CRN 95–21

A PARTICLE IDENTIFICATION METHOD FOR RING IMAGING CHERENKOV DETECTORS

Marcos DRACOS

Centre de Recherches Nucléaires, IN2P3-CNRS/Université Louis Pasteur,

BP 28, F-67037 Strasbourg Cedex, France

To be submitted to Nuclear Instruments and Methods in Physics Research

CENTRE DE RECHERCHES NUCLEAIRES

STRASBOURG

IN2P3

CNRS

UNIVERSITE

LOUIS PASTEUR

A PARTICLE IDENTIFICATION METHOD FOR RING IMAGING CHERENKOV DETECTORS

Marcos DRACOS
Centre de Recherches Nucléaires, IN2P3-CNRS/Université Louis Pasteur,
BP 28, F-67037 Strasbourg Cedex, France

Abstract

A particle identification method for RICH's is presented. This method computes the probabilities for the known charged particles (e, μ, π, K, p) and provides also an unbiased mean Cherenkov angle. A maximum likelihood binning procedure is used taking into account the measured Cherenkov angle for each detected photoelectron and their local density inside the detector. The space in which the method is applied is separated into cells, the number of observed photoelectrons in each cell is compared to the expected one and a global probability for all the cells is computed. The method can easily take into account local problems in the detector and thus it can be well adapted to the experimental reality.

1 Introduction

In the Ring Imaging Cherenkov detectors [1] very often the background contribution is not negligible [2] compared to the number of Cherenkov photoelectrons. This is mainly due to the fact that the charged particles to be identified cross also the sensitive parts of the detector producing secondary effects as ionization electrons and δ rays. Furthermore, these detectors must be able to detect single electrons requiring high chamber gain inducing feedback electrons [3]. Neighbouring Cherenkov rings also contribute to the background. For these reasons, the search of the Cherenkov ring position for each studied charged particle and thus identify it becomes difficult.

All the information coming from the detector and the characteristics of the Cherenkov phenomenon have to be used in order to maximize the particle identification efficiency. We present here a method to extract the mean Cherenkov angle of a Cherenkov ring using only the Cherenkov effect lows without taking into account the known particle masses that could bias the result.

2 Cherenkov effect

The Cherenkov light emitted by the passage of a charged particle through a transparent medium (radiator) forms a cone around the particle direction. The angle θ_c of the cone (Cherenkov angle) is related to the particle velocity β by the formula:

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

where n is the refractive index of the radiator. For $\beta \longrightarrow 1$ the Cherenkov angle saturates to the value $\theta^{sat} = \arccos(1/n)$ while for $\beta < 1/n$ there is not Cherenkov light emission (Cherenkov threshold). Figure 1 presents the Cherenkov angle versus the momentum for electrons, muon, pions, kaons and protons for a liquid (C_6F_{14}, $n = 1.276$) and a gas (C_5F_{12}, $n = 1.0019$) radiator.

The Ring Imaging Cherenkov technic uses two methods to detect the Cherenkov light, the "proximity" focussing and the focussing by mirrors [2]. The Cherenkov images, projected on a sphere having its centre on the track at the middle of the radiator, are circles (Cherenkov rings). The radius of the ring is proportional to $\sin\theta_c$. Circles with radius proportional to $\tan\theta_c$ are also obtained when the Cherenkov images are projected on a plane perpendicular to the track.

The number of detected photoelectrons (electrons created by the Cherenkov photons) is given by the relation [1]:

$$N_{pe} = N_0 l \sin^2\theta_c \tag{2}$$

where N_0 is the detector quality factor and l is the radiator length.

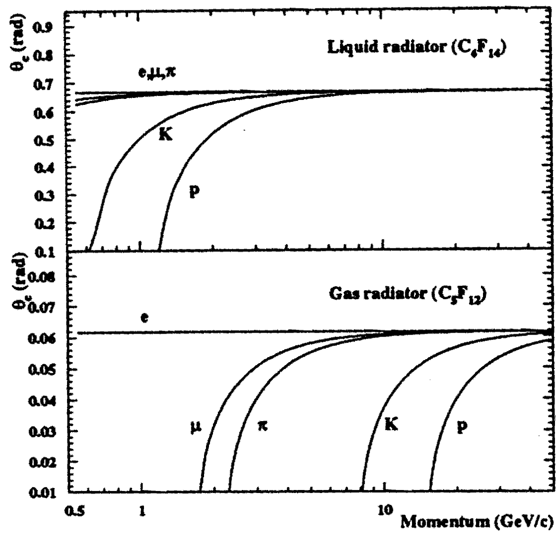

Figure 1: Cherenkov angle versus the particle momentum for electrons, muons, pions, kaons and protons for a liquid (C_6F_{14}) and a gas (C_5F_{12}) radiator.

The RICH, for each photoelectron, detects its conversion point, i.e. the location where the Cherenkov photon has been converted into electron in order to be observed. Using this location and the particle direction, given by the tracking detectors of the experiment, a Cherenkov angle θ_c is reconstructed for each detected electron (signal and background).

The Cherenkov angle resolution depends on the chromatic dispersion of the radiator and the experimental device (width of the radiator, spatial resolution etc...) and can be calculated for each particle and each location in the detector [4].

The background behaviour, specific to each detector and experiment, has to be studied carefully in order to correctly take it into account during the probability evaluation for each Cherenkov ring candidate. For a uniform background electron population inside the detector, in first approximation, the background increases linearly with the Cherenkov angle.

All the above characteristics can be used in order to find the right Cherenkov ring position. For cases free of background, a single weighted mean Cherenkov angle for all the detected photoelectrons is enough. For particles below the threshold, the role of the background is very important because in this case the probability evaluation relies only on the absence or not of signal. A high background contribution or a detector malfunctioning could favor the hypotheses where no Cherenkov light is expected.

3 Identification Method

If G_i is the probability to detect one photoelectron (coming from Cherenkov light) at location i (cell having finite dimensions), for a particle where the expected number of photoelectrons is N^h, the mean number of photoelectrons detected at cell i is $N^h G_i$. If K^h is the total expected number of electrons coming from the background and B_i is the probability to detect one background electron at cell i, the mean number of background electrons per particle detected at cell i is $K^h B_i$. The probability to detect n^i electrons coming from both signal and background is given by the poissonian distribution (see appendix):

$$P_i^n = \frac{(N^h G_i + K^h B_i)^{n_i}}{n_i!} e^{-(N^h G_i + K^h B_i)}. \tag{3}$$

The total probability for each ring hypothesis h is defined as:

$$P^h = \prod_i \{ \frac{(N^h G_i + K^h B_i)^{n_i}}{n_i!} e^{-(N^h G_i + K^h B_i)} \}. \tag{4}$$

If the cell dimensions are chosen infinitely small, G and B become also infinitely small and the probability to detect in one cell more than one electron is negligible. In this case the formula (4) can be written:

$$\begin{aligned} P^h &\approx \prod_{j_1=1}^{N_{obs}} \{(N^h G_{j_1} + K^h B_{j_1})\} \prod_{j_0} \{1 - (N^h G_{j_0} + K^h B_{j_0})\} \\ &\approx \prod_{j_1=1}^{N_{obs}} \{(N^h G_{j_1} + K^h B_{j_1})\} e^{-(N^h + K^h)} \end{aligned} \tag{5}$$

using:

$$\prod_{j_0} \{1 - (N^h G_{j_0} + K^h B_{j_0})\} \sim e^{-(N^h + K^h))}$$

where j_1 is the index of cells having one electron, j_0 is the index of cells without electrons and N_{obs} is the number of cells with one detected electron. The formula (5) has already been proposed in [5].

In the case where no electrons are observed in the considered region, the probability given by the formula (4) becomes:

$$P^h = e^{-(N^h + K^h)} \tag{6}$$

If all the detected electrons are projected on the surface of a sphere as explained above, called in the following (θ_c, φ_c) space, the probability G to detect one photoelectron at (θ, φ) can be written as:

$$G(\theta,\varphi) = \frac{\sin\theta d\varphi d\theta e^{-\frac{(\theta-\theta^h)^2}{2\sigma^2}}}{\int_{\theta_1}^{\theta_2} \sin\theta' e^{-\frac{(\theta'-\theta^h)^2}{2\sigma'^2}} d\theta' \int_{\varphi_1}^{\varphi_2} d\varphi'} \tag{7}$$

where:

θ	:	the Cherenkov angle of cell i
φ	:	the azimuthal angle of cell i around the track
θ^h	:	expected Cherenkov angle of hypothesis h
σ	:	expected θ resolution for cell i
$\theta_1, \theta_2, \varphi_1, \varphi_2$	:	θ and φ limits of the (θ_c, φ_c) space
$\sin\theta d\varphi d\theta$	:	surface of the cell i.

In the case where the number of electrons coming from the background is proportional to the surface of the cell (in the (θ_c, φ_c) space) the probability B to detect a background electron at (θ, φ) is:

$$B(\theta,\varphi) = \frac{\sin\theta d\varphi d\theta}{\int_{\theta_1}^{\theta_2} \sin\theta' d\theta' \int_{\varphi_1}^{\varphi_2} d\varphi'} \tag{8}$$

In practice, the cell dimensions $d\theta$ and $d\varphi$ can be chosen according to the detector performance. $d\theta$ can be chosen in order to have $d\theta = \Delta\theta \preceq \sigma$. The cell dimension in φ direction $d\varphi = \Delta\varphi$ can be chosen in order to check if the electrons are well around the track or they just cover a small region as it is very often the case for background electrons. In this way, absolute quality criteria for each ring can be established (particles having all the associated electrons in a part of the expected ring will have lower probability than those where the electrons are uniformly distributed around the track). The cell dimension $\Delta\theta$ and $\Delta\varphi$ can vary from location to location according to the expected resolution and the expected number of photoelectrons.

Using a maximum likelihood method, P^h can be maximized for each hypothesis by varying the background contribution K^h as in [5].

For Fast RICH's [6] only two coordinates are measured (pixel position) for each electron while for slow RICH's [2] where the photon conversion is done in a big drift volume, the measurement of a third coordinate is necessary (figure 2). This third coordinate allows the measurement of the photon penetration length inside the photosensitive gas. For the "signal" the probability to observe the photoelectron between λ and $\lambda + d\lambda$ is:

$$P_s(\lambda) = \frac{e^{-\frac{\lambda}{\lambda_0}} d\lambda}{\lambda_0} \tag{9}$$

where: λ is the penetration length for cell i and λ_0 is the photon mean free path.

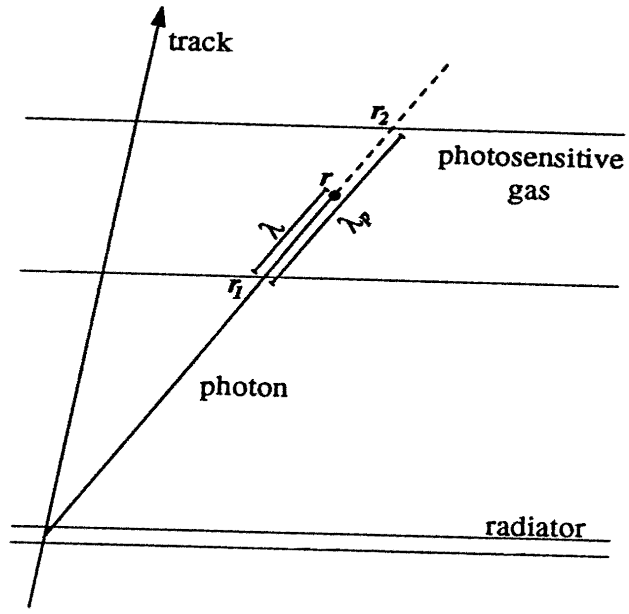

Figure 2: Measurement of the photon penetration path inside the photosensitive volume.

If the drift tube limits (photosensitive region) are taken into account, (9) can be written:

$$P_s(\lambda) = \frac{e^{-\frac{\lambda}{\lambda_0}} d\lambda}{\int_0^{\lambda_p^i} e^{-\frac{\lambda'}{\lambda_0}} d\lambda'} \tag{10}$$

where λ_p^i is the potential length (maximum available penetration length) of cell i. We can consider that the background distribution is uniform in λ direction.

If the spherical coordinates (θ, φ, r) are considered where r is the radial cell position (the origin being the photon emission point) the signal and background probabilities can be written as follow:

$$G(\theta, \varphi, r) = \frac{r \sin\theta d\varphi d\theta dr e^{-\frac{(\theta-\theta^h)^2}{2\sigma^2}} e^{-\frac{\lambda}{\lambda_0}}}{\int_{\theta_1}^{\theta_2} \sin\theta' e^{-\frac{(\theta'-\theta^h)^2}{2\sigma'^2}} d\theta' \int_{\varphi_1}^{\varphi_2} d\varphi' \int_{r_1}^{r_2} r' e^{-\frac{\lambda'}{\lambda_0}} dr'} \tag{11}$$

$$B(\theta, \varphi, r) = \frac{r \sin\theta d\varphi d\theta dr}{\int_{\theta_1}^{\theta_2} \sin\theta' d\theta' \int_{\varphi_1}^{\varphi_2} d\varphi' \int_{r_1}^{r_2} r dr'} \tag{12}$$

where $\lambda = r - r_1$ with r_1 and r_2 the entry and exit points in the drift volume, and r the conversion position (figure 2).

In the case where the expected number of photoelectrons N^h for hypothesis h is not zero, $P^h(N^h, K^h)$ is the probability to have observed signal and background while $P^h(0, K^h)$ is the probability to have observed only background. The quantity:

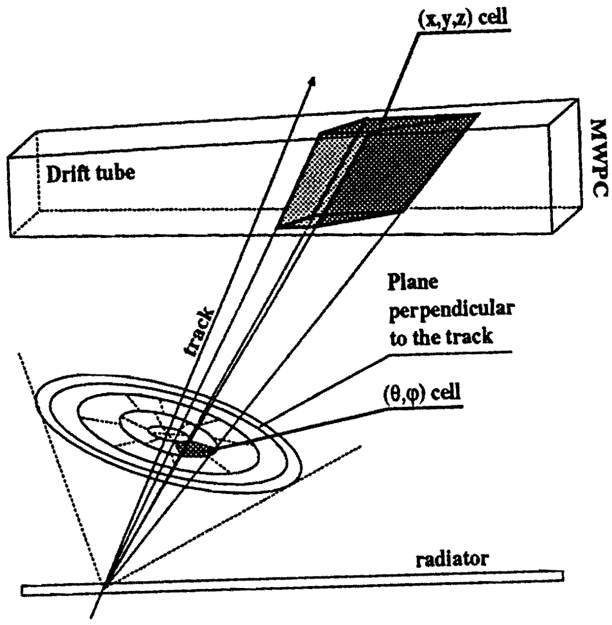

Figure 3: Projection of the Cherenkov images on a plane perpendicular to the particle direction and extrapolation of the cells of this plane to the detection volume.

$$\alpha^h = \frac{(signal + background)\ probability}{background\ probability} = \frac{P^h(N^h, K^h)}{P^h(0, K^h)} \tag{13}$$

can be used for each particle as an absolute quality criterion. The probability of particles below the Cherenkov threshold ($N^h = 0$) is also $P^h(0, K^h)$ and in this case $\alpha^0 = 1$ ($h = 0$ is defined as the hypothesis where $N^h = 0$). Finally, α^h can replace the probability P^h in which case all the given probabilities are relative to the probability to have observed only background. For particles above the Cherenkov threshold ($N^h > 0$), for the best hypothesis, an absolute lower value α_{min} (e.g. $\succeq 1$) can be requested for α^h. If this requirement is not satisfied, the hypothesis $N^h = 0$ can be chosen. If, in this case, for all the tested hypotheses, N^h is greater than 0, it can be considered that the RICH cannot give a reliable information for the current particle. The parameter α_{min} can be fixed according to the desired confidence level using for example known physics channels or a Monte Carlo simulation where the background contribution is well simulated.

4 Experimental application of the method

The method is very flexible for taking into account detector dead regions and all local problems as problematic electronic channels, electronic buffer saturations or electron attachment during drift.

For each cell in (θ_c, φ_c) space the corresponding volume in the photosensitive region can be found (figure 3). Each cell i can be characterized by (θ^i, φ^i) and the corresponding

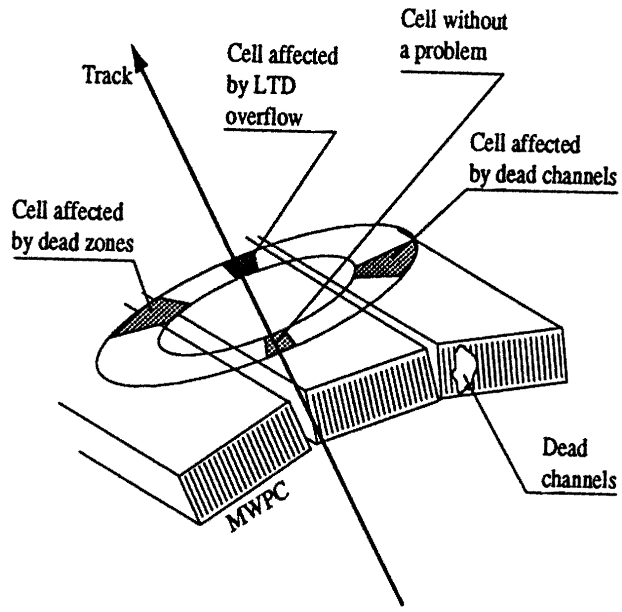

Figure 4: Illustration of the cells affected by possible "experimental" problems.

volume $V^i(x,y,z)$. All problems affecting the cell i can easily be taken into account for the evaluation of the expected number of electrons for this cell. Furthermore, the Cherenkov angle reconstruction for each observed electron is not any more necessary. Each (x,y,z) electron will be placed in its volume $V^i(x,y,z)$ to which corresponds the cell (θ^i,φ^i) choosing $\Delta\theta^i \preceq \sigma^i$. Of course, some computer time will be spent to find the correspondence between cells (θ^i,φ^i) and volumes $V^i(x,y,z)$ for each particle. For that, all points (θ,φ) in (θ_c,φ_c) space corresponding to the four cell nodes have to be propagated (taking into account possible refractions on windows delimiting the different volumes and reflections on mirrors) up to the photosensitive volume (figure 3). The computing time spent for that must not be much higher than for the case where the Cherenkov angles are reconstructed only for the detected electrons. In the majority of the RICH's, for each electron, several iterations are necessary in order to reconstruct the corresponding Cherenkov angle taking into account all refractions and reflections in the detector (analytical solutions to reconstruct the photon trajectory knowing the emission and detection points are very complicated).

To find an unbiased mean Cherenkov angle for each particle, the maximum value of $P^h(\theta)$ or $\alpha^h(\theta)$ can be found by considering continue θ values varying from θ_{min} to θ_{max} (e.g. $\theta_{min} = 0$ and $\theta_{max} = \theta_{sat} + 10\sigma$ with θ_{sat} being the saturated Cherenkov angle corresponding to $\cos\theta_{sat} = 1/n$). The method has been applied on the DELPHI Barrel RICH data and allowed the first $s-$quark asymmetry measurement [7] by identifying fast charged kaons. Figure 5 presents the mean Cherenkov angle versus the particle momentum using the liquid radiator C_6F_{14} [8] while figure 6 [7] is for gas radiator C_5F_{12}. The mass squared distribution ($m^2 = p^2(n^2\cos^2\theta - 1)$) corresponding to figure 6 is shown by figure 7. A clear kaon signal is observed.

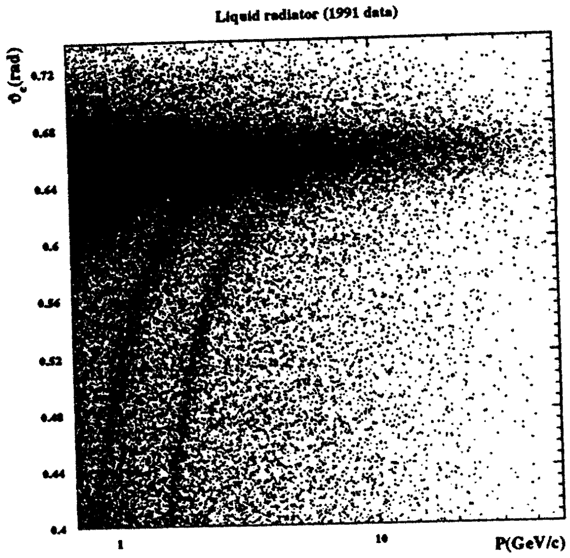

Figure 5: Mean Cherenkov angle versus particle momentum for DELPHI RICH liquid radiator C_6F_{14}.

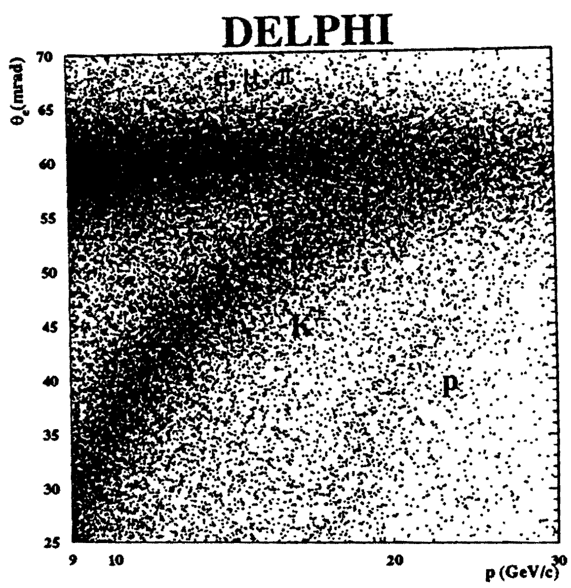

Figure 6: Mean Cherenkov angle versus particle momentum for DELPHI RICH gas radiator C_5F_{12}.

5 Conclusion

The particle identification method proposed for RICH detectors is able to use the whole information coming from the detector. In this way all detector problems can be taken

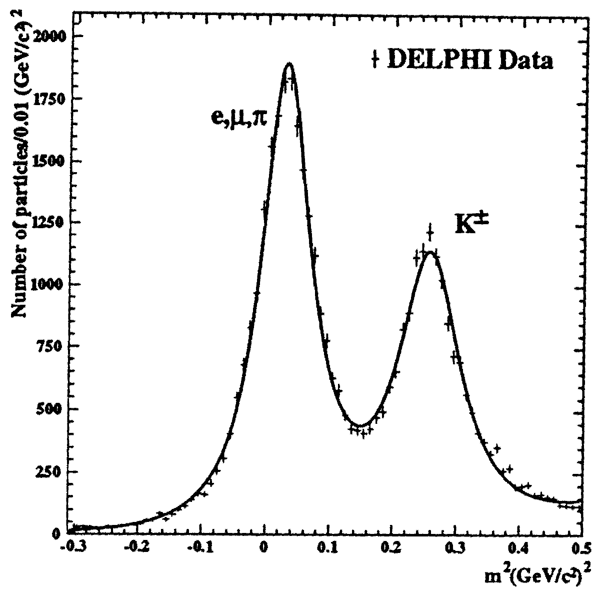

Figure 7: Mass squared distribution using the DELPHI RICH gas radiator C_5F_{12} for all charged particles with momentum between 10 GeV/c and 18 GeV/c.

into account in a natural way. The "blind" application of the method on a continue mass hypothesis spectrum can give an unbiased mean Cherenkov angle. The method has been applied with success on real data.

Appendix

We consider that we observe a RICH ring (liquid or gas) in a certain space (of one or more dimensions) which is subdivided in cells. If we call H the probability to observe 1 photoelectron in the cell i, the probability to observe j photoelectrons in this cell for a total number of k photoelectrons detected in the whole space is:

$$P_j = C_k^j H^j (1-H)^{k-j} \tag{14}$$

The probability to observe k photoelectrons following the Poisson distribution with mean value M and from these k photoelectrons have j photoelectrons in the cell i is:

$$\begin{aligned} P_{j,k} &= \frac{M^k}{k!} e^{-M} C_k^j H^j (1-H)^{k-j} && (15) \\ &\Longrightarrow \\ P_j &= \sum_{k=j}^{\infty} \frac{M^k}{k!} e^{-M} C_k^j H^j (1-H)^{k-j} \\ &= \frac{e^{-MH}}{j!} (MH)^j && (16) \end{aligned}$$

If we assume that in our sample we have, m photoelectrons coming from the "signal" with a probability distribution G, l photoelectrons coming from the background with a probability distribution B and if we assume that the number of photoelectrons for these two categories follow the Poisson distribution with mean values N and K (resp.), the probability to observe n photoelectrons (signal+background) in the cell i is ($l = n - m$):

$$\begin{aligned} P_n &= \sum_{m=0}^{n} \underbrace{\frac{e^{-NG}}{m!} (NG)^m}_{signal} \times \underbrace{\frac{e^{-KB}}{(n-m)!} (KB)^{(n-m)}}_{background} \\ &= \frac{(NG+KB)^n}{n!} e^{-(NG+KB)} && (17) \end{aligned}$$

which is a Poisson distribution with mean value $NG + KB$.

References

[1] J.Séguinot and T.Ypsilantis, Nucl.Instr. and Meth. 142(1977)377.

[2] DELPHI Technical Proposal, CERN/LEPC/83-3, 83-86(1983).
DELPHI Progress Report, CERN/LEPC/84-16 (1984).
Anassontzis et al, Nucl.Instr. and Meth. A323(1992)351.

[3] M.Dracos, *"Identification des particules dans l'expérience LEP-DELPHI"*, PhD Thesis, Université Louis Pasteur de Strasbourg, CRN/HE 87-10.
R.Arnold et al, Nucl.Instr. and Meth. A270(1988)255.
M.Dracos and D.Loukas, Nucl.Instr. and Meth. A302(1991)241.

[4] T.Ekelöf, *"The Experimental Method of Ring Imaging Cherenkov (RICH) Counters"*,CERN EP 84-168 (1984).
T.Ypsilantis, *"Particle Identification at hadron colliders"*, CERN-EP/89-150.
J.Séguinot and T.Ypsilantis, *"Ring Imaging Cherenkov counters"*, CERN-LAA/PI/91-004.

[5] P. Baillon, Nucl.Instr. and Meth. A238(1985)341.

[6] R. Arnold et al., Nucl. Instr. and Meth. A273(1988)466.

[7] DELPHI Collaboration, *"First Measurement of the Strange Quark Asymmetry at the Z^0 Peak"*, CERN-PPE/94-219.

[8] M. Dracos, *"Production of Light Quark Resonances in Z^0 Decays"*, Proceedings of the XXVI International Conference on High Energy Physics, 1992, Dallas, Texas.