Introduction to ROOT: part 2

Mirco Dorigo
mirco.dorigo@ts.infn.it

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INFN
TRIESTE

Breve annuncio (per studenti di particelle exp)

- Ogni anno la CSN1 (esperimenti ad acceleratori) dell'INFN offre O(10) borse di **3 mesi per progetti in lab internazionali**: CERN, KEK (Giappone), Fermilab (US), PSI (Svizzera), BEPC (Cina)

- Sono rivolte a **laureandi e/o neolaureati magistrali**.

- Progetti: presentati da ricercatori/prof. solitamente verso ottobre/novembre, generalmente **legati a progetti di tesi**.

- Bando esce a dicembre/gennaio, risultato selezione a fine marzo. Il progetto puo' essere fatto nel periodo da aprile a fine ottobre.
  Per farvi un'idea, vedete quello del 2024.

- A Trieste abbiamo avuto un buon record di studenti vincitori.
  Se interessati per il 2025, meglio prendere contatti già verso ottobre.

Previous lesson

- Done a very quick (and incomplete) touch on `C++`.
  NOT sufficient to learn `C++`.
- Sufficient to follow the course. We will do very simple coding (might not be really `C++` kosher).
- Important to understand basic concepts, such that you are not lost when navigating the ROOT class reference
  (eg. https://root.cern.ch/doc/master/classTH1.html)
- Writing macros will come with examples.

Let's make a data analysis together

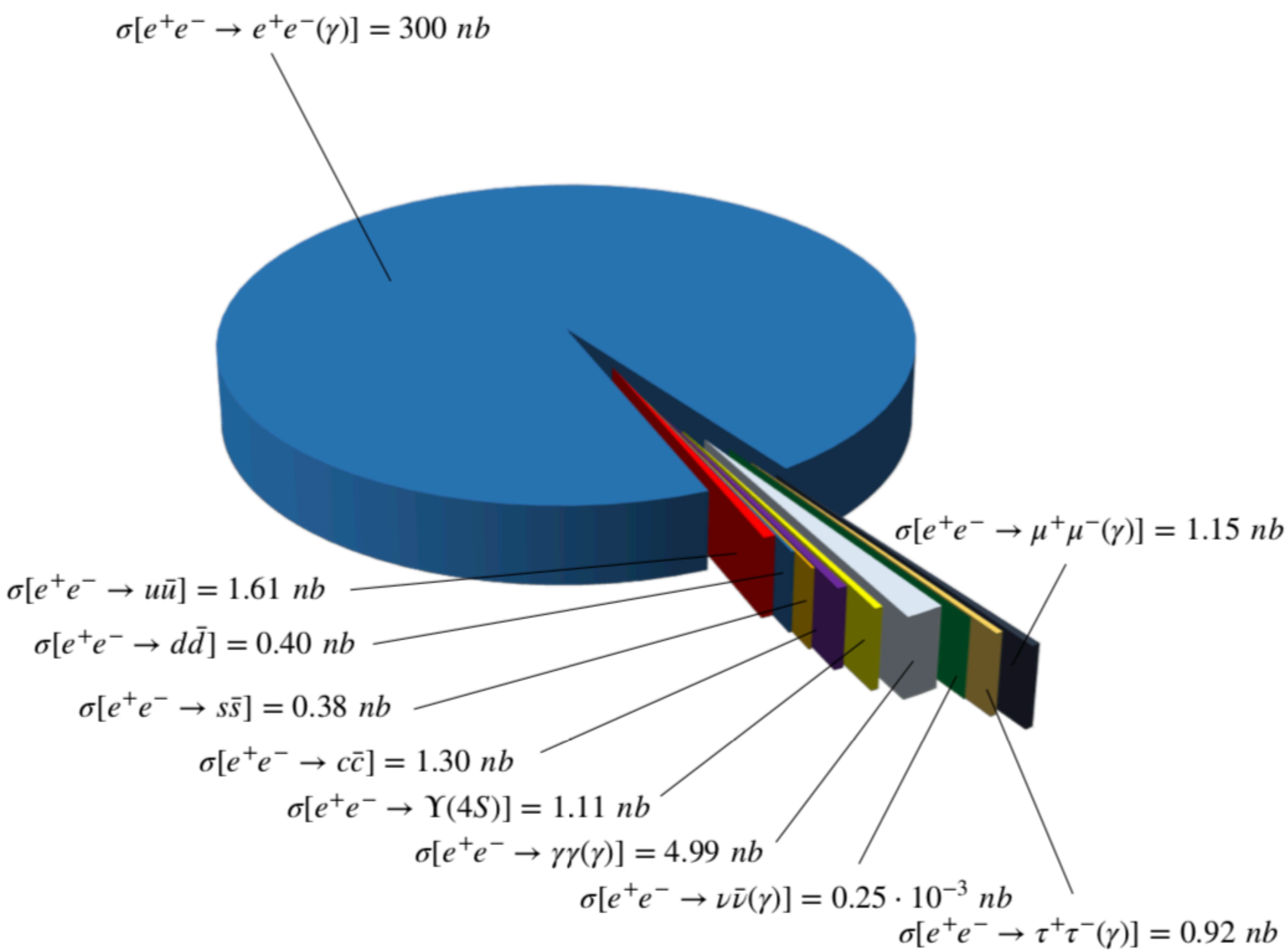
- We will learn ROOT by doing an analysis using (simulated) data from a real experiment, Belle II.
- Our goal is to see the signal peak of a rare *B* decay (branching fraction ~10^{-5}):

$$B^0 \to K^+\pi^-$$

- With ROOT we will optimise a selection to enhance our signal and measure its yield in our data.

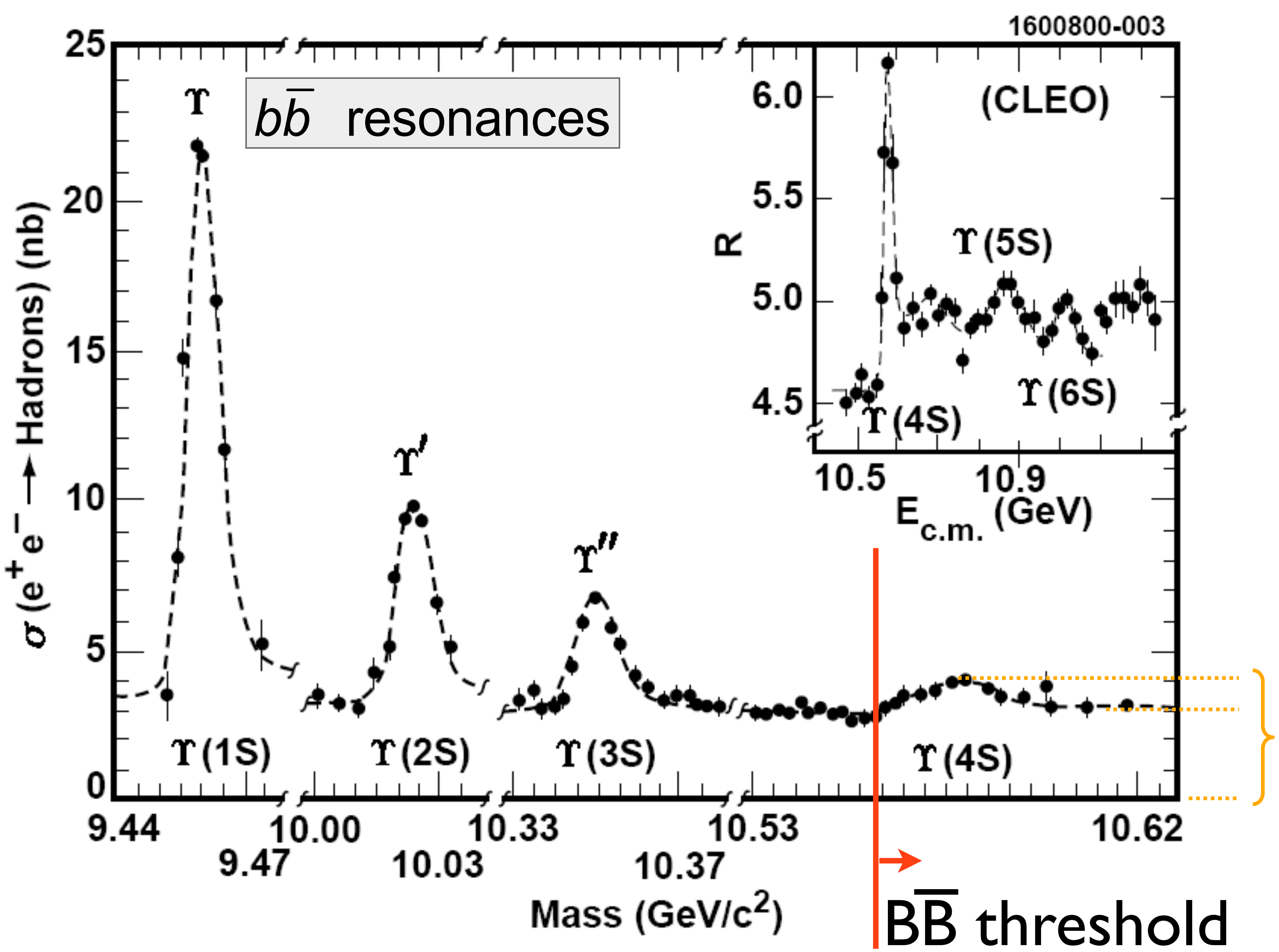
Data from Belle II

- Collisions of $(7+4)\,\mathrm{GeV}$ electron-positron beams at $\sqrt{s} \simeq 10.5794\,\mathrm{GeV}$



Data from Belle II

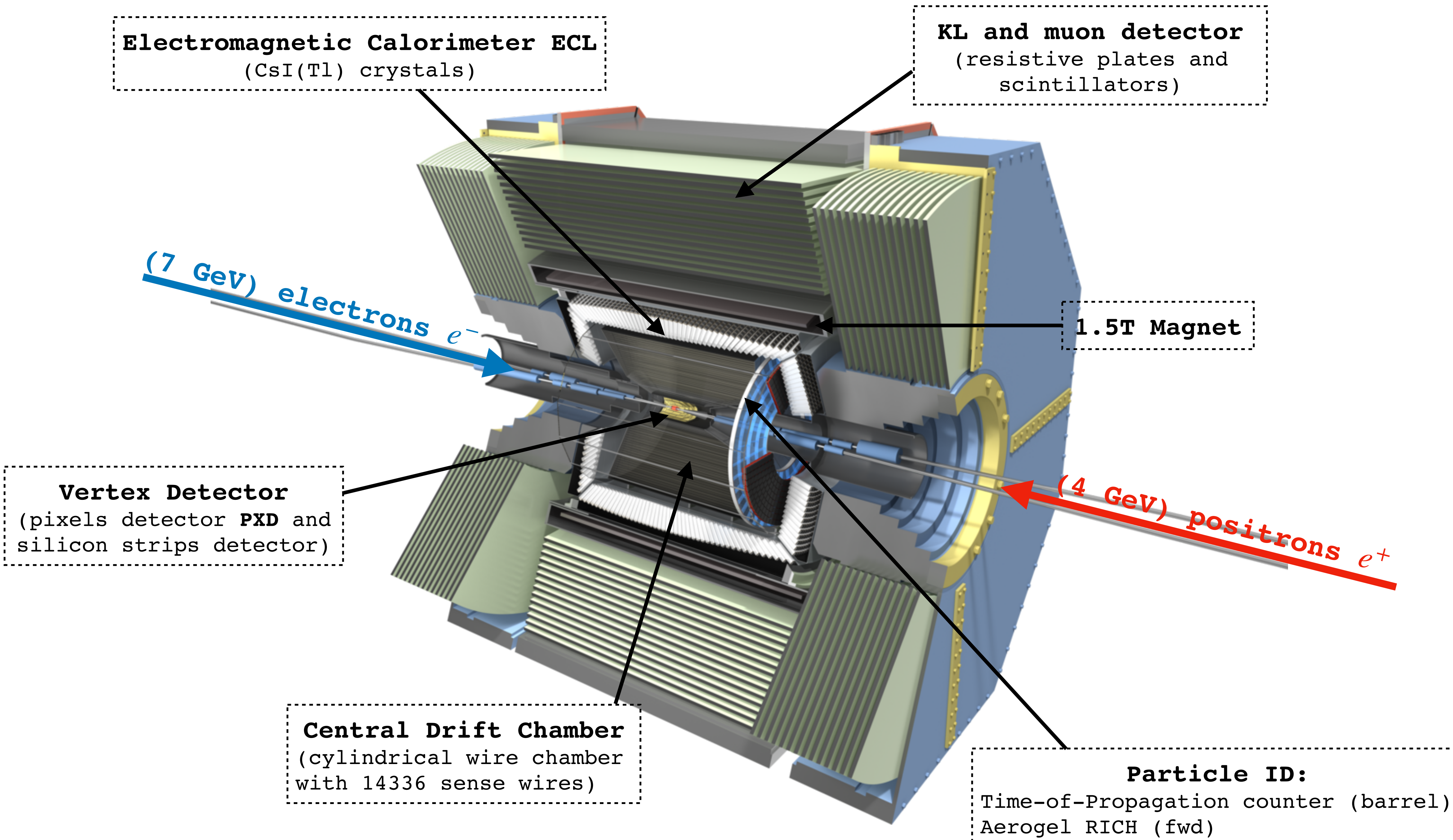
- Collisions of $(7+4)\,\mathrm{GeV}$ electron-positron beams at $\sqrt{s} \simeq 10.5794\,\mathrm{GeV}$
- $e^+e^-\rightarrow$ hadrons produce ~28% of the times a $\Upsilon(4S)\rightarrow B\overline{B}$



$$\frac{\sigma(b\bar{b})}{\sigma(hadrons)} = 0.28$$

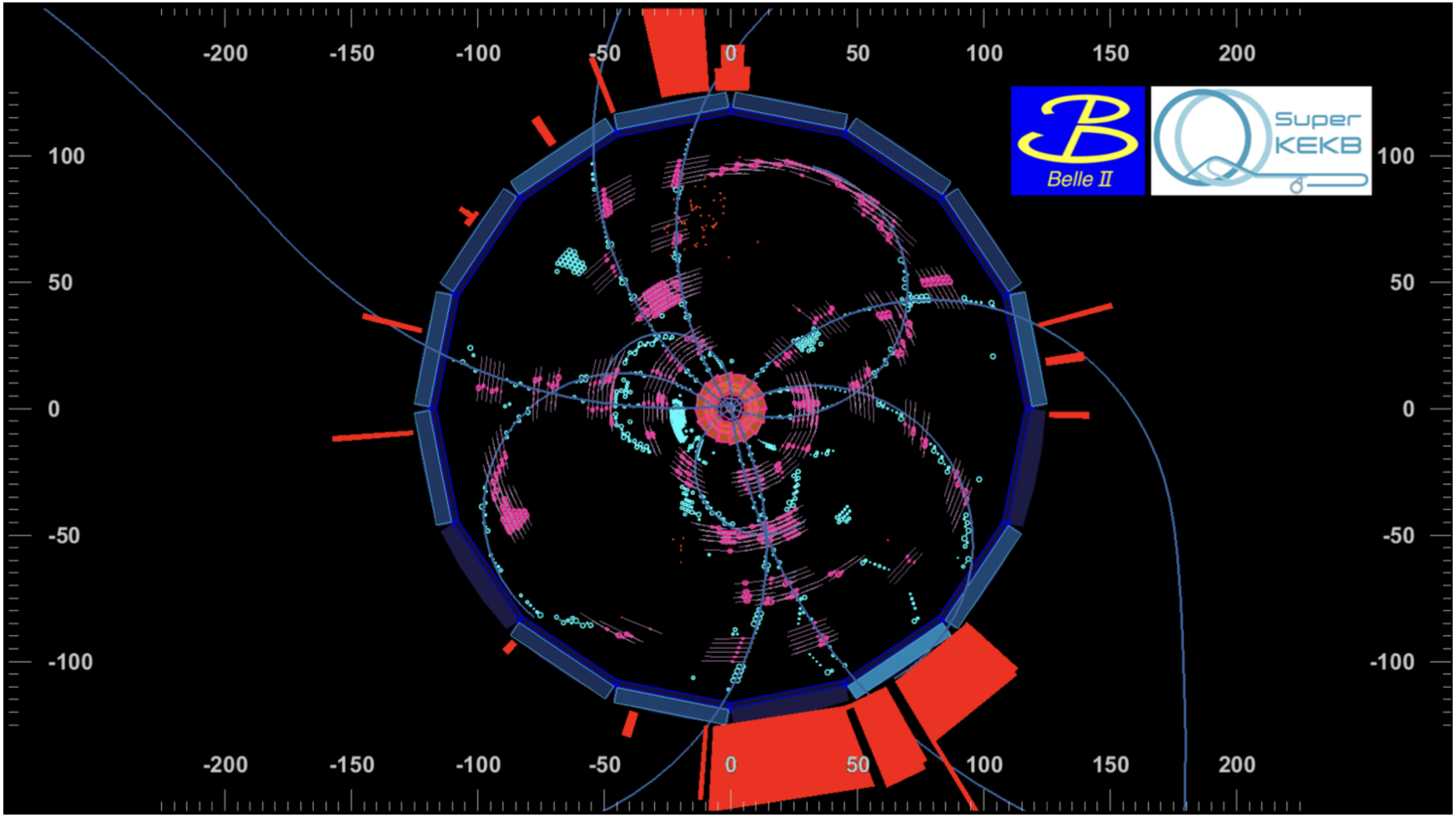
Data from Belle II

- *B* mesons have a lifetime of ~1.5 ps*: we detect the decay products.



**how much does it travel in the detector?*

Data from Belle II



Data from Belle II

- We start from a txt file which contains the momenta of candidates kaon and pion of selected events (as measured in the CM of the $\Upsilon(4S)$ system)

- $B^0 \to K^+\pi^-$ candidates are searched for by computing the invariant mass of the kaon-pion system: the signal should peak at the expected B^0 mass.

- In $\Upsilon(4S) \to B\overline{B}$ decays, the B mesons in the CM of $\Upsilon(4S)$, have both energy $\sqrt{s}/2$. Since this energy is well known, let's exploit it in the mass calculation, to have a better mass resolution:

$$M = \sqrt{s/4 - |\vec{p}_B^{\,*}|^2}$$

Our data

K			π		
p_x^*	p_y^*	p_z^*	p_x^*	p_y^*	p_z^*
0.193687	-2.00117	-1.32568	0.060917	2.53833	1.11248
0.753111	2.46267	-0.931541	-0.891277	-2.01095	0.971655
-2.13514	1.34968	-0.693332	2.35859	-1.1042	0.79431
0.0305453	2.03618	1.59718	-0.204699	-1.69236	-1.92447
-2.31804	-0.747861	0.964579	2.18732	1.17039	-1.05308
-1.85069	0.557923	1.60877	1.53409	-0.841219	-1.93897
-1.0612	1.86811	1.67097	1.23339	-1.68585	-1.61119
0.936175	1.83101	-1.85589	-0.979103	-1.58107	1.75001
1.64432	0.0979302	-2.07102	-1.53113	-0.0245924	1.99033
-1.11439	1.51882	2.00723	1.00509	-1.0165	-1.89929
-0.459256	-2.09789	-1.69227	0.219982	1.67985	2.02722
-1.07834	-0.299723	-2.3634	0.91339	0.892909	2.4356
0.911784	0.89264	2.42608	-1.07651	-0.299878	-2.3489
0.233934	2.16318	1.48514	0.1323	-1.79962	-1.77417
-1.56779	-1.57578	1.15762	1.86769	1.40043	-1.14583
1.01496	1.44624	-1.68575	-0.957066	-1.99439	1.55816
0.797147	-2.48212	-0.0348265	-0.634267	2.43209	0.114049
0.597294	-2.25237	-1.35079	-1.04192	2.04739	0.929552
1.74844	1.65814	1.65216	-1.44217	-1.1239	-1.60946
-0.979769	2.00133	-1.02641	0.794014	-2.44144	1.35458
1.79225	-0.894297	1.01274	-2.25295	1.2013	-1.27669
1.54127	2.03435	-1.0719	-0.97392	-1.98406	0.777642

Reading the data

- We need to read the data from the txt file to compute the invariant mass for each event. Make a script for that.
- Need to be sure that we are correctly reading the file:
  - Am I opening the correct file?
  - Check the first 10 events (10 lines) while reading
  - Do I read all events?

Reading the data

- Let's have a look at the macro `readData.C`

```
#include "Riostream.h"
#include <string>

using namespace std;

void readData(){

    //name of file for the stream of data
    string file_name ="data_file.txt";
    //initialise and open the input stream
    ifstream file_in(file_name);

    //check that the file is open
    if(!file_in.is_open()) {
        //if not, complain,
        cout << "Cannot open data file!" << endl;
        //exit and do nothing
        return;
    }
```

Riostream.h File Reference

```
#include <fstream>
#include <iostream>
#include <iomanip>
```

Avoid writing `std::` all the times when using objects from the standard `C++` library

`if(condition)` statement

Reading the data

- Nothing special …

```
        //the variable in the file to read
        //px, py, pz coordinates for K and pi
        double k_px,  k_py,  k_pz;
        double pi_px, pi_py, pi_pz;

        //counter to check the total number of candidates
        int icand = 0;

```

Reading the data

- The interesting part

```
    //loop till the end of the file, line-by-line
    while(file_in.is_open()){

        //read the data in a line
        file_in >> k_px  >> k_py  >> k_pz
                >> pi_px >> pi_py >> pi_pz;

        //when reach end-of-file, exit the loop
        if(file_in.eof()) break;

        //just make a check
        if(icand<10)
            printf("cand %i \t k_p(%f,%f,%f) \t pi_p(%f,%f,%f) \n",
                   icand,k_px,k_py,k_pz,pi_px,pi_py,pi_pz);

        //for each line read, increment the check counter
        ++icand;

    }
```

`while(condition)` statement

use `cin` operator

to exit the loop when reaching the end of the file

Reading the data

- Closing…

```
    //close input stream
    file_in.close();

    // just print the total number
    cout << "Total data is: " << icand << endl;

    return;

}

```

- The output is

```
mb-md-01:secondLesson dorigo$ root -l readData.C
root [0]
Processing readData.C...
cand 0    k_p(0.193687,-2.001170,-1.325680)       pi_p(0.060917,2.538330,1.112480)
cand 1    k_p(0.753111,2.462670,-0.931541)        pi_p(-0.891277,-2.010950,0.971655)
cand 2    k_p(-2.135140,1.349680,-0.693332)       pi_p(2.358590,-1.104200,0.794310)
cand 3    k_p(0.030545,2.036180,1.597180)         pi_p(-0.204699,-1.692360,-1.924470)
cand 4    k_p(-2.318040,-0.747861,0.964579)       pi_p(2.187320,1.170390,-1.053080)
cand 5    k_p(-1.850690,0.557923,1.608770)        pi_p(1.534090,-0.841219,-1.938970)
cand 6    k_p(-1.061200,1.868110,1.670970)        pi_p(1.233390,-1.685850,-1.611190)
cand 7    k_p(0.936175,1.831010,-1.855890)        pi_p(-0.979103,-1.581070,1.750010)
cand 8    k_p(1.644320,0.097930,-2.071020)        pi_p(-1.531130,-0.024592,1.990330)
cand 9    k_p(-1.114390,1.518820,2.007230)        pi_p(1.005090,-1.016500,-1.899290)
Total data is: 31523
root [1]
```

Reading the data

- Download the material.
- Try the macro yourself. Try also to compile it and run.

Compute a momentum

- Look at `computeP.C`

```
#include "Riostream.h"
#include <string>
#include "TVector3.h"
#include <vector>
#include <numeric>

using namespace std;

void computeP(){

    //File to read
    string file_name ="data_file.txt";
    ifstream file_in(file_name);

    if(!file_in.is_open()) {
        cout << "Cannot open data file!" << endl;
        return;
    }

    //the variable in the file to read
    double k_px,  k_py,  k_pz;
    double pi_px, pi_py, pi_pz;

    //counter to check the total number of candidates
    int icand = 0;

    vector<double> k_p_all;
```

A ROOT class to use 3D vector

`C++` standard libraries:

- vector to store a collection of a types, a container that can change in size
- numeric to use some convenient algorithms

Compute a momentum

- Look at `computeP.C`

```
    while(file_in.is_open()){

        //read the data in a line
        file_in >> k_px  >> k_py  >> k_pz
                >> pi_px >> pi_py >> pi_pz;

        //when reach end-of-file, exit the loop
        if(file_in.eof()) break;

        //let's compute the momentum vector
        //using the class TVector3
        TVector3 k_3p(k_px,k_py,k_pz);
        //compute the magnitude of the vector
        double k_p = k_3p.Mag();

        k_p_all.push_back(k_p);

        //just have a look
        if(icand<10)
            printf("cand %i: \t k_p=%0.3f GeV/c \n",icand, k_p_all.at(icand));
                                                           //k_p_all[icand]

        ++icand;
    }
```

Construct the object and use a method

Append an element at the end, the size of the vector grows.

Easily access any element of the vector

Compute a momentum and an average

- Just std-library show-off

Number of elements in the vector

```
    //close input stream
    file_in.close();

    // just print the total number
    cout << "Total data is: " << k_p_all.size() << endl;

    //compute the mean of the K mometum
    //using the vector and the std library numeric
    double k_p_mean = accumulate(k_p_all.begin(), k_p_all.end(), 0.0) / k_p_all.size();

    //now goes the mean in the squares, again with std library numeric
    double k_p_meanSquares =
        inner_product(k_p_all.begin(), k_p_all.end(), k_p_all.begin(), 0.0) / k_p_all.size();
    //to get the standard deviation
    double k_p_stdDev = sqrt(k_p_meanSquares - k_p_mean * k_p_mean);

    cout << "Mean value of K_p (GeV/c): " << k_p_mean << endl;
    cout << "Std dev of K_p (GeV/c): " << k_p_stdDev << endl;

    return;

}
```

Compute a momentum and an average

…and what do you expect???

Notice: $m(B)$ = 5280 MeV/c^2, $m(K)$ = 494 MeV/c^2, $m(\pi)$ = 140 MeV/c^2

Compute a momentum and an average

- The output

```
root [1] computeP()
cand 0:            k_p=2.408 GeV/c
cand 1:            k_p=2.739 GeV/c
cand 2:            k_p=2.619 GeV/c
cand 3:            k_p=2.588 GeV/c
cand 4:            k_p=2.620 GeV/c
cand 5:            k_p=2.515 GeV/c
cand 6:            k_p=2.722 GeV/c
cand 7:            k_p=2.770 GeV/c
cand 8:            k_p=2.646 GeV/c
cand 9:            k_p=2.753 GeV/c
Total data is: 31523
Mean value of K_p (GeV/c): 2.6146
Std dev of K_p (GeV/c): 0.150434
root [2]
```

Look at the distribution

- Take `histoP.C`

```
#include "Riostream.h"
#include "TVector3.h"
#include <vector>
#include <numeric>
#include "TString.h"
#include "TH1D.h"
#include "TCanvas.h"

using namespace std;

void histoP(){

    //Let's see the distribution of the K momentum
    //we will create an histogram to bin the data in the file
    //using the class TH1D: https://root.cern.ch/doc/master/classTH1.html
    int nbins = 40;  //number of bins
    double min = 1.5; //min value of the x axis
    double max = 3.5; //max value of the x axis
    TString h_name = "h_K_p"; //name of the object (eg. when saved in a root file)
    TString h_title = "K momentum distribution; p(K) [GeV/c]; "; //the histo title,
        can also leave blank; the x-axis title; could put also the y-axis title

    //The constructor
    TH1D* h_p = new TH1D(h_name,h_title,nbins,min,max);

    //Just set the axis title
    h_p->GetYaxis()->SetTitle(Form("Candidates per %.1f [Gev/c]",
                                h_p->GetXaxis()->GetBinWidth(1)));
    //the x axis was just set in the constructor, otherwise
    //h_p->GetXaxis()->SetTitle("p(K) [GeV/c]");
```

[ROOT class](https://root.cern.ch/doc/master/classTH1.html) for histograms of double variables, you will use it a lot

An empty space, to draw object on it

Look at the distribution

- Take `histoP.C`

```
    while(file_in.is_open()){

        file_in >> k_px  >> k_py  >> k_pz
                >> pi_px >> pi_py >> pi_pz;

        if(file_in.eof()) break;

        TVector3 k_3p(k_px,k_py,k_pz);
        double k_p = k_3p.Mag();

        k_p_all.push_back(k_p);

        h_p->Fill(k_p);

        ++icand;

    }
```

Can be easier than this?

Look at the distribution

- Can take a lot of information from the histogram

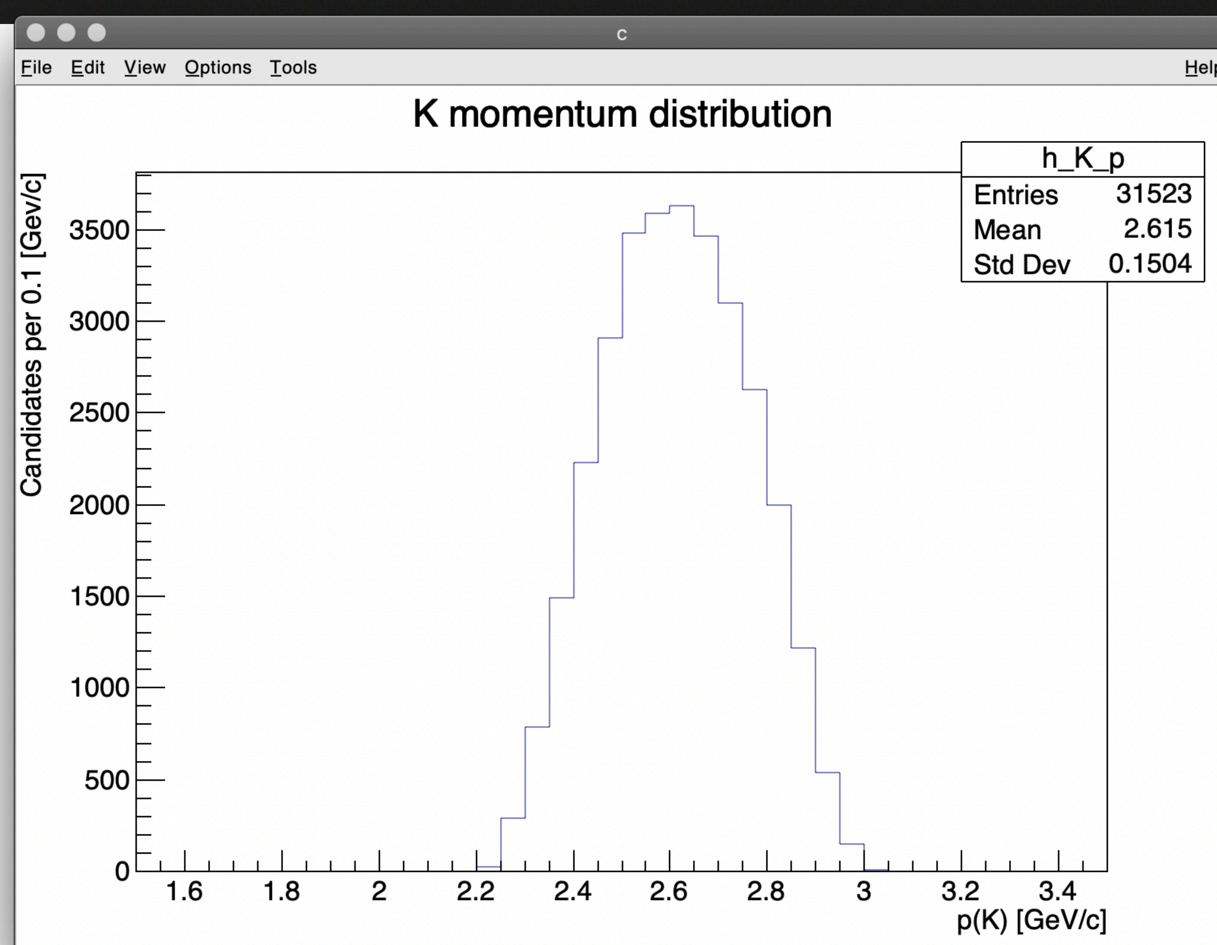
```
    cout << "Total data is:                  " << k_p_all.size() << endl;
    cout << "Mean value of K_p (GeV/c):      " << k_p_mean << endl;
    cout << "Std dev of K_p (GeV/c):         " << k_p_stdDev << endl;

    //let's print a few information from the histogram
    cout << "Total entries in the histogram: " << h_p->GetEntries() << endl;
    cout << "Integral of the histogram:      " << h_p->Integral() << endl;
    cout << "Mean of the distribution:       " << h_p->GetMean()  << " +- " << h_p->GetMeanError() << " GeV/c \n";
    cout << "Std. dev. of the distribution:  " << h_p->GetStdDev() << " +- " << h_p->GetStdDevError() << " GeV/c \n";

    //finally, draw it!
    TCanvas* c = new TCanvas("c","c",800,600);
    h_p->Draw();

    return;

}
```

Make a canvas and draw it

Look at the distribution

- The output

```
root [1] histoP()
Total data is:                   31523
Mean value of K_p (GeV/c):       2.6146
Std dev of K_p (GeV/c):          0.150434
Total entries in the histogram:  31523
Integral of the histogram:       31523
Mean of the distribution:        2.6146 +- 0.00084729 GeV/c
Std. dev. of the distribution:   0.150434 +- 0.000599125 GeV/c
root [2]
```



Look at the distribution

- Plot the histogram yourself.
- What happens if:
  - you use 40000 o 4 bins?
  - you change the range to be 0.0–2.0 or 2.6–4.0 GeV/c?
- Let’s explore the histogram “live”

Saving data in a ROOT format

- Can save data (and any ROOT object) in a compressed binary form in a ROOT file.
- ROOT provides a tree-like data structure, extremely powerful for fast access of huge amounts of data. ROOT files can have a sub-structure: they can contain directories.
- The file is in a **machine-independent** compressed binary format, including both data and their description

Data structures

- Simple model: many copies of the same linear data-structure (a "record"), ending up into a bidimensional data structure (a "table").
- The tables are named "n-tuples", as in mathematics,
  the records are called "events", as in physics,
  and the column headers are called "variables", as in computer science.
- ROOT provides more than n-tuples, "tree": same data structure used in OS to save files into folders that may contain other folders.
- A tree have "branches": simple variables or more complex objects
- A variable is the end point of a branch, a "leaf" in the ROOT jargon.

Make a Tree

- Take `makeTree.C`

```
#include "Riostream.h"
#include "TVector3.h"
#include "TString.h"
#include "TH1D.h"
#include "TCanvas.h"
#include "TTree.h"
#include "TFile.h"

using namespace std;

void makeTree(){

```

ROOT class for the TTree

Class for making a ROOT file

Make a Tree

- Here it is the structure of our tree:

```
    int icand = 0;
    double k_px,  k_py,  k_pz;
    double pi_px, pi_py, pi_pz;
    double k_p;

    //Will store all variables in a format
    //called a TTree, a root dataformat
    //very conveniet to aggregate data
    //in several dimensions
    //https://root.cern.ch/doc/master/classTTree.html
    TTree* dataTree = new TTree("dataTree","B0toKpi data");
    //define a branch of the tree for each variable
    //first the branch name, then the address of the variable,
    //then the leaf list, which is optional in case of one leaf only
    dataTree->Branch("icand",&icand,"icand/I");
    //the K momentum components
    dataTree->Branch("k_px",&k_px,"k_px/D");
    dataTree->Branch("k_py",&k_py,"k_py/D");
    dataTree->Branch("k_pz",&k_pz,"k_pz/D");
    //the pi momentum components
    dataTree->Branch("pi_px",&pi_px,"pi_px/D");
    dataTree->Branch("pi_py",&pi_py,"pi_py/D");
    dataTree->Branch("pi_pz",&pi_pz,"pi_pz/D");
    //the k momentum that we will calculate
    dataTree->Branch("k_p",&k_p,"k_p/D");
```

Variables I want to put in, to be referenced in the tree

Constructor

List of branches with their leaves: here we put a leaf for each branch, a very simple structure

Make a Tree

- Fill the tree

```
    while(file_in.is_open()){

        file_in >> k_px  >> k_py  >> k_pz
                >> pi_px >> pi_py >> pi_pz;

        if(file_in.eof()) break;

        TVector3 k_3p(k_px,k_py,k_pz);
        k_p = k_3p.Mag();

        h_p->Fill(k_p);

        dataTree->Fill();

        ++icand;
    }
```

Make a Tree

- Save in a ROOT file. We can also store the histogram.

```
    cout << "Total data is:          " << icand << endl;

    //make a trivial check...
    cout << "Candidates in the tree: " << dataTree->GetEntries() << endl;
    //look at the content
    dataTree->Print();

    //store now in a root file
    TFile* dataFile = new TFile("data_B0toKpi.root","RECREATE");
    dataTree->Write();
    h_p->Write();
    dataFile->Close();

    return;

}
```

Make a Tree

- The output
- Try it and then explore the tree from `TBrowser`

```
root [1] makeTree()
Total data is:          31523
Candidates in the tree: 31523
******************************************************************************
*Tree    :dataTree  : B0toKpi data                                           *
*Entries :    31523 : Total =         1905173 bytes  File  Size =          0 *
*        :          : Tree compression factor =   1.00                       *
******************************************************************************
*Br    0 :icand     : icand/I                                                *
*Entries :    31523 : Total  Size=     127225 bytes  All baskets in memory   *
*Baskets :        3 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    1 :k_px      : k_px/D                                                 *
*Entries :    31523 : Total  Size=     253945 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    2 :k_py      : k_py/D                                                 *
*Entries :    31523 : Total  Size=     253945 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    3 :k_pz      : k_pz/D                                                 *
*Entries :    31523 : Total  Size=     253945 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    4 :pi_px     : pi_px/D                                                *
*Entries :    31523 : Total  Size=     253965 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    5 :pi_py     : pi_py/D                                                *
*Entries :    31523 : Total  Size=     253965 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    6 :pi_pz     : pi_pz/D                                                *
*Entries :    31523 : Total  Size=     253965 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
*Br    7 :k_p       : k_p/D                                                  *
*Entries :    31523 : Total  Size=     253925 bytes  All baskets in memory   *
*Baskets :        7 : Basket Size=      32000 bytes  Compression=   1.00     *
*............................................................................*
```

Exercises

- We still have to see a signal peak…
- Let's build the variables. Calculate the mass M defined in slide 10, by using the class TLorentzVector.
- Another useful variable is the difference between the B-candidate energy in the CMS and half of the collision energy, $\Delta E = E^{*} - \sqrt{s}/2$. Calculate the variable.
- Plot the distribution of M and that of ΔE into two canvas.
  Is this what you expected? Describe the distributions (mean, standard dev…).
- Add the variable to your tree, and save the tree in a file, adding also the two canvas showing the distributions.