Cherenkov detectors

HyperKamiokande experiment (Japan)
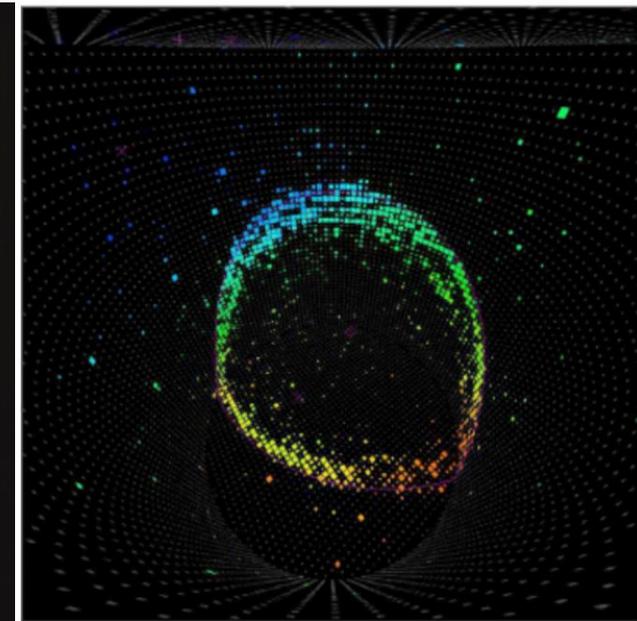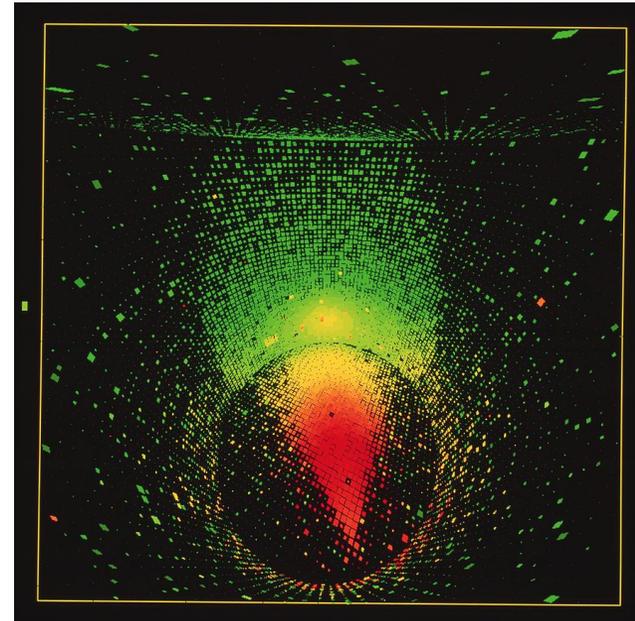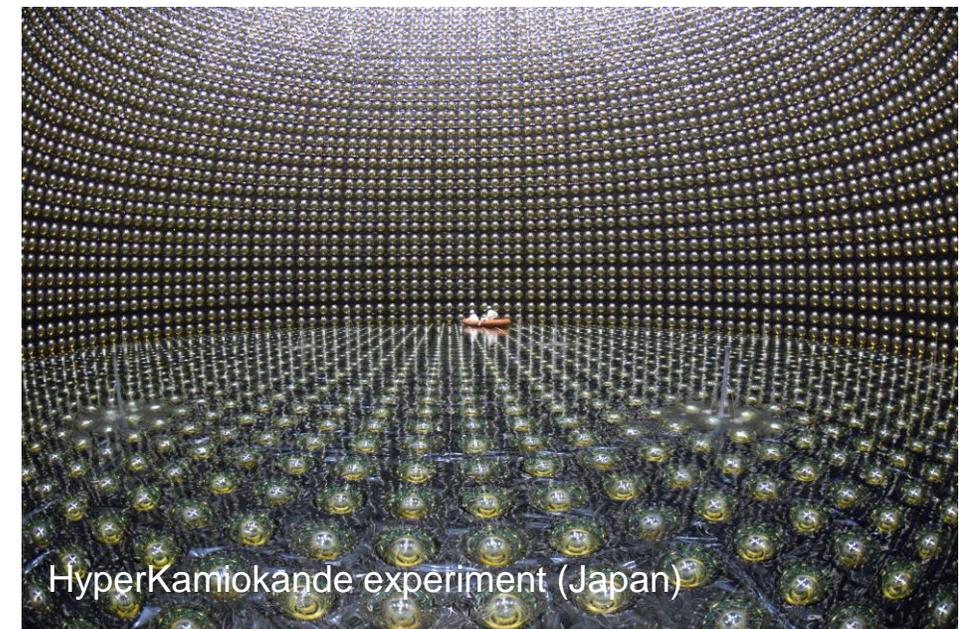
So….what is Cherenkov light?

- **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**
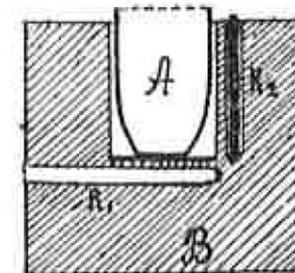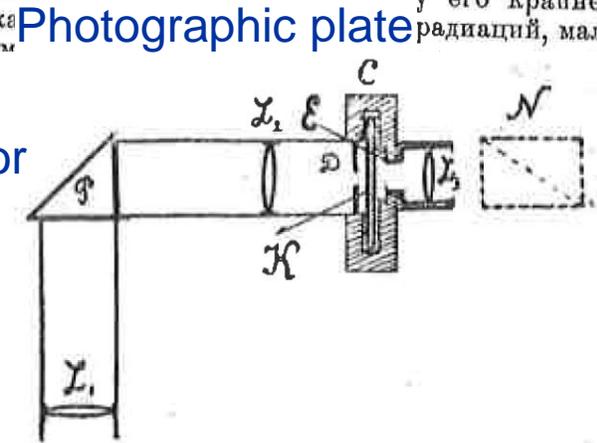 - Vavilov was dead at this point

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 урановых 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 ввиду его крайней слабости и наличия в окружающей радиации, мало пригоден фотографический метод фотометрирования раздражения для глаза установ... на рисунке.

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

Photographic plate

Silvered mirror

Pavel Cherenkov   Ilya Frank   Igor Tamm

Radioactive salt in liquid

Cherenkov light

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

- **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

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

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

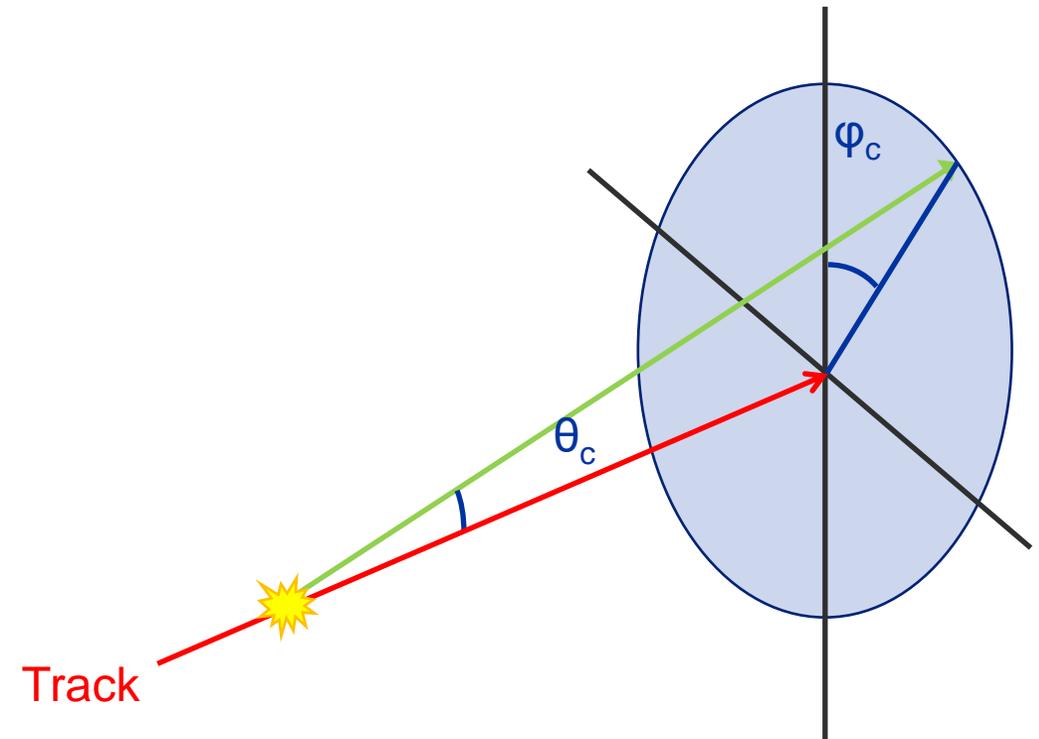$$n_g = n_p + E\frac{dn_p}{dE}$$

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

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

- **So how much light do we get?**

  - The Frank-Tamm relation expresses the number of photons emitted per unit energy (spectrum)

  - Note that it *also* says that there is only light for **charged particles**

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

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

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

IM SO EXCITED
LETS DESIGN SOME CHERENKOV DETECTORS
imgflip.com

Refractive index is the name of the game

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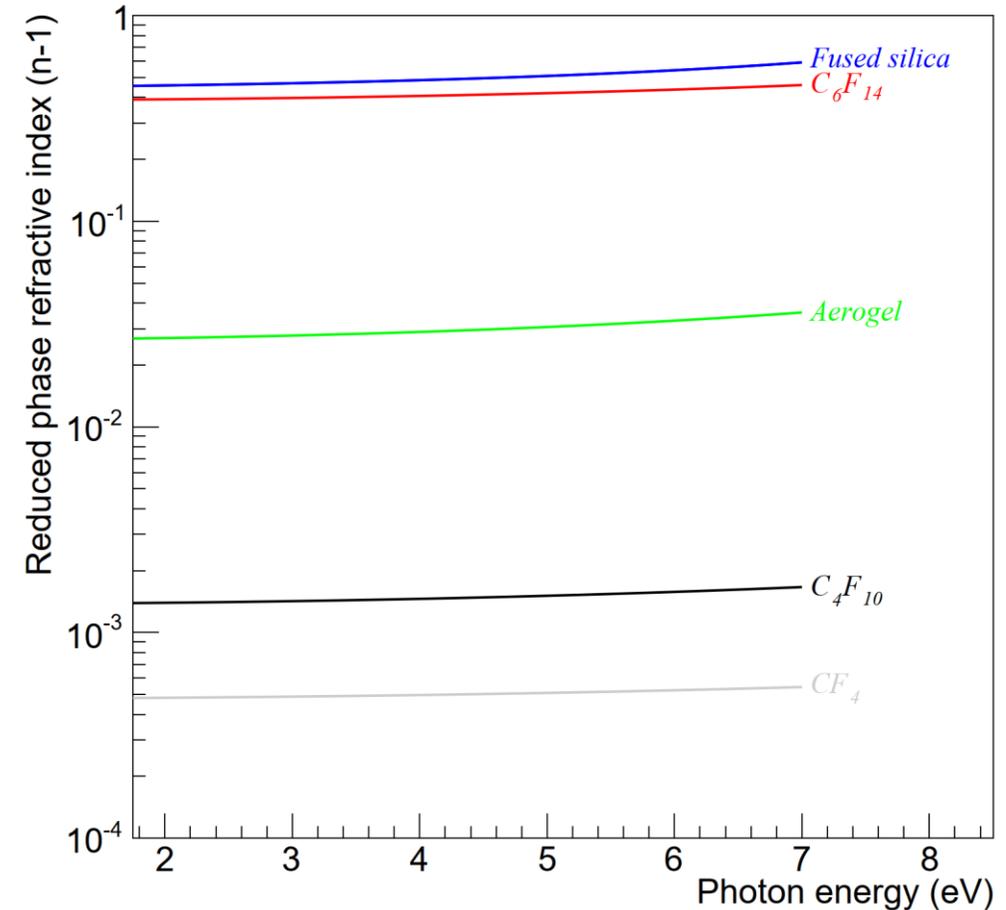
  - It sets the angle of emission

  - 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

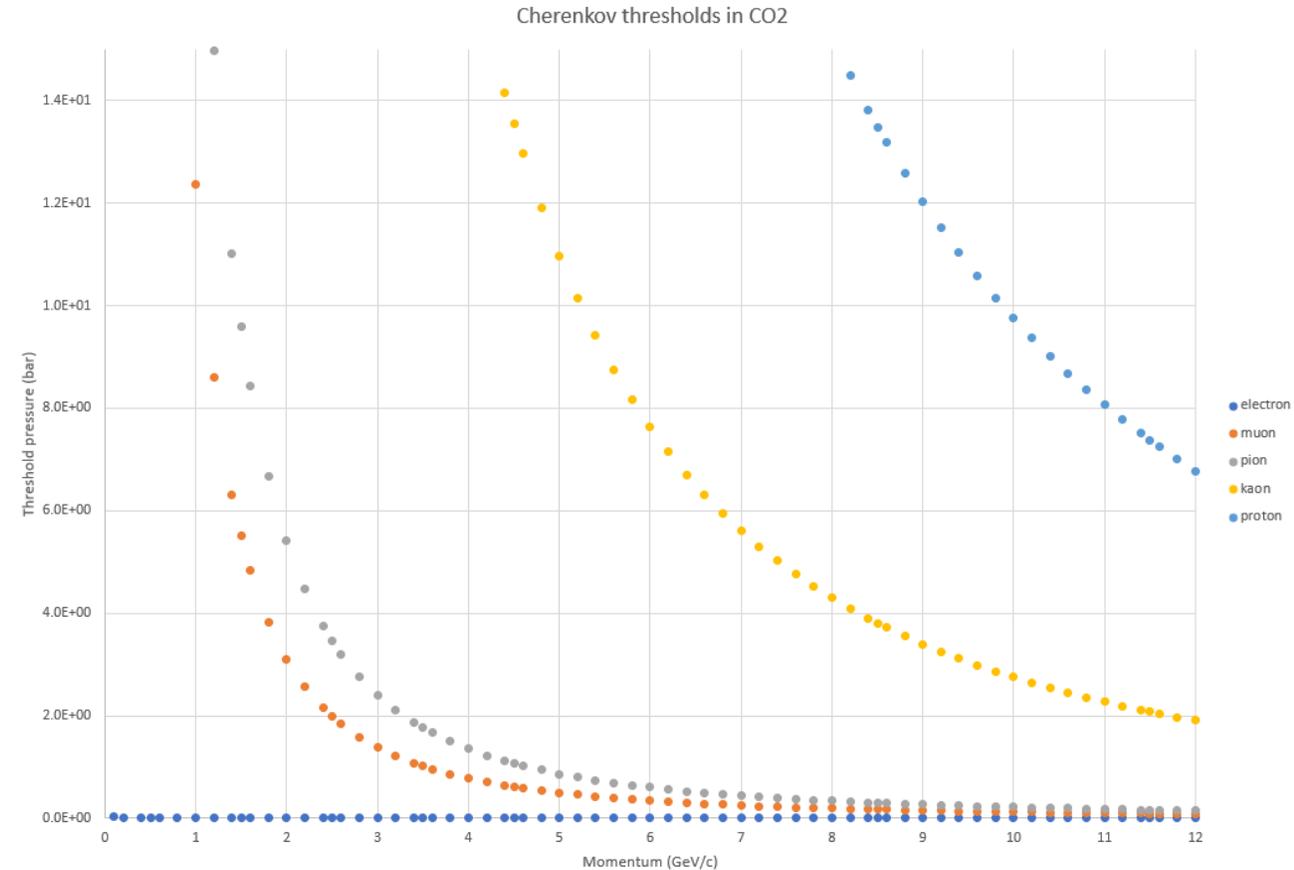- **Light yield scales as** $\left(1 - \dfrac{1}{n^2\beta^2}\right)$

  - Some cm of solid can be equivalent to a few meters of gas

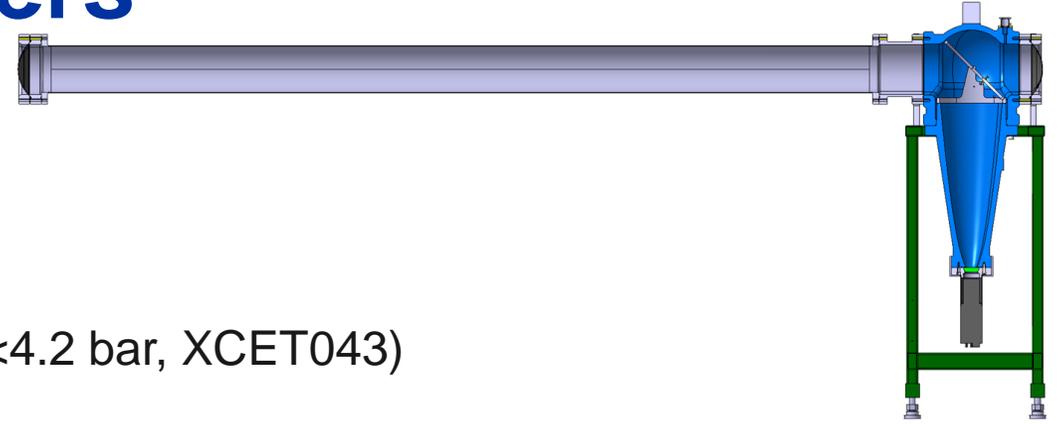 - But the behaviour of the emitted Cherenkov light is quite different

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: $\quad n = 1 + k \cdot P \text{ (bar)}$

    - 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

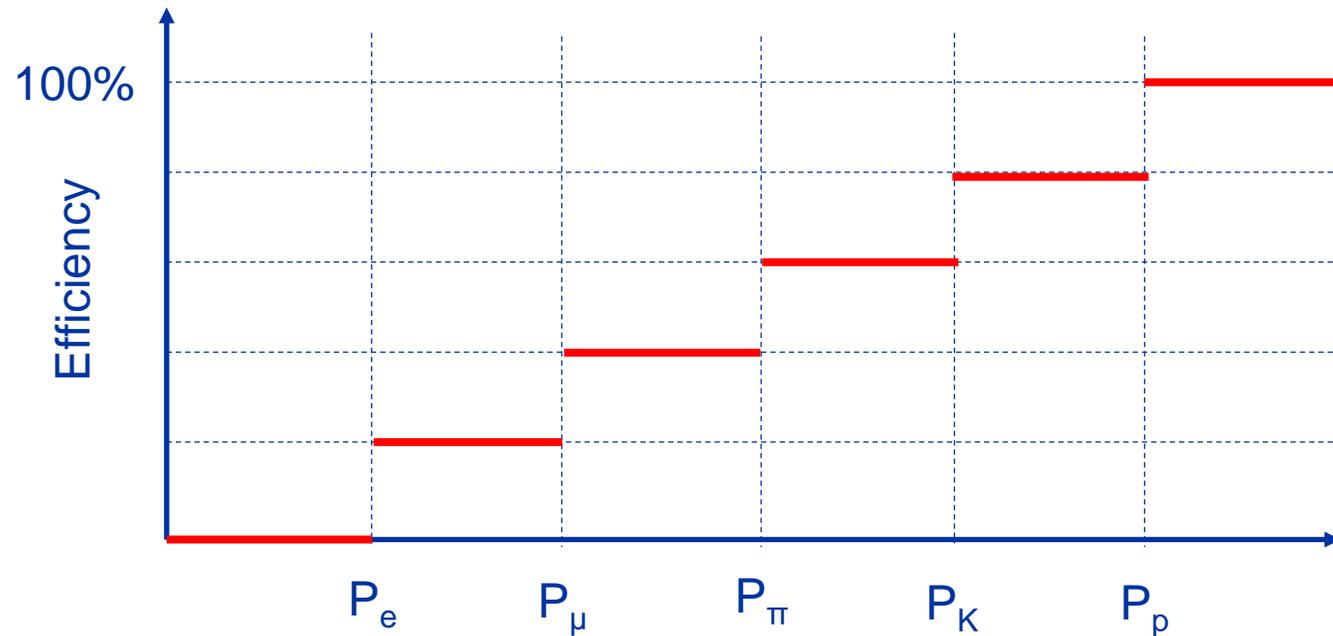Cherenkov thresholds in CO2

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**
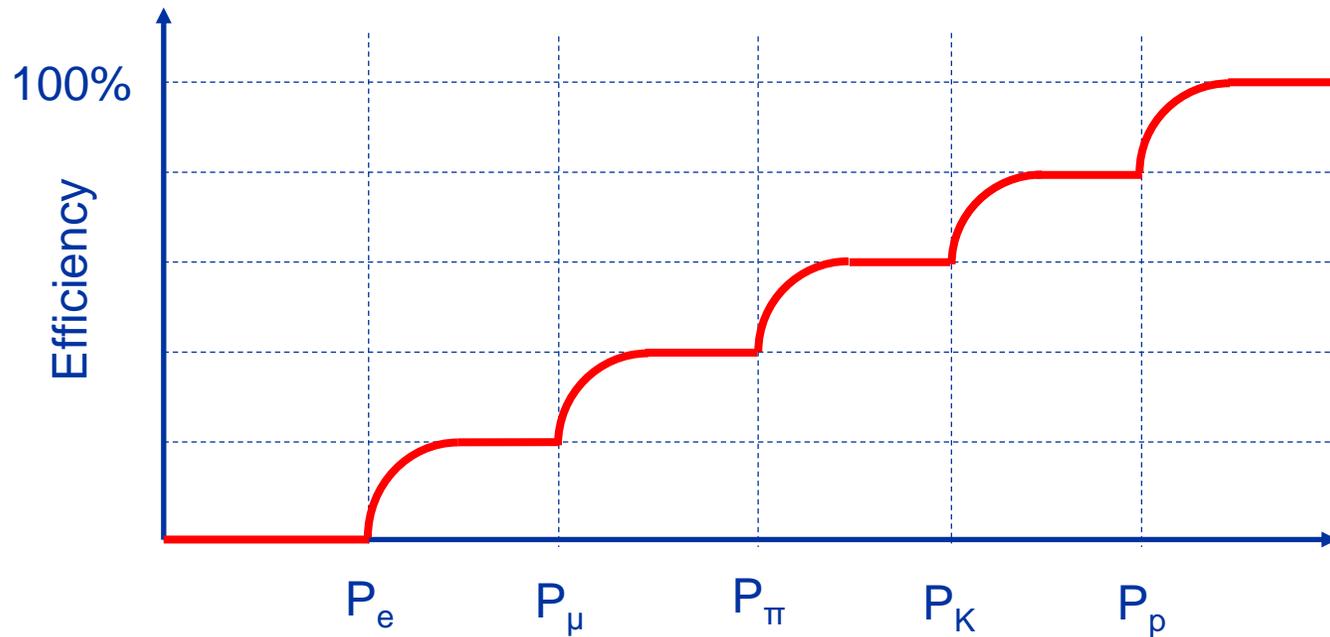
Under pressure

- **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!

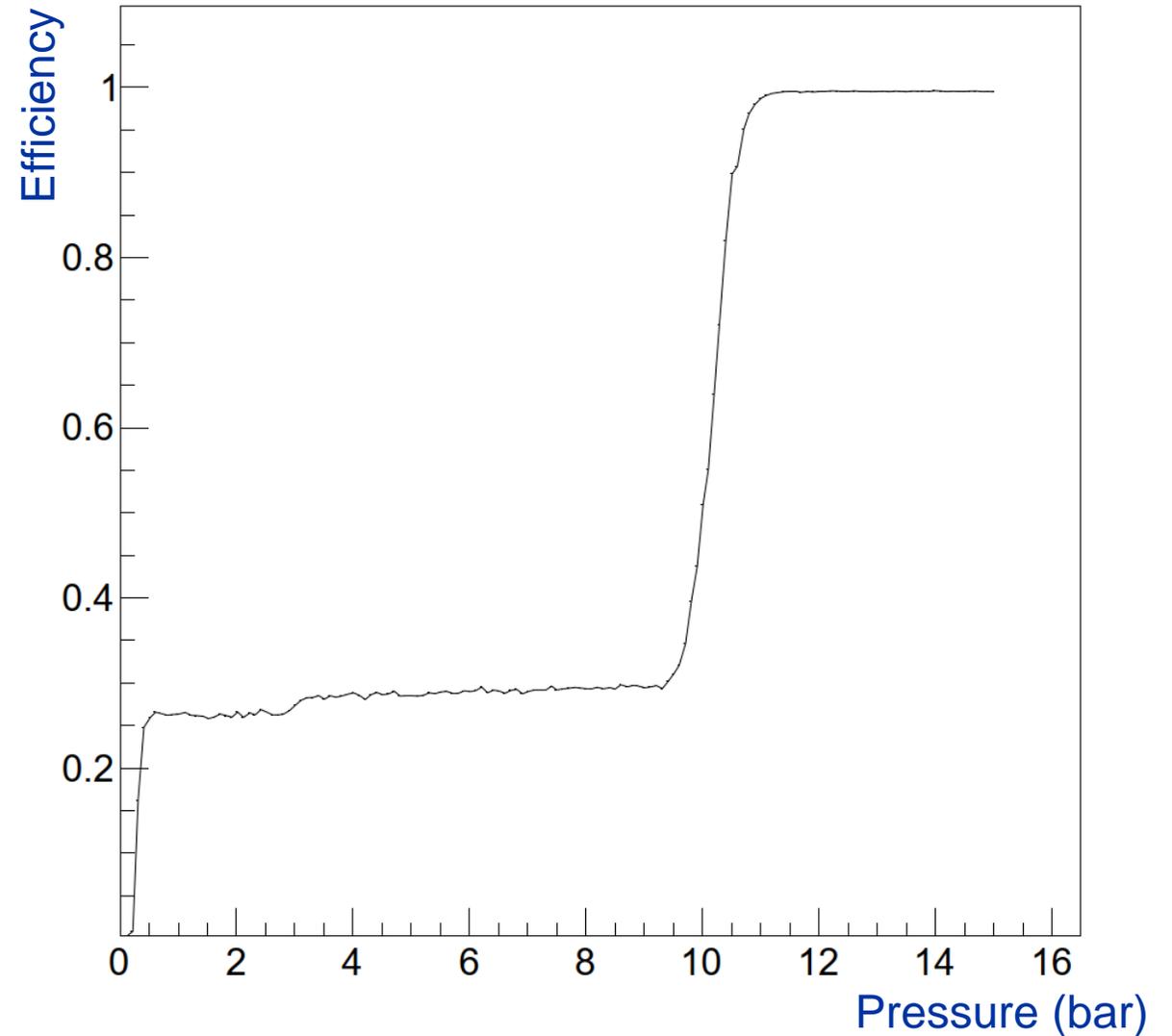   - If thresholds too close together, cannot see difference!

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}

…but why is the step larger sometimes??
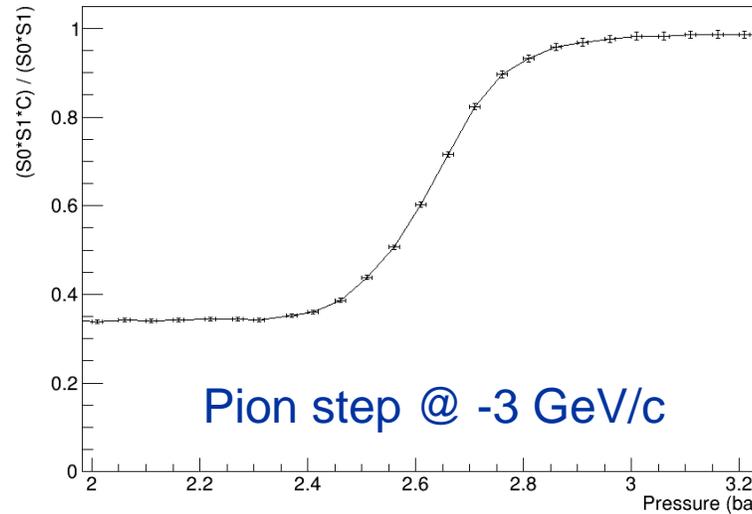
- **Length of pressure needed for turn-on seems variable**

  - We must go deeper!

- **Let's look a bit closer at the refractive index**

  - $n = 1 + k*P$ (bar)

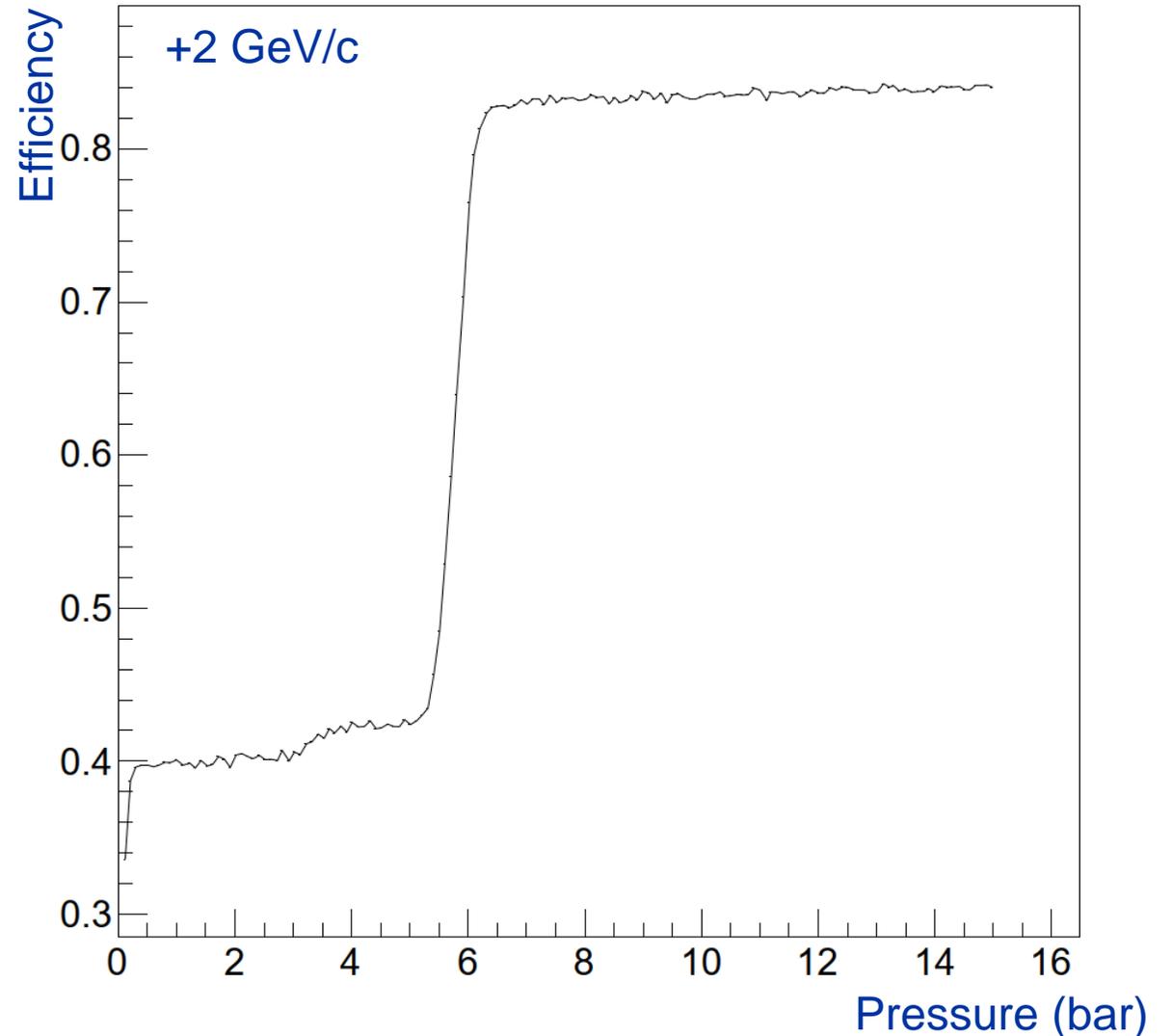   for CO_2, k=4.5e-4

  - Higher refractive index at smaller wavelength: chromatic dispersion

  - Range of n at given pressure sets the width of the step for turn-on

  - This effect scales with pressure

- **Show in bottom right plot number of generated photons as function of pressure**

Pion step @ -3 GeV/c

Proton step @ +8.5 GeV/c

CO2 refractive index at P=1 bar

Light yield @ 11.5 GeV/c

From data to paper

- **Fixed thresholding is by far the simplest**

  - Take two XCETs

  - Pick particle that you want to tag

  - One goes at pressure below the threshold

  - One goes at pressure above the threshold

  - Count signals that appear in the one above the threshold but do NOT appear in the other

- **This was the measurement we did in 2023 with the BL4S students**

  - In addition we took some data with time-of-flight

  - We also took some data with a calorimeter

  - Not going into details here, ask me about it after

Finally deriving the particle content

- **The good stuff**

  - Method of thresholding worked well (we can conclude afterwards)
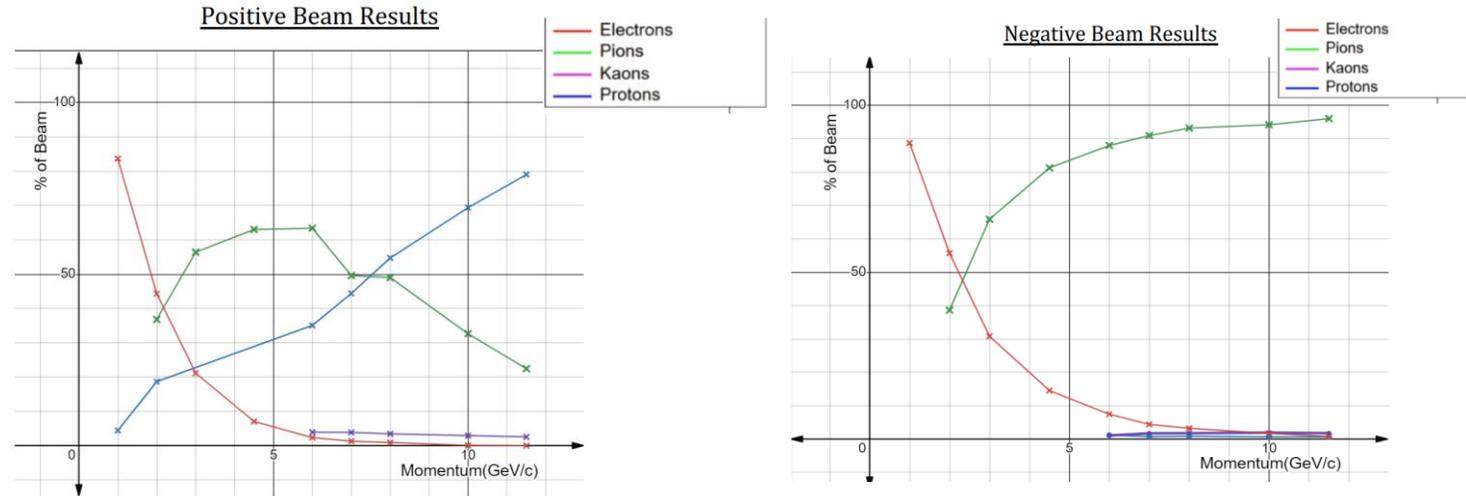
- **The more difficult stuff**

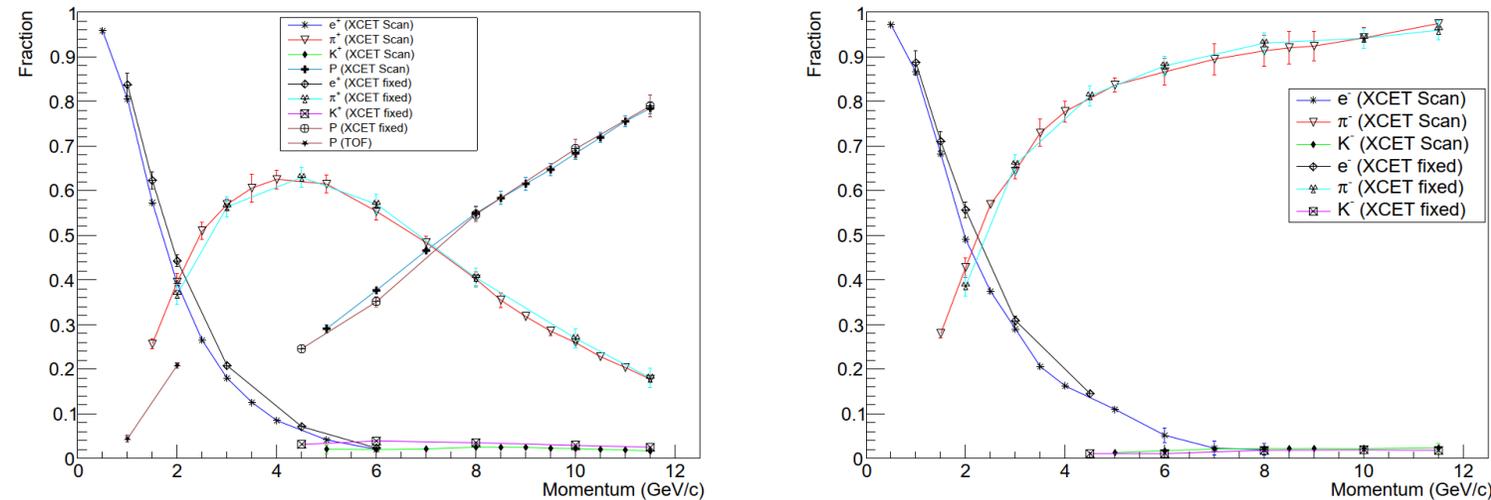 - Thresholding requires two XCETs (which are not fully identical)

- **The hard decision**

  - Decided to retake all possible points with XCET scans and derive differences from plateaus

  - Error analysis much more solid

  - Publication now ongoing

Initial analysis Team Particular Perspective (2023)

Full analysis including XCET scans (2025)
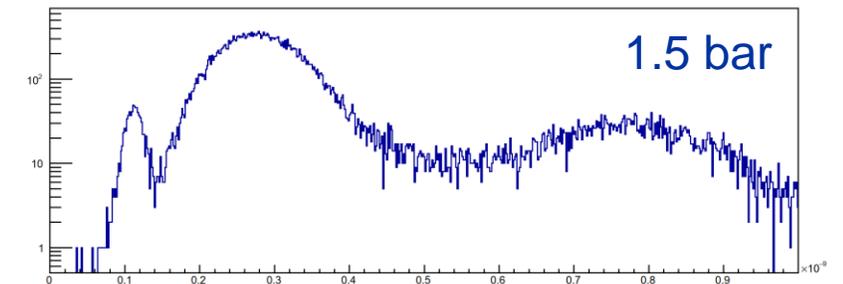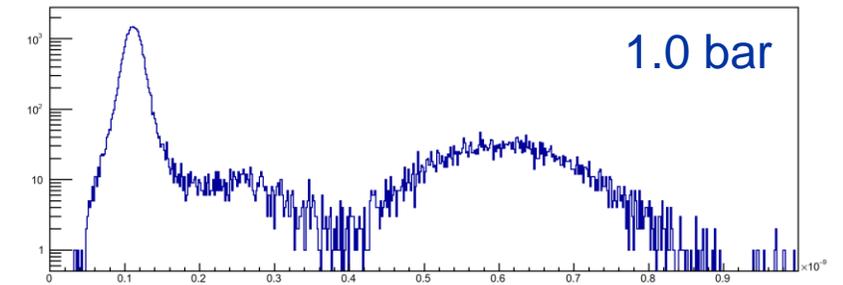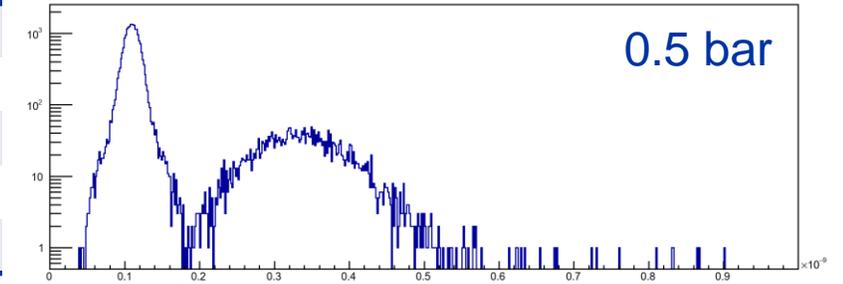
Could we do better?

- **We still don't have all the data for all the particles**

  - TOF analysis indicated a fraction of deuterons in the beam (<0.5%)

  - We don't have any anti-proton data yet!

    - Why not???

- **Anti-protons are particularly challenging because there are so few of them**

  - Not possible to find them with the threshold scans as we performed them

  - The reason is mostly error analysis: the fraction of the beam is very tiny, and the errors (this comes from some doing a bit of math I don't want to do here) go as:

    $$\varepsilon = \frac{1}{\sqrt{N}}$$

  - Typically, each data point we take has around 100.000 particles (this is the number of triggers)

  - We think the anti-proton content is around 0.2%, so this would mean $\varepsilon = 1/\sqrt{100000} \approx 0.3\%$

  - We get a bit better from combining points in the plateau but we can't really beat this

  - Need to take higher statistics! Gather 10-100 spills, sum across them to beat the statistical error

  - The fixed thresholding is probably the best way forward here, homework is, how many spills do we need?

    - Discuss this with your BL4S support scientists! Ask them about DAQ limits

More Cherenkov stuff!

- **There's another method I want to tell you about: working with the signal size**

  - We talked before about the amount of light, and that it scales with the pressure delta to the threshold

  - But this means *also* that for particles that are further away from the threshold, we have a larger signal!

    - *Light particles generate more Cherenkov light at a given pressure than heavy ones!*

  - This means that for the particles where we cannot separate them by scan or threshold we can look at the signal size! Change pressure and record signal amplitudes (at same momentum)

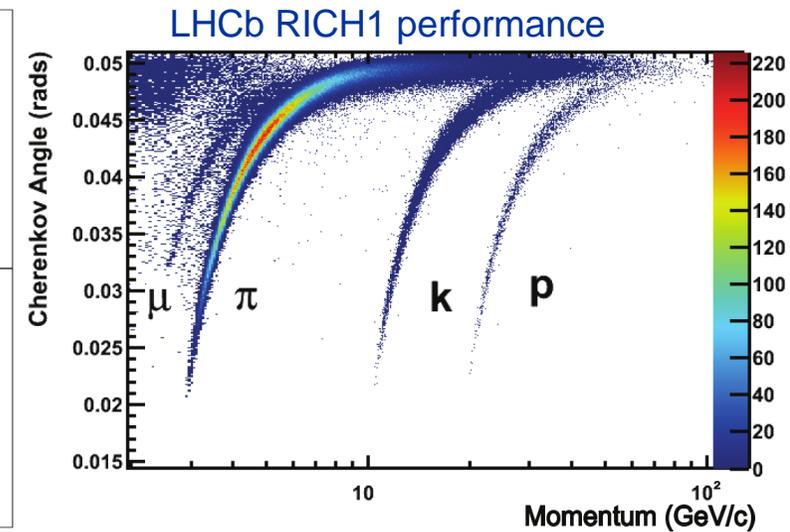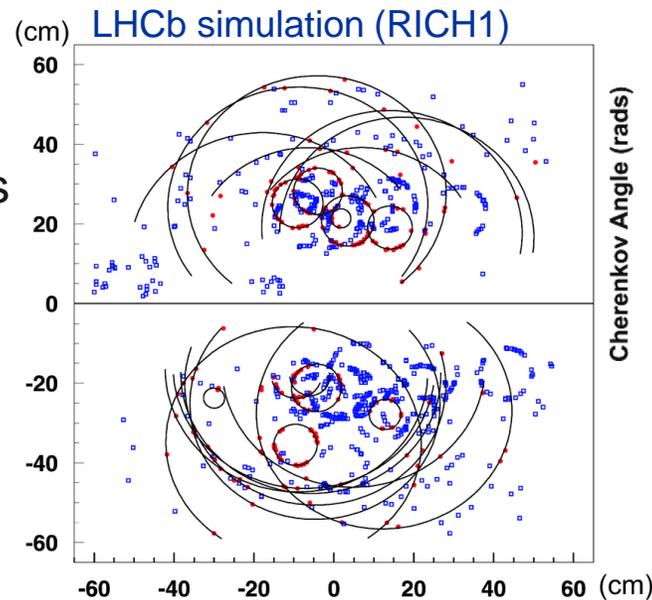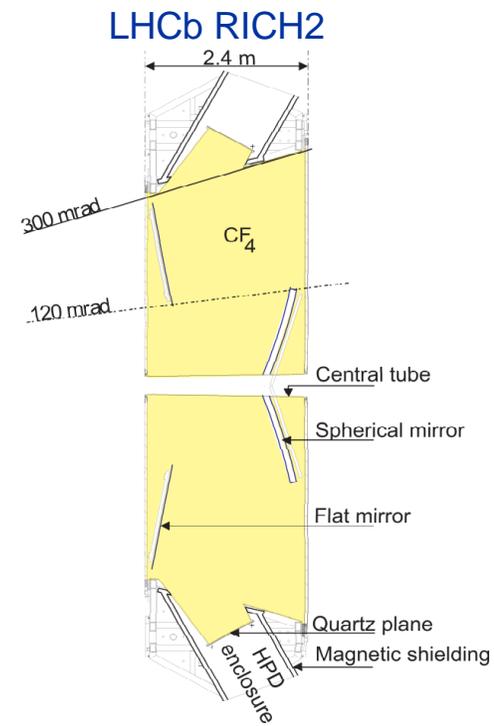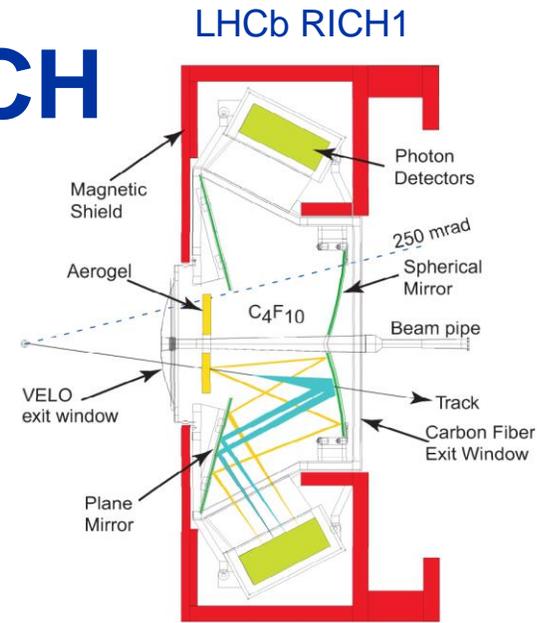| Particle	Thr. (bar) in CO_2
Electron	0.000014
Muon	0.61
Pion	1.07
Kaon	13.6
Proton	47.8

The finish line

- **Cherenkov light is generated in gas when particles go faster than local speed of light**

  - Can define simple threshold where light turns on, dependent on particle mass

  - Number of photons (amount of light) linear with distance over threshold

  - But wavelength dependence of refractive index (dispersion) gives a variation in light turning on

- **Multiple methods illustrated to use XCET detectors in particular**

  - Fixed thresholding, pressure scan and signal amplitude analysis

- **Cherenkov light is an excellent tool for particle identification**

  - From a few simple formulas still quite complex behaviour

  - Operating the detector and explaining all the features challenging but rewarding

- **T10 particle identification paper available on arXiv and attached to Indico**
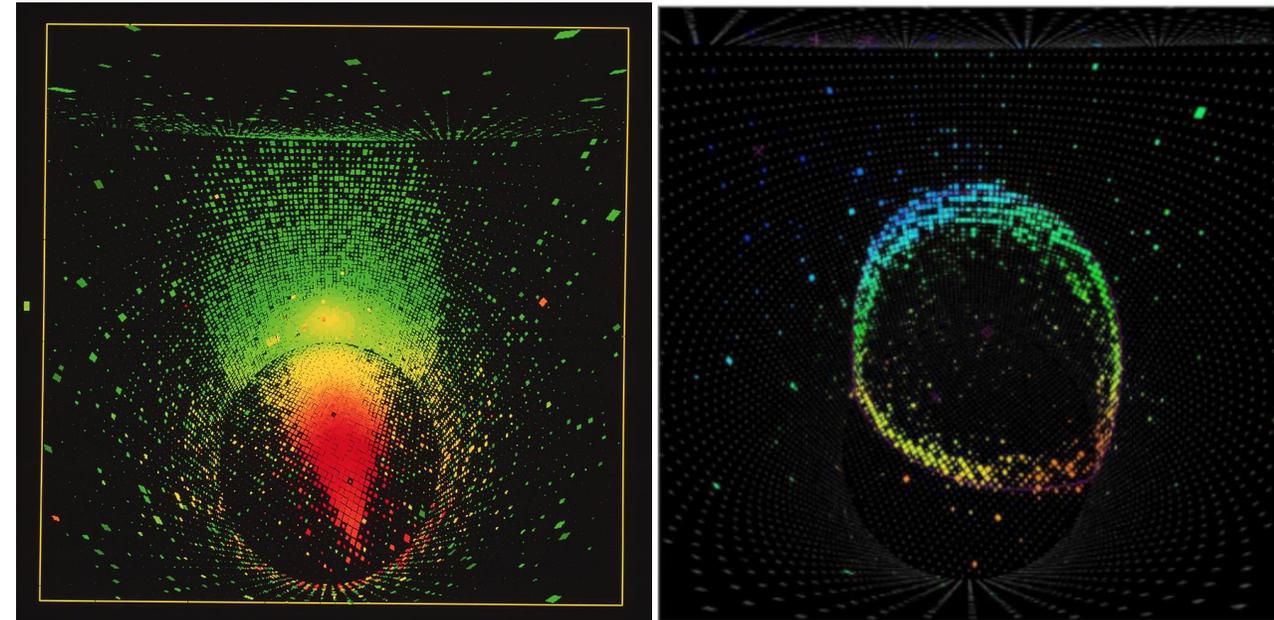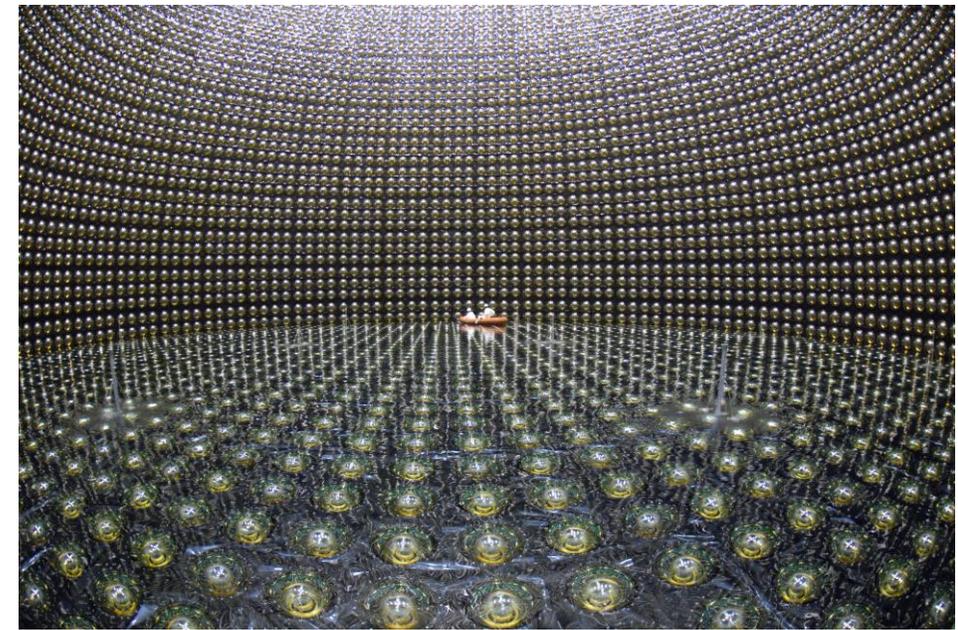
home.cern

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

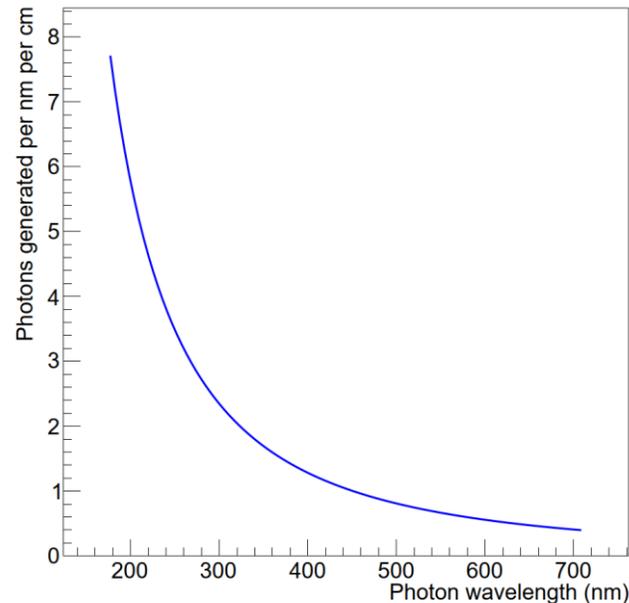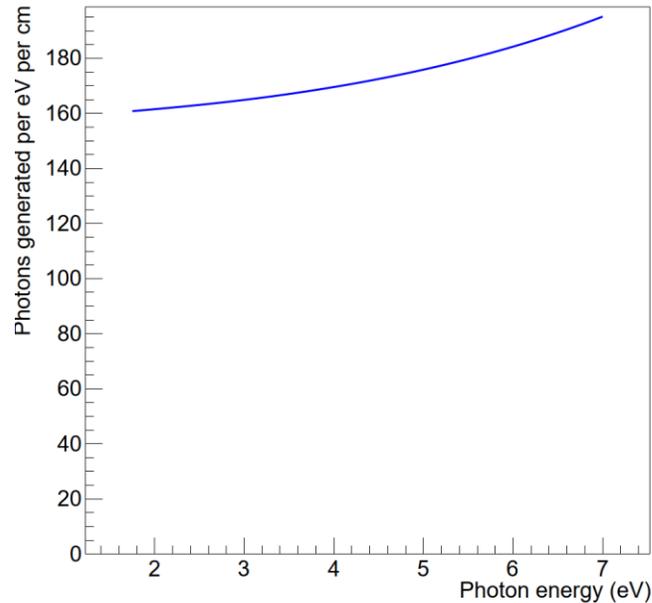 - Different shapes and sizes give more information about event

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?