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Physics with ring imaging cherenkov detectors¹

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¹Invited talk at the 1995 International Workshop on Ring Imaging Cherenkov Detectors, 12-16 june 1995, Uppsala, Sweden

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1. Introduction

The aim of this paper is to review the physics results obtained with Ring Imaging CHerenkov (RICH) detectors. In the first RICH workshop [1] no session was dedicated to physics and thus physics results were not yet reviewed. Therefore, physics results are selected starting from older and ending with the more recent experiments. For the older experiments only published results are reviewed, while for the more recent ones also preliminary physics results are discussed.

RICH detectors are used in various experiments for particle identification and precise measurements are performed in various fields ranging from fragmentation, QCD, charm, strange, bottom, tau, electroweak physics to astrophysics.

Two main questions will be addressed. Firstly, are significant physics results obtained with RICH detectors? Secondly, is the RICH technique competitive with other techniques? Other techniques are for instance particle identification based on time-of-flight counters, transition radiation detectors or measurements of the ionisation loss dE/dx . The emphasis of this paper lies not on the technical side (no prototype results) but on the results of experiments with RICH detectors. For the discussion of the performance of RICH detectors the reader is referred to [1], and [2]. For details on the RICH detectors the reader can consult the references.

A selection of experiments is made and their results are discussed in quasi historical order: E605 particle production in proton-nucleus interactions, UA2 charm production in proton-antiproton collisions, four fixed target experiments using the Ω RICH: WA69

photo-hadroproduction, WA82 charm production, WA89 hyperon production, and WA94 heavy ion physics, further CERES heavy ions, CRID and DELPHI for $e^+e^- \rightarrow Z^0$ physics and CAPRICE in astrophysics. Results from HY-POLIT [3], NA35 [4], JETSET [5] and the astrophysics RICH [6] will not be discussed. They are discussed in the review talks on heavy ion physics and astrophysics as indicated in the references.

2. First experiments

The first operational experiment using a RICH detector was the E605 experiment at Fermilab. The experiment was equipped with a gas RICH consisting of a 15 meter helium vessel. More details can be found in [7]. Using a proton beam extracted from the Tevatron particle ratios in p-Be and p-W interactions around $\sqrt{s} = 38.8$ GeV were measured. Five physics papers were published [8],[9]. The last paper giving precise measurements of particle ratios will be discussed here [9]. Measurements of (anti) protons and kaon fractions are performed at high z ($= p_{hadron}/p_{jet}$) and high x_t ($= 2p_t/\sqrt{s}$) from $0.19 < x_t < 0.62$. Protons and kaons are identified with the RICH, where the proton Cherenkov threshold lies above momenta of 111 GeV/c. Thus the fragmentation function at high z and x_t is probed. Data from other experiments reach lower x_t values. Comparing the measured ratio of K^+ to π^+ and protons to π^+ a steep drop is observed that sets on around $p_t=4$ GeV/c ([9] Fig. 2 p.3032). This drop can be accounted for by a model based on diquarks with a steeply falling fragmentation function. Comparing $K^+ : \pi^+$ to $K^- : \pi^-$ or $p : \pi^+$ to $\bar{p} : \pi^-$ ([9] Fig. 3 p.3033) reveals important information on the quark model of matter. The K^+ has

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a u quark in common with the incoming beam and target. The K^- on the other hand does not have a quark in common and thus the $\bar{u}$ either comes from a gluon or it is present in the sea of quarks surrounding the proton. A comparison with other experiments shows that a new domain at high transverse momenta is measured and a new effect is observed.

The UA2 RICH detector was operational in 1984 in the UA2 experiment at the $S\bar{p}pS$ collider. It consist of a gas radiator with a pion threshold around 3.5 GeV/c [10]. It is used for electron identification below the pion threshold. One physics paper is published on the measurement of the charm cross section at $\sqrt{s}=630$ GeV [11]. The signature for charm used in this analysis is the presence of low momentum electrons with $p < 3.5$ GeV/c. Combining the RICH with the calorimeter information a pion rejection - defined as the ratio of the efficiency for an electron to the efficiency for a pion - of around 10^5 is reached, see Fig.1 . The charm cross section was measured: $\sigma(c\bar{c}) = 684 \pm 557(\text{stat}) \pm 253(\text{sys.exp}) \pm 205(\text{sys.theory}) \mu\text{b}$. The result is consistent with theoretical expectations ranging from 200 to 900 μb . It is clear that such a measurement - requiring a rejection of pions above 10^4 - is difficult to perform without a RICH detector.

3. Experiments using the Ω RICH

A series of fixed target experiments were performed at the Ω RICH detector using beams from the SPS at CERN. The Ω RICH is a gas RICH providing pion/kaon separation from 5 to around 100 GeV/c. For the different experiments the apparatus has been optimized, as discussed in [12].

The WA69 experiment started data taking in 1984 and studied photo-hadroproduction for γ -p energies from 60 to 175 GeV and π/K -proton interactions at 80 or 140 GeV. One physics paper was published [13] on the charge asymmetry for kaons and pions and one - which will be discussed in more detail - on the production of ϕ and $K^{*0}(892)$ particles [14]. The ϕ particle is reconstructed in the K^+K^- mode and the K^{*0} in the $K^+\pi^-$ channel. The charged kaons are identified in the RICH and a clean signal for the ϕ

Figure 1. Pion rejection versus momentum.

is obtained. Cross sections were measured over the range $0 < x_{Feynman} < 1.0$ and $0 < p_t < 1.8$ GeV/c. The three different data sets for photon pion and kaon-proton interactions are compared and fitted to the parton fusion model. A good description of the data is obtained.

The WA82 fixed target experiment studied charm hadroproduction and started data taking in 1986. Charmed D^0 and D^+ mesons were reconstructed in different modes. The kaon identification of the Ω RICH was used to reduce combinatorial pion background. Several physics papers were published [15],[16],[17]. The paper on the semileptonic D decays [15] with the measurement of the branching ratio: $B(D^+ \rightarrow K^{*0}e^+\nu)/B(D^+ \rightarrow K^-\pi^+\pi^+) = 0.62 \pm 0.15 \pm 0.09$ is still quoted, because of the rather precise measurement of the longitudinal to transverse cross section $\sigma_L : \sigma_t = 0.63 \pm 0.3^{+0.3}_{-0.1}$. Other branching ratios or limits were quite competitive at the time of publication as for instance the limit on the $B(D^+ \rightarrow K^+\pi^+\pi^-) < 3.3 \times 10^{-3}$, while the PDG gave $< 4 \times 10^{-3}$ (90%CL) [16]. A full review of the charm branching ratios measured by WA82 can be found in [17].

The WA89 experiment used a hyperon Σ beam

to look for charmed strange baryons and started data taking in 1988. Also here the kaons in the final state were identified in the Ω RICH. Physics results were reported at the LISHEP 95 conference [18]. The reader is also referred to [19]. First evidence for a Ξ_c^{+} signal is obtained in the radiative decay $\Xi_c^{+} \rightarrow \Xi_c^+ \gamma$. The Ξ_c^+ is reconstructed in the $\Lambda K \pi \pi$ and $\Xi \pi \pi$ channels. The mass difference $\Delta m = m_{\Xi_c^{+}} - m_{\Xi^+}$ is around $100 \text{ MeV}/c^2$. Quite large statistics (approx. 200 events) is obtained for the Ω_c using seven decay modes involving intermediate states with an Ω^- , Ξ^- or Λ . From these events the Ω_c lifetime will be extracted. It is clear that high quality physics results are obtained by WA89.

The WA94 heavy ion physics experiment took its first data in 1991. Heavy ion physics searches for a new state of matter called the quark gluon plasma. In this experiment one looks for an enhancement in the strangeness production expected by theory. This is done by searching for an excess of kaons identified in the Ω RICH. No physics paper has yet been published and preliminary results, showing a clean kaon band and production fractions, have been presented at this workshop [20].

4. The CERES experiment

The CERES experiment is a heavy ion experiment at CERN that started data taking 1992. The detector - almost a RICH-only device - contains two gas RICHes for the identification of electrons-positron pairs below the pion threshold [21]. As a signature for the quark gluon plasma the enhanced production of electron-positron pairs is used. Several physics papers have been published [22], [23]. For proton-gold interactions the mean charged multiplicity per unit of rapidity is 7, while for sulphur-gold interactions it is 125. To run a detector and isolate the electron-positron pairs in such a dense environment is not easy, but manageable. The last paper is in particular relevant as it shows an excess of produced e^+e^- pairs with an invariant mass above twice the pion mass in sulfur-gold interactions with a significance of $5.0 \pm 0.7 \pm 2.0$

above Monte Carlo expectations [23], see Fig.2. The proton-gold data do not show this excess. Another experiment HELIOS/3 has found a similar - but less significant - excess in produced $\mu^+\mu^-$ pairs referred to in [23]. The excess is interpreted as coming from two pion annihilation $\pi\pi \rightarrow e^+e^-$.

Figure 2. Cross section vs e^+e^- invariant mass from CERES.

5. Electron positron collider experiments

The CRID, a 4π RICH detector consisting of a gas and a liquid radiator [24], is situated at SLAC in the SLD experiment. Polarized electron-positron beams collide and produce Z^0 particles that subsequently decay. The CRID allows for the identification of protons, kaons and pions (electrons or muons) from 1 to around 30 GeV/c . Physics results are not yet published. Two results were shown at this workshop [25]: a measurement of particle fractions in $b\bar{b}$ and $q\bar{q}$ events and a measurement of the forward-backward b quark asymmetry using charged kaons. The measurement of the cross sections for kaons from 1 to 3 GeV/c and 10 to 20 GeV/c and for protons from 1 to 5 GeV/c and 10 to 20 GeV/c is based

on approx. 30,000 hadronic Z^0 decays. The precise proton measurements in the high momentum region are of particular interest to test different fragmentation models.

The DELPHI RICH, a 4 π RICH detector consisting of a gas and a liquid radiator [26], is situated in the DELPHI experiment at the Large Electron Positron Collider (LEP) in CERN. Z^0 particles are produced and the RICH allows for the identification of protons, kaons and pions (electrons, muons) in the final state for particle momenta from 1 to around 30 GeV/c. Several papers based on the 1992 data set have been published [27],[28],[29], [30], and [31]. The more recent data are being analyzed and preliminary results in various fields have been shown at this workshop. Four fields will be discussed here: QCD, tau, bottom and strange quark physics.

The QCD results on particle fractions [30],[31] are presented at this workshop [32]. First results on the effect of Bose-Einstein correlations in identified charged kaons have been obtained using kaons identified in the RICH. For other particles (like charged pions) this effect was already observed.

In the field of tau physics the following branching ratios were determined $B(\tau \rightarrow K \nu_\tau) = (0.85 \pm 0.18)\%$, and $B(\tau \rightarrow K \nu_\tau \geq 0 \text{ neutrals}) = (1.54 \pm 0.24)\%$ [28]. The analysis of the 1993-1994 data will allow for an improved measurement [33]. First preliminary results were shown for multi-prong tau decays for the decays $\tau \rightarrow K \pi \pi$ and $\tau \rightarrow K K \pi$ [33]. The last channel is of particular interest for a limit on the ν_τ mass.

The RICH is extensively used in the field of beauty physics. In the first publication [27], the RICH is used to identify kaons in fully reconstructed events. Thus a precise measurement of the mass B_s^0 meson of $(5374 \pm 16 \pm 2) \text{ MeV}/c^2$ is obtained.

The lifetime of the Λ_b baryon is measured in different channels using proton or kaon identification information from the RICH. The average τ_{Λ_b} is $(1.19 \pm 0.15 \pm 0.10) \text{ ps}$ as discussed in these proceedings [34].

Rare B decays are reconstructed using the precise tracking information of the DELPHI detector and the particle identification provided by

the RICHes. Evidence for charmless B decays has been obtained based on three cleanly reconstructed events with a background of 0.29 ± 0.07 events [35]. In Fig.3 for an event display is of a charmless B decay is shown. Results have been shown [36] for radiative B decays $b \rightarrow s \gamma$, where the s quark is tagged as a kaon in the RICH or in the TPC using the ionisation loss dE/dx . These analyses show the performance of a RICH as it might be used in future B physics experiments, when looking for CP violation and rare B decays.

Evidence for new B particles has been obtained using the RICH. After the discovery of the orbitally excited B^{**} particles [37], a signal has been obtained for the $B_s^{**} \rightarrow B^{(*)} K$, where the charged kaon is identified in the RICH or in the TPC using the ionisation loss dE/dx . Furthermore, a first signal for $\Sigma_b^{(*)} \rightarrow \Lambda_b \pi$ is obtained. A B baryon enriched sample was obtained by requiring that an energetic Λ or proton identified in the RICH was present. Preliminary values for the masses of these new particles can be found in [38].

Figure 3. A charmless B decay with an identified kaon from DELPHI.

Strange quark physics is another field of physics where the RICH is used. Different ways to tag

the s quark are discussed in these proceedings [39]. The s quark can be tagged requiring a fast (momentum between 9 and approx. 20 GeV/c) charged kaon identified in the gas radiator of the RICH. With identified kaons a measurement of the strange quark forward-backward asymmetry can be performed. The result for the 1992 data is $A_{fb}^{s\bar{s}} = 0.118 \pm 0.027 \pm 0.015$, compatible with the Standard Model expectation [29]. Preliminary results for tagged kaons in the forward and barrel RICHes based on the 1994 data were shown at this workshop [40]. Also first studies for a measurement of $\Gamma_{s\bar{s}}$ were presented [39].

6. Astrophysics

CAPRICE is an astrophysics experiment using a balloon flight, equipped with a NaF radiator that took data in 1994 [41]. Its objective is the search for antimatter in space. Physics results have been presented at this workshop and the Cosmic Ray 1995 conference [42]. The RICH gives clear bands for protons, kaons and pions (muons electrons). A few events with antiprotons were found. Positrons were selected with a rejection of above 10^5 . The experiment can also separate isotopes and measure deuterium, tritium and ^3He present in space and look for the presence anti-helium.

7. Discussion and Summary

Evidently it takes much effort to build, run, maintain and extract physics results from a RICH detector. One could address the question: what is the typical time scale between data taking and publication? If one goes through the experiments, two groups should be distinguished. For the first group of general purpose RICH detectors it takes 5-6 years, with a trend that for the more recent RICHes the time scale lies around 4-5 years. For the second group of 'RICH only' experiments like CERES and CAPRICE it takes only 2 years.

The second question is the following: are significant results obtained with RICH detectors? The answer is positive: in various fields ranging from fragmentation, QCD, charm, strange, bottom, tau, electroweak physics to astrophysics sig-

nificant results have been obtained. Of course the success of a particular experiment does not only depend on the RICH detector, but also on good tracking devices and available statistics.

The third question concerns the comparison with other experiments and techniques. The E605 measurements access the fragmentation in a new kinematical domain. CERES (similarly the UA2 RICH) identifies electrons with a very high pion rejection. It is a unique experiment with significant physics contributions. For the experiments using the Ω RICH competitive results on strange and charmed particles have been obtained. Other experiments without RICH detector can (and do) obtain similar results. By WA89 some first results on charmed baryons are shown.

For the large e^+e^- experiments CRID and DELPHI a comparison can be made with particle identification based on the ionisation loss dE/dx . The difference between these methods is the following. A RICH performs a track by track identification of particles, while the ionisation loss provides a statistical separation. Comparing the ALEPH and OPAL experiments with CRID and DELPHI, one observes that precise measurements are performed in QCD, tau and B physics. A RICH has the advantage that cleaner samples of identified particles can be made and smaller systematic errors on measurements are reached. Some physics topics, like multi-prong tau decays and strange quark physics, are (still) unique as no measurements are done by the other LEP experiments. To give a balanced overview and draw conclusions we still have to wait a few years till the experiments have produced their final results. The astrophysics experiment CAPRICE gives unique physics results on (anti)matter in space.

To conclude, RICH detectors require a big effort to build, run, maintain and extract physics results. Secondly, significant physics results have been obtained. In certain cases a RICH gives unique results, as no other measurements exists, in most cases competitive results are obtained.

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