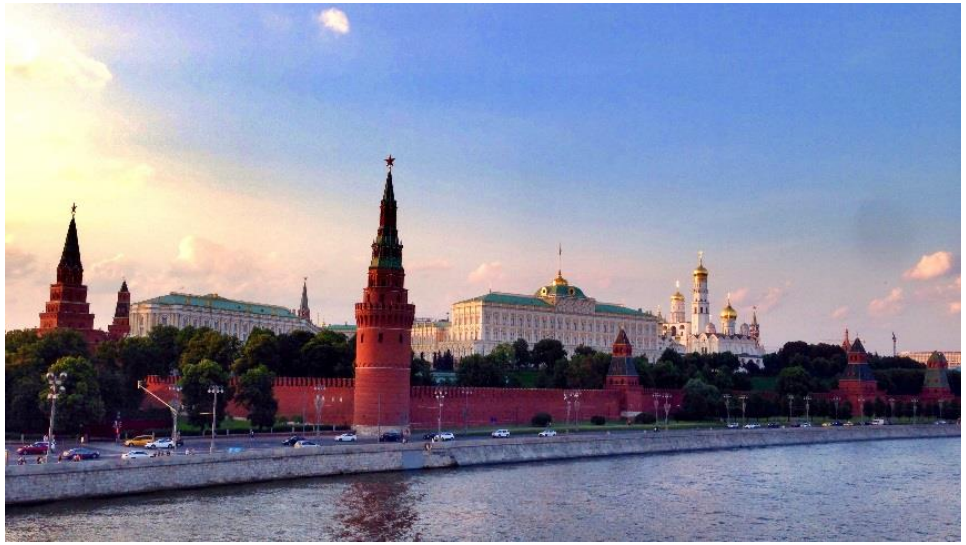
Photonic crystals as novel radiators

RICH 2018 conference
Moscow, Russia



On behalf of: S.Easo, X.Lin, I.Kaminer, M.Blago et.al.

Sajan Easo

04-08-2018

Outline

- Limitations of conventional radiators
- Photon production and propagation from photonic crystals
- Example configurations for particle identification
- Issues for design and optimization
- Testing with prototypes

Some limitations of conventional radiators

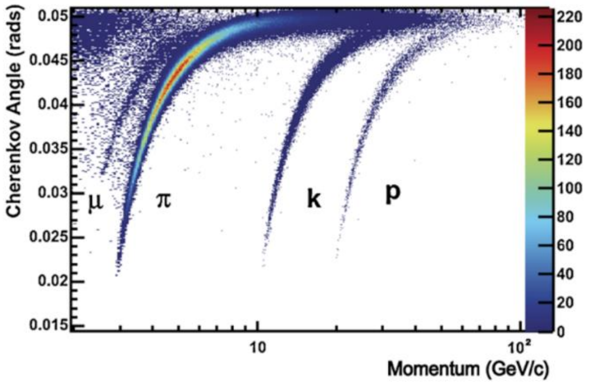
- For identification of particles with momenta in GeV/c range:
  - Dearth of materials to cover the full momentum range 1-10 GeV/c

    limited set includes Quartz (n~1.47) , aerogel (n~1.03)
  - Above 10 GeV/c, long gas radiators are used (n ~ 1.0013 or lower); thin radiators are desirable
  - Electron-pion discrimination difficult for momenta above a few GeV/c

- Dielectric materials with n > ~ 1.8 not suitable:
  - Saturated Cherenkov angles for most of the momentum range
  - Photon trapped inside due to total internal reflection at the boundary with ambient air/gas

    Exception: DIRC like configuration for limited momentum region

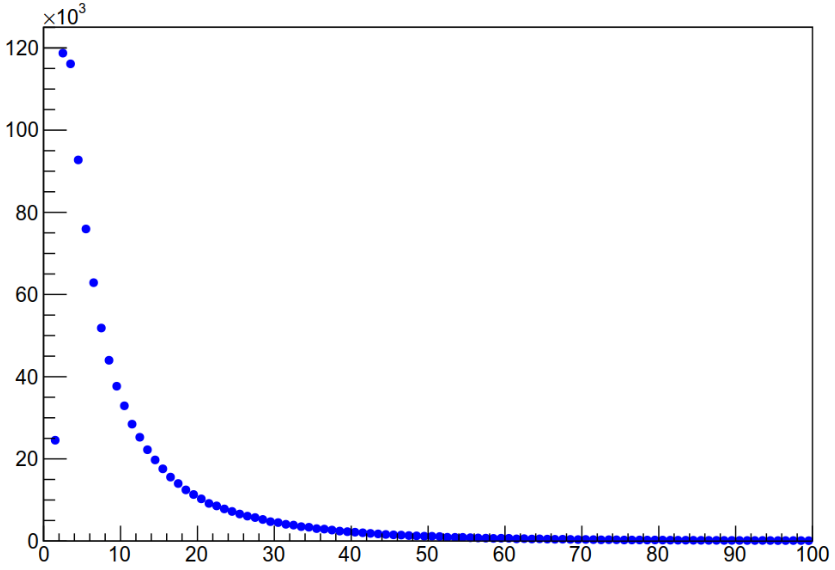
Radiator limitation in LHCb



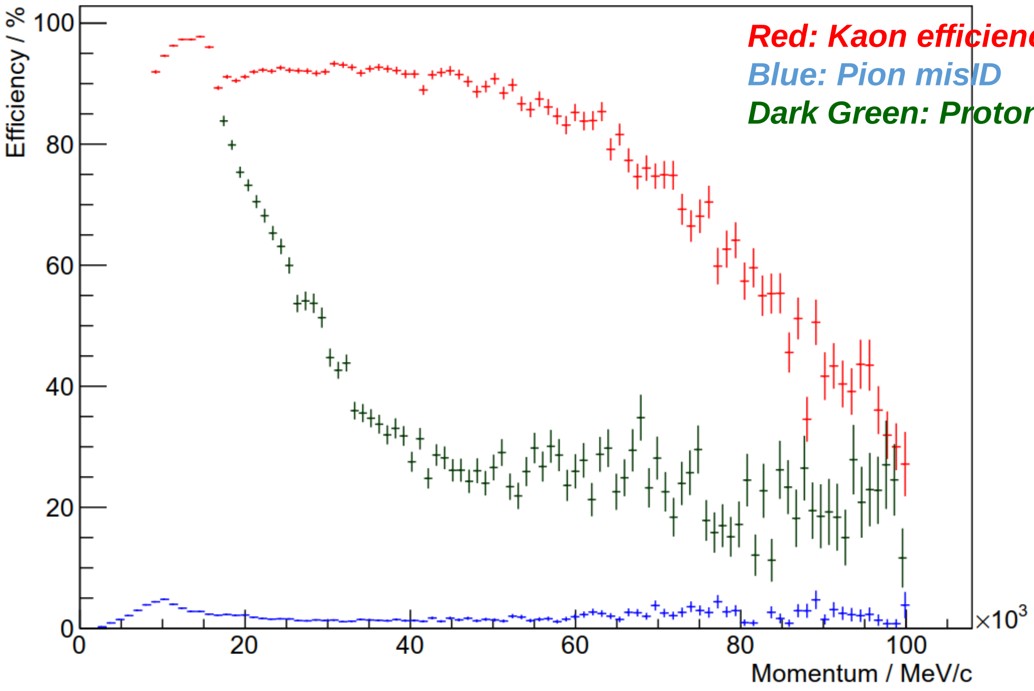
Real data
C_4F_{10}

- Large number of particles in low momentum range

Particle momentum



Example of PID performance

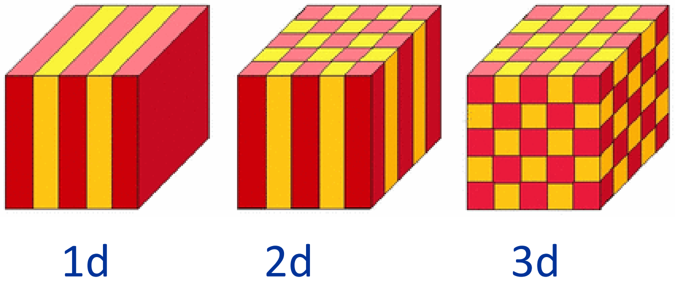


Thresholds in C_4F_{10}
Kaon : 9.3 GeV/c Proton : 17.8 GeV/c

- *For now, using 'veto mode' for PID in low momentum*
- *Aerogel was used in RUN1 , but was removed in 2015*
- *Illustration using LHCb upgrade configuration*

Radiator R&D

- One approach:
  - Assemble materials to produce the desired 'effective refractive index'
  - Requires designing photonic crystals from transparent dielectrics

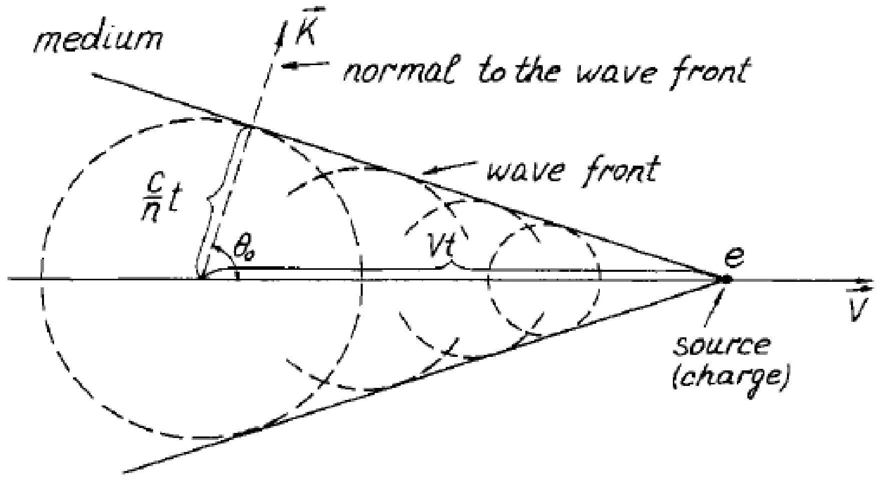


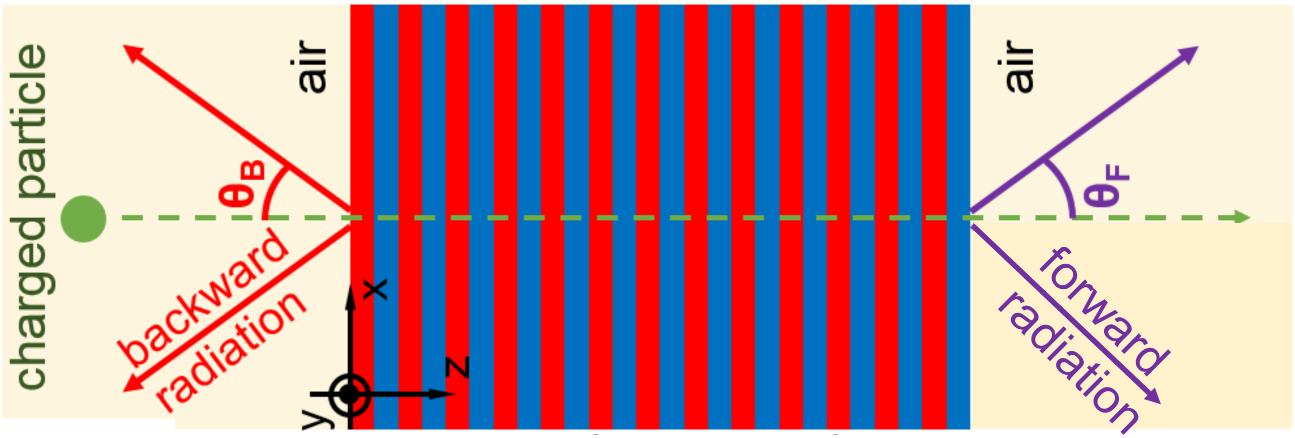
- Photonic Crystals :
  - Typically made from two materials with different refractive indices, in alternating layers.
  - The magnitude of layer thickness is similar to that of the photon wavelengths.
  - Production of layers as thin as optical wavelengths, feasible in recent years. This creates the current interest in using the crystals, as radiators
- This presentation:
  - Concept and prospects for this approach

Photon Production

Conventional Cherenkov Radiation:

- *Frank and Tamm theory*

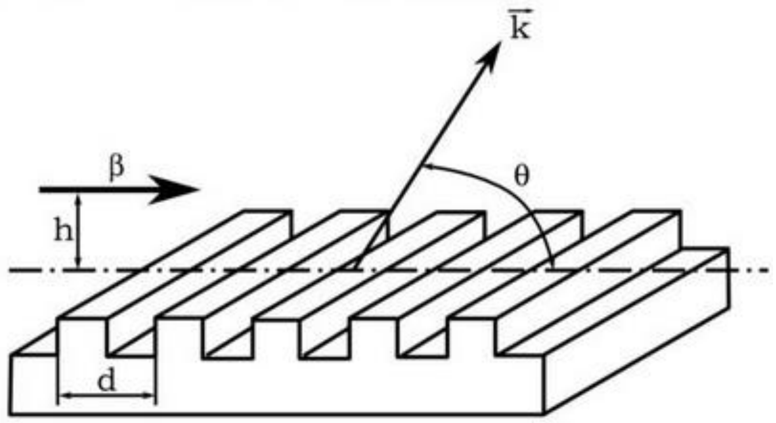




1d photonic crystal

Smith-Purcell Radiation :

- *Particle travels near a diffraction grating*



Resonance Transition Radiation :

- *Has the features of conventional Cherenkov radiation*

Photon production from photonic crystal

- Photon production and propagation in a periodic structure can be determined from solving Maxwell's equations. This extends the *Ginzburg and Frank* theory on transition radiation.

- This results in a linear equation:

$$\left[\nabla\times\nabla\times - \left(\frac{\omega}{c}\right)^2 \varepsilon(\vec{r})\right]\vec{E}(\vec{r}) = i\omega\mu_0\vec{J}(\vec{r})$$

$\vec{E}, \vec{H}$: electric and magnetic fields

ε, μ = permittivity, permeability , $\vec{J}$=current density

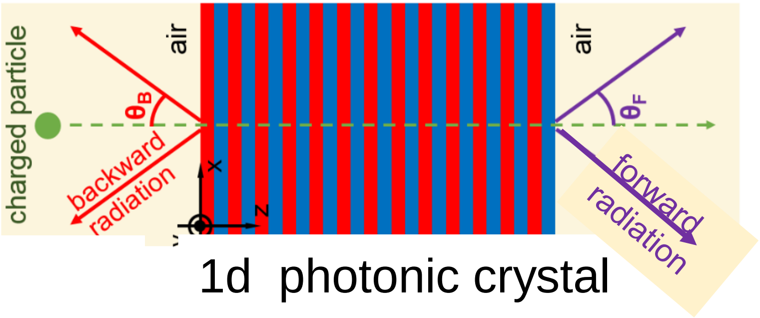
z, ρ : directions along and normal to that of the particle

ω,k : frequency, wave vector

To be solved using boundary conditions.

- Solution: Particle generates Bloch modes of the crystal which have the form: $\vec{E}(\vec{r})\exp\left(i(\vec{k}.\vec{r} - \omega t)\right)$

- For a particle traversing a 1d photonic crystal along z :



1d photonic crystal

Components of the wave vector for the modes which transmit into air : $k_z = \frac{\omega}{c}\frac{1}{\beta}$, $k_\rho = \frac{\omega}{c}\sin(\theta)$

Here θ *= effective Cherenkov angle at exit from crystal into air*

- Periodicity leads to coherent interference of electromagnetic waves in the air, from the various interfaces

  Constructive interference : Resonance Transition Radiation

Resonance Transition Radiation

- From the solution, the energy radiated into air can be determined
  - Involves integrating over angular spectral energy density, which is the distribution of radiation as a function of (ω, θ).
  - In this context, Poynting vector: $\vec{S} = \frac{1}{2}\mathrm{Re}\left[\vec{E}\times\vec{H}^*\right]$

- Typically use $\varepsilon_{r1}, \varepsilon_{r2} >> 1$. Hence conventional Cherenkov radiation gets trapped inside due to total internal reflection :

$$k_\rho = \frac{\omega}{c}\sqrt{\varepsilon_r - \beta^{-2}} > \frac{\omega}{c}$$

- Solutions for the 1d system are described in a recent paper:

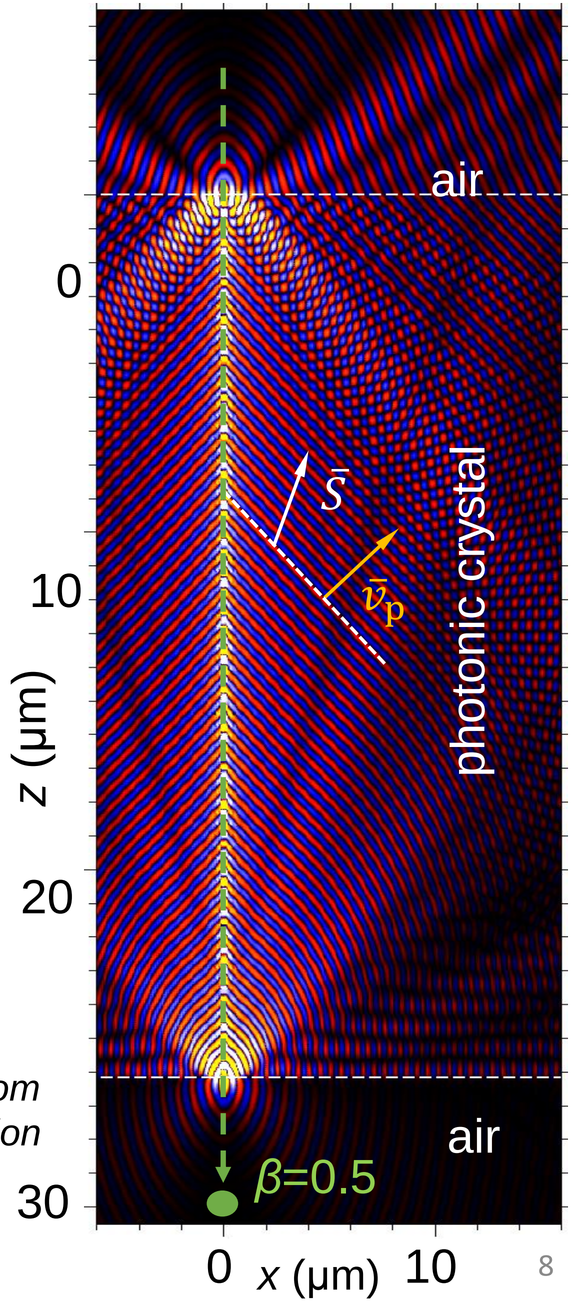
"Controlling Cherenkov angles with resonance transition radiation",

X.Lin, S.Easo, Y.Shen, H.Chen, B.Zhang,J.D.Joannopoulos,M.Soljacic,I.Kaminer ,

Nature Physics 14, 816-821 (2018)

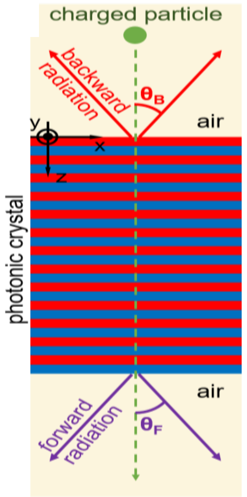
also https://doi.org/10.1038/S41567-018-0138-4

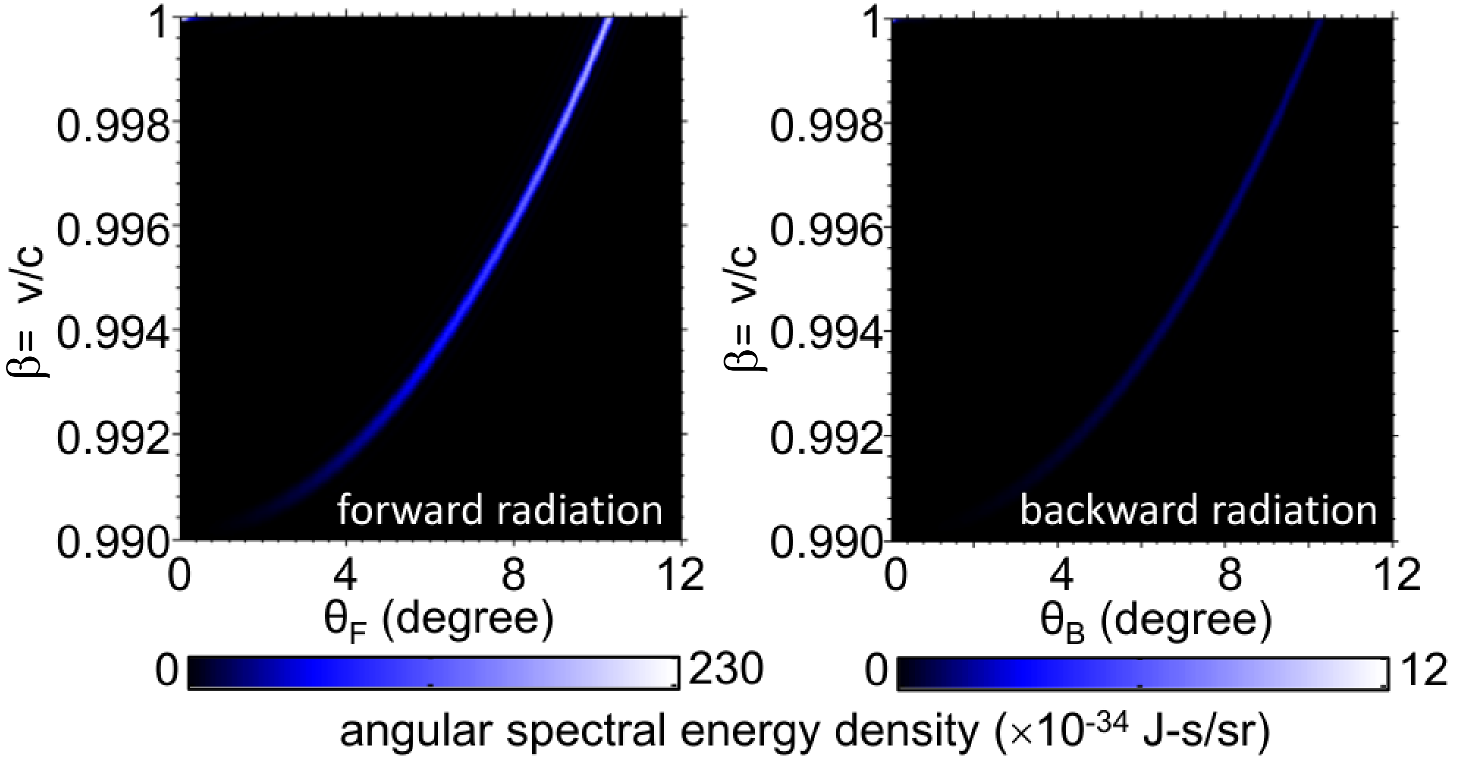
- Some inferences from this paper, in the following pages



Example of radiation field from Resonance transition radiation

Forward configuration : example





- *Constructive interference in the forward radiation: strong signal*
- *Destructive interference in the backward radiation: weak signal*

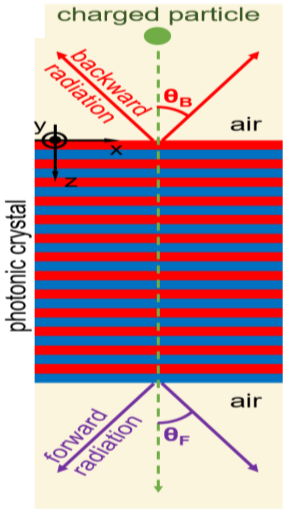
Forward: θ_F increases with β=v/c

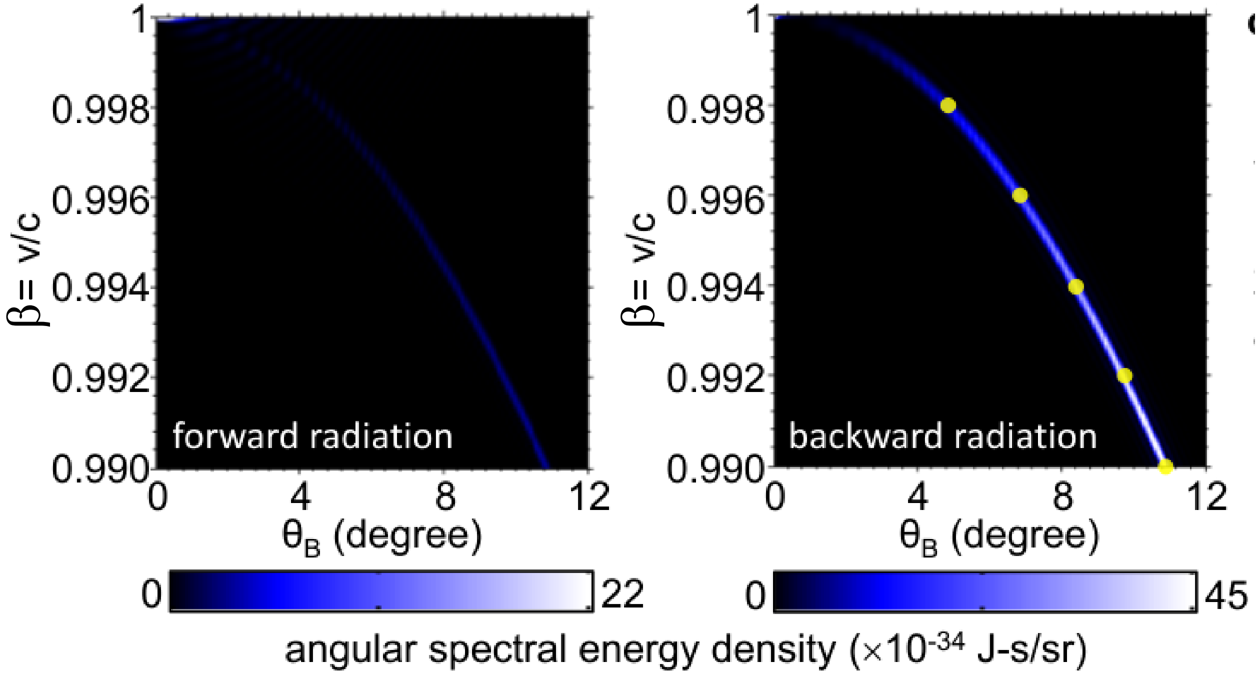
Example configuration 1:

Overall thickness = 2 mm, ε_1 = 10.6 (GaP), ε_2=2.1 (SiO2)

Forward setup: 2800 periods with (214.3 nm+ 500nm)

Backward configuration: example





- *Destructive interference in the forward radiation: weak signal*
- *Constructive interference in the backward radiation: strong signal*

Backward: $\theta_B = 180^0 - \theta_F$, θ_B decreases with β=v/c

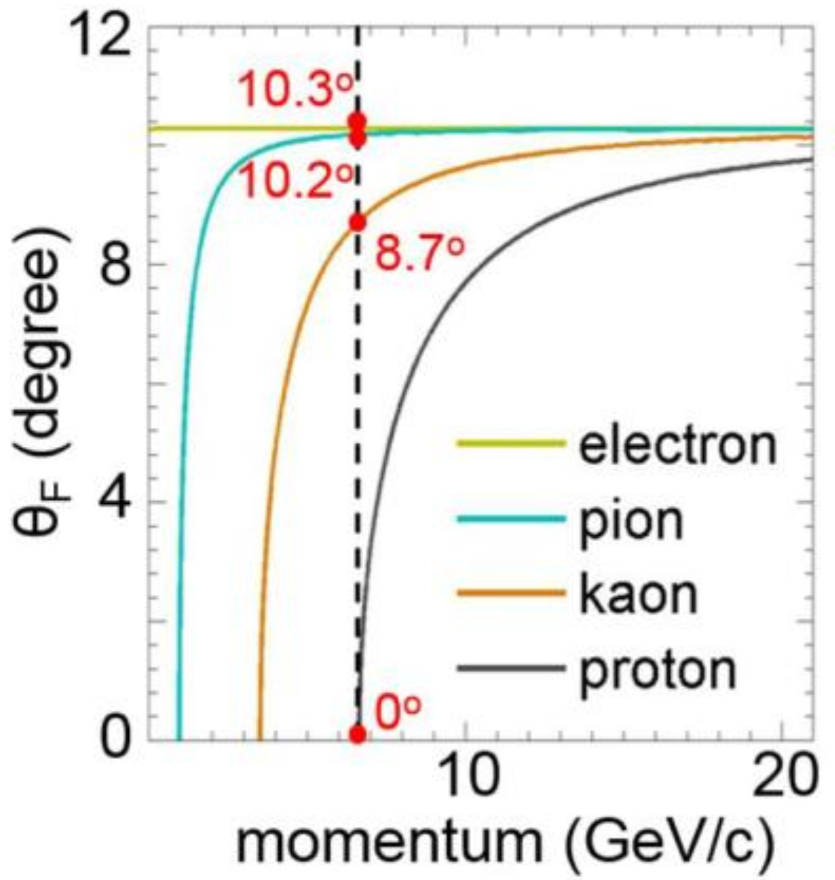
Example configuration 2:

Overall thickness = 2 mm, ε_1 = 10.6 (GaP), ε_2=2.1 (SiO2)

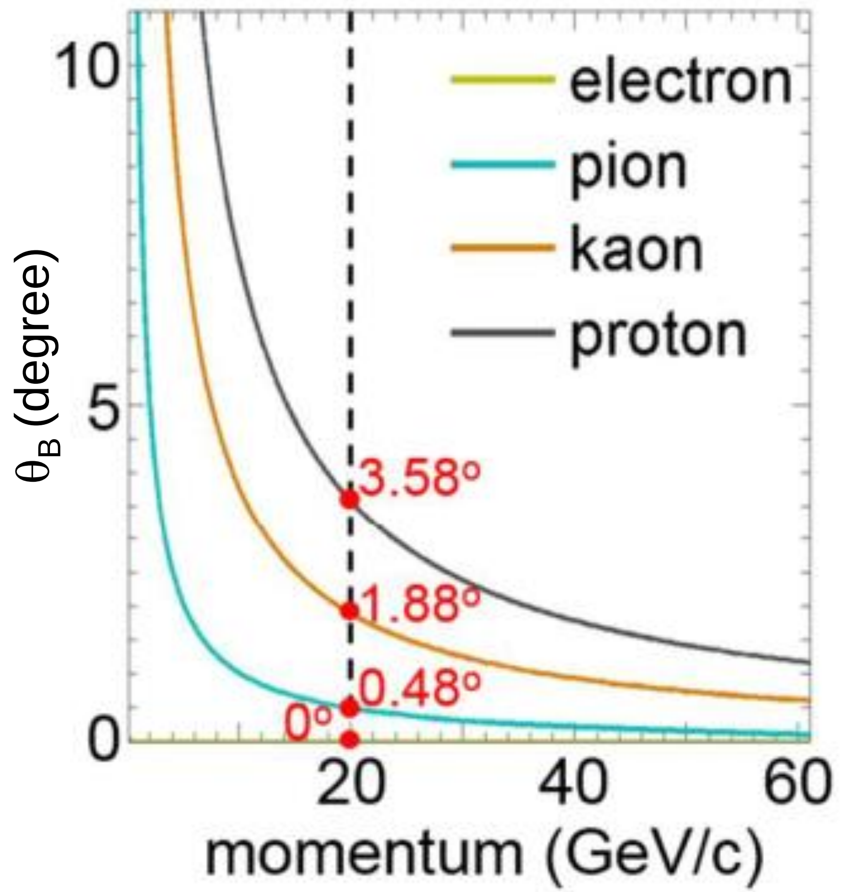
Backward setup: 10200 periods with (117.3 nm+ 78.1nm)

Results from different particle types

Forward configuration example



Backward configuration example



- The features are similar to those of conventional Cherenkov radiation
- Can be configured for different momentum ranges

Another option

- Existence of negative index of refraction, first proposed by Victor Veselago in 1968.
  - Experimentally verified in 1999-2000, and gave rise to the creation of meta materials

- Meta materials:
  - Layer thickness smaller than the wavelengths considered
  - Particles 'see' an 'effective medium' instead of the atoms
  - Normally made from resonant structure of metallic wires or nanomaterials
  - They can also have positive refractive index.

- Proposal to use meta materials as radiators for Cherenkov detectors :

  "Controlling Cherenkov radiation with transformation-optical metamaterials"

  Ginis V. , Danckaet J, Veretennicoff I., Tassin P. Phys. Rev. Lett. 113, 167402 (2014).

- The meta materials suggested for this are made from highly anisotropic materials.

  Effective refractive index near 1.0 along one axis and large values along other axes.

more info :
Backup pages,
paper listed on page 8

- This leads to "photon loss" at optical frequencies and thus the Cherenkov signal is significantly reduced. Hence, for now, the option to use meta materials is not pursued.

- On the other hand, photonic crystals are made from 'almost' transparent dielectric materials and hence the photon loss is minimal. So this option is pursued.

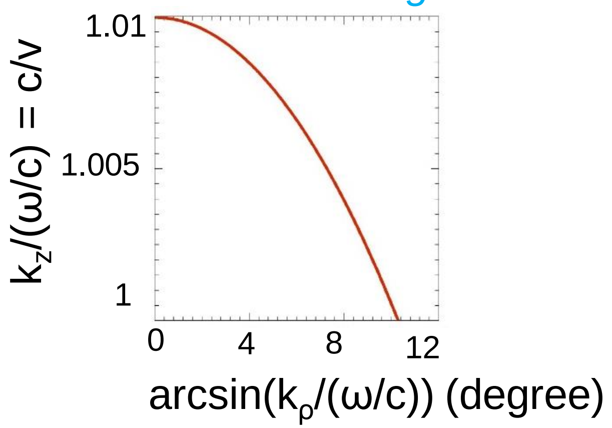
Designing photonic crystals

- Normally a crystal may be designed for a specific momentum range of particles

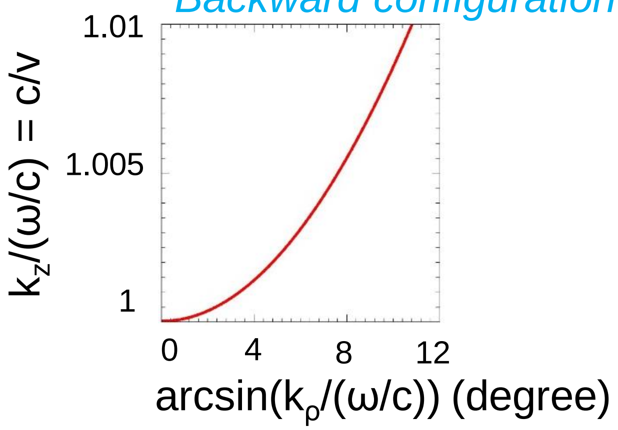
  It is envisaged to be used in forward or backward configuration, in a given momentum range

  In principle, a crystal can even be designed for forward/backward in different momentum ranges

Forward configuration



Backward configuration



- For any design:
  - Find materials with the appropriate refractive indices
  - Optimize the layer thickness, number of layers etc.
  - Optimize for optical/near-UV frequencies where the photon detectors are sensitive

- In general, numerical solutions needed using software frameworks:
  - *FDTD (Finite Difference Time Domain)*
  - *COMSOL*

- Proprietary software:
  - *Analytical solution for 1d system*
  - *Allows simulation and design of 1d photonic crystals*

Theory to Practice

- Production:
  - Crystals need to be designed and produced
  - This requires R&D

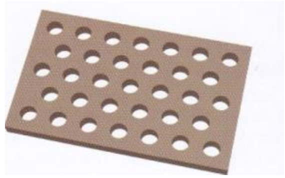
Phys. Rev. E 72, 010902(2005)

Examples of natural photonic crystals

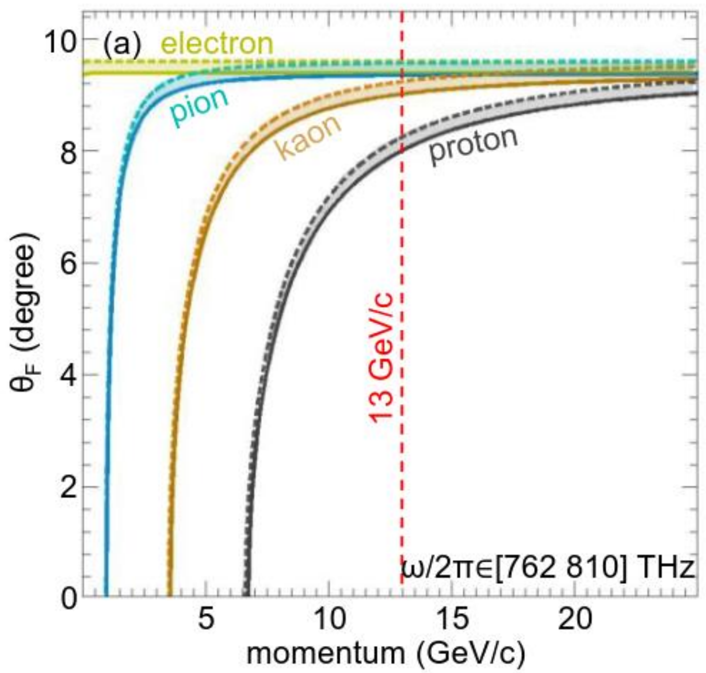
- 1d crystals:
  - Can be produced in large scales
  - Use techniques like optical lithography, 3d printing
  - Some of these can attain single nanometer precision in layer thickness
  - Using some type of polymers, also seems to be an option for large areas

Zhurin et.al., J.Vac. Sci.Tech. A 18 , 37-41 (2000)
Ponting. M. et.al., Macromol. Symp. 294-I , 19-32(2010)

- 2d crystals:
  - Only produced in small scales so far.
  - Typically a periodic array of holes. They can be made thinner than 1d crystals



Theory to Practice



Example of optimization

- Issues in optimizing a design:
  - Periodicity can cause chromatic error, depending on the configuration
  - Many options to mitigate this effect.
    - *Use materials with anisotropy, which can directly compensate for the achromaticity from periodicity*
    - *Use filters to use only a small wavelength range*
  - Improving photon yield:
    - *Increase the number of layers*
    - *Upper limit from limitations of manufacturing and material budget*
    - *Use gain materials, which can increase the yield in a small wavelength range*
- Ensure radiation hardness:
    - *There are many low Z materials to create the crystals from. (SiC, SiO_2 etc.)*
    - *They would need to be tested for radiation hardness*

Testing Prototypes

- Goal: To verify the predictions from simulations
  R&D work in early stages

- Few 1d samples obtained from industry

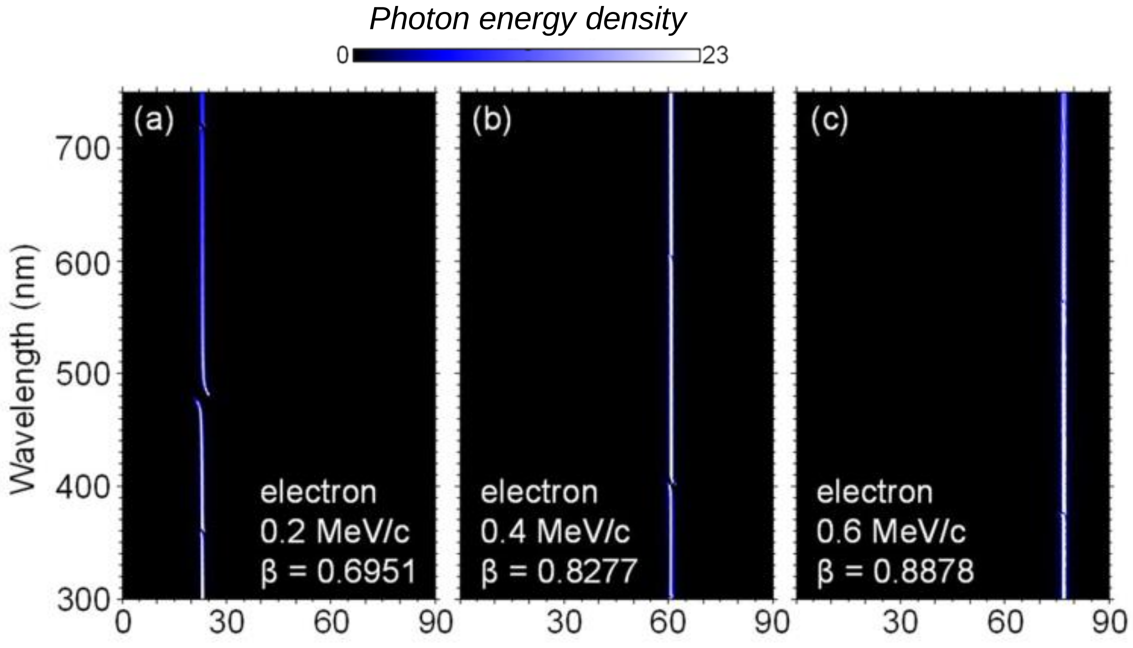
- Example used here:

  - PVDF (n1=1.414) + PET (n2=1.567)
    1024 layers, each with 250 nm thickness

  - This sample has negligible chromatic error

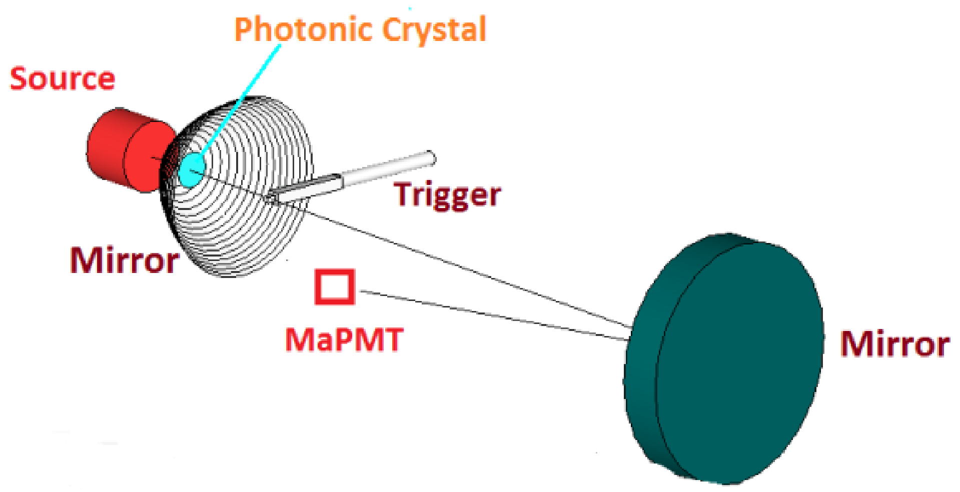
  - Sensitive to low momentum particles
    from a radio active source

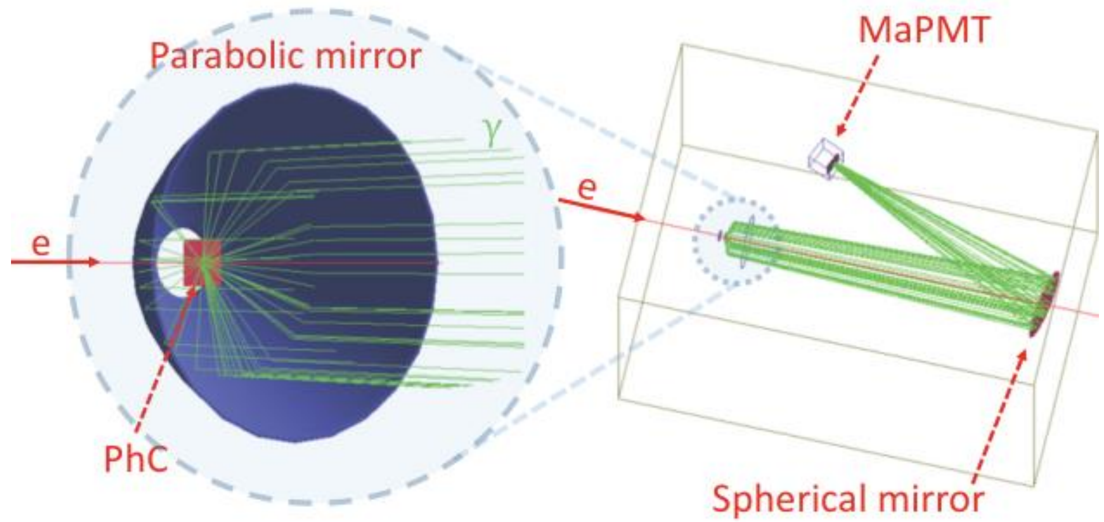
Prediction from simulations

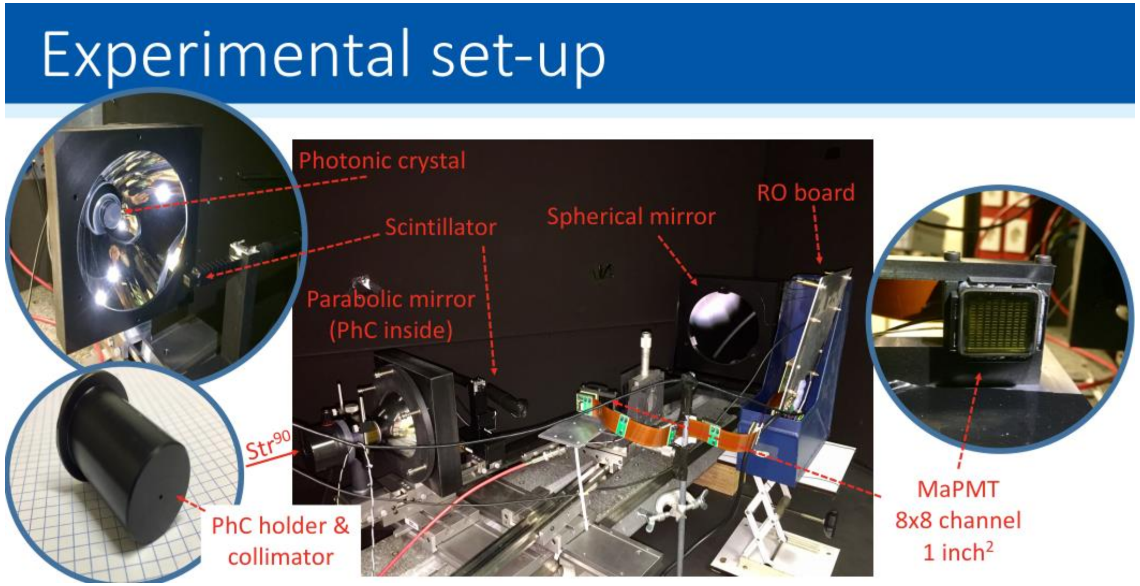


Wavelength vs forward Cherenkov angle

Testing Prototypes





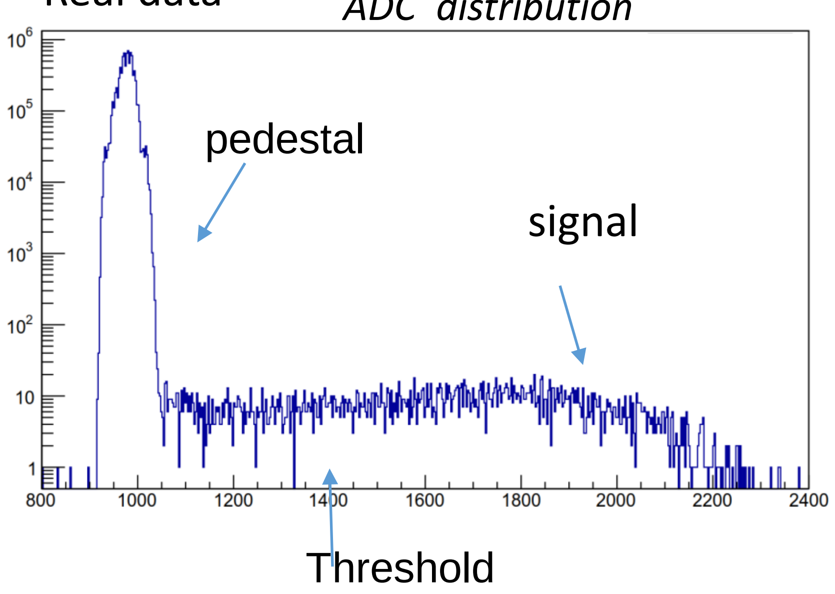


With support from D.Piedigrossi, S.Jakobsen , F.Cindolo et.al.

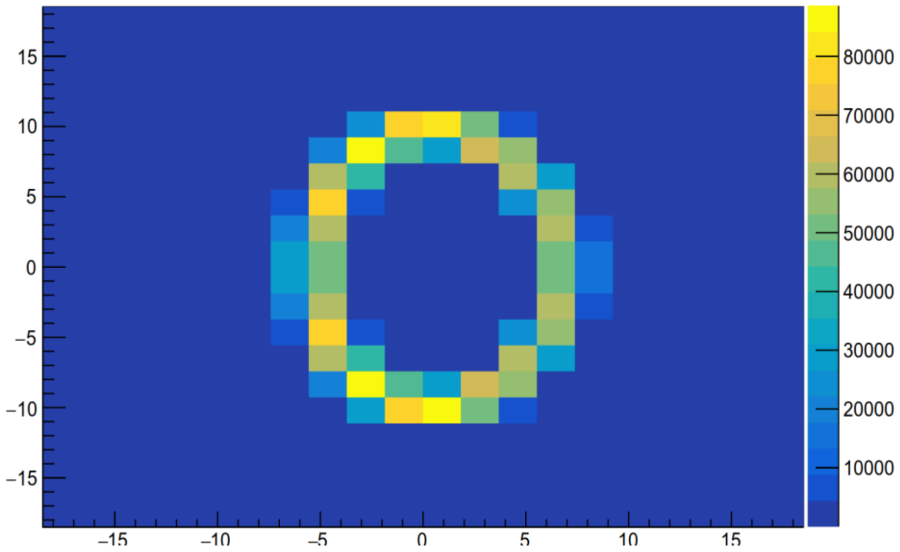
- Using Sr-90 source to produce electrons
- DAQ : MaPMT with MAROC2+FPGA

Testing Prototypes

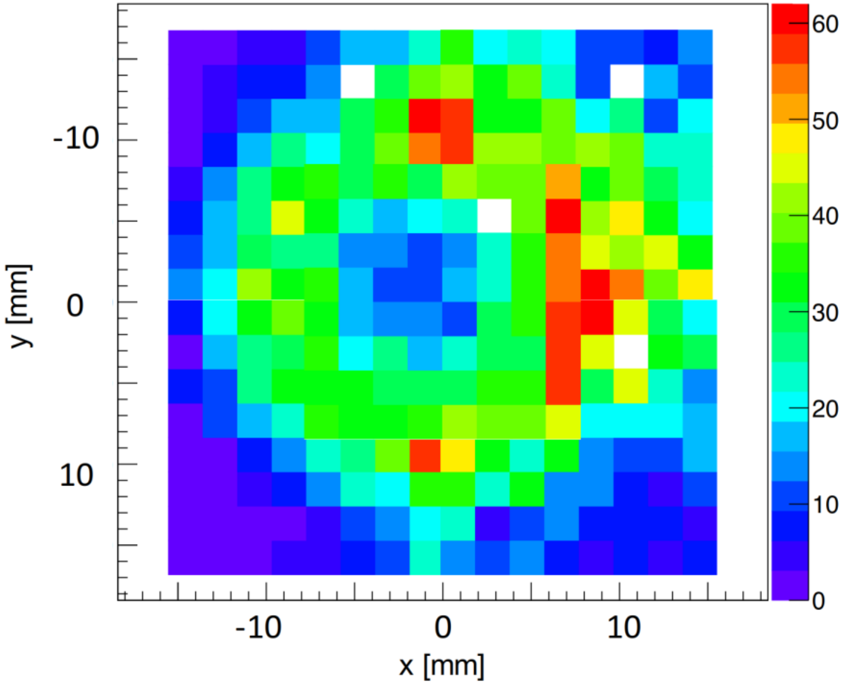
Real data



Simulation: Hits on detector plane



Optics simulation:
0.5 MeV/c electron



Preliminary

- Real data
  Hits on MaPMT

- *Electron momenta 0.2 – 0.7 MeV/c creating a thick ring*

- Further R&D in progress to improve this
- Plan to test more prototypes

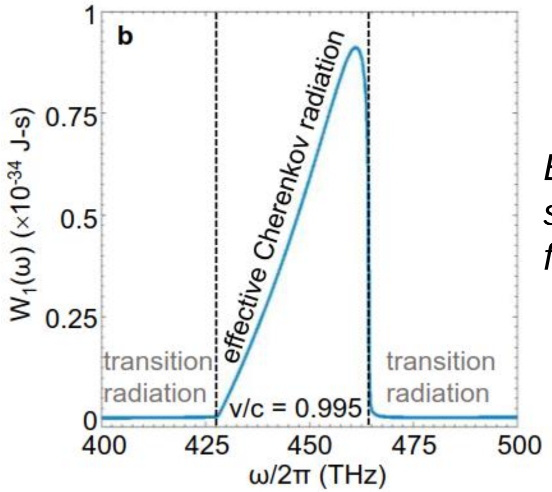
Summary

- It would be desirable to develop radiators which can overcome the limitations of conventional radiators
- Using photonic crystals made from transparent materials is a potential option for this
- The concept for usage of such crystals for particle identification is described
- Issues related to optimizing a design, are being considered
- Tests with prototypes have started

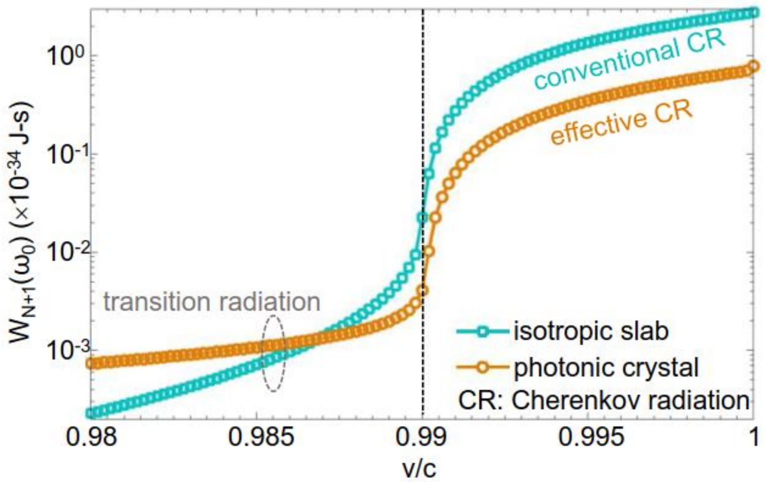
Backup slides

Comparison between different radiations

- From a photonic crystal:
  - Constructive interference:
    - Resonance transition radiation occurs
    - “Effective Cherenkov radiation” since it has the features of conventional Cherenkov radiation
    - Has a threshold for particle velocity
  - Destructive interference:
    - Conventional transition-like radiation occurs
    - Has no threshold for particle velocity



Example of radiation spectrum
from a photonic crystal.

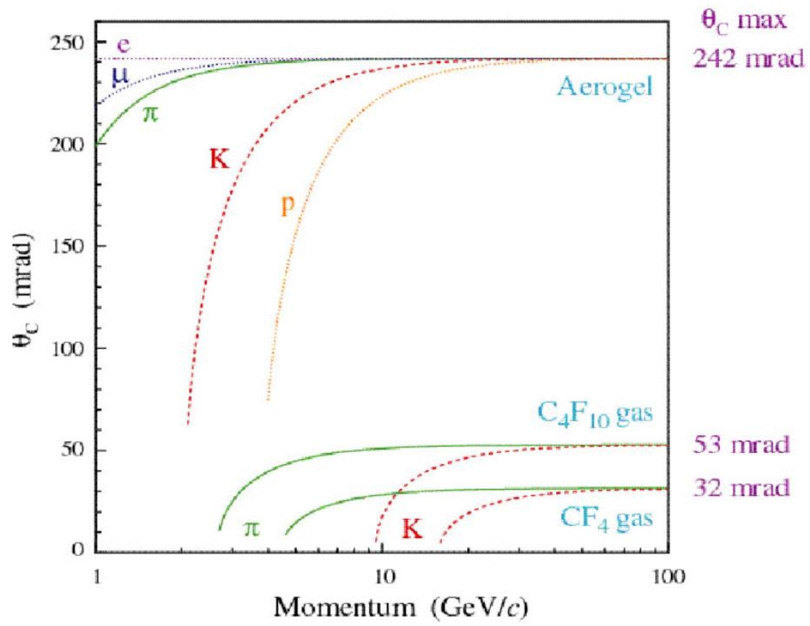


Example of radiation spectra
from a photonic crystal
and isotropic slab

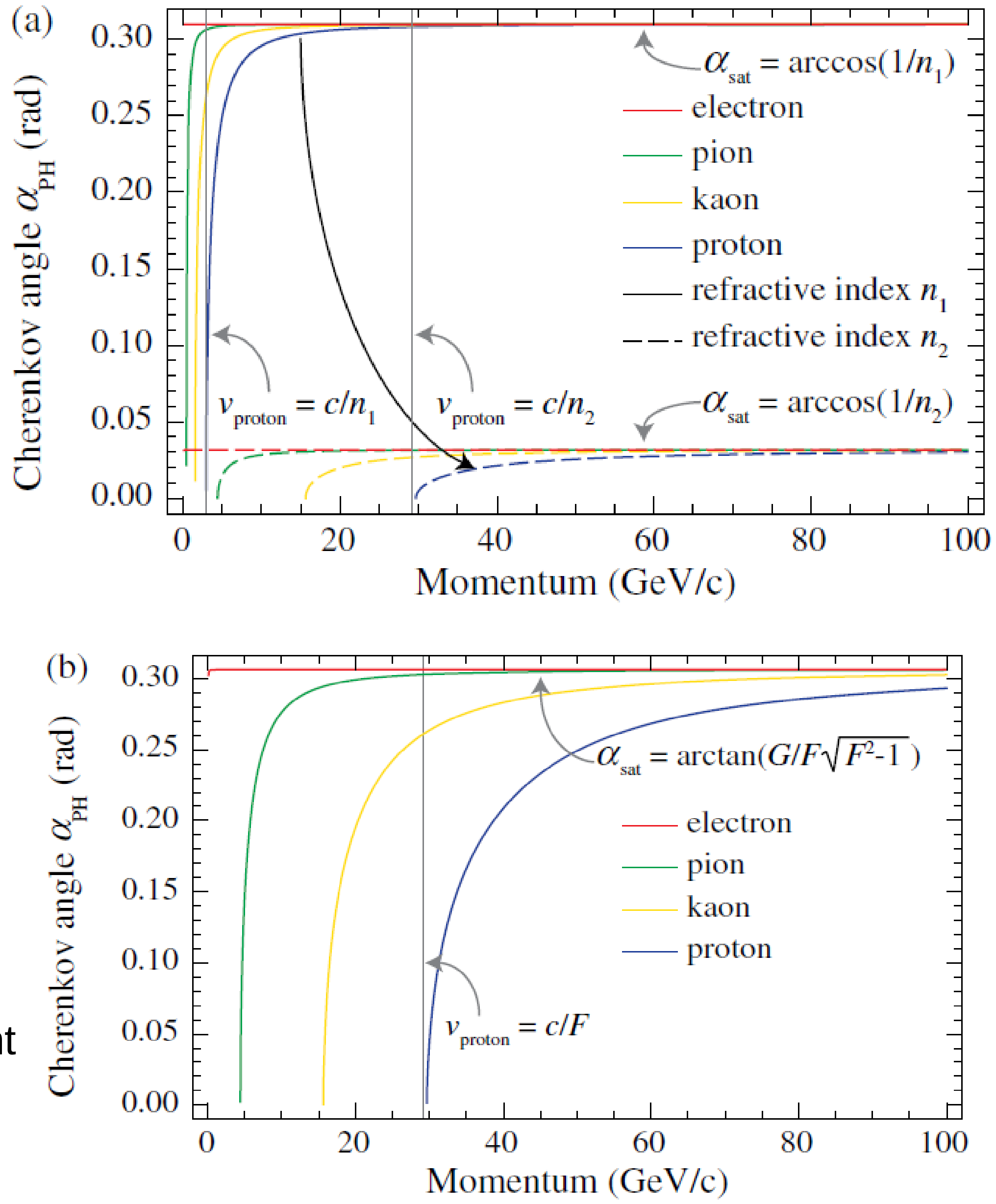
- Isotropic medium:
  - Conventional Cherenkov and transition radiation occurs

Meta materials: Particle Identification

PRL 113, 167402 (2014)



LHCb RICH1 EDR: LHCb-2004-121



Sensitivity= $\theta_{\text{eletron}} - \theta_{\text{proton}}$

Transformation optics:

Longitudinal stretching=F=1.005 : Shift curves to right
Transverse stretching = G=10 : Increase θ