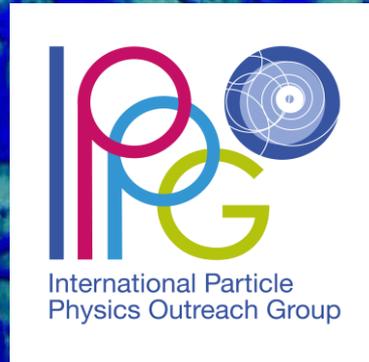


Observing Invisible Particles

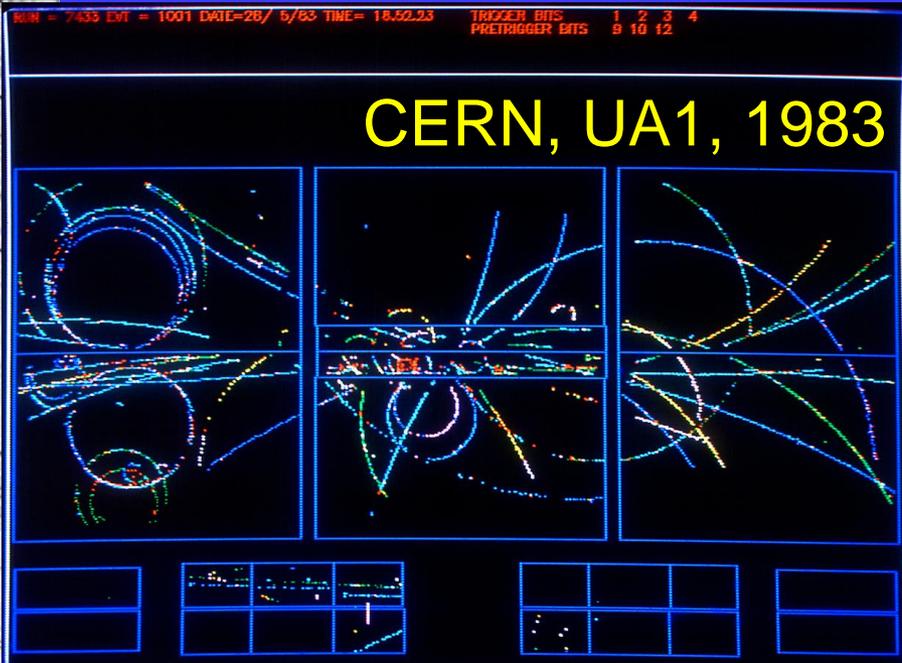
“The ATLAS Z path”

Pedro Abreu

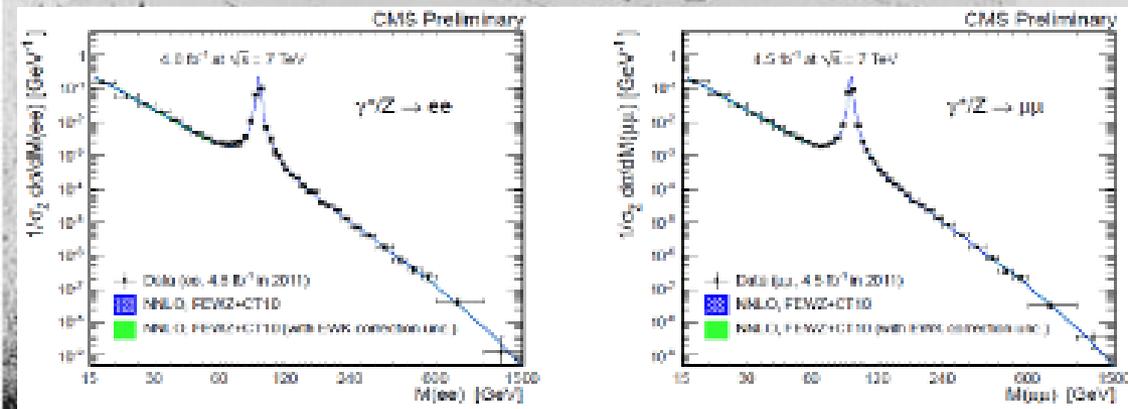
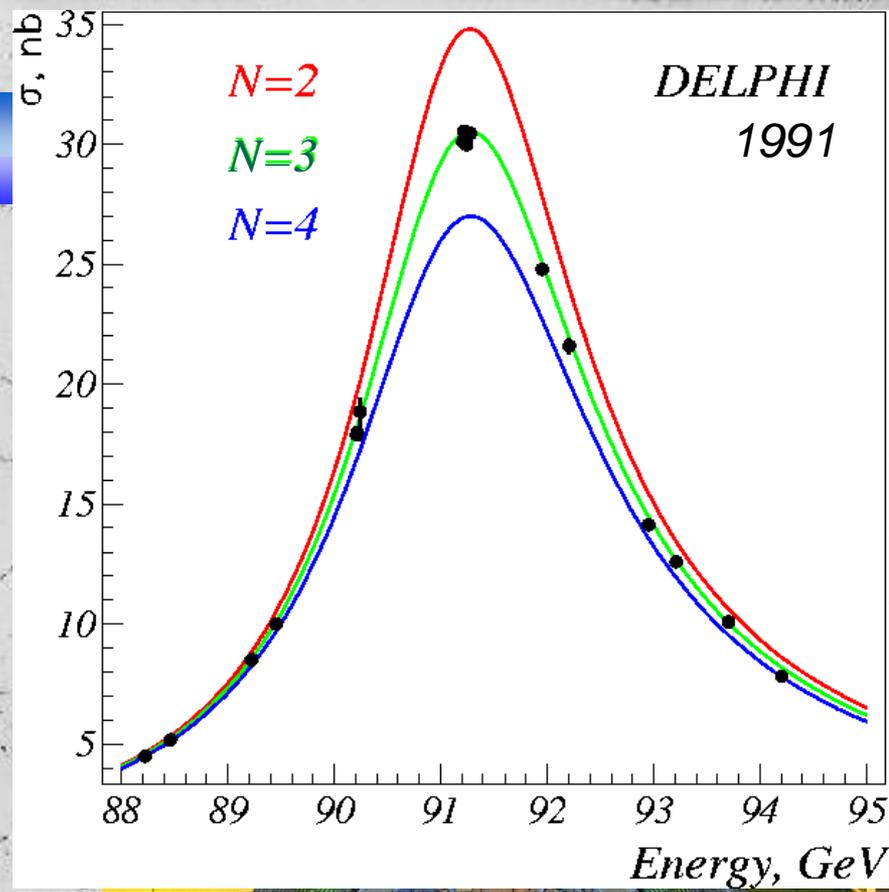


26/10
2022

The Z path



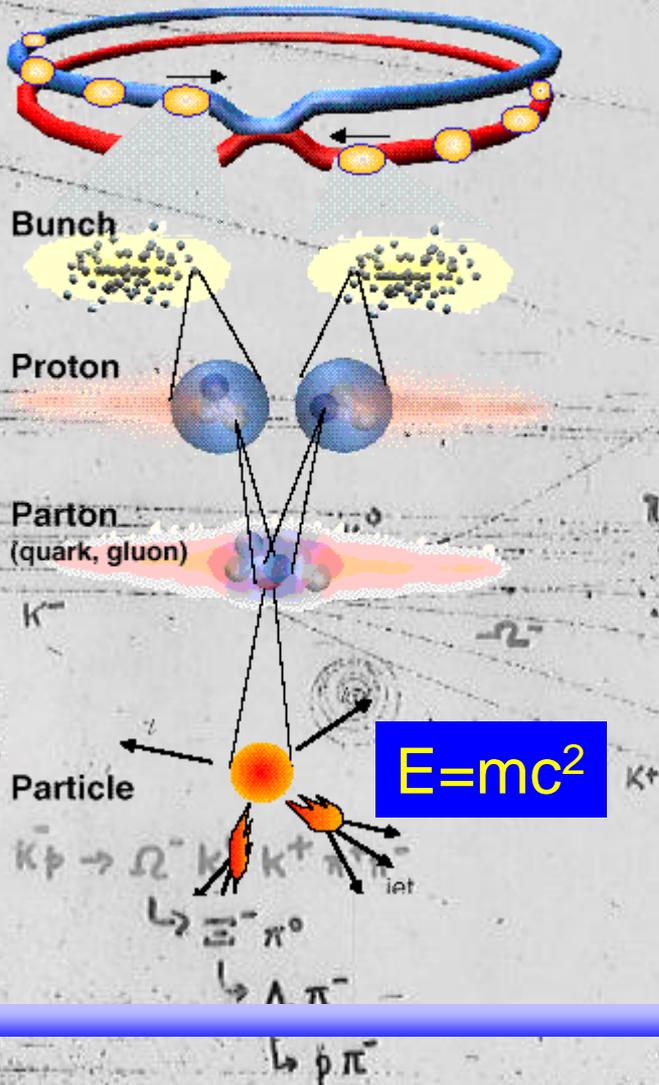
Z Invariant Mass Distribution



It all starts with an hydrogen bottle

$\Lambda \pi^-$
 $\rho \pi^-$

Colliding protons



Some numbers at the LHC:

Number of bunches / beam = 2808

Number of protons / bunch = 10^{11}

Energy_{beams} = $3,9 \times 10^{15}$ TeV ~ **0,6 GJ**

0,6 GJ is the kinetic energy of a TGV running at **200 km/h** !

...or of my car at 3000 km/h !

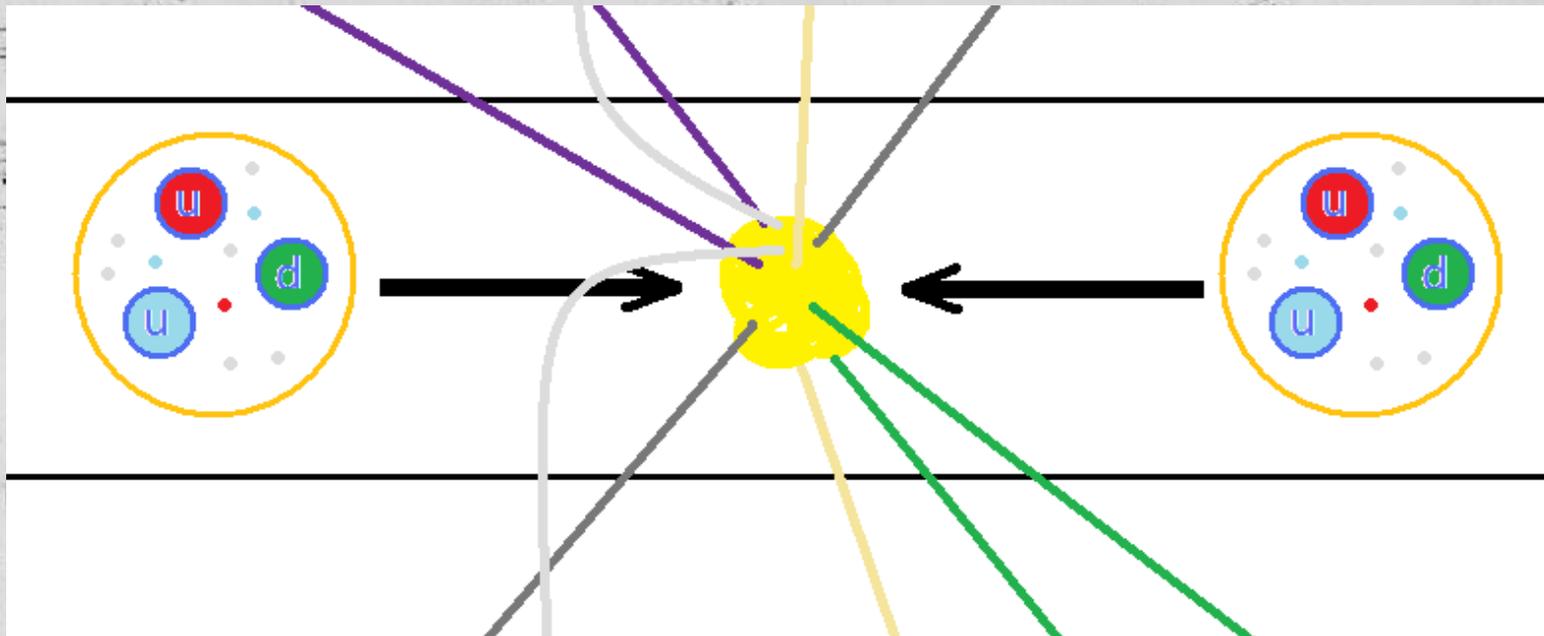


Proton-proton interactions

In our data, protons had a maximum energy of 3.5(4) TeV each:

$$2 \times 3.5(4) \text{ TeV} = 7(8) \text{ TeV}$$

The **quarks and gluons**, constituents of the proton, that collide only **have a fraction of this energy**. New particles created in the collision *always* have a mass smaller than this fraction of energy.

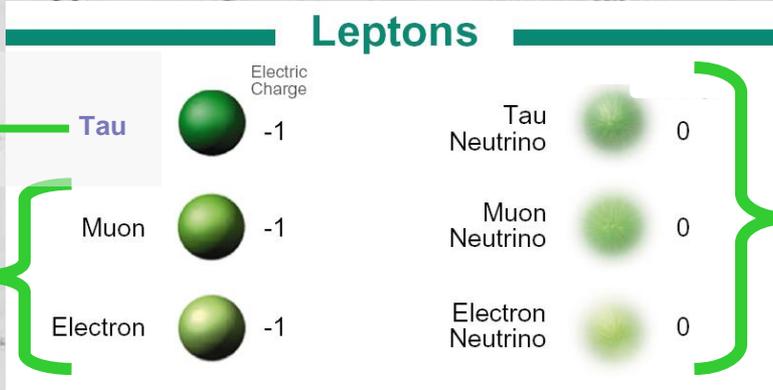


$\hookrightarrow p\pi^-$

What particles can we detect?

Indirect detection

Direct detection



Very weak interaction.
Very difficult to detect!

Indirect detection through jets of particles or composite particles



Decays in other particles

Indirect detection through jets of particles or composite particles

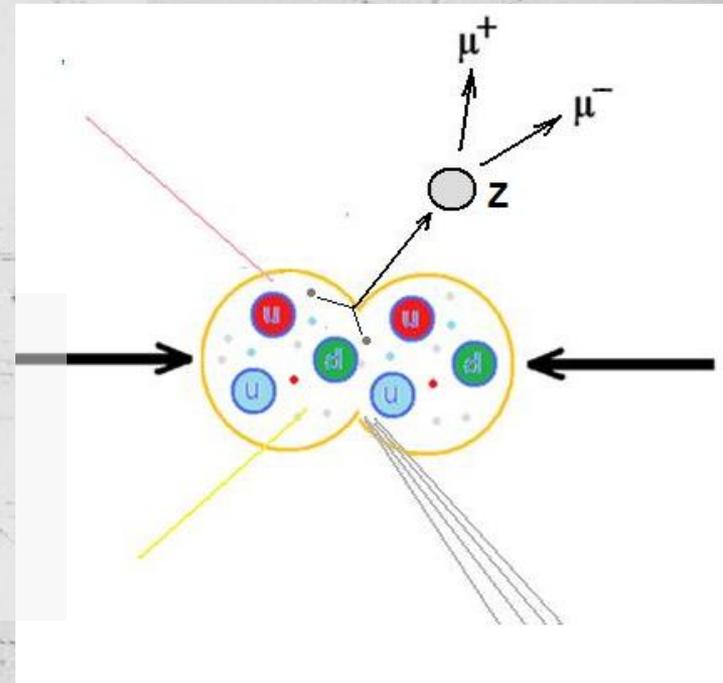
How do we detect them?

+ the photon!

Production and decay of particles

We're **looking** for the **Z** boson, a particle **without electric charge** that decays quickly in a **muon-antimuon pair** or in an **electron-positron pair***

What do we know of the total electric charge of the pairs?
What is the electric charge of the Z?



**The Z boson has other decays... but we are not interested in those.*

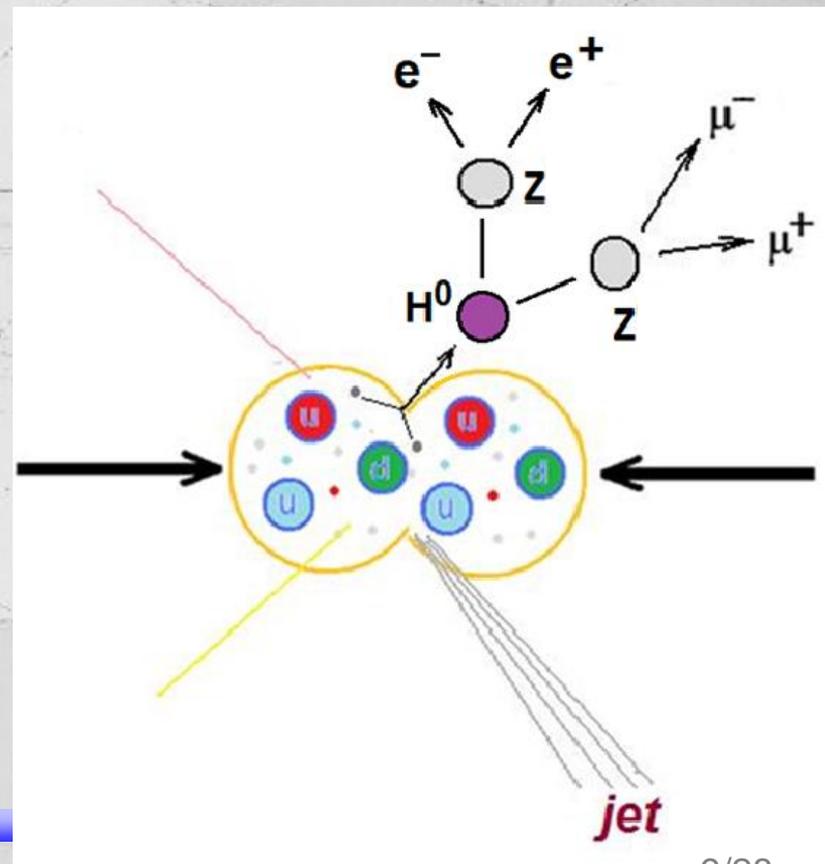
Production and decay of particles

The long sought **Higgs boson (H)** was discovered in the ATLAS and CMS experiments at the LHC/CERN in 2012.

We can have Higgs boson candidate events in the decays:

- $H \Rightarrow ZZ^* \Rightarrow 4 \text{ leptons}^*$
- $H \Rightarrow \gamma\gamma$ (2 photons)

$(^*)e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, \mu^+\mu^-\mu^+\mu^-$



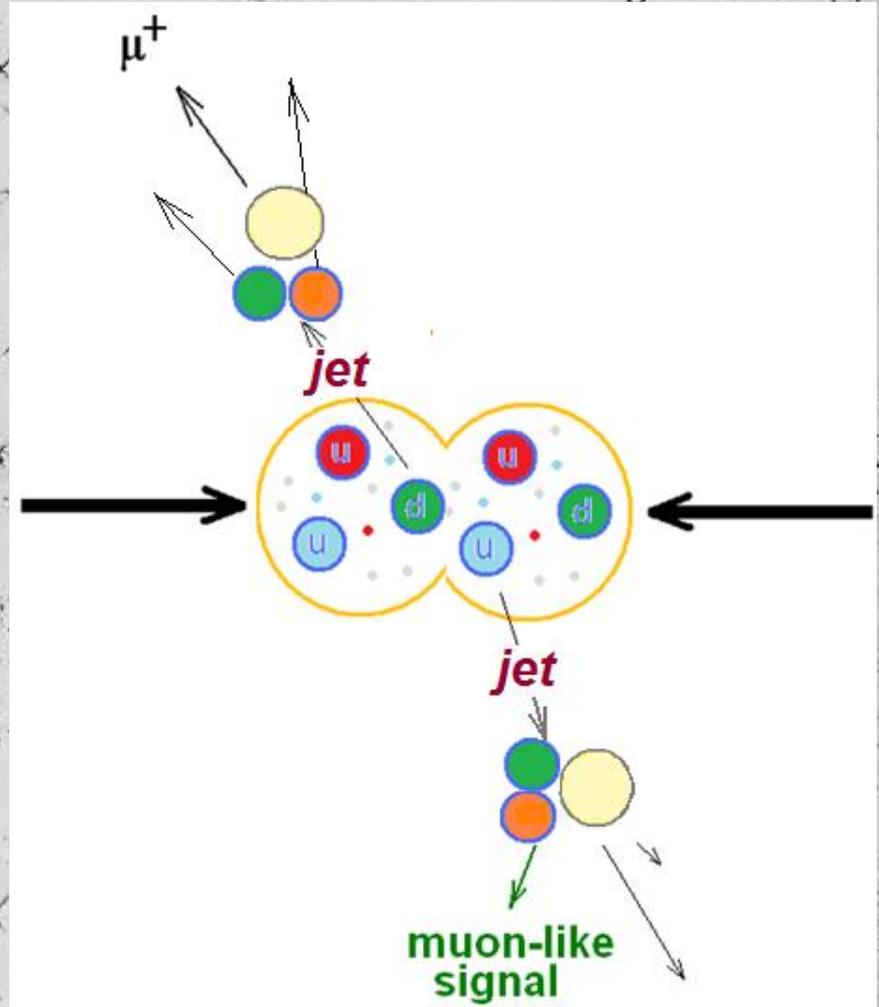
Background events

Often, quarks are scattered in collisions.

These quarks originate jets of particles.

Low energy electrons and muons can be produced in the jets.

They are NOT what we are looking for!

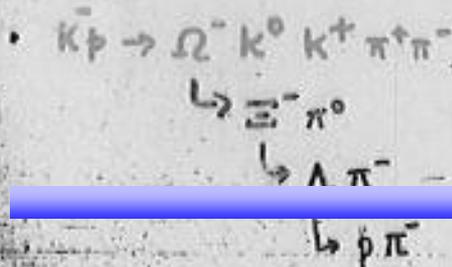
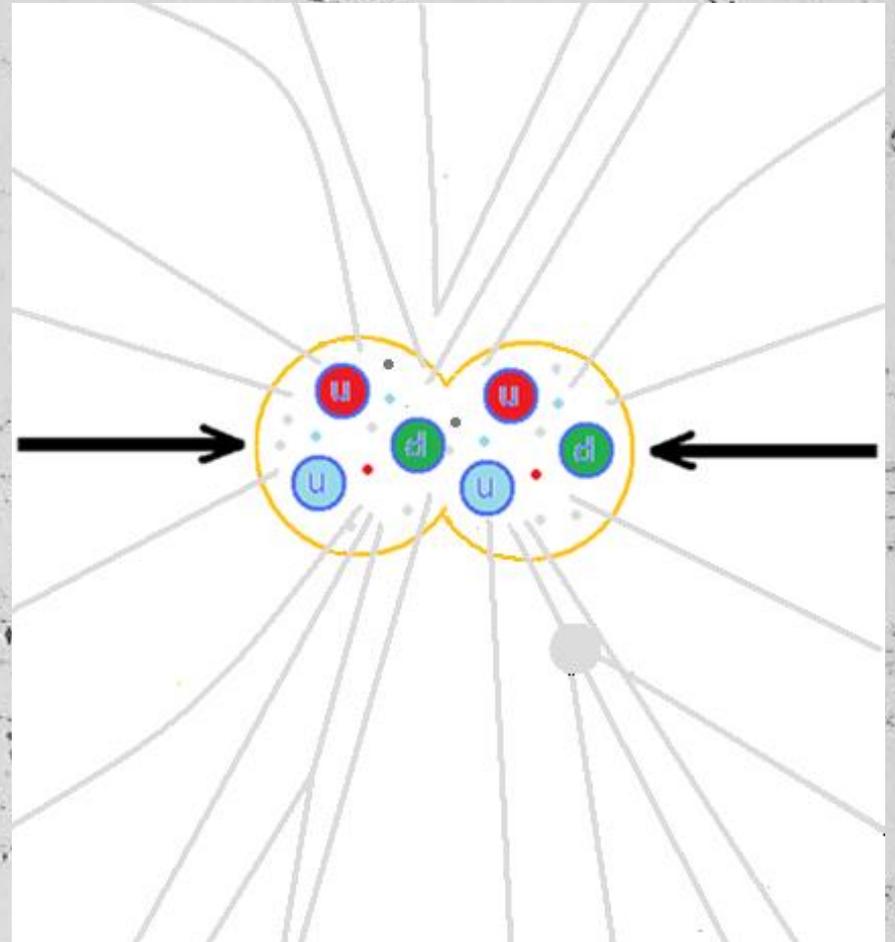


$K^+ p \rightarrow \Omega^- K^0 K^+ \pi^+ \pi^-$
 $\hookrightarrow \Xi^- \pi^0$
 $\hookrightarrow \Lambda \pi^-$
 $\hookrightarrow p \pi^-$

Particle decays

A “di-muon” or “di-electron” **may be** the decay of the particle in which we are interested.

It may be difficult to tag the tracks we want, if we don't eliminate the tracks due to particles with low transverse momentum.



Invariant mass – our discovery tool!

If we select only tracks with transverse momentum higher than 10 GeV, we get a picture more clean.

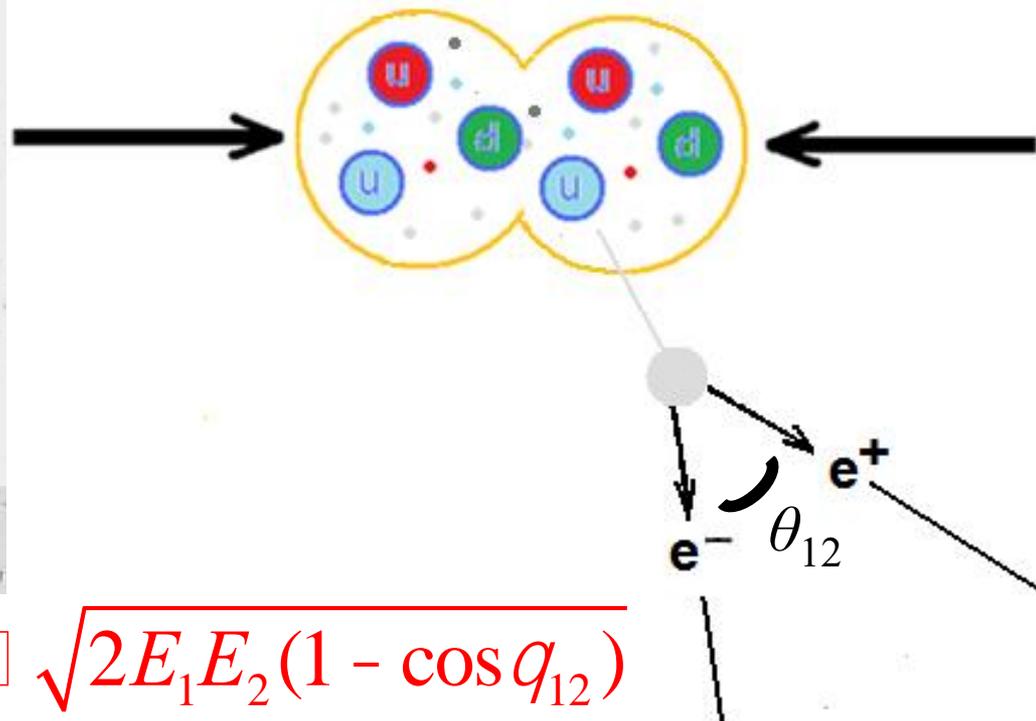
Today we shall select several candidate events

$Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$
and use the information from the [invariant] **mass**, $m[c^2]$ to know if we discovered the Z boson or other particles.

$$E = mc^2 \implies E^2 = m^2c^4 + c^2p^2$$

$$E = E_1 + E_2 \quad p = |\vec{p}| = |\vec{p}_1 + \vec{p}_2|$$

$$m = \sqrt{(E_1 + E_2)^2 - c^2(\vec{p}_1 + \vec{p}_2)^2} / c^2$$

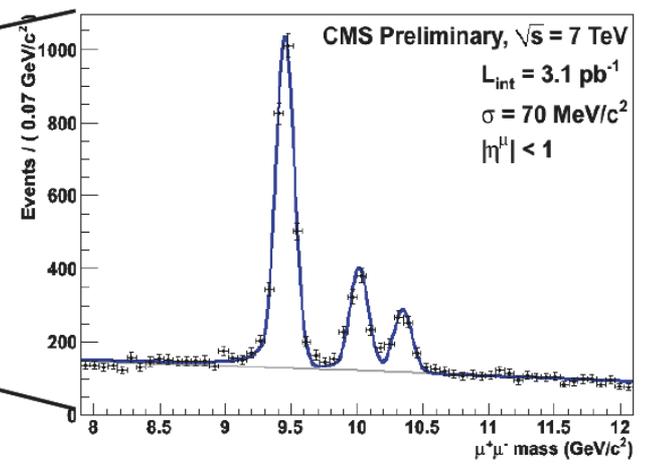
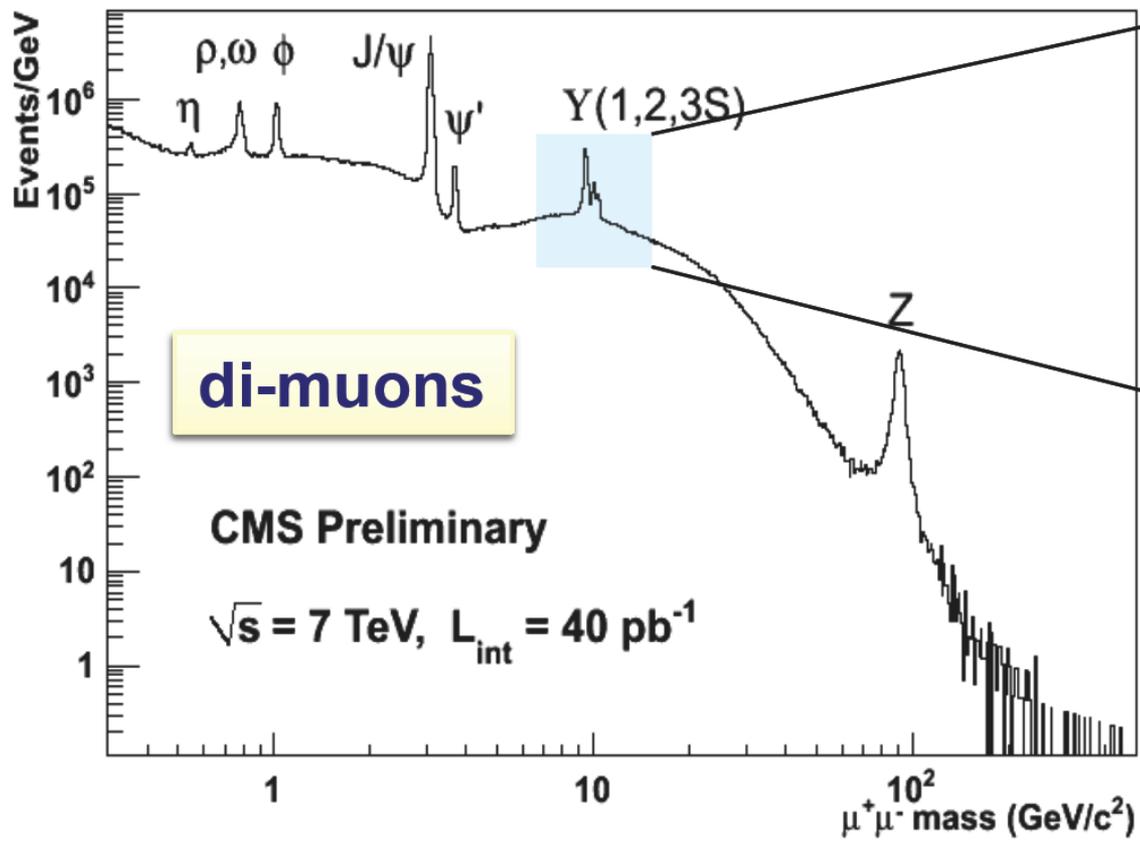


$$mc^2 \simeq \sqrt{2E_1E_2(1 - \cos\theta_{12})}$$

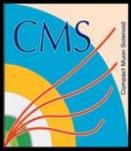
Di-muons mass spectrum

- Events with a muon-antimuon
- Search for X particles that decay into two *muons*;
- ...and build a distribution of:

$$m(X) = \frac{\sqrt{2E_1E_2(1 - \cos \theta_{12})}}{c^2}$$



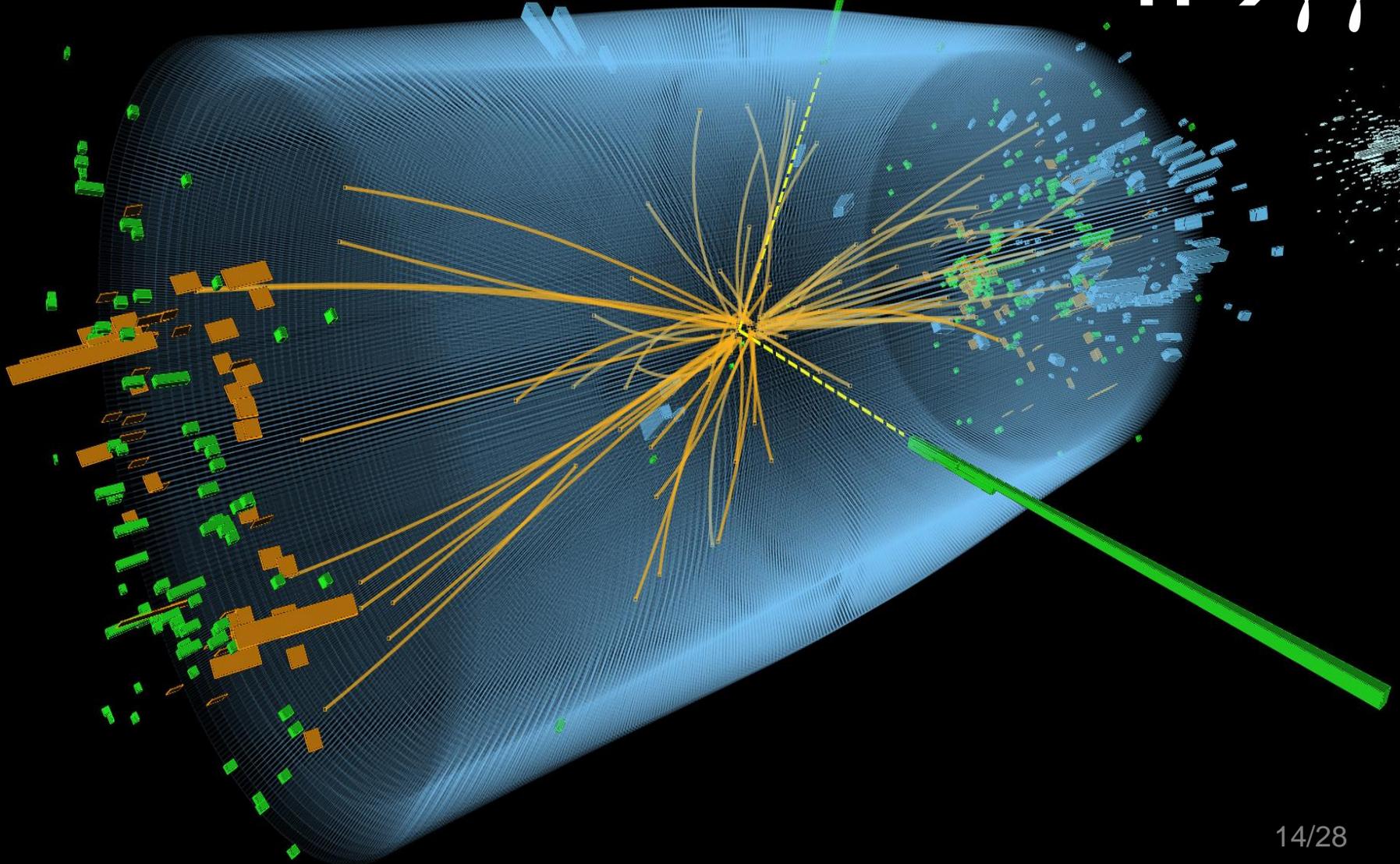
Mass spectrum:
number of events as
a function of mass



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

Higgs to 2 photons

$H \rightarrow \gamma\gamma$



H $\rightarrow\gamma\gamma$ results:

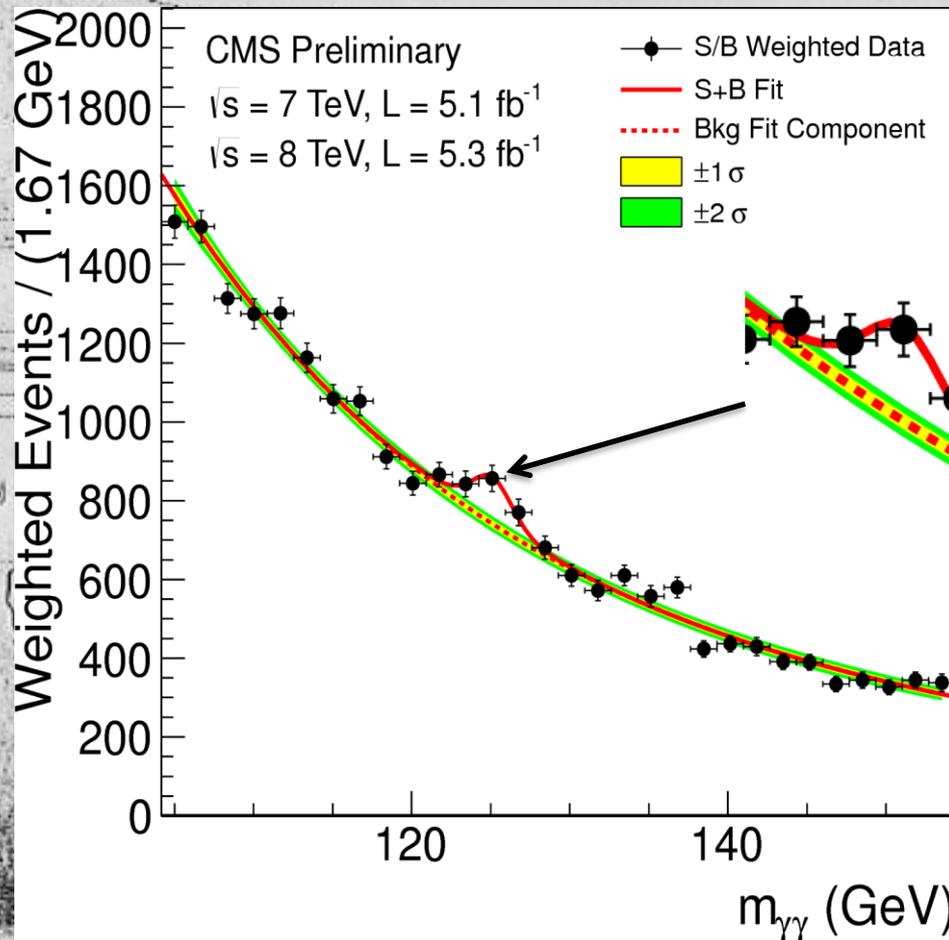


The invariant mass distribution of a photon pair, $m(\gamma\gamma)$

Sum of distributions from event classes, weighted by Signal/Noise ratio

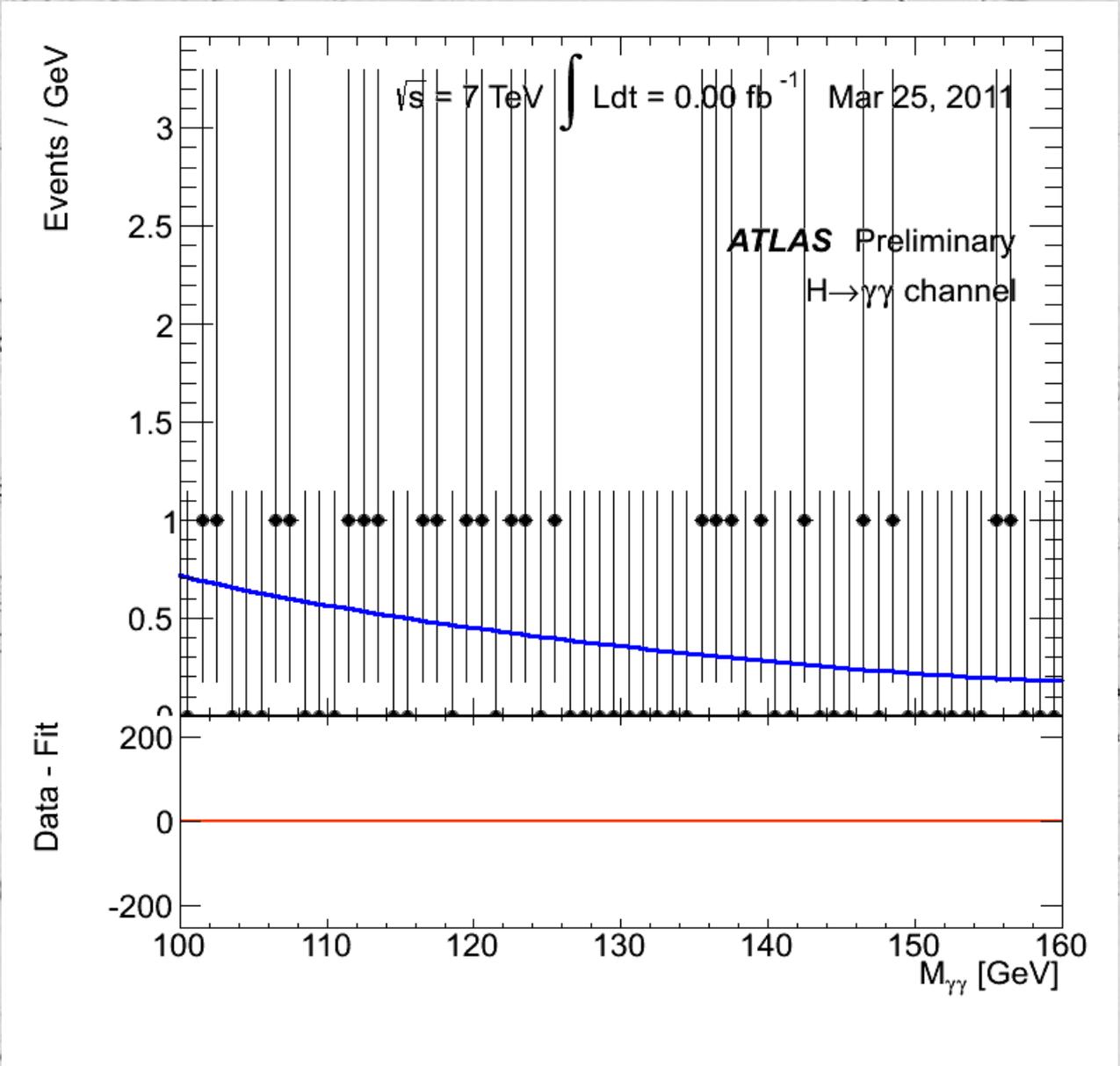
In the $\gamma\gamma$ invariant mass distribution, an excess of events over background, for masses ~ 125 GeV/ c^2 , is seen.

The observation of the final state in two photons implies that the **new particle is a boson**, not a fermion, and that **cannot be a “spin 1” particle.**



There is no other fundamental particle with such characteristics!

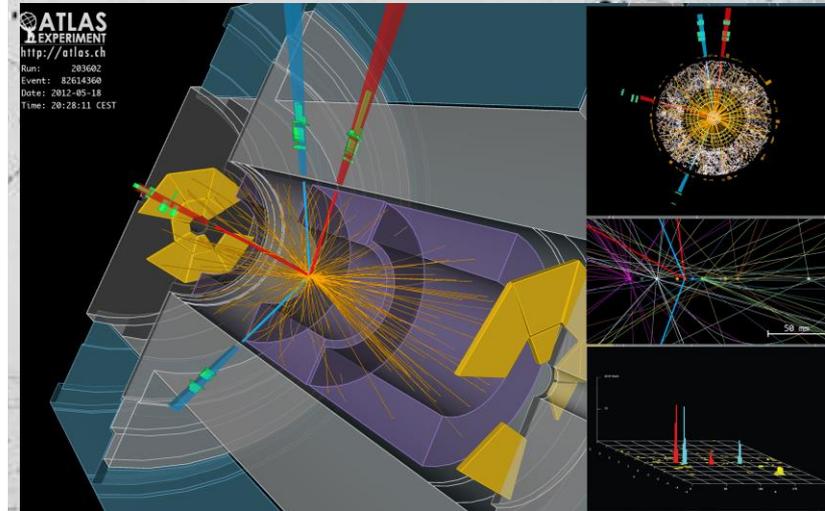
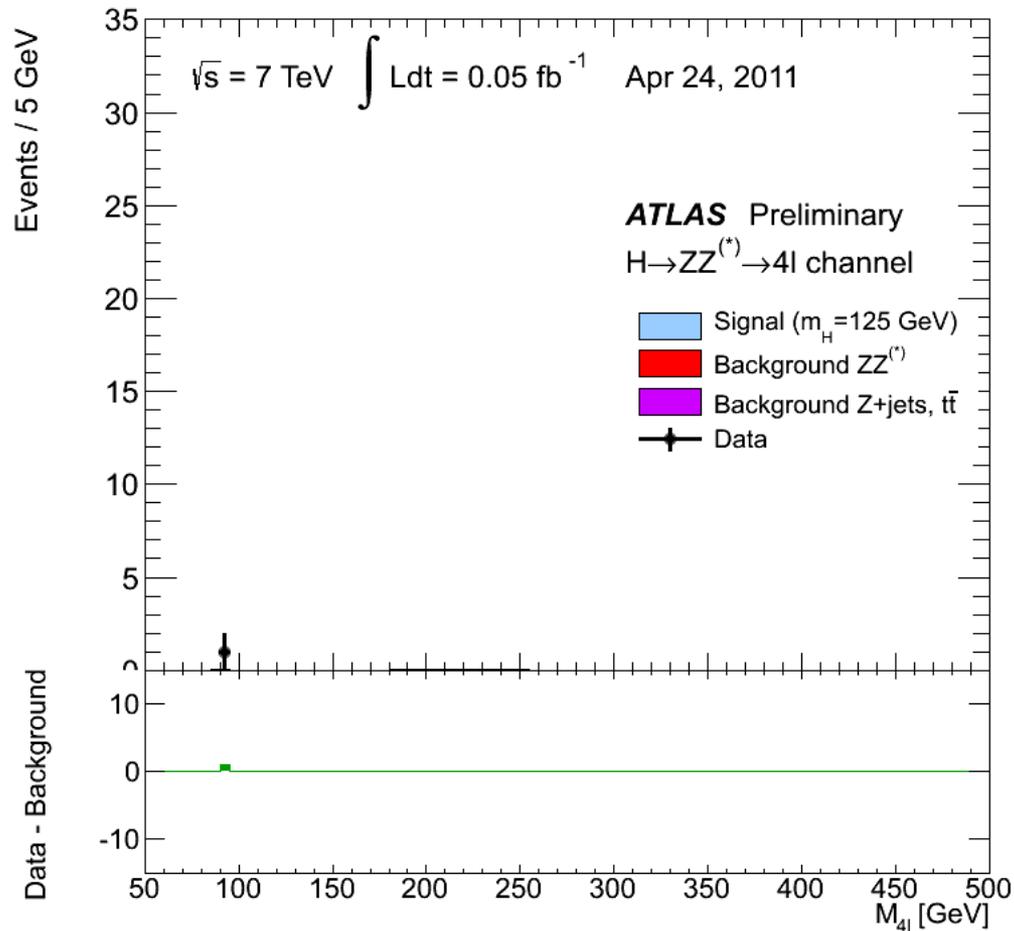
ATLAS: Distribution of the di-photon mass, $m(\gamma\gamma)$



H decaying into ZZ*



4 leptons mass distribution, m(4l)



Mass distribution for the 4 leptons

(two electron-positron pairs, or two muon pairs, or an electron-positron pair and a muon-antimuon pair).

HYPATIA – ATLAS Events Visualizer

=> cuts: $P_t > 10.0$ GeV

The screenshot displays the HYPATIA software interface with several windows:

- Hybrid pupils' analysis tool for interactions in ATLAS - version 6.0 - Invariant Mass Window:** A table showing event parameters.
- Canvas Window:** A 2D plot of the ATLAS detector cross-section with tracks overlaid. A 3D histogram is visible in the bottom right corner.
- HYPATIA - Track Momenta Window:** A table of reconstructed tracks with their kinematic properties.
- HYPATIA - Control Window:** A panel for setting analysis cuts, with the $|P_t|$ cut set to 5.0 GeV.

File Name	ETMis [GeV]	Track	P [GeV]	+/-	Pt [GeV]	ϕ	η	M(2) [GeV]	M(4) [GeV]	e/ μ
00036_JiveXML_166964_987982.xml	19.626	Tracks 3	112.6	+	49.4	1.441	-1.464	95.325		μ
		Tracks 69	96.8	-	45.9	-1.720	-1.378			μ

Track	+/-	P [GeV]	Pt [GeV]	ϕ	θ
Tracks 3	+	112.57	49.42	1.441	2.687
Tracks 69	-	96.83	45.88	-1.720	2.648
Tracks 127	-	37.93	30.81	1.803	0.948
Tracks 128	+	25.73	12.70	0.303	2.625
Tracks 134	+	121.30	89.22	-0.597	2.315
Tracks 136	-	34.18	8.63	-3.123	0.255
Tracks 154	+	14.19	8.35	-2.346	2.513
Tracks 176	-	13.53	12.74	0.259	1.915

Projection	Data	Cuts	InDet	Calo	MuonDet	Objects	Geometry
InDet							
Calo							
MuonDet							
Objects							
ATLAS							

HYPATIA: $Z \Rightarrow e^+ e^-$ (*electrons*)

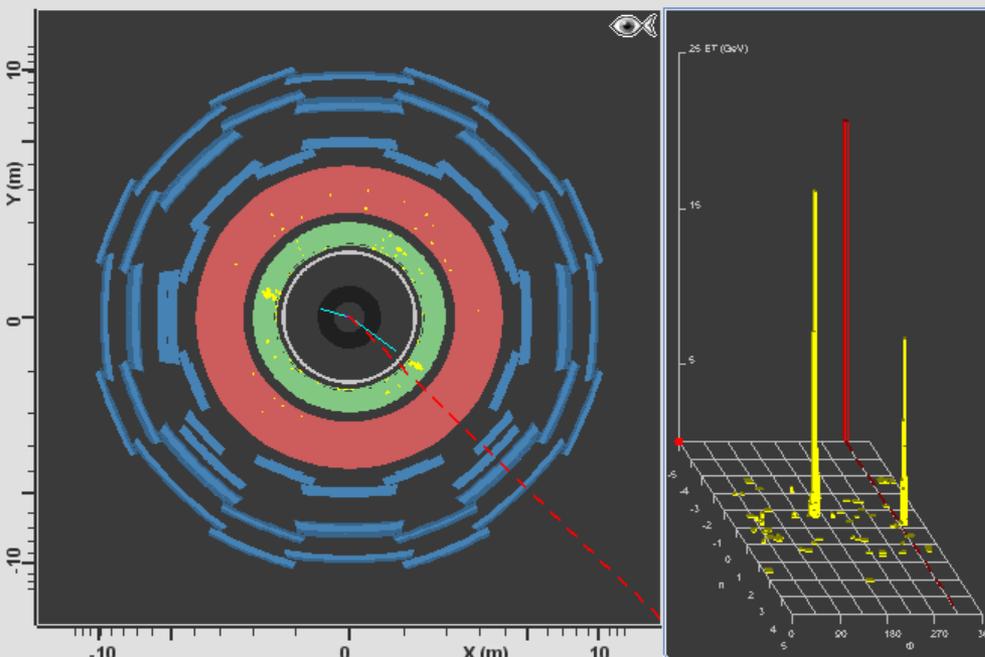
Hybrid pupils' analysis tool for interactions in ATLAS - version 7.2.1 - Invariant Mass Window

File View Histograms Preferences Help

File Name ETMis [GeV] Track P [GeV] +/- Pt [GeV] ϕ η M(2l) [GeV] M(4l) [GeV] e/j

Canvas Window - File: event008.xml Run: 180664 Event: 1605858

ATLAS 2011-05-01 19:11:06 CEST source:event008 run:180664 ev:1605858 HYPATIA



25 ET [GeV]

HYPATIA - Track Momenta Window

File Previous Event Next Event Insert Electron Insert Muon Delete Track Reset Canvas

ETMis: 20,600 GeV ϕ : -0,777 rad Collection: MET_RefFinal

F:\exercises\ATLAS\hypatia\events\dir01\groupK.zip\event008.xml

Reconstructed Tracks

Track	+/-	P [GeV]	Pt [GeV]	ϕ	θ
Tracks 2	-	37,04	36,60	-0,637	1,726
Tracks 12	+	63,58	52,84	2,877	2,161

HYPATIA - Control Window

Parameter Control Interaction and Window Control Output Display

Projection Data Cuts InDet Calo MuonDet Objects Geometry

Data

Name	Value
<input checked="" type="checkbox"/> Status	
<input checked="" type="checkbox"/> InDet	
<input checked="" type="checkbox"/> Calo	
<input checked="" type="checkbox"/> MuonDet	
<input checked="" type="checkbox"/> Objects	

$\Lambda \pi^-$
 $\hookrightarrow \rho \pi^-$

HYPATIA: $Z \Rightarrow \mu^+ \mu^-$ (*muons*)

Hybrid pupils' analysis tool for interactions in ATLAS - version 7.2.1 - Invariant Mass Window

File View Histograms Preferences Help

File Name ETMis [GeV] Track P [GeV] +/- Pt [GeV] ϕ η M(2l) [GeV] M(4l) [GeV] e/j

Canvas Window - File: event020.xml Run: 180400 Event: 58192244

ATLAS 2011-04-28 01:53:31 UTC source:event020 run:180400 ev:58192244 HYPATIA

HYPATIA - Track Momenta Window

File Previous Event Next Event Insert Electron Insert Muon Delete Track Reset Canvas

ETMis: 12,076 GeV ϕ : -2,803 rad Collection: MET_RefFinal

F:\exercices\ATLAS\hypatia\events\dir01\groupK\zip\event020.xml

Reconstructed Tracks

Track	+/-	P [GeV]	Pt [GeV]	ϕ	θ
Tracks 3	+	51,86	48,93	-2,194	1,908
Tracks 73	-	55,00	52,57	1,046	1,869

HYPATIA - Control Window

Parameter Control Interaction and Window Control Output Display

Projection Data Cuts InDet Calo MuonDet Objects Geometry

SiClusterRDO	Track	Zoom Next Track	
TRT DriftCircle	Segment	Name	Value
SimChargedTrack	SpacePoint	Track Collections	Tracks
SimVertex	PixelCluster	Color Function	Constant
RecVertex	SCT_Cluster	Constant Color	25
Hit Filter	Trig SiSpacePoint		
Drawing Order	PixelRDO		

$\Lambda \pi^-$
 $\hookrightarrow p \pi^-$

HYPATIA: $Z \Rightarrow \mu^+ \mu^-$ (*muons*)

Hybrid pupils' analysis tool for interactions in ATLAS - version 7.2.1 - Invariant Mass Window

File View Histograms Preferences Help

File Name ETMis [GeV] Track P [GeV] +/- Pt [GeV] ϕ η M(2I) [GeV] M(4I) [GeV] e/j

Canvas Window - File: event020.xml Run: 180400 Event: 58192244

ATLAS 2011-04-28 01:53:31 UTC source:event020 run:180400 ev:58192244 HYPATIA

3 ET (GeV)

Y (m)

X (m)

ϕ

HYPATIA - Track Momenta Window

File Previous Event Next Event Insert Electron Insert Muon Delete Track Reset Canvas

ETMis: 12,076 GeV ϕ : -2,803 rad Collect Insert selected muon track

F:\exercices\ATLAS\hypatia\events\dir01\groupK\zip\event020.xml

Reconstructed Tracks

Track	+/-	P [GeV]	Pt [GeV]	ϕ	θ
Tracks 3	+	51,86	48,93	-2,194	1,908
Tracks 73	-	55,00	52,57	1,046	1,869

HYPATIA - Control Window

Parameter Control Interaction and Window Control Output Display

Projection Data Cuts InDet Calo MuonDet Objects Geometry

SiClusterRDO Track
 TRT DriftCircle Segment
 SimChargedTrack SpacePoint
 SimVertex PixelCluster
 RecVertex SCT_Cluster
 Hit Filter Trig SiSpacePoint
 Drawing Order PixelRDO

Zoom Next Track

Name	Value
Track Collections	Tracks
Color Function	Constant
Constant Color	25

$\Lambda \pi^-$
 $\rightarrow \rho \pi^-$

HYPATIA: $H \Rightarrow \gamma \gamma$ [$\gamma \gamma$] (*photons*)

HYbrid Pupils' Analysis Tool for Interactions in ATLAS - version 7.4 - Invariant Mass Window

File View Histograms Preferences Help

File Name	ETMis [GeV]	Track	P [GeV]	+/-	Pt [GeV]	ϕ	η	M(2) [GeV]	M(eeee) [GeV]	M(eemm) [GeV]	M(mmmm) [GeV]	e/m/g
-----------	-------------	-------	---------	-----	----------	--------	--------	------------	---------------	---------------	---------------	-------

HYPATIA - Track Momenta Window

File Previous Event Next Event Electron Muon Photon Delete Track Reset Canvas

ETMis: 18.247 GeV ϕ : -1.337 rad Collection: MET_RefFinal

each/Masterclasses/hypatia2015_Z_Dados/dir08/groupj.zip/event006.xml

Tracks	Physics Objects			
Track	P [GeV]	Pt [GeV]	ϕ	θ
Object 0	44.60	44.57	1.640	1.609
Object 1	111.89	44.71	-1.936	2.731

HYPATIA - Control Window

Parameter Control Interaction and Window Control Output Display

Projection Data Cuts InDet Calo MuonDet Objects Geometry

InDet	Name	Value
Calo	<input checked="" type="checkbox"/> Pt	> 10.0 GeV
MuonDet	<input type="checkbox"/> Pt2	< 700.0 MeV
Objects	<input checked="" type="checkbox"/> d0	< 2.5 mm
ATLAS	<input checked="" type="checkbox"/> z0	< 20.0 cm
	<input type="checkbox"/> d0 Loose	< 2.0 cm
	<input type="checkbox"/> z0-zVtx	< 2.5 mm

$\hookrightarrow p \pi^-$

HYPATIA: $Z \Rightarrow$ jets (*background*)

Hybrid pupils' analysis tool for interactions in ATLAS - version 7.2.1 - Invariant Mass Window

File View Histograms Preferences Help

File Name ETMis [GeV] Track P [GeV] +/- Pt [GeV] ϕ η M(2) [GeV] M(4) [GeV] e/j

Canvas Window - File: event018.xml Run: 179725 Event: 11852865

ATLAS 2011-04-15 16:56:41 CEST source:event018 run:179725 ev:11852865 HYPATIA

HYPATIA - Track Momenta Window

File Previous Event Next Event Insert Electron Insert Muon Delete Track Reset Canvas

ETMis: 37,280 GeV ϕ : -1,982 rad Collection: MET_RefFinal

F:\exercises\ATLAS\hypatia\events\dir01\groupK\zip\event018.xml

Reconstructed Tracks

Track	+/-	P [GeV]	Pt [GeV]	ϕ	θ
Tracks 27	+	34,29	25,82	-2,551	0,852
Tracks 34	-	39,83	26,40	-2,525	0,725
Tracks 42	+	12,11	10,16	0,519	0,996
Tracks 48	-	12,34	10,14	0,491	2,176
Tracks 118	+	21,75	13,92	-2,494	0,694
Tracks 150	-	20,44	16,31	0,428	2,218
Tracks 161	+	21,30	15,32	0,888	2,339

HYPATIA - Control Window

Parameter Control Interaction and Window Control Output Display

Projection Data Cuts InDet Calo MuonDet Objects Geometry

Data

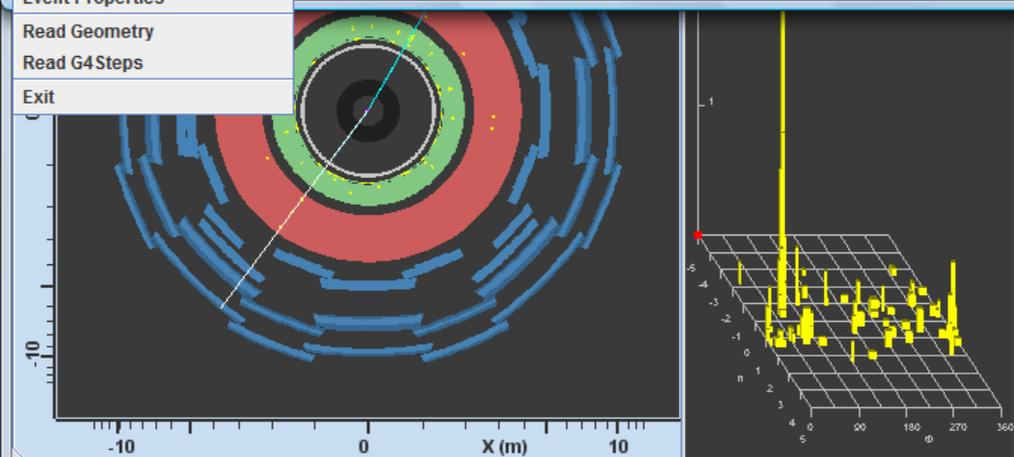
Name	Value
<input checked="" type="checkbox"/> Status	
<input checked="" type="checkbox"/> InDet	
<input checked="" type="checkbox"/> Calo	
<input checked="" type="checkbox"/> MuonDet	
<input checked="" type="checkbox"/> Objects	

$\hookrightarrow p, \pi$

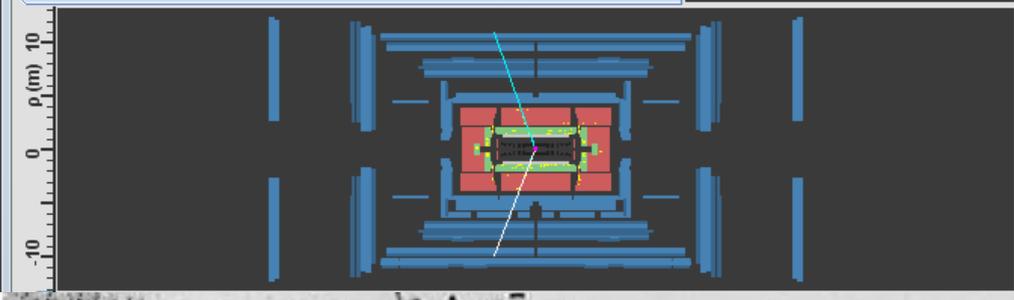
HYPATIA: Save the data!!!

Hybrid pupils' analysis tool for interactions in ATLAS - version 7.2.1 - Invariant Mass Window

	ETMis [GeV]	Track	P [GeV]	+/-	Pt [GeV]	ϕ	η	M(2I) [GeV]	M(4I) [GeV]	e/ μ
Read Event Locally	12,703	Tracks 3	51,9	+	48,9	-2,194	-0,344	101,333		μ
Read Event From URL (live)		Tracks 73	55,0	-	52,6	1,046	-0,303			μ
Clear Hypatia Project	10,522	Tracks 1	42,3	+	42,1	2,683	0,094	83,908		e
Load Hypatia Project		Tracks 6	41,8	-	40,9	-0,515	-0,213			e
Save Hypatia Project	17,210	Tracks 2	174,4	+	43,0	-2,826	2,079	87,252		μ
Export Invariant Masses (MII)	3,793	Tracks 3	208,3	-	44,0	0,326	2,236			μ
Loop over events		Tracks 17	37,9	+	37,8	1,872	-0,071			e
Save Image of Canvas	9,760	Tracks 0	435,8	+	69,4	-0,811	2,524	95,702		μ
Animated Event	13,491	Tracks 1	83,8	-	28,5	2,411	1,742			μ
Event Properties		Tracks 8	100,3	-	49,0	1,841	1,344	87,607		e
Event Properties		Tracks 58	101,7	+	38,5	-1,410	1,626			e



Use the name:
Invariant_masses.txt
and choose **Desktop**
as destination folder



HYPATIA - Control Window

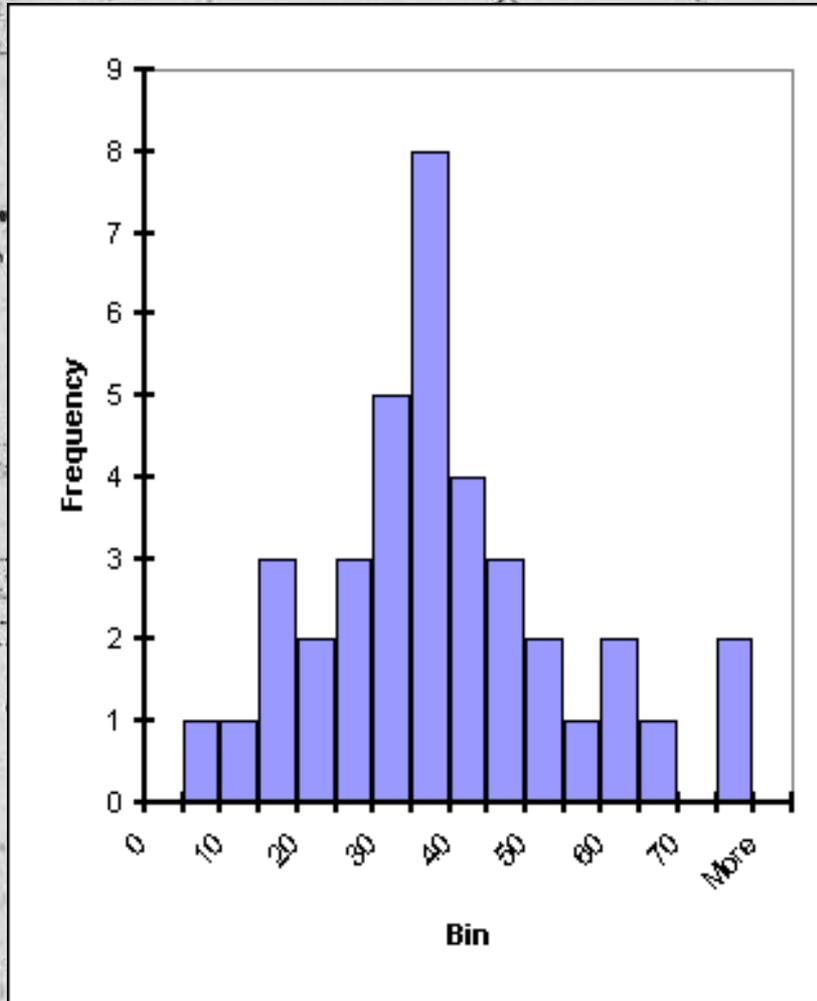
Parameter Control | Interaction and Window Control | Output Display

Projection | Data | Cuts | InDet | Calo | MuonDet | Objects | Geometry

SiClusterRDO	Track	Name	Value
TRT DriftCircle	Segment	Track Collections	Tracks
SimChargedTrack	SpacePoint	Color Function	Constant
SimVertex	PixelCluster	Constant Color	25
RecVertex	SCT_Cluster		
Hit Filter	Trig SiSpacePoint		
Drawing Order	PixelRDO		

UPLOAD para: <http://cernmasterclass.uio.no/OPIoT/>

Look to the plots!



Well defined peak?

Tails: low frequencies

Where are the peaks?

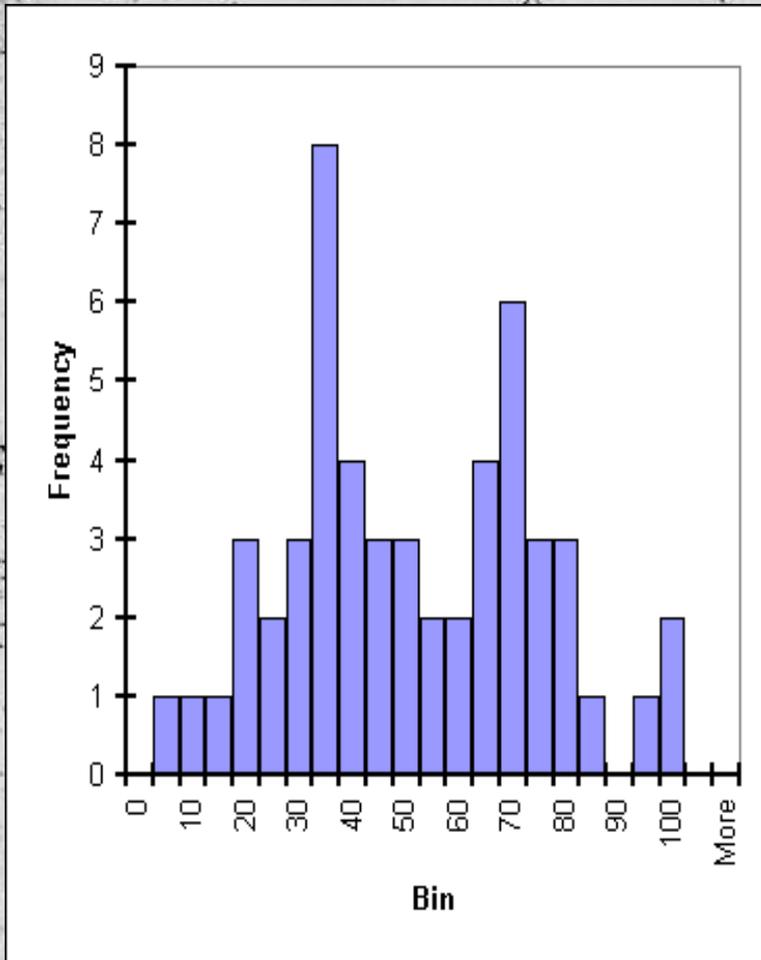
What particles do we identify?

Any peak in $m(4l)$ distribution?

Any peak in $m(\gamma\gamma)$ distribution?

$\Lambda \pi^-$
 $\rho \pi^-$

Look to the plots!



Two peaks?:

- Poor signal definition or
- Two different signals?

In Particle Physics, we could get:

- Two different particles
or
- Large background contribution with a little heap associated to the searched particle.

Let's go to work on the Z!

Teams of two.

Practice a little (for example, do a 1st pass over all data).

Talk to the scientists.

Find good Z candidate events.

What events will you include in your $M(X)$ plot?

What particles will you choose to make the Z mass?

Have you found any Higgs candidate event?

...and Make the Distribution!

Report! Laugh! Relax! Enjoy!

**Thank you for your
PATIENCE!**

$$\begin{aligned} \bullet \quad K^+ &\rightarrow \Omega^- K^0 K^+ \pi^+ \pi^- \\ &\hookrightarrow \Xi^- \pi^0 \\ &\hookrightarrow \Lambda \pi^- \\ &\hookrightarrow p \pi^- \end{aligned}$$