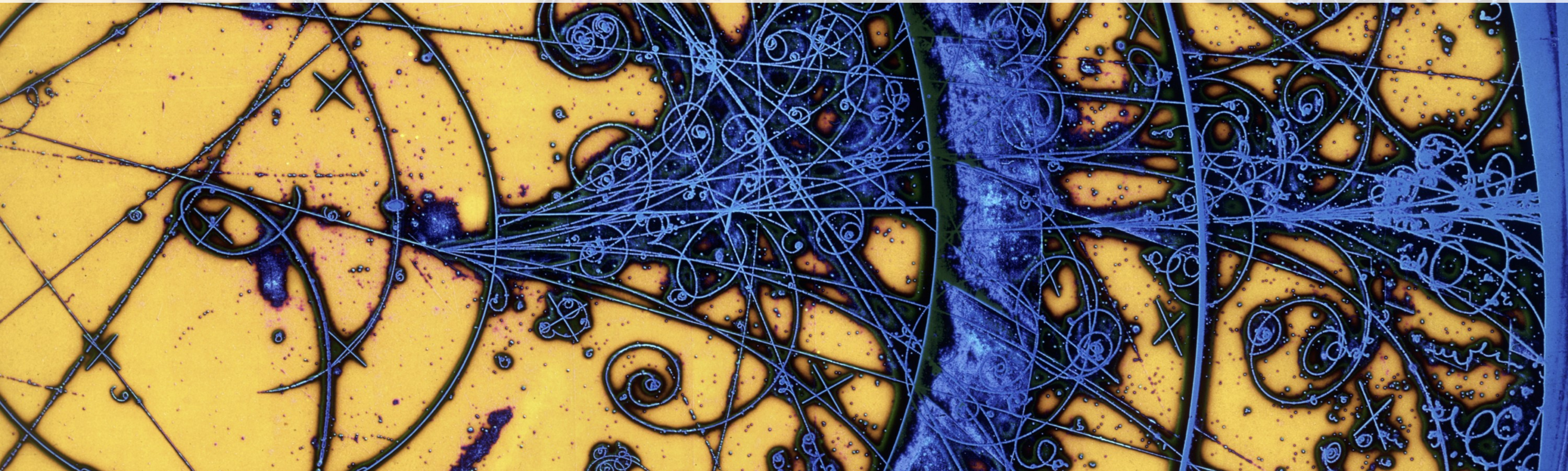


Particle Detection and Belle II

2025 Belle II International masterclass



Valerio Bertacchi
11 March 2025
Bonn



UNIVERSITÄT



Why studying the Standard Model?

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



something missing!

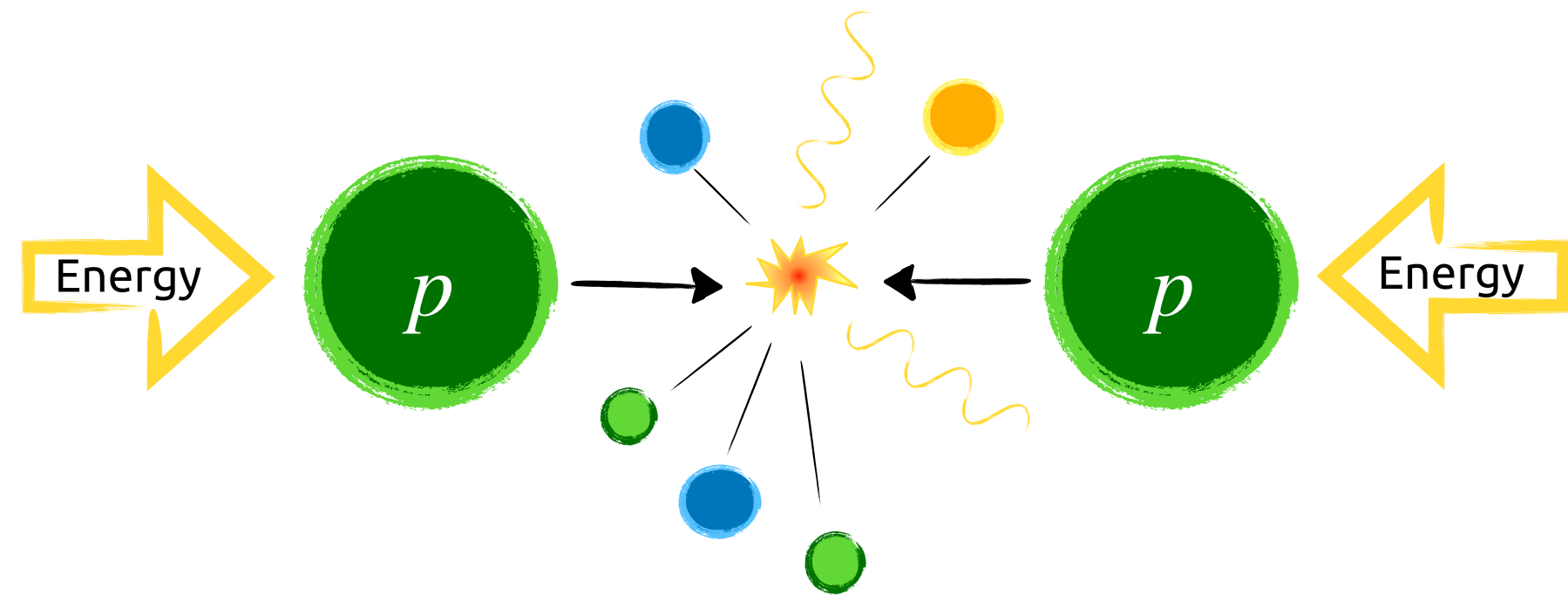
- **(about)1967-2012:** Theoretical development and experimental confirmation of the Standard Model
- **2012-???** : Search of New Physics beyond the Standard Model



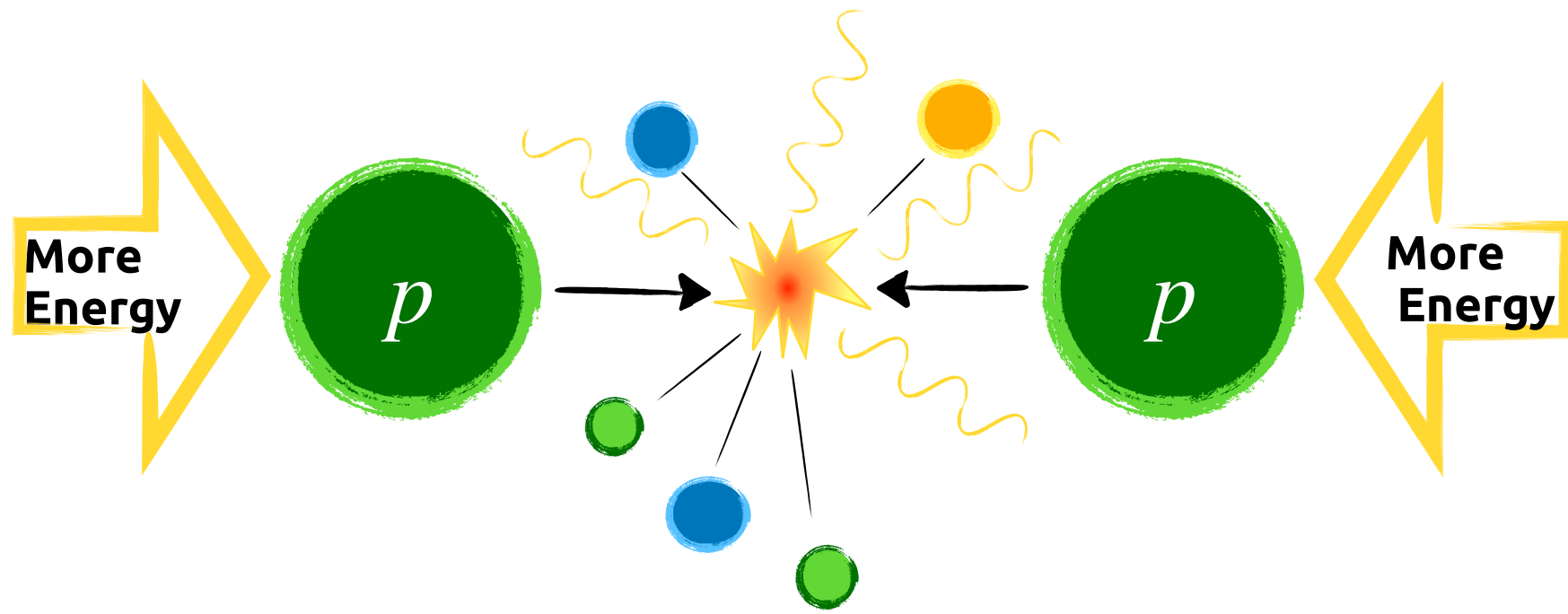
We are pushing the limits of the Standard Model to try to observe, in laboratory, where is not working anymore. We are pursuing two approaches:

- **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!

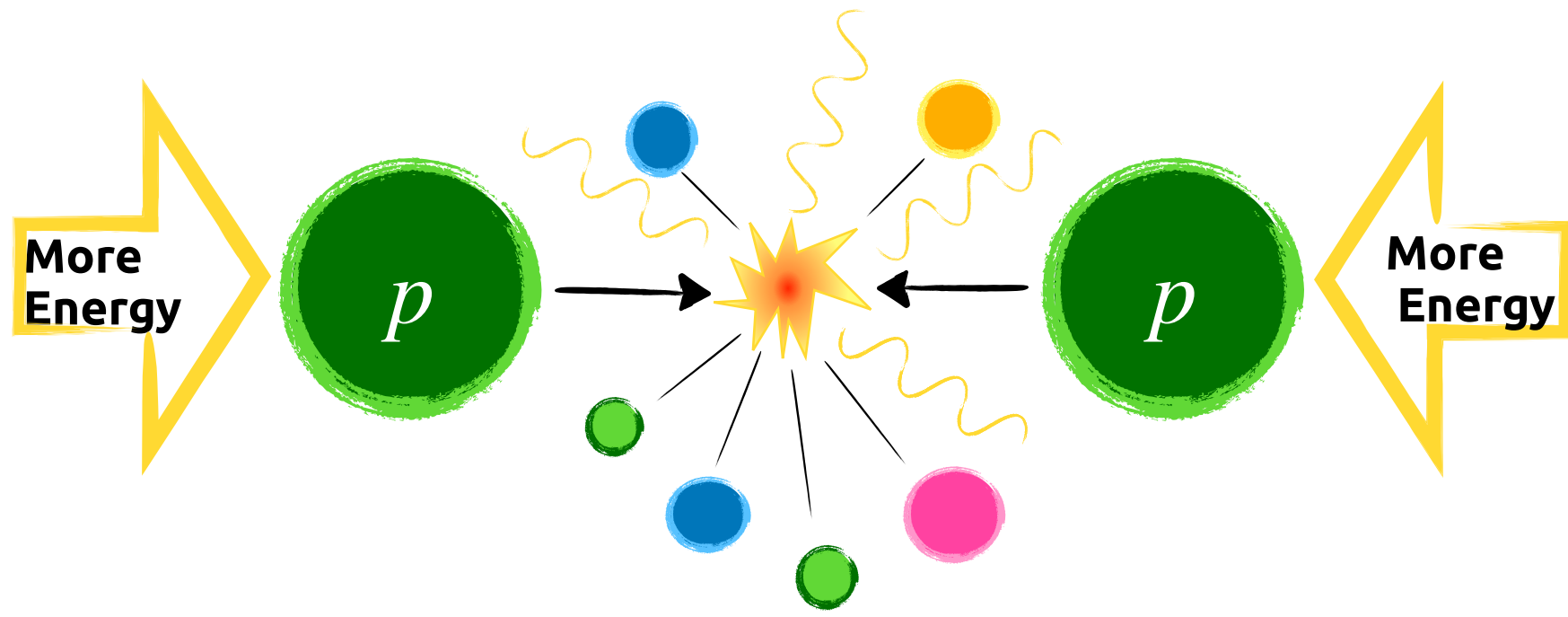


More energy out



We can create additional particles

Energy frontier



More energy in!



More energy out



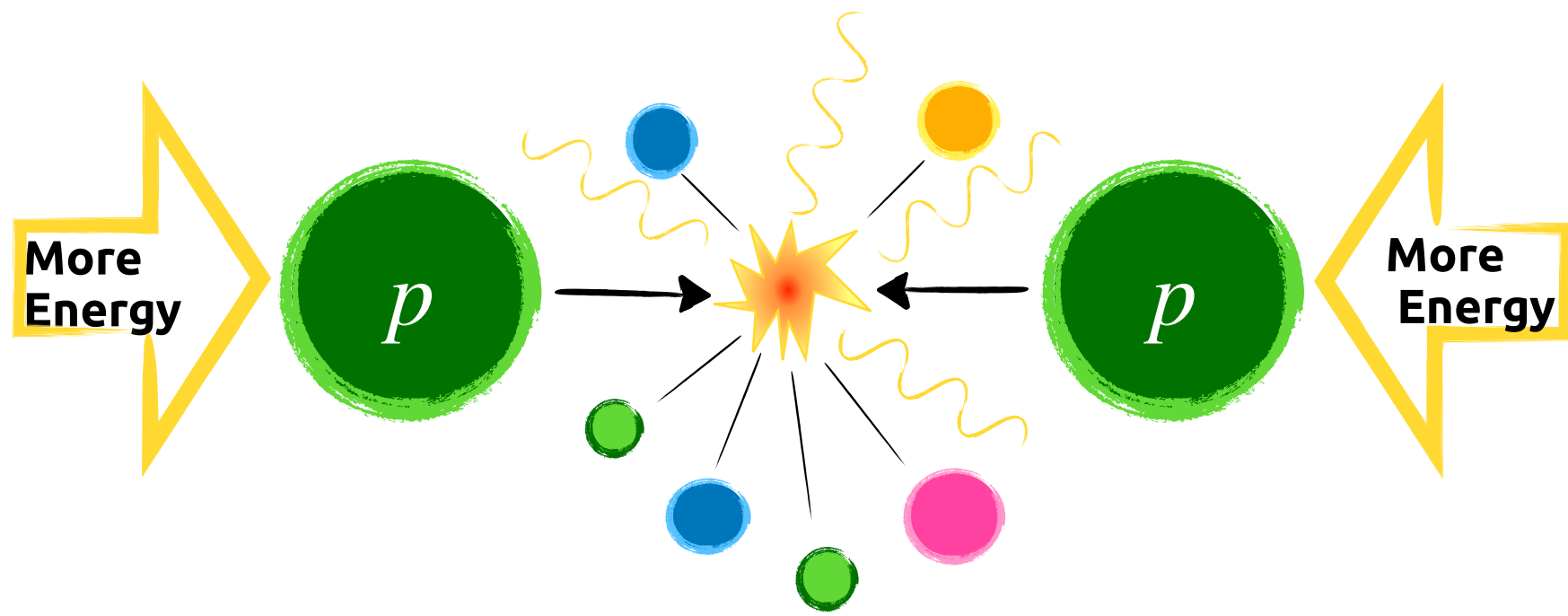
We can create additional particles



Maybe something **unexpected** will pop up!



Energy frontier



More energy in!



More energy out



We can create additional particles

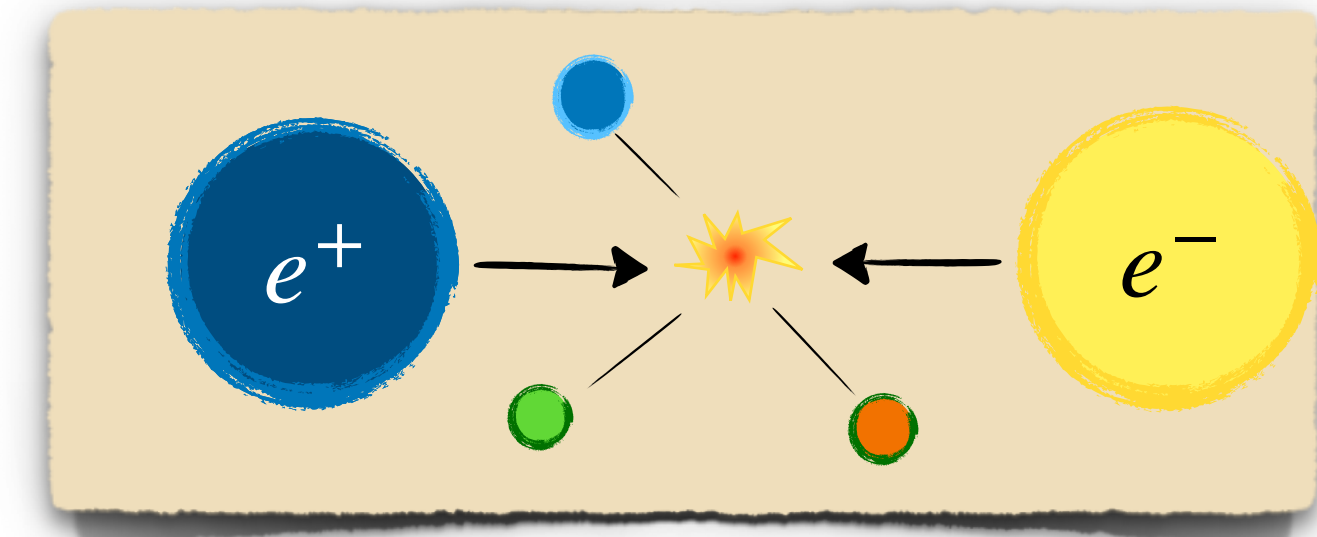


Maybe something **unexpected** will pop up!

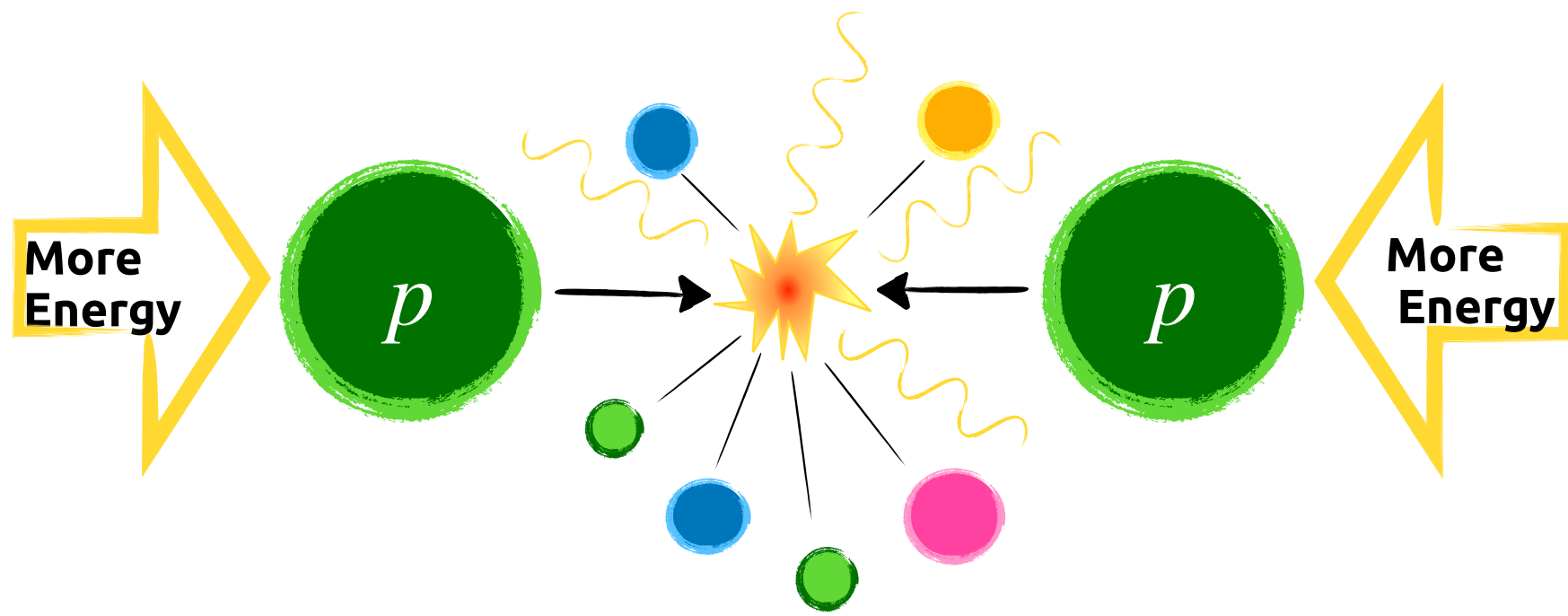


Intensity frontier

SM Probability: $\mathcal{P}(\text{blue } e^+ \text{ yellow } e^- \rightarrow \text{green } e^+ \text{ orange } e^-) = X\%$



Energy frontier



More energy in!

More energy out

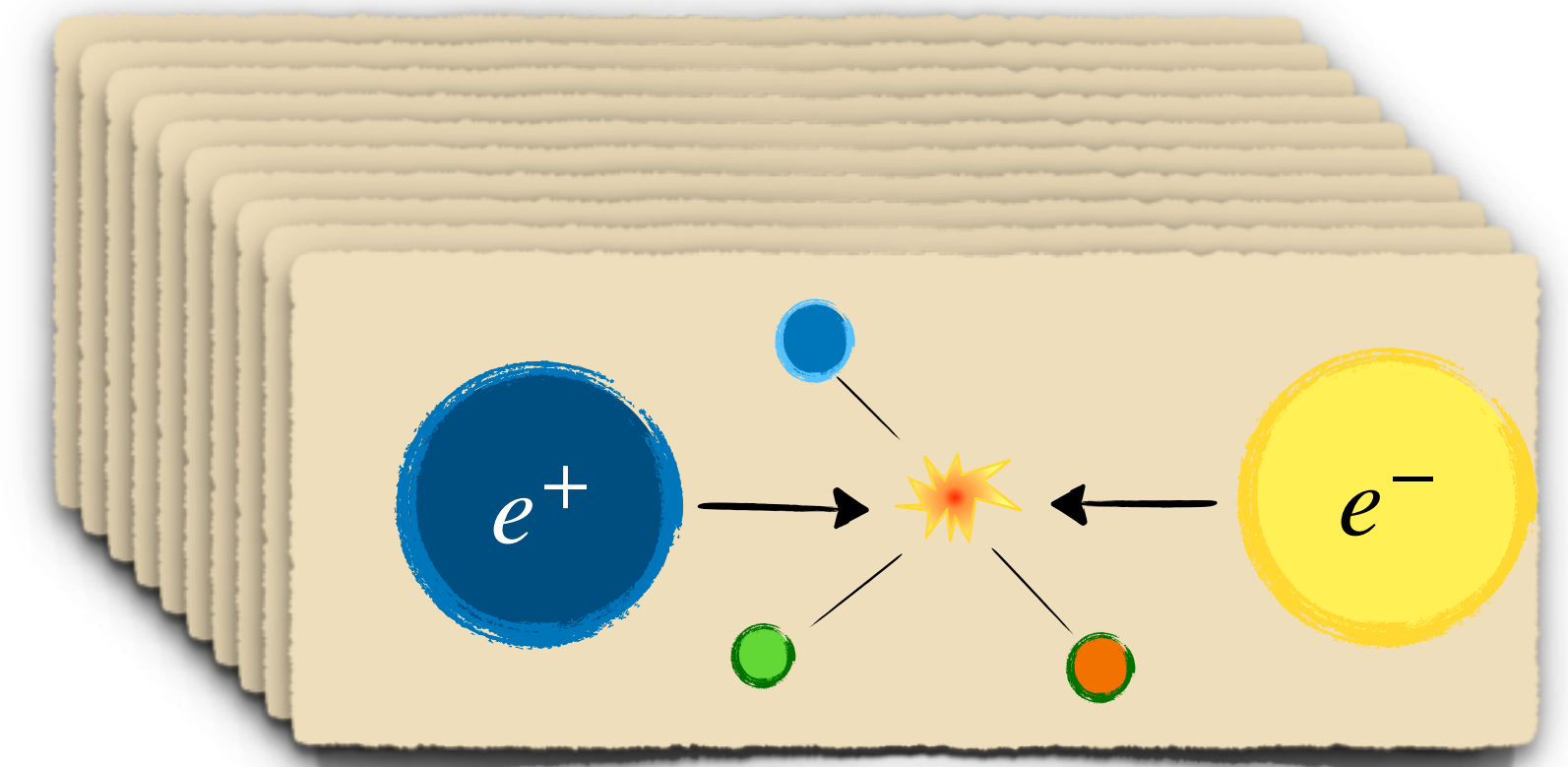
We can create additional particles

Maybe something **unexpected** will pop up!



Intensity frontier

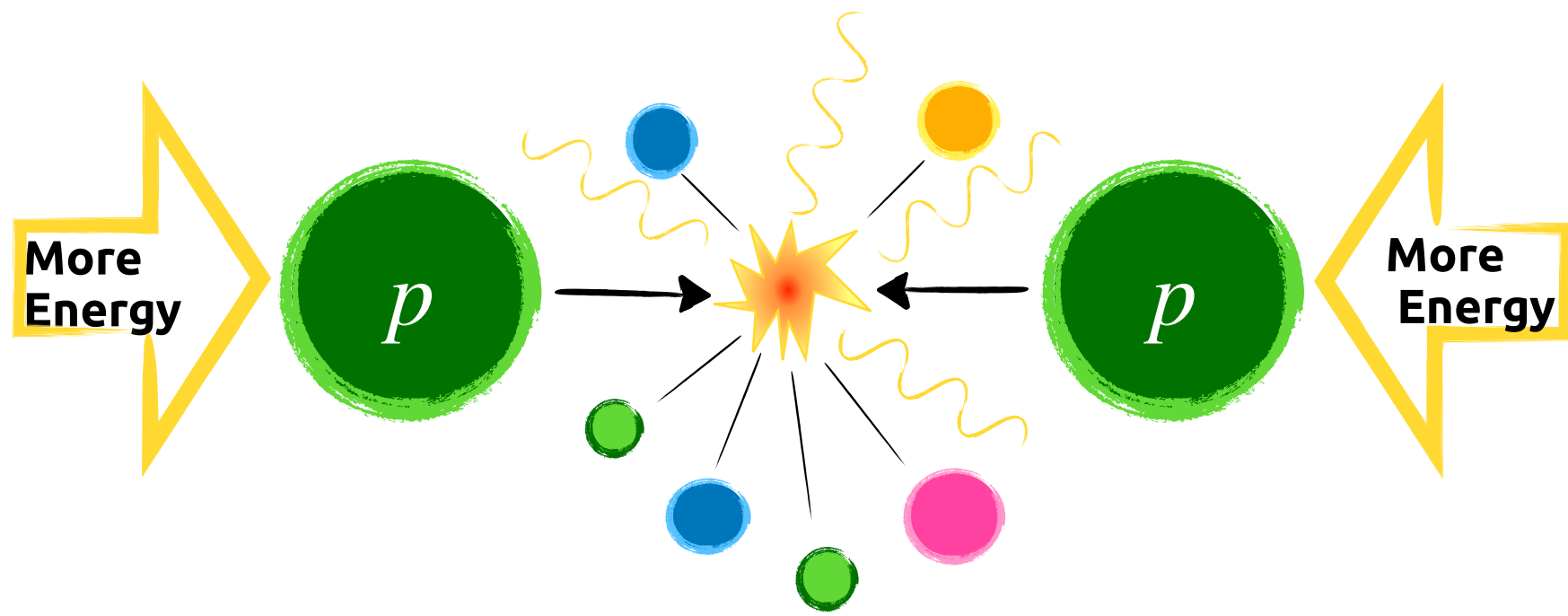
SM Probability: $\mathcal{P}(\text{blue circle} \text{ yellow circle} \rightarrow \text{green circle} \text{ orange circle} \text{ blue circle}) = X\%$



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

Are we finding exactly what we expect
from SM?

Energy frontier



More energy in!

More energy out

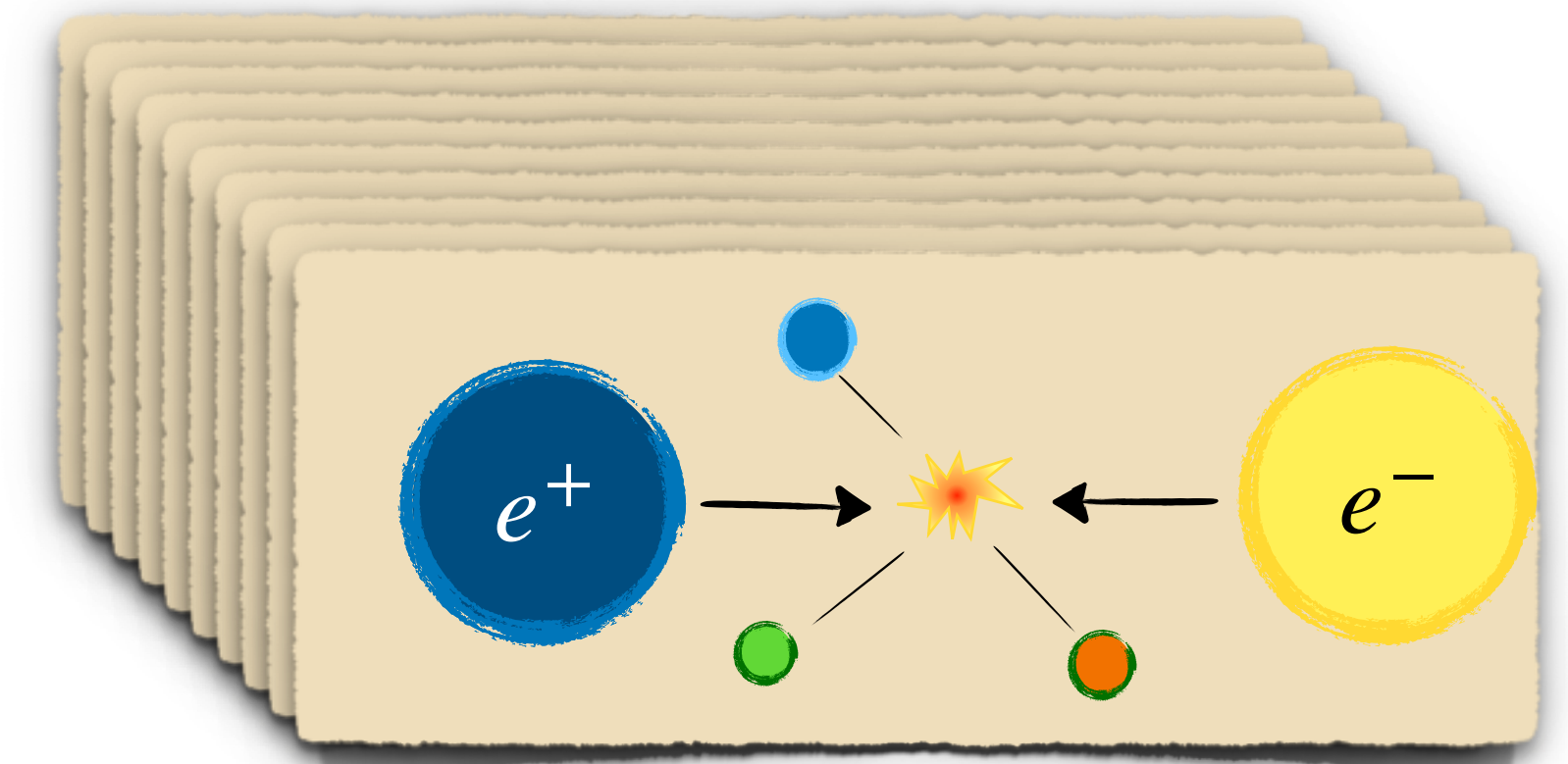
We can create additional particles

Maybe something **unexpected** will pop up!



Intensity frontier

SM Probability: $\mathcal{P}(\text{blue circle} \text{ yellow circle} \rightarrow \text{green circle} \text{ orange circle} \text{ blue circle}) = X\%$



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

Are we finding exactly what we expect from SM?

yes

No New Physics today

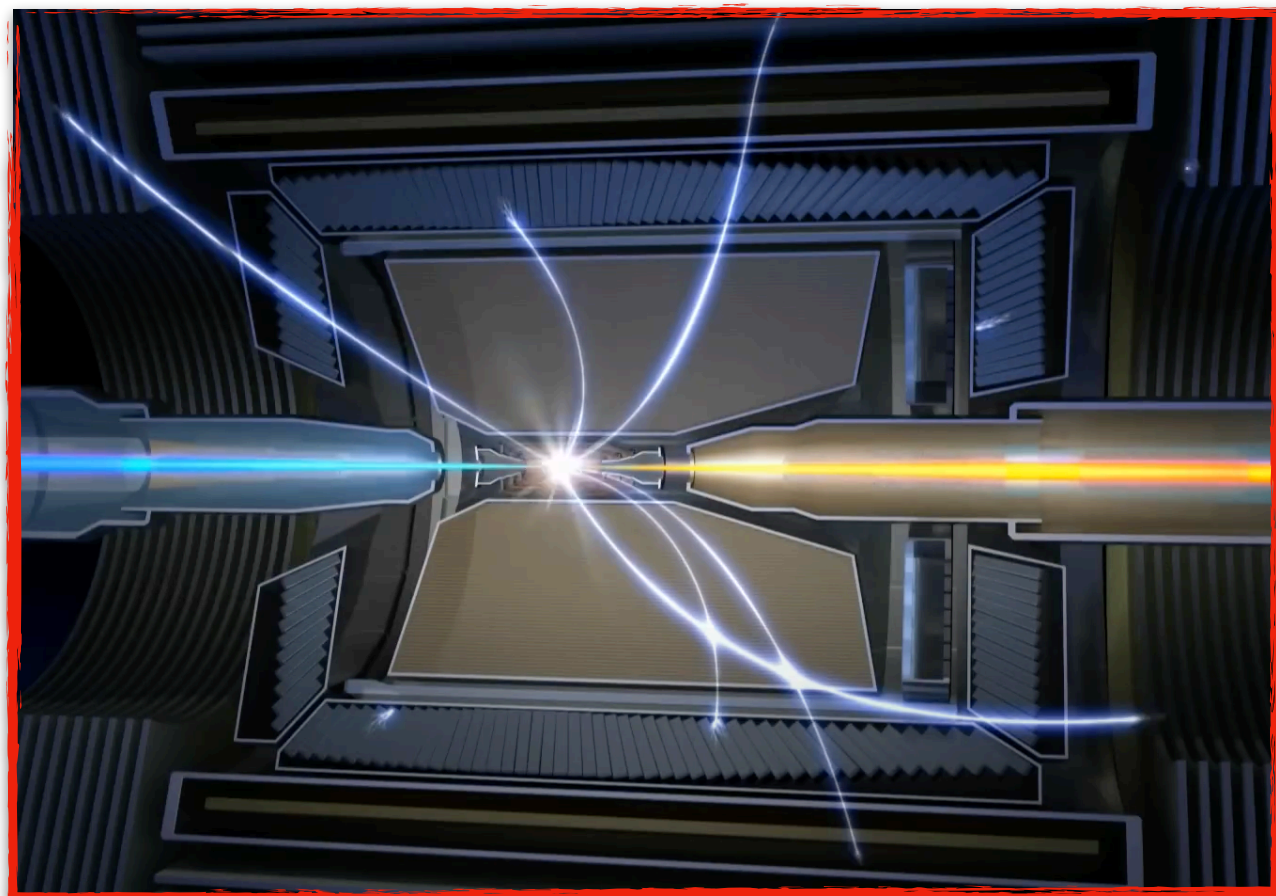
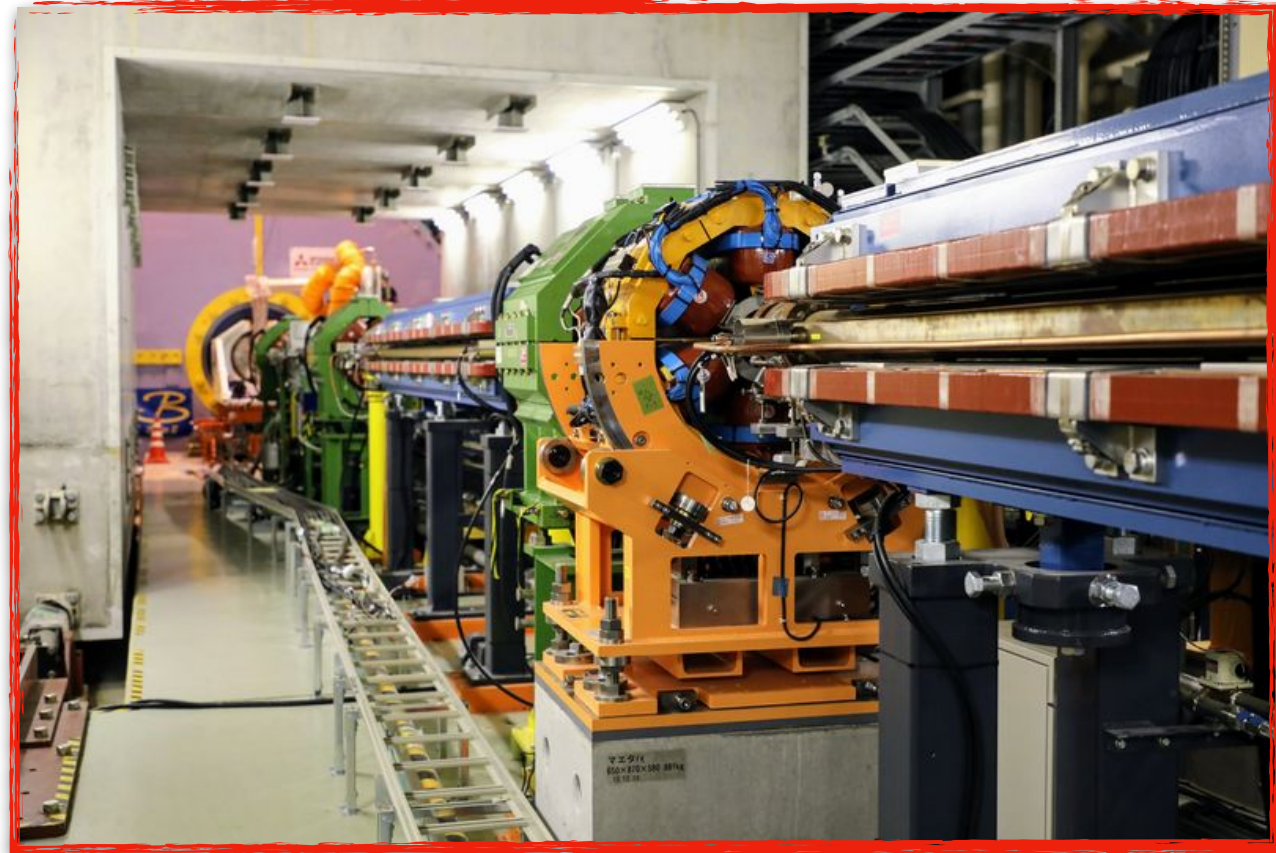
no

We broke the SM!



How to

Accelerate particles and
make them **collide**

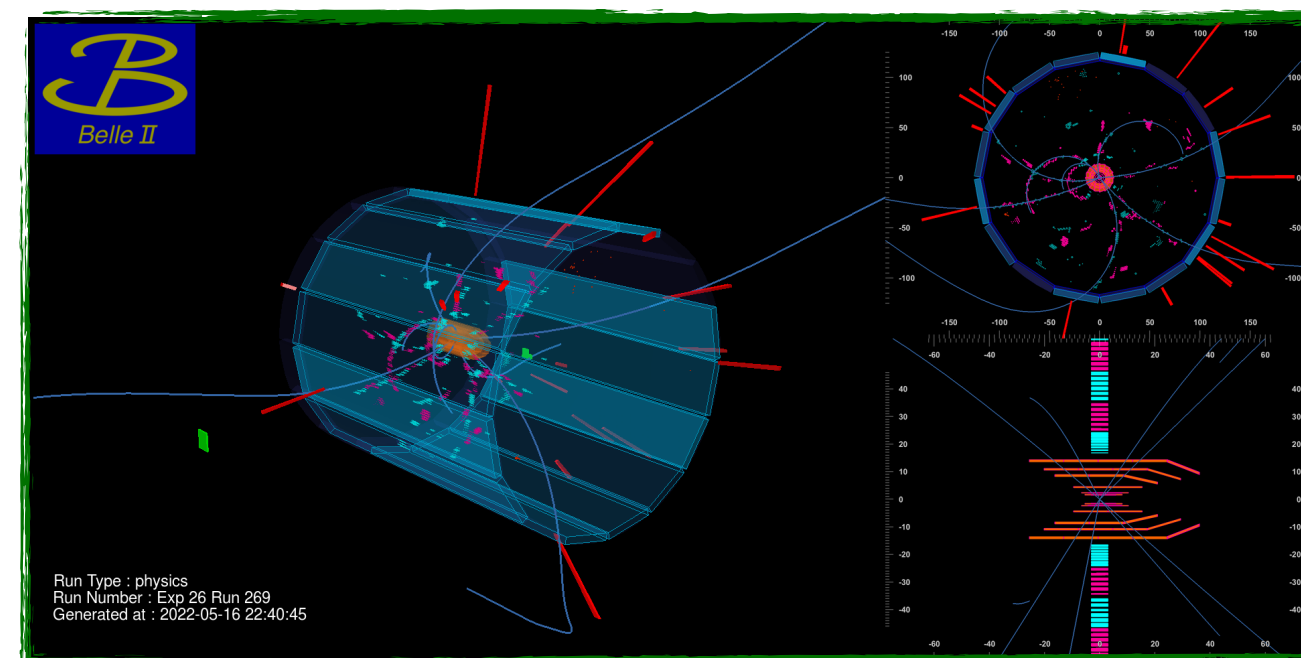
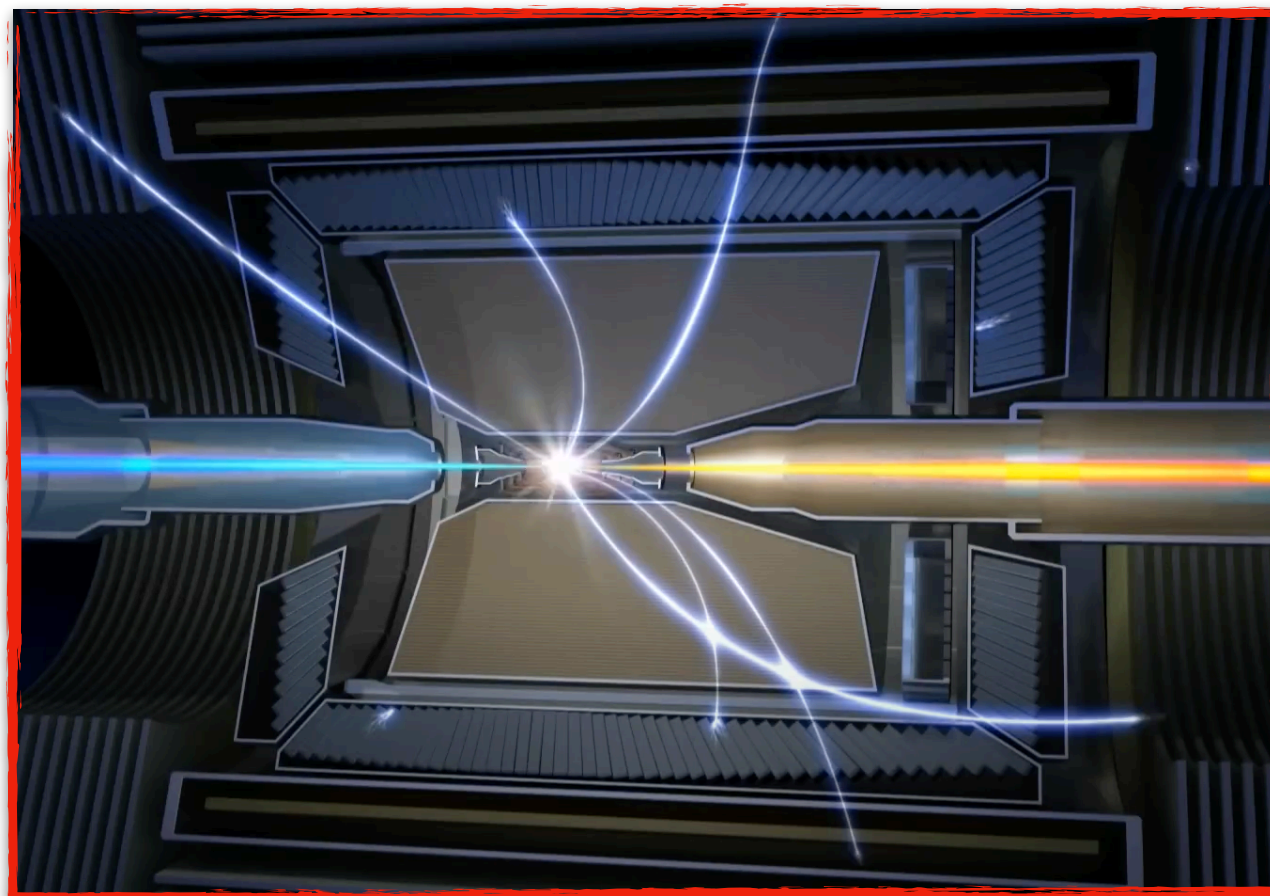
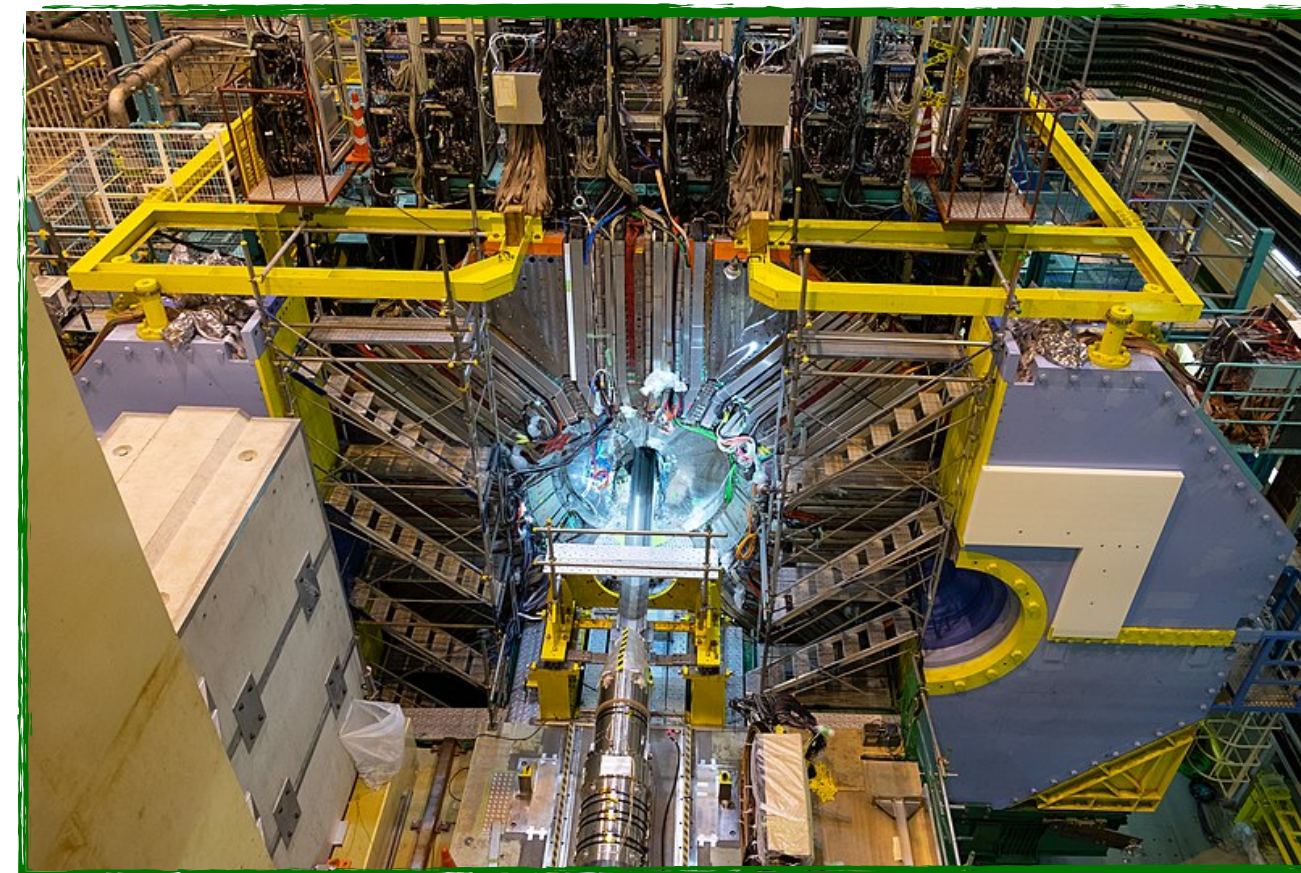


How to

Accelerate particles and
make them **collide**



Detect the particles
resulting from the collision
and measure their properties

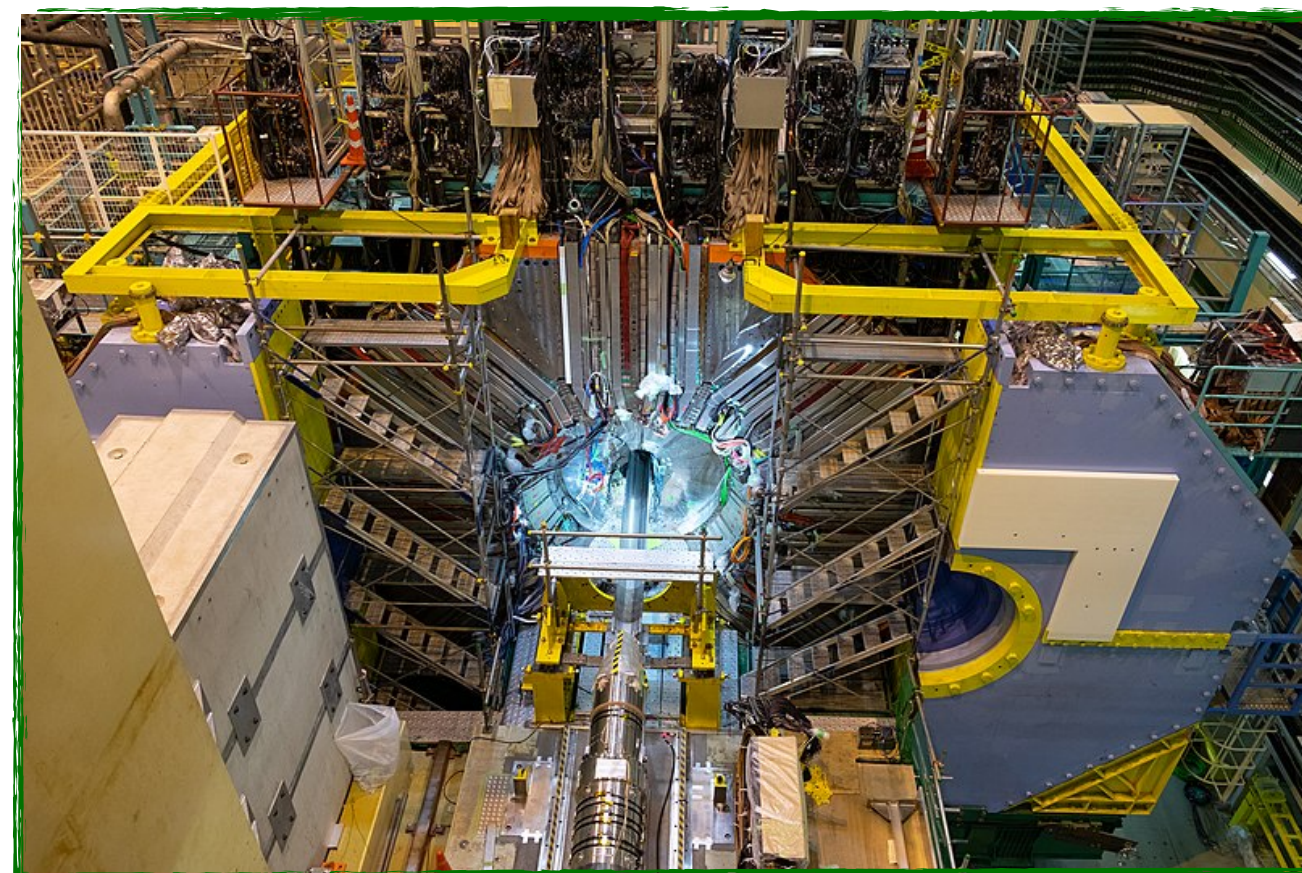


How to

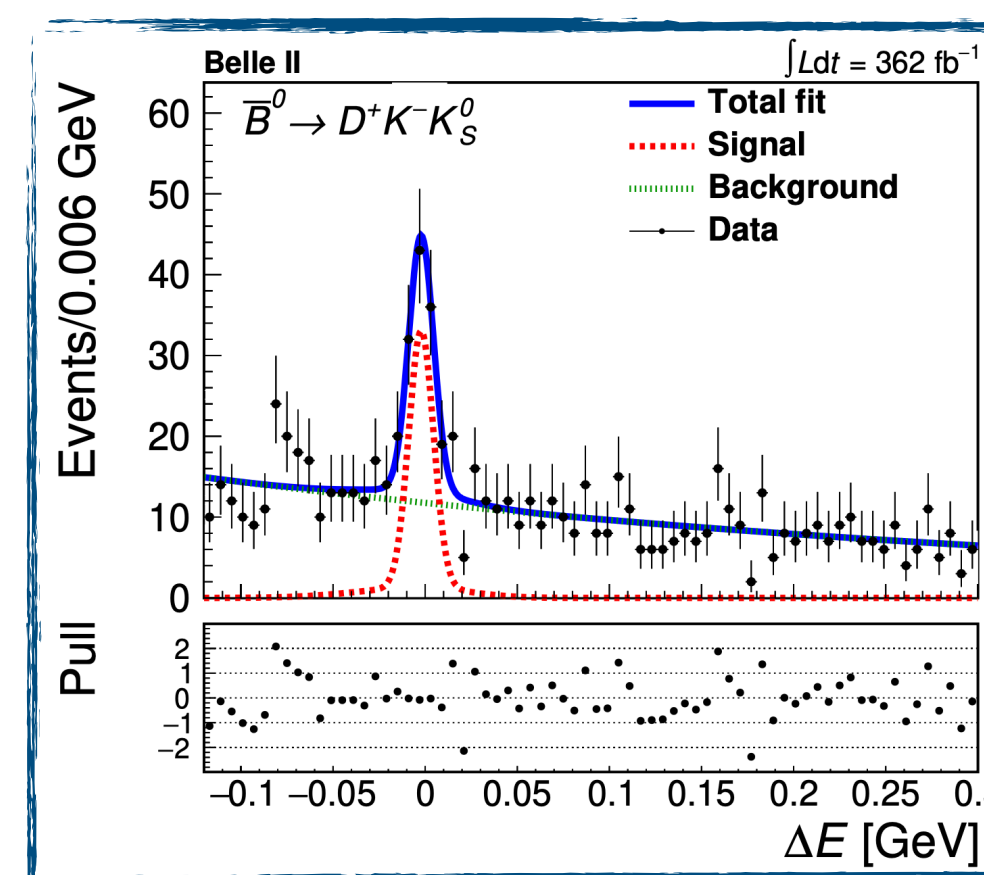
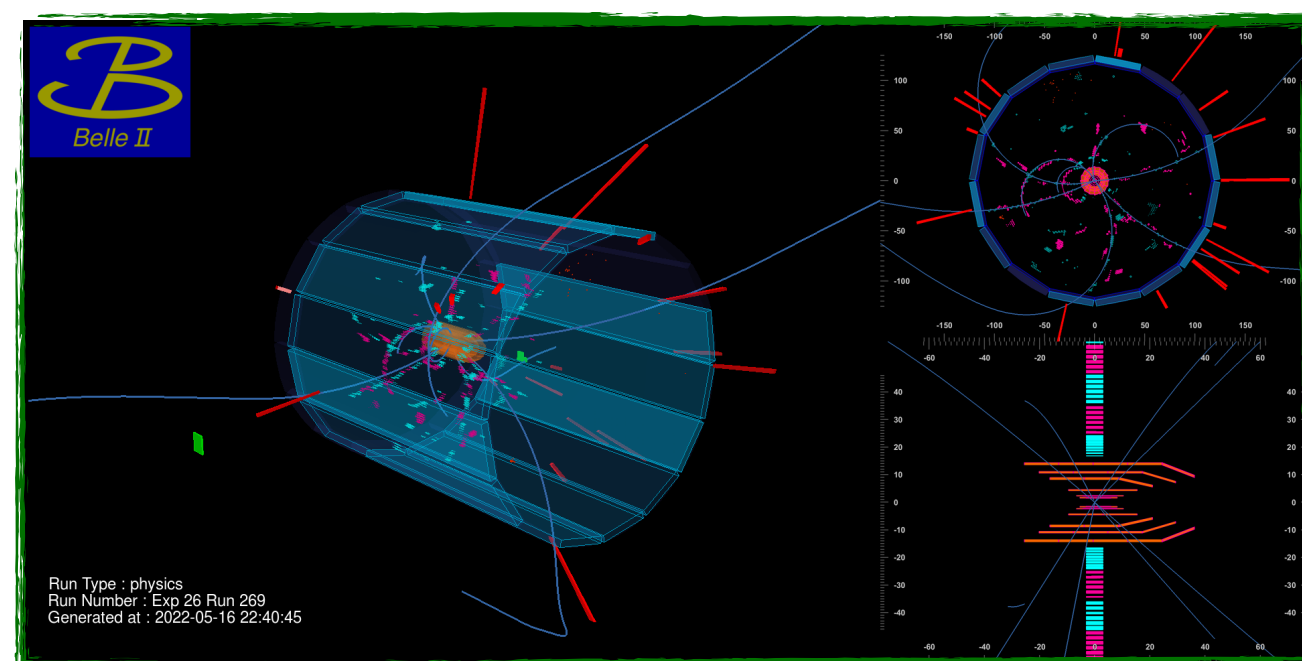
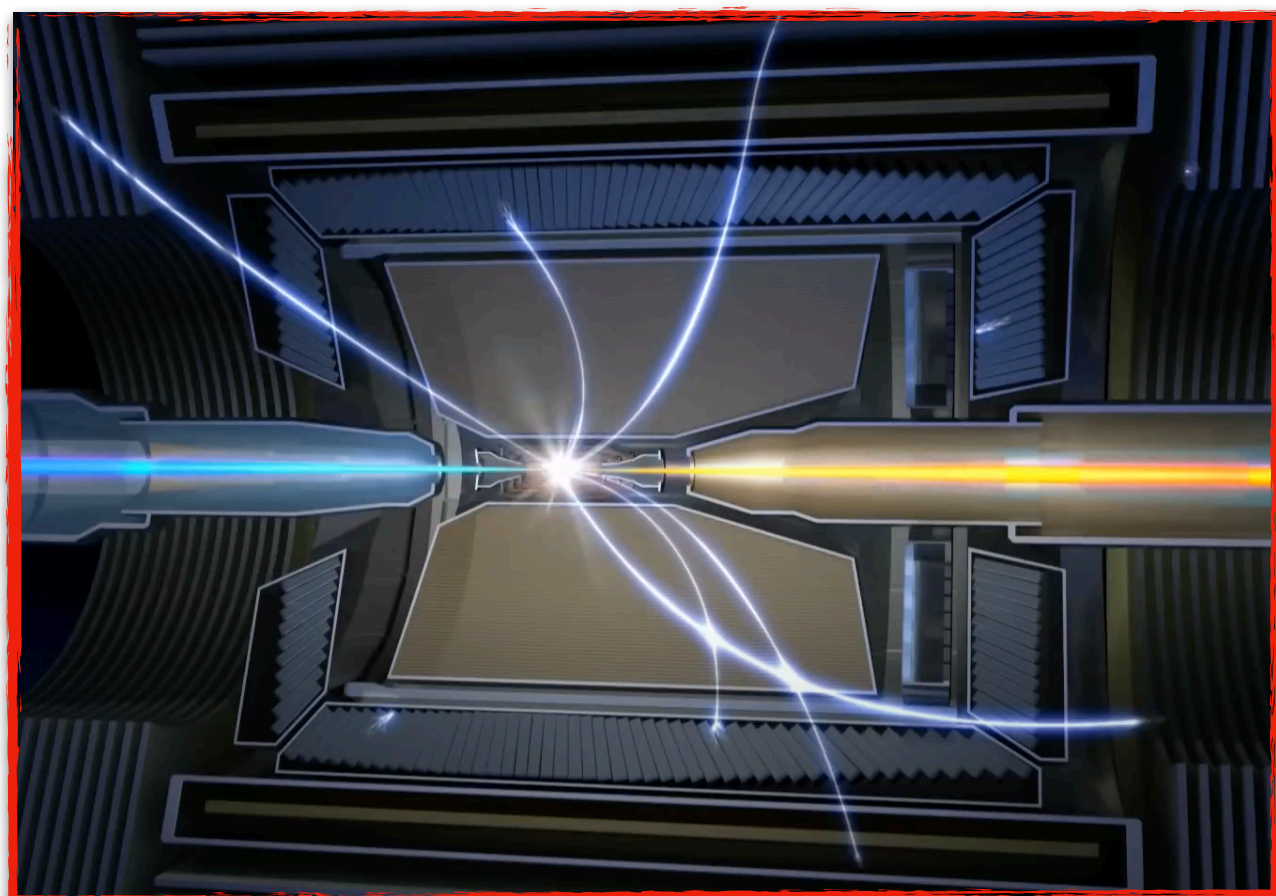
Accelerate particles and
make them **collide**



Detect the particles
resulting from the collision
and measure their properties

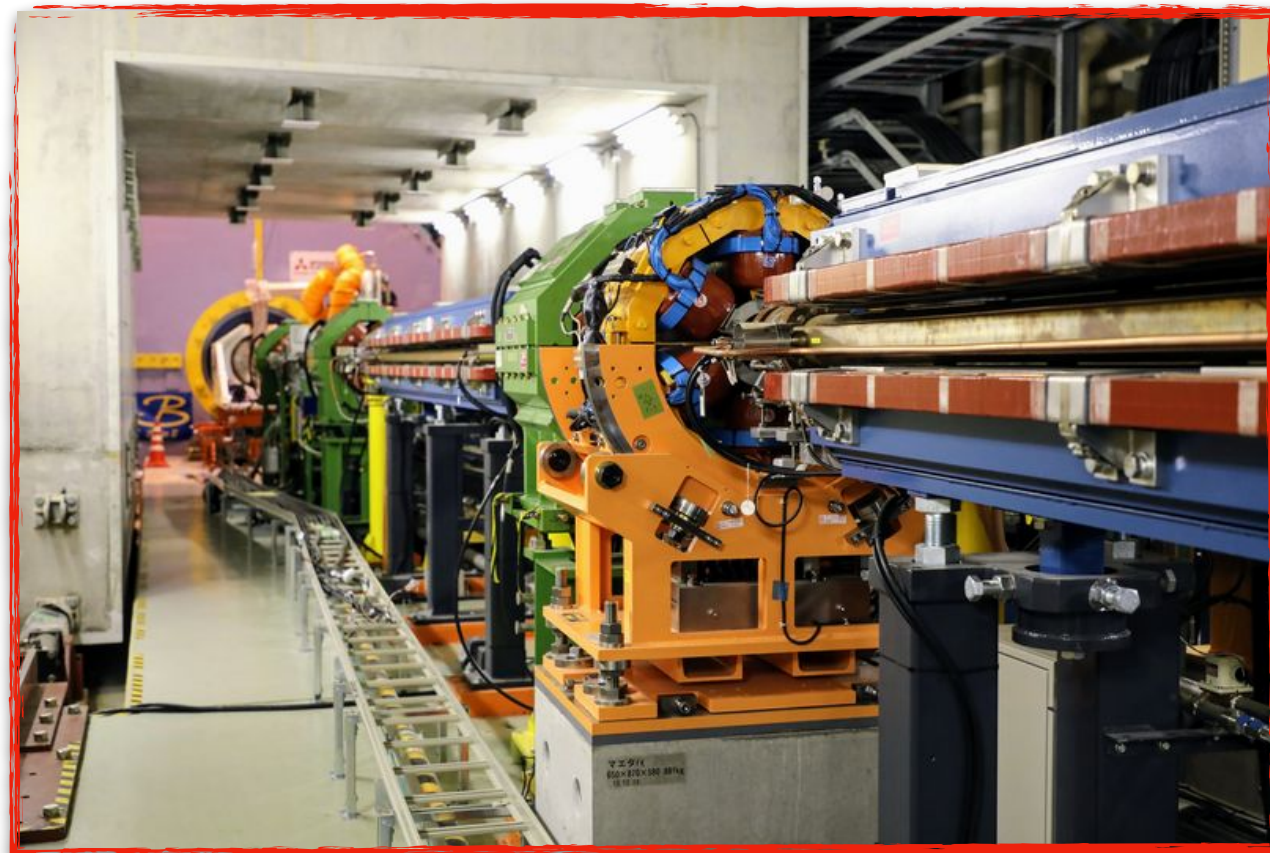


Analyze data coming
from billions of collisions

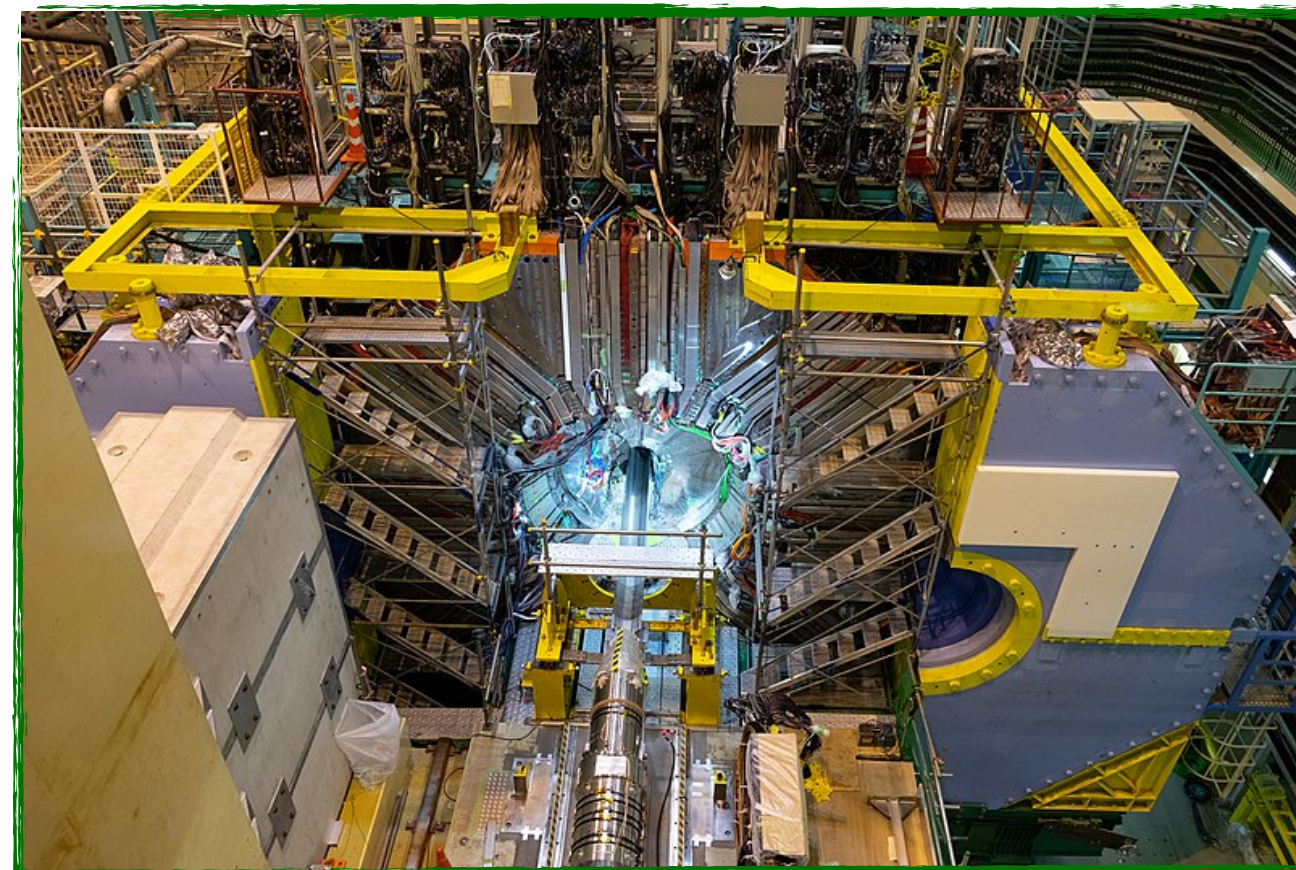


How to

Accelerate particles and make them collide

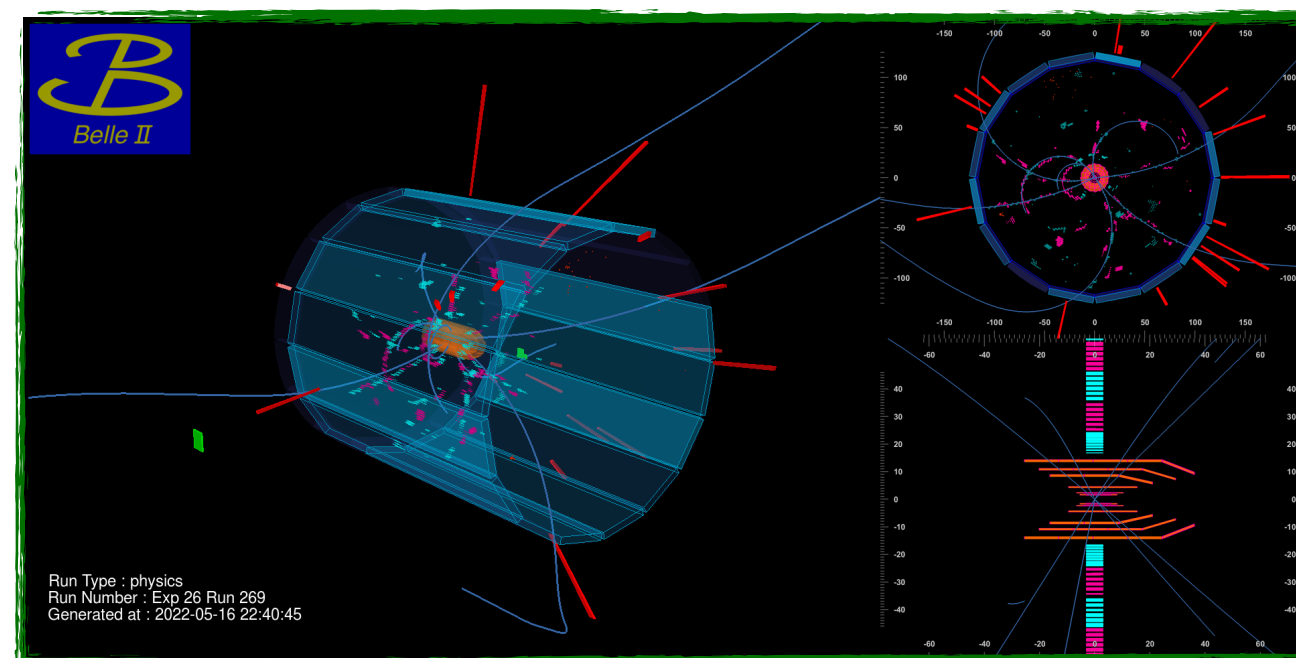
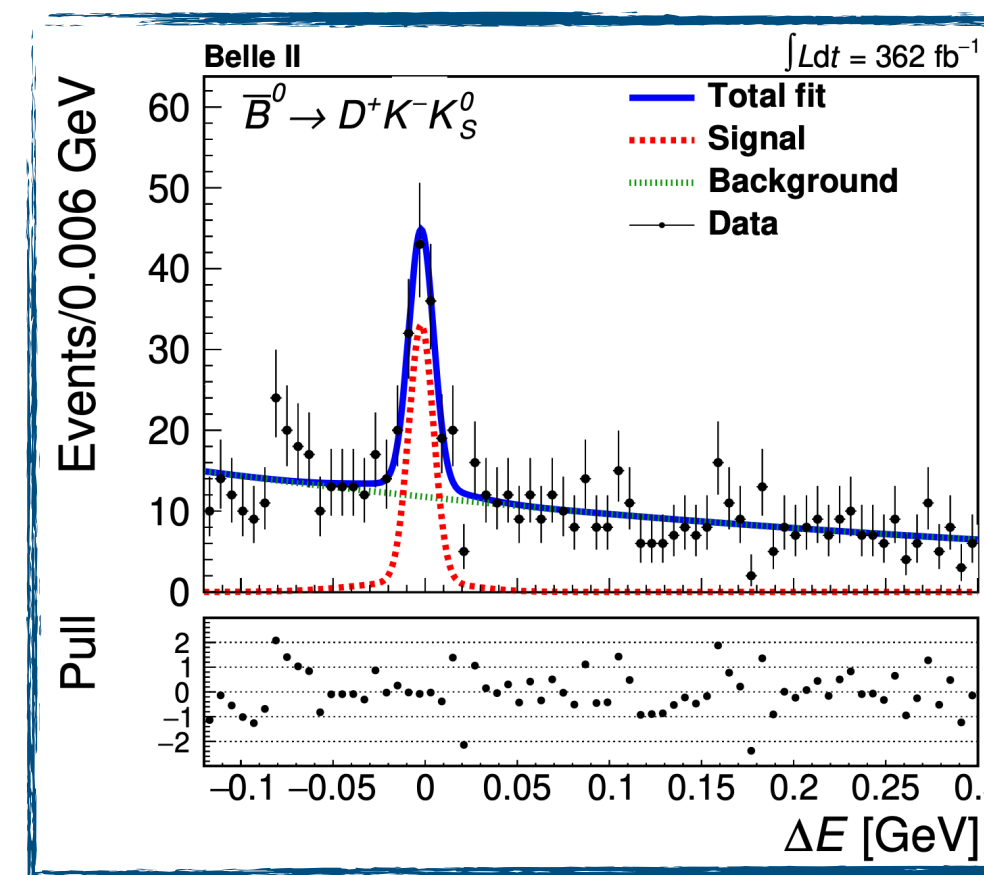
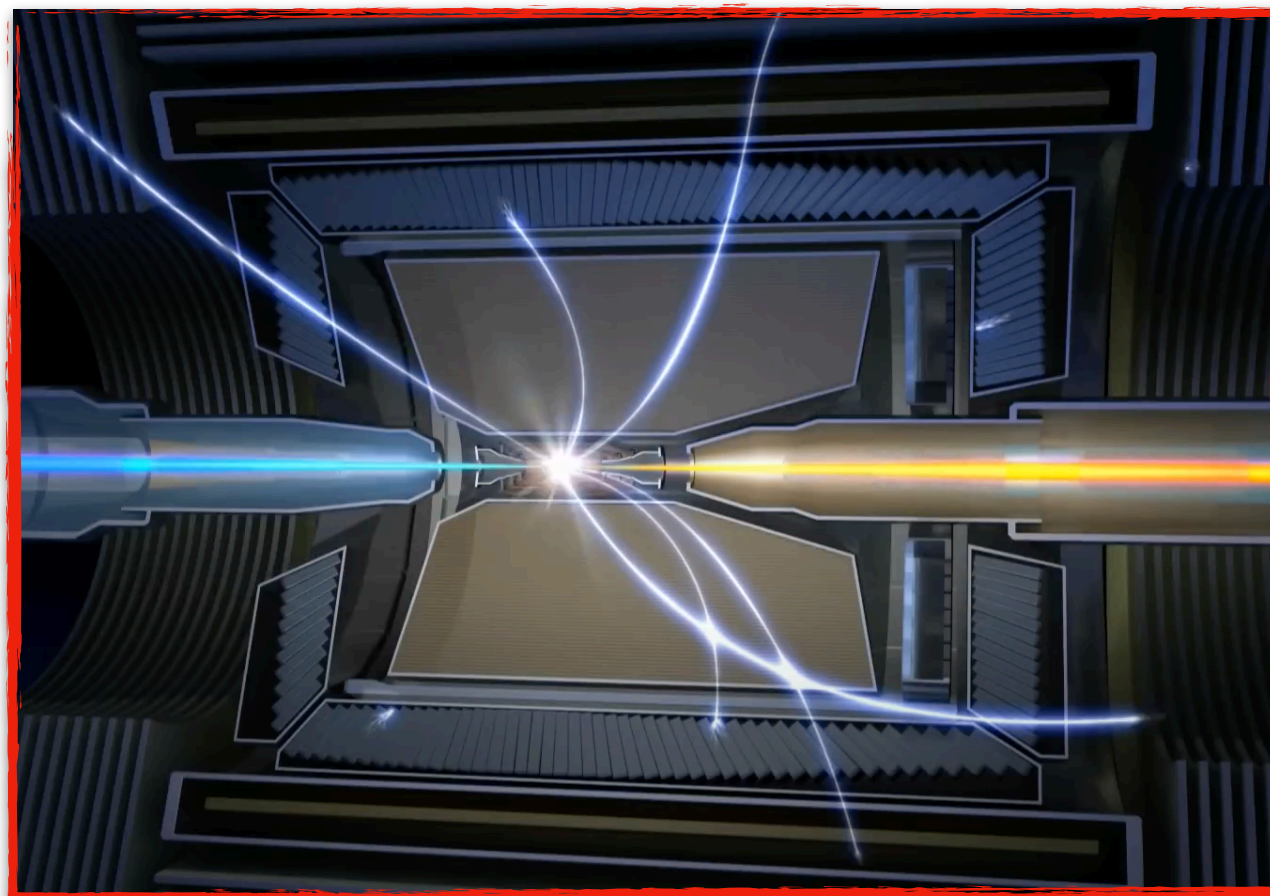


Detect the particles resulting from the collision and measure their properties



Analyze data coming from billions of collisions

Publish the results



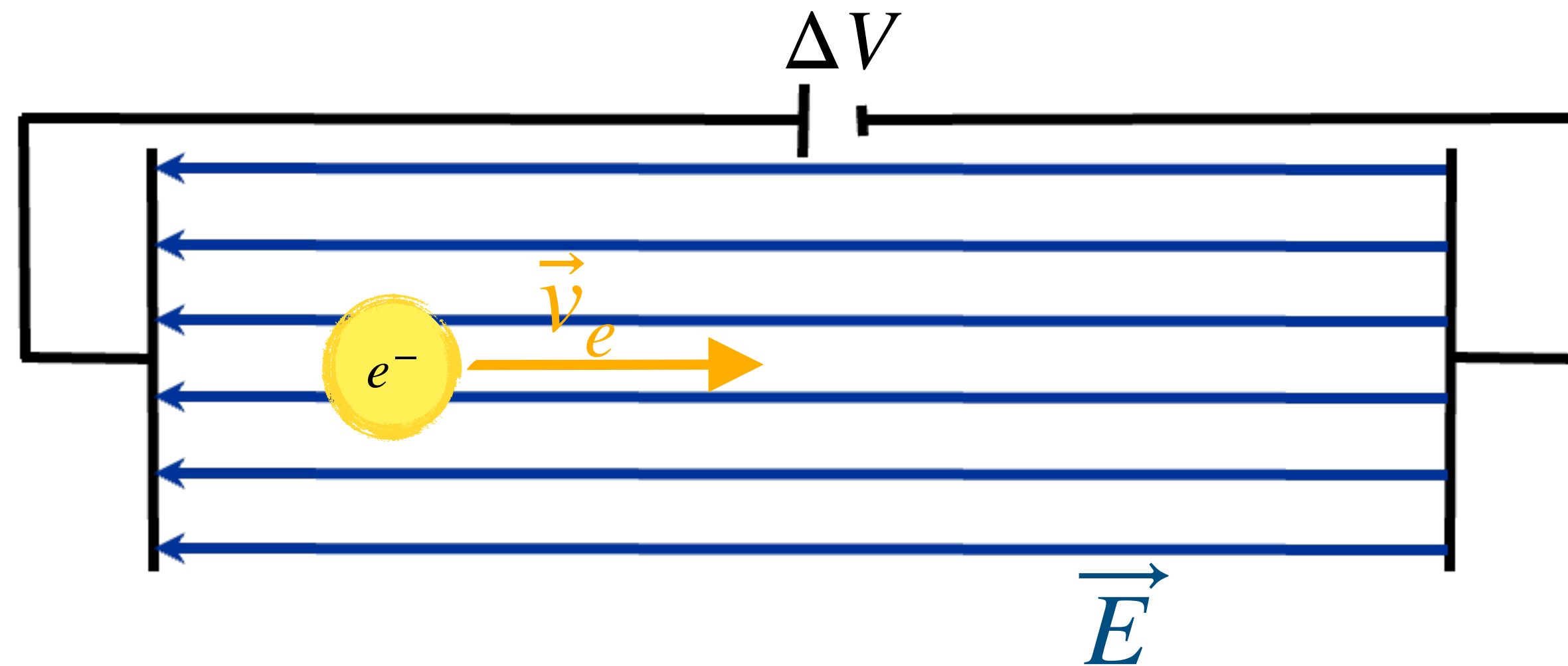
PHYSICAL REVIEW D 109, 112006 (2024)

Evidence for $B^+ \rightarrow K^+ \mu^+ \mu^-$ decays

I. Adachi¹, K. Adamczyk², L. Aggarwal³, H. Ahmed⁴, H. Aihara⁵, N. Akopov⁶, A. Aloisio⁷, N. Anh Ky⁸, D. M. Asner⁹, H. Armasian¹⁰, T. Aunev¹¹, V. Aunev¹², M. Averanov¹³, V. Babu¹⁴, H. Bae¹⁵, S. Bahmani¹⁶, P. Banerjee¹⁷, S. Banerjee¹⁸, S. Banerji¹⁹, M. Barrett²⁰, J. Basile²¹, M. Bauer²², A. Bauer²³, A. Bouchard²⁴, F. Bouchard²⁵, J. Becker²⁶, P. K. Behera²⁷, J. V. Bennett²⁸, F. U. Bernlochner²⁹, V. Bertacchi³⁰, M. Bertemes³¹, E. Bertholet³², M. Bessner³³, S. Bettarini³⁴, B. Bhowmik³⁵, F. Bianchi³⁶, T. Bilka³⁷, D. Biswas³⁸, A. Bobrov³⁹, D. Bodrov⁴⁰, A. Bolz⁴¹, J. Brach⁴², A. Brack⁴³, P. Branchini⁴⁴, T. A. Brice⁴⁵, T. E. Browder⁴⁶, A. Budano⁴⁷, S. Busini⁴⁸, M. Campajola⁴⁹, L. Cao⁵⁰, G. Casarosa⁵¹, C. Cecchi⁵², J. Cerasola⁵³, M.-C. Chang⁵⁴, P. Chang⁵⁵, R. Cheaib⁵⁶, P. Cheema⁵⁷, V. Chelkian⁵⁸, C. Chen⁵⁹, B. G. Cheon⁶⁰, K. Chilikin⁶¹, K. Chirapatimol⁶², H.-E. Cho⁶³, K. Cho⁶⁴, S.-J. Cho⁶⁵, S.-K. Choi⁶⁶, S. Choudhury⁶⁷, J. Cochran⁶⁸, L. Coornaert⁶⁹, L. M. Cremaldi⁷⁰, S. Cunliffe⁷¹, S. Das⁷², F. Dattalo⁷³, E. De La Cruz-Burelo⁷⁴, S. A. De La Motte⁷⁵, G. De Nardo⁷⁶, M. De Nuccio⁷⁷, G. De Pietri⁷⁸, R. de Sangro⁷⁹, M. Destefanis⁸⁰, S. Dey⁸¹, A. De Vita Hernandez⁸², R. Dhamija⁸³, A. Di Canto⁸⁴, F. Di Capua⁸⁵, J. Dingfelder⁸⁶, Z. Dolezal⁸⁷, I. Dominguez Jimenez⁸⁸, T. V. Dorigo⁸⁹, M. Dorigo⁹⁰, K. Dost⁹¹, D. Doucet⁹², S. Dreyer⁹³, S. Dubev⁹⁴, G. Dujany⁹⁵, P. Ecker⁹⁶, M. Eliahevich⁹⁷, D. Epifanov⁹⁸, Y. Fan⁹⁹, P. Felchinger¹⁰⁰, T. Ferber¹⁰¹, D. Ferlic¹⁰², T. Fillingim¹⁰³, C. Finck¹⁰⁴, G. Finocchiaro¹⁰⁵, A. Fodor¹⁰⁶, F. Forti¹⁰⁷, B. G. Fulom¹⁰⁸, A. Gabrielli¹⁰⁹, E. Ganiev¹¹⁰, M. Garcia-Hernandez¹¹¹, R. Garg¹¹², A. Garmash¹¹³, G. Gaudino¹¹⁴, V. Gaur¹¹⁵, A. Gao¹¹⁶, A. Gelich¹¹⁷, G. Gheorghiyan¹¹⁸, K. Ghosh¹¹⁹, H. Ghurayyan¹²⁰, G. Giakoustidis¹²¹, R. Giordano¹²², A. Giria¹²³, A. Glazov¹²⁴, B. Gobbo¹²⁵, R. Godang¹²⁶, O. Gogota¹²⁷, P. Goldenzweig¹²⁸, P. Grace¹²⁹, W. Grad¹³⁰, T. Grammatico¹³¹, S. Grandjean¹³², E. Graziani¹³³, D. Greenwald¹³⁴, Z. Gruberovc¹³⁵, T. Guo¹³⁶, Y. Guan¹³⁷, K. Goukova¹³⁸, S. Halder¹³⁹, Y. Han¹⁴⁰, T. Hara¹⁴¹, K. Hayasaka¹⁴², H. Hayashi¹⁴³, S. Hazra¹⁴⁴, C. Hearty¹⁴⁵, M. T. Hedgcock¹⁴⁶, A. Heidebach¹⁴⁷, I. Heredia de la Cruz¹⁴⁸, M. Hernandez Villaverde¹⁴⁹, A. Hershenov¹⁵⁰, T. Higuchi¹⁵¹, E. C. Hill¹⁵², M. Hoek¹⁵³, M. Hohmann¹⁵⁴, P. Horak¹⁵⁵, C.-L. Hsu¹⁵⁶, T. Humair¹⁵⁷, T. Iijima¹⁵⁸, K. Inami¹⁵⁹, G. Ingugliano¹⁶⁰, N. Iqbal¹⁶¹, A. Ishikawa¹⁶², S. Ino¹⁶³, R. Itoh¹⁶⁴, M. Iwasaki¹⁶⁵, P. Jackson¹⁶⁶, W. W. Jacobs¹⁶⁷, D. E. Jaffe¹⁶⁸, E. J. Jang¹⁶⁹, Q. P. Ji¹⁷⁰, S. Jari¹⁷¹, Y. Jari¹⁷², A. Johnson¹⁷³, K. K. Joo¹⁷⁴, H. Junker-Kalodjera¹⁷⁵, H. Kagan¹⁷⁶, M. Kalata¹⁷⁷, D. Kalita¹⁷⁸, A. B. Kalyan¹⁷⁹, J. Kanda¹⁸⁰, K. H. Kang¹⁸¹, S. Kang¹⁸², G. Karyan¹⁸³, T. Kawasaki¹⁸⁴, F. Keil¹⁸⁵, C. Ketter¹⁸⁶, C. Kiesling¹⁸⁷, C.-H. Kim¹⁸⁸, D. Y. Kim¹⁸⁹, K.-H. Kim¹⁹⁰, Y.-K. Kim¹⁹¹, H. Kindo¹⁹², K. Kinoshita¹⁹³, P. Kodlyo¹⁹⁴, T. Kojima¹⁹⁵, S. Kohri¹⁹⁶, K. Kojima¹⁹⁷, T. Komori¹⁹⁸, A. Korobov¹⁹⁹, S. Koppa²⁰⁰, E. Kovalevskiy²⁰¹, R. Kowalewski²⁰², T. M. G. Kraetzschmar²⁰³, P. 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Tkabidze⁴⁰², M. Uchida⁴⁰³, I. Ueda⁴⁰⁴, Y. Uematsu⁴⁰⁵, T. Ugliov⁴⁰⁶, K. Unger⁴⁰⁷, Y. Uno⁴⁰⁸, S. Uno⁴⁰⁹, P. Unzueta⁴¹⁰, Y. Ushioda⁴¹¹, S. E. Vahsen⁴¹², R. van Tonder⁴¹³, G. S. Varner⁴¹⁴, K. E. Varvell⁴¹⁵, M. Venesese⁴¹⁶, A. Vinokurova⁴¹⁷

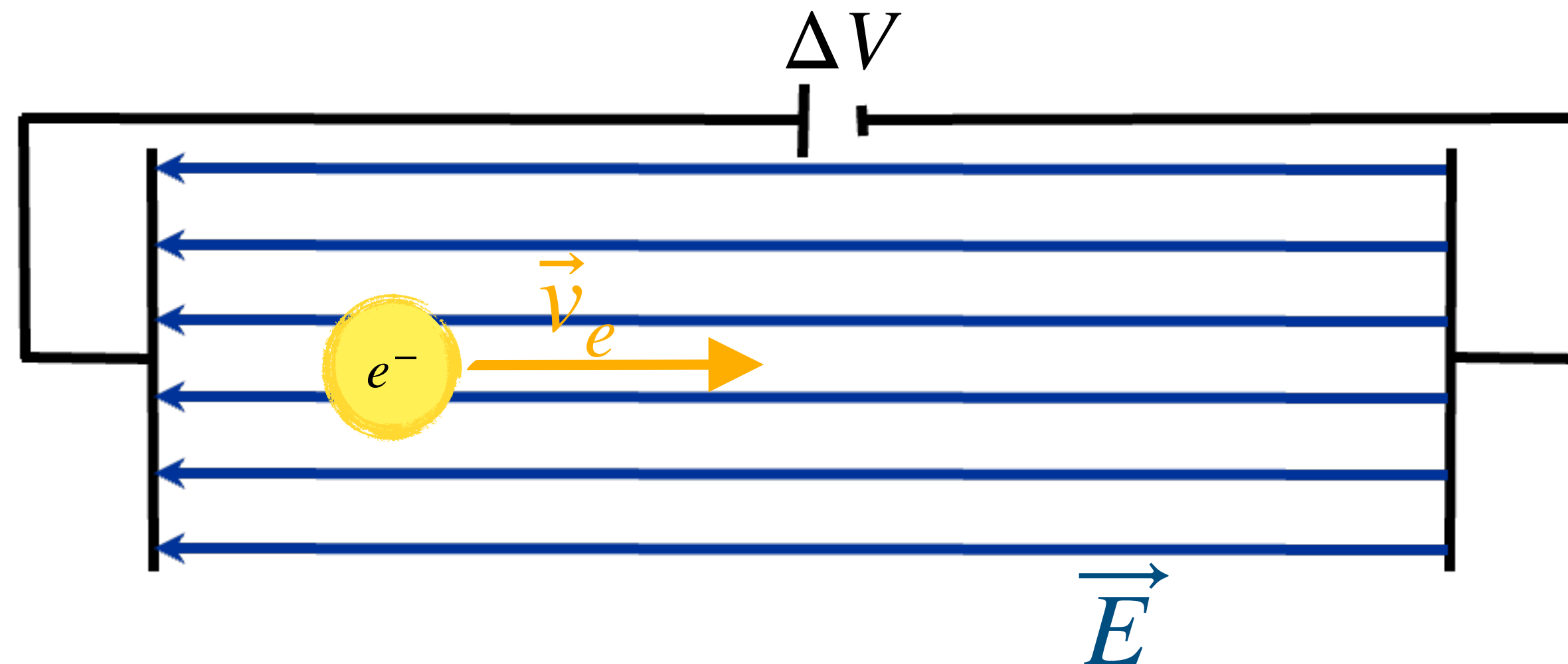
Particle acceleration

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



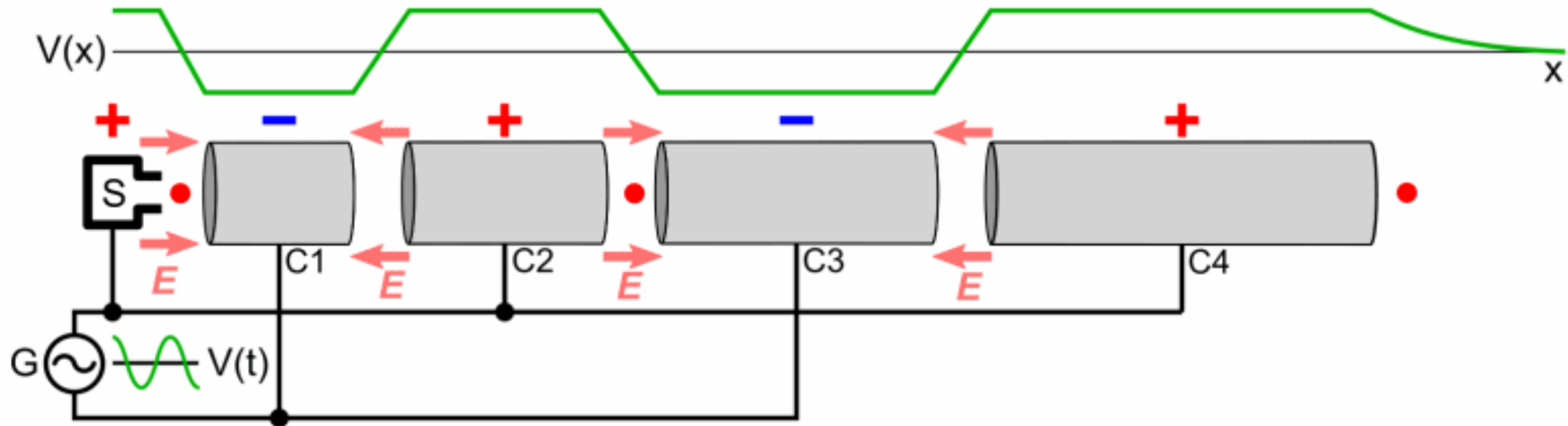
Particle acceleration

- Generate an electric field \vec{E}
- The e^- will be accelerated with $\vec{F} = q\vec{E}$, gaining an energy: $E = q\Delta V$
- Some numbers:
 - if $\Delta V = 1 \text{ V} \Rightarrow E = 1 \text{ eV}$
 - if $\Delta V = 100 \text{ kV} \Rightarrow E = 100 \text{ keV}$... we can't go much further with a single element



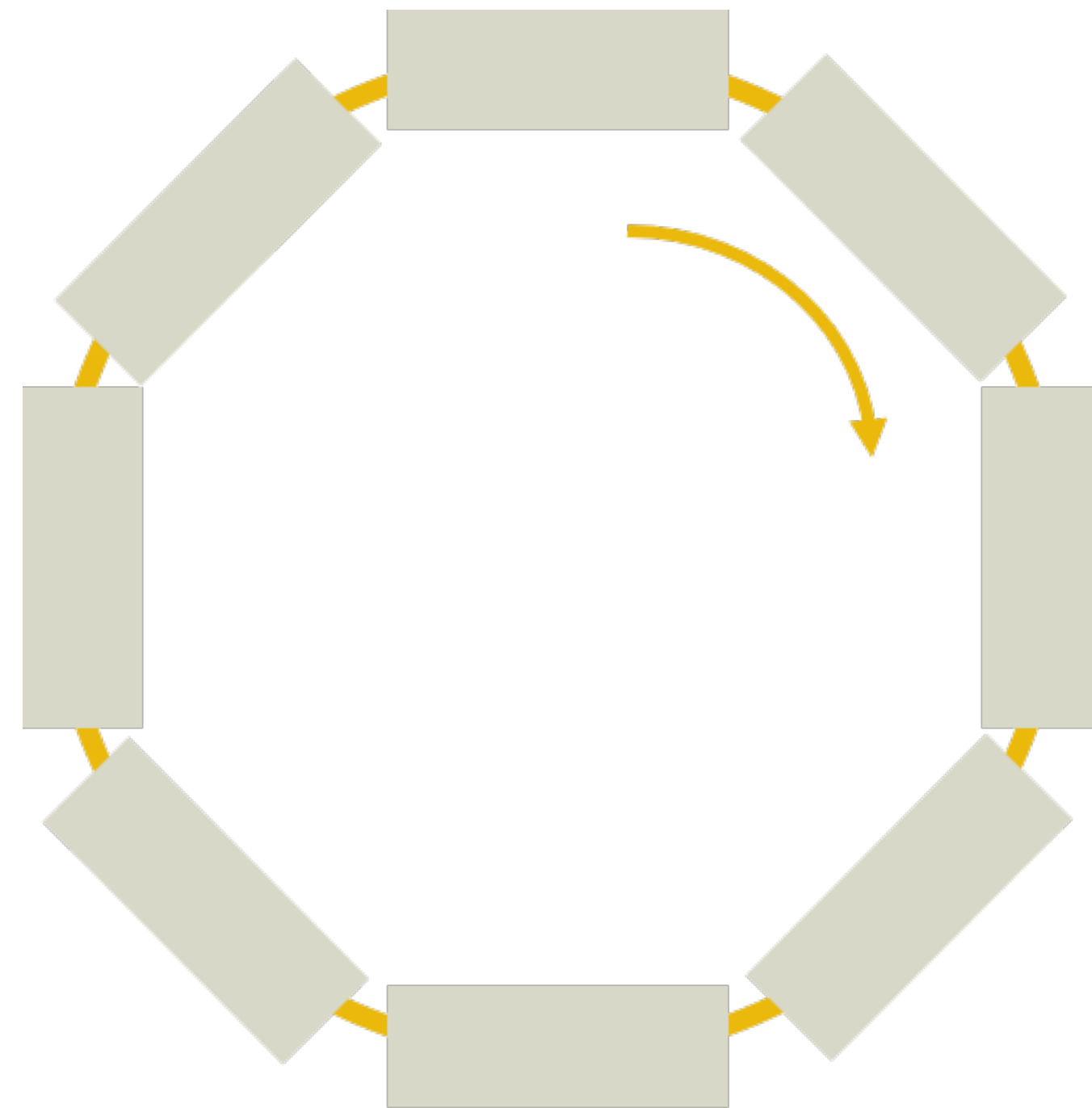
Particle acceleration

- 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 veery long accelerator



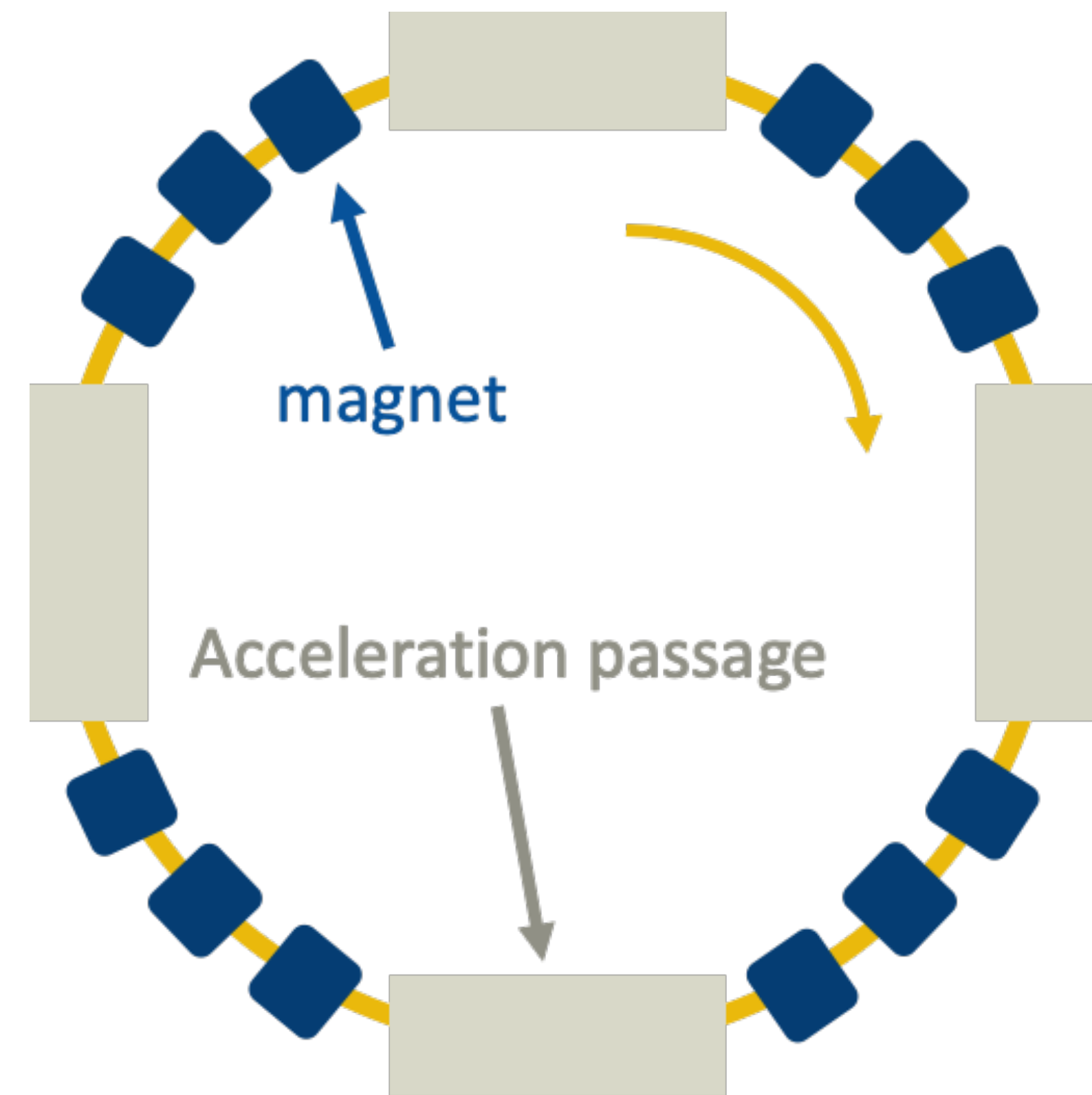
Particle acceleration

- 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?



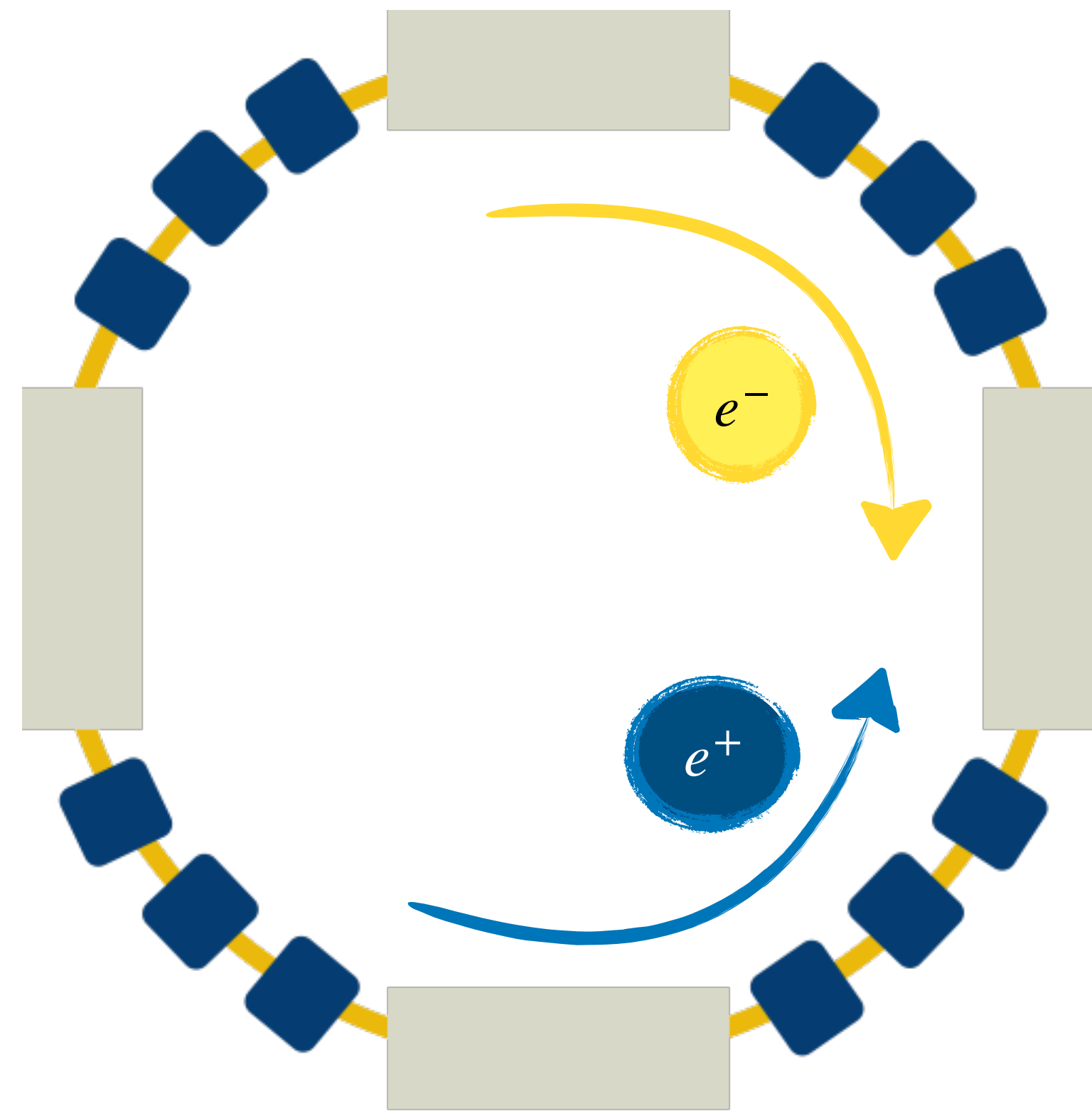
Particle acceleration

- 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** \vec{B} :
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



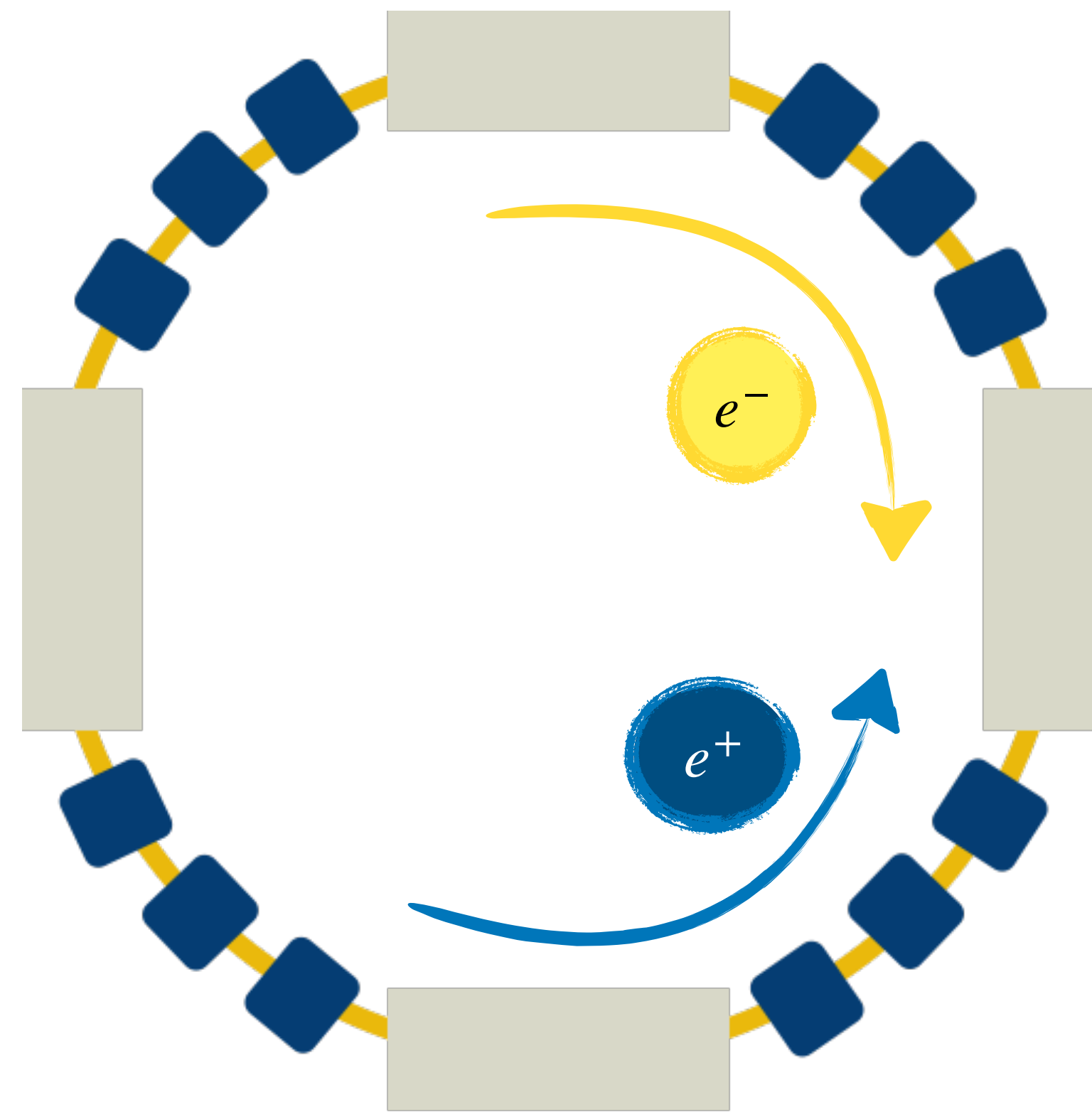
Particle acceleration + collision

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



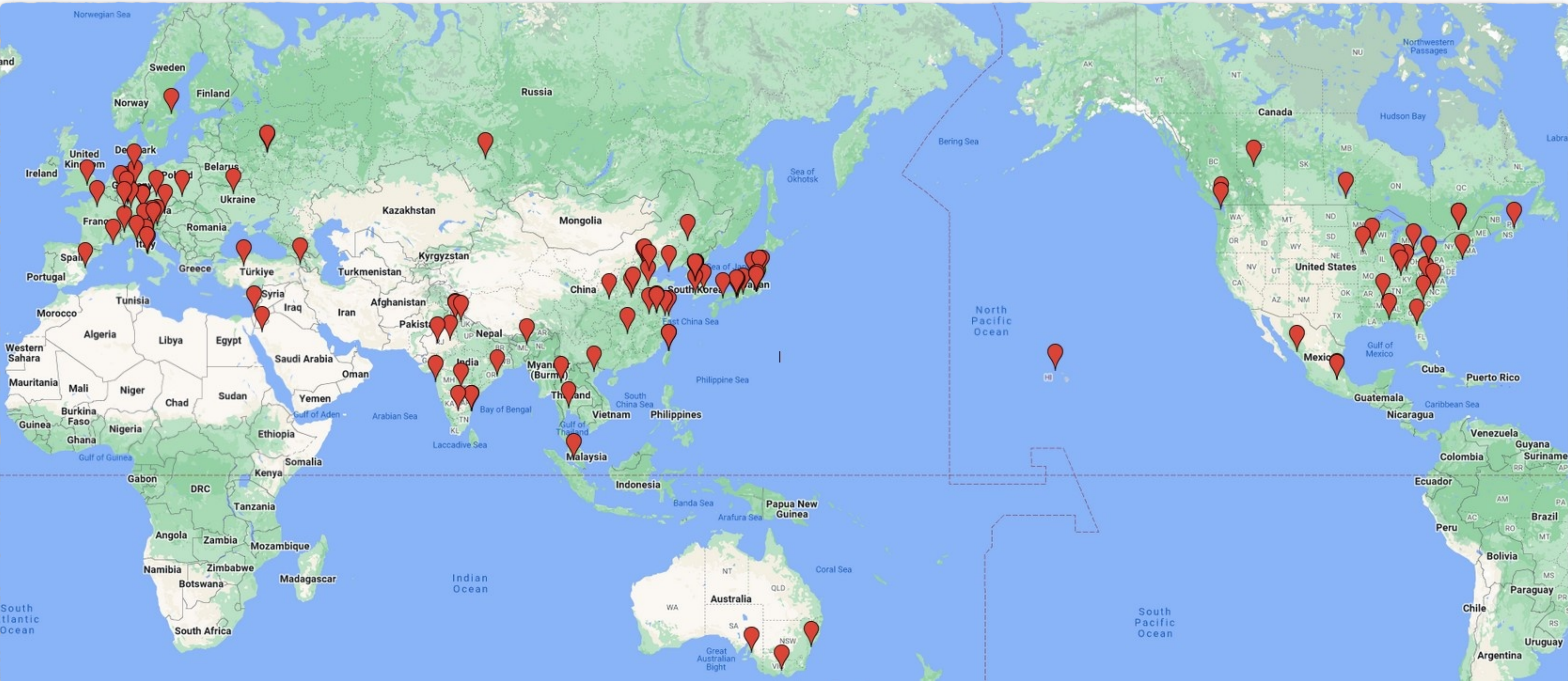
Particle acceleration + collision

- 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
($E \simeq 2\sqrt{E_{e^+}E_{e^-}}$)



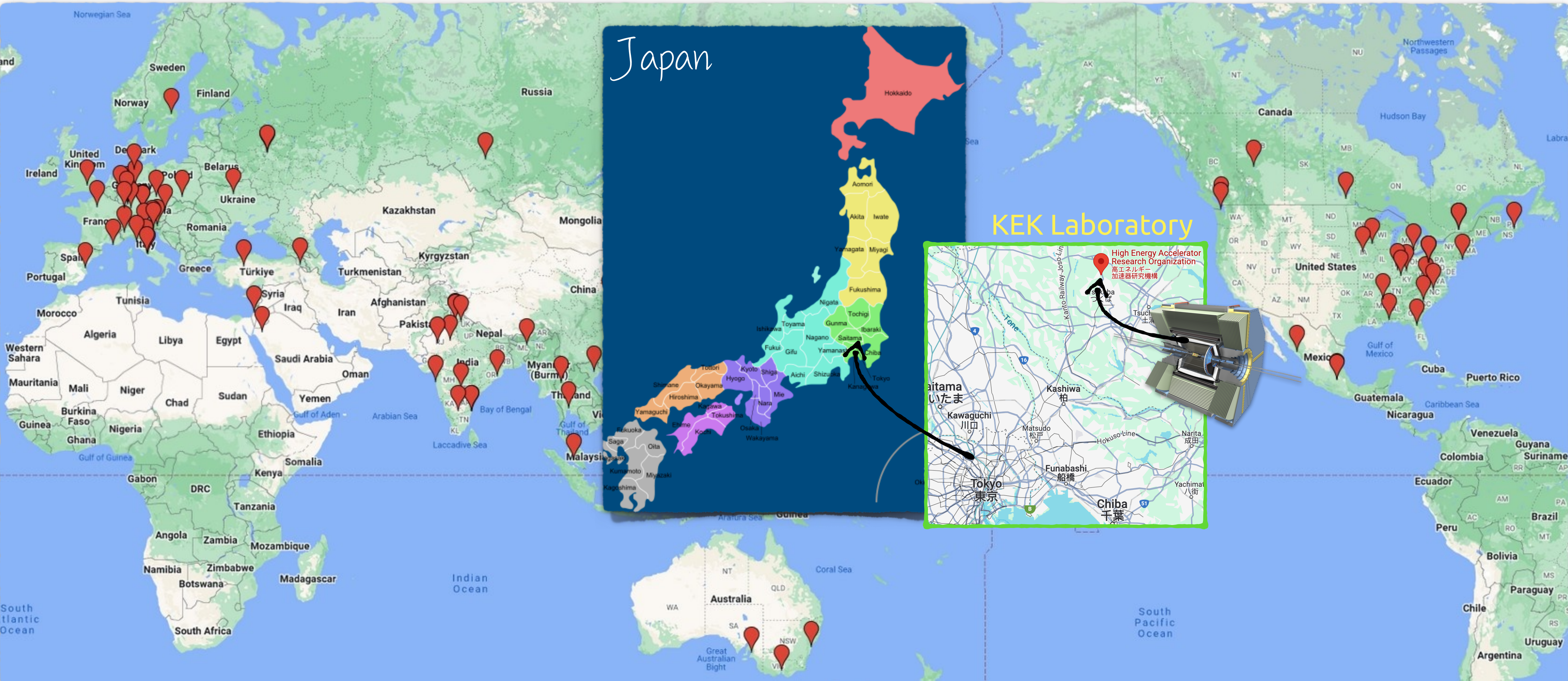
Belle II collaboration

over 1100 physicists and engineers from 122 institutions in 27 countries



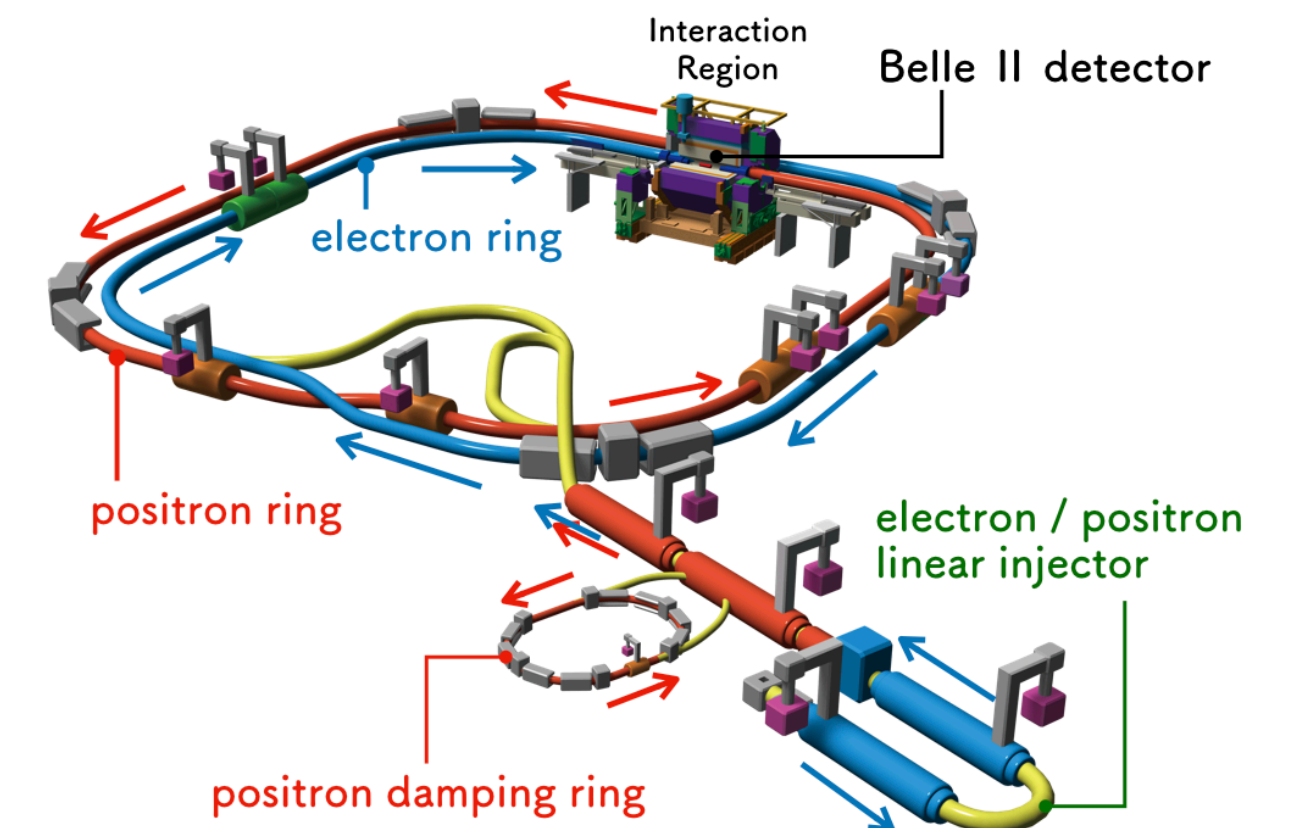
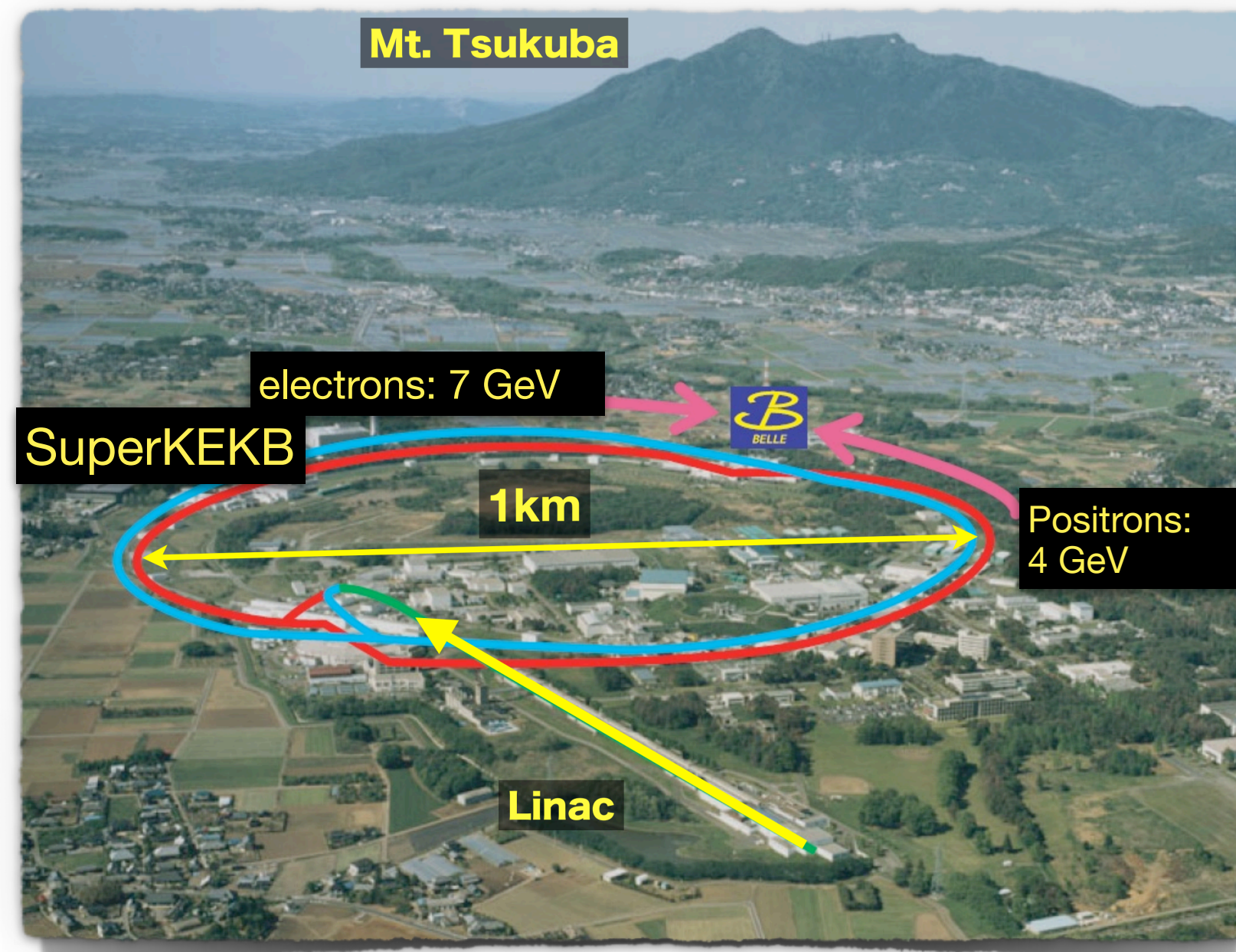
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KEK Laboratory and SuperKEKB collider

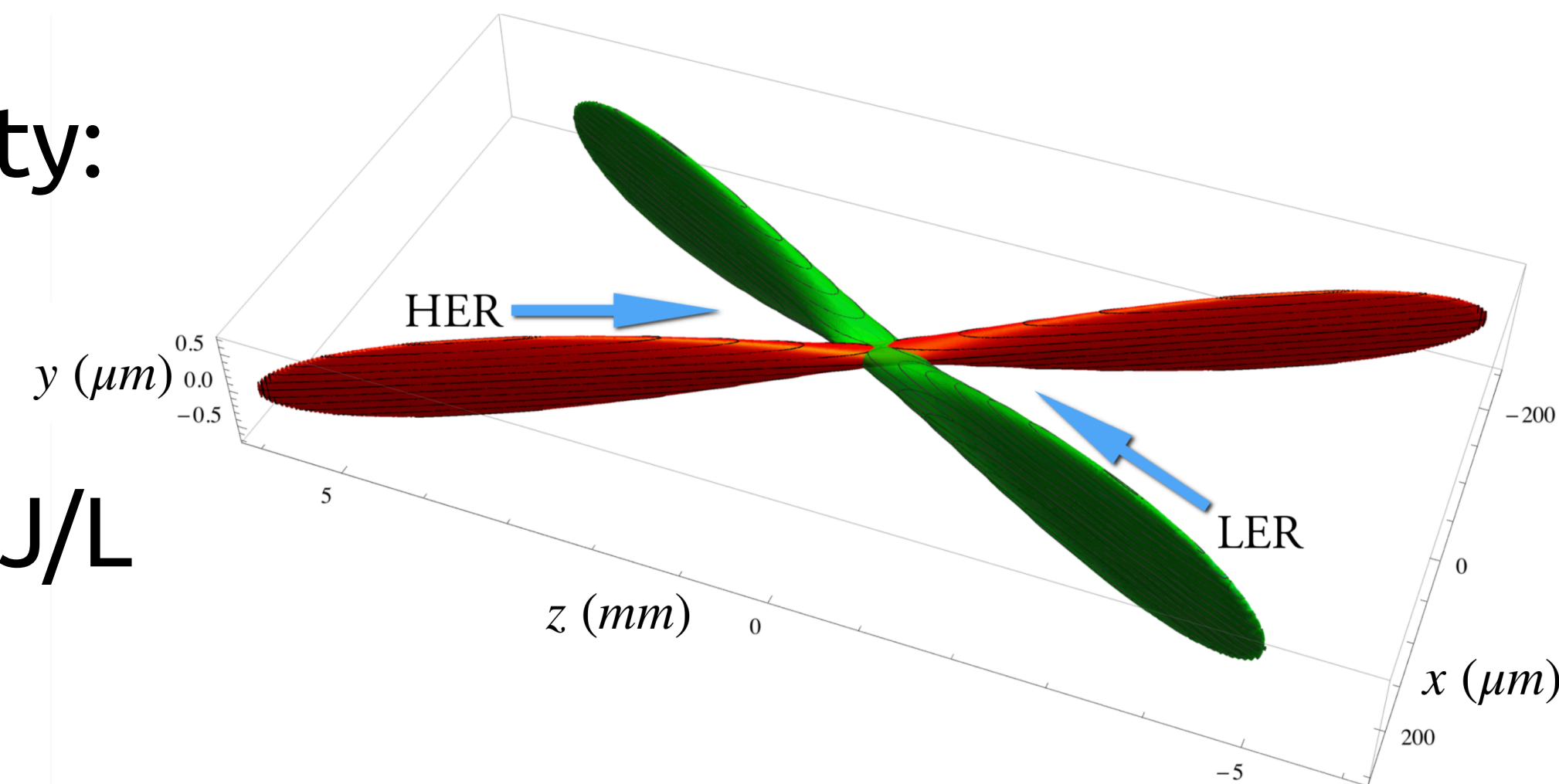
In Tsukuba, about 60 Km from Tokyo



- **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**

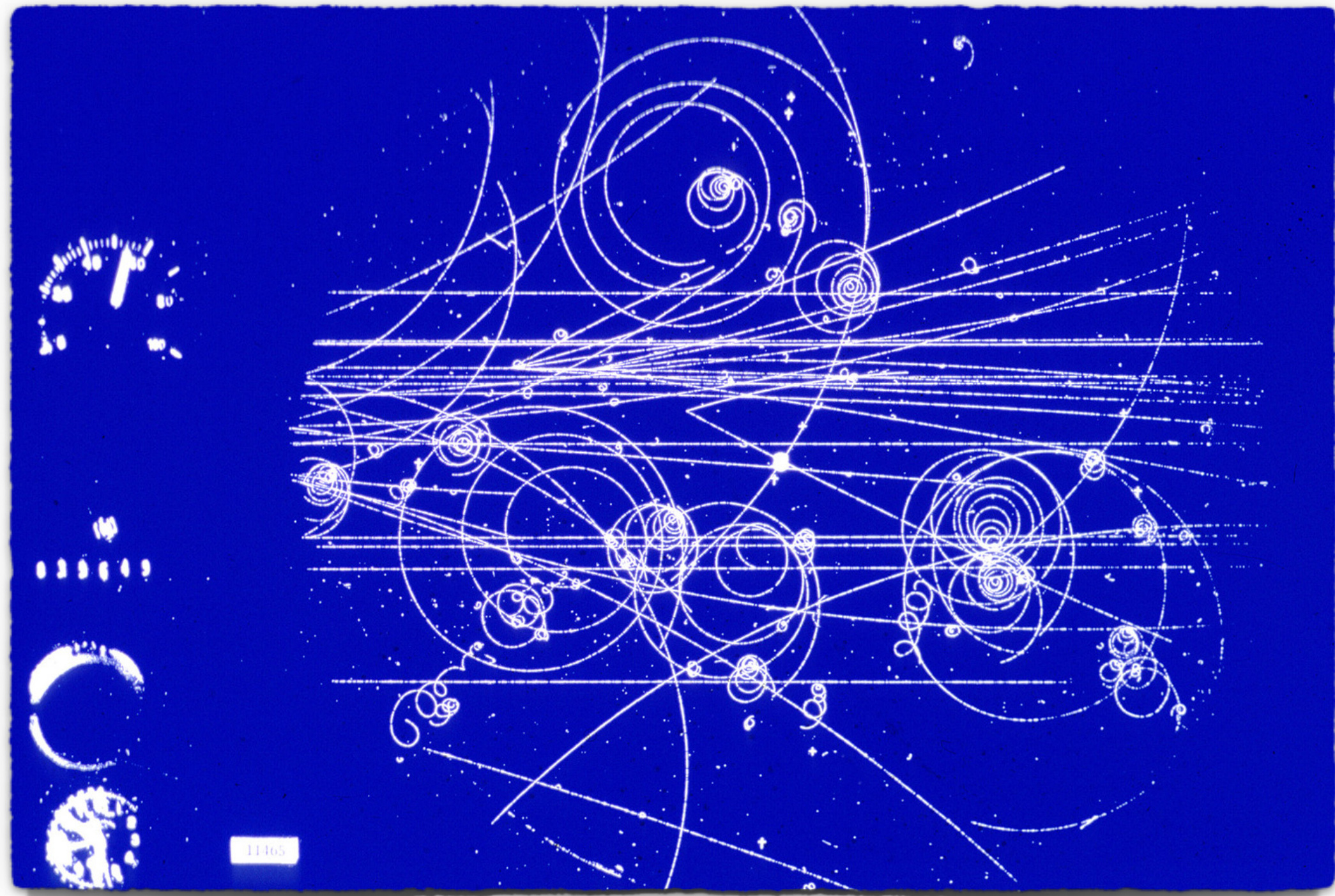
10 GeV?

- 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>]



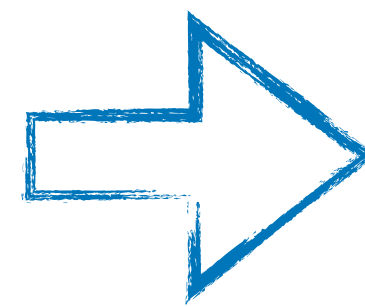
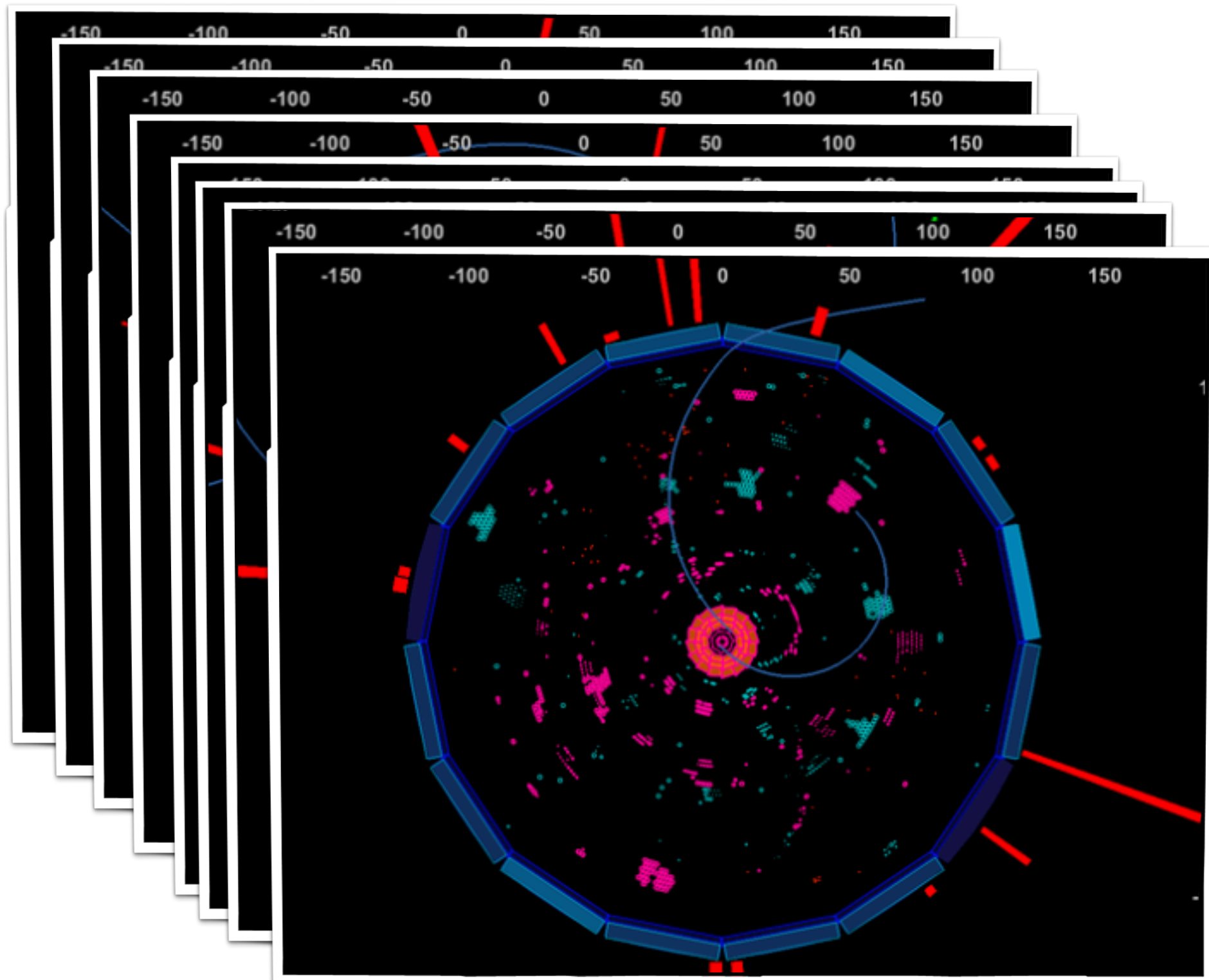
[CERN Courier, June 1973 – Esperimento Gargamelle]

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

- statistic limited --> precise/rare measurement impossible

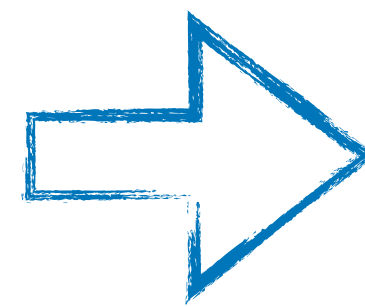
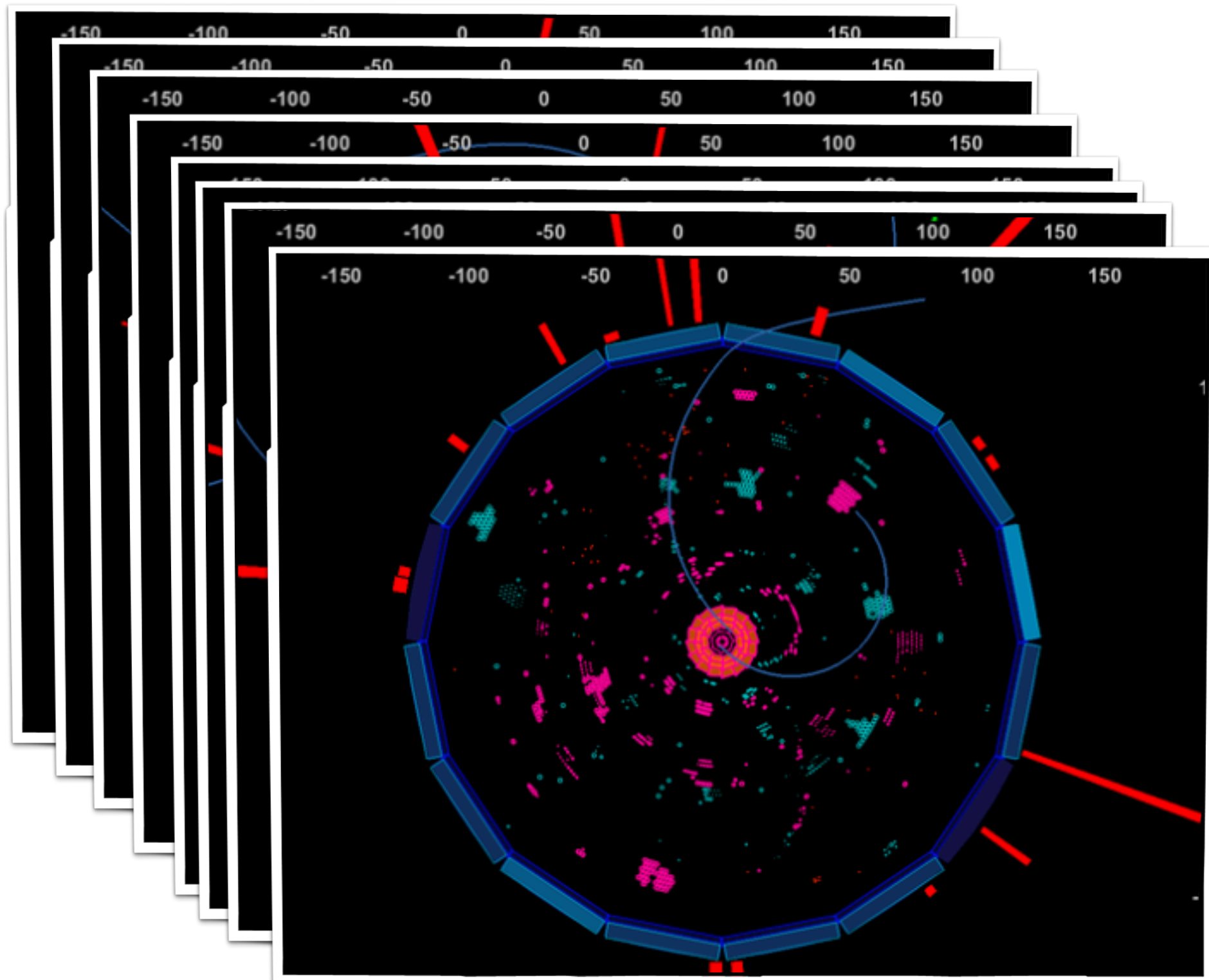
Data taking at SuperKEKB

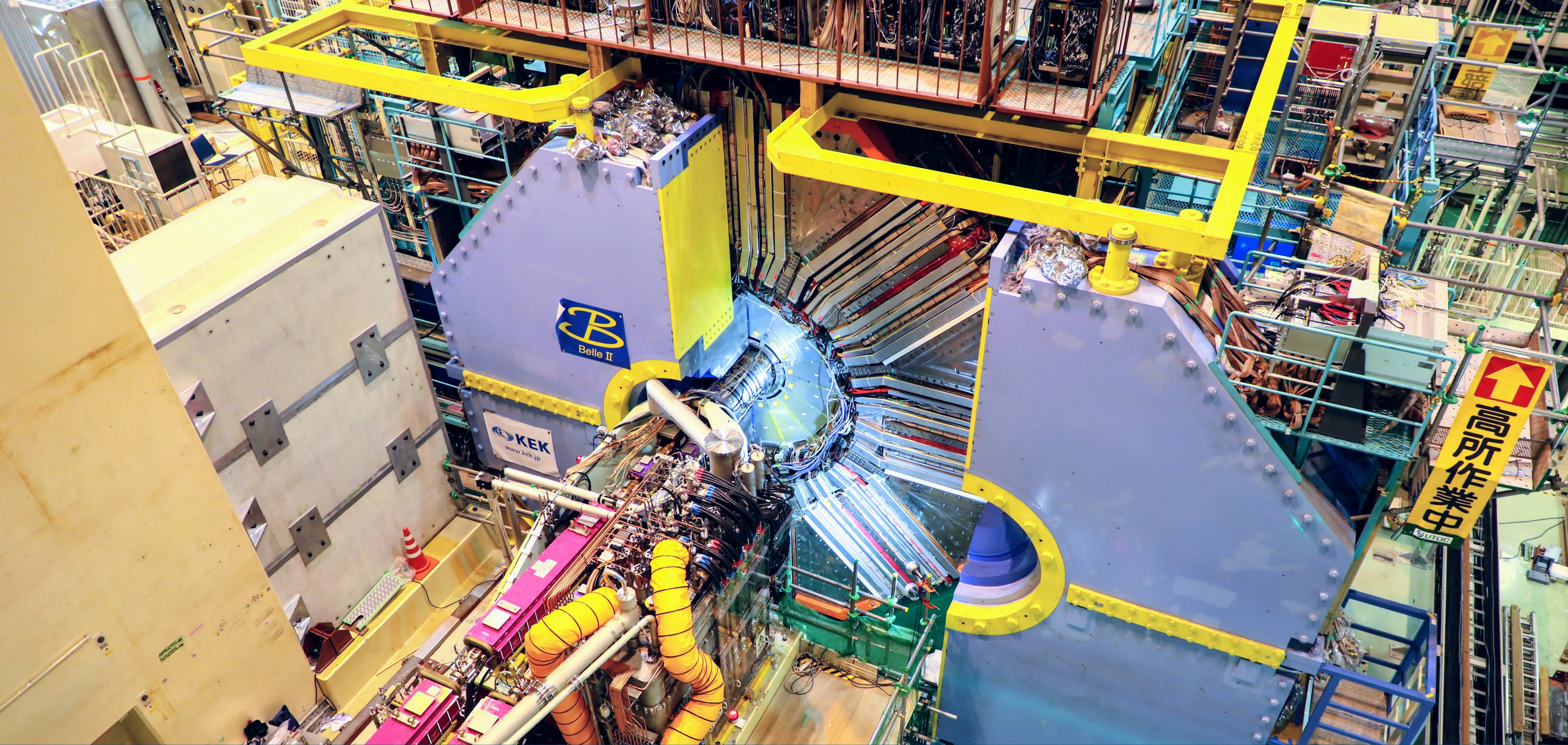
- An event is e^+e^- collision
- There are 250 Million collisions per second, for about 100 days per year
- We need to "take a picture" of each collision, choose which one must be recorded permanently, and analyze the interesting ones



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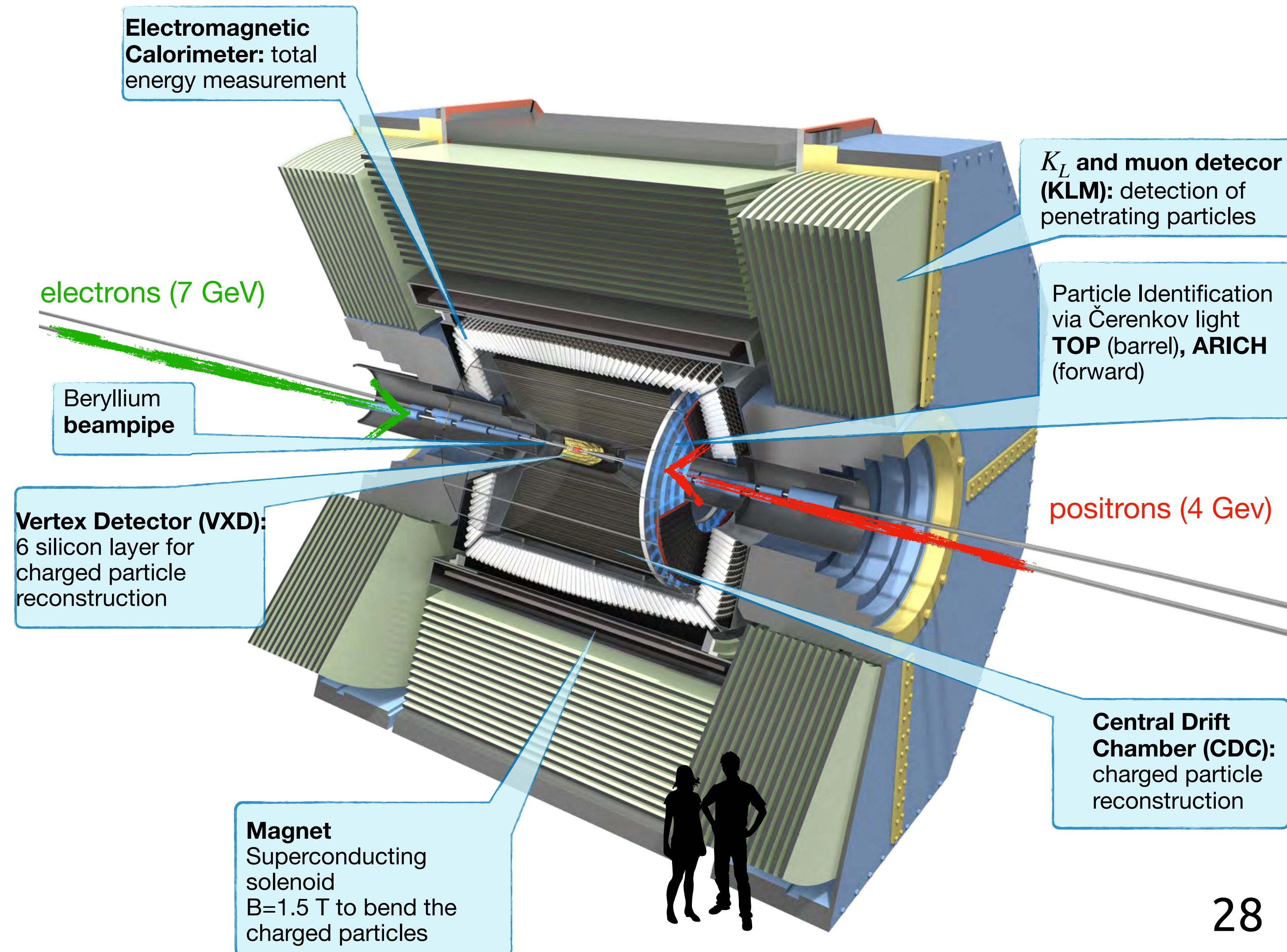




Belle II

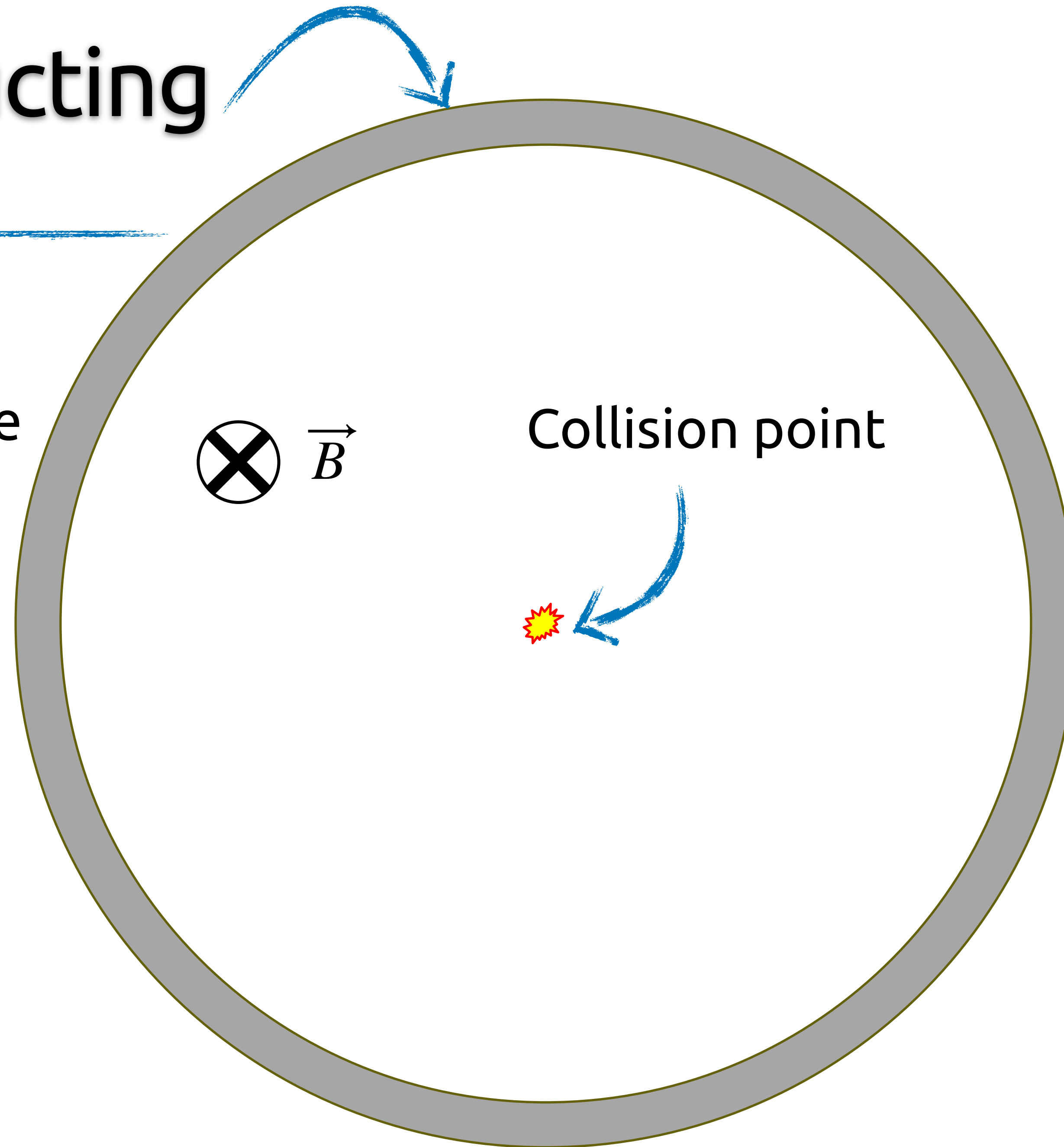
Belle II detector

- 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



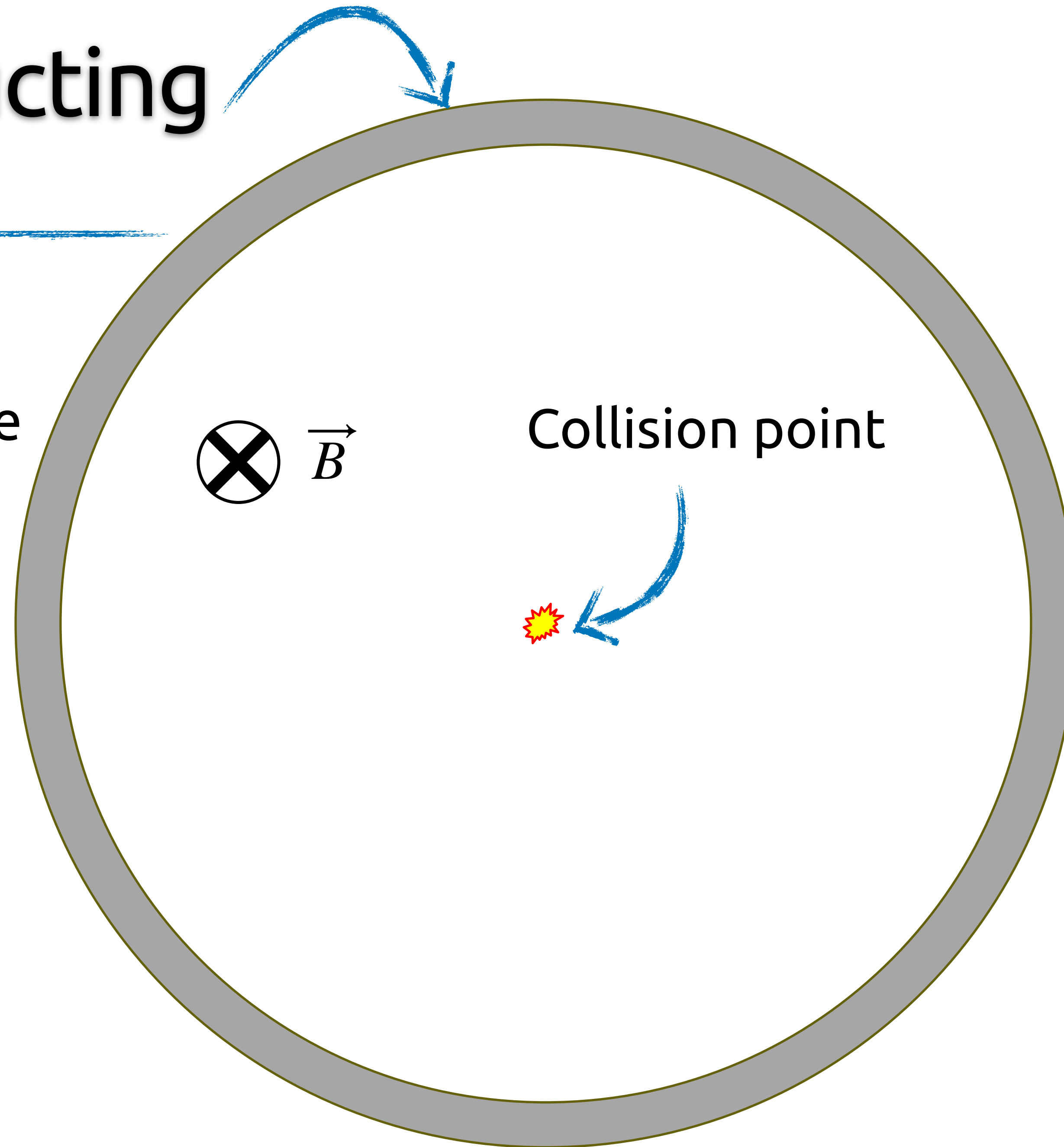
Superconducting solenoid

- Produces a uniform magnetic field inside
- $$p_T[\text{GeV}] = 0.3qB[\text{T}]R[\text{m}]$$
- The magnetic field makes the particles **bend**



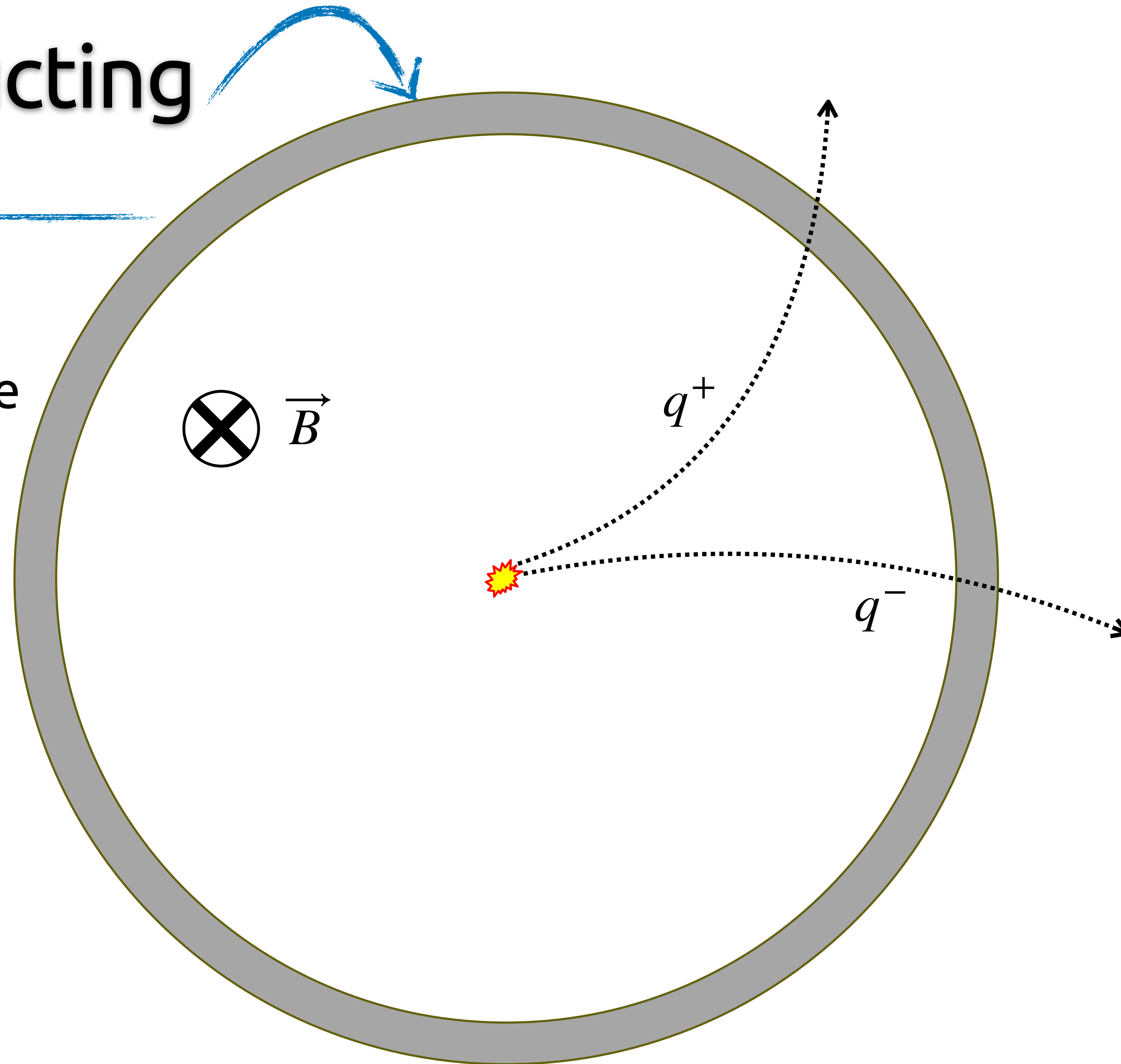
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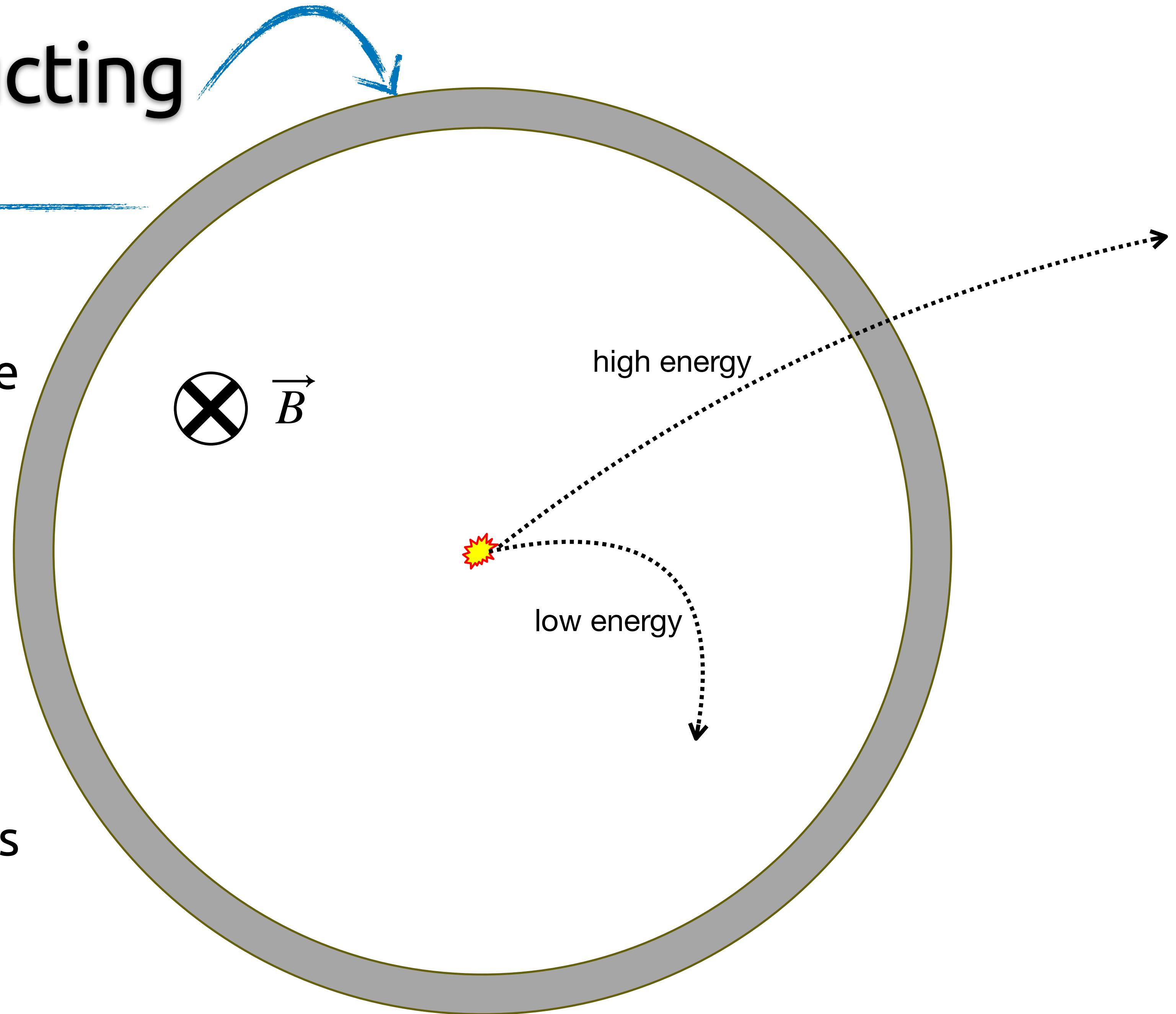
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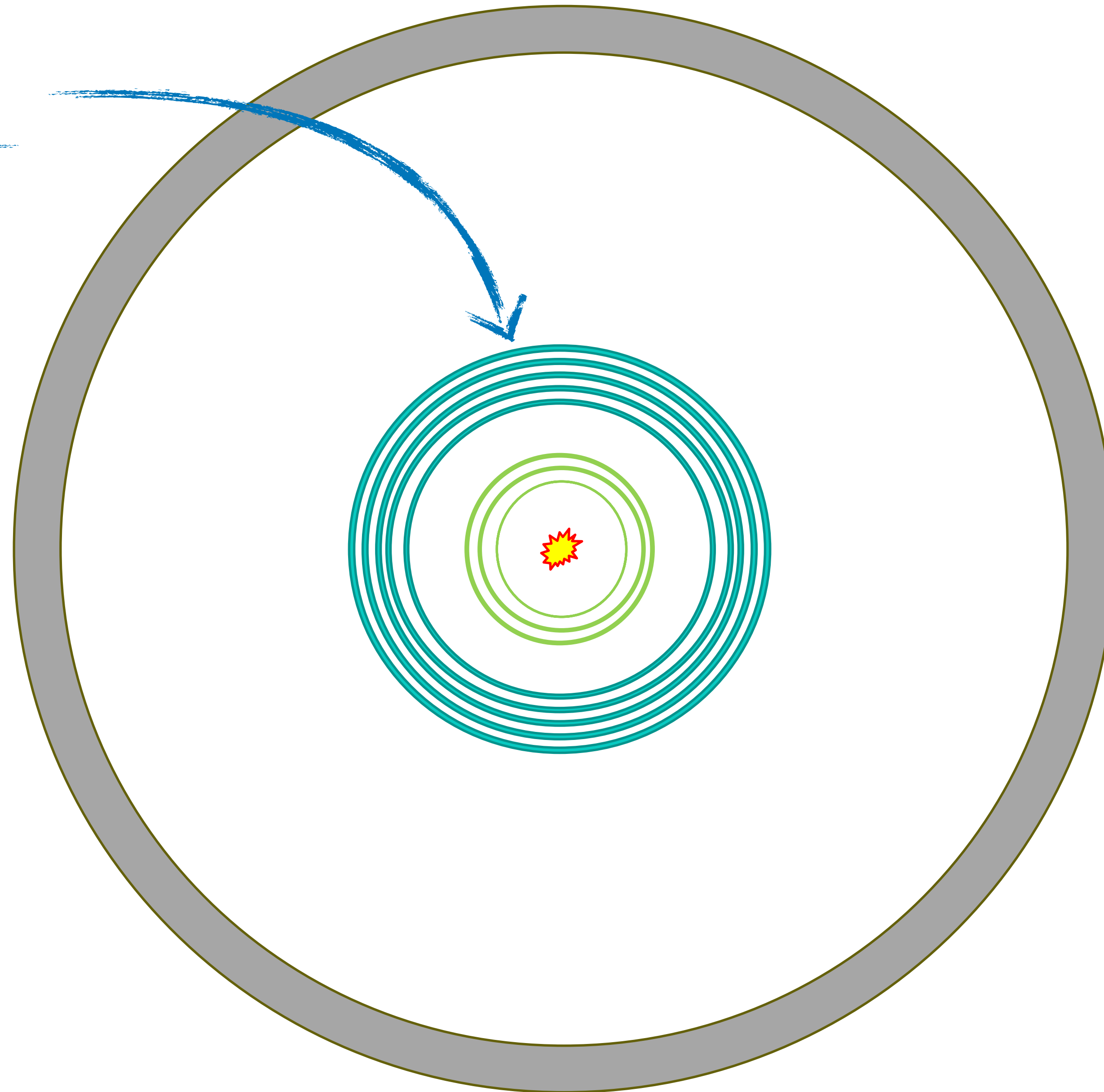
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 - More **energetic**, less bend



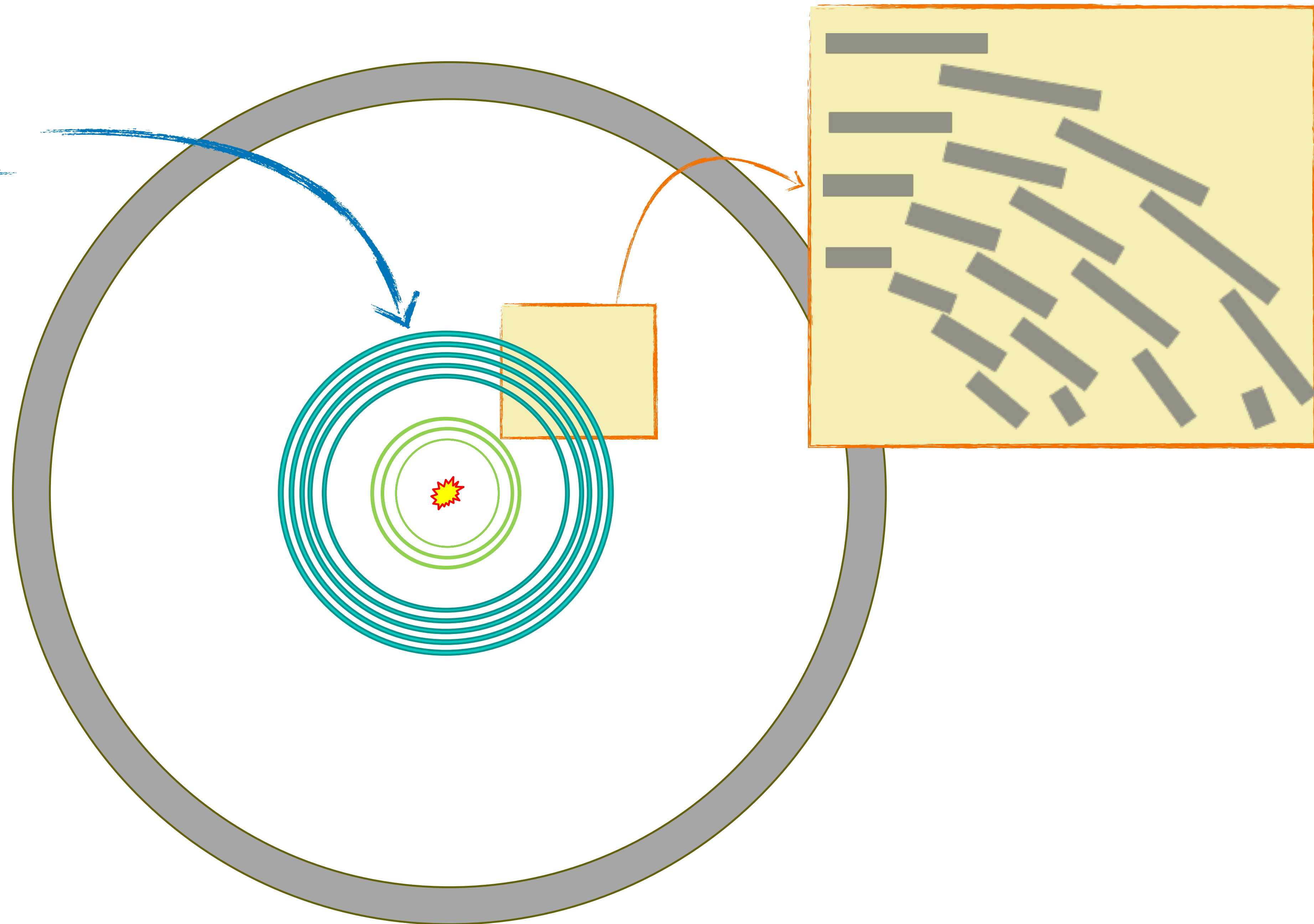
Tracker

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



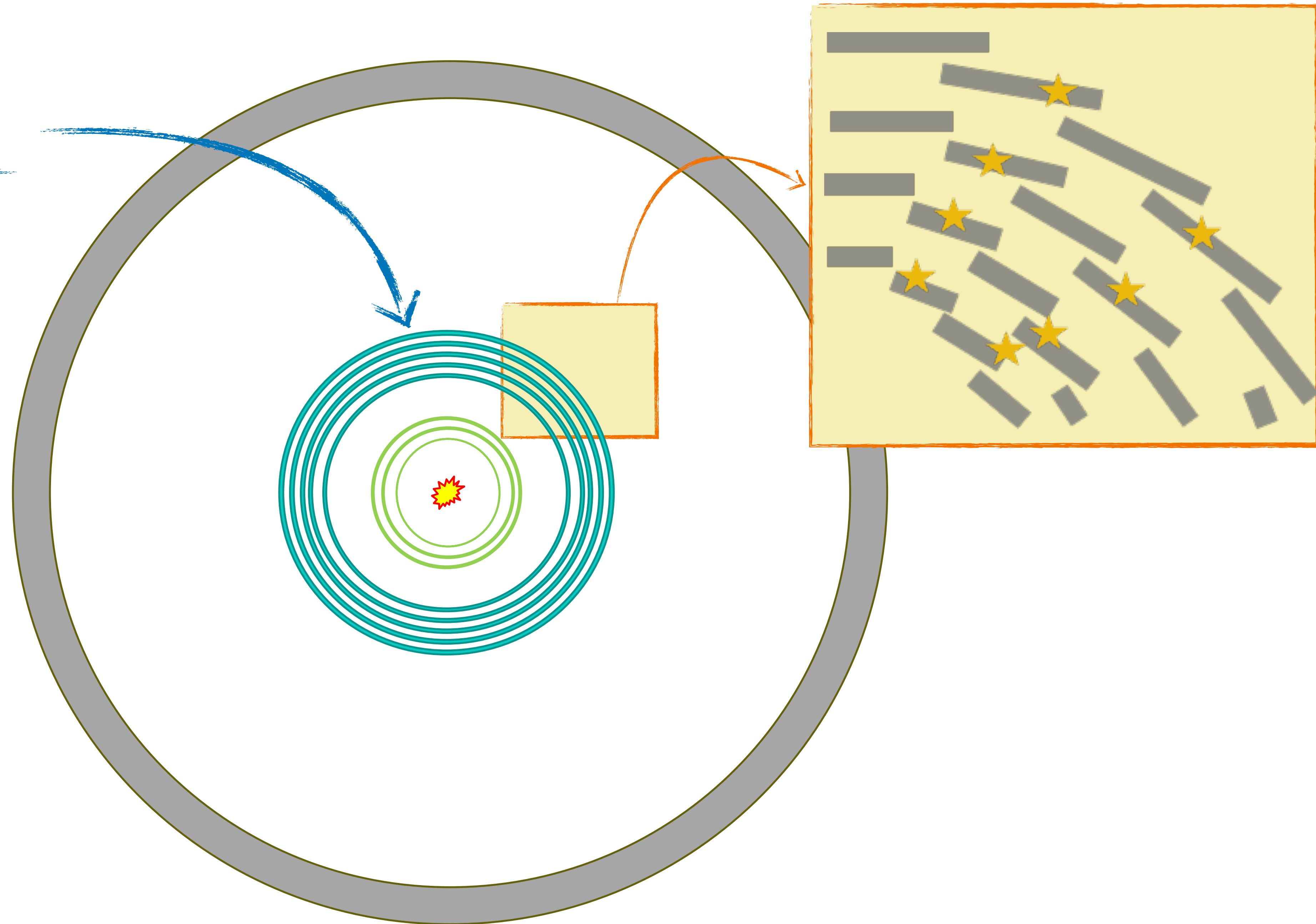
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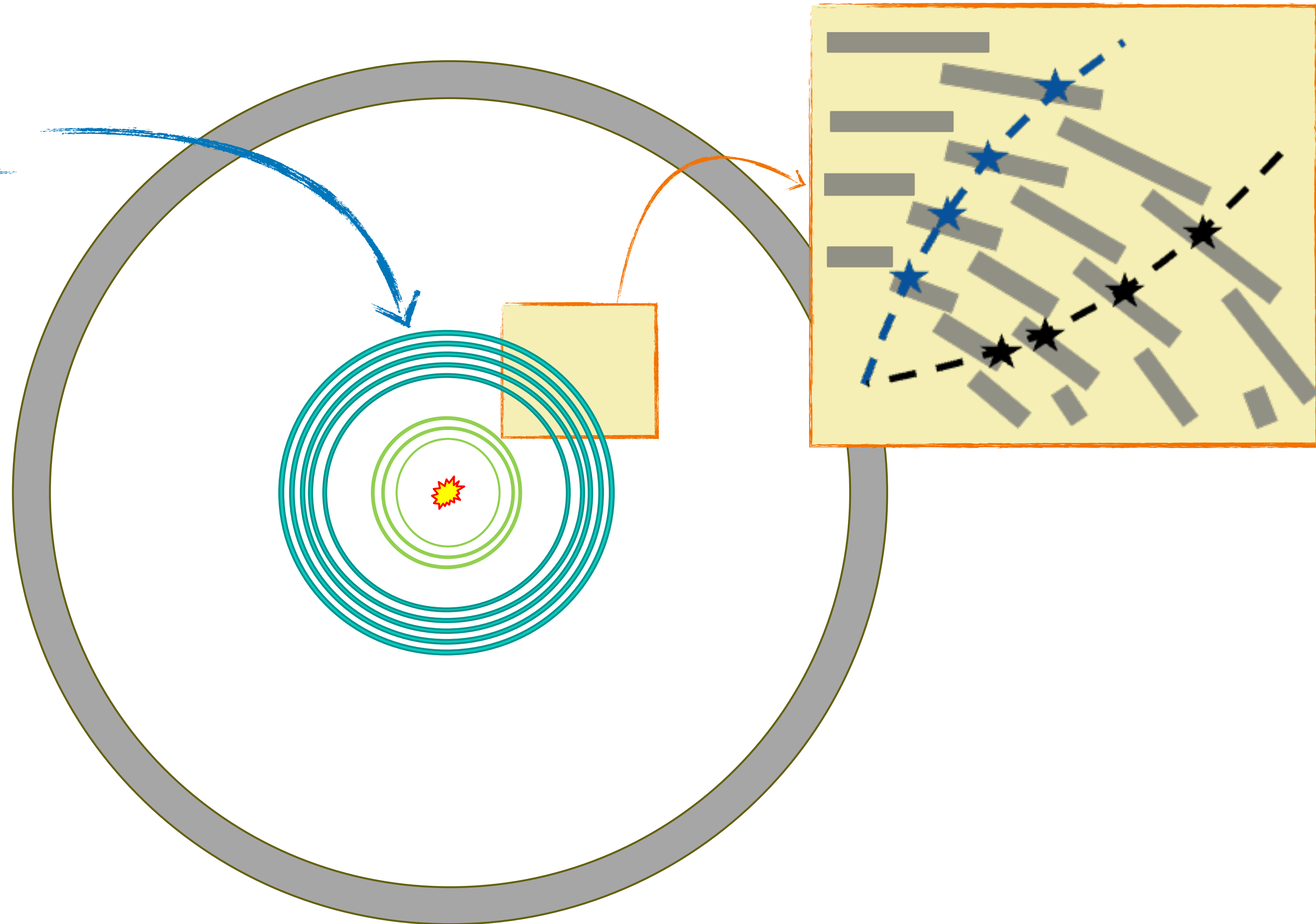
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- Often built with different technologies (more precise inside, less precise outside)



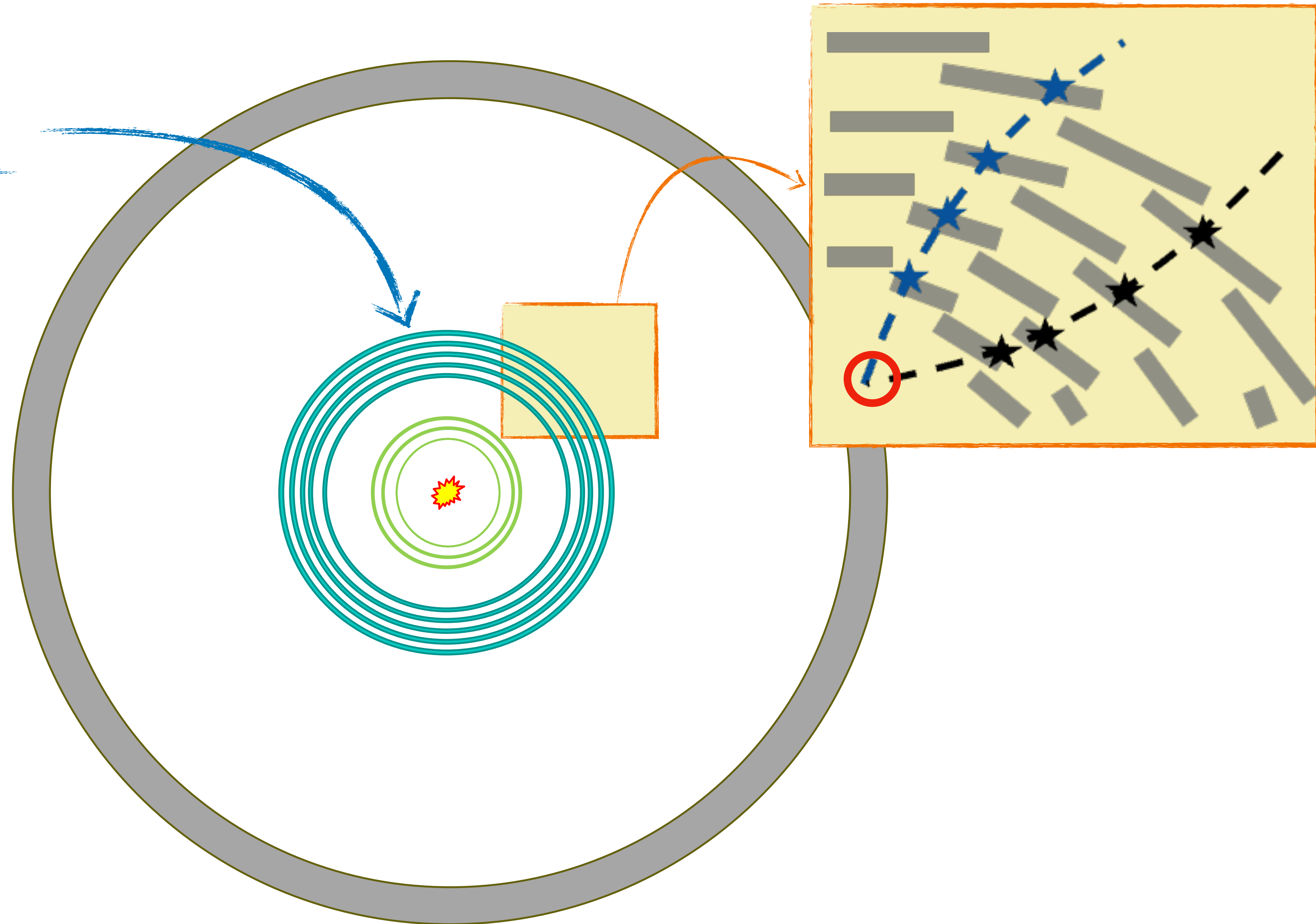
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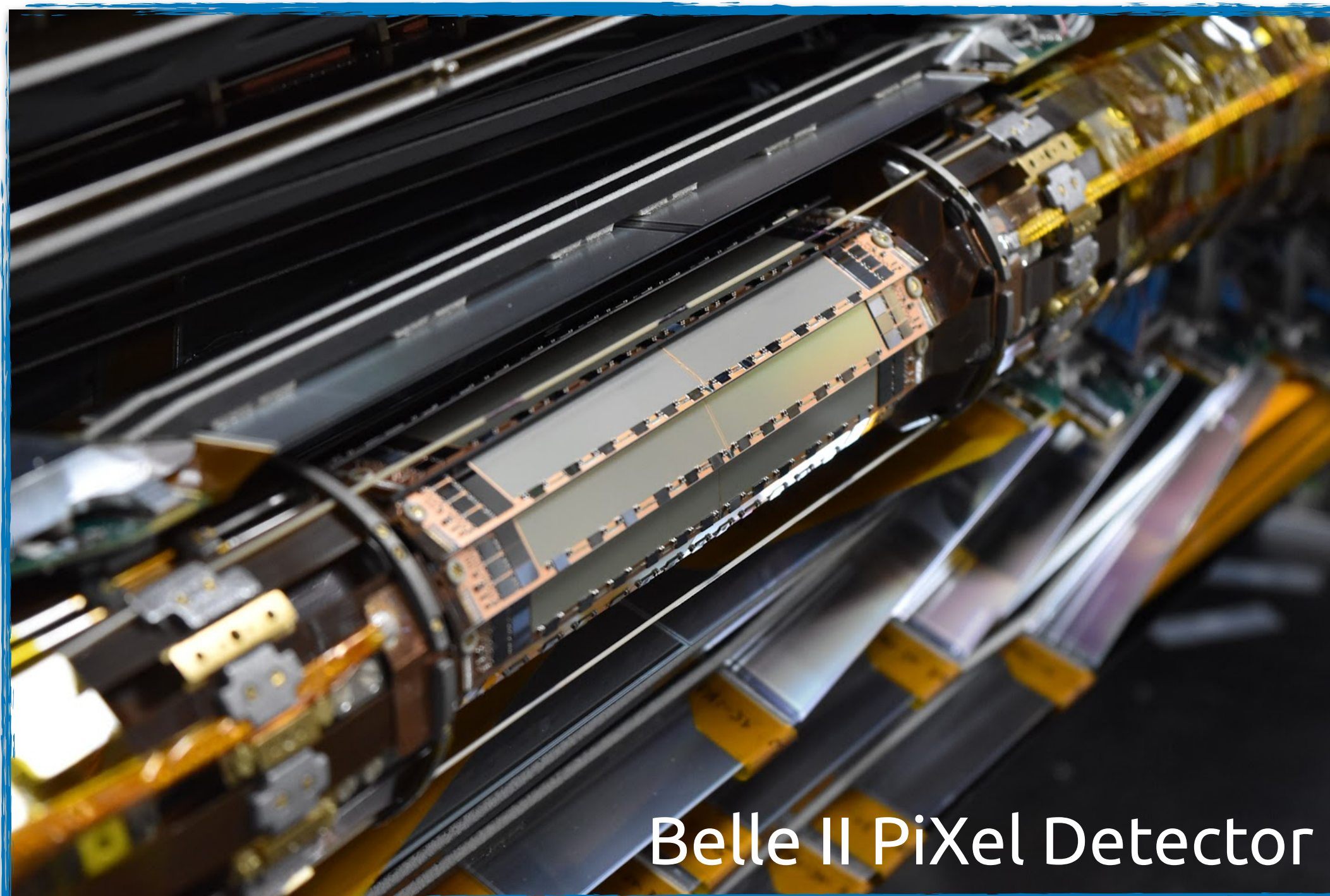
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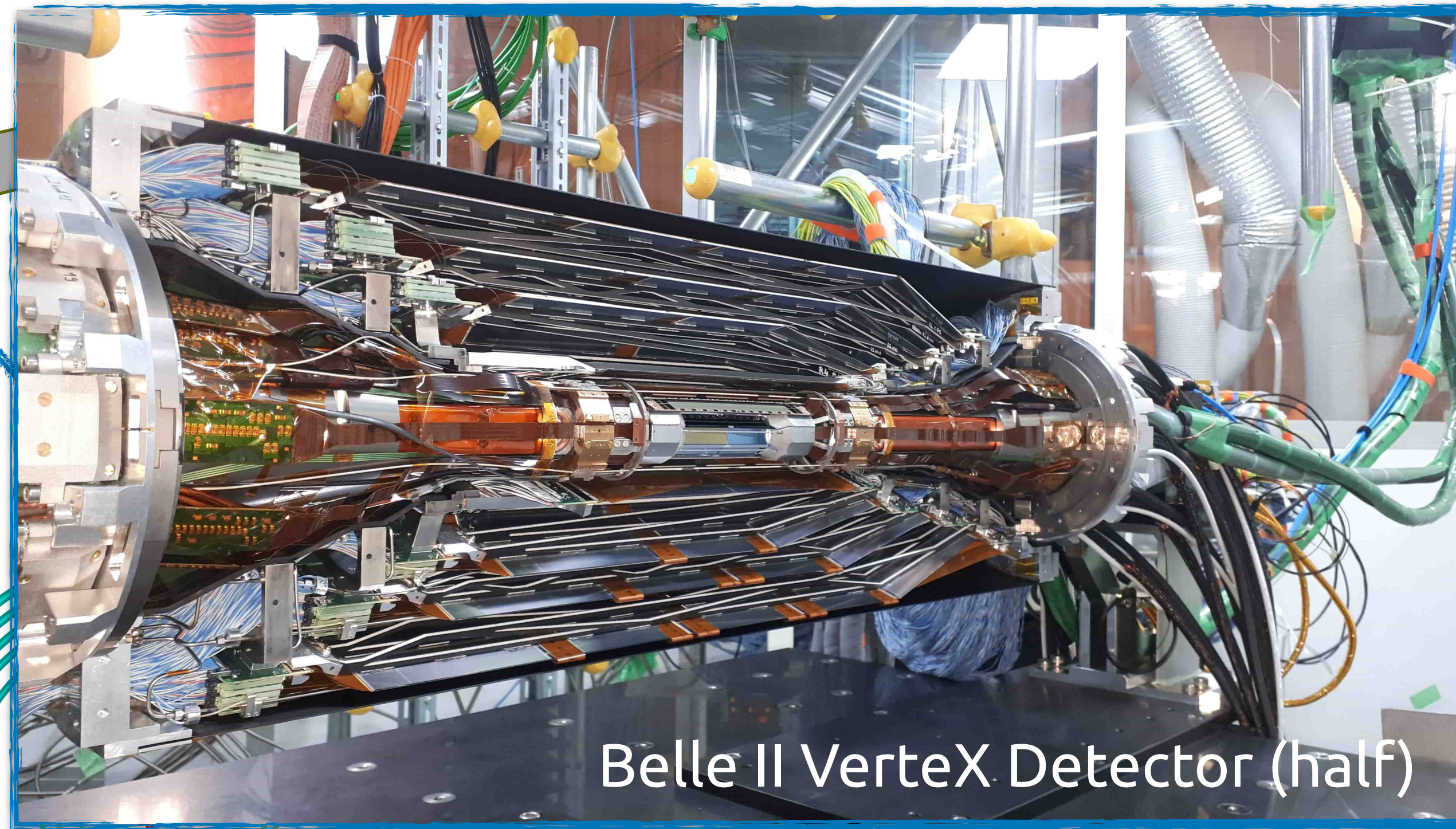
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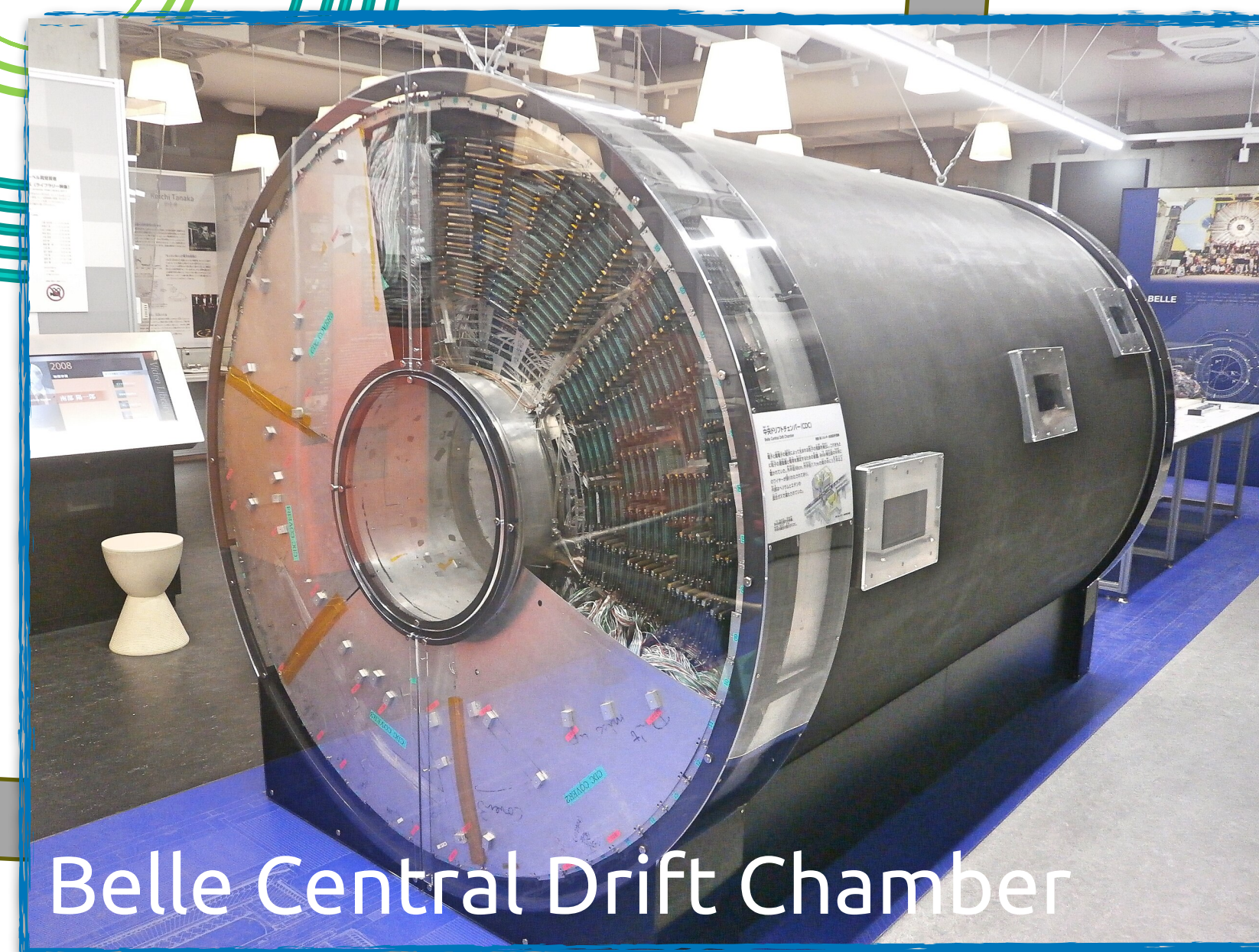
Belle II PiXel Detector



Belle II Vertex Detector (half)

with the tracker

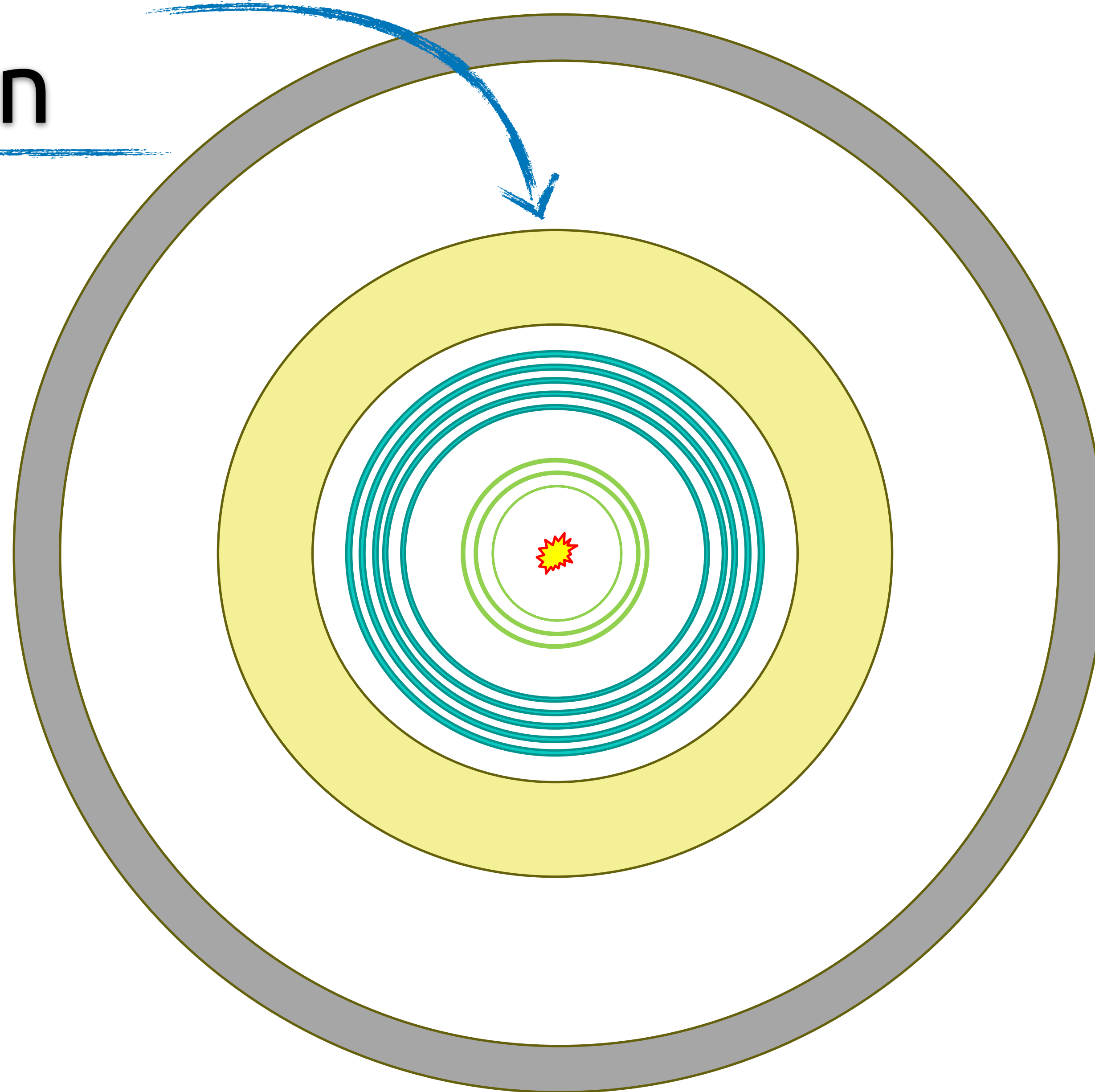
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Belle Central Drift Chamber

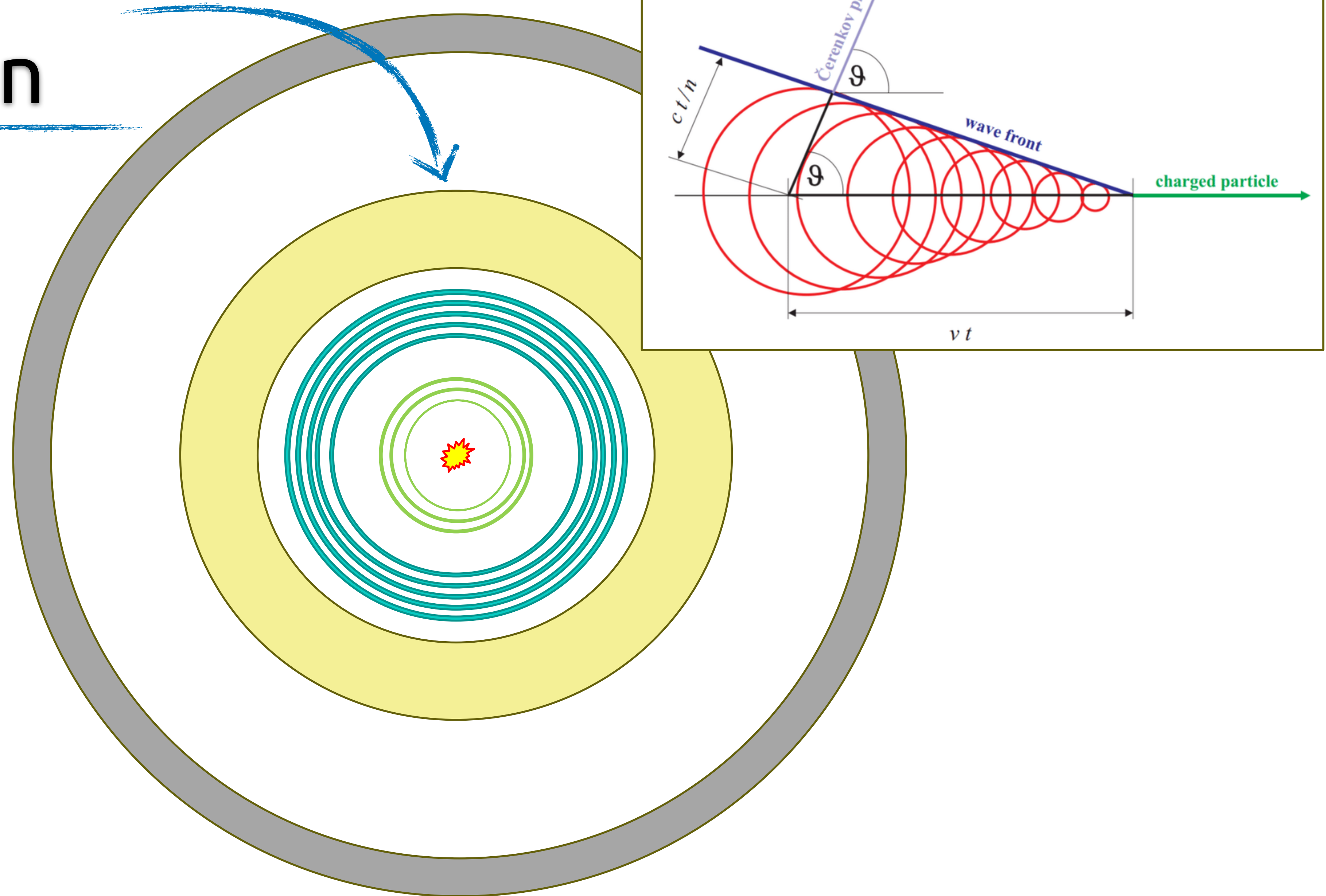
Particle Identification

- 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!



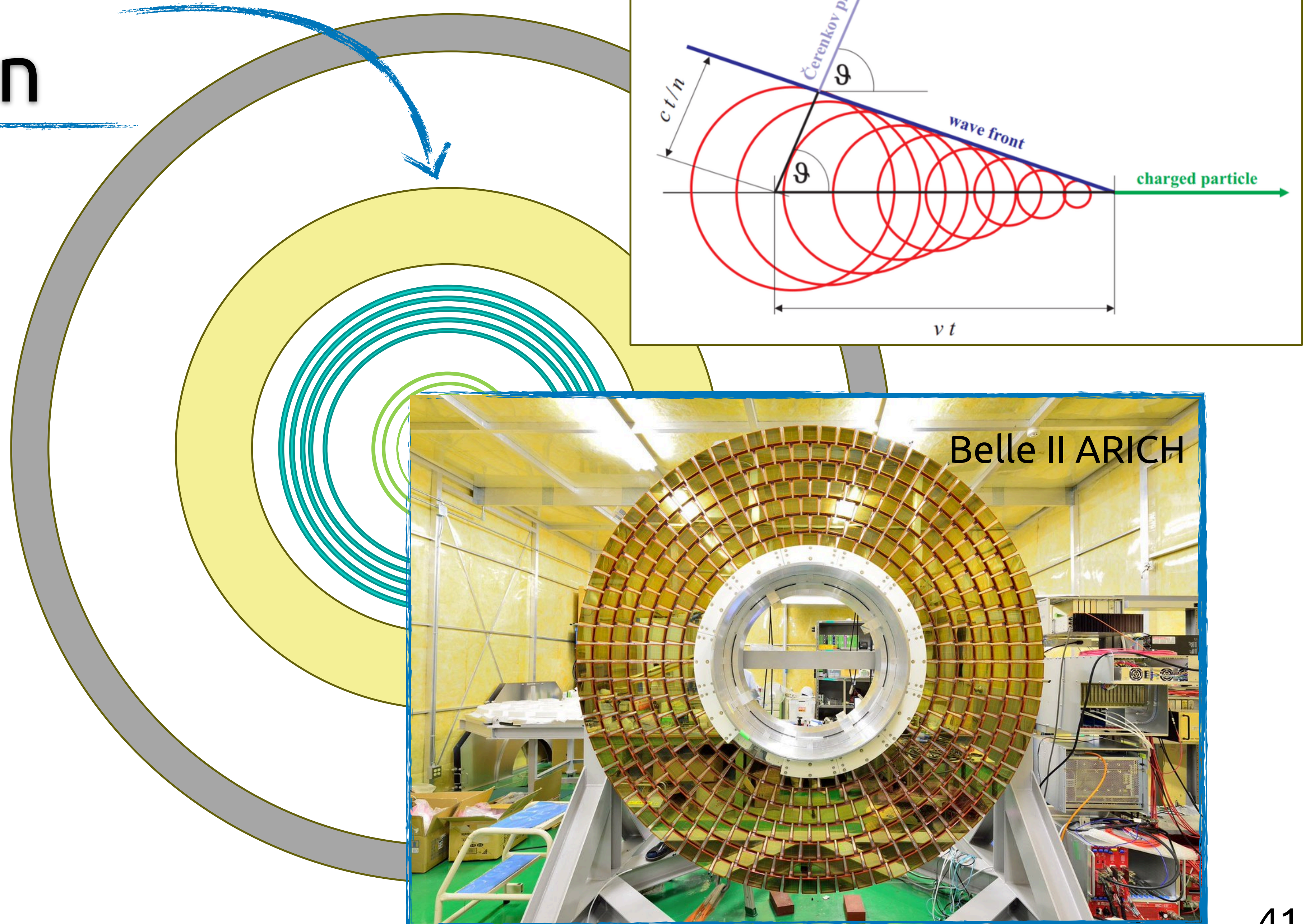
Particle Identification

- 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



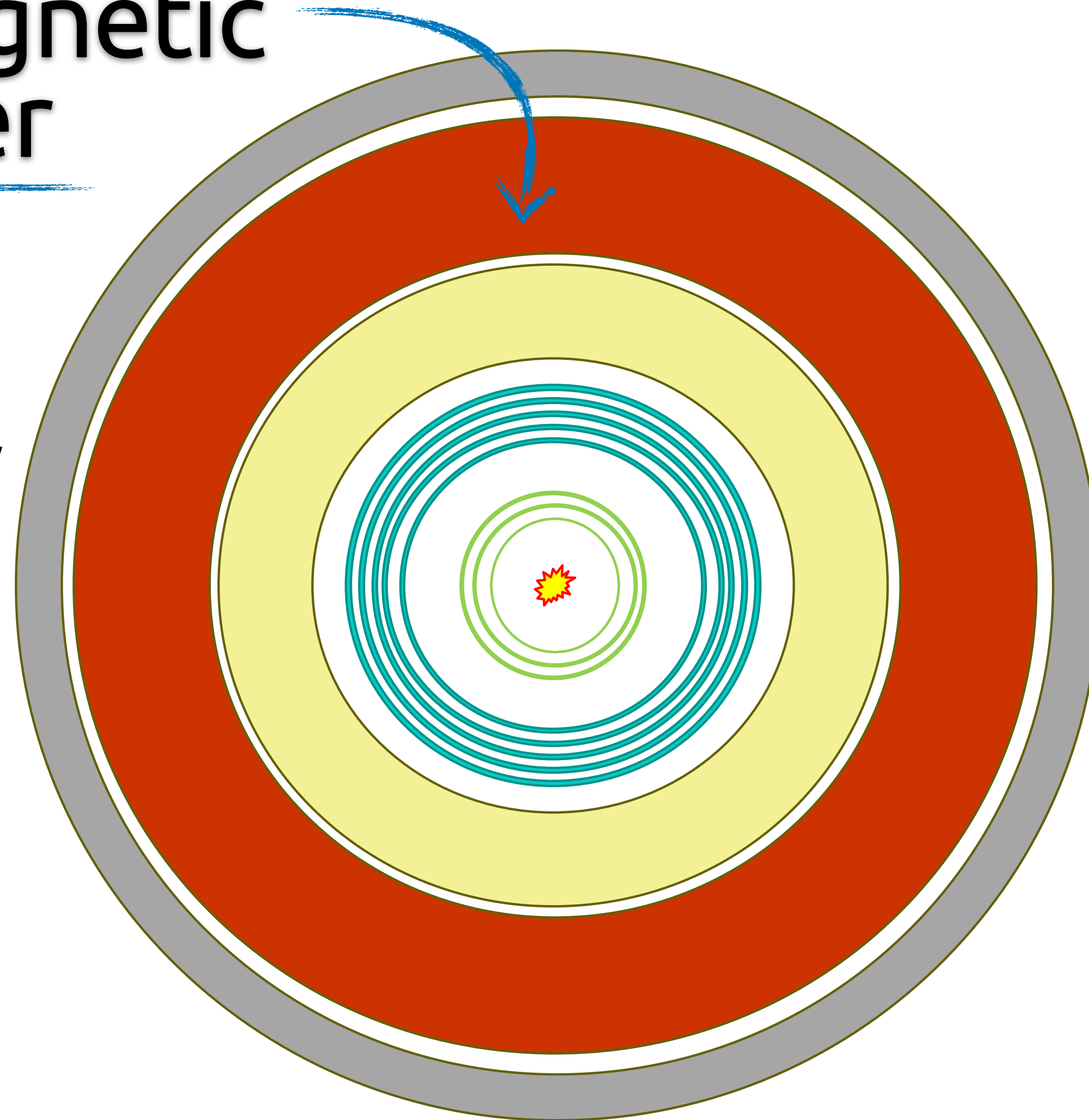
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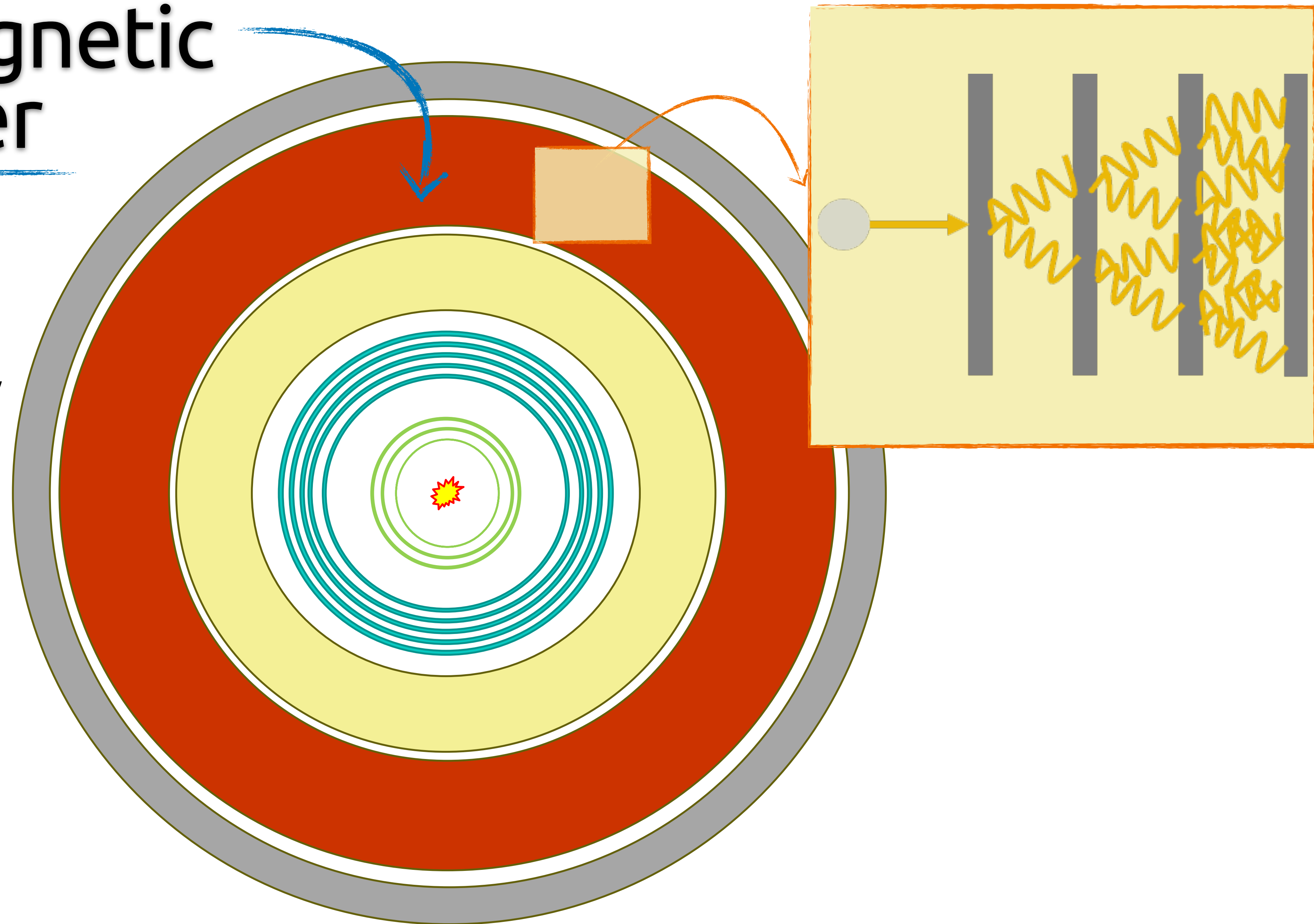
Electromagnetic Calorimeter

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



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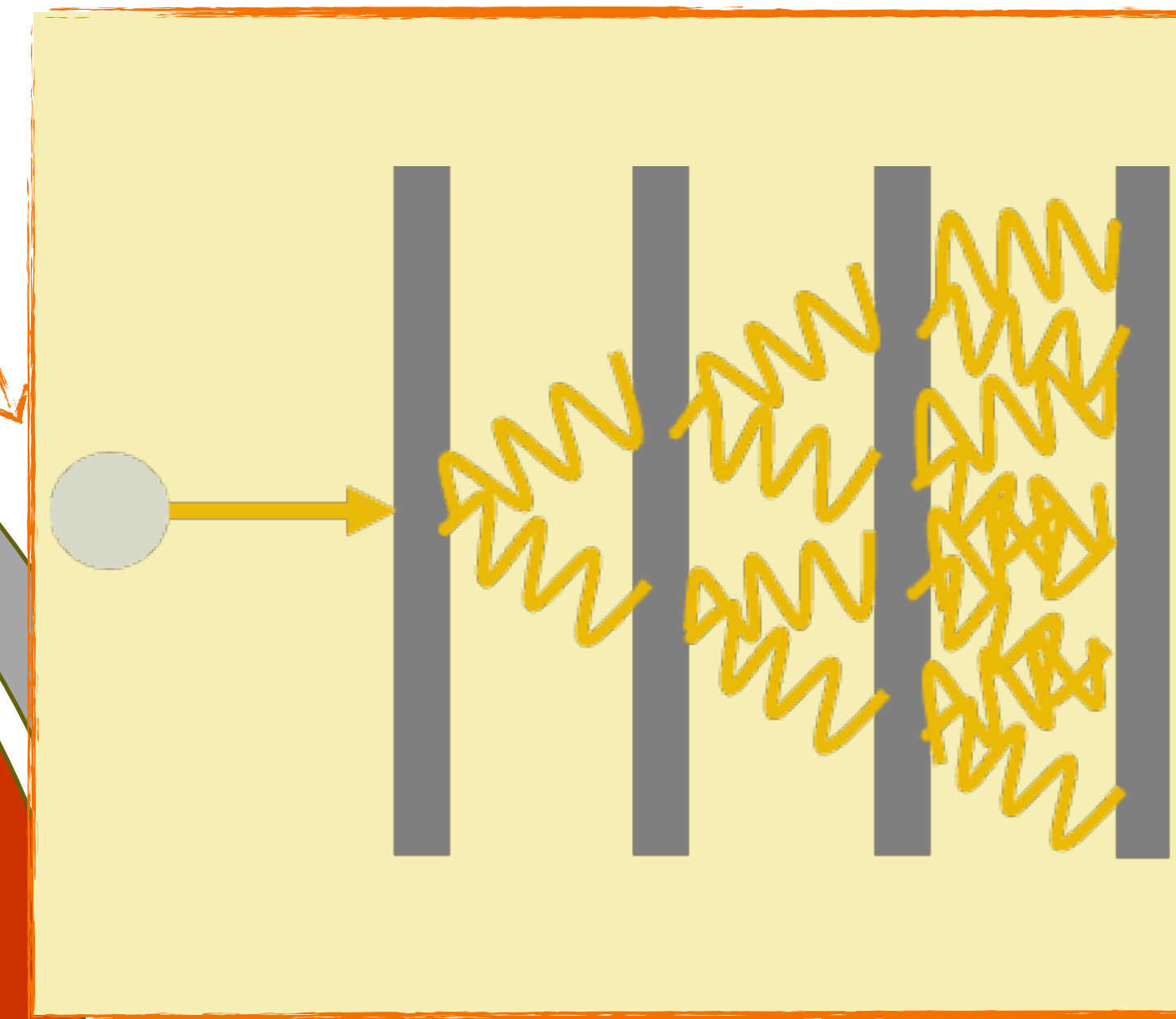


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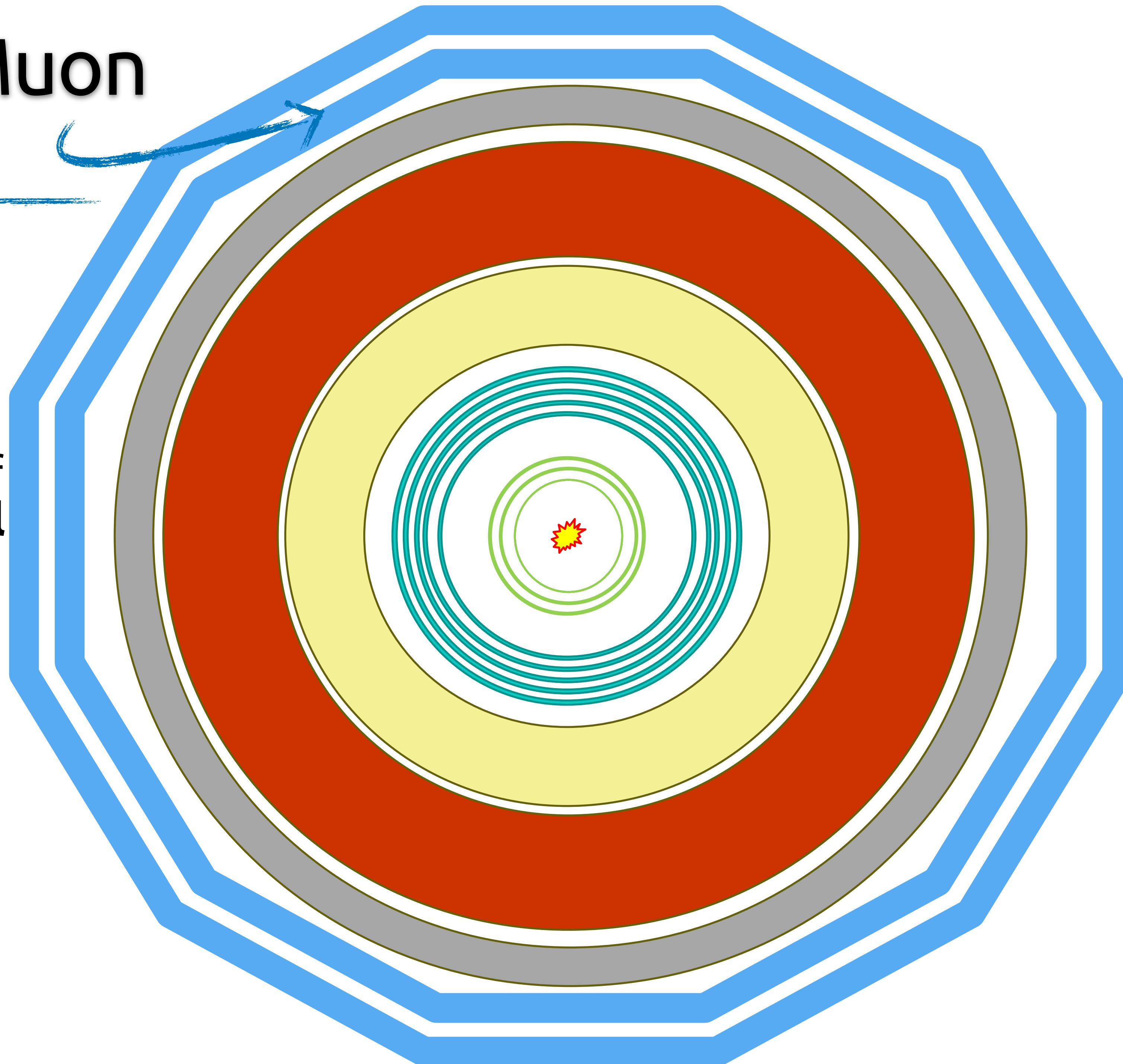


Belle II Electromagnetic CaLorimeter



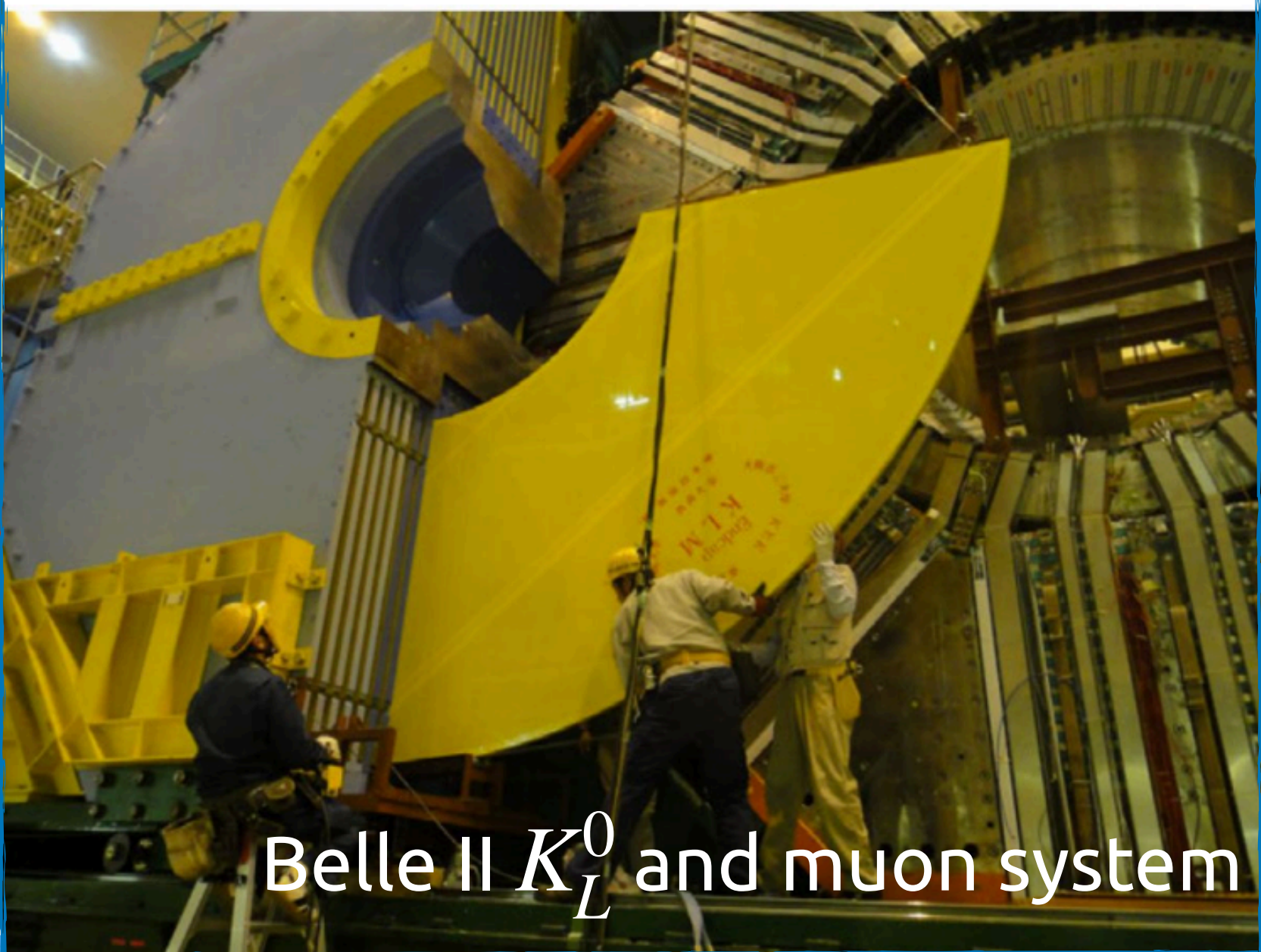
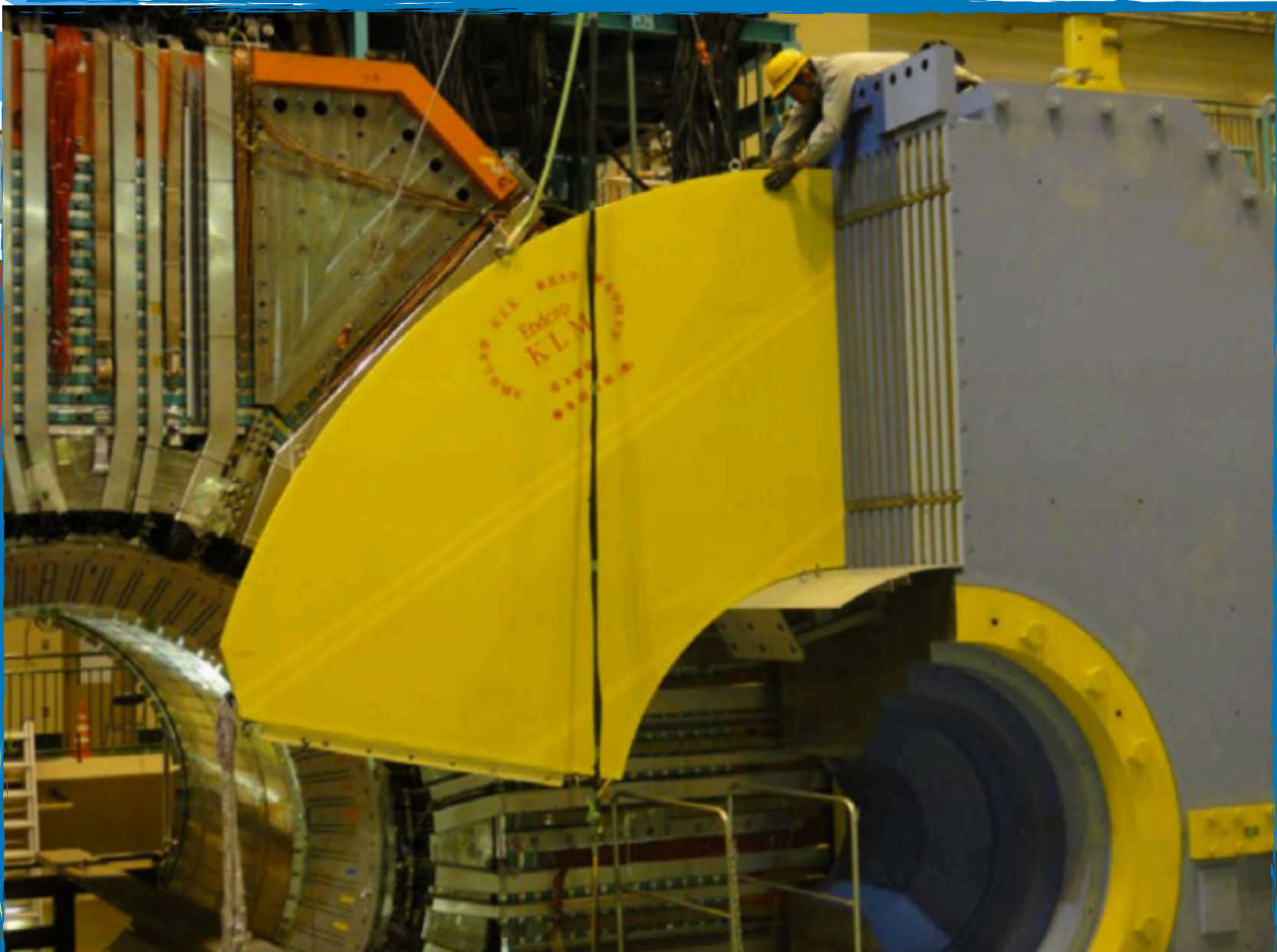
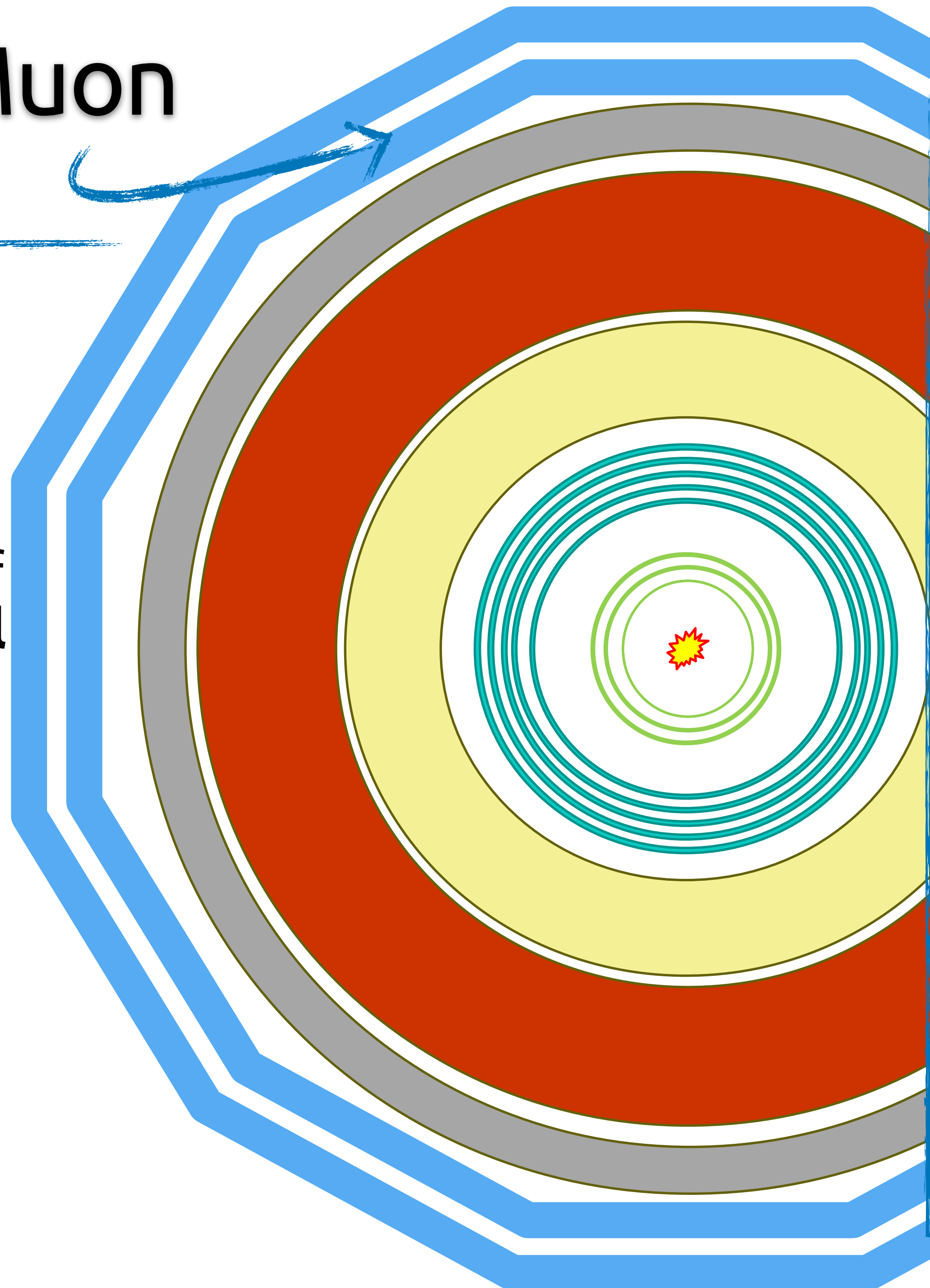
K_L^0 and Muon system

- 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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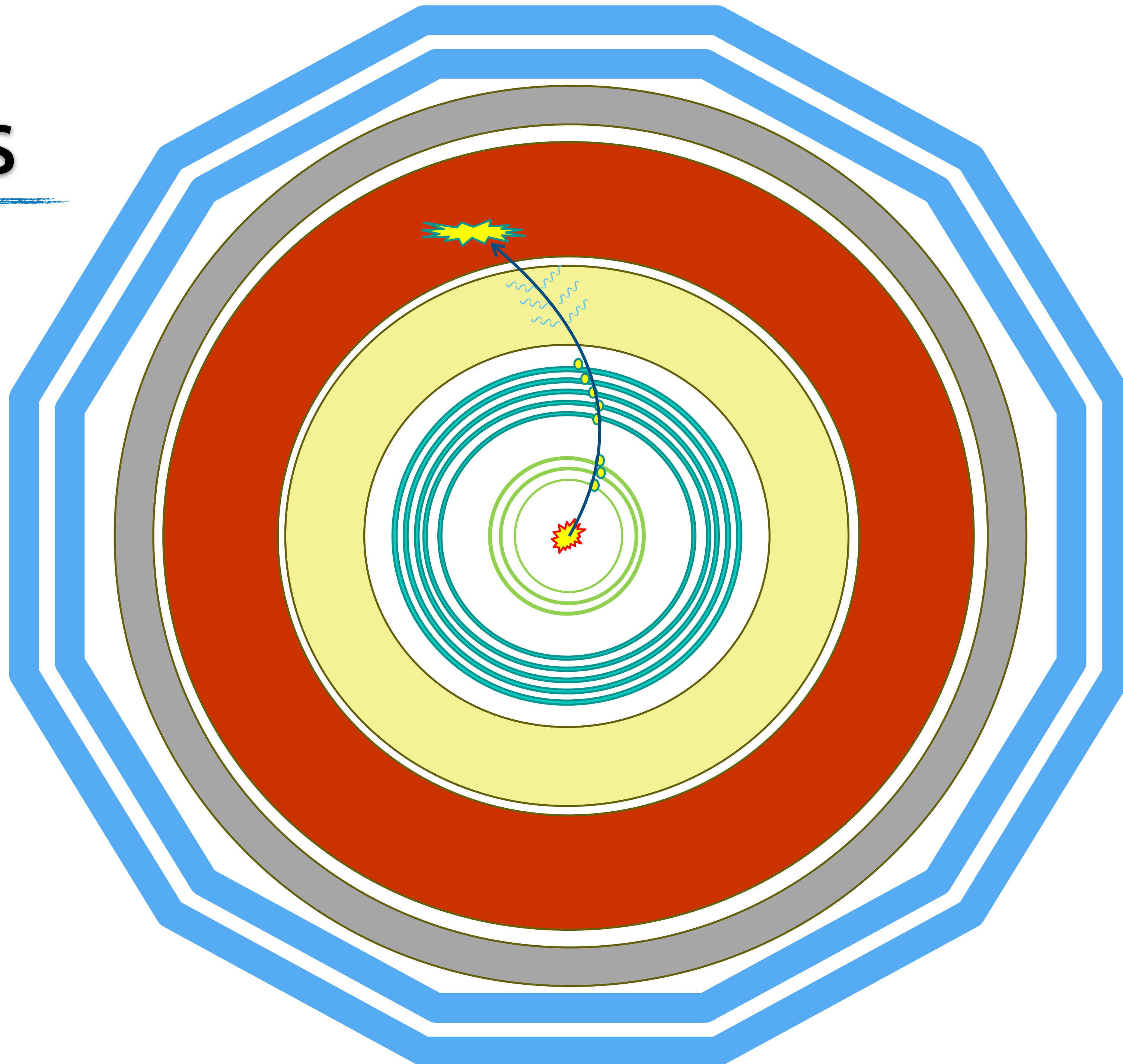


Belle II K_L^0 and muon system

Particles

Charged Lepton (electron):

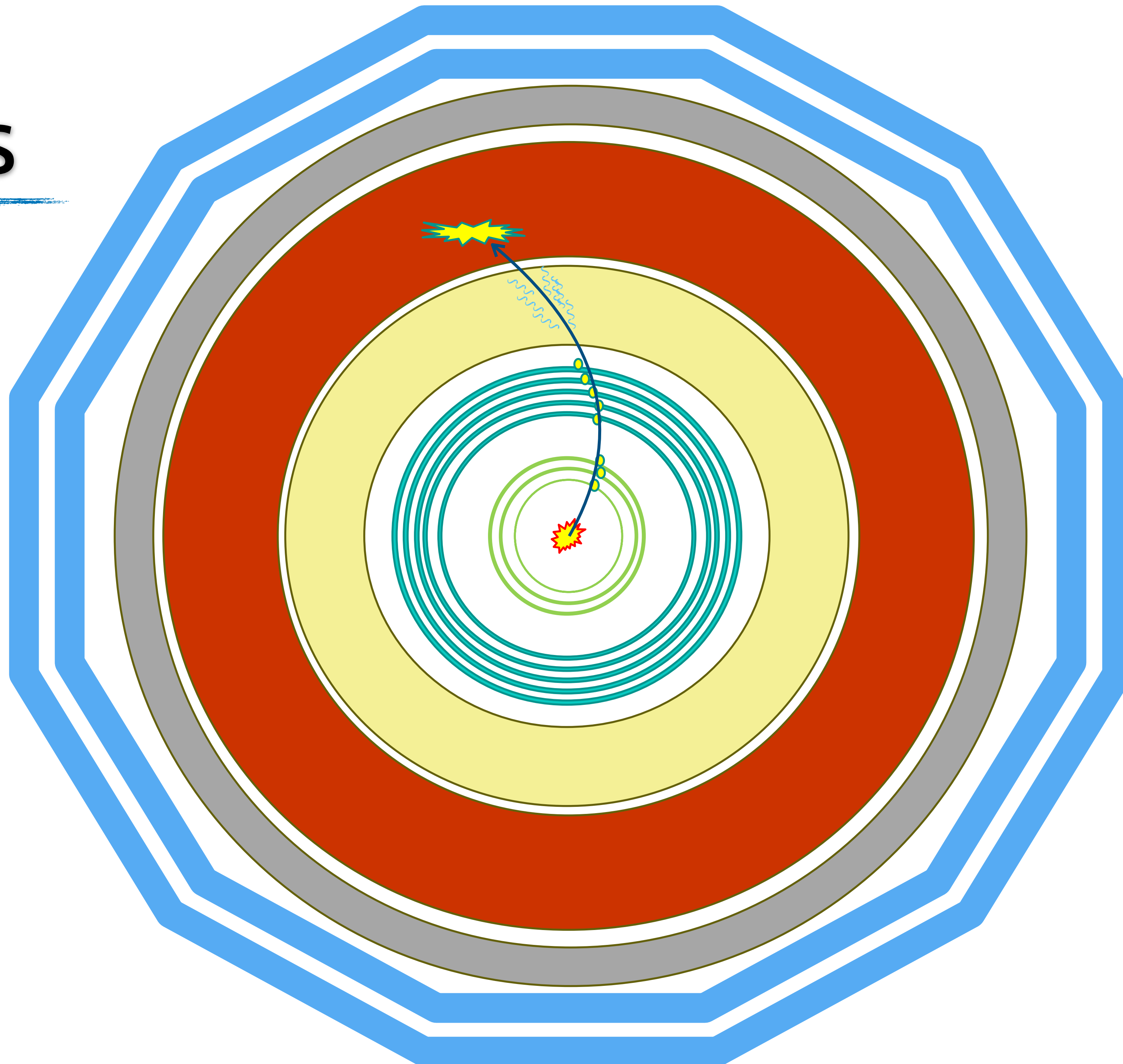
- Hits in the tracker
- Čerenkov light
- stopped in the calorimeter



Particles

Charged hadron:

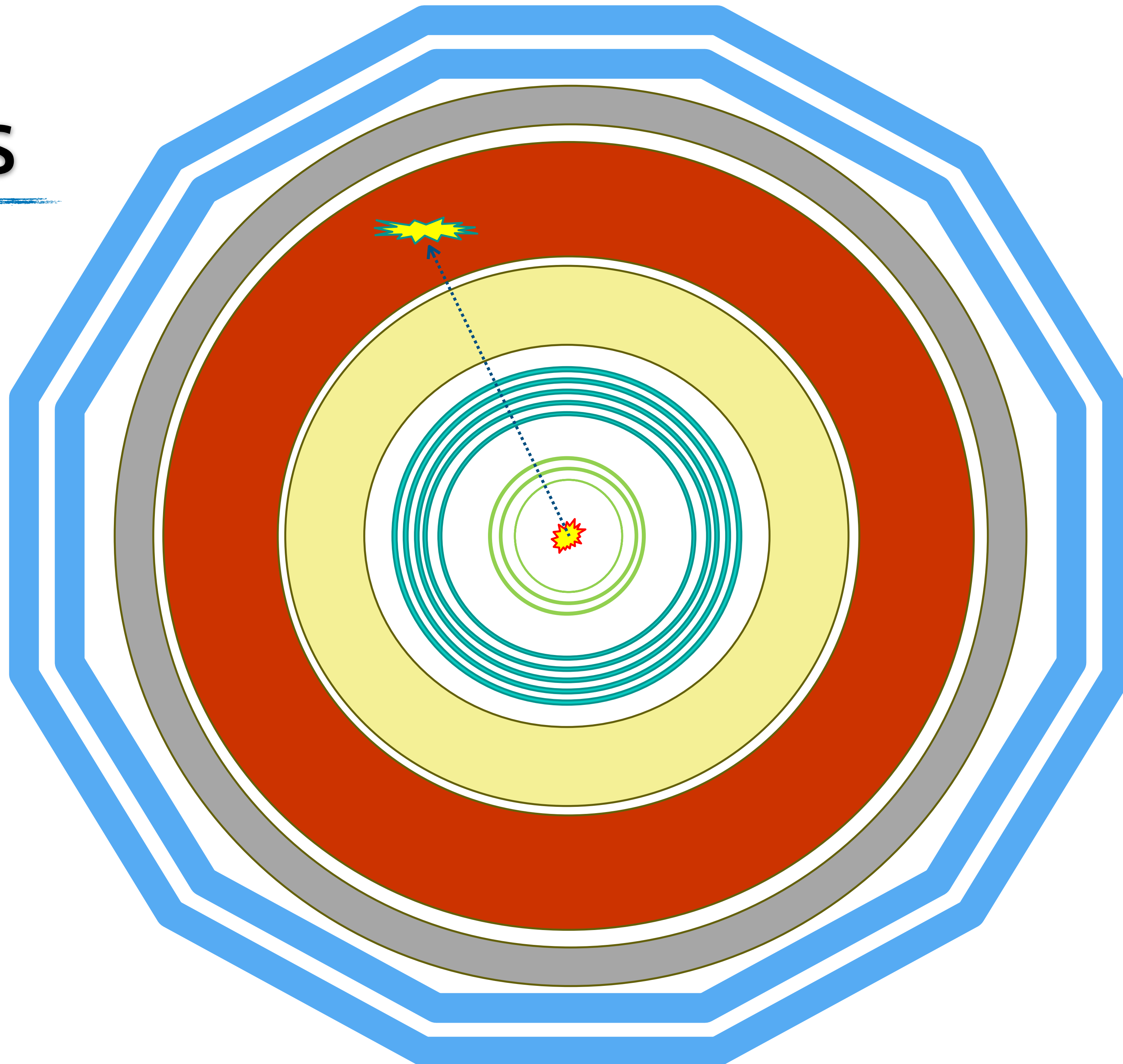
- Hits in the tracker
- (different) Čerenkov light
- stopped in the calorimeter



Particles

Photon

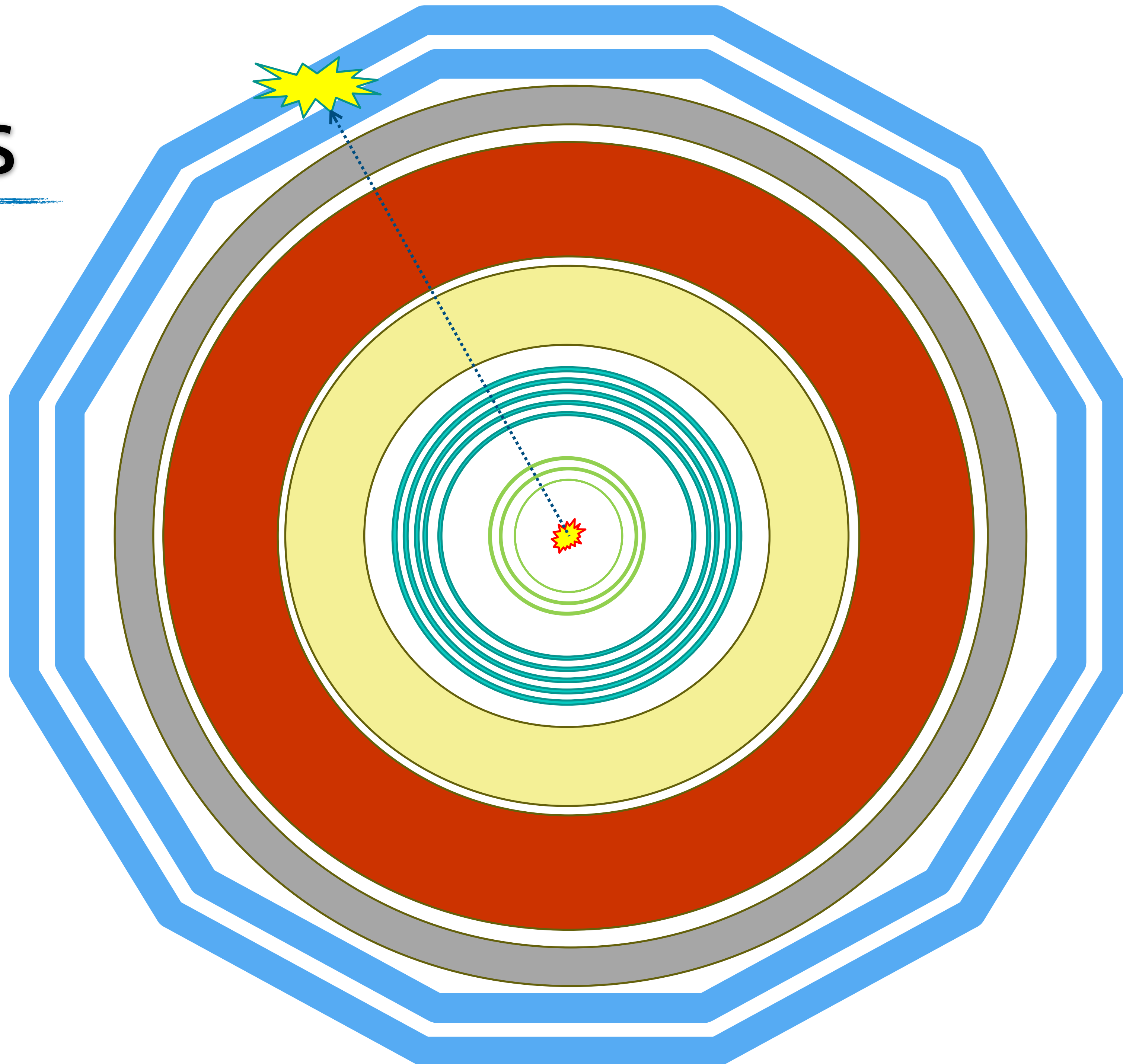
- Released energy in the calorimeter
- Stopped in the calorimeter



Particles

Neutral hadron

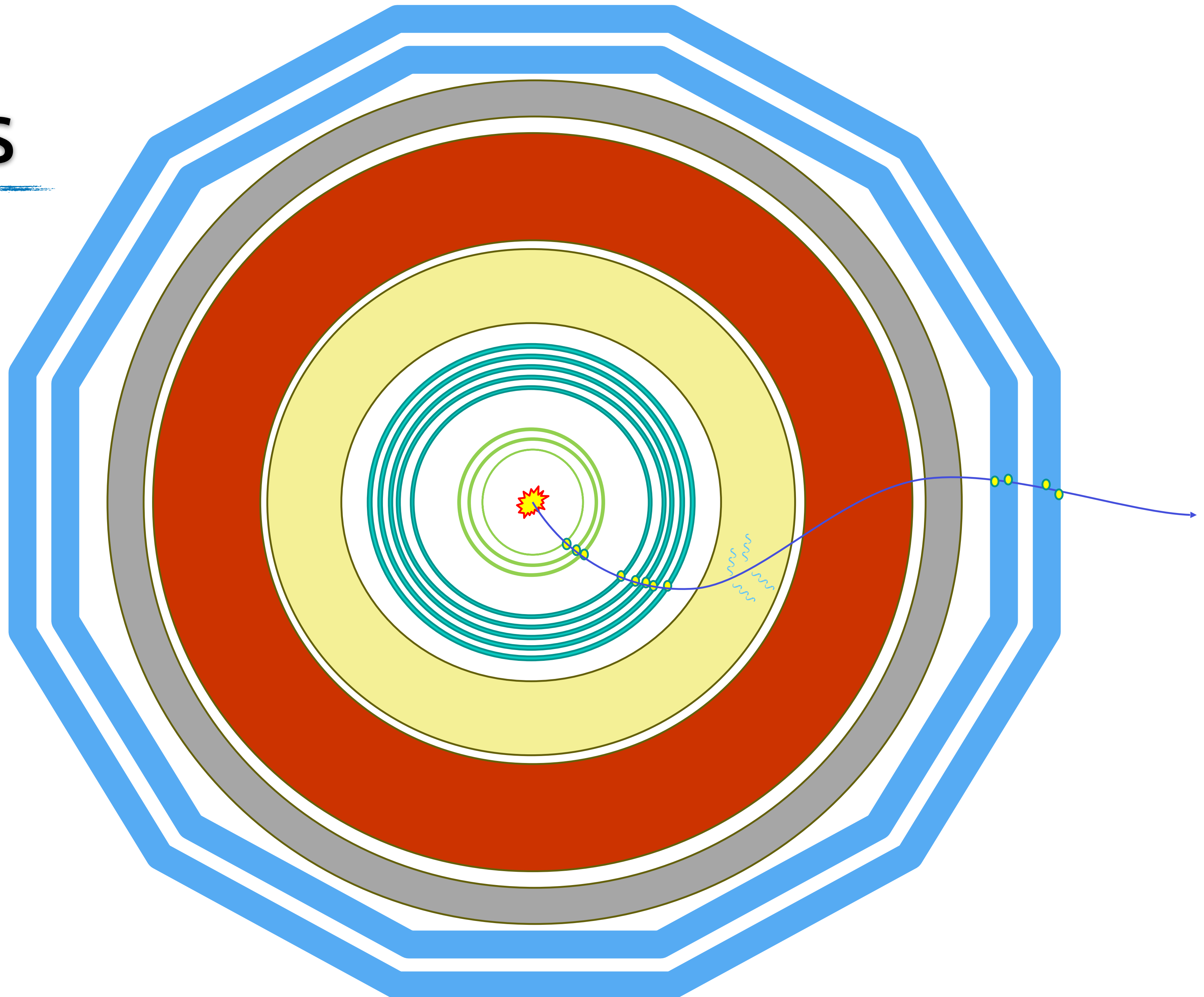
- Cross the entire detector
- Release energy in the KLM
- Stopped in the KLM



Particles

Muon

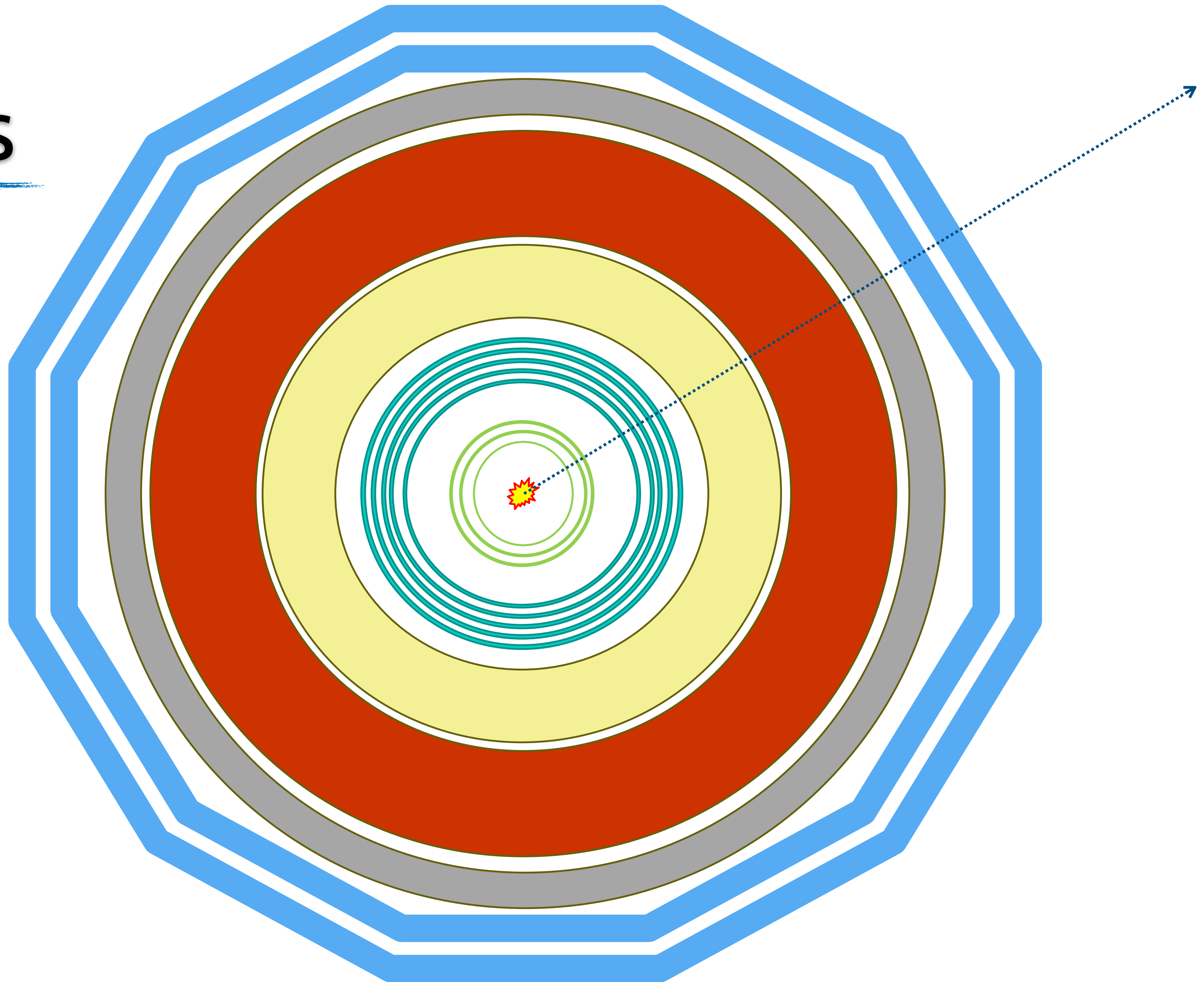
- Hit in the tracker
- Cross the entire detector
- Hit in the KLM
- Čerenkov light
- Double curvature



Particles

Neutrino

- Undetected
- (Interact only via weak interaction!)

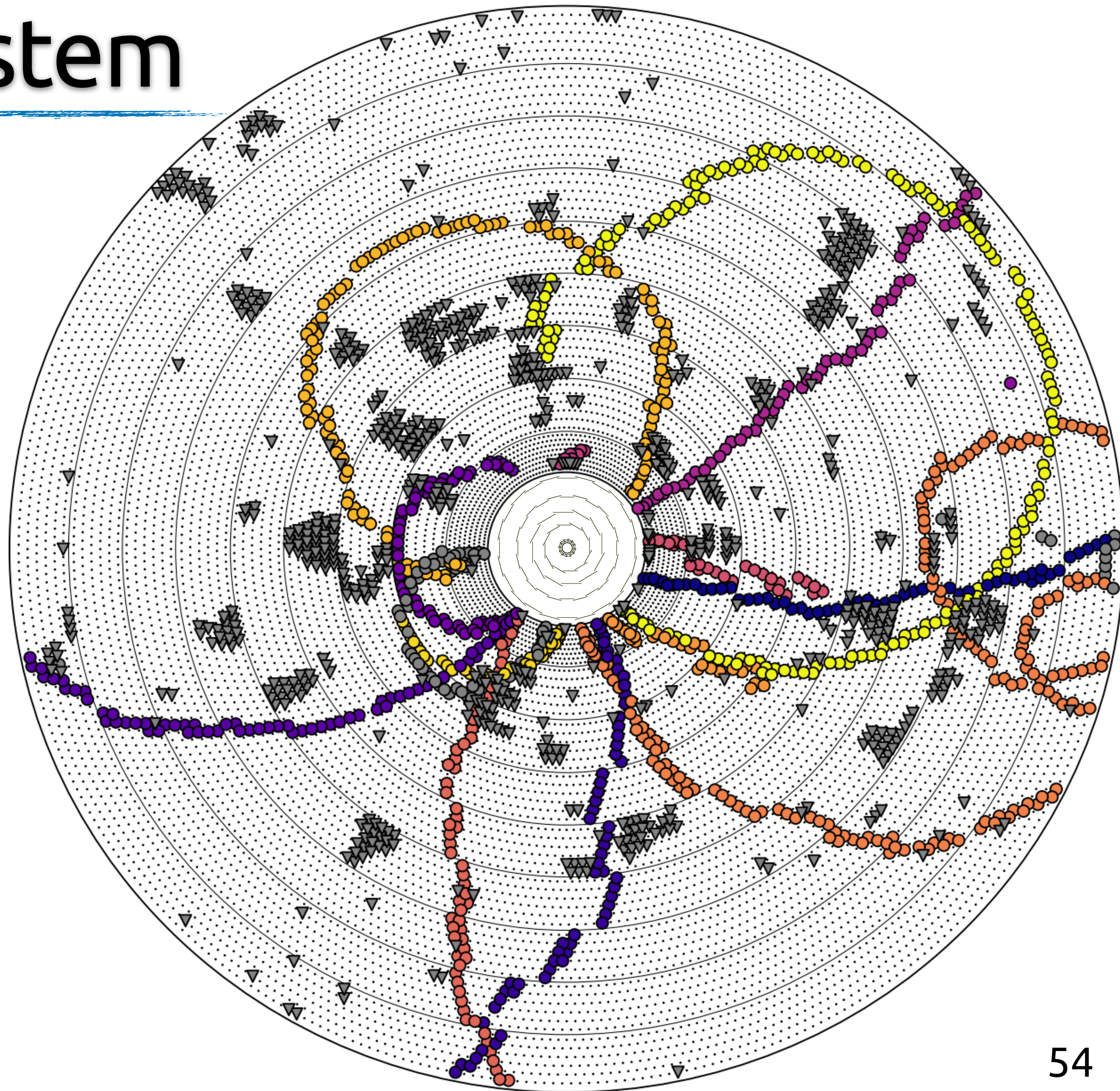


BACKUP SLIDES



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 \vec{E} field



CMS Detector slice: particle interaction

