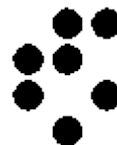# International Masterclasses: The Belle II experiment

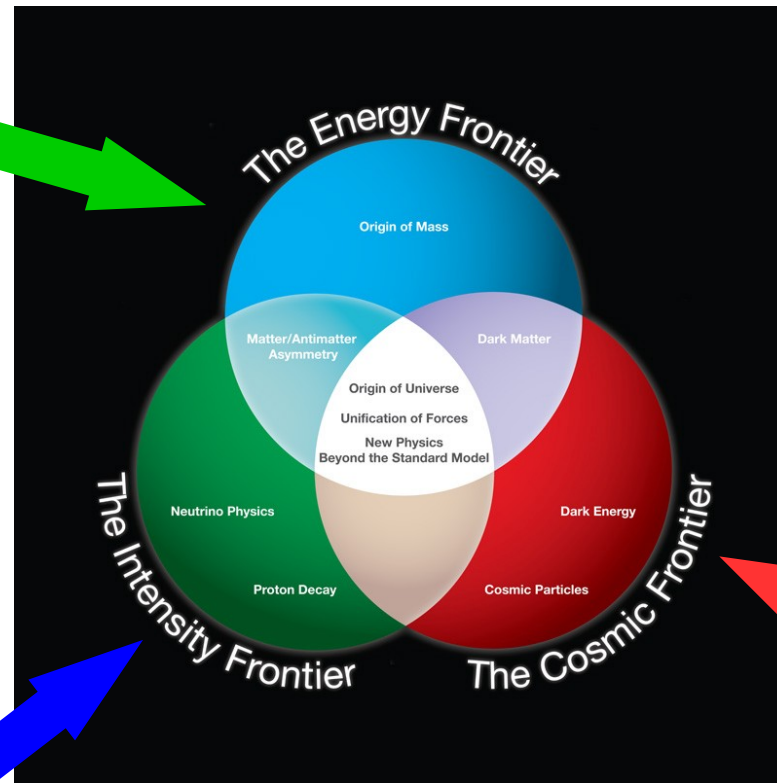## Marko Bračko

**University of Maribor**

&

**J. Stefan Institute, Ljubljana**

**(On behalf of the Belle II Collaboration)**

**2021CERN-Fermilab Hadron Collider Physics Summer School, 4th September 2021**

# Three Frontiers of Particle Physics



- **LHC experiments**

- **Astroparticle experiments**

- **Neutrino experiments**
- **Particle factories, such as Belle (II), and tau-charm factories**

**Intensity Frontier** researchers use a combination of intense particle beams and highly sensitive detectors to make extremely precise measurements of particle properties, study some of the rarest particle interactions predicted by the Standard Model of particle physics, and search for new physics.
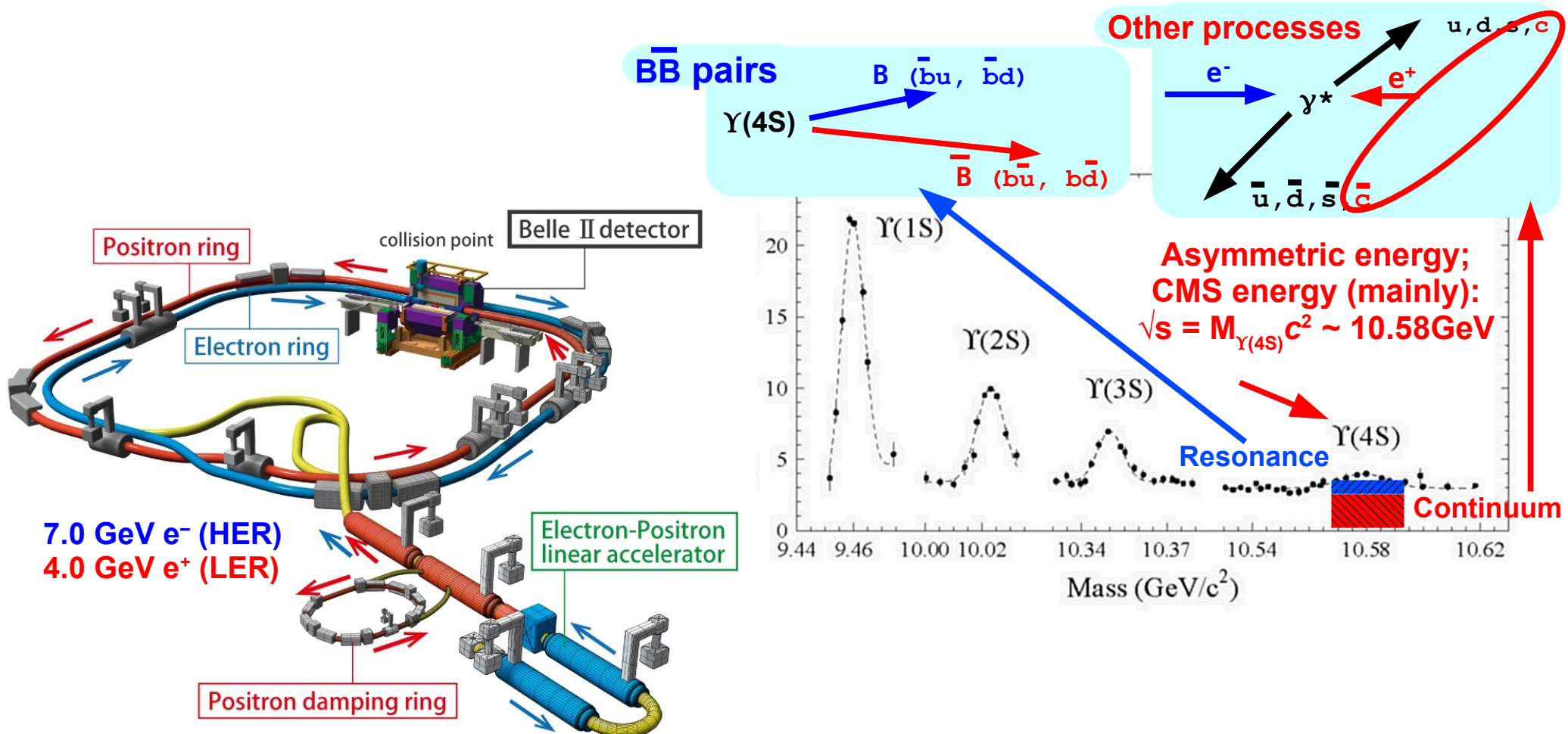
https://science.energy.gov/hep/research/

**Increased sensitivity**: Belle II data sample will be **50-times** larger than Belle's, by collecting data from the SuperKEKB collider with **40-times** higher luminosity
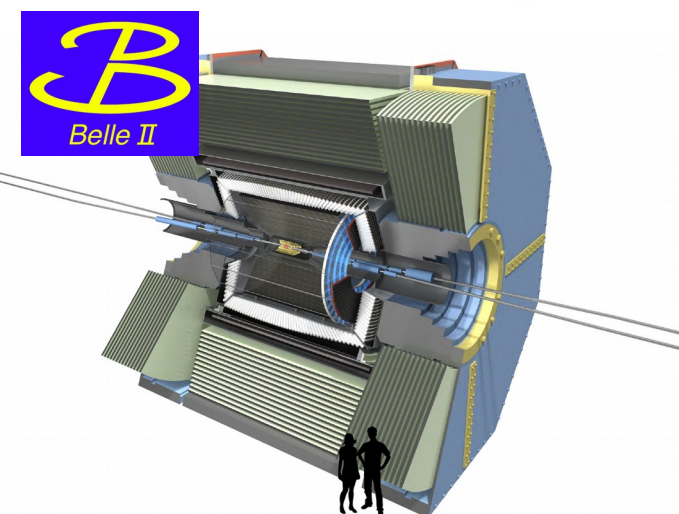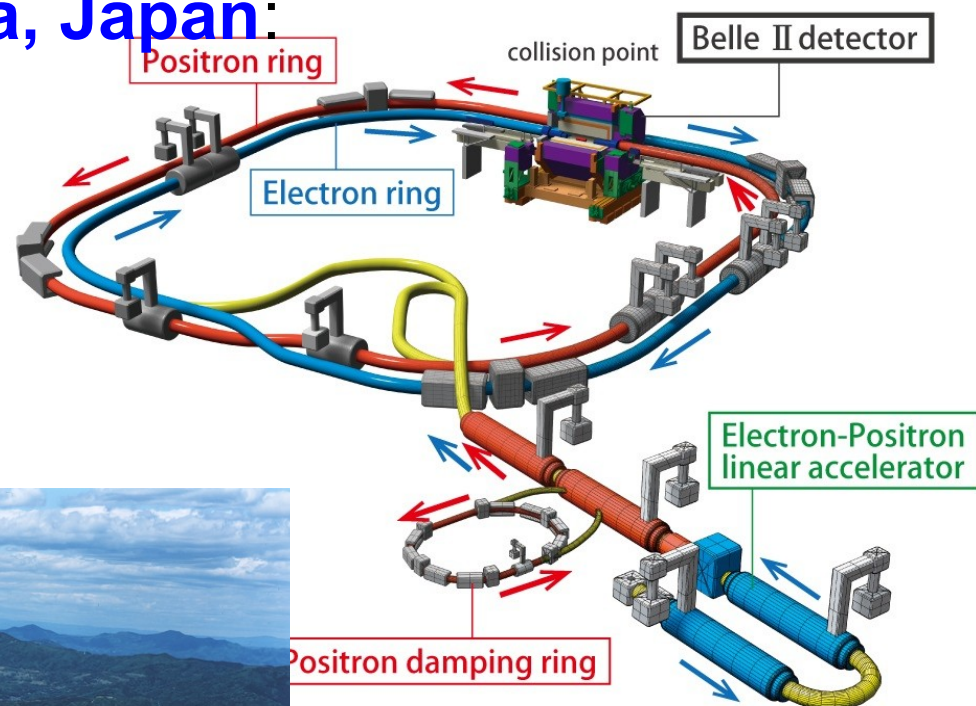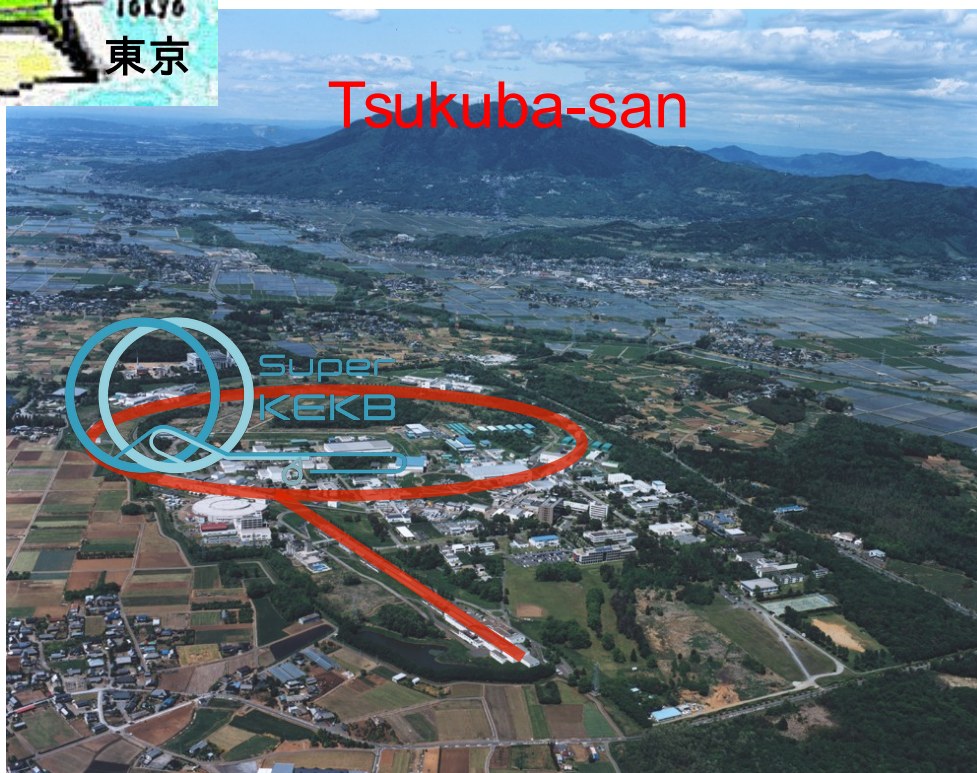
$8 \times 10^{35}$ cm$^{-2}$s$^{-1}$
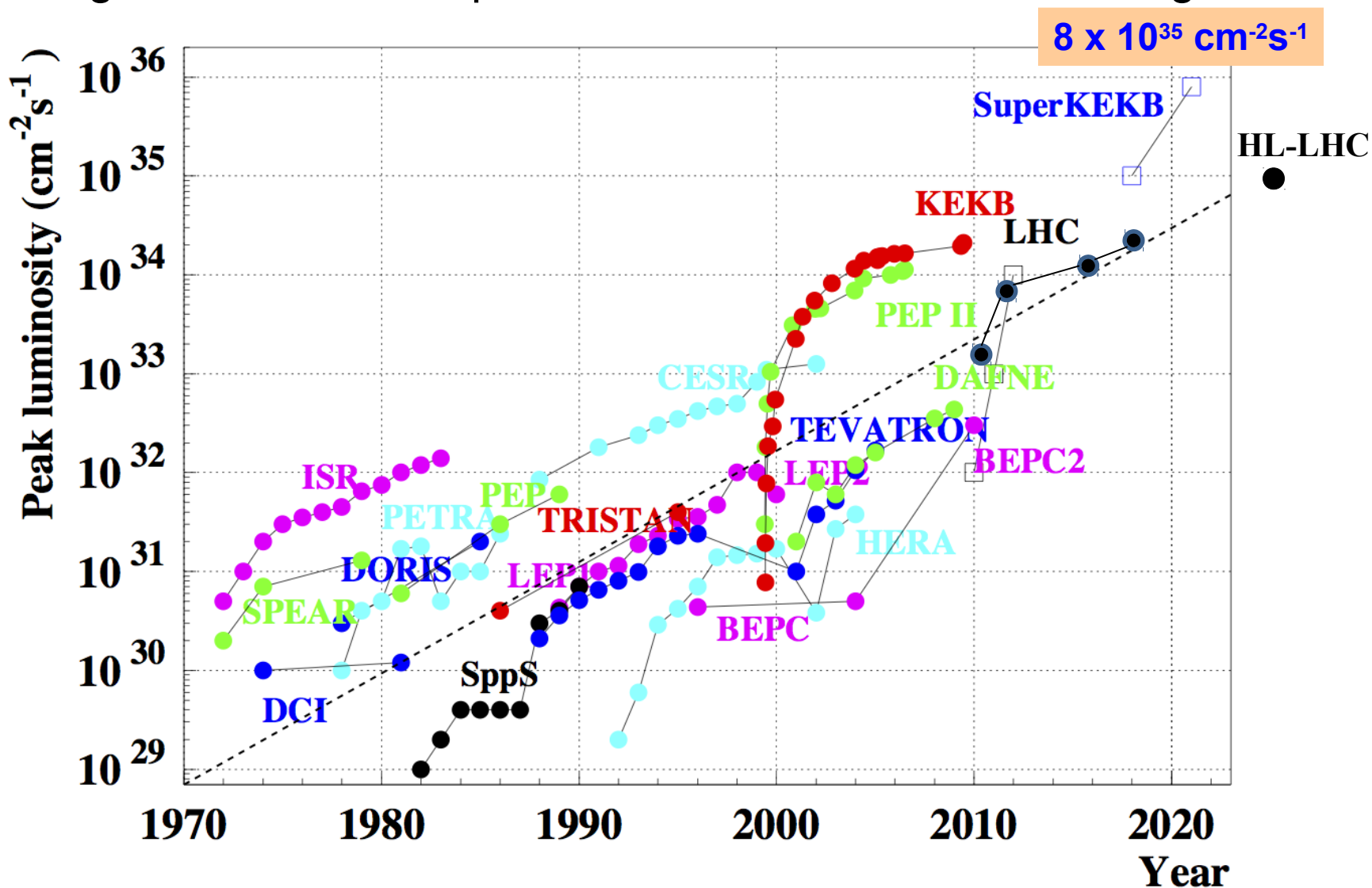
- **Super B-Factory**:

High lumi. asymmetric-energy e⁺e⁻ colliders (SuperKEK/Belle II) operating at $E_{CMS} \sim m_{\Upsilon(4S)}c^2 = 10.58\,GeV$ to produce $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$



**B̄B pairs**

B (b̄u, b̄d)
$\Upsilon(4S)$
B̄ (bū, bd̄)

**Other processes**

e⁻ → γ* ← e⁺

u,d,s,c
ū,d̄,s̄,c̄

**Asymmetric energy;
CMS energy (mainly):
$\sqrt{s} = M_{\Upsilon(4S)}c^2 \sim 10.58\,GeV$**

Resonance

Continuum

7.0 GeV e⁻ (HER)
4.0 GeV e⁺ (LER)

Positron ring
Electron ring
collision point
Belle II detector
Electron-Positron linear accelerator
Positron damping ring

- **SuperKEKB @ KEK, Tsukuba, Japan**:

日本
JAPAN

茨城県

**KEK**

つくば

東京

Tsukuba-san

Positron ring

collision point | Belle Ⅱ detector

Electron ring

Electron-Positron linear accelerator

Positron damping ring

*Belle Ⅱ*

Belle II

**$K_L$ and μ Detector:**
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's
(end-caps , inner 2 barrel layers)

**EM Calorimeter:**
CsI(Tl), waveform sampling
(barrel+ endcap)

electrons (7 GeV)

**Particle Identification:**
Time-of-Propagation Counter (TOP) (barrel)
Proximity focusing Aerogel RICH (ARICH) (fwd)
dE/dx in CDC (centre)

**Beryllium beam pipe:**
2cm diameter

**Vertex Detector:**
**PXD:** 2 layers DEPFET
**SVD:** 4 layers DSSD

positrons (4 GeV)

**Central Drift Chamber:**
He(50%):$C_2H_6$(50%),
smaller cell size, longer lever arm,
fast electronics

The Belle II collaboration:
- Over **1000 researchers** from about **25 countries** (over **120 institutions**) have joined efforts to built and operate the detector, and explore the physics potential of collected data;

# Comment on dataset used

As you might know, in 2020 the Belle II experiment did not stop because of the Covid-19 pandemic

A huge effort have been made by all collaborators to let this happened and this have been appreciated worldwide

This is one of the reasons why the 2020 data collected so far has even more importance than usual

The BelleII experiment gave us the possibility to use the most recent data to give you the possibility to have the most realistic and up to date experience possible

We want to thank the Belle II collaboration for that

# Belle II Lab Manual

## *Rok Pestotnik*

*Jožef Stefan Institute*, Ljubljana, Slovenia

You Tube introduction:
- Start: https://youtu.be/q6M2_dnp3pI
- Particle distribution: https://youtu.be/q6M2_dnp3pI
- J/psi to mumu: https://youtu.be/xUYmXoPfZOU
- J/psi to ee: https://youtu.be/3TGsHJ8j8pE
- Fit: https://youtu.be/wWbjWYHVaLU
- B to J/psi K http://youtube.com/watch?v=e-GErqzY3HM

# Quick start to analyze the data

Belle II Masterclass: Describe process →Run analysis →Fit results →Save/load process locally

Run Analysis    Save Diagram    Load Diagram

**Blocks**

The exercises are any carried out by transferring blocks on the workspace and connecting them together. That represents parts of the data analysis code:

Inside "Blocks" we find:

A BLUE block that allows you to load events.
    You can choose between two data sources:
    hadron-1 Which contains 629,000 events
    hadron-2 Which contains 5 600 000 events
    You can select the number of events to analyze
    Note: processing of 10.000 events takes about 1 second.

A BROWN block that allows you to produce histograms
– distributions of selected variables,  you can define a range
and  a variable to plot

**Belle II Masterclass**
Number of events:  10000
First event:  0
Data Source  hadron-1 ▾
Print particle list?  No ▾
Particle List

**Histogram**
Title  mu neg  Mass
Number of bins  40
Min:  0
Max:  5
Variable  mass ▾

# Quick start to analyze the data

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Run Analysis  Save Diagram  Load Diagram

Blocks

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A BROWN block that allows you to produce histograms – distributions of selected variables, you can define a range and a variable to plot

**Belle II Masterclass**
Number of events: 10000
First event: 0
Data Source hadron-1 ▾
Print particle list? No ▾
Particle List

**Histogram**
Title mu neg Mass
Number of bins 40
Min: 0
Max: 5
Variable mass ▾

# Basic blocks

**Select particle type** for analysis and append histogram for plotting the properties

**Define main analysis parameters**
- ❑ Number of events to process
- ❑ First event to process
- ❑ Data Source
- ❑ Print particle list for first 100 events
- ❑ Particle list to process/ by default the list from the file is used

**Make a combination** of particles from two lists

**Plot a distribution**

Define a range and a variable to plot

# Particle list

- Without any connected blocks the particle list is listed if only a main block is included in the sketch

**Belle II Masterclass**

Number of events: 10000

First event: 0

Data Source: hadron-1 ▾

Print particle list? Yes ▾

Particle List


Number of particles in the event
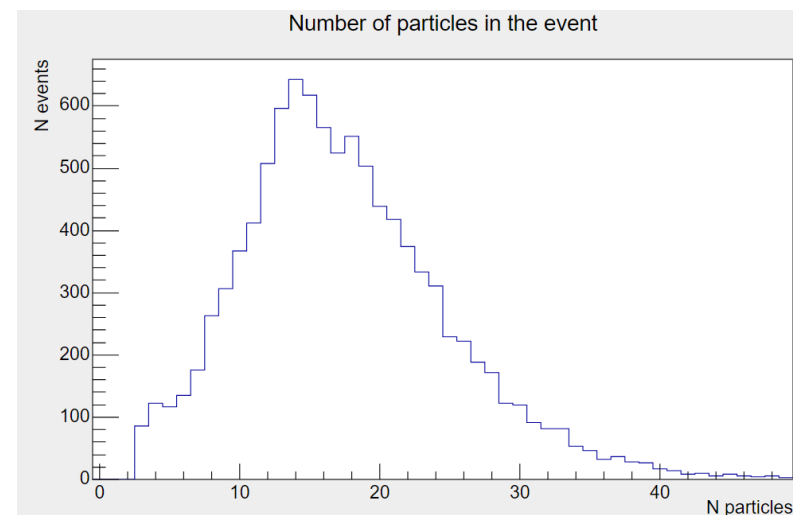
Primary particle list for Event 1

| N | px(GeV/c) | py(GeV/c) | pz(GeV/c) | p(GeV/c) | Energy(GeV) | Charge | ID |
|---|---|---|---|---|---|---|---|
| 1 | -0.99205 | 0.255215 | -0.298016 | 1.06682 | 1.06682 | -1 | electron |
| 2 | 0.379417 | 0.416063 | 0.292391 | 0.634475 | 0.634475 | -1 | electron |
| 3 | 0.448819 | 0.279332 | 0.857395 | 1.00727 | 1.01689 | 1 | pion |
| 4 | -0.381274 | 0.317797 | 0.666425 | 0.830956 | 0.842596 | -1 | pion |
| 5 | -0.404262 | 0.0618774 | 0.419536 | 0.58589 | 0.602285 | -1 | pion |
| 6 | 0.0363708 | -0.337713 | 0.696636 | 0.775032 | 0.787499 | 1 | pion |
| 7 | -0.125205 | 0.251112 | 0.201202 | 0.345276 | 0.372418 | -1 | pion |
| 8 | 0.111522 | 0.10243 | 0.139017 | 0.205559 | 0.248464 | 1 | pion |
| 9 | 0.0599534 | 0.0198644 | 0.0726116 | 0.0962364 | 0.169532 | -1 | pion |
| 10 | -0.0335806 | 0.0421883 | 0.0666954 | 0.0857659 | 0.163816 | 1 | pion |
| 11 | 0.180846 | -0.00941455 | 0.265317 | 0.321227 | 0.321227 | 0 | photon |
| 12 | 0.354789 | 0.0498766 | 0.227253 | 0.424272 | 0.424272 | 0 | photon |
| 13 | 0.393443 | -0.310244 | 0.28901 | 0.578425 | 0.578425 | 0 | photon |
| 14 | 0.254512 | -0.0893971 | 0.113315 | 0.29259 | 0.29259 | 0 | photon |
| 15 | 0.152624 | -0.0325375 | 0.296991 | 0.335494 | 0.361627 | 0 | pion |
| 16 | 0.650451 | -0.401558 | 0.403939 | 0.864582 | 0.875054 | 0 | pion |

# Combine the blocks

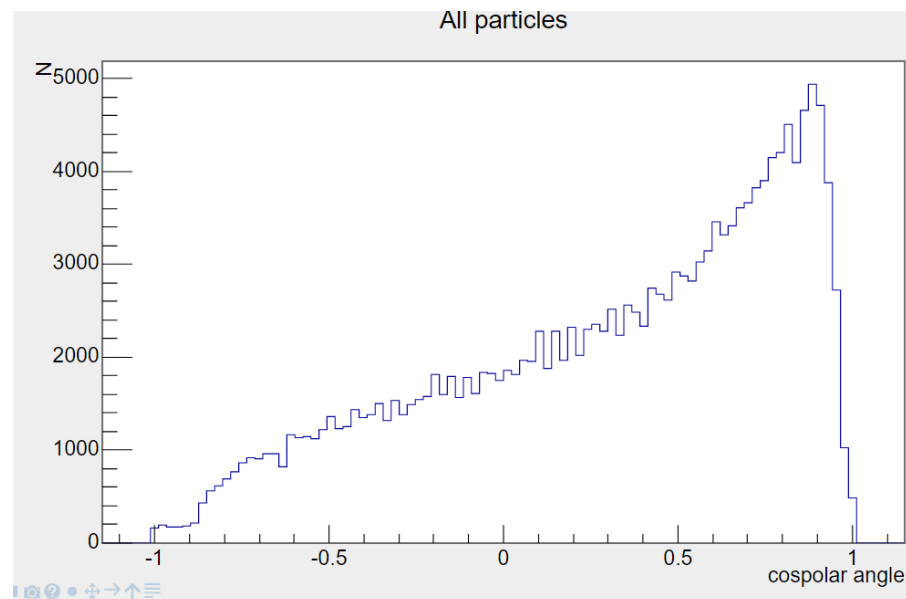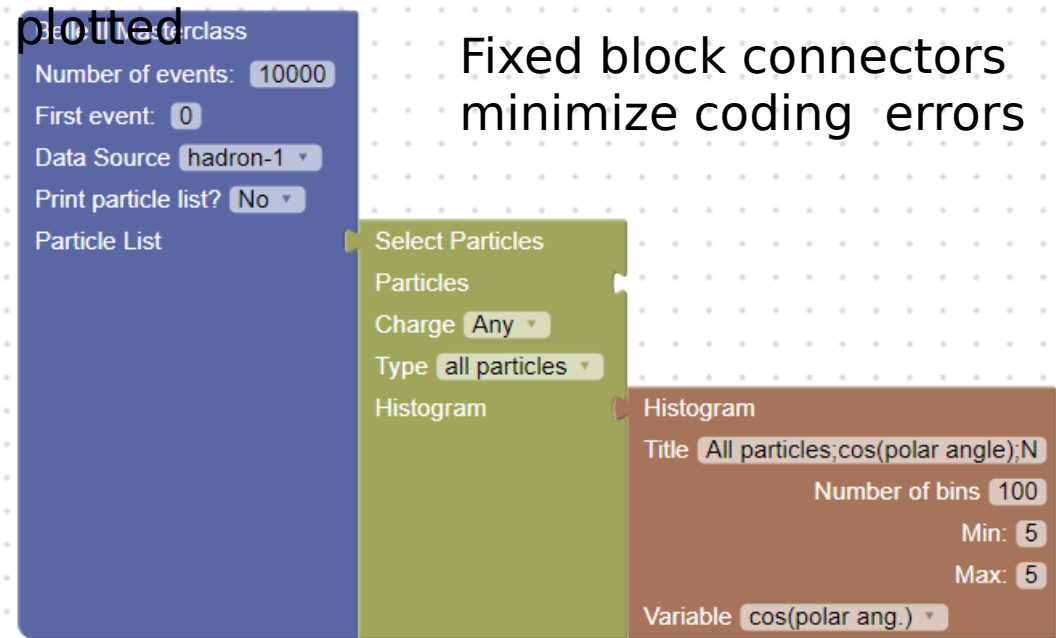The particle lists for each event are stored in an ROOT tree.

By combining different blocks the event loop is generated.
Inside the loop, new particle lists can be generated by combining the existing lists.

Plot different variables :
- ❑ mass,
- ❑ momentum,
- ❑ energy,
- ❑ charge,
- ❑ identity,
- ❑ px,py,pz,pT
- ❑ cos(theta),
- ❑ theta

Distribution of different particle quantities can be plotted

Fixed block connectors minimize coding errors

# Decay to two particles

# Combination of three particles
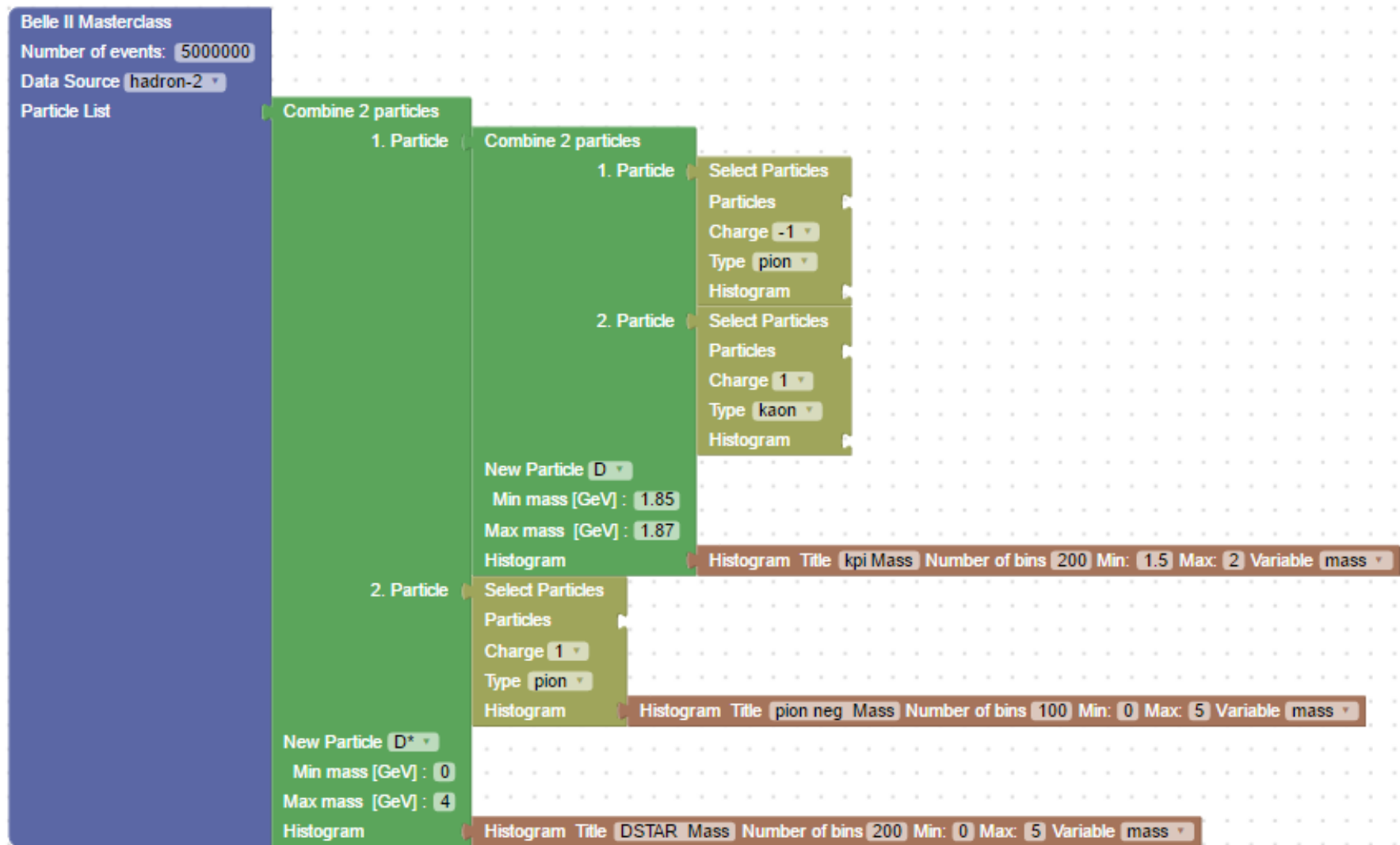
# Different decays

Invariant mass plots for different decays
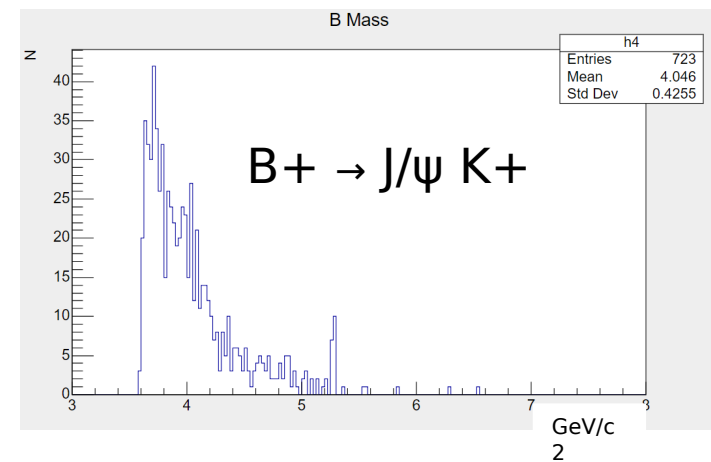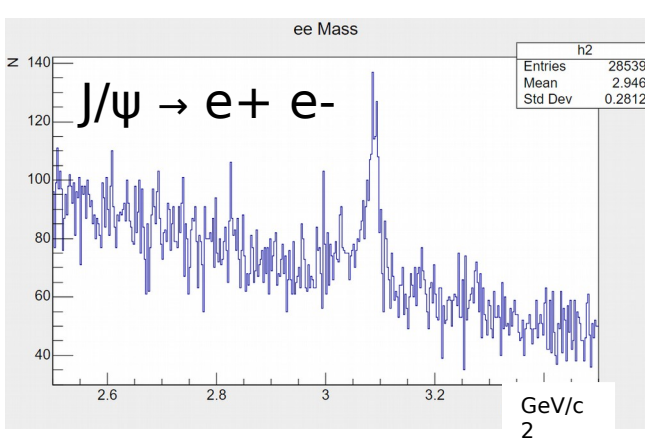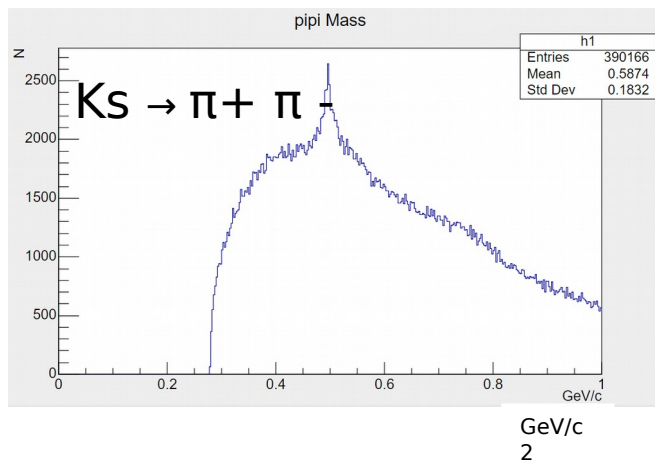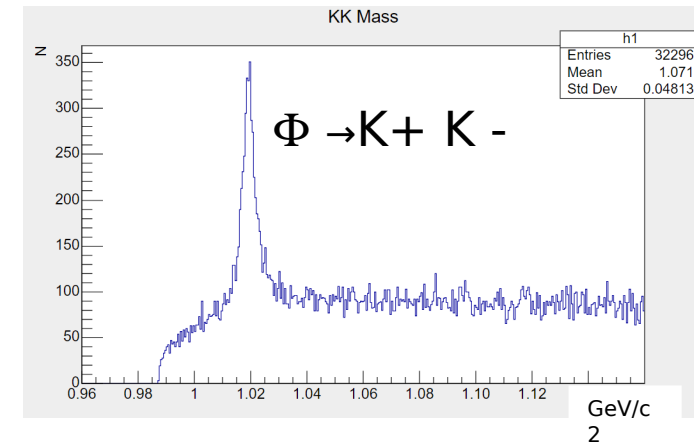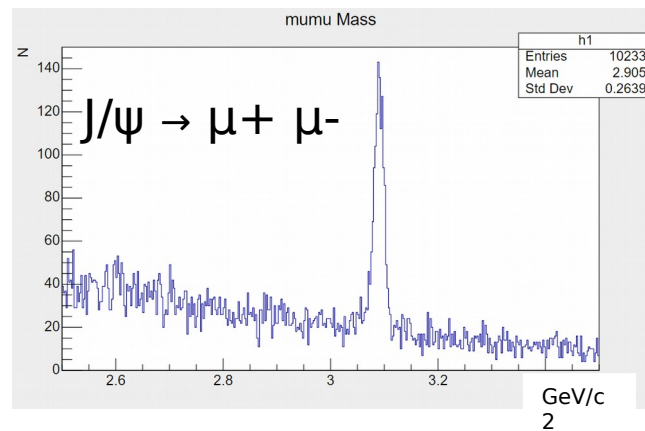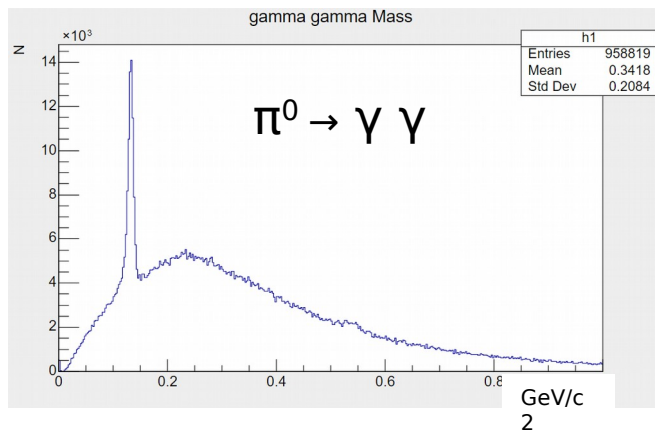
# Advanced level

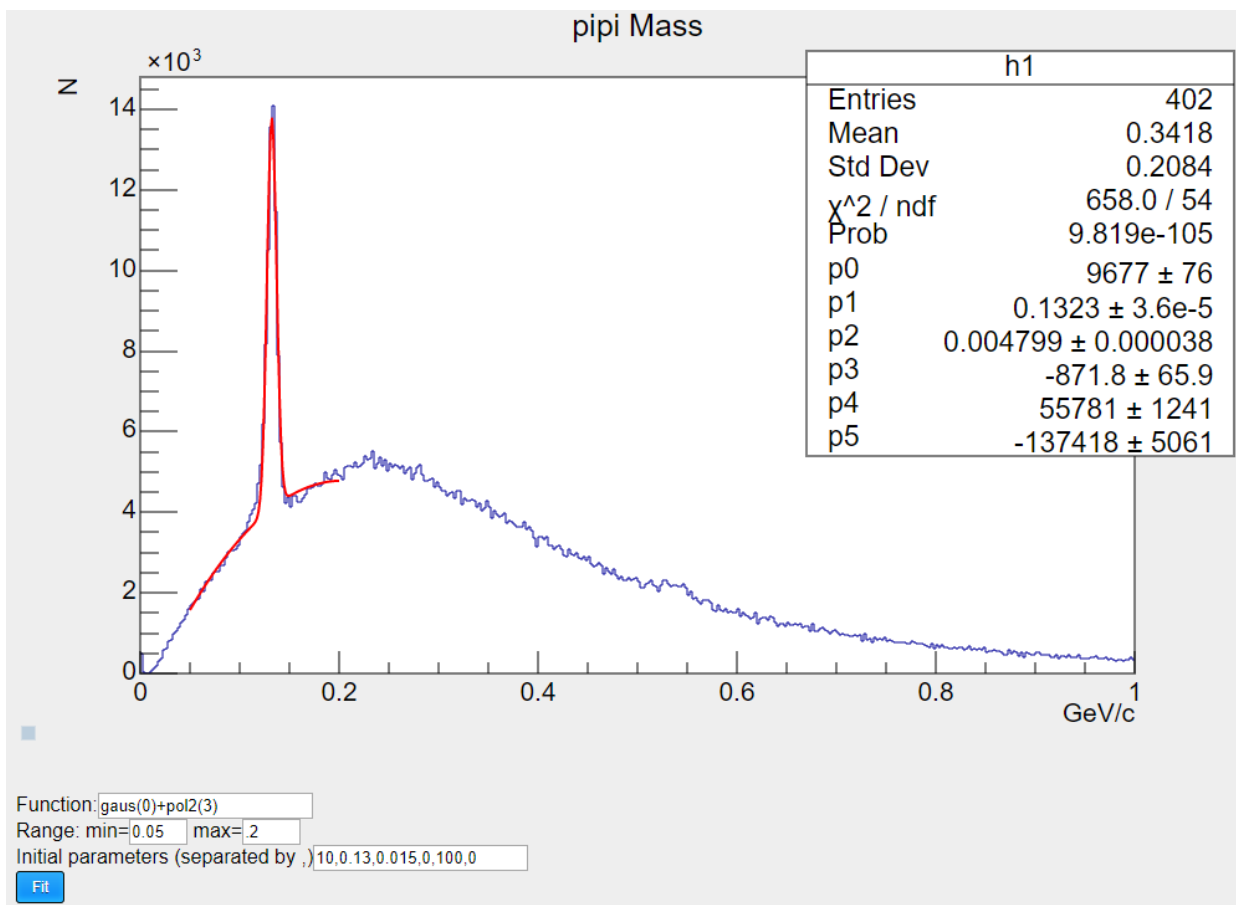A resulting panel offers the possibility to **fit a resulting distribution** with a ROOT function and calculate width and number of events in the peaks
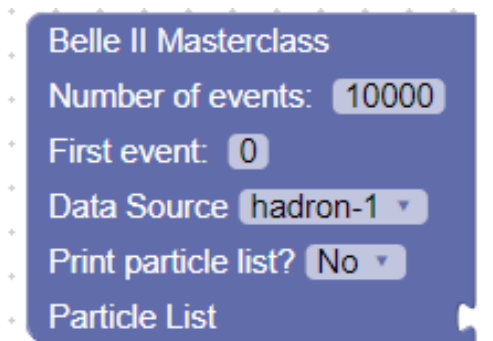
# Exercises ...

# Worksheet

## Exercise table with the list of decays to examine

| Particle | Quark content | Process | Mass (GeV/c²) | Number of processed events | Number of detected particles | Decay width (GeV/c²) |
|---|---|---|---|---|---|---|
| $\pi^0$ | | $\pi^0 \rightarrow \gamma\ \gamma$ | | | | |
| Ks | | Ks $\rightarrow \pi+\ \pi-$ | | | | |
| $\varphi$ | | $\varphi\ \rightarrow$ K+ K - | | | | |
| J/$\psi$ | | J/$\psi \rightarrow$ e+ e- | | | | |
| | | J/$\psi \rightarrow \mu+\ \mu-$ | | | | |
| D⁰ | | D⁰ $\rightarrow$ K+$\pi$- | | | | |
| | | D⁰ $\rightarrow$ K-$\pi$+ | | | | |
| D*+ | | D*+ $\rightarrow$ D⁰ $\pi$+ | | | | |
| D*- | | D*- $\rightarrow$ D⁰ $\pi$- | | | | |
| B+ | | B+ $\rightarrow$ J/$\psi$ K+ | | | | |
| B- | | B- $\rightarrow$ J/$\psi$ K- | | | | |

# Exercise 1 – Particles in the data sample

- In the data we have a list of reconstructed particles for each event with the following information:
  - momentum p=(px,py,pz), energy E, charge and identity
- List the particles in the data and plot number of reconstructed particles in each event
- This is done by using the main block and pressing
  Run Analysis button



- Try to change number of events and a data source file

# Exercise 2 – Mass distributions for different particles

- Mass of the particle defined as

    -

    - In the application it is already calculated

- Plot the distribution of particles according to their mass

- Change particle identity and see how the distribution changes in the following ranges:

    - From 0 to 3 GeV/c$^2$

    - From  0 to 0.0005 GeV/c$^2$

# Exercise 3 – Decay of a particle to two particles

- From the measured momentum and energy of two particles (, ) and (, ) the mass of the mother particle can be calculated as

-

  - By using a particle combiner block, the mass of the particle can be calculated for each combination of particles.

- Plot the mass distribution of  neutral pion  $\pi_0$ which decay to two γ photons:

$$\pi^0 \rightarrow \gamma\ \gamma$$

- You will find a peak at 0.135 GeV/c2, which is exactly the mass of the pion

# Exercise 4 – Decay of a kaons to charged pions

- Plot the mass distribution of neutral kaon Ks which decays to two charged pions:

$$Ks \rightarrow \pi+ \, \pi -$$

- You will find a peak at 0.498 GeV/c2 , which is exactly the mass of the neutral kaon Ks

**Exercise 5 – Decay of a Phi to charged kaons**

- Plot the mass distribution of neutral kaon Ks which decays to two charged kaons:

$$\varphi \rightarrow K+ K-$$

- You will find a peak at 1.02 GeV/c2, which is exactly the mass of the $\varphi$

**Exercise 6 – Decay of a J/ψ to leptons**

- Plot the mass distribution of a J/ψ which decays to two leptons:

J/ψ → e+ e-                    or            J/ψ → μ+ μ-

You will find a peak at a mass of J/ψ at 3.10 GeV/c2

Probability for a production of J/ψ is very small. You will have to process at least 100.000 events.

**Exercise 7 – Decay of a $D^0$ to charged kaons and leptons**

- Plot the mass distribution of a neutral $D^0$ which decays to a combination of K+π- or K-π+:

$D^0 \rightarrow$ K+π-        or        $D^0 \rightarrow$ K-π+

You will find a peak at a mass of $D^0$ at 1.86 GeV/c$^2$
Probability for a production of $D^0$ is very small. You will have to process at least 100.000 events.

# Exercise 8 – Decay of  B+ → J/ψ K+

- Plot the mass distribution of  a charged B  which decays to a combination of J/ψ K

B+ → J/ψ K+      or            B- → J/ψ K-

You will find a peak at a mass of charged B at 5.28 GeV/c$^2$

Use the block Combine 2 particles and describe the process in two stages.

Be sure to select only the particles with a correct invariant mass of J/ψ for further analysis.

# Exercise 9 – Decay of $D^*(2010) \rightarrow D^0 \pi$

- Plot the mass distribution of a charged $D^*$ which decays to a combination of $D^0 \pi-$ or $D^0 \pi+$:

$D^0 \rightarrow K+\pi-$     or     $D^0 \rightarrow K-\pi+$

You will find a peak at a mass of $D^*$ at 2.01 GeV/c$^2$

Use the block Combine 2 particles and describe the process in two stages.

Be sure to select only the particles with a correct invariant mass of $D^0$ for further analysis.