

# BELLE II INTERNATIONAL MASTERCLASS SESSION

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Jožef Stefan Institute, Ljubljana, Slovenia

APS April 2021  
(Online)



# Outline

- General information about Belle II Masterclass
- Web analysis tool
- Hands-on: online analysis of decay channels



# Belle II International Masterclasses

Students come to the HEP Institute and become researchers for several hours.

## Suggested program:

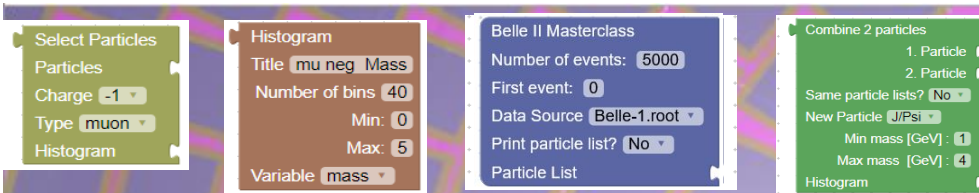
<b>8:45</b>	<b>Registration</b>
9:00 - 9:15	Introduction
9:15 - 10:00	Physics of elementary particles
10:15 - 11:00	Experimental methods in high energy physics
11:00 - 11:30	Belle II Virtual reality
11:30 - 12:00	Introduction Data Analysis
12:00 - 13:30	Lunch – meet the HEP researchers
13:30 - 16:00	Belle Data Analysis + preparation of the presentations
16:00 - 17:00	Joint Video conference



# Belle II Lab Manual

(version 2021-03-01)

Rok Pestotnik, Jožef Stefan Institute, Ljubljana, for the Belle II collaboration



Select Particles  
Particles  
Charge  $-1$   
Type muon  
Histogram

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

Belle II Masterclass  
Number of events: 5000  
First event: 0  
Data Source Belle-1.root  
Print particle list? No  
Particle List

Combine 2 particles  
1. Particle  
2. Particle  
Same particle lists? No  
New Particle J/psi  
Min mass [GeV]: 1  
Max mass [GeV]: 4  
Histogram

BelleII experiment @ KEK, Japan  
study of rare decays of B and D mesons  
and tau leptons

## Resources

Exercises with data: <http://belle2.ijs.si/public>

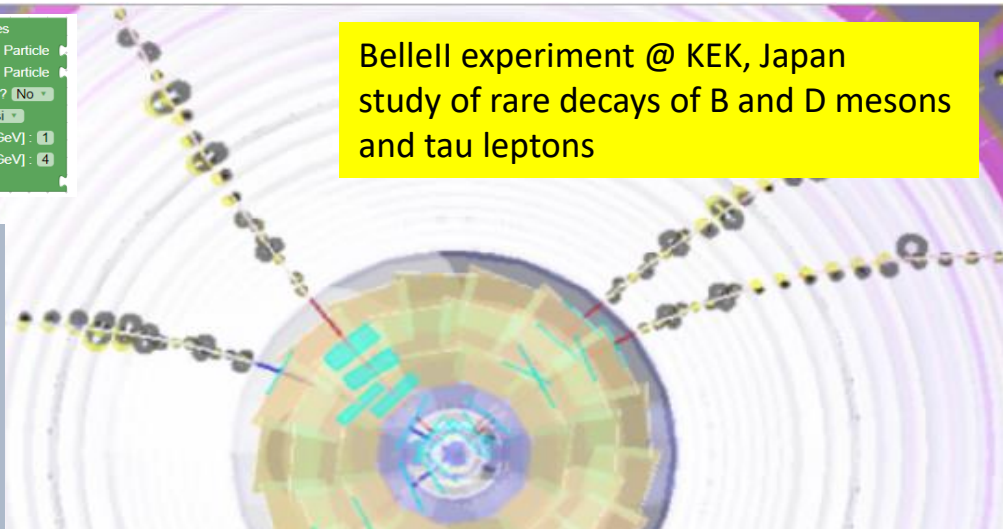
You Tube introductions:

- Start: [https://youtu.be/q6M2\\_dnp3pl](https://youtu.be/q6M2_dnp3pl)
- Particle distribution: [https://youtu.be/q6M2\\_dnp3pl](https://youtu.be/q6M2_dnp3pl)
- J/psi to mumu: <https://youtu.be/xUYmXoPfZOU>
- J/psi to ee: <https://youtu.be/3TGsHJ8j8pE>
- Fit: <https://youtu.be/TbozJR2eQUM>
- B to J/psi K <http://youtube.com/watch?v=e-GErgzY3HM>

•Virtual Reality <http://www1.phys.vt.edu/~piilonen/VR/>



**MASTERCLASS**  
Belle II Particle Adventure





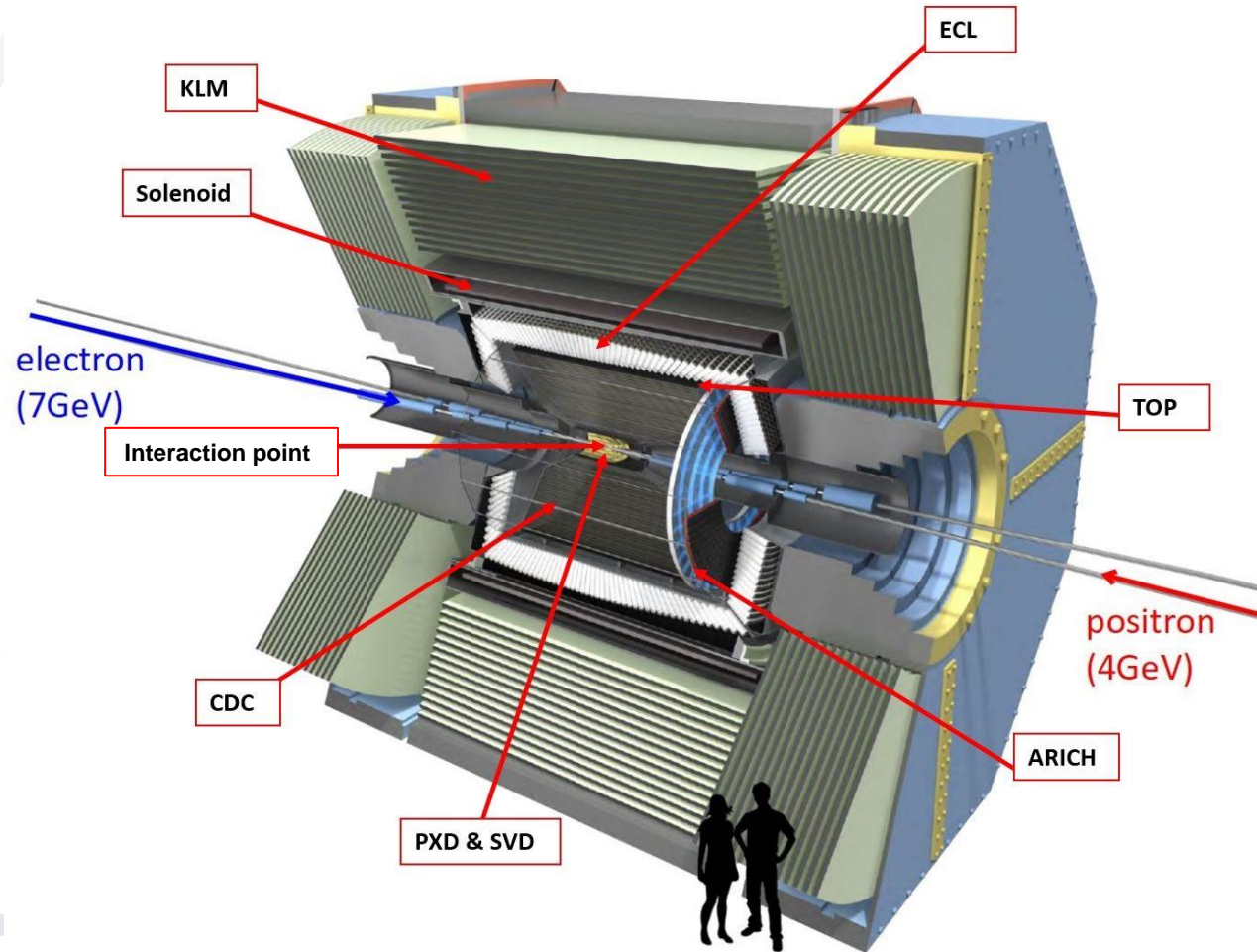
# BELLE II

- Measurements of:
  - Momentum
  - Energy
  - Identity
- Long lived particles
  - $e$ ,  $\mu$ ,  $\pi$ ,  $K$ ,  $p$ ,  $\gamma$ ,  $K_L$

**Reconstruction**



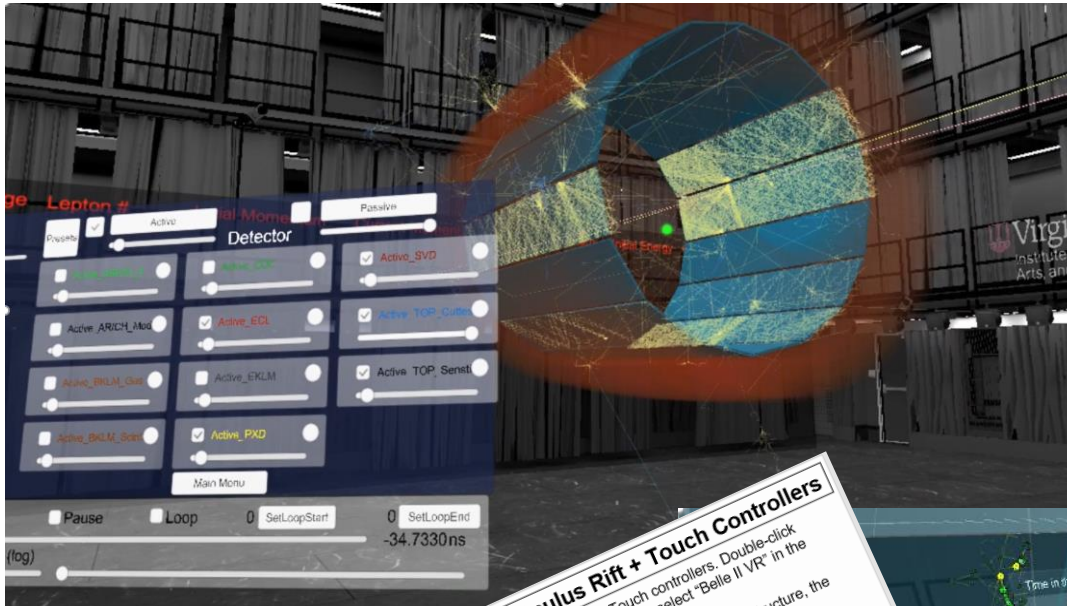
B, D mesons  
 $\tau$  leptons,  
...





# Virtual reality - Belle II detector

[https://store.steampowered.com/app/810020/Belle\\_II\\_in\\_Virtual\\_Reality/](https://store.steampowered.com/app/810020/Belle_II_in_Virtual_Reality/)



### Belle II in Virtual Reality: Oculus Rift + Touch Controllers

- Put on the Oculus Rift headset and pick up the Touch controllers. Double-click the "Belle\_II\_VR\_OculusRift" icon on the computer or select "Belle II VR" in the headset's menu. Wait for the VR world to appear.
- After the loading scene and an introductory fade-out of the Belle II structure, the animation will begin automatically. The first event is typically  $e^-e^+ \rightarrow \mu^+\mu^-$ .

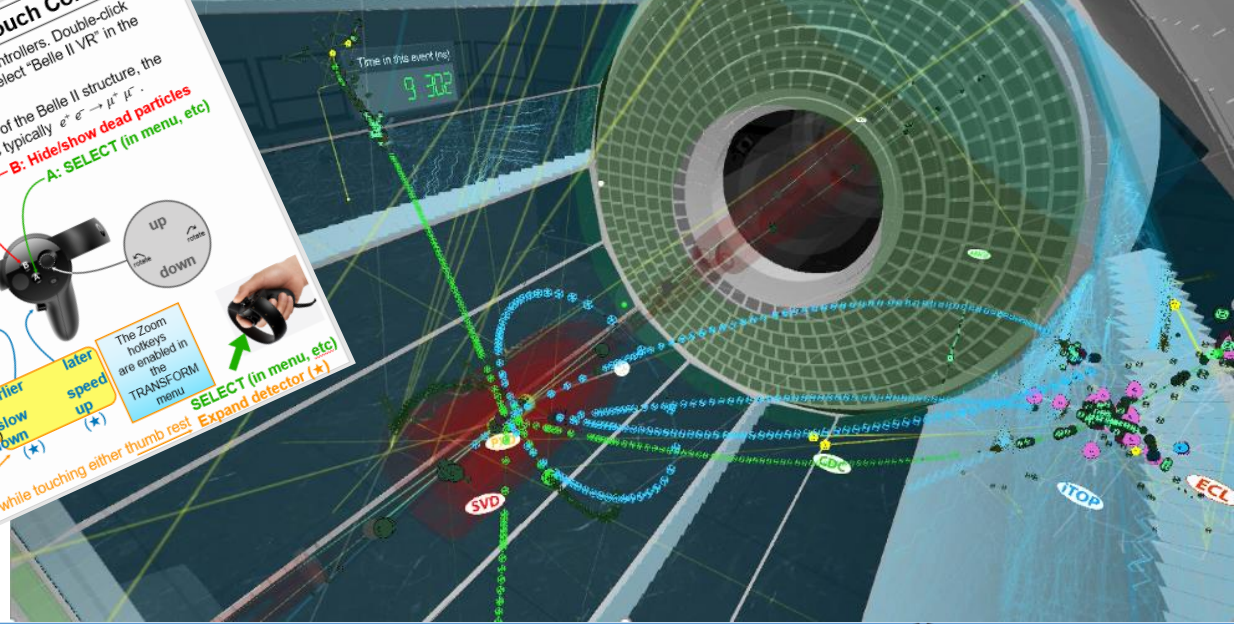
**Y: Hide/show detector-hits**  
**X: Pause / Resume**  
**B: Hide/show dead particles**  
**A: SELECT (in menu, etc)**

forward, right, left, backward, up, down, later, speed up, earlier, slow down

Show/Hide Menu, Previous Scene, SELECT (in menu, etc), Shrink detector (\*)

The Zoom hotkeys are enabled in the TRANSFORM menu. SELECT (in menu, etc), Expand detector (\*)

(\*): while touching either thumb rest



# EVENT DISPLAY

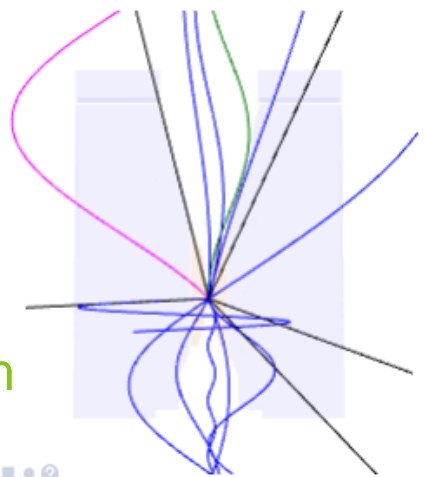
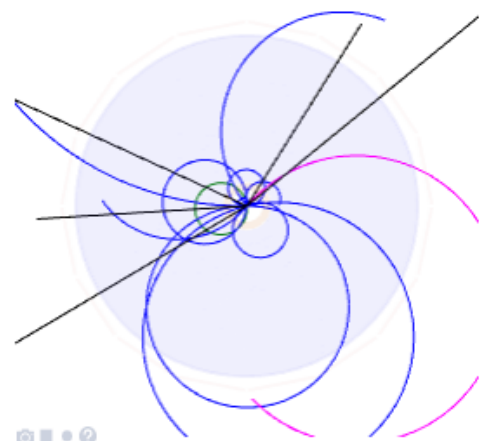
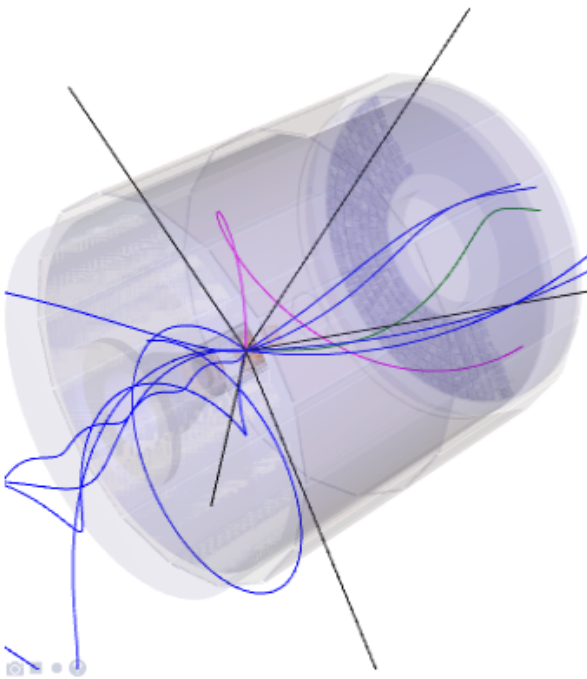


## Event display with mouse interactions

Belle II Masterclass Event Display

Event: < 1 > Close Window

Load event data



Reconstructed particles of Event 1

N	px(GeV/c)	py(GeV/c)	pz(GeV/c)	p(GeV/c)	Energy(GeV)	Charge	ID
1	0.0294873	-0.273614	0.194669	0.3370910	353262	1	muon
2	-0.229449	-0.005890370	2.43925	0.3349340	362851	1	pion
3	0.249353	0.138971	-0.133726	0.3152340	34475	-1	pion
4	0.617004	0.147713	-0.0178898	0.6346910	649856	-1	pion
5	-0.852846	-0.013393	0.58309	1.03321	1.04259	-1	pion
6	0.542409	0.00413217	-0.207596	0.5807930	597328	-1	pion
7	-0.0786903	-0.0881519	-0.0326394	0.12259	0.185764	1	pion
8	-0.0337178	-0.35194	-0.0885627	0.3644750	390284	1	pion
9	-0.269283	-0.331059	0.736212	0.8509540	862324	1	pion
10	-0.342041	0.433614	-0.520645	0.7590020	771728	-1	pion
11	-0.0889358	0.20194	0.351623	0.4151240	437959	-1	pion
120	0.417001	0.488208	0.280684	0.7007291	171106	1	proton
130	0.180873	0.288436	0.716277	0.7930710	793071	0	photon
14	-0.12108	-0.00755525	0.261905	0.2886370	288637	0	photon
150	0.15715	0.128819	-0.0075916	10.2033420	203342	0	photon
16	-0.211126	-0.125556	-0.0770802	0.2574490	257449	0	photon
17	-0.134099	0.0615151	-0.140303	0.2035970	203597	0	photon

List of reconstructed particles

Helix track propagation from interaction point





Run Analysis Interrupt Save Diagram Load Diagram

Interactive web application

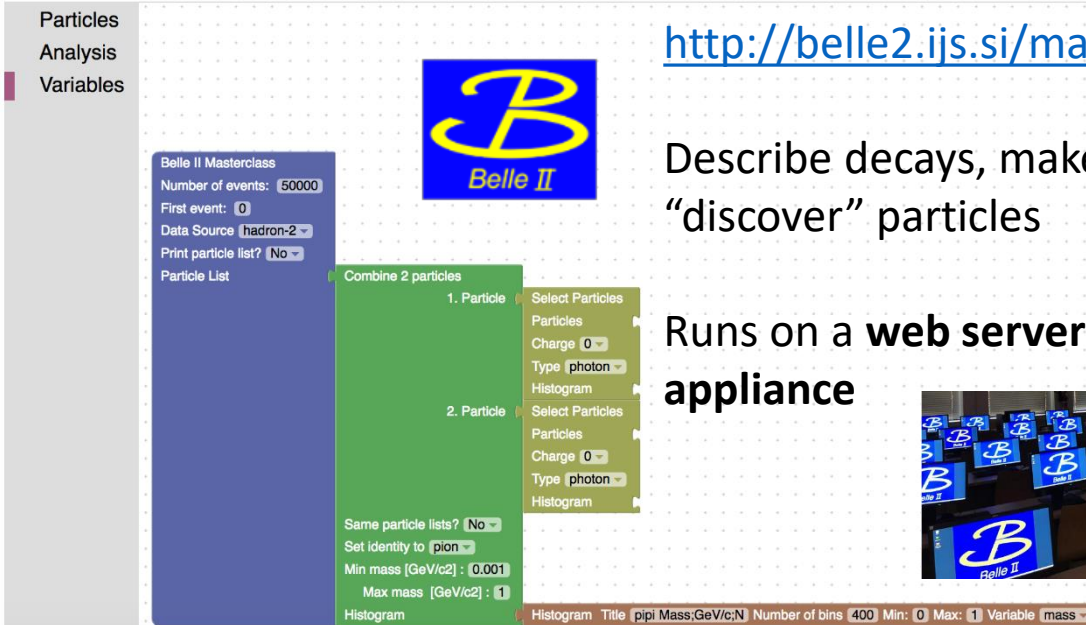
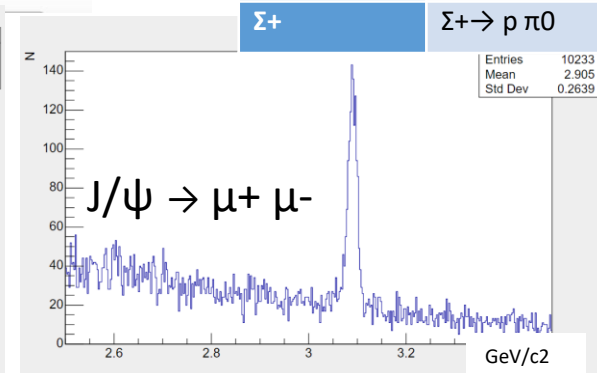
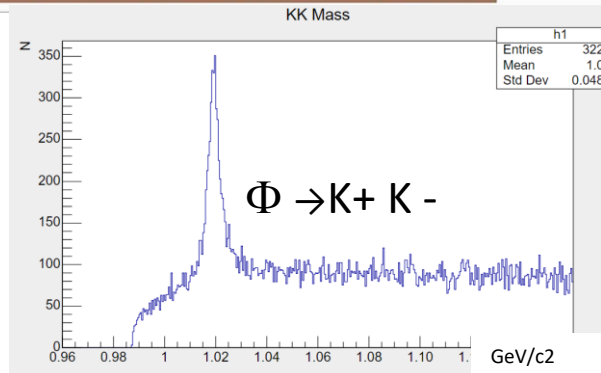
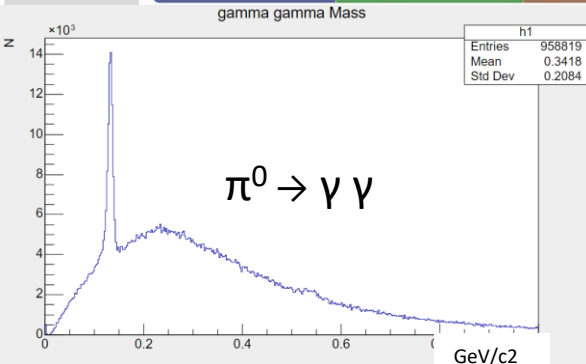
<http://belle2.ijs.si/masterclass>

Describe decays, make simple cuts,  
"discover" particles

Runs on a **web server** or in a **virtual appliance**



Particle	Process
$\pi^0$	$\pi^0 \rightarrow \gamma \gamma$
Ks	$K_s \rightarrow \pi^+ \pi^-$
$\phi$	$\phi \rightarrow K^+ K^-$
J/ $\psi$	$J/\psi \rightarrow e^+ e^-$
	$J/\psi \rightarrow \mu^+ \mu^-$
$D^0$	$D^0 \rightarrow K^+ \pi^-$
	$D^0 \rightarrow K^- \pi^+$
$D^{*+}$	$D^{*+} \rightarrow D^0 \pi^+$
$D^{*-}$	$D^{*-} \rightarrow D^0 \pi^-$
B+	$B^+ \rightarrow J/\psi K^+$
B-	$B^- \rightarrow J/\psi K^-$
$\Lambda$	$\Lambda \rightarrow p \pi^-$
$\Sigma^+$	$\Sigma^+ \rightarrow p \pi^0$



# EXERCISE

- Display missions
- Describe process
- Run

Next Run Analysis



## Mission 1

In the data you fill find a list of reconstructed particles with their properties stored for each event. Each particle is described by its:

- momentum  $\mathbf{p} = (p_x, p_y, p_z)$ ,
- energy  $E$ ,
- electric charge and
- identity

List the particles in the data for several events and plot a frequency histogram of a number of reconstructed particles per event. This is done by using the "main block" and by pressing "Run Analysis button"

Try to change the number of events and a data source file and observe how the distribution changes.

Blocks

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

Combine 2 particles

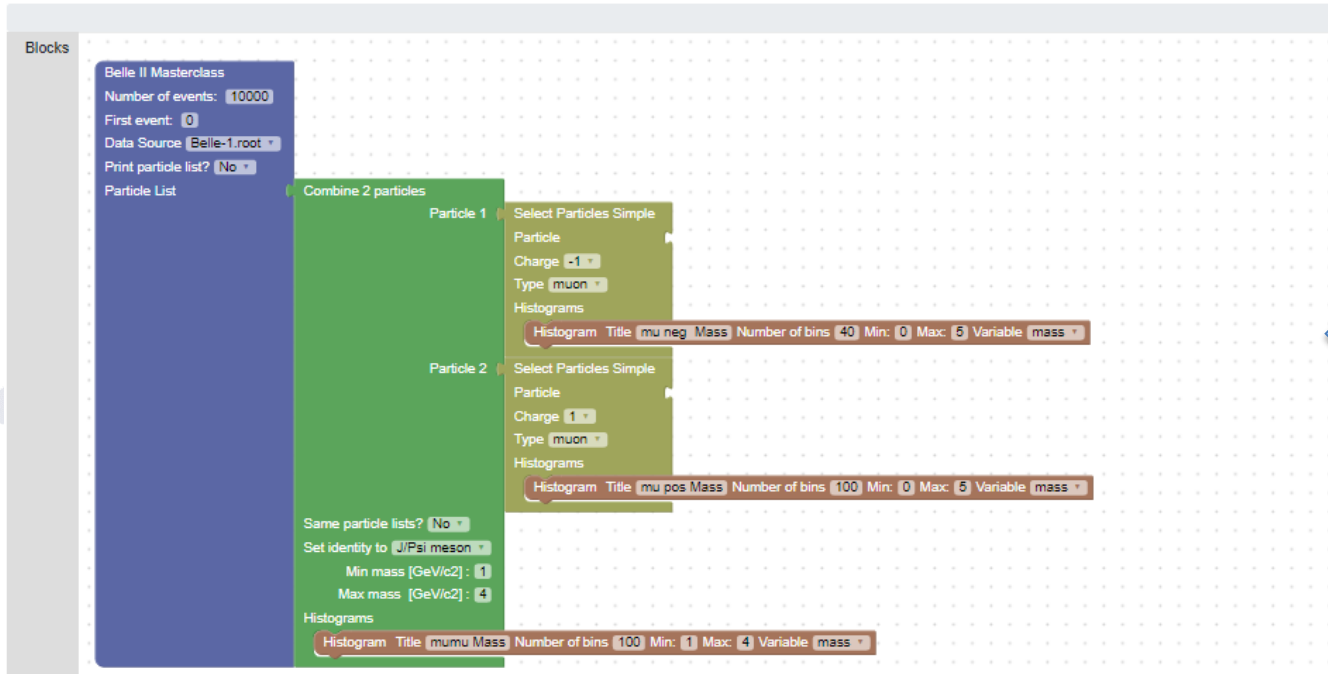
Particle 1

Select Particles Simple  
Particle  
Charge -1  
Type muon  
Histograms  
Histogram Title mu neg Mass Number of bins 40 Min: 0 Max: 5 Variable mass

Particle 2

Select Particles Simple  
Particle  
Charge 1  
Type muon  
Histograms  
Histogram Title mu pos Mass Number of bins 100 Min: 0 Max: 5 Variable mass

Same particle lists? No  
Set identity to J/Psi meson  
Min mass [GeV/c<sup>2</sup>]: 1  
Max mass [GeV/c<sup>2</sup>]: 4  
Histograms  
Histogram Title mumu Mass Number of bins 100 Min: 1 Max: 4 Variable mass



# 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 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:

Belle-1 Which contains 629,000 events

Belle-2 Which contains 5 600 000 events

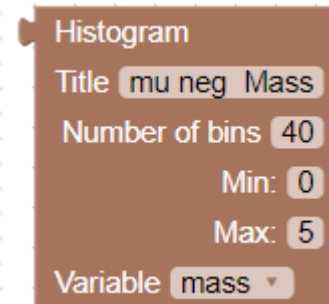
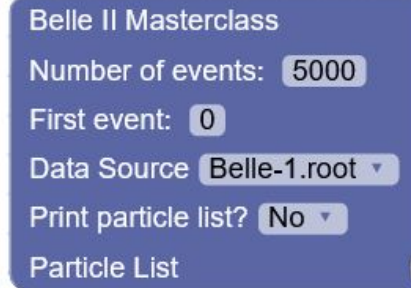
BelleII Which contains 7 085 000 events

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



# 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

A GREEN block that allows you to combine two particles and to calculate their invariant mass

You can choose to combine different particles and avoid considering the same particle twice.

The minimum and maximum of the invariant mass can be specified for further analysis

A MUSTARD block that allows to select only certain particles (electrons, muons, kaons, protons, photons) and also allows to choose the charge of the particle (-1, 0, +1, any).

Combine 2 particles

1. Particle

2. Particle

Same particle lists? No

New Particle J/Psi

Min mass [GeV] : 1

Max mass [GeV] : 4

Histogram

Select Particles

Particles

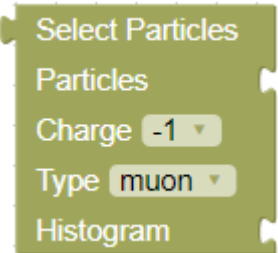
Charge -1

Type muon

Histogram

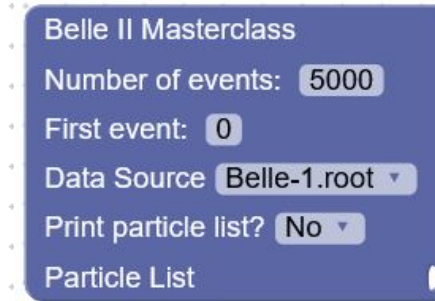


# Basic blocks



Select Particles  
Particles  
Charge   
Type   
Histogram

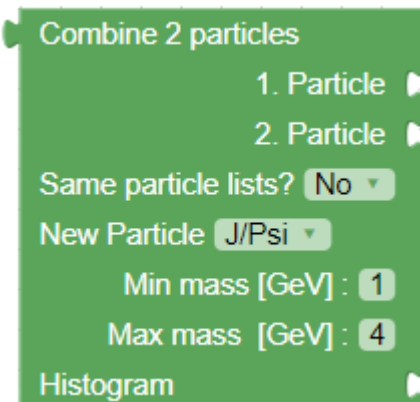
**Select particle type**  
for analysis and  
append histogram for  
plotting the  
properties



Belle II Masterclass  
Number of events:   
First event:   
Data Source   
Print particle list?   
Particle List

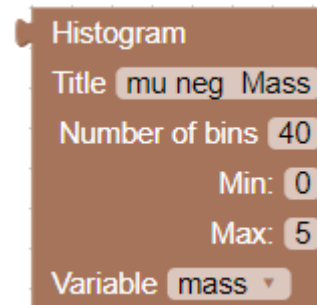
## Define main analysis parameters

- 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



Combine 2 particles  
1. Particle  
2. Particle  
Same particle lists?   
New Particle   
Min mass [GeV] :   
Max mass [GeV] :   
Histogram

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



Histogram  
Title   
Number of bins   
Min:   
Max:   
Variable

## Plot a distribution

Define a range and  
a variable to plot

# 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.

Distribution of different particle quantities can be plotted

Plot different variables :

- mass,
- momentum,
- energy,
- charge,
- identity,
- px,py,pz,pT
- cos(theta),
- theta

Belle II Masterclass

Number of events: 10000

First event: 0

Data Source hadron-1

Print particle list? No

Particle List

Select Particles

Particles

Charge Any

Type all particles

Histogram

Histogram

Title All particles;cos(polar angle);N

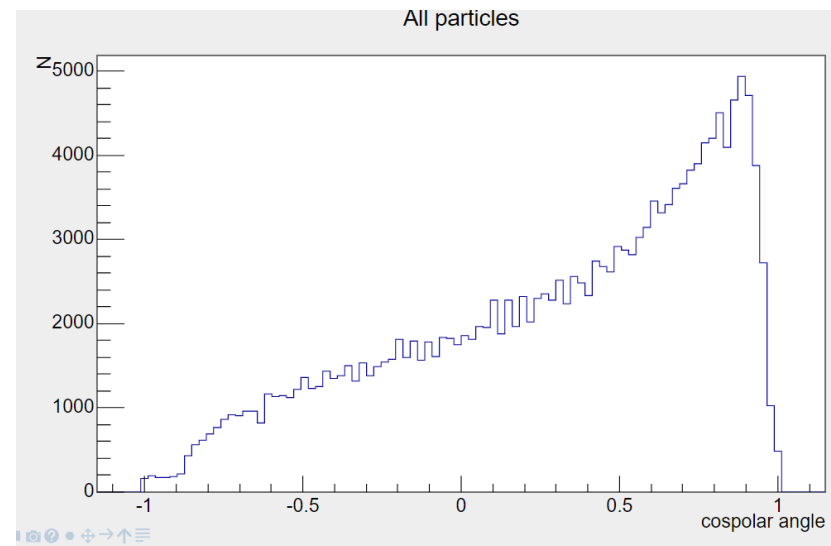
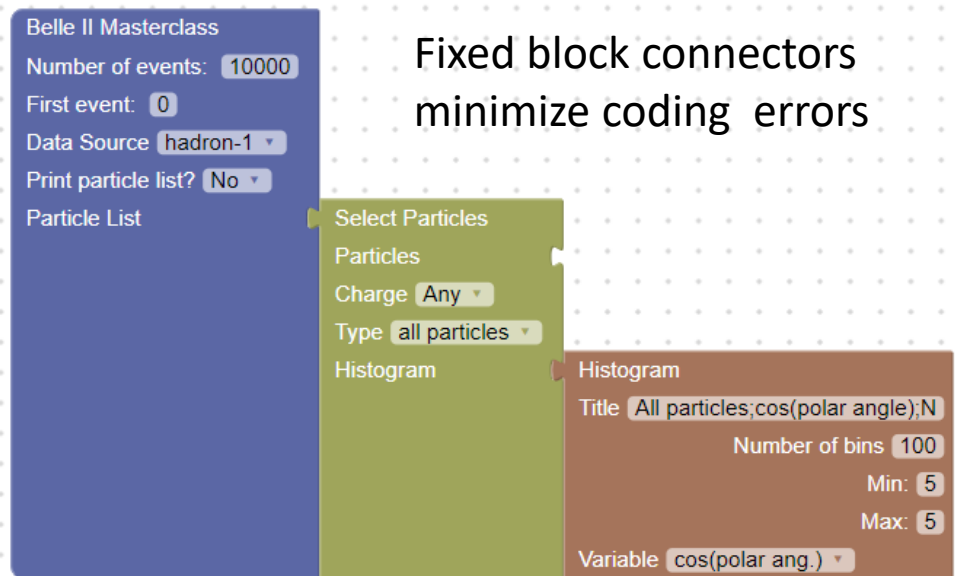
Number of bins 100

Min: 5

Max: 5

Variable cos(polar ang.)

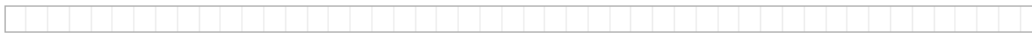
Fixed block connectors  
minimize coding errors



# Decay to two particles

Belle II Masterclass: Define process → Analyse data → Visualise results → Save/load process locally

Run Analysis Interrupt Switch between Diagram and Results Save Diagram Load Diagram



Particles  
Analysis  
Variables

Belle II Masterclass  
Number of events: 50000  
Data Source: hadron-2  
Particle List

Combine 2 partides

1. Particle  
Select Particles  
Particles  
Charge 0  
Type photon  
Histogram

2. Particle  
Select Particles  
Particles  
Charge 0  
Type photon  
Histogram

New Particle pion  
Min mass [GeV] : 0.001  
Max mass [GeV] : 1  
Histogram

Variable mass

Particle properties combined from two particles

px [GeV/c]	py [GeV/c]	pz [GeV/c]	E [GeV/c <sup>2</sup> ]	charge	ID
0.0529848	0.380323	0.300759	0.693993	1	kaon
0.0501458	0.103633	0.0817934	0.141226	-1	electron
<b>0.1031</b>	<b>0.4840</b>	<b>0.3826</b>	<b>0.8352</b>	<b>0</b>	

Invariant mass = 0.5535 GeV/c<sup>2</sup>

Close

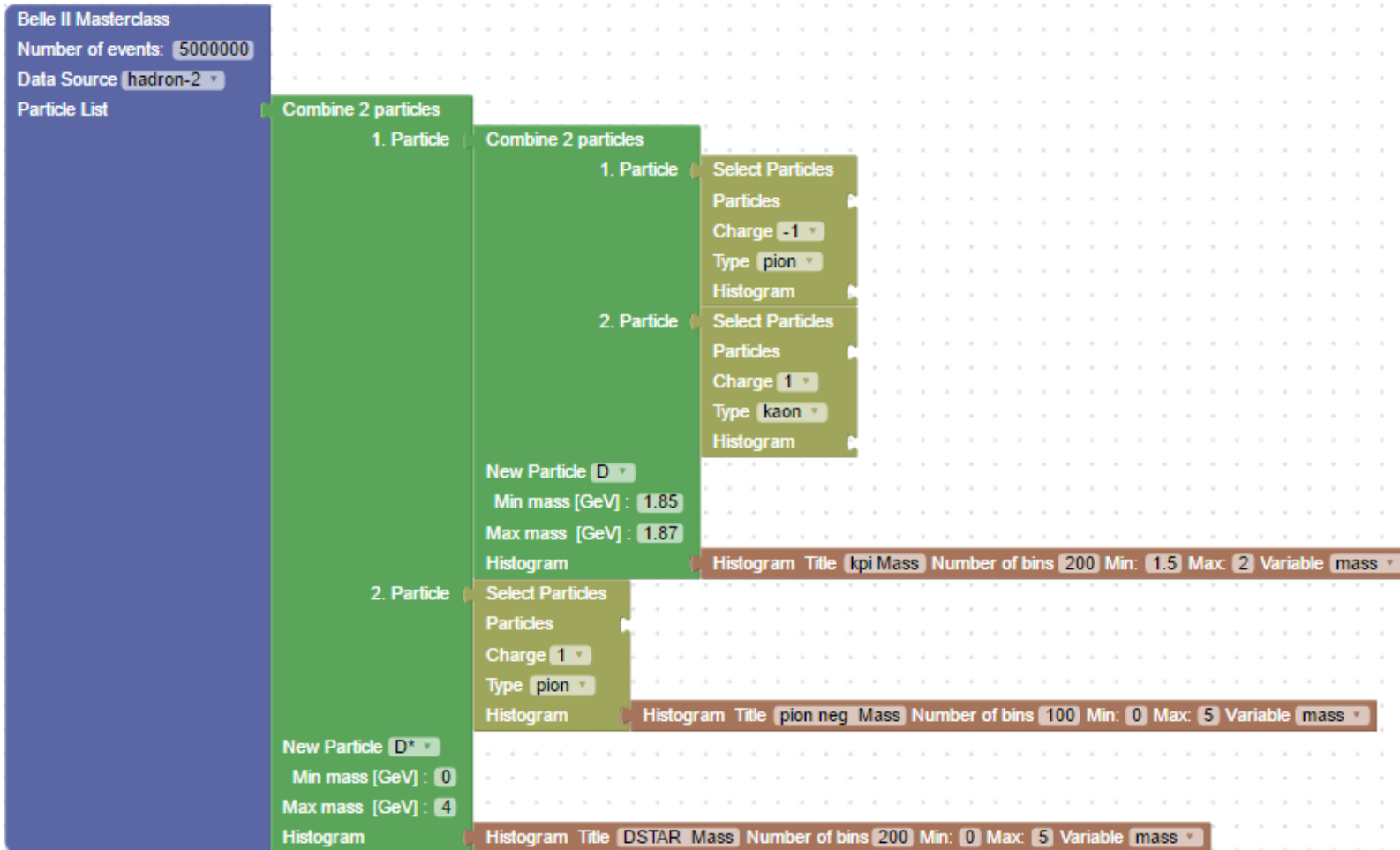
Select two particles by mouse click and display properties of the combined „particle“

Energy(GeV)	Charge	ID
1.06682	-1	electron
0.634475	-1	electron
1.01689	1	pion
0.842596	-1	pion
0.602285	-1	pion
0.787499	1	pion
0.372418	-1	pion
0.248464	1	pion
0.169532	-1	pion
0.163816	1	pion
0.321227	0	photon
0.424272	0	photon
0.578425	0	photon
0.29259	0	photon
0.361627	0	pion
0.875054	0	pion

15	0.152624	-0.0325375	0.296991	0.335494
16	0.650451	-0.401558	0.403939	0.864582

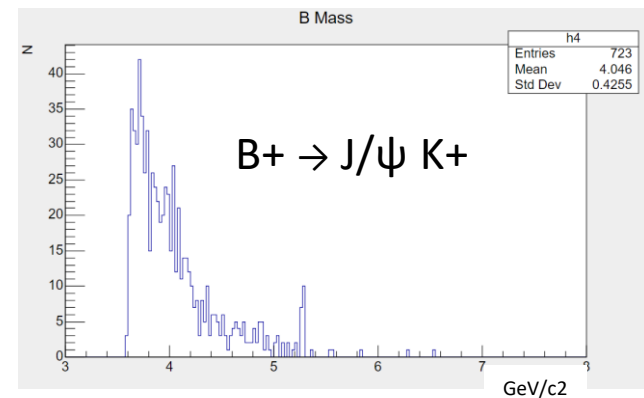
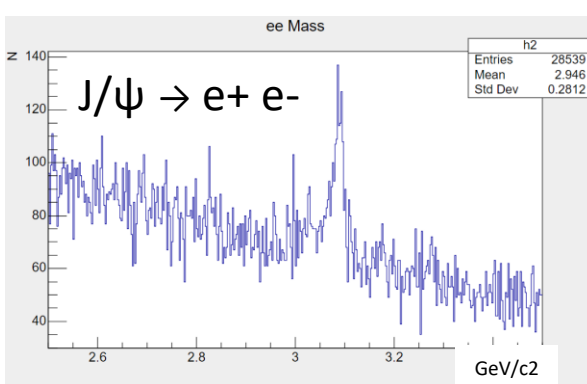
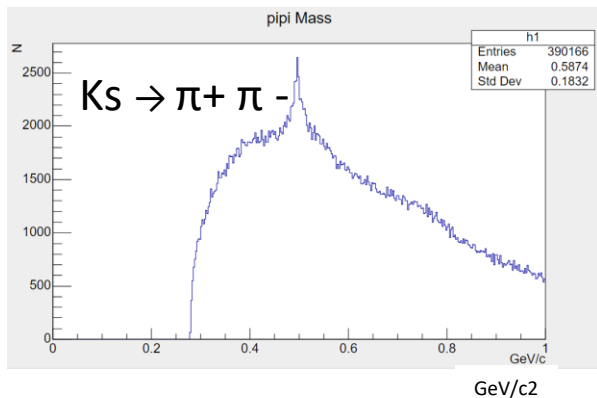
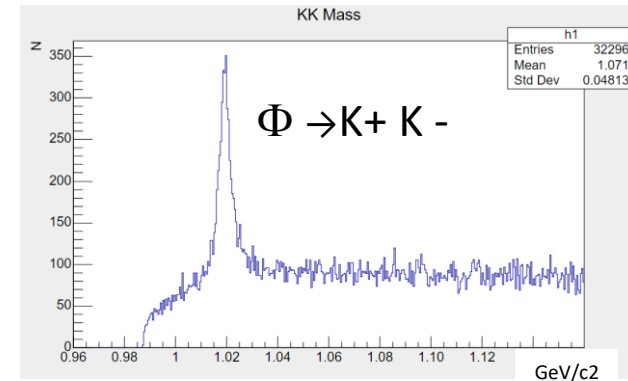
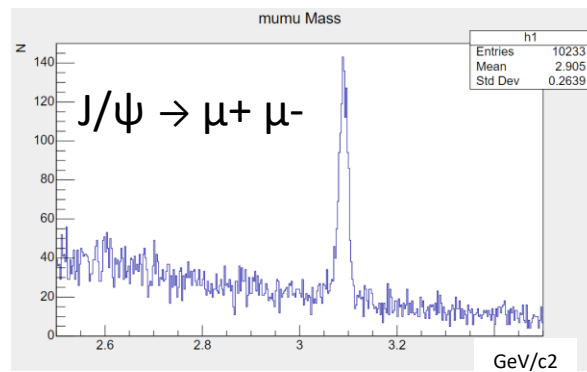
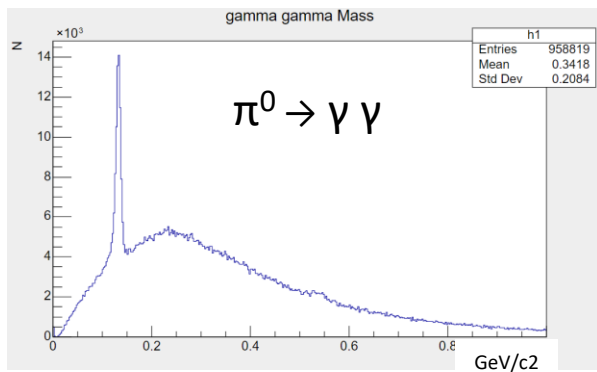


# Combination of three particles



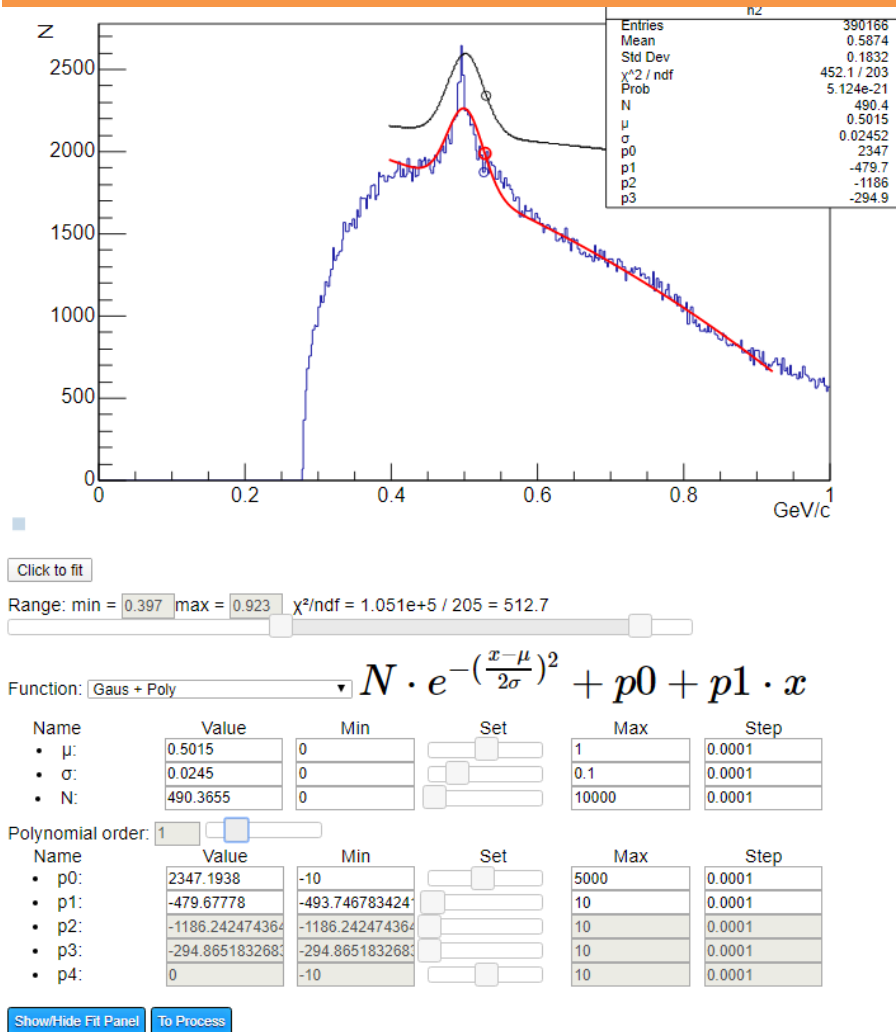
# Different decays

Invariant mass plots for different decays



# Advanced features

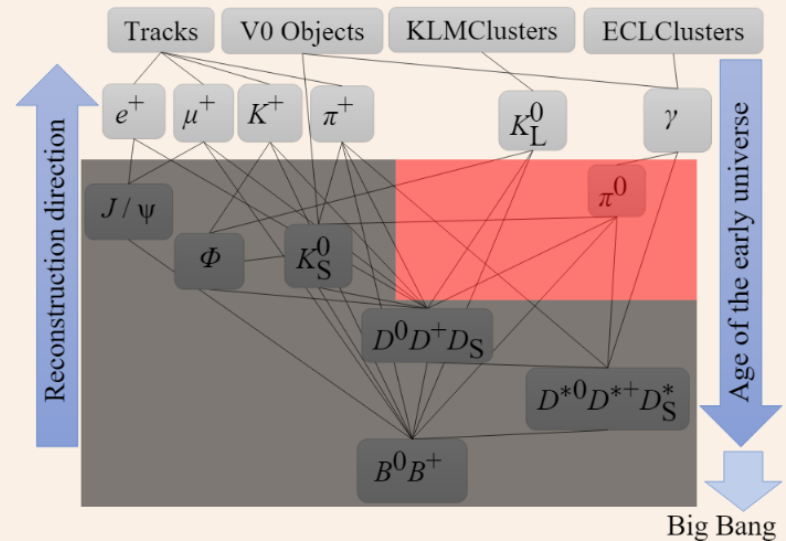
Fitting tools for interactive fitting to calculate width and number of events in the peaks



## Check your results

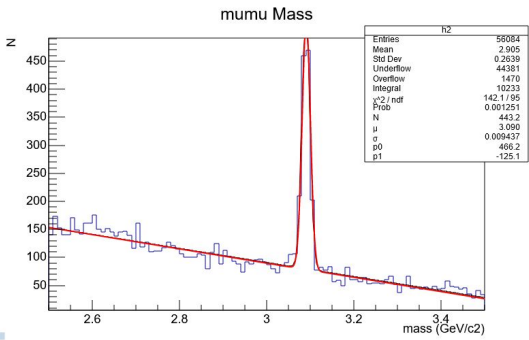
### On the way to a B meson

1.	$\pi^0 \rightarrow ???$	$\pi^0$ mass	<input type="text"/>	GeV/c <sup>2</sup>	Sadly not correct. Did you find the right peak?	
2.	$K_S \rightarrow ???$	$K_S$ mass	<input type="text"/>	GeV/c <sup>2</sup>	Please start to enter a number!	
3.	$\Phi \rightarrow ???$	$\Phi$ mass	<input type="text"/>	GeV/c <sup>2</sup>	Please start to enter a number!	
4.	$J/\Psi \rightarrow \mu^+ \mu^-$	$J/\Psi$ mass	<input type="text"/>	GeV/c <sup>2</sup>	Please start to enter a number!	
5.	$J/\Psi \rightarrow e^+ e^-$	$J/\Psi$ mass	<input type="text"/>	GeV/c <sup>2</sup>	Please start to enter a number!	
6.	$D^0 \rightarrow K^+ \pi^-$ $D^0 \rightarrow K^- \pi^+$	avg. $D^0$ mass	<input type="text"/>	GeV/c <sup>2</sup>	<input type="text"/>	GeV/c <sup>2</sup> Please start to enter a number!
7.	$D^{*+} \rightarrow D^0 \pi^+$ $D^{*-} \rightarrow D^0 \pi^-$	$D^{*+}$ mass $D^{*-}$ mass	<input type="text"/> <input type="text"/>	GeV/c <sup>2</sup> GeV/c <sup>2</sup>	<input type="text"/> <input type="text"/>	GeV/c <sup>2</sup> Please start to enter a number!
8.	$B^+ \rightarrow J/\Psi K^+$ $B^- \rightarrow J/\Psi K^-$	avg. $B^+$ mass	<input type="text"/>	GeV/c <sup>2</sup>	<input type="text"/>	GeV/c <sup>2</sup> Please start to enter a number!





# COLLECT & SUBMIT THE RESULTS



Particle name:

Particle charge:

Mass [GeV/c<sup>2</sup>]:

Width [GeV/c<sup>2</sup>]:

Events:

- Collect results on the student worksheet
- Send the worksheet to server



Range: min = 2.5 max = 3.5  $\chi^2 / \text{ndf} = 142.2 / 95 = 1.497$  N<sub>signal</sub> = 1044 N<sub>background</sub> = 9093

Function:   $N \cdot e^{-\left(\frac{x-\mu}{\sigma}\right)^2} + p0 + p1 \cdot x$

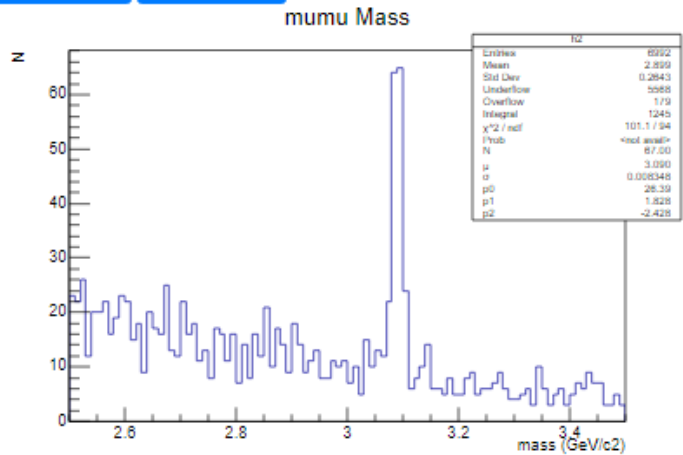
Name	Value	Min	Set	Max	Step
$\mu$ :	3.08985	2.304752489	<input type="text"/>	3.5	0.0001
$\sigma$ :	0.0094	0	<input type="text"/>	0.629469602	0.0001
N:	443.2165	0	<input type="text"/>	938	0.0001

Polynomial order:

Name	Value	Min	Set	Max	Step
p0:	466.2242	-10	<input type="text"/>	12100	0.0001
p1:	-125.0953	-1000	<input type="text"/>	10	0.0001

Belle II Masterclass Student worksheet

mission: 0  
 particle: K  
 charge: +  
 mass: 3.14  
 width: 0.0083  
 events: 122  
  
[Delete this mission](#)



Belle II Masterclass  
 Number of events: 1000000  
 First event: 0  
 Data Source:

Print particle list?

Particle List

Combine 2 particles

Particle 1:

Particle:

Charge:

Type:

Histograms:

Title:  Number of bins:  Min:  Max:  Variable:

Particle 2:

Particle:

Charge:

Type:

Histograms:

Title:  Number of bins:  Min:  Max:  Variable:

Same particle list?

Set identity to:

Min mass [GeV/c<sup>2</sup>]:

Max mass [GeV/c<sup>2</sup>]:

Histograms:

Title:  Number of bins:  Min:  Max:  Variable:

# TWO LEVELS: BEGGINER

Switch the level via menu tab Settings

# ADVANCED

Belle II Masterclass  
Number of events: 1000000  
First event: 0  
Data Source: Belle-1.root  
Print particle list? No  
Particle List

Combine 2 particles

Particle 1  
Select Particles Simple  
Particle  
Charge -1  
Type muon  
Histograms

Particle 2  
Select Particles Simple  
Particle  
Charge 1  
Type muon  
Histograms

Same particle lists? No  
Set identity to J/psi meson  
Min mass [GeV/c<sup>2</sup>]: 1  
Max mass [GeV/c<sup>2</sup>]: 4  
Histograms

Histogram Title: mumu Mass Number of bins: 100 Min: 2.5 Max: 3.5 Variable: mass

Main Blocks  
Selectors  
Combiners

Belle II Masterclass  
Number of events: 1000000  
First event: 0  
Data Source: Belle-1.root  
Print particle list? No  
Particle List

Combine 2 particles

Particle 1  
Select particles Advanced  
Particle list  
Cuts  
Cut Identity: muon  
Cut Variable: charge Operator: = Value: 1  
Histograms  
Set identity to do not set

Particle 2  
Select particles Advanced  
Particle list  
Cuts  
Cut Identity: muon  
Cut Variable: charge Operator: = Value: 1  
Histograms  
Set identity to do not set

Same particle lists? No  
Histograms

Histogram Title: mass Number of bins: 100 Min: 2 Max: 4 Variable: mass

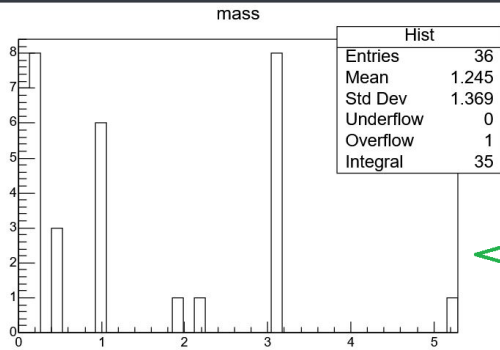
- Simple blocks
- Only two fitting functions

- Blocks enable stacking of cut variables
- Wider range of fitting functions



# TUTOR PANEL

Get the results submitted by your students



← Click on variable to get statistics



User:  Group:  Mission:  Particle:  Charge:  [Get Results from the server](#) [Clear selection](#) [Hide histo](#)

id	ip	user	group	mission	particle	charge	mass	masswidth	events	histogram	code	time
1	93.103.224.8	abcde	external	0	mu	0	1	1	2		<a href="#">Diagram</a>	2021-02-04 21:13:10
2	93.103.224.8	abcde	IJS	1	pi	+	3.14	0.0082	100		<a href="#">Diagram</a>	2021-02-08 08:24:32

Only logged users (tutors) can gain access



# SUPPORT MATERIALS FOR INSTRUCTORS & TUTORS

Collaboration Belle II IMC 2021 page:  
<https://confluence.desy.de/display/BI/IMC+2021>

Public IMC 2020 Web  
<http://belle2.ijs.si/public>

Exercise web:  
<http://belle2.ijs.si/masterclass>

Organisation section of International Masterclasses web:  
[https://physicsmasterclasses.org/index.php?cat=local\\_organisation&page=organisation](https://physicsmasterclasses.org/index.php?cat=local_organisation&page=organisation)

2020 B2GM Tutorial:  
<https://indico.cern.ch/event/882471/>

Belle II introduction video:  
<https://belle2.ijs.si/video/2020-12-01-IPPOG-HandsOn-BelleII-IMC.mp4>



# Exercises



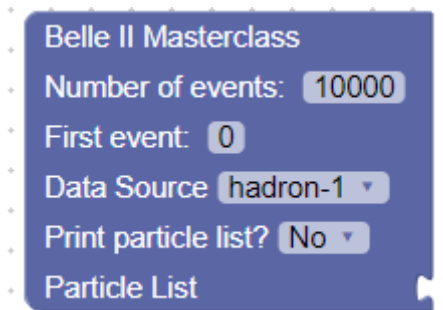
# Worksheet

Exercise table with the list of decays to examine

Particle	Quark content	Process	Mass (GeV/c <sup>2</sup> )	Number of processed events	Number of detected particles	Decay width (GeV/c <sup>2</sup> )
$\pi^0$	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$\pi^0 \rightarrow \gamma \gamma$				
Ks	$\frac{1}{\sqrt{2}}(d\bar{s} + \bar{d}s)$	$K_s \rightarrow \pi^+ \pi^-$				
$\phi$	$s\bar{s}$	$\phi \rightarrow K^+ K^-$				
J/ $\psi$	$c\bar{c}$	J/ $\psi \rightarrow e^+ e^-$				
		J/ $\psi \rightarrow \mu^+ \mu^-$				
D <sup>0</sup>	$c\bar{u}$	D <sup>0</sup> $\rightarrow K^+ \pi^-$				
		D <sup>0</sup> $\rightarrow K^- \pi^+$				
D <sup>*+</sup>		D <sup>*+</sup> $\rightarrow D^0 \pi^+$				
D <sup>*-</sup>	$d\bar{c}$	D <sup>*-</sup> $\rightarrow D^0 \pi^-$				
B <sup>+</sup>	$u\bar{b}$	B <sup>+</sup> $\rightarrow J/\psi K^+$				
B <sup>-</sup>	$\bar{u}b$	B <sup>-</sup> $\rightarrow J/\psi K^-$				

# 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  $p=(p_x,p_y,p_z)$ , 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
  - $mc^2 = \sqrt{E^2 - p^2c^2}$
  - 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<sup>2</sup>
  - From 0 to 0.0005 GeV/c<sup>2</sup>

## Exercise 3 – Decay of a particle to two particles

- From the measured momentum and energy of two particles  $(p_1, E_1)$  and  $(p_2, E_2)$  the mass of the mother particle can be calculated as

- $mc^2 = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2 c^2}$

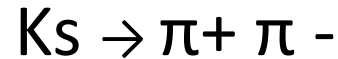
- By using a particle combiner block, the mass of the particle can be calculated for each combination of particles.
- Plot the mass distribution of neutral pion  $\pi_0$  which decay to two  $\gamma$  photons:

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

- You will find a peak at 0.135 GeV/c<sup>2</sup>, which is exactly the mass of the pion

## Exercise 4 – Decay of a kaons to charged pions

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



- You will find a peak at  $0.498 \text{ GeV}/c^2$ , which is exactly the mass of the neutral kaon  $K_S$



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

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

$$\phi \rightarrow K^+ K^-$$

- You will find a peak at 1.02 GeV/c<sup>2</sup>, which is exactly the mass of the  $\phi$

## Exercise 6 – Decay of a $J/\psi$ to leptons

- Plot the mass distribution of a  $J/\psi$  which decays to two leptons:

$$J/\psi \rightarrow e^+ e^- \quad \text{or} \quad J/\psi \rightarrow \mu^+ \mu^-$$

You will find a peak at a mass of  $J/\psi$  at  $3.10 \text{ GeV}/c^2$

Probability for a production of  $J/\psi$  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  $K^+\pi^-$  or  $K^-\pi^+$ :



You will find a peak at a mass of  $D^0$  at  $1.86 \text{ GeV}/c^2$

Probability for a production of  $D^0$  is very small.

You will have to process at least 100.000 events.

## Exercise 8 – Decay of $B^+ \rightarrow J/\psi K^+$

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

$$B^+ \rightarrow J/\psi K^+ \quad \text{or} \quad B^- \rightarrow J/\psi K^-$$

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

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  $J/\psi$  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  $D^0 \pi^+$ :

$$D^0 \rightarrow K^+ \pi^- \quad \text{or} \quad D^0 \rightarrow K^- \pi^+$$

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

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.