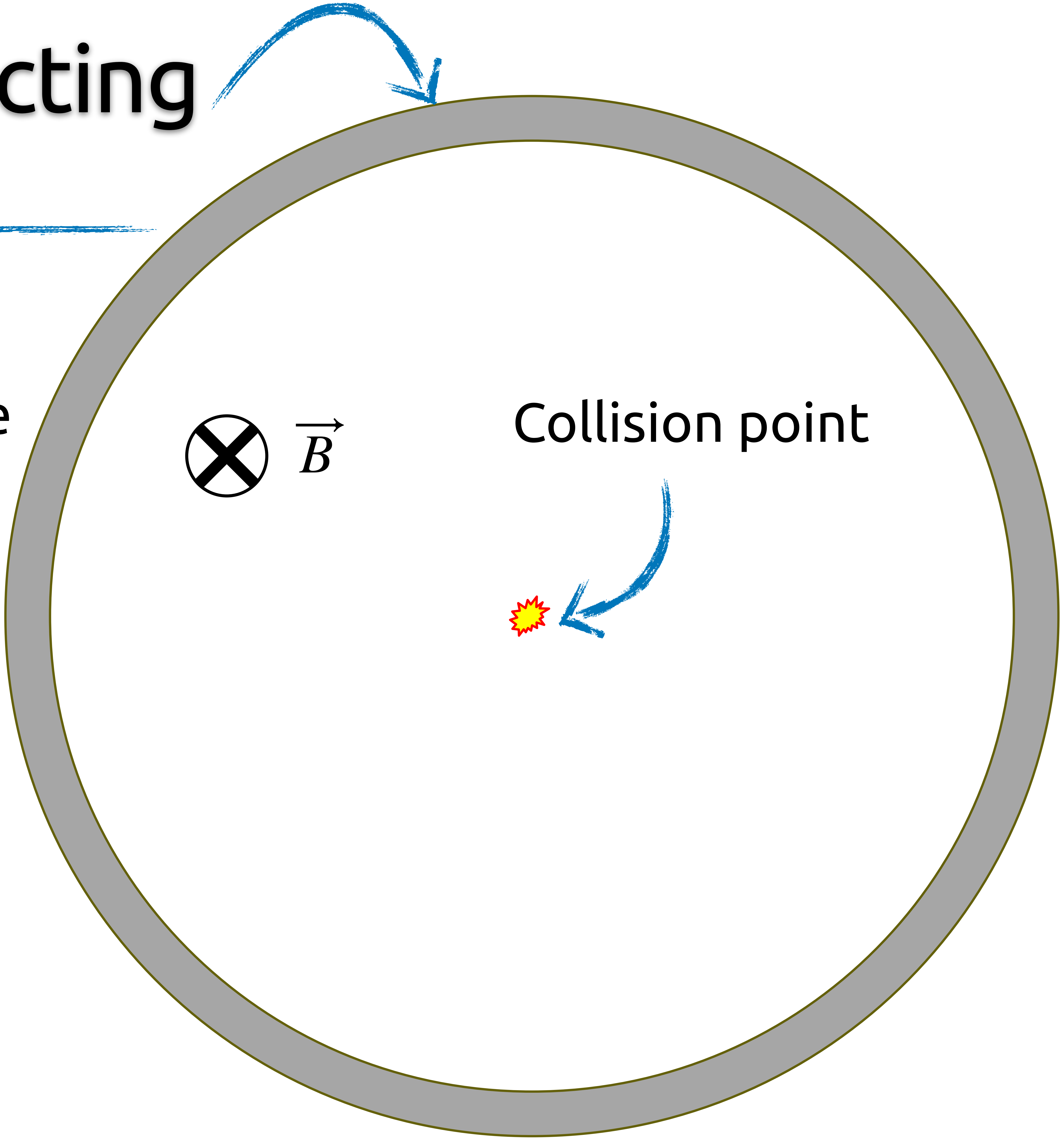

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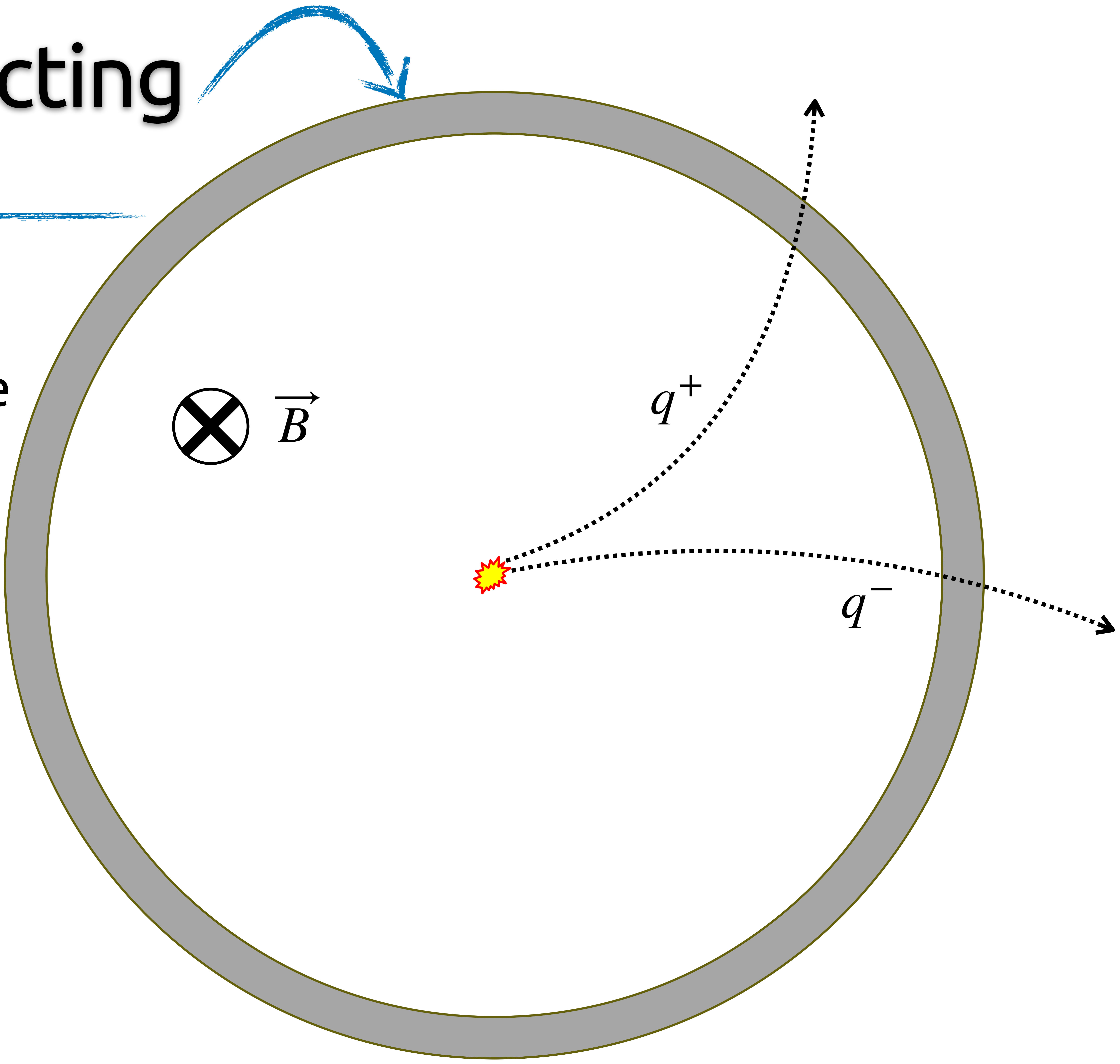

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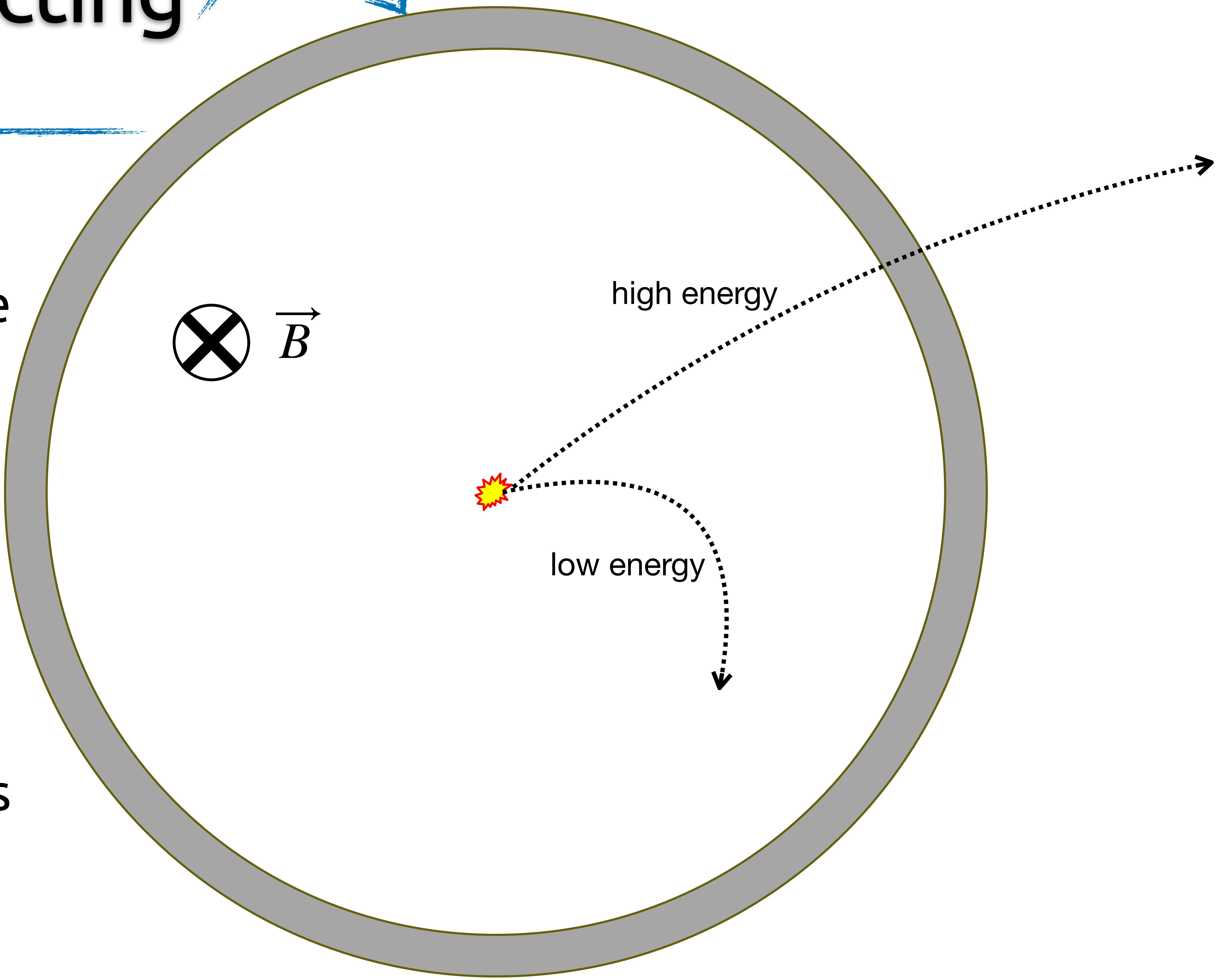
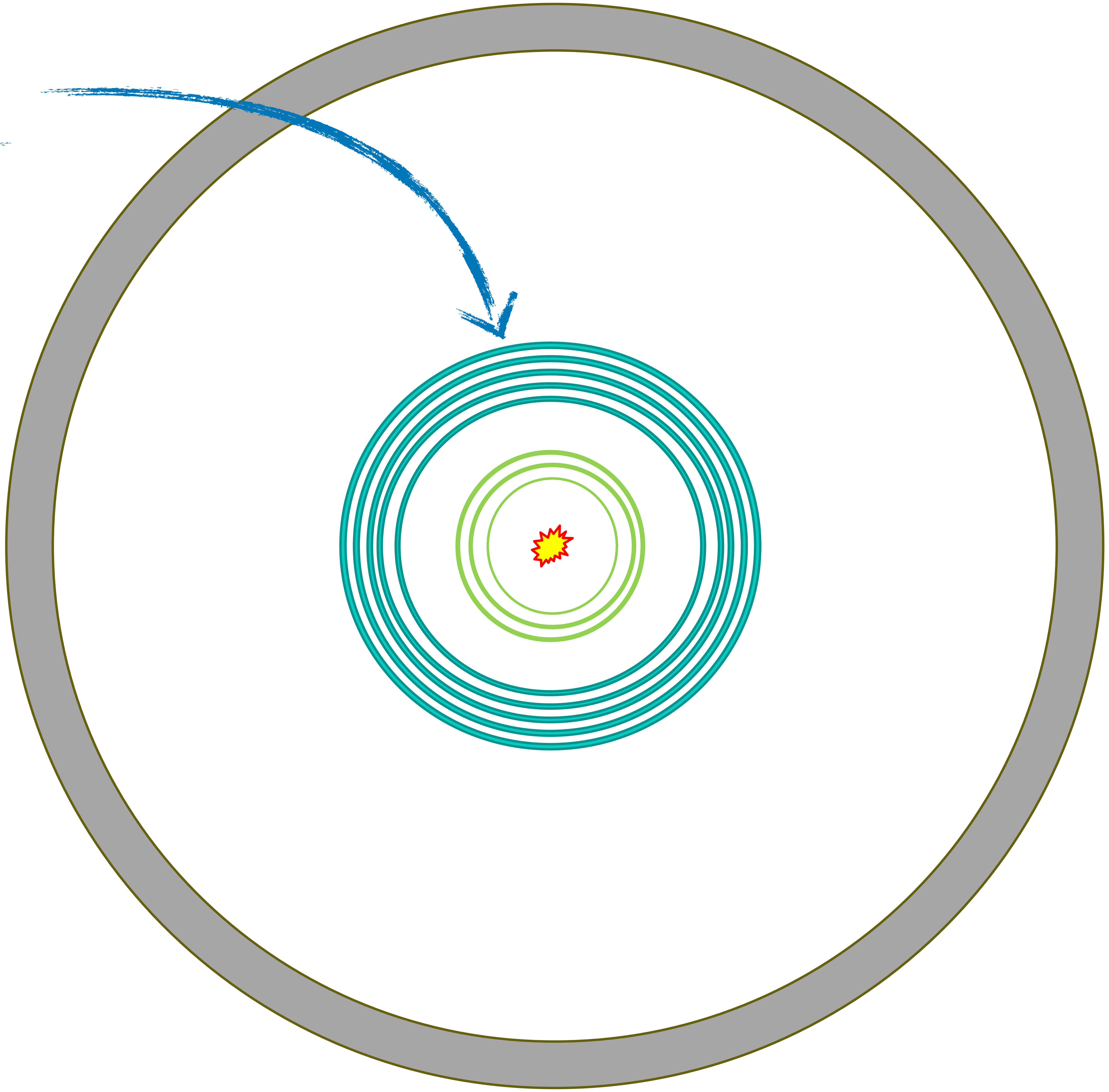
- Different **charges** bends in **opposite directions**
- More **energetic**, less bend



Tracker

- Often built of **multiple layer of silicon** (in Belle II is actually more complex than that…)



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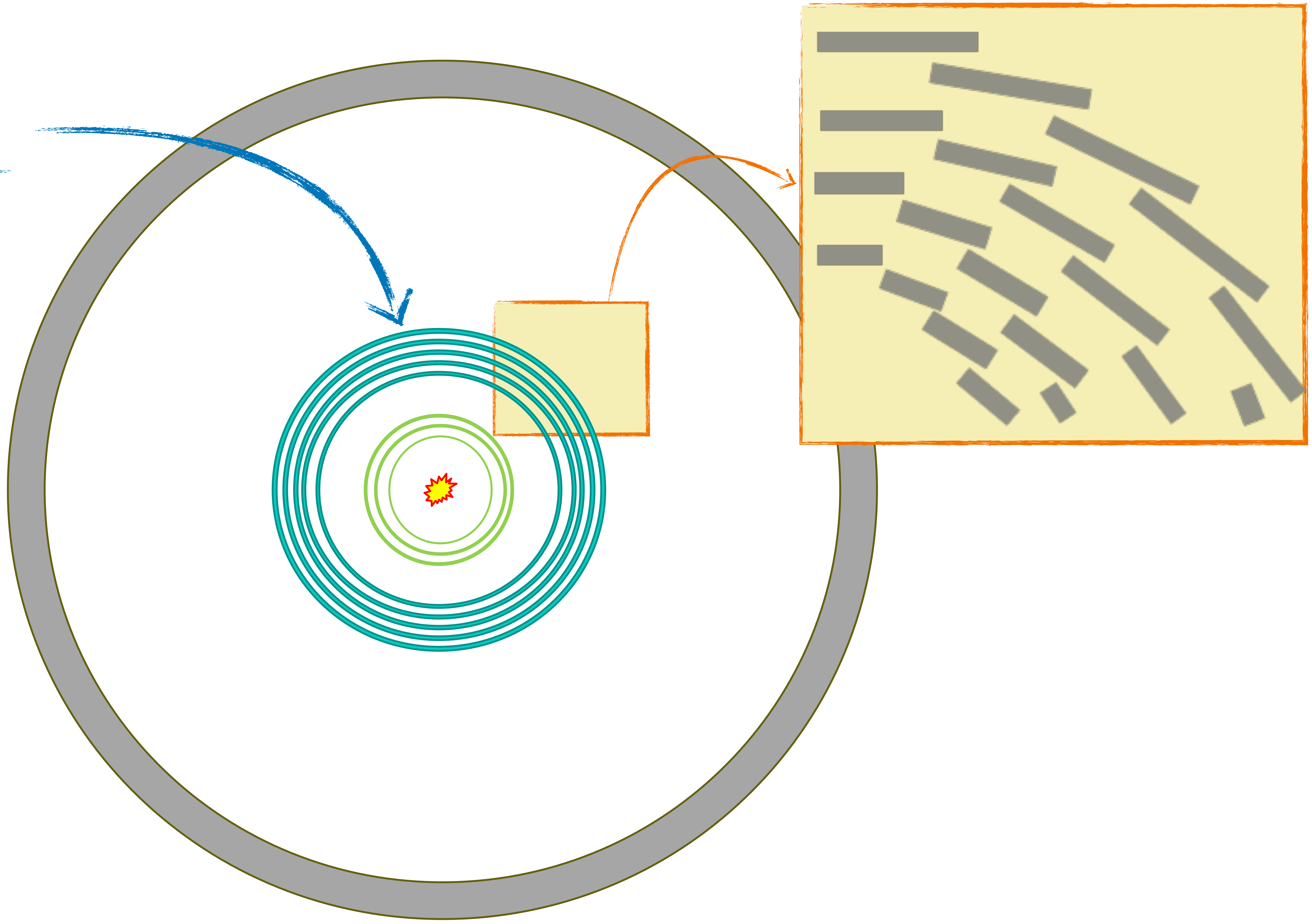

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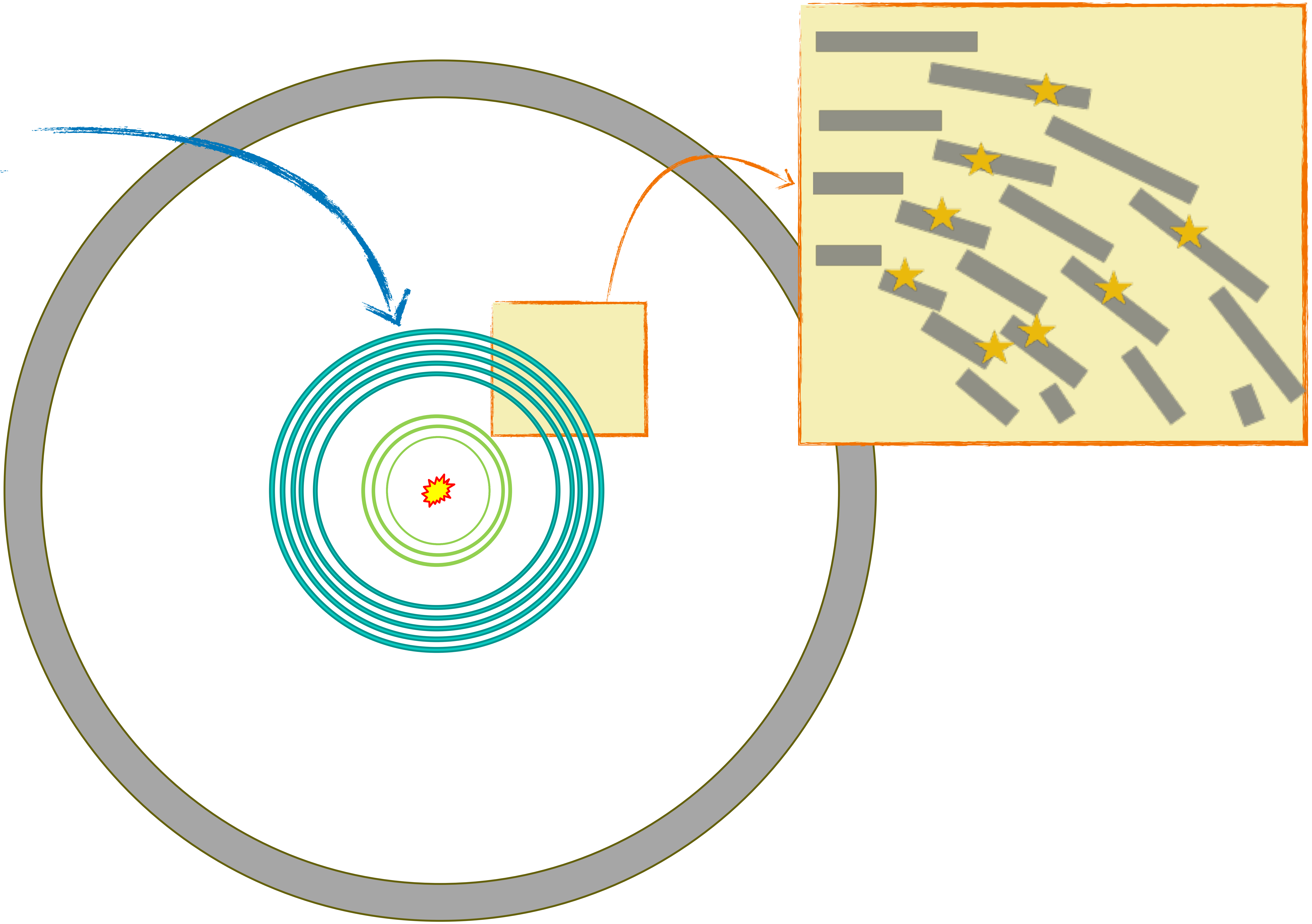
- All the **electrically charged** particles interact with the tracker
- Often built with different technologies (more precise inside, less precise outside)



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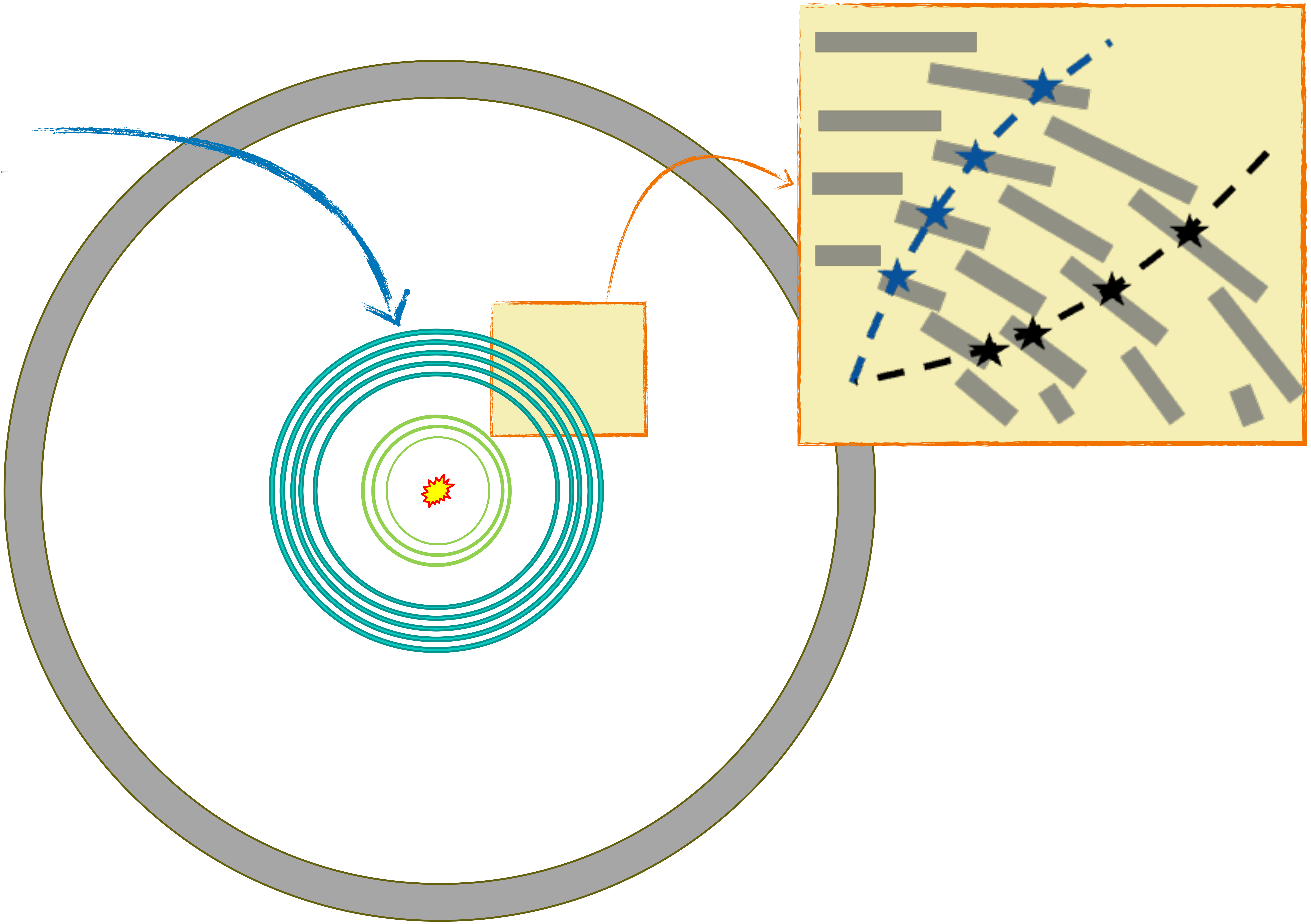

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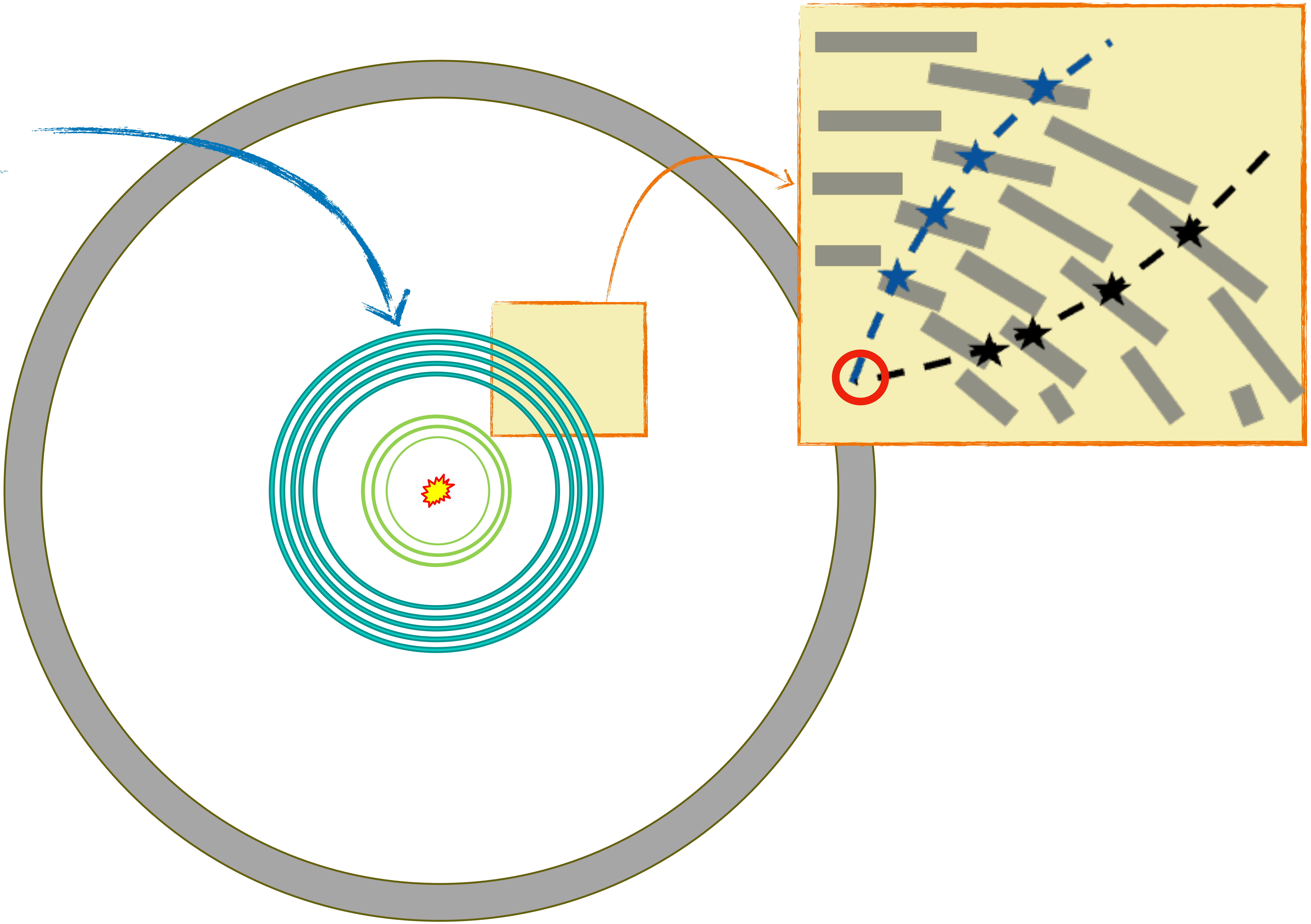
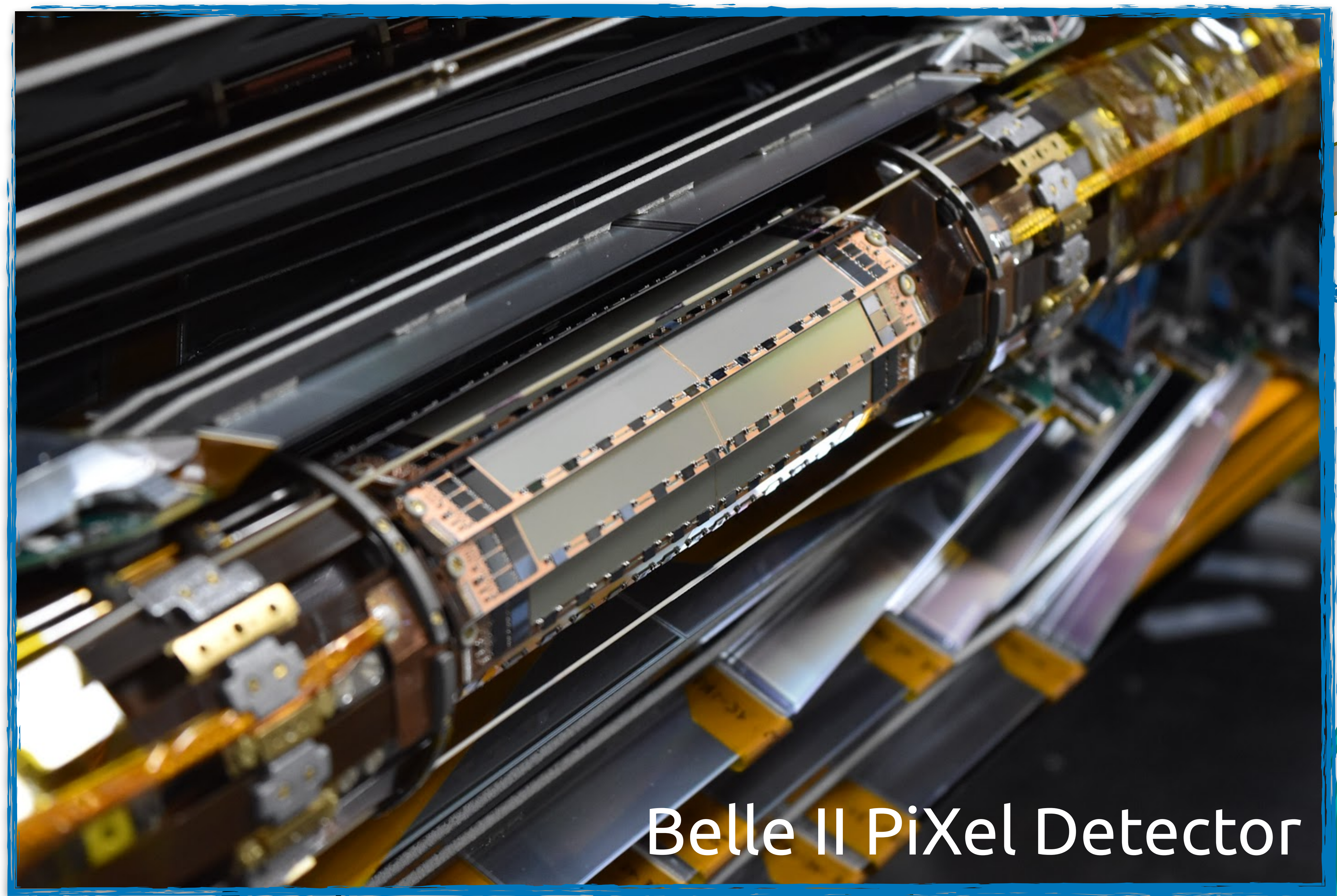
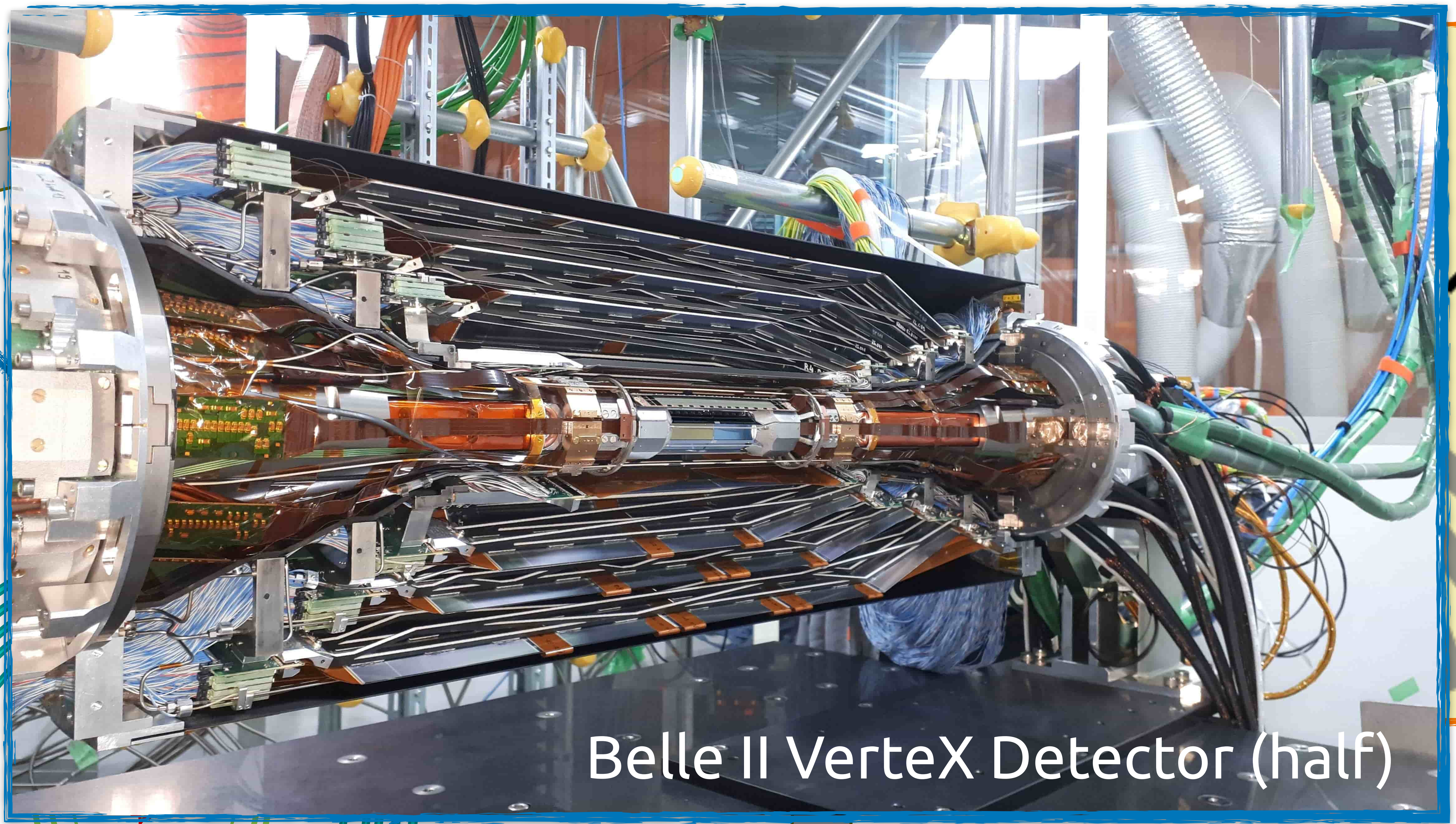




Belle II PiXel Detector



Belle II VerteX Detector (half)

with the tracker

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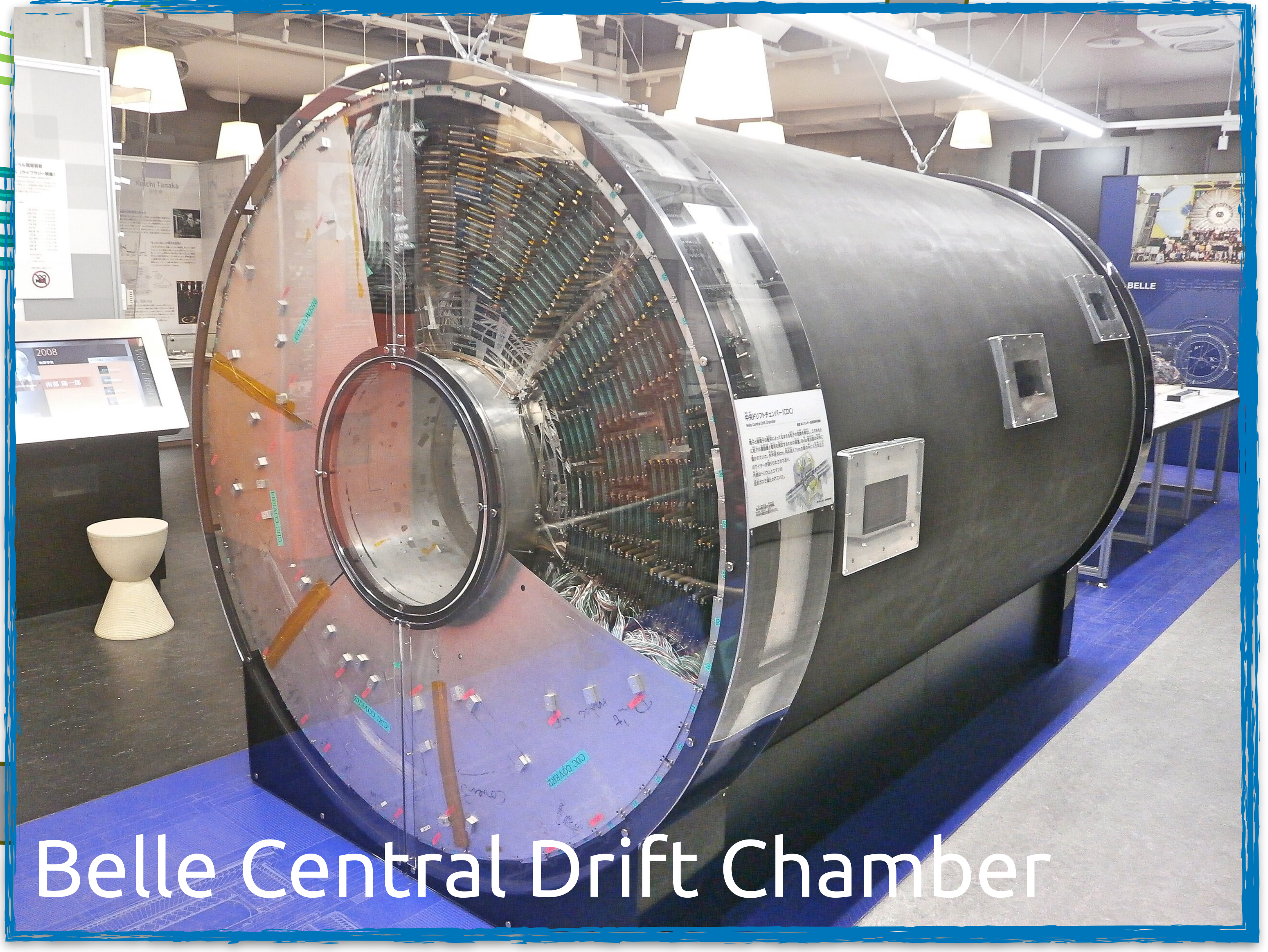
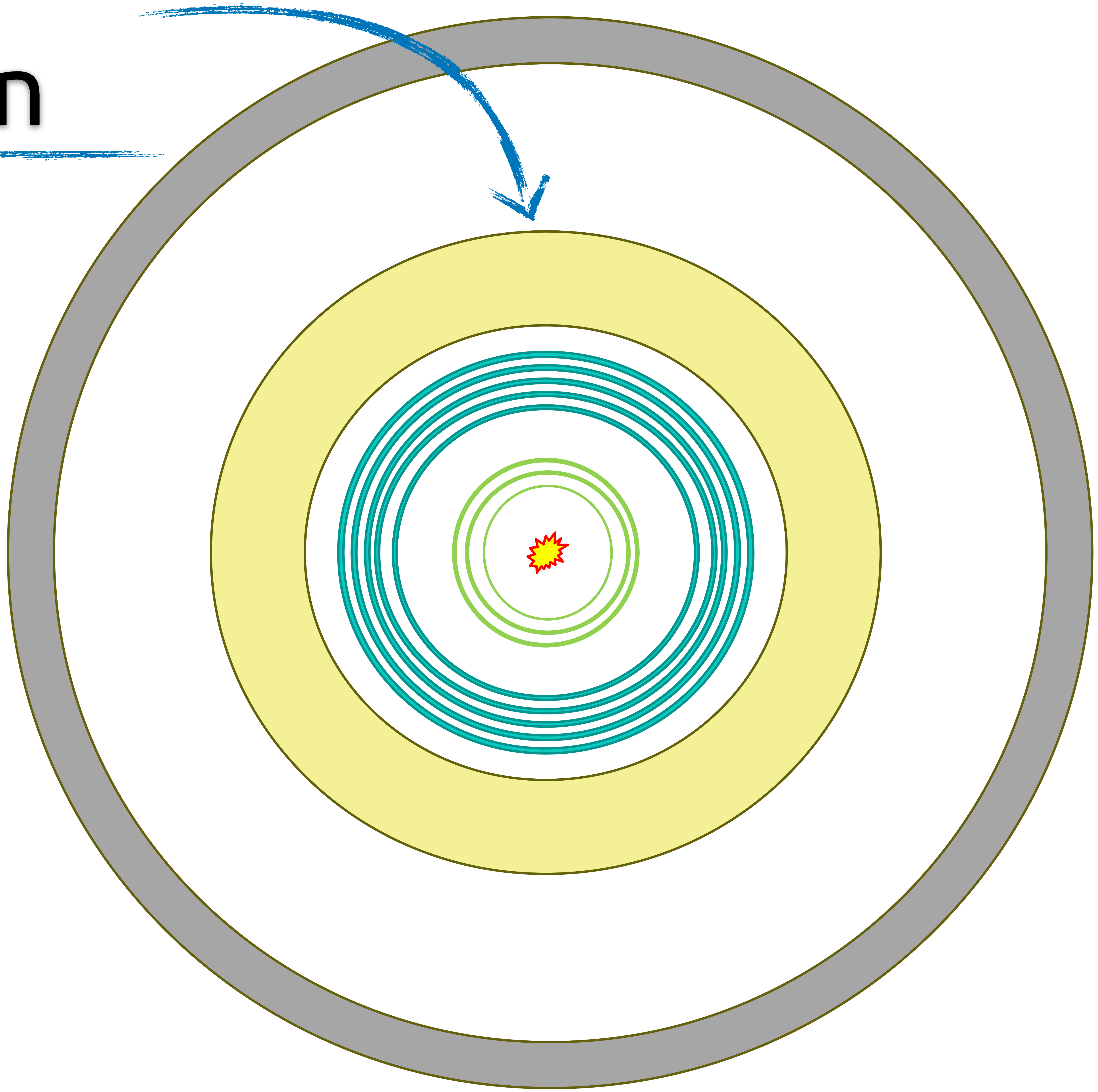


Belle Central Drift Chamber

Particle Identification

- Task: identify the **mass** of the crossing particles
- The speed of a particle is related to its mass: $\vec{p} = m\gamma\vec{v}$
- Providing external $\vec{p}$ measurement (eg. from the tracker) we can have the mass!



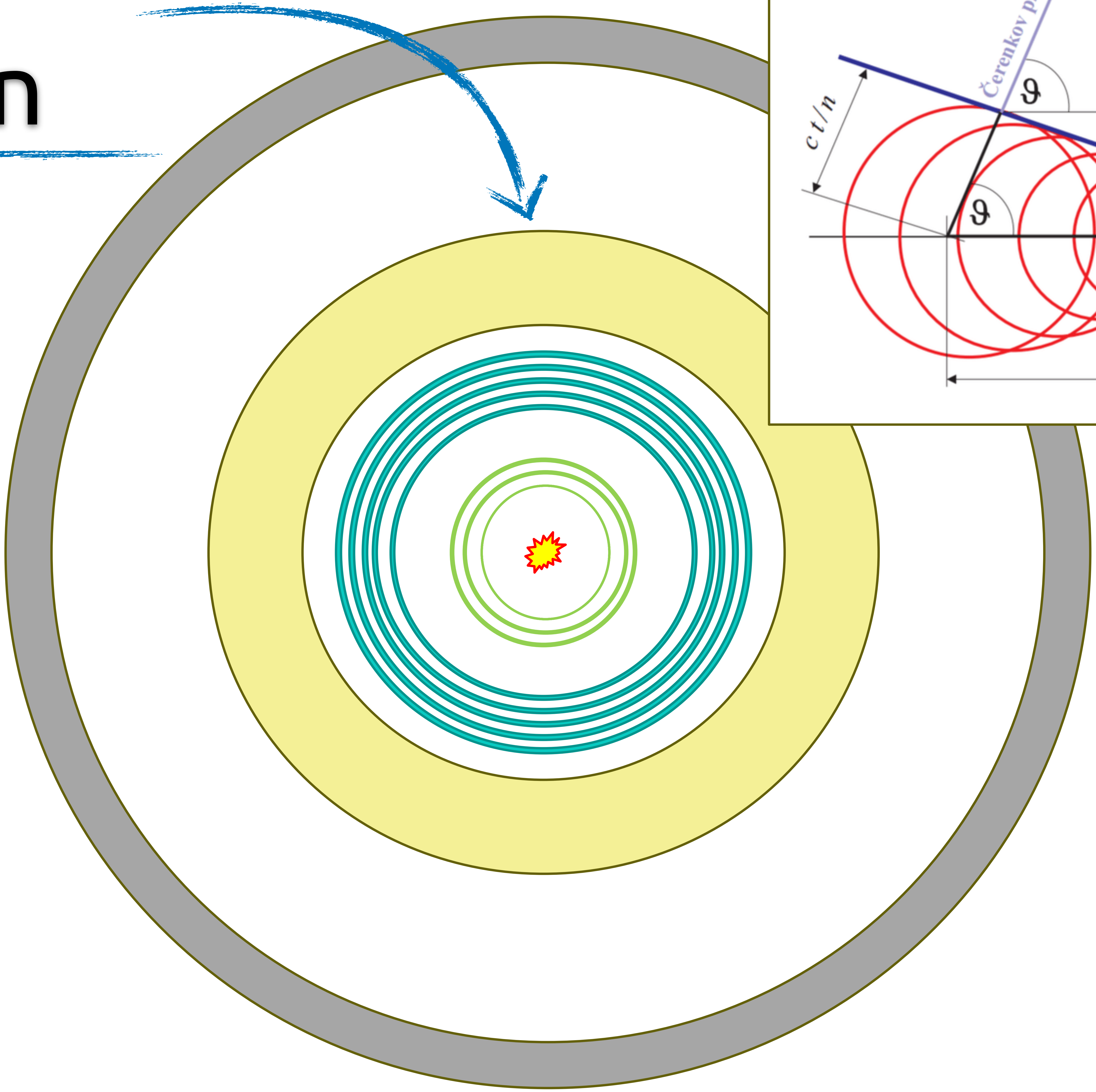
Particle Identification

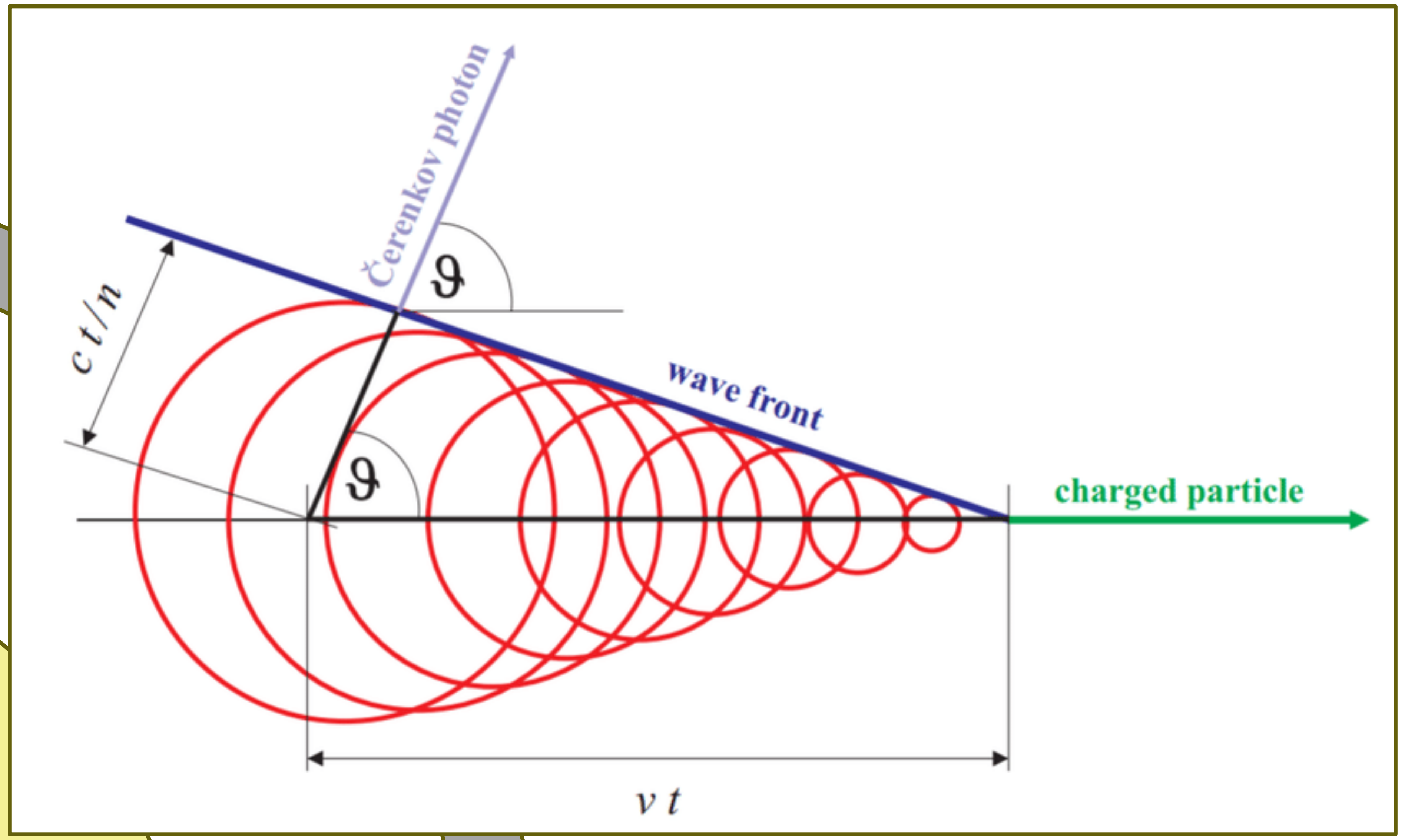
- We will exploit the **Čerenkov** effect: a charged particle travelling faster than the speed of light in a medium emits light

- $v = \cos\theta c_m$

  - c_m is the speed of light IN the medium

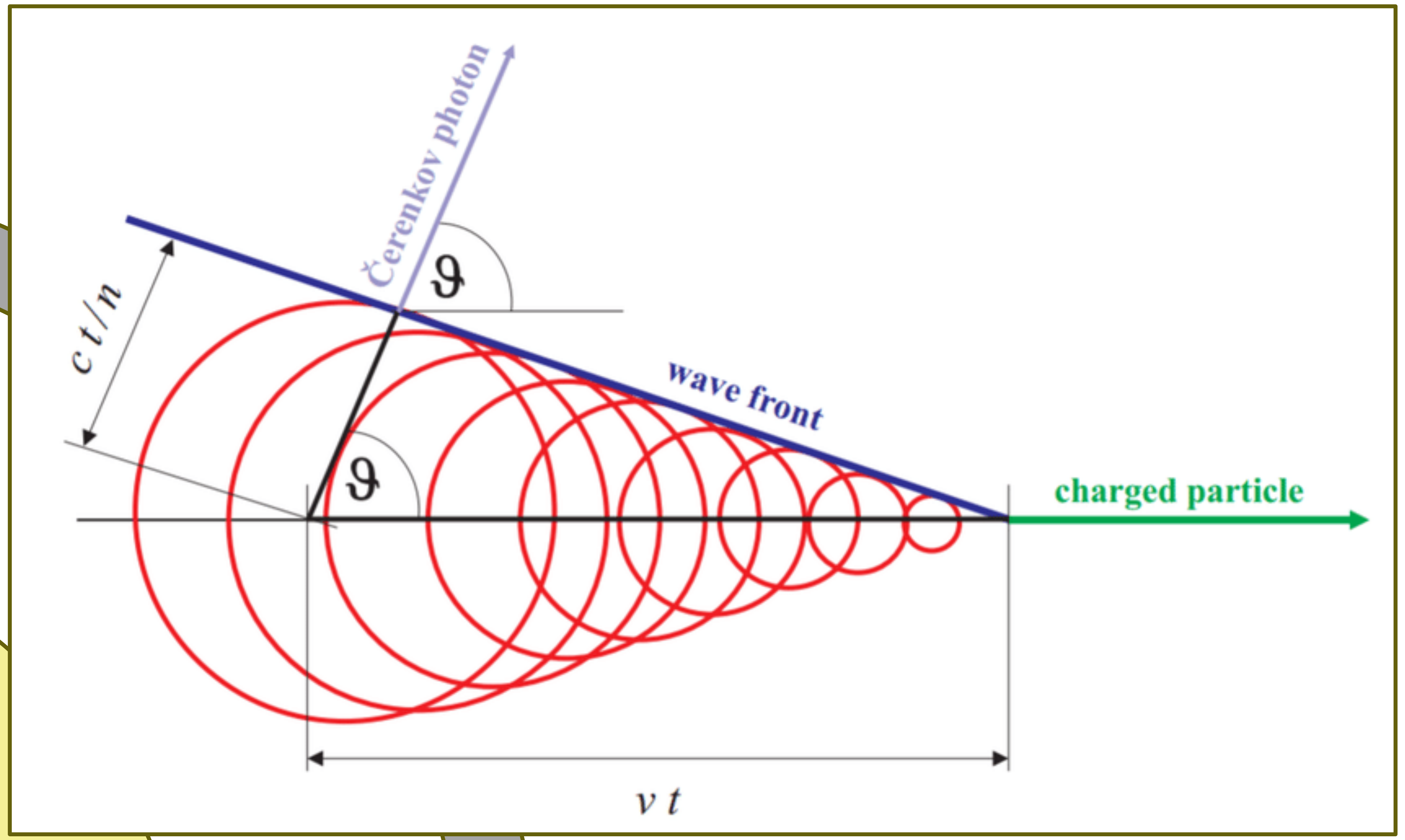
- Measuring θ we can measure v and so access to mass

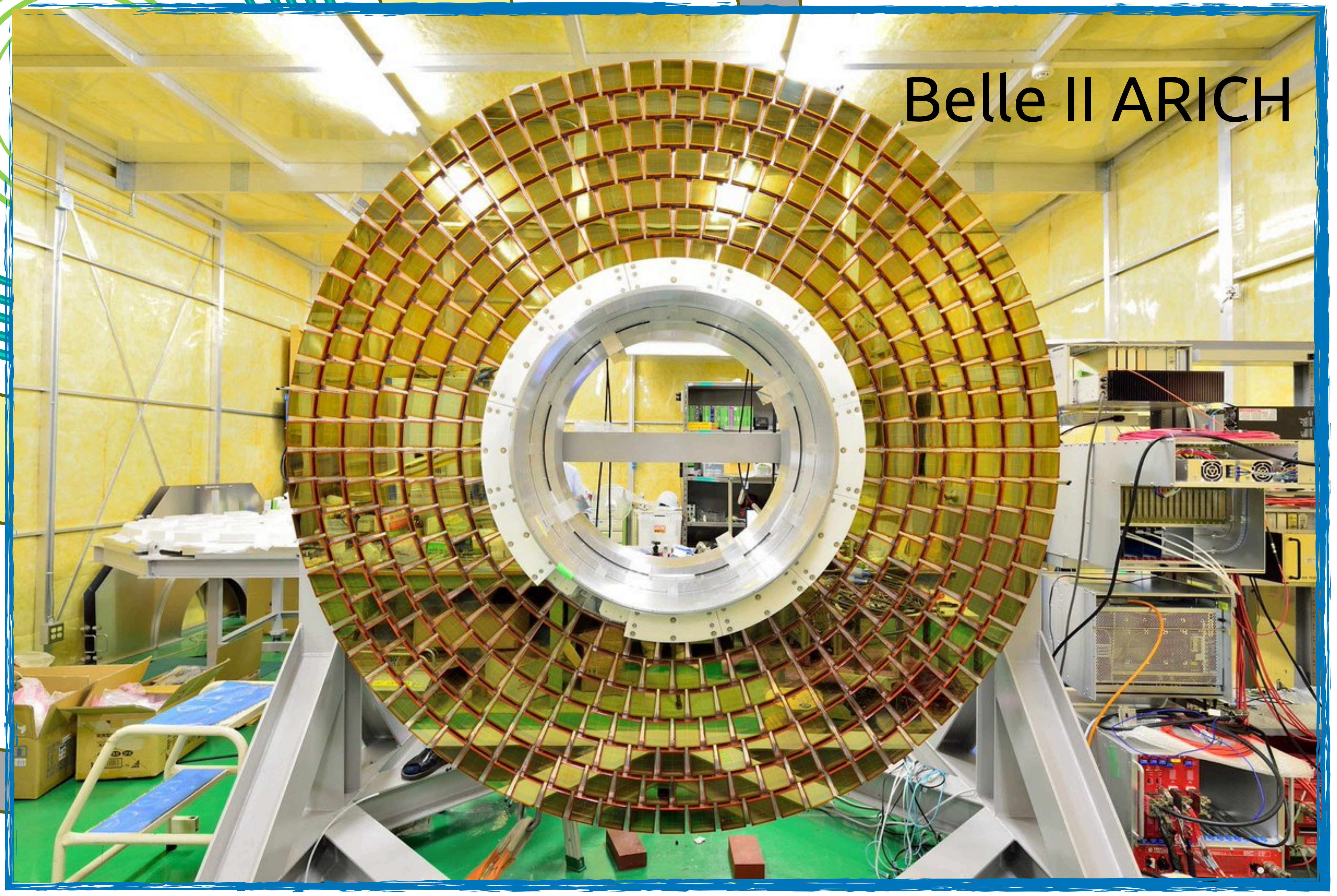




Particle Identification

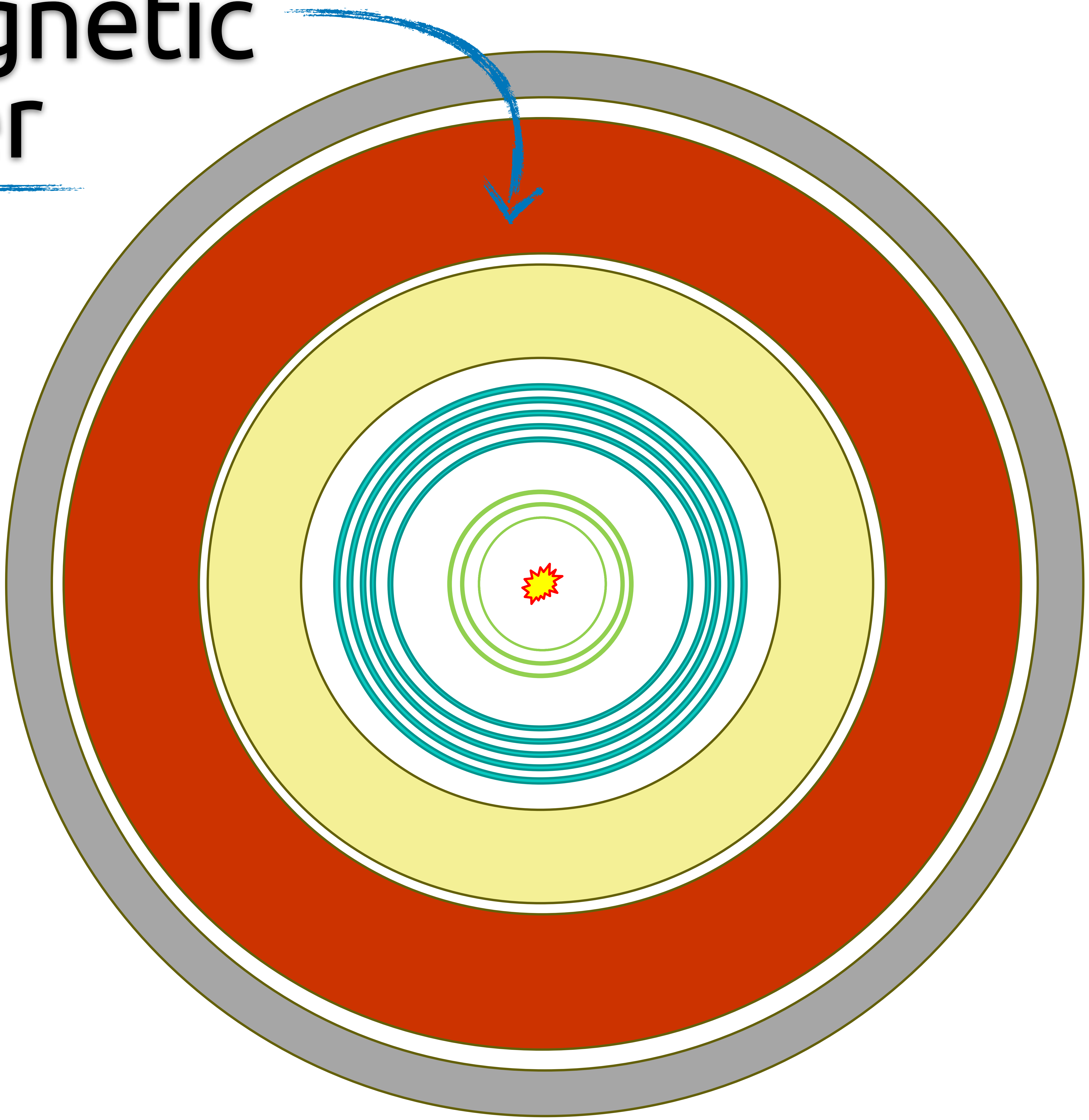
- We will exploit the **Čerenkov** effect: a charged particle travelling faster than the speed of light in a medium emits light
- $v = \cos\theta c_m$
  - c_m is the speed of light IN the medium
- Measuring θ we can measure v and so access to mass





Electromagnetic Calorimeter

- Must stop all the particles which interact **electromagnetically**
- Measure the **total energy** of these particles



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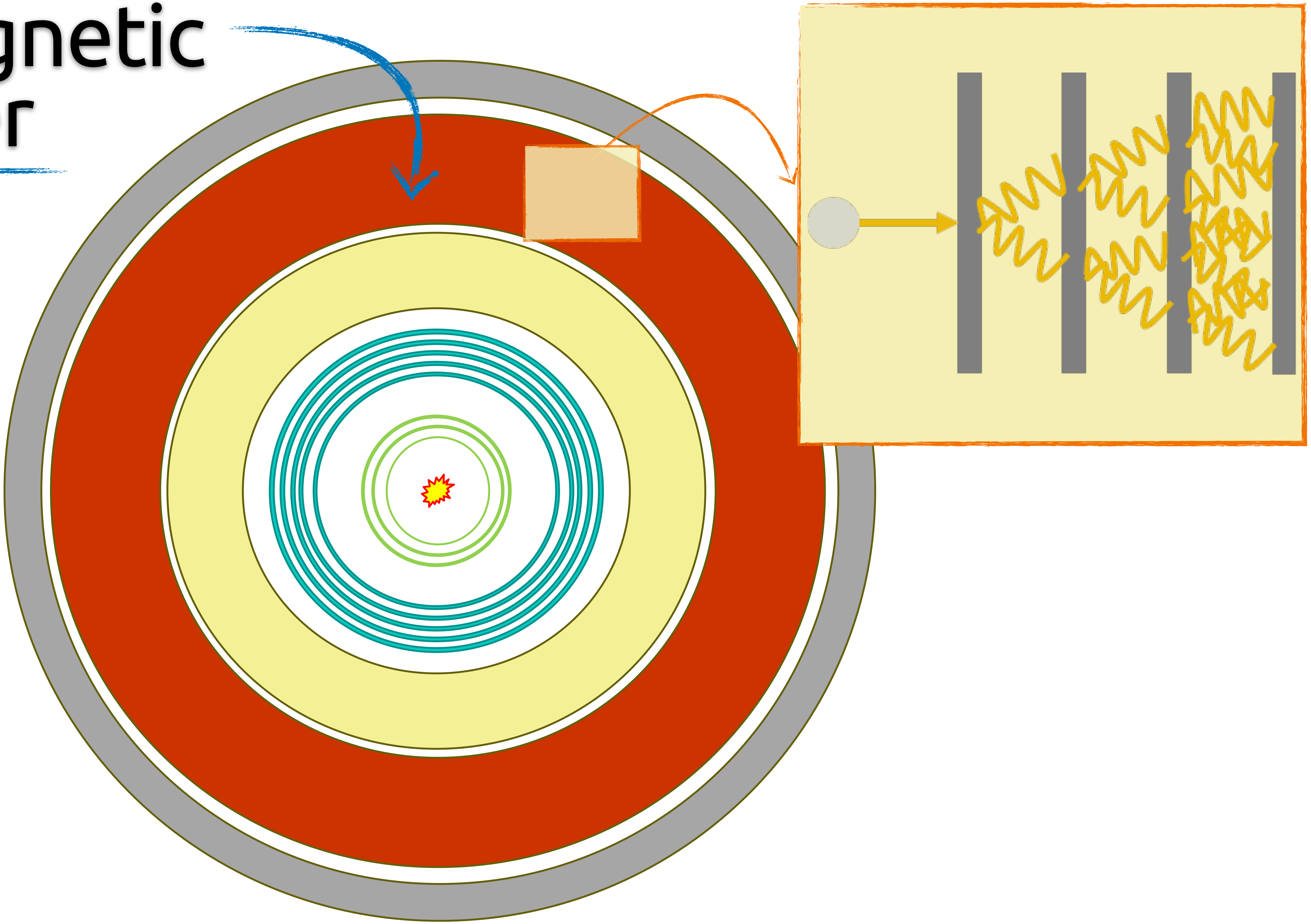
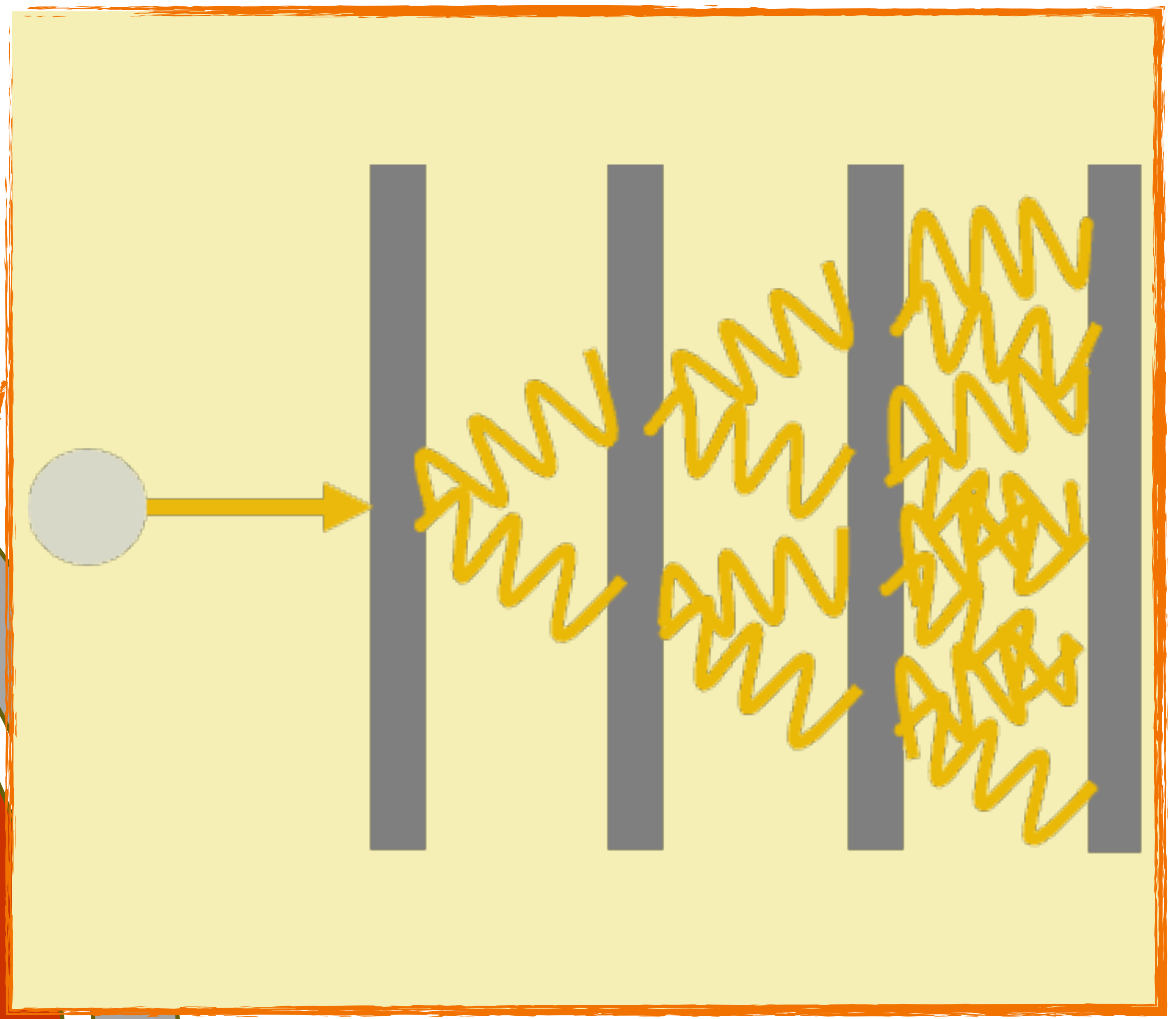


Electromagnet Calorimeter

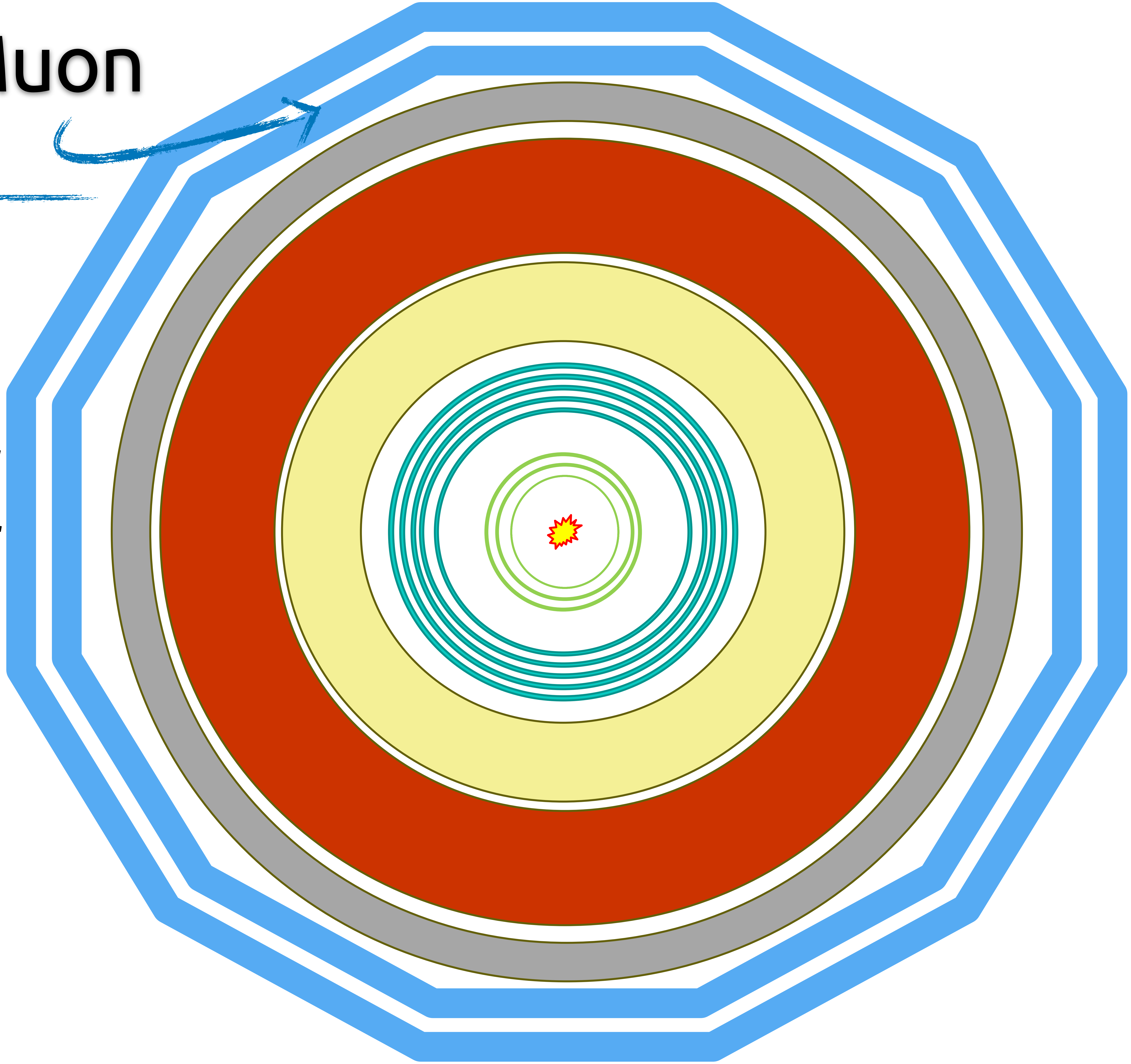
- Must stop all the particles which interact **electromagnetically**
- Measure the **total energy** of these particles

Belle II Electromagnetic CaLorimeter



K_L^0 and Muon system

- Additional **tracking layer** for muons, which are very penetrating
- Additional layer of **stopping material** for particles not stopped by the calorimeter, like K_L^0
- Material optimized to stop all the particles which **interact strongly**



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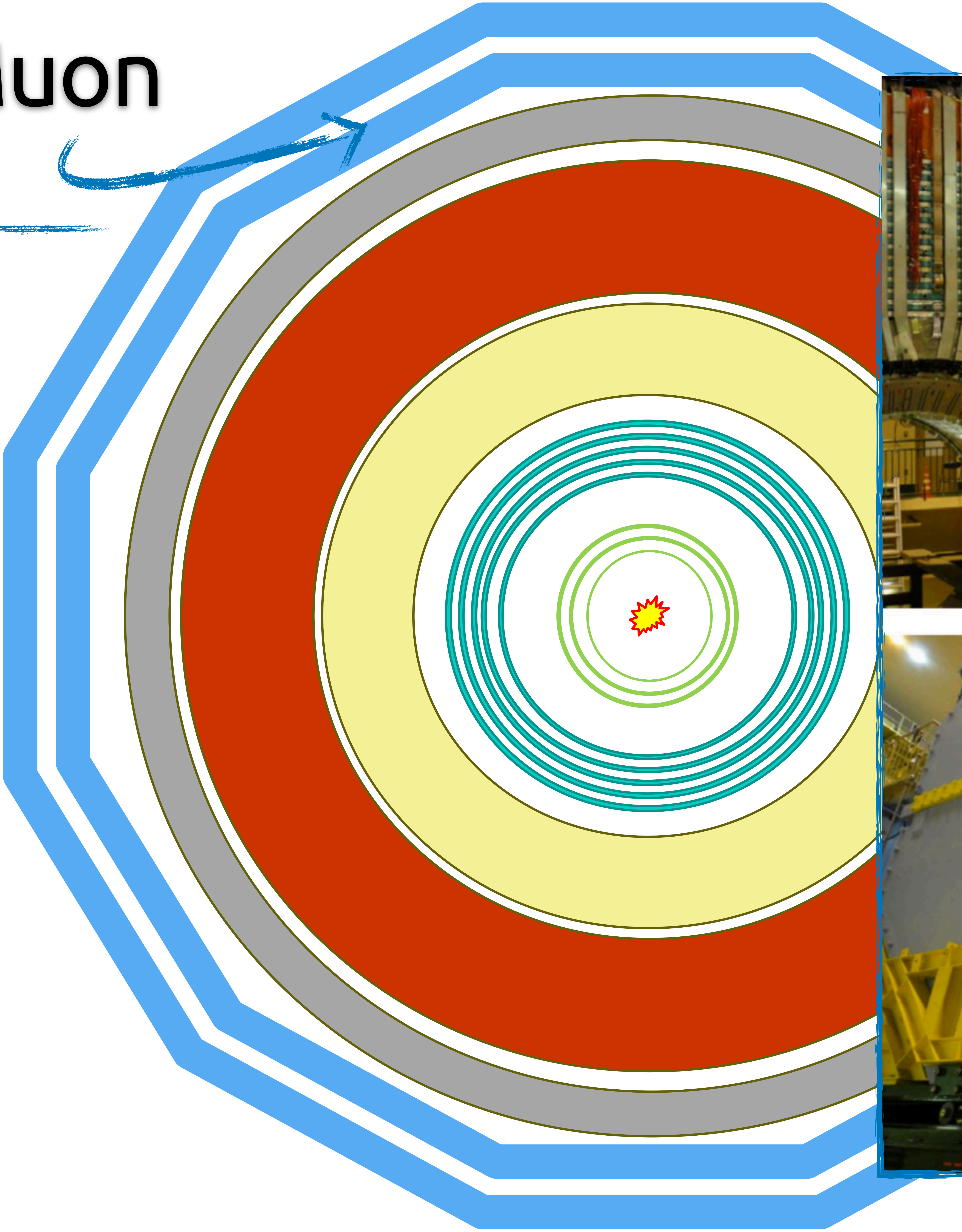
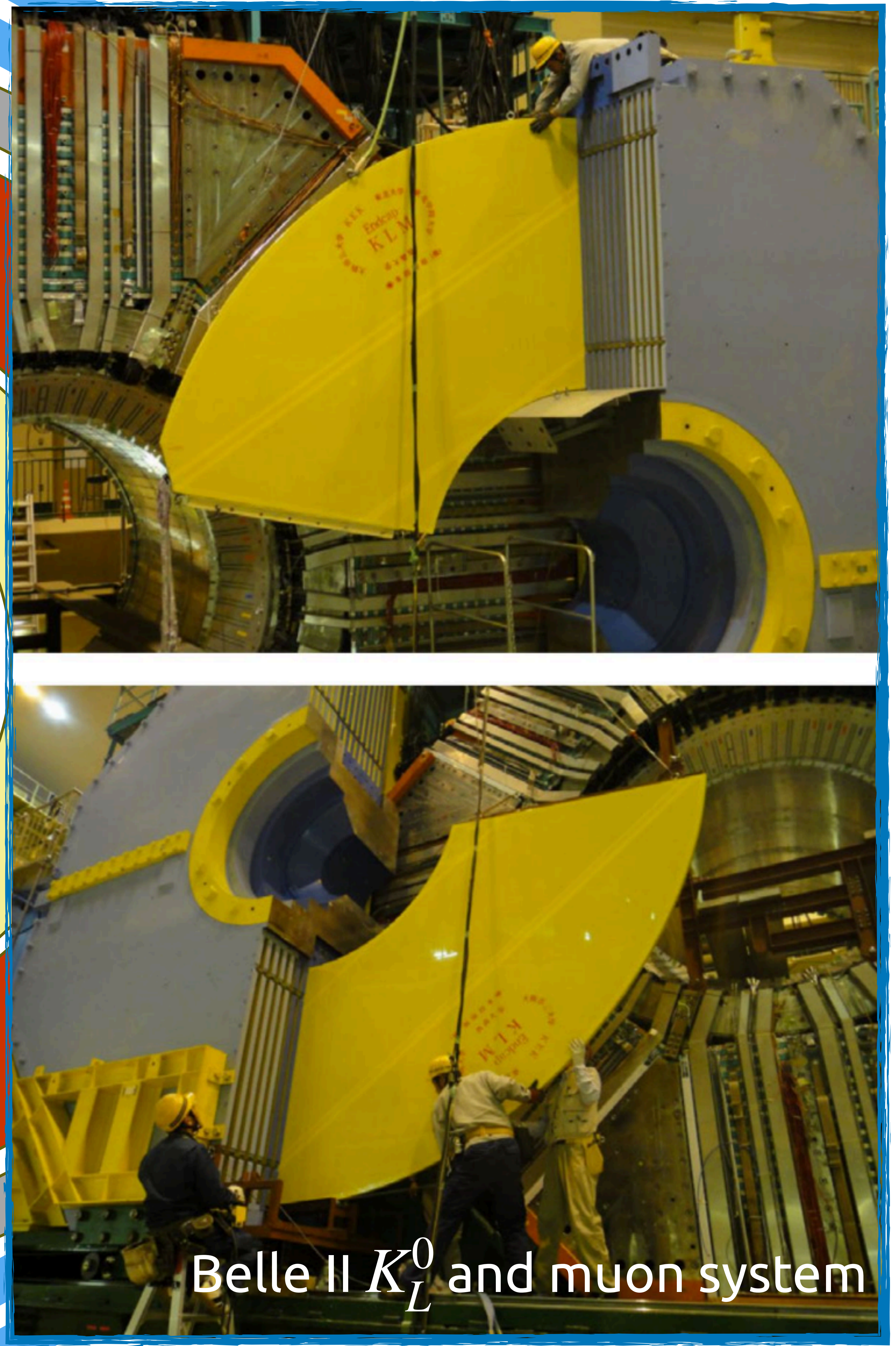


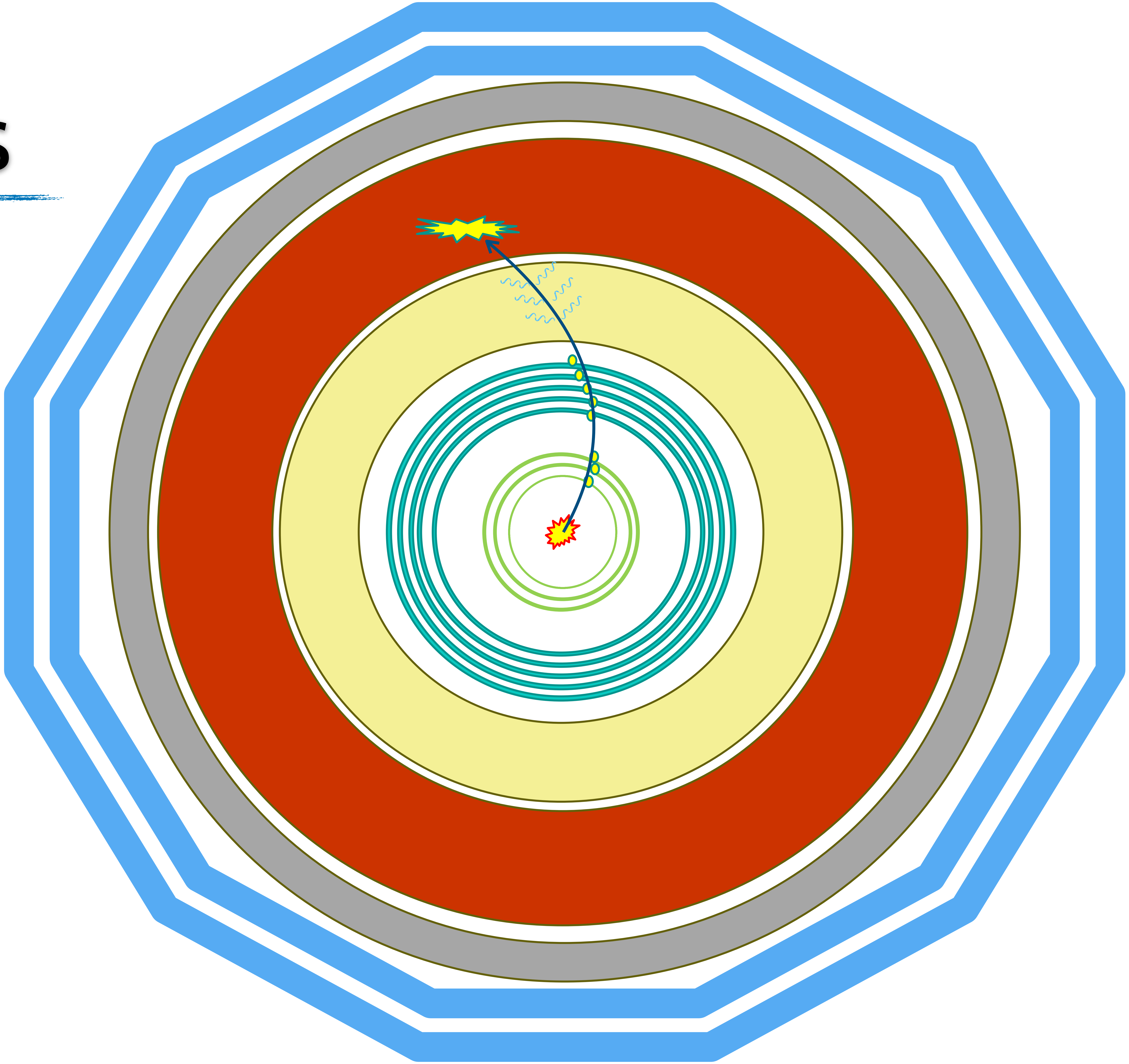


Belle II K_L^0 and muon system

Particles

Charged Lepton (electron):

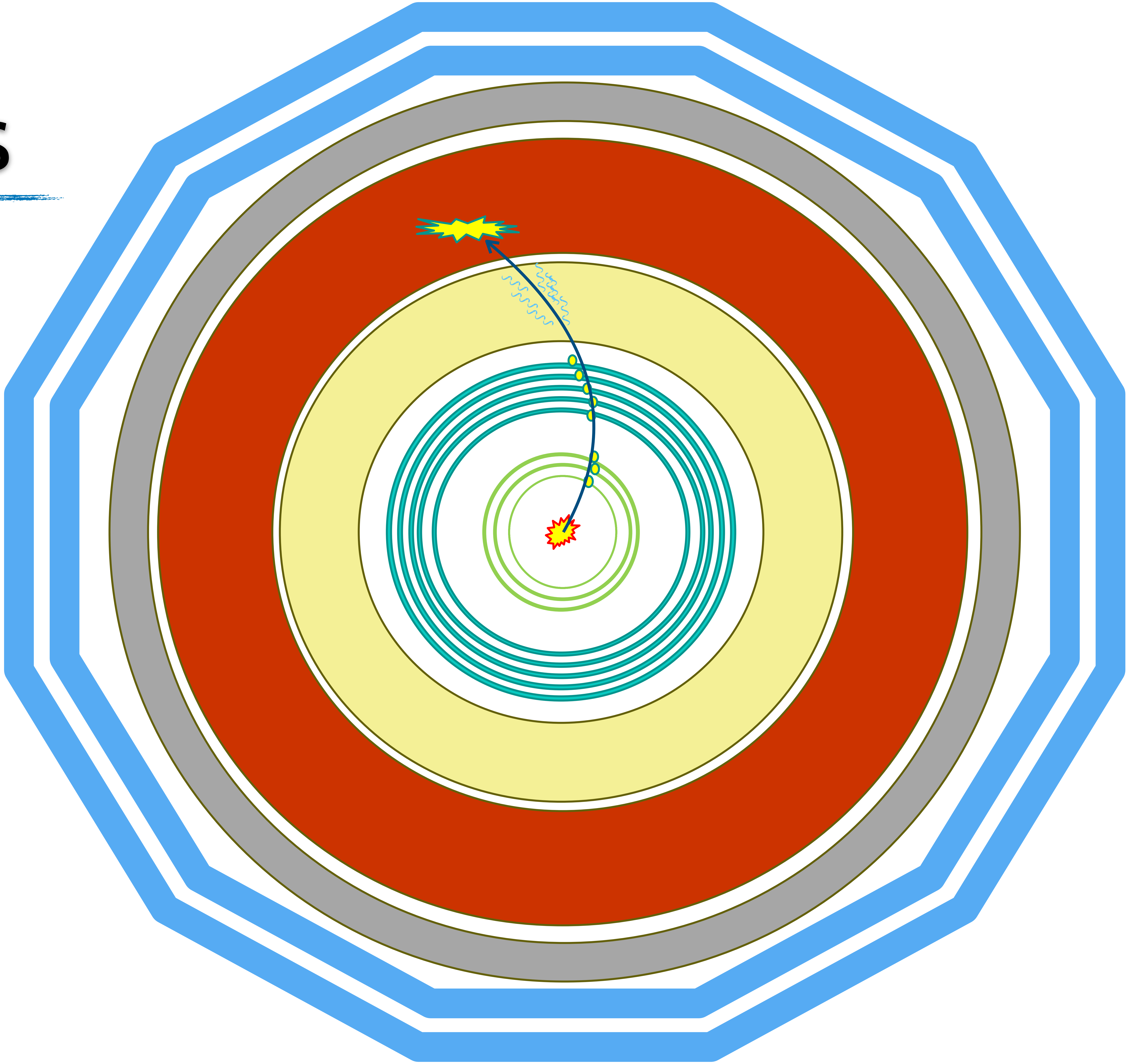
- Hits in the tracker
- Čerenkov light
- stopped in the calorimeter



Particles

Charged hadron:

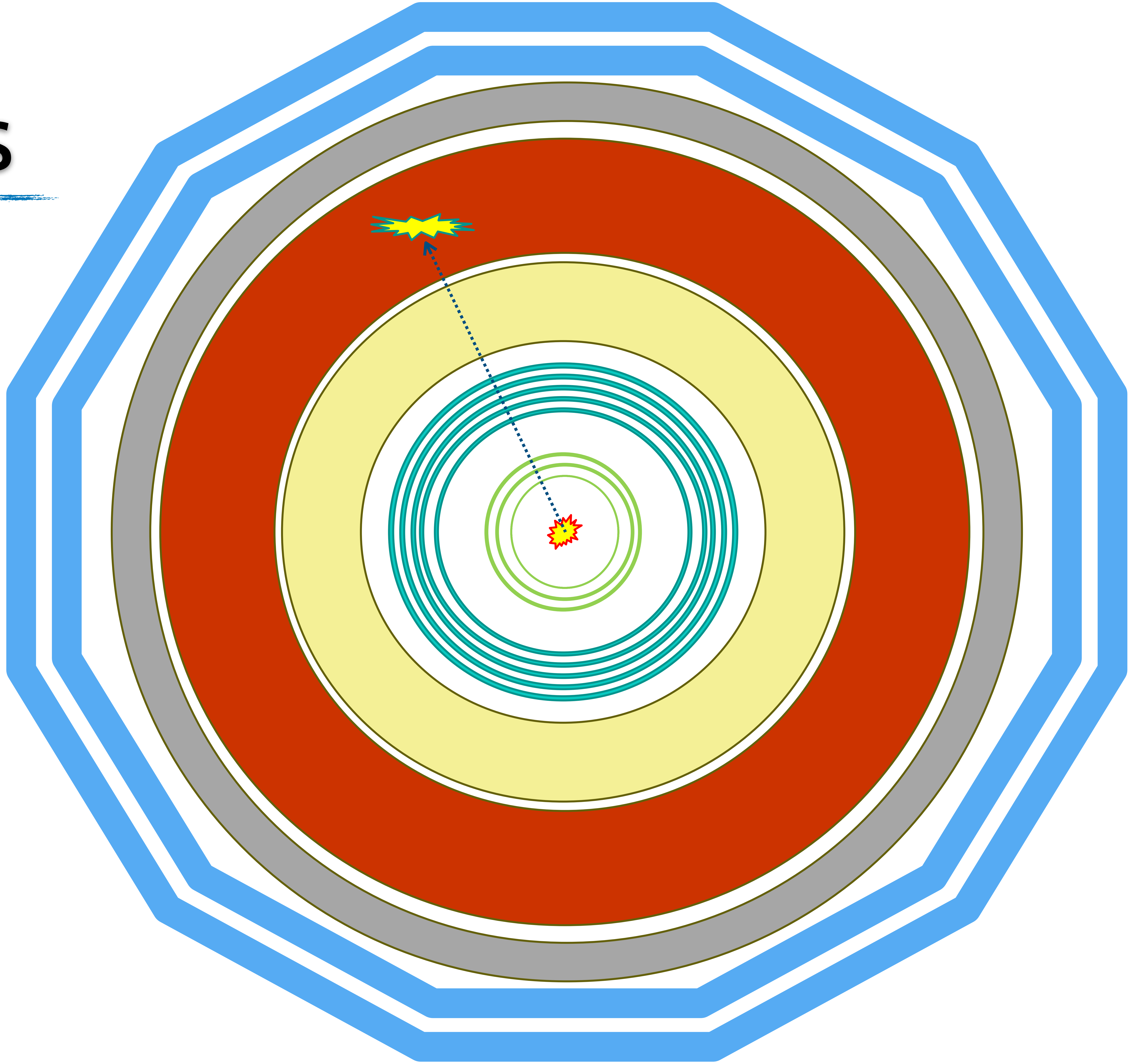
- Hits in the tracker
- (different) Čerenkov light
- stopped in the calorimeter



Particles

Photon

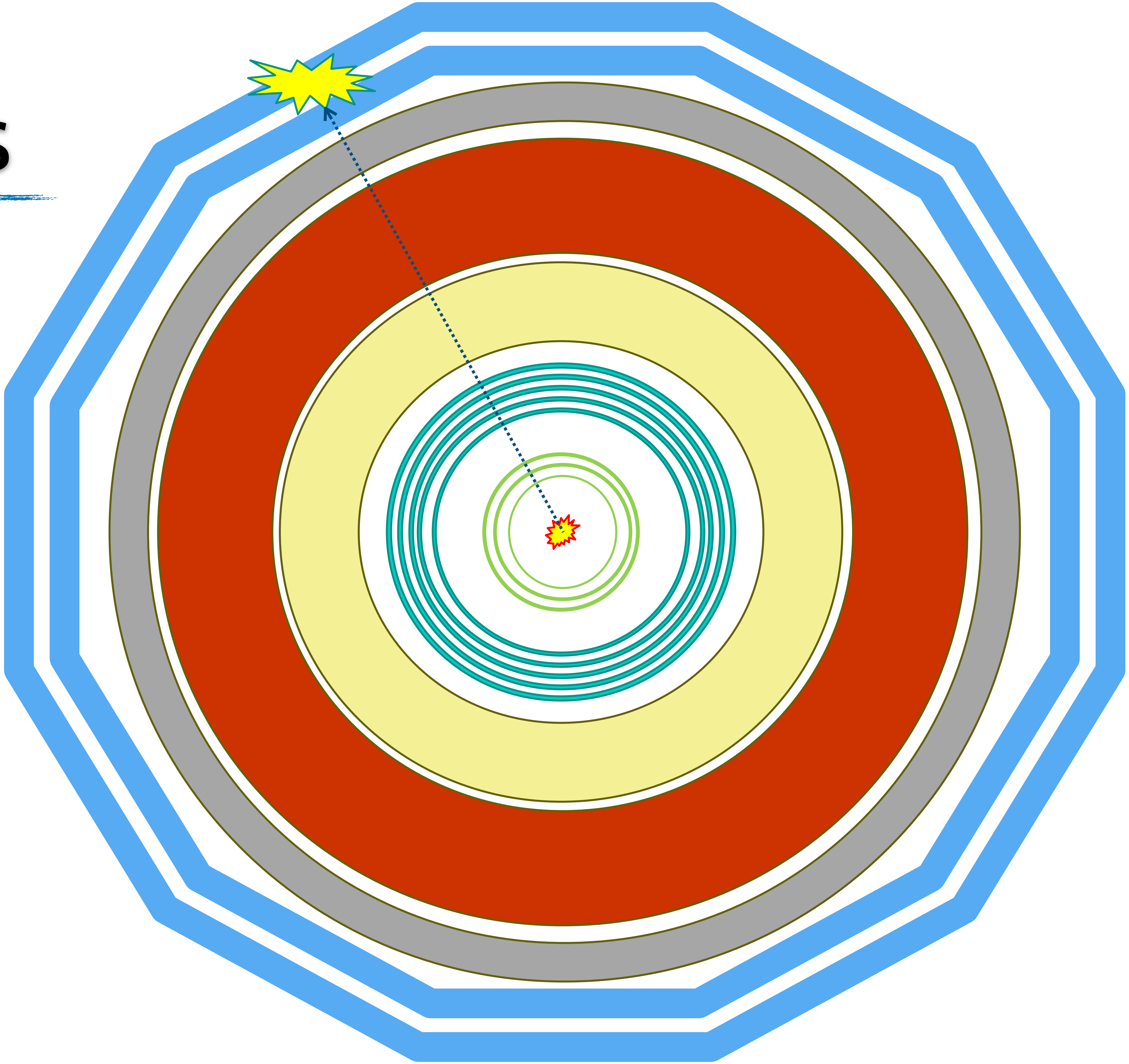
- Released energy in the calorimeter
- Stopped in the calorimeter



Particles

Neutral hadron

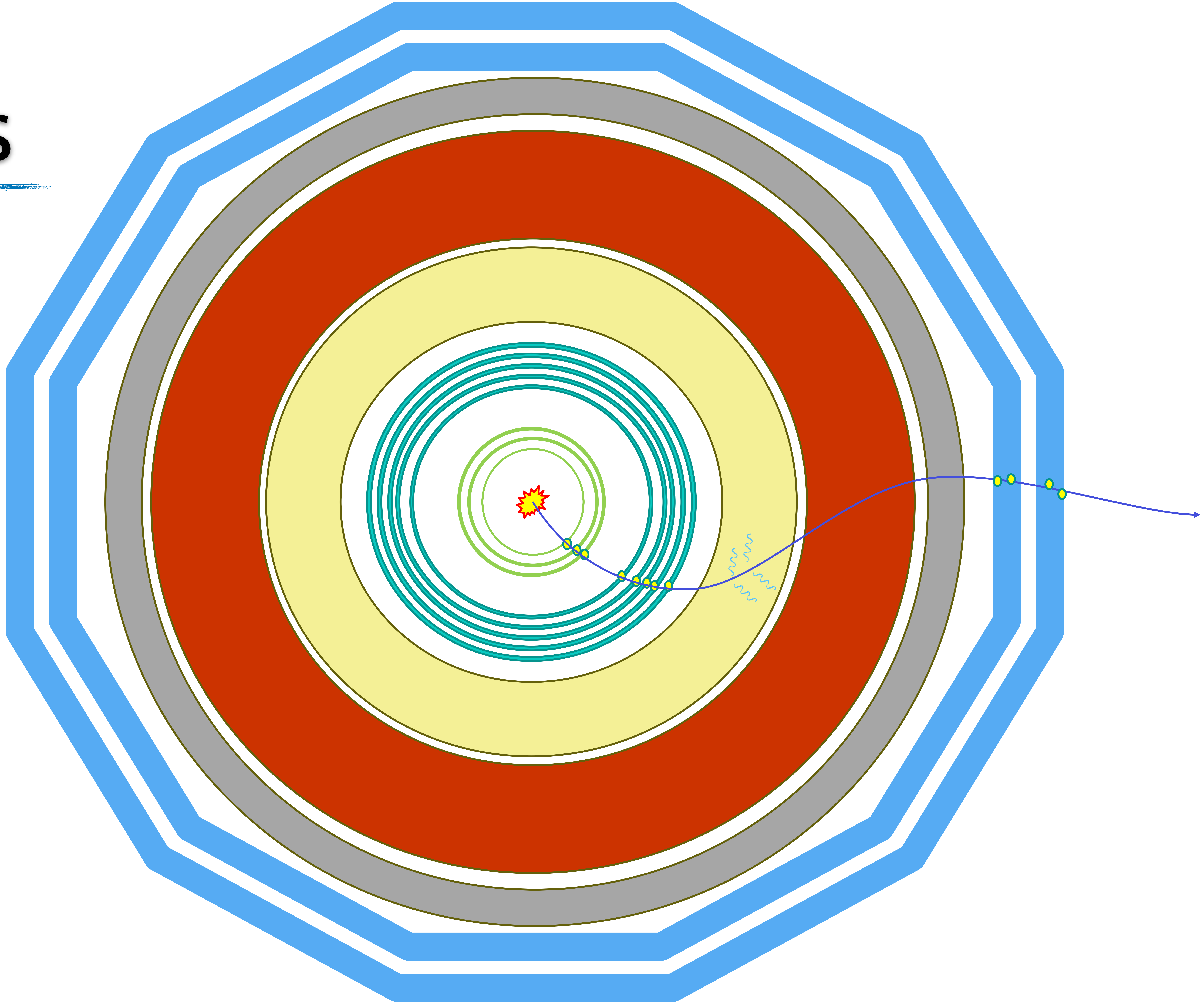
- Cross the entire detector
- Release energy in the KLM
- Stopped in the KLM



Particles

Muon

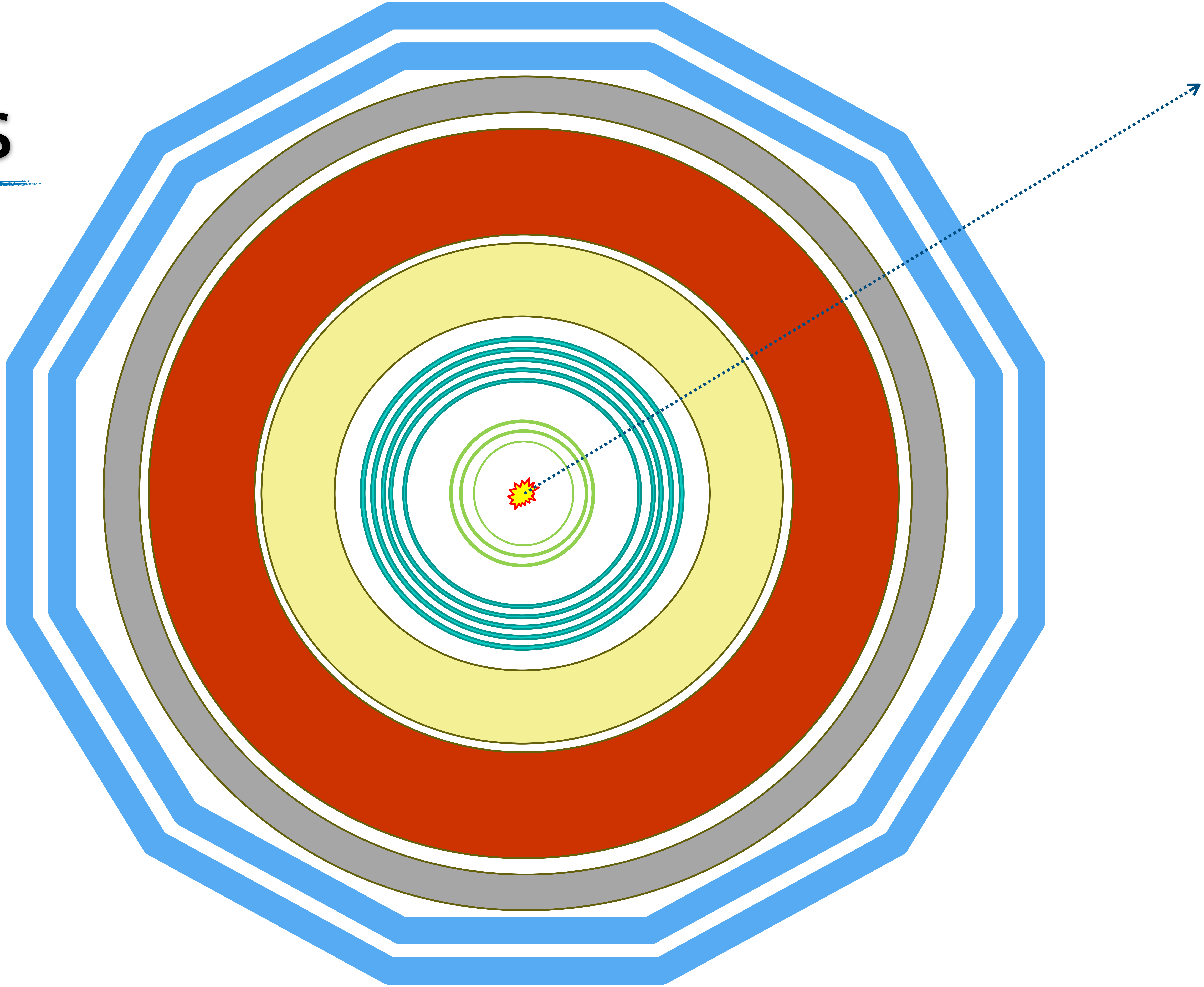
- Hit in the tracker
- Cross the entire detector
- Hit in the KLM
- Čerenkov light
- Double curvature



Particles

Neutrino

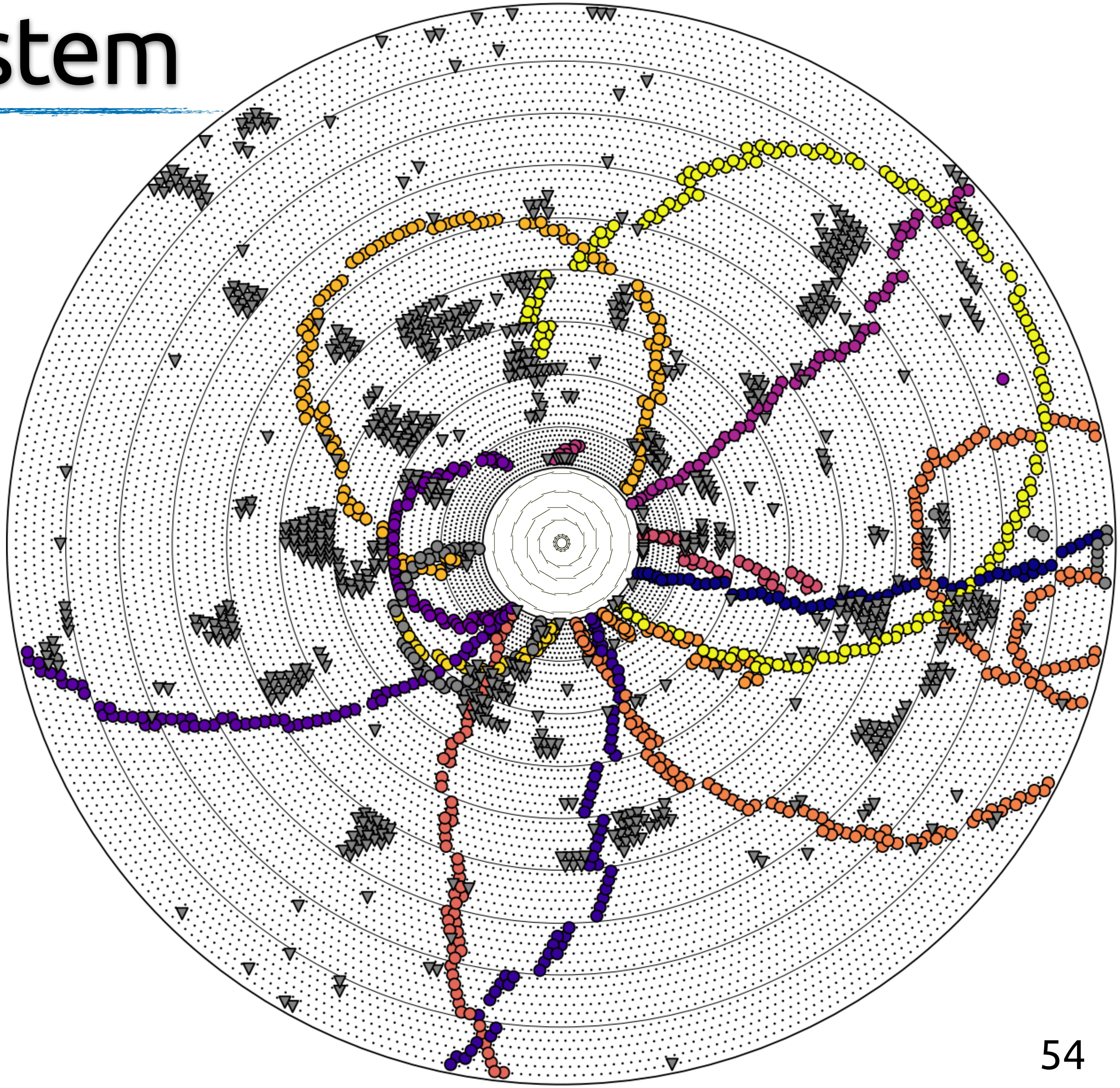
- Undetected
- (Interact only via weak interaction!)



BACKUP SLIDES

Belle II tracking system

- PXD: 2 layer silicon of pixel detector
- SVD: 4 layer of double-sided silicon strip detector
- CDC (Central Drift Chamber): 56 layer of wires, within a gas chamber with a strong accelerating $\overrightarrow{E}$ field



CMS Detector slice: particle interaction