

Notes on the **FSRoot** Package

Ryan Mitchell

May 11, 2022 (v4.0)

Abstract

FSRoot is a set of utilities, built around the CERN **ROOT** framework, that can be used to analyze a variety of final states (FS) produced in particle physics experiments. This document provides a short introduction to **FSRoot**.

Contents

1	Installation and Initial Setup	2
2	Using this Document: the Examples/Tutorial directory	3
3	Basic Conventions: the TTree format	3
4	Basic Operations: the FSBasic directory	3
4.1	Basic Histogram Utilities: the FSHistogram class	3
4.2	Basic Cut Utilities: the FSCut class	5
4.3	Basic Tree Utilities: the FSTree class	6
5	Final State Operations: the FSMode directory	7
5.1	Mode Numbering and Conventions	7
5.2	Mode Information: the FSModeInfo class	8
5.3	Collections of Modes: the FSModeCollection class	10
5.4	Histograms for Multiple Modes: the FSModeHistogram class	12
5.5	Information about MC Components	13
5.6	Operations on Multiple Trees: the FSModeTree class	13
6	Fitting Utilities: the FSFit directory	14
7	Organizing Data and Data Sets: the FSData directory	14

1 Installation and Initial Setup

The FSRoot utilities are built around the ROOT framework, so a working version of ROOT is a prerequisite. Notes on ROOT versions:

- v6.18 and after: FSRoot should be fully functional.
- v5.34.09 up to v6.18: FSRoot should work, but without some functionality (e.g. RDataFrame).
- v5.34.08 and before: FSRoot may or may not work.

The FSRoot source code is on GitHub:

<https://github.com/remitch66/FSRoot>

1. To download the most recent version of FSRoot (*recommended*), use `git clone`:

```
> git clone https://github.com/remitch66/FSRoot.git FSRoot
```

You can then switch to an older version (*not recommended unless necessary*) using a specific tag (v4.0 for example):

```
> git checkout tags/v4.0
```

Alternatively, download and unpack (`tar -xzf`) a released version (*not recommended unless necessary*) from here:

<https://github.com/remitch66/FSRoot/releases>

2. Set the location of FSRoot in your login shell script (e.g. `.cshrc`):

```
setenv FSRROOT [path]/FSRoot
```

3. (*optional*) Build a static library (which will appear as `$FSROOT/lib/libFSRoot.a`) and build a few executables that use this static library:

```
> cd $FSROOT
> make
> cd $FSROOT/Executables
> make
```

4. To use FSRoot interactively within a ROOT session, add these lines to your `.rootrc` file (usually found in your home directory):

```
Unix.*.Root.DynamicPath: .:$ (FSROOT):$(ROOTSYS)/lib:
Unix.*.Root.MacroPath: .:$ (FSROOT):
Rint.Logon: $(FSROOT)/rootlogon.FSROOT.C
Rint.Logoff: $(FSROOT)/rootlogoff.FSROOT.C
```

The last two lines load and unload FSRoot whenever you open and close ROOT. Alternatively, you could load FSRoot manually from ROOT:

```
root> .x $FSROOT/rootlogon.FSROOT.C
```

When FSRoot is loaded and compiled, you should see a message saying “Loading the FSRoot Macros” along with output from the compilation.

5. It may sometimes be necessary to add the FSRoot directory to library path variables:

```
setenv DYLD_LIBRARY_PATH $DYLD_LIBRARY_PATH:$FSROOT
setenv LD_LIBRARY_PATH $LD_LIBRARY_PATH:$FSROOT
```

2 Using this Document: the Examples/Tutorial directory

All examples shown in this document can be run within the `Examples/Tutorial` directory. They use two `ROOT` files, each containing one `TTree`, that can be created using:

```
root> .x makeExampleTrees.C
```

This produces one `ROOT` file named `ExampleTree_0_221.root` containing one `TTree` named `ntExampleTree_0_221` for the reaction $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ with $J/\psi \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$. And one file named `ExampleTree_0_101120.root` with a tree named `ntExampleTree_0_101120` for the reaction $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ with $J/\psi \rightarrow K^+K_S\pi^-$ and $K_S \rightarrow \pi^+\pi^-$. The `TTree` format follows the conventions described in the next section.

3 Basic Conventions: the TTree format

Some `FSRoot` operations on `ROOT TTree` variables assume a particular format for the `TTree`:

- `FSRoot` uses “flat” `TTree`’s with branches holding numbers (usually `double`).
- Four-vectors are assumed to have the form:

`[AB]EnP[CD]`, `[AB]PxP[CD]`, `[AB]PyP[CD]`, `[AB]PzP[CD]`

where `[CD]` is a particle label (often 1, 2, 3, 2a, etc., but it could also be `CM` or `BEAM` or anything else) and `[AB]` labels the type of four-vector (for example, it could be `R` for raw or `K` for kinematically fit or `MC` for Monte Carlo, etc.). The `FSRoot` code has no requirements on `[AB]`: it could be anything up to two characters long (or nothing). For `[CD]`, the final state utilities described in Sec. 5 use the numbering convention described in Sec. 5.1. Otherwise, `[CD]` could be anything and any length (but not empty).

- Other variables associated with a given particle (like the χ^2 of a track fit) should use the same particle labels `[CD]` as above. For example, for a pion with four-momentum (`EnP5`, `PxP5`, `PyP5`, `PzP5`), the corresponding track χ^2 should be something like `TkChi2P5`.
- To use MC tagging utilities, `FSRoot` uses tree variables named `MCDecayCode1`, `MCDecayCode2`, and `MCEXtras` (see Sec. 5.5).

4 Basic Operations: the FSBasic directory

4.1 Basic Histogram Utilities: the FSHistogram class

Basic histogram functions are provided within the `FSHistogram` class in the `FSBasic` directory. Like many other functions within `FSRoot`, the functions within the `FSHistogram` class are static member functions, so there is no need to deal with instances of `FSHistogram`.

The basic functions are `FSHistogram::getTH1F` and `FSHistogram::getTH2F`. Here are examples that can be run from either the ROOT command line or from a macro. The first draws a 1d histogram and the second draws a 2d histogram. The arguments are: (1) the file name; (2) the tree name; (3) the variable to plot (or a function of multiple variables in the tree); (4) the number of bins and bounds; (5) the cuts (which can also be functions of multiple variables).

```
root> FSHistogram::getTH1F("ExampleTree_0_221.root", "ntExampleTree_0_221",
    "Chi2DOF", "(60,0.0,6.0)", "")->Draw();
root> FSHistogram::getTH2F("ExampleTree_0_221.root", "ntExampleTree_0_221",
    "Chi2DOF:Event", "(100,0.0,100.0,100,0.0,6.0)", "")->Draw("colz");
```

This example places a cut on `Chi2DOF`:

```
root> FSHistogram::getTH1F("ExampleTree_0_221.root", "ntExampleTree_0_221",
    "Chi2DOF", "(60,0.0,6.0)", "Chi2DOF<2.0")->Draw("hist");
```

The variable and cut arguments can contain shortcuts. For example, `MASS(1,2)` is expanded into the total invariant mass of particles 1 and 2, where 1 and 2 are not necessarily numbers (they are the [CD] in Sec. 3). Characters in front of `MASS` (for example) are prepended to the variable names (the [AB] in Sec. 3). This is all done in the function `FSTree::expandVariable`, which can also be run independently for testing. A list of all macros can be seen using `FSTree::showDefinedMacros` (for example, `RECOILMASS`, `MOMENTUM`, `COSINE`, etc.). An example for `FSHistogram::getTH1F`:

```
root> FSHistogram::getTH1F("ExampleTree_0_221.root", "ntExampleTree_0_221",
    "MASS(2,4,5)", "(100,3.0,3.2)",
    "Chi2DOF<2.0&&abs(MASS(2,4)-1.0)<0.2")->Draw();
```

Examples for `FSTree::expandVariable`:

```
root> cout << FSTree::expandVariable("MASS(1,2)+MASS(2,3)") << endl;
==> (sqrt(pow(((EnP1+EnP2)),2)-pow(((PxP1+PxP2)),2)
==>      -pow(((PyP1+PyP2)),2)-pow(((PzP1+PzP2)),2)))
==> +(sqrt(pow(((EnP2+EnP3)),2)-pow(((PxP2+PxP3)),2)
==>      -pow(((PyP2+PyP3)),2)-pow(((PzP2+PzP3)),2)))

root> cout << FSTree::expandVariable("ABMASS(1,C)") << endl;
==> (sqrt(pow(((ABEnP1+ABEnPC)),2)-pow(((ABPxP1+ABPxPC)),2)
==>      -pow(((ABPyP1+ABPyPC)),2)-pow(((ABPzP1+ABPzPC)),2)))

root> cout << FSTree::expandVariable("RECOILMASS(CM;D,2)") << endl;
==> (sqrt(pow(((EnPCM)-(EnP2+EnPD)),2)-pow(((PxPCM)-(PxP2+PxPD)),2)
==>      -pow(((PyPCM)-(PyP2+PyPD)),2)-pow(((PzPCM)-(PzP2+PzPD)),2)))
```

Histograms are automatically cached so they are made only once. To save histograms at the end of a session, use the function:

```
root> FSHistogram::dumpHistogramCache();
```

To read in the cache at the beginning of a session:

```
root> FSHistogram::readHistogramCache();
```

To clear a cache from memory during a session:

```
root> FSHistogram::clearHistogramCache();
```

To see the contents of the cache:

```
root> FSHistogram::showHistogramCache();
```

Every histogram is given a number when it is created. When histogram 1 is created, for example, a line like this is displayed to the screen: `CREATING HISTOGRAM... FSRootHist:000001`. To see details about histogram 1 use:

```
root> FSHistogram::showHistogramCache(1,true);
```

4.2 Basic Cut Utilities: the FSCut class

Additional shortcuts for making plots are available through the `FSCut` class in the `FSBasic` directory. The following example (not using `FSCut`) defines two cuts and then uses them to make a plot, as above:

```
root> TString cutCHI2("Chi2DOF<2.0");
root> TString cutMASS("abs(MASS(2,4)-1.0)<0.2");
root> FSHistogram::getTH1F("ExampleTree_0_221.root","ntExampleTree_0_221",
    "MASS(2,4,5)","(100,3.0,3.2)",cutCHI2+"&&" + cutMASS)->Draw();
```

As a shortcut to do the exact same thing, give the cuts names and then implement them using the keyword `CUT()`:

```
root> FSCut::defineCut("chi2",cutCHI2);
root> FSCut::defineCut("mass",cutMASS);
root> FSHistogram::getTH1F("ExampleTree_0_221.root","ntExampleTree_0_221",
    "MASS(2,4,5)","(100,3.0,3.2)","CUT(chi2,mass)"->Draw();
```

The `FSCut` class can also be used to define sidebands, which can then be implemented using the keyword `CUTSB()`:

```

root> TString cutCHI2SB("Chi2DOF>3.0&&Chi2DOF<7.0");
root> // the relative size of signal to sideband is 0.5
root> FSCut::defineCut("chi2",cutCHI2,cutCHI2SB,0.5);
root> FSHistogram::getTH1F("ExampleTree_0_221.root","ntExampleTree_0_221",
    "MASS(2,4,5)","(100,3.0,3.2)","CUT(mass)&&CUTSB(chi2)"->Draw();

```

If multiple sidebands are used simultaneously, then all combinations of sideband regions are considered and the resulting histogram is a sum of sideband regions with weights determined by the weights for individual regions:

```

root> TString cutMASSSB("abs(MASS(2,4)-1.8)<0.6");
root> // the relative size of signal to sideband is 1.0/3.0
root> FSCut::defineCut("mass",cutMASS,cutMASSSB,1.0/3.0);
root> FSHistogram::getTH1F("ExampleTree_0_221.root","ntExampleTree_0_221",
    "MASS(2,4,5)","(100,3.0,3.2)","CUTSB(chi2,mass)"->Draw();

```

To see how the cuts are formed and what the scales are, use `FSHistogram::showHistogramCache` on each of the histograms created.

4.3 Basic Tree Utilities: the `FSTree` class

The `FSTree` class is also located in the `FSBasic` directory and provides basic utilities to operate on trees. Besides the static `FSTree::expandVariable` member function mentioned in Sec. 4.1, the most useful function is for skimming trees. For example:

```

root> FSTree::skimTree("ExampleTree_0_221.root","ntExampleTree_0_221",
    "SKIM1_0_221.root","Chi2DOF<2.0");
root> FSHistogram::getTH1F("ExampleTree_0_221.root","ntExampleTree_0_221",
    "Chi2DOF","(60,0.0,6.0)","")->Draw();
root> FSHistogram::getTH1F("SKIM1_0_221.root","ntExampleTree_0_221",
    "Chi2DOF","(60,0.0,6.0)","")->Draw("hist,same");

```

This will take the tree named `ntExampleTree_0_221` from the file `ExampleTree_0_221.root`, loop over all events and select only those that pass the cut on `Chi2DOF`, then output the selected events to the file named `SKIM1_0_221.root` in a tree with the same name as the input tree. The shortcuts mentioned in Sec 4.1 can also be used here, for example:

```

root> FSTree::skimTree("ExampleTree_0_221.root","ntExampleTree_0_221",
    "SKIM2_0_221.root","abs(MASS(1,2)-0.5)<0.1");

```

5 Final State Operations: the FSMode directory

5.1 Mode Numbering and Conventions

A “final state” (also called “mode”) is made from a combination of: $\Lambda(\rightarrow p\pi^-)$, $\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$, e^+ , e^- , μ^+ , μ^- , p , \bar{p} , $\eta(\rightarrow \gamma\gamma)$, γ , K^+ , K^- , $K_S^0(\rightarrow \pi^+\pi^-)$, π^+ , π^- , $\pi^0(\rightarrow \gamma\gamma)$.

As strings, these final state particles are: $\Lambda(\rightarrow p\pi^-) \equiv \text{Lambda}$, $\bar{\Lambda}(\rightarrow \bar{p}\pi^+) \equiv \text{ALambda}$, $e^+ \equiv \text{e+}$, $e^- \equiv \text{e-}$, $\mu^+ \equiv \text{mu+}$, $\mu^- \equiv \text{mu-}$, $p \equiv \text{p+}$, $\bar{p} \equiv \text{p-}$, $\eta(\rightarrow \gamma\gamma) \equiv \text{eta}$, $\gamma \equiv \text{gamma}$, $K^+ \equiv \text{K+}$, $K^- \equiv \text{K-}$, $K_S^0(\rightarrow \pi^+\pi^-) \equiv \text{Ks}$, $\pi^+ \equiv \text{pi+}$, $\pi^- \equiv \text{pi-}$, $\pi^0(\rightarrow \gamma\gamma) \equiv \text{pi0}$.

In a **TTree**, the final state particles should be listed in the order they are given above. The numbering for the [CD] (Sec. 3) starts at 1. For final state particles that decay ($\Lambda(\rightarrow p\pi^-) \equiv \text{Lambda}$, $\bar{\Lambda}(\rightarrow \bar{p}\pi^+) \equiv \text{ALambda}$, $\eta(\rightarrow \gamma\gamma) \equiv \text{eta}$, $K_S^0(\rightarrow \pi^+\pi^-) \equiv \text{Ks}$, $\pi^0(\rightarrow \gamma\gamma) \equiv \text{pi0}$), the four-momenta of the decay particles are listed using **a** and **b** in the same order as above. No assumptions about ordering are made for identical particles.

For example, for the final state $\gamma K^+ K_S^0 \pi^+ \pi^- \pi^- \pi^0$, the four-momenta are:

EnP1	PxP1	PyP1	PzP1	(for the gamma)
EnP2	PxP2	PyP2	PzP2	(for the K+)
EnP3	PxP3	PyP3	PzP3	(for the Ks)
EnP3a	PxP3a	PyP3a	PzP3a	(for the pi+ from Ks)
EnP3b	PxP3b	PyP3b	PzP3b	(for the pi- from Ks)
EnP4	PxP4	PyP4	PzP4	(for the pi+)
EnP5	PxP5	PyP5	PzP5	(for one pi-)
EnP6	PxP6	PyP6	PzP6	(for the other pi-)
EnP7	PxP7	PyP7	PzP7	(for the pi0)
EnP7a	PxP7a	PyP7a	PzP7a	(for one gamma from pi0)
EnP7b	PxP7b	PyP7b	PzP7b	(for the other gamma from pi0)

Every final state can be specified in three different ways:

(1) `pair<int,int> modeCode`: a pair of two integers (`modeCode1`, `modeCode2`) that count the number of particles in a decay mode:

```
modeCode1 = abcdefg
a = # gamma      d = # Ks      g = # pi0
b = # K+          e = # pi+
c = # K-          f = # pi-
modeCode2 = abcdefghi
a = # Lambda      d = # e-      g = # p+
b = # ALambda     e = # mu+     h = # p-
c = # e+          f = # mu-     i = # eta
```

(2) `TString modeString`: a string version of `modeCode1` and `modeCode2` in the format “`modeCode2_modeCode1`”.

It can contain a prefix (for example, FS or EXC or INC or anything longer) that isn't used here, but can help with organization elsewhere.

(3) `TString modeDescription`: a string with a list of space-separated particle names (for example, "K+ K- pi+ pi+ pi- pi-"). The final state particles can appear in any order.

For example, the final state $\gamma K^+ K_S^0 \pi^+ \pi^- \pi^- \pi^0$ has `modeCode1` = 1101121, `modeCode2` = 0, `modeString` = "0_1101121", and `modeDescription` = "gamma K+ Ks pi+ pi- pi- pi0".

5.2 Mode Information: the `FSModeInfo` class

Information about an individual final state is carried by the `FSModeInfo` class. Here are examples of a few of its basic member functions:

```
root> FSModeInfo mi("K+ K- K+ K- pi+ pi- pi0 eta");
root> mi.modeString(); // ==> "1_220111"
root> mi.modeCode1(); // ==> 220111
root> mi.modeCode2(); // ==> 1
root> mi.modeString("this is the code: (MODECODE1,MODECODE2)");
==> "this is the code: (220111,1)"
root> mi.modeString("MODESTRING corresponds to MODEDESCRIPTION");
==> "1_220111 corresponds to K+ K+ K- K- pi+ pi- pi0 eta "
root> mi.modeString("The K- mesons have indices LIST([K-]).");
==> "The K- mesons have indices 4,5."
```

The `FSModeInfo` class also handles particle combinatorics within a given final state through the `modeCombinatorics` member function. This is done using place holders like `[pi+]`, `[pi-]`, `[K+]`, `[K+3]`, `[tk+]`, `[pi0]`, etc., which are replaced by particle indices. While the `modeCombinatorics` function is rarely used explicitly by the user, it can be useful for cross-checking the behavior of the combinatorics. For example:

```
root> mi.modeCombinatorics("iK+ = [K+], iK- = [K-], iK+ = [K+], iK+2 = [K+2]",true);
==> *****
==> *** MODE COMBINATORICS TEST ***
==> *****
==> mode = K+ K+ K- K- pi+ pi- pi0 eta
==> input = iK+ = [K+], iK- = [K-], iK+ = [K+], iK+2 = [K+2]
==> combinations:
==> (1) iK+=2,iK-=4,iK+=2,iK+2=3
==> (2) iK+=2,iK-=5,iK+=2,iK+2=3
==> (3) iK+=3,iK-=4,iK+=3,iK+2=2
==> (4) iK+=3,iK-=5,iK+=3,iK+2=2
==> *****
```

The `modeCuts` member function uses the results of `modeCombinatorics` to combine combinatorics into a single string using the keywords AND, OR, MAX, MIN, and LIST. It is also called by

the `modeString` member function. Examples:

```

root> mi.modeCuts("OR((ABC[K+]+DEF[K-])>0)")
==> (((ABC2+DEF4)>0)||((ABC2+DEF5)>0)||((ABC3+DEF4)>0)||((ABC3+DEF5)>0))
root> mi.modeCuts("AND((ABC[K+]+DEF[K-])>0)")
==> (((ABC2+DEF4)>0)&&((ABC2+DEF5)>0)&&((ABC3+DEF4)>0)&&((ABC3+DEF5)>0))
root> mi.modeCuts("MAX(ABC[K+])")
==> (((ABC[K+])>=(ABC2))&&((ABC[K+])>=(ABC3)))
root> mi.modeCuts("MIN(ABC[K+])")
==> (((ABC[K+])<=(ABC2))&&((ABC[K+])<=(ABC3)))
root> mi.modeCuts("LIST(ABC[K+])")
==> ABC2,ABC3

```

Note that most of the functionality of the `FSModeInfo` class is rarely used explicitly. It is more often combined with other functions and used in higher-level classes (like `FSModeHistogram`), often producing large strings (used only internally), like:

```

root> FSTree::expandVariable(mi.modeCuts("AND(MASS2([K+],[K-])>MASS2([pi+],[K-]))"))
==> (((pow((EnP2+EnP4)),2)-pow((PxP2+PxP4)),2)
==> -pow((PyP2+PyP4)),2)-pow((PzP2+PzP4)),2))>
==> (pow((EnP4+EnP6)),2)-pow((PxP4+PxP6)),2)
==> -pow((PyP4+PyP6)),2)-pow((PzP4+PzP6)),2))&&
==> ((pow((EnP2+EnP5)),2)-pow((PxP2+PxP5)),2)
==> -pow((PyP2+PyP5)),2)-pow((PzP2+PzP5)),2))>
==> (pow((EnP5+EnP6)),2)-pow((PxP5+PxP6)),2)
==> -pow((PyP5+PyP6)),2)-pow((PzP5+PzP6)),2))&&
==> ((pow((EnP3+EnP4)),2)-pow((PxP3+PxP4)),2)
==> -pow((PyP3+PyP4)),2)-pow((PzP3+PzP4)),2))>
==> (pow((EnP4+EnP6)),2)-pow((PxP4+PxP6)),2)
==> -pow((PyP4+PyP6)),2)-pow((PzP4+PzP6)),2))&&
==> ((pow((EnP3+EnP5)),2)-pow((PxP3+PxP5)),2)
==> -pow((PyP3+PyP5)),2)-pow((PzP3+PzP5)),2))>
==> (pow((EnP5+EnP6)),2)-pow((PxP5+PxP6)),2)
==> -pow((PyP5+PyP6)),2)-pow((PzP5+PzP6)),2)))

```

The `FSModeInfo` object also contains a list of “categories” that are used by the `FSModeCollection` class (next section) for organization. The `display` method shows information about a given mode, including a list of categories, some of which are added by default. In the following, the first use of `display` will show the default list of categories; the second will also show the added categories:

```

root> mi.display();
==> (0)   K+  K+  K-  K-  pi+  pi-  pi0  eta
==>           Categories:
==>           Hadronic  HasGammas  HasEtas  HasKaons
==>           HasPions  HasPi0s  6TKOV2GGOG  8Body
==>           4Gamma   CODE=1_220111  CODE1=220111  CODE2=1

```

```

==>                                Keyword Substitutions:
==>                                MODESTRING      -> 1_220111
==>                                MODEDESCRIPTION -> K+ K+ K- K- pi+ pi- pi0 eta
==>                                MODECODE       -> 1_220111
==>                                MODECODE1      -> 220111
==>                                MODECODE2      -> 1
==>                                MODEGLUEXFORMAT -> _7_8_9_11_11_12_12_17
==>                                MODEGLUEXNAME   -> pi0pippimkpkpkmkmeta
==>                                MODELATEX      -> K^{+} K^{+} K^{-} K^{-} \pi^{+}...
==>                                MODECOMBO      -> [pi00],[pi+0],[pi-0],[K+0],[K+1],[K-0]...
==>                                MODECOUNTER    -> 0
root> mi.addCategory("TEST1");
root> mi.addCategory("TEST2");
root> mi.display();
==> (0) K+ K+ K- K- pi+ pi- pi0 eta
==>                                Categories:
==>                                Hadronic HasGammas HasEtas HasKaons
==>                                HasPions HasPi0s 6TKOV2GGOG 8Body
==>                                4Gamma CODE=1_220111 CODE1=220111 CODE2=1
==>                                TEST1 TEST2
==>                                Keyword Substitutions:
==>                                MODESTRING      -> 1_220111
==>                                ...

```

5.3 Collections of Modes: the FSModeCollection class

A list of final states (FSModeInfo objects) is managed by the FSModeCollection class through static member functions. The FSModeCollection class uses the categories associated with different final states to produce sublists. The initial list of final states is empty. There are a few methods to add final states to the list. Here is one, where the optional additions to the end of the final state strings add categories:

```

root> FSModeCollection::addModeInfo("K+ K-      2K phi EXA");
root> FSModeCollection::addModeInfo("pi+ pi-      2pi rho EXB");
root> FSModeCollection::addModeInfo("pi+ pi- pi0    3pi omega EXA");

```

The display method will show final states associated with different combinations of categories. Boolean operators (and = & or &&; or = , or ||; not = !) and wildcards (* and ?) are allowed:

```

root> FSModeCollection::display();           // shows all three
root> FSModeCollection::display("2K");       // shows just the 2K mode
root> FSModeCollection::display("2K,2pi");   // shows 2K and 2pi
root> FSModeCollection::display("EXA");      // shows 2K and 3pi
root> FSModeCollection::display("EX*");      // shows all three
root> FSModeCollection::display("2K&2pi");   // shows none
root> FSModeCollection::display("2K&!2pi");   // shows 2K

```

```

root> FSModeCollection::display("HasPions");          // shows 2pi,3pi
root> FSModeCollection::display("HasPions&!3pi");    // shows 2pi

```

The same list could be created from a text file (the format resembles that for EvtGen; blank lines are ignored; everything after a # is ignored):

```

----- file: ThreeModes.modes -----
Decay ThreeModes
  K+ K-          2K  phi    EXA
  pi+ pi-        2pi rho   EXB
  pi+ pi- pi0    3pi omega EXA
Enddecay
----- end file -----
root> FSModeCollection::addModesFromFile("ThreeModes.modes");

```

Nested lists can also be used:

```

----- file: NestedModes.modes -----
Decay psi'
  pi+ pi- JPSI      pipiJpsi
  eta JPSI          etaJpsi
Enddecay
Decay JPSI
  mu+ mu-          MM
  e+ e-            EE
Enddecay
----- end file -----
root> FSModeCollection::addModesFromFile("NestedModes.modes");
root> FSModeCollection::display(""); // shows all four combinations
root> FSModeCollection::display("MM"); // shows two modes with mu+ mu-
root> FSModeCollection::display("etaJpsi"); // shows two modes with eta JPSI
root> FSModeCollection::display("etaJpsi&MM"); // shows one mode

```

Other methods also operate on combinations of categories:

```

root> FSModeCollection::addModesFromFile("NestedModes.modes");
root> vector<FSModeInfo*> modes = FSModeCollection::modeVector("MM");
root> TString FN("file.MODECODE.root"); TString NT("tree.MODECODE");
root> for (unsigned int i = 0; i < modes.size(); i++){
root>   cout << "a file name: " << modes[i]->modeString(FN) << endl;
root>   cout << "a tree name: " << modes[i]->modeString(NT) << endl;
root> }

```

5.4 Histograms for Multiple Modes: the FModeHistogram class

The `FModeHistogram` class combines features from the classes described above to make histograms for multiple final states and to manage the particle combinatorics within those final states.

The primary member function is `FModeHistogram::getTH1F`, which closely resembles the `FSHistogram::getTH1F` function described in Sec. 4.1. It takes an additional argument that specifies the modes to loop over. In addition to `FSTree::expandVariable`, it also incorporates methods like `ModeInfo::modeString`, `ModeInfo::modeCombinatorics`, `ModeInfo::modeCuts`, and `ModeCollection::modeVector`, all illustrated above.

Here is an example that makes plots using the ROOT files constructed in Sec. 2. The two J/ψ decay modes are specified in the file `ExampleModes.modes` (also in the `Examples/Tutorial` directory).

```
---- file: ExampleModes.modes ----
Decay psi'
  pi+ pi- JPSI      pipiJpsi
Enddecay
Decay JPSI
  pi+ pi- pi0      3pi
  K+  Ks  pi-      KKpi
Enddecay
----- end file -----

root> FModeCollection::addModesFromFile("ExampleModes.modes");
root> TString FN("ExampleTree_MODECODE.root");
root> TString NT("ntExampleTree_MODECODE");
// plot the pi+ pi- mass for all pi+ pi- combinations from both modes
root> FModeHistogram::getTH1F(FN,NT,"", "MASS([pi+],[pi-])",
    "(100,0.0,3.0)","Chi2DOF<5.0")->Draw();
// plot the J/psi mass from both modes
root> FModeHistogram::getTH1F(FN,NT,"", "MASS(CM,-[pi+],[-pi-])",
    "(100,3.0,3.2)","Chi2DOF<5.0")->Draw();
// plot the same using a cut on track chi2
root> TString cutTRACK("AND(TkChi2P[tk]<1)");
root> FModeHistogram::getTH1F(FN,NT,"", "MASS(CM,-[pi+],[-pi-])",
    "(100,3.0,3.2)","Chi2DOF<5.0&&"+cutTRACK->Draw("hist,same");
// only plot the 3pi mode
root> FModeHistogram::getTH1F(FN,NT,"3pi", "MASS(CM,-[pi+],[-pi-])",
    "(100,3.0,3.2)","Chi2DOF<5.0&&"+cutTRACK->Draw("hist,same");
```

To explicitly see how the histograms are constructed, use:

```
root> FSControl::DEBUG = true;
```

The histogram caches also work here: methods like `FSHistogram::dumpHistogramCache` work

as before. You can also use `FSHistogram::showHistogramCache` to see information about any individual histogram.

5.5 Information about MC Components

The `FSModeHistogram` class also includes methods that operate on Monte Carlo truth information. These methods assume trees include variables called `MCDecayCode1`, `MCDecayCode2`, and `MCEExtras` that contain truth information about the final state contents. `MCDecayCode1` and `MCDecayCode2` have the same format as `modeCode1` and `modeCode2` described in Sec. 5.1. `MCEExtras` has the format:

```
MCEExtras = abcd
  a = # neutrinos      c = # neutrons
  b = # K long         d = # anti-neutrons
```

The `FSModeHistogram::drawMCComponents` method takes the same arguments (file name, tree name, category, etc.) as the `FSModeHistogram::getTH1F` method, but draws the histogram with different colors representing different MC components.

Other methods, like `FSModeHistogram::getMCComponents`, return lists of MC components, where the components are labeled by a single string with format `MCEExtras_MCDecayCode2_MCDecayCode1`.

5.6 Operations on Multiple Trees: the `FSModeTree` class

The `FSModeTree` class contains static member functions that operate on multiple trees.

The `FSModeTree::skimTree` method is the same as the `FSTree::skimTree` method (Sec. 4.3), except it takes an argument to specify a combination of categories. To skim trees for the final states listed in `NestedModes.modes`, and to make track quality cuts on tracks, for example:

```
root> FSModeCollection::addModesFromFile("ExampleModes.modes");
root> TString FN("ExampleTree_MODECODE.root");
root> TString NT("ntExampleTree_MODECODE");
root> TString cutTRACK("AND(TkChi2P[tk]<1)");
root> FSModeTree::skimTree(FN,NT,"","SKIM.MODECODE.root",cutTRACK);
```

It often happens in particle physics experiments that a given event can be reconstructed multiple times under different hypotheses. This can happen within a single final state – for example, an event from the final state $K^+K^-\pi^+\pi^-\pi^0$ could be reconstructed once correctly and one or more times incorrectly by misidentifying pions as kaons and vice versa. It can also happen within multiple final states – for example, the same event from the $K^+K^-\pi^+\pi^-\pi^0$ final state could also be reconstructed as $K^+K^-\pi^+\pi^-$ by missing the π^0 .

The different hypotheses in the above scenarios would lead to different values of the χ^2 from kinematic fits. The `createChi2RankingTree` method uses the `TTree` variables `Run`, `Event`, and

Chi2 to rank hypotheses by χ^2 . It does this by creating a friend tree in a new file – the name of the new file name is the same as the old file name except with a “.Chi2Rank” appended. The friend tree contains the variables:

```
// Chi2RankCombinations: number of combinations within this final state
// Chi2Rank: rank of this combination within this final state
// Chi2RankCombinationsGlobal: number of combinations in all final states
// Chi2RankGlobal: rank of this combination in all final states
// Chi2RankVar: the value of the variable used for ranking
// Chi2RankVarBest: the best value of Chi2RankVar within this final state
// Chi2RankVarBestOther: the best value of Chi2RankVar in all other final states
```

The friend tree is used automatically by FSHistogram by setting:

```
root> FSTree::addFriendTree("Chi2Rank");
```

A generalized version of the `createChi2RankingTree` method is called `createRankingTree` and works in the same way. In this version, the variable ranked, its name, and the variables used to group combinations (like `Run` and `Event`) can be customized.

6 Fitting Utilities: the FSFit directory

The fitting utilities (contained in the directory `FSFit`) work, but are still under development. See the examples in the directory `Examples/Fitting` for the general idea.

7 Organizing Data and Data Sets: the FSData directory

The `FSData` directory contains utilities to manipulate data and data sets. The `FSXYPPoint` classes are general, while the `FSEEDataSet` and `FSEEXS` classes are specific to e^+e^- data sets and cross sections, respectively.

Points can be read from files using the `FSXYPPointList::addXYPointsFromFile` method. Data sets (for e^+e^-) can be read from files using the `FSEEDataSetList::addDataSetsFromFile` method. Cross sections (for e^+e^-) are read using the `FSEEXSList::addXSFromFile` method. The resulting lists can then be manipulated using “categories” (in a way similar to the way final states are manipulated by the `FSMode` classes). A selection of data sets and reactions from BESIII can be found in the files `BESLUMINOSITIES.txt` and `BESREACTIONS.txt`, respectively.