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# A MINIMAL COMPREHENSIVE SET OF MUON BACKGROUND TOPOLOGICAL FINDERS FOR HIGH $P_T$ PHYSICS ANALYSIS

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**Abstract**

We present a global set of topological background finders resulting from an analysis, simplification and optimization of the large family of existing H1 background finders. This study is intended as a first step in clarifying the main concepts relevant for muon background topological recognition, and in providing a simple framework for further developments. The present results are implemented as code using DST data from most useful H1 subdetectors, with no redundancy between one finder and another. The package is described in detail and its performance evaluated on several background and physics data samples.

# 1 INTRODUCTION

The goal of this work is to develop a minimal set of muon induced background topological finders, for rejection of the residual background left after application of the standard high $P_t$ physics selection criteria such as vertex, $P_t$ cut, jets or e-identification. The study was conducted with the following philosophy:

- Extract from the large family of existing H1 background finders the key ideas which are efficient in rejecting the various kinds of muon induced background.
- Implement these ideas into a minimal but exhaustive set of background finders, adapting parts of the existing code when possible, with emphasis on simplicity.
- Provide code using DST information only.
- Separate halos and cosmics induced background finders.
- Use every relevant subdetector piece of information, with one dedicated finder per kind of subdetector or subdetectors correlations, ie no redundancy between the various finders. This feature is important in order to allow deactivation of finders involving a subdetector which is crucial for a dedicated physics channel ( for ex : the Muon Detector in exclusive muon production ), while still keeping the other finders in use.
- Induce as little inefficiency as possible on most of high $P_t$ physics channels.

The present output of the study is not intended as a final answer to all these questions, but as a simple framework making further improvements or extensions easier and clearer. It includes the following six finders :

- HALAR : Halo finder based on Liquid Argon information only.
- HAMULAR : Halo finder correlating the Backward Iron Endcap with the Liquid Argon deposits.
- COSMUMU : Cosmic finder based on Muon Detectors only.
- COSMULAR : Cosmic finder correlating the Muon Detectors and the Liquid Argon Calorimeter.
- COSTALAR : Cosmic finder correlating the Tail-Catcher and the Liquid Argon Calorimeter.
- COSTRACK : Cosmic finder based on CJC information only.

These finders are described in detail in section 2 and their performance evaluated in section 3. Their technical implementation for practical use is given in appendix.

# 2 TOPOLOGICAL FINDERS DESCRIPTION

Each topological finder is described in detail, with :

- A "one sentence" summary of the basic philosophy.
- Mention of the inspiring sources.
- The adapted optimized algorithm. Here no detailed argumentation of the cuts optimization will be given, performance can be judged from section 3.
- An event display of a typical background event ( from section 3 background test sample ) rejected exclusively by this finder.

### 2.1 HALAR

**Basic idea : Pure LAr "halo" longitudinal horizontal pattern**

Sources : S. Riess, K. Rüter, A. Schöning.

Algorithm ( adapted from K. Rüter ) :

- Divide the LAr Calo Barrel ( wheels 0-5 ) into 36 x 26 ($\phi$,z) sectors each of size $10^0$ x 20 cm.
- Define for each $\phi$ sector :
  - $n1(\phi)$ the number of z sectors with $E(\phi, z)$ above noise threshold.
  - $n3(\phi)$ the number of z sectors with either $E(\phi - 1, z)$,$E(\phi, z)$ or $E(\phi + 1, z)$ above noise threshold.
  - $E(\phi)$ the energy of the $\phi$ sector integrated in z.
- Define $Emax = max(E(\phi))$, $n1max = max(n1(\phi))$.
- Flag as halo if there exists one $\phi_0$ sector with :
  - $[n3(\phi_0) \geq 19]$
    OR
  - $[n3(\phi_0) \geq 14]$ AND
    [no $\phi$ sector outside ($\phi_0 - 1$, $\phi_0$, $\phi_0 + 1$) with $E(\phi) > Emax$ ] AND
    [at most one $\phi$ sector outside ($\phi_0 - 1$,$\phi_0$,$\phi_0 + 1$) with $E(\phi) > \frac{Emax}{8}$ ] AND
    [at most one $\phi$ sector outside ($\phi_0 - 1$,$\phi_0$,$\phi_0 + 1$) with $n1(\phi) \geq \frac{n1max}{2}$ ].
    OR
  - $[n1(\phi_0) \geq 12]$ AND $[n1(\phi) \leq 7$ for all other $\phi$ sectors].

One example of background event rejected exclusively by HALAR ( see section 3 ) is shown in figure 1.

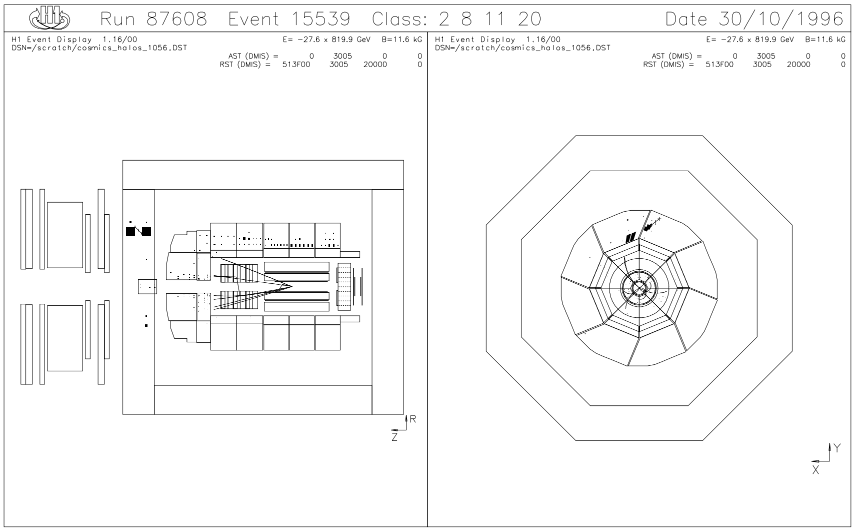


Figure 1: Example of background event rejected exclusively by HALAR.

## 2.2 HAMULAR

**Basic idea : relaxed LAr "halo" longitudinal pattern matching a deposit inside the Backward Iron Endcap**

Sources : Y. Ban, M. David, Z. Zhang, S. Riess, K. Rüter

Algorithm ( adapted from K. Rüter and Y. Ban ) :

- Define :
  - LAr Calo sectors as for HALAR.
  - $D_T(\phi, \mu)$ the transverse distance between the center of gravity of a $\phi$ sector energy and the impact point of a backward muon track.
  - $D_T(\phi, TC)$ the transverse distance between the center of gravity of a $\phi$ sector energy and a backward Tail-Catcher cluster.
- Flag as halo if there exists one $\phi_0$ sector with :
  - $[E(\phi_0) > 5GeV]$ AND
    [there exists one backward muon track with $D_T(\phi_0, \mu) < 30cm$].

    OR
  - $[E(\phi_0) > 5GeV]$ AND
    $[n3(\phi_0) \geq 10]$ AND
    [there exists one Backward Tail-Catcher cluster with $D_T(\phi_0, TC) < 30cm$].

One example of background event rejected exclusively by HAMULAR ( see section 3 ) is shown in figure 2.

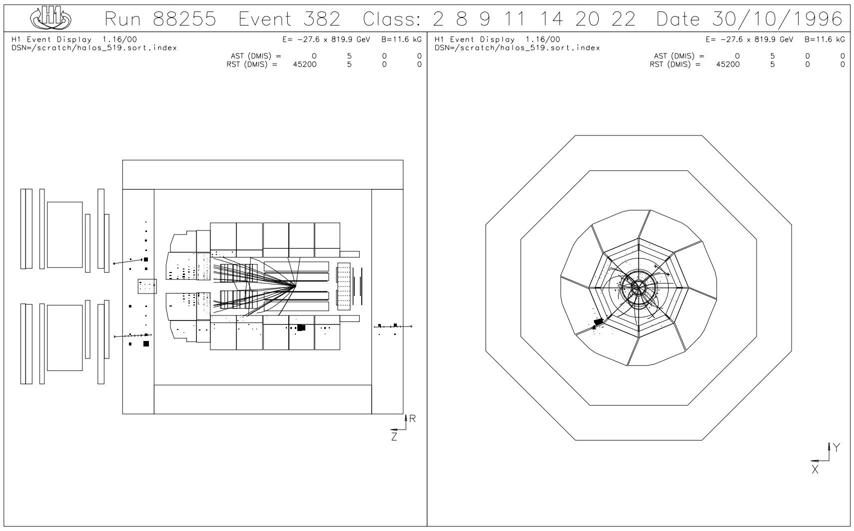


Figure 2: Example of background event rejected exclusively by HAMULAR.

### 2.3 COSMUMU

**Basic idea : 2 opposite muon tracks of comparable direction**

Source : L. Büngener.

Algorithm ( directly adapted from L. Büngener ) :

- Flag as cosmics if there exists 2 Barrel or Backward muon tracks with :
  - Each track polar angle between $10^0$ and $170^0$.
  - The 2 track impact points distant by more than 4 meters.
  - Tracks directions in space matching each other within $26^0$ ( computed from the scalar product of the 2 unitary director vectors ).

One example of background event rejected exclusively by COSMUMU ( see section 3 ) is shown in figure 3.

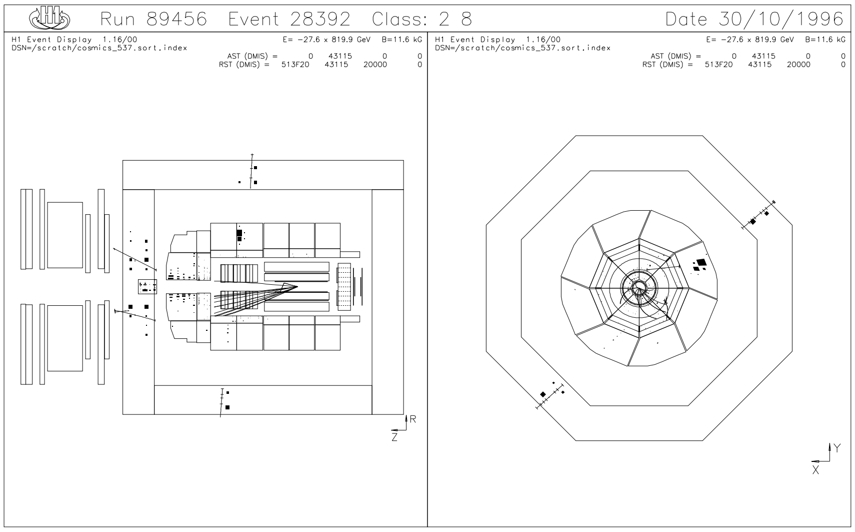


Figure 3: Example of background event rejected exclusively by COSMUMU.

## 2.4 COSMULAR

**Basic idea : all LAr energy matching the direction of a muon track**

Sources : Y. Ban and Z. Zhang.

Algorithm ( rewritten ) :

- Flag as cosmic if there exists one Barrel or Backward muon track with :
  - A polar angle between $10^0$ and $170^0$.
  - more than 8 hits ( in order to allow a reliable direction estimation ).
  - More than 90 % of the LAr energy contained inside a cylinder of radius 90 cm centered on the muon track extrapolation.

One example of background event rejected exclusively by COSMULAR ( see section 3 ) is shown in figure 4 .

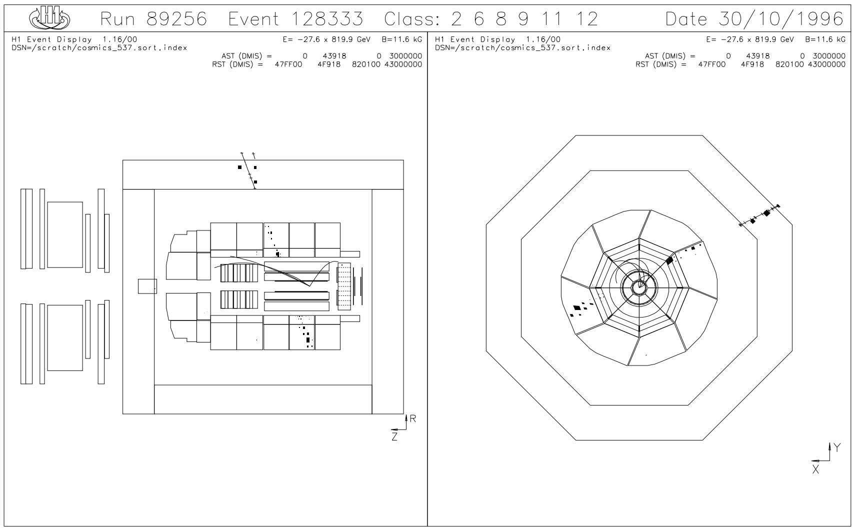


Figure 4: Example of background event rejected exclusively by COSMULAR.

## 2.5 COSTALAR

**Basic idea : all LAr energy matching the direction of 2 opposite Tail-Catcher clusters**

Sources : Y. Ban, K. Rüter, A. Schöning, Z. Zhang.

Algorithm ( adapted from Y. Ban ):

- Flag as cosmic if there exists 2 Barrel or Backward Tail-Catcher clusters with :
  - Each cluster energy greater than 0.5 GeV.
  - The center of gravity of each cluster having a polar angle to the vertex between $30^0$ and $140^0$.
  - The centers of gravity of the 2 clusters distant by more than 2 meters from each other.
  - More than 85 % of the LAr energy contained inside a cylinder of radius 90 cm centered on the axis defined by the 2 centers of gravity.

One example of background event rejected exclusively by COSTALAR ( see section 3 ) is shown in figure 5 .

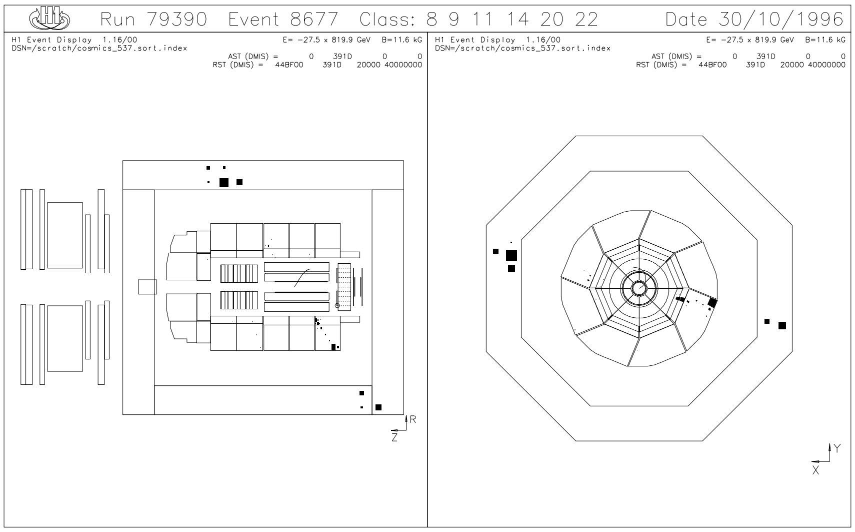


Figure 5: Example of background event rejected exclusively by COSTALAR.

### 2.6 COSTRACK

**Basic idea : 2 CJC tracks with directions exactly opposite in space**

Sources : V. Blobel, S. Riess.

Algorithm ( extra constraint on DCOS tracks ) :

- Flag as cosmic if there exists no more than 20 DTNV tracks, and if there exists a DCOS track with :
  - A $\chi^2$ smaller than 30.
  - A polar angle between $10^0$ and $170^0$.
  - The sum of the polar angles of the 2 associated DTNV tracks between $175^0$ and $185^0$.

One example of background event rejected exclusively by COSTRACK ( see section 3 ) is shown in figure 6 .

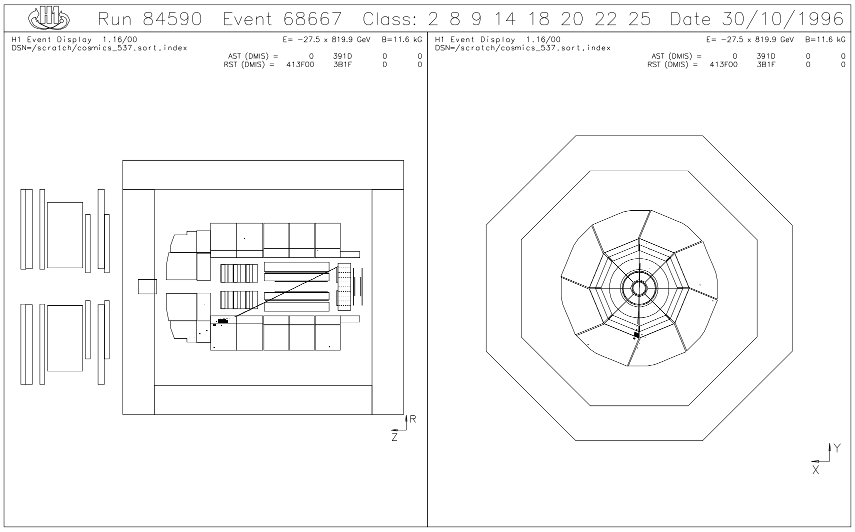


Figure 6: Example of background event rejected exclusively by COSTRACK.

# 3 PERFORMANCE

The rejection power of the above background finders is estimated using the 94 sample of Charged Current candidates remaining after application of the standard CC physics criteria ( run quality, existing vertex, missing $P_t > 25GeV$, etc ). This sample was extensively studied within the EW group [1]. It contains 519 halo induced and 536 cosmic induced events, for an associated signal of 47 CC's.

The inefficiency on various physics high $P_t$ channels is checked using :

- 3300 data (94) and 48000 Monte-Carlo NC's with $P_t^e > 15GeV$.
- 600 data (94) Pseudo CC's with missing $P_t > 25GeV$ and 50000 Monte-Carlo CC's with missing $P_t > 15GeV$.
- 1600 data (94) tagged gamma-p and 8900 Monte-Carlo gamma-p events with 2 jets of $P_t > 7GeV$ each.
- 10000 Monte-Carlo QED Compton events.
- 6000 Monte-Carlo excited quarks.

In case of the physics data samples, the events rejected by the topological finders are checked visually to ensure they are real physics events.

The resulting rejection powers and physics inefficiencies are summarized in table 1. For comparison and completion, table 1 also quotes the corresponding performance of the independent LAr and CJC timing estimators [2], with the following cuts : $|TLAr| < 0.5BC$ or $|TCJC| < 0.1BC$.

| | Rejection power (% of BG events found) | | Physics inefficiency (% of physics events rejected) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Topological | Background | | NC | | CC | | $\gamma$p | | Compton | q* |
| finders | HALOS | COSMICS | Data | MC | PsCC | MC | Data | MC | | |
| HALAR | 90 (56) | 0.9 (0.4) | 0.03 | 0.04 | 0.7 | 0.1 | 0.1 | 0.06 | 0 | 0.07 |
| HAMULAR | 39 (4) | 0 | 0.03 | 0.01 | 0 | 0.02 | 0.1 | 0.03 | 0 | 0 |
| COSMUMU | 0 | 54 (6) | 0 | 0 | 0 | 0.01 | 0.1 | 0.03 | 0 | 0 |
| COSMULAR | 0 | 72 (11) | 0 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0 |
| COSTALAR | 0 | 50 (2) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| COSTRACK | 0.8 | 22 (4) | 0 | 0.06 | 0 | 0.1 | 0.1 | 0.02 | 0 | 0.05 |
| Total Topo | 94.4 | 86.6 | 0.06 | 0.1 | 0.7 | 0.3 | 0.4 | 0.1 | 0 | 0.1 |
| Timing | | | | | | | | | | |
| LAr | 69 (66) | 19 (11) | 1.8 | - | 1.7 | - | 2.0 | - | - | - |
| CJC | 8 (5) | 67 (59) | 1.0 | - | 1.3 | - | 0 | - | - | - |
| Total Timing | 74 | 78 | 2.5 | - | 3.0 | - | 2.0 | - | - | - |
| Timing + Topo | 99.4 | 98.9 | 2.6 | - | 3.7 | - | 2.4 | - | - | - |

Table 1: Rejection power and physics inefficiency ( in percents ) of the topological and timing background finders. Numbers in () refer to the events identified by the given finder alone within its topo or timing category. See main text for a full description of the event samples.

Table 1 raises the following comments :

- As regards the topological finders :
  - They altogether reject 94.4 % of halos and 86.6 % of cosmics.
  - Halos and cosmics separation is efficient , with a mutual mis-identification at the % level.

- Each finder has a significant rejection power and personal apport. Scanning shows that the background events found by none of the finders are mostly halos crossing the detector in the tracker region, or cosmics with poor instrumented iron information.
- The inefficiency on physics channels is small, at the per mil level. Scanning shows that the physics events misidentified as background are mostly interactions with widespread jets (flagged as halos) or with a muon emerging from the hadronic final state (flagged as cosmics).

- As regards the timing cuts :
  - They altogether reject 74 % of halos and 78 % of cosmics, with TLAr cutting mainly halos and TCJC mainly cosmics, as explained in [1].
  - The inefficiency on physics channels is at the % level. This is higher than for the topological finders, with however less bias on topological patterns. This is expected to be improved soon thanks to a better statistical precision of the Big Towers time calibration [2].

- As regards the combination of both cuts :
  - Timing and topological finders put together identify 99.4 % of the halos and 98.9 % of the cosmics.
  - Combining the two classes of finders allows a quantitative estimate of the background lost by both of them, as discussed in [1]. Given:
    - $n1$ the number of events identified by the topological finders only.
    - $n2$ the number of events identified by the timing only.
    - $N$ the number of events identified by both classes.

    and assuming no correlation between both categories, a simple calculation yields $\frac{n1 \times n2}{N}$ as the number of events lost by both of them.
    The uncorrelation assumption can be made safely only for non-muon finders since the time of response of the muon chambers is short. As an illustration, restricting the topological finders to HALAR, COSTALAR and COSTRACK, one predicts $16 \pm 3$ halos and $46 \pm 7$ cosmics found by none of them nor timing, in good agreement with the actual 14 halos and 45 cosmics lost.

# 4 CONCLUSION AND PROSPECTS

We have defined and optimized a simple set of topological muon induced background finders, running on DST data and using most of the relevant subdetectors pieces of information and correlations in a non-redundant way. The resulting finders identify 94.4 % of the halos and 86.6 % of the cosmics left after a typical high $P_t$ physics selection. The associated inefficiency on inclusive physics channels is at the level of the permil. Combining the topological finders with timing estimators increases the above rejection powers to 99.4 % and 98.9 % respectively and allows a quantitative estimate of the background lost by both categories . The code is released in H1PHAN version 2.03/09. A technical description is given in appendix.

This package is not supposed to be in a final stage, but to serve as a clear and simple framework for further developments. The present finders are designed to induce minimal inefficiency on high $P_t$ inclusive physics. Care should be taken when using them to select particular exclusive final states like muon production. They can also be complemented by additional finders dedicated to special physics channels.

Developping the package should be done respecting its philosophy, especially:

- Improving or replacing the finders based on a given type of detector information or correlation.
- Adding new finders when using a new kind of detector information or correlation.

For example, scanning the presently non-identified background events shows good prospects to extend HAMULAR to a match between the Forward Iron Endcap, the Forward LAr Calorimeter and the Backward Iron Endcap, and to implement a new cosmic finder COSLAR based on LAr patterns only.

## Acknowledgements

We are particularly greatful to Y. Ban, V. Blobel, L. Büngener, M. David, S. Riess, K. Rüter, A. Schöning and Z. Zhang for providing ideas and code in their various powerful background finders. We apologize in advance for possibly omitting other authors of background finders we may not be aware of.

## References

[1] H1 Collab. , "Measurement of the $e^+$ and $e^-$ Induced Charged Current Cross Sections at HERA", Z. PHYS. C 67, 565-575 (1995).

[2] A. Pieuchot et al., "Pile-up Energy Detection Using the Liquid Argon Big Tower Timing Information", H1 note H1-01/95-423.

# 5 APPENDIX : package technical description

Package location : CMZ file part of the H1PHAN version 2.03/09.
Main routine : QBGFIND(VECTOR)
Input parameters : none
Steering bank : QBGD

```
*=============================================================================
*                           QBGD
*
*   Steering bank for cosmics/halos finder QBGFIND
QBGD 0 /
*=============================================================================
*                   global steering
*
 'IHL1'  1  ! D = 1    ! (1/0) enabled/disabled the halo finder HALAR
*
 'IHL2'  1  ! D = 1    ! (1/0) enabled/disabled the halo finder HAMULAR
*
 'ICO1'  1  ! D = 1    ! (1/0) enabled/disabled the cosmic finder COSMUMU
*
 'ICO2'  1  ! D = 1    ! (1/0) enabled/disabled the cosmic finder COSMULAR
*
 'ICO3'  1  ! D = 1    ! (1/0) enabled/disabled the cosmic finder COSTALAR
*
 'ICO4'  1  ! D = 1    ! (1/0) enabled/disabled the cosmic finder COSTRACK
*=============================================================================
```

Output parameter: VECTOR(6) with values set to 0 or 1 depending on whether the event is flagged (value 1) or not flagged (value 0) by the finders ( ordered as above ).