Photon Analysis Code

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Contents

1 Introduction

This document describes a set of routines to analyze the photon part of an E852 event. The analysis techniques are mature since they were deduced from experience with P2. The methods for passing results to and from these routines should be considered under development and I would appreciate feedback if anyone has a preferences as to how this should be done.

The input to these routines consists of a list of the indicies of struck blocks and the pulse heights in these struck blocks. The output is an integer giving the "topology" of the event, e.g. $b_1 \rightarrow \omega\pi$, pointers that connect the photons to their massive parent, the fitted photon monenta, the momenta of the massive parents and the results from the cluster finder.

The arguments passed to and from this routine are consistant with the "utility" routines it calls, for example the IU cluster finder. I have attempted to design the arguments so that it should be straightforward to interface these routines to a driver routine using our defined structures. Experience will no doubt lead us to re-arrange these structures or perhaps even create new ones.

In the current version, HBOOK histograms are created and filled. I have made an attempt to use a rational numbering scheme for these histograms but I am aware that you can't please all of the people all of the time. I am planning to create a production version without histogramming.

These routines are based on the experience from P2 and have been tested using this data. Several "modes" of analysis are possible. This release version is configured with the default behavior appropriate for the start-up of the experiemnt. I discuss these "modes" in the appropriate sections below.

2 Analyis Methods

The behavior of the analysis depends on the number of photons found by the cluster finder. An attempt is made to connect the photons to a massive parent, usually $\pi's$ and/or $\eta's$, but, when possible, $\omega's$. Pointers, connecting the photons to their parents are passed to the calling routine. A number, denoted by ICASE below, is returned defining the final state found. Constrained fits are performed using the masses of the parents and the photon momenta are modified to reflect the result of this fit.

The first stage of the analysis is cluster finding. The IU algorithm is described in an E852 man page and I discuss it no further here. The results of the cluster finding are returned as arguments to the calling routine.

The next stage of the analysis consists of connecting the photons to massive parents. The methods available depend on the number of photons in the event and are discussed below in specfic sections relating to each available photon multiplicity.

2.1 Hypothesis Sorting

Two methods for hypothesis testing are currently implemented with a third being a near certainty. These methods are referred to as:

- The Window Method
- The χ^2 by Energy Method
- The χ^2 by Hypothesis Method

The window method, useful for events with a photon multiplicity of less than about 4, defines a range of values around the mass of a presumed parent where a given pair of photons can be taken as decay products of the parent, that is, photons i and j could be considered decay products of an η if

$$\mid m_{ij} - m_\eta \mid \leq \delta_\eta \tag{1}$$

where m_{ij} is the effective mass of photons i and j. This method is most useful during the early stages of analysis when, for example, the calibration constants have not reached their final values.

The χ^2 by energy method, useful for photon multiplicites of 4 or higher, attempts to find an arrangement of photons that minimizes

$$\chi^2 = \sum_{pairs} ((m_{ij} - m_h)/\sigma_{ij})^2 \tag{2}$$

where m_h is the mass of the π or η. σ_{ij} is the expected error in m_{ij} and is calculated from the energies of the photons using

$$\frac{\sigma}{E} = \frac{k}{\sqrt{E}} + b \tag{3}$$

with reasonable values for k and b defined by default. This method, most extensively tested for 4 photon events, tends to reduce the yield and increase the purity of "common" topologies (read $\pi\pi$) while increasing the yield of uncommon topologies (read $\eta\pi$). The signal to noise ratio tends to remain unchanged for the uncommon topologies.

This method is very sensitive to the values of its parameters and *requires* a well converged calibration. Furthermore, the actual values of the χ^2 calculated by this method tend not to be distributed properly when reasonable values for the photon energy resolution parameters are used. A scale factor for the χ^2 has been introduced to force a proper distribution. Even with these limitations, this method is useful for selecting pure samples of a given topology and for determining the relative numbers of events in different topologies.

I currently believe that the limitations of the χ^2 by energy method are an artifact of the calibration method. The calibration does not optimize the energy resolution for photons but rather optimizes the resolution of the effective mass of pairs of photons. This observation has led me to investigate a third hypothesis sorting algorithm, the χ^2 by hypothesis method. This method seeks combinations of photons and massive parents that minimizes

$$\chi^2 = \sum_{pairs} ((m_{ij} - m_h)/\sigma_h)^2 \tag{4}$$

where σ_h is simply the observed width of the π or η for a given multiplicity. This method is not implemented in this release and has not been investigated throughly. Preliminary results, using the small 6 photon sample from P2, are encouraging and future releases may exploit this method.

Once an acceptable hypothesis has been found, constrained fits using the masses of the parents are performed. The 4-vectors of the parents are calculated using these fitted photon momenta. The effective masses of combinations of massive particles are evaluated, as are the effective masses of combinations of massive particles and any remaining “loose” photons.

An integer, referred to as ICASE below, is given a value to communicate the results of comparisons of the effective masses of massive pairs to the masses known resonances. Table 1 gives a list of values for ICASE and the correspondance to physical final states. The conditions for becomming a specific ICASE are discussed below in the appropriate sections for specific photon multiplicites.

TABLE 1. ICASE values

Number of photons	2	3	4	5	6
ICASE=0	2γ	3γ	4γ	5γ	6γ
1	π^0	$\pi\gamma$	$\pi\gamma\gamma$	$\pi 3\gamma$	$\pi 4\gamma$
2	η	$\eta\gamma$	$\eta\gamma\gamma$	$\eta 3\gamma$	$\eta 4\gamma$
3	η'		$\pi\pi$	$\pi\pi\gamma$	$\pi\pi\gamma\gamma$
4			$\eta\pi$	$\eta\pi\gamma$	$\eta\pi\gamma\gamma$
5			$\eta\eta$	$\eta\eta\gamma$	$\eta\eta\gamma\gamma$
6			$\omega\gamma$	$\omega\pi$	3π
7			K_s	$\omega\eta$	$\eta\pi\pi$
8			f_2	$a_0\gamma$	$\eta\eta\pi$
9			a_0	$a_2\gamma$	3η
10			a_2	b_1	$\omega\pi\gamma$
11				$f_2\gamma$	$\omega\omega$
12				$K_s\gamma$	$\omega\eta\gamma$
13					$\eta \rightarrow 3\pi$
14					$\eta' \rightarrow \eta\pi\pi$
15					$a_0\pi$
16					$a_2\pi$
17					$a_0\eta$
18					$a_2\eta$
19					$b_1\gamma$
20					$K_s\pi$
21					$K_s\eta$
22					$f_2\pi$
23					$f_2\eta$

2.2 Histograms

Several histograms are filled by this analysis. A histogram ID is a four digit number. The first digit is the number of photons in the event. The second digit gives the level of cut used to select the events used to fill the histogram. The last two digits are read from the ID suffix column of the table 2. 1 and 2 are currently undefined for the second digit. x3xx histograms have no events with a photon near the hole or an edge of the LGD. x4xx histograms satisfy the hole and edge cuts and have more that 10 GeV deposited in the LGD. x5xx histograms are like the x4xx histograms but have more than 13 GeV deposited in the LGD. The values of 10 and 13 GeV are provided as defaults and can be changed at set-up time.

TABLE 2. Defined Histograms

ID suffix	2γ	3γ	4γ	5γ	6γ
00		3γ	4γ	5γ	6γ
01	$\gamma\gamma$	$\gamma\gamma$	$\gamma\gamma$	$\gamma\gamma$	$\gamma\gamma$
02		$\pi\gamma$		$\gamma\gamma$ from $\pi 3\gamma$	
03		$\eta\gamma$		$\pi\pi$ from $\pi\pi\gamma$	
04		t from $\pi\gamma$	$\pi\pi$	$\pi\gamma$ from $\pi\pi\gamma$	$\pi\pi$ from 3π
05		mm from $\pi\gamma$	$\eta\pi$	$\omega\pi$	$\pi\pi$ from $\eta\pi\pi$
06			$\eta\pi$	$\eta\pi$	$\eta\pi$ from $\eta\pi\pi$
07			$\pi\pi$ for 2^{++}	$\eta\gamma$ from $\eta\pi\gamma$	3π
08			$\pi\pi$ for 4^{++}	$\pi\gamma$ from $\eta\pi\gamma$	$\eta\pi\pi$
09			$\pi\pi$ for 6^{++}	$a_0\gamma$	$\eta\pi\pi$ near a_0
10			t from $\pi\pi$	$\eta\omega$	
11			mm from $\pi\pi$		
12			$\pi\gamma$ from $\pi\gamma\gamma$		
13			$\omega\gamma$		
14			$\eta\gamma$ from $\eta\gamma\gamma$		$\eta\eta\pi$
15					$\eta\pi$ from $\eta\eta\pi$
16					$\eta\eta$ from $\eta\eta\pi$
17					$\eta\eta\pi$ near a_0
18					$\pi\gamma$ from $\pi\pi\gamma\gamma$
19					$\omega\omega$
20					$\omega\pi$ from $\pi\pi\gamma\gamma$
21					$\omega\pi\gamma$
22					$b_1\gamma$

Table 2 Some predifined histograms from the neutral analysis package. An example of how to read a table entry: if ID suffix=06 and the number of photons in the event is 6, histogram 6306 will contain both combinations of $\eta\pi$ effective mass from $\eta\pi\pi$ events satisfying the fiducial cut. mm means missing mass. $\eta\pi\pi$ near a_0 means the $\eta\pi\pi$ mass when one or more $\eta\pi$ effective mass combinations was near the mass of the a_0.

2.3 The Calling Sequence

This analysis is invoked by calling: process_lgd(*arguments*) with the following list (discussed below) of arguments (in this order):

- input variables
  - real pbeam(3)
  - real ebeam
  - real vertex(3)
  - real zlgd
  - real cc(3053)
  - integer ipeds(3053)
  - integer madc
  - integer kadc(3053)
- return variables (from the cluster finder)
  - real eblk(500)
  - integer iblk(500)
  - integer nblk
  - integer nclus
  - integer nbclus(8,25)
  - real ebclus(8,25)
  - integer mbclus(8)
  - real eclus(8)
  - real xclus(8)
  - real yclus(8)
  - real sigmac(8)
- return variables (from the hypothesis sorter)
  - real etotc
  - logical fidcut
  - real efmass(28)
  - real rgamma(3,8)

- real pgamma(3,8)
- real eprime(8)
- integer icase
- integer nmp
- integer itype(4)
- integer ipoint(4,2)
- integer nomg
- integer iomg(2,2)
- real chi6
- real ichi(2)
- real p1(3)
- real ep1
- real p2(3)
- real ep2
- real p3(3)
- real ep3

pbeam and ebeam are the beam energy and momentum and are are used to calculate momentum transfers to the neutral system. If process_lgd is being called before the beam analysis, an (as yet undetermined) average value for these quantities can be used.

vertex will be used to determine one end of the photon tracks, the position in the LGD determining the other. If process_lgd is called before charged particle reconstruction a good approximation to this quantity is the center of the target.

zlgd is the z-coordinate of the LGD. This variable is provided in case it becomes desireable to use these routines to process, for example, P2 data.

cc and ipeds are the calibration constants and pedestals appropriate for the run being analyzed. These are used to convert pulse heights into block energies.

madc is the number of ADC channels that were read out for a particular event. kadc contains the pulse heights. These are dimensioned as they are to allow the possibility of processing laser or pedestal events in these routines. (Currently, no such capability exists)

Variables returned from the cluster finder are discussed in the documentation for the cluster finder. They are included here for use with the calibrator.

etotc and fidcut are used for selecting events for histogramming. etotc is the sum of the un-fitted cluster energies. fidcut is .true. if no photon is near the hole or an edge of the LGD.

efmass is mostly useful internally but contains the effective masses of the un-fitted photon pairs. Filled by a do loop that looks like this:

```
k=0
do i=1,ngamma-1
   do j=i+1,ngamma
      k=k+1
      efmass(k)=mass(i,j)
   enddo
enddo
```

rgamma contains the photon 3-vector positions. These are currently identical to the corresponding quantities in xclus,yclus and zlgd but may be adjusted by future versions.

pgamma contains the fitted photon 3-vectors. If no fit was possible, e.g. the event failed the hypothesis sorts, pgamma is calculated from rgamma and the un-fitted cluster energy. If a fit was possible, the fitted photon energy is used.

eprime contains the fitted photon energies. If no fit was possible for the $i'th$ photon, eprime(i) will contain the un-fitted cluster energy of the $i'th$ photon.

icase determines the final state and is discussed above.

nmp, ipoint and itype connect photons to their massive parents. nmp is the number of massive parents *decaying into 2 photons* found. An example is in order for ipoint: Suppose nmp=3 and itype=(1,3,2,0) The first massive parent was a pion (because itype(1)=1), the second was an η' and the third was an η. The 3'rd massive parent found (the η) decayed into photons ipoint(3,1) and ipoint(3,2).

nomg is the number of $\omega \rightarrow \pi\gamma$ decays found. iomg(1,1) contains the pointer to ipoint that tells you which two photons decayed into the π^0 for the 1'st omega. iomg(1,2) points to the bachelor photon for the first omega. An example:

Suppose nomg=1, iomg(1,1)=2 and iomg(1,2)=5. Then the π^0 decayed into photons ipoint(2,1) and ipoint(2,2) and the bachelor photon is number 5.

chi6 is the value of the χ^2 from the six-photon analysis routine. ichi contains the hypothesis index of the best and second best χ^2 values. These are useful for checking ambiguous hypothesis assignments but I have'nt fully thought out how to pass this information to the calling routines. I promise to devote further thought to this and will update the code and documentation soon.

p1,ep1, etc. contain the 3-vector momentum and total energy of fitted massive parents. These variables are configured as they are to allow those who do not respect IUPAP 4-vector indexing conventions to create their own convention. (and you know who you are)

2.4 Configuring the Analysis

The analysis is configured by giving values to elements of common blocks used only by these routines. The exact mechanism for this has not yet been decided but will be when the code is installed in the analyzer. I will update this document appropriately when these decisions have been reached. For the time being, I list the common blocks, their content, the default values and a description of the variables.

The parameters describing the energy resolution for photons are conatined in

- common/resp/stat,floor,dangle
  - real stat /0.07/ k of eqn.3
  - real floor /0.02/ b of eqn. 3
  - real dangle /0.00/ currently unused
- common/concutp/elim1,elim2
  - real elim1 /10./ energy required for a x4xx histogram
  - real elim2 /13./ energy required for a x5xx histogram

3 Multiplicity Specific Analysis

Diferent methods are appropriate for different photon multiplicities. The following sections give details pertaining to these methods.

3.1 2 Photon Events

The $\gamma\gamma$ effective mass is evaluated. If this mass is within a window around the π, η or η' mass, the photon energies are recalculated using the parent mass as a constraint and the momenta modified using these new energies. The mass windows are selected by giving values to elements of the common block.

- common/config2/do2,dpi2,deta2,detap2
  - logical do2 /.true./ if .false. skip 2-photon analysis
  - real dpi2 /0.025/ window cut defining π^0
  - real deta2 /0.040/ window cut defining η
  - real detap2 /0.060/ window cut defining η'

If the $\gamma\gamma$ mass does not fall within any of these windows, icase=0 is returned and no fits are performed.

3.2 3 Photon Events

The effective mass of pairs of photons are compared to the π^0 mass with the window method. If a pion is found, the $\pi\gamma$ mass is compared to the ω mass with the window method. If the event is consistant with the ω window, all three photons are fitted. If not, the two photons consistant with the π^0 mass are fitted to this hypothesis. If no π^0 is found, the effective mass pairs are compared to the η mass. If an η is found the photons consistant with the η are fitted. If no η is found icase is set to zero and no fits are performed.

The windows can be re-defined with the following variables:

- common/config3/do3,dpi3,deta3,domega3
  - logical do3 /.true./ if .false. skip 3-photon analysis
  - real dpi3 /0.025/ window cut defining π^0
  - real deta3 /0.050/ window cut defining η
  - real domega3 /0.060/ window cut defineing ω

3.3 4 Photon Events

Two analysis methods are currently available for 4 photon events.

If usechi4 (see below) is .false. a window method sort is used. The hypotheses are tested in the following order: $\pi\pi, \eta\pi$ and $\eta\eta$. To satisfy a hypothesis two pairs of photons must be found such that both lie inside the windows defining the hypothesis. Once a hypothesis is satisfied, no further hypotheses are tested.

If usechi4 is .true. the χ^2 by energy method is used. The smallest χ^2 for the three hypotheses $\pi\pi, \eta\pi$ and $\eta\eta$ are found. If the minimum χ^2 for the $\pi\pi$ hypothesis is less than chipipi(2) the event is tagged as $\pi\pi$. If $\chi^2_{\pi\pi}$ is greater than chipipi(2) and $\chi^2_{\eta\pi}$ is less than chietapi(2) the event is tagged as $\eta\pi$. If the event failed both of the above tests and $\chi^2_{\eta\eta}$ is less than chietaeta(2) the event is tagged as $\eta\eta$. If any of the above hypotheses were satisfied, the photons are fitted. Histograms are filled if, for example, $\chi^2_{\pi\pi}$ is less than chipipi(1).

The effective mass of the two massive parents parents is computed and compared to the mass of several mesons. If this mass falls inside the windows defined below, the events are tagged as comming from a single parent.

If (with either the window method or the χ^2 by energy method) two massive parents could not be found the window method is used to search for photons from $\pi \to \gamma\gamma$ or $\eta \to \gamma\gamma$. The pair of photons with an effective mass closest to the pion is found. If this mass is within the pion window the $\pi\gamma$ effective masses are compared to the ω mass. If no pair can be found within the pion window, the pair closest to the η mass is found. If this mass is inside the η window the event is tagged as $\eta\gamma\gamma$. The events are fitted appropriately based on the results of this sort.

Due to the limitations of the χ^2 by energy method it is neseccary to scale the χ^2 to get an appropriate distribution. This factor is contained in the following common block.

- common/config4/do4, dpi4, deta4, domega4, dk04, df24, da04, da24, usechi4, chi4cut, chiscale, chipipi(2), chietapi(2), chietaeta(2)
  - logical do4 /.true./ if .false. skip 4-photon analysis
  - real dpi4 /0.030/ window cut defining pi0
  - real deta4 /0.040/ window cut defining eta
  - real domega4 /0.060/ window cut defining omega
  - real dk04 /0.020/ window cut defining k0
  - real df24 /0.100/ window cut defining f2(1270)
  - real da04 /0.050/ window cut defining a0(980)
  - real da24 /0.075/ window cut defining a2(1320)
  - logical usechi4/.true./ if .true. use chi-squared method for sorting
  - real chi4cut /35./ maximum acceptable chi-squared
  - real chiscale /2.621/
  - real chipipi /3.39,4./
  - real chietapi /1.85,2./
  - real chietaeta /0.5,1.0/

3.4 5 Photon Events

Currently, only the window method is available for 5 photon events. The effective mass of all combinations of pairs of photons is evaluated. If the mass of the pair closest to the pion mass is within the pion window those photons are tagged as daughters of a pion. The remaining pairs are searched for pion candidates. If another pion is found, the event is tagged as $\pi\pi\gamma$. If another pion cannot be found, the remaining pairs are searched for $\eta \rightarrow \gamma\gamma$. If an η is found the event is tagged as $\eta\pi\gamma$.

If no pion could be found in the first search, all photon pairs are searched for $\eta \rightarrow \gamma\gamma$ If an η is found, the remaining pairs are also searched for $\eta \rightarrow \gamma\gamma$. The events are tagged as $\eta\eta\gamma$ or $\eta 3\gamma$ based on the results of these searches.

$\pi\pi\gamma$ events are further searched for $\omega \rightarrow \pi\gamma$ combinations. If an effective mass pair falls within the ω window the event is tagged as $\omega\pi$. These events are taken as $b_1 \rightarrow \omega\pi$

candidates. The $\omega\pi$ mass is compared to the b_1 mass and icase set appropriatly based on this comparison.

$\eta\pi\gamma$ events are searched for $\omega \to \pi\gamma$. If the $\pi\gamma$ mass is inside the ω window, the event is tagged as $\omega\eta$. The $\eta\pi$ mass is compared to several mesons and if this mass is within the proper window the event is tagged as, for example, $a_0\gamma$.

Future versions will have χ^2 by energy sorting available.

The program can be configured with the following variables:

- common/config5/do5, dpi5, deta5, domega5, da05, da25, dk05, db15, df25
  - logical do5 /.true./ if .false. skip 5-photon analysis
  - real dpi5 /0.030/ window cut defining pi0
  - real deta5 /0.050/ window cut defining eta
  - real domega5 /0.070/ window cut defining omega
  - real da05 /0.100/ window cut defining a0(980)
  - real da25 /0.100/ window cut defining a2(1320)
  - real dk05 /0.025/ window cut defining Ks
  - real db15 /0.100/ window cut defining b1(1235)
  - real df25 /0.100/ window cut defining f2(1270)

3.5 6 Photon Events

Currently, only the χ^2 by energy sorting method exists for 6 photon events. The window method was abandonded at an early stage of program development because of problems with combinatorics.

The window method is attempted if the χ^2 method fails. The window method does not produce three parent final states but does produce $\omega\omega$ candidates. This is unfortunate because the $\omega\omega$ final state is very interesting but, since we have other channels available for this final state and the branching ratio into photons is small, I don't consider this a serious drawback *at this time.*

The smallest χ^2 from all photon combinations with the $3\pi, \eta\pi\pi, \eta\eta\pi$ and 3η hypotheses is found. If this χ^2 is less than chi6cut (see below) the event is tagged appropriately. Combinations of massive parent effective masses are evaluated and compared to several mesons and, based on these compairisons, the event tag may be modified.

If the χ^2 was unacceptable, a method identical to the 4-photon window method search is used to attempt to identify events with, for example, a final state like $\pi\eta\gamma\gamma$.

$\pi\pi\gamma\gamma$ events are searched for $\omega\omega, \omega\pi\gamma$ and $b_1\gamma$ candidates. $\eta\pi\gamma\gamma$ events are searched for $\omega\eta\gamma$ candidates.

No attempt at further reconstruction is made for $\pi 4\gamma$ or $\eta 4\gamma$ events.

Experience is very limited here and any results should be viewed cautiously. The only six photon final states observed to date are $\eta \to 3\pi$ and $\eta' \to \eta\pi\pi$. The default values of the parameters have been chosen conservatively in the hope that certain other obvious final states may be quickly observed.

The program can be configured with the following variables:

- common/config6/do6, chi6cut, dpi6, deta6, domega6, da06, da26, db16, df26, dk06
  - logical do6/.true./ if .false. skip 6-photon analysis
  - real chi6cut/7.5/ maximum acceptable chi-squared
  - real dpi6 /0.030/ window cut defining pi0
  - real deta6 /0.050/ window cut defining eta
  - real domega6 /0.070/ window cut defining omega
  - real da06 /0.075/ window cut defining a0(980)
  - real da26 /0.100/ window cut defining a2(1320)
  - real db16 /0.100/ window cut defining b1(1235)
  - real df26 /0.100/ window cut defining f2(1270)
  - real dk06 /0.025/ window cut defining Ks