МИСИС
УНИВЕРСИТЕТ

Basic principles of tracking and particle identification

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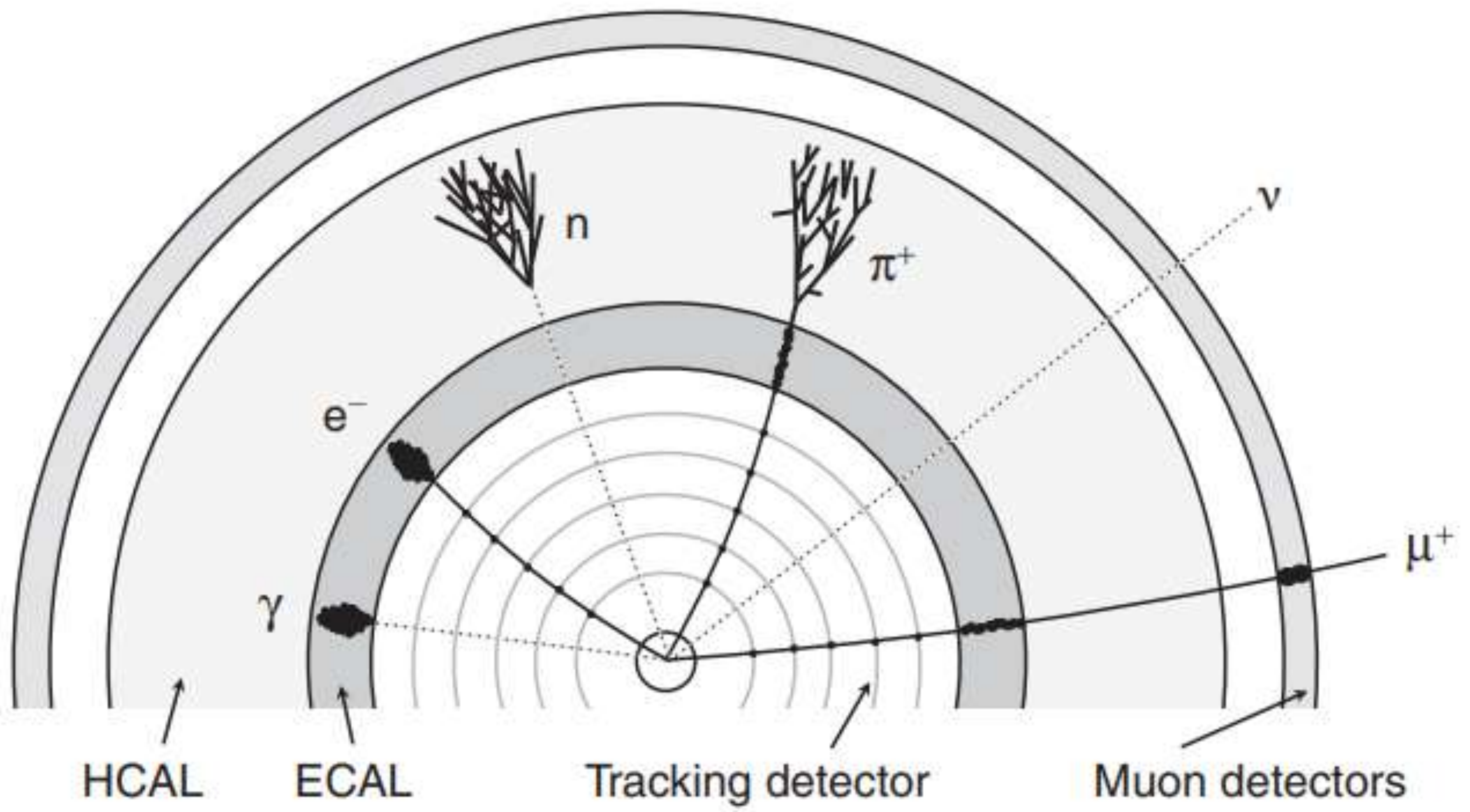
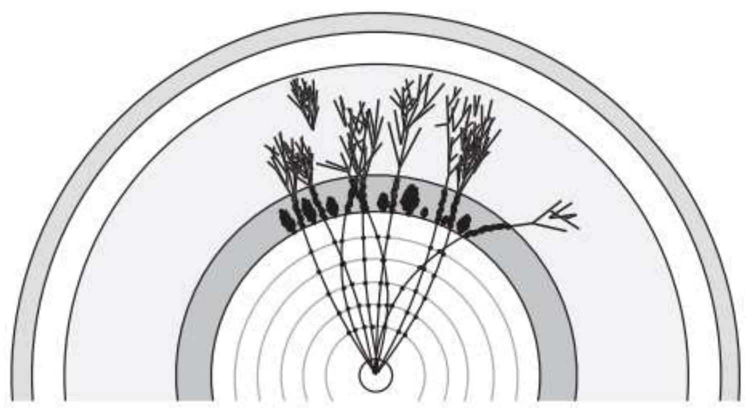
Plan of the seminar

- Detection of different particles
- Long-lived charged hadron identification
  - Time of flight (TOF)
  - Ionization (dE/dx)
    - Tracking
  - Transition radiation
  - Cherenkov radiation
- Real-life application: detection of antiHe at the LHCb experiment

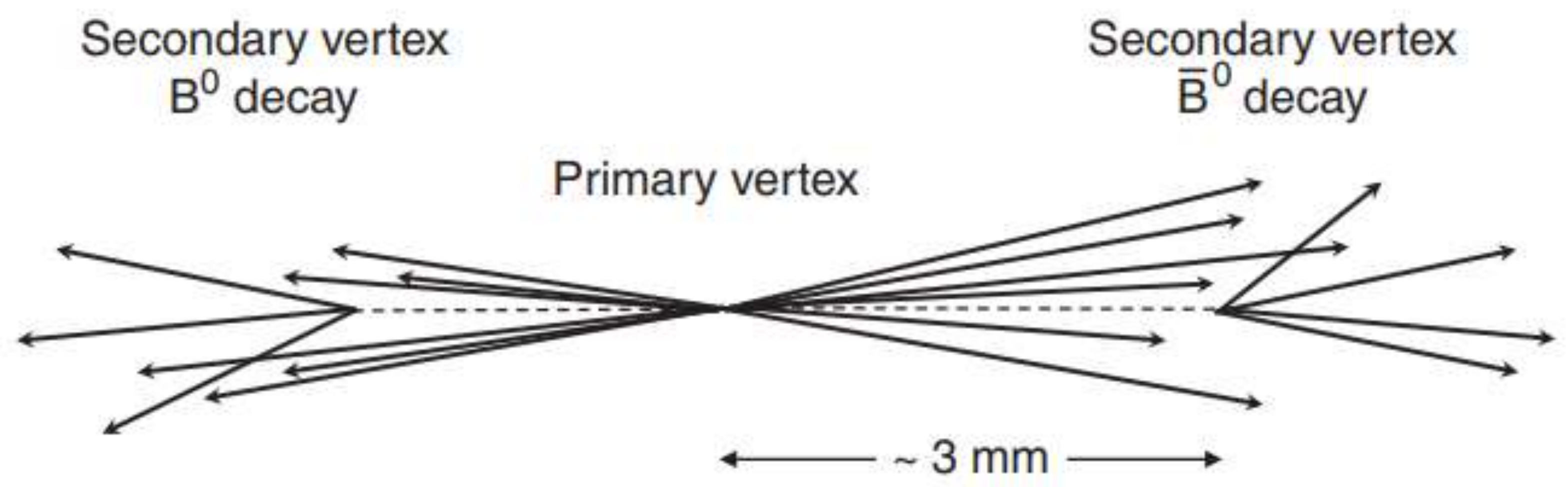
Detection of different particles



- Jet in a detector



- b-tagging



Task 1

Tungsten has a radiation length of $X_0 = 0.35$ cm and a critical energy of $E_c = 7.97$ MeV. Roughly what thickness of tungsten is required to fully contain a 500 GeV electromagnetic shower from an electron?

Task 1 solution

The number of particles in a shower doubles every radiation length. The typical paticle energy after n radiation lengths is

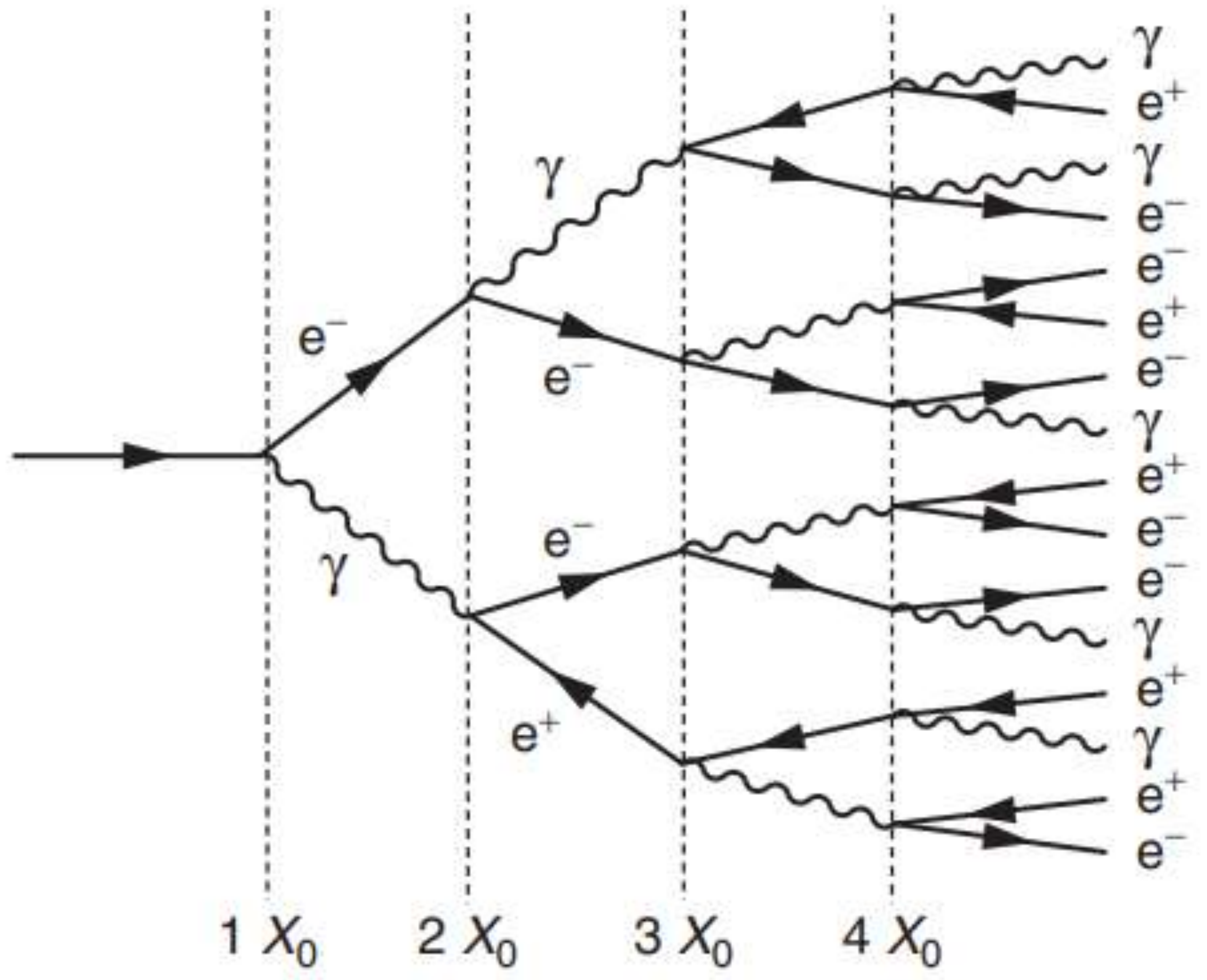
$$E_n = E/2^n$$

Roughly, the shower terminates when $E_n = E_c$ for the material

$$E_c = E/2^n$$

$$n \ln 2 = \ln(E/E_c)$$

This gives us $n = 16$ radiation lengths or 5.6 cm of tungsten



Time-of-flight detectors

Time difference for two particles with masses m_1 and m_2 for length L

$$\Delta t = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left[\sqrt{\left(1 + \frac{m_1^2 c^2}{P^2}\right)} - \sqrt{\left(1 + \frac{m_1^2 c^2}{P^2}\right)}\right]$$

$$P^2 \gg m^2 c^2$$

$$\Delta t \sim \frac{Lc(m_1^2 - m_2^2)}{2P^2}$$

Mass resolution depends on time resolution of detectors and distance L

Types of detectors:

- Scintillators
- Gaseous
- Silicon
- Cherenkov

Ionization (dE/dx)

$$-\frac{dE}{dx}(\mathrm{eVcm^2g^{-1}}) = Kq^2 \frac{Z}{A\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

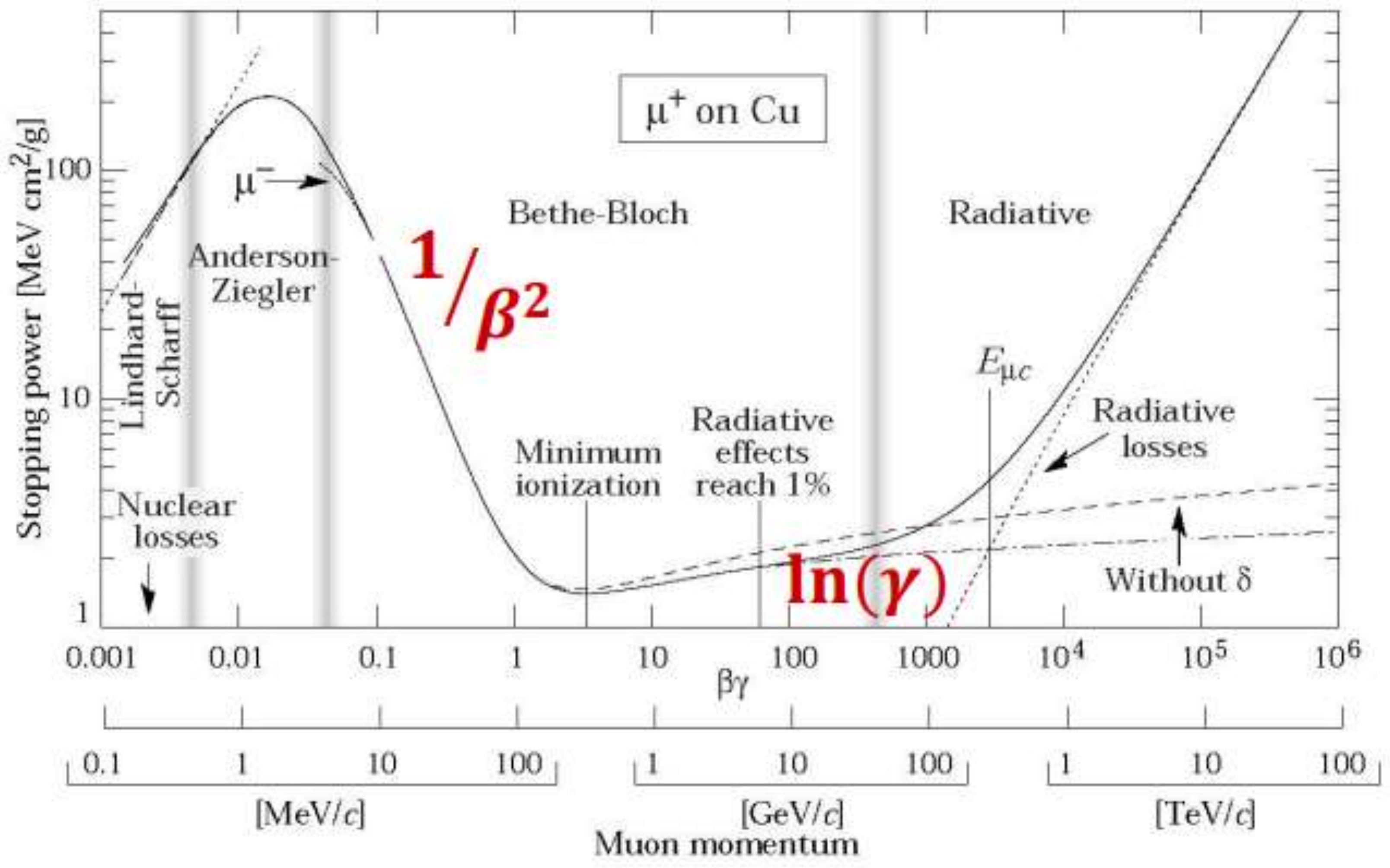
Ionisation Constant for material

Density correction

$$T_{max} \approx 2m_ec^2\beta^2\gamma^2$$

Max energy in single collision

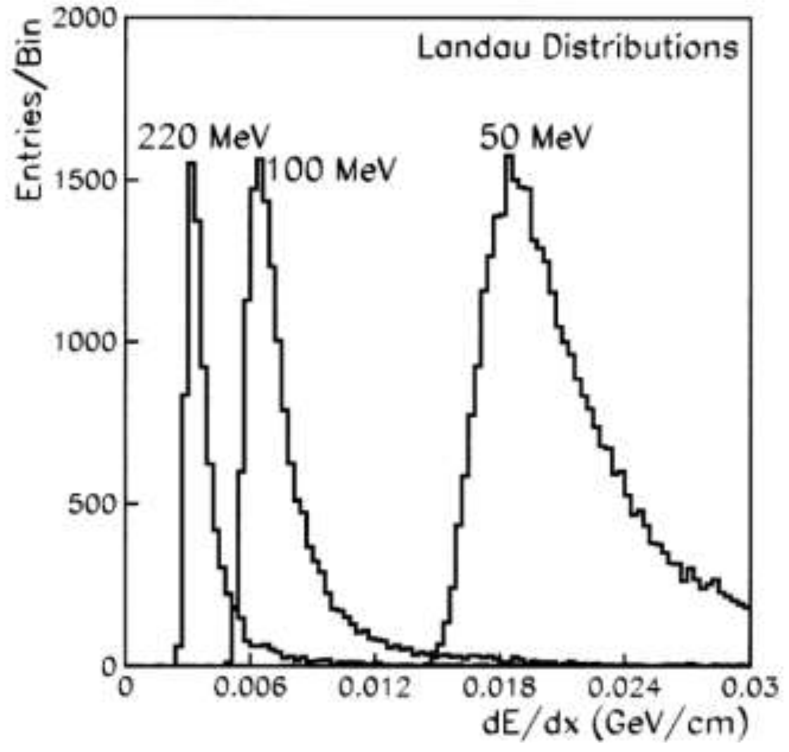
$$K = 4\pi N r_e^2 m_e c^2$$



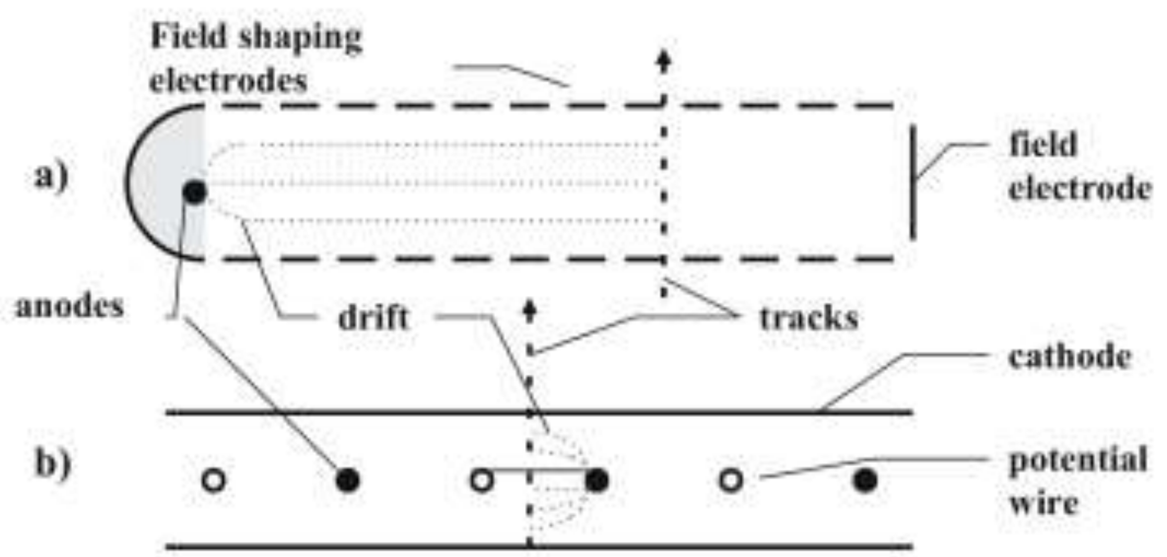
- Silicon detectors

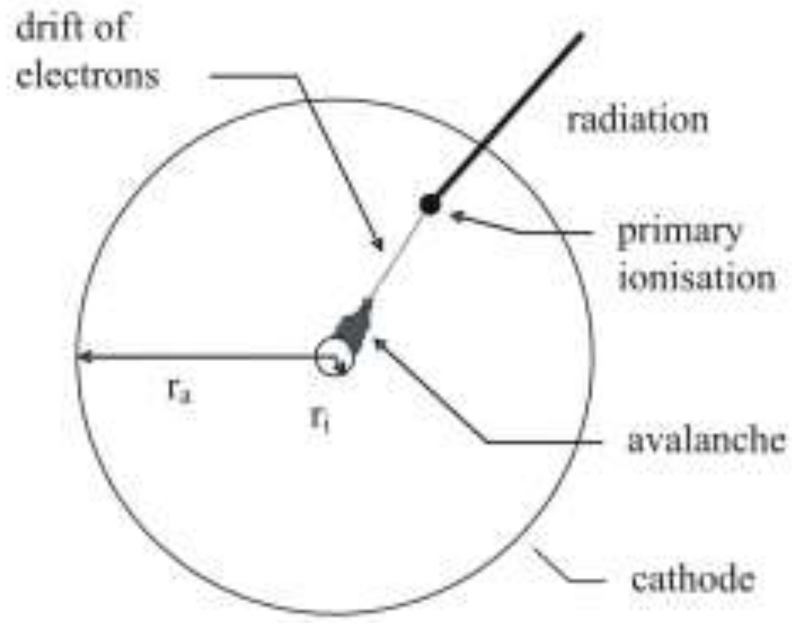
Bethe-Block formula (for 2 γ m/M << 1)

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi Ne^4}{mc^2\beta^2}z^2\left(\ln\frac{2mc^2\beta^2\gamma^2}{I} - \beta^2\right)$$



- Drift chambers based on proportional counters





Task 2

High-energy muons traversing matter lose energy according to

$$-\frac{1}{\rho}\frac{dE}{dx} \approx a + bE,$$

where a is due to ionisation energy loss and b is due to the bremsstrahlung and e^+e^- pair-production processes. For standard rock, taken to have $A = 22$, $Z = 11$ and $\rho = 2.65\ \mathrm{g\ cm^{-3}}$, the parameters a and b depend only weakly on the muon energy and have values $a \approx 2.5\ \mathrm{MeV\ g^{-1}\ cm^2}$ and $b \approx 3.5 \times 10^{-6}\ \mathrm{g^{-1}\ cm^2}$.

(a) At what muon energy are the ionisation and bremsstrahlung/pair production processes equally important?

(b) Approximately how far does a 100 GeV cosmic-ray muon propagate in rock?

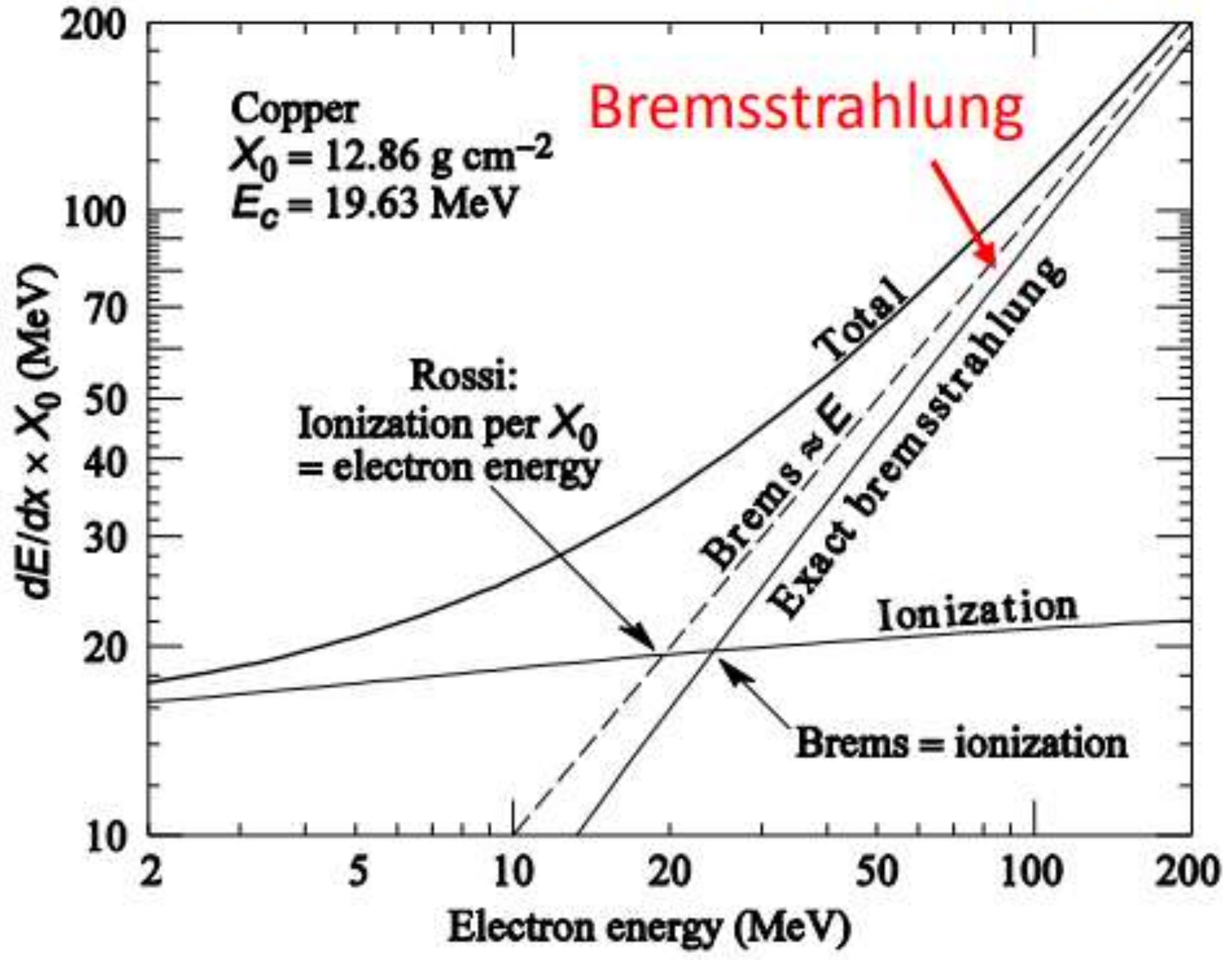
Task 2 solution

a) Ionisation and pair production or bremsstrahlung processes are equally likely when $a = bE$.

Plugging in the numbers we get $E = 714 GeV$

b) We just need to integrate the equation:

[PDG]



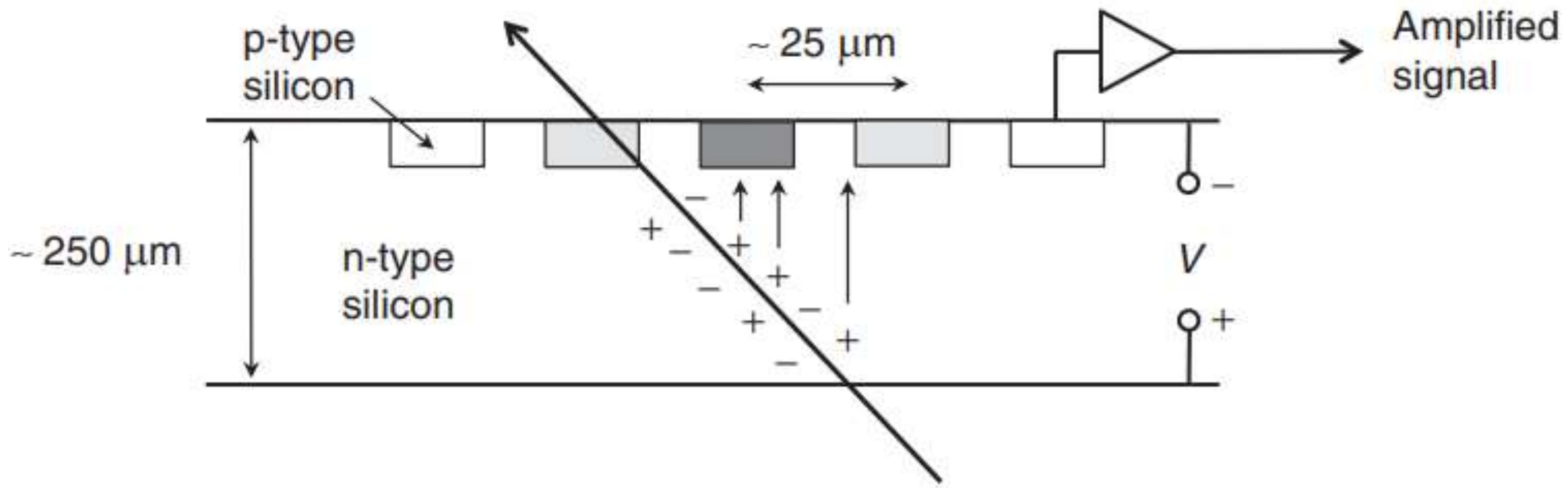
$$-\frac{dE}{a+bE} = \rho dx$$

We get

$$-\frac{\ln(a+bE)|_{E_0}^{0}}{b} = \rho x|_0^L$$

$$L = \frac{1}{\rho b}\ln(1+\frac{b}{a}E_0) = 141.3m$$

Tracking



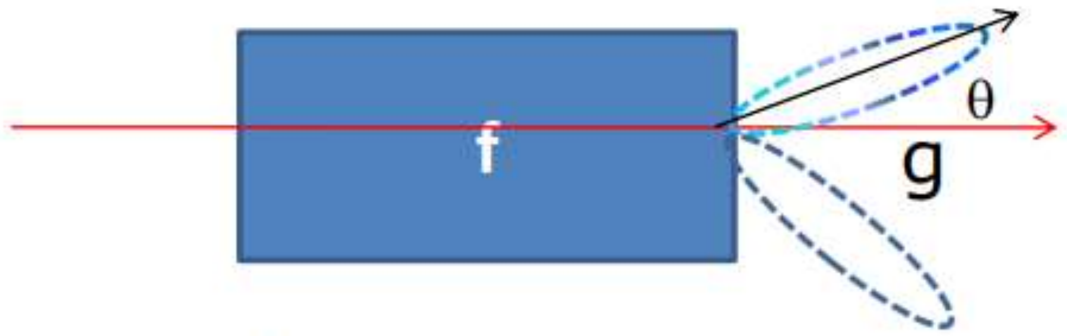
- Electron-hole pairs are created when a charged particle traverses the silicon wafer.
- Charge, collected from one particle passage is considered a hit.
- Hits are combined into tracks, using reconstruction algorithms.
- Combining several tracking stations and a magnetic field allows to measure the momentum of charged particles via track curvature.

Transition radiation

- Transition Radiation: Radiation in the x-ray region when ultra relativistic particles cross the boundary between 2 media with different dielectric constants.
- Mainly for e-π separation in 0.5 GeV/c → 200 GeV/c.

Number of photons produced = $N(>\omega) = \frac{\alpha}{\pi}\left\{\ln\frac{\omega_c}{\omega}\left(\ln\frac{\omega_c}{\omega} - 2\right) + \frac{\pi^2}{12} + 1\right\}$

For ω_c=100 keV and ω=1 keV, N= 0.03 for a single surface.
Hence to get sufficient number of photons , large number of interfaces are used: a stack of many foils with gaps in between.



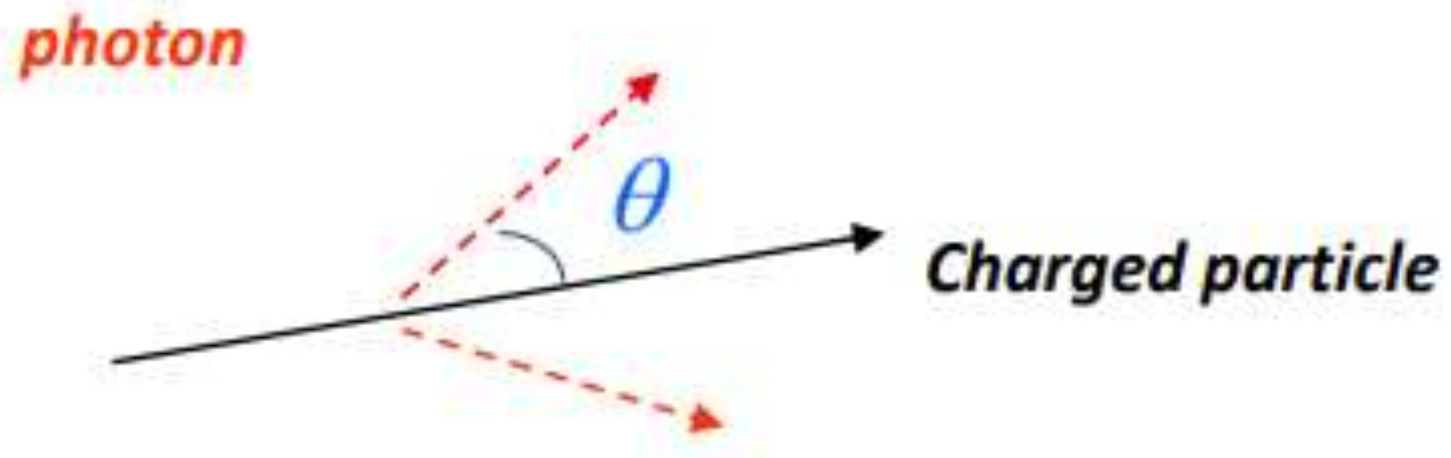
The radiation is peaked at a small angle:
$\theta = 1/\gamma$

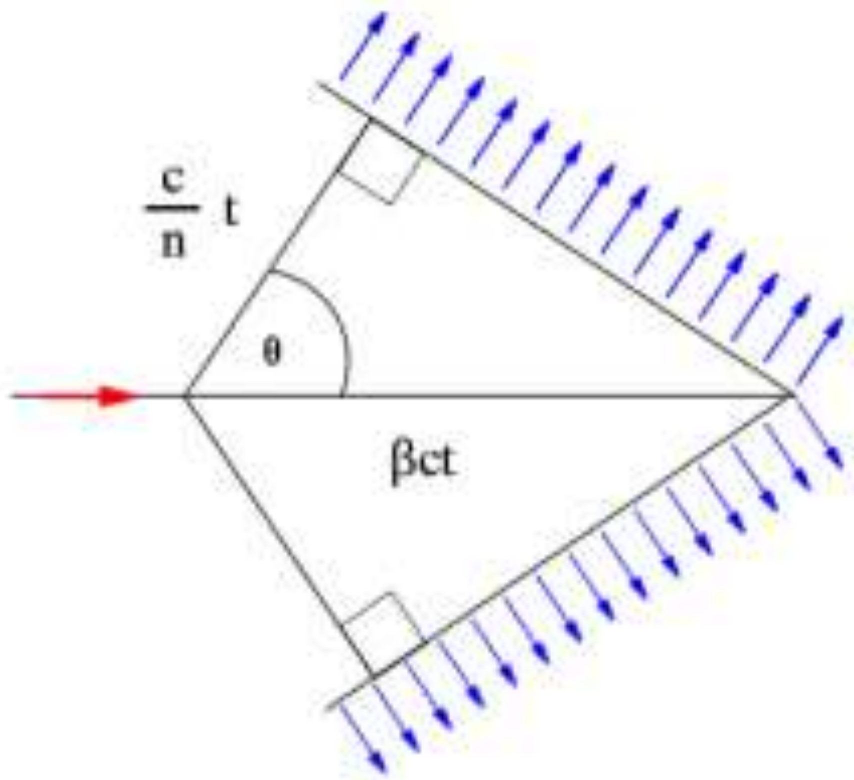
$$\frac{dW}{d\omega\, d\theta} = \frac{2\alpha}{\pi} f_0(\theta)$$

$$f_0(\theta) = \theta^3\left(\frac{1}{\gamma^{-2}+\theta^2+\xi_g^2} - \frac{1}{\gamma^{-2}+\theta^2+\xi_f^2}\right)$$

$\xi_i = {\omega_i}/{\omega}$ ω_i =plasma freq of medium i

Cherenkov radiation





$$\cos(\theta) = \frac{1}{n(\lambda)\beta}$$

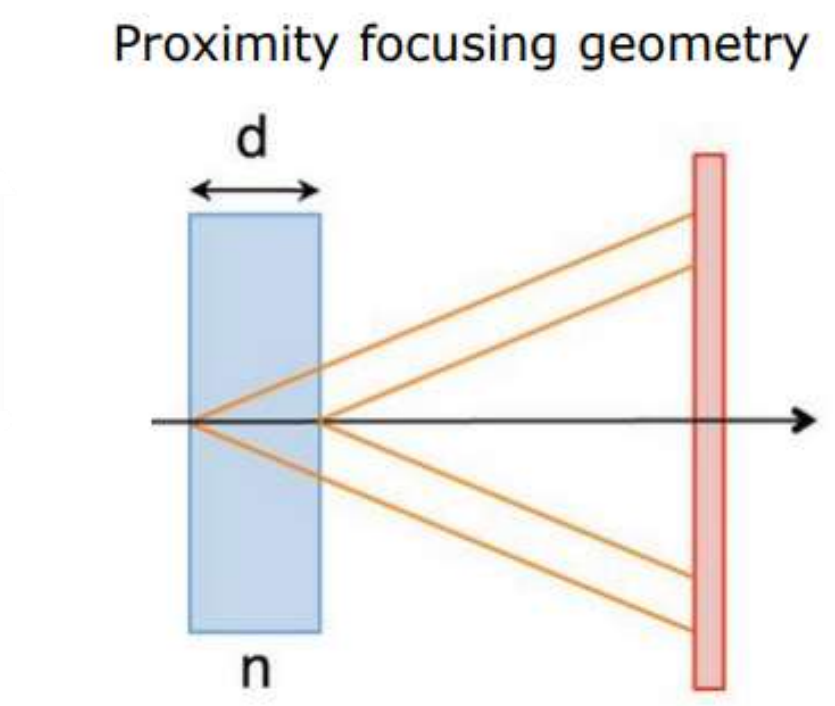
$$n(E_{ph}) = c/c_M$$ Refractive index

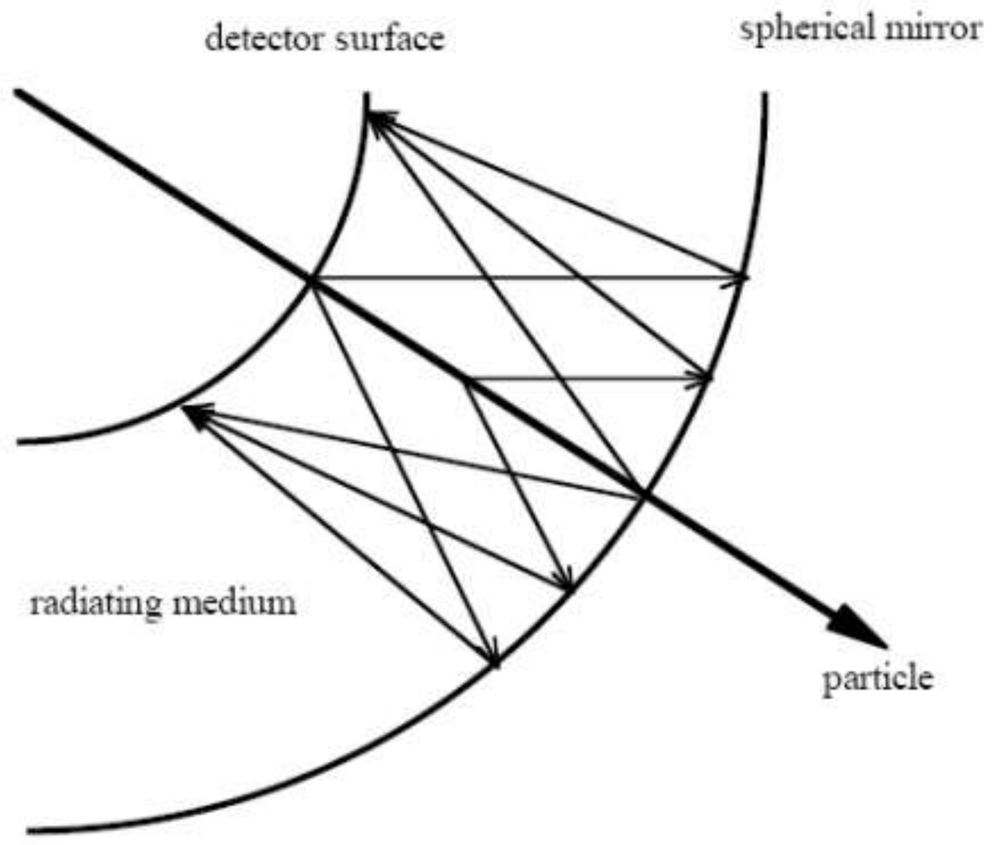
$$\beta = v/c = P/E = P/\sqrt{P^2 + m^2} = \frac{1}{\sqrt{1 + (m/p)^2}}$$

β= velocity of the charged particle in units of speed of light (c) vacuum
P, E ,m = momentum, energy, mass of the charged particle
C_M = speed of light in the medium (phase velocity)
E_{ph} = photon energy
λ = Photon wavelength

Cherenkov radiation

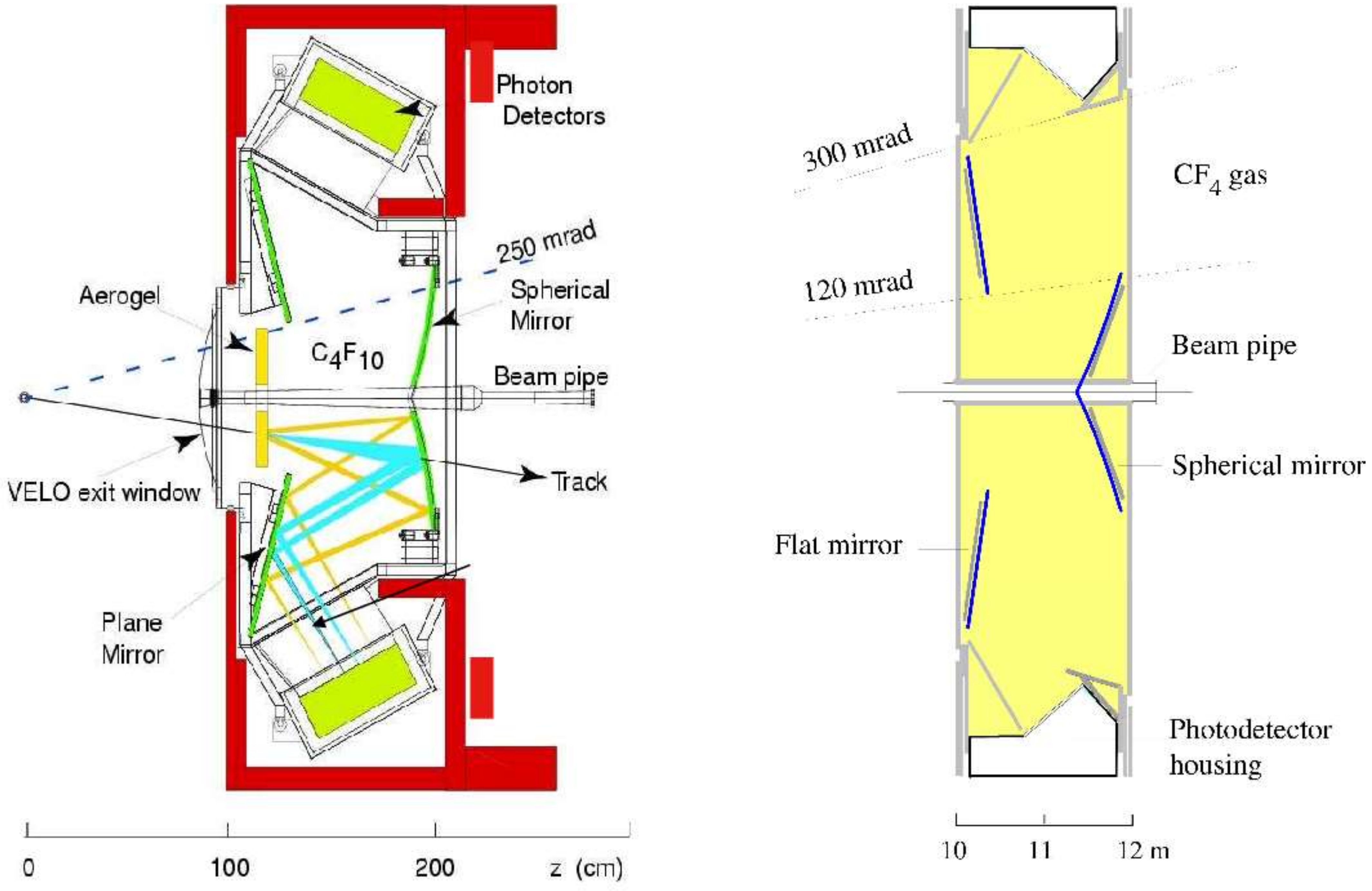
RICH detectors





- Measures both the Cherenkov angle and the number of photoelectrons detected.
- Can be used over particle identification over large surfaces.
- Requires photodetectors with single photon identification capability.

RICH system of LHCb

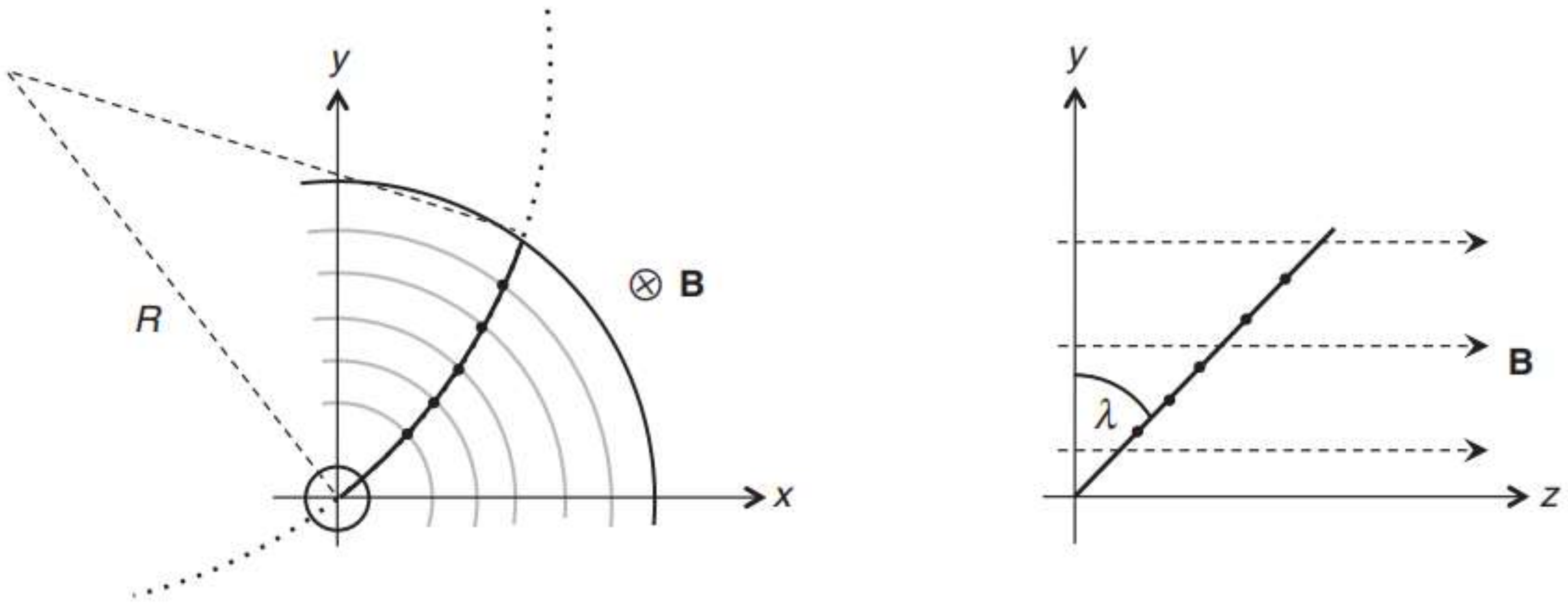


(a) (b)

Task 3

A detector consists of tracking detectors, electromagnetic calorimeter and a Cherenkov detector with a radiator of refractive index $n = 1.25$. A charged particle travelling perpendicular to the magnetic field of $B = 0.44T$ leaves a track with the radius of curvature $R = 4m$ and a Cherenkov signal. Is it possible to distinguish between a pion with $m_\pi = 138MeV$ and a kaon with $m_\pi = 494MeV$?

Task 3 solution



We know that $p\cos\alpha = 0.3BR$, with p in $[GeV]$, R in $[m]$ and B in $[T]$. In our case the pitch angle $\alpha = 0$

From $E = \gamma m$ and $p = \beta\gamma m$ (in natural units), we can get the particle's velocity β:

$$\beta = p/E = \frac{p}{\sqrt{p^2 + m^2}} = \frac{0.3BR}{\sqrt{(0.3BR)^2 + m^2}}$$

,

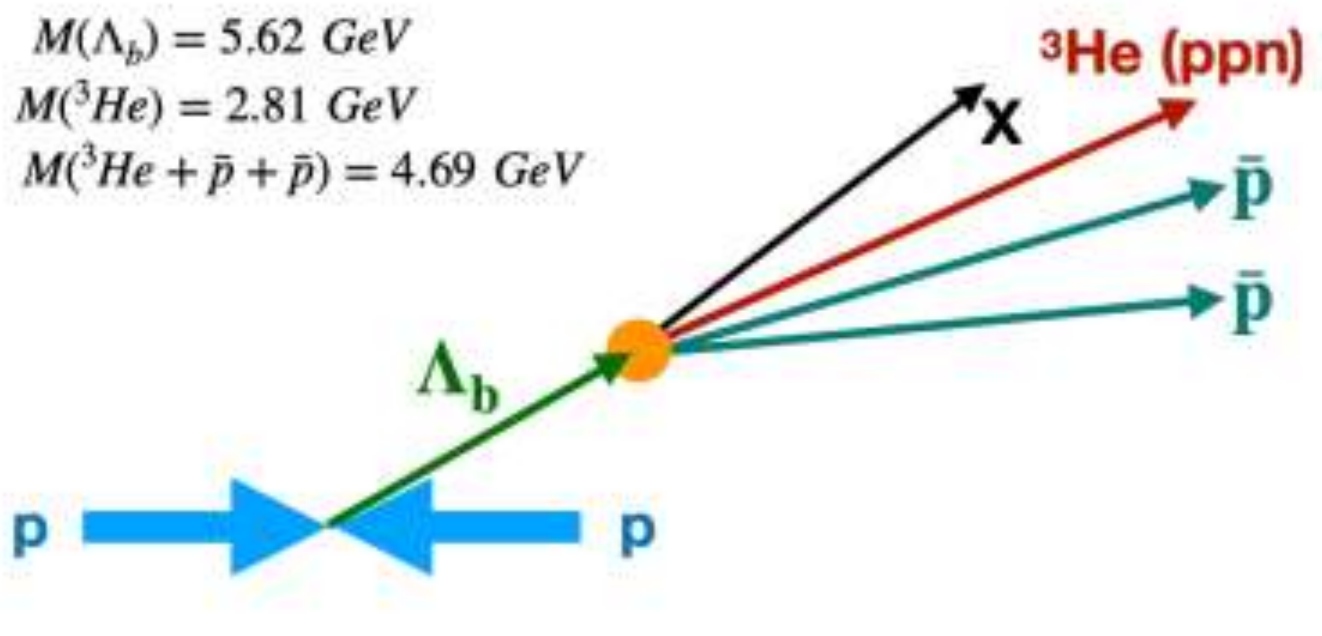
$$\beta_\pi = 0.97, \beta_K = 0.73$$

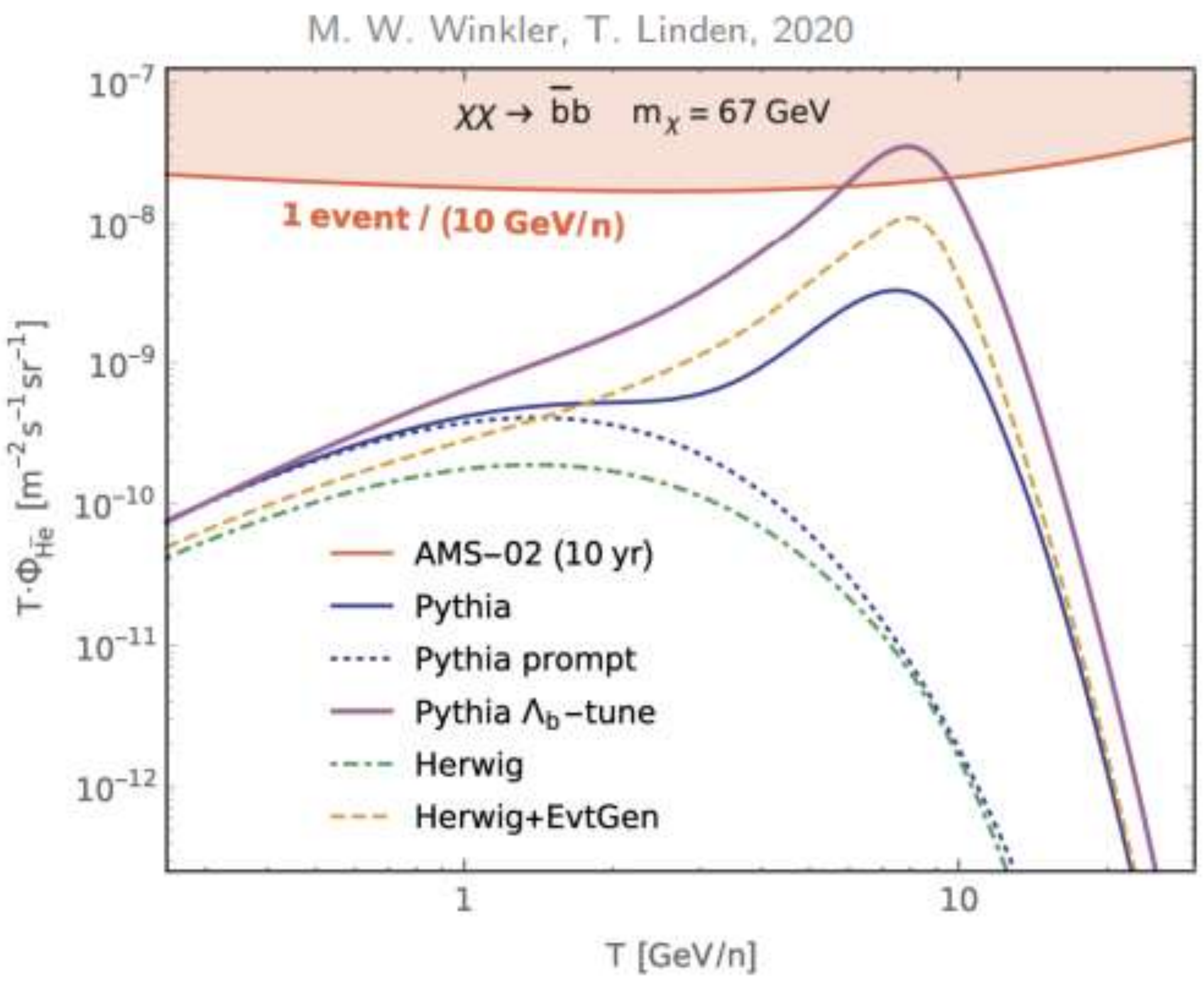
To produce a Cherenkov signal, $\beta > 1/n = 0.8$ should be satisfied. As we can see, it could be a pion, but not a kaon.

Real-life example: detection of antihelium at LHCb

Following LHCb startertalk by Gediminas Sarpis

- Estimated ^{3}He production via Λ_b: $\mathcal{B}(\Lambda_b \to {}^3\text{He} + X) \simeq 3 \times 10^{-6}$
- **Coalescence** enhanced by small Λ_b phase-space
- A special tuning of Pythia gives ^{3}He rate consistent with AMS observation (Λ_b-tune)
- Large uncertainties in non-perturb. QCD

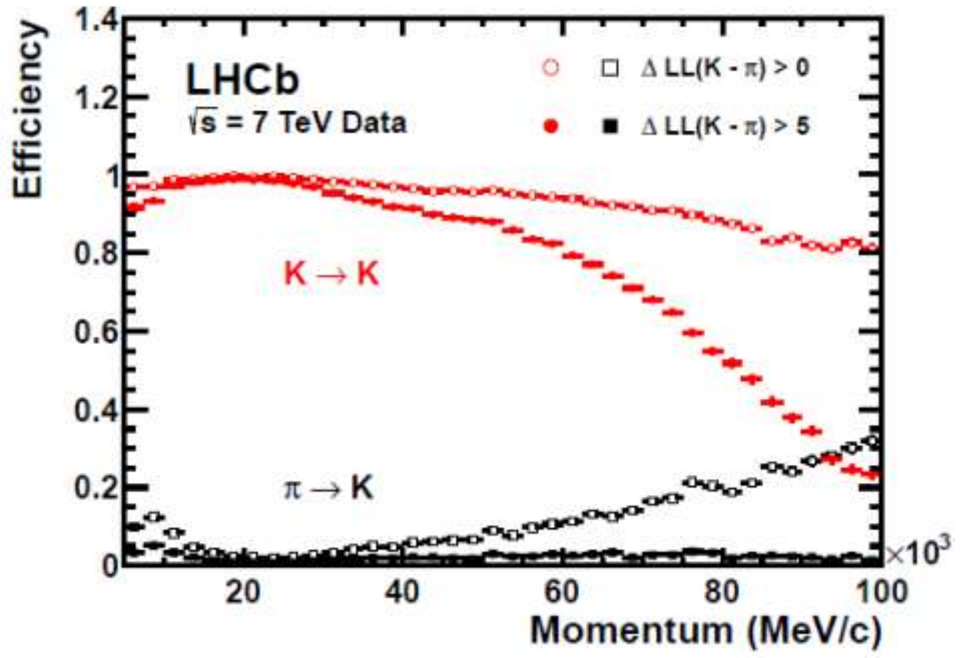




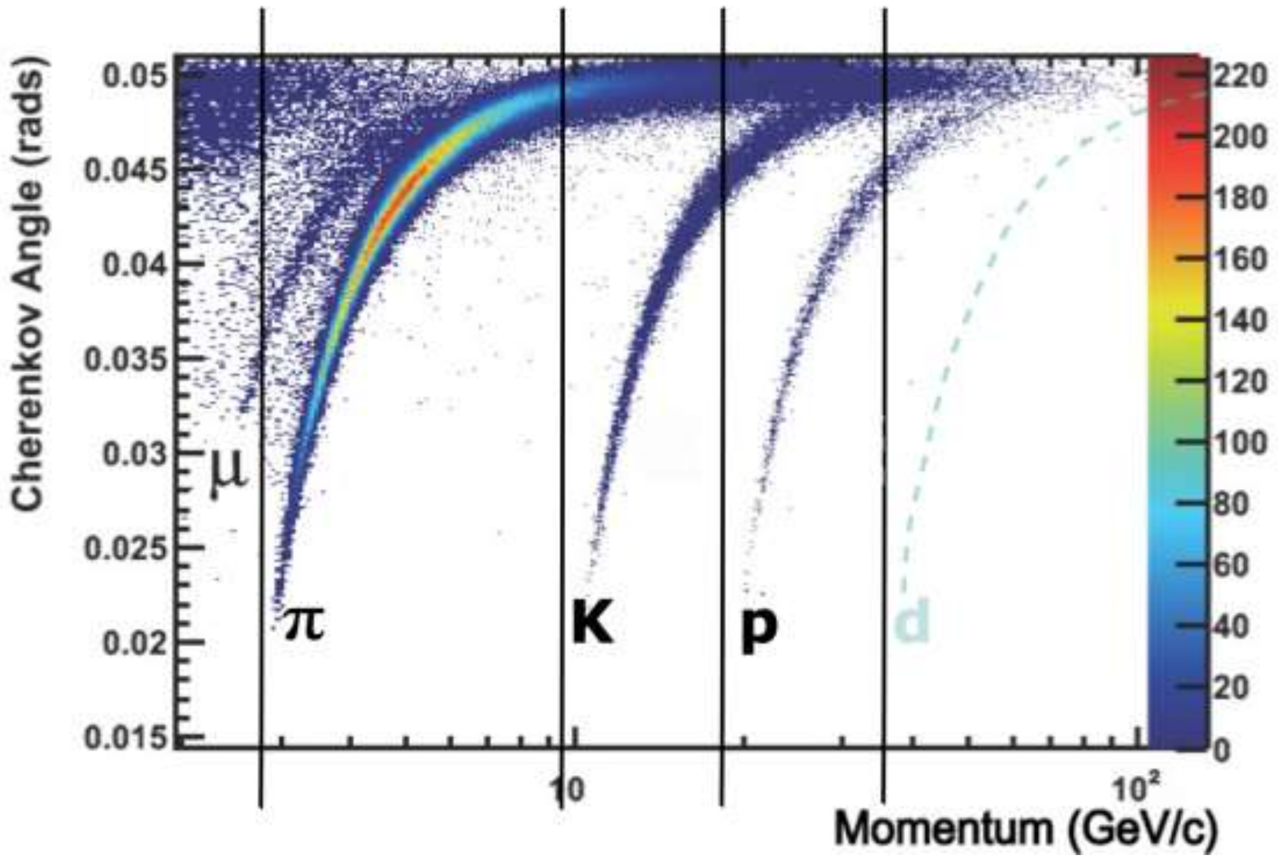
Real-life example: detection of antihelium at LHCb

Following LHCb startertalk by Gediminas Sarpis

RICH detector output



	Threshold momentum (GeV/c)	
Particle	RICH 1	RICH 2
μ	2.0	3.3
π	2.6	4.4
K	9.3	15.6
p	17.7	29.7
d	35.4	59.3



Likelihood function reminder

$$\text{probability that } x_i \text{ in } [x_i, x_i + dx_i] \text{ for all } i = \prod_{i=1}^{n} f(x_i;\theta)dx_i .$$

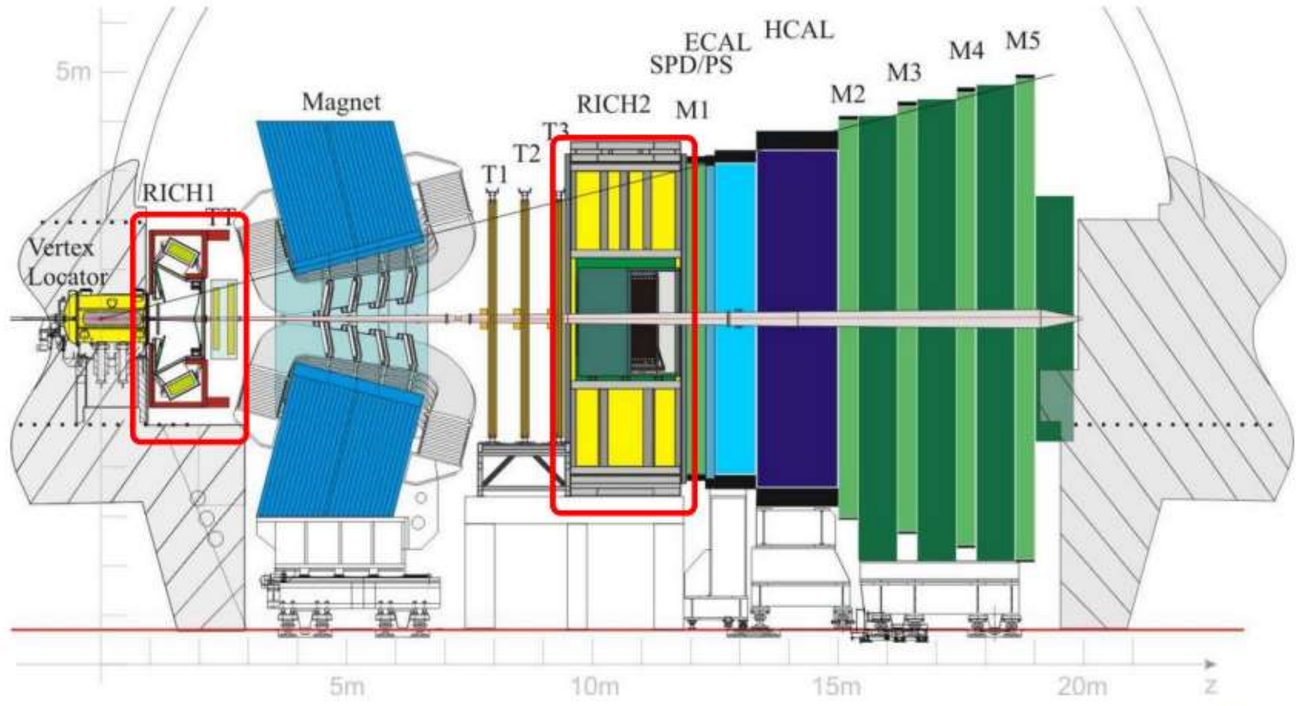
If the hypothesized p.d.f. and parameter values are correct, one expects a high probability for the data that were actually measured. Conversely, a parameter value far away from the true value should yield a low probability for the measurements obtained. Since the dx_i do not depend on the parameters, the same reasoning also applies to the following function L,

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta)$$

- For each of the track in the event, for a given mass hypothesis, create photons and project them to the detector plane using the knowledge of the geometry of the detector and its optical properties. Repeat this for all the other tracks.
- From this calculate the probability that a signal would be seen in each pixel of the detector from all tracks.
- Compare this with the observed set of photoelectron signal on the pixels, by creating a likelihood.
- Repeat all the above after changing the set of mass hypothesis of the tracks. Find the set of mass hypothesis, which maximize the likelihood.

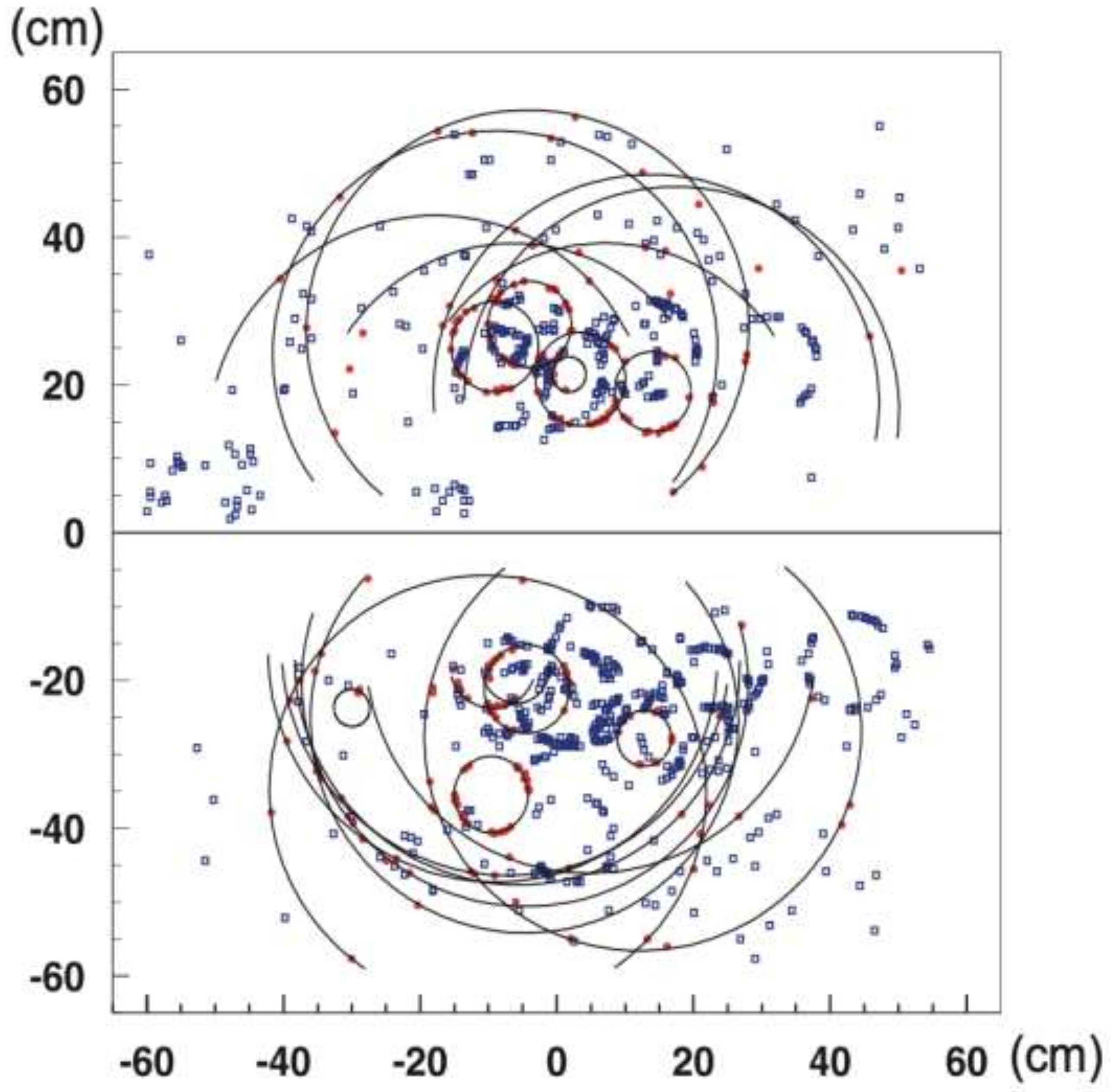
Real-life example: detection of antihelium at LHCb

Following LHCb startertalk by Gediminas Sarpis



Tracking: $\Delta p/p = 0.5 - 1\%$; PID: 95% K_{eff}, 5% $\pi \to K$ misID; ECAL resolution: $1\% + 10\%/\sqrt{E[GeV]}$

RICH detector signal in simulation



RICH detector signal in real data

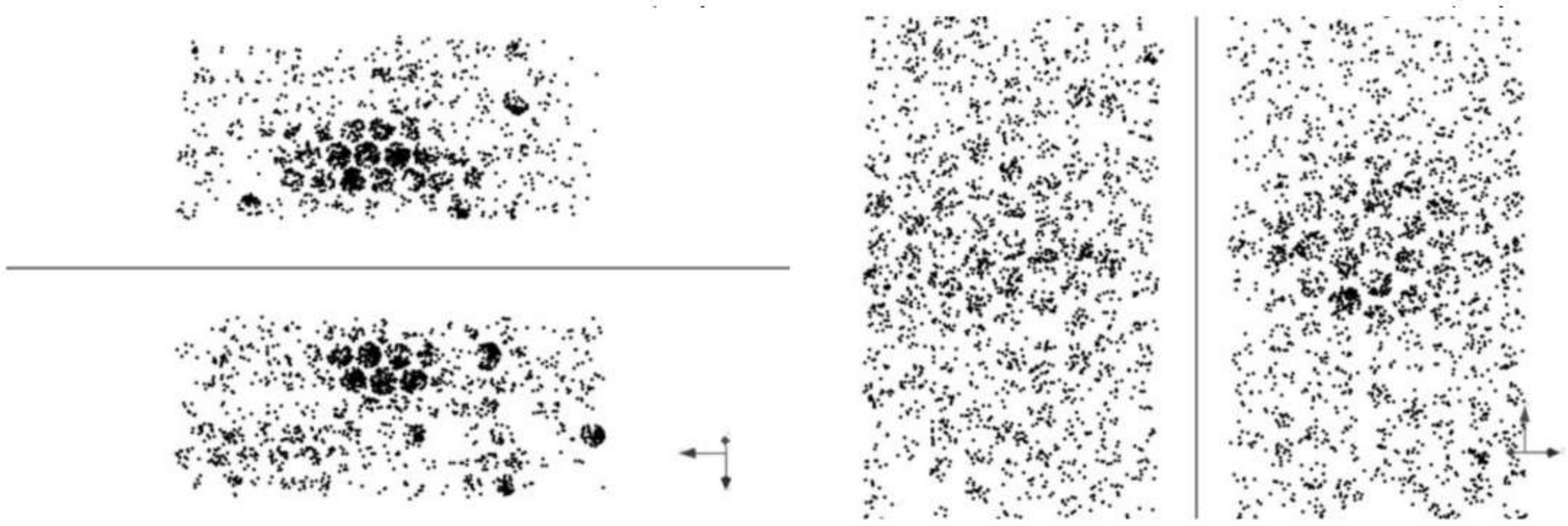
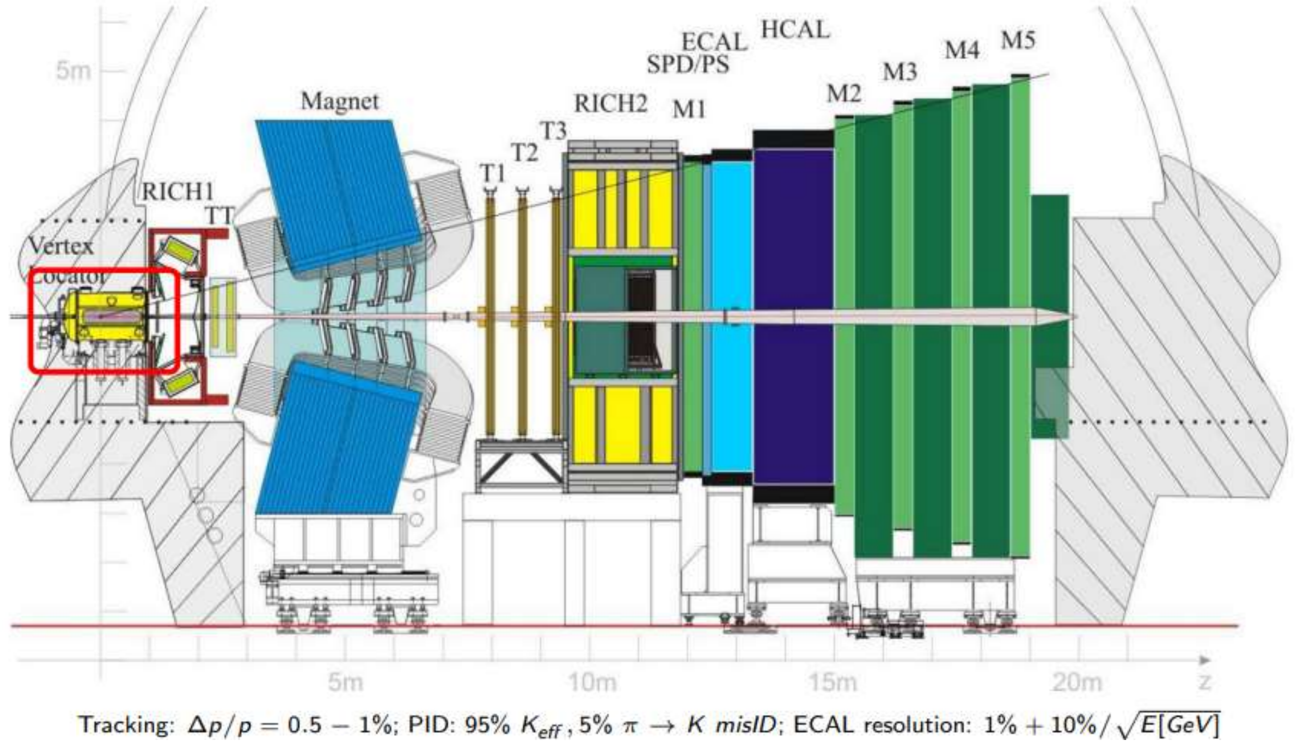


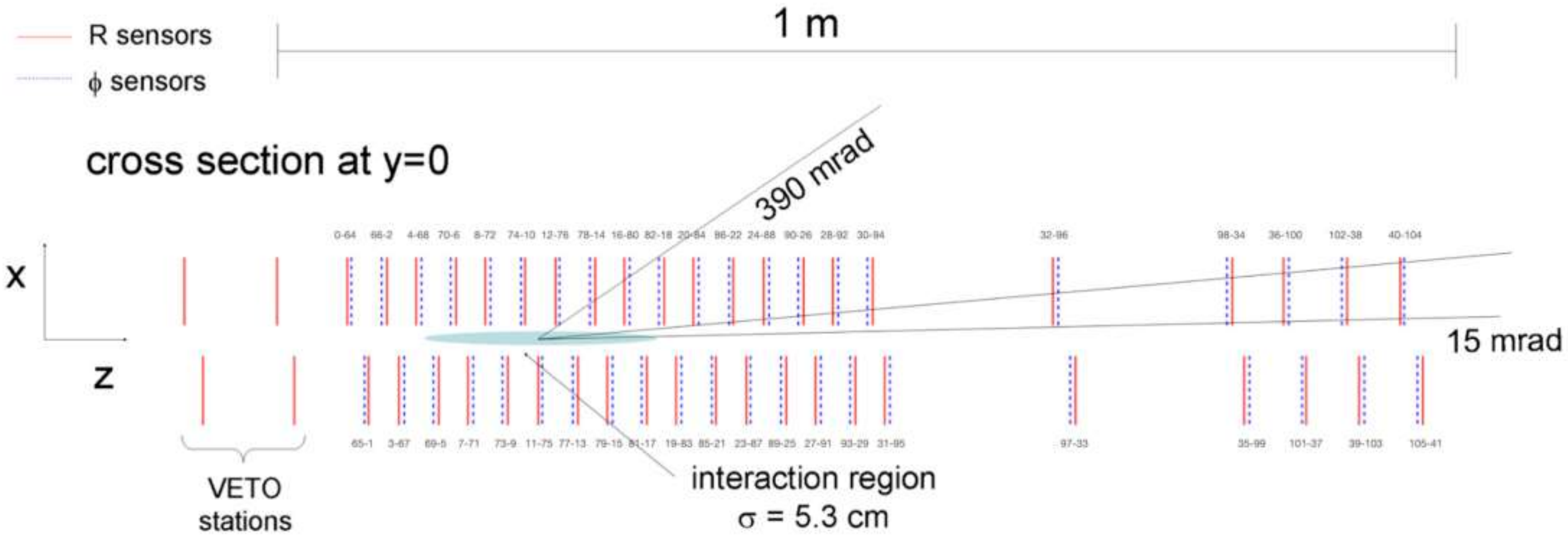
Fig. 13 Distribution of the number of pixel hits per event in (**a**) RICH 1 and (**b**) RICH 2. An example of a typical LHCb event as seen by the RICH detectors, is shown below the distributions. The *upper*/*lower* HPD panels in RICH 1 and the *left*/*right* panels in RICH 2 are shown separately

Real-life example: detection of antihelium at LHCb

Following LHCb startertalk by Gediminas Sarpis

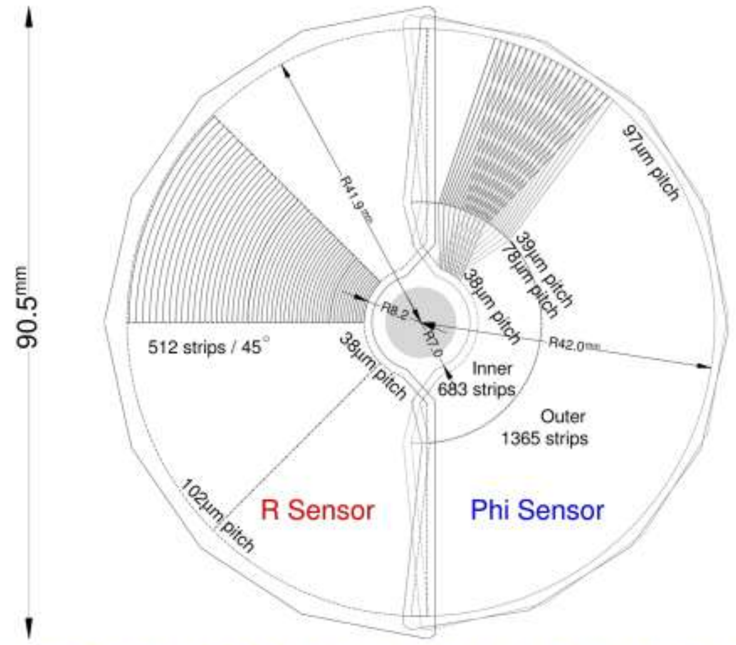


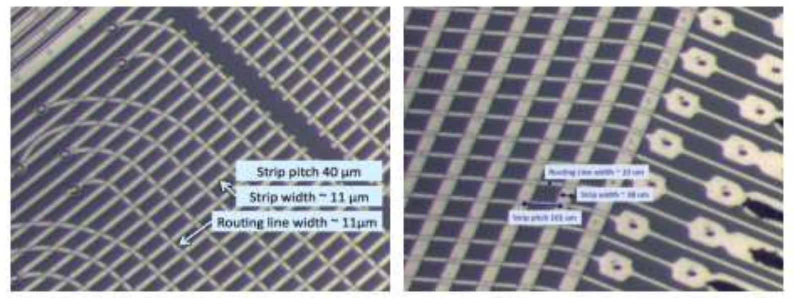
VELO detector at LHCb



- Each sensor has 2048 conductive strips
- Strips collect charge
- Signal is processed by FPGAs
- Clusters are formed from **7bit ADC** digitized signal

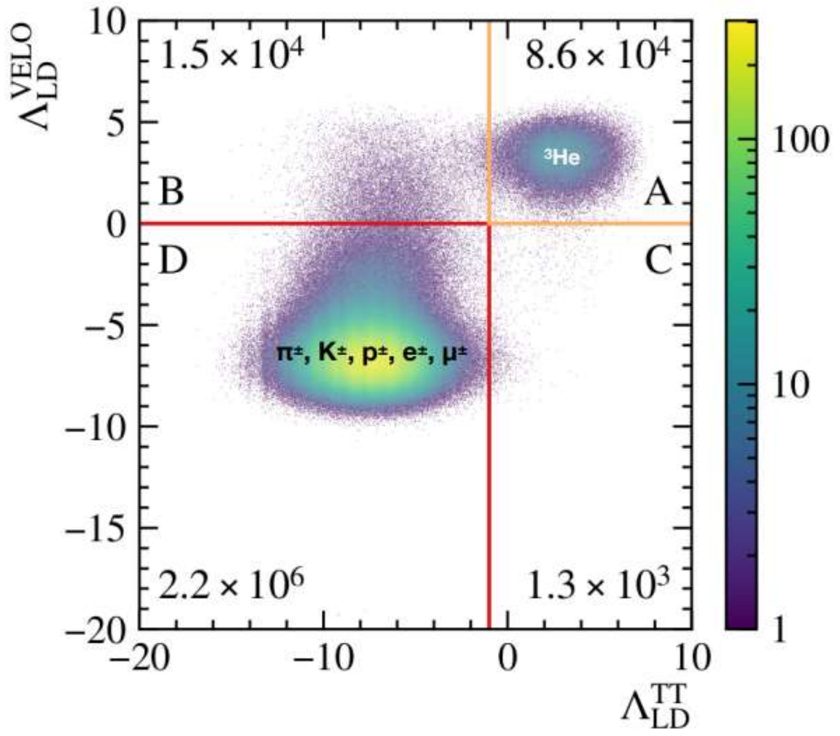
- Velo Module - R/Φ sensor pair
- Sensors are 300μm thick silicon semicircles
- Closest active part only 8.3mm away from the beam





Real-life example: detection of antihelium at LHCb

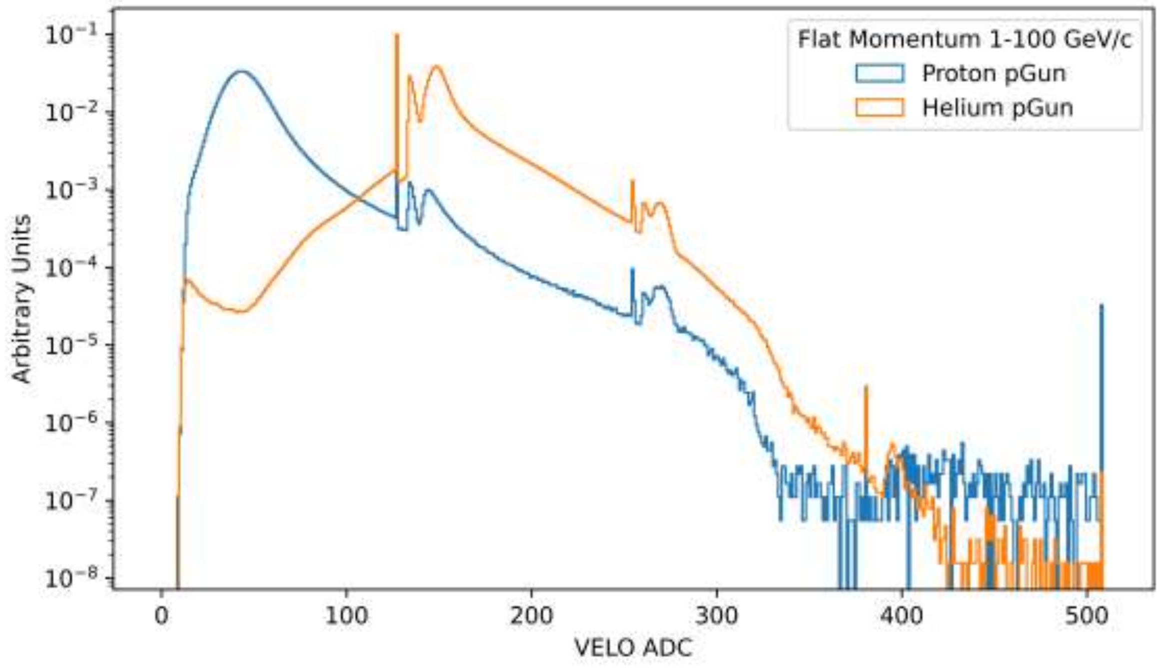
Following LHCb startertalk by Gediminas Sarpis

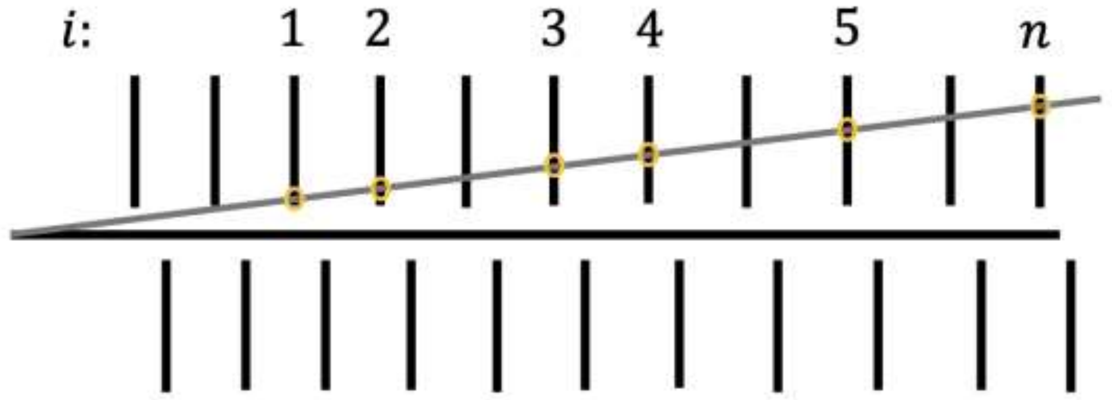


Λ_{LD} - Combination of VELO Measurements

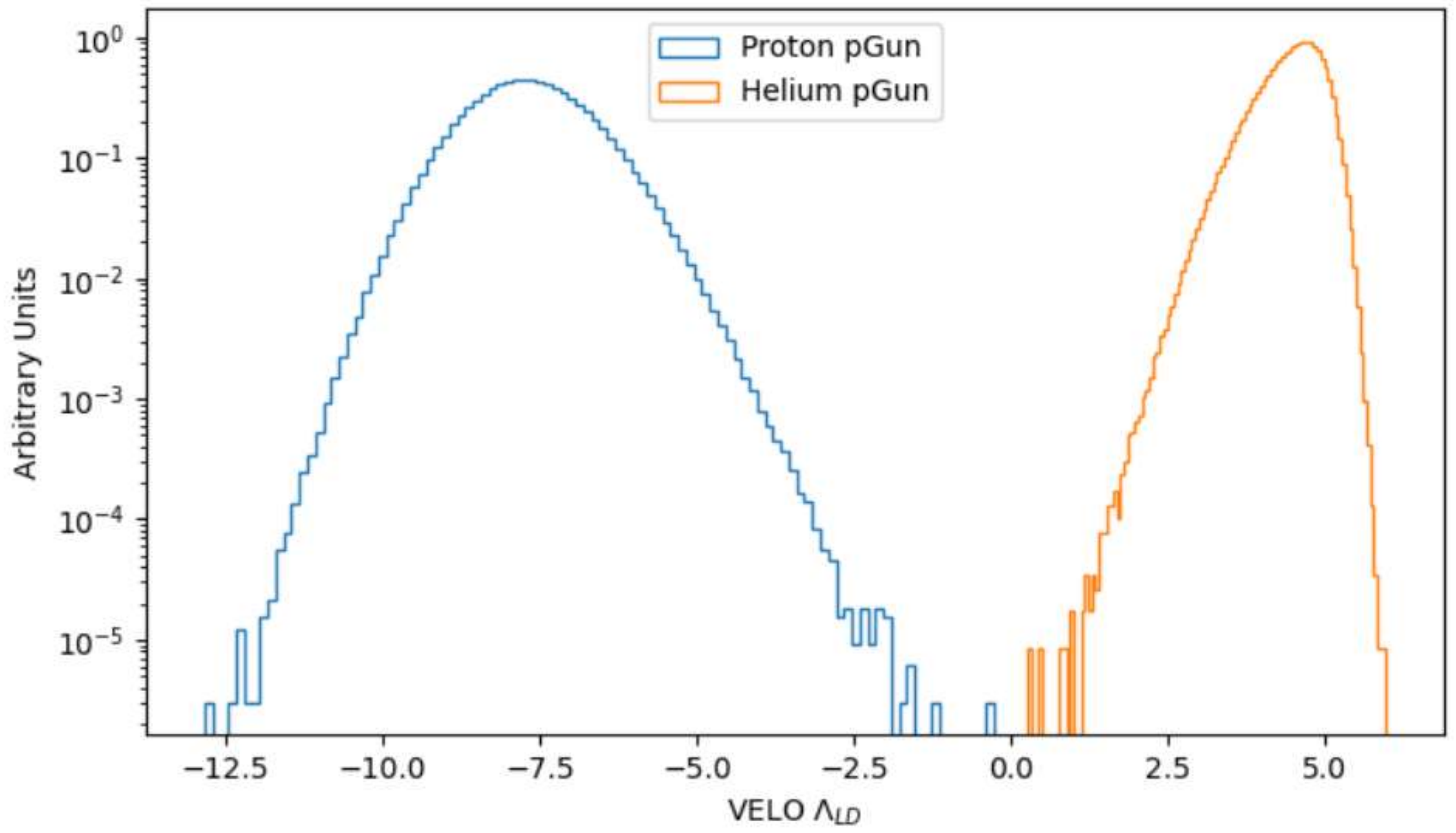
1. Use ADC distributions as PDFs
2. Derive a p/^3He probability to each cluster
3. Combine the probabilities to likelihoods
4. Define a log-likelihood estimator for the whole track

- $L_{He} = (\prod_{i=1}^{n} p_{He}(ADC)_i)^{\frac{1}{n}}$
- $L_p = (\prod_{i=1}^{n} p_p(ADC)_i)^{\frac{1}{n}}$
- $\Lambda_{LD} = log(L_{He}) - log(L_p)$





Construction of Λ_{LD} Discriminant - Early Example



Thanks for listening!

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