



Imperial College
London

CMS HZZ analysis exercise

IC Masterclass 2026

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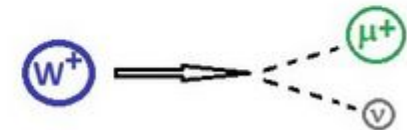
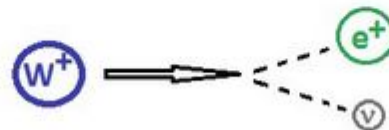
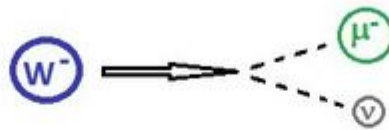
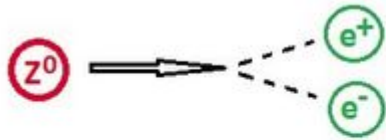
Overview of the task

<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



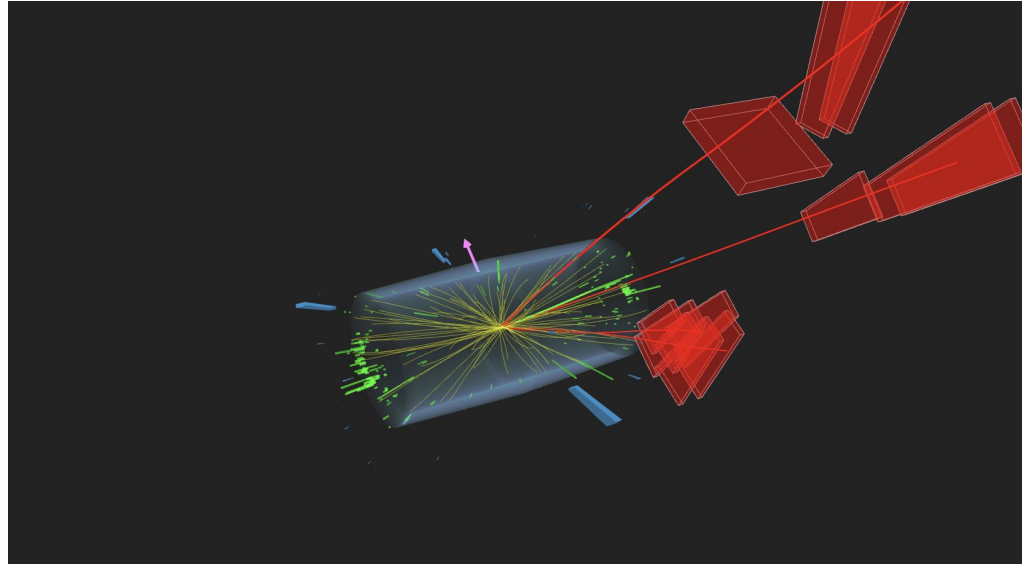
H boson decays

- 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



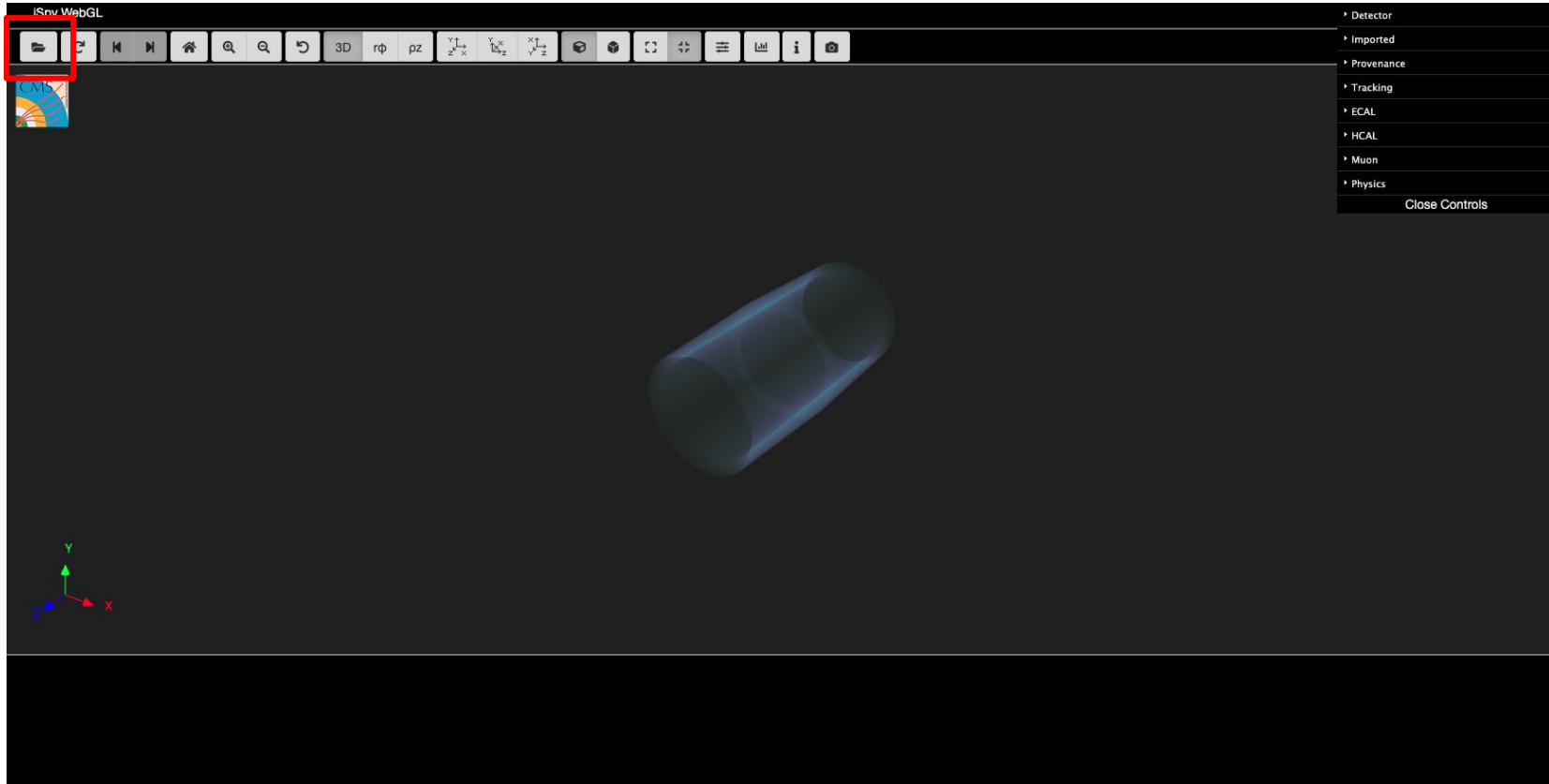
Let's look at some real events

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



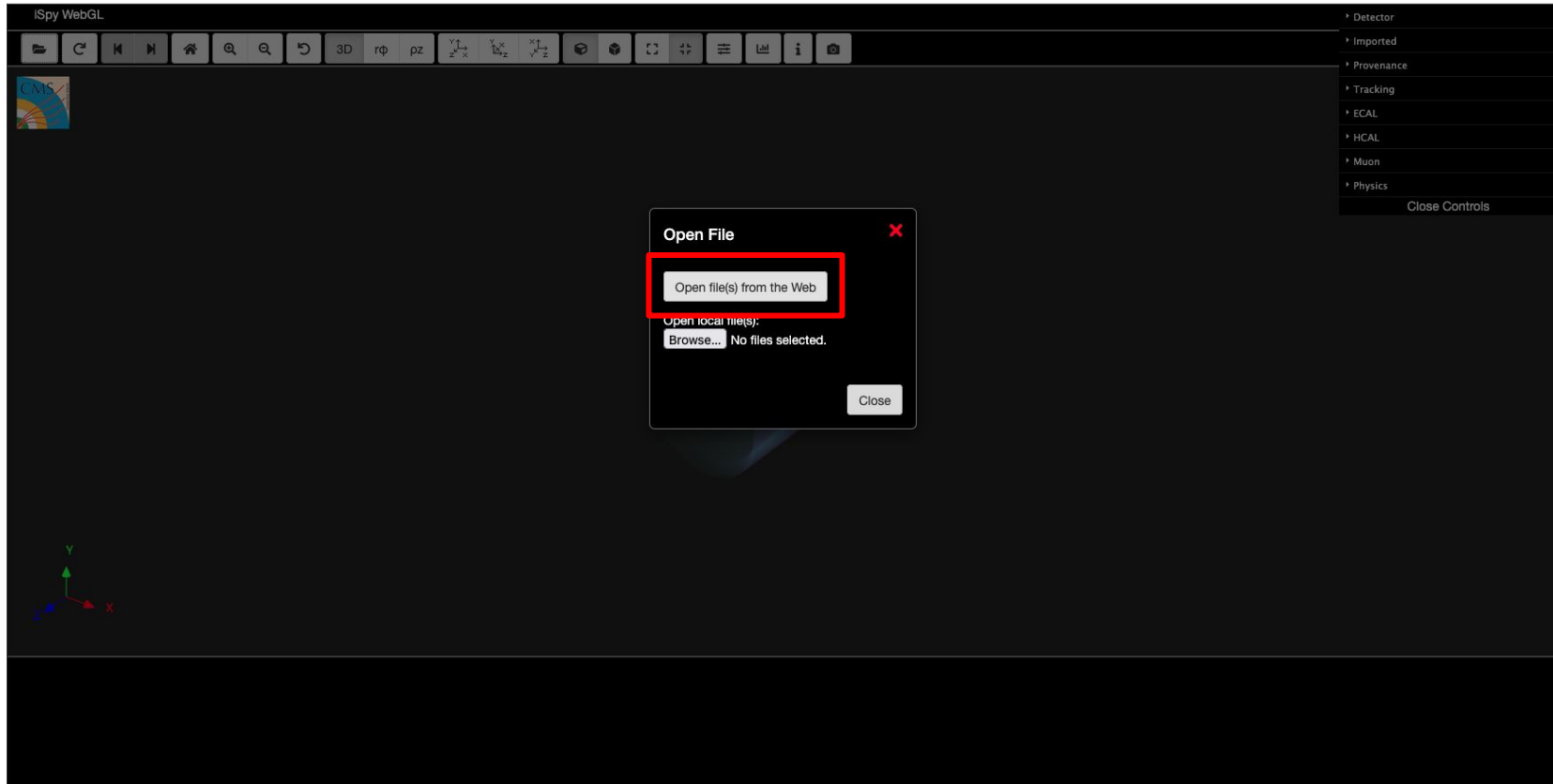
How to use the event display

<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

Open Event

Files	Events
N5/	
N10/	
N25/	
N50/	
N100/	

Selected event

Close Load

Detector
Imported
Provenance
Tracking
ECAL
HCAL
Muon
Physics
Close Controls

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. On the left, a 3D detector model is visible. The top toolbar contains various navigation and viewing tools. The right sidebar lists navigation options: Detector, Imported, Provenance, Tracking, ECAL, HCAL, Muon, and Physics, with a 'Close Controls' button at the bottom. In the center, an 'Open Event' dialog is open. It features two columns: 'Files' and 'Events'. The 'Files' column lists several masterclass files (masterclass_1.iq to masterclass_6.iq). The 'Events' column lists individual events (Events/Run_1/Event_1 to Events/Run_1/Event_7), with 'Events/Run_1/Event_1' highlighted by a red box. Below the event list, a text field displays 'N25: Events/Run_1/Event_1'. At the bottom right of the dialog are 'Close' and 'Load' buttons.

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

N25: Events/Run_1/Event_1

Close Load

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

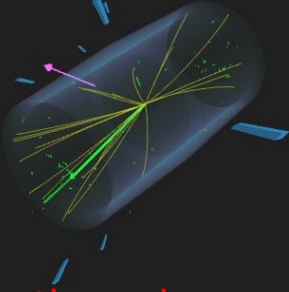
<https://indico.global/event/18516/>

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

◀ ▶ ⏮ ⏭ 🔍 🔍 ↺ 3D rφ pz $\vec{p}_T \rightarrow x$ $\vec{p}_T \rightarrow y$ $\vec{p}_T \rightarrow z$ 🔄 📐 📏 📊 📋 📄 📷

 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



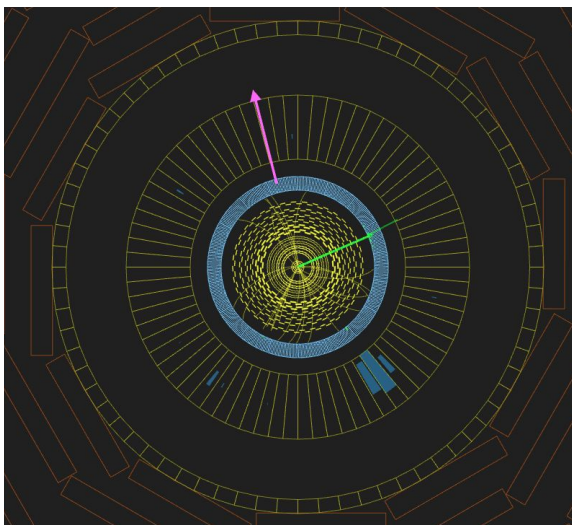
 You can use these buttons to go through the different events

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

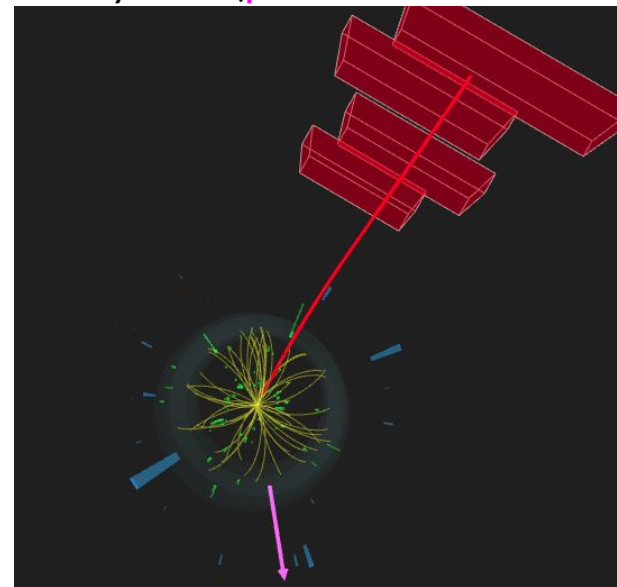
Identifying W bosons

<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



$W \rightarrow e \nu$

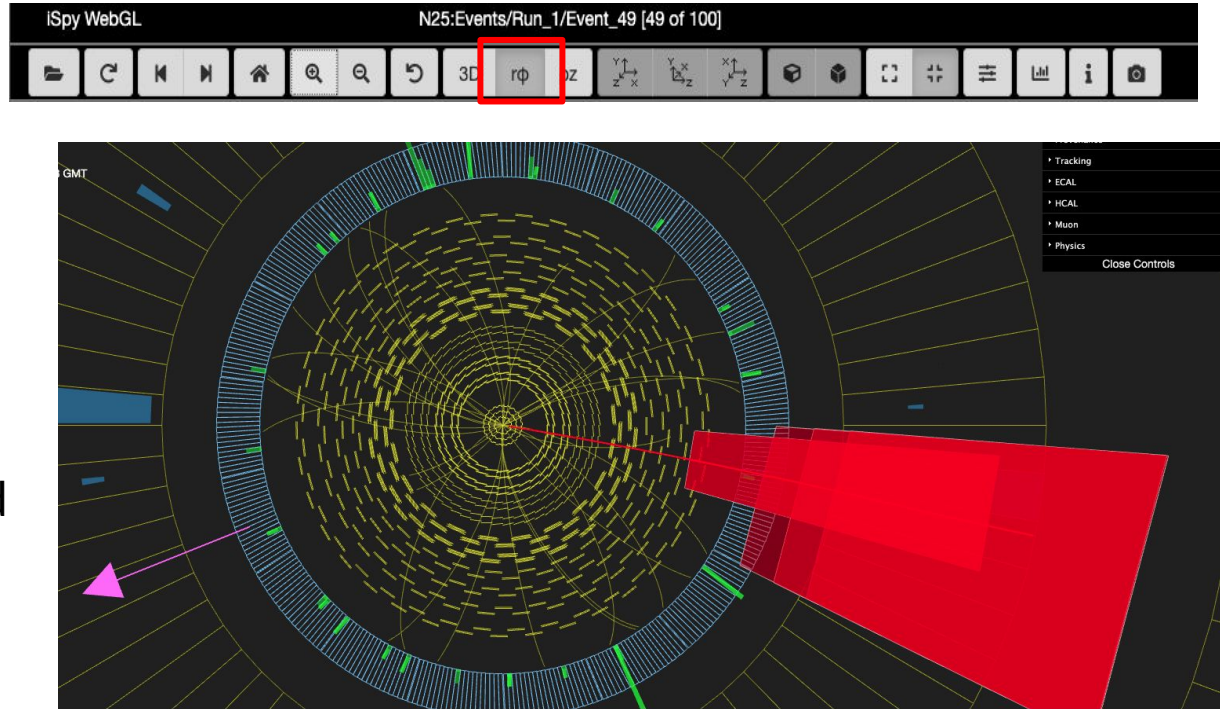


$W \rightarrow \mu \nu$

Measuring charges

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

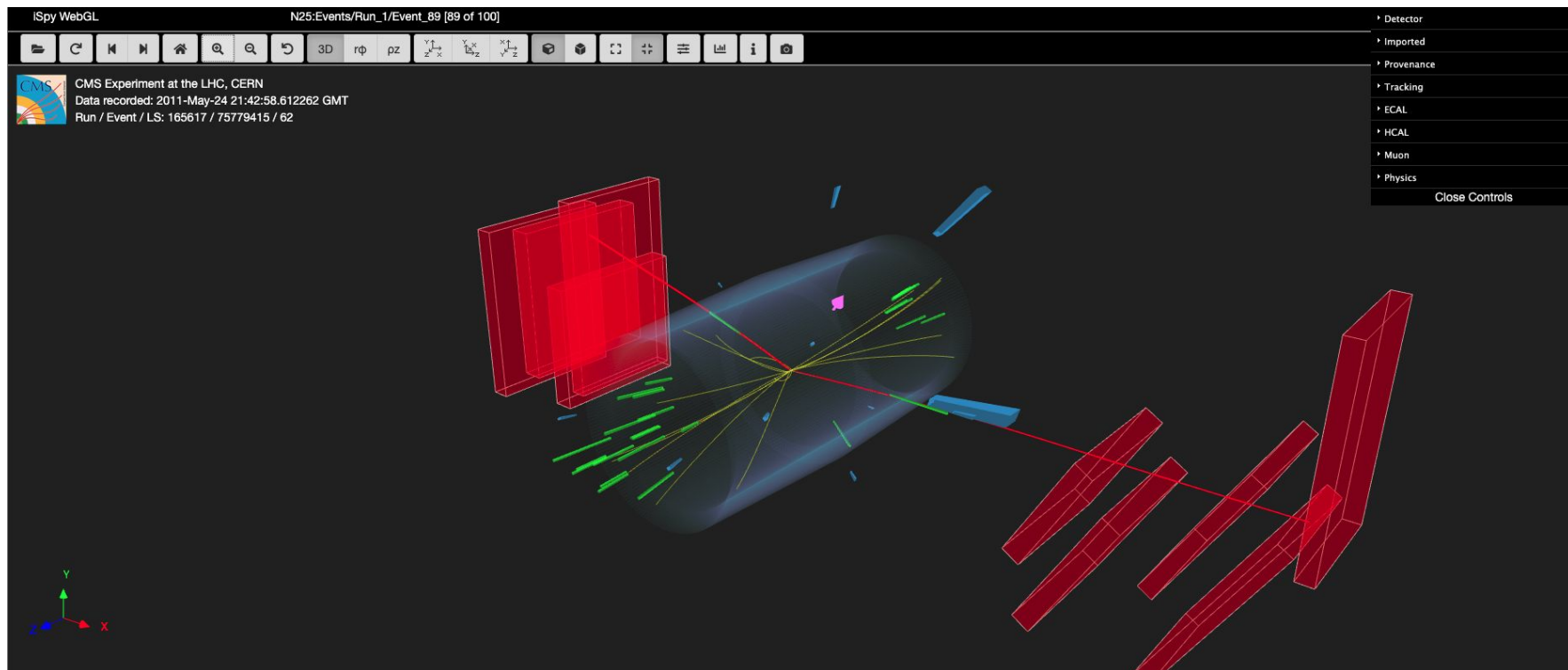
- Charged leptons bend in magnetic field
- The direction that they bend in depends on their charge
- **Positive** leptons will bend **clockwise**
- **Negative** leptons will bend **anti-clockwise**
- Select y-x view, zoom in to see curvature and then identify the charge



Identifying Z bosons

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

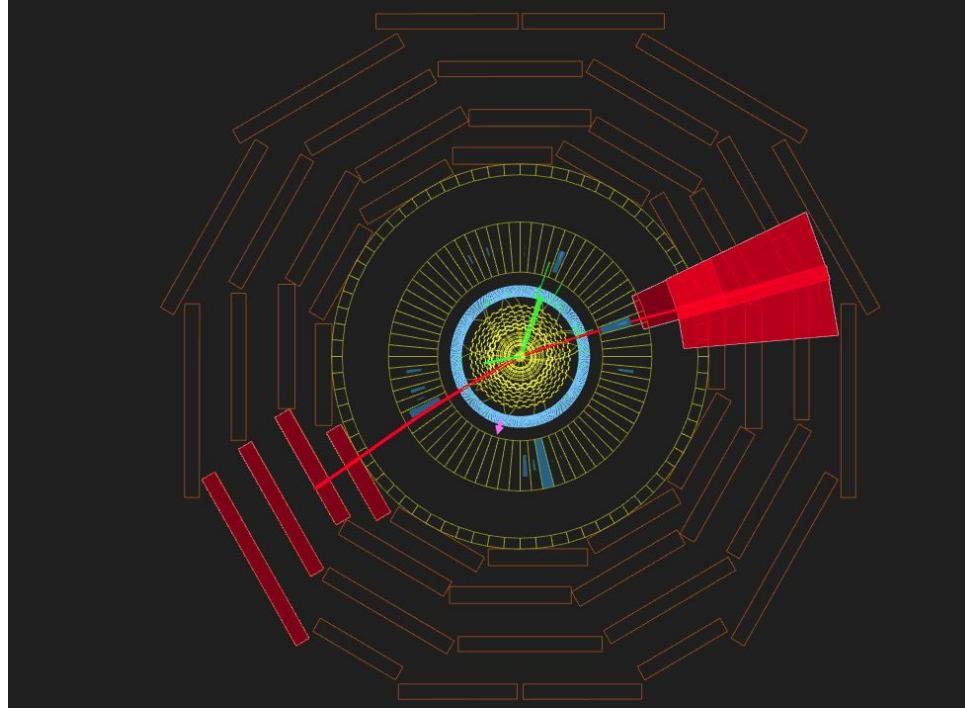
Z bosons decay into two oppositely charged electrons or muons



Identifying Higgs boson events

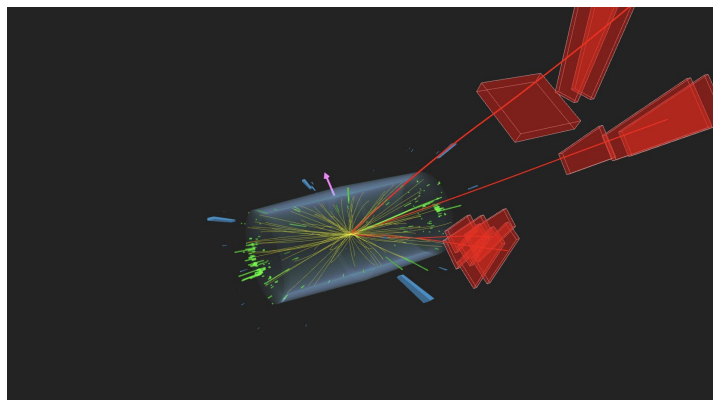
<https://indico.global/event/18516/>

- 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-
E: 311.627 GeV
pT: 131.058 GeV

lepton 1: e+
E: 98.651 GeV
pT: 95.842 GeV

lepton 2: e-
E: 92.348 GeV
pT: 90.408 GeV

lepton 3: e+
E: 101.035 GeV
pT: 35.439 GeV

Possible pairings

Pairing A
leptons 0 + 1
E: 307.8313
E: 410.047 GeV
pT: 35.806 GeV
charge: 0

Pairing B
leptons 2 + 3
E: 104.8324
E: 193.583 GeV
pT: 70.585 GeV
charge: 0

Pairing C
leptons 0 + 3
E: 402.7254
E: 412.893 GeV
pT: 136.518 GeV
charge: 0

Pairing D
leptons 1 + 2
E: 170.2829

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

Realize histogram

Plot settings

VALUES
39,148

EVENTS KEPT
19,574 / 87,000

1/s (NOISE)
0.09

MEASUREMENT (FIT AG)
94.1 ± 1.2
11-Jan-16 - 0.02-0.07 - 1.00E-04

add current event

add next 1000 events

clear histogram

The displayed 1/s is divided by ΔR . The measurement is a Gaussian fit to the maximum bin and the configured number of bins on each side. Its uncertainty is the fit uncertainty on μ .

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.

17

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 **new event**

No event requirements selected.

Event view η - ϕ map: circle size follows p_T

ϕ around detector

3 Build the histogram 0 values - p **Resize histogram** bins: 60 min: 0 max: 600 fit: 5

VALUES: 0 EVENTS KEPT: 0/0 $S/\sqrt{B}$ (NOBKS) MEASUREMENT (FIT μ)

add current event add next 1000 events clear histogram

The displayed $S/\sqrt{B}$ is divided by $\sqrt{B}$. The measurement is a Gaussian fit to the maximum bin and the configured number of bins on each side. Its uncertainty is the fit uncertainty on μ .

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.

Build a quantity

Click a variable or type any allowed combination.

Variables:

- E: Energy
- pt: Transverse momentum
- py: y momentum
- Σp_T : scalar p_T
- dr: Separation ΔR
- p : Momentum (magnitude of the combined three-dimensional momentum)
- px: x momentum
- pz: z momentum
- Q: Charge
- θ : Opening angle

Combinations:

- momentum
- p_T balance
- p_T cancellation

MASS

- mass
- mass from E and p

ANGLES

- angular separation
- opening angle

OTHER

- charge magnitude
- energy - momentum
- energy + momentum
- ΔR -weighted p_T
- angle-weighted p_T

Formula help

Pairing strategy

Closest Distance

Selects the pairing with the smallest total angular separation.

Inspect an event

Event: 244029 - 4 leptons

Event view

η - ϕ map: circle size follows p_T

ϕ around detector

Lepton 0: μ^-

- PAIR A: 311.627 GeV
- p_T : 131.058 GeV

Lepton 1: e^+

- PAIR B: 98.651 GeV
- p_T : 95.842 GeV

Lepton 2: e^-

- PAIR B: 92.348 GeV
- p_T : 90.408 GeV

Lepton 3: μ^+

- PAIR A: 101.035 GeV
- p_T : 35.439 GeV

Possible pairings

Pairing A leptons 0 + 1

- p : 307.8313
- E: 410.047 GeV
- p_T : 35.806 GeV
- charge: 0

Pairing B leptons 2 + 3

- p : 104.8324
- E: 105.582 GeV
- p_T : 70.585 GeV
- charge: 0

Pairing C leptons 0 + 2

- p : 279.3163
- E: 403.805 GeV
- p_T : 92.081 GeV
- charge: 0

Pairing D leptons 1 + 3

- p : 156.0398
- E: 109.845 GeV
- p_T : 100.29 GeV
- charge: 0

Pairing E leptons 0 + 3

- p : 402.7254
- E: 412.902 GeV
- p_T : 136.518 GeV
- charge: 0

Pairing F leptons 1 + 2

- p : 170.2829
- E: 105.582 GeV
- p_T : 70.585 GeV
- charge: 0

1. Choose a variable, mix of variables, or predefined combination you want to measure
2. There are at least 4 leptons (electrons or muons) in this event, from 2 Z boson decays. Choose how you want to pair the leptons

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 **new event**

No event requirements selected.

Event view η - η map, circle size follows p_T

ϕ around detector

lepton 0: μ^- Pair A: E 311.627 GeV p_T 98.651 GeV p_T 95.842 GeV

lepton 1: e^+ Pair B: E 403.805 GeV p_T 35.439 GeV

lepton 2: e^- Pair B: E 92.348 GeV p_T 101.035 GeV p_T 35.439 GeV

lepton 3: μ^+ Pair A: E 403.805 GeV p_T 35.439 GeV

Possible pairings

Pairing A: leptons 0 + 1 χ^2 307.8313 E 410.047 GeV p_T 35.806 GeV charge 0

Pairing B: leptons 0 + 2 χ^2 279.3163 E 403.805 GeV p_T 92.081 GeV charge 0

Pairing C: leptons 0 + 3 χ^2 104.8324 E 105.302 GeV p_T 70.585 GeV charge 0

Pairing D: leptons 1 + 2 χ^2 156.0398 E 109.845 GeV p_T 100.29 GeV charge 0

Pairing E: leptons 1 + 3 χ^2 170.2829 E 136.518 GeV p_T 0 charge 0

3 Build the histogram 0 values: p **Resize histogram** bins min max Fit a bins **VALUES** 0 **EVENTS KEPT** 0/0 **S/VB (NOBIL)** **MEASUREMENT (FIT A)**

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

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.

Formula help

Pairing strategy Same Type, Different Charge $\downarrow$ Prefers pairs with the same lepton type and different charges.

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

- The image shows a web-based interface for particle physics analysis, titled "Particle Physics Analysis Tool" in the top left corner. The interface is divided into several panels and sections:

 - Top Bar:** "IMPERIAL • CMS MASTERCLASS" on the left and "V4.1.3" on the right.
 - Navigation Tabs:** "1 Z search", "2 H search", and "Find a resonance using two-lepton pairs".
 - Panel 1: Build a quantity**
 - Sub-panel: "Build a quantity" with a text input "p" and a "clear" button.
 - Buttons: "Energy", "Momentum", "Transverse momentum", "x momentum", "y momentum", "z momentum", "scalar pT", "Charge", "Separation", "Opening angle".
 - Section: "Combinations" with "p - Momentum" (description: "Magnitude of the combined three-dimensional momentum").
 - Buttons: "pT balance", "pT cancellation".
 - Section: "MASS" with "mass" and "mass from E and p".
 - Section: "ANGLES" with "angular separation" and "opening angle".
 - Section: "OTHER" with "charge magnitude", "energy - momentum", "energy - momentum", "energy - scalar pT", "delta-weighted pT", "angle-weighted pT".
 - Section: "Formula help" with "Pairing strategy" (dropdown menu showing "Same Type, Different Charge").
 - Panel 2: Inspect an event**
 - Sub-panel: "Inspect an event" with "Event 263200 - 4 leptons" and a "new event" button.
 - Text: "No event requirements selected."
 - Diagram: "Event view" showing a top-down view of the detector with four leptons (1, 2, 3, 4) and a central detector region.
 - Table: "Possible pairings" showing combinations of leptons and their properties (E, pT, charge).
 - Table: "Pairing A", "Pairing B", "Pairing C" showing specific pairings and their properties.
 - Panel 3: Build the histogram**
 - Sub-panel: "Build the histogram" with "Current event added" and "Resize histogram" button.
 - Buttons: "add current event", "add next 1000 events", "clear histogram".
 - Plot: A histogram showing the distribution of "p" (momentum) with a peak around 100. The x-axis is labeled "p" and the y-axis is labeled "entries".
 - Text: "The displayed S/B is divided by the measurement fit to the maximum bin and the configured number of bins on each side; its uncertainty is the fit uncertainty on μ ."
 - Panel 4: Event requirements**
 - Sub-panel: "Event requirements" with "Only events passing every current requirement are added."
 - Text: "Exactly four leptons in the event" (dropdown menu) and "add" button.
 - Text: "The event lepton count is the number of reconstructed leptons and muons in the event."
 - Text: "No requirements selected." and "Changing the formula, mode, pairing, channel, or requirements starts a new histogram."

Annotations (blue arrows) point to the "p" input field in the "Build a quantity" panel, the "add current event" button in the "Build the histogram" panel, and the "Pairing strategy" dropdown menu in the "Build a quantity" panel.

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

<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

ΔR Separation

θ Opening angle

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

Combinations

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

Same Type, Different Charge

Prefers pairs with the same lepton type and different charges.

2 Inspect an event

Event 153372 - 4 leptons

new event

No event requirements selected.

Event view

η-φ map, circle size follows pT

φ around detector

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

lepton 0: μ-

PAIR A

lepton 1: μ-

PAIR B

lepton 2: μ+

PAIR A

lepton 3: μ+

PAIR B

Possible pairings

Pairing A

Pairing B

Pairing C

3 Build the histogram

Added 446 values from 223 accepted events.

Resize histogram

Plot settings

bins min max **Fit a bins**

60 0 500 10

VALUES **EVENTS KEPT** **S/BR (WORK)** **MEASUREMENT (FIT M)**

10,496 5,248 / 23,120 0.14 2.48

The maximum needs 10 bins on each side.

add current event **add next 1000 events** **clear histogram**

The displayed S/BR is divided by $\sqrt{s}$. The measurement is a Gaussian fit to the maximum bin and the configured number of bins on each side, its uncertainty is the fit uncertainty on μ .

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.

You can also add events in batches of 1000

<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.

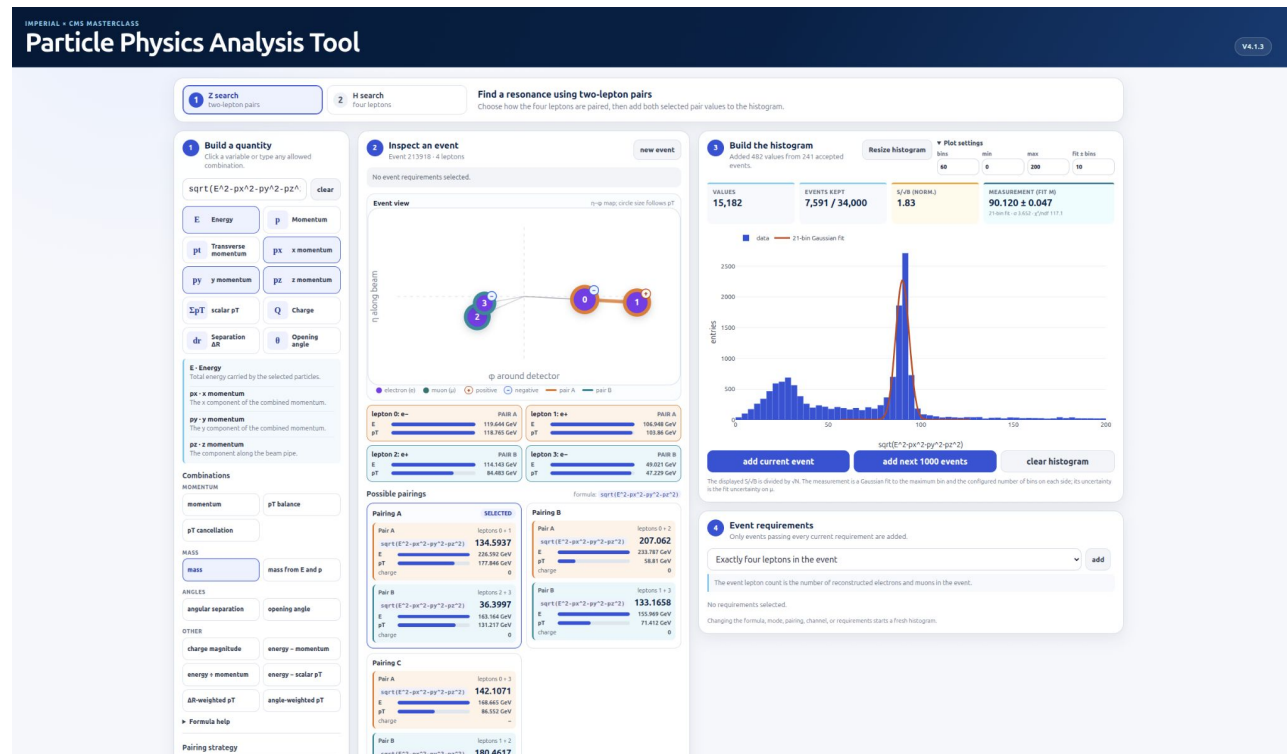
If you plot the mass, what can you learn about the Z boson?

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?

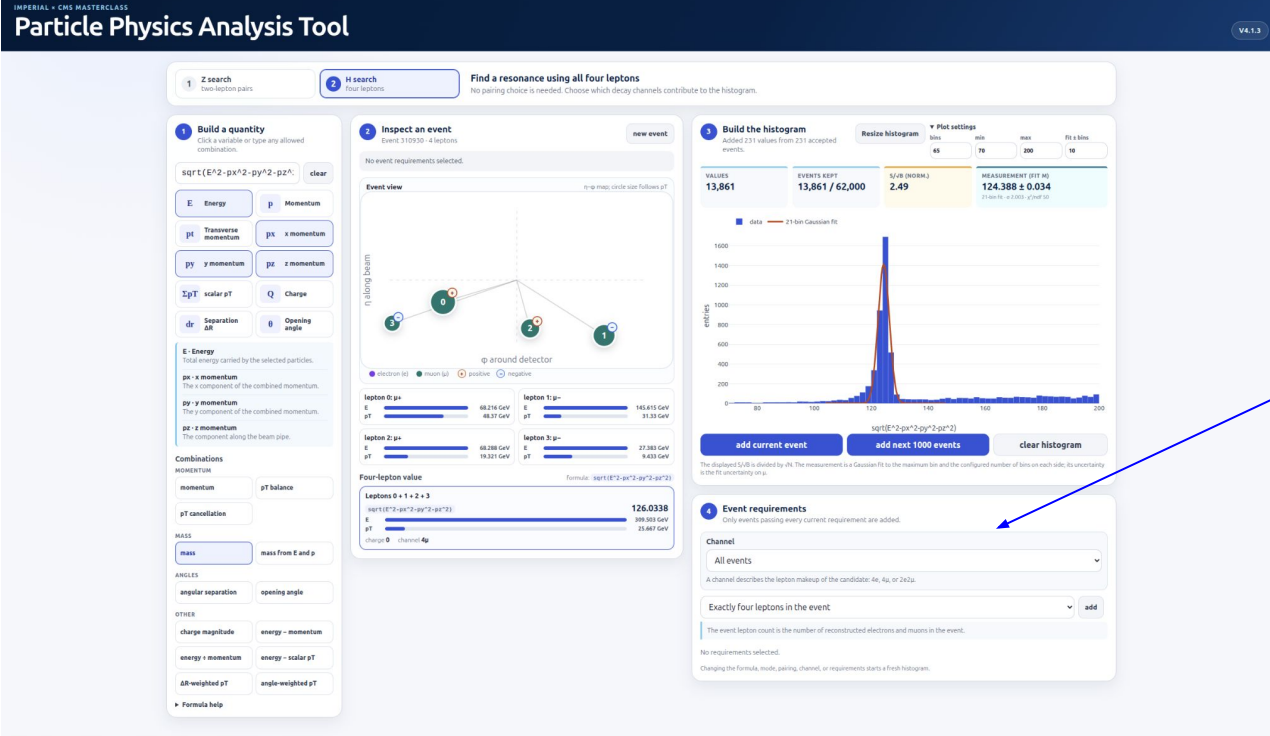
The screenshot displays the 'Particle Physics Analysis Tool' interface. The top navigation bar includes 'IMPERIAL + CMS MASTERCLASS' and 'Particle Physics Analysis Tool'. The main interface is divided into several panels:

- 1 Z search** (two-lepton pairs) and **2 H search** (four leptons) tabs. The 'H search' tab is active.
- 3 Build a quantity**: A panel for selecting variables to plot. It includes a formula input field with $\sqrt{E^2 - p^2}$ and a 'clear' button. Below are buttons for Energy, Momentum, Transverse momentum, x momentum, y momentum, z momentum, scalar pT, Charge, Separation, and Opening angle. A section for 'E - Energy' and 'p - momentum' is also present.
- 4 Inspect an event**: A panel showing event details. It includes a 'new event' button and a 'No event requirements selected' message. The 'Event view' shows a diagram of the event with four leptons (0, 1, 2, 3) and their momenta. Below the diagram are four horizontal bars representing the energy and momentum of each lepton.
- 5 Build the histogram**: A panel for configuring the histogram. It includes a 'Resize histogram' button and a 'Plot settings' dropdown. The 'VALUES' section shows '0' for 'EVENTS KEPT' and '0/0' for 'S/N (30000)'. The 'MEASUREMENT (FIT W)' section shows '0'. The 'Channel' dropdown is set to 'All events'. The 'Exactly four leptons in the event' checkbox is checked. The 'Event requirements' section shows 'Only events passing every current requirement are added'.

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!

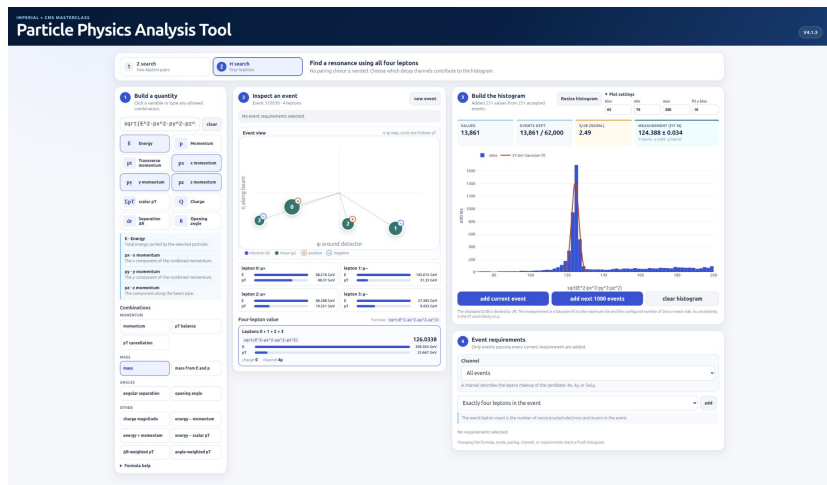
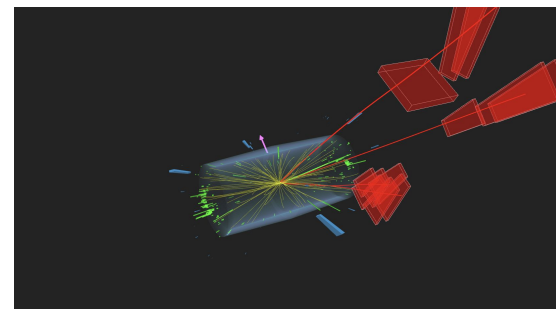
<https://www.hep.ph.ic.ac.uk/masterclass/>

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!