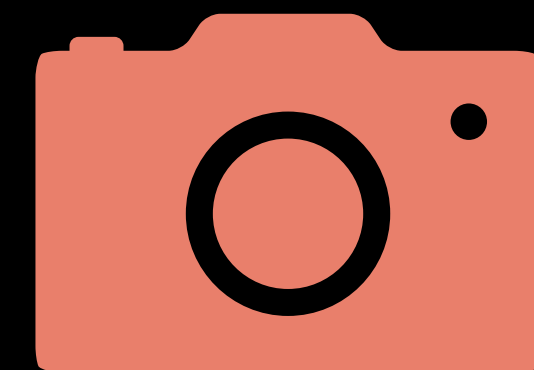
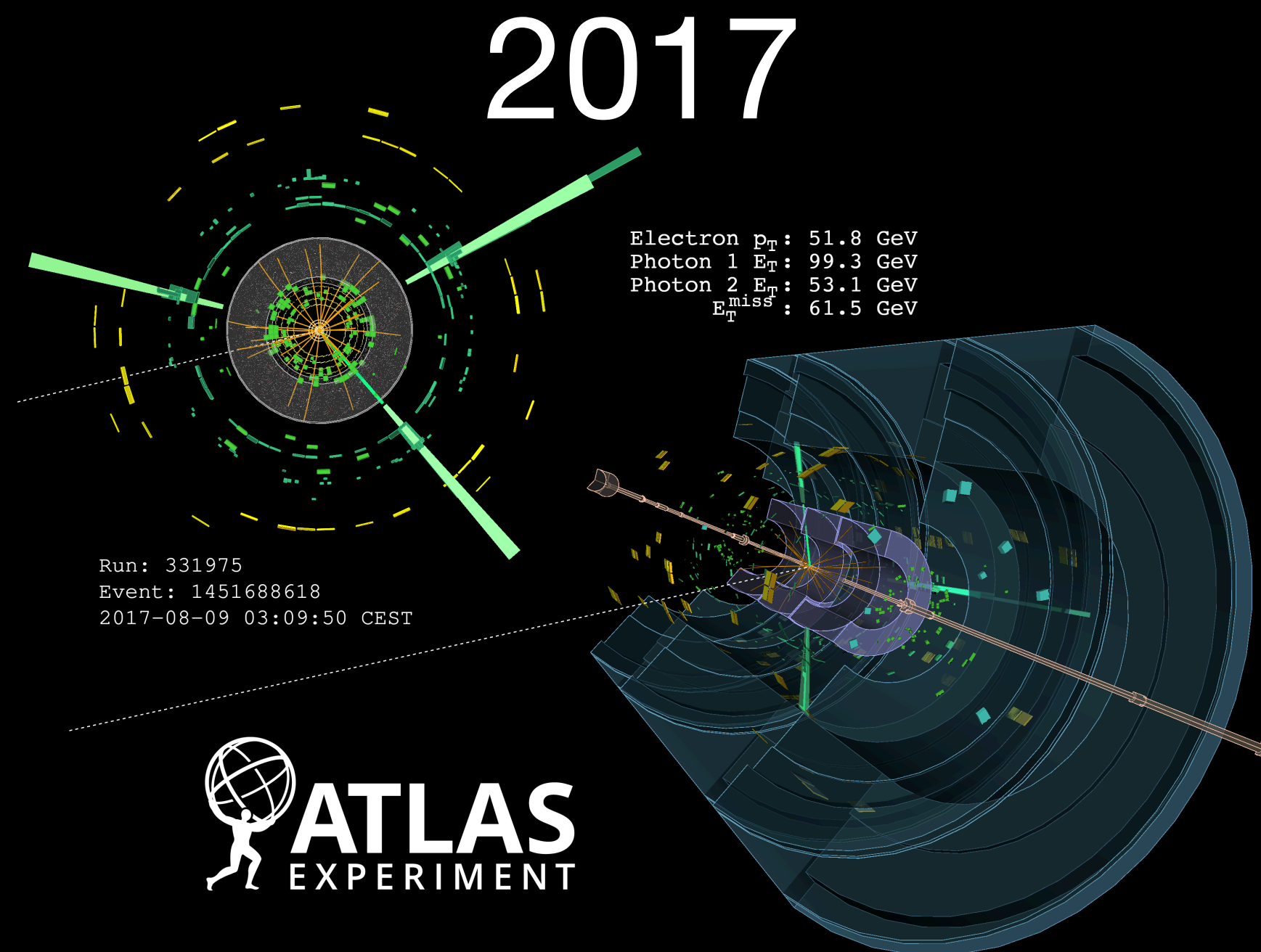


# PHYS 7363 - Experimental Particle Detection and Detectors I



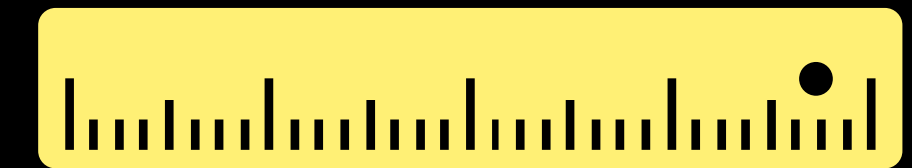
Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection and identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we “see” subatomic particles, this course is for you!



Detect



Identify



Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: [saptaparnab@smu.edu](mailto:saptaparnab@smu.edu)



# Schedule

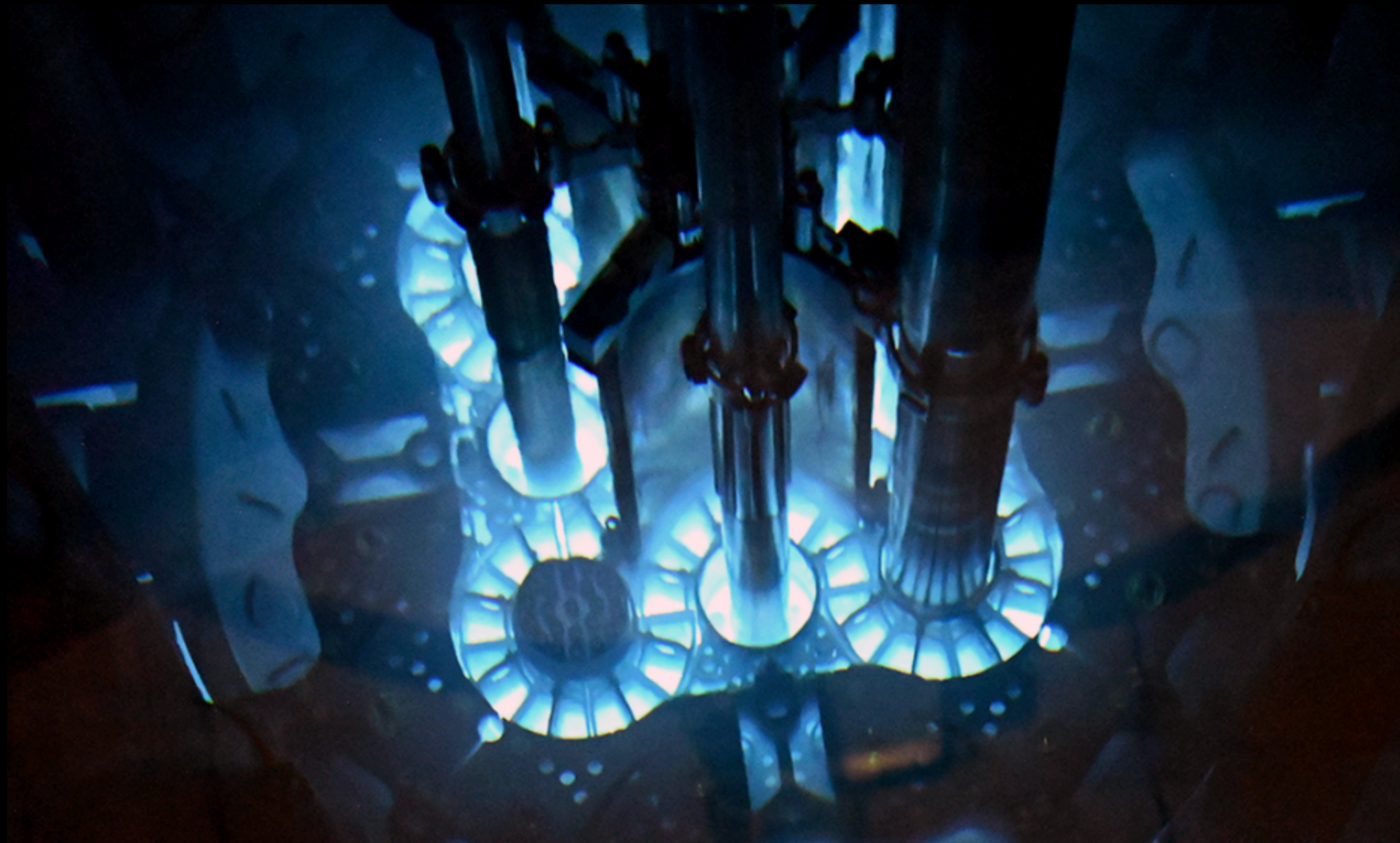
Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
October	6 <input checked="" type="checkbox"/> 1.5 hours	7	8 <input checked="" type="checkbox"/> 1.5 hours	9	10	11	12
	13 <input checked="" type="checkbox"/> 1.5 hours	14	15 <input checked="" type="checkbox"/> 1.5 hours	16	17 <input checked="" type="checkbox"/> 1.5 hours	18	19
	20	21	22	23	24	25	26
	27	28	29	30	31	1	2
November	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
December	1	2	3	4	5	6	7
	8	9	10	11	12	13	14

# Relevant parts of the book

- Chapters: 1-3
- Chapter: 8 (Semiconductor detectors)
- Chapter: 9 (Track model)
- Chapter: 15 (Calorimeters)
- What we will cover (at a minimum):
  - Chapter 12-13 (Cherenkov (today: Chapter 11) and Scintillation detectors), 14 (particle identification), 18 (triggers)
  - Accelerator basics: Friday (started and today)

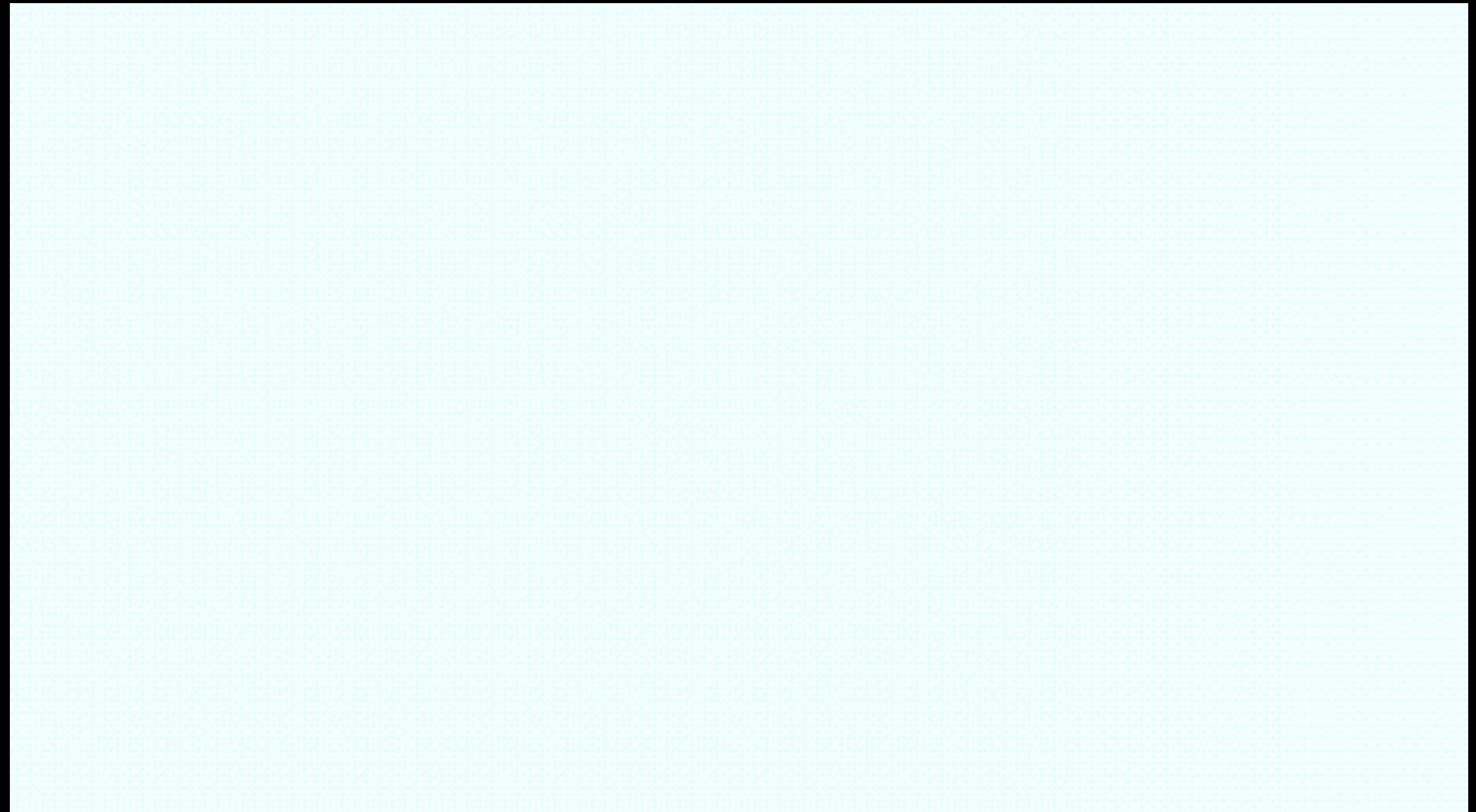
# Cherenkov Radiation

- Have you ever seen photos of a nuclear reactor, you might notice a blue glow surrounding the core
- Phenomena: Cherenkov radiation
  - Shockwave of light
  - Occurs when electrically charged particles, such as protons or electrons, travel faster than light in a clear medium like water
  - Water molecules and particles interact to give off light
- Light slows down to 75 percent of its normal speed when it travels through water
  - This allows the particles emitted from nuclear fuel to move faster than light in water



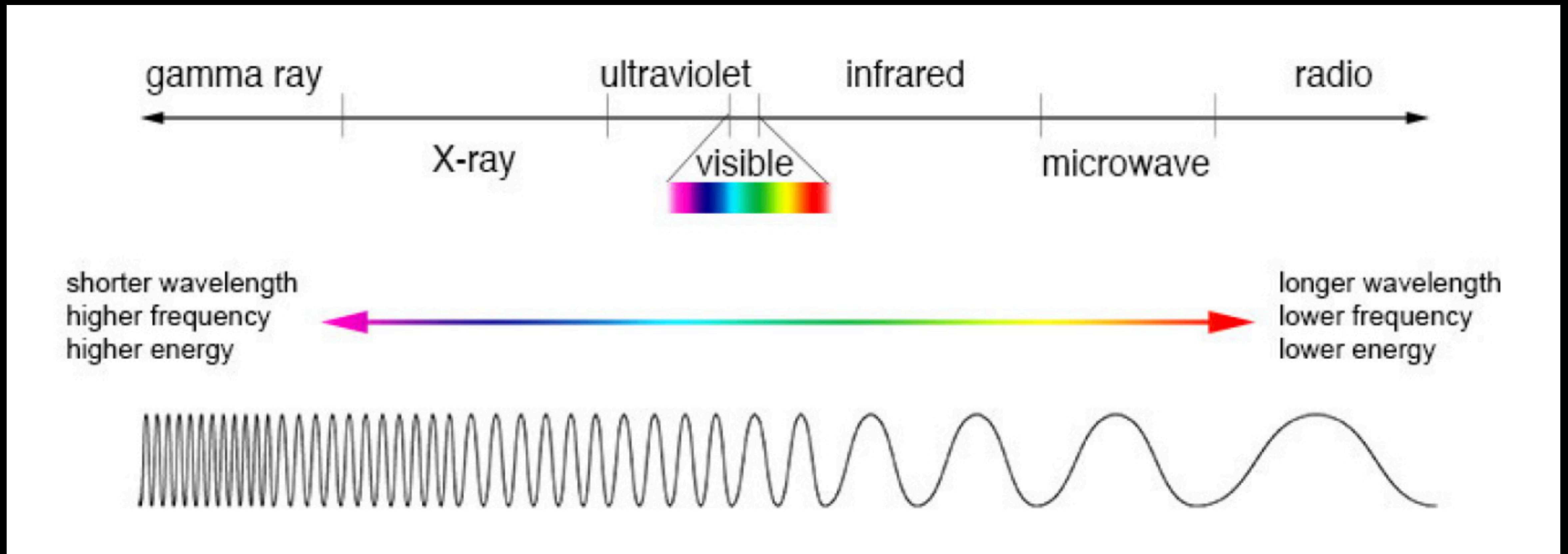
# Cherenkov Radiation

- Charged particles from nuclear reactors disrupt water molecules in their path, light particles, known as photons, are released — creating a visible “shockwave” of blue or violet light
- This is similar to a sonic boom when objects move faster than the speed of sound
- Sound waves generated by the aircraft travel at the speed of sound, which is slower than the aircraft, and cannot propagate forward from the aircraft, instead forming a conical shock front
- In a similar way, a charged particle can generate a “shock wave” of visible light as it travels through an insulator.

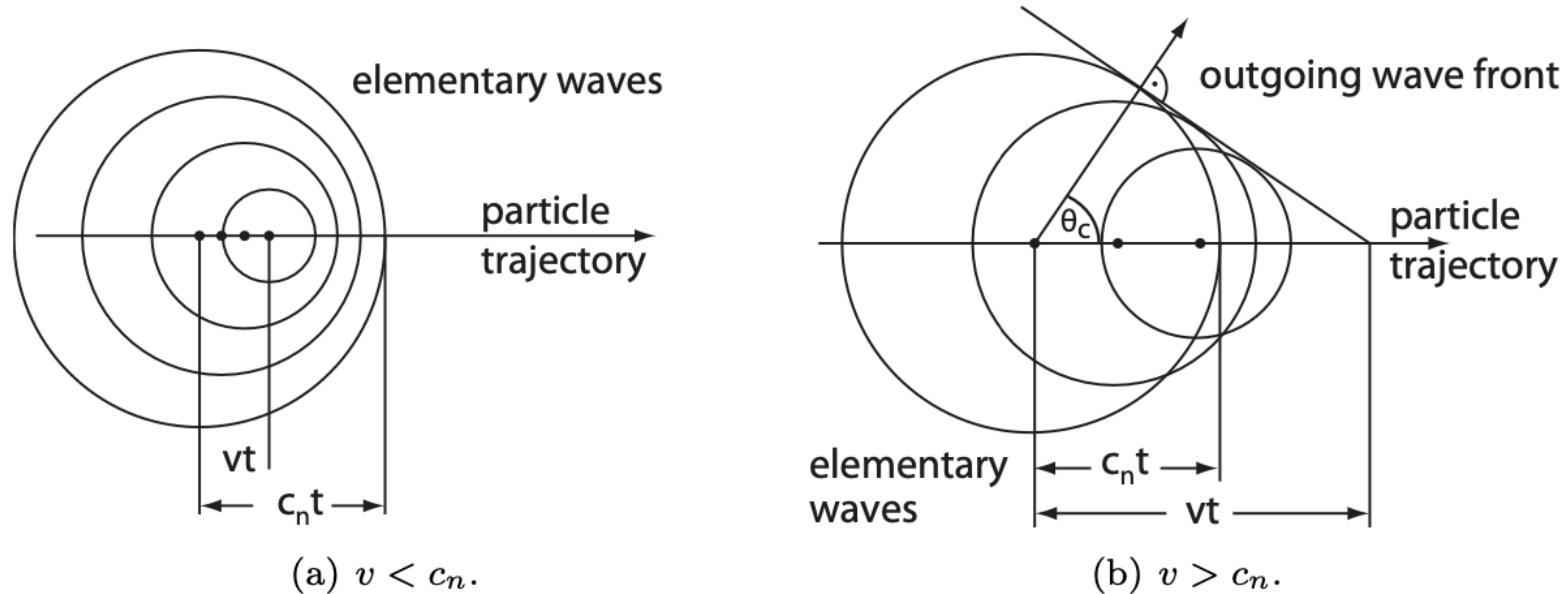


# Cherenkov Radiation

- Photons resulting from Cherenkov radiation have a high frequency and short wavelength. This appears to the human eye as blue or violet on the electromagnetic spectrum
- The light intensity can be used for accounting of nuclear material at nuclear facilities
- Conducting physics experiments to determine the energy and trajectory of subatomic particles



# Cherenkov Radiation



**Fig. 11.2** If a charged particle traverses a medium with a velocity greater than the speed of light  $c_n$  in that medium, an electromagnetic shock wave can be formed by constructive interference of many elementary waves emitted along the particle track: (a)  $v < c_n$ , no radiation, (b)  $v > c_n$ , Cherenkov radiation is emitted under a fixed angle  $\theta_c$  while the wave front forms under an angle  $90^\circ - \theta_c$ .

# Cherenkov Radiation

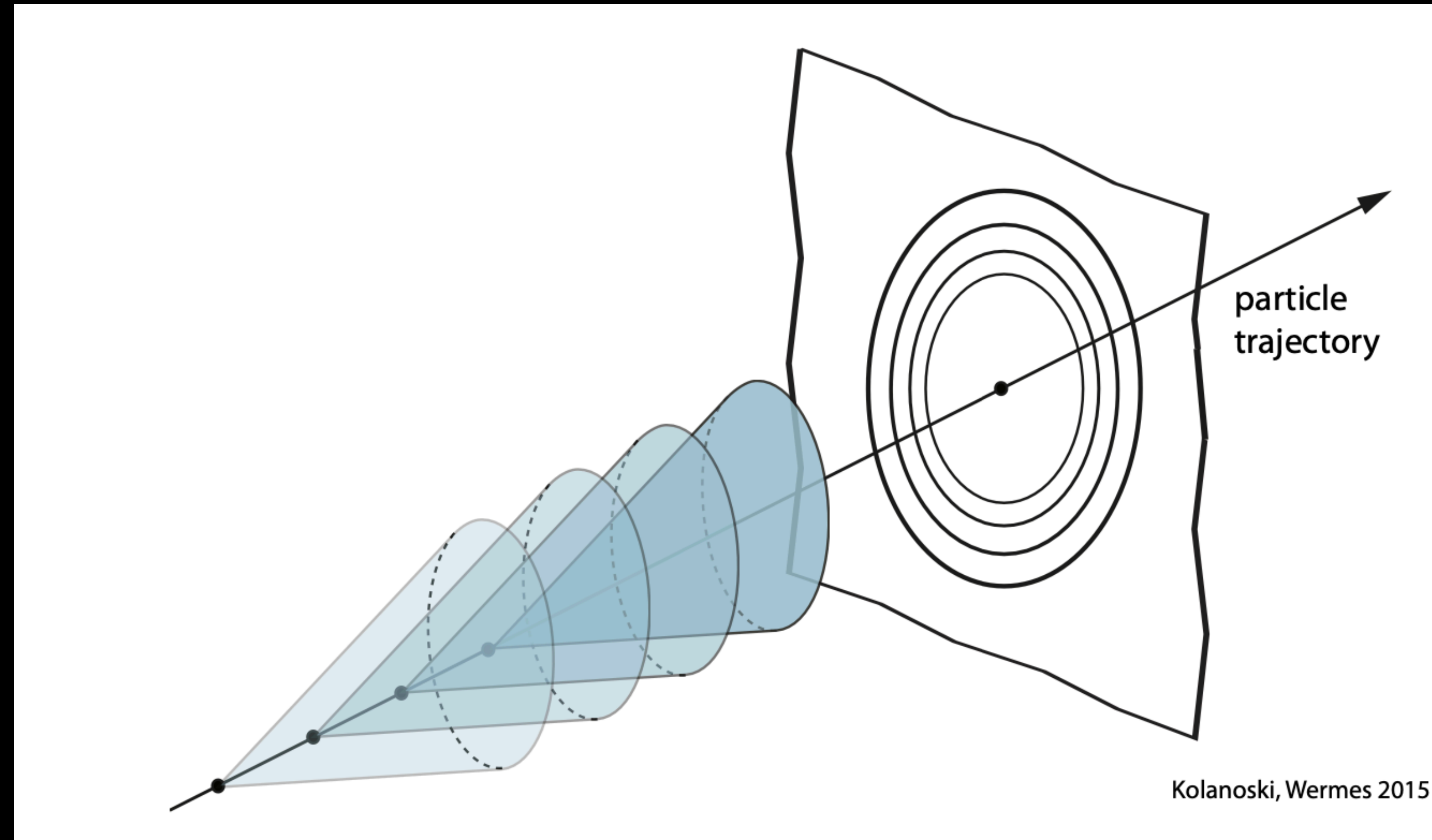
- Previous figure: snapshot of elementary waves along the particle trajectory
- They propagate with the medium speed of light ( $c_n = c_0/n$ ) and interfere constructively to a wave front under a fixed angle  $\theta_c$ , the Cherenkov angle:

- $$\cos \theta_c = \frac{\frac{c_0}{n}t}{vt} = \frac{1}{\beta n}$$

- Exact quantum mechanical calculations show that approximation is valid for most cases
- Radiation occurs if:
  - The particle velocity is larger than the phase velocity of electromagnetic waves of this frequency in the medium  $v > c_0/n(\omega)$
  - Radiator medium is optically transparent and its length  $L$  is much larger than the wavelength of the radiation,  $\lambda \ll L$ , such that coherent superposition of the elementary waves can occur

# Designing Cherenkov Detectors

- The Cherenkov angle increases with velocity or momentum of the particle
- Maximum angle of Cherenkov radiation (“asymptotic angle”) is obtained when the charged particle approaches the velocity of light in vacuum,  $\beta \rightarrow 1, \gamma \rightarrow \infty$
- $\cos \theta_{max} = \frac{1}{\beta}$
- $\beta \geq 1/n$  must hold for Cherenkov radiation, threshold velocity
  - $\beta_{th} = \frac{1}{n}$
  - Emission angle at threshold velocity is zero ( $\theta_{th} = 0^\circ$ )
- No radiation is emitted outside the cone



# Cherenkov Radiation

- The threshold energy of the particle belonging to  $\theta_{max}$  can be expressed by the Lorentz factor  $\gamma$  at threshold

- $$\frac{E_{th}}{mc^2} = \gamma_{th} = \frac{1}{\sqrt{1 - \beta_{th}^2}} = \frac{n}{\sqrt{n^2 - 1}}$$

- $$\sin \theta_c = \sqrt{1 - \cos^2 \theta_c} = \sqrt{1 - \frac{1}{n^2}} = \frac{1}{\gamma_{th}}$$

- A relation between the actual emission angle  $\theta_c$  and the maximum (asymptotic) angle  $\theta_{max}$  results:

- $$\sin^2 \theta_c = 1 - \cos^2 \theta_c = 1 - \frac{1}{\beta^2 n^2} = 1 - \frac{\beta_{th}^2}{\beta^2} = \frac{1}{\gamma_{th}^2} \frac{\gamma^2 - \gamma_{th}^2}{\gamma^2 - 1}$$

- $$\sin^2 \theta_c = \sin^2 \theta_{max} \frac{\gamma^2 - \gamma_{th}^2}{\gamma^2 - 1}$$

# Cherenkov Radiation

- For relativistic particles ( $\gamma^2 \gg 1$ ) and small Cherenkov angles, the ratio of actual emission angle (for a particle with energy  $\gamma = \frac{E}{mc^2}$ ) and the maximum possible angle  $\theta_{max}$  (depending on the refractive index  $n$  of the radiator) is:

- $$\frac{\theta_c}{\theta_{max}} = \frac{R_c}{R_{max}} \approx \sqrt{1 - \frac{\gamma_{th}^2}{\gamma^2}}$$

- Here  $R_c$  and  $R_{max}$  are the actual and maximum radius of a Cherenkov ring

# Detection of Cherenkov Radiation

- Cherenkov radiation is used in various ways for particle detection, ranging from the sheer detection of emitted Cherenkov radiation to the explicit reconstruction of Cherenkov rings
- Detectors exploit the characteristics of Cherenkov radiation:
  - radiation sets in above a velocity threshold
  - the emission has velocity dependent intensity and direction
  - it is prompt, allowing for precise timing
  - contrast with scintillation light (delay and emitted in all directions)
- Prominent application of Cherenkov light: distinguish pions from electrons
- Photon yield:

- $$N_{opt} = \int_{optical} d\lambda \frac{dN}{d\lambda} = N_{\delta\lambda} z^2 L \sin^2 \theta_c$$
 ( $z$  is the charge of the particle as a multiple of

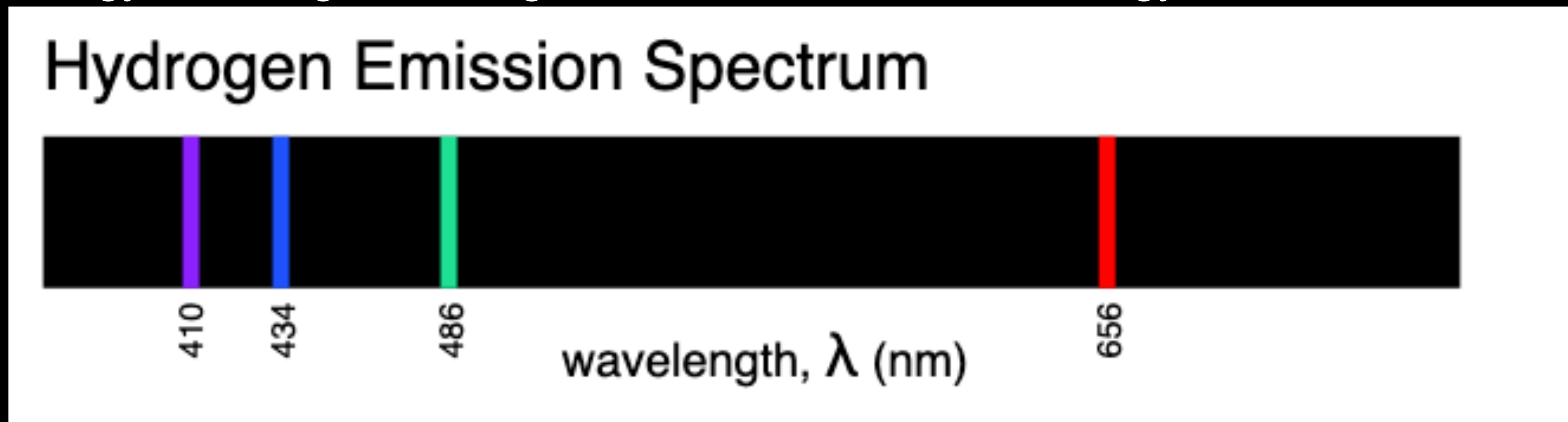
the elementary charge (e.g.,  $z=1$  for an electron).)

- For optical wavelengths (400 nm-700 nm), this becomes:

- $$N_{\delta\lambda} = \int_{optical} \frac{2\pi\alpha}{\lambda^2} d\lambda = 491 \text{ photons/cm}$$

# Spectrometers

By looking at the specific wavelengths of light that are either absorbed or emitted from a sample of H atoms, we discover something about the energy of the electrons in the atom. First, we notice that only specific wavelengths are associated with transitions. This means that there are discrete energy levels that the electron is moving between. The energy of the light of the transition corresponds to the difference in energy between two of these levels. If the energy of the electron is increasing, this is from absorption of the light energy. If the light is being emitted, this is from the energy of the electron decreasing

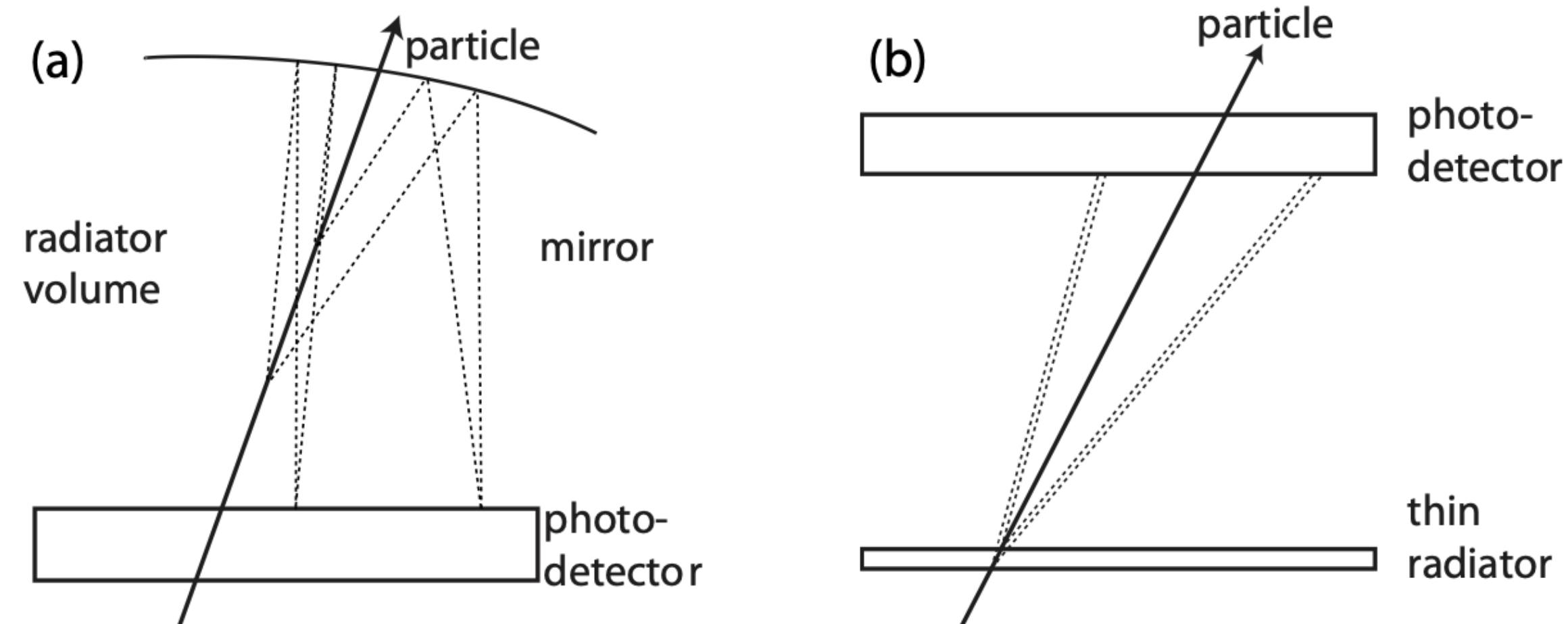


# Threshold Cherenkov Detector

- To distinguish particles of different mass, the Cherenkov threshold detector employs the mass dependence of the particle velocity for a given energy. The threshold velocity
  - $\beta_{th} = \frac{1}{n}$  only depends on the index of refraction of the radiator
- Explicit detection of Cherenkov rings is not intended
- Particle of mass  $m$  the threshold momentum, below which no Cherenkov radiation is emitted is:
  - $$p_{th} = mc^2(\beta\gamma)_{th} = \frac{mc^2}{\sqrt{n^2 - 1}}$$
- If the momentum of a particle is known:
  - choose a suitable radiator medium with refractive index  $n$
  - Cherenkov counters can be designed which are only sensitive to particles light enough so that their velocity exceeds the Cherenkov threshold

# Ring imaging Cherenkov detector (RICH)

- Complete reconstruction of Cherenkov rings is accomplished in so-called *ring imaging Cherenkov* (RICH) counters or RICH detector
- Two focusing methods are used:
  - *Mirror focusing* : mirror focuses parallel light rays, emitted (under the same azimuthal angle) from different points along the particle trajectory, onto a point on a circle in the focal plane where the photons are detected
  - *Proximity focusing*: here the radiator is thin—in general a solid or a liquid—such that the Cherenkov radiation generated in the radiator along the particle trajectory can be regarded to approximately come from the same point in space (pinhole camera principle). The projection of the radiation onto the detector surface represents a ring, also without focusing elements. Its width depends primarily on the thickness of the radiator and the distance to the detector



**Fig. 11.12** Detection of Cherenkov rings with RICH detectors. (a) Focusing of Cherenkov radiation by a mirror onto a photon detector, (b) thin radiator with *proximity focusing* for which the image merely is a cross-sectional cut through the Cherenkov cone.

# Resolution of RICH detectors

- The RICH resolution on  $\beta$  ( $\sigma_{\theta_i}$  denotes angular resolution per photoelectron,  $\sigma_{\theta_c} = \sigma_{\theta_i}/\sqrt{N}$  is the Cherenkov angle for  $N$  photoelectrons)

- $$\sigma_{\beta} = \frac{\partial \beta}{\partial \theta_c} \sigma_{\theta_c}$$

- $$\frac{\sigma_{\beta}}{\beta} = \tan \theta_c \sigma_{\theta_c} = \tan \theta_c \frac{\sigma_{\theta_i}}{\sqrt{N}}$$

- Particle identification by Cherenkov radiation is the determination of a particle's mass at a given momentum by measuring its velocity through a measurement of the angle under which Cherenkov radiation has been emitted. The resolution of this measurement can hence be written as:

- $$\frac{\sigma_m}{m} = \frac{1}{2} \frac{\sigma_{m^2}}{m^2} = \frac{\gamma^2}{\beta} \left[ \left( \frac{\partial \beta}{\partial \theta_c} \sigma_{\theta_c} \right)^2 + \left( \frac{\partial \beta}{\partial n} \sigma_n \right)^2 \right]^{\frac{1}{2}}$$

- $$\frac{\sigma_m}{m} = \gamma^2 \left( \tan \theta_c \sigma_{\theta_c} \oplus \frac{1}{n} \sigma_n \right) = \left( \frac{p}{m} \right)^2 \frac{1}{\beta^2} \left( \kappa_R \oplus \frac{1}{n} \sigma_n \right)$$

# Resolution of RICH detectors

- $\frac{\sigma_m}{m} = \gamma^2 \left( \tan \theta_c \sigma_{\theta_c} \oplus \frac{1}{n} \sigma_n \right) = \left( \frac{p}{m} \right)^2 \frac{1}{\beta^2} \left( \kappa_R \oplus \frac{1}{n} \sigma_n \right)$
- The first term  $\kappa_R$  called the RICH constant, is the contribution to the measurement error due to the angular resolution ( $L$  = length of the radiator)

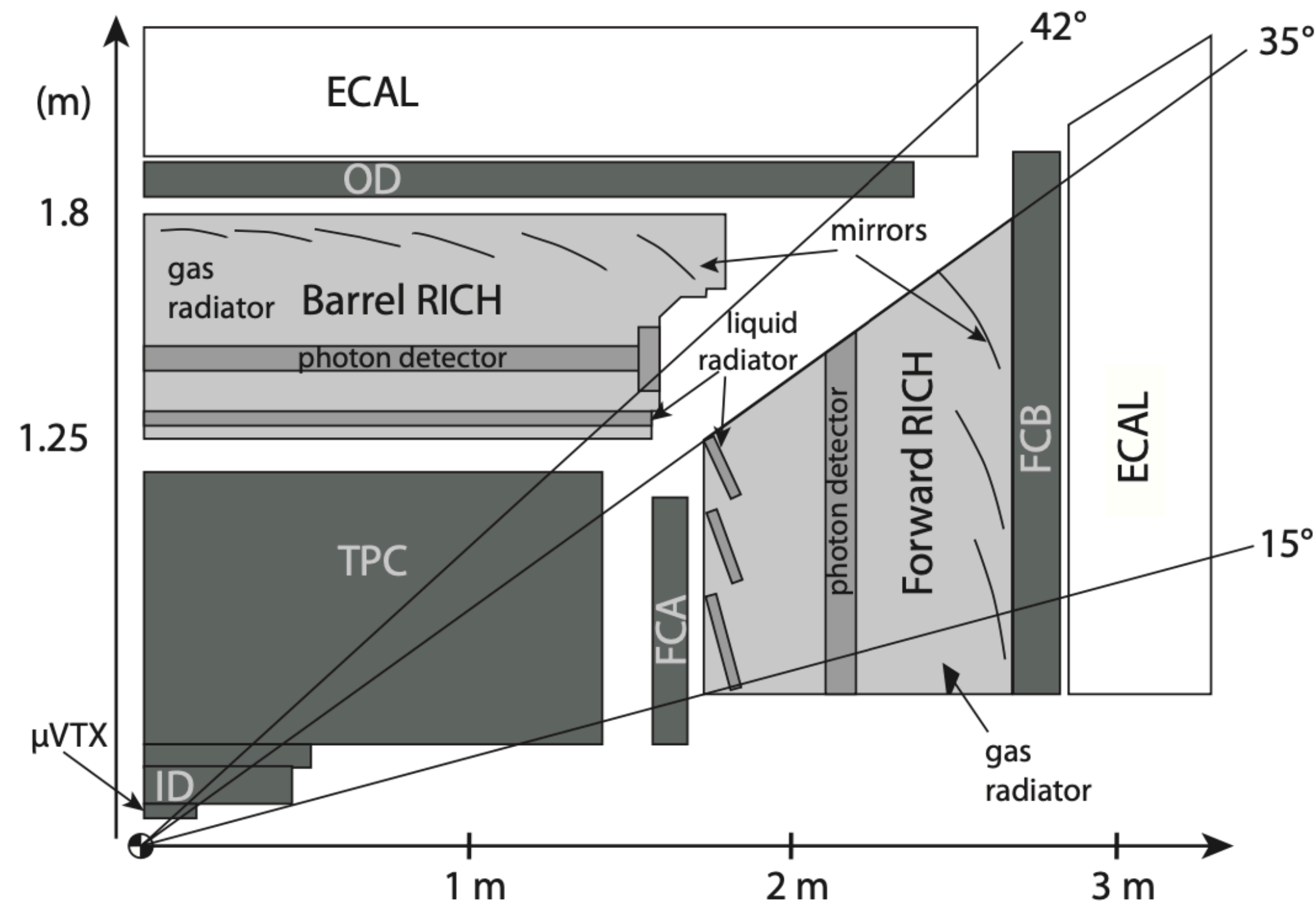
- $\kappa_R = \left( \frac{\sigma_\beta}{\beta} \right)_{\text{angle}} = \tan \theta_c \frac{\sigma_{\theta_i}}{\sqrt{N}} = \frac{n\beta\sigma_{\theta_i}}{z\sqrt{N_0L}}$

- Particle separation:

- The capability of a RICH detector to separate two particles with the same momentum  $p$  and with masses  $m_1$  and  $m_2 > m_1$  from each other at  $n_\sigma$ :

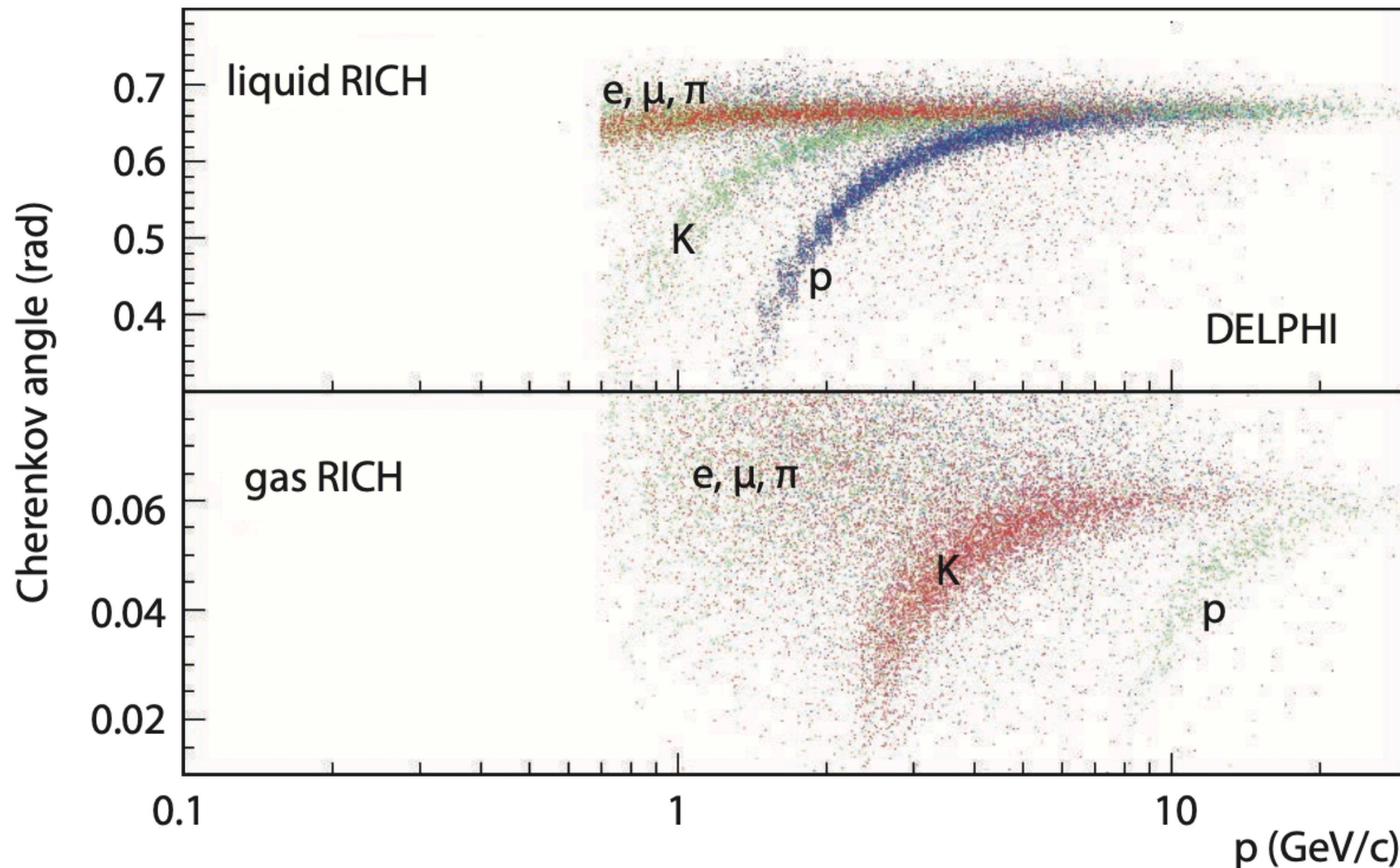
- $\frac{m_2^2 - m_1^2}{\sigma_{m^2}} = \frac{\beta_2^2 m_2^2 - \beta_1^2 m_1^2}{2p^2 \left( \kappa_R \oplus \frac{1}{n} \sigma_n \right)} > n_\sigma$

# RICH detectors



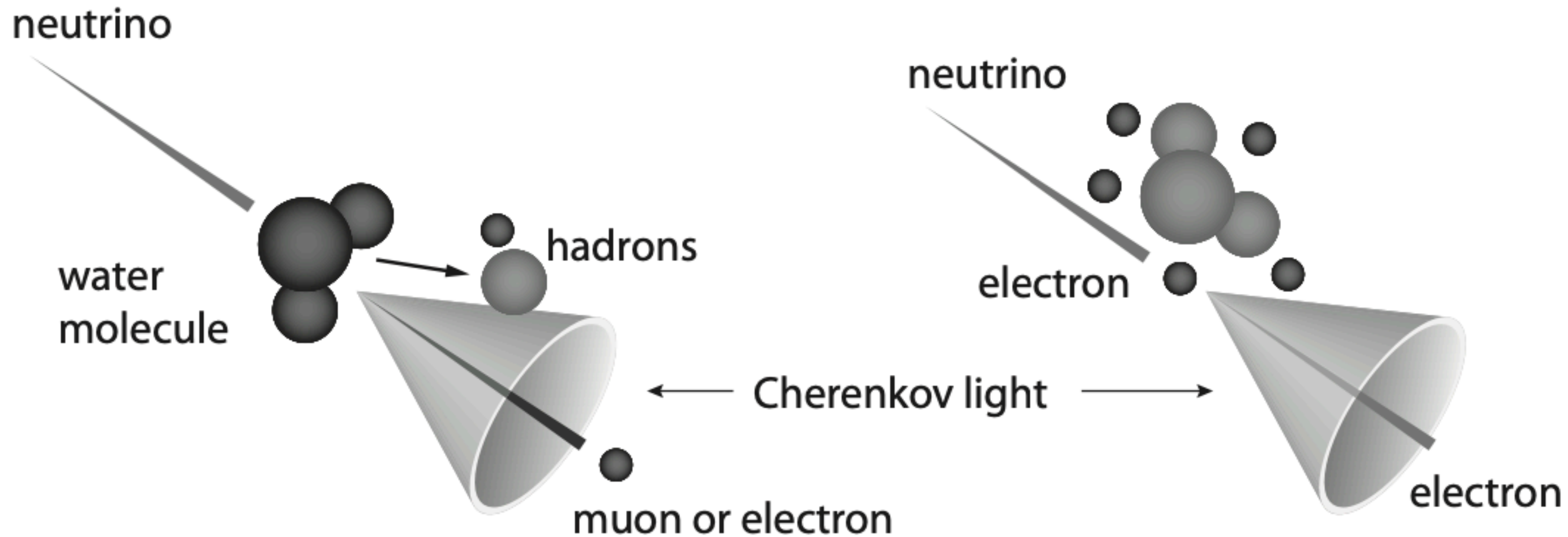
**Fig. 11.19** Arrangement of RICH detectors in the DELPHI experiment operated at the electron–positron storage ring LEP. Shown is one quarter of the DELPHI detector in a cut parallel to the beam line. The interaction point is at the origin of the coordinate frame. In the ‘barrel’ as well as in the ‘forward’ angular region of the experiment Double-RICH systems are implemented in which the two respective Cherenkov rings of a gas and of a liquid radiator are focused onto the same photon detector (see also fig. 11.13), where the Cherenkov rings are reconstructed. The drawing illustrates the space requirements needed for the voluminous gas radiators. Abbreviations are: ID/OD = inner/outer detector, TPC =time projection chamber, FCA/B = forward chamber A/B, ECAL = electromagnetic calorimeter. Adapted from [72] with kind permission of Elsevier.

# Particle Identification



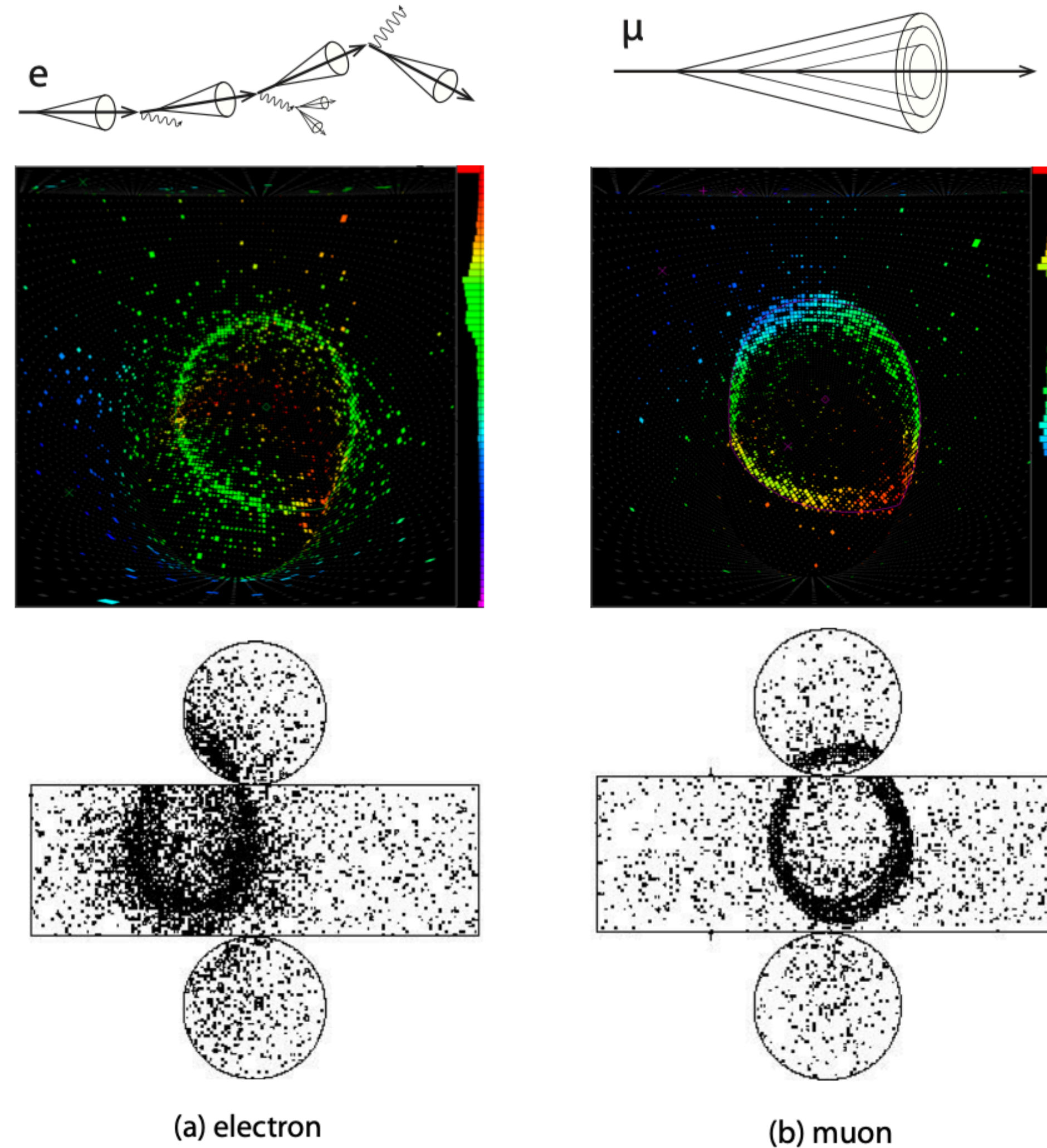
**Fig. 11.21** Particle identification with the RICH system of the DELPHI experiment. Plotted are measured Cherenkov angles as a function of (measured) momentum. One observes bands corresponding to different particle species which are well separated at not too high momenta (from [347]).

# Particle Identification: Neutrino detection



**Fig. 11.25** Neutrino induced reactions [921] in the Super-Kamiokande detector. Neutrinos scatter off nuclei (left) or off shell electrons (right) generating electrons or muons in the final state which emit Cherenkov radiation. Since there are no focusing elements the radiation is emitted over the  $e$  or  $\mu$  travel distance within cones around their flight direction (see also fig. 11.3).

# Super-K displays



**Fig. 11.26** Two different examples each of electron and muon events in the Super-Kamiokande experiment. (a) Electrons lose energy by bremsstrahlung and they can shower (top). Their Cherenkov ring edges are blurred as the two examples of different energy (middle and bottom) show [583]. (b) Muons create rings if they are stopped still in the detector. This corresponds to the case of proximity focusing, discussed at the start of section 11.6. Or they create rings with PMT hits filling the area near the circumference from the outside in, as the muons slow down (high energetic muons, top). The ring edges are comparatively sharp (middle and bottom [583]). The colour code indicates the arrival time of the Cherenkov photons. Source: Kamioka Observatory, Univ. Tokyo, and Super-Kamiokande, with kind permission.