RICH R&D

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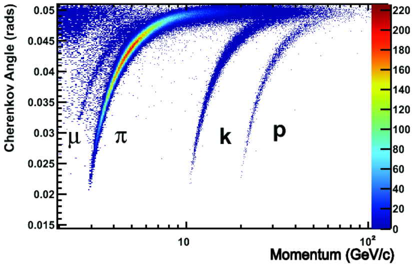
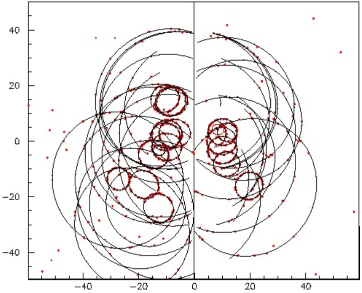
Reminder of a RICH

- Distinguish between particle species using Cherenkov radiation
- Via different emission angles at measurement momentum
  $\cos\theta = \frac{\sqrt{p^2+m^2}}{np}$
- "Measure" angle by focusing cones into rings
- In high occupancy, must statistically separate patterns

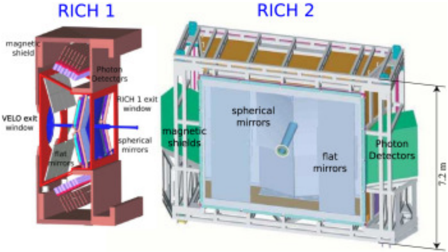




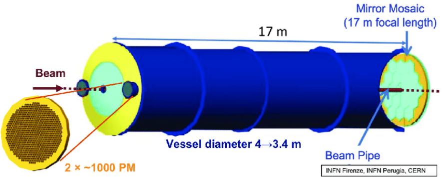
UK RICH involvement

Prominent UK collaborations with RICH detectors

LHCb



NA62



Similar projects with potential synergies

- TORCH (See T. Blake's talk)
- Cherenkov Telescope Array

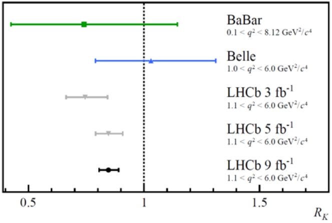
Wider into Europe

BELLE 2 PANDA COMPASS

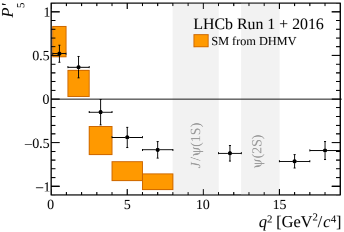
The importance of RICH detectors to UK science

UK's highest profile results would be impossible without RICH

arXiv:2103.11769 (Submitted to Nature Physics)



B anomalies



Phys. Rev. Lett. 125 (2020) 011802

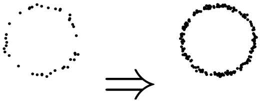
Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay

The NA62 Collaboration

arXiv:2103.15389 (Submitted to JHEP)

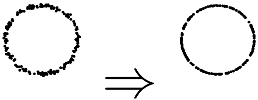
Fundamental challenges facing RICH detectors

- Yields



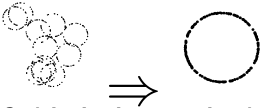
We want to increase photon yields

- Angle resolution



Decrease angle resolution (interplay with yield)

- Occupancy



Decrease occupancy to better isolate signal from a particle

All of this in increasingly harsh environments

General R&D areas

To accomplish these goals R&D is being performed in:

- Photon detection
  - Yield and resolution
- Fast readout
  - Occupancy
- Mirrors and geometries
  - Resolution
- Improved radiators
  - Yield and resolution
- Simulation and reconstruction
  - Occupancy

Photon detectors

Why we need photon detector R&D

- Need detectors with good spatial resolution
  - Over a 2D detector plane (area $\mathcal{O}(\text{several m}^2)$)
- We'd like to have high detection efficiency to maximise photon yield
  - With high yields can remove photons with low resolutions
- Need to operate in magnetic fields
- Need detectors that can cope with high occupancy
- Need detectors that survive in high radiation environments
- Need to be able to meet timing requirements

See S. Gambetta's talk for specifics, I've been asked to comment on SiPMs due to other impacts

SiPMs

There's lot's of synergies in the development of SiPMs

- Many detectors and experiments use SiPMs
  - Use in tracking/calorimetry to detect scintillation
  - Future generations of Kaon experiments
- Many industrial applications

Main questions to do with SiPMs for RICH operation

- How effectively can they be used for single photon detection?
- Radiation hardness
  - Can they survive operation in, e.g. an HL-LHC environment?
- Complications of cryogenic operation
  - Related to above, how cold do they need to run to reduce dark noise?
  - How do you build a large, cold 2D array, optically coupled to radiator?

On-going R&D programmes in UK to answer these questions

Fast readout

Why is a fast read out important?

- At LHC and beyond, expect 1000s of overlapping rings
  - Huge background for single track identification
- Useful quirk of RICH geometry, photons from a track arrive together
  - At LHCb, typically within 25 ps
- Track arrival times distributed over $\mathcal{O}(1\ \text{ns})$
- If signal can be isolated in time, can reduce occupancy
- Very hard to isolate a track, but all tracks from a single collision vertex is feasible

Requires full detector chain to $\mathcal{O}$(ns) response or better

Fast readout R&D

Fast digital readout being developed in UK

- Aim for better than 100 ps resolutions
- Looking at using short timing windows
- Also adding timing information to hits
- Needs to deal with increased readout bandwidth
- Has tighter constraints on synchronisation

Several synergies with digital readout for any high occupancy detector, especially with timing

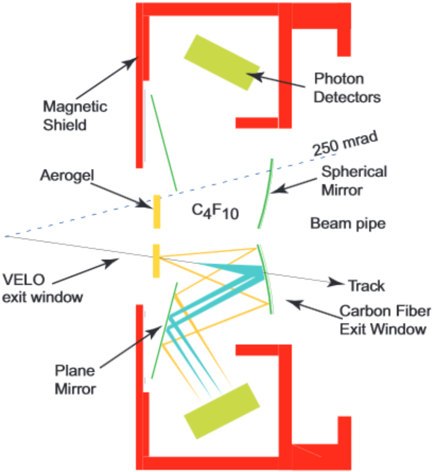
Fast ASICs under development by European collaborators, many fast signal processing cross-overs

Mirrors & geometry

Several geometrical properties impact angle resolution

- Spherical mirrors often used (easier to build that parabolic)
- Mirrors tilted with respect to particle origin to place photon detector plane

These introduce spherical aberration, and dependency on position a photon was emitted, worsening resolution



R&D on mirrors and new geometries

Can we tilt the mirrors less?

- Can we put flat mirrors in the particle acceptance?
- Tight constraints on materials, would need to abandon glass
- Carbon fibre harder to make sufficiently flat
- How do you make large, very flat but light, mirrors?

On going R&D into developing flat carbon fibre mirrors

Can we use alternative geometries?

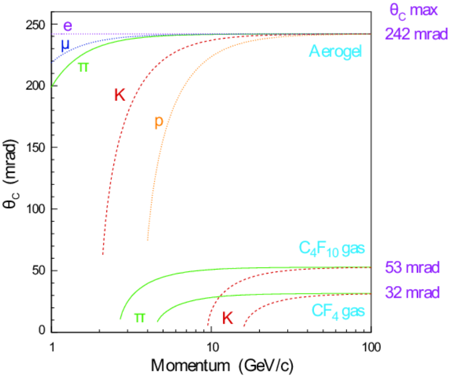
- Parabolic mirrors?
  - Can they be manufactured with the right tolerances?
- Can we place photon detector plane far away?
  - Large optical volumes? Transport with fibres?

On-going UK R&D into new geometries

Radiators

Why are radiators important?

- Useful momentum range limited by refractive index of radiator
- Lower limit one particle must be above threshold for production $\beta = \frac{1}{n}$
- At high momentum $\cos\theta$ saturates to 1, separation limited by angle resolution
- General solution to use multiple radiators



Radiator R&D

Impact of the radiators

- Control the generated yield of photons ($\propto n^2$)
- Control the generated angle, and so drive the optics and geometry
- If refractive index is a strong function of wavelength or position, angle resolution degrades

Radiator R&D is focused on three areas

- New gases
- New solid radiators
- Advanced radiators

New gas radiators

Gas radiators often employed

- NA62 uses Helium
- LHCb C_4F_{10} (also COMPASS) and CF_4

Problems with Fluorocarbon gases

- Fluorocarbons are being phased out of industrial use
- Makes them difficult and expensive to obtain
- **VERY** bad for the environment
  - Use of Fluorocarbons is large component of LHCb's environmental footprint
  - Tight constraints on containment systems

R&D into potential replacement gases

- e.g. Can CF_4 be replace with CO_2?

Potential synergies with other gas detectors

New solid radiators

Can we use low density solid radiators?

- LHCb's experience with Aerogel wasn't brilliant
- Manufacturing techniques of Aerogel have improved
  - Now large panels of optical quality Aerogel are available
- BELLE 2 has used new Aerogel successfully
- R&D by collaborators on its use in HL-LHC environment
- Impacts for geometry and reconstruction

Synergies with other experiments, e.g. BELLE 2/PANDA

Advanced radiators

Traditional materials have issues:

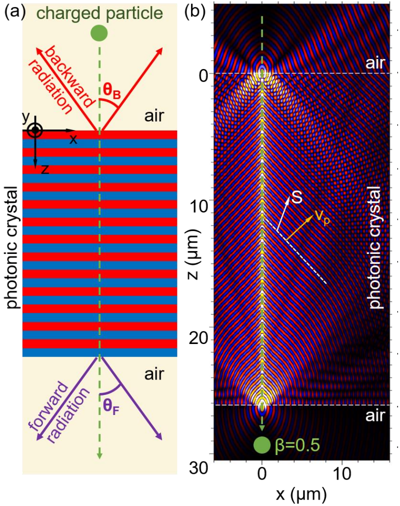
- Momentum range requirement need refractive indices close to one
- Low refractive index leads to small photon yields
- Need to avoid total internal reflection
- Needs to avoid scattering particles

Can we find better/make materials by talking to our material science/metamaterial friends?

- A field with precision control over material properties
- Many of the tools are already in place
  - Lots of measurements use charged particles to excite materials to investigate materials properties
  - Mature manufacturing techniques; many metamaterials already "in the wild"

Photonic crystals as new Cherenkov radiators

- Simple metastructure
  - 1D array of alternating transparent dielectrics
- Each layer generates standard Cherenkov radiation
  - Assuming large refractive index this is trapped by TIR
- Charged particle can excite resonance in the structure
- Produces Cherenkov radiation outside structure with effective refractive index
- Forwards **and backwards** emission



Nature Phys. **14**, 816-821(2018)

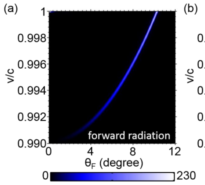
Photonic crystals as new Cherenkov radiators

- Generation of separately tunable forward and backward emission
  - Can create purely forward/backward emission or a mix

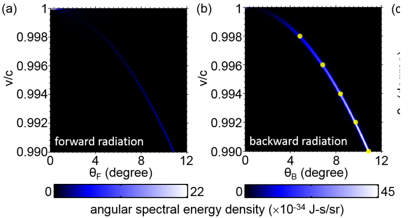
- The thicknesses of the layers determine the effective refractive index, and so emission angles

- Decoupling of the photon yield from this effective refractive index

Forward-optimised



Backward-optimised



Nature Phys. **14**, 816-821(2018)

Advantages photonic crystals

- Number of photons not as coupled to angle
  - Potentially not much performance gain from increased stats
  - Can throw away photons that reduce resolution (large chromatic uncertainty with gases)
- Huge improvement in knowledge of emission point
  - Can be a large uncertainty in the reconstruction
  - Can also speed up reconstruction
- Allows interesting optical geometries
  - Maybe proximity focusing to remove spherical
  - Could use the backward emission
- No complications of gas circulation, etc
  - Working with gases is very difficult

R&D into metamaterals

On going UK R&D into using metamaterial radiators

- Studying the range of refractive index that could be made
- Studying the radiation tolerance of the structures
- Studying the yields & scattering of the structures
- Studying the new geometries that are available
- Finding other quantum effects that could be useful

Plenty of synergies with other detectors. Potentially new funding streams, e.g. EPSRC

Reconstruction

Reconstruction of the data an increasingly complicated prospect

- Desire for real-time analysis to act in triggers
- Increasing data rates
  - Make handling the quantities of data slow
- Increasing track occupancy
  - Number of potential photon-track combinations becomes unwieldy

UK R&D on reconstruction

- Efficiently unpacking data in off-detector electronics
- Hardware acceleration of the geometry heavy algorithms
- Making use of timing information to reduce occupancy
- Including timing as part of particle discrimination

Synergies with other high throughput detectors

Simulation

Detector simulation suffers similar problems

- With increasing data collection simulation needs ever more statistics
- Drive for increasing accuracy means more time consuming simulations

UK R&D in simulation

- Use of hardware acceleration in ray tracing
- Fast approximations to use
  - Limiting phase space
  - Ring libraries for uninteresting tracks
- Major input into geometry R&D

Conclusions

- RICH detectors play, and will continue to play, pivotal role in UK HEP
- Several areas of dedicated R&D in UK and Europe for RICH detectors
- Many overlapping requirements with other detector technologies
- Synergies with other experiments and industry
- Potential to attract funding from other sources