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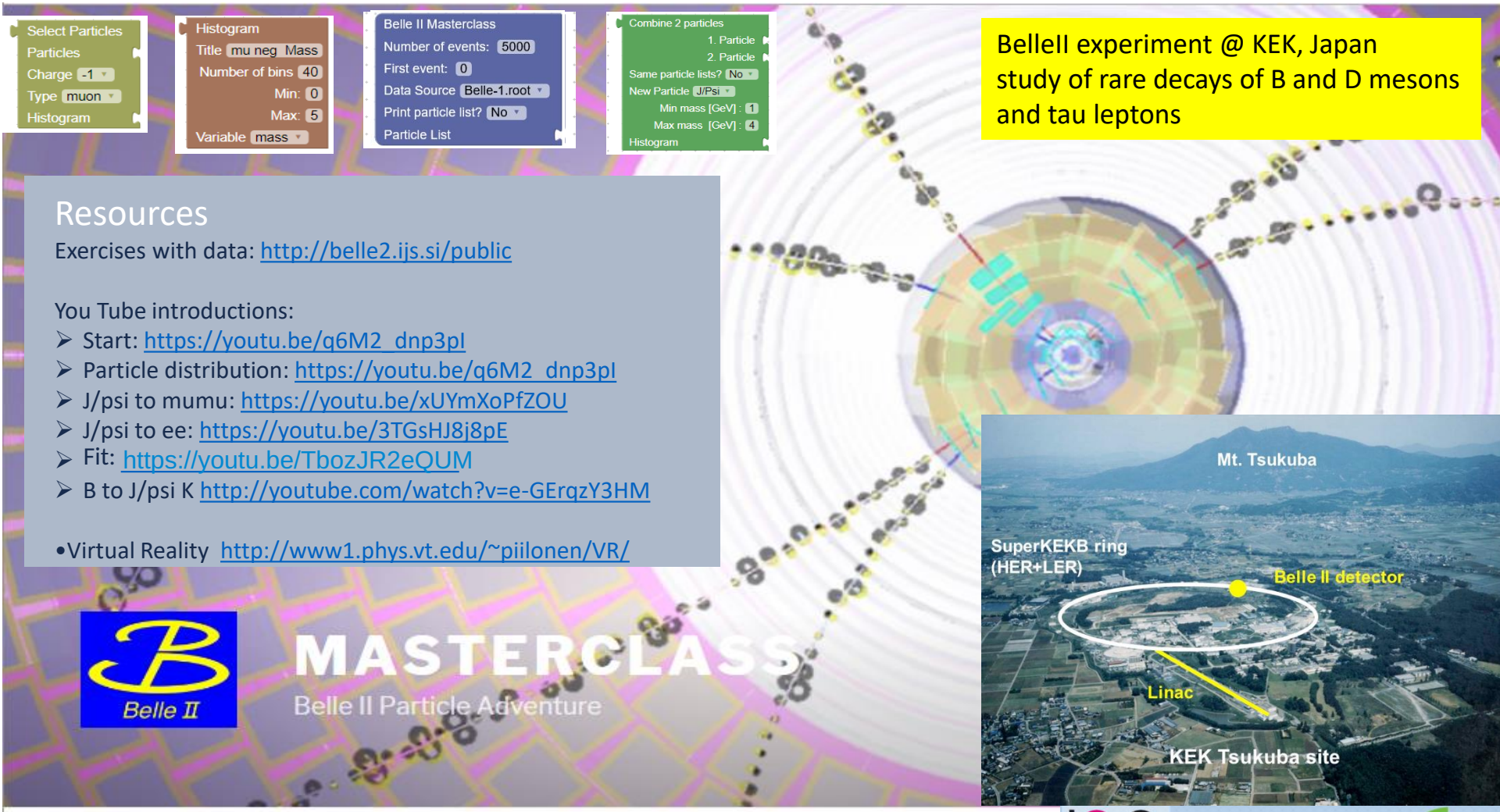
Ljubljana, Slovenija

Belle II Lab Manual

(version 2021-03-01)

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



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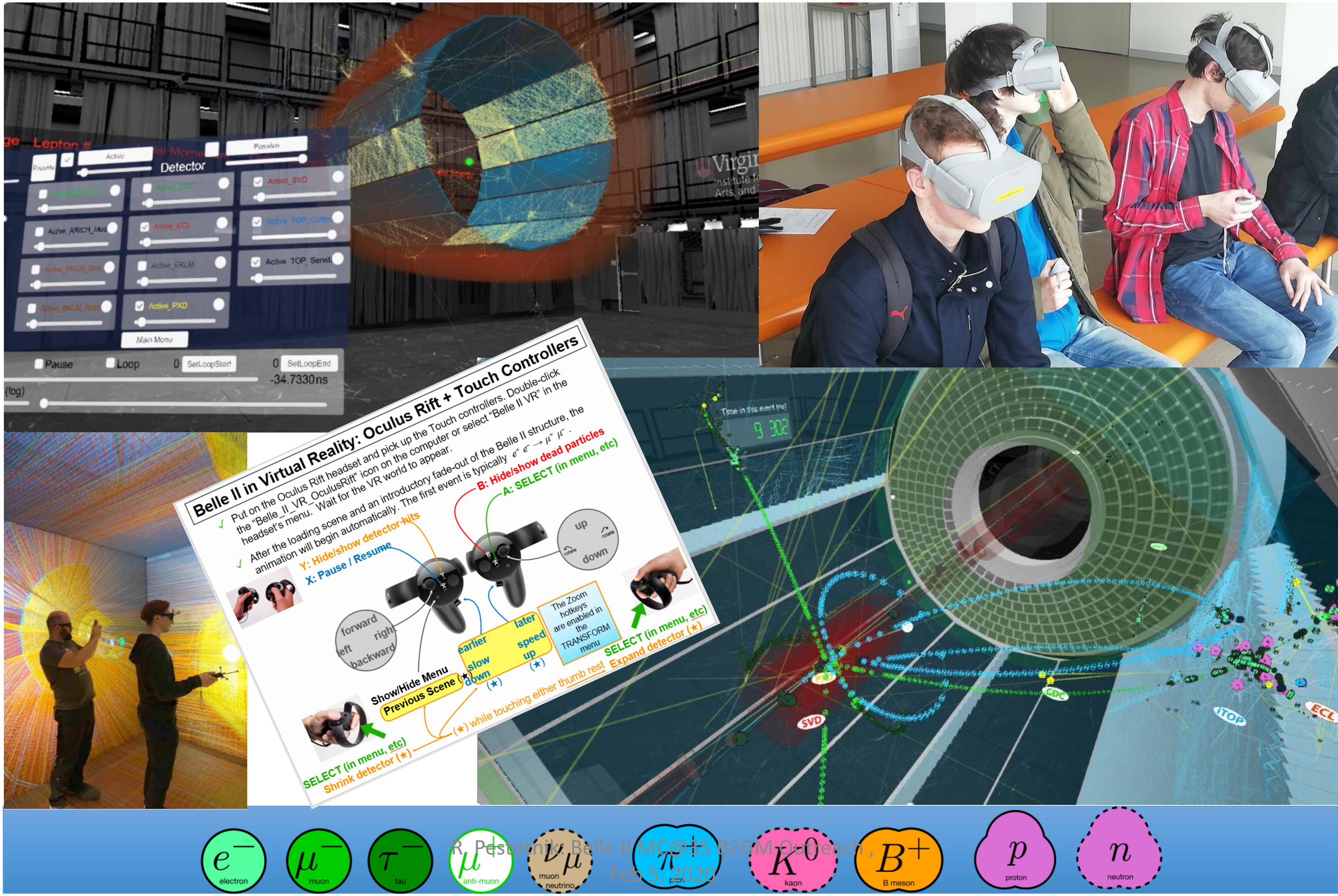
Virtual reality - Belle II detector



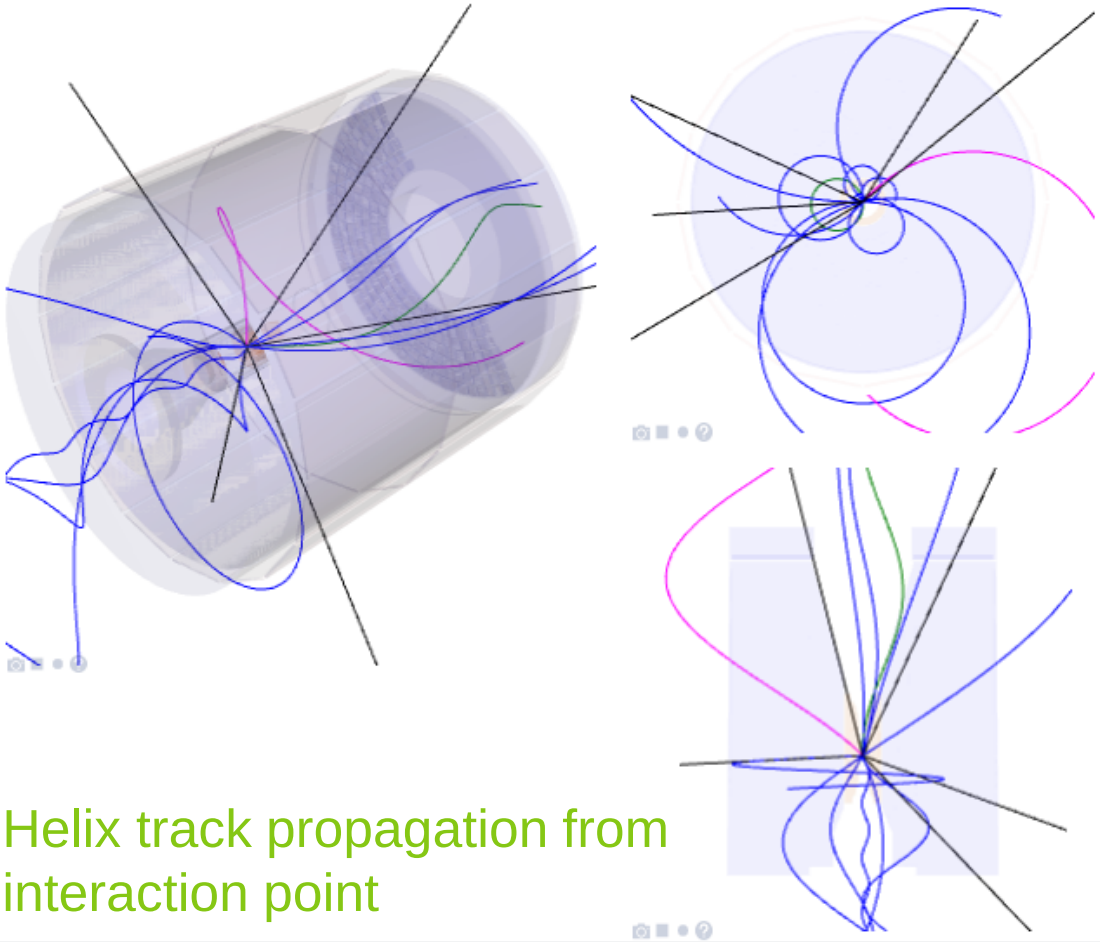
EVENT DISPLAY

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	0.337091	0.353262	1	muon
2	-0.229449	-0.00589037	0.243925	0.334934	0.362851	1	pion
3	0.249353	0.138971	-0.133726	0.315234	0.34475	-1	pion
4	0.617004	0.147713	-0.0178898	0.634691	0.649856	-1	pion
5	-0.852846	-0.013393	0.58309	1.03321	1.04259	-1	pion
6	0.542409	0.00413217	-0.207596	0.580793	0.597328	-1	pion
7	-0.0786903	-0.0881519	-0.0326394	0.12259	0.185764	1	pion
8	-0.0337178	-0.35194	-0.0885627	0.364475	0.390284	1	pion
9	-0.269283	-0.331059	0.736212	0.850954	0.862324	1	pion
10	-0.342041	0.433614	-0.520645	0.759002	0.771728	-1	pion
11	-0.0889358	0.20194	0.351623	0.415124	0.437959	-1	pion
12	0.417001	0.488208	0.280684	0.700729	1.17106	1	proton
13	0.180873	0.288436	0.716277	0.793071	0.793071	0	photon
14	-0.12108	-0.00755525	0.261905	0.288637	0.288637	0	photon
15	0.15715	0.128819	-0.00759161	0.203342	0.203342	0	photon
16	-0.211126	-0.125556	-0.0770802	0.257449	0.257449	0	photon
17	-0.134099	0.0615151	-0.140303	0.203597	0.203597	0	photon

List of reconstructed particles

Helix track propagation from interaction point

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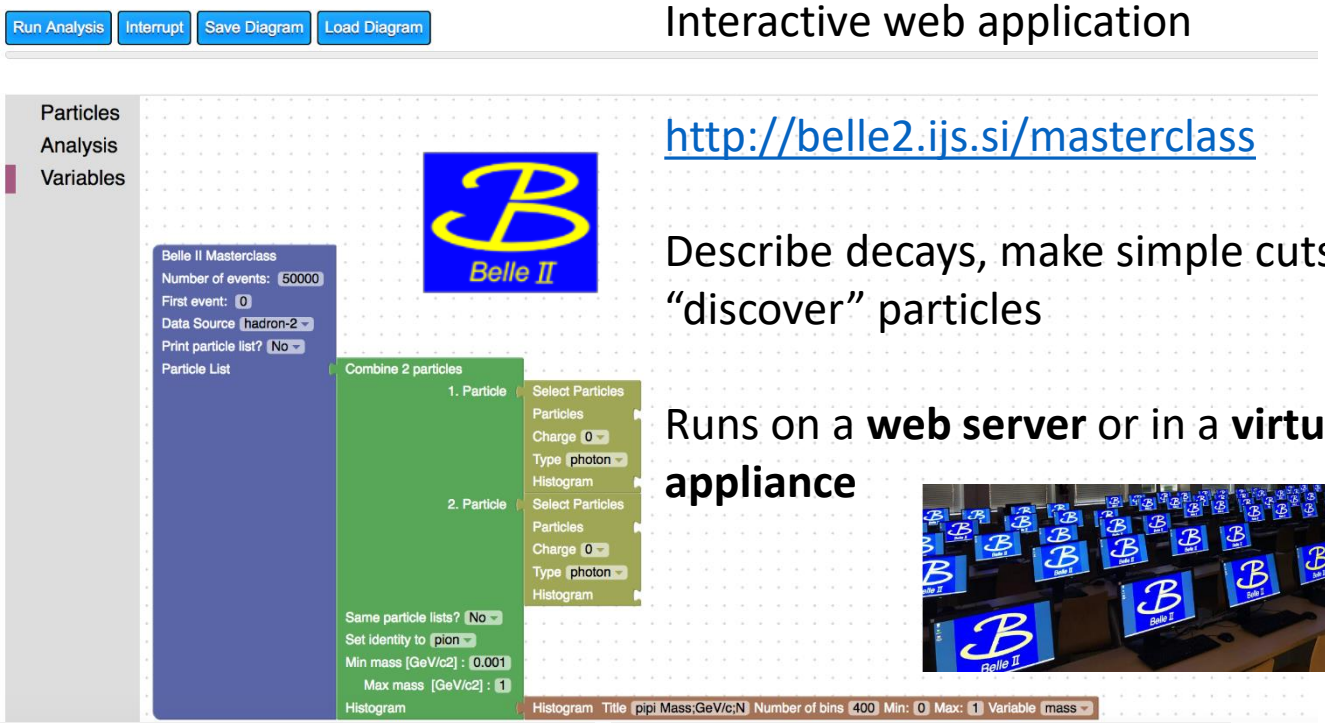
Public analysis of 6M events from Belle

Interactive web application

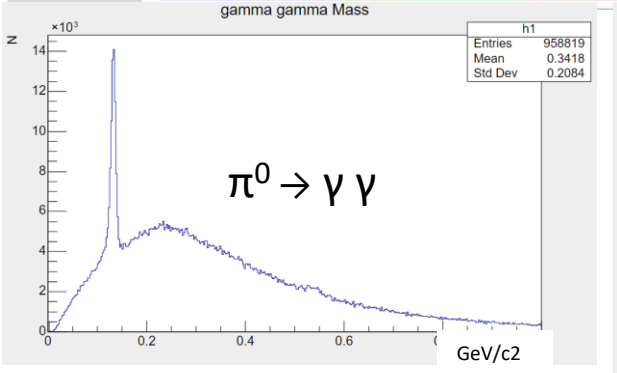


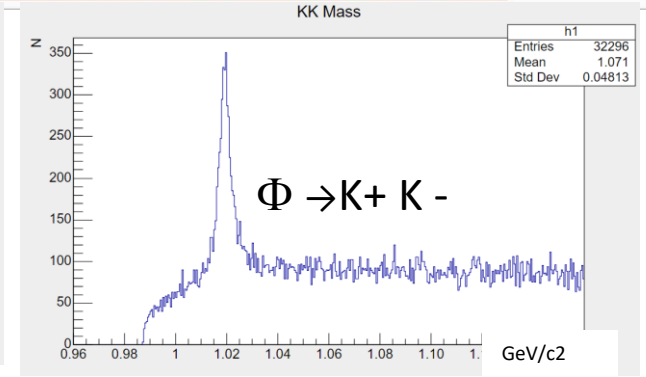
http://belle2.ijs.si/masterclass

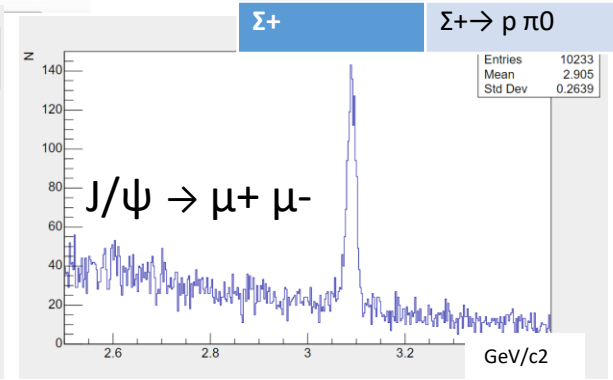
Describe decays, make simple cuts, "discover" particles

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

Particle	Process
π^0	$\pi^0 \rightarrow \gamma\ \gamma$
Ks	Ks → π+ π -
ϕ	ϕ → K+ K -
J/ψ	J/ψ → e+ e-
	J/ψ → μ+ μ-
D^0	D^0 → K+π-
	D^0 → K-π+
D*+	D*+ → D^0 π+
D*-	D*- → D^0 π-
B+	B+ → J/ψ K+
B-	B- → J/ψ K-
Λ	Λ→ p π-
Σ+	Σ+→ p π0

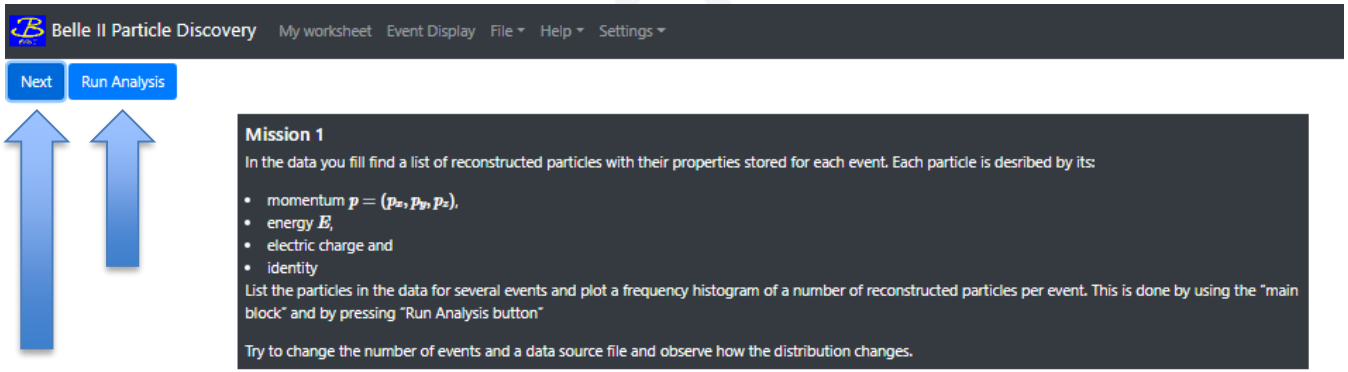


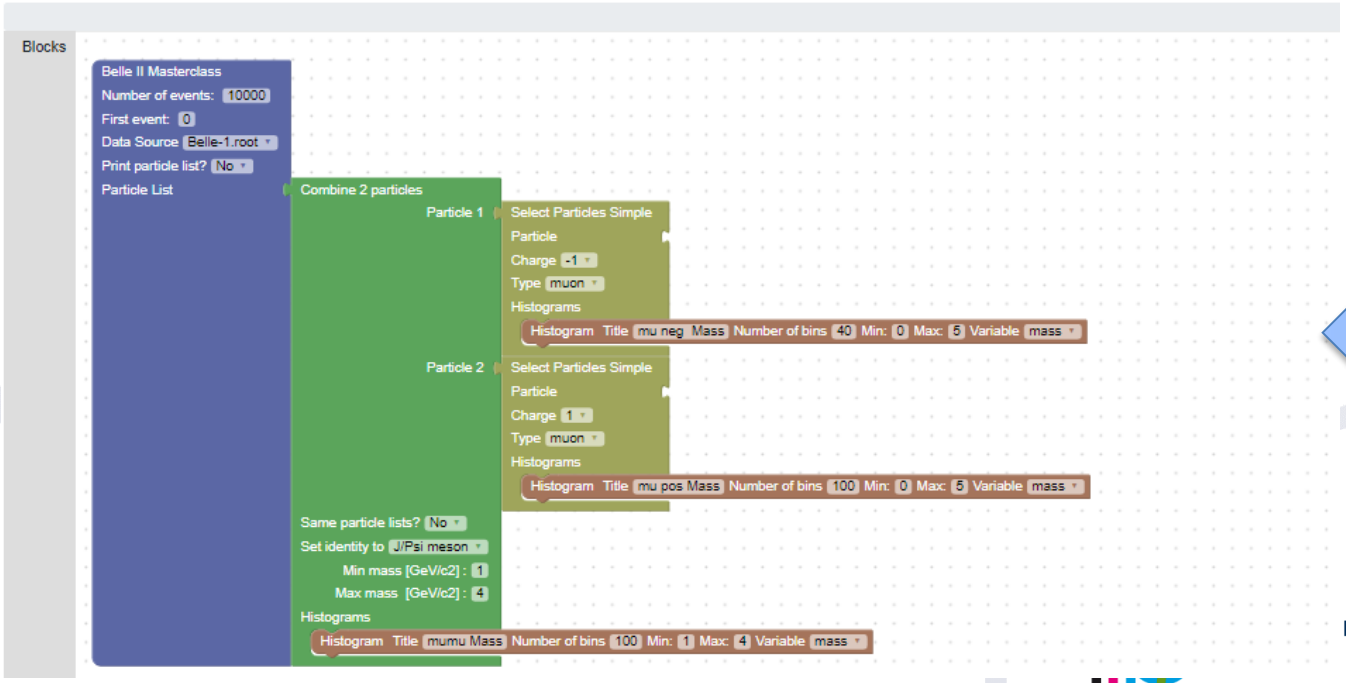




EXERCISE

- Display missions
- Describe process
- Run





NTERNATIONAL MASTERCLASSES
hands on particle physics

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Quick start to analyze the data

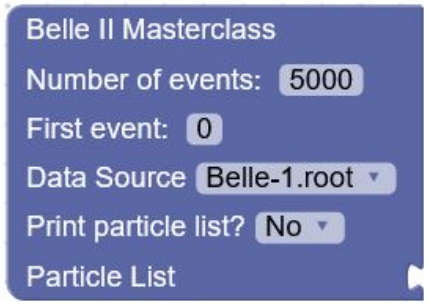
Belle II Masterclass: Describe process →Run analysis →Fit results →Save/load process locally

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:

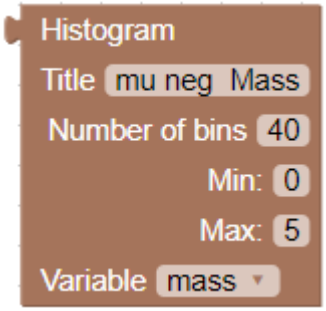
Inside “Blocks" we find:



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



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Quick start to analyze the data

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

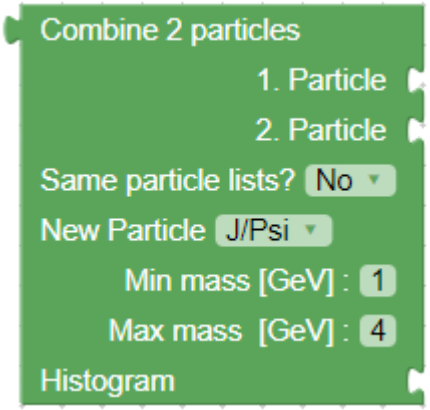
Run Analysis | Save Diagram | Load Diagram

Blocks

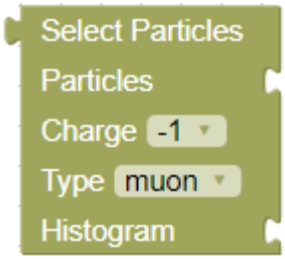
A GREEN block that allows you to combine two particles and to calculate their invariant mass

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

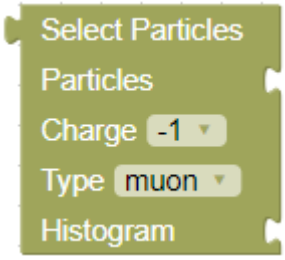
The minimum and maximum of the invariant mass can be specified for further analysis



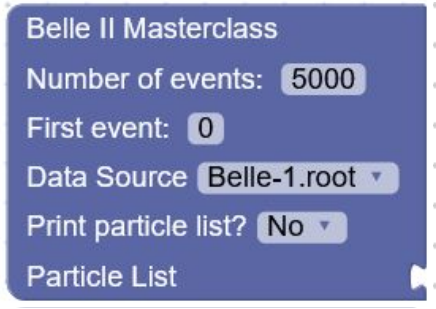
A MUSTARD block that allows to select only certain particles (electrons, muons, kaons, protons, photons) and also allows to choose the charge of the particle (-1, 0, +1, any).



Basic blocks

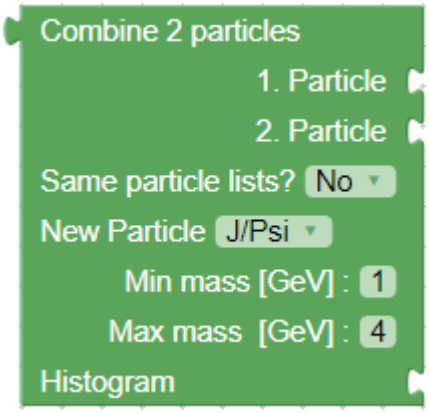


Select particle type for analysis and append histogram for plotting the properties

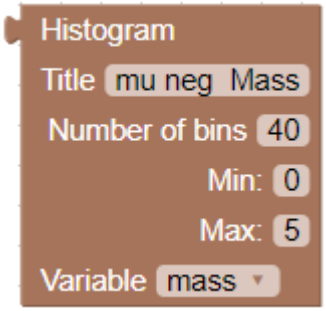


Define main analysis parameters

- ❑ 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

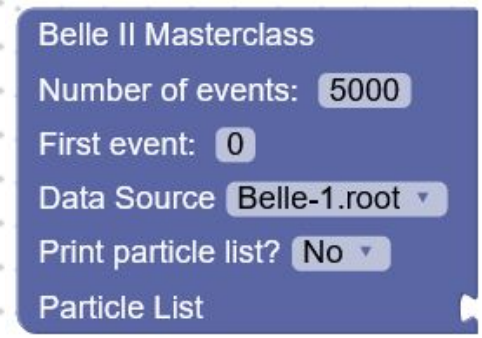


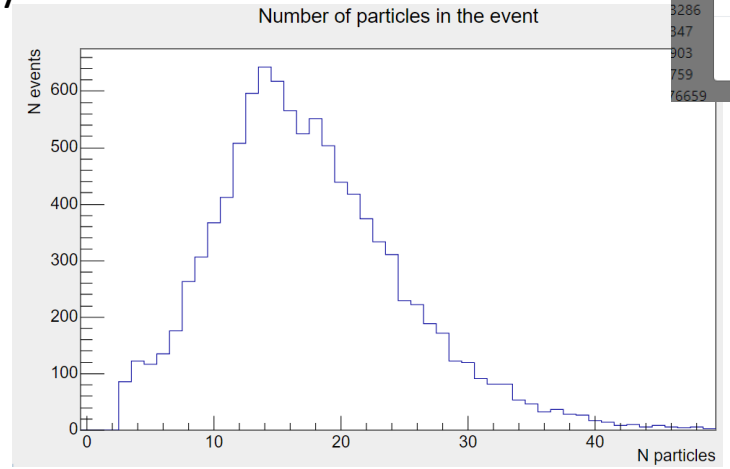
Plot a distribution

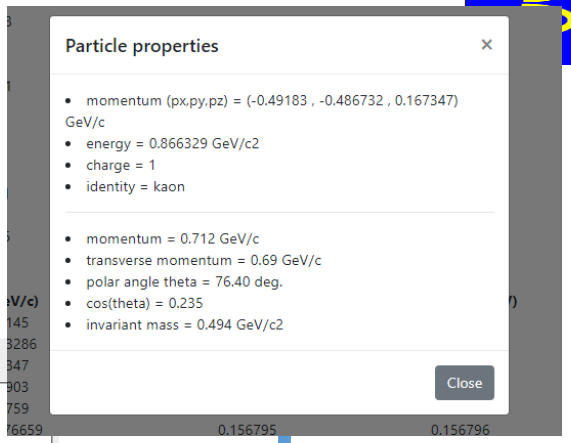
Define a range and a variable to plot

Particle list

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







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	0.63[illegible]475	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

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

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

- 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

0.171981 0.546651 0.564187

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

Particle properties combined from two particles

px [GeV/c]	py [GeV/c]	pz [GeV/c]	E [GeV/c2]	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

Charge ID

TERNATIONAL MASTERCLASSES

hands on particle physics

Combine the blocks

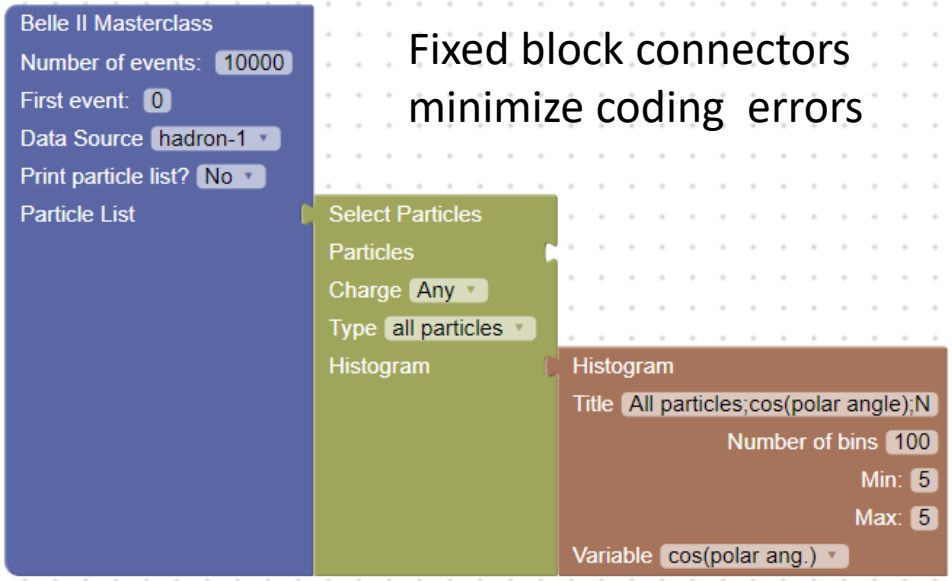
The particle lists for each event are stored in an ROOT tree.

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

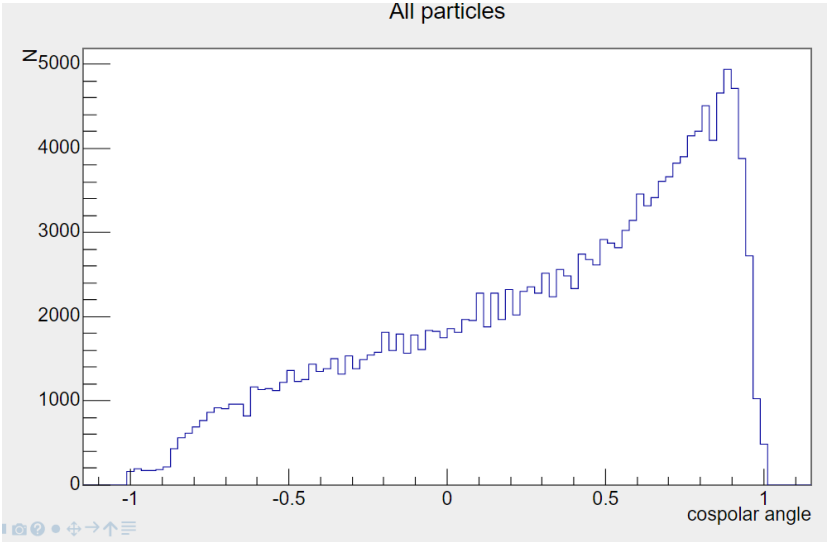
Distribution of different particle quantities can be plotted

Plot different variables :

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



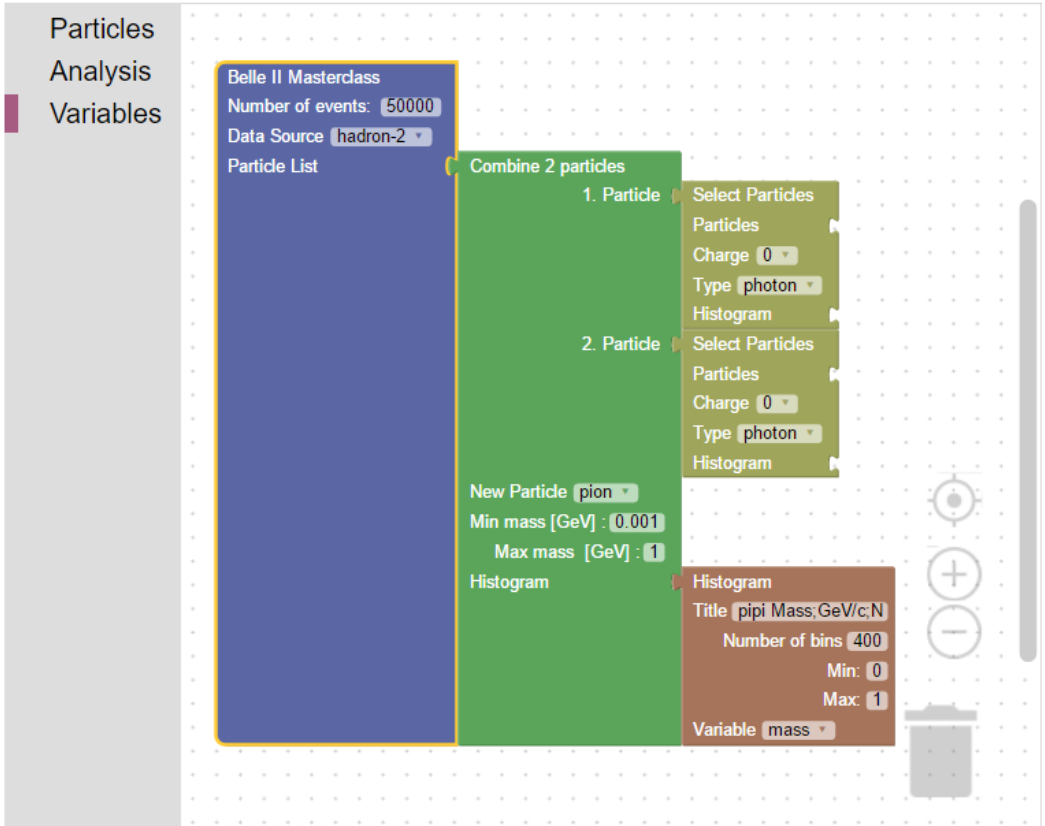
Fixed block connectors minimize coding errors



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



Particle properties combined from two particles

px [GeV/c]	py [GeV/c]	pz [GeV/c]	E [GeV/c2]	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

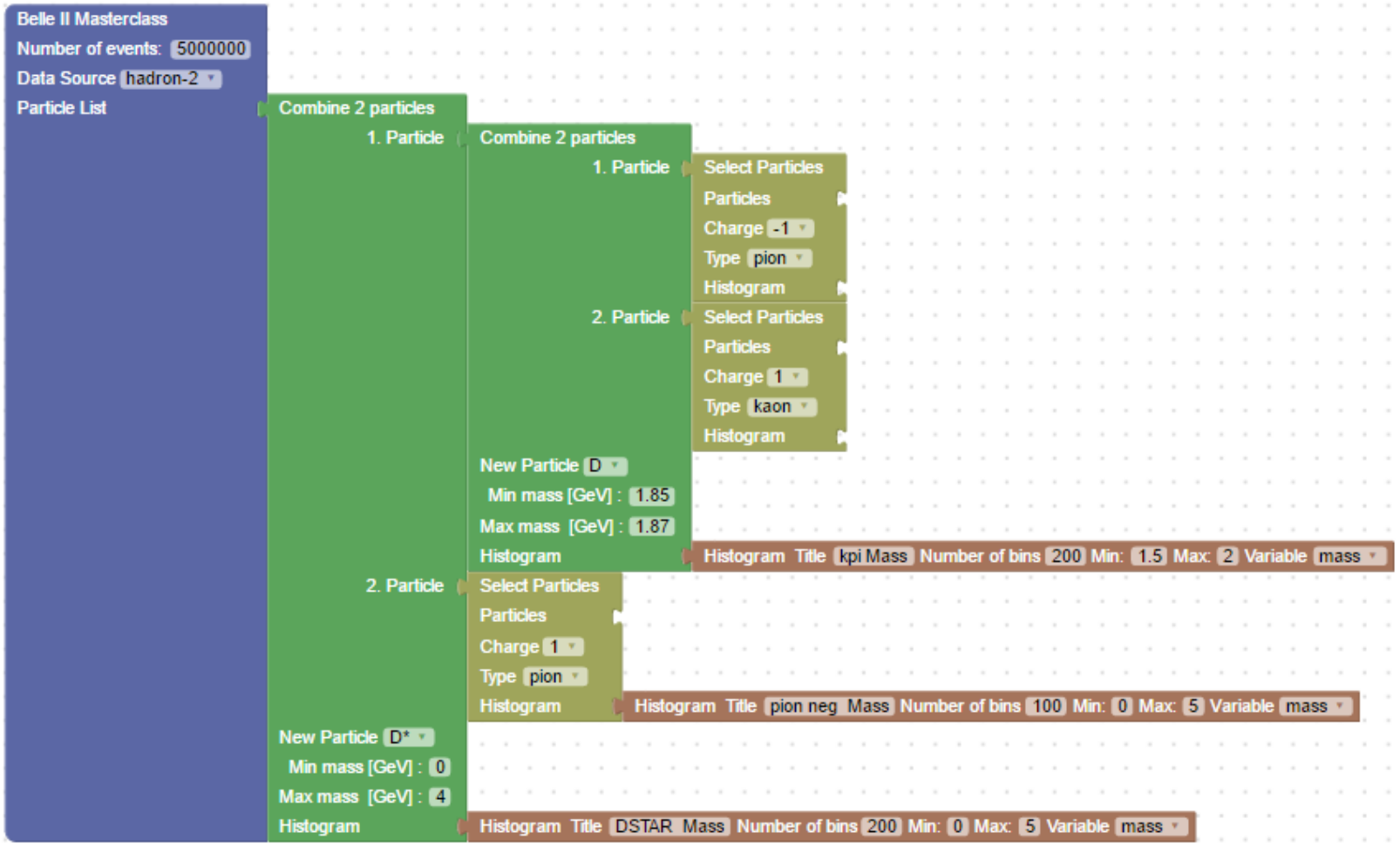
Close

Select two particles by mouse click and display properties of the combuined „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
15	0.361627	0	pion
16	0.875054	0	pion

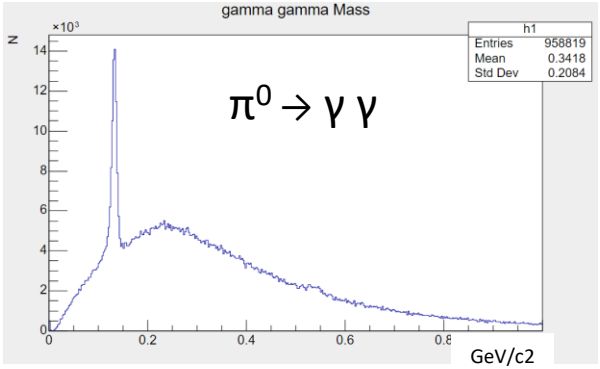
15	0.152624	-0.0325375	0.296991	0.335494
16	0.650451	-0.401558	0.403939	0.864582

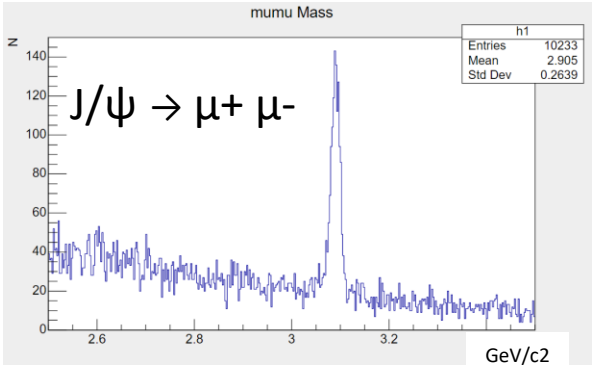
Combination of three particles

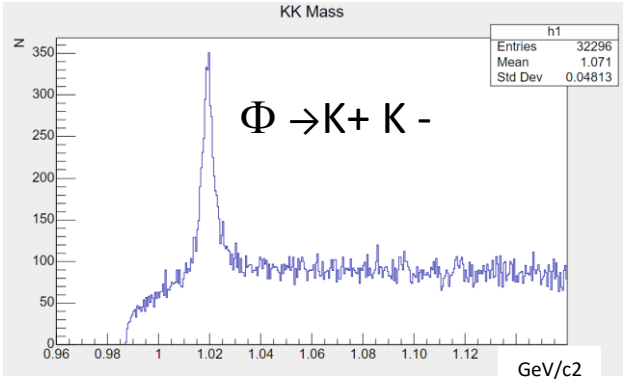


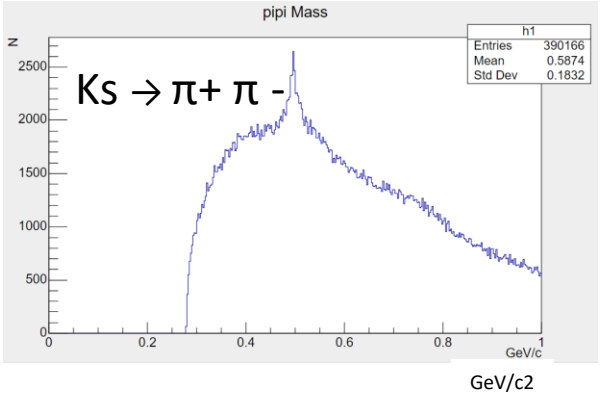
Different decays

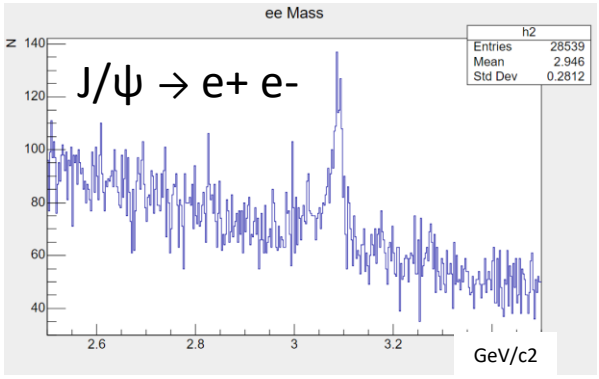
Invariant mass plots for different decays

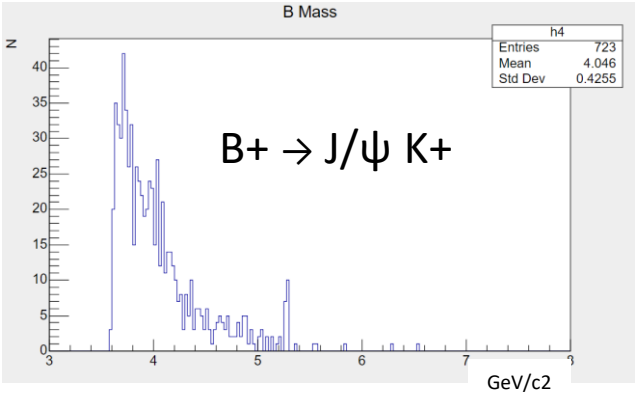






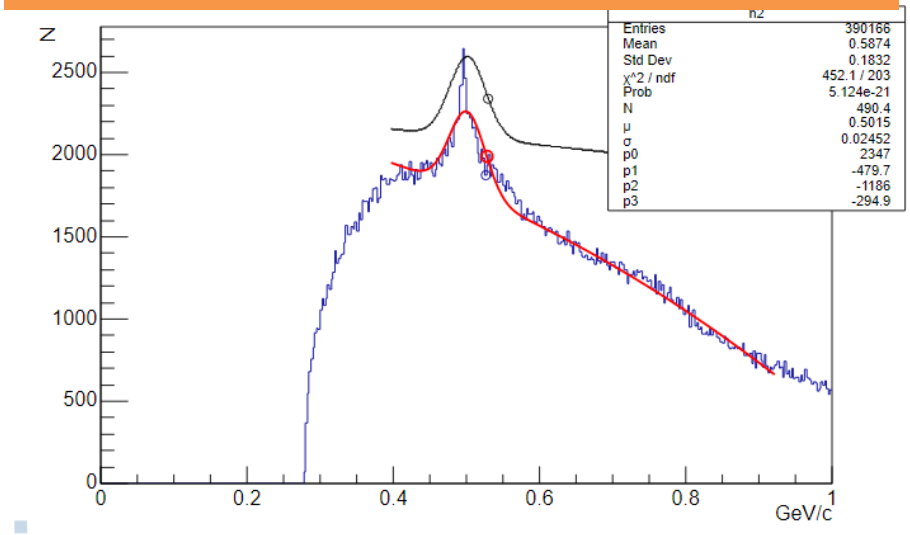






Advanced features

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



Click to fit

Range: min = 0.397 max = 0.923 χ²/ndf = 1.051e+5 / 205 = 512.7

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

Name	Value	Min	Set	Max	Step
μ:	0.5015	0		1	0.0001
σ:	0.0245	0		0.1	0.0001
N:	490.3655	0		10000	0.0001

Polynomial order: 1

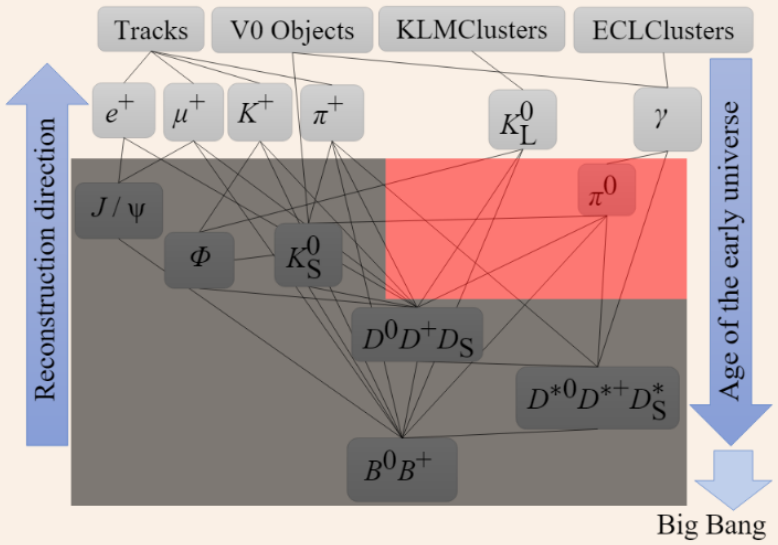
Name	Value	Min	Set	Max	Step
p0:	2347.1938	-10		5000	0.0001
p1:	-479.67778	-493.746783424		10	0.0001
p2:	-1186.242474364	-1186.242474364		10	0.0001
p3:	-294.8651832683	-294.8651832683		10	0.0001
p4:	0	-10		10	0.0001

Show/Hide Fit Panel | To Process

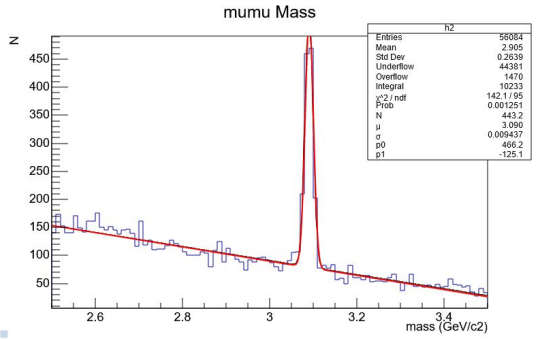
Check your results

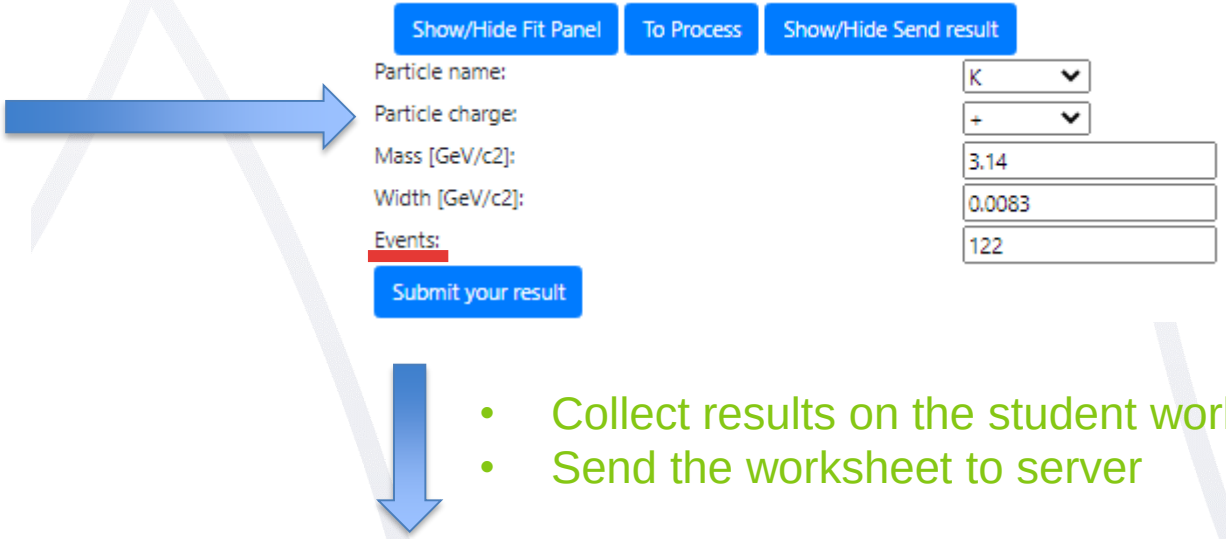
On the way to a B meson

1.	$\pi^0 \to$???	π^0 mass	1 GeV/c²		Sadly not correct. Did you find the right peak?
2.	$K_S \to$???	K_S mass	GeV/c²		Please start to enter a number!
3.	$\Phi \to$???	Φ mass	GeV/c²		Please start to enter a number!
4.	$J/\Psi \to \mu^+\mu^-$	J/Ψ mass	GeV/c²		Please start to enter a number!
5.	$J/\Psi \to e^+e^-$	J/Ψ mass	GeV/c²		Please start to enter a number!
6.	$D^0 \to K^+\pi^-$ $D^0 \to K^-\pi^+$	avg. D^0 mass	GeV/c² GeV/c²	GeV/c²	Please start to enter a number!
7.	$D^{*+} \to D^0\pi^+$ $D^{*-} \to D^0\pi^-$	D^{*+} mass D^{*-} mass	GeV/c² GeV/c²	GeV/c²	Please start to enter a number!
8.	$B^+ \to J/\Psi K^+$ $B^- \to J/\Psi K^-$	avg. B^+ mass	GeV/c² GeV/c²	GeV/c²	Please start to enter a number!

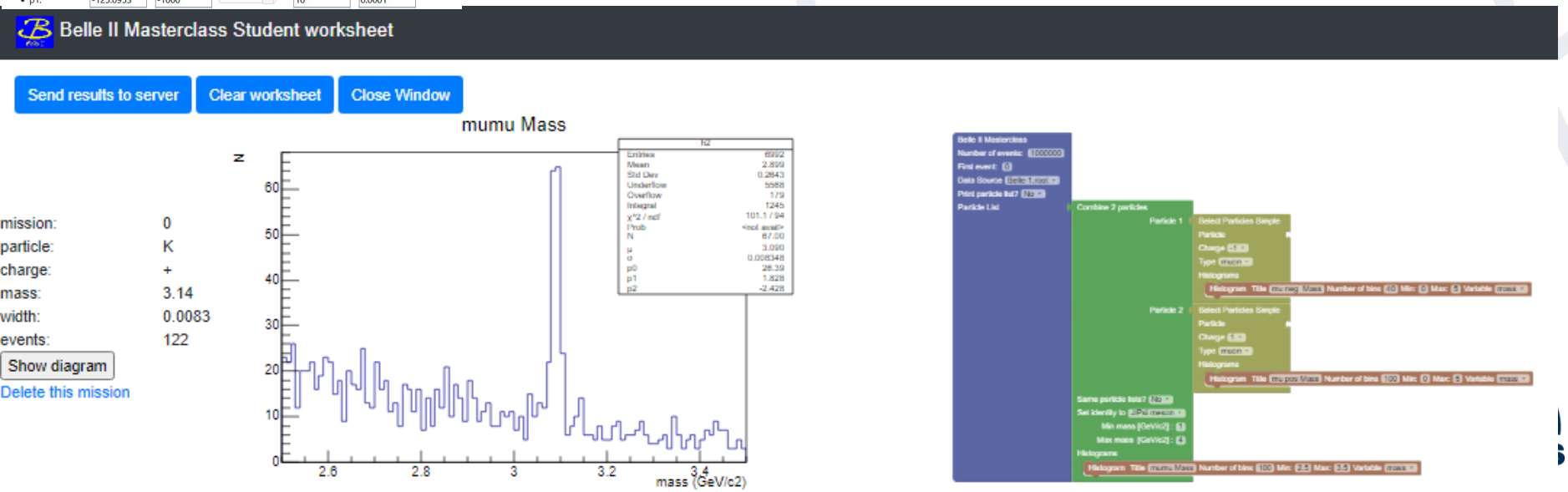


COLLECT & SUBMIT THE RESULTS





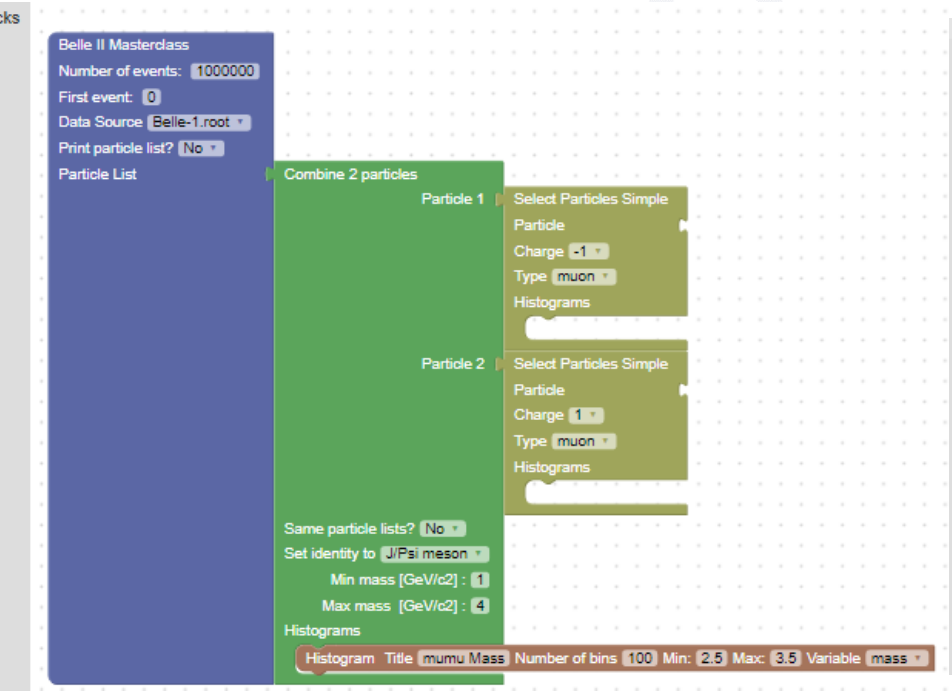
- Collect results on the student worksheet
- Send the worksheet to server



TWO LEVELS:

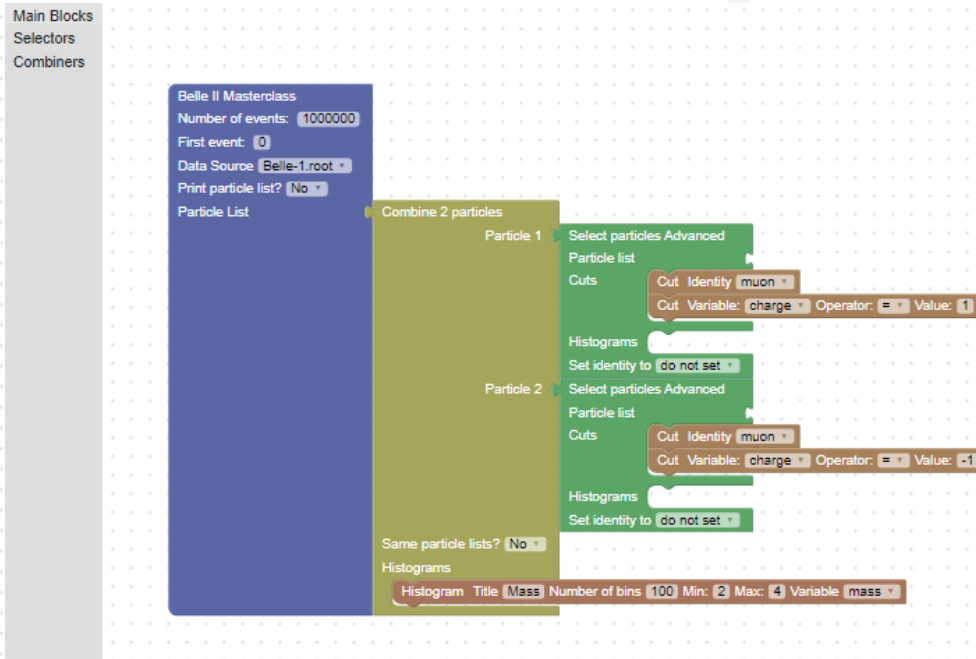
Switch the level via menu tab Settings

BEGGINER



- Simple blocks
- Only two fitting functions

ADVANCED



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

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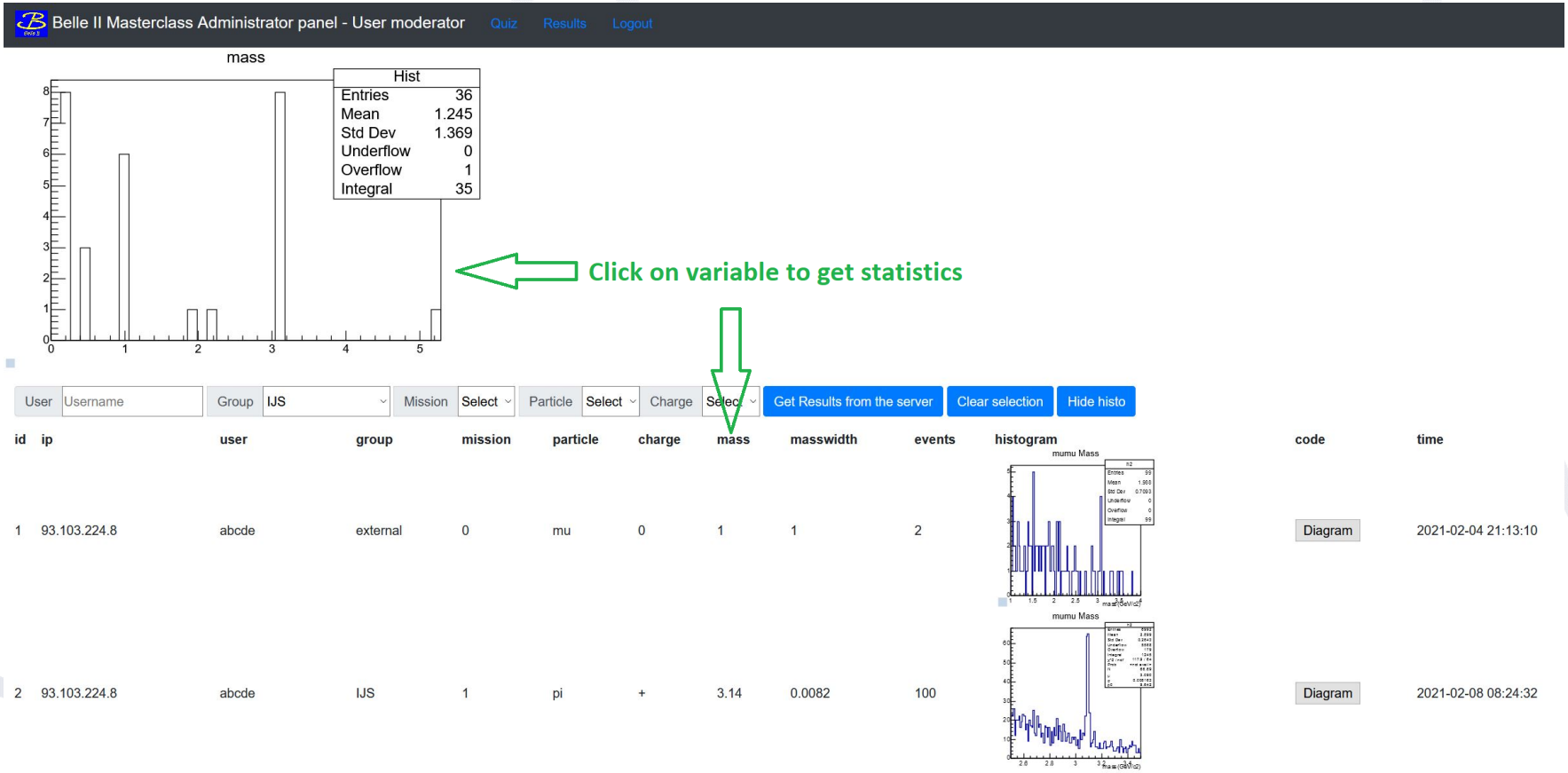
TUTOR PANEL

Get the results submitted by your students



Only logged users (tutors) can gain access

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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

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Exercises

Worksheet

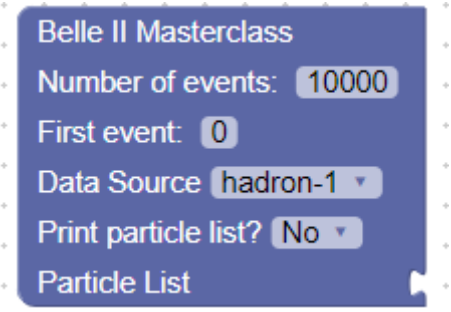
Exercise table with the list of decays to examine

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	$\frac{1}{\sqrt{2}}(d\bar{s} + \bar{s}s)$	Ks → π+ π -				
ϕ	$s\bar{s}$	ϕ → K+ K -				
J/ψ	$c\bar{c}$	J/ψ → e+ e-				
		J/ψ → μ+ μ-				
D^0	$c\bar{u}$	D^0 → K+π-				
		D^0 → K-π+				
D*+		D*+ → D^0 π+				
D*-	$d\bar{c}$	D*- → D^0 π-				
B+	$u\bar{b}$	B+ → J/ψ K+				
B-	$\bar{u}b$	B- → J/ψ 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
  - $mc^2 = \sqrt{E^2 - p^2c^2}$
  - 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^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 (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 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:

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

- 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/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 $K^+\pi^-$ or $K^-\pi^+$:

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

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 $B^+ \rightarrow J/\psi\, K^+$

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

$B^+ \rightarrow J/\psi\, K^+$ or $B^- \rightarrow J/\psi\, K^-$

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.