Cherenkov detectors

So….what is Cherenkov light?

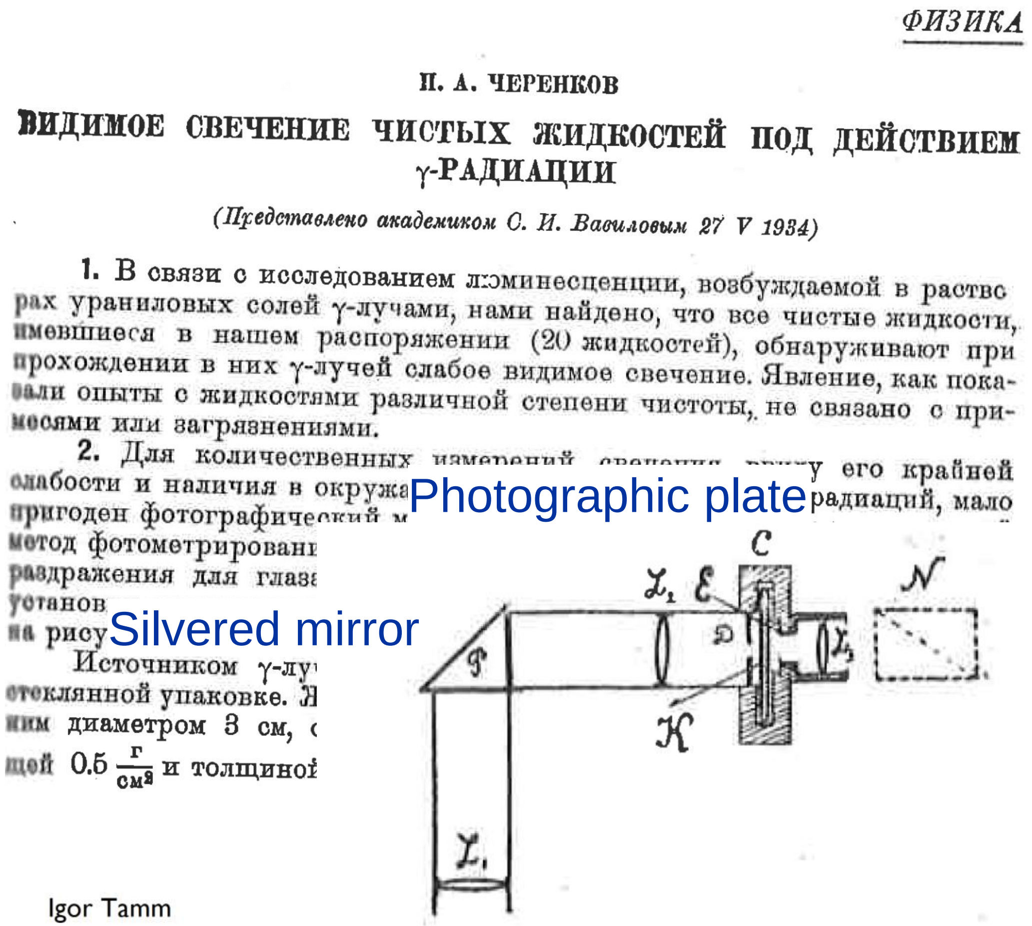
- **Electromagnetic shock wave (sonic boom) emitted by charged particles**
  - This is not an explanation, let's try again
- **Light emitted by a charged particle going faster than the local speed of light**
  - This is not an explanation, let's try again
- **"Coherent response of a medium to the passage of a relativistic particle that causes the emission of radiation"**
  - This is an explanation, are there any catches?
- **All the above statements are true – but as you get more "precise" it also becomes harder to understand….**
- **Some conditions turn up**
  - Particle needs to go "fast enough" (explanations on later slide)
  - Medium needs to be transparent (if only for practical reasons)

What do we use Cherenkov detectors for?

- **Detecting particles is not so easy**
  - Can only detect particles if they leave some kind of trace
  - Only a few fundamental processes allow for this: charge deposition, scintillation, transition radiation, Cherenkov light (disclaimer: I may have missed some – but not many)
- **What are the specific advantages of Cherenkov detectors?**
  - Light emission is instantaneous
  - Light yield is highly deterministic (linear with path length)
  - Wide spectrum light source
  - **Properties of emitted light are dependent on the particle species generating it**
    - If built well, Cherenkov light is an excellent method of particle identification
- **Any disadvantages?**
  - Efficiency relatively low (compared to scintillation or charge deposition)
  - Needs transparent medium

Discovery

- **Also known as the “Vavilov-Cherenkov” effect**
  - Cherenkov was a PhD student
  - Vavilov was his professor
    - Worked also on the interpretation of the effect
- **Frank and Tamm found the complete theoretical description of the effect**
- **Nobel prize awarded in 1958**
  - Vavilov was dead at this point


ФИЗИКА

П. А. ЧЕРЕНКОВ

ВИДИМОЕ СВЕЧЕНИЕ ЧИСТЫХ ЖИДКОСТЕЙ ПОД ДЕЙСТВИЕМ γ-РАДИАЦИИ

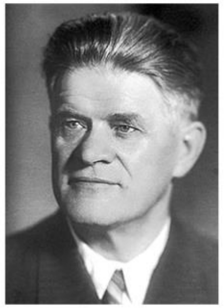
(Представлено академиком С. И. Вавиловым 27 V 1934)

1. В связи с исследованием люминесценции, возбуждаемой в растворах урaниловых солей γ-лучами, нами найдено, что все чистые жидкости, имевшиеся в нашем распоряжении (20 жидкостей), обнаруживают при прохождении в них γ-лучей слабое видимое свечение. Явление, как показали опыты с жидкостями различной степени чистоты, не связано с примесями или загрязнениями.

2. Для количественных измерений свечения ... его крайней слабости и наличия в окружа... радиаций, мало пригоден фотографический м... метод фотометрировани... раздражения для глаза... установ... на рису...

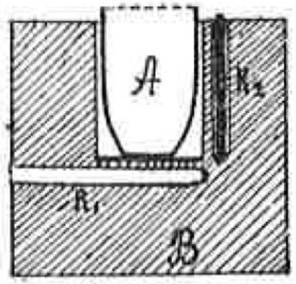
Источником γ-лу... стеклянной упаковке. ... ним диаметром 3 см, ... щей 0.5 $\frac{г}{см^3}$ и толщиной...

Pavel Cherenkov



Ilya Frank

Igor Tamm



Cherenkov light

- **Foundational formula for Cherenkov light**
  - θ_c is the “Cherenkov angle”
  - β is the speed of the particle as a fraction of the speed of light in vacuum (c_0 = 299792458 m/s)
    - c_0 is the fundamental speed barrier in the universe
    - Particles moving at speeds close to c_0 are known as “relativistic” particles
    - When you put more energy in a particle, it will come closer to (but never exceed) c_0
  - n is the (phase) refractive index of a material
    - Probably well known from your optics classes?
    - n sets the **local** speed of light
    - This explains why particles can go faster than the local speed of light

$$\cos\theta_c = \frac{1}{n\beta}$$

$$\beta = \frac{v}{c} = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$$

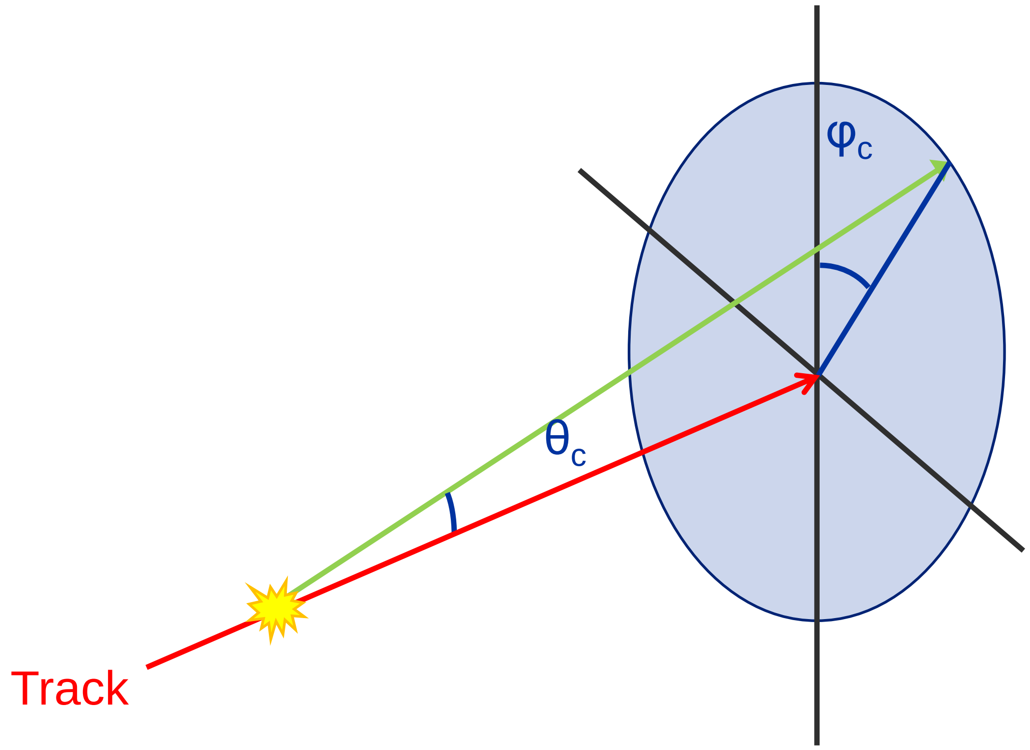
$$c_{local} = \frac{c_0}{n_g}$$

$$n_g = n_p + E\frac{dn_p}{dE}$$

Cherenkov light

$$\cos\theta_c = \frac{1}{n\beta}$$

- **Only one angle? What about the other one?**
  - Let's call this one φ
  - Turns out it is random! Light is emitted in a ring / cone at an angle to the particle passing through the medium
- **Let's put in some numbers**
  - n = 1.5 β=1 θ_c = 0.841 rad = 48.2 deg
    - This is a relativistic particle in water
  - n = 1.001 β=1 θ_c = 0.0447 rad = 2.56 deg
    - This is a relativistic particle in gas
  - n = 1.001 β=0.9 θ_c cannot be solved for
    - Particle does not meet the speed requirement
- **Important input for detector design!**



Cherenkov light

- **Light is a funny thing**
  - Wave/particle duality – a photon is both a wave and a particle
  - The particle is a packet of energy E and has a wavelength λ
    - Fundamental unit of energy: electron volt (eV)
    - Energy acquired by one electron accelerated by 1 Volt
  - These two numbers are linked by a simple proportionality
  - For example:

	Red light	700nm	1.77 eV
	Green light	550nm	2.25 eV
	Blue light	450nm	2.76 eV
	UV light	250nm	4.96 eV

$$E(eV) = \frac{1240}{\lambda(nm)}$$

  - Note that it *also* says that there is only light for **charged particles**
- **So how much light do we get?**
  - The Frank-Tamm relation expresses the number of photons emitted per unit energy (spectrum)

$$\frac{d^2N}{dEdx} = \frac{\alpha}{\hbar c_0} Z^2 \left(1 - \frac{1}{n^2\beta^2}\right)$$

$$\frac{dN}{dE} = 370L \left(1 - \frac{1}{n_p^2\beta^2}\right)$$

So what's the use of all of this?

- **Let's have a look at how we can use this in reality!**

Projecting a Cherenkov angle

$$\cos\theta_c = \frac{1}{n\beta}$$

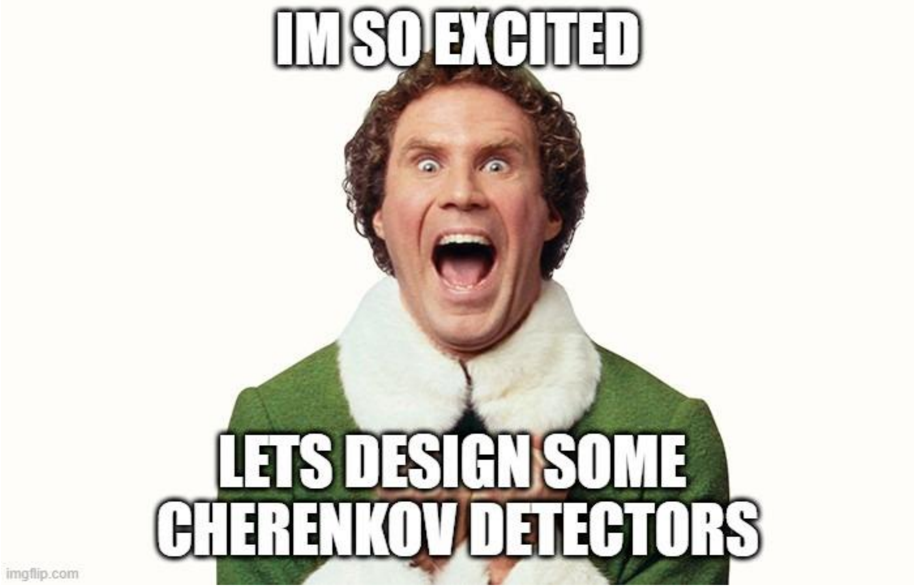
$$\beta = \frac{p}{\sqrt{p^2 + m^2}}$$

- **The relativistic factor β is dependent on the particle mass**
  - Pick a typical momentum for T10 5 GeV/c

Particle	Mass	Relativistic β
Electron	0.000511 GeV/c^2	1
Muon	0.104 GeV/c^2	0.99978
Pion	0.135 GeV/c^2	0.99964
Kaon	0.494 GeV/c^2	0.9952
Proton	0.938 GeV/c^2	0.983

  - This is then FINALLY what can give us particle ID!
    - Different particles give different Cherenkov angles!

- **Particle identification through two methods**
  - Ring Image Cherenkov
  - Threshold Cherenkov counters

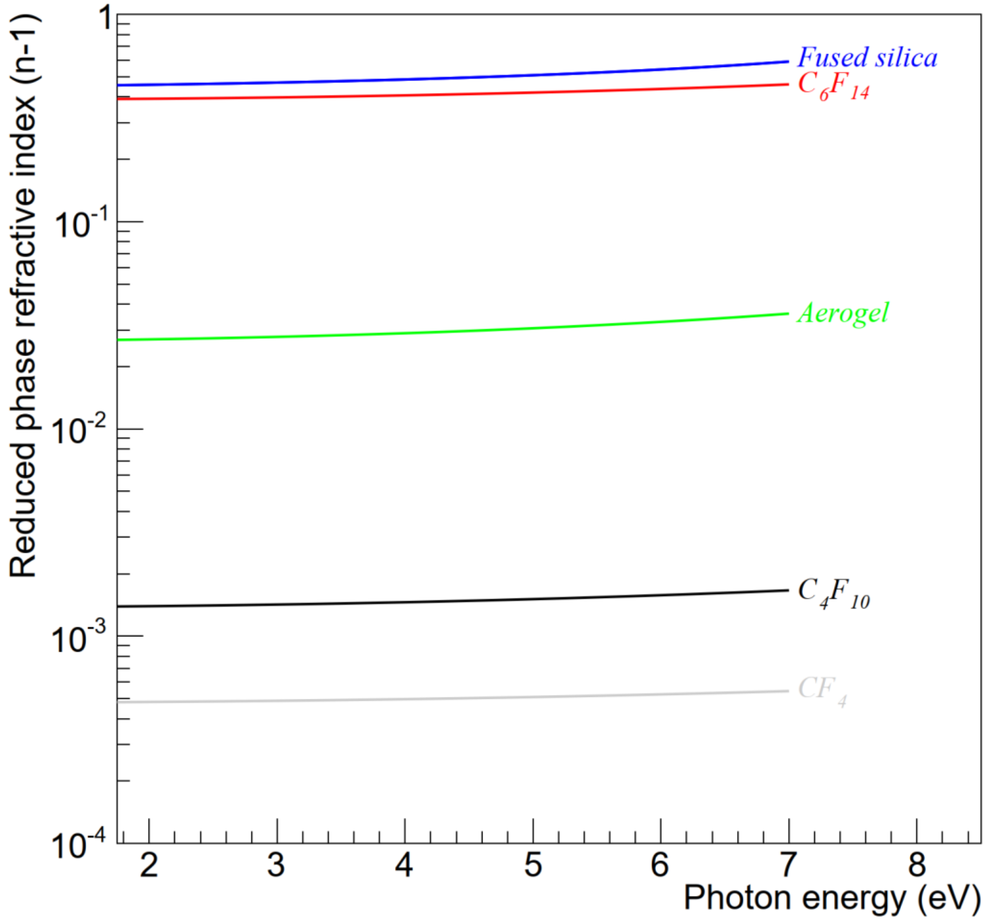


Refractive index is the name of the game

- **Refractive index is the key to Cherenkov light**
  - It sets the angle of emission
  - It sets the quantity of light you get

- **Different properties for different media**
  - Gas 1.000-1.005
  - Aerogel 1.01-1.05
  - Solid 1.40-1.70

- **Light yield scales as $\left(1-\frac{1}{n^2\beta^2}\right)$**
  - Some cm of solid can be equivalent to a few meters of gas
  - But the behaviour of the emitted Cherenkov light is quite different

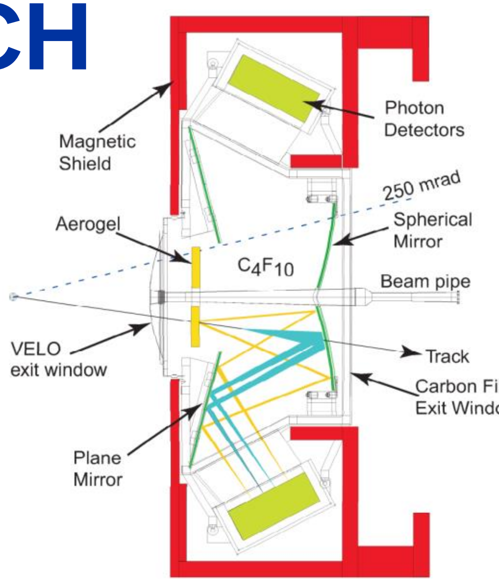


Ring Imaging Cherenkov – RICH

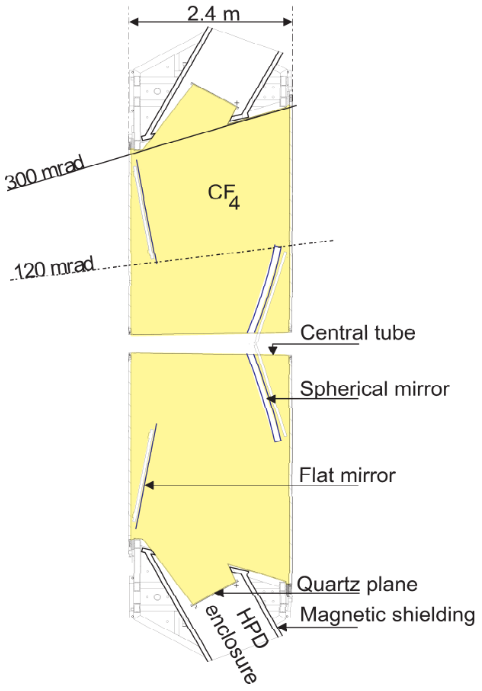
- **The core idea of the RICH technique is to project the ring forward so that the angle of the photons can be measured**
  - Use gaseous medium (Č angle ~few degrees)
  - Cherenkov angle + momentum = PID
  - Gathering enough light takes O(1m) of gas

- **Example case: LHCb RICH**
  - LHCb has two RICH detectors
  - Filled with two different refractive index gases
  - Used for particle identification
    - Different from beamline: mix of different momenta so needs external information

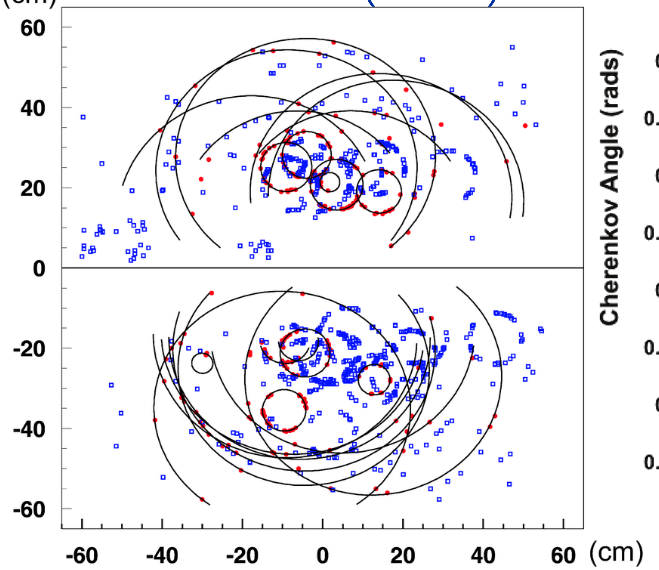
LHCb RICH1



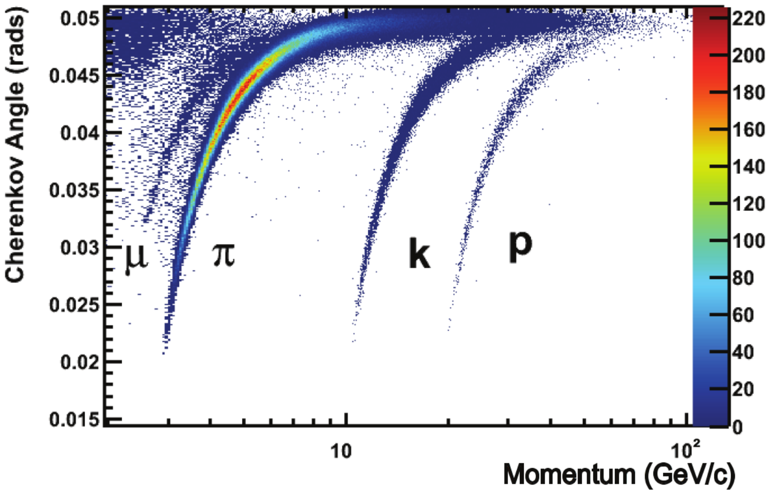
LHCb RICH2



LHCb simulation (RICH1)

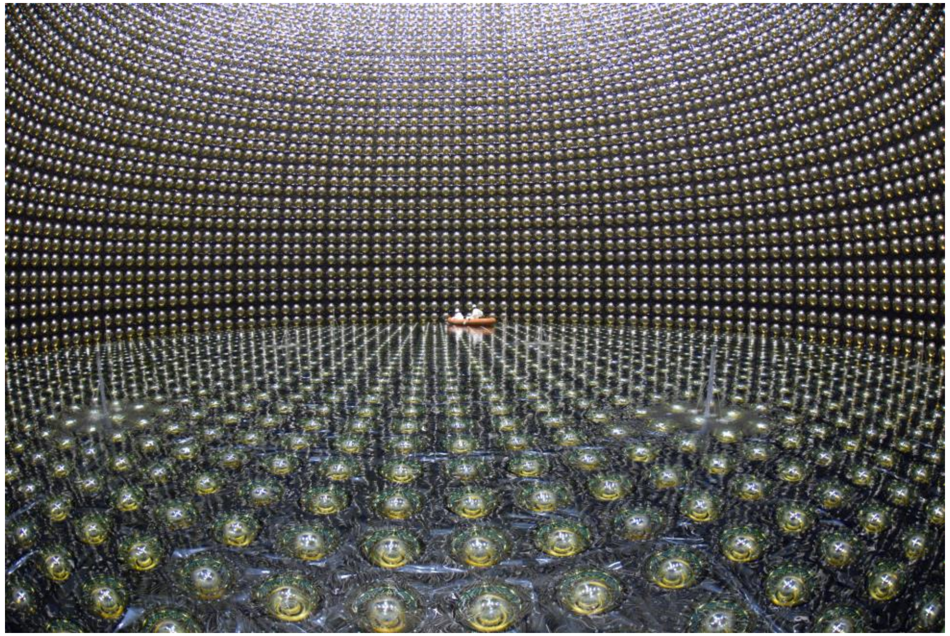


LHCb RICH1 performance

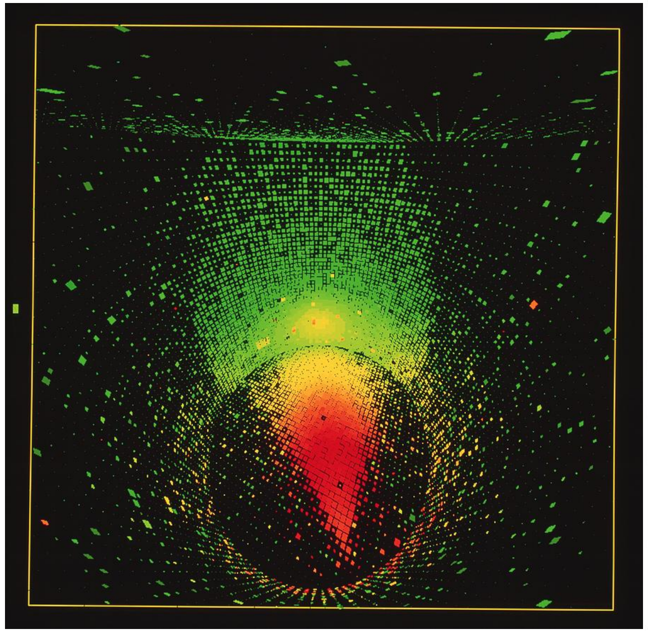


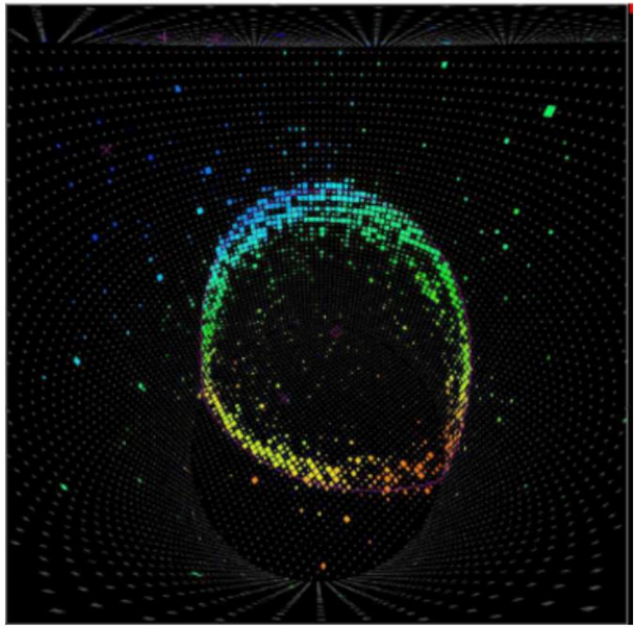
Super Kamiokande

- **Neutrino detection experiment in Japan**
  - Giant tank of pure water (41.4m high, 39.3m Ø)
  - So, uses liquid medium (Č angle ~45 deg)
  - Light detectors around and on top and bottom



- **Physics with cosmic rays as “beam”**
  - Radiation from space
  - “Disk” event indicates track passing through
  - “Ring” event indicates track stopping in tank
  - Center and orientation of ring / disk gives point of impact and direction of track
  - Different shapes and sizes give more information about event



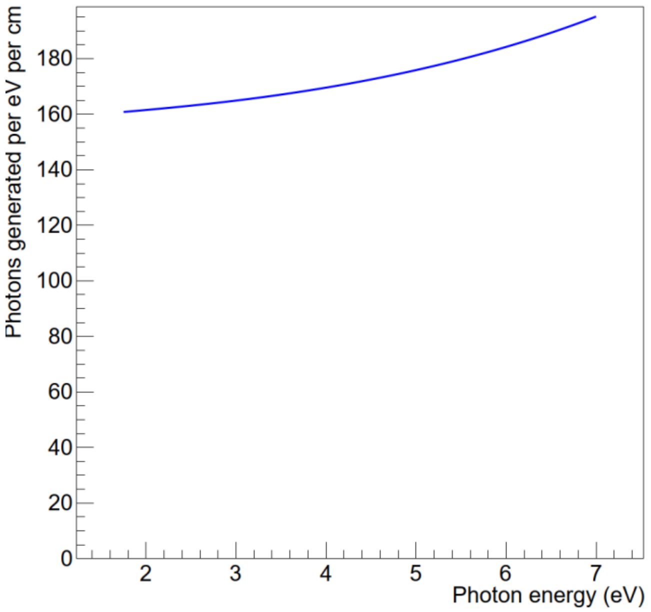


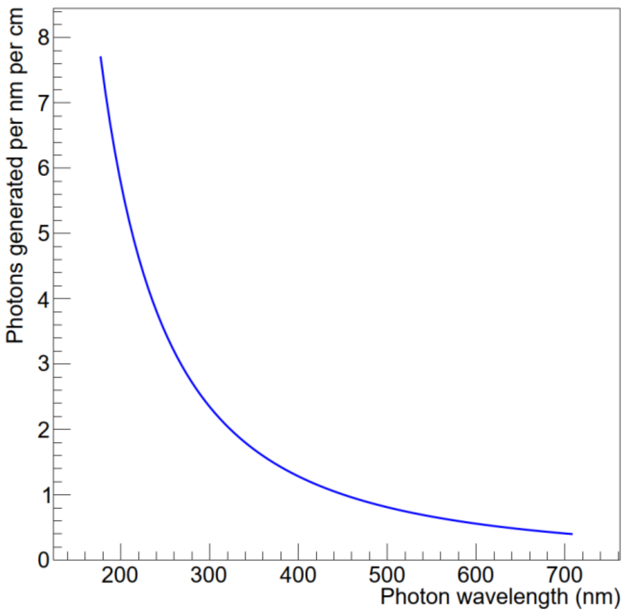
What's up with the blue glow?

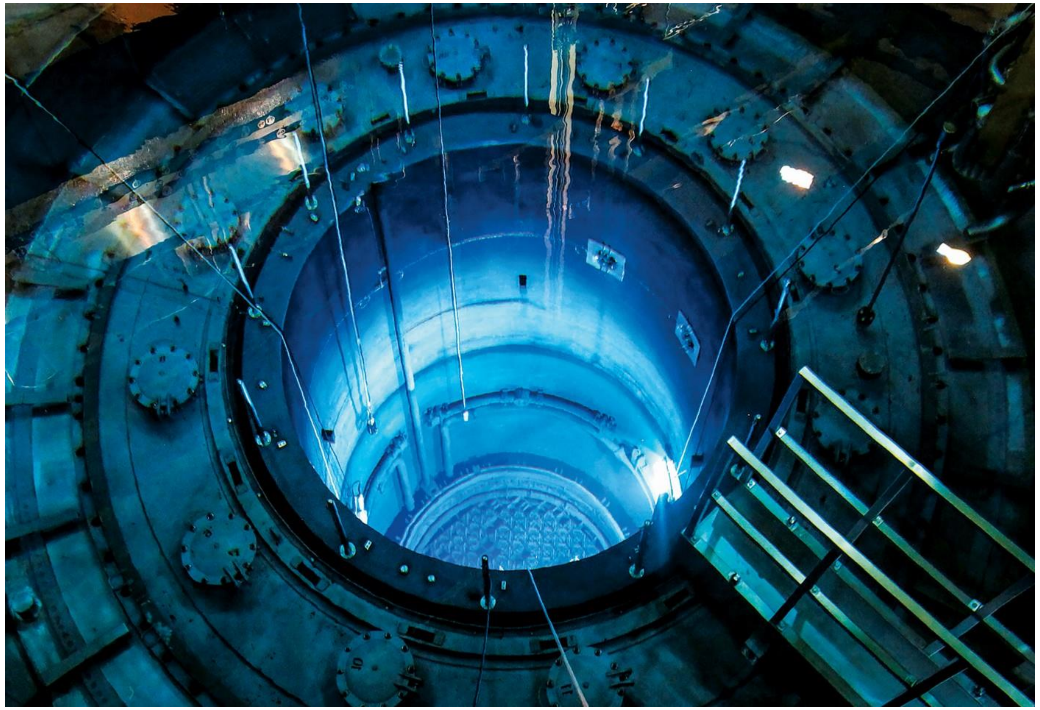
$$\frac{dN}{dE} = 370L\left(1 - \frac{1}{n_p^2\beta^2}\right)$$

- **Why does a nuclear reactor glow blue?**
  - Take the Frank-Tamm relation and plot it for water
  - In energy space (eV) and in wavelength space (nm)

Red light	700nm	1.77 eV
Green light	550nm	2.25 eV
Blue light	450nm	2.76 eV
UV light	250nm	4.96 eV





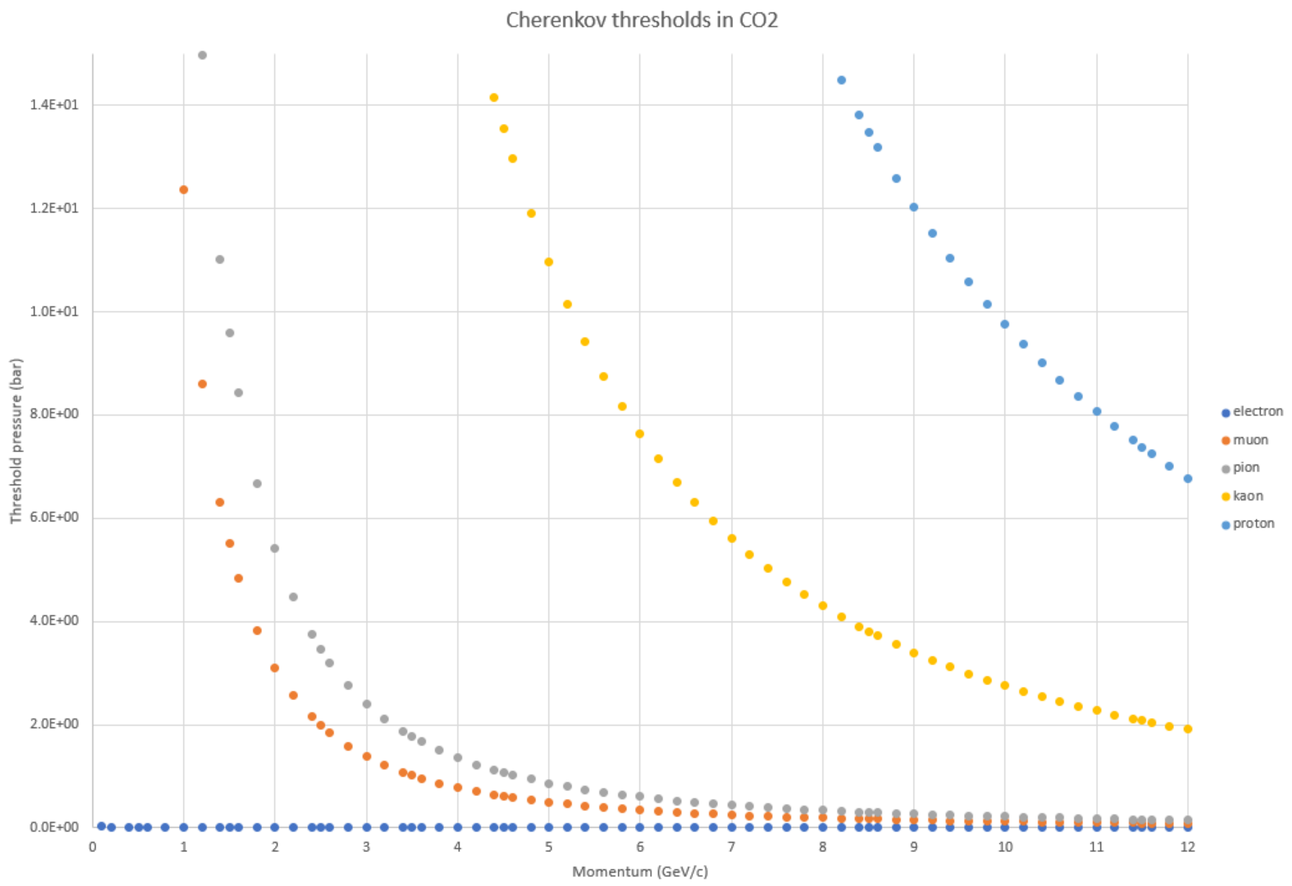


- **Still – where does the blue glow come from?**
  - After all, a nuclear reactor produces neutrons?

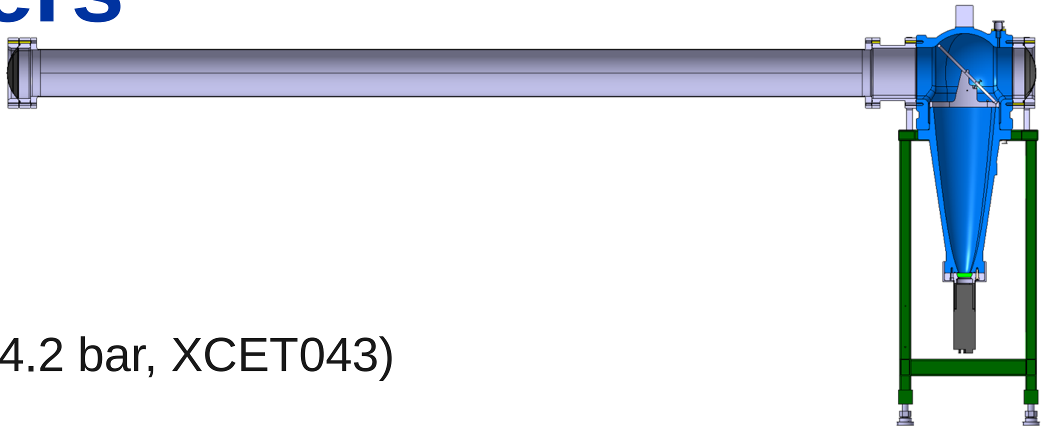
Controlling the refractive index

Gas	k-value
Helium	3.50×10^{-5}
CO_2	4.50×10^{-4}

- **In the previous examples, the refractive index of the medium was fixed**
  - However, in the beamline we can play with it
- **Refractive index of a gas is dependent on its absolute pressure**
  - The refractive index is **linear** with pressure
    - Dependency is: $n = 1 + k \cdot P \text{ (bar)}$
    - Different gases have different k values
  - This gives rise to the idea of a Cherenkov threshold – as a pressure
  - It is defined as the threshold at which a particle starts emitting light
  - For example, CO_2 with a beam of 3 GeV/c has a pion threshold of 2.4 bar



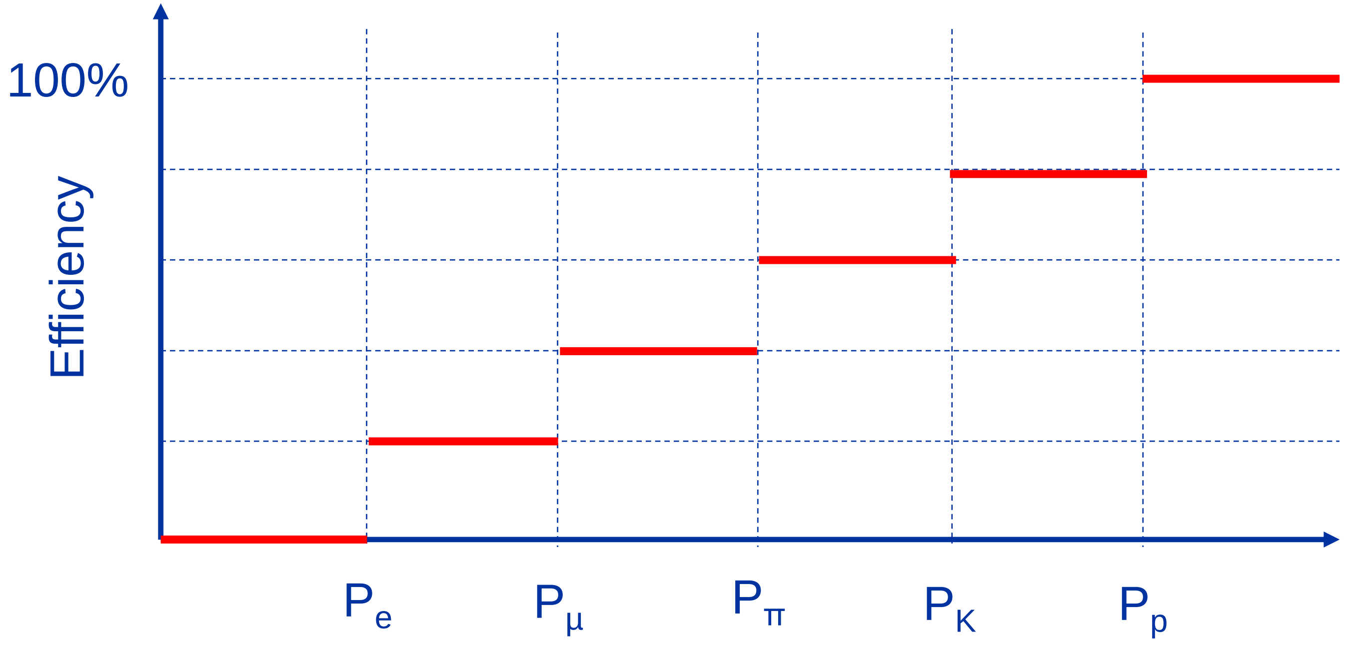
Cherenkov Threshold Counters



- **Device also known as XCET**
  - Key beamline equipment for PID
  - Both the T9 and T10 beamlines have two
  - High pressure (<16 bar, XCET040) and low pressure (<4.2 bar, XCET043)
- **Combination of signals from two XCETs lets experiments take one species of particles from the beam**
  1. Calculate thresholds for different particles
  2. Set one just below threshold of desired particle, the other above
  3. Combine what you need to see in the two detectors
     a. *No signal* in detector set **below** threshold
     b. Signal in detector set **above** threshold
- **This combination gives the users the flexibility to select (tag) a desired particle species**

Under pressure

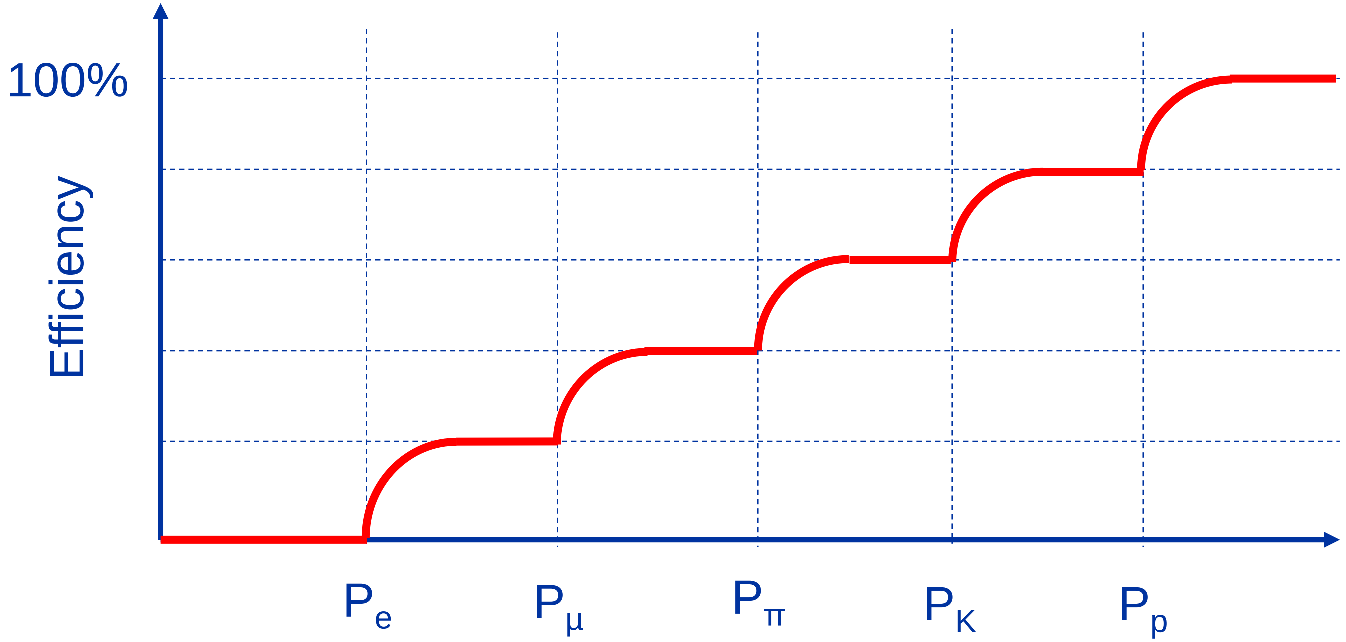
- **We use a small trick: we use the coincidence of the scintillators before and after the XCET to normalize the XCET: definition of XCET efficiency!**
  - Technically, we use the coincidence of the XCET with the trigger divided by the trigger
- **What do we expect to find when we do a pressure scan?**
  - Let's put in an expected beam of 20% of all five particles (e, μ, π, K, p) and label the thresholds



Under pressure

- **Add some more reality: remember Drs Frank and Tamm?**
  - At the threshold pressure, nβ = 1 (this is the definition!)
  - So….we get no light at all at the Cherenkov threshold!
  - Light yield scales linearly with $(P - P_{thr})$

$$\frac{dN}{dE} = 370L\left(1 - \frac{1}{n_p^2\beta^2}\right)$$



Under pressure

- **Keeping the momentum stable, and then scanning the pressure should eventually show all particles**
  - However, limited in practice by the maximum pressure of the vessel
  - For example, for particles at 10 GeV/c shown in table

- **Reality is not always nice to physicists!**
  - Cannot see all with one gas
    - If threshold is over the maximum – cannot see it!
    - If thresholds too close together, cannot see difference!
  - We can pick one gas to go up to 16 bar and one to 4.2 bar
  - Helium and CO_2 have complementary properties
  - We picked for you (for now) CO2 to high pressure and helium to low pressure – the detector is still being worked on

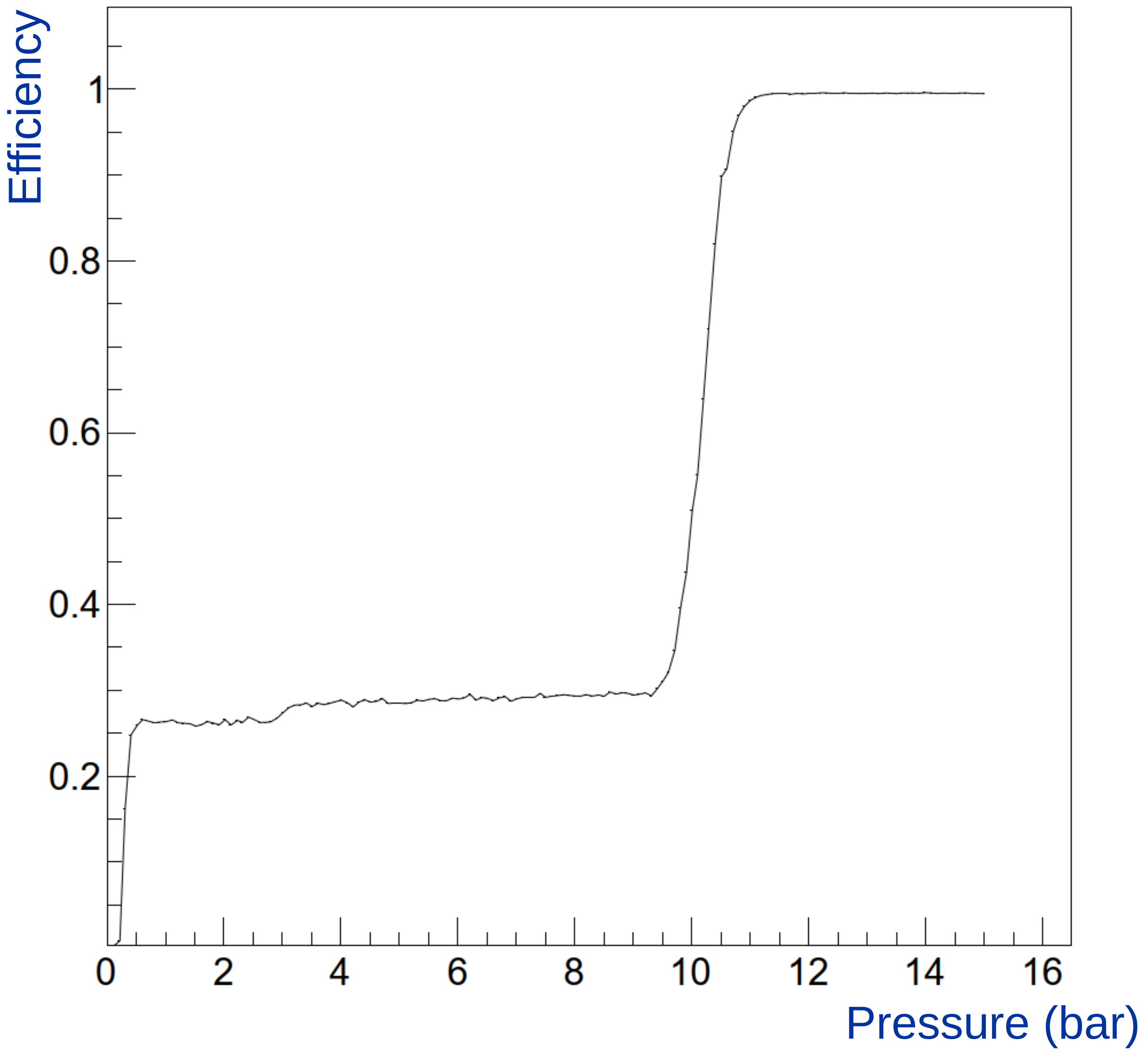
Thresholds for 10 GeV/c particles

Particle	Threshold (bar) in helium	Threshold (bar) in CO_2
Electron	3.73×10^{-5}	2.90×10^{-6}
Muon	1.60×10^{0}	1.24×10^{-1}
Pion	2.78×10^{0}	2.17×10^{-1}
Kaon	3.54×10^{1}	2.75×10^{0}
Proton	1.25×10^{2}	$9.76 \text{ x } 10^{0}$

Finally, some actual data!

- **Let's interpret the plot!**
  - Data taken at +10 GeV/c with CO_2

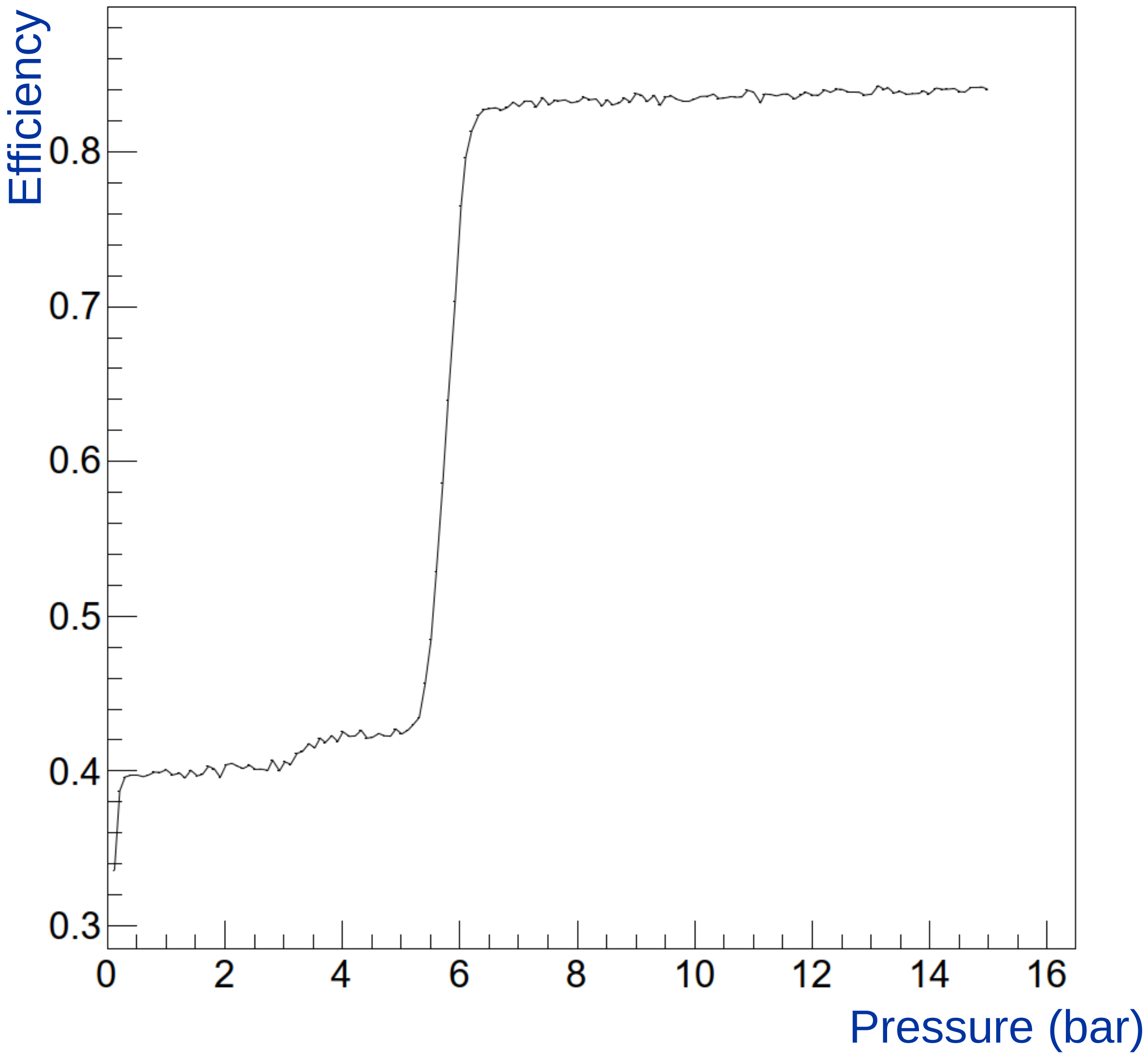
Particle	Threshold (bar) in CO_2
Electron	2.90×10^{-6}
Muon	1.24×10^{-1}
Pion	2.17×10^{-1}
Kaon	2.75×10^{0}
Proton	9.76×10^{0}



Finally, some actual data!

- **Let's interpret the plot!**
  - Data taken at +2 GeV/c with CO_2

Particle	Threshold (bar) in CO_2
Electron	7.25×10^{-5}
Muon	3.10×10^{0}
Pion	5.41×10^{0}
Kaon	6.78×10^{1}
Proton	2.32×10^{2}

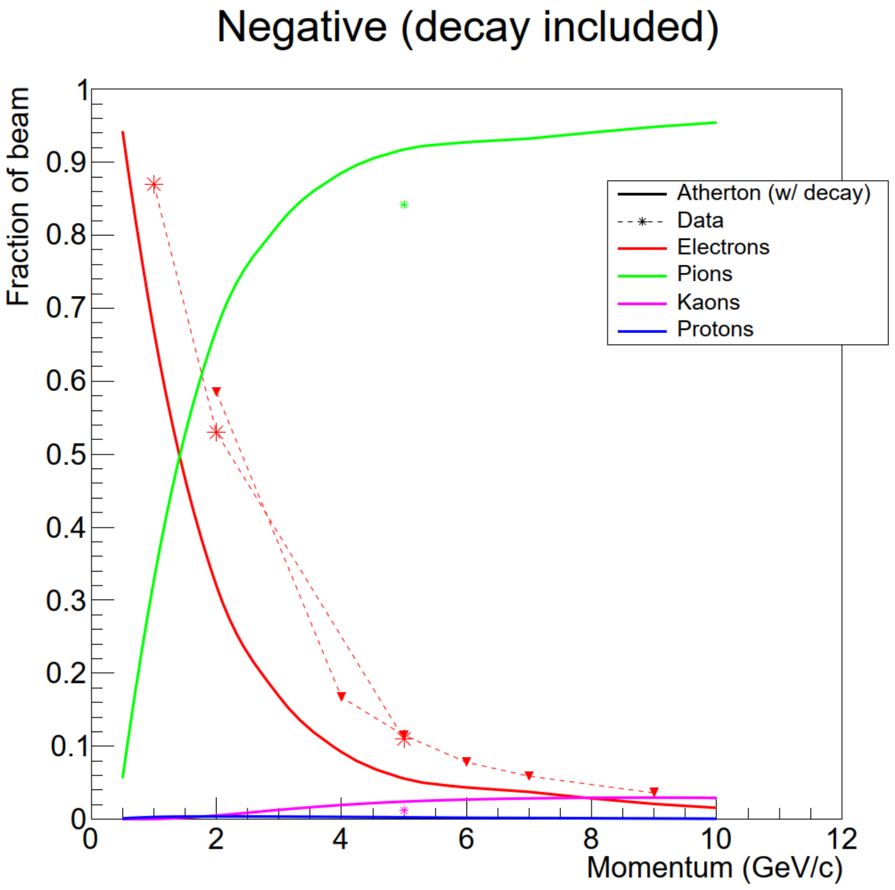


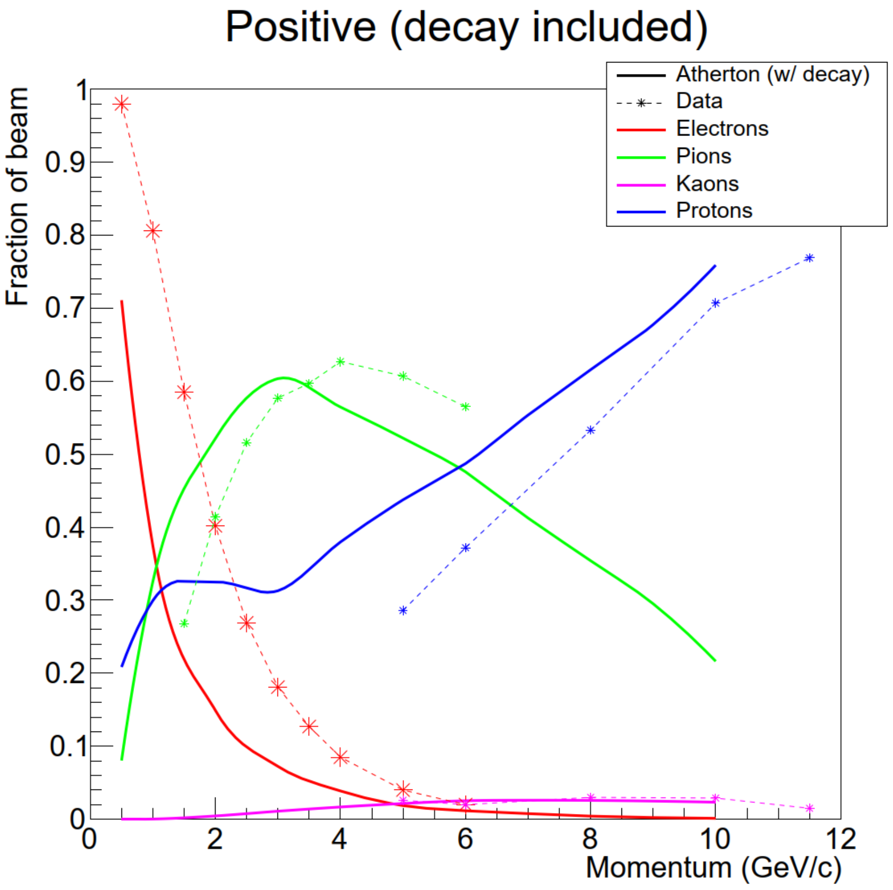
Some further hints for the data analysis

- **Muons are very strange creatures**
  - The beam contains a mixture of different momenta of muons (!!!!)
  - I expect you to figure out for yourself (and with Berare and Martin, of course!) to figure out what the impact of this is on the Cherenkov scans
- **Behavior of the low-pressure XCET with helium not yet well understood!**
  - Discuss as things go on with Berare, Martin and me!
- **If the threshold pressures are close together, be careful about saying you know!**
- **What is the difference between the negative and the positive beam?**
- **Can we see if the XCET is fully efficient at any point?**
  - Is it possible that, for example, we miss some 5% of particles always?
  - How would we know this?
  - If protons are the only particle left we cannot see, can we still estimate their number?

What do we know at the moment?

- **All preliminary – in other words, not finished, and needs verification**
  - This is also an open invitation to CHECK these numbers with the available data!





Conclusions

- **Cherenkov light has many applications – in particular it is excellent for PID**
  - Used in the secondary beamlines in Cherenkov Threshold counters

- **The goal (for the Particular Perspective!) is to use <u>*all*</u> techniques to fill the particle identification plot**
  - XCET counters, calorimeters, time of flight, ….?

- **We very much look forward to see how much of this plot we can finish!**

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