Karlsruhe Institute of Technology

# Particle Physics 1
# Lecture 4: Detectors

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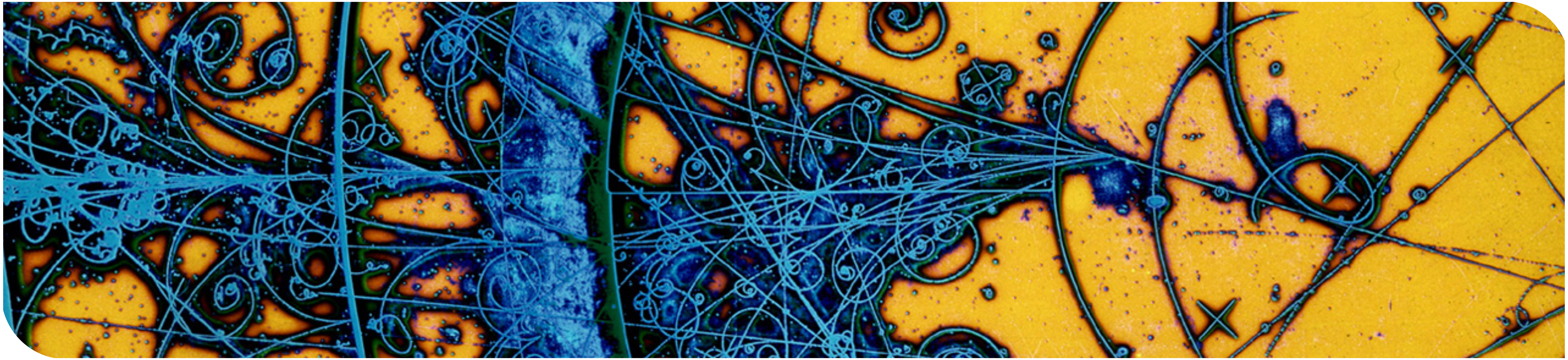
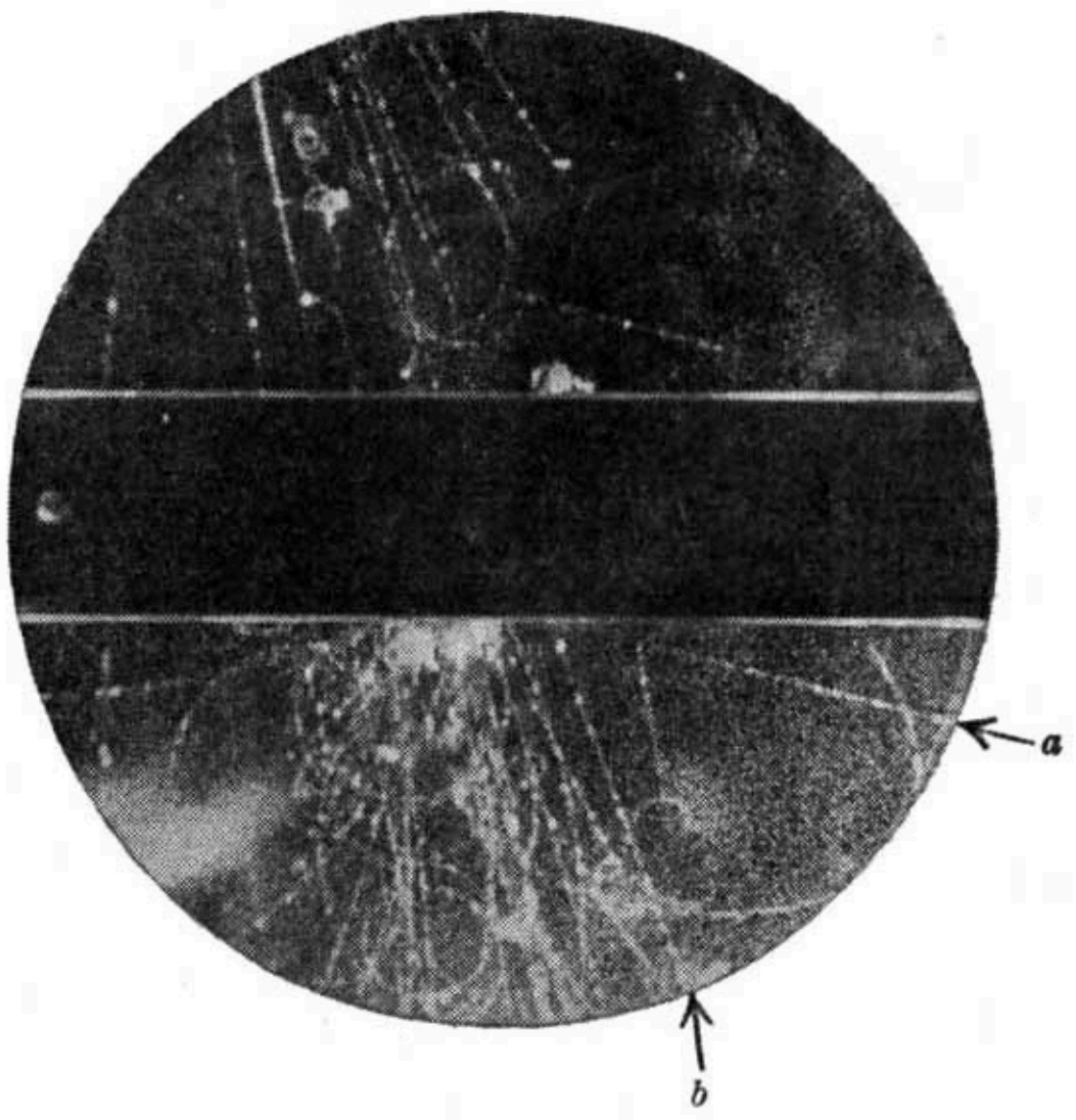
Winter 2023/2024



Credit: CERN

# Questions from past lectures




Credit: G. D. Rochester, C. C. Butler, Nature 160 (1947), 855-857

- Q: How is this picture taken?
  - A: Cloud chamber with lead converter plate.

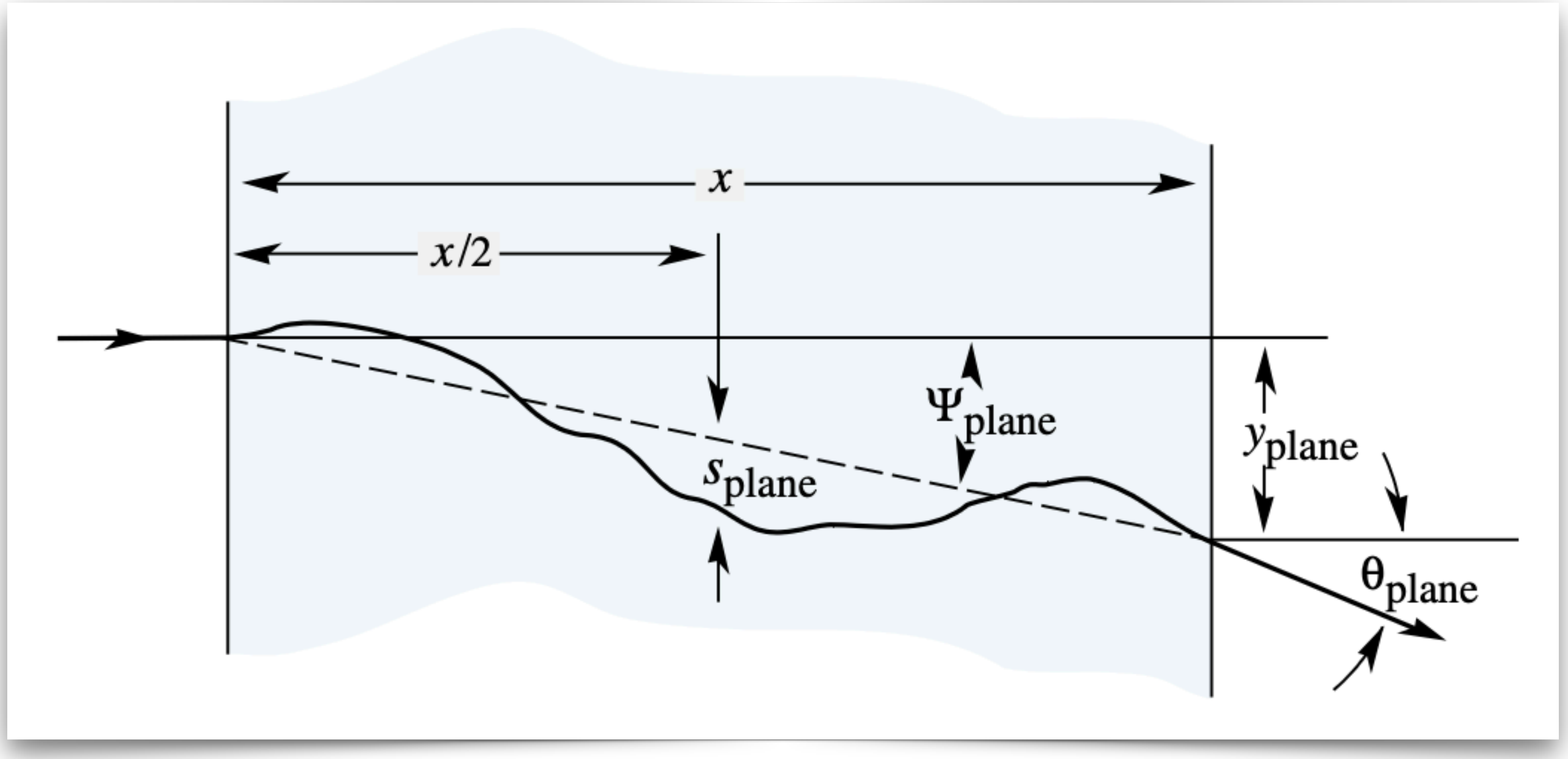
# leftover from Lecture 3

- Charged particles
  - multiple scattering
  - Cerenkov radiation
  - Transition radiation
- Hadronic interactions (charged or neutral)
- Electromagnetic showers

# Charged Particles: Multiple scattering

- Charged particles in a medium do not only loose energy… they are deflected by many small Coulomb-scatters: multiple scattering
- Central-limit theorem: After many random scatters, the net scattering angle is approximately Gaussian
- Standard deviation after distance x:

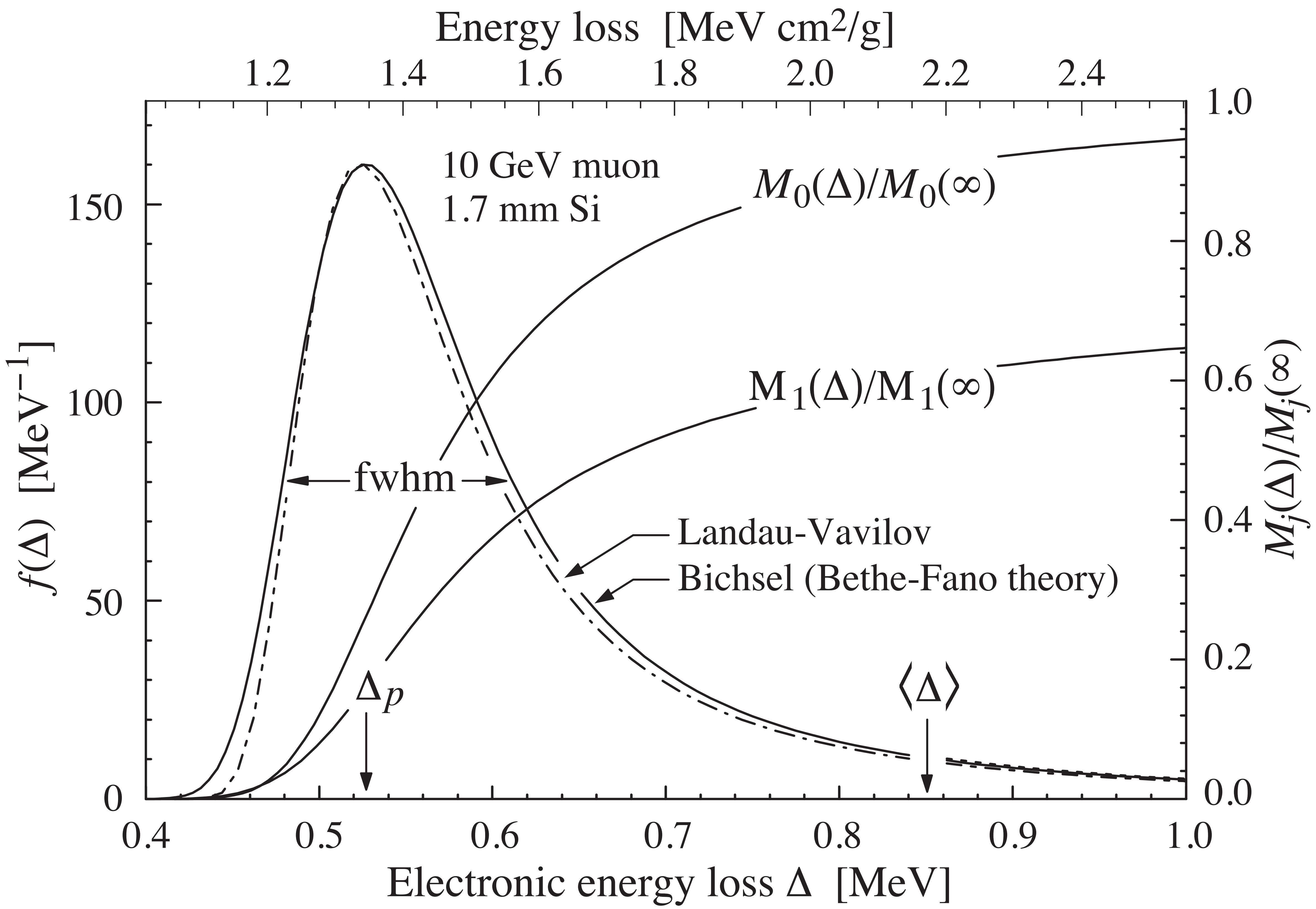
$$\sqrt{\langle \theta^2_{\mathrm{plane}} \rangle} = \theta_0 \approx 13.6\,\mathrm{MeV} \frac{q}{p\beta} \sqrt{\frac{x}{X_0}}$$




Credit: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

# Charged Particles: Energy loss fluctuations

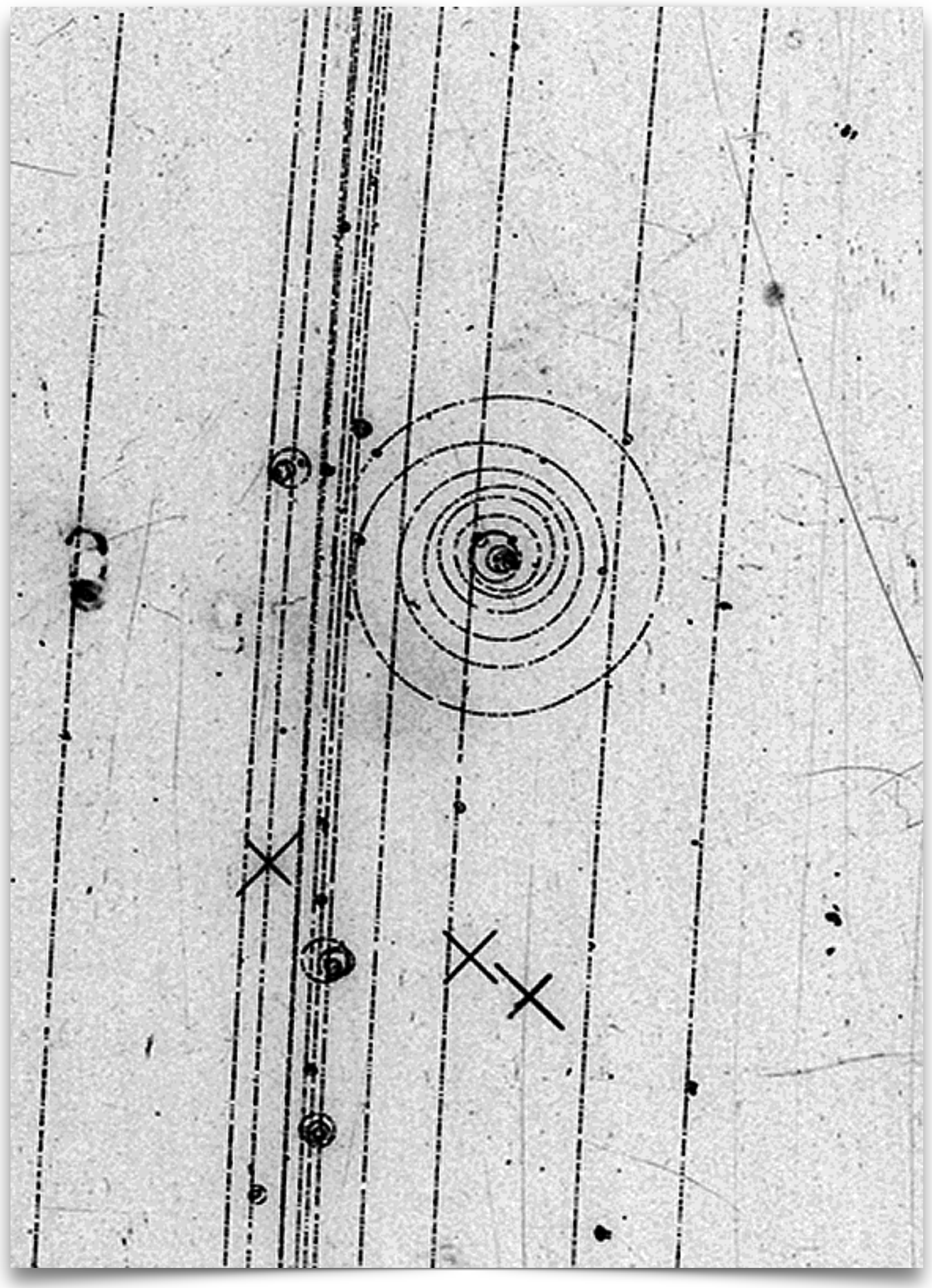
- Bethe-formulate describe the mean energy loss
- There are sizeable fluctuations in energy loss
  - strongly asymmetric distribution around most probable value described by Landau-Vavilov-distribution
  - too make things worse: mean of the Landau distribution is not defined (see CgDA lecture)

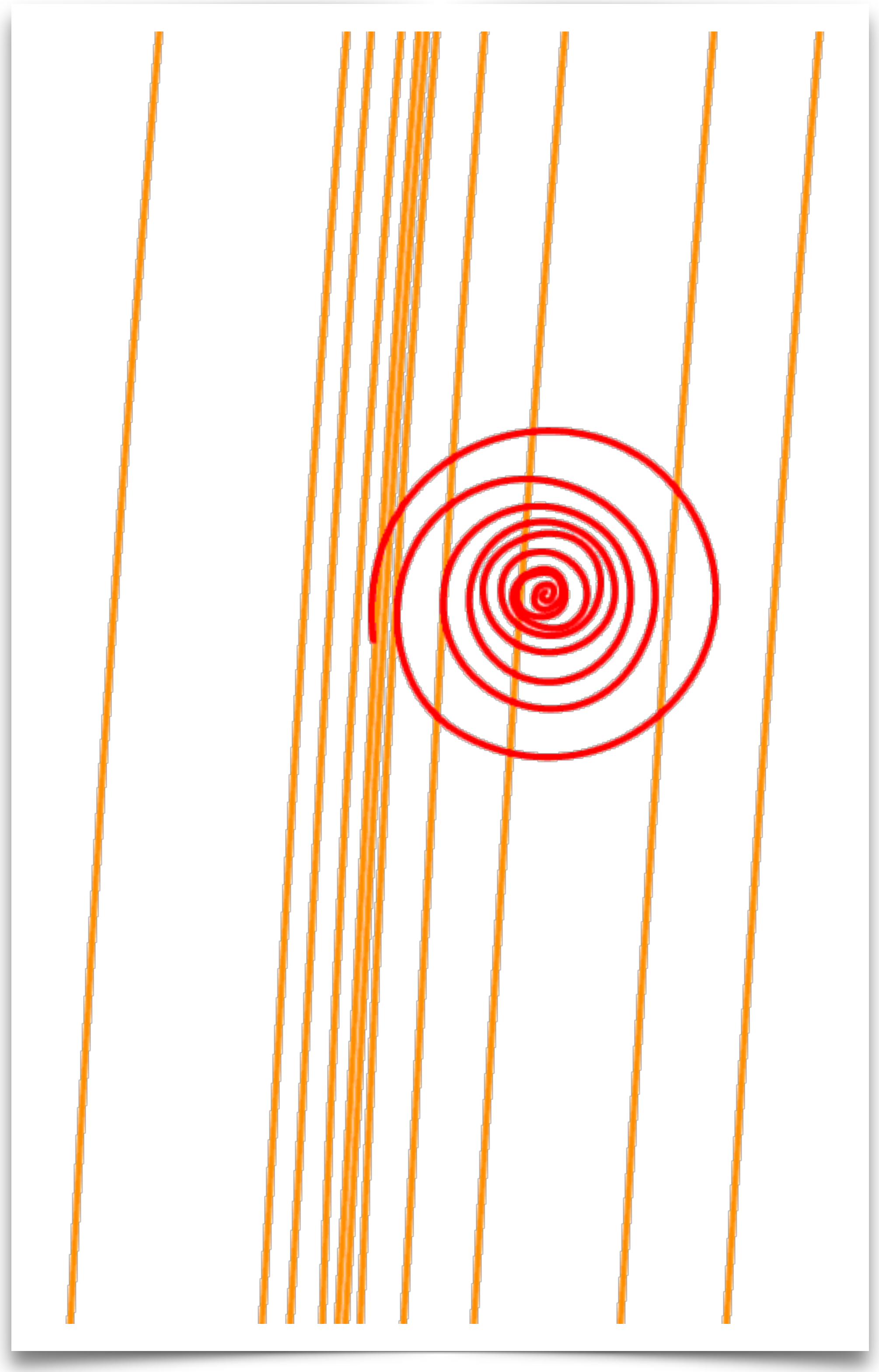



Credit: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

# Charged Particles: δ-rays

- Close to maximal energy transfer to a single electron (tail of Landau distribution)
  - called δ-electrons or “knock-on”-electrons that have enough energy to ionize material on their own…

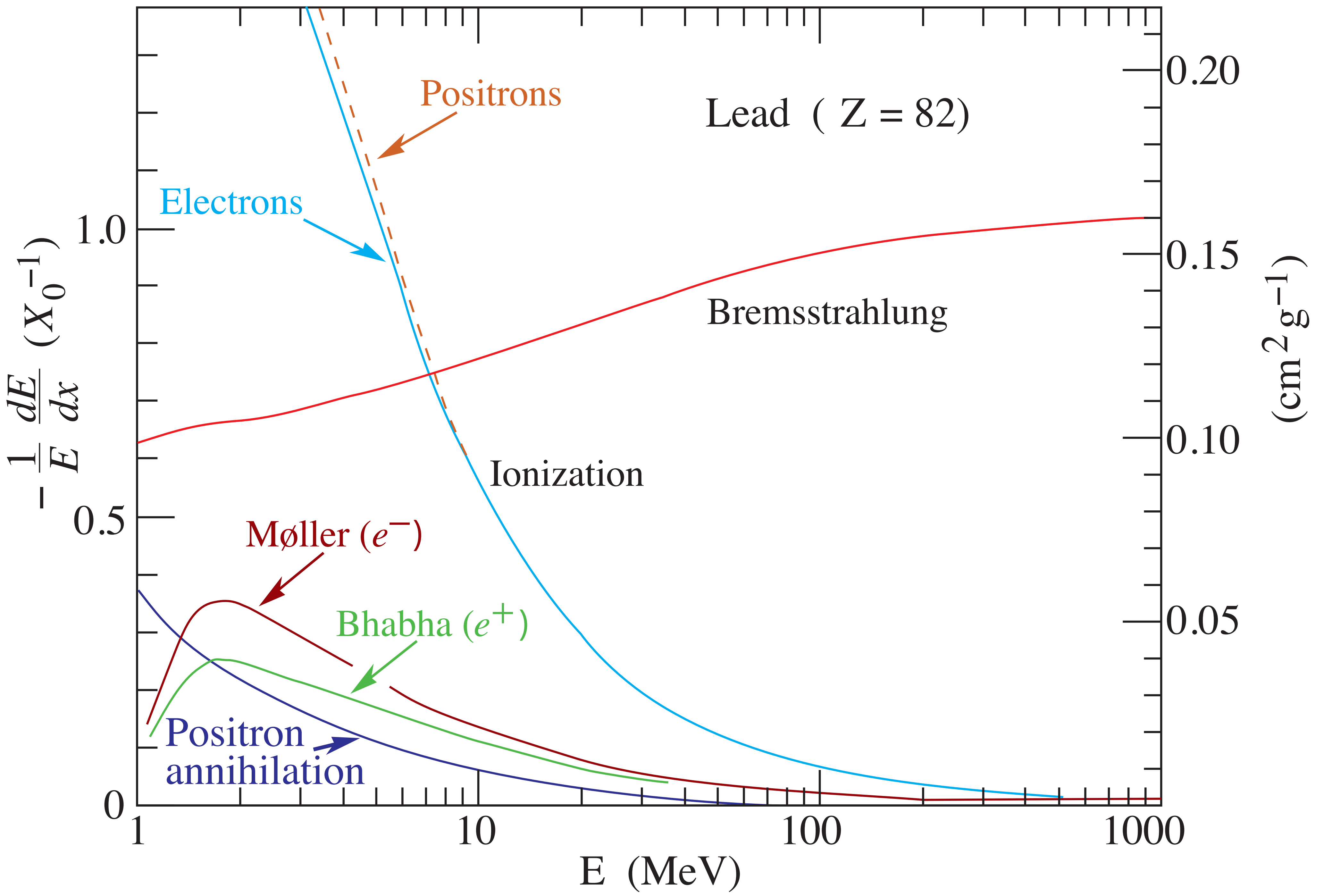


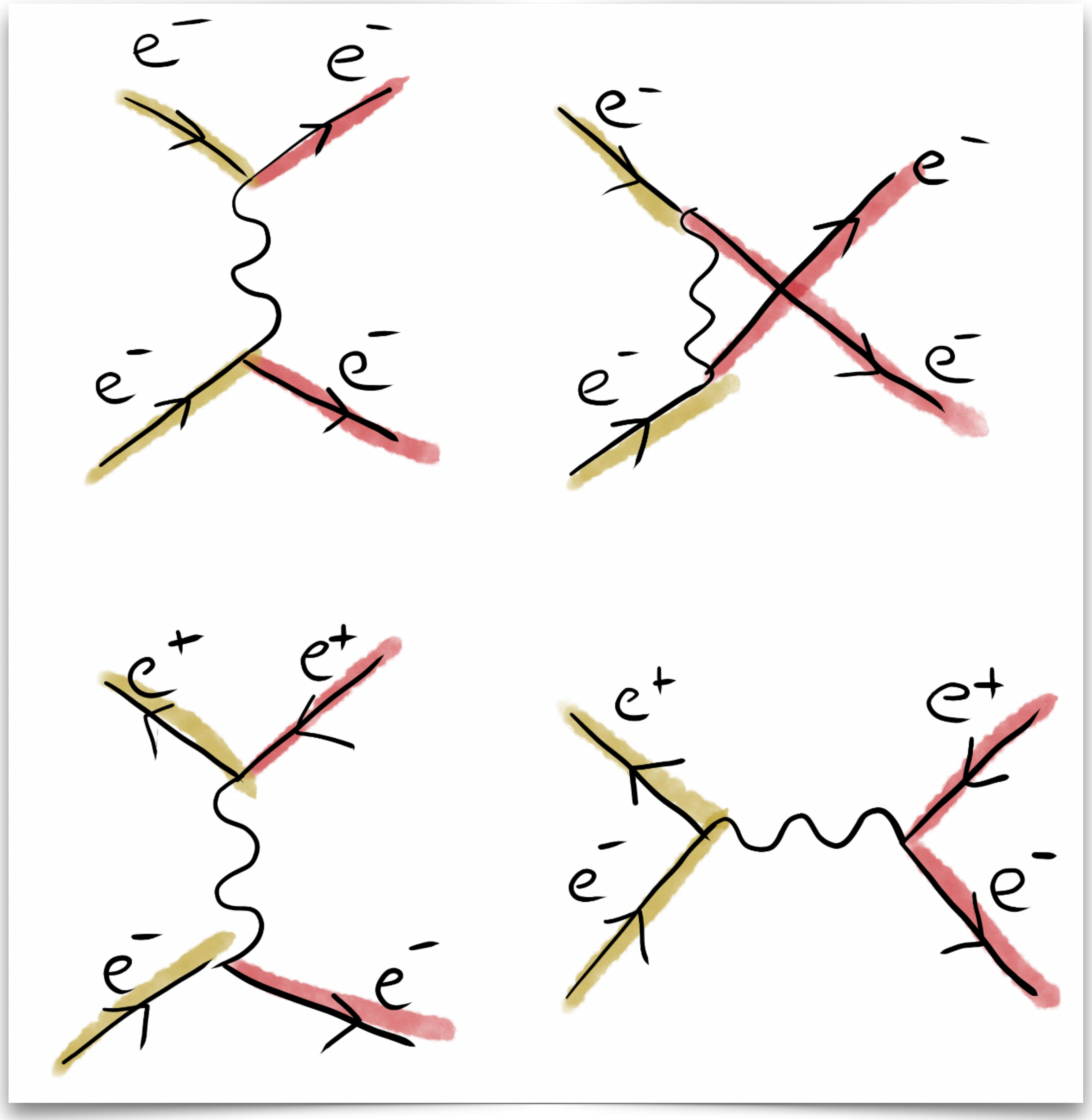


Credit: https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/gallery/gal2_12.htm

# Charged Particles: energy loss for electrons

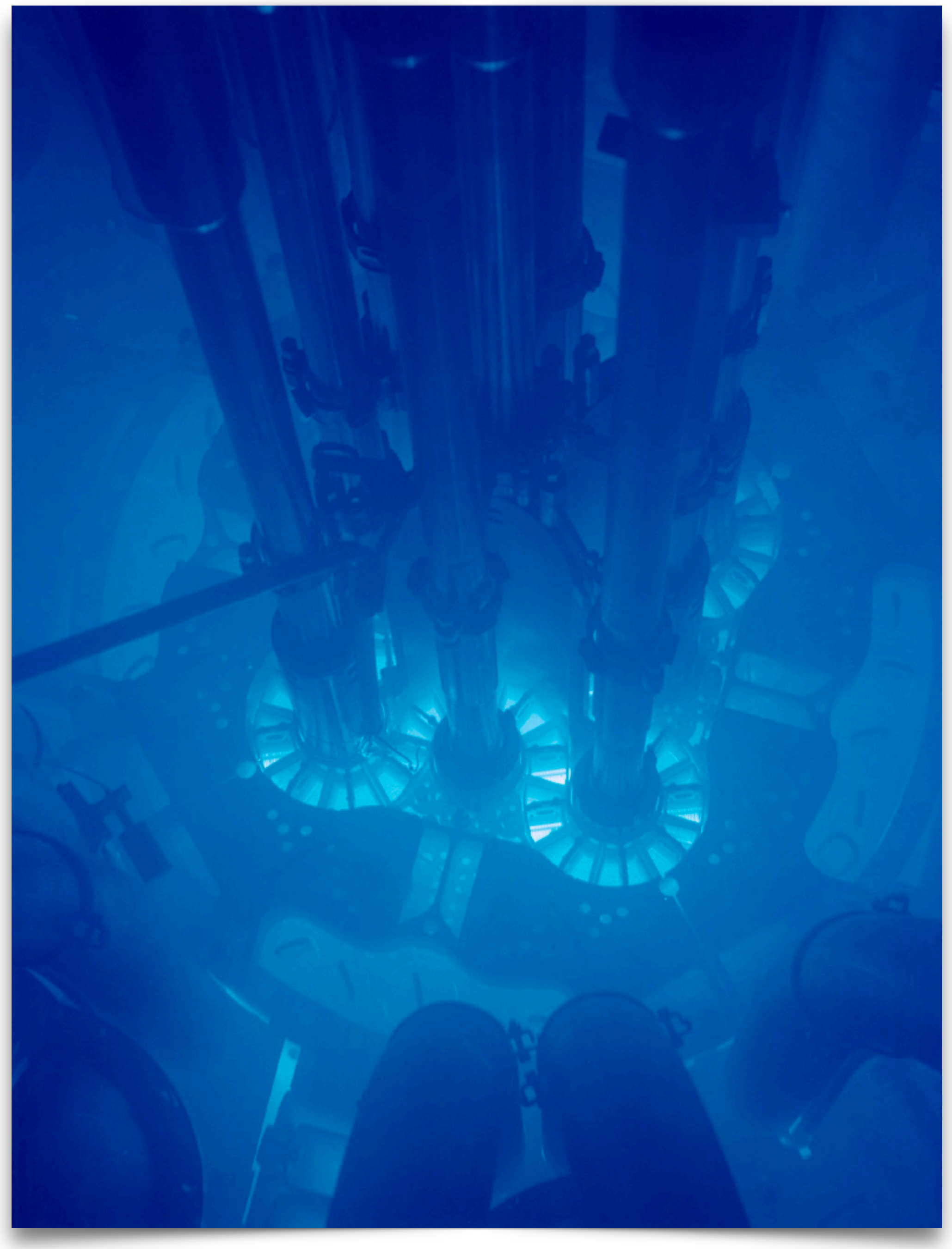
- At low energies in addition to Bremsstrahlung and ionization:
  - electrons: Møller scattering
  - positrons: Bhabha scattering, pair annihilation



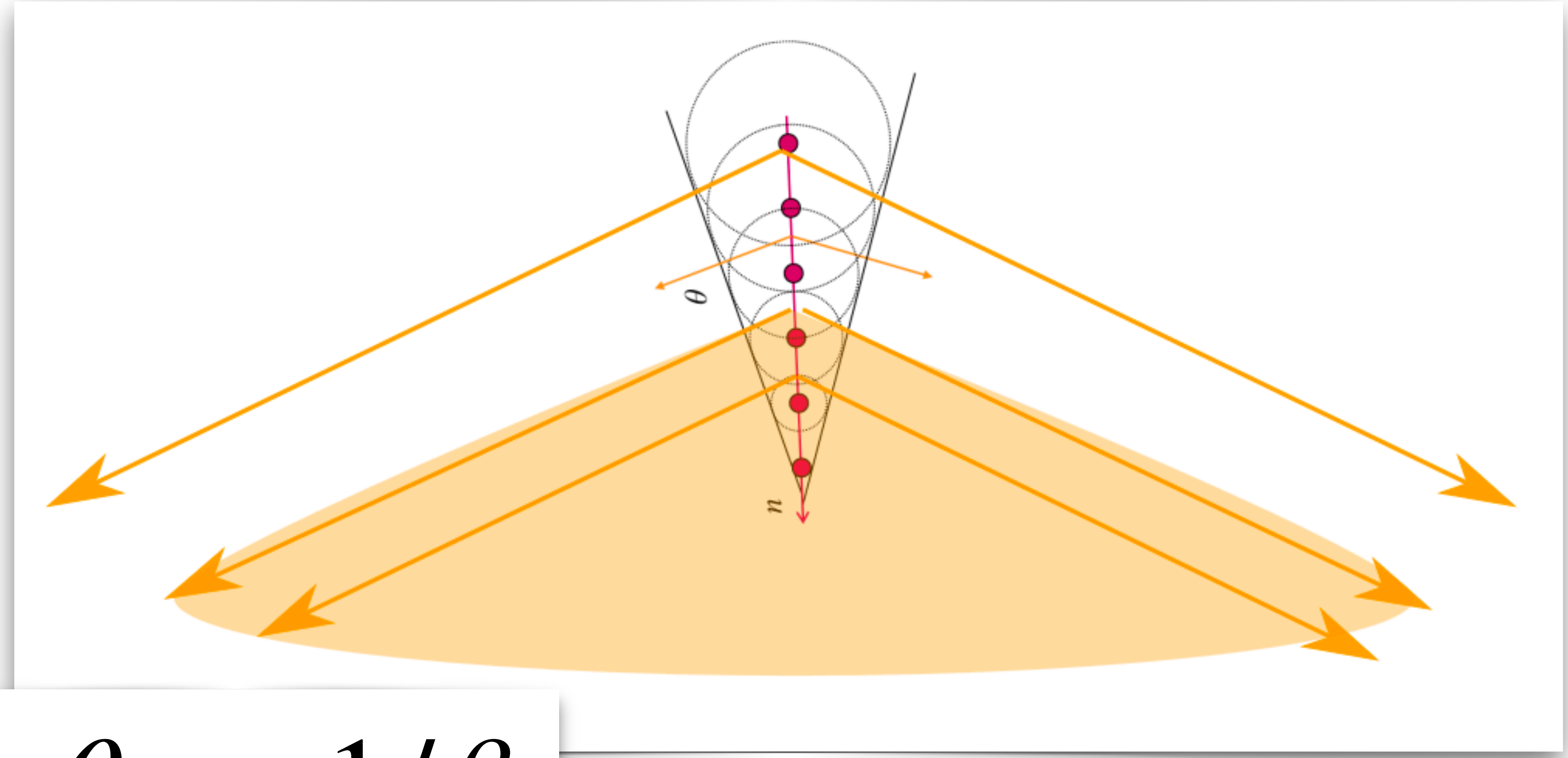
# Charged Particles: Cerenkov radiation

- Radiation emitted by charged particles when passing a **homogenous** dielectric medium at a speed β greater than the phase velocity of light in that medium ($\beta > 1/n$).
  - caused by polarization of material and subsequent photon emission
  - if particle is slow, destructive interference destroys macroscopic light emission
  - visible if medium is transparent to ~blue light
- Cerenkov angle $\theta_C$ depends on material and particle speed: $\cos\theta_C = 1/(n\beta)$.



Cerenkov radiation in cooling water of the Idaho nuclear test reactor

Credit: Argonne National Laboratory, CC BY-SA 2.0



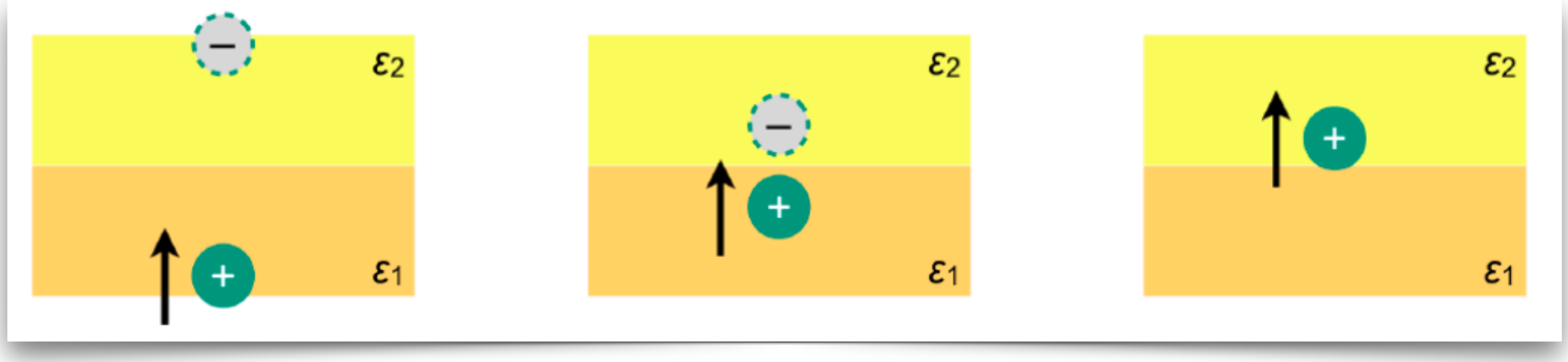

Credit: https://physics.stackexchange.com/

$$\theta_c \propto 1/\beta$$

# Charged Particles: Transition radiation

- Radiation emitted when a charged particle passes through the boundary between two homogenous media with different permittivity ε.
- Classical explanation: Radiation of a time-dependent dipole between the charge and its mirror charge
- Intensity:

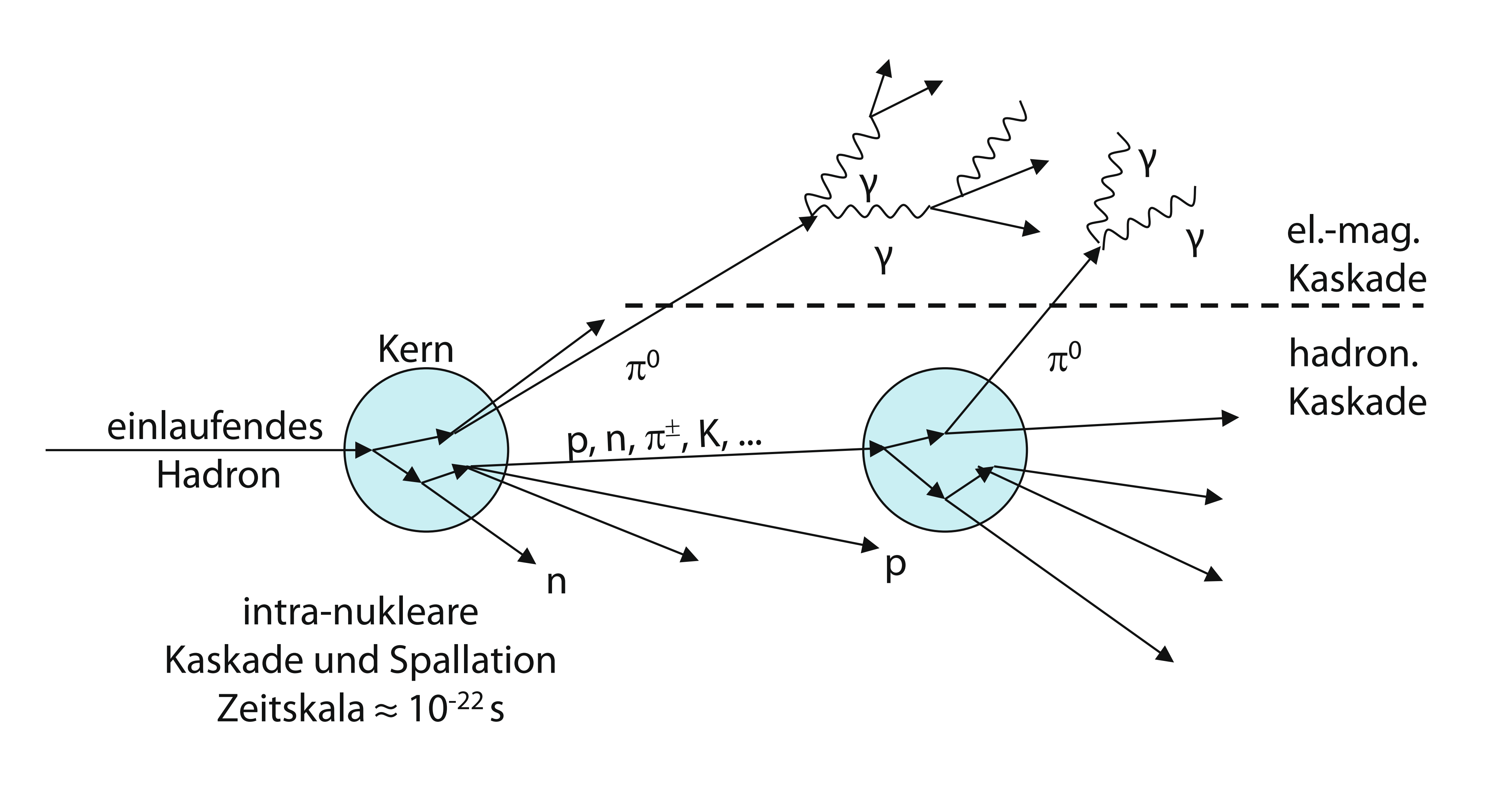
$$I = \alpha q^2 \gamma \frac{\omega_p}{3}$$ with $\omega_p^2 = \frac{n_e e^2}{\epsilon_r \epsilon_o m_e}$ of the medium with larger $\omega$



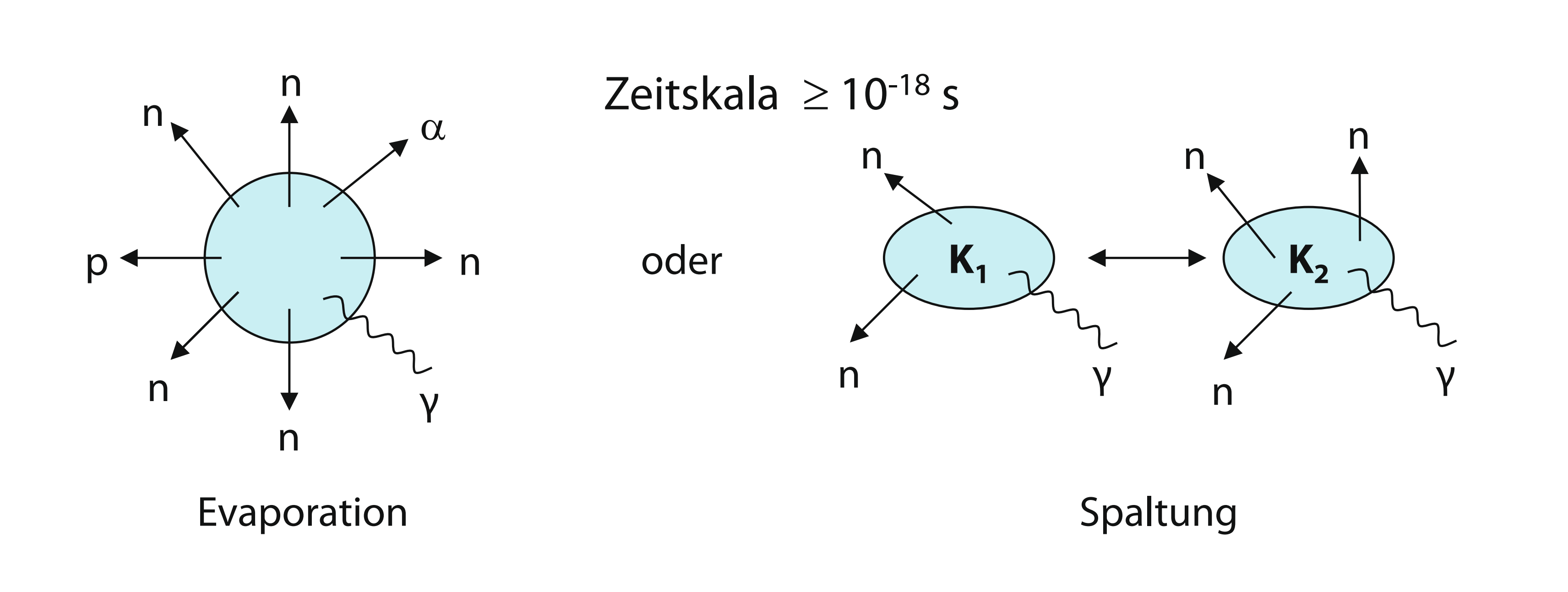

$$I \propto \gamma$$

# Charged Particles: Hadronic Interactions

- Strong interactions between hadrons and nuclei
  - production of secondary hadrons (mostly pions), about 1/3 of those will be neutral pions decaying to two photons*
  - delayed nuclear evaporation and spallation
  - production of "invisible" neutrinos in hadron decays
  - production of long lived hadrons carry energy away ("split-offs" or "satellites")
- Huge fluctuations, "missing" energy (from neutrinos) and "extra" energy (e.g. from nuclear fission and evaporation)
- This is a mess!




Credit: Wermes & Kolanoski, 2016




* This is a good chance to practice how to use the Particle Data Group website

# Charged Particles: Hadronic Interactions

- Absorption of hadrons in matter is parametrized by hadronic interaction length $\lambda$:

$$I(x) = I_0 \exp\left(\frac{x}{\lambda}\right) \text{ with } \lambda = \left(\sigma_{\text{inel.}} \frac{N_A}{A} \rho\right)^{-1}$$

- $\lambda$ is material dependent and typically 20-30× larger than the radiation length $X_0$
- $\lambda$ is tabulated for most used materials

Atomic and nuclear properties of iron (Fe)

| Quantity | Value | Units | Value | Units |
|---|---|---|---|---|
| Atomic number | 26 | | | |
| Atomic mass | 55.845(2) | g mol$^{-1}$ | | |
| Density | 7.874 | g cm$^{-3}$ | | |
| Mean excitation energy | 286.0 | eV | | |
| Minimum ionization | 1.451 | MeV g$^{-1}$cm$^2$ | 11.43 | MeV cm$^{-1}$ |
| Nuclear interaction length | 132.1 | g cm$^{-2}$ | 16.77 | cm |
| Nuclear collision length | 81.7 | g cm$^{-2}$ | 10.37 | cm |
| Pion interaction length | 160.7 | g cm$^{-2}$ | 20.41 | cm |
| Pion collision length | 107.0 | g cm$^{-2}$ | 13.59 | cm |
| Radiation length | 13.84 | g cm$^{-2}$ | 1.757 | cm |
| Critical energy | 21.68 | MeV (for $e^-$) | 21.00 | MeV (for $e^+$) |
| Muon critical energy | 347. | GeV | | |
| Molière radius | 13.53 | g cm$^{-2}$ | 1.719 | cm |
| Plasma energy $\hbar\omega_p$ | 55.17 | eV | | |
| Melting point | 1811. | K | 1538. | C |
| Boiling point @ 1 atm | 3134. | K | 2861. | C |

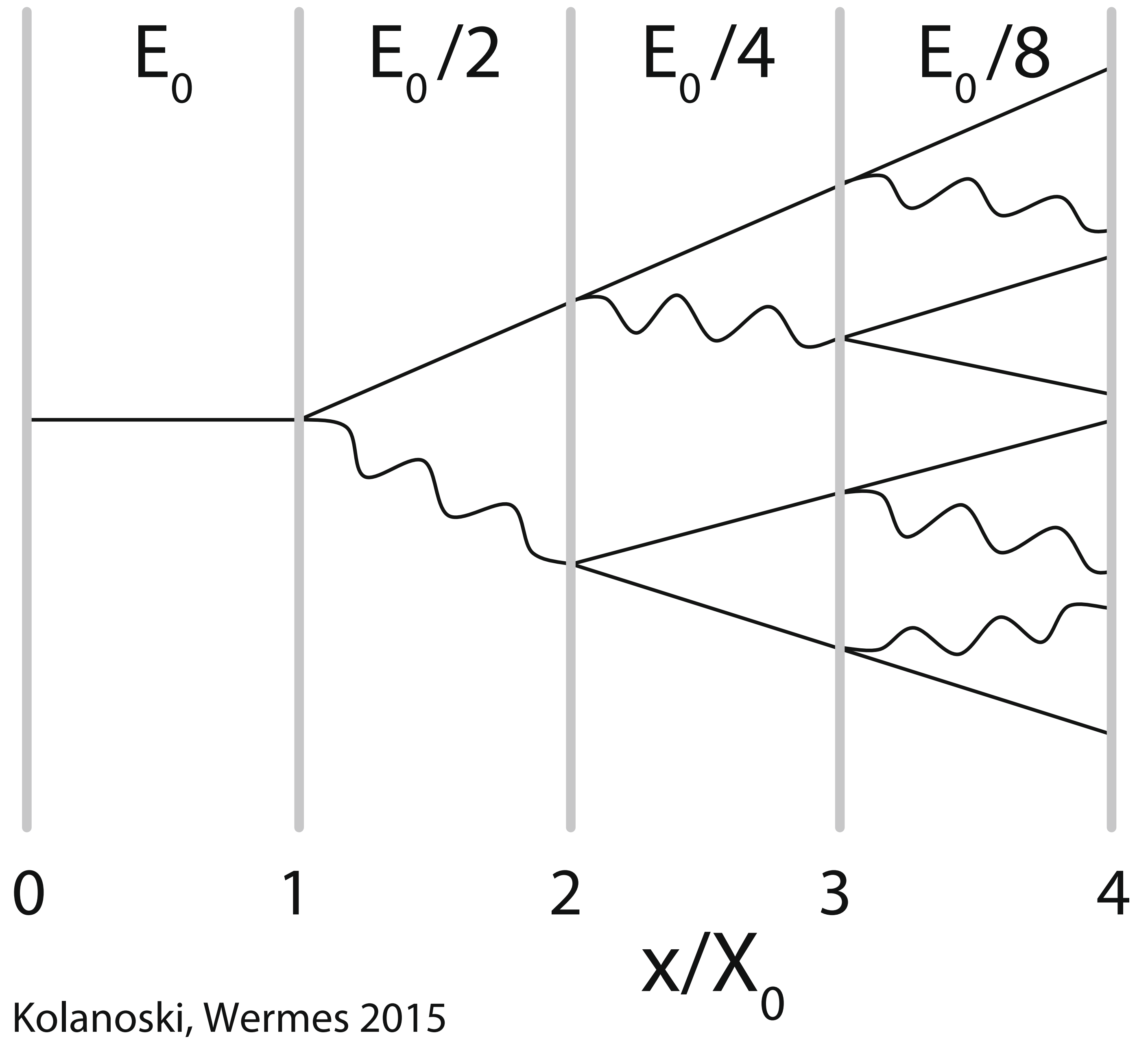
# Charged Particles: Kaons are special

- Interactions of charged low energy (~GeV) Kaons show a strong charge asymmetry:
  - The detector medium typically only contains protons (and neutrons) but not anti-protons
  - Strangeness is a conserved quantum number
  - Flavour hypercharge Y = B + S must be conserved
- e.g. $K^-(\bar{u}s) + p(uud) \rightarrow \pi^0(u\bar{u}) + \Lambda(uds)$ allows hyperon* production, but $K^+(u\bar{s}) + p(uud) \rightarrow \Delta^{++}(uuu) + K^0(d\bar{s})$ does not!

* Hyperons are baryons that contain strange quarks

# Photons, electrons and positrons: Electromagnetic showers

- High energetic photons and electrons (and positrons) can be described by the (very) simplified Heitler model
  - using only two processes: pair production (photons) and bremsstrahlung (electrons), until the energy of the particle is below the critical energy $E_C$ (after which ionization dominates)
  - assume that one of these processes happens after one radiation length $X_0$

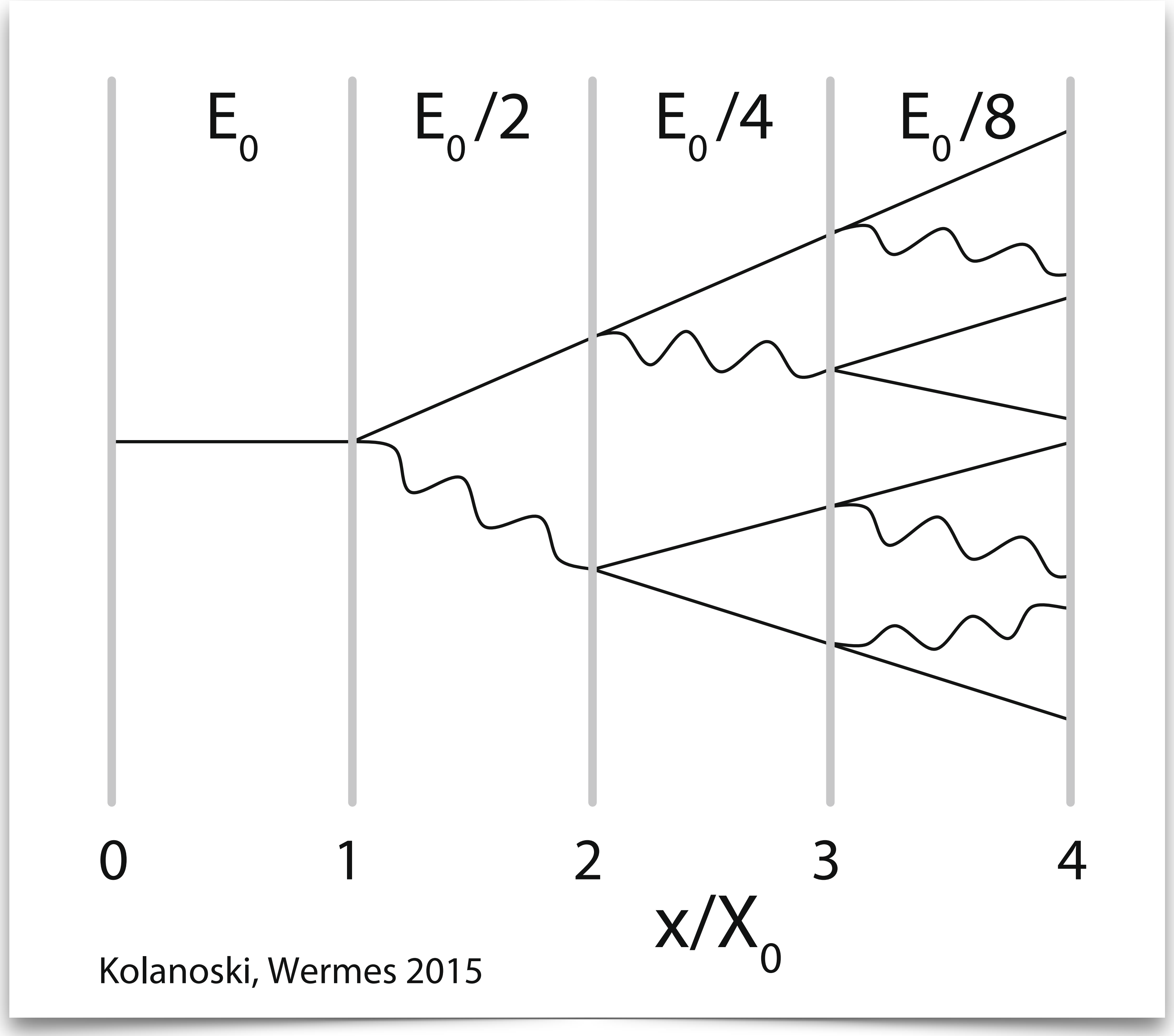



Kolanoski, Wermes 2015

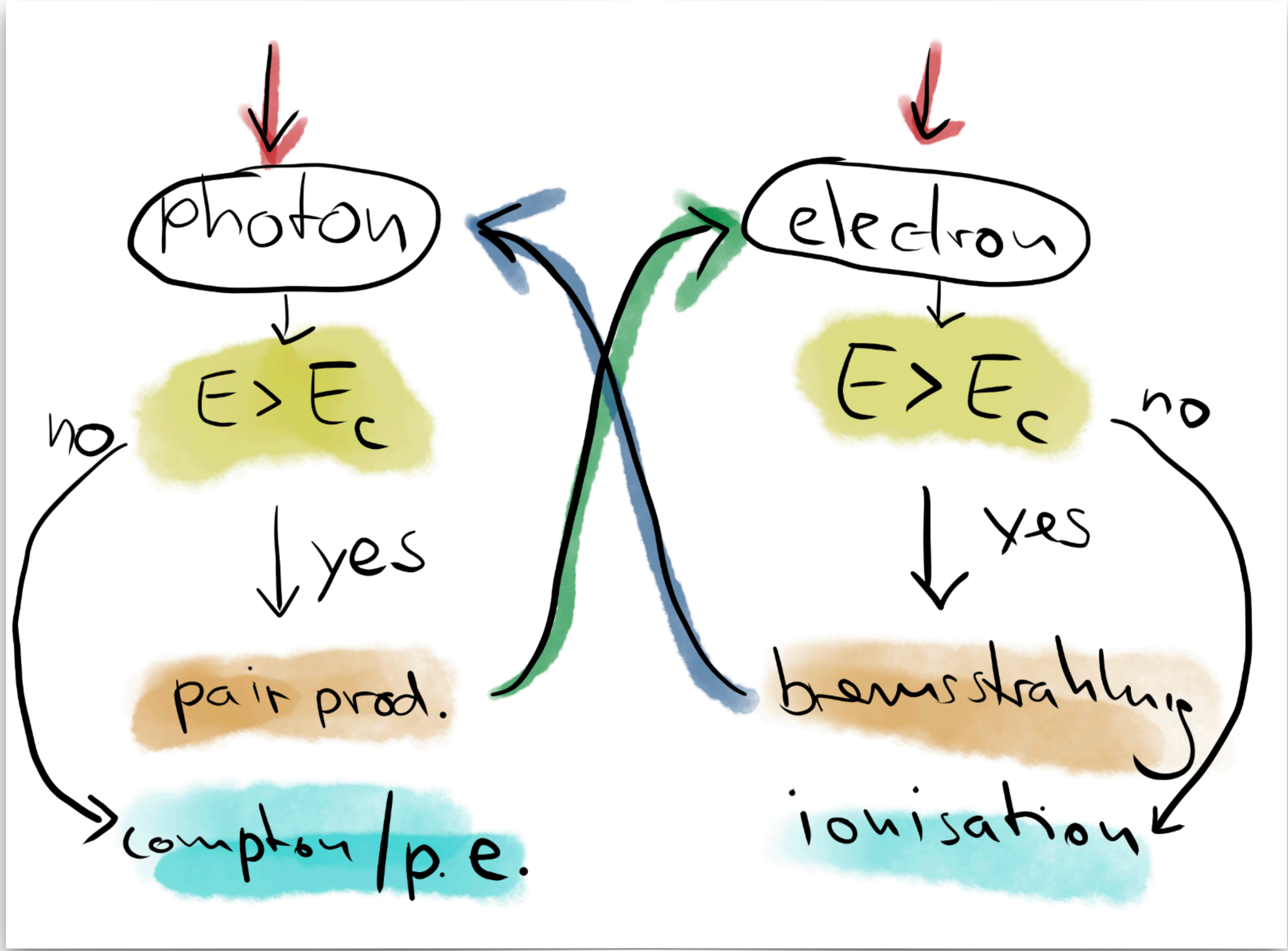
# Photons, electrons and positrons: Electromagnetic showers

- Total number of particles: $n = \frac{E_0}{E_C} \propto E_0$
  - Sum of all distances by all particles: $s = \frac{E_0}{E_C} X_0$
  - Particles after t steps: $(t) = 2^t$ and energy per particle at this point $\frac{E_0}{2^t}$
  - Process continues until energy falls below $E_C$ after $E_C = \frac{E_0}{2^{t_{max}}}$
- At this point, no new particles are created, but all generated ones get absorbed. This “maximum shower depth” is given by

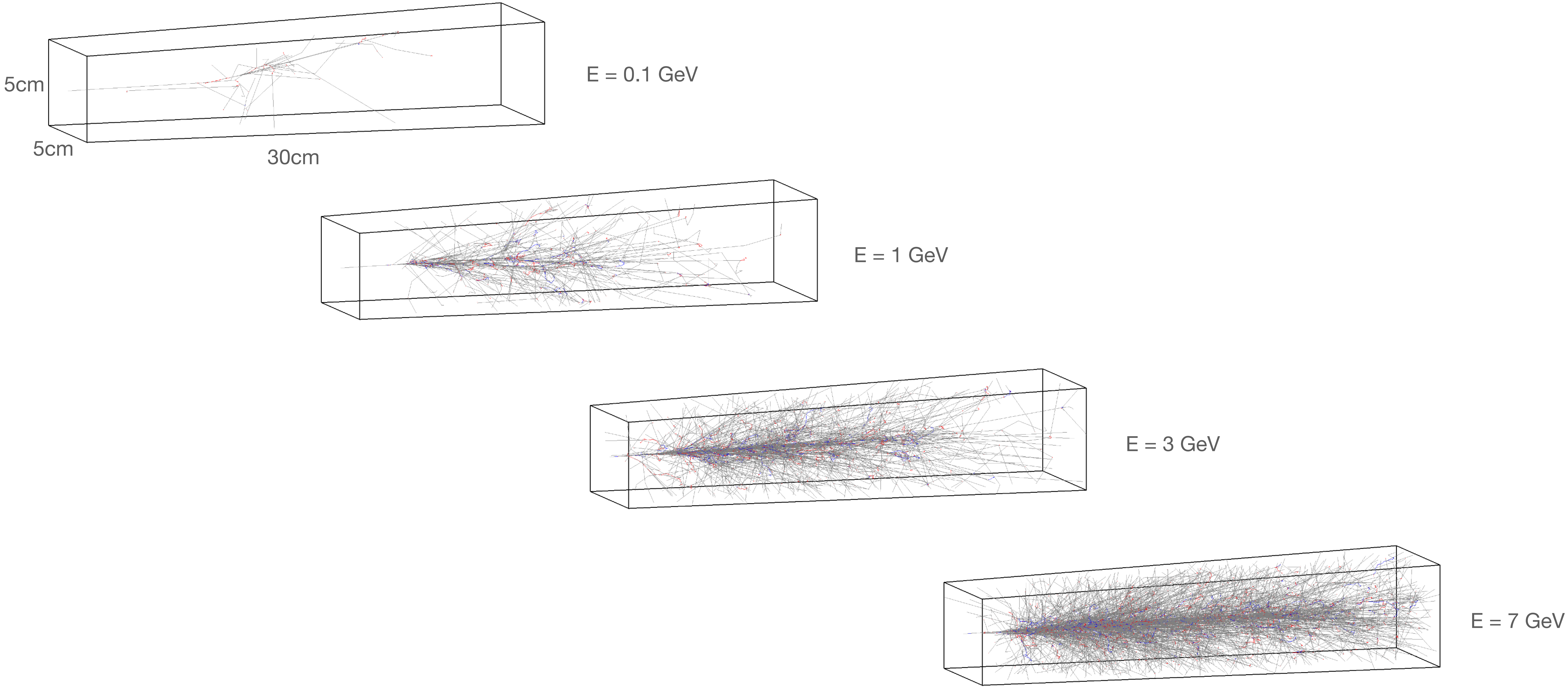
$$t_{\mathrm{max}} = \frac{\ln(E_0/E_C)}{\ln 2} \propto \ln E_0$$ i.e. the “length” of a shower only increases logarithmically with energy!



# Photons and electrons: Electromagnetic showers



# Photons and electrons: Electromagnetic showers




GEANT4 simulation, Belle II crystals, photons

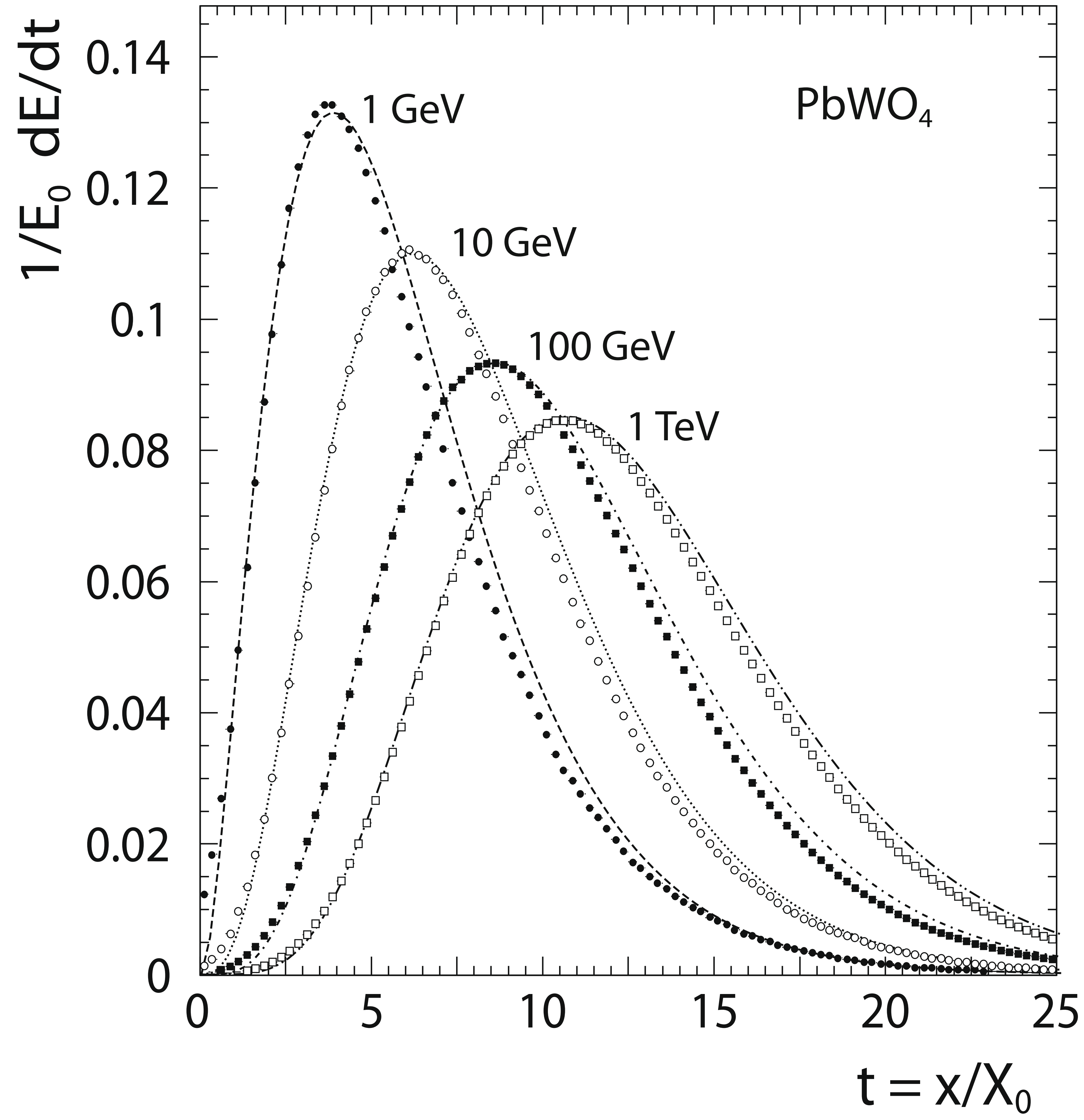
# Photons and electrons: Electromagnetic showers

- Longitudinal shower profile parametrization:

$$\frac{dE}{dt} = E_0 \frac{b^a}{\Gamma(a)} t^{a-1} \exp(-bt)$$

  - Maximum: $t_{\text{max}} = \ln\left(\frac{E_0}{E_C}\right) + \begin{cases} -0.5 & \text{(electrons)} \\ 0.5 & \text{(photons)} \end{cases}$
  - Containment: $t_{98\%} \approx t_{\text{max}} + 13.6 \pm 2.0$
    - Example for a 5 GeV photon in CsI (Belle II):

$$t_{98\%} \approx \left(\ln(5000/11.17) - 0.5 + 13.6\right) X_0 \approx 19.2\, X_0 \approx 36\,\text{cm}$$



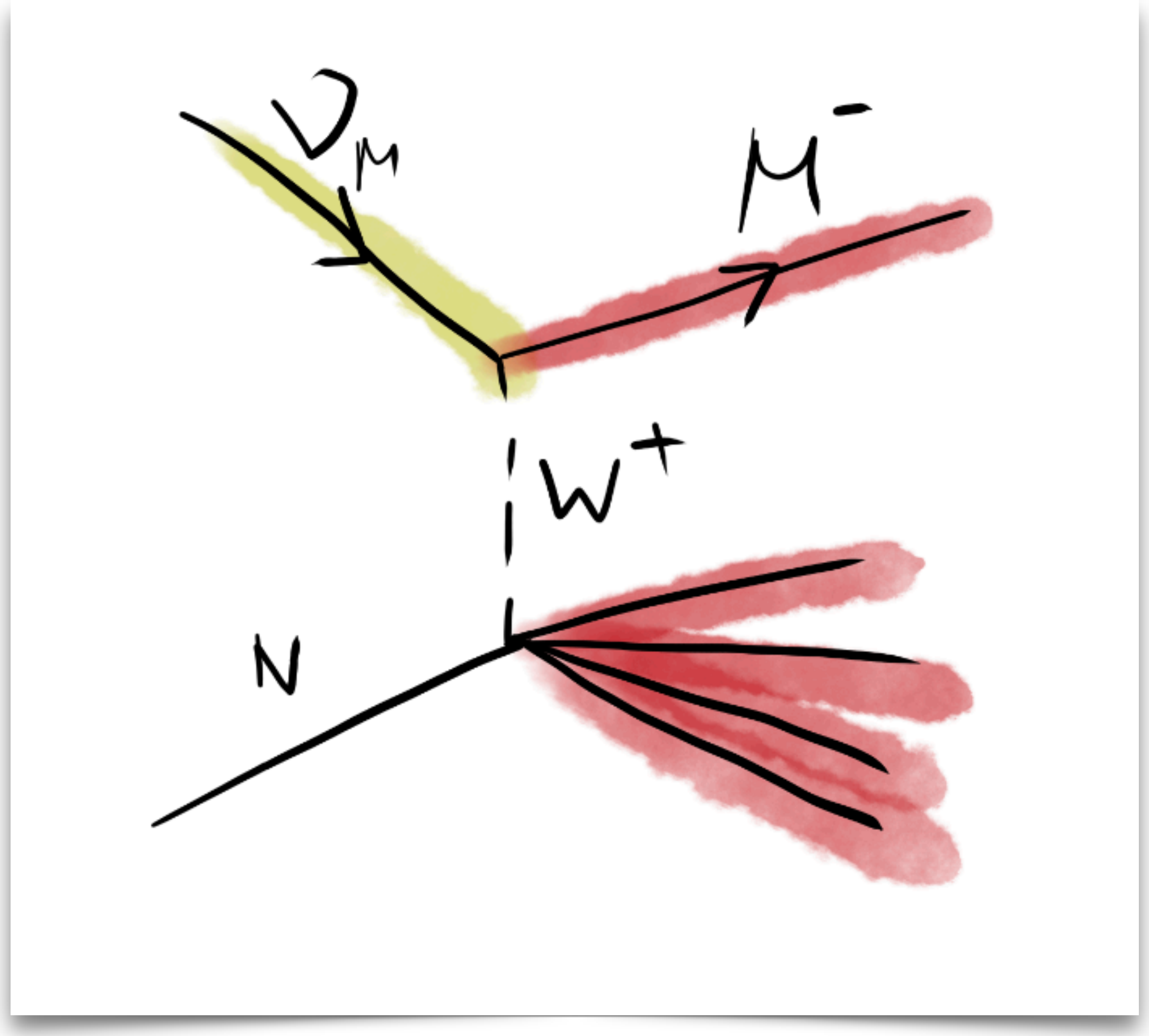

Credit: Wermes & Kolanoski, 2016

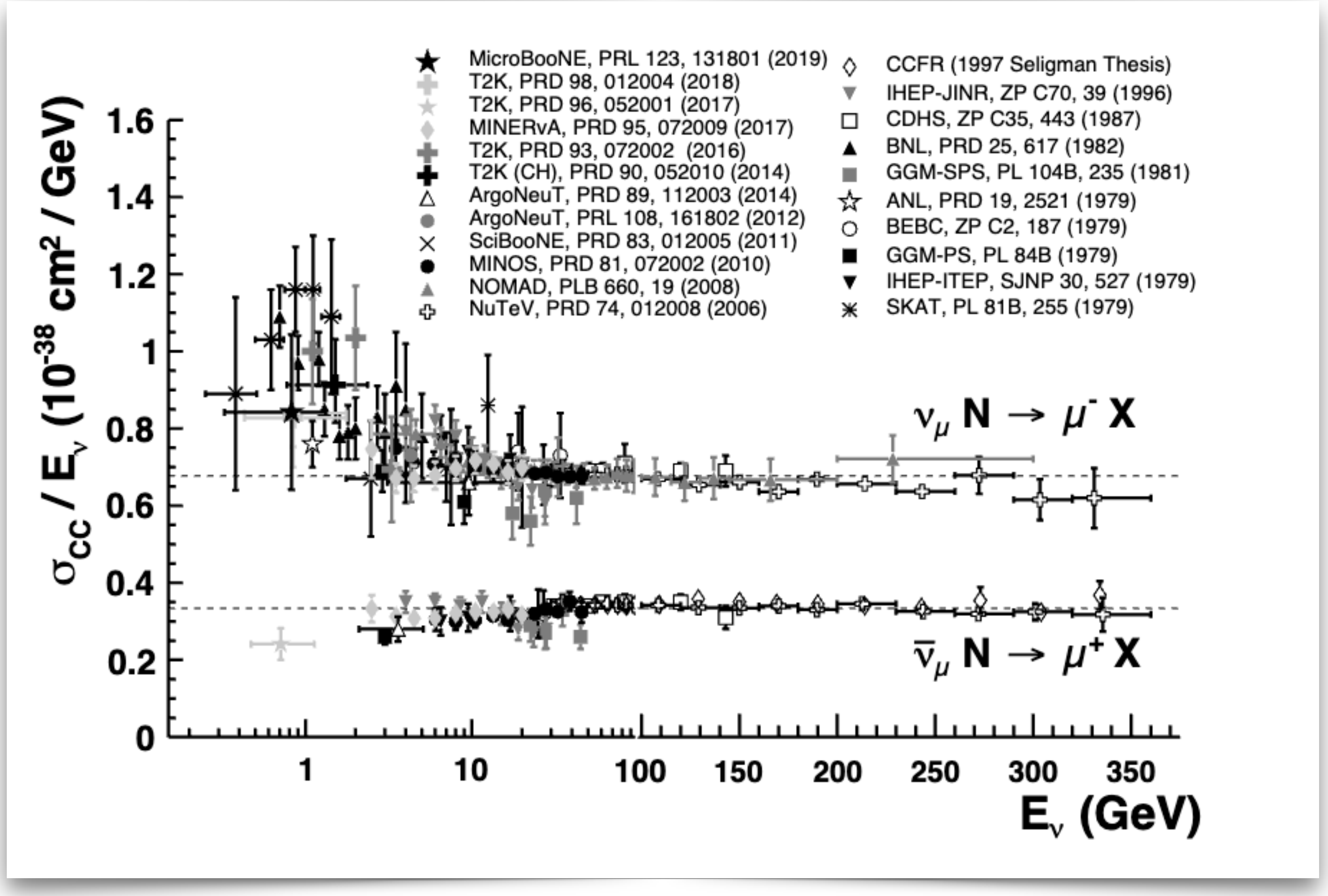
# Intermediate summary particle interactions

- Many different processes contribute to the energy loss depending on energy range, material, and particle
  - **Photons**: Photoelectric effect, Compton-scatterung, pair production
  - **Charged particles**: Ionization and to much less extend Cerenkov and transition radiation
    - special case **electrons**: Bremsstrahlung dominates over ionization at high energies
    - special case **positrons**: Bhabha scattering, pair annihilation
  - **Hadrons**: Nuclear reaction resulting in complicated hadron showers
- Parametrization:
  - Photons and electrons: Radiation length $X_0$
  - Hadrons: Nuclear interaction length $\lambda$

# Neutrinos

- Neutrinos can interact only via the weak force
- Cross section are very small (but they increase with energy)
- Typical absorption length for a a MeV neutrino in lead is ~1 lightyear
- For all collider experiments, the probability to see a neutrino interaction, is zero*



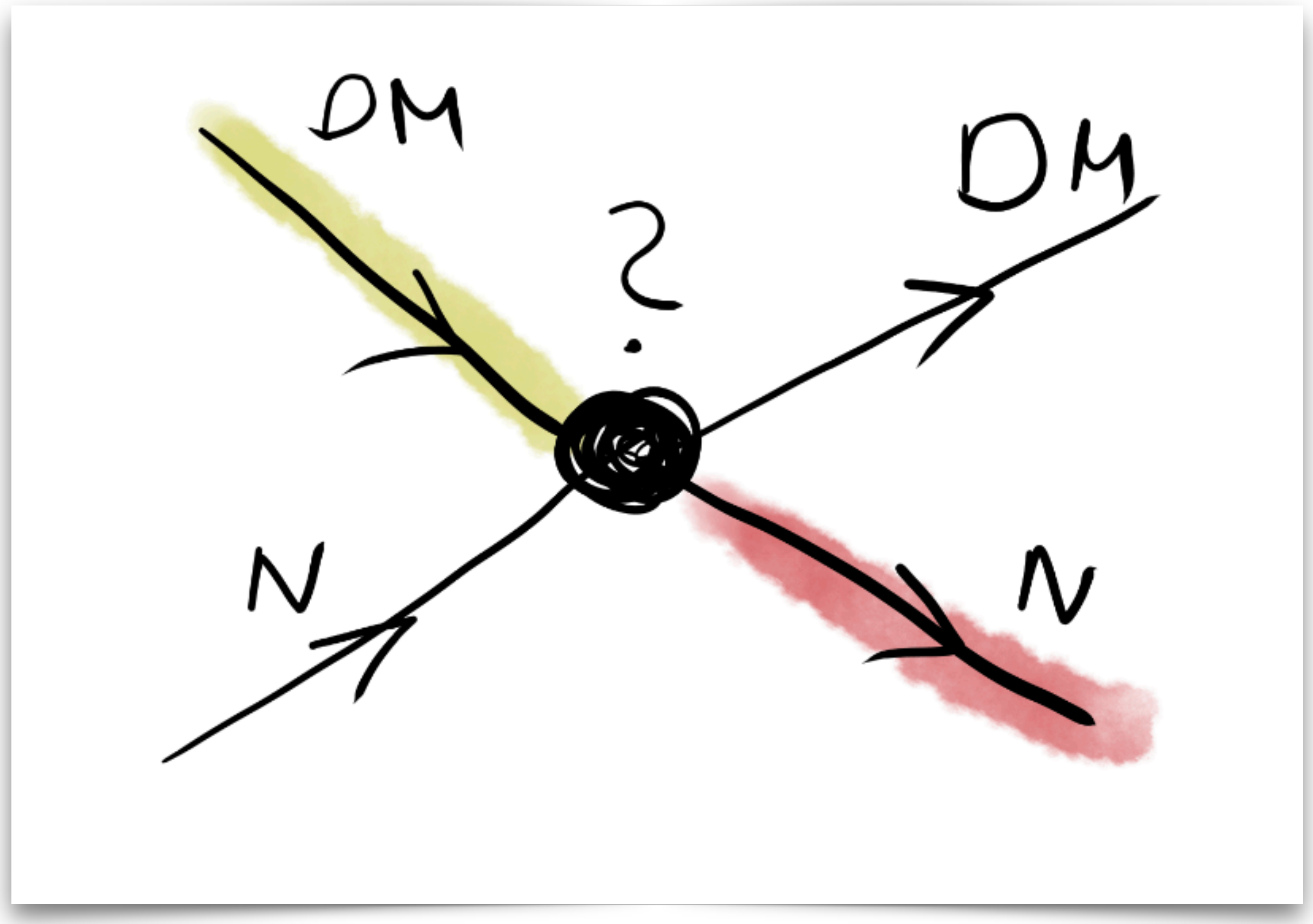



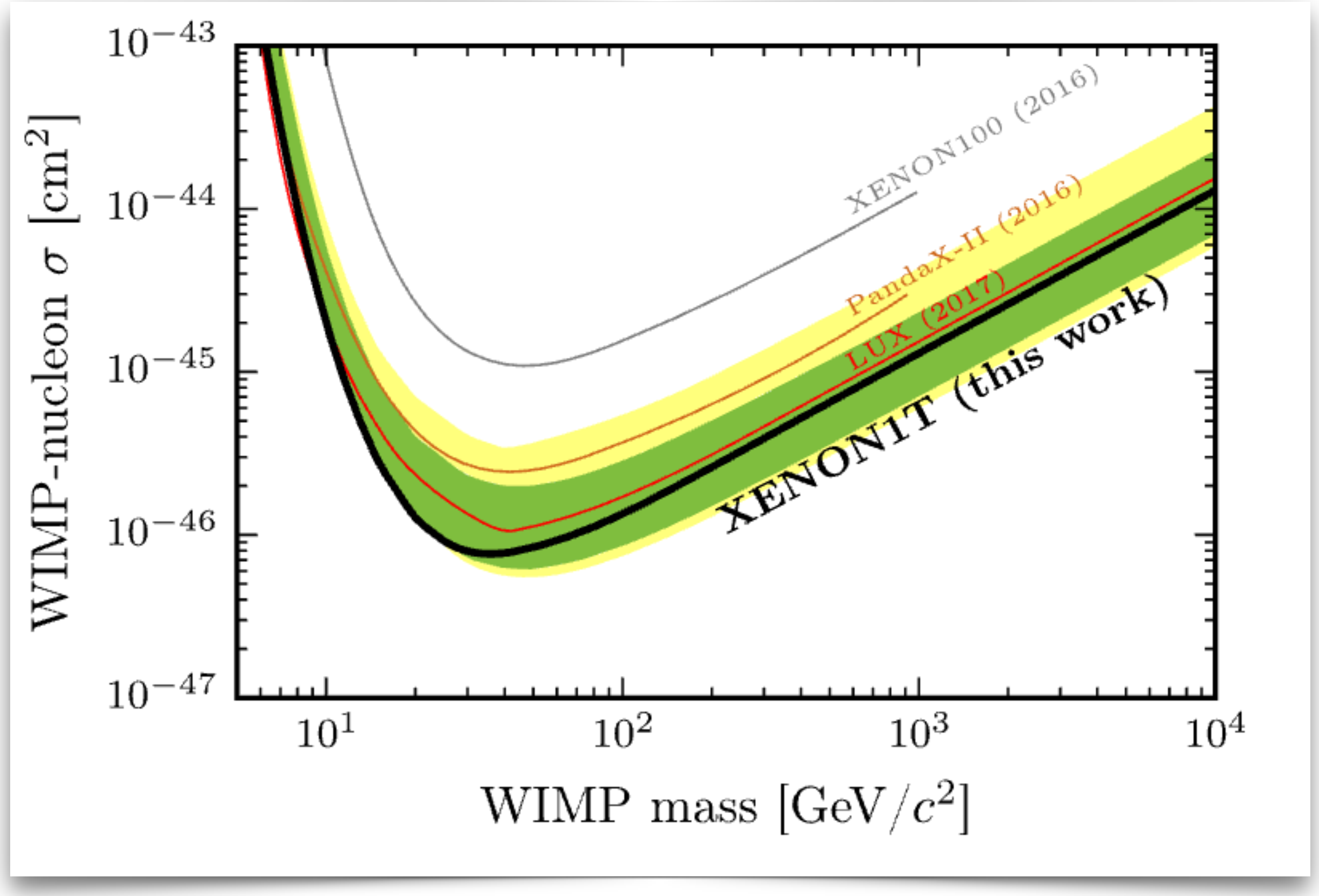

Credit: /https://pdg.lbl.gov/2022/reviews/rpp2022-rev-nu-cross-sections.pdf

* We will have lectures in TP1 on neutrino physics later.

# Dark Matter

- Dark matter are hypothetical particles, we do not know the cross section
- From cosmological evidence, we know that the cross section with normal matter must be very small
- We have determined upper limits for cross sections, i.e. maximal values, that are even smaller than for neutrinos
- For all collider experiments, the probability to see a dark matter interaction, can safely be assumed to be zero*




Credit: Phys. Rev. Lett. **119**, 181301 (2017)

* We will have lectures in TP1 on dark matter physics later.

“Fred” (by Tristan Brandes)

# Learning goals

- Basic principles of GEANT4 simulation

- Understanding of typical particle physics detector designs
- Understanding of main sub-detector types used in particle physics

- Develop an intuitive understanding of a particle detectors using VR

# Simulation

- Before building a (expensive) new prototype of a real detector, detectors are studied and optimized via **simulation**
- Once an experiment is running, the observation must be compared to an expectation that is typically determined by using **simulation**

# Simulation vs reality

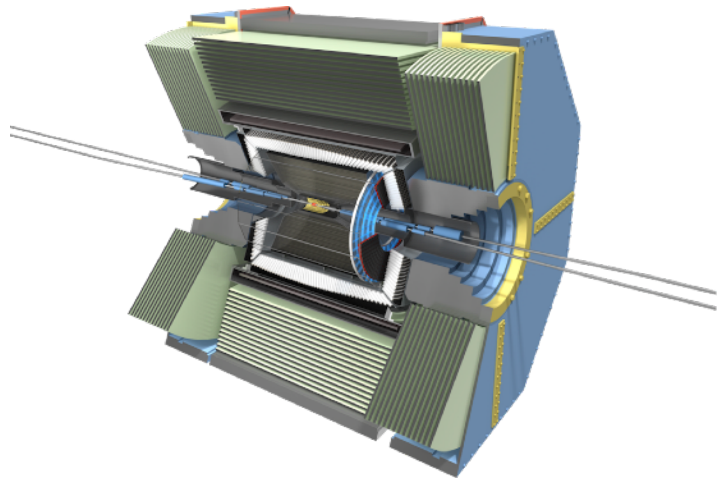
compare with theory

**Reality**

real experiment

**Simulation**

software “twin”



- theory calculation
- event generator
- hadronization (quarks → hadrons)
- propagation through detector
- simulated electronics response

- detector readout

- digitized and calibrated detector hits → e.g. “calorimeter cell 105 has recorded a puls-height of 234 counts that is calibrated to 12.6 MeV, at clocktick 12 that is calibrated to 2.1ns”
- reconstruction → e.g. multiple calorimeter cells are grouped into a cluster object
- object calibration → e.g. the reconstructed cluster object energy is corrected for longitudinal leakage
- user analysis → e.g. reconstruct Higgs mass via $H \to \gamma\gamma$

# Simulation vs reality

compare with theory

**Reality**

real experiment

→ VL 4, 6

detector readout

theory calculation → VL 7, 8 and TTP

event generator

hadronization (quarks → hadrons) → VL 9

propagation through detector → VL 4

simulated electronics response

digitized and calibrated detector hits (→ VL 5)

reconstruction → VL 5

object calibration → VL 5

user analysis → VL 5

→ VL 10-22

# Simulation vs reality

**Reality**

real experiment

detector readout

theory calculation

event generator

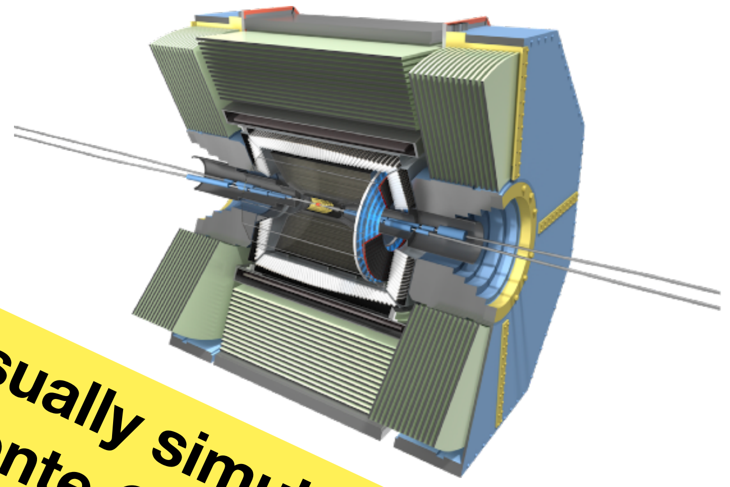
hadronization
(quarks → hadrons)

propagation through detector

simulated electronics
response

**Simulation**

software "twin"



**Usually simulated with Monte Carlo methods**

digitized and calibrated
detector hits

reconstruction

object calibration

user analysis

compare with theory

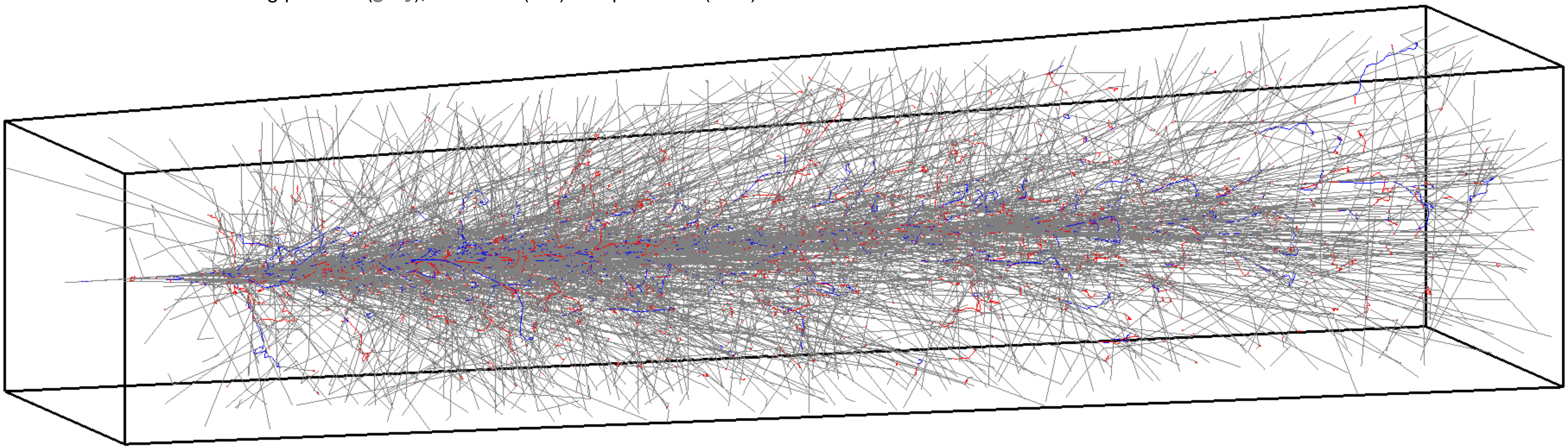
# Monte Carlo detector simulation

- Trace every particle from the primary interaction, e.g. the two muons from a collision $e^+e^- \to \mu^+\mu^-$
- Calculate the interaction probability for every possible (and relevant) interaction in (small) volume elements of the detector
  - Draw a random number to select a process, for example:
    - additional photon from Bremsstrahlung
    - energy loss via ionisation
    - deflection of a charged particle
    - pair production of an electron/positron pair
    - nuclear interaction
    - …
  - Repeat this process until until all particles, including the new ones that may have been created in the above process, are either full destroyed or have left the detector
  - Then repeat the process with a new set of primary particles
- The result is a statistical distribution of number of produced particles and derived quantities like energy depositions

# Monte Carlo detector simulation: Example visualization

**Example: Single incoming photon into a CsI crystal (5×5×30 cm³)**

Several thousand resulting photons (gray), electrons (red) and positrons (blue)



# Monte Carlo detector simulation: Probabilities

- Probabilities $P(L)$ for (non-)interaction along a step of length $L$ are defined via interaction length $\lambda$:
  (do not confuse this with the hadronic interaction length or the radiation length!)

$$P(L) = \exp\left(-\int_0^L \frac{dl}{\lambda}\right) = \eta$$

- Probability density via differentiation for $L$: $w(L) = \frac{1}{\lambda}\exp\left(-\frac{L}{\lambda}\right)$

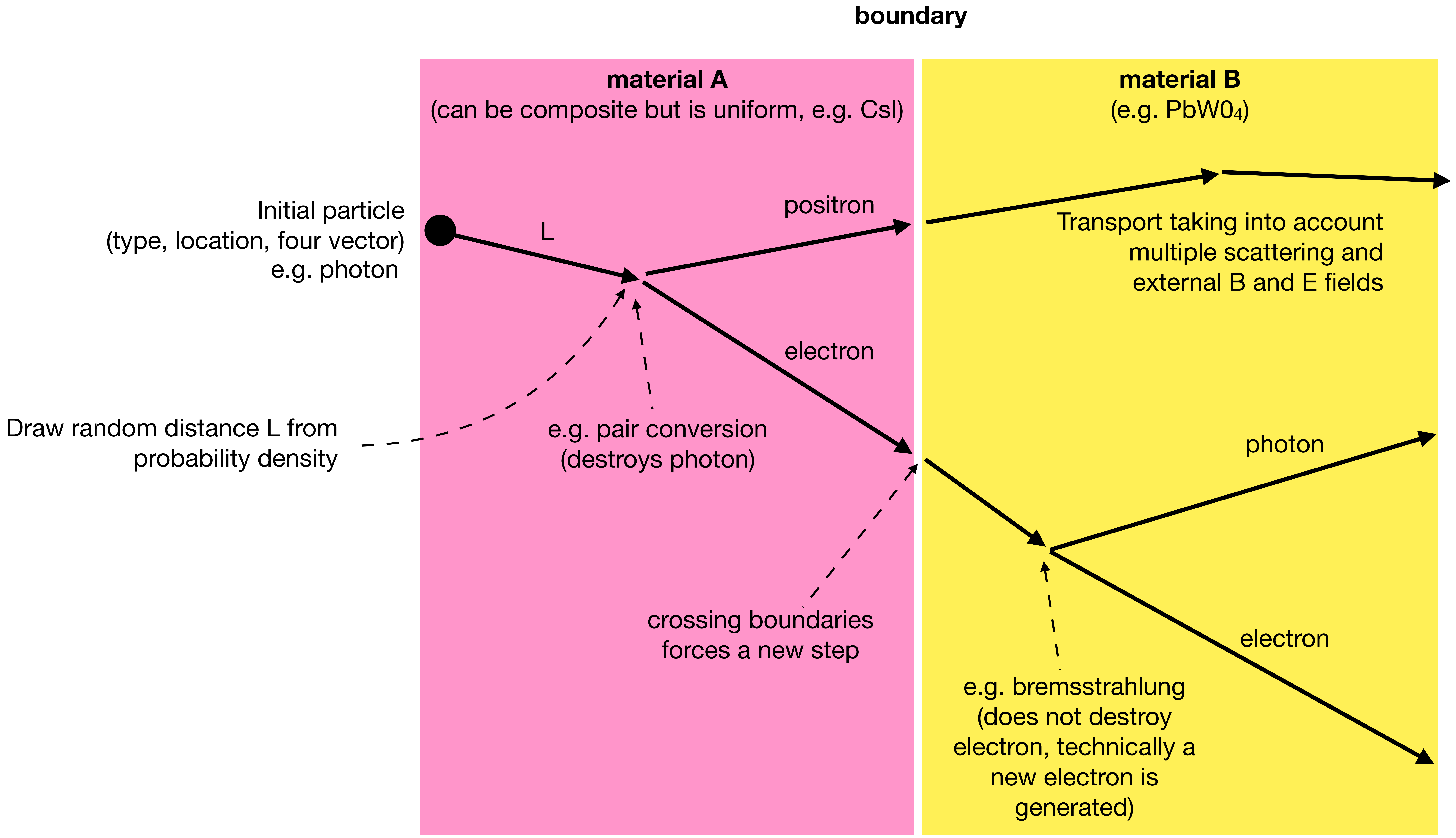
- Three things can happen:
  - 1) nothing (or only elastic interactions): “transport” to end of current volume
  - 2) particle decays in flight (independent of material)
  - 3) interaction with material

# Monte Carlo detector simulation: Decay and interaction

- **Decay in flight**: $-\ln(\eta) = \dfrac{L}{\gamma\beta c\tau}$
  with velocity $v = \beta c$, Lorentz factor $\gamma$ and mean lifetime in the particle restframe $\tau$

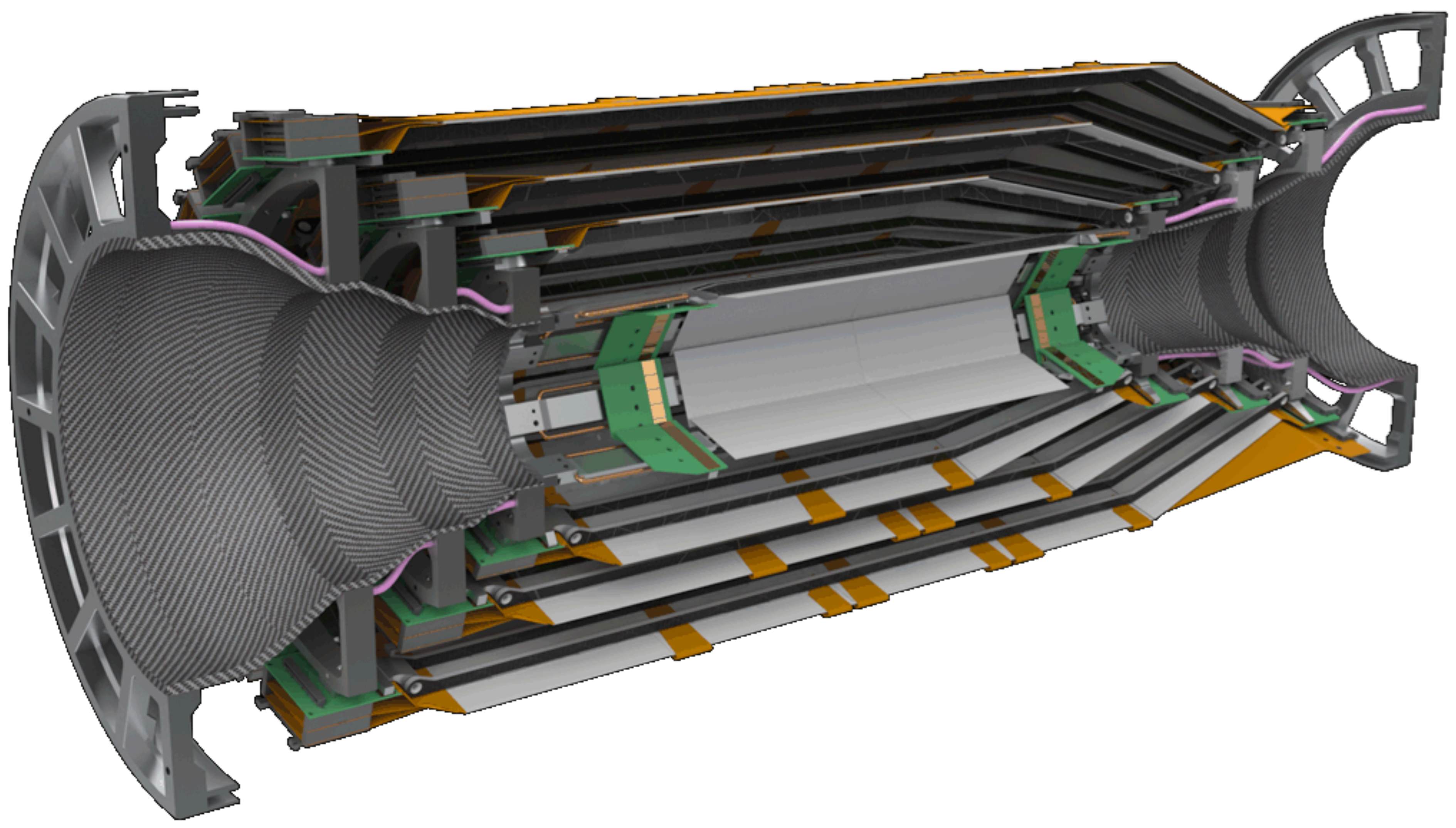
- **Interaction with material**: $-\ln(\eta) = L\rho \sum_i f_i\sigma_i/m_i = \dfrac{L}{\lambda}$
  with $\lambda = \dfrac{1}{\rho \sum_i f_i\sigma_i/m_i}$ (material density $\rho$, isotope mass $m_i$, mass fraction $f_i$, cross section for this isotope $\sigma_i$)

# Monte Carlo detector simulation: Example

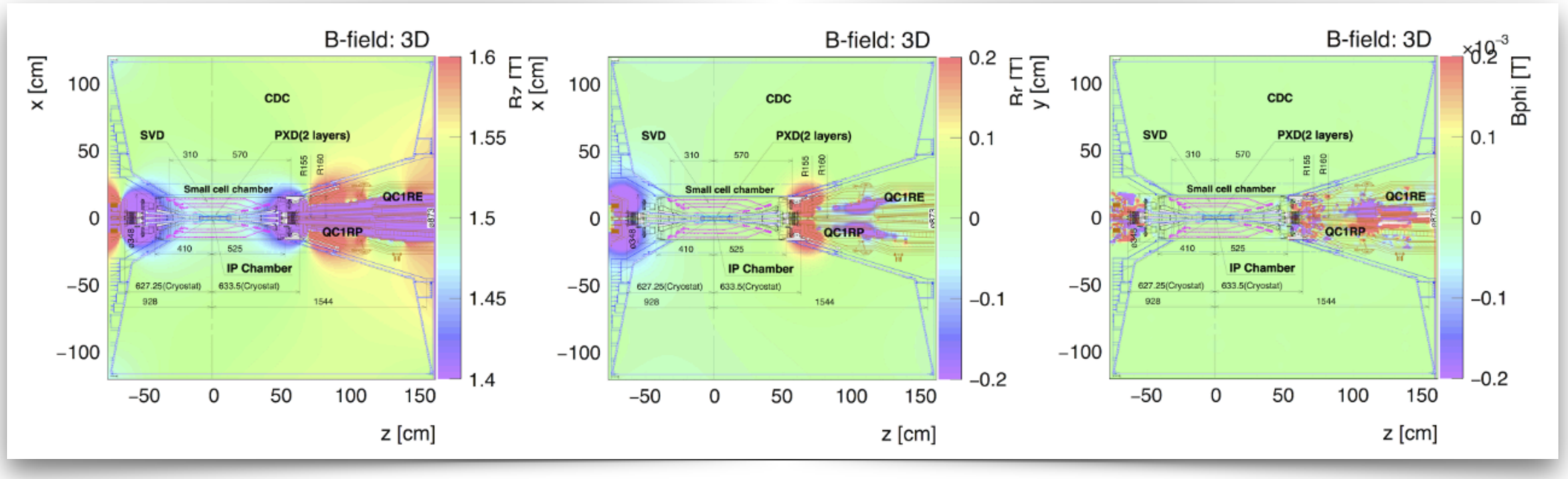


# Simulation summary

- To simulate a full detector you need:
  - A list of all possible “processes”
    - For each process, you need a “model” that describes the differential cross section behaviour
  - properties of all materials (composition, density, …)
  - All property boundaries (typically requires CAD drawings)
  - transport rules for 3D B- and E-fields
- You have to simulate every single particle that is created during the steps
- This is one the most **computationally demanding** tasks in particle physics (many approximations, speed-up, parallel processing, generative networks, …). Simulating a single event can take several ten seconds.



Source: CAD drawing of Belle II vertex detector



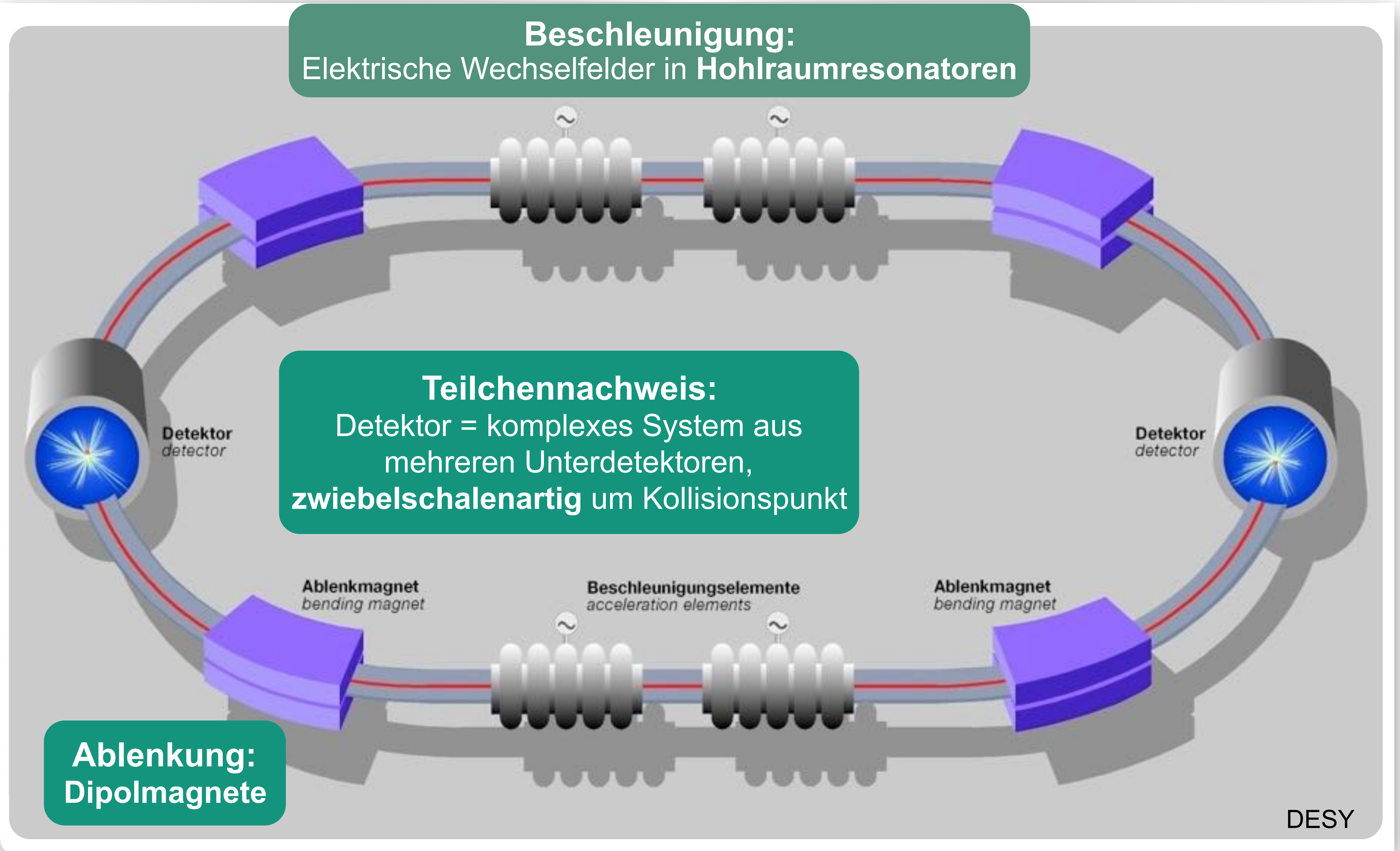

Source: Belle II magnetic field maps used in simulation

# Simulation toolkit: GEANT4

- De-facto standard in particle and nuclear physics: GEANT4 (https://geant4.web.cern.ch/) developed since 20+ years
  - Often used synonymously for “simulation” or “Monte Carlo”
- Detector simulation is a tricky business → GEANT4 is rather complex
  - written in C++
  - You will find most things discussed before as C++ classes (with sometimes slightly confusing names, don’t give up)
  - also provides interfaces to inputs (“event generation”) and user-defined outputs and visualization tools

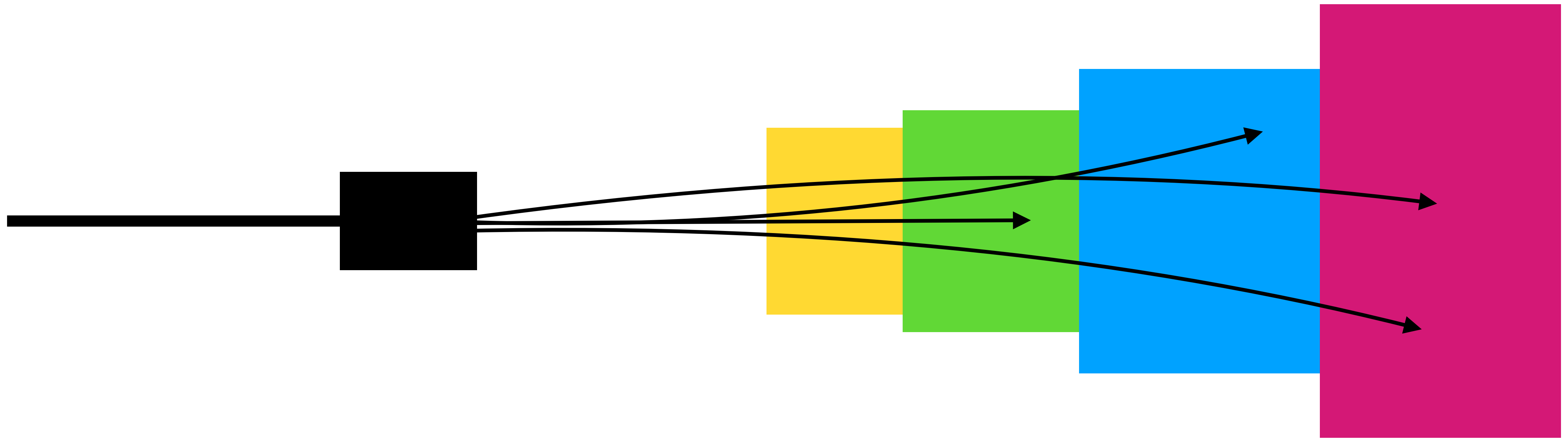
    → we have dedicated two exercises to this and provide work environments with running GEANT4

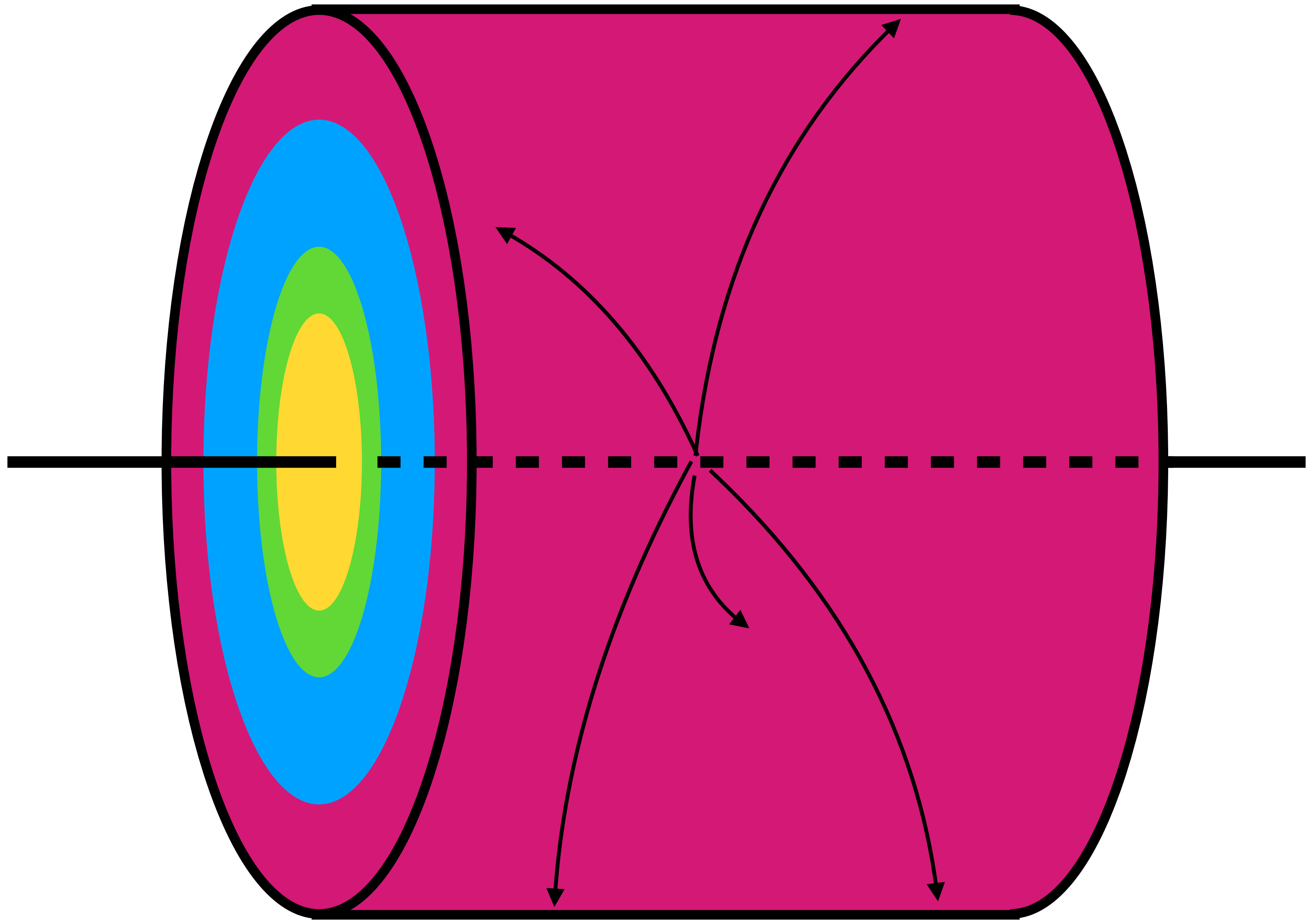
# Particle physics at colliders




Credit: DESY

# Particle detectors at colliders



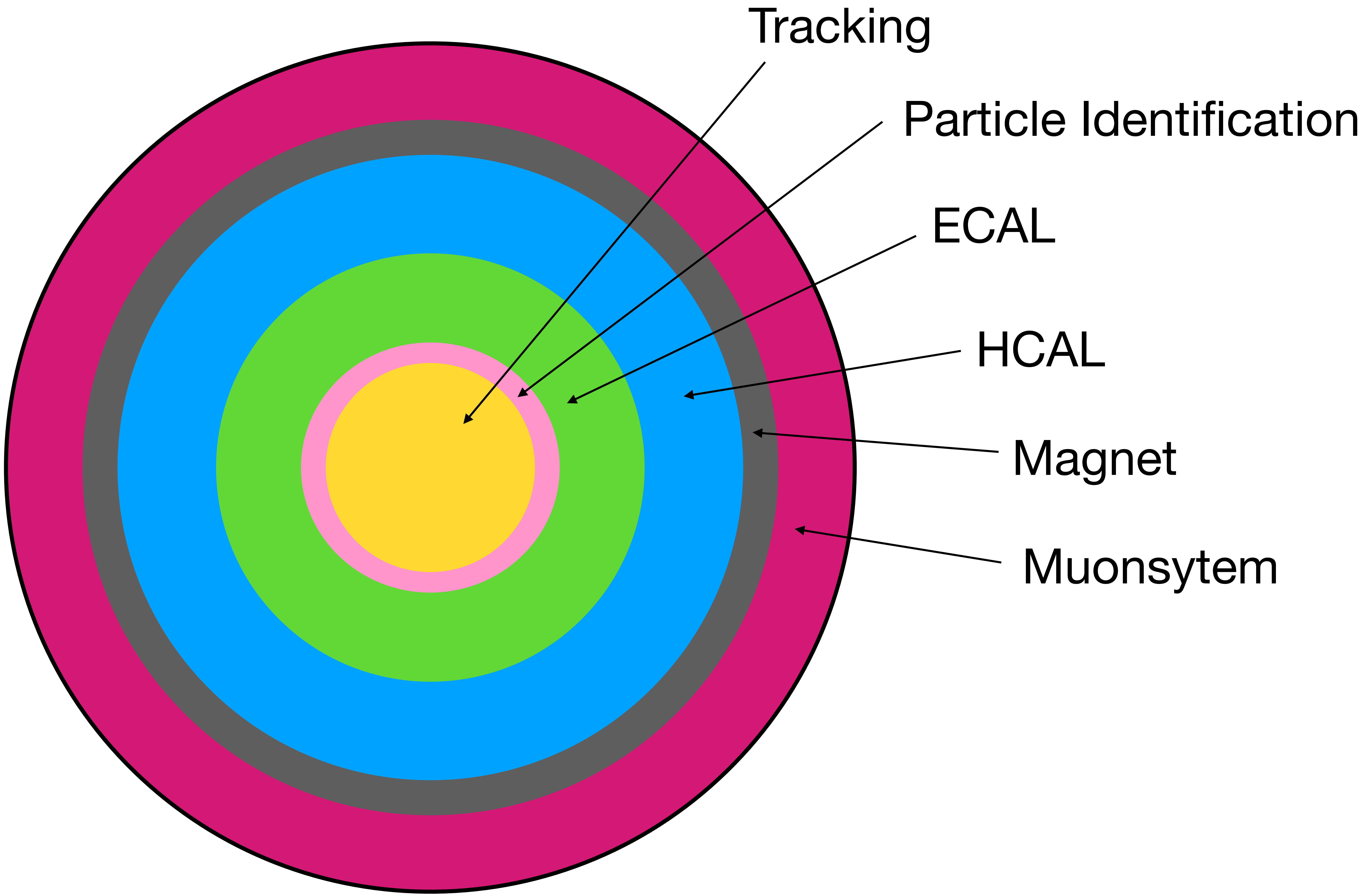


- Fixed target:
  - particle beam hits target
  - collision products in forward direction
  - detector: forward-spectrometer (e.g. LHCb)
- Collider:
  - two particle beams collide
  - collision products in all directions
  - detector: cylindrical 4π (e.g. Belle II, CMS)

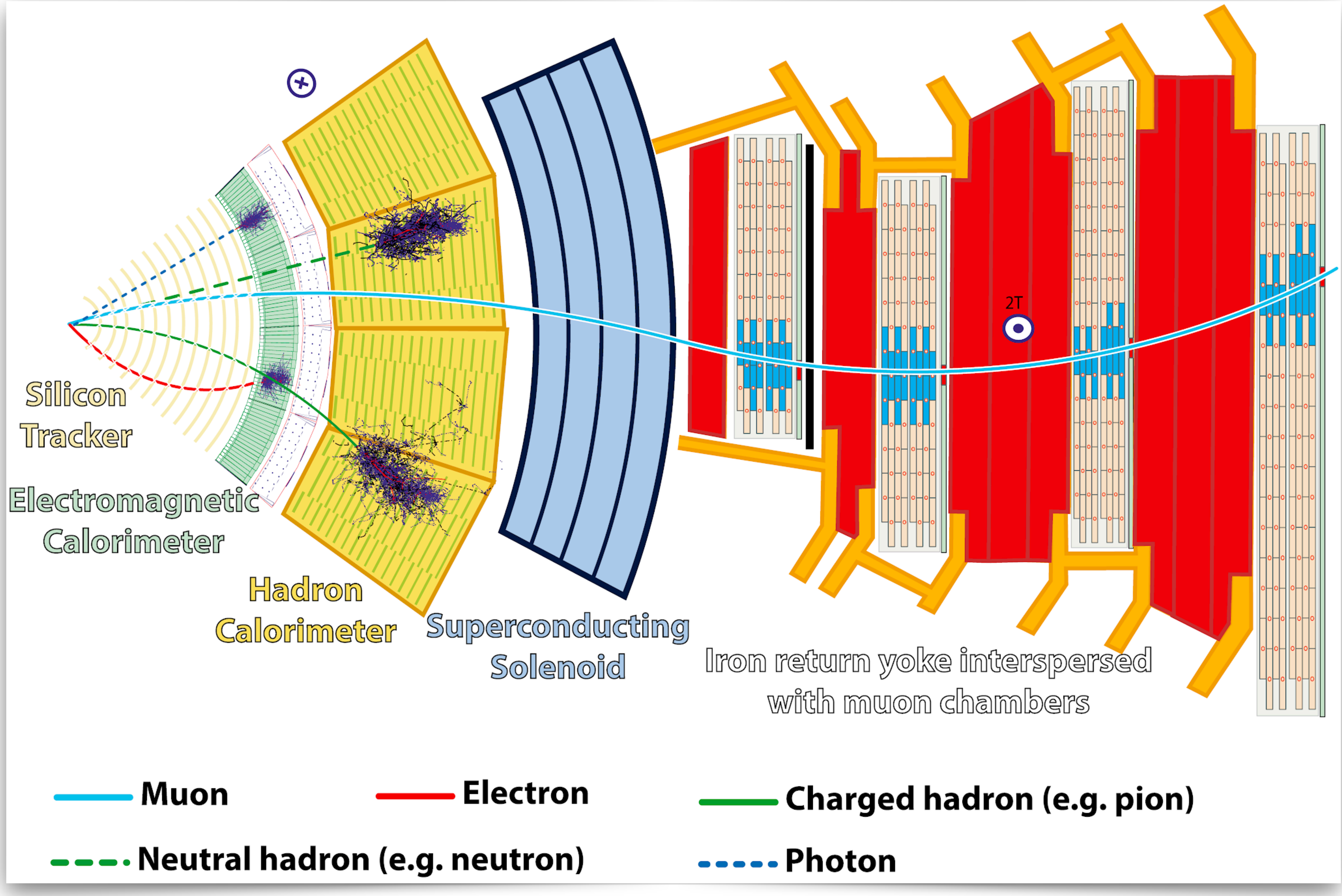
# Particle detectors: Shopping list

- Goal: Measure all properties of all particles
  - identify particle species ($\pi$, e, $\mu$, $\gamma$, …)
  - measure momenta and/or energy
  - measure point of origin ("vertex")
- Reject backgrounds
- Cover the full solid angle around the collision point
- Be very fast: Several ten thousand (!) collisions per second
- Technically feasible (including externals constraints like heat dissipation, space, power consumption, radiation damage …)
- "Low" cost

# Particle detectors

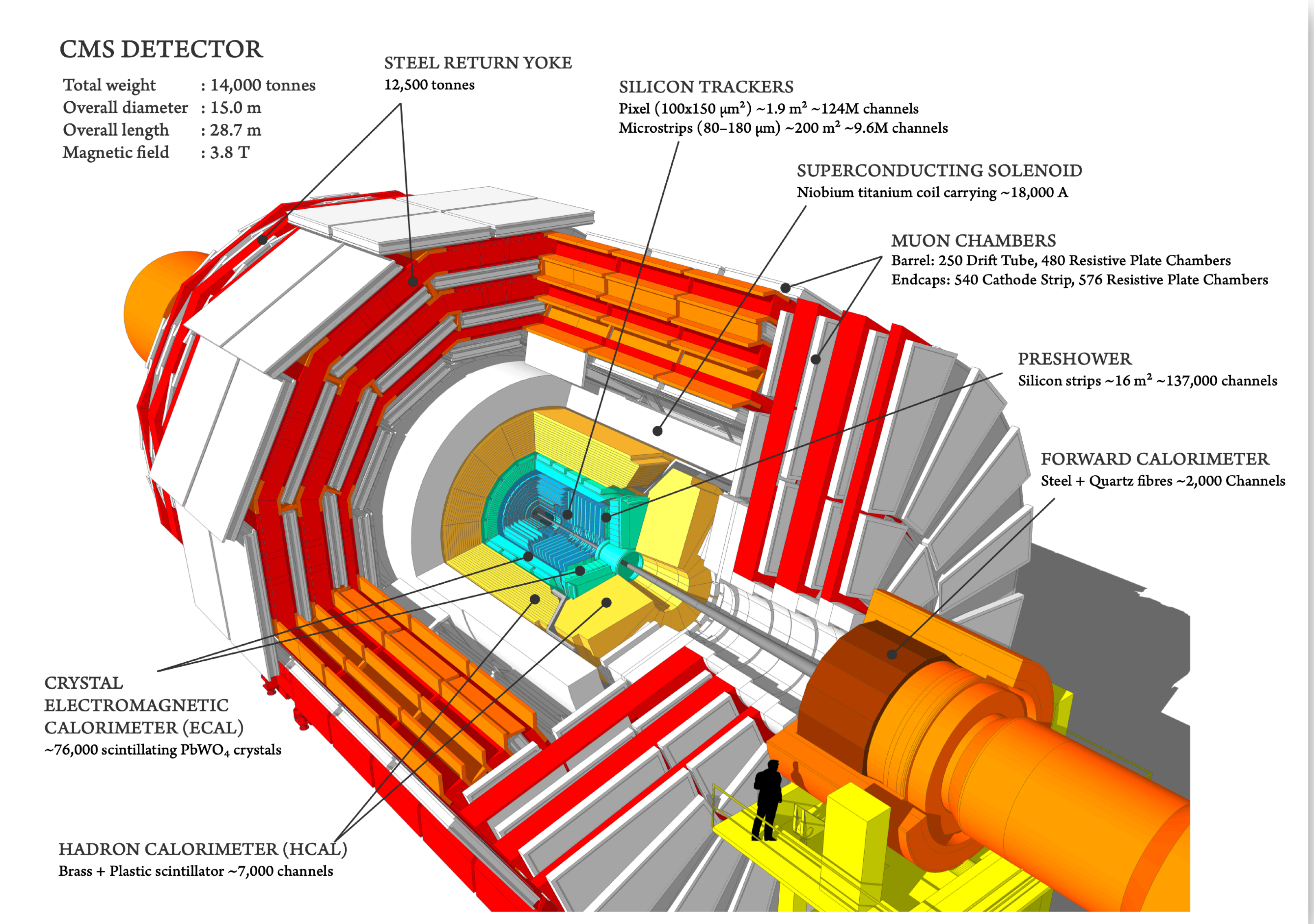


# Particle interactions in subdetectors (example CMS)



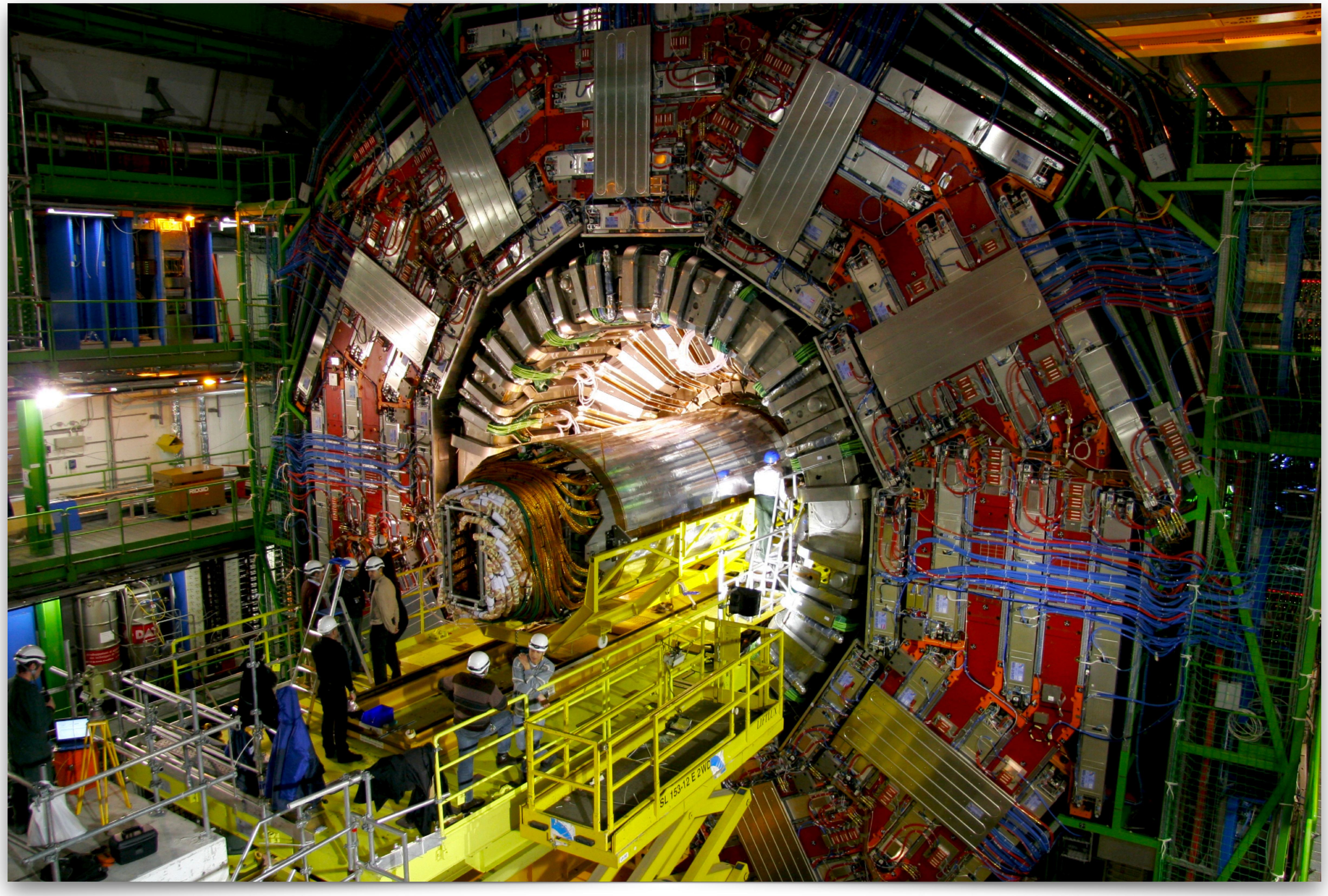

Source: https://blog.tensorflow.org/2021/04/reconstructing-thousands-of-particles-in-one-go-at-cern-lhc.html

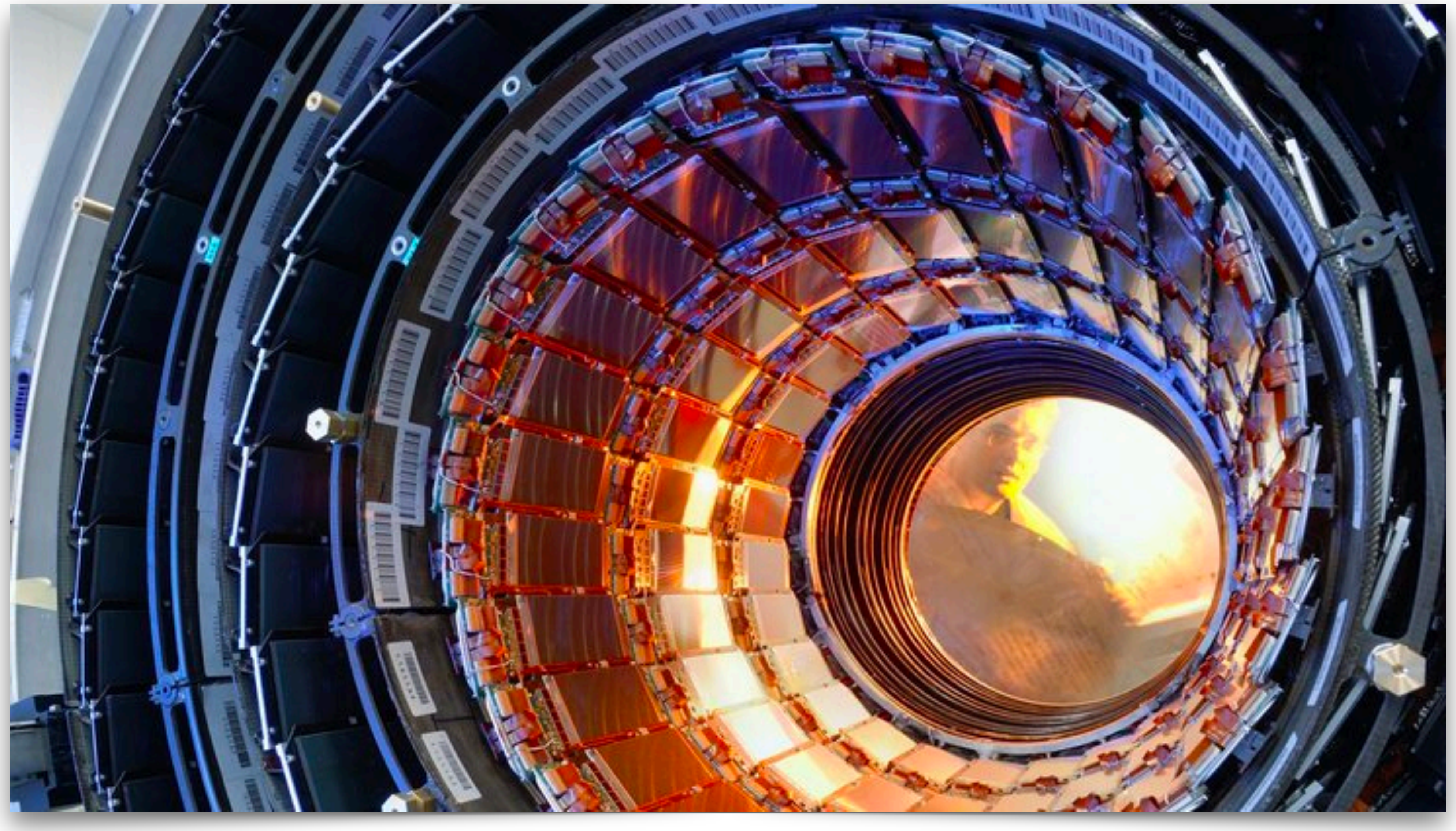
# Example: CMS

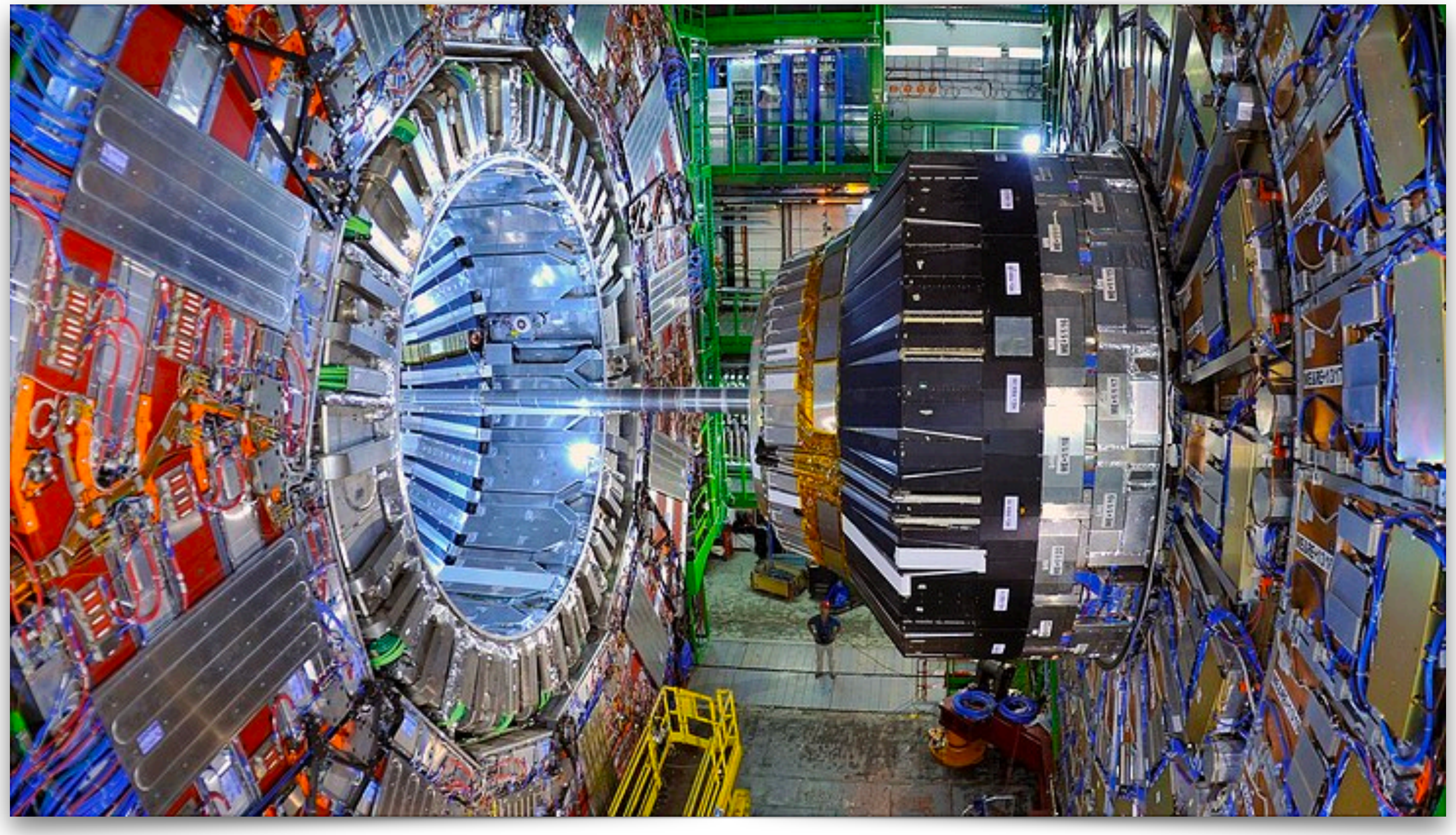



Source: https://cms-docdb.cern.ch/

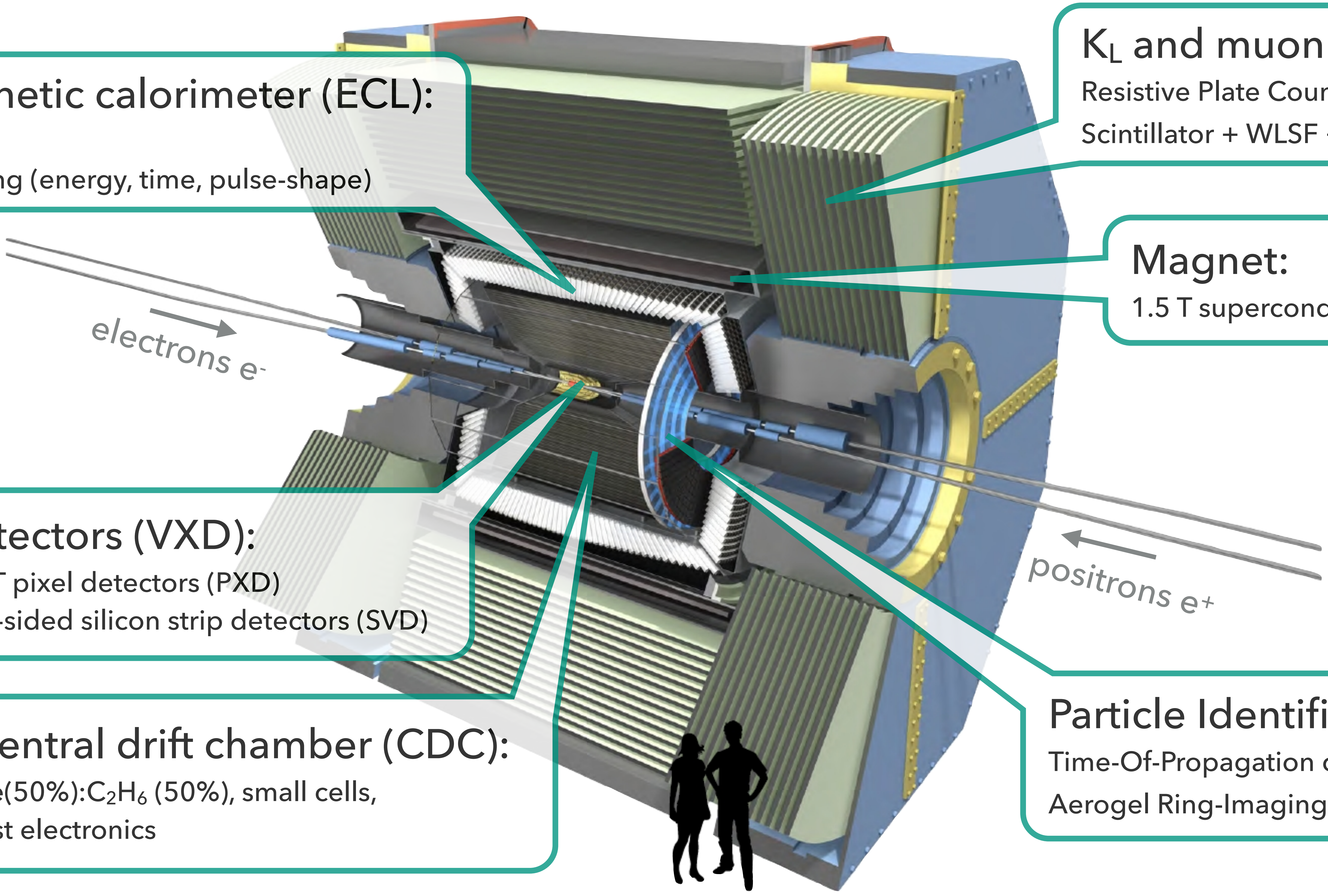
# CMS in pictures







# Example: Belle II




**Electromagnetic calorimeter (ECL):**
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

**$K_L$ and muon detector (KLM):**
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

**Magnet:**
1.5 T superconducting

**Trigger:**
Hardware: < 30 kHz
Software: < 10 kHz

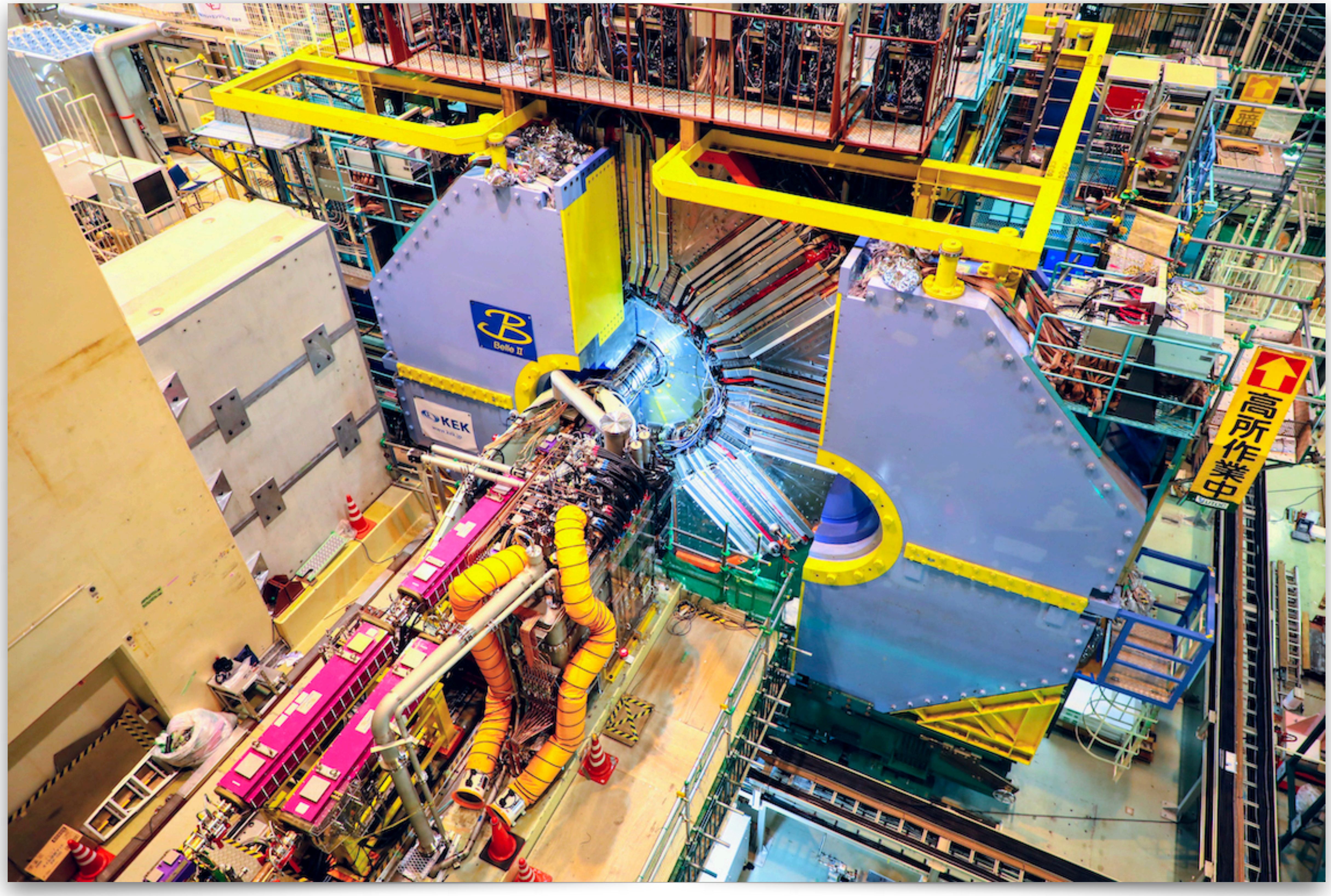
**Vertex detectors (VXD):**
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

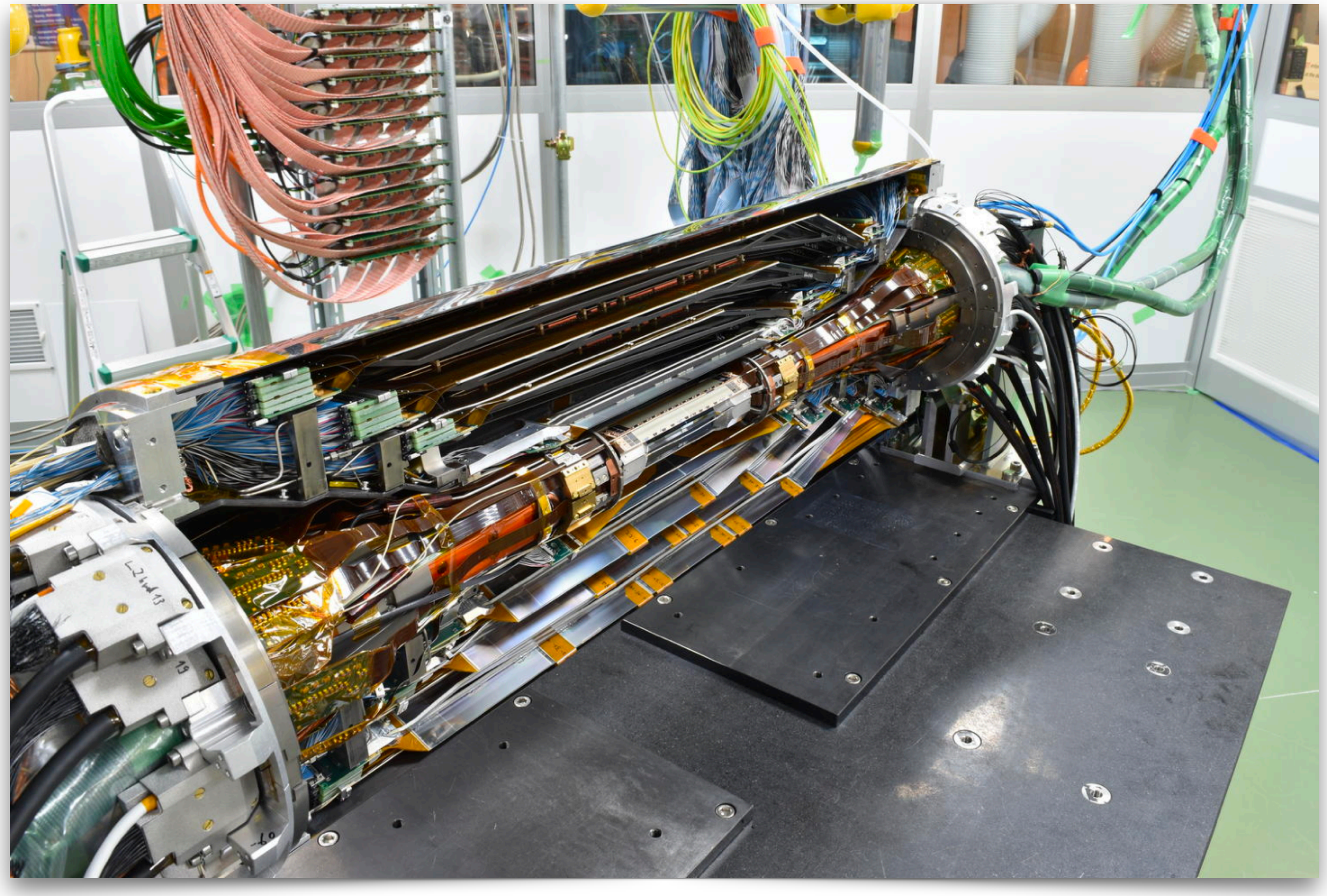
**Central drift chamber (CDC):**
He(50%):$C_2H_6$ (50%), small cells,
fast electronics

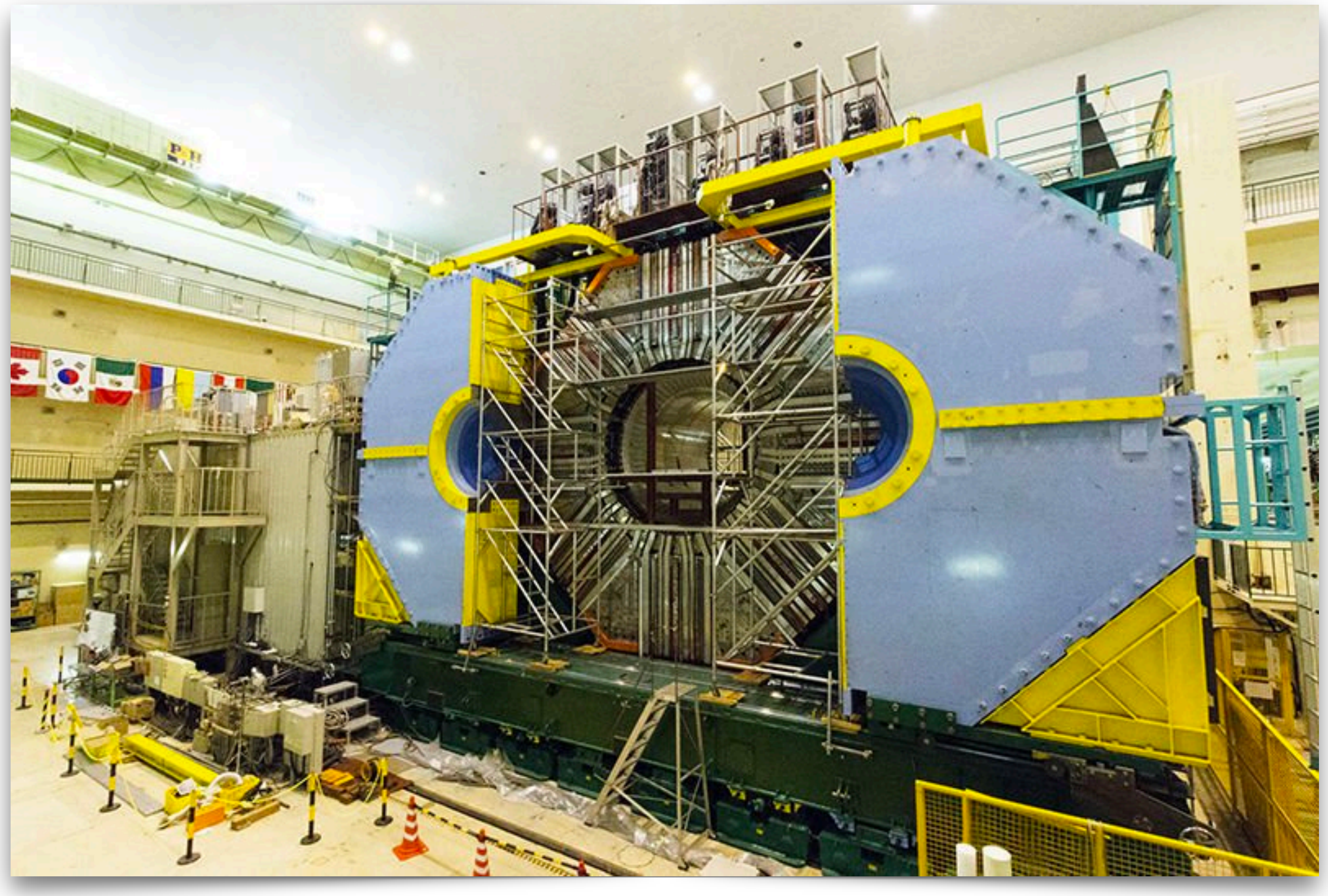
**Particle Identification (PID):**
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

# Belle II in pictures



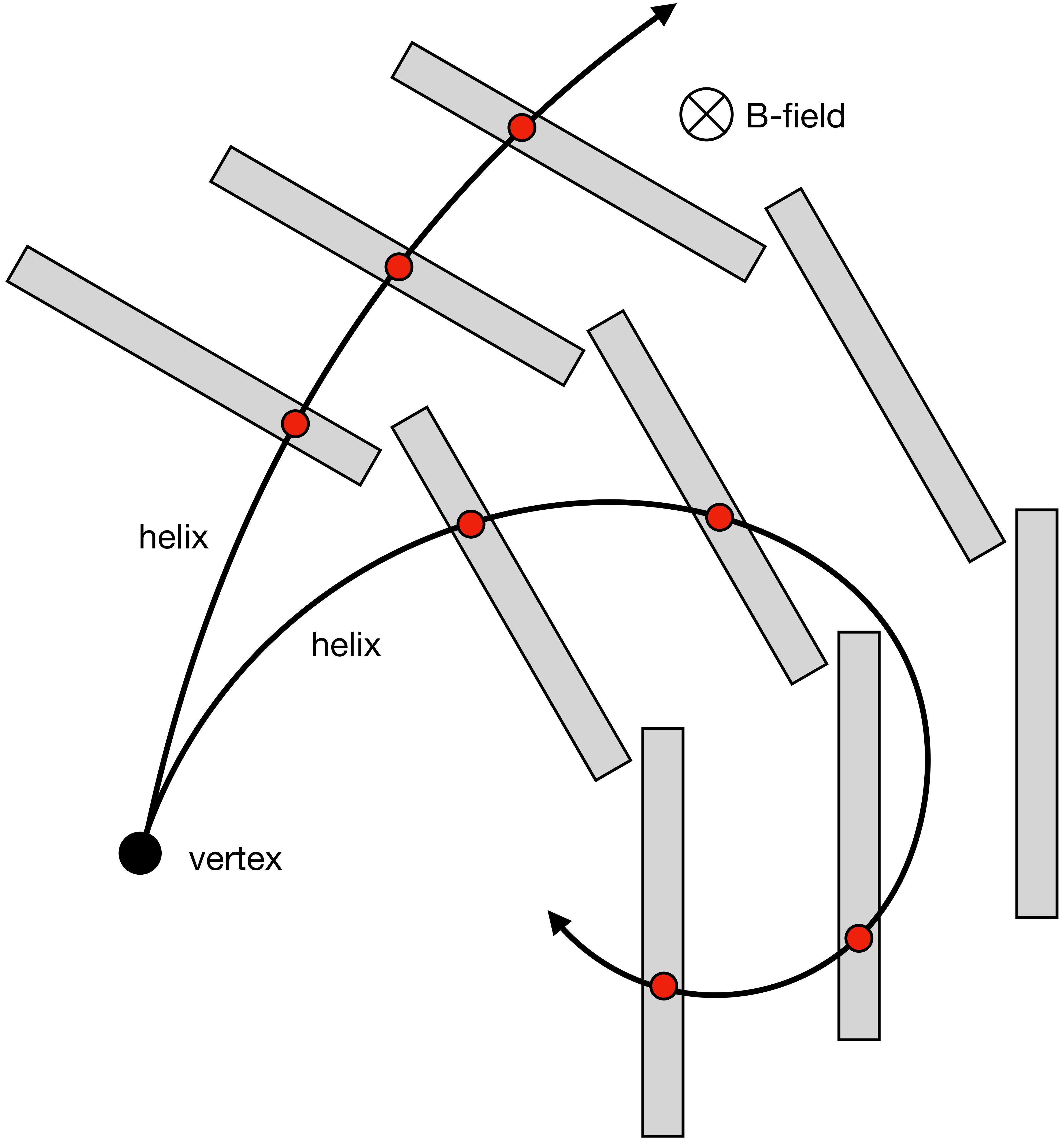


“Gioia” (by Sandro Stamenkovic)

# Tracking detectors

- Mainly used interaction: Ionization by charged particles
- Two main detector types:
  - gas-filled: multi-wire proportional chamber (MWPC), driftchamber, time projection chamber (TPC)
  - solid-state: silicon strip, silicon pixel
- Performance metrics:
  - Relative (transverse) momentum resolution $\Delta p/p$ (“how good can we measure the momentum”)
  - Impact parameter resolution (“how precisely can we measure that a particle came from the primary interaction”)
  - Track efficiency (“how often do we miss a real track”)

# Tracking detectors



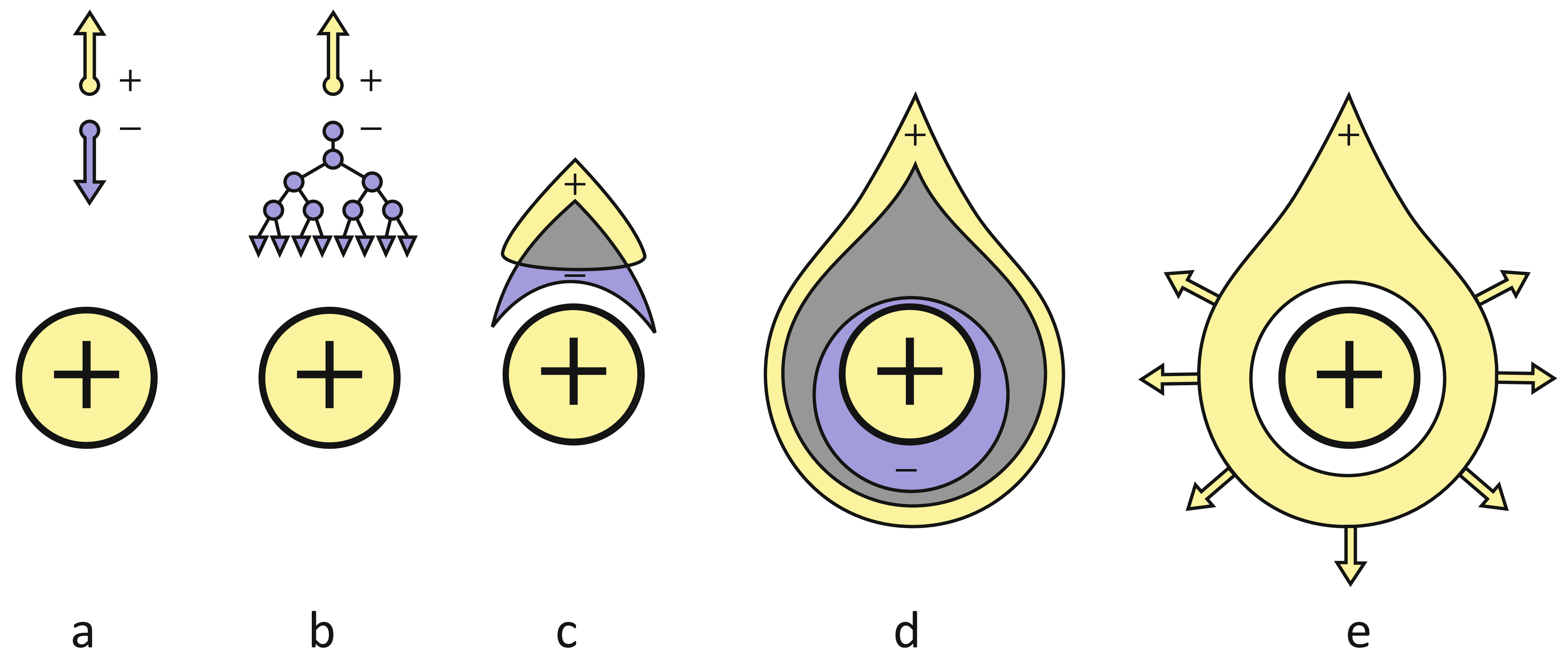

- Tracks are measured in several sensitive layers
- Electrical signals in each layer: **hits**
- Track reconstruction:
  - pattern recognition ("**track finding**"): which hits belong to the same helix (with energy loss)
  - parameter estimation via minimization ("**track fitting**"): which helix parameters describe the data
  - **vertex fitting**: find common origin of two or more tracks

# Tracking detectors: Gas-based

- Basic principle: proportional counter
  - traversing charged particle ionises inert gas
    - choice of gas: low Z, high dE/dx, high ionisation density, safety (non-flamable), environmental friendly, …
  - high voltage between anode wire and cathode wall: drift of electrons and heavy ions to respective electrode
  - electric field close to anode large enough for charge amplification (Townsend-avalanche)
  - problem: ions emit UV photons during recombination → absorb UV photons by adding a so-called **quenching gas** with many free parameters that can be excited (e.g. $CO_2$)

| Gas | $Z$ | $A$ | $\rho$ (g/cm$^3$) | $E_{ex}$ (eV) | $E_{ion}$ (eV) | $I$ (eV) | $w_i$ (eV) | $dE/(\rho dx)$ (MeV cm$^2$/g) | $dE/dx$ (keV/cm) | $n_p$ (cm$^{-1}$) | $n_{tot}$ (cm$^{-1}$) | $X_0$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_2$ | 2 | 2 | $8.38 \cdot 10^{-5}$ | 10.8 | 15.4 | 19.2 | 37 | 4.03 | 0.34 | 5.2 | 9.2 | 7522 |
| He | 2 | 4 | $1.66 \cdot 10^{-4}$ | 19.8 | 24.5 | 41.8 | 41 | 1.94 | 0.32 | 5.9 | 7.8 | 5682 |
| $N_2$ | 7 | 28 | $1.17 \cdot 10^{-3}$ | 8.1 | 15.6 | 82 | 35 | 1.68 | 1.96 | (10) | 56 | 325 |
| $O_2$ | 8 | 32 | $1.33 \cdot 10^{-3}$ | 7.9 | 12.1 | 95 | 31 | 1.69 | 2.26 | 22 | 73 | 257 |
| Ne | 10 | 20.2 | $8.39 \cdot 10^{-4}$ | 16.6 | 21.6 | 137 | 36 | 1.68 | 1.41 | 12 | 39 | 345 |
| Ar | 18 | 39.9 | $1.66 \cdot 10^{-3}$ | 11.5 | 15.8 | 188 | 26 | 1.47 | 2.44 | 29.4 | 94 | 118 |
| Kr | 36 | 83.8 | $3.49 \cdot 10^{-3}$ | 10.0 | 14.0 | 352 | 24 | 1.32 | 4.60 | 31.6 | 192 | 33 |
| Xe | 54 | 131.3 | $5.49 \cdot 10^{-3}$ | 8.4 | 12.1 | 482 | 22 | 1.23 | 6.76 | 44 | 307 | 15 |
| $CO_2$ | 6,8 | 44 | $1.86 \cdot 10^{-3}$ | 5.2 | 13.8 | 85 | 33 | 1.62 | 3.01 | 35.5 | 91 | 183 |
| $CH_4$ | 6,1 | 16 | $0.71 \cdot 10^{-3}$ | 9.8 | 15.2 | 41.7 | 28 | 2.21 | 1.48 | 25 | 53 | 646 |
| $C_2H_6$ | 6,1 | 30 | $1.34 \cdot 10^{-3}$ | 8.7 | 11.7 | 45.4 | 27 | 2.30 | 1.15 | 41 | 111 | 340 |
| i-$C_4H_{10}$ | 6,1 | 58 | $2.59 \cdot 10^{-3}$ | 6.5 | 10.6 | 48.3 | 23 | 1.86 | 5.93 | 84 | 195 | 169 |
| $CF_4$ | 6,9 | 88 | $3.78 \cdot 10^{-3}$ | 12.5 | 15.9 | 115 | 34.3 | 1.69 | 7 | 51 | 100 | 92 |
| $C_2H_6O$ (DME) | 6,1,8 | 46 | $2.2 \cdot 10^{-3}$ | 6.4 | 10.0 | 60 | 23.9 | 1.77 | 3.9 | 55 | 160 | 222 |

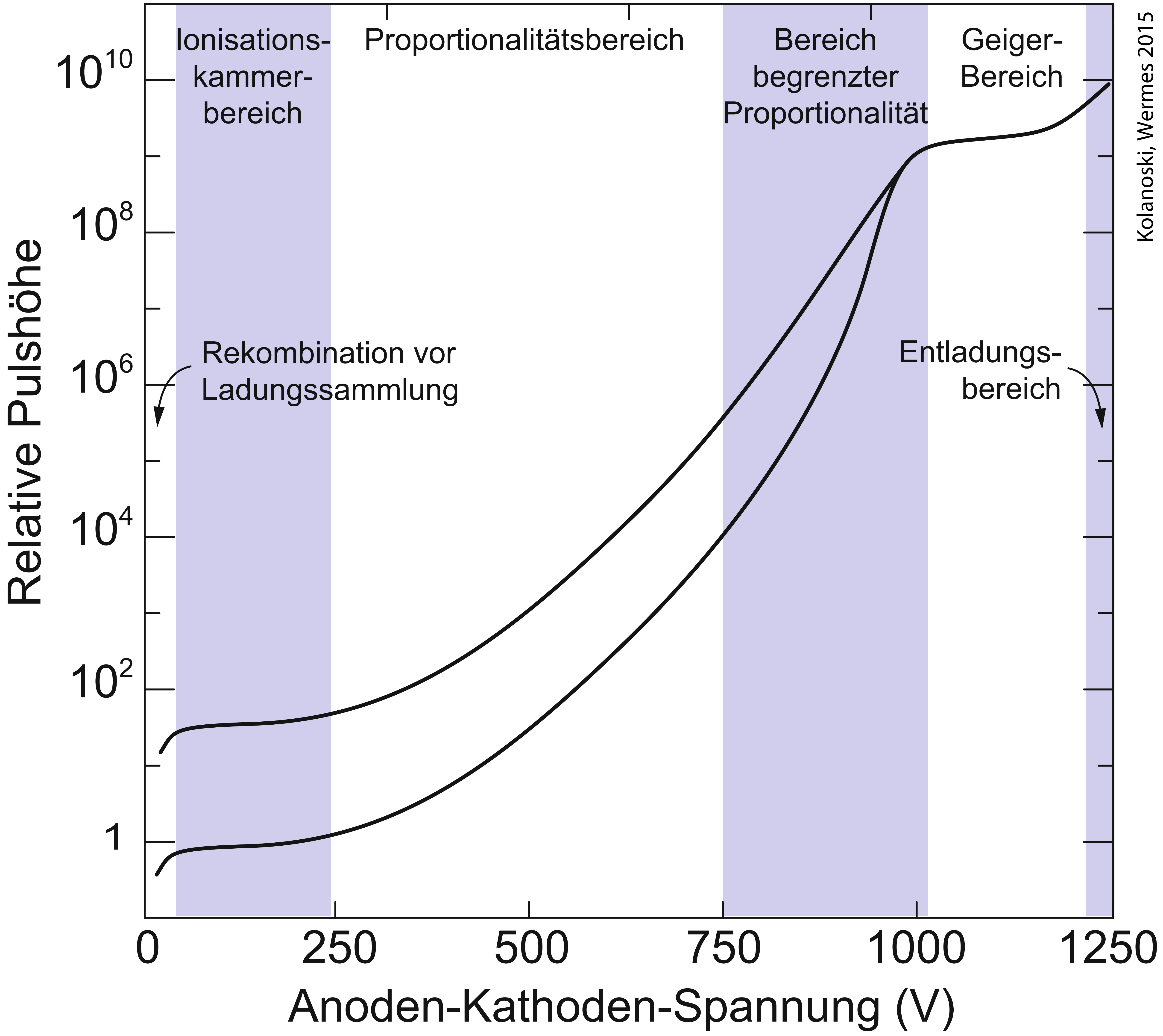
Credit: Wermes & Kolanoski, 2016




Credit: Wermes & Kolanoski, 2016

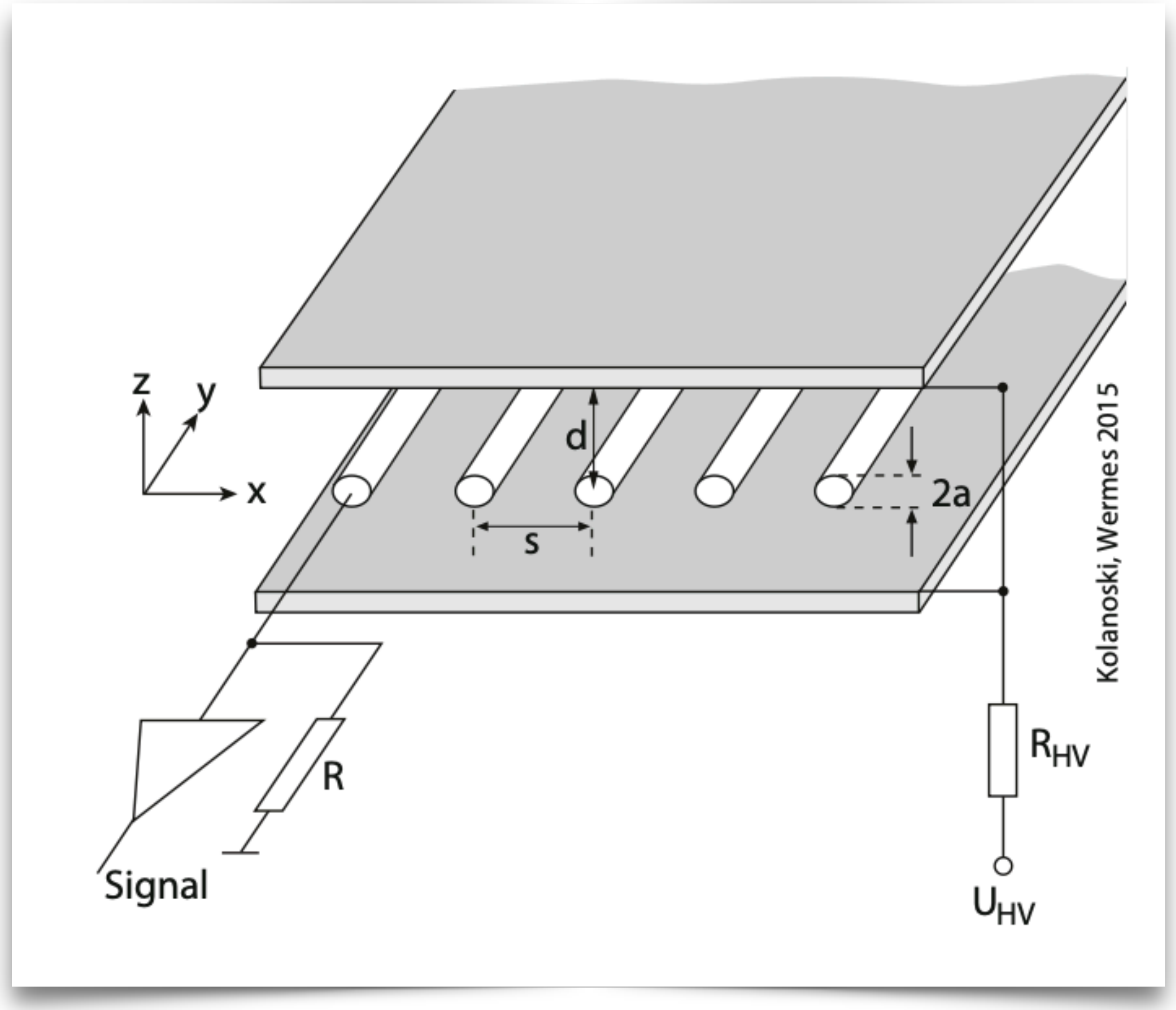
a: electron-ion pair
b: secondary ionisation close to anode
c: charge separation
d: lateral electron diffusion (nanoseconds)
e: droplet-shape ion cloud drift to kathode (milliseconds)

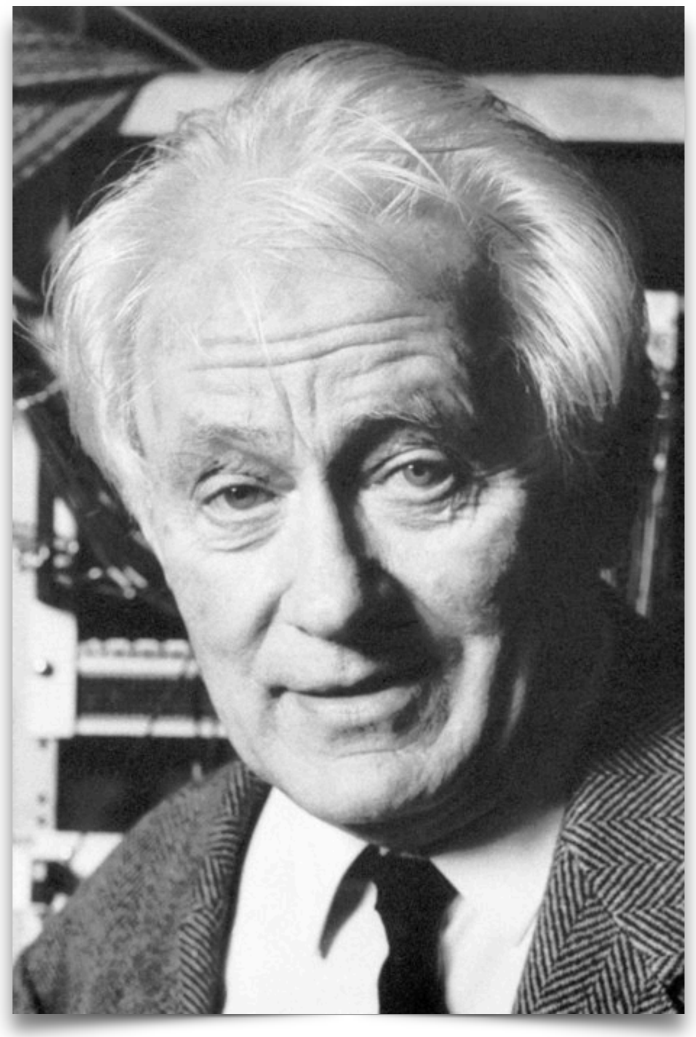
# Tracking detectors: Gas-based



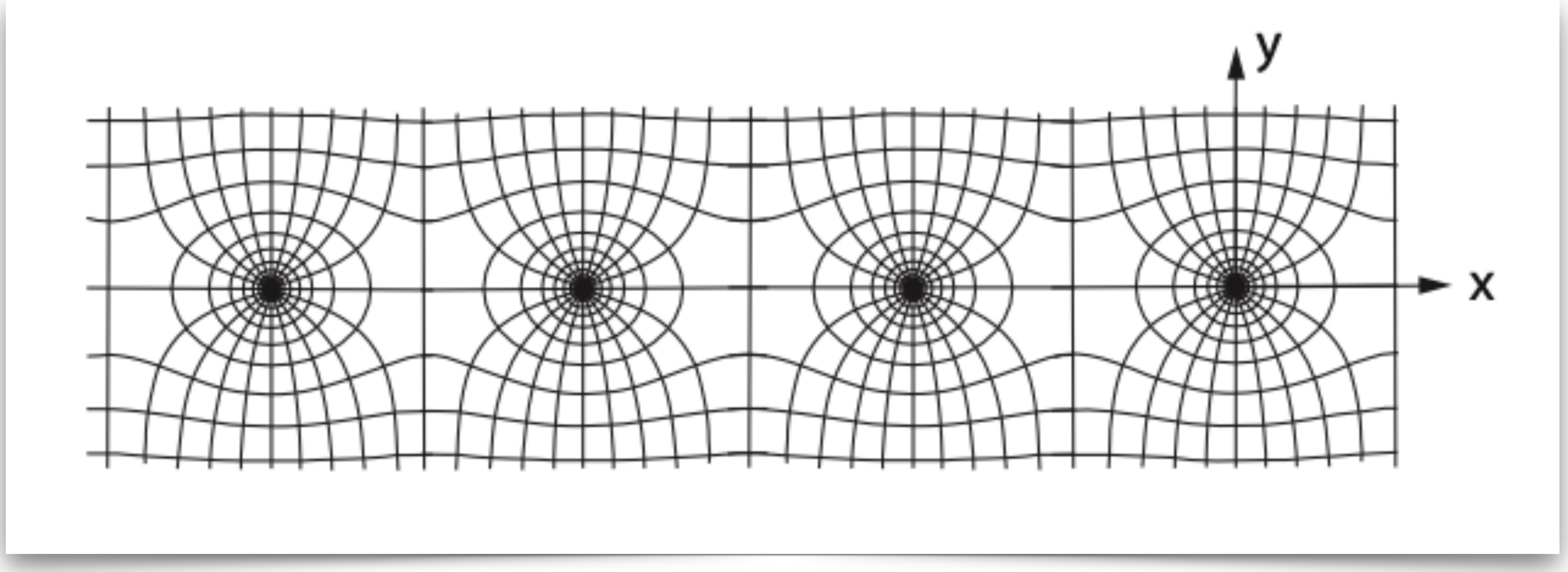
# Tracking detectors: multi-wire proportional counter

- Many anode wires in parallel, operated in proportional region: MWPC (nobel prize for Charpak 1992)
  - planar arrangement of proportional counter without separating walls
  - Typical dimensions: $\mathcal{O}(100\mu m)$ wires, $\mathcal{O}(1mm)$ distances between wires
- Electrical field: radial in vicinity of the wire, homogeneous far away
- Wire that give signal → position information
  - single-hit spatial resolution: $d/\sqrt{12}$



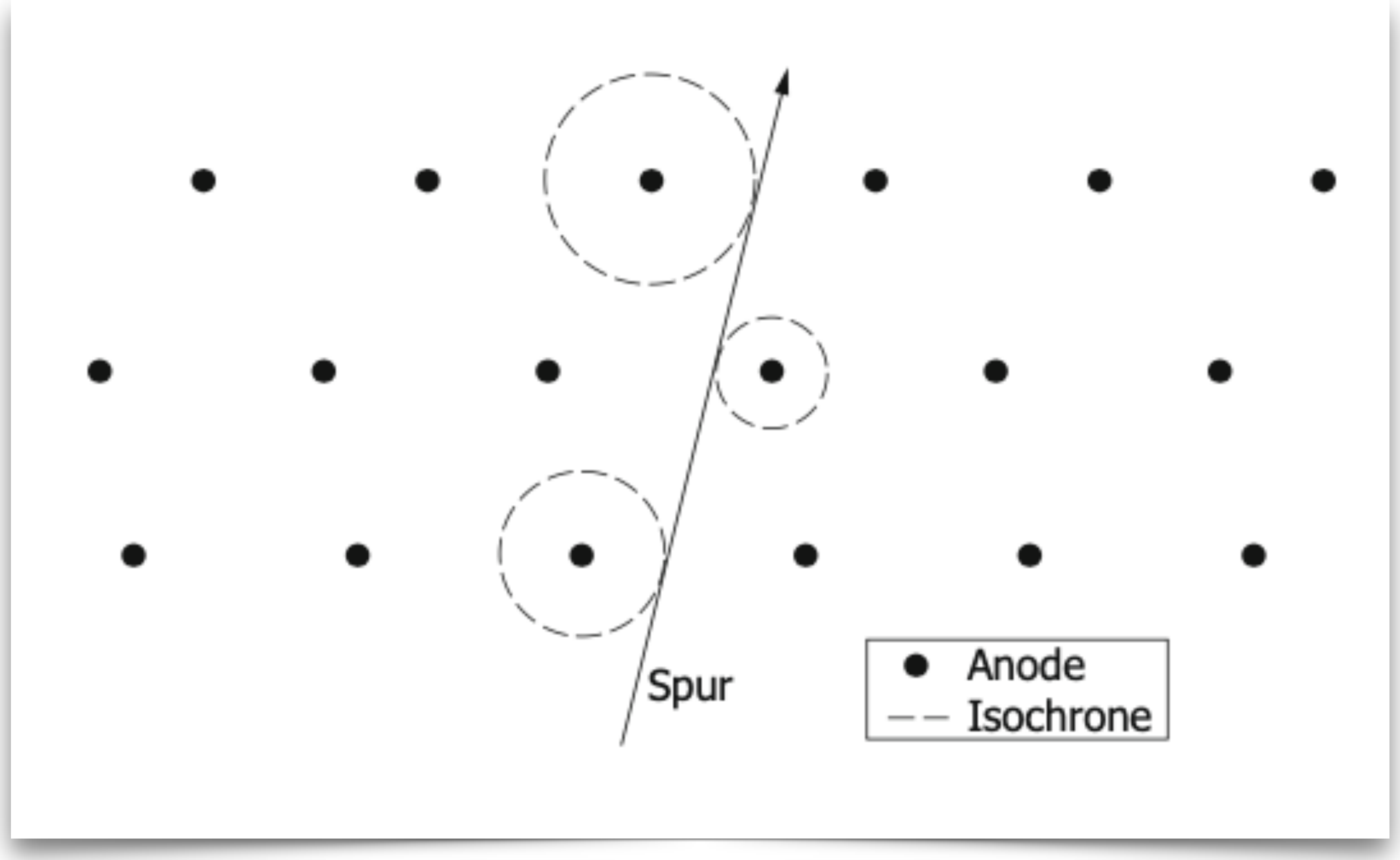



Credit: Nobel foundation
https://www.nobelprize.org/prizes/physics/1992/charpak/facts/

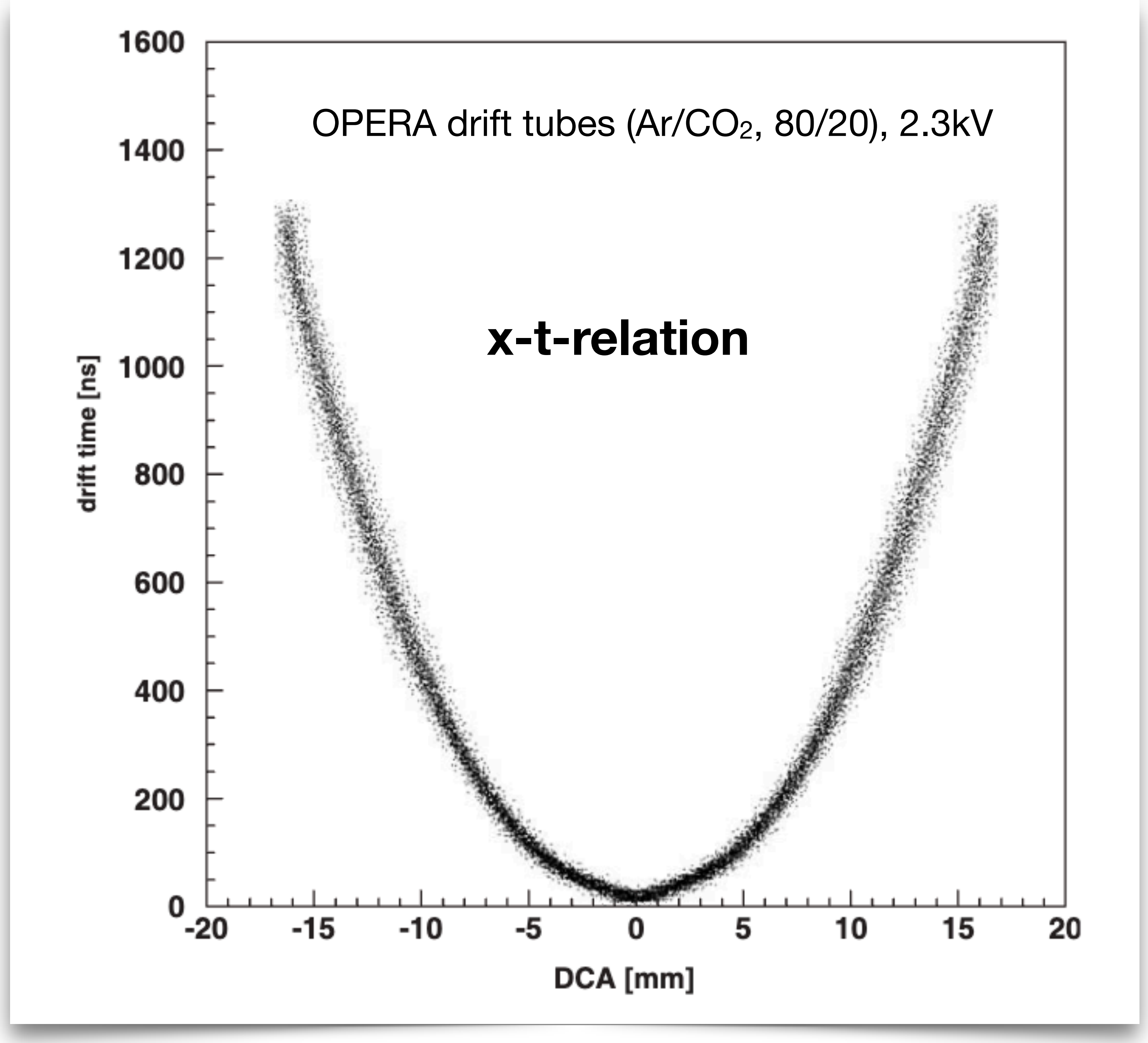


# Tracking detectors: drift chamber

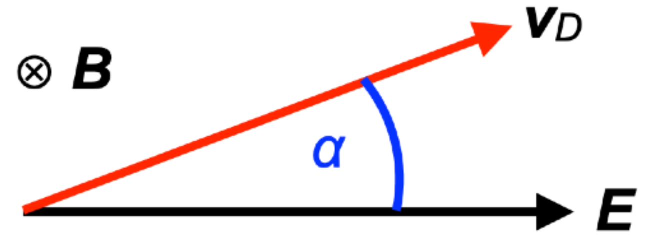
- Drift time of charge used to determine the distance of a track to a wire: “Isochrones” require precise knowledge of **x-t-relation**
- Staggered layers of wires to resolve left/ right disambiguities
- Wires rotated to extract third dimension (axial and stereo-wires)
- Charges drift in a complicated combined E and B field (**Lorentz-angle α**)
- Spatial resolution limited by drifttime variations due to diffusion




Credit: Wermes & Kolanoski, 2016

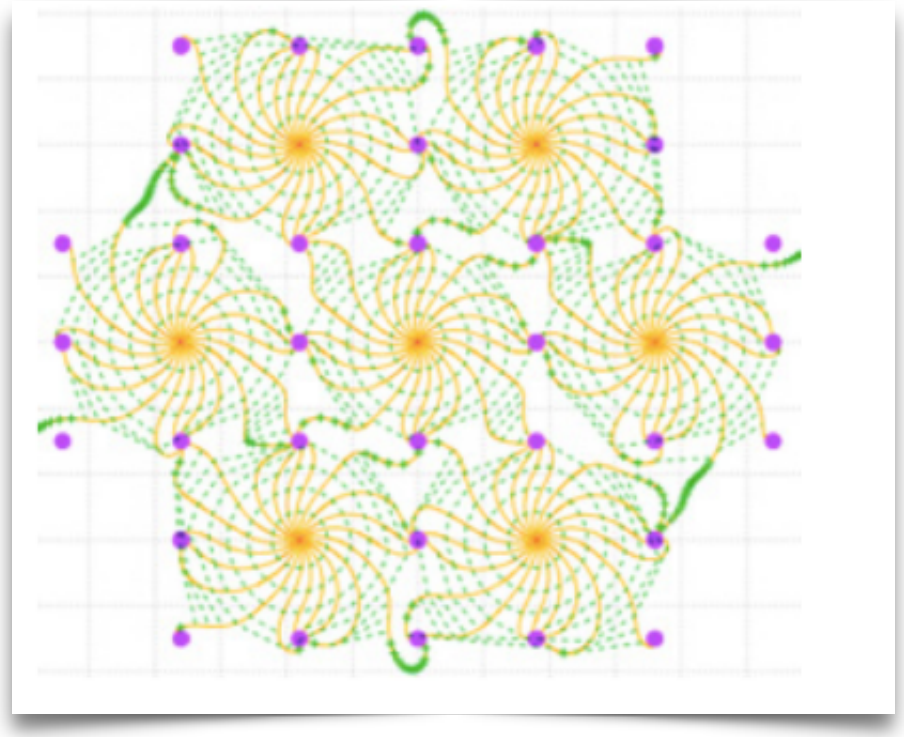



Credit: Nucl.Instrum.Meth.A 555 (2005) 435-450

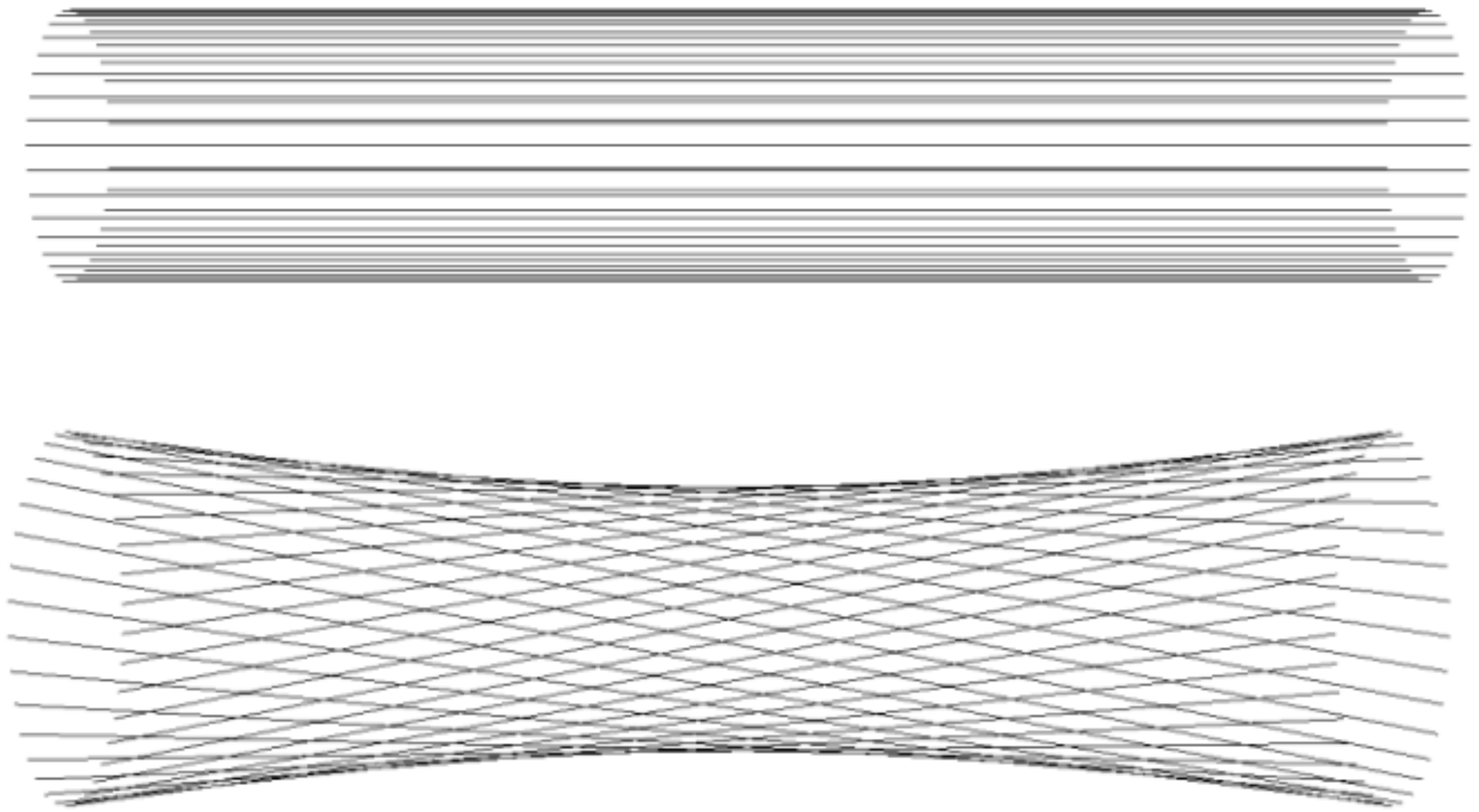


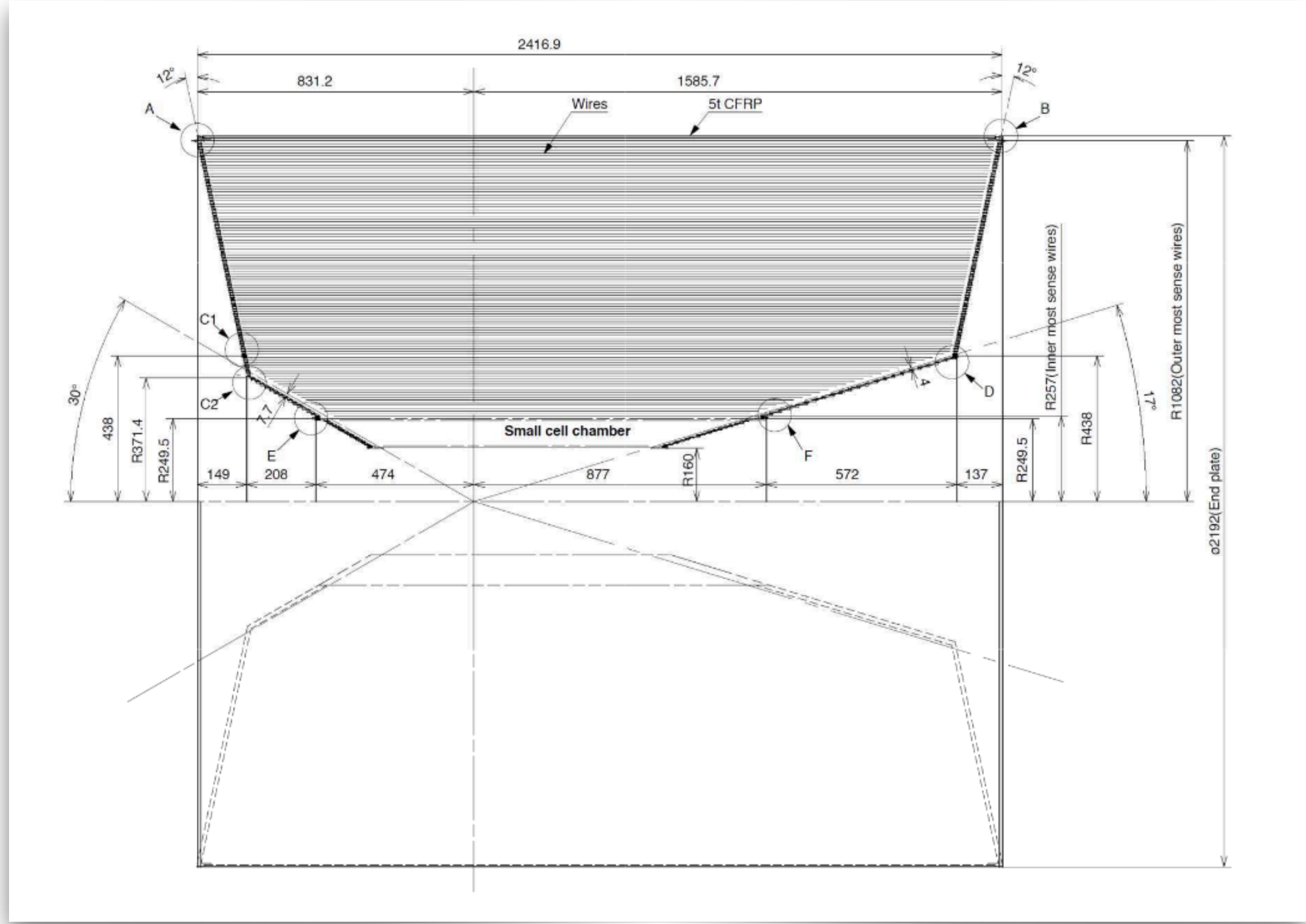
# Tracking detectors: Example Belle II central drift chamber

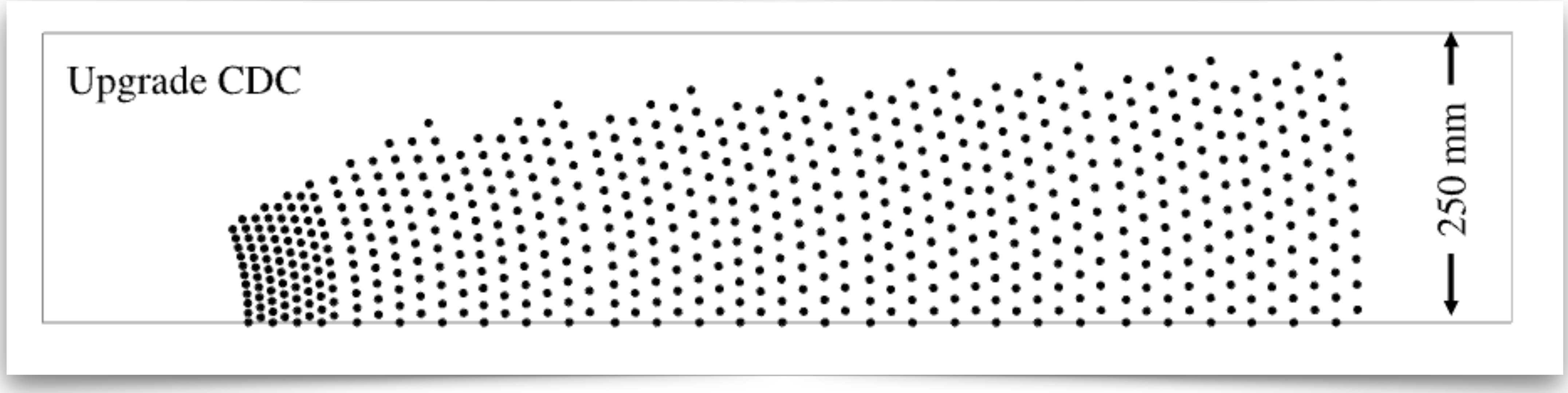
- ~15.000 wires (30μm) in 56 layers
  - 1 sense wire, surrounded by 8 field wires



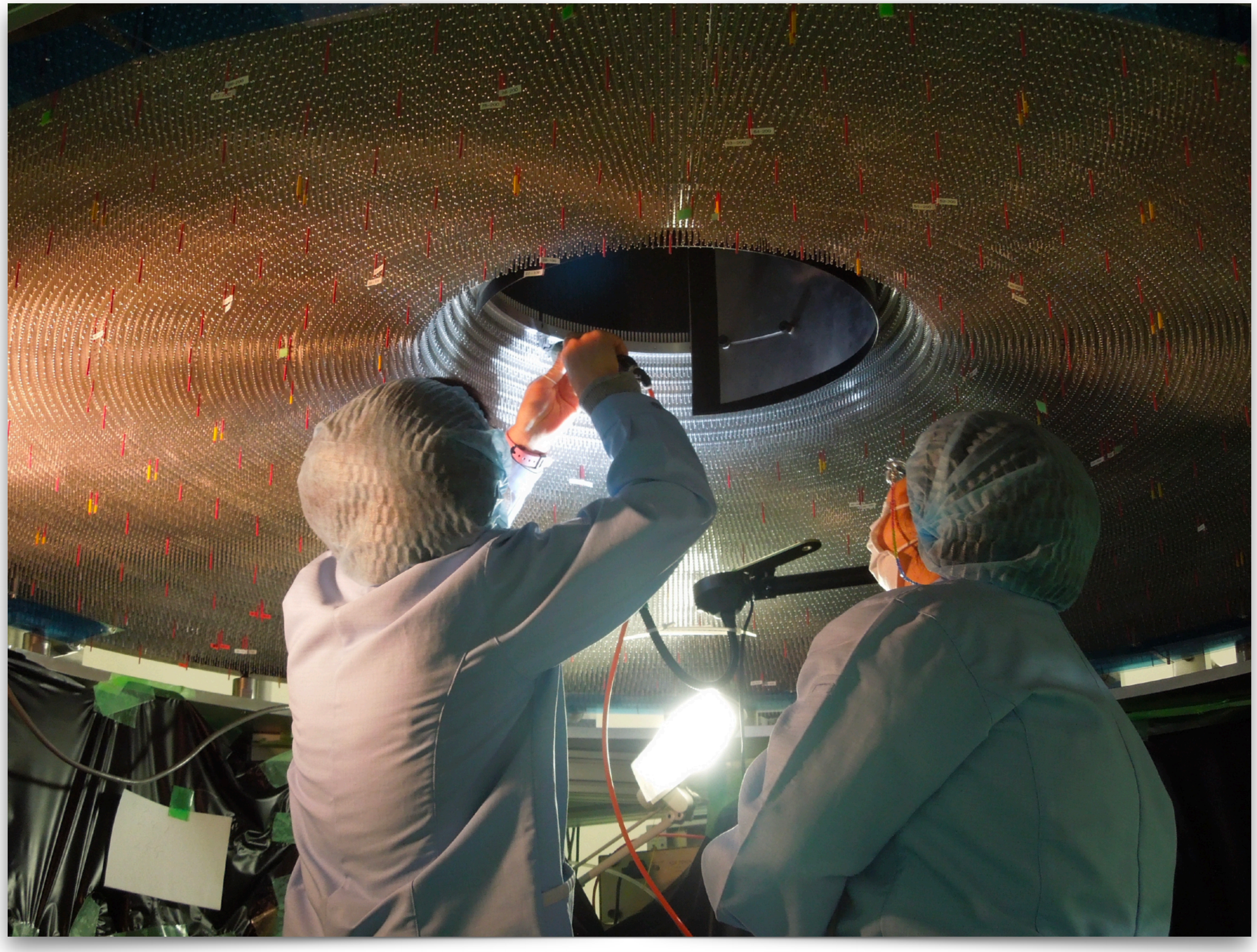
  - axial and stereo layers

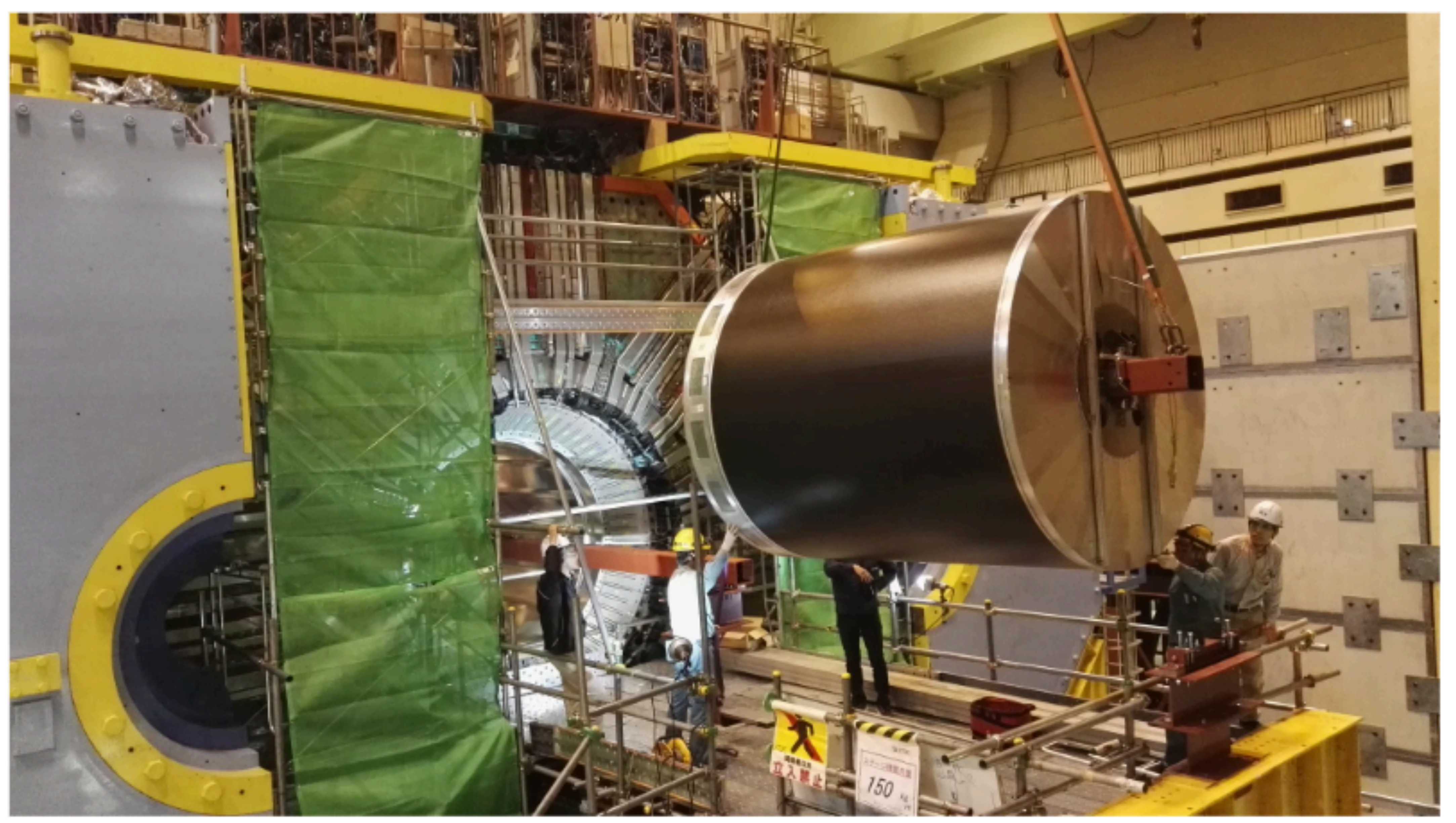




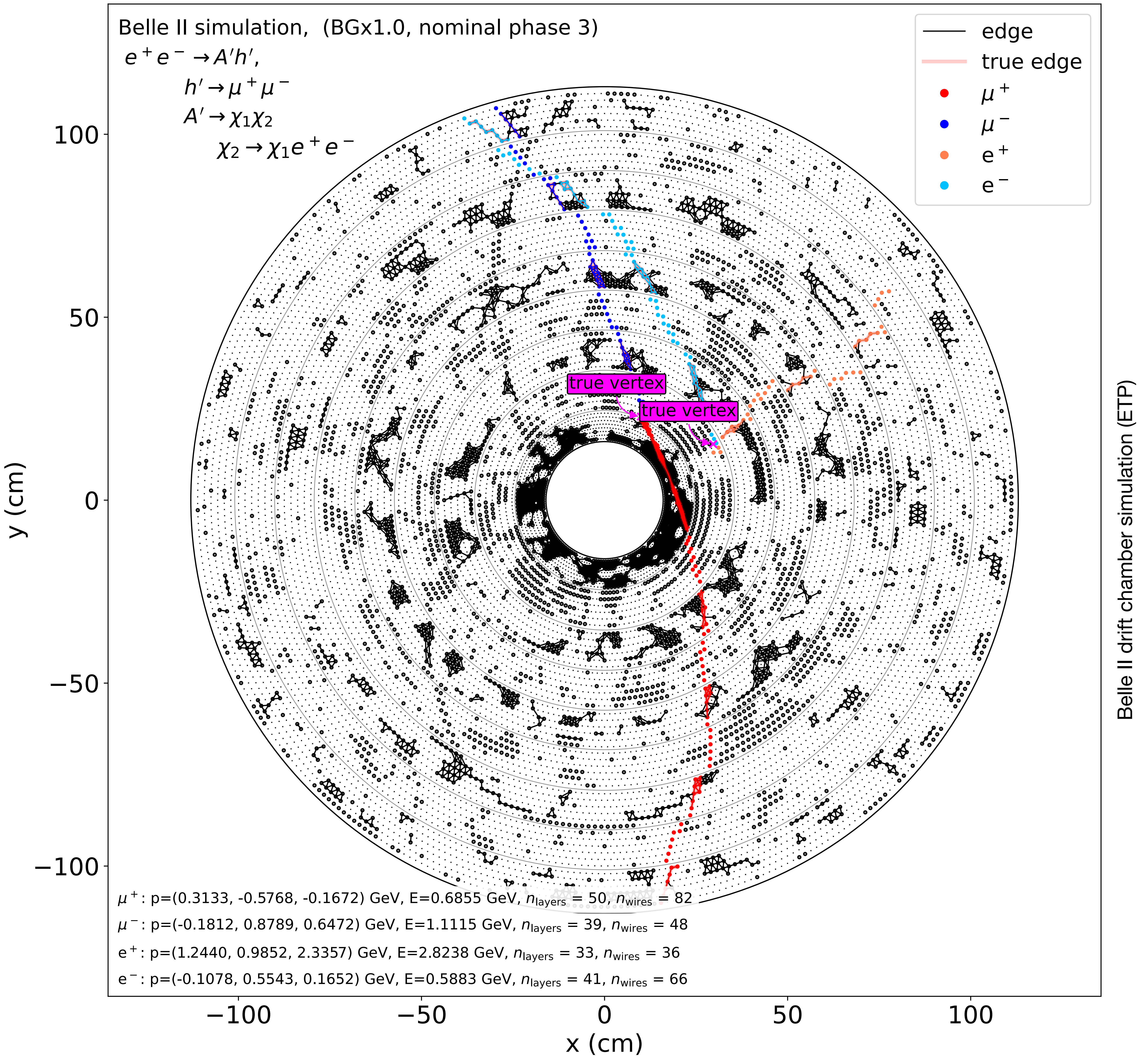



# Tracking detectors: Example Belle II central drift chamber



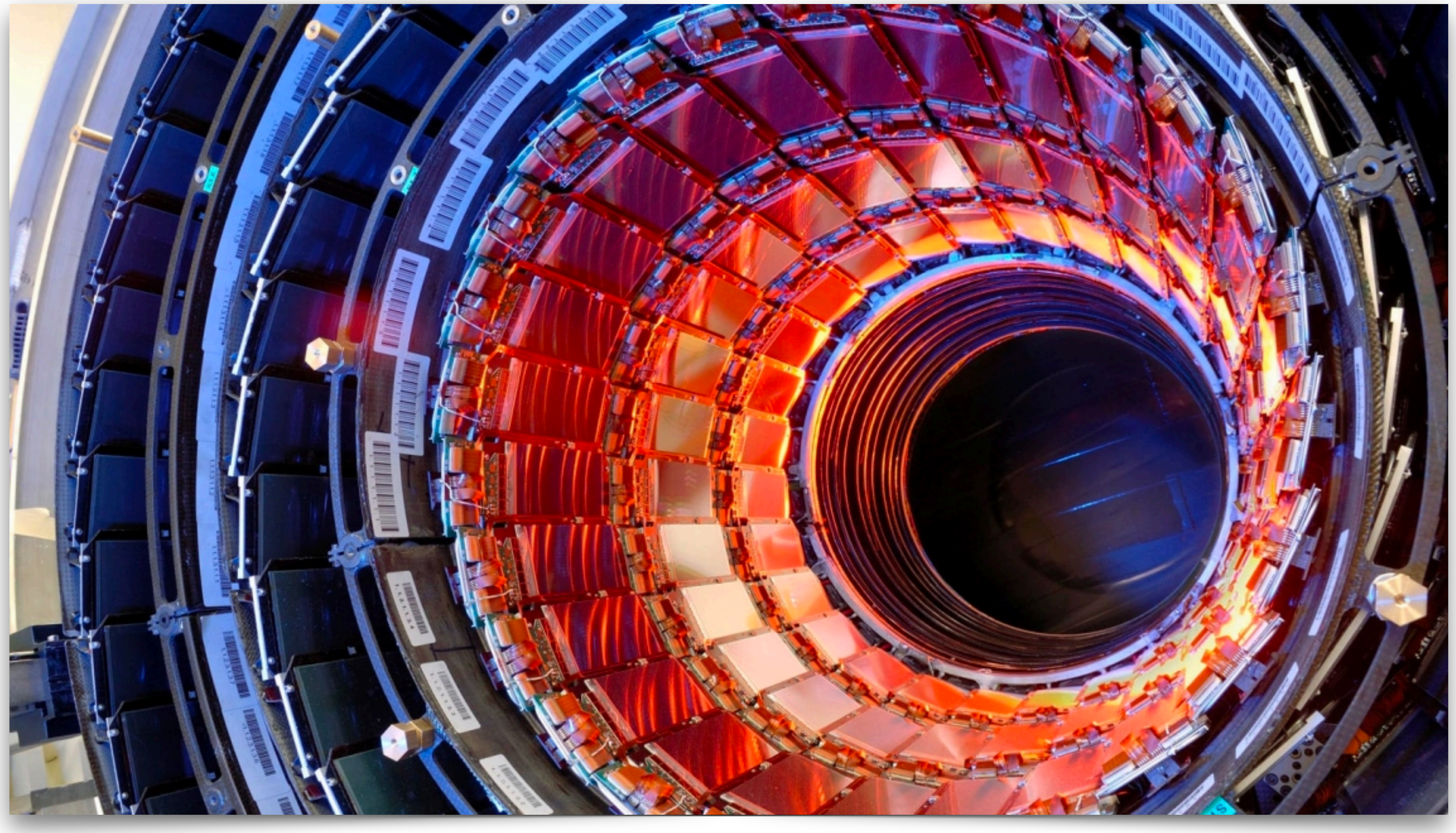


# Tracking detectors: Example Belle II central drift chamber

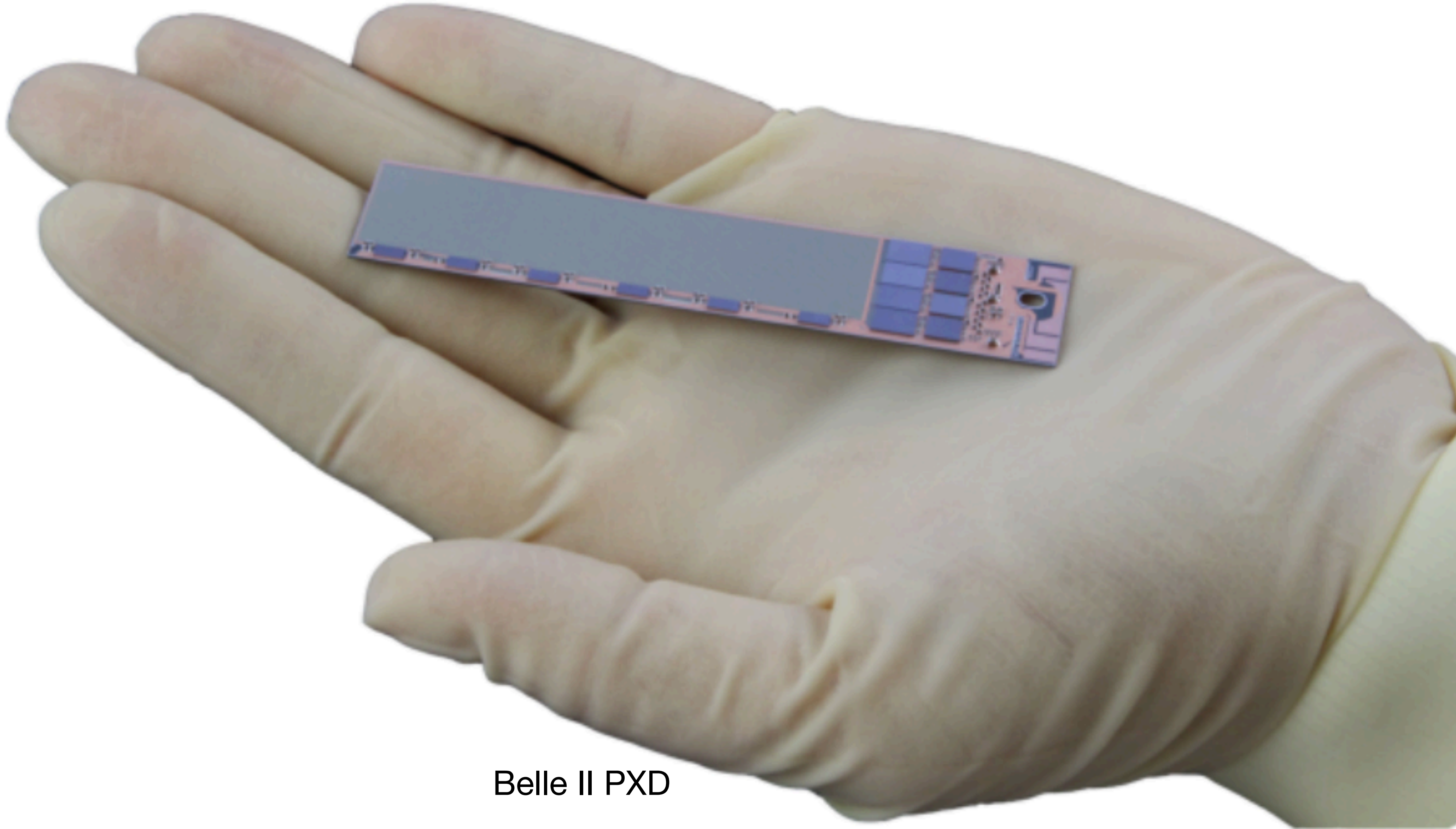


# Tracking detectors: semiconductors

- working principle: semiconductor ionization chamber
  - detector: diode in reverse bias
  - most common design: Hybriddetector
    - ionization and charge collection in silicon
    - amplification and readout in separate chip
- Typical segmentation:
  - 1D “strips”: pitch 25-200µm, length 10cm
  - 2D “pixels”:
    CMS 100×150 µm$^2$, Belle II 50×55 µm$^2$



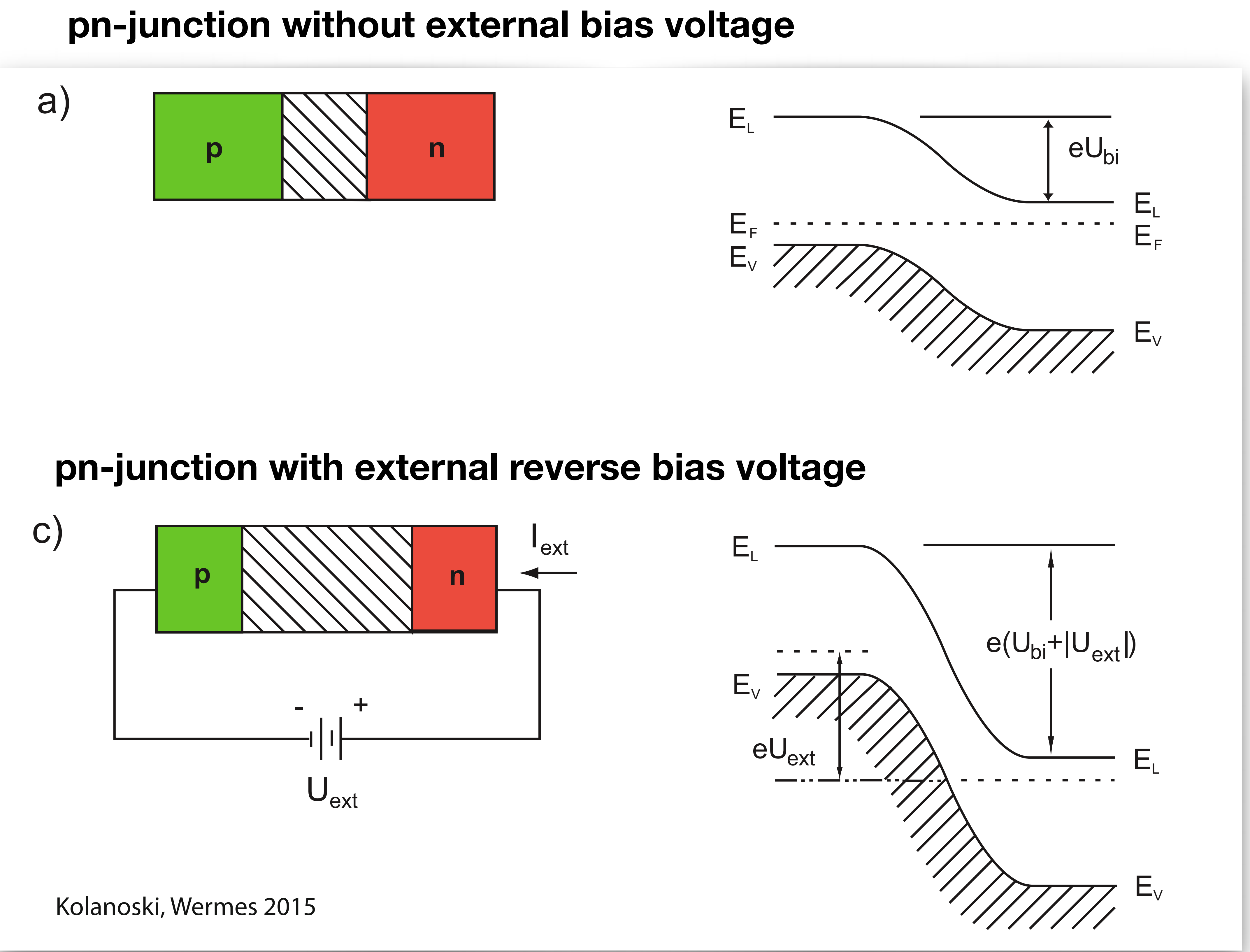
CMS tracker



Belle II PXD

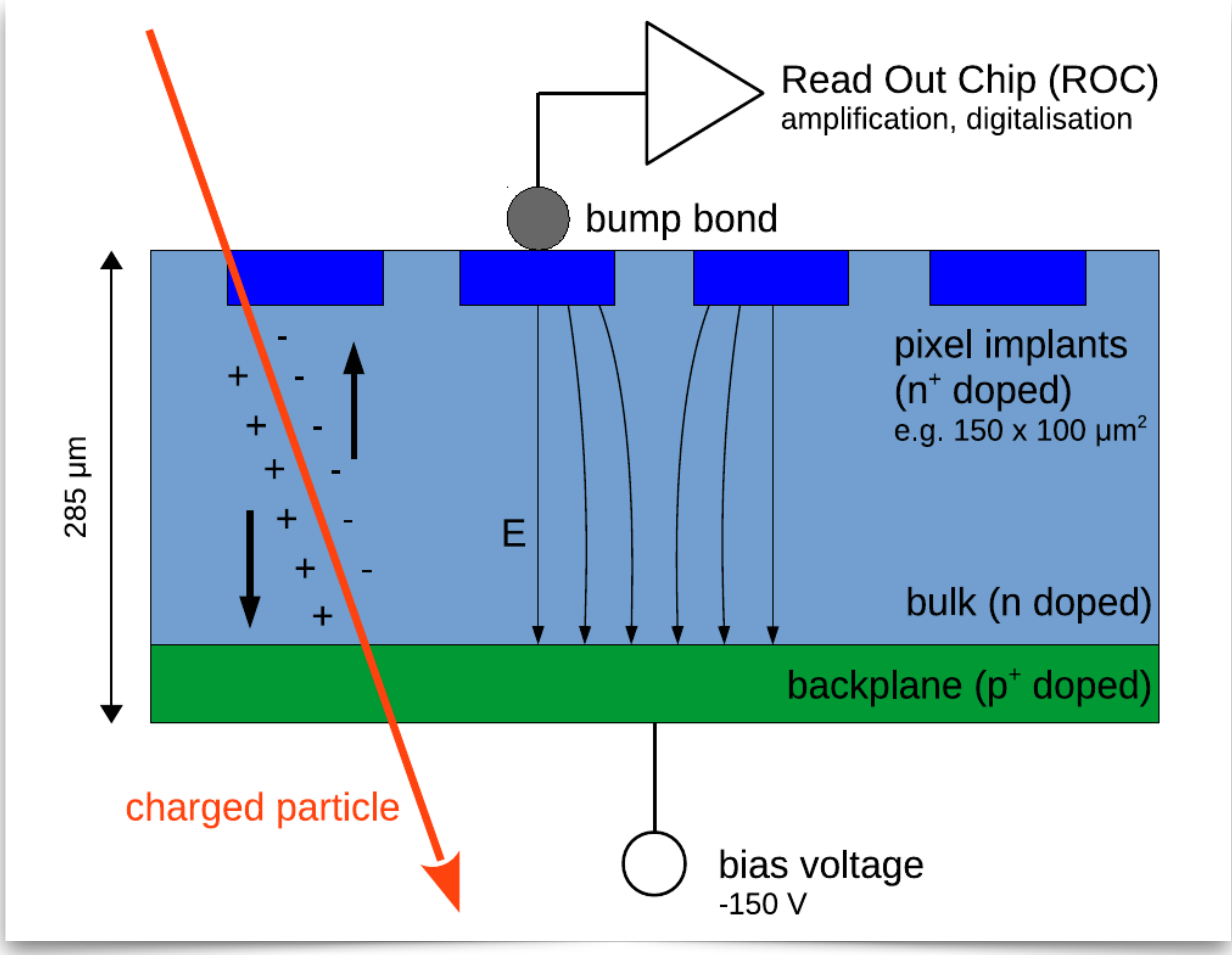
# Tracking detectors: semiconductors

- Boundary between p-n and n-doped semiconductors
  - Majority charge carriers diffuse to other side
  - Charge-density gradient: E-field counteracts diffusion
  - Formation of non-conductive depletion zone ("Verarmungszone") without free charge carriers
- Apply reverse bias current:
  - Increase depletion zone
  - Charged particle traversing depletion zone: Creation of free charges via ionization

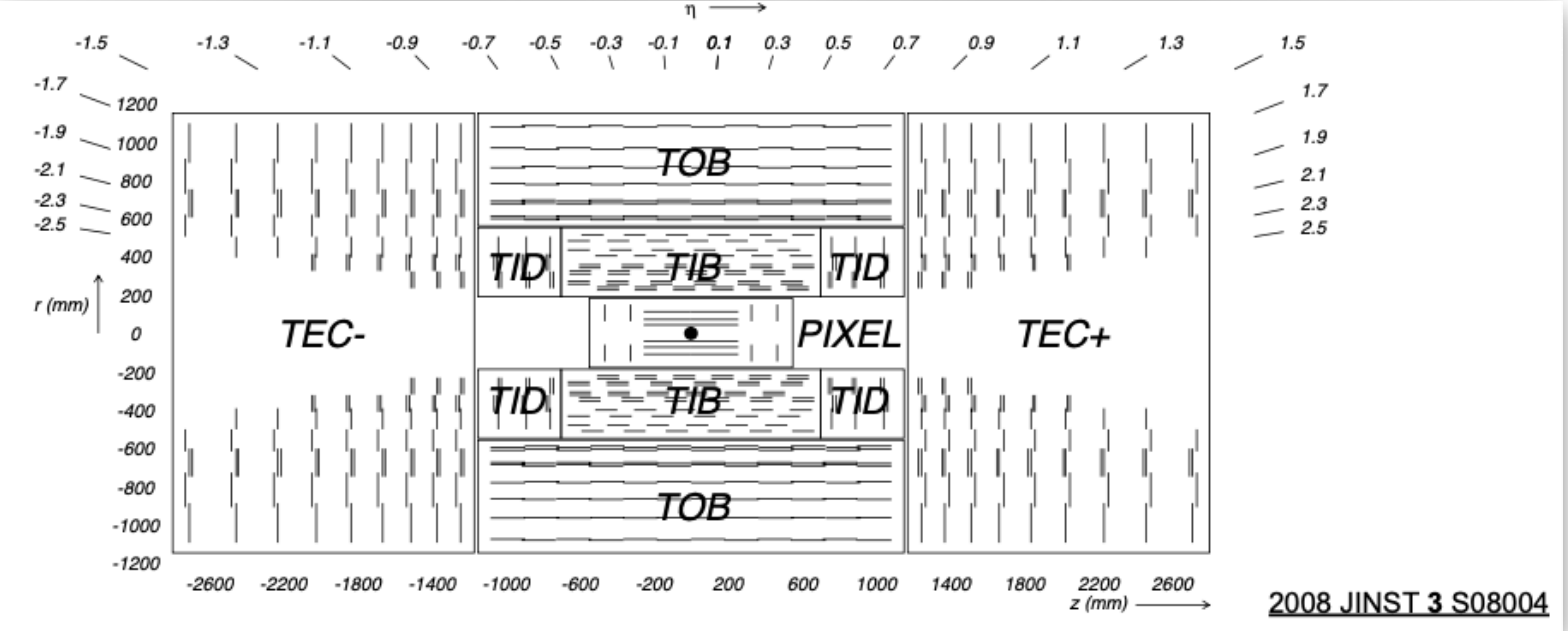


Kolanoski, Wermes 2015

# Tracking detectors: Example CMS Pixel Sensor



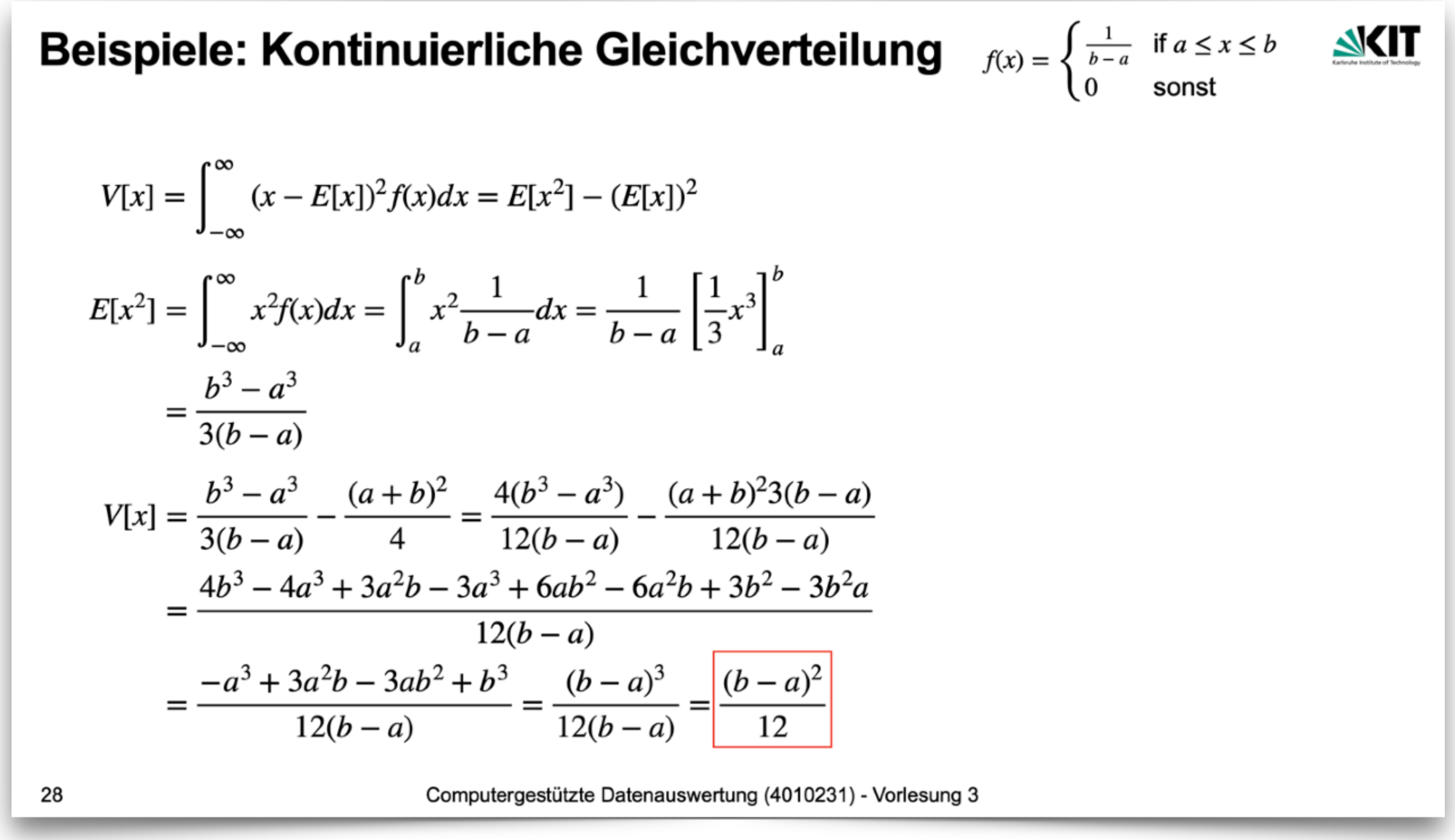
# Tracking detectors: Example CMS




- CMS tracking detector from silicon: more than 200m² sensitive area
  - ~25,000 sensors with ~75,000,000 channels
  - Inner layers: pixel sensors with high resolution
  - Outer layers: strip detectors with large coverage

# Tracking detectors: Hit resolution

- Binary readout: Sensor hit or sensor not hit → Resolution $\sigma = d/\sqrt{12}$
  - Calculate variance of a uniform distribution



**Beispiele: Kontinuierliche Gleichverteilung** $f(x) = \begin{cases} \frac{1}{b-a} & \text{if } a \le x \le b \\ 0 & \text{sonst} \end{cases}$

$$V[x] = \int_{-\infty}^{\infty} (x - E[x])^2 f(x)dx = E[x^2] - (E[x])^2$$

$$E[x^2] = \int_{-\infty}^{\infty} x^2 f(x)dx = \int_a^b x^2 \frac{1}{b-a}dx = \frac{1}{b-a}\left[\frac{1}{3}x^3\right]_a^b$$

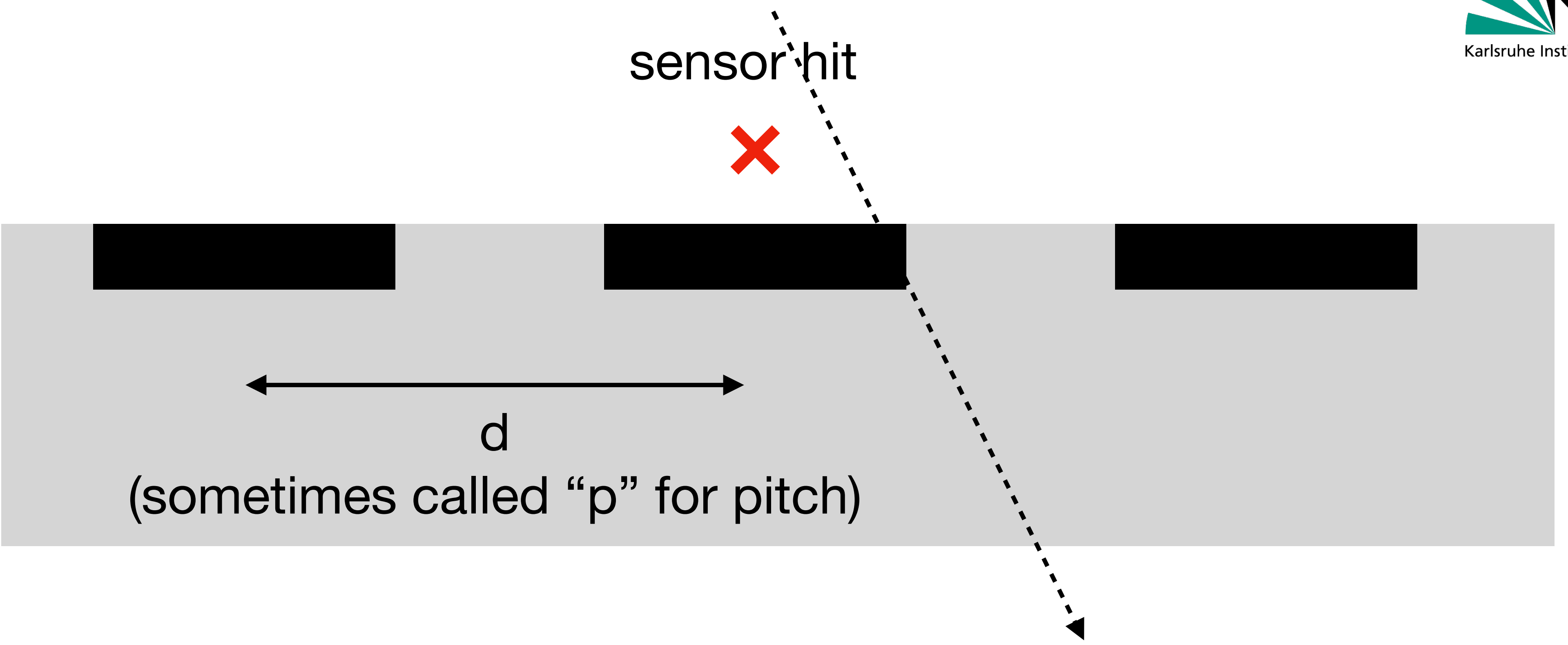
$$= \frac{b^3 - a^3}{3(b-a)}$$

$$V[x] = \frac{b^3 - a^3}{3(b-a)} - \frac{(a+b)^2}{4} = \frac{4(b^3 - a^3)}{12(b-a)} - \frac{(a+b)^2 3(b-a)}{12(b-a)}$$

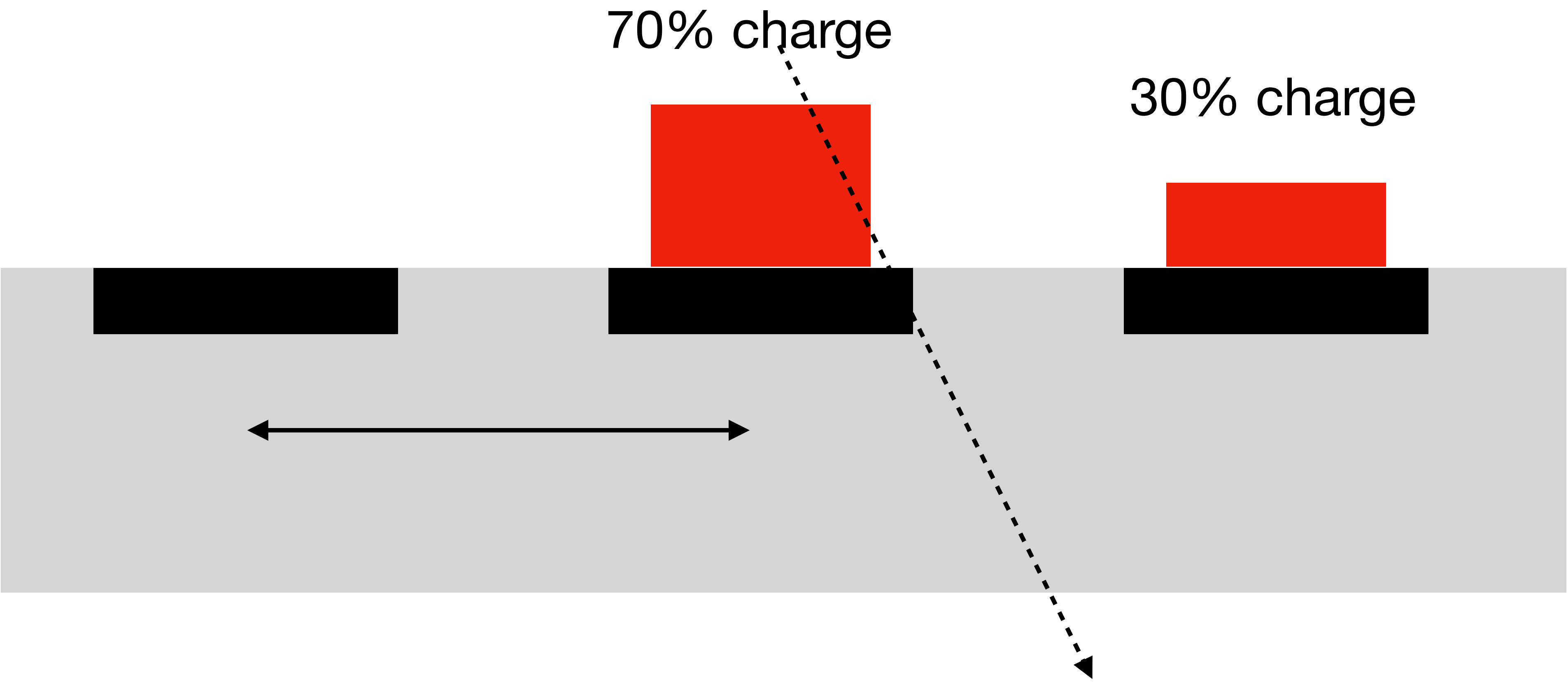
$$= \frac{4b^3 - 4a^3 + 3a^2b - 3a^3 + 6ab^2 - 6a^2b + 3b^2 - 3b^2a}{12(b-a)}$$

$$= \frac{-a^3 + 3a^2b - 3ab^2 + b^3}{12(b-a)} = \frac{(b-a)^3}{12(b-a)} = \boxed{\frac{(b-a)^2}{12}}$$

28 Computergestützte Datenauswertung (4010231) - Vorlesung 3




- Digital readout: additional information about charge or time → Resolution better than $\sigma < d/\sqrt{12}$



# Tracking detectors: Comparison

| gas | semiconductor |
|---|---|
| high ionisation energy ~30 eV | low ionisation energy ~3.6eV<br>→ larger signal, better S/N |
| slow signal ~μs | fast(er) signal ~ns |
| many hits per track | few hits per track |
| low granularity | high granularity |
| low material budget | high material budget |
| ages under high radiation | radiation hard |

- Design decision (simplified):
  - Highest rates: Semiconductors (e.g. CMS, ATLAS)
  - Highest precision: Gas (e.g. Belle II, future ILC)
  - often: semiconductors in inner layers, gas in outer layers (e.g. Belle II)

# What questions do you have?