Cherenkov detectors

So….what is Cherenkov light?

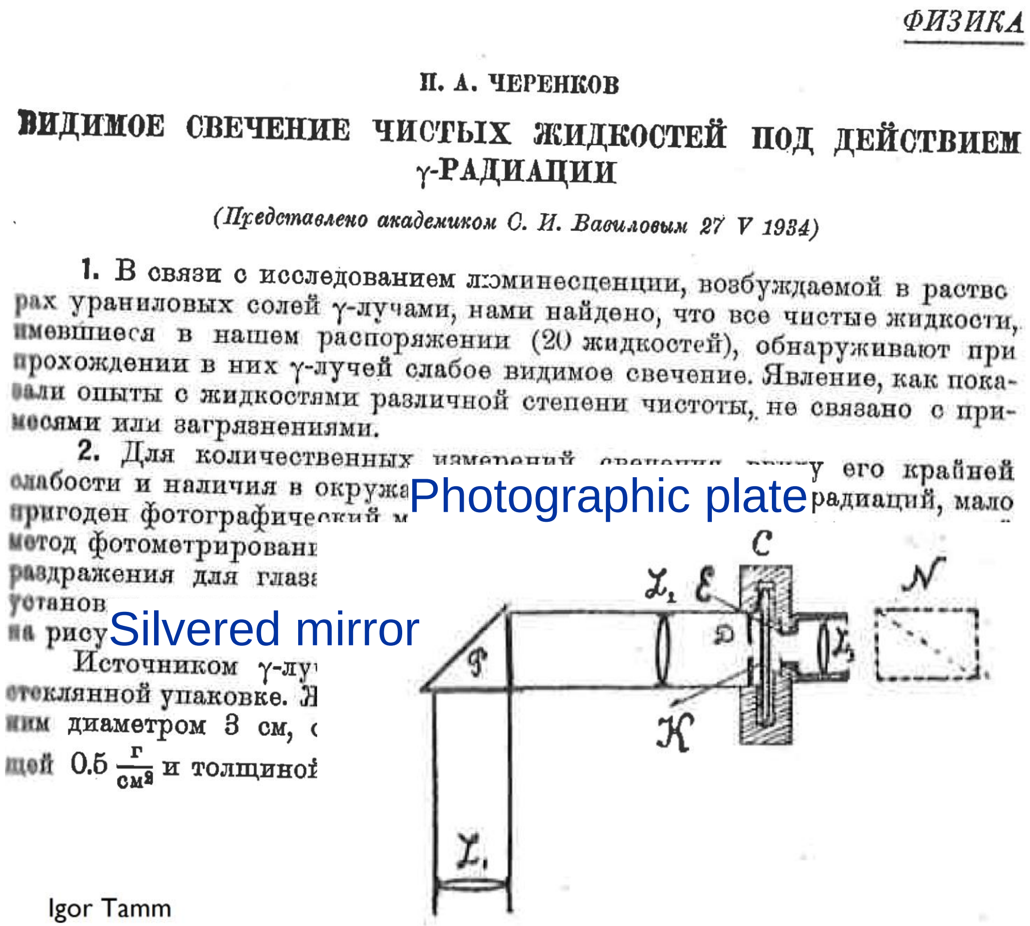
- **Electromagnetic shock wave (sonic boom) emitted by charged particles**
  - This is not an explanation, let's try again
- **Light emitted by a charged particle going faster than the local speed of light**
  - This is not an explanation, let's try again
- **"Coherent response of a medium to the passage 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

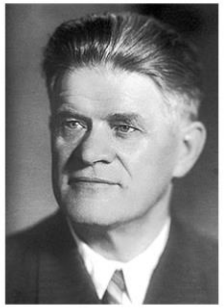
ВИДИМОЕ СВЕЧЕНИЕ ЧИСТЫХ ЖИДКОСТЕЙ ПОД ДЕЙСТВИЕМ γ-РАДИАЦИИ

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

1. В связи с исследованием люминесценции, возбуждаемой в растворах ураниловых 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.

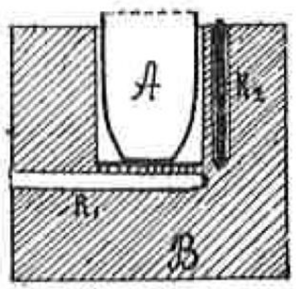
2. Для количественных ... его крайней слабости и наличия в окружа ... радиаций, мало пригоден фотографический ... метод фотометровани ... раздражения для глаз ... установ ... на рису ...
Источником γ-лу ... стеклянной упаковке. ... ним диаметром 3 см, ... щей 0.5 $\frac{г}{см^3}$ и толщиной ...

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

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

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

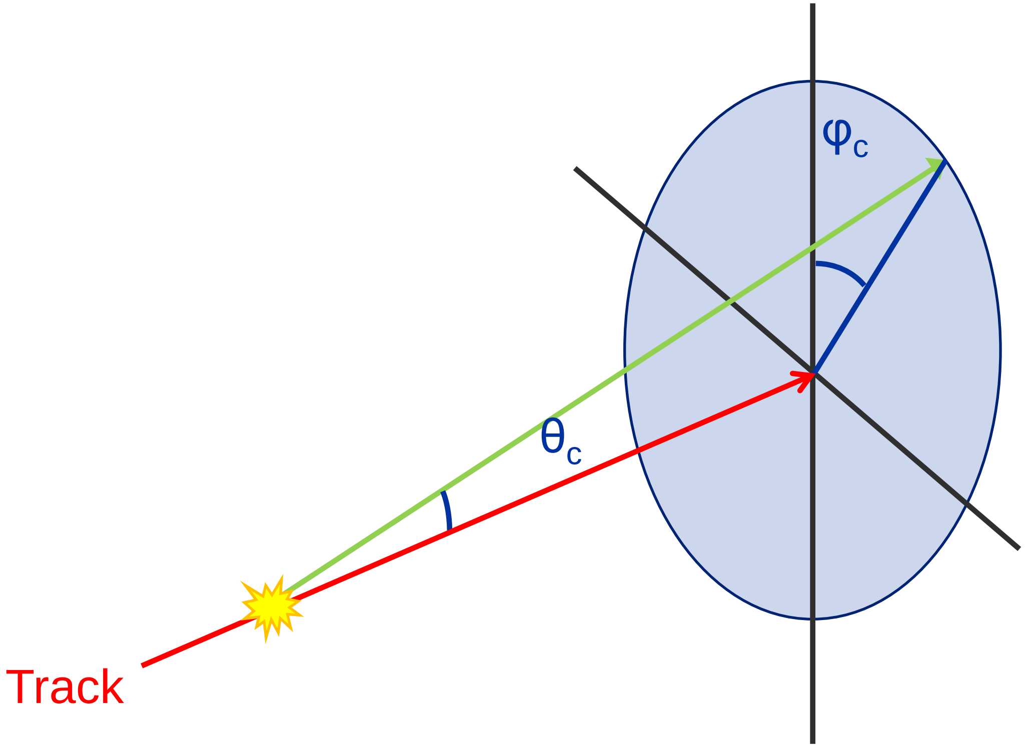
$$c_{local} = \frac{c_0}{n_g}$$

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

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

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

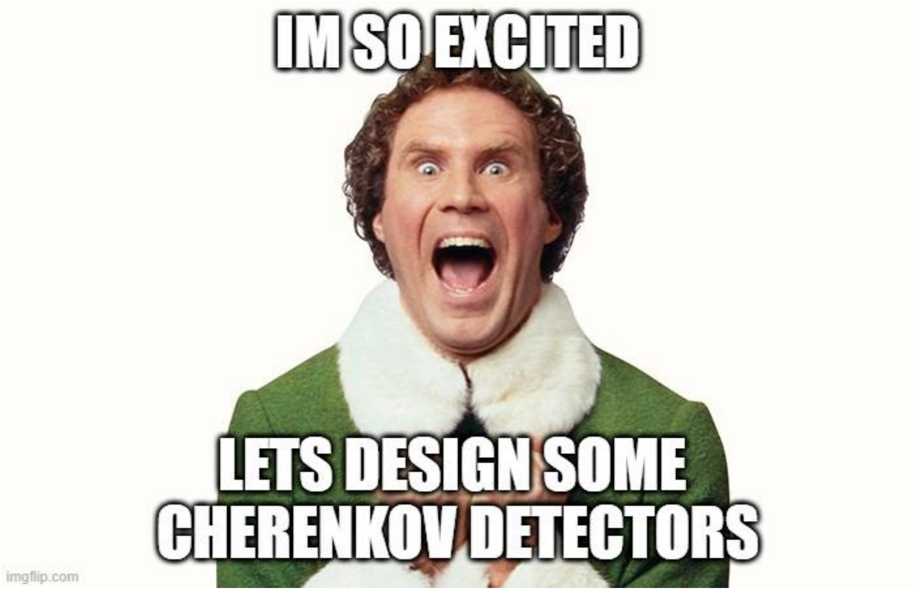
$$\beta = \frac{p}{\sqrt{p^2 + m^2}}$$

- **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

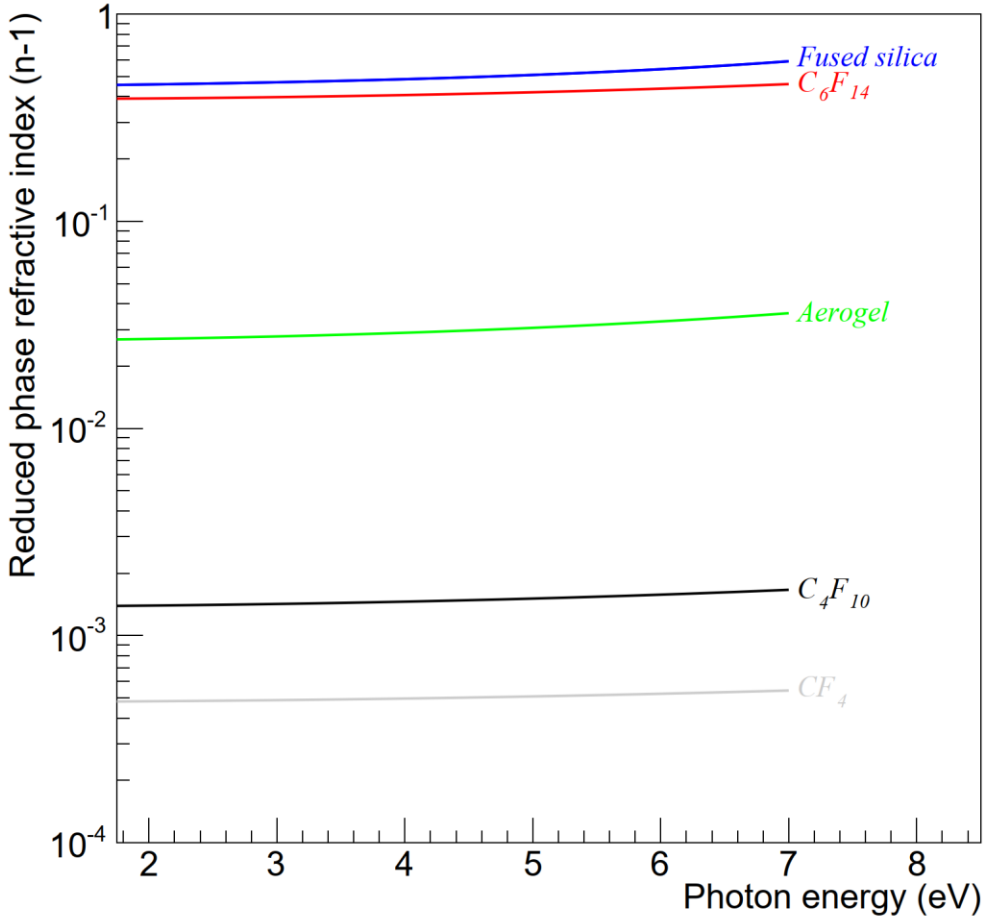


Refractive index is the name of the game

- **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

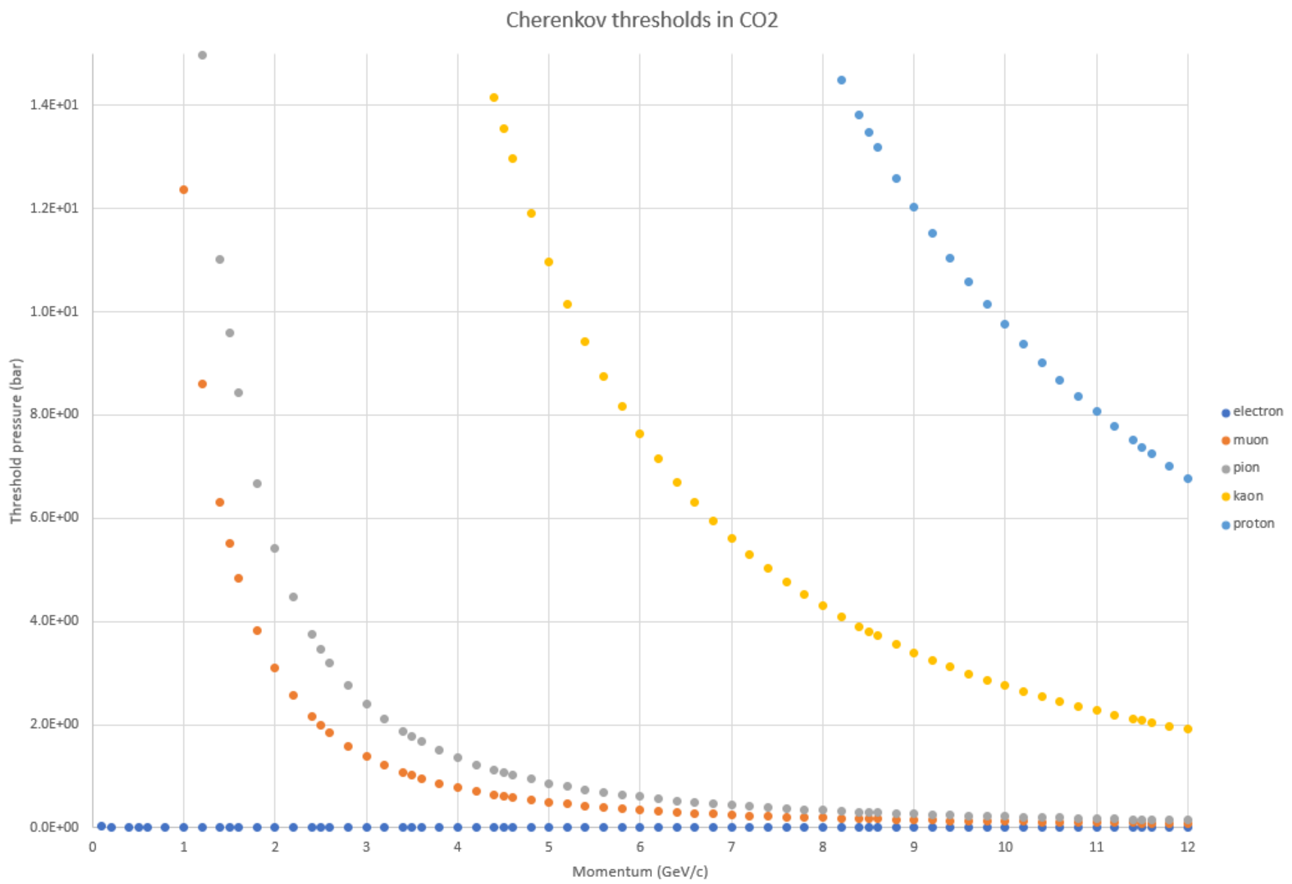
- **Light yield scales as** $\left(1 - \frac{1}{n^2\beta^2}\right)$
  - Some cm of solid can be equivalent to a few meters of gas
  - But the behaviour of the emitted Cherenkov light is quite different



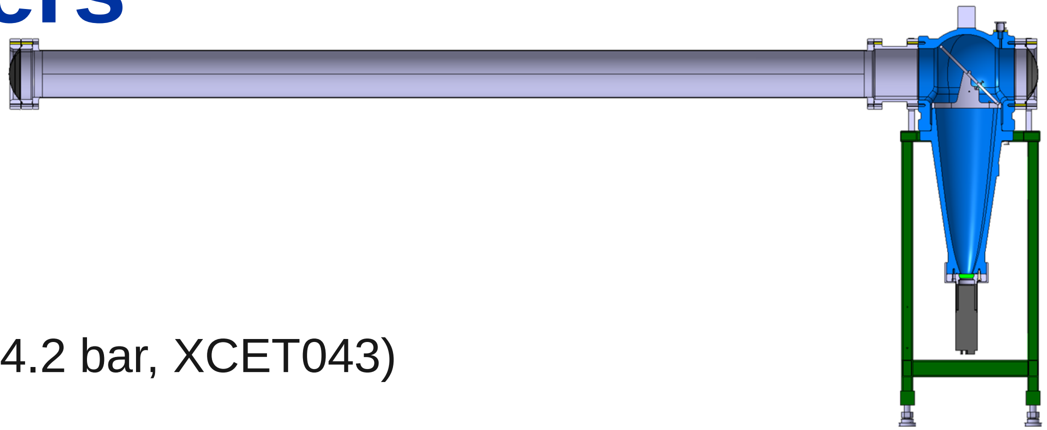
Controlling the refractive index

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



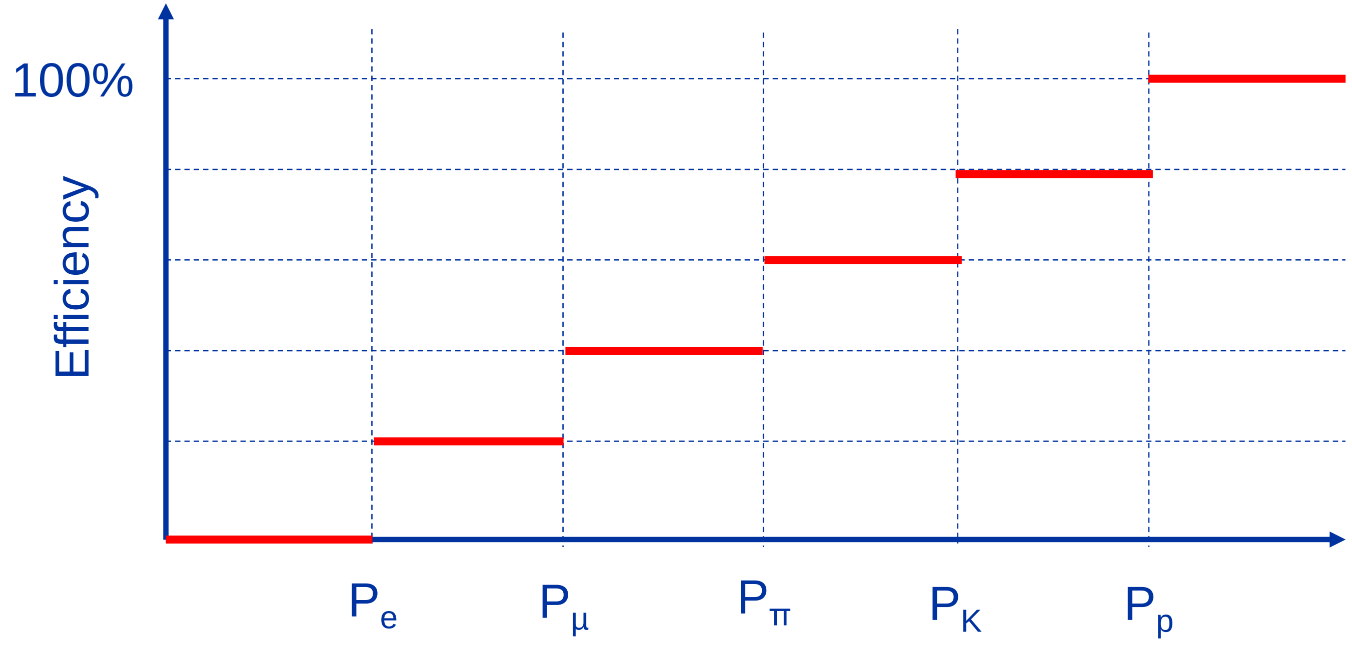
Cherenkov Threshold Counters



- **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

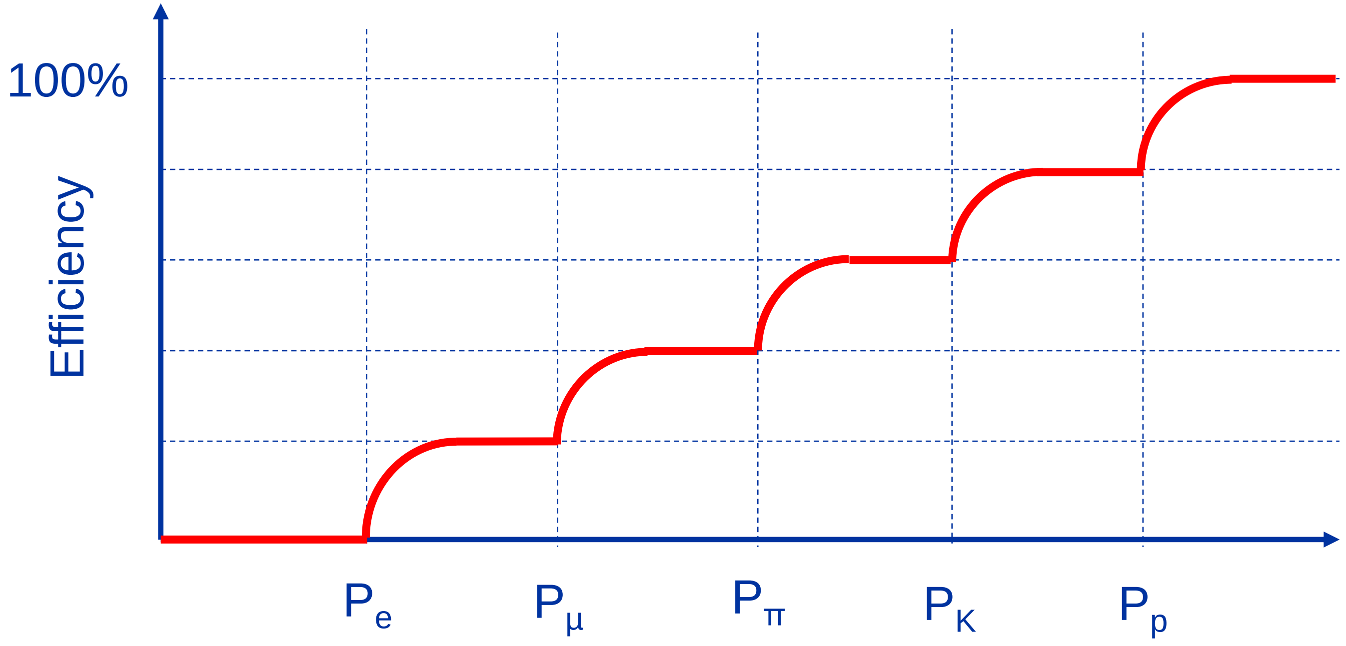
- **We use a small trick: we use the coincidence of the scintillators before and after the XCET to normalize the XCET: definition of XCET efficiency!**
  - Technically, we use the coincidence of the XCET with the trigger divided by the trigger
- **What do we expect to find when we do a pressure scan?**
  - 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!

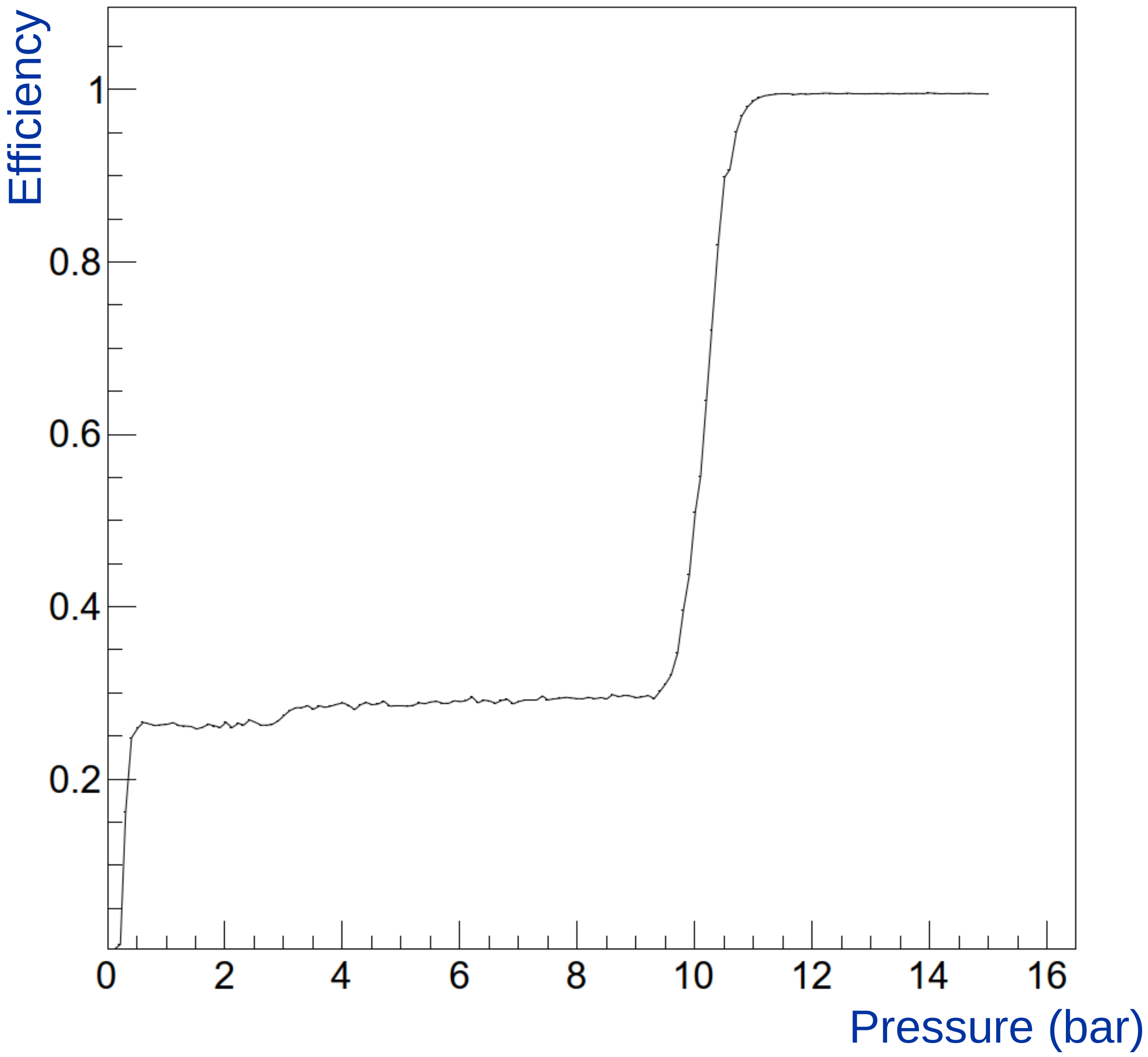
Thresholds for 10 GeV/c particles

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}	9.76×10^{0}

Finally, some actual data!

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

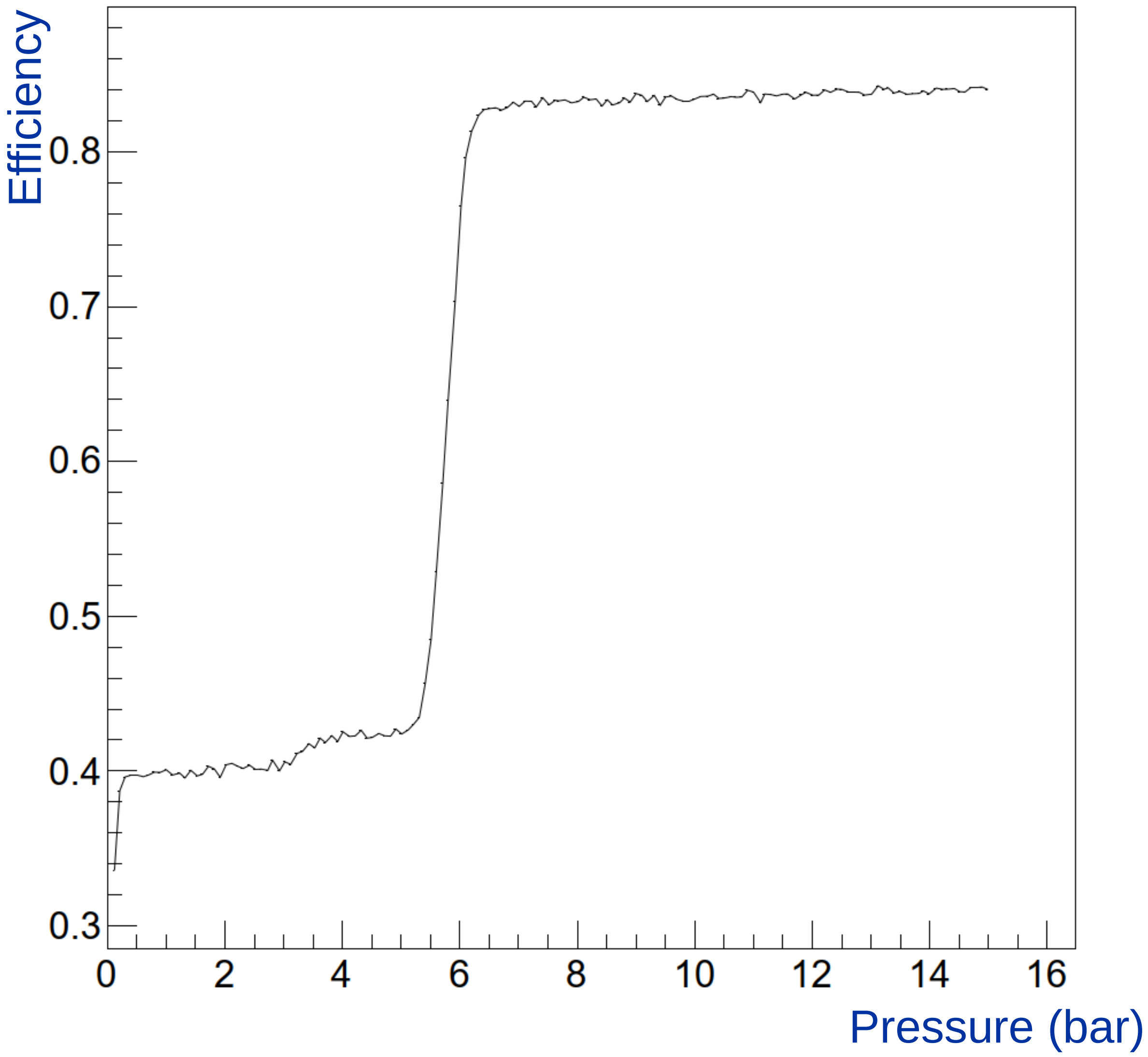
Particle	Threshold (bar) in CO_2
Electron	2.90×10^{-6}
Muon	1.24×10^{-1}
Pion	2.17×10^{-1}
Kaon	2.75×10^{0}
Proton	9.76×10^{0}



Finally, some actual data!

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

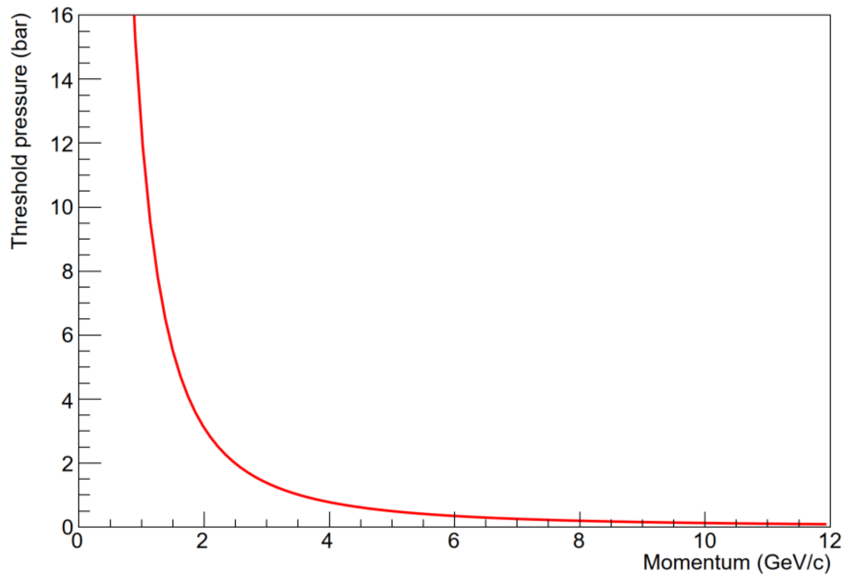
Particle	Threshold (bar) in CO_2
Electron	7.25×10^{-5}
Muon	3.10×10^{0}
Pion	5.41×10^{0}
Kaon	6.78×10^{1}
Proton	2.32×10^{2}

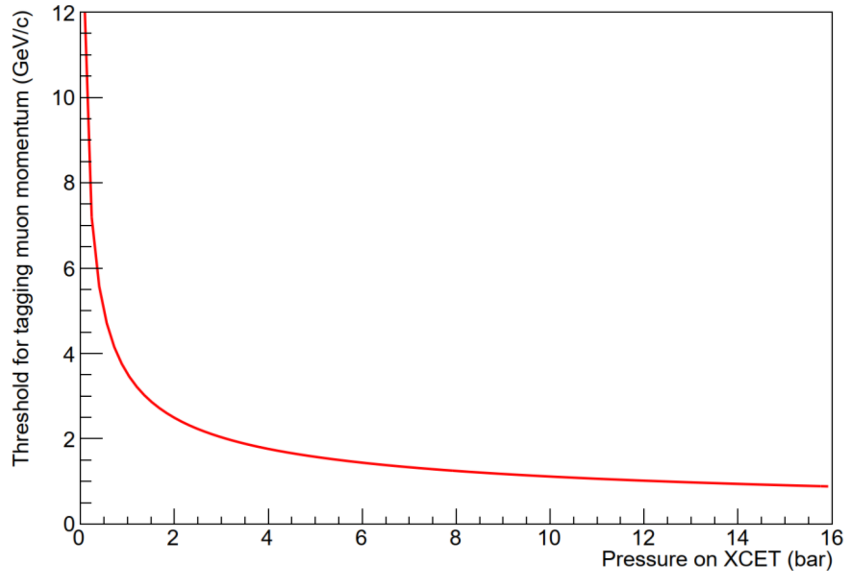


Now what about them muons?

- **We make the muon beam by putting the mixed hadron beam into the beam stopper**
  - Only the muons should survive, so now we know the mass!
  - However, we are not so sure about the momentum spread of the beam….

  - We can use the XCET signal to check it
    - Reformulate Cherenkov light threshold in function of pressure and momentum
    - The higher the pressure is, the more momenta muons we can tag
    - Reinterpret: at a given pressure, we tag all muons of threshold momentum ***and higher***
    - ***So a pressure scan can give us the momentum spectrum, with some limitations***

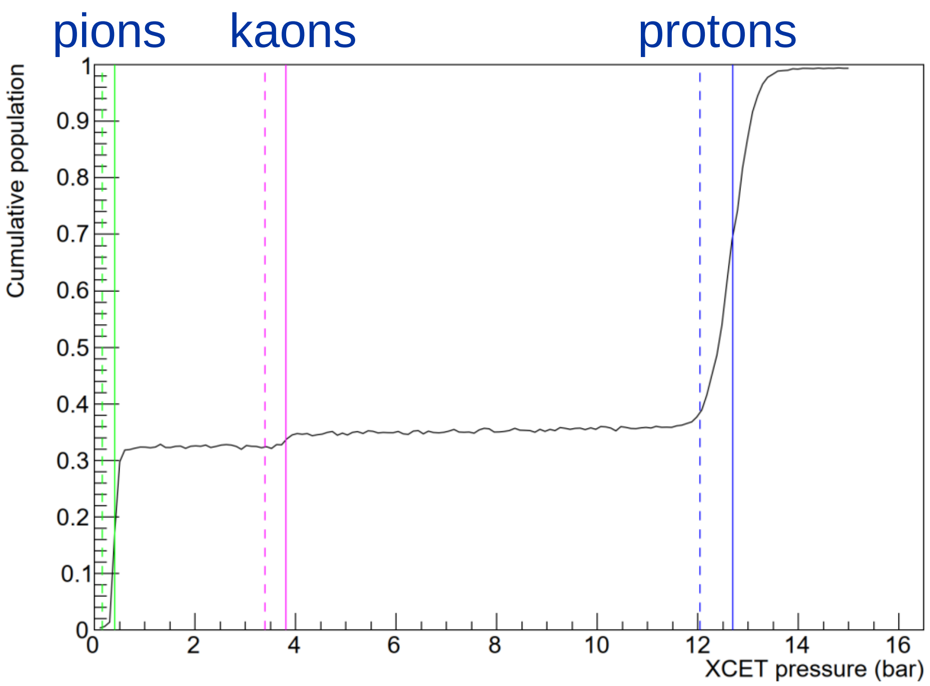


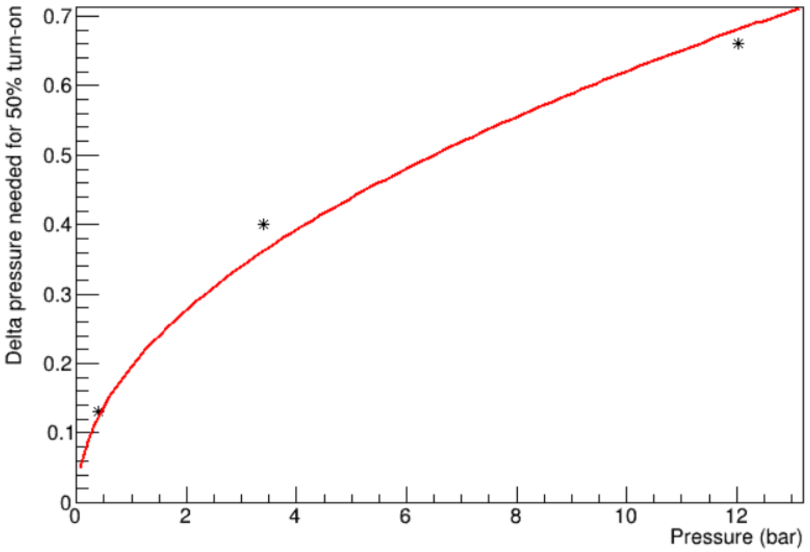


Where is the threshold really?

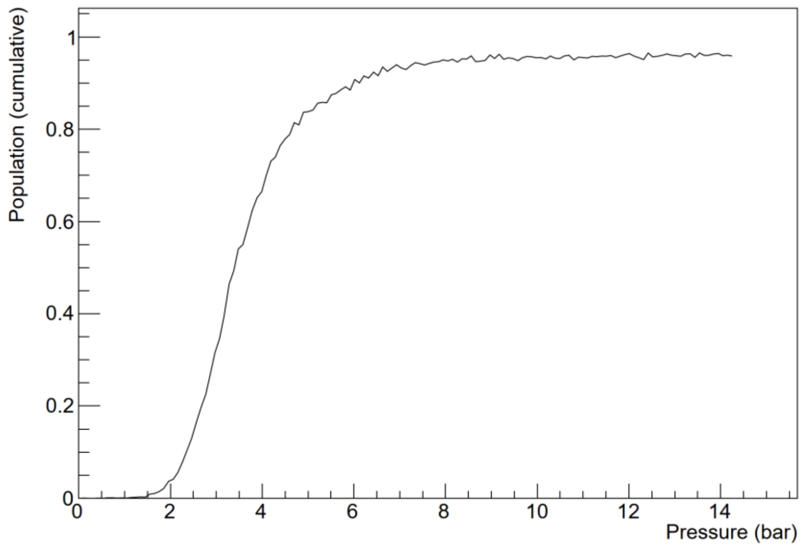
- **Unfortunately, the place where the muons turn on does not match exactly where they should**
  - Amount of light at turn-on pressure is zero
  - Need to go “a bit” higher (how much??)
  - Commit some crimes against statistics
    - Plot distance between what it should be and what it is – and fit with some function
      - [0]*sqrt(x) with [0] ~= 0.197
    - We need more data to do this well ☺

- **Apply correction as a function of absolute pressure**
  - Scale “observed” pressure down by this quantity

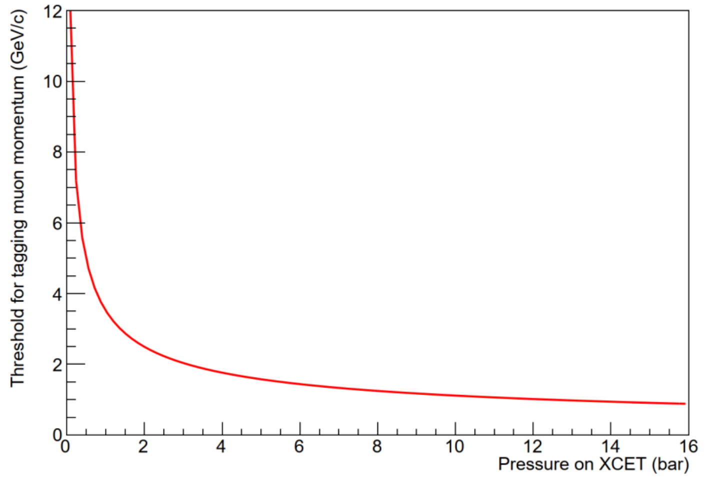


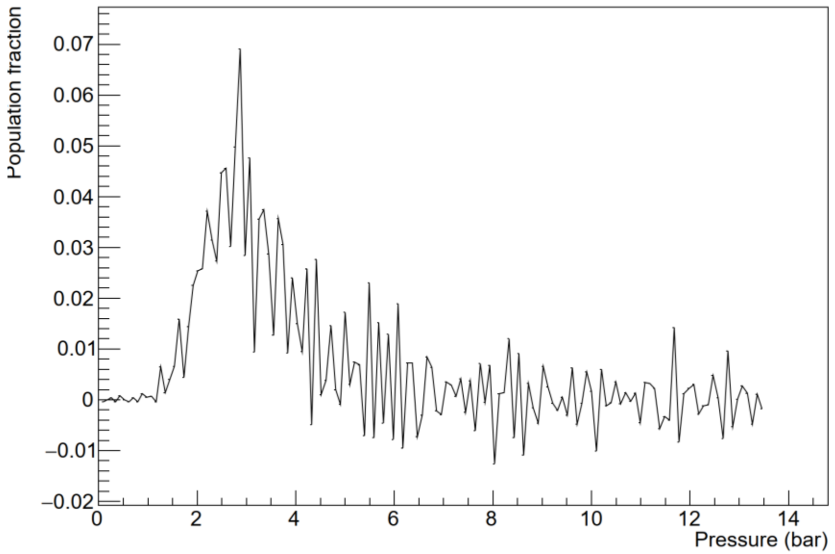


Threshold scans!



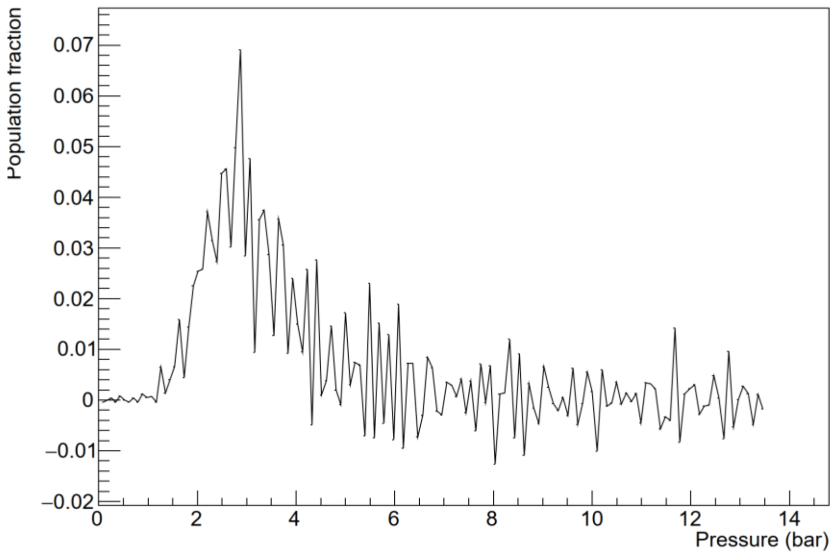
- **Plot shows fraction of tagged muons as function of pressure**
  - We have to take the differential to find the spectrum
  - Vertical step as a function of pressure
    - Don’t forget to subtract the fit from the previous page
- **And then map pressure to momentum (next slide!)**



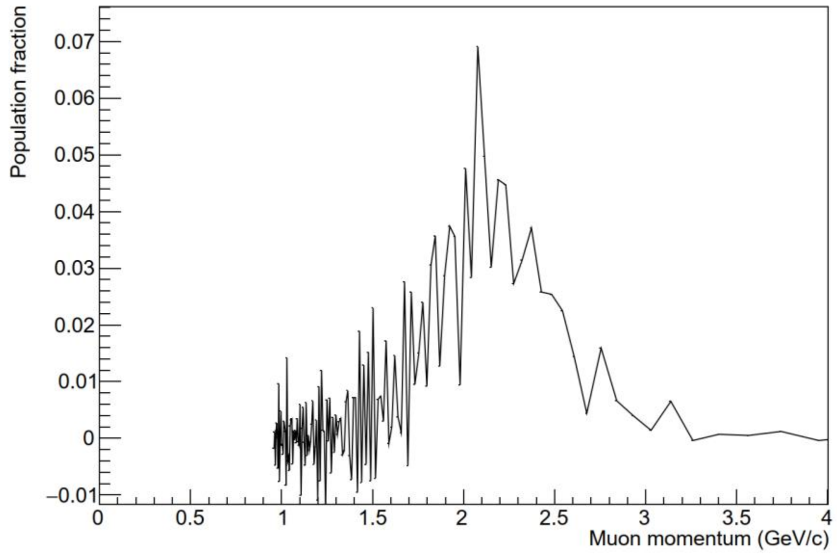


Are we there? YES!

- **The step size of the pressure is not so nice**
  - Mapping from pressure to momentum is tricky
  - But it scales nicely – no need for further correction



- **2 GeV/c muon beam has a wide momentum spread**
  - Fit to spectrum gives 2.17 mean with a sigma of 0.31 GeV/c
  - Not perfect, but not bad!



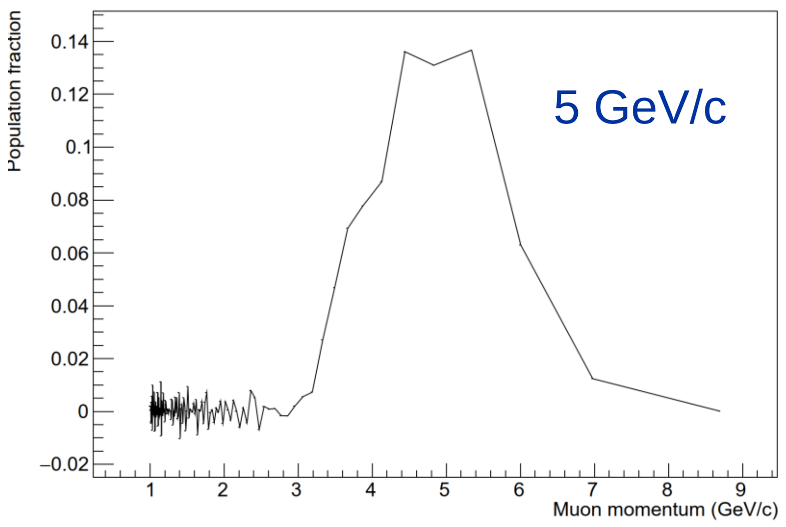
What about the other momenta?

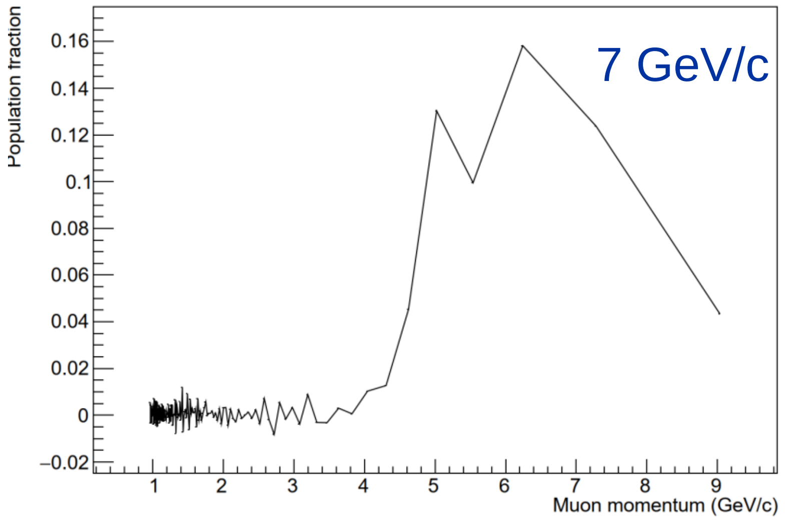
- 2 GeV/c gives 2.17 +/- 0.31 GeV/c (14% spread)

- 5 GeV/c gives 4.91 +/- 0.9 GeV/c (18% spread)

- 7 GeV/c gives 6.5 +/- 1.2 GeV/c (18% spread)

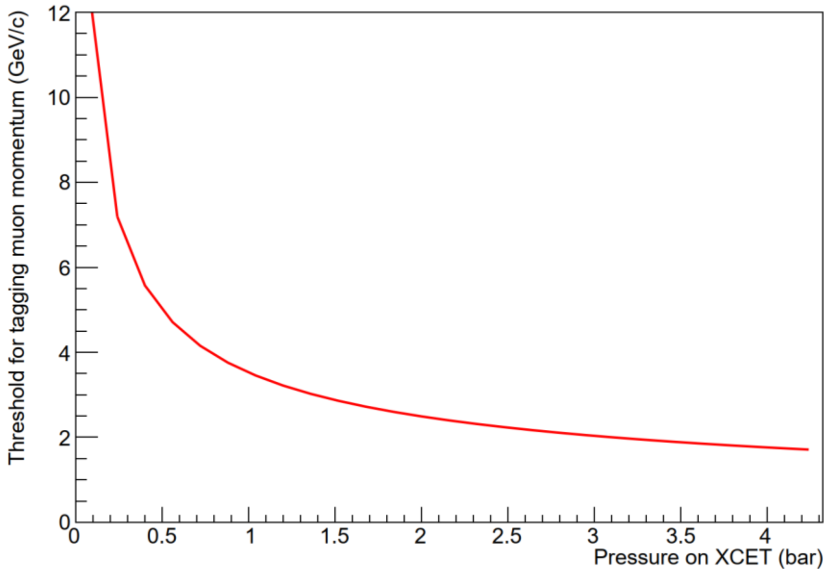
- Wide momentum spread present in the beam!





And now what?

- **This is where your work begins!**
  - You can use the Cherenkovs to “bracket” the momentum
    - Set low-pressure XCET to, for example, 2.5 bar (~2.2 GeV/c)
    - High pressure XCET to, for example, 3.8 bar (~1.8 GeV/c)
  - All the particles tagged by low-pressure but not by high-pressure are then particles in your momentum range!
  - Remember that you can only use the low-pressure XCET for “high” momentum (ie, for tagging all above 2 GeV/c or so)
  - High pressure XCET goes a bit further, down to 0.9 bar or so



- **Need to do a better job for mapping correction factor for momentum determination**
  - Needed for both XCETs, I did not have the data to do it for the low-pressure unfortunately
  - Scans with hadrons at 3, 5, 7, 9 GeV/c will probably give a good result? For discussion!!

Conclusions: a lot of new stuff!

- **It should be mentioned that most of this *has never been done like this before***
  - The tagging of muon momentum by means of the Cherenkov counter is a novel technique
  - For discussion with your support scientists – could be a nice part of a publication?
  - Gather nice data, discuss everything with everyone!

- **Spoiler technique for the next few days**
  - Advanced technique: since the amount of light detected scales with the distance from the threshold, the signal size of the XCET by itself is also proportional to the distance it is away from the threshold
  - In short, we can perhaps the signal size as a direct measurement of the momentum – to be seen!
  - Attach a paper where we employed this proportionality for a regular hadron beam for a mirror test (see indico)

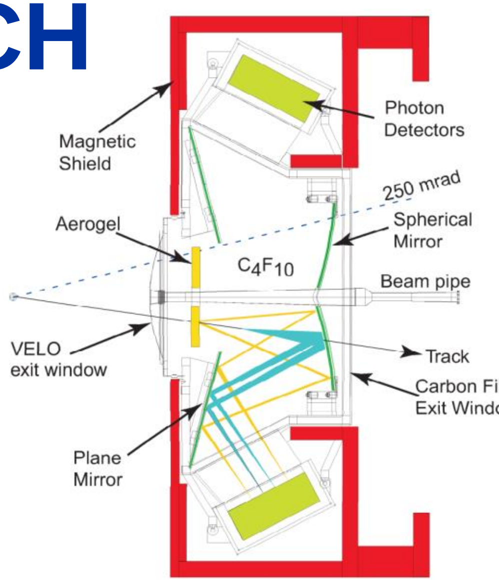
home.cern

Ring Imaging Cherenkov – RICH

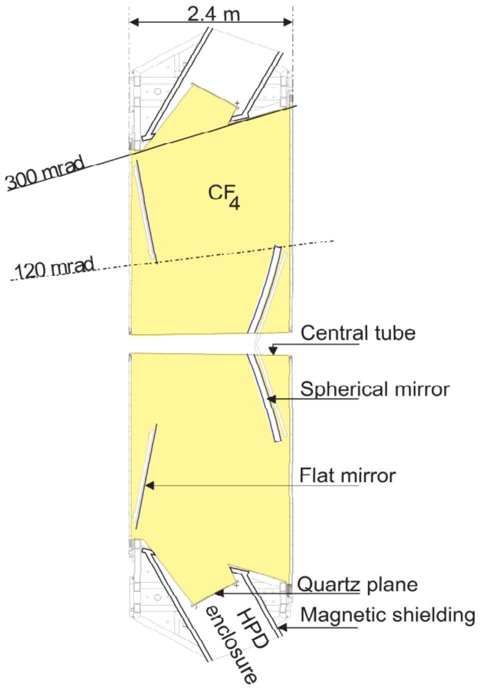
- **The core idea of the RICH technique is to project the ring forward so that the angle of the photons can be measured**
  - Use gaseous medium (Č angle ~few degrees)
  - Cherenkov angle + momentum = PID
  - Gathering enough light takes O(1m) of gas

- **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

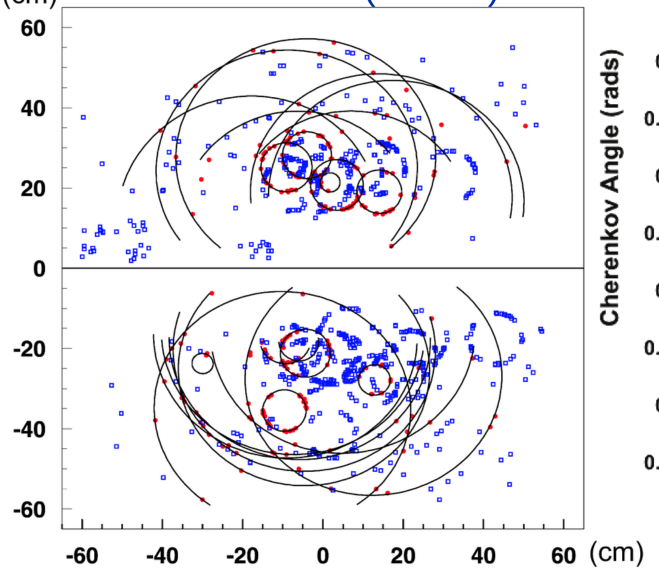
LHCb RICH1



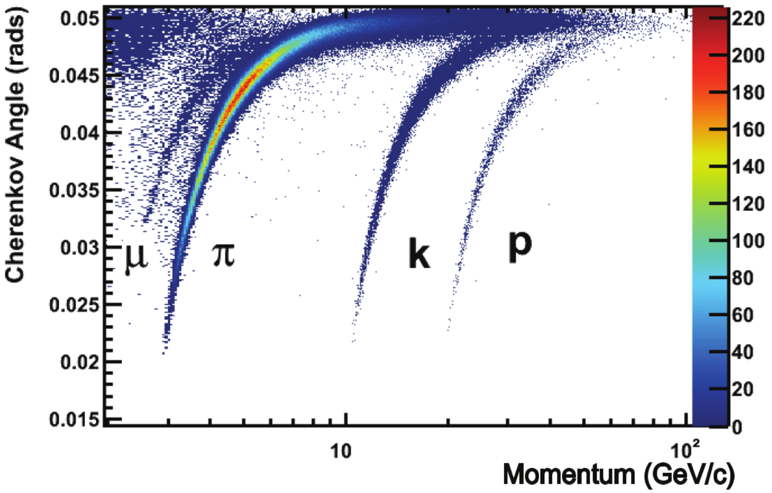
LHCb RICH2



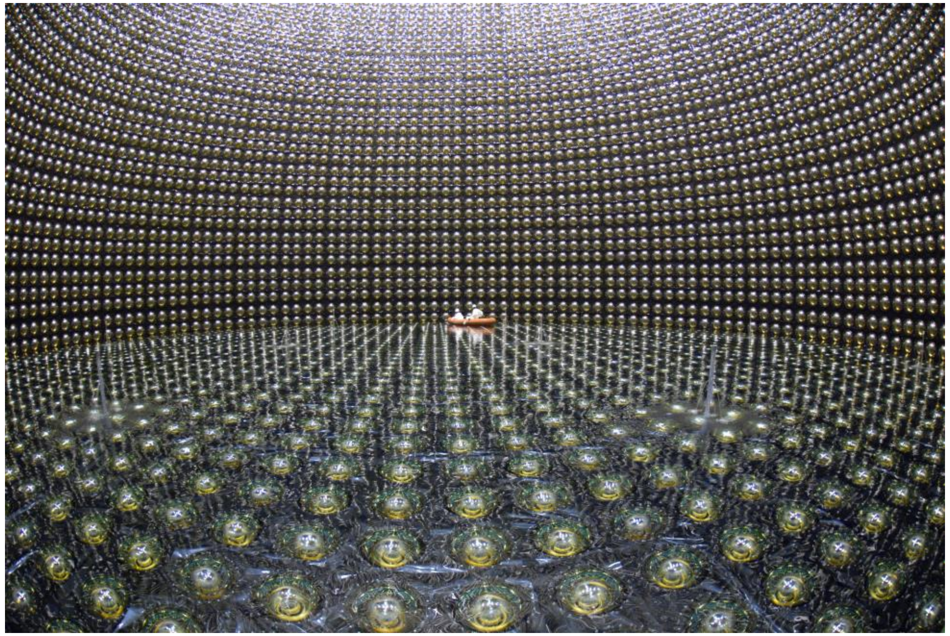
LHCb simulation (RICH1)



LHCb RICH1 performance

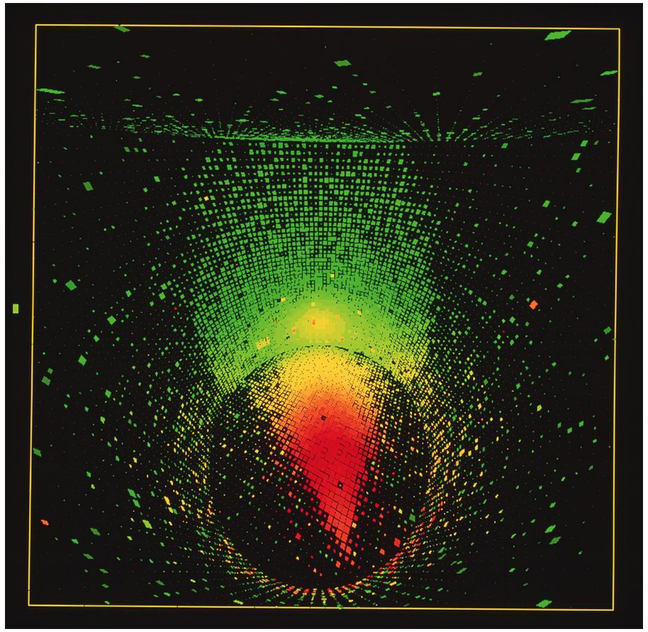


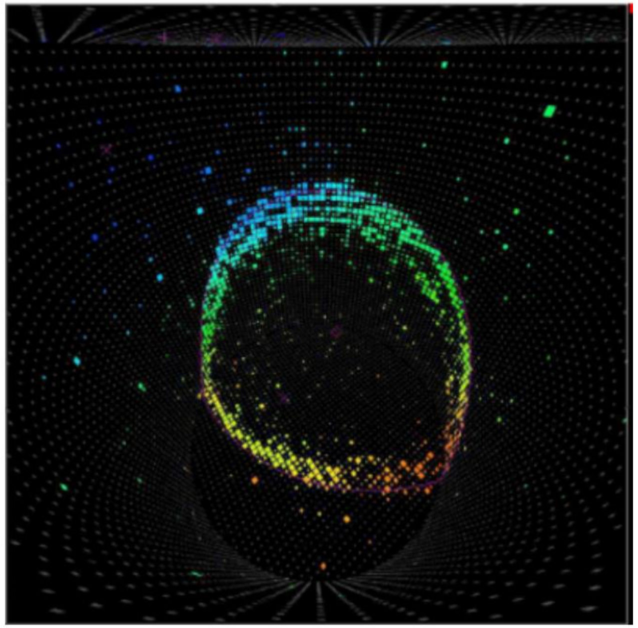
Super Kamiokande



- **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



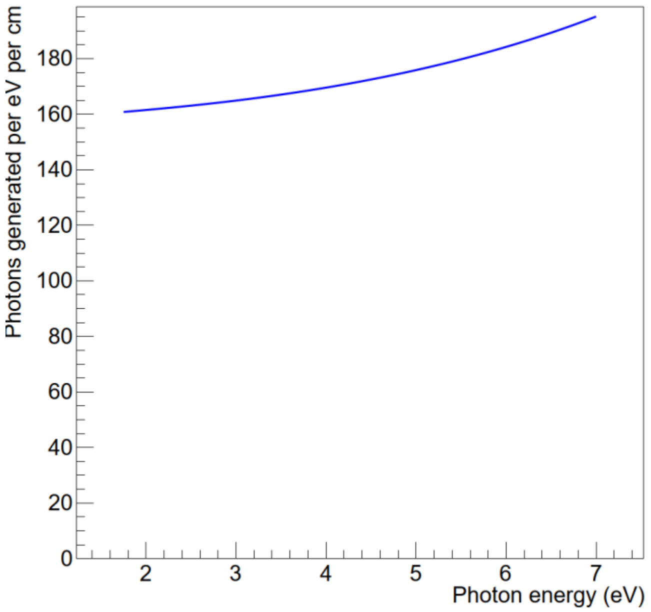


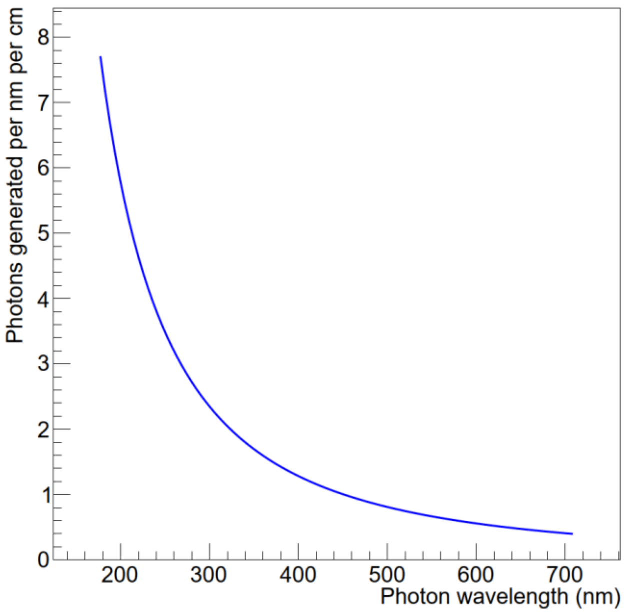
What's up with the blue glow?

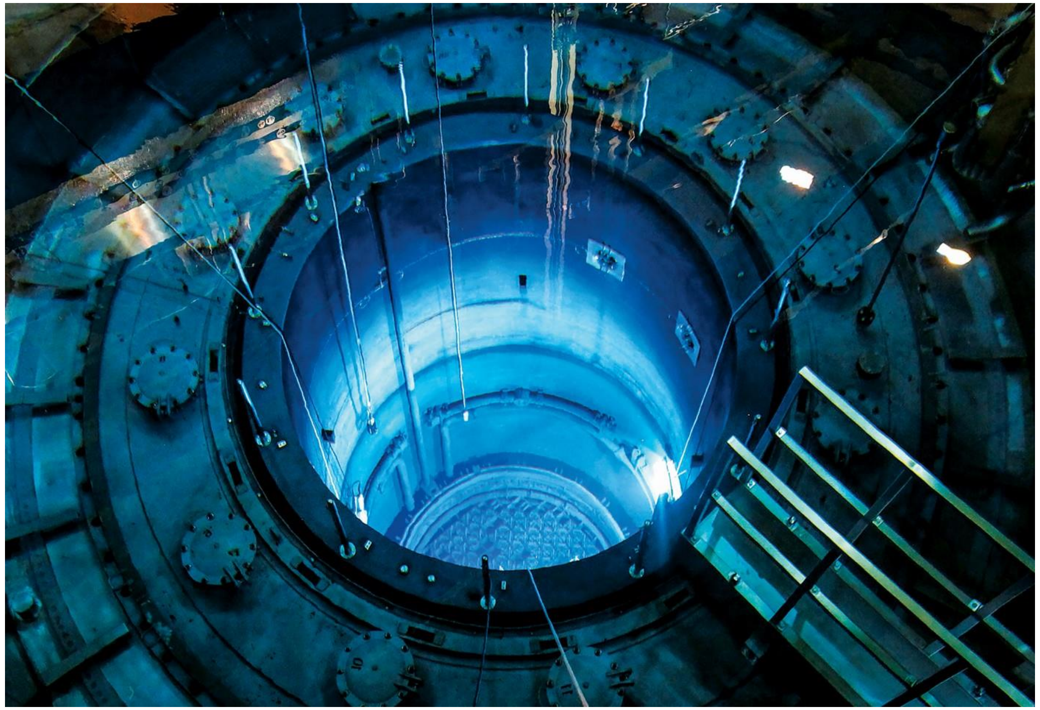
$$\frac{dN}{dE} = 370L\left(1 - \frac{1}{n_p^2\beta^2}\right)$$

- **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?

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!