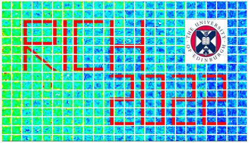
XI International Workshop on Ring Imaging Cherenkov Detectors



RICH detectors in particle and nuclear physics experiments

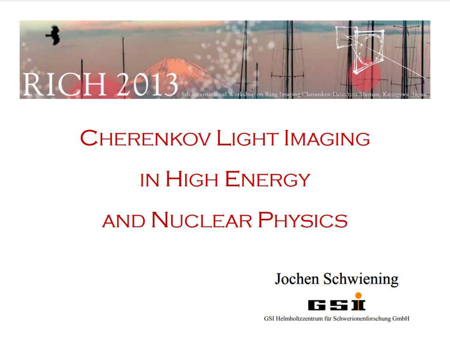
Silvia Gambetta
University of Edinburgh

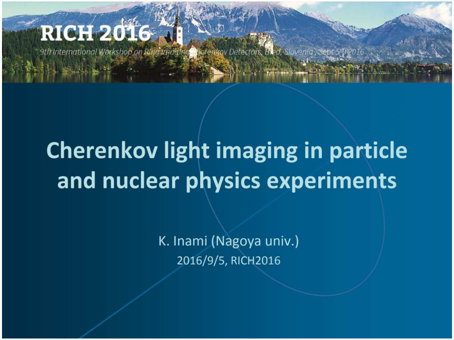
September 12, 2022

THE UNIVERSITY *of* EDINBURGH

LHCb

Introduction





- my fourth RICH conference
- many in depth reviews in the past years
- a multitude of topics to cover including:
  - historical view
  - current projects
  - future detector
  - technological challenges

Introduction

Review talks this week

Overview of RICH detectors in particle and nuclear physics experiments
Silvia Gambetta (Edinburgh, UK)

Overview of RICH detectors in astroparticle physics experiments
Christian Spiering (DESY, Germany)

The control of refractive index and chromaticity in gas radiators of large Cherenkov detectors:a challenge in the era of diminishing fluorocarbon gas availability
Gregory Hallewell (Marseille, France)

Status and perspectives of micro-pattern gaseous photon detectors
Florian Brunbauer (CERN, Switzerland)

Status and perspectives of SiPM
Alberto Gola (FBK Trento, Italy)

Status and perspectives of vacuum-based photon detectors
Albert Lehmann (Erlangen, Germany)

Introduction

Talks in this session:

- "The Ring Imaging Cherenkov detector of the NA62 experiment at CERN: technical aspects, operational characteristic and basic performance" F. Bucci
- "The Large-area Hybrid-optics CLAS12 RICH: First Years of Data-Taking" M. Contalbrigo
- "The LHCb RICH Upgrade" A. Sergi
- "Long term stability and perspective of the ALICE-HMPID detector at LHC during Run3" G. De Cataldo
- "Performance of the new hadron blind HADES RICH in heavy ion collisions" J. Förtsch
- "Operation and performance of the Belle II Aerogel RICH detector" K. Uno
- "Status and Initial Performance of the GlueX DIRC" J. Stevens
- "The PANDA Barrel DIRC" R. Dzhygadlo

and many more contributions in the sessions on:

- Pattern recognition and data analysis
- R&D for future experiment
- Photon detection techniques for Cherenkov imaging counters
- Technological aspects and applications

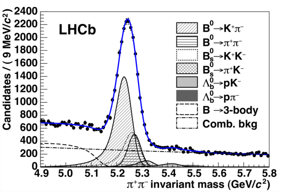
Importance of particle identification

Distinguishing between final states with the same topology

b-hadrons two-body decays into charmless charged hadrons at LHCb

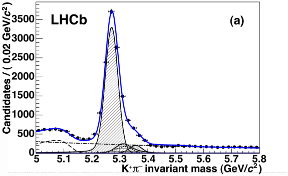
$\rightarrow$ with PID

$\downarrow$ without PID

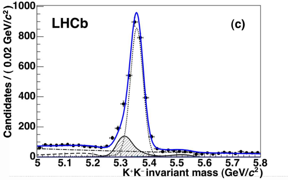


[LHCb, JHEP 10 (2012) 37]

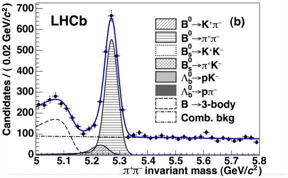
$B^0 \to K\pi$



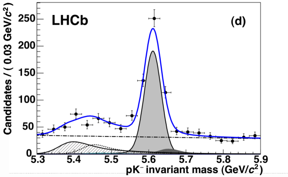
$B^0_s \to KK$



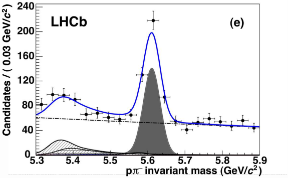
$B^0 \to \pi\pi$



$\Lambda_b \to pK$

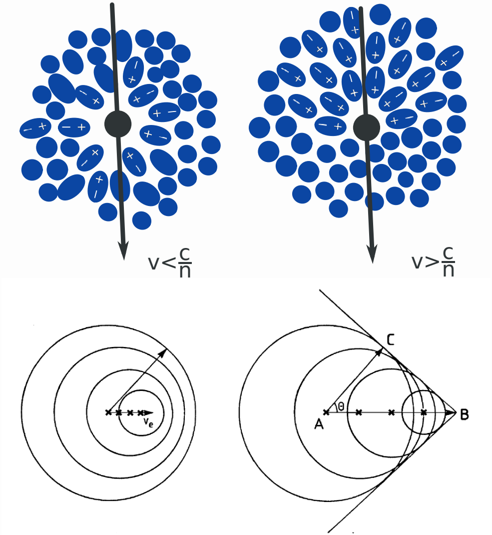


$\Lambda_b \to p\pi$



Hadron identification is a key ingredient in b-physics & hadron spectroscopy

Cherenkov radiation: principle



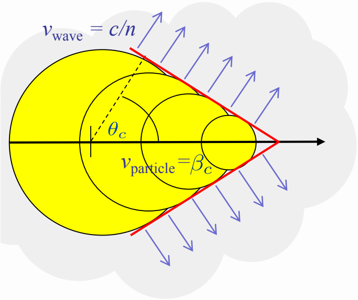
charged particle traversing medium

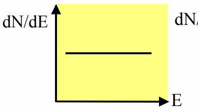
- atoms in the medium are polarised along track: emission of electromagnetic pulse
- particle slower than local the speed of light: symmetric polarised field and destructive interference
- particle faster than local the speed of light: asymmetric polarisation and coherent wavefront produced
- Huygen's principle: coherent wavefront only at a specific angle θ with respect to the particle trajectory

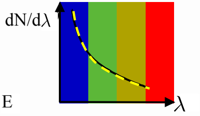
P. A. Cerenkov. "Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light", Phys. Rev. 52 (4 Aug. 1937), pp. 378-379.

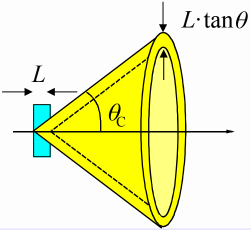
DOI: 10.1103/PhysRev.52.378.

Cherenkov radiation: properties









threshold

$$\beta_{threshold} = \frac{v_{threshold}}{c} = \frac{1}{n(\lambda)}$$

angle

$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

photons

$$N_{photons} = L \frac{\alpha^2 z^2}{r_e m_e c^2} \int \sin^2\theta_c(E) dE$$

$$N_{photons} \propto \frac{1}{\lambda^2}$$

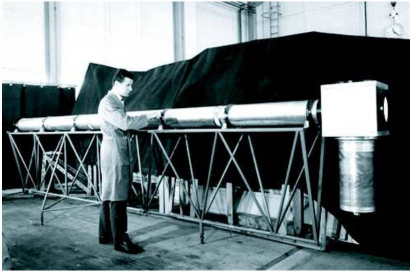
number of Cherenkov photons per unit path length and per unit energy interval of the photons:

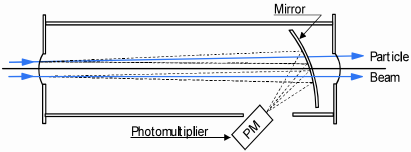
$$d^2N/dEdx \approx 370 \sin^2\theta_C(E)\ [\mathrm{eV}^{-1}][\mathrm{cm}^{-1}]$$

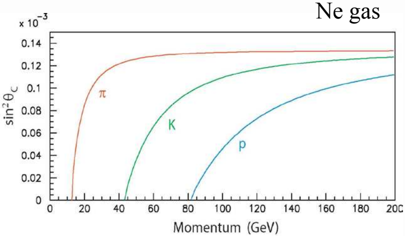
low number of Cherenkov photons ⇒ negligible energy loss of the charged particle under identification

Threshold detectors

- threshold Cherenkov detectors typically employed in beams with fixed energy
- example: spot proton contamination in 50 GeV π^+ beam
- choose radiator with refractive index to have Cherenkov radiation from π and not p
- multiple radiators to widen the momentum range





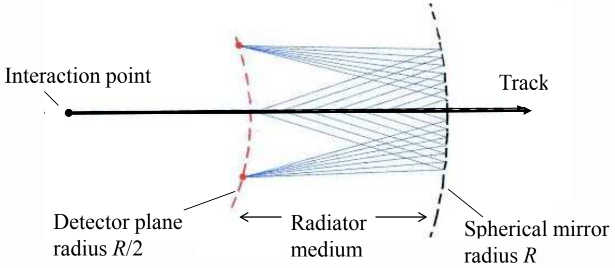


O. Chamberlain, E. Segre, C. Wiegand and Th. Ypsilantis, Observation of antiprotons, Phys. Rev. 100, No. 3, 947 (1955)

Ring Imaging Cherenkov detectors

the Cherenkov cone can be magnified and imaged into a ring using a spherical mirror profiting from all information provided by Cherenkov radiation:

- threshold of Cherenkov radiation emission
- dependence of the number of photons
- dependence of Cherenkov angle on the velocity of the particle
- introduce capability of single photon detection with:
  - high efficiency
  - high spatial resolution



measuring the ring radius r the Cherenkov angle θ_c can be reconstructed: $r \sim R\theta_c/2$
J. Seguinot and T. Ypsilantis [NIM 142 (1977) 377]

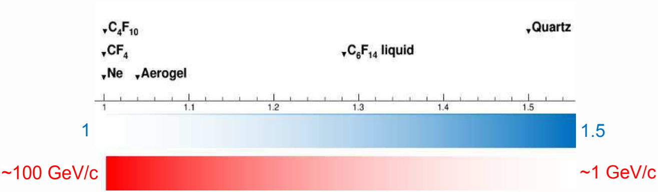
Elements of a RICH detector

- radiator: appropriate refractive index to cover a good range of momenta and with low dispersion to minimise the chromatic error
- mirrors: high reflectivity to minimise photon losses, emission point error, traditionally glass substrate, with coating. In applications where minimising the material budget is important, carbon fibre or Be substrates are used
- photon detectors: need position sensitive photon detectors with good spatial resolution and large active area

this talk will not be a review of the state of the art of each ingredient, more details available in the reports on design and performance of detectors and from the R&D session on the latest technological challenges in the field

Radiators

Three main types of radiators:

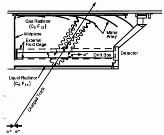


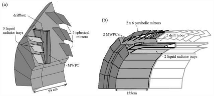
- gas: fluorocarbon gases have low chromatic dispersion, narrow Cherenkov angle, large optics region using mirrors, cover large area
- aerogel: limit detector volume, good for low momenta, lower photon yield
- quartz: allow compact designs, limited to low momenta

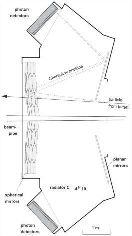
Three main families of RICH detectors:

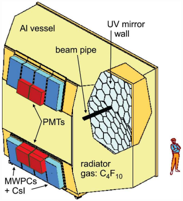
- mirror focused RICH counters: gas radiator
- proximity focused RICH counters: thin liquid or solid radiator
- detection of internally reflected Cherenkov light: solid radiator

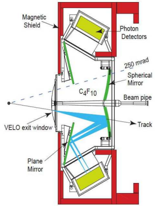
Mirror focused RICH counters

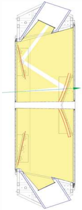


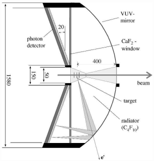


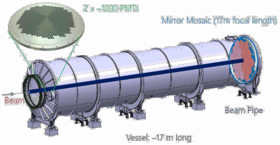


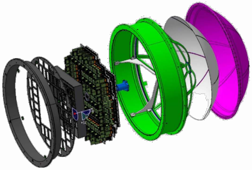


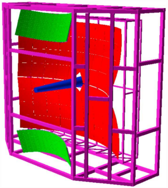








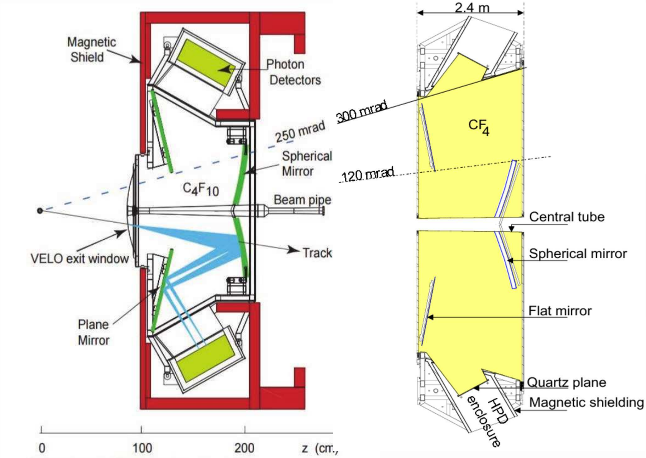


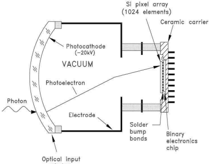


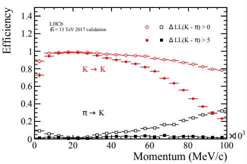
large gas volume, wide momentum range (the only RICH covering high momenta)

LHCb RICH detectors

- RICH 1 (C_4F_{10}): upstream, 2 GeV/c - 60 GeV/c over 25 mrad - 300 mrad
- RICH 2 (CF_4): downstream, 30 GeV/c - 100 GeV/c over 15 mrad - 120 mrad



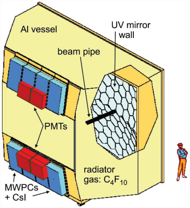


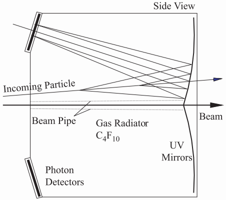


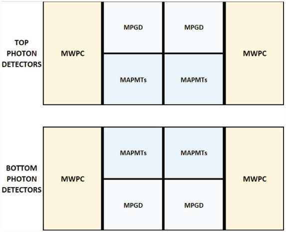
- Charged particles produce Cherenkov radiation then focused on Hybrid Photon Detectors (HPD) plane; Multi-anode PhotoMultiplier Tubes (MaPMTs) installed during the Upgrade

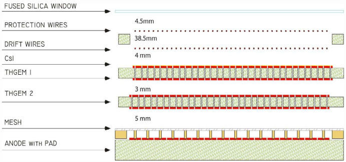
Compass RICH

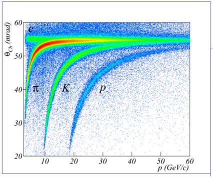
- large volume of C_4F_{10}: π-K separation up to 45 GeV/s (60 GeV/c) with CL >95% (90%)

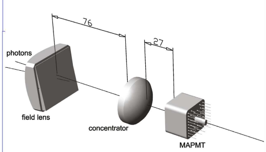






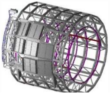


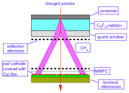


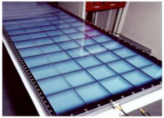


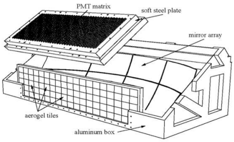
- Photon detection system evolved across the years: MultiWire Proportional Chamber (MWPC) equipped with solid state CsI photocathodes, first upgrade with Multi-anode PhotoMultiplier Tubes (MaPMTs) equipped with lenses in high momentum region, novel MicroPattern Gaseous Detectors (MPGD) installed as next upgrade

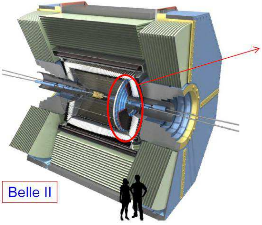
Proximity focused

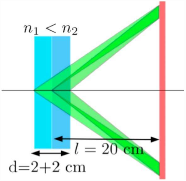


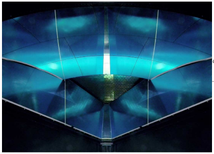


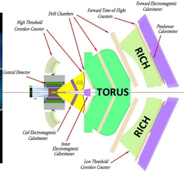










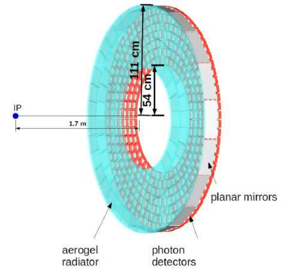


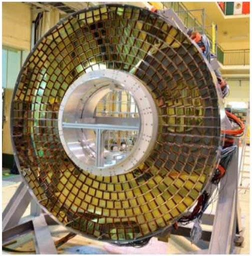
Based on Aerogel tiles or liquid radiators. Next generation profiting from major technological advances in Aerogel quality:

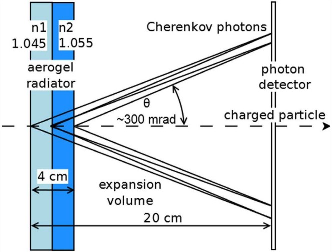
- better transparency
- tunable refractive index
- larger tile

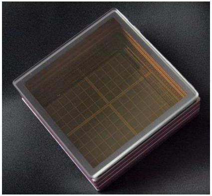
Aerogel: ARICH Belle2

- π/K separation for 1-4 GeV/c





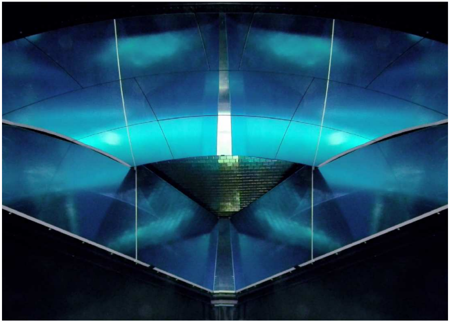


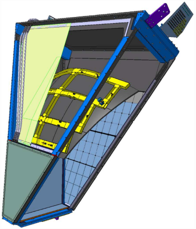


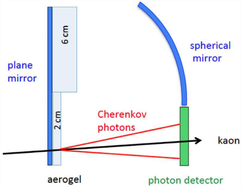
- two layer aerogel (n1=1.045, n2=1.055) coupled with Hybrid Avalanche Photo Detectors (HAPD) resilient to magnetic field up to 1.5T

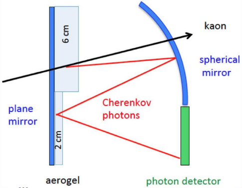
Aerogel: CLAS12

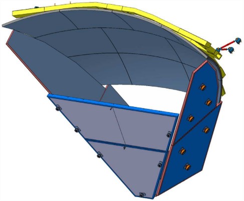
- π/K separation for 3-8 GeV/c

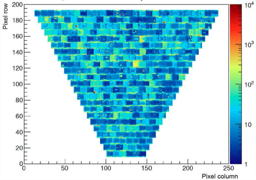






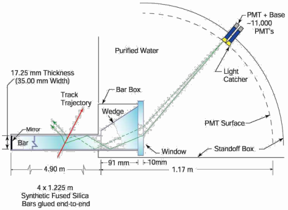


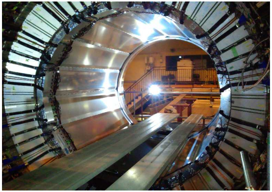


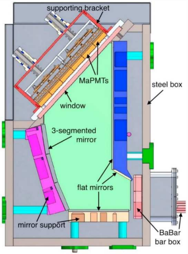


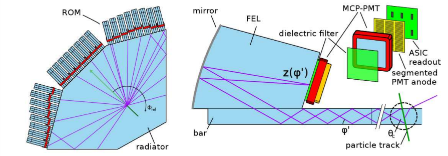
- combination of aerogel radiator with focusing mirrors to reduce the detection area instrumented with Multi-anode Photomultiplier Tubes (MaPMTs)

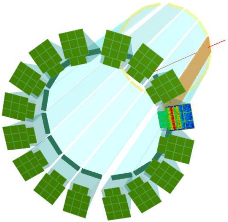
Internally reflected Cherenkov light

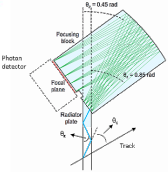








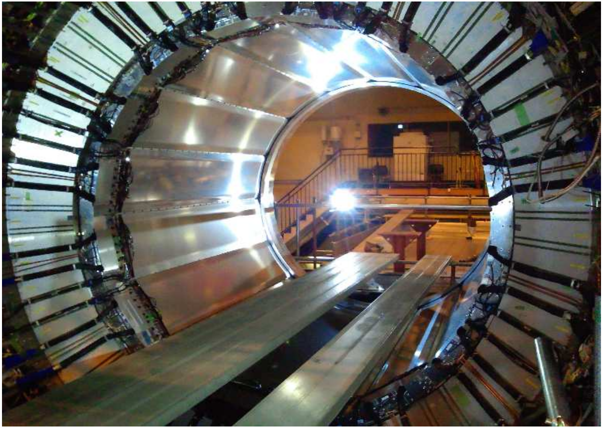


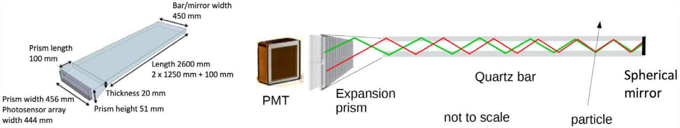


Cherenkov photons totally internally reflected and propagated through the radiator (bar, plate) made of Synthetic Fused Silica. Photons exit to expansion region with focusing optics: Cherenkov angles conserved through the radiator. intrinsically a 3D device measuring x, y and time; limited to low momentum range

Belle II Time Of Propagation

- π/K separation for 0.5-4 GeV/c

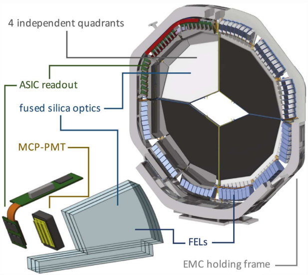


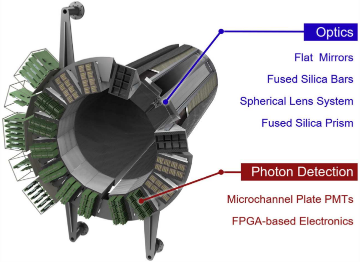


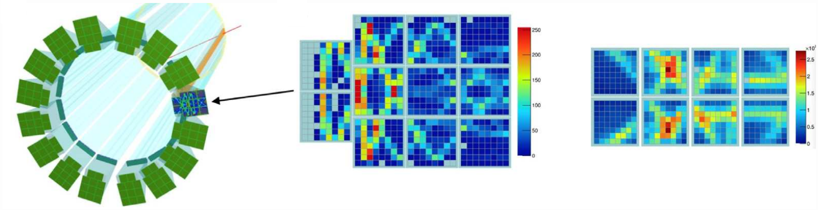
- measure time of arrival of Cherenkov photons with resolution better than 100 ps: Micro Channel Plate PMT (MCP-PMTs) developed to have TTS<50ps and resilient to magnetic field up to 1.5T

PANDA Barrel and End-cap Disc DIRC

- π/K separation up to 4 GeV/c



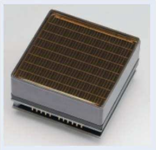


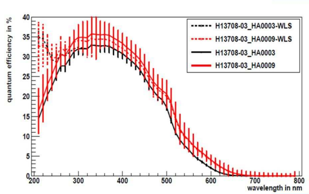


- based on Babar DIRC design with improvements: focusing optics, compact expansion block, fast photon detectors (MCP-PMTs) to measure time of arrival with precision better than 100ps, able to operate in 1.5T magnetic field

Photon detectors: the success of MaPMTs

- Hamamatsu R12699 installed in LHCb RICH Upgrade, CLAS12 and CBM
- Hamamatsu R11265 installed in LHCb RICH Upgrade



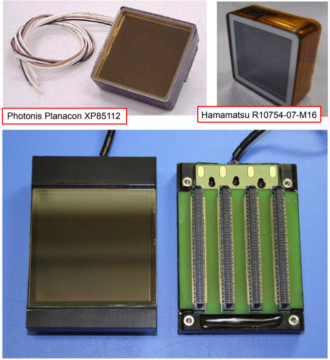


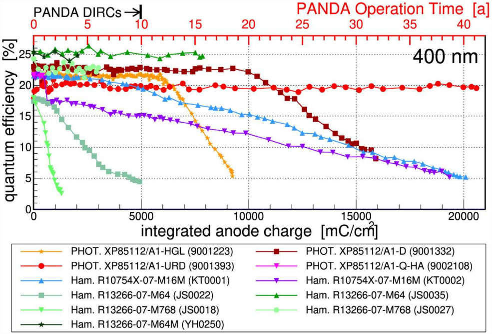
Improved active area, high QE, low Dark Counts, high gain

limited granularity, limited time resolution, limited resilience to magnetic field

Photon detectors: the challenge of timing

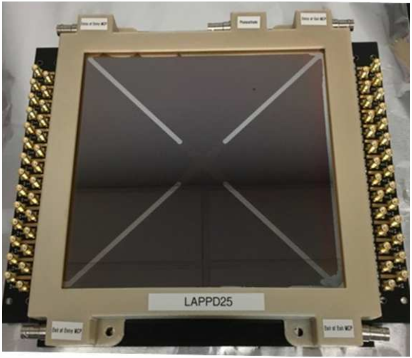
- MCP-PMTs natural candidates for detectors requiring time resolution <100 ps
- several developments focused especially on DIRC detectors
- main concerns still related to lifetime and rate capability
- R&D ongoing for mitigation strategies
- custom pixelisations tailored for individual application

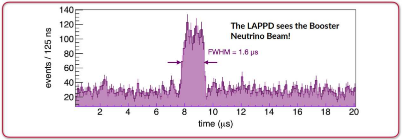




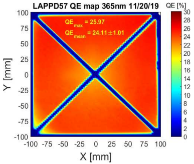
Photon detectors: the challenge of timing

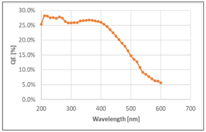
Large Area Picosecond PhotoDetector: MCP-based technology with intrinsic excellent time resolution, designed to equip large area (20x20cm^2)





first detection of neutrinos in Annie presented at ICHEP



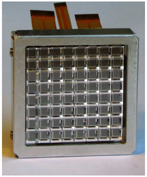


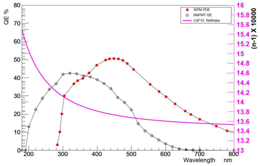
Fused Silica 3.8mm Window (LAPPD #63)

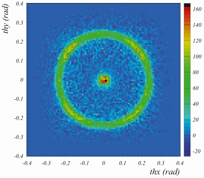
Photon detectors: the challenge of granularity

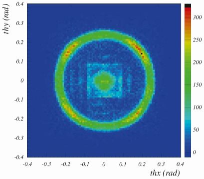
SiPM are particularly attractive option for future experiment and Upgrades:

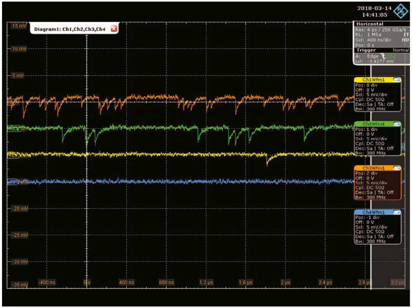
- robust and low voltage needed
- extremely resilient to magnetic field
- high PDE and high granularity and good timing









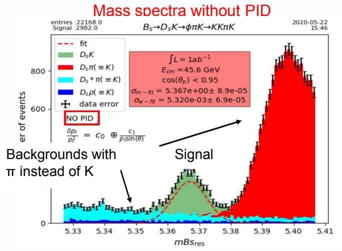


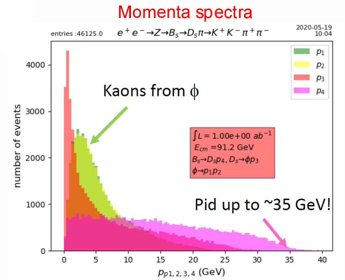
challenges for single photon detection:

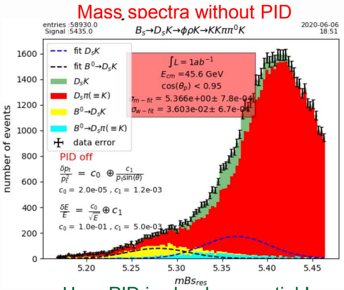
- high DCR, especially when irradiated
- cooling and annealing

Future challenges: PID at Z-pole

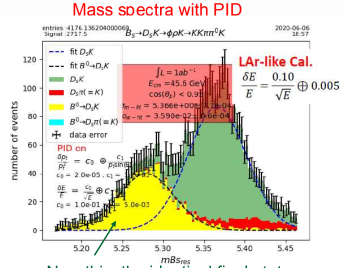
PID will still play a central role in flavour physics: study of benchmark CP-violation channel $B_s \to D_s K$ with toy MC, presented at the 4th FCC Workshop





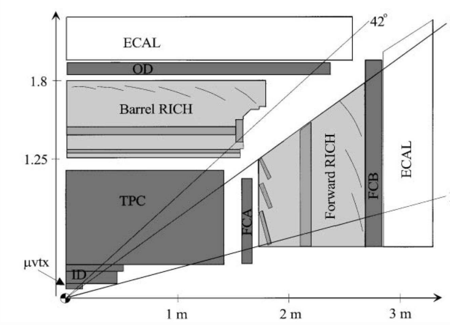


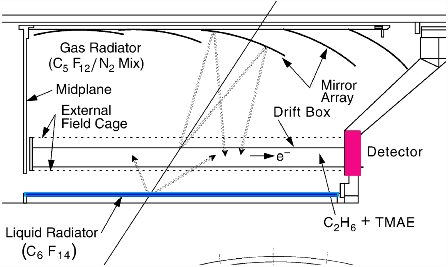
Here PID is clearly essential !

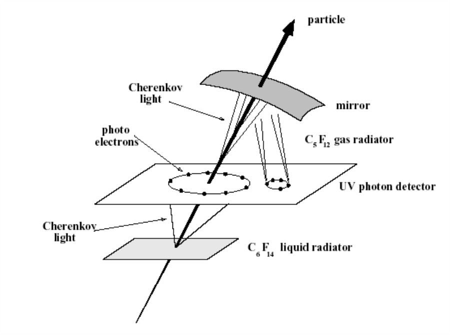


Now this, the identical final-state from B^0 decays, is the problem.

Historical barrel detectors







- SLD and DELPHI barrel
- similar concepts: Liquid / gas / gas (C6F14 / TMAE / C5F12) together in tight, inaccessible volume → very complicated implementation
- photoconverter gas TMAE (Tetrakis diMethylAmine Ethylene) very difficult to manage
- long TPC-like drift distances for the photoelectrons → sensitive to distortions

Candidate detector solutions

Classical RICH detector

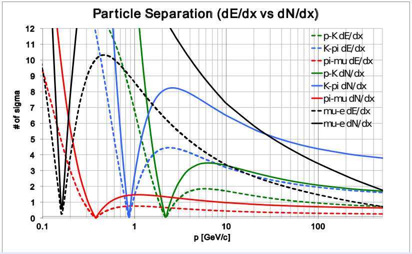
- challenge of designing low material, compact system to cover large range of momentum

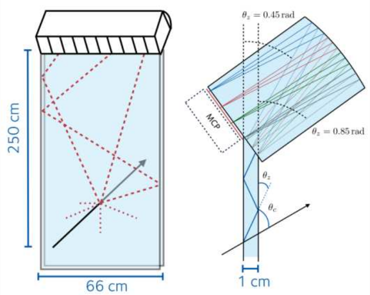
DIRC detectors

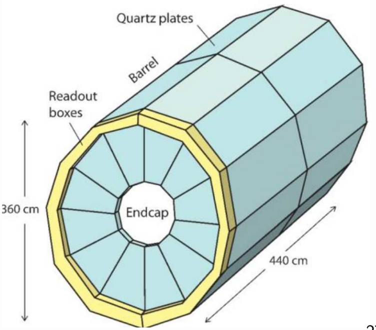
- PANDA/TOP/TORCH-like detectors requiring little space
- limited to lower momenta

dE/dx / cluster counting

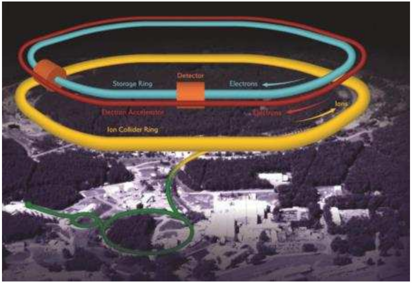
- classical dE/dx in drift chamber limited to low momentum
- cluster counting proposed for IDEA drift chamber would go much higher

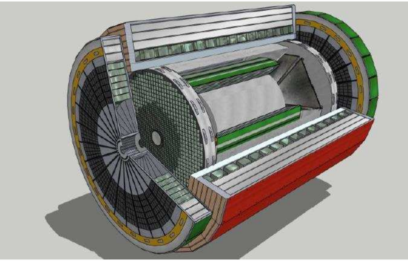






PID at EIC





General purpose experiment

Asymmetric kinematics impose different π/K/p separation requirements in different regions of the detector

- dE/dx and cluster counting
- hpDIRC (barrel)
- Aerogel + gas RICH (forward)
- Aerogel RICH (backward) /transition radiation (for e-id)

aim for PID up to 50 GeV/c in forward endcap, up to 10 GeV/c in backward endcap, up to around 6 GeV/c in barrel

hybrid approach $\rightarrow$ possible new ideas

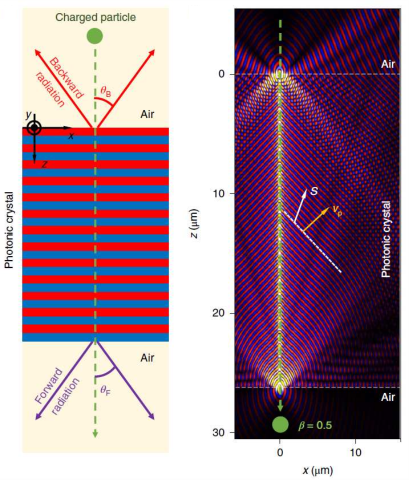
Novel radiators

Take advantage of recent developments in metamaterials to produce a new solid radiator with very nice properties

- 1D array of alternating transparent dielectrics
- each layer generates standard Cherenkov radiation
- charged particle can excite resonance in the structure

R&D still in primordial phase for RICH application but clear advantages if successful:

- no issues with fluorocarbon radiators
- different metamaterials could provide large momentum coverage
- possibility to tune emission angle and completely rethink the geometry of RICH detectors



Nature Physics volume 14, pages 816-821 (2018)
review talk at RICH2016

Conclusions

- RICH detectors are playing a major role in many experiments in nuclear and particle physics: not enough time to cover all the detectors currently or soon to be operational
- R&D on new radiators, mirrors, photon detectors is active
- new and innovative ideas needed for the future facilities
- many exciting studies and results will be presented at this conference!

Thank you for your attention!