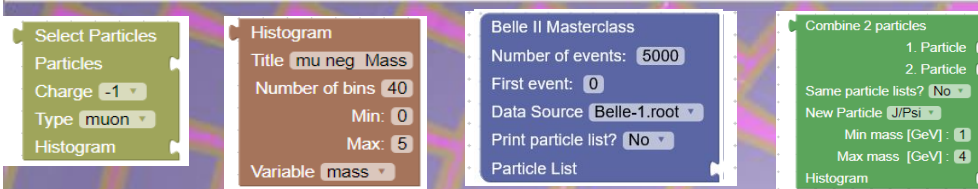


Belle II Lab Manual

(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
- Particle distribution: 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>

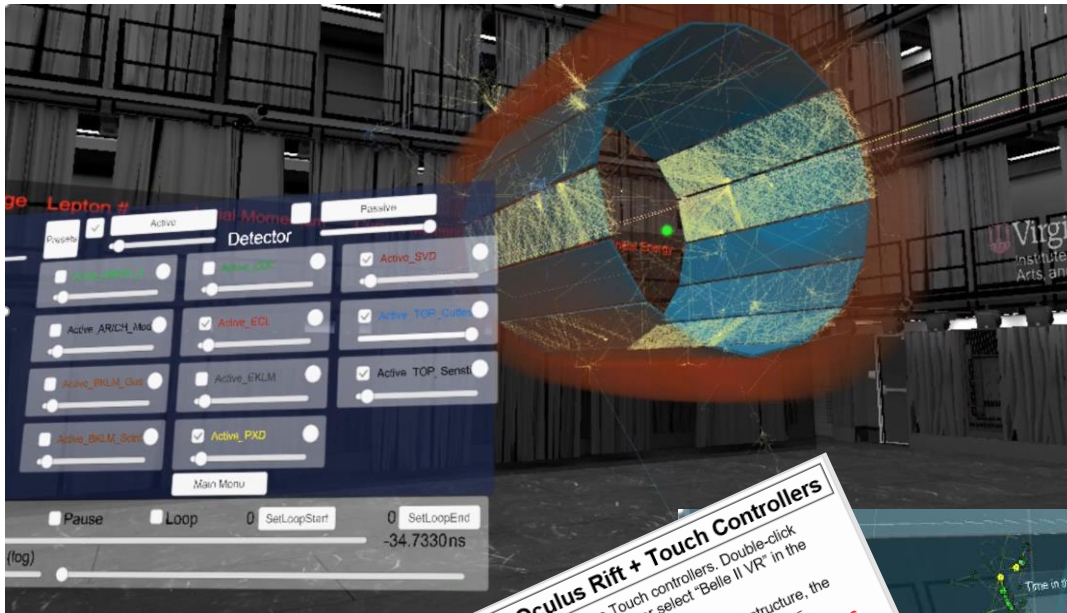
•Virtual Reality <http://www1.phys.vt.edu/~piilonen/VR/>



MASTERCLASS
Belle II Particle Adventure



Virtual reality - Belle II detector



Belle II in Virtual Reality: Oculus Rift + Touch Controllers

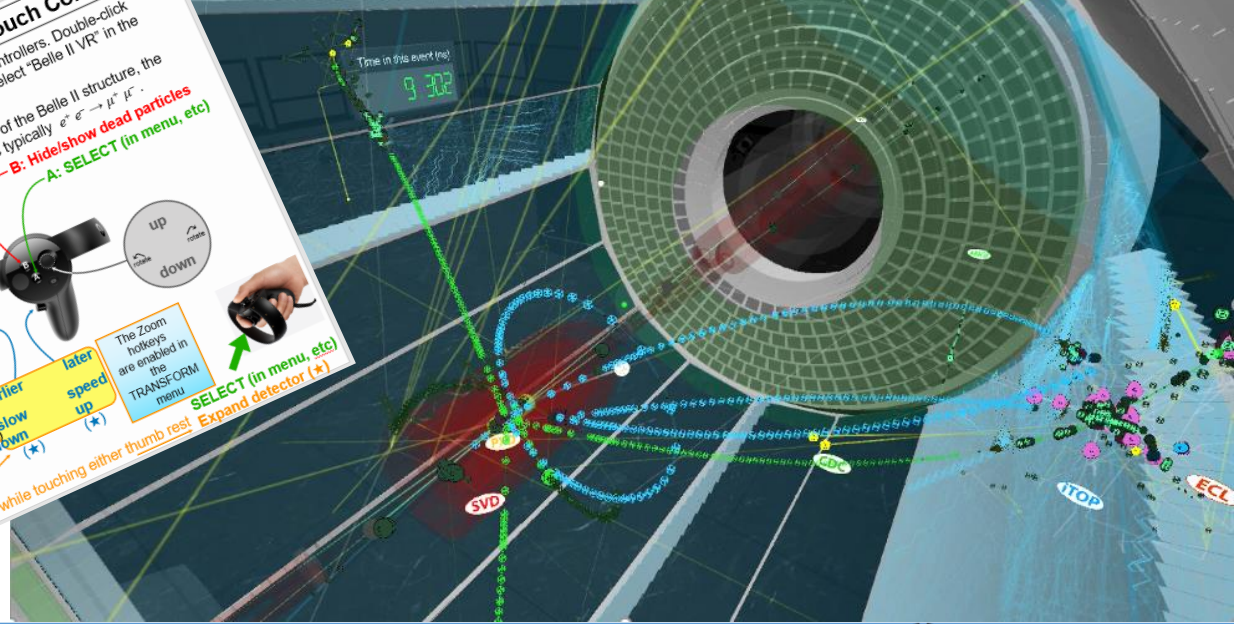
- Put on the Oculus Rift headset and pick up the Touch controllers. Double-click the "Belle_II_VR_OculusRift" icon on the computer or select "Belle II VR" in the headset's menu. Wait for the VR world to appear.
- After the loading scene and an introductory fade-out of the Belle II structure, the animation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

Controller actions:

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

Touch controller actions:

- forward, right, backward, left
- later speed up (*)
- earlier slow down (*)
- Show/Hide Menu
- Previous Scene
- SELECT (in menu, etc) Shrink detector (*)
- SELECT (in menu, etc) Expand detector (*)
- The Zoom hotkeys are enabled in the TRANSFORM menu
- up, down, right, left



EVENT DISPLAY

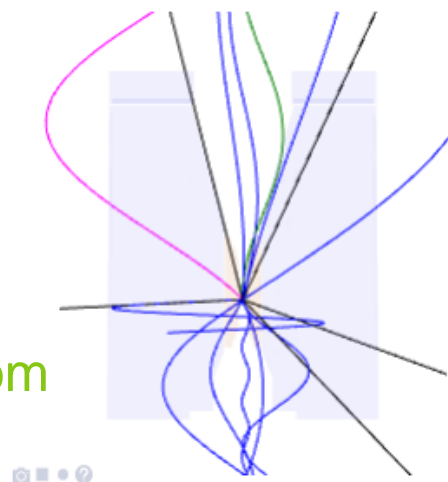
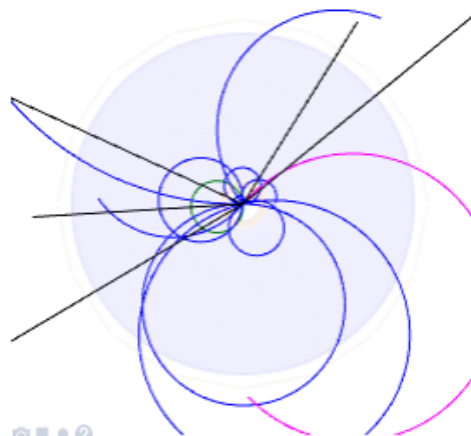
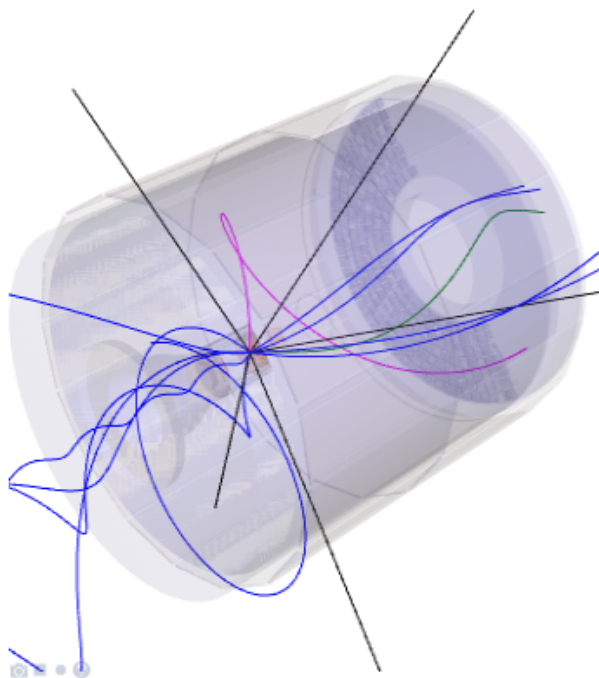


Event display with mouse interactions

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	-0.08893580	2.0194	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	-0.007555250	2.61905	0.2886370	288637	0	photon
150	0.15715	0.128819	-0.007591610	2.033420	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

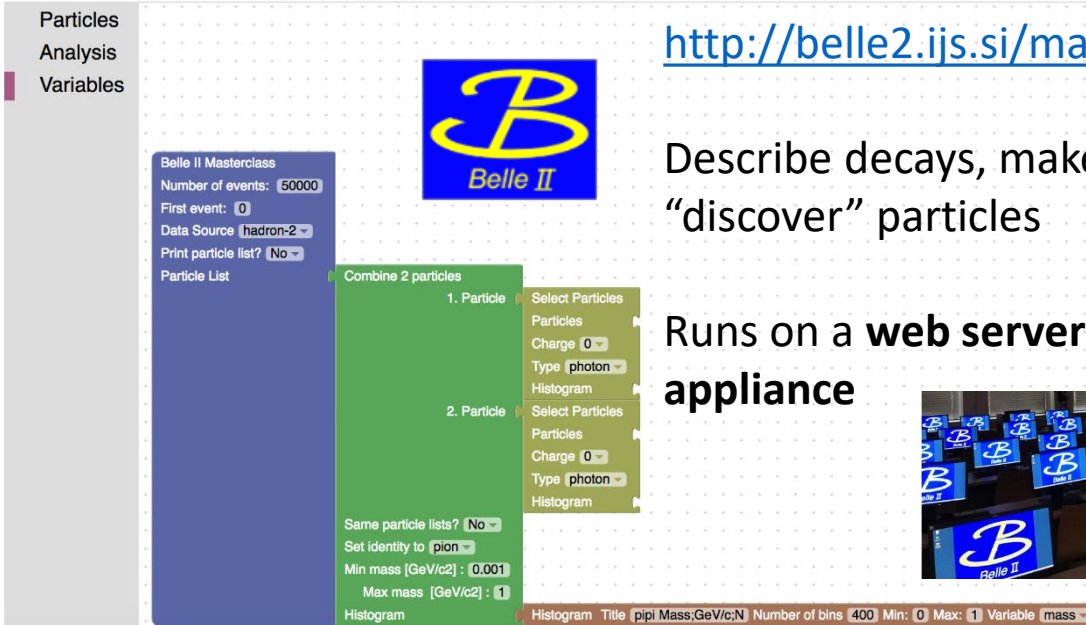
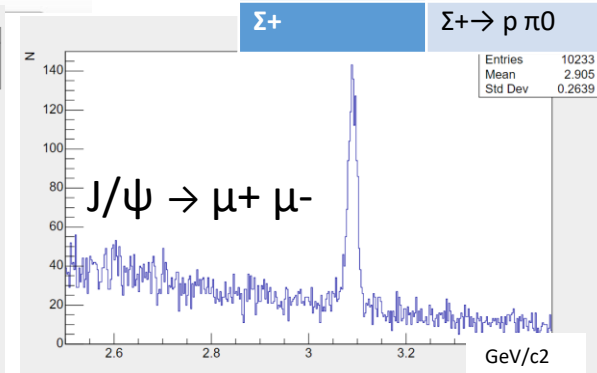
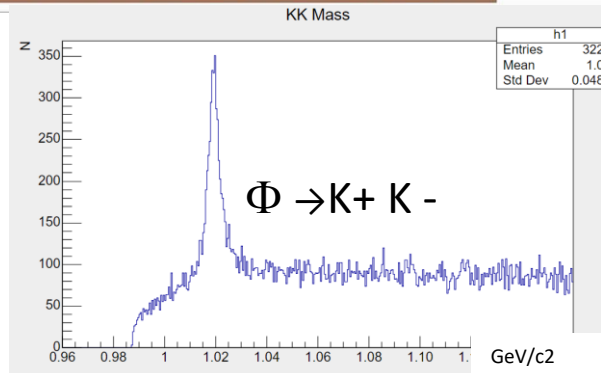
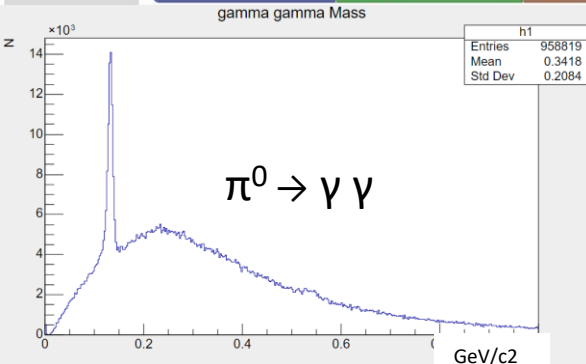
<http://belle2.ijs.si/masterclass>

Describe decays, make simple cuts,
"discover" particles

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



Particle	Process
π^0	$\pi^0 \rightarrow \gamma \gamma$
Ks	$K_s \rightarrow \pi^+ \pi^-$
ϕ	$\phi \rightarrow K^+ K^-$
J/ψ	$J/\psi \rightarrow e^+ e^-$
	$J/\psi \rightarrow \mu^+ \mu^-$
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 ⁻	$B^- \rightarrow J/\psi K^-$
Λ	$\Lambda \rightarrow p \pi^-$
Σ ⁺	$\Sigma^+ \rightarrow p \pi^0$

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

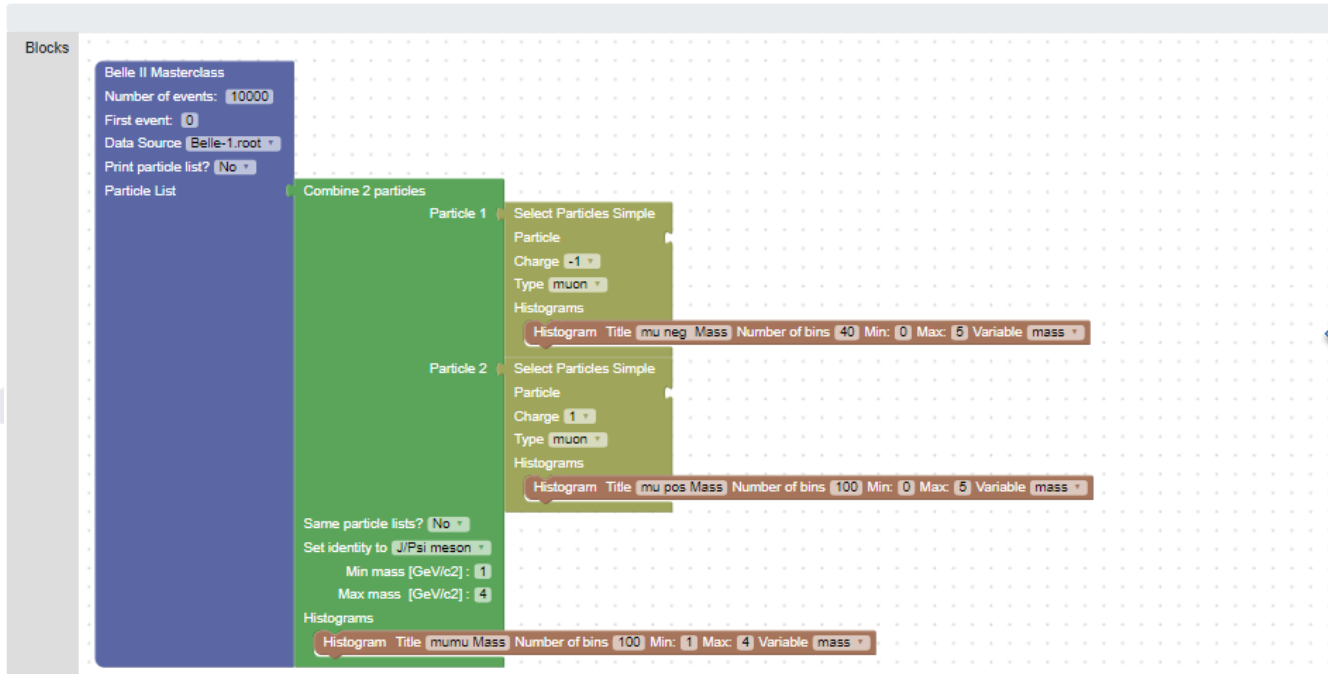
Belle II Masterclass
Number of events: 10000
First event: 0
Data Source: Belle-1.root
Print particle list? No
Particle List

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/c²]: 1
Max mass [GeV/c²]: 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

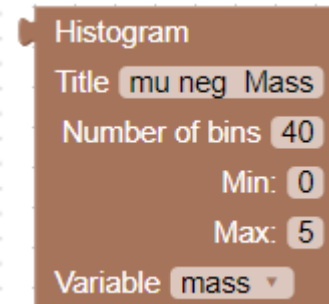
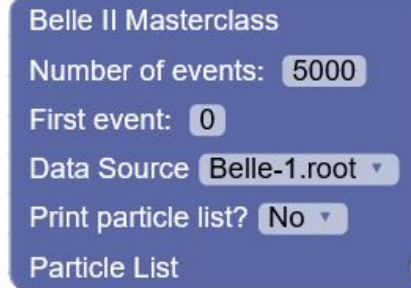
BelleII Which contains 7 085 000 events

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

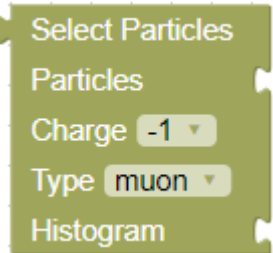
Particles

Charge -1

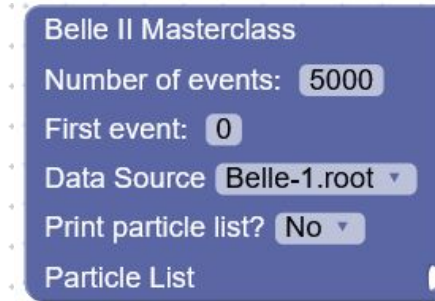
Type muon

Histogram

Basic blocks

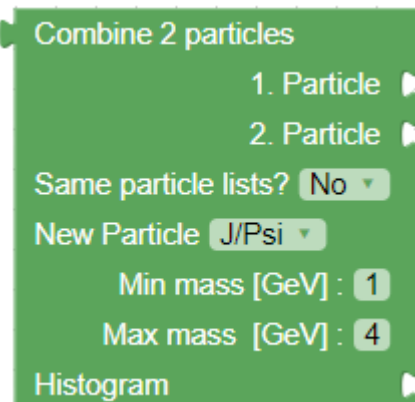


Select particle type
for analysis and
append histogram for
plotting the
properties

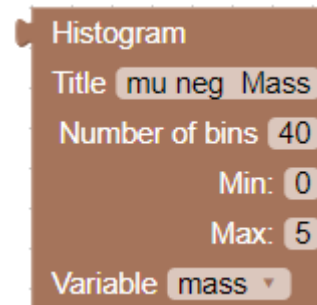


**Define main analysis
parameters**

- 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

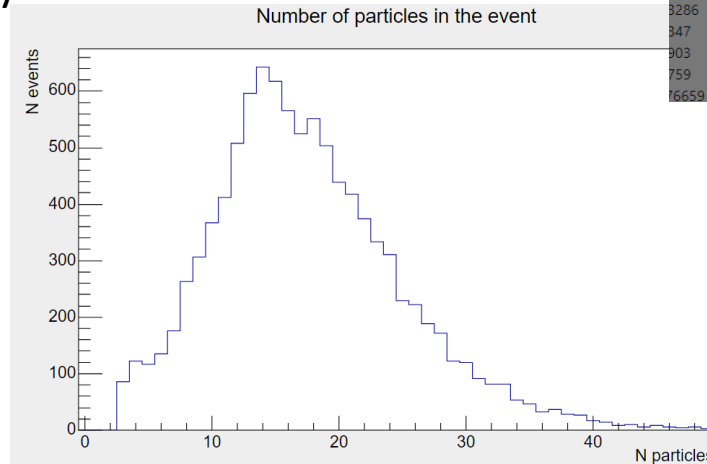
Number of events:

First event:

Data Source

Print particle list?

Particle List



Particle properties ✕

- momentum (px,py,pz) = (-0.49183, -0.486732, 0.167347) GeV/c
- energy = 0.866329 GeV/c²
- charge = 1
- identity = kaon

- momentum = 0.712 GeV/c
- transverse momentum = 0.69 GeV/c
- polar angle theta = 76.40 deg.
- cos(theta) = 0.235
- invariant mass = 0.494 GeV/c²

Win key + mouse click on the row

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

INVARIANT MASS & COMBINATION OF PARTICLES

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

Reconstructed particles of Event 26

N	px(GeV/c)	py(GeV/c)
1	0.0773758	0.972459
2	0.659583	-0.326957
3	0.223407	-0.680056
4	0.328163	-0.0625171
5	0.35006	-0.41387
6	-0.88167	0.0105236
7	-0.543176	0.575449
8	-0.0728633	0.107907
9	-0.629569	0.695791

Reconstructed particles of Event 27

N	px(GeV/c)	py(GeV/c)
1	1.58134	-1.13479
2	-0.670415	0.902964
3	-0.568484	0.553977
4	-0.474964	0.388314
5	-0.190492	0.482662

Particle properties

- momentum (px,py,pz) = (-0.543176 , 0.575449 , -0.307604) GeV/c
- energy = 0.849 GeV/c²
- charge = 0
- identity = photon

- momentum = 0.849 GeV/c
- transverse momentum = 0.79 GeV/c
- polar angle theta = 111.24 deg.
- cos(theta) = -0.362
- invariant mass = NaN GeV/c²

Close

Ctrl+Click on a single row



Click on two different rows



Reconstructed particles of Event 26

N	px(GeV/c)	py(GeV/c)
1	0.0773758	0.972459
2	0.659583	-0.326957
3	0.223407	-0.680056
4	0.328163	-0.0625171
5	0.35006	-0.41387
6	-0.88167	0.0105236
7	-0.543176	0.575449
8	-0.0728633	0.107907
9	-0.629569	0.695791

Reconstructed particles of Event 27

N	px(GeV/c)	py(GeV/c)
1	1.58134	-1.13479
2	-0.670415	0.902964
3	-0.568484	0.553977
4	-0.474964	0.388314
5	-0.190492	0.482662

Particle properties combined from two particles

px [GeV/c]	py [GeV/c]	pz [GeV/c]	E [GeV/c ²]	charge	ID
-0.543176	0.575449	-0.307604	0.849	0	photon
0.35006	-0.41387	1.45082	1.54877	0	photon
-0.1931	0.1616	1.1432	2.3978	0	

Invariant mass = 2.0926 GeV/c²

Close

Charge	ID
-1	pion
1	proton
1	pion
-1	muon
0	photon
0	photon
0	photon
0	photon
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.

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

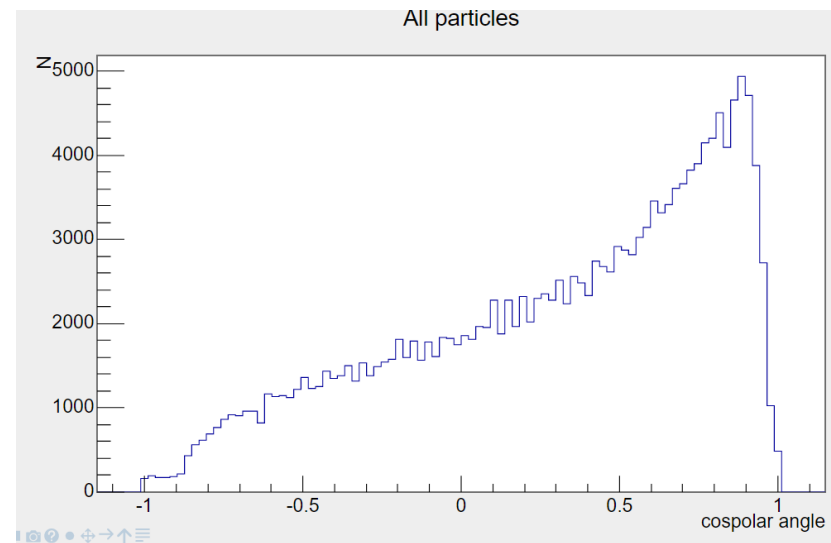
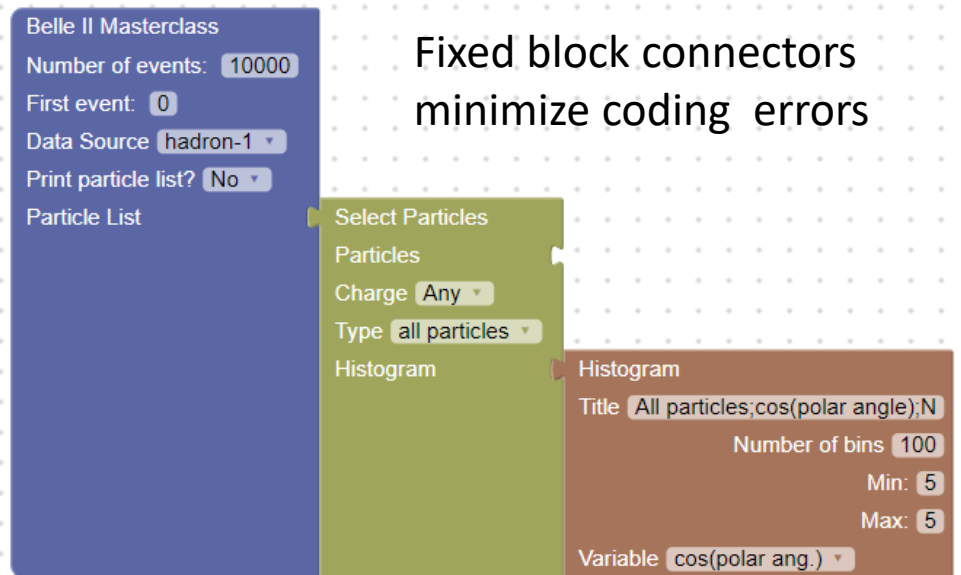
Number of bins 100

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

Number of bins 400

Min: 0

Max: 1

Particle properties combined from two particles

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

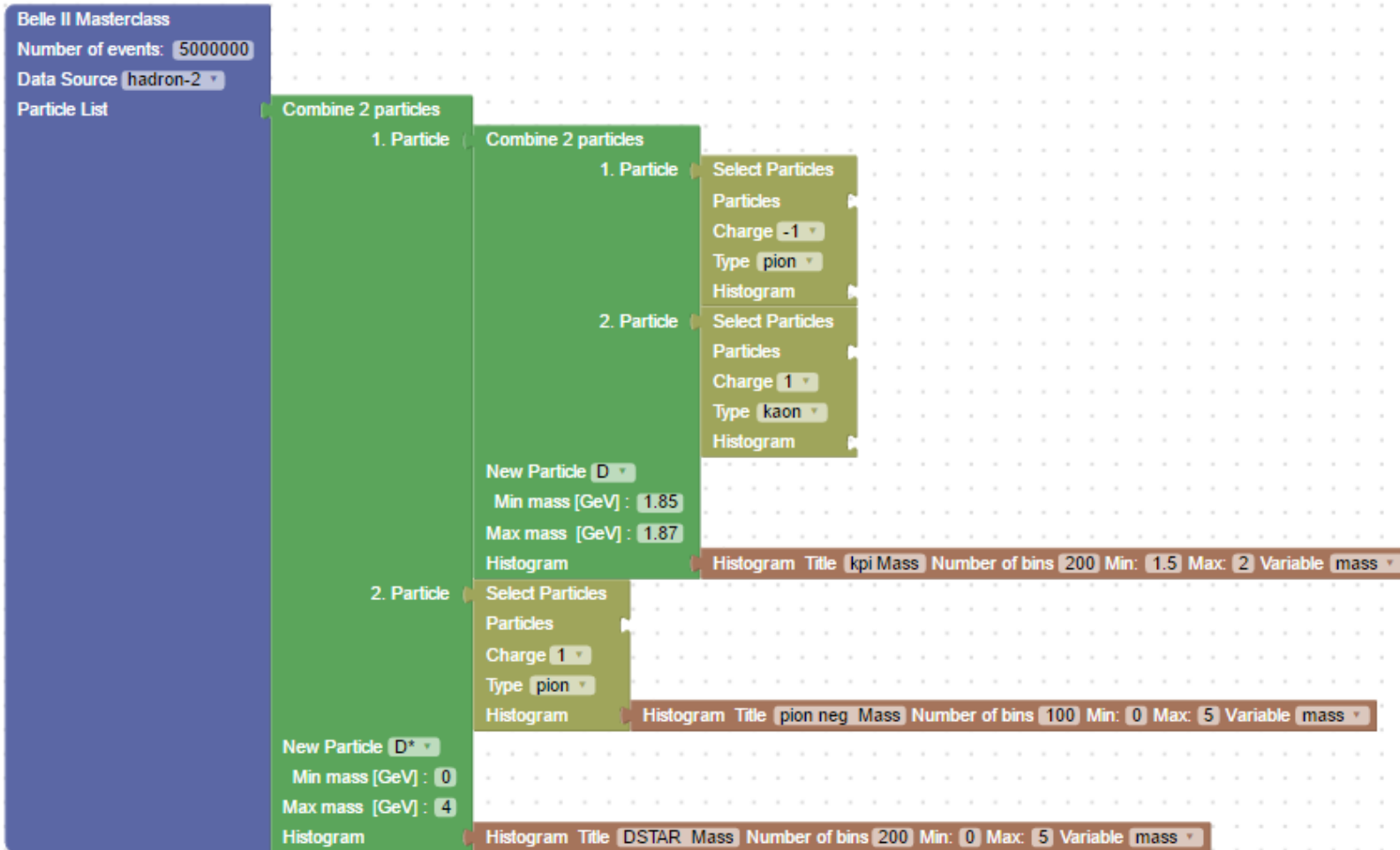
Invariant mass = 0.5535 GeV/c²

Close

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

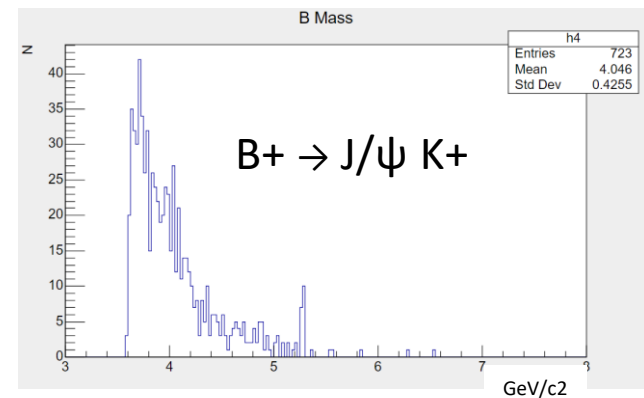
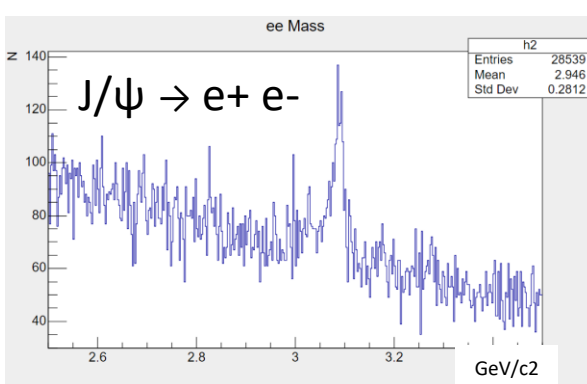
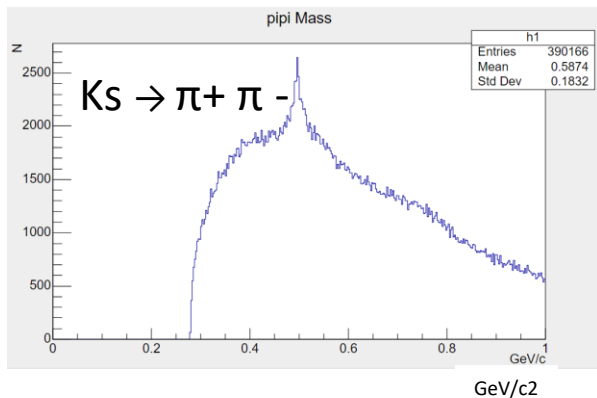
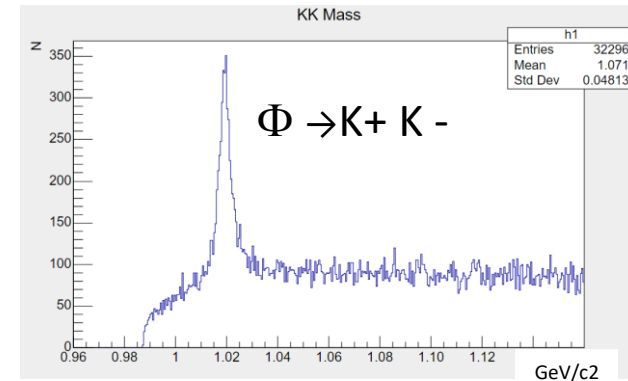
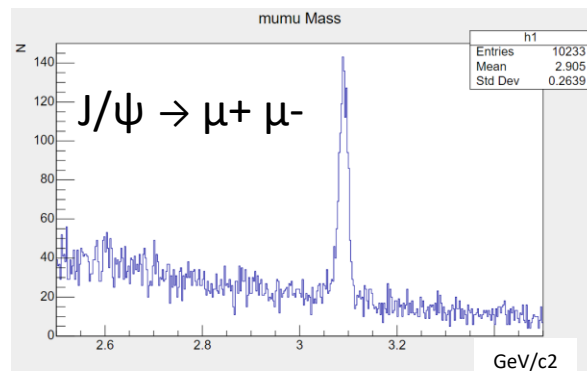
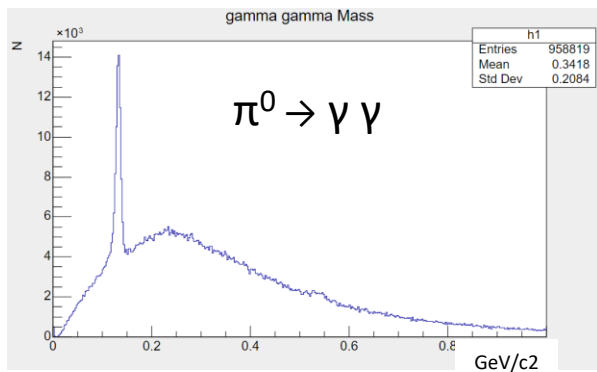
Energy(GeV)	Charge	ID
1.06682	-1	electron
0.634475	-1	electron
1.01689	1	pion
0.842596	-1	pion
0.602285	-1	pion
0.787499	1	pion
0.372418	-1	pion
0.248464	1	pion
0.169532	-1	pion
0.163816	1	pion
0.321227	0	photon
0.424272	0	photon
0.578425	0	photon
0.29259	0	photon
0.361627	0	pion
0.875054	0	pion

Combination of three particles



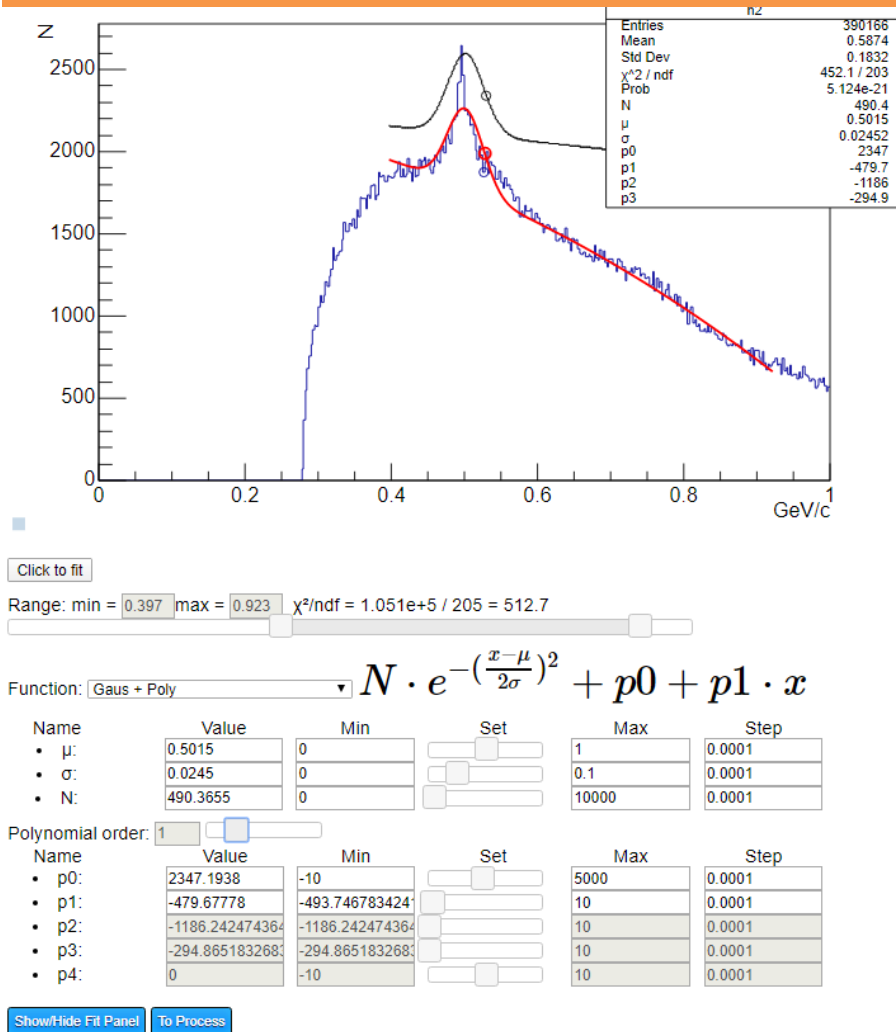
Different decays

Invariant mass plots for different decays



Advanced features

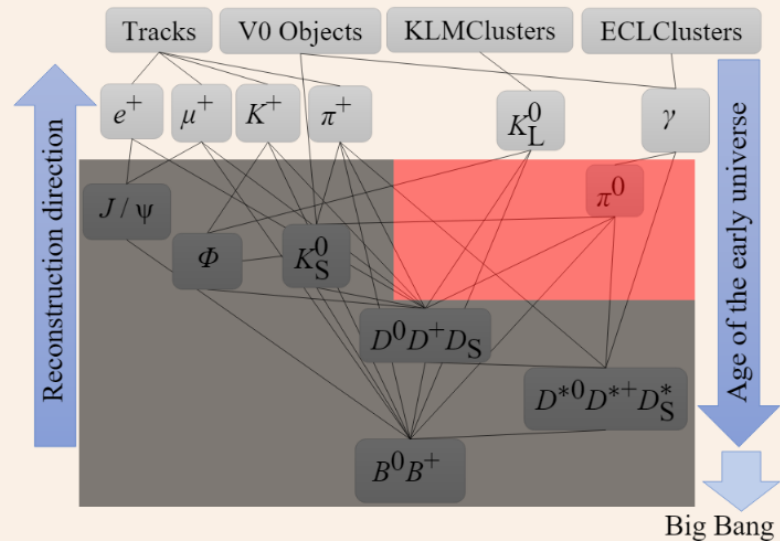
Fitting tools for interactive fitting to calculate width and number of events in the peaks



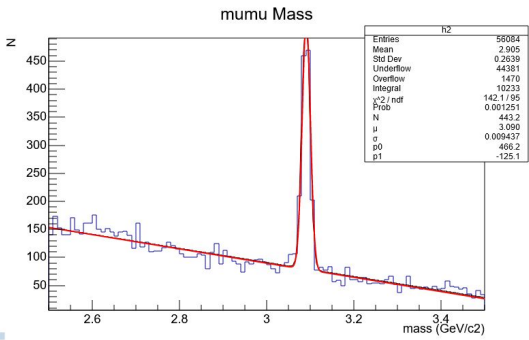
Check your results

On the way to a B meson

1.	$\pi^0 \rightarrow ???$	π^0 mass	<input type="text"/>	GeV/c ²	Sadly not correct. Did you find the right peak?	
2.	$K_S \rightarrow ???$	K_S mass	<input type="text"/>	GeV/c ²	Please start to enter a number!	
3.	$\Phi \rightarrow ???$	Φ mass	<input type="text"/>	GeV/c ²	Please start to enter a number!	
4.	$J/\Psi \rightarrow \mu^+ \mu^-$	J/Ψ mass	<input type="text"/>	GeV/c ²	Please start to enter a number!	
5.	$J/\Psi \rightarrow e^+ e^-$	J/Ψ mass	<input type="text"/>	GeV/c ²	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 ²	<input type="text"/>	GeV/c ² 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 ² GeV/c ²	<input type="text"/> <input type="text"/>	GeV/c ² 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 ²	<input type="text"/>	GeV/c ² Please start to enter a number!



COLLECT & SUBMIT THE RESULTS



Particle name:

Particle charge:

Mass [GeV/c²]:

Width [GeV/c²]:

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_{signal} = 1044 N_{background} = 9093

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

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

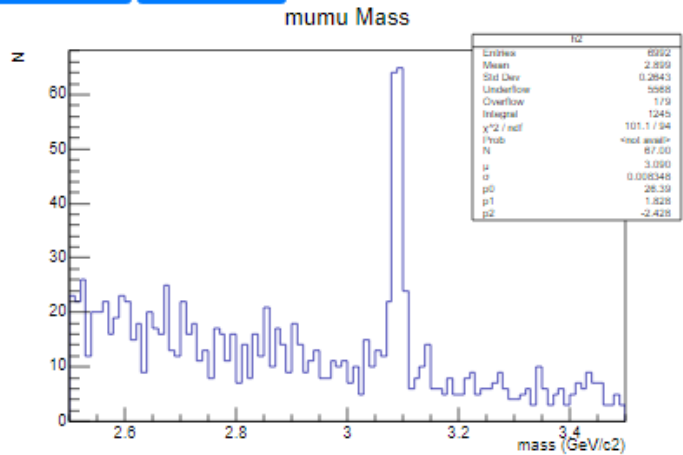
Polynomial order:

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:

Particle 2:
 Particle:
 Charge:
 Type:
 Histograms:

Same particle list?

Set identity to:

Min mass [GeV/c²]:
 Max mass [GeV/c²]:
 Histograms:

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/Ψ meson

Min mass [GeV/c²]: 1

Max mass [GeV/c²]: 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

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

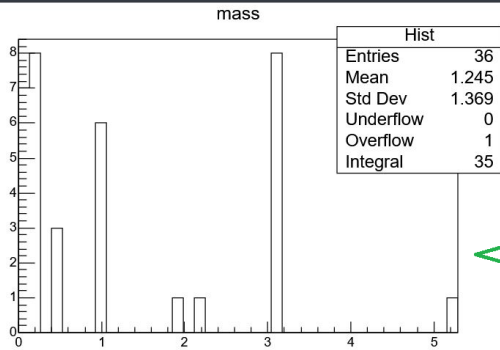
- Simple blocks
- Only two fitting functions

- 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		Diagram	2021-02-04 21:13:10
2	93.103.224.8	abcde	IJS	1	pi	+	3.14	0.0082	100		Diagram	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

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

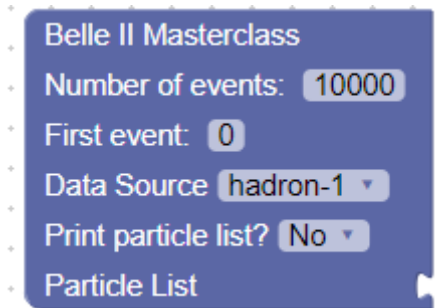
Worksheet

Exercise table with the list of decays to examine

Particle	Quark content	Process	Mass (GeV/c ²)	Number of processed events	Number of detected particles	Decay width (GeV/c ²)
π^0	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$\pi^0 \rightarrow \gamma \gamma$				
Ks	$\frac{1}{\sqrt{2}}(d\bar{s} + \bar{d}s)$	$K_s \rightarrow \pi^+ \pi^-$				
ϕ	$s\bar{s}$	$\phi \rightarrow K^+ K^-$				
J/ ψ	$c\bar{c}$	J/ $\psi \rightarrow e^+ e^-$				
		J/ $\psi \rightarrow \mu^+ \mu^-$				
D ⁰	$c\bar{u}$	D ⁰ $\rightarrow K^+ \pi^-$				
		D ⁰ $\rightarrow K^- \pi^+$				
D ^{*+}		D ^{*+} $\rightarrow D^0 \pi^+$				
D ^{*-}	$d\bar{c}$	D ^{*-} $\rightarrow D^0 \pi^-$				
B ⁺	$u\bar{b}$	B ⁺ $\rightarrow J/\psi K^+$				
B ⁻	$\bar{u}b$	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 $p=(p_x,p_y,p_z)$, 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/c²
 - From 0 to 0.0005 GeV/c²

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

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

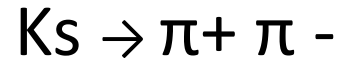
- By using a particle combiner block, the mass of the particle can be calculated for each combination of particles.
- Plot the mass distribution of neutral pion π_0 which decay to two γ photons:

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

- 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 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/c², which is exactly the mass of the ϕ

Exercise 6 – Decay of a J/ψ to leptons

- Plot the mass distribution of a J/ψ 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/ψ at $3.10 \text{ GeV}/c^2$

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 $K^+\pi^-$ 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/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 $D^0 \pi^+$:

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

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.