



Imperial College
London

CMS HZZ analysis exercise

IC Masterclass 2026

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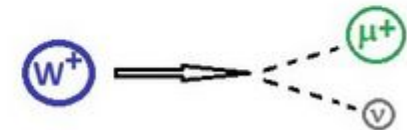
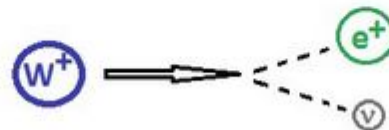
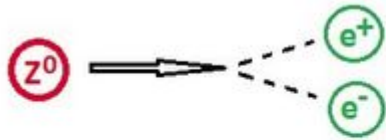
Overview of the task

<https://indico.global/event/18516/>

- Your task today is to analyse some genuine LHC data collected by CMS
- You will look at event display and identify and study W, Z, and H boson events
- Then, you'll try to measure Z and H bosons in a Higgs decay,
- At the end of the session we will collect the results from everyone and analyse/discuss the collective results

W and Z boson decays

- W and Z bosons decay into particles called leptons
 - Electrons, muons, and neutrinos are all types of leptons
- Z boson has no charge and therefore decays into two leptons with opposite charge (e.g $e^+ e^-$)
- W boson has +1 or -1 charge and therefore decays into a single charged lepton (electron or muon) and a neutrino



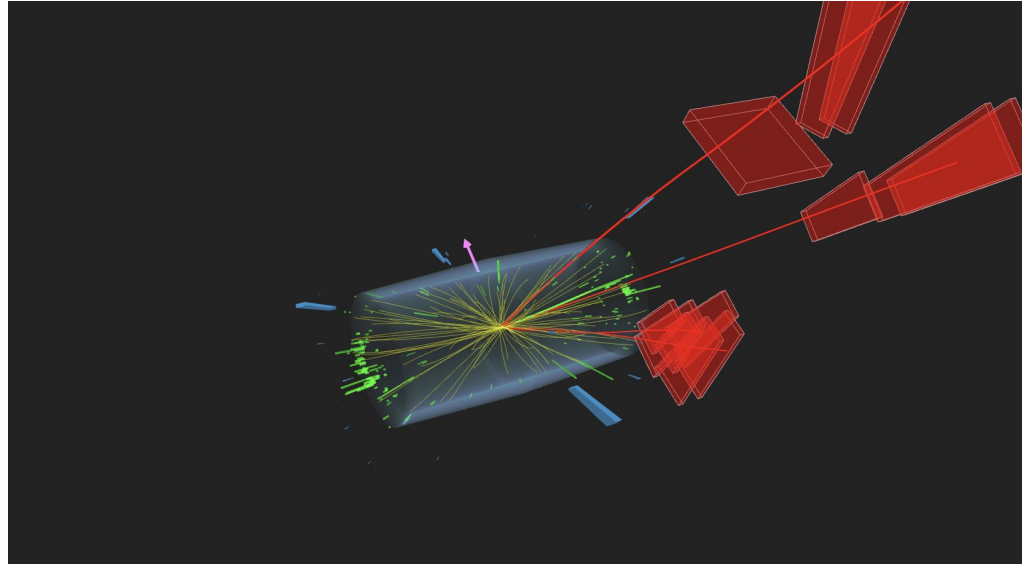
H boson decays

- Higgs bosons can decay into two Z bosons
- Z bosons subsequently decay into leptons (electron or muons) and therefore we get 4 leptons in the final state



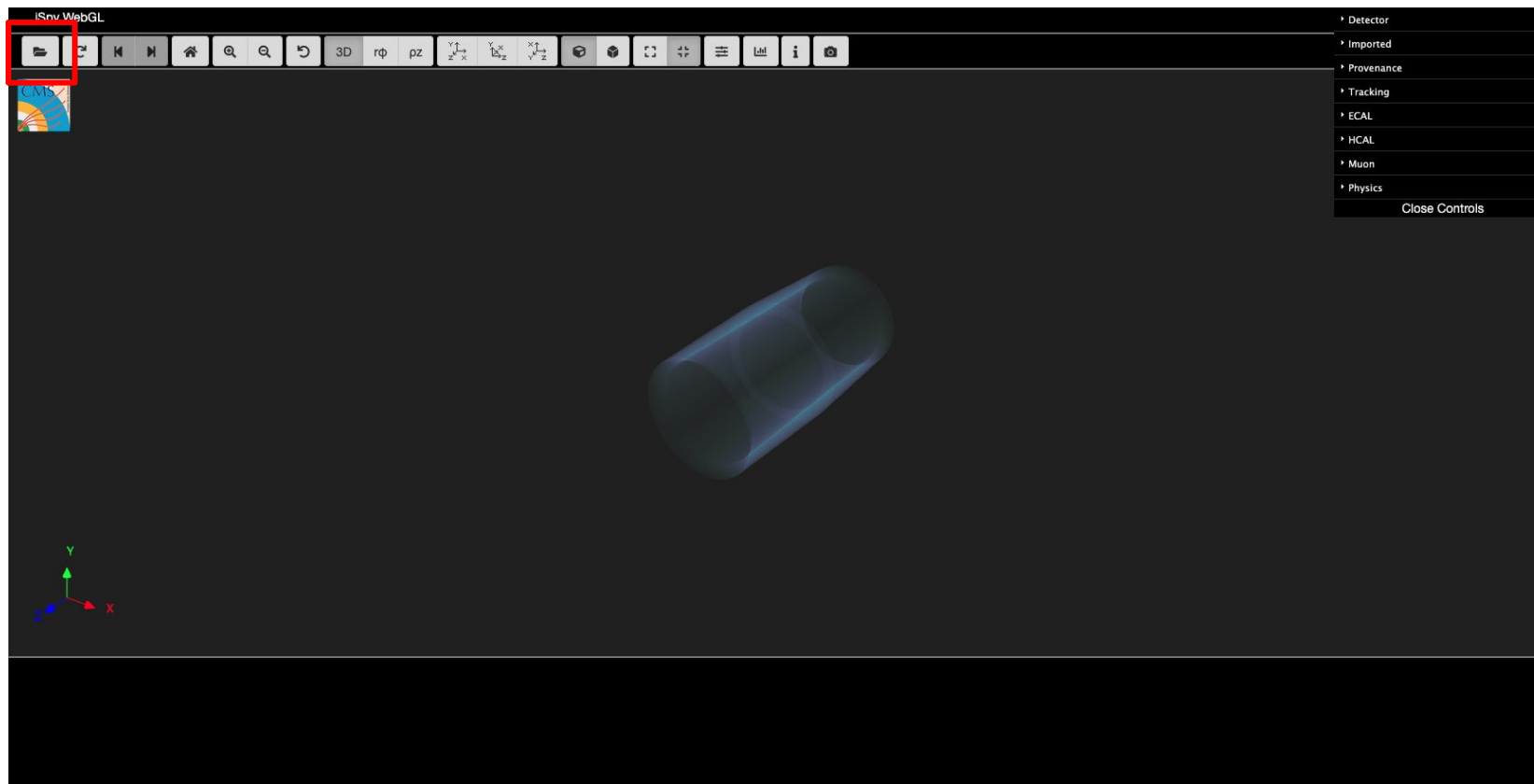
Let's look at some real events

Navigate to <https://tinyurl.com/ispycms>



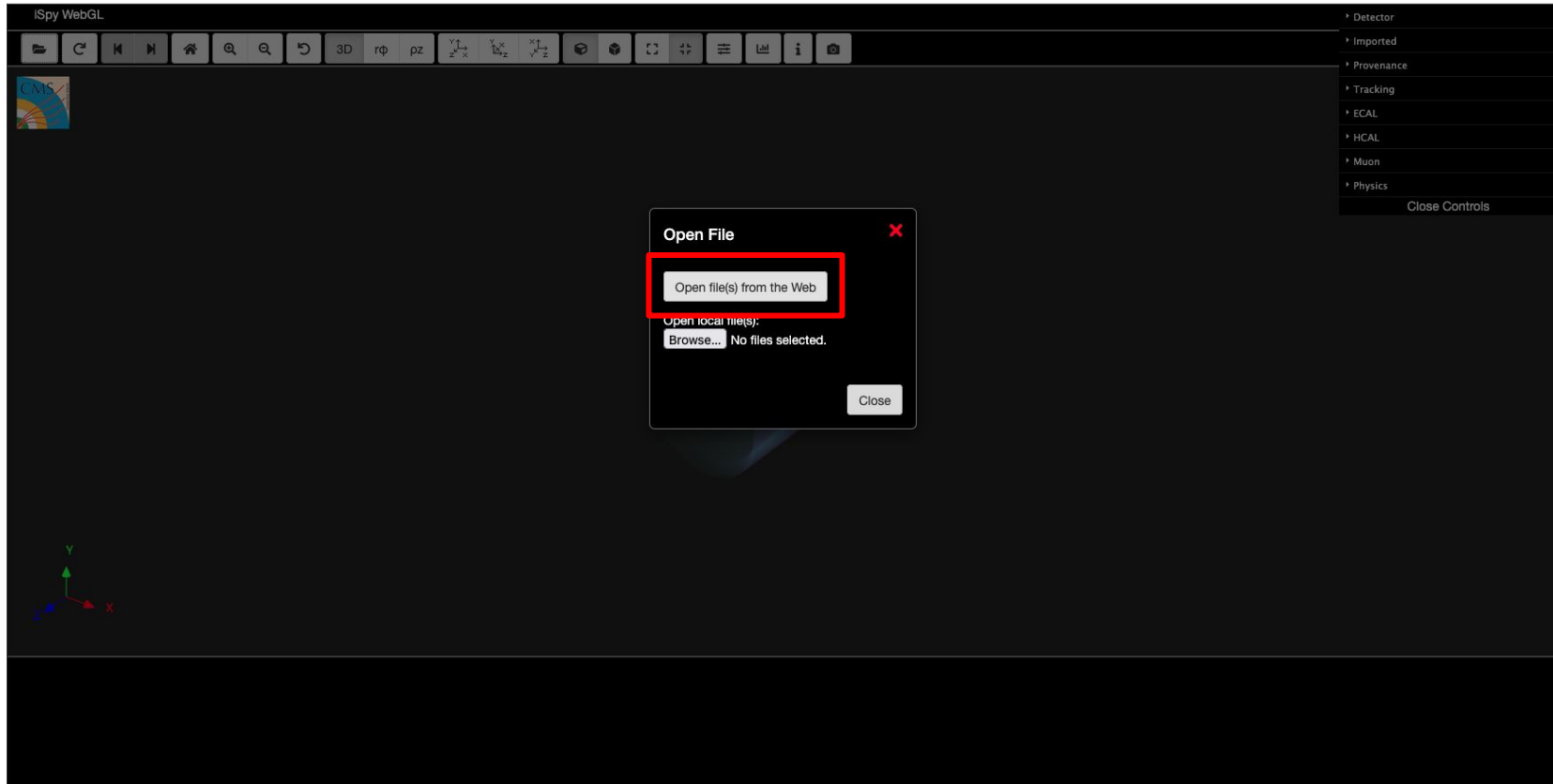
How to use the event display

<https://indico.global/event/18516/>



How to use the event display

<https://indico.global/event/18516/>



How to use the event display

<https://indico.global/event/18516/>

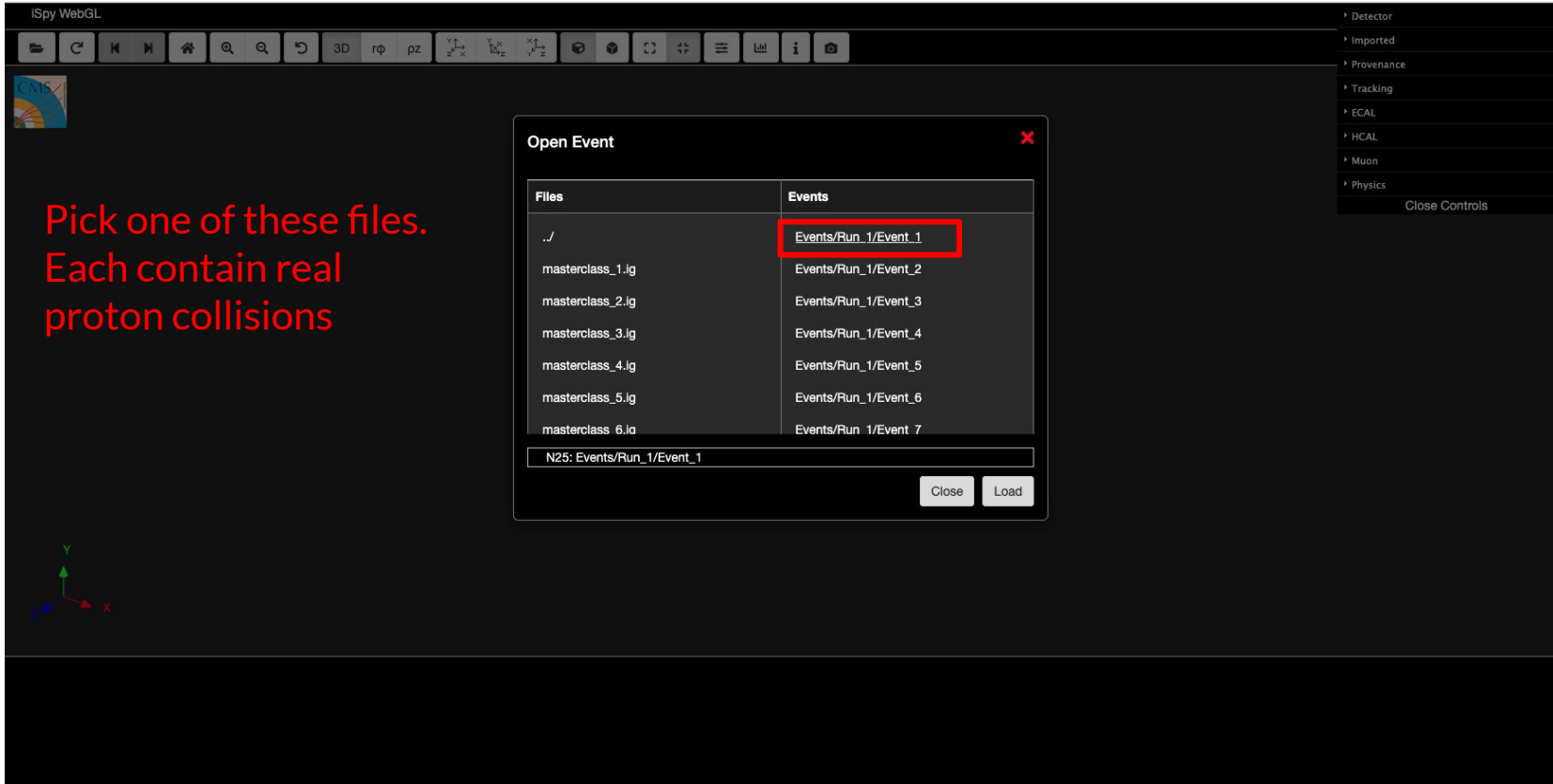
Pick one of these files.
Each contain real
proton collisions

The screenshot shows the iSpy WebGL interface. At the top is a toolbar with various icons for navigation and viewing. On the right side, there is a sidebar with a list of components: Detector, Imported, Provenance, Tracking, ECAL, HCAL, Muon, and Physics. Below this list is a 'Close Controls' button. In the center, an 'Open Event' dialog box is open. It contains a table with two columns: 'Files' and 'Events'. The 'Files' column lists five files: N5/, N10/, N25/, N50/, and N100/. A red rectangular box highlights the 'Files' column. The 'Events' column is currently empty. Below the table, there is a text input field labeled 'Selected event'. At the bottom right of the dialog are two buttons: 'Close' and 'Load'. The background of the interface shows a 3D visualization of a particle detector with a coordinate system (x, y, z) and a CMS logo in the top left corner.

How to use the event display

<https://indico.global/event/18516/>

Pick one of these files.
Each contain real
proton collisions



The screenshot displays the iSpy WebGL interface. A central 'Open Event' dialog box is open, showing a list of files and events. The 'Files' column lists several 'masterclass_*.lg' files. The 'Events' column lists 'Events/Run_1/Event_1' through 'Events/Run_1/Event_7', with 'Events/Run_1/Event_1' highlighted by a red box. Below the list, a text field contains 'N25: Events/Run_1/Event_1'. At the bottom of the dialog are 'Close' and 'Load' buttons. The background shows a 3D detector visualization with a coordinate system (X, Y, Z) and a sidebar with various physics-related controls like Detector, Imported, Provenance, Tracking, ECAL, HCAL, Muon, and Physics.

How to use the event display

<https://indico.global/event/18516/>

iSpy WebGL

Pick one of these files.
Each contain real
proton collisions

Open Event

Files	Events
../	Events/Run_1/Event_1
masterclass_1.lg	Events/Run_1/Event_2
masterclass_2.lg	Events/Run_1/Event_3
masterclass_3.lg	Events/Run_1/Event_4
masterclass_4.lg	Events/Run_1/Event_5
masterclass_5.lg	Events/Run_1/Event_6
masterclass_6.lg	Events/Run_1/Event_7

N25: Events/Run_1/Event_1

Close Load

Detector
Imported
Provenance
Tracking
ECAL
HCAL
Muon
Physics
Close Controls

How to use the event display

<https://indico.global/event/18516/>

ISpy WebGL

N25:Events/Run_1/Event_1 [1 of 100]

CMS Experiment at the LHC, CERN
Data recorded: 2011-Jun-25 10:31:22.783304 GMT
Run / Event / LS: 167676 / 329087308 / 368

Detector
Imported
Provenance
Tracking
ECAL
HCAL
Muon
Physics
Close Controls

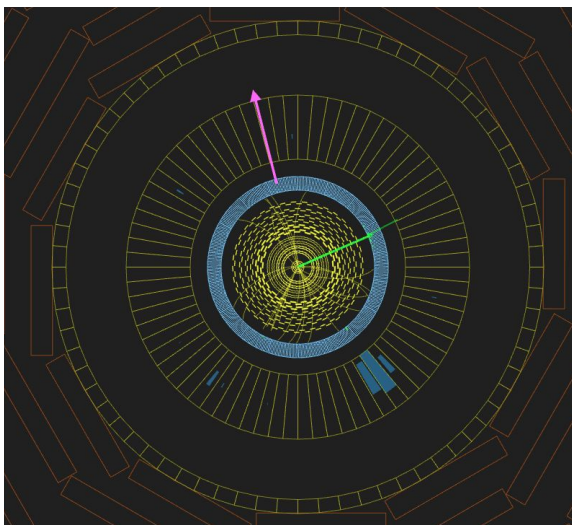
You can use these buttons to go through the different events

Click on a name under "Provenance", "Tracking", "ECAL", "HCAL", "Muon", and "Physics" to view contents in table

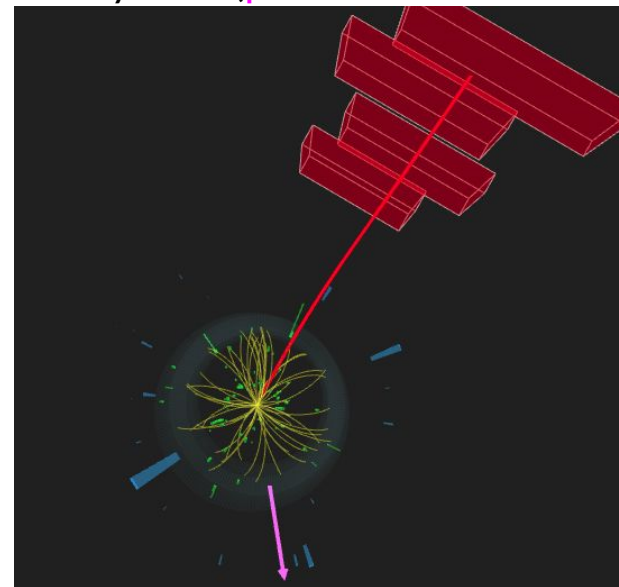
Identifying W bosons

<https://indico.global/event/18516/>

- Electrons identified as tracks in inner tracker pointing to deposits in the ECAL, muons are track in the inner tracker and muon system
- Electrons coloured green, Muons coloured red
- Neutrinos are undetected but missing momentum in the system (pink coloured thick straight line) indicates their presence



$W \rightarrow e \nu$

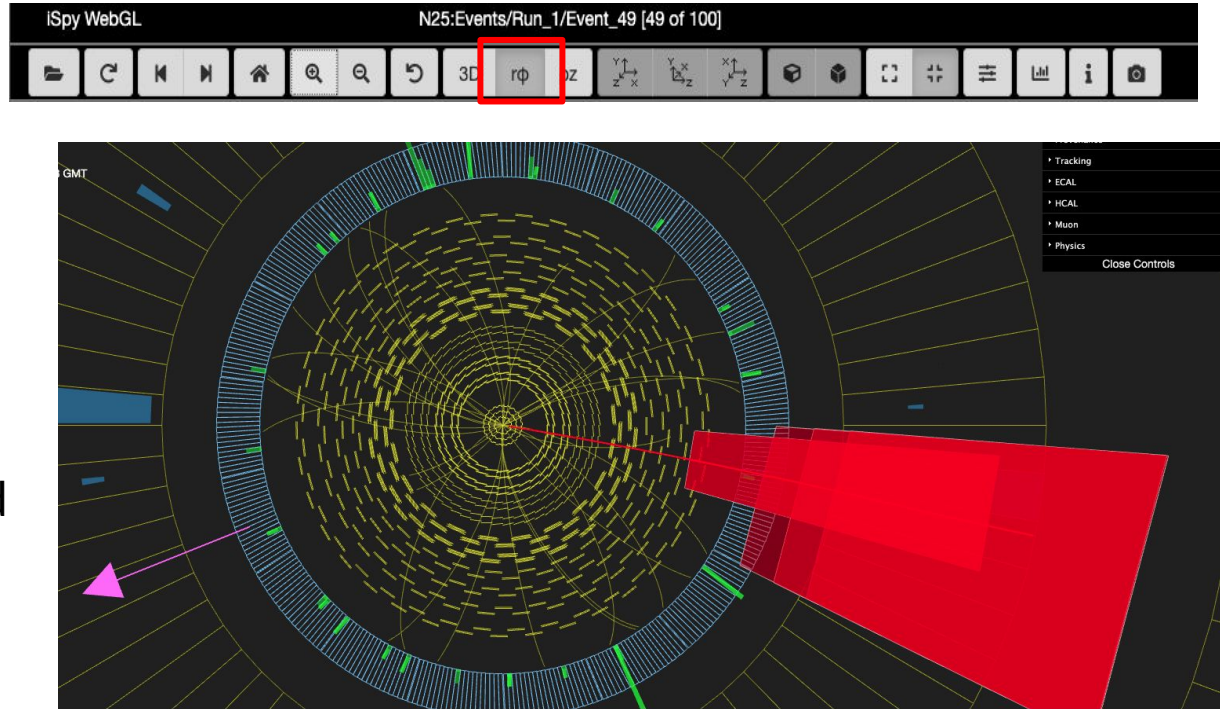


$W \rightarrow \mu \nu$

Measuring charges

<https://indico.global/event/18516/>

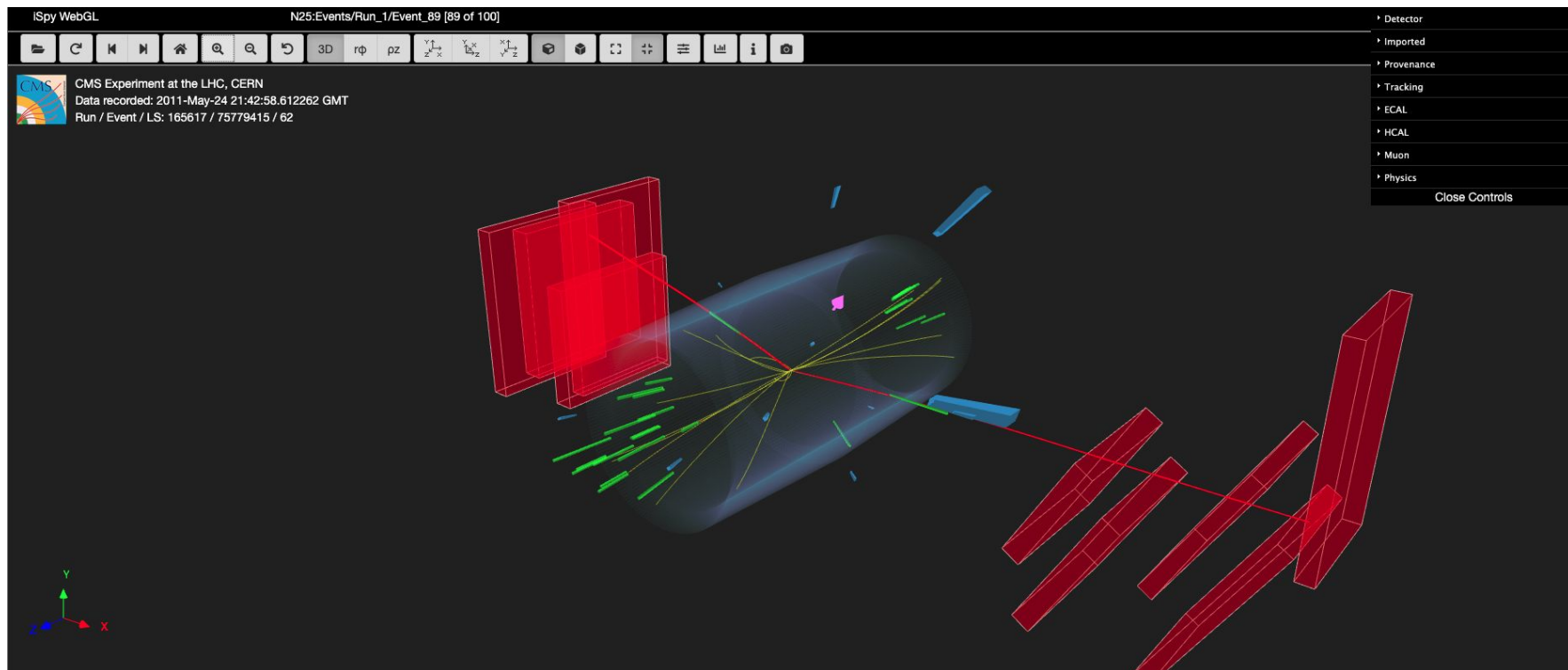
- Charged leptons bend in magnetic field
- The direction that they bend in depends on their charge
- **Positive** leptons will bend **clockwise**
- **Negative** leptons will bend **anti-clockwise**
- Select y-x view, zoom in to see curvature and then identify the charge



Identifying Z bosons

<https://indico.global/event/18516/>

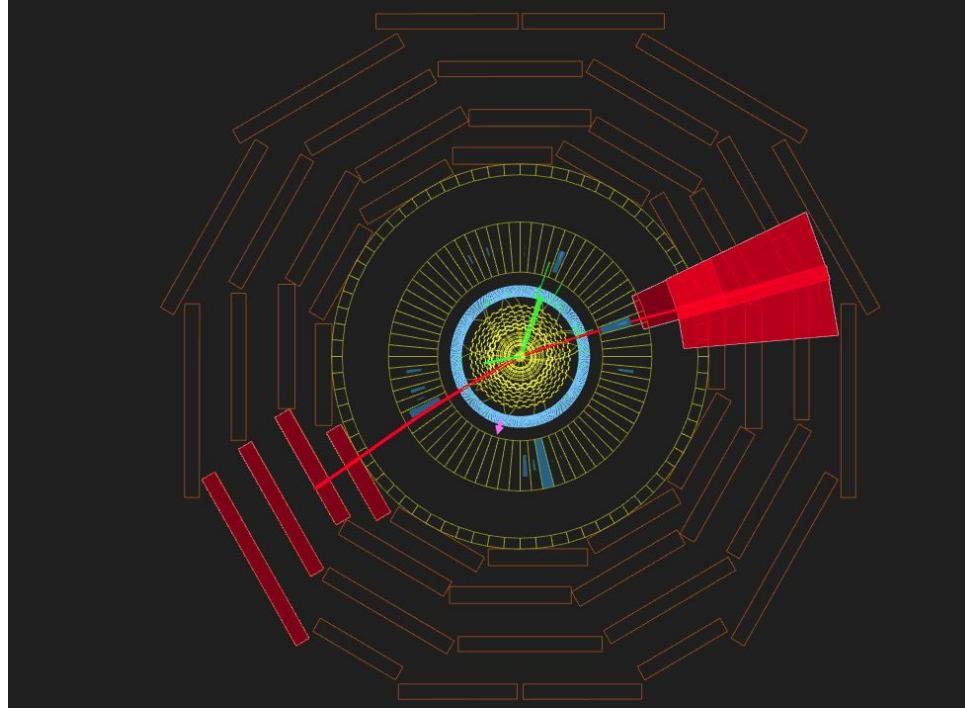
Z bosons decay into two oppositely charged electrons or muons



Identifying Higgs boson events

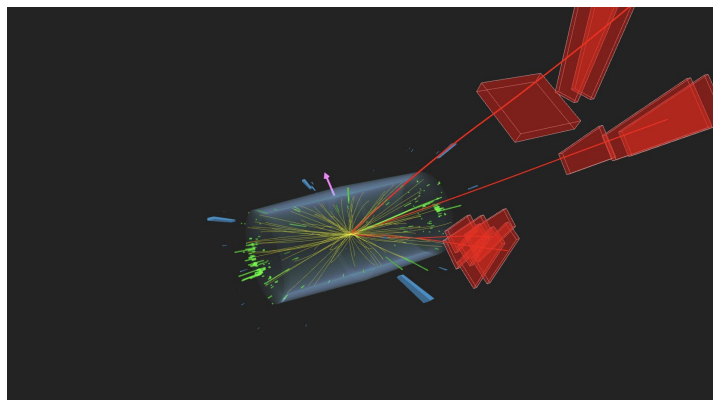
<https://indico.global/event/18516/>

- Higgs bosons can be identified by looking for 4 lepton events ($4e$, 4μ , or $2e2\mu$)



Let's get started

- Follow the instructions in the slides to open your dataset
- Talk to a demonstrator if you have any issues - If you spot any events that are unclear/odd you can also discuss these with your demonstrators!
- You can also open this slides on: <https://indico.global/event/18516/> under 'Particle Physics Computer Exercise'
- In 15 minutes we'll start analyzing some data from events like the ones you see here



<https://tinyurl.com/ispycms>

Analyzing data

Now, let's analyze some data!

We'll use $H \rightarrow ZZ \rightarrow 4L$ data, which contains Higgs boson and Z boson decays

What can we learn about the H and Z by measuring their decay products?

IMPERIAL • CMS MASTERCLASS

Particle Physics Analysis Tool

V4.1.3

1 Z search
two-lepton pairs

2 H search
four leptons

Find a resonance using two-lepton pairs
Choose how the four leptons are paired, then add both selected pair values to the histogram.

1 Build a quantity
Click a variable or type any allowed combination.

E Energy

pt Transverse momentum

py y momentum

zpt scalar pT

dr Separation ΔR

p-Momentum
Magnitude of the combined three-dimensional momentum.

p Momentum

px x momentum

pz z momentum

Q Charge

Opening angle

pT balance

pT cancellation

mass

mass from E and p

opening angle

energy - momentum

energy - scalar pT

angle-weighted pT

Combinations

Formula help

Pairing strategy
Closest Distance

2 Inspect an event
Event: 244029 - 4 leptons

Event view

lepton 0: e-

lepton 1: e+

lepton 2: e-

lepton 3: e+

Pairing A

Pairing B

Pairing C

3 Build the histogram
Added 450 values from 225 accepted events.

Realize histogram

Plot settings

VALUES

EVENTS KEPT

1/S (1/NOISE)

MEASUREMENT (FIT AG)

add current event

add next 1000 events

clear histogram

4 Event requirements
Only events passing every current requirement are added.

Exactly four leptons in the event

The event lepton count is the number of reconstructed electrons and muons in the event.

No requirements selected.

Changing the formula, mode, pairing, channel, or requirements starts a fresh histogram.

1. Choose a variable, mix of variables, or predefined combination you want to measure

IMPERIAL • CMS MASTERCLASS

Particle Physics Analysis Tool

V4.1.3

1 Z search
Four leptons

2 H search
Four leptons

Find a resonance using two-lepton pairs
Choose how the four leptons are paired, then add both selected pair values to the histogram.

1 Build a quantity
Click a variable or type any allowed combination.

2 Inspect an event
Event: 244029 - 4 leptons
No event requirements selected.

3 Build the histogram
0 values - p
VALUES: 0
EVENTS KEPT: 0/0
S/VB (NOBIL) 0
MEASUREMENT (FIT M) 0

4 Event requirements
Only events passing every current requirement are added.
Exactly four leptons in the event

Build a quantity
Click a variable or type any allowed combination.

Variables:
E: Energy
p: Momentum
pt: Transverse momentum
px: x momentum
py: y momentum
pz: z momentum
SpT: scalar pT
Q: Charge
dr: Separation ΔR
θ: Opening angle
p-Momentum: Magnitude of the combined three-dimensional momentum.

Combinations:
MOMENTUM
momentum
pT balance
pT cancellation

MASS
mass
mass from E and p

ANGLES
angular separation
opening angle

OTHER
charge magnitude
energy - momentum
energy + momentum
energy - scalar pT
ΔR-weighted pT
angle-weighted pT

Formula help
Pairing strategy
Closest Distance
Selects the pairing with the smallest total angular separation.

Inspect an event
Event: 244029 - 4 leptons
No event requirements selected.

Event view
η-φ map: circle size follows pT
φ around detector

Lepton Data:

Lepton	Type	Pair	E (GeV)	pT (GeV)
lepton 0: μ-	μon	PAIR A	311.627	131.058
lepton 1: e+	e	PAIR B	98.651	95.842
lepton 2: e-	e	PAIR B	92.348	101.035
lepton 3: μ+	μon	PAIR A	90.408	35.439

Possible pairings

Pairing	Leptons	Value
Pairing A	leptons 0 + 1	307.8313
Pairing B	leptons 2 + 3	104.8324
Pairing C	leptons 0 + 3	402.7254

Build the histogram
0 values - p
VALUES: 0
EVENTS KEPT: 0/0
S/VB (NOBIL) 0
MEASUREMENT (FIT M) 0

Event requirements
Only events passing every current requirement are added.
Exactly four leptons in the event

<https://www.hep.ph.ic.ac.uk/masterclass/>

- IMPERIAL • CMS MASTERCLASS
- Particle Physics Analysis Tool
- V4.1.3
- 1 Z search
two-lepton pairs
- 2 H search
four leptons
- Find a resonance using two-lepton pairs
- Choose how the four leptons are paired, then add both selected pair values to the histogram.
- 1 Build a quantity
- Click a variable or type any allowed combination.
- p clear
- E Energy p Momentum
- pt Transverse momentum px x momentum
- py y momentum pz z momentum
- ΣpT scalar pT Q Charge
- dr Separation θ Opening angle
- p - Momentum
Magnitude of the combined three-dimensional momentum.
- Combinations
- MOMENTUM
- momentum pT balance
- MASS
- mass mass from E and p
- ANGLES
- angular separation opening angle
- OTHER
- charge magnitude energy - momentum
- energy - momentum energy - scalar pT
- ΔR-weighted pT angle-weighted pT
- Formula help
- Pairing strategy
- Same Type, Different Charge
- Prefers pairs with the same lepton type and different charges.
- 2 Inspect an event
- Event 248020 - 4 leptons
- new event
- No event requirements selected.
- Event view
- n-g map, circle size follows pT
- φ around detector

● electron (e) ● muon (μ) ○ positive ○ negative — pair A — pair B
- lepton 0: e-
- PAIR A 311.457 GeV
- E 131.058 GeV
- pT
- lepton 1: e+
- PAIR B 98.811 GeV
- E 93.842 GeV
- pT
- lepton 2: e-
- PAIR B 92.368 GeV
- E 90.608 GeV
- pT
- lepton 3: e+
- PAIR A 402.885 GeV
- E 39.439 GeV
- pT
- Possible pairings
- Formula
- Pairing A
- leptons 0 + 1
- p 307.8313
- E 410.167 GeV
- pT 35.806 GeV
- charge 0
- Pair B leptons 2 + 3
- p 104.8324
- E 193.383 GeV
- pT 70.585 GeV
- charge 0
- Pairing B
- leptons 0 + 2
- p 279.3163
- E 402.885 GeV
- pT 92.661 GeV
- charge -
- Pairing C
- leptons 0 + 3
- p 402.7254
- E 412.492 GeV
- pT 134.518 GeV
- charge 0
- Pairing D
- leptons 1 + 2
- p 170.2829
- E 199.645 GeV
- pT 100.29 GeV
- charge +
- 3 Build the histogram
- Resize histogram
- Plot settings
- 0 values - p
- bins min max fit x bins
- 60 0 400 5
- VALUES
- EVENTS KEPT
- 0/0
- S/ΔS (NORM.)
- MEASUREMENT (FIT Δ)
- Add events to measure the peak.
- 1
- 0.8
- 0.6
- 0.4
- 0.2
- 0
- 100 200 300 400 500 600
- entries
- p
- add current event
- add next 1000 events

<https://www.hep.ph.ic.ac.uk/masterclass/>

-
- IMPERIAL • CMS MASTERCLASS
- # Particle Physics Analysis Tool
- V4.1.3
- 1 Z search
Two-lepton pairs

2 H search
Four leptons

Find a resonance using two-lepton pairs
Choose how the four leptons are paired, then add both selected pair values to the histogram.

1 Build a quantity
Click a variable or type any allowed combination.

p clear

E Energy p Momentum

pt Transverse momentum px x momentum

py y momentum pz z momentum

ΣpT scalar pT Q Charge

dr Separation θ Opening angle

p • Momentum
Magnitude of the combined three-dimensional momentum.

Combinations

MOMENTUM

momentum pT balance

pT cancellation

MASS

mass mass from E and p

ANGLES

angular separation opening angle

OTHER

charge magnitude energy - momentum

energy • momentum energy - scalar pT

AR-weighted pT angle-weighted pT

Formula help

Pairing strategy

Same Type, Different Charge

Prefers pairs with the same lepton type and different charges.

2 Inspect an event
Event: 2000801 - 4 leptons

No event requirements selected.

Event view

η along beam

ϕ around detector

electron (e⁻) muon (μ⁻) positive negative pair A pair B

lepton 0: e⁻ PAIR A
E 105.464 GeV
pT 133.659 GeV

lepton 1: μ⁻ PAIR B
E 119.955 GeV
pT 68.965 GeV

lepton 2: μ⁻ PAIR B
E 118.113 GeV
pT 69.652 GeV

lepton 3: e⁺ PAIR A
E 69.226 GeV
pT 43.428 GeV

Possible pairings

Pairing A
leptons 0 + 1
p 248.0045
E 206.299 GeV
pT 146.729 GeV
charge 0

Pair B
leptons 2 + 3
p 178.3646
E 207.338 GeV
pT 56.453 GeV
charge 0

Pairing B
leptons 0 + 2
p 259.1333
E 227.557 GeV
pT 75.718 GeV
charge -

Pair B
leptons 1 + 3
p 124.7538
E 169.181 GeV
pT 29.614 GeV
charge +

Pairing C
leptons 0 + 3
p 199.3516
E 218.647 GeV
pT 135.309 GeV
charge 0

Pair B
leptons 1 + 2
p 264.2887
E 207.338 GeV
pT 56.453 GeV
charge 0

3 Build the histogram
Current event added

Resize histogram

Plot settings

bins 60 min 0 max 500 fit x bins 10

VALUES 240

EVENTS KEPT 120 / 120

S/AB (NORMAL) 0.12

MEASUREMENT (FIT Δ)

The maximum needs 10 bins on each side.

add current event

add next 1000 events

clear histogram

The displayed S/AB is divided by Δ measurement, is a Gaussian fit to the maximum bin and the configured number of bins on each side, its uncertainty is the fit uncertainty e.g. ± 0.01 .

4 Event requirements
Only events passing every current requirement are added.

Exactly four leptons in the event

The event lepton count is the number of reconstructed leptons and muons in the event.

No requirements selected.

Changing the formula, mode, pairing, channel, or requirements starts a new histogram.
- You can add the event you're viewing to the

You can add the event
you're viewing to the
histogram here

<https://www.hep.ph.ic.ac.uk/masterclass/>

Try plotting different variables. Talk to your neighbors and helpers about what you found.



Hint: Try plotting the mass of the dilepton pair

The **invariant mass** of the dilepton pair is calculated using the following, solving for m :

$$E^2 = (mc^2)^2 + (pc)^2$$

This tells us the amount of energy available in the decay.

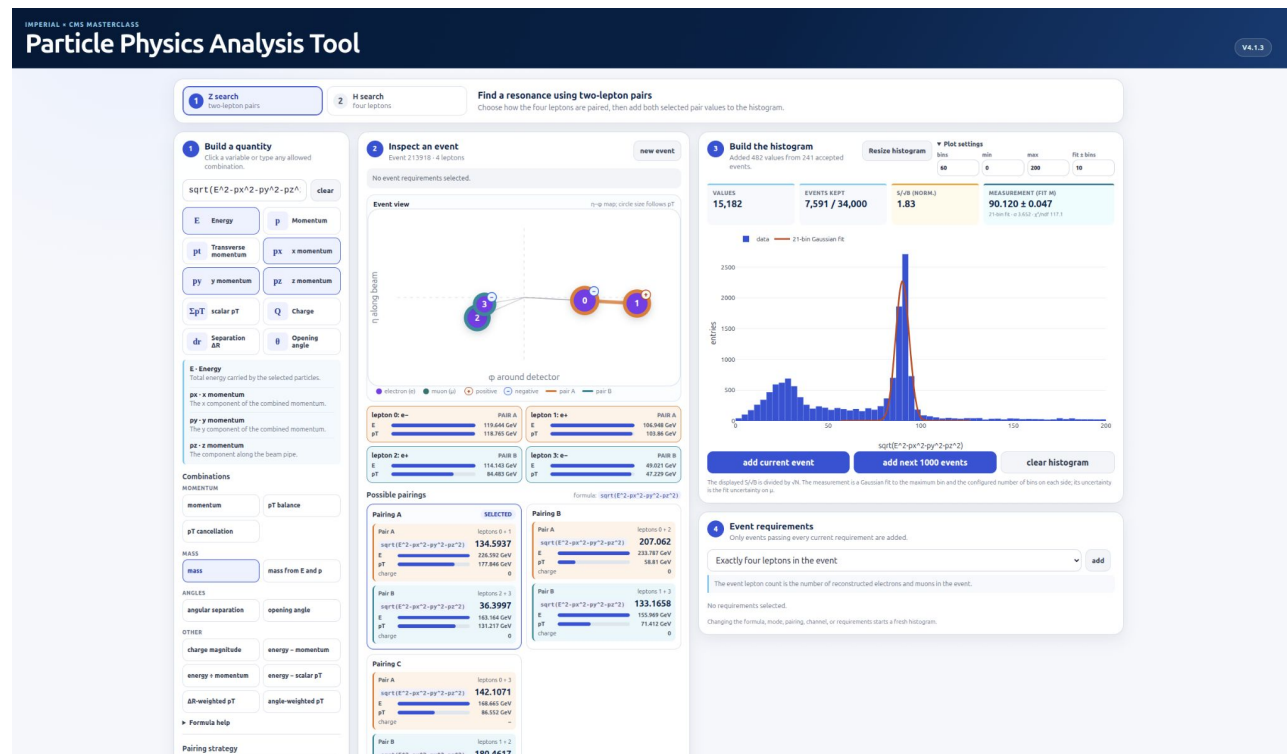
If you plot the mass, what can you learn about the Z boson?

How can we find the Z?

<https://www.hep.ph.ic.ac.uk/masterclass/>

If we plot the mass of our electron and muon pairs, we can see a peak!

This is a measurement of the energy before the decay– or, a measurement of the mass of the Z boson!



How can we find the H?

<https://www.hep.ph.ic.ac.uk/masterclass/>

Task #2: Now, let's try adding all the leptons in the event together

The event is $H \rightarrow ZZ \rightarrow 4L$: a Higgs boson decay into two Z, and Z boson decays into 4L

What will you find if you plot the mass of all leptons in the event?
What does it tell you about the Higgs boson?

IMPERIAL + CMS MASTERCLASS
Particle Physics Analysis Tool

1 Z search
two-lepton pairs

2 H search
four leptons

Find a resonance using all four leptons
No pairing choice is needed. Choose which decay channels contribute to the histogram.

3 Build the histogram
Formula: $\sqrt{s}(E^2 - p_x^2 - p_y^2 - p_z^2)$
Plot settings: Size 45, Min 65, Max 200, Fit 2 line

4 Event requirements
Channel: All events
Exactly four leptons in the event

Build a quantity
Click a variable or type any allowed combination.
 $\sqrt{s}(E^2 - p_x^2 - p_y^2 - p_z^2)$ clear

Inspect an event
Event 21402 - 4 leptons
No event requirements selected.

Event view
Event diagram showing particle tracks and detector components.

Lepton 0: $E = 199.776$ GeV, $p_T = 178.857$ GeV
Lepton 1: $E = 126.353$ GeV, $p_T = 120.204$ GeV
Lepton 2: $E = 75.526$ GeV, $p_T = 74.833$ GeV
Lepton 3: $E = 85.384$ GeV, $p_T = 83.116$ GeV

Four-lepton value
Formula: $\sqrt{s}(E^2 - p_x^2 - p_y^2 - p_z^2)$
Leptons 0 + 1 + 2 + 3
 $\sqrt{s}(E^2 - p_x^2 - p_y^2 - p_z^2)$
381.1942
 $E = 451.859$ GeV
 $p_T = 178.104$ GeV

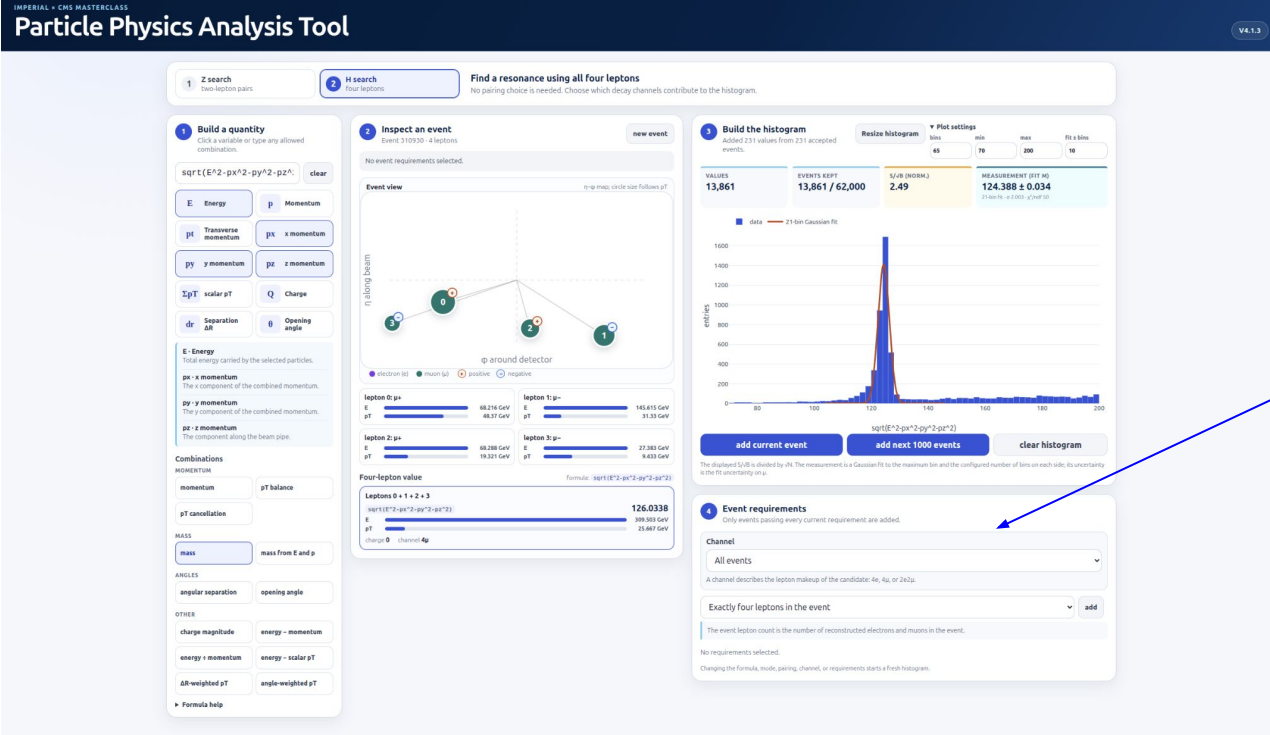
Combinations
momentum, p_T balance, p_T cancellation, MASS, mass from E and p, ANGLES, angular separation, opening angle, OTHER, charge magnitude, energy - momentum, energy + momentum, energy - scalar p_T , ΔR -weighted p_T , angle-weighted p_T

Formula help

Question: Does the mass depend on the channel: whether the event contained electrons or muons?

Measuring the Higgs mass

<https://www.hep.ph.ic.ac.uk/masterclass/>



Final Task: How good a measurement can you make?

4. We can use event requirements to remove bad events and improve our precision

Try to improve your **Z, H mass measurements** by decreasing fit uncertainty (+/-)!

Explore!

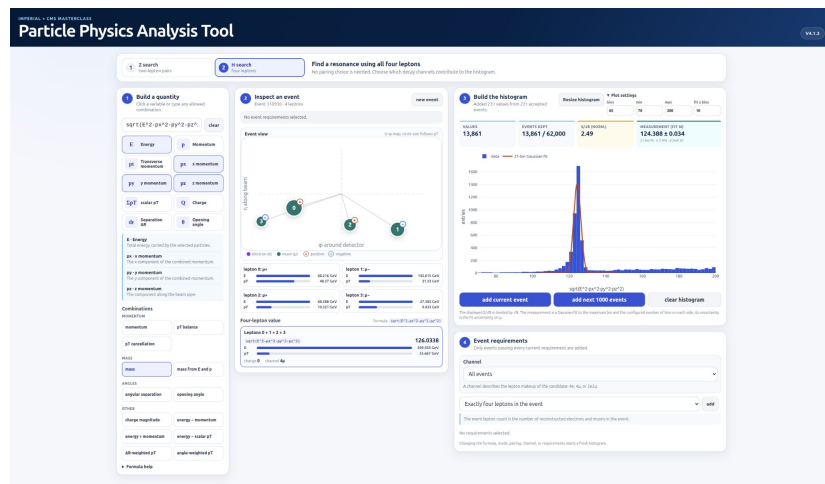
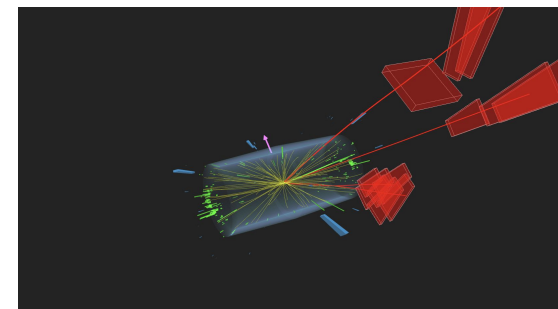
<https://www.hep.ph.ic.ac.uk/masterclass/>

Submit your best **Z, H mass measurements and uncertainties** in this form. We'll compile our results at the end to see how we did:

<https://tinyurl.com/zhmass>



<https://tinyurl.com/ispycms>



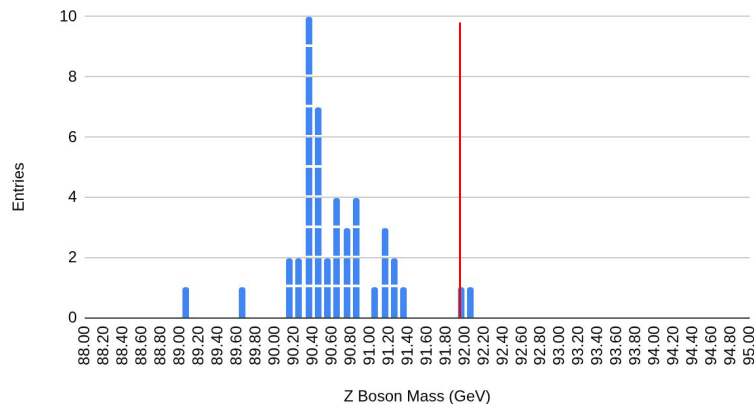
You're welcome to look at more event displays, plot new variables, and ask questions about what you see!

Results

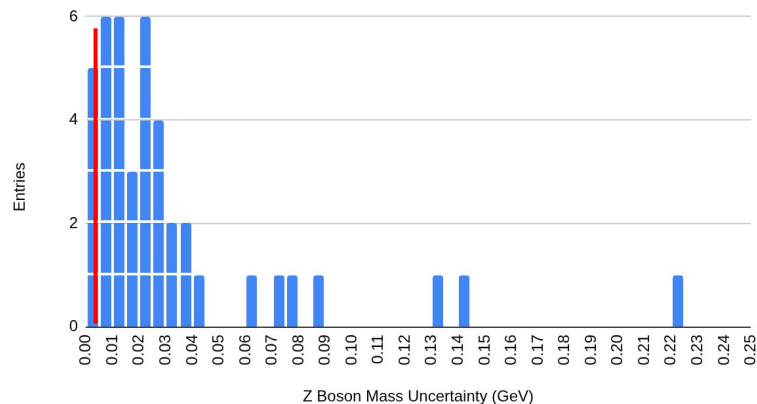
Actual Z mass: 91.1879 ± 0.002 GeV

30 billion Z bosons have been produced at the LHC

Z Boson Mass Measurement



Z Boson Mass Uncertainty



Our median: 90.45 ± 0.02 GeV (stat) $\pm$??? (sys)

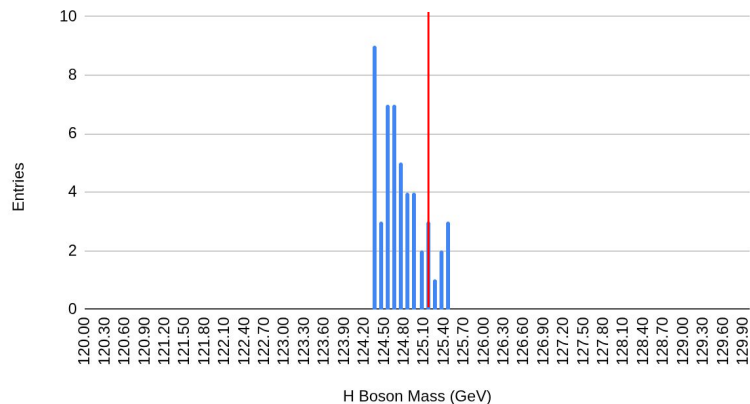
Agreement: 37σ

Results

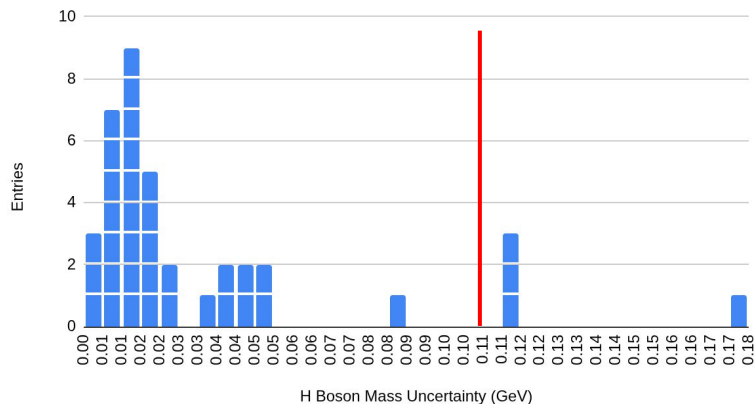
Actual H mass: 125.13 ± 0.11 GeV

30 million Higgs bosons have
been produced at the LHC
1000x rarer than Z!

H Boson Mass Measurement



H Boson Mass Uncertainty



Our median: 124.68 ± 0.02 GeV (stat) $\pm$??? (sys)

Agreement: 4.0σ