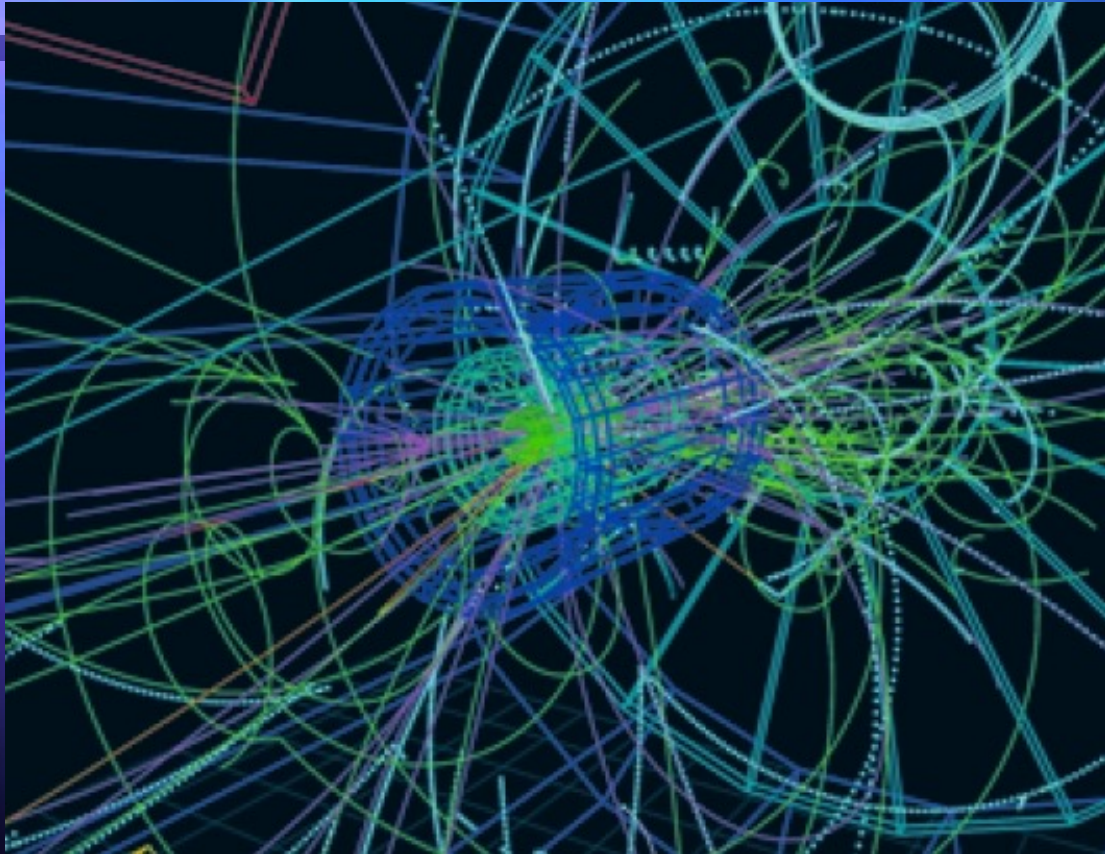


Counting Quarks



Prof. Nick Evans & Dr. Ken Mimasu
University of Southampton

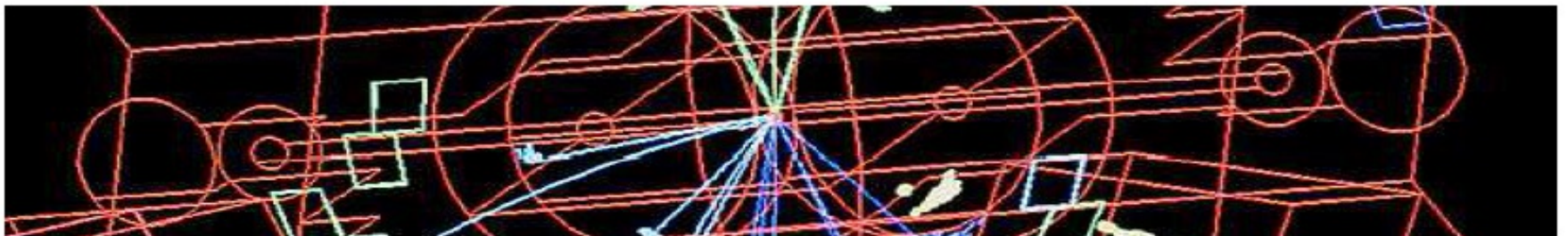
The Particle World



Our goal is to learn about the particles of nature using real data from accelerators

We will not explore the theory too much just what you see...

Nuclear matter (“hadrons”) is made of quarks – we are going to experimentally determine how many quarks there are...



How to vote using Vevox

You are going to have a go at identifying events from a particle collider

We will use the Vevox app so you can all vote on what type of event we are looking at

You should see a welcome page



<https://vevox.app/#/m/179861440>

A question to test Vevox

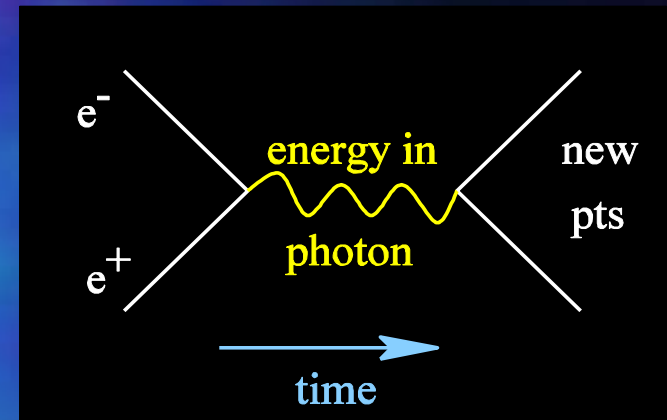
What did you drink with your breakfast this morning?

1. Tea
2. Coffee
3. Fruit Juice
4. Water
5. Other
6. Nothing

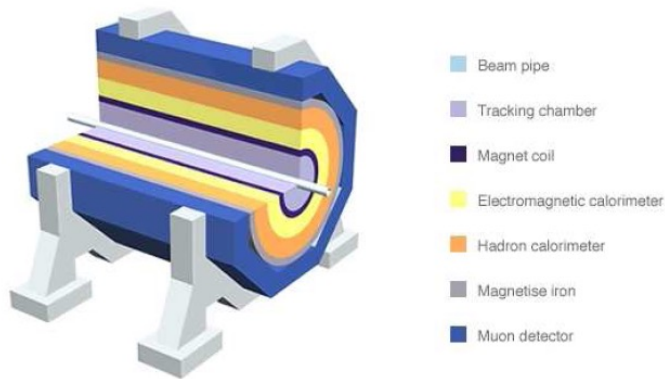
LEP: the Large Electron Positron Collider



27 km long tunnel,
100 m underground,
straddling
French-Swiss border,
just outside Geneva.

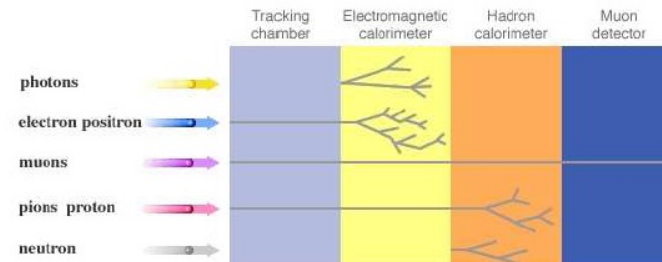


OPAL

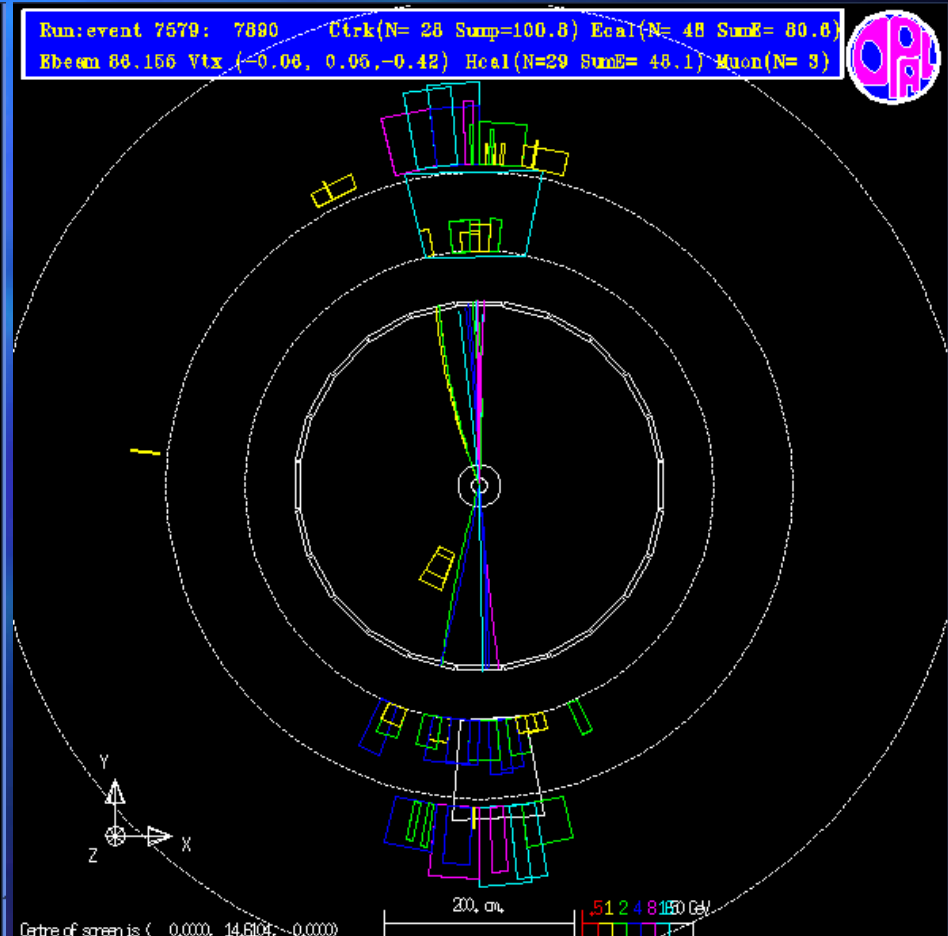
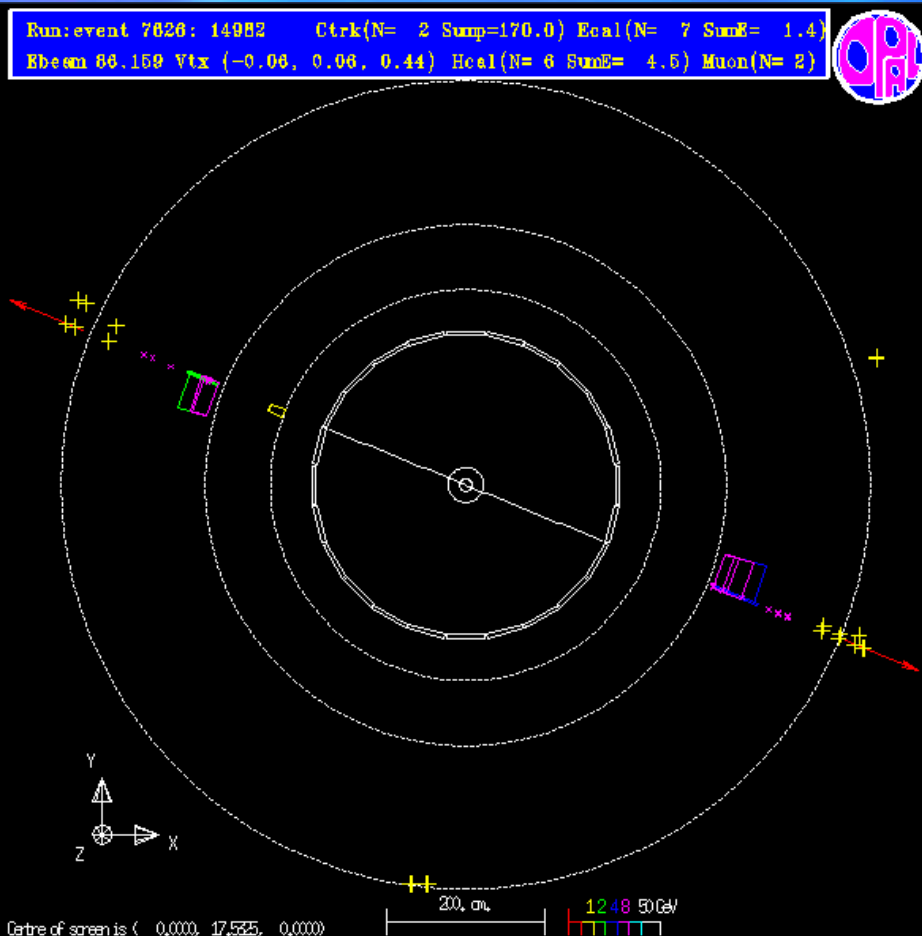
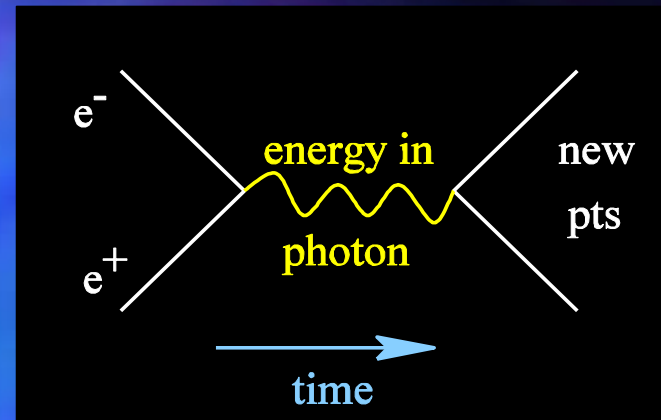


Detector Ingredients

- **Tracking chamber:** records the tracks of charged particles
- **Electromagnetic calorimeter or ecal:** measures energy of light particles (electrons, photons) as they interact with electrically charged particles inside matter
- **Hadron calorimeter:** measures energy of hadrons as they interact with atomic nuclei
- **Muon detectors:** muons get right through the calorimeters; outer muon detectors observe charged particles (rather like the tracking detectors)



Some Simple Events



Electrons

An e^+e^- event at LEP

Electrons are the lightest charged particle

They can't decay

They are stopped by the first layer of the detector: the electromagnetic calorimeter

Signature:

- Single tracks
- Only electromagnetic calorimeter hits



Muons (μ)

A $\mu^+\mu^-$ event at LEP

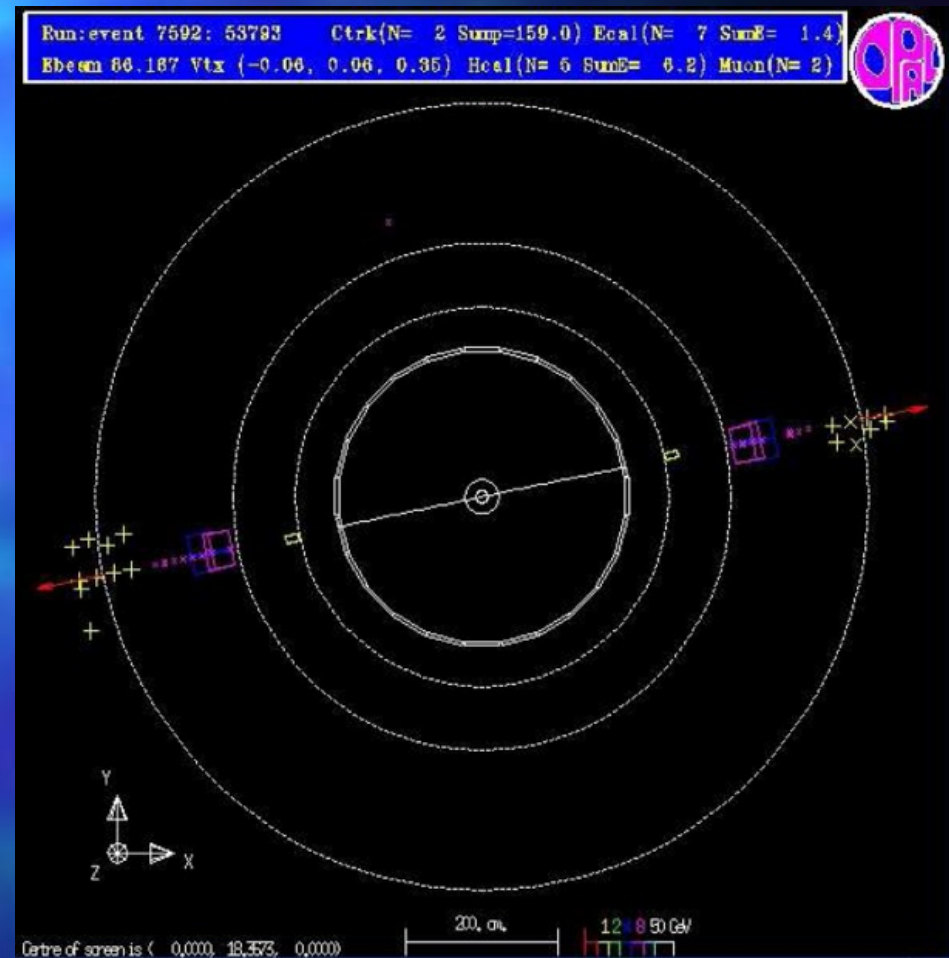
Muons are copies of the electron but 200 times heavier

They don't decay within the detector

They punch through all layers of the detector!

Signature:

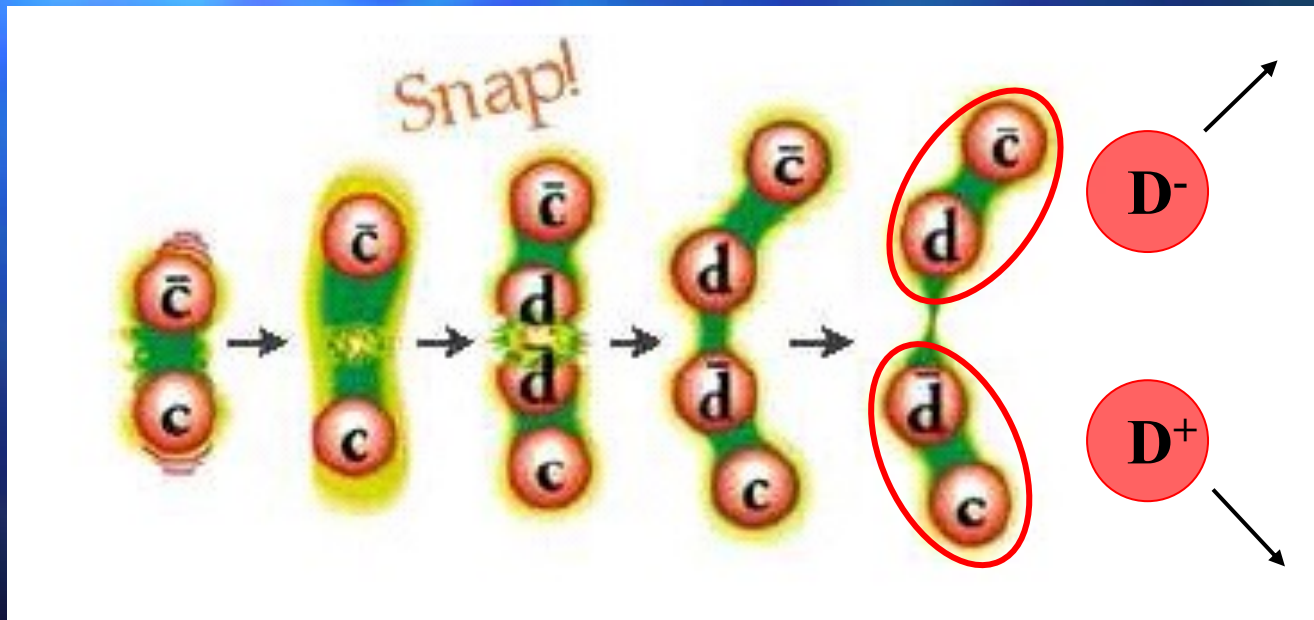
- Single tracks
- Hits in the electromagnetic, hadronic & muon calorimeters



Strong Nuclear Force

The force between quarks grows with distance !!!!!

Energy builds up between them until many quarks are produced that arrange themselves into strong force neutral hadrons – we see **jets**...



Quarks (jets)

A 2-jet event at LEP

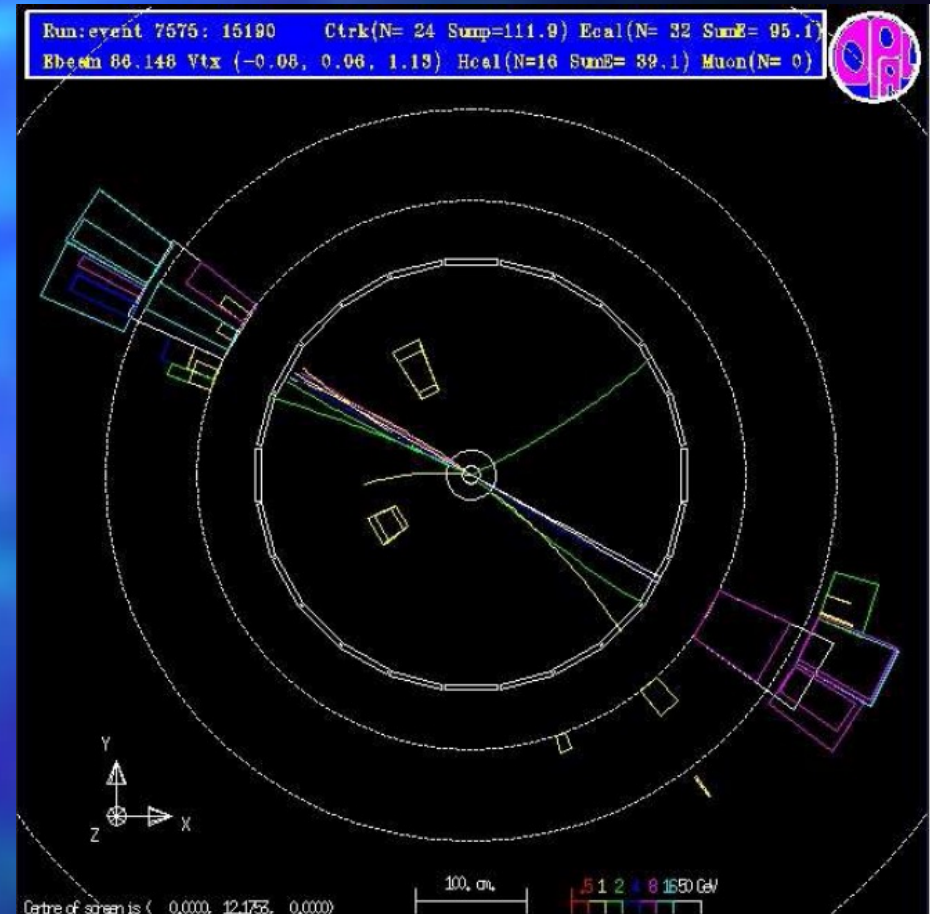
Because of the strong force, quarks cannot be observed.

Instead, they generate a shower of hadrons (jet)

Hadrons can be neutral or charged and are stopped by the hadronic calorimeter

Signature:

- Multiple tracks heading in a similar direction
- Many hits in the electromagnetic & hadronic calorimeters



Taus (τ)

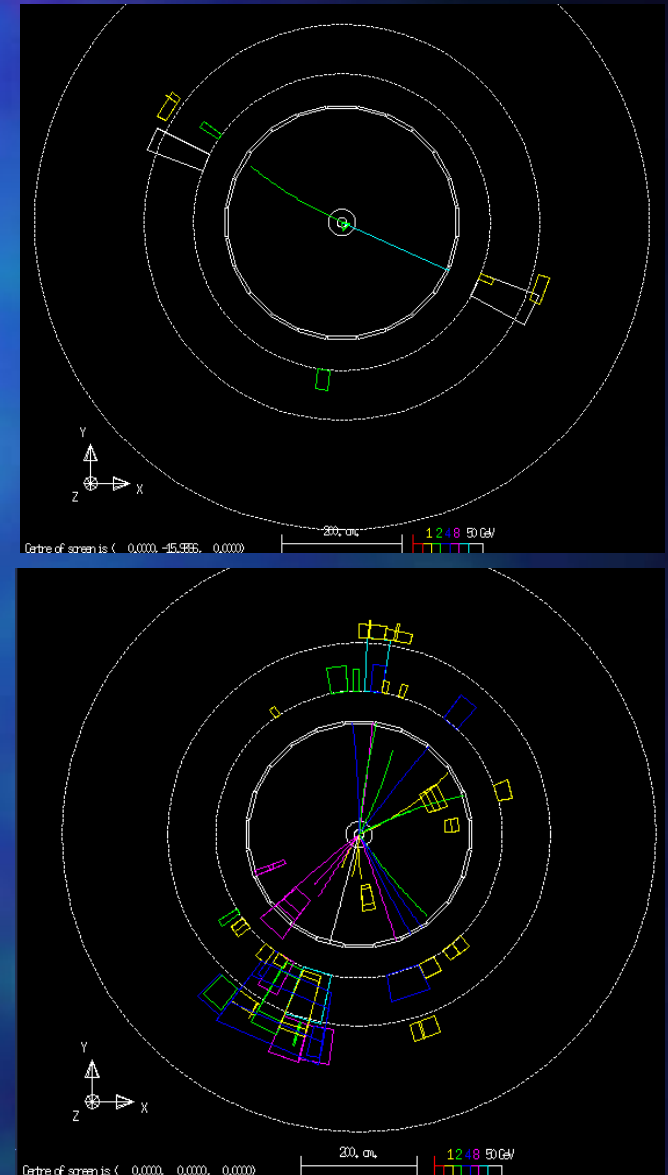
Taus are heavier electrons again
– 3500 times heavier...

They can decay to 1 or 3
hadrons and/or electrons/muons
in the detector.... Yuk!

Signature:

- Electron or muon (will correctly be identified as leptonic decay)
 - 1 or 3 jets (tracks + electromagnetic & hadronic calorimeter hits)
- Difficult to distinguish from jets!

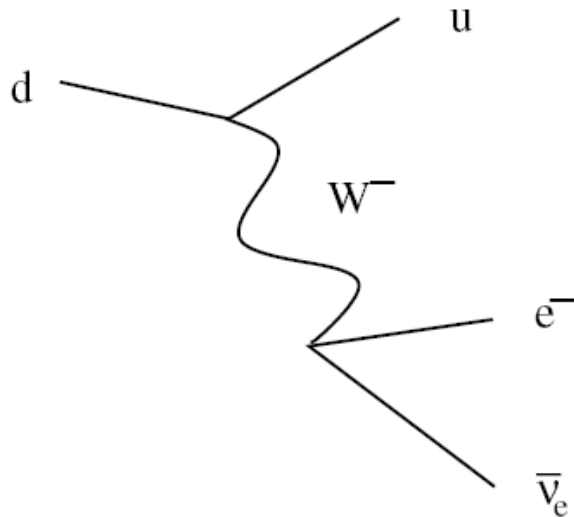
Two $\tau^+\tau^-$ events at LEP



The Weak Nuclear Force (Beta Decay)

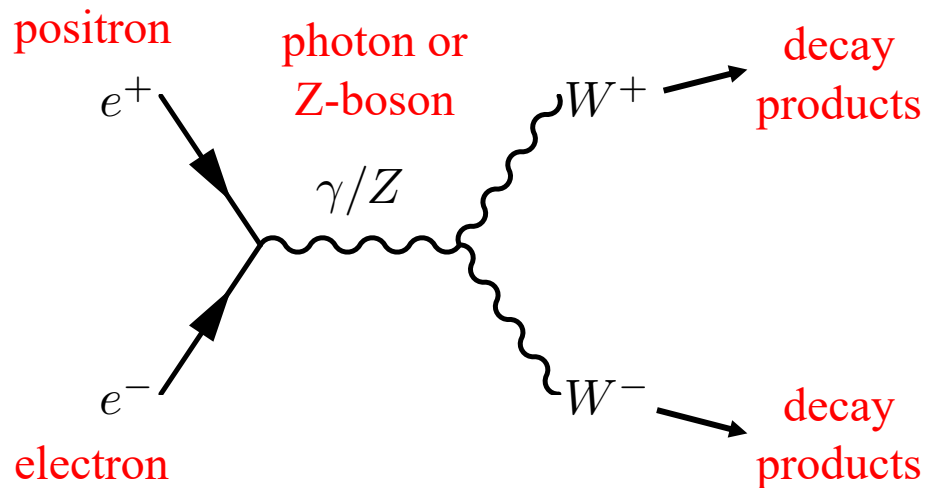
Weak decays, eg β -decay,
 $n \rightarrow p + e^- + \bar{\nu}_e$ is understood as decay of
a d quark, mediated by a W^- particle.

Neutrinos only interact by
the weak force – once
produced we never see them
again (thanks Pauli!)

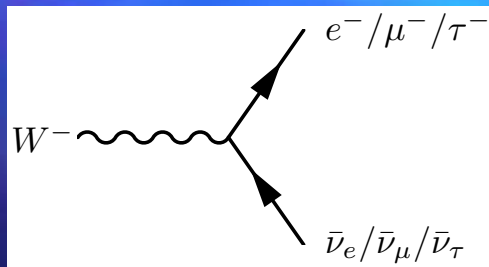


The likelihood that a W
will decay to quarks or
leptons is the same.. If we
produce W s and count the
relative probabilities of
outcomes we can count
how many quarks there
are...

WW Events at LEP

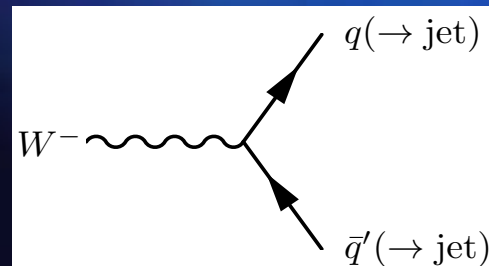


The decays are so fast you'll only see the final products in the detector...



Each W can decay to e, μ, τ plus a neutrino

LEPTONIC DECAY



Each W can decay to two quarks

HADRONIC DECAY

WW Events at LEP

W⁺W⁻ decay signatures		W⁺ decay	
		Hadronic (quarks)	Leptonic (e/ μ / τ)
W⁻ decay	Hadronic (quarks)	4 jets	2 jets + e, μ or τ
	Leptonic (e/ μ / τ)	2 jets + e, μ or τ	any 2 of e, μ or τ

“Double hadronic”

“Double leptonic”

“Semi-leptonic” or “Mixed”

Time to become a particle physicist!

Can you correctly identify different WW decay events?

Use data to count the number of types of quark decays

Cheatsheet provided to help you along the way:

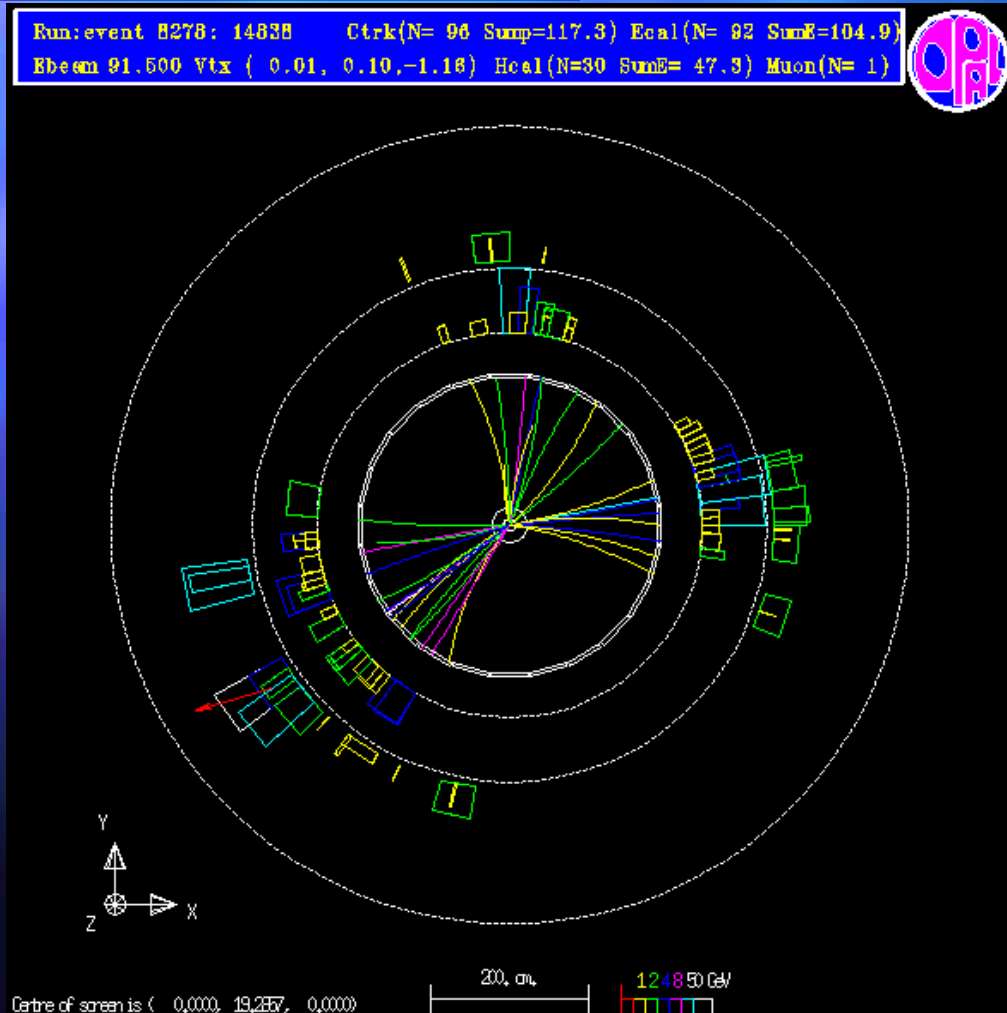
[Link to cheatsheet](#)

“Double hadronic” **“Double leptonic”**

“Semi-leptonic” or “Mixed”

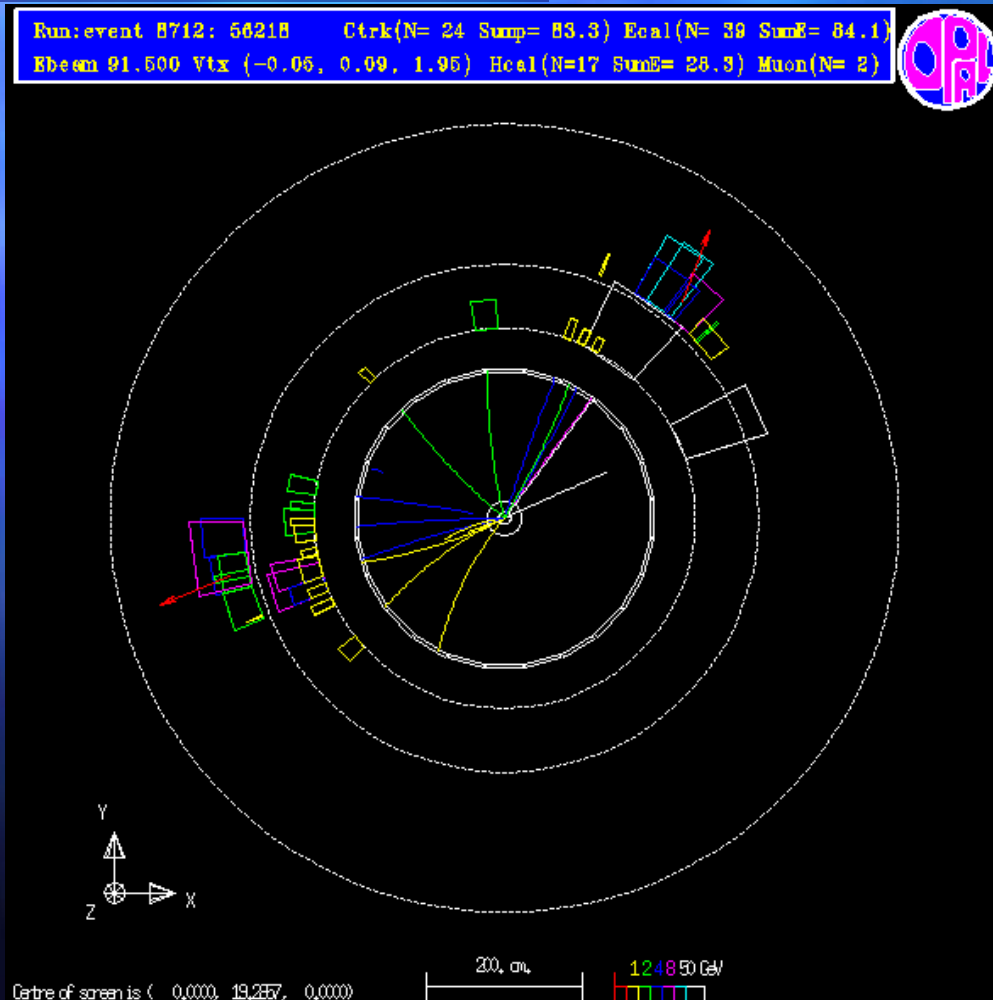
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



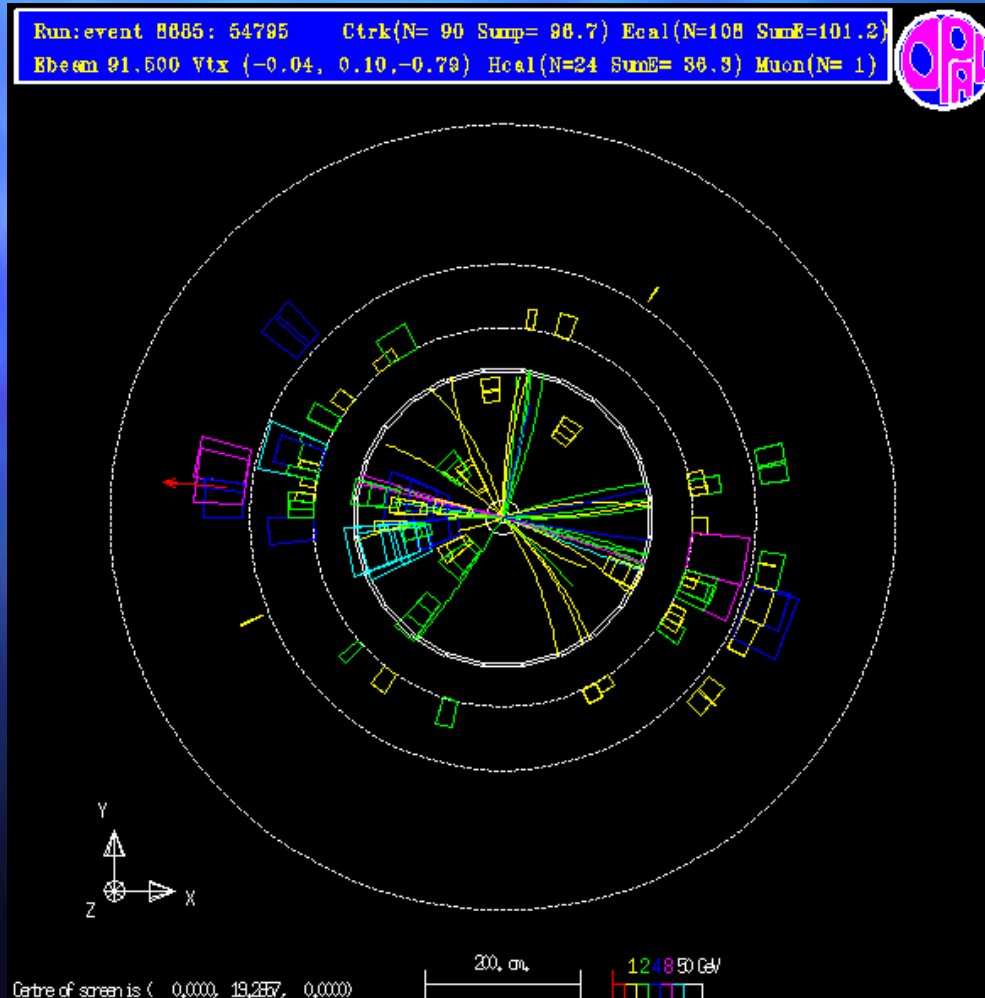
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

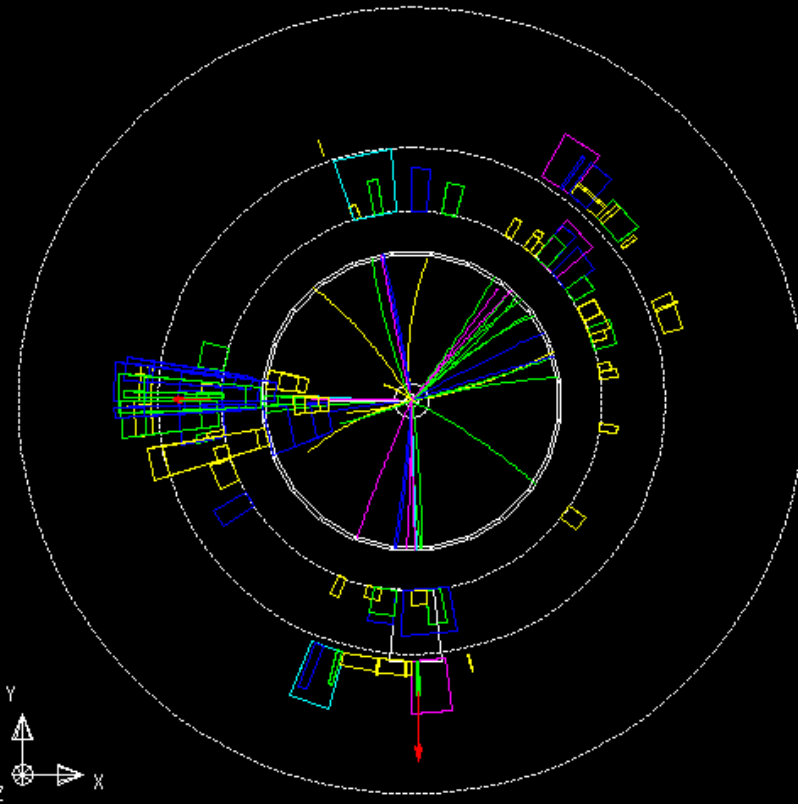
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

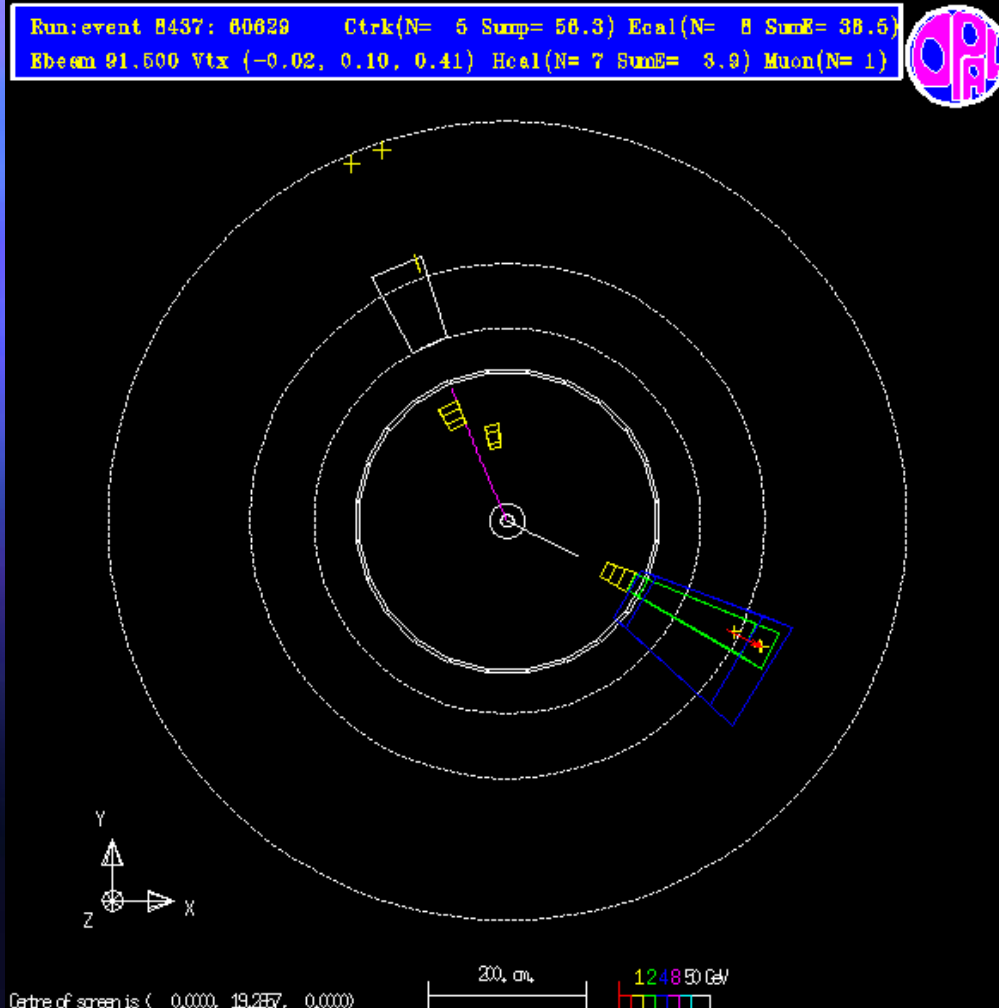
Run: event 8717: 9017 Ctrk(N= 78 SumP=121.3) Ecal(N= 80 SumE= 98.2)
Ebeam 91.500 Vtx (-0.06, 0.09, -1.17) Hcal(N=38 SumE= 30.8) Muon(N= 3)



Centre of screen is (0.000, 19.257, 0.000) 200 cm 124850 GeV

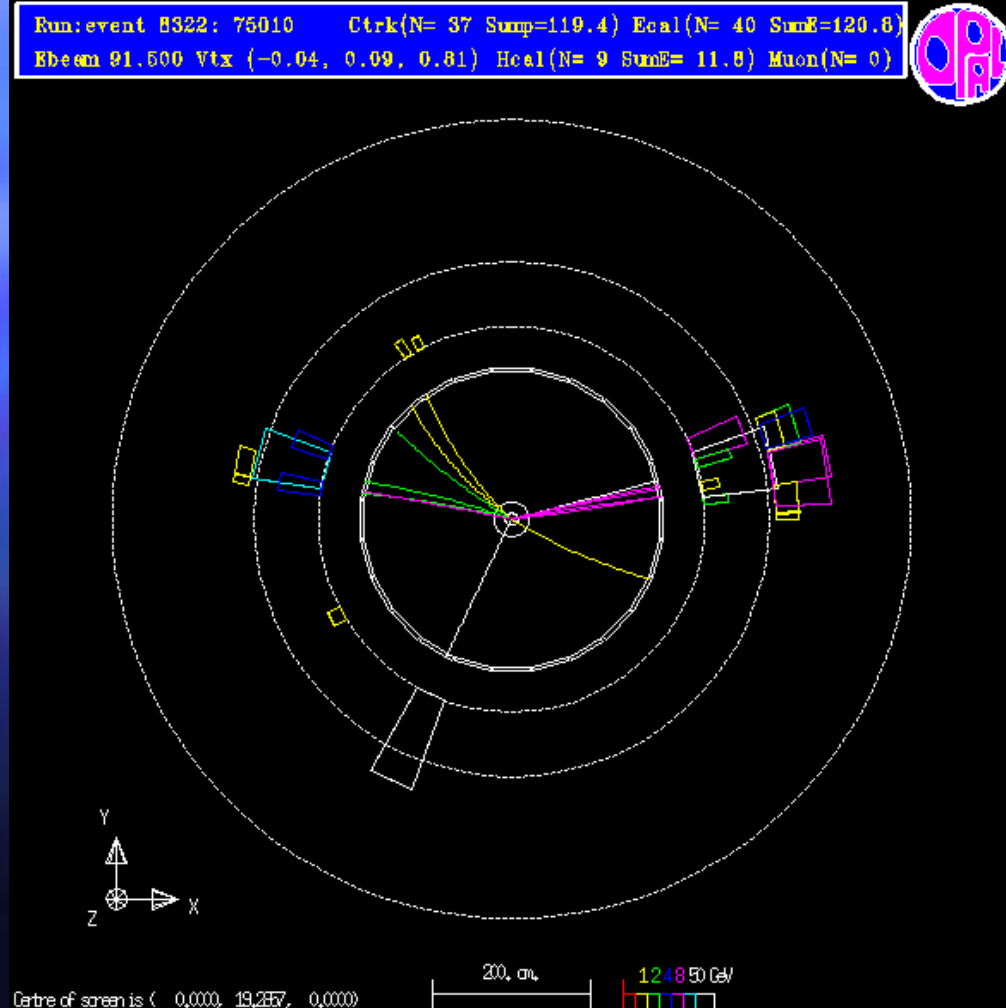
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



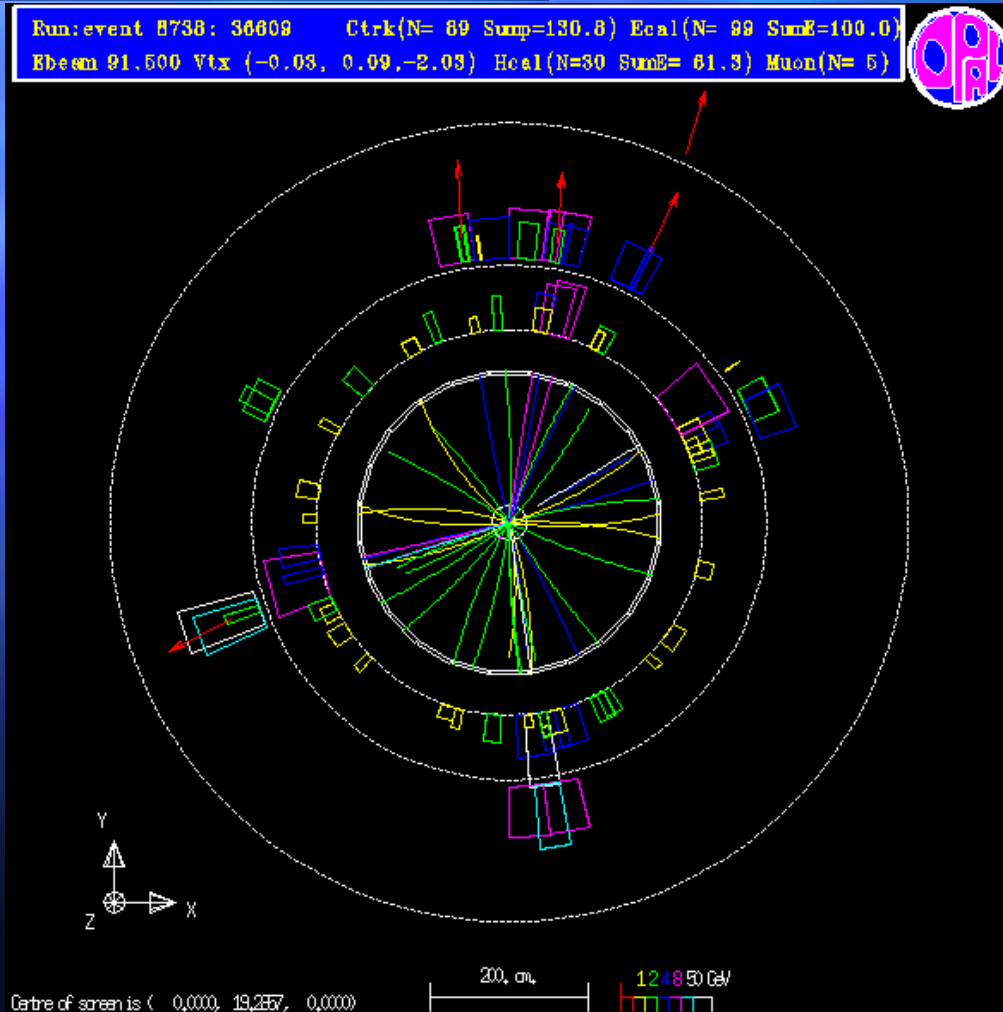
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



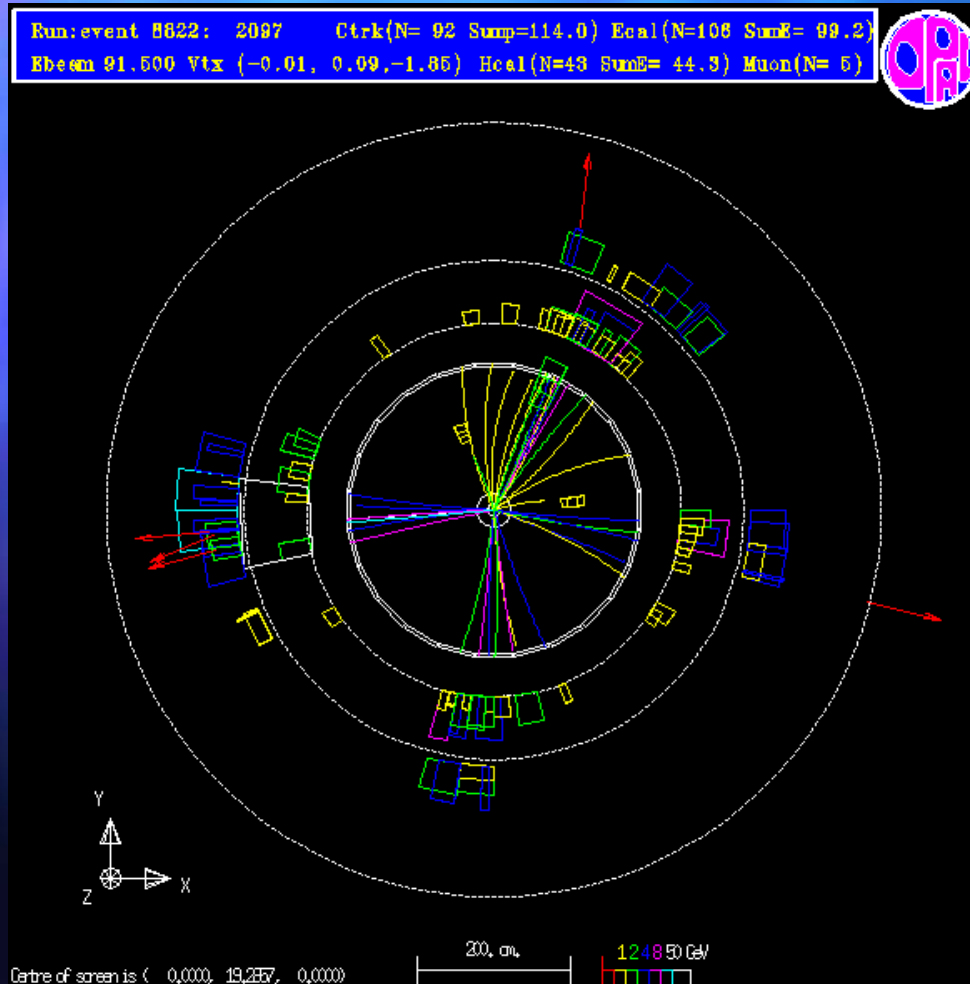
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

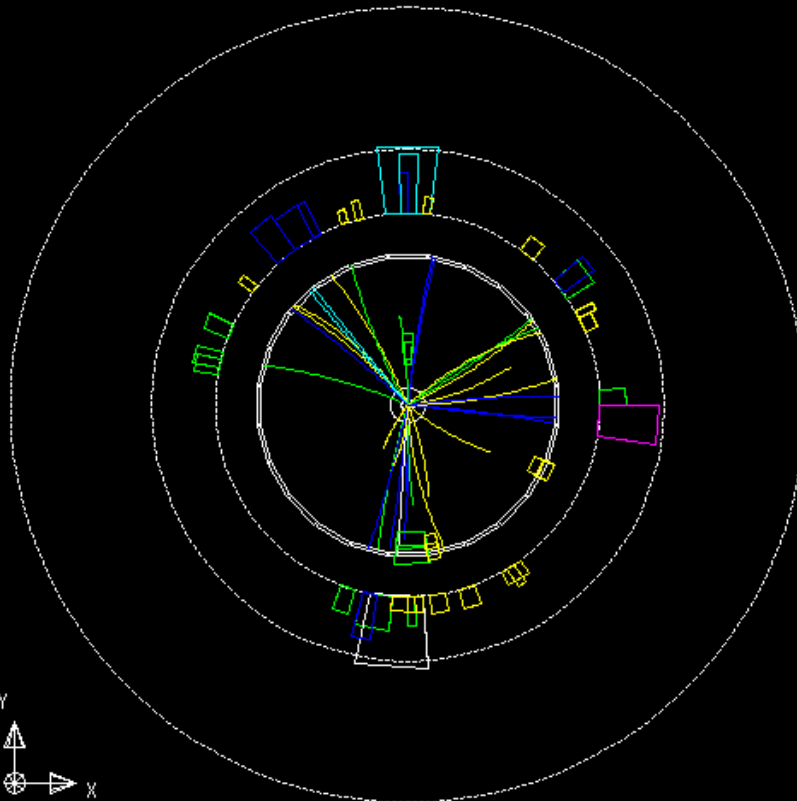
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

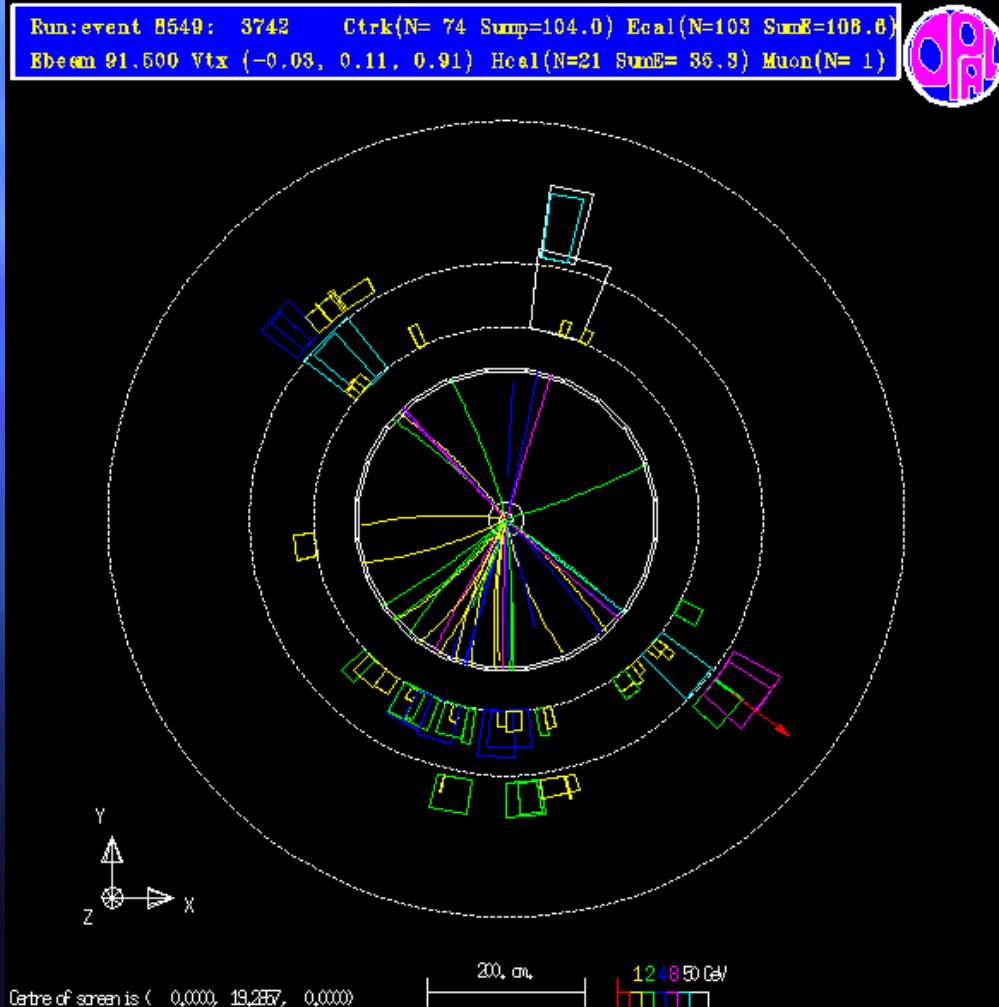
Run: event 8773: 23551 Ctrk(N= 57 Sump=112.6) Ecal(N= 88 SumE= 94.6)
Ebeam 91.000 Vtx (-0.03, 0.10, 0.45) Hcal(N= 0 SumE= 0.0) Muon(N= 0)

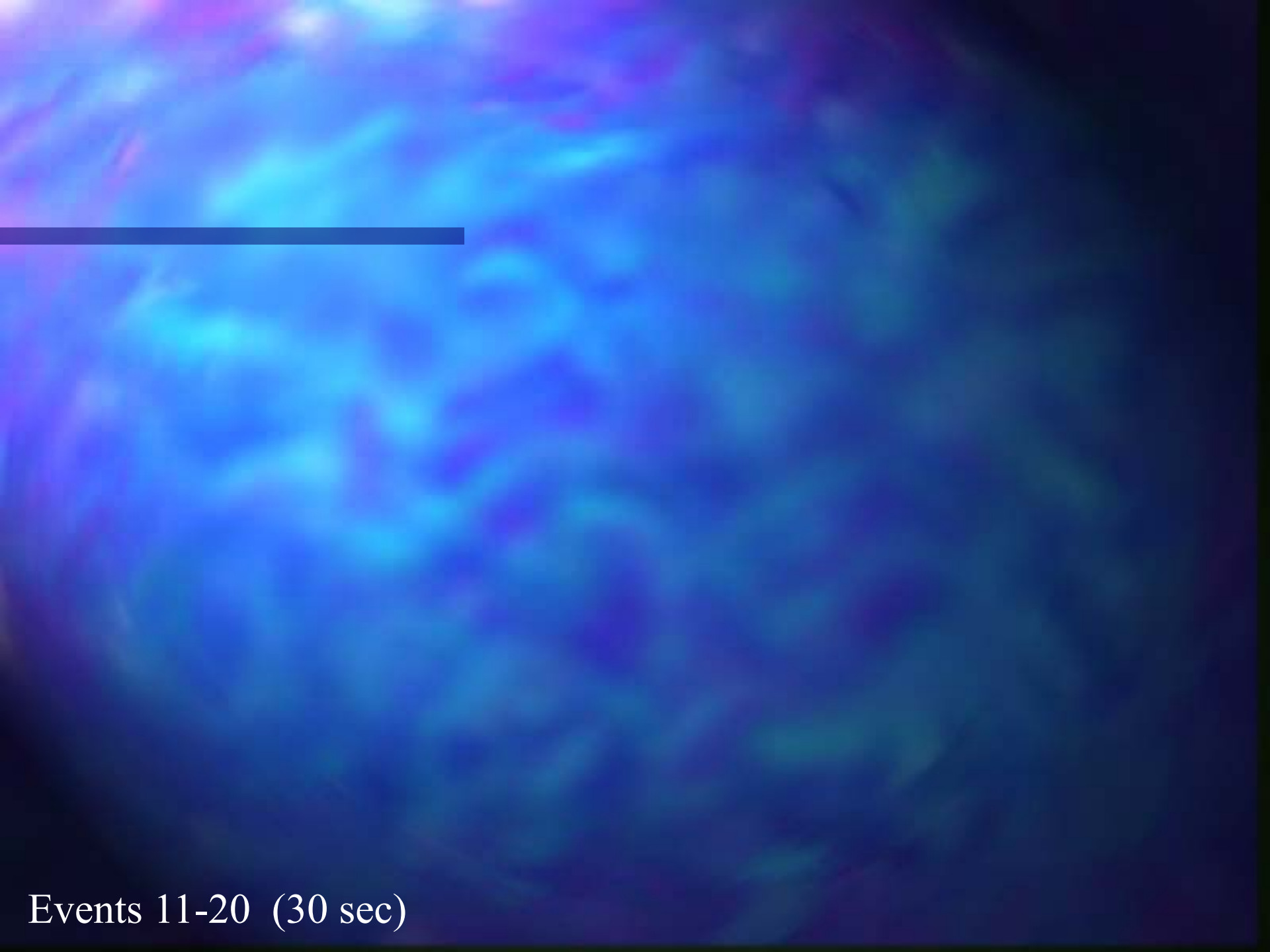


Centre of screen is (0.000, 19.2857, 0.000) 200. cm 124850 GeV

What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

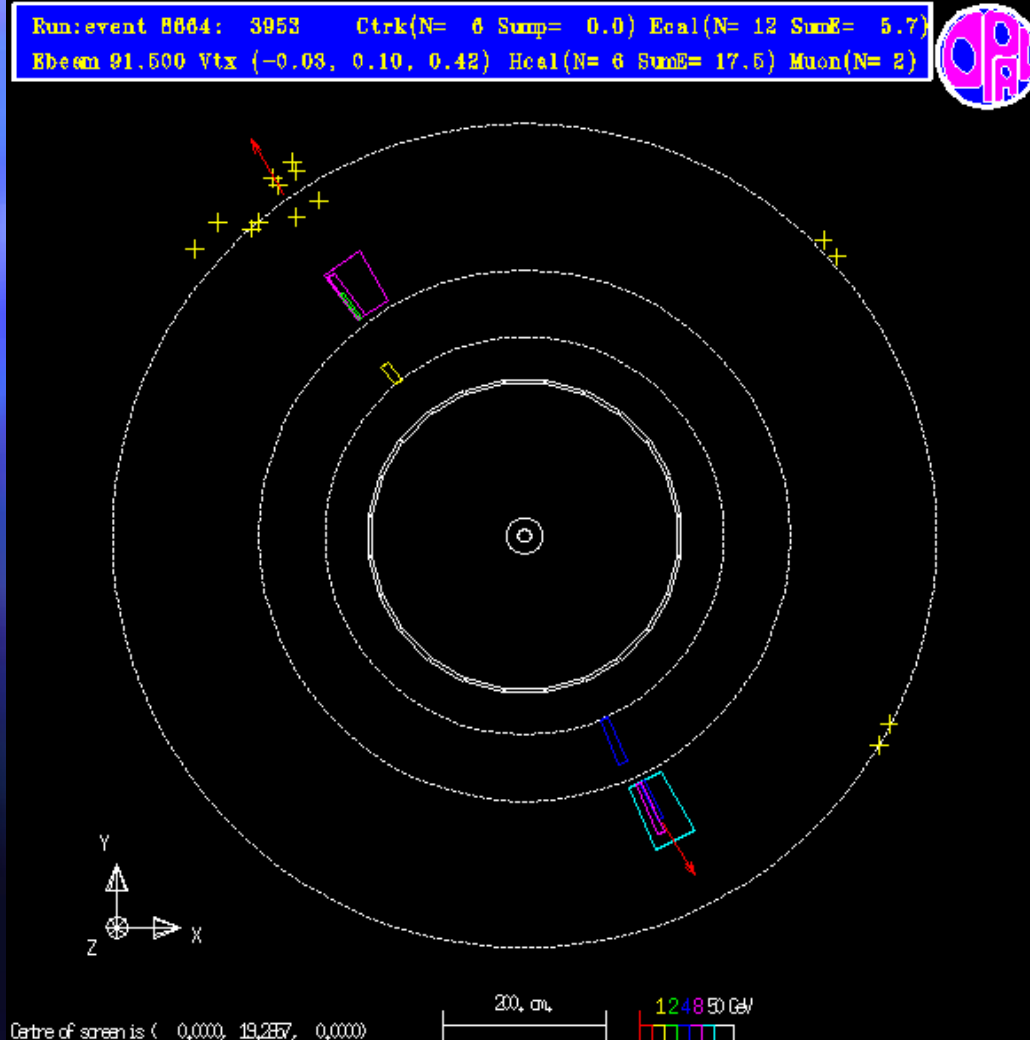




Events 11-20 (30 sec)

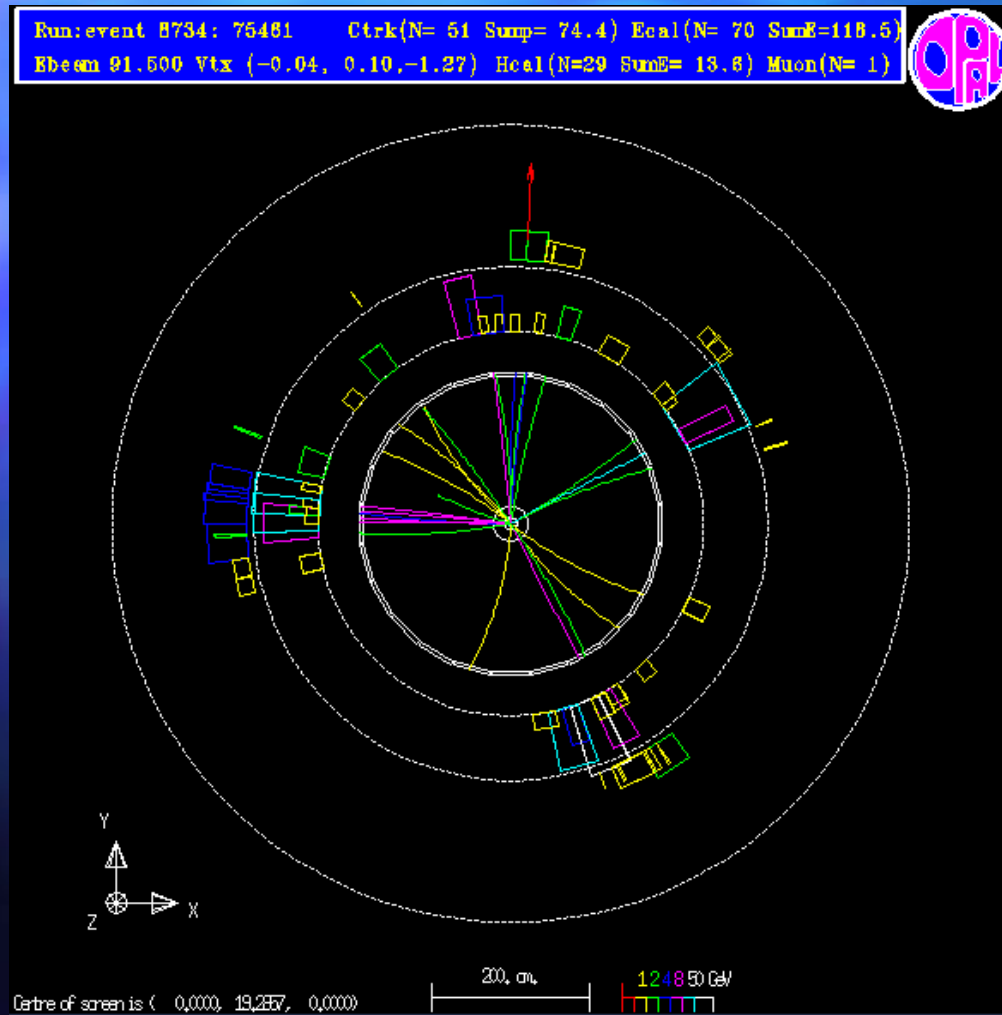
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



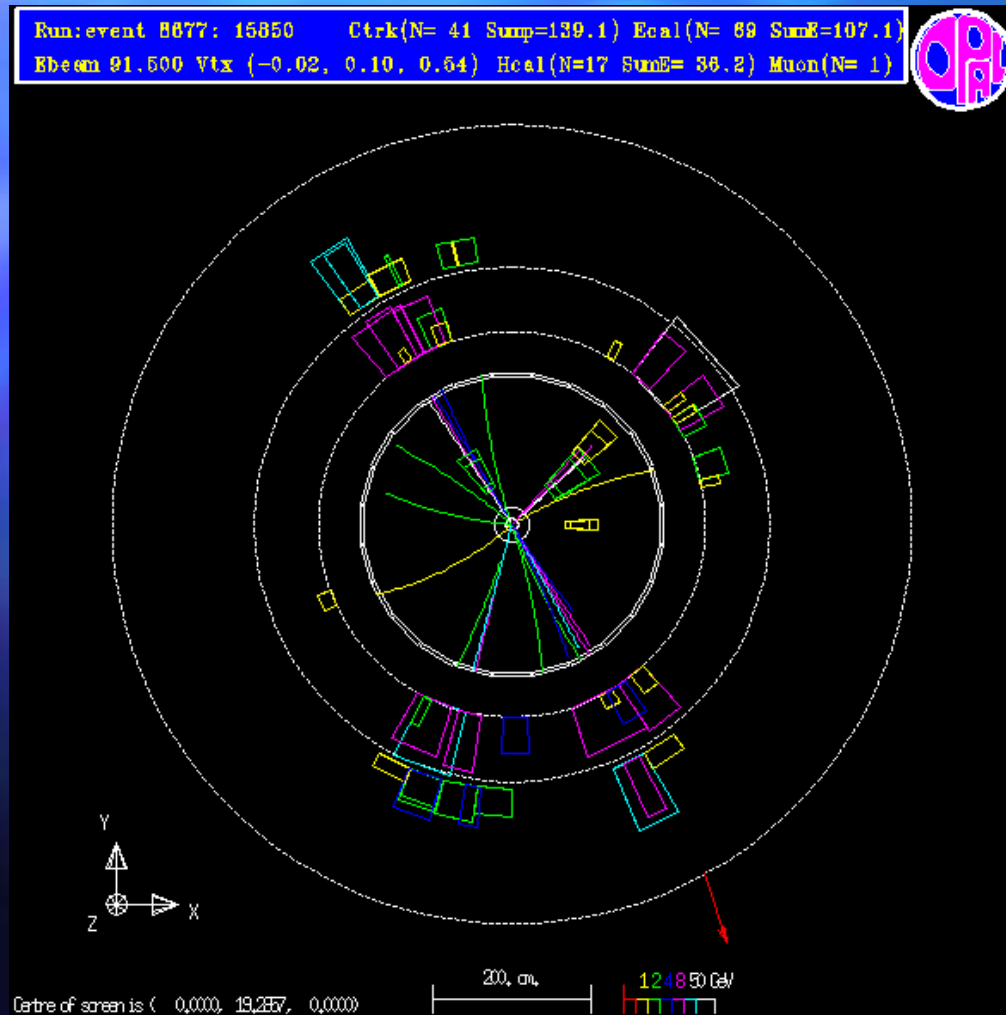
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



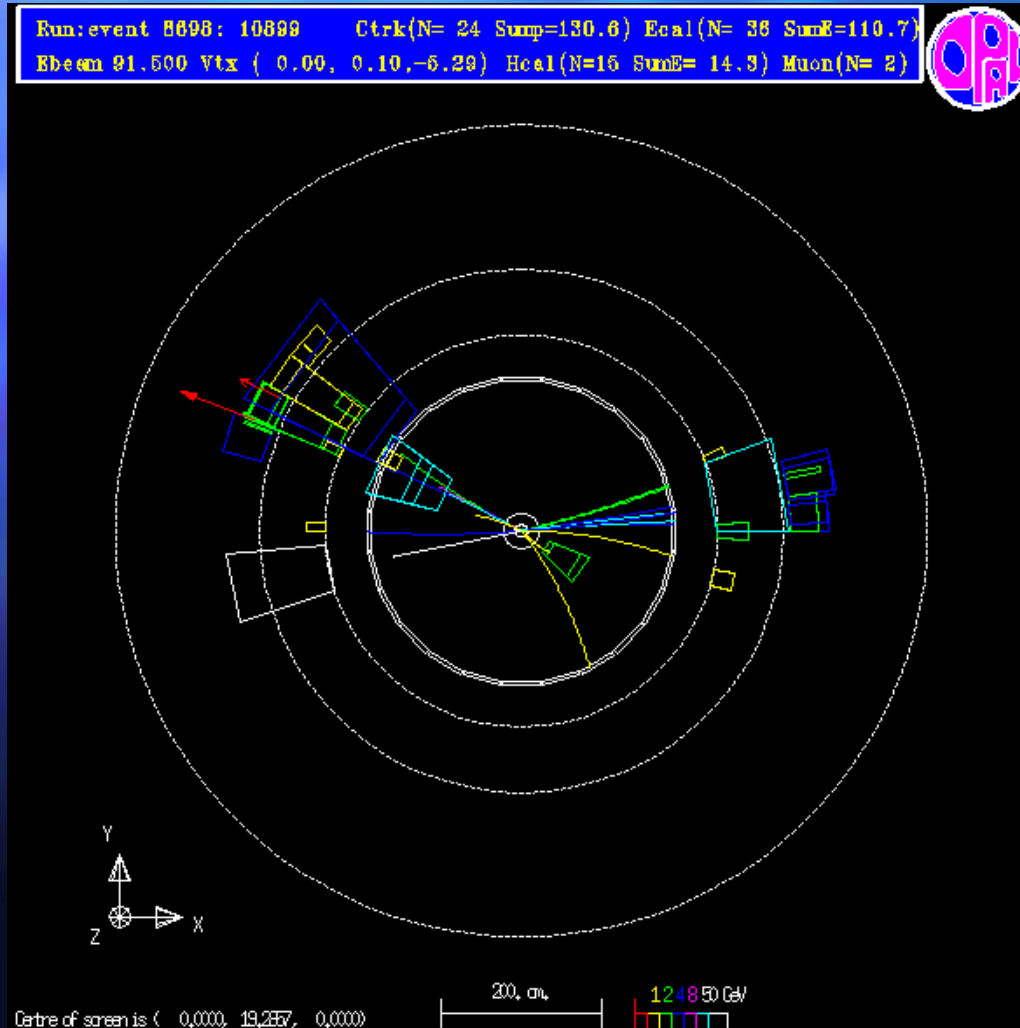
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



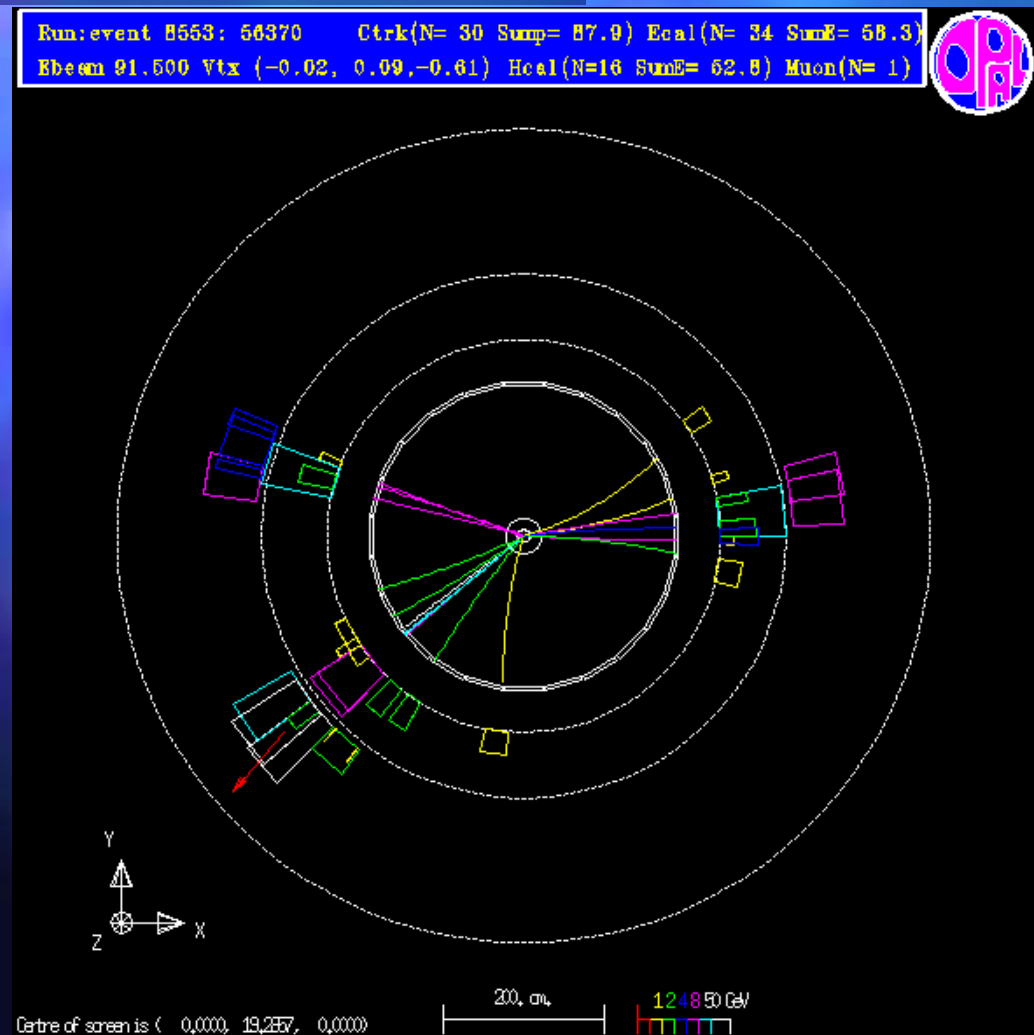
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



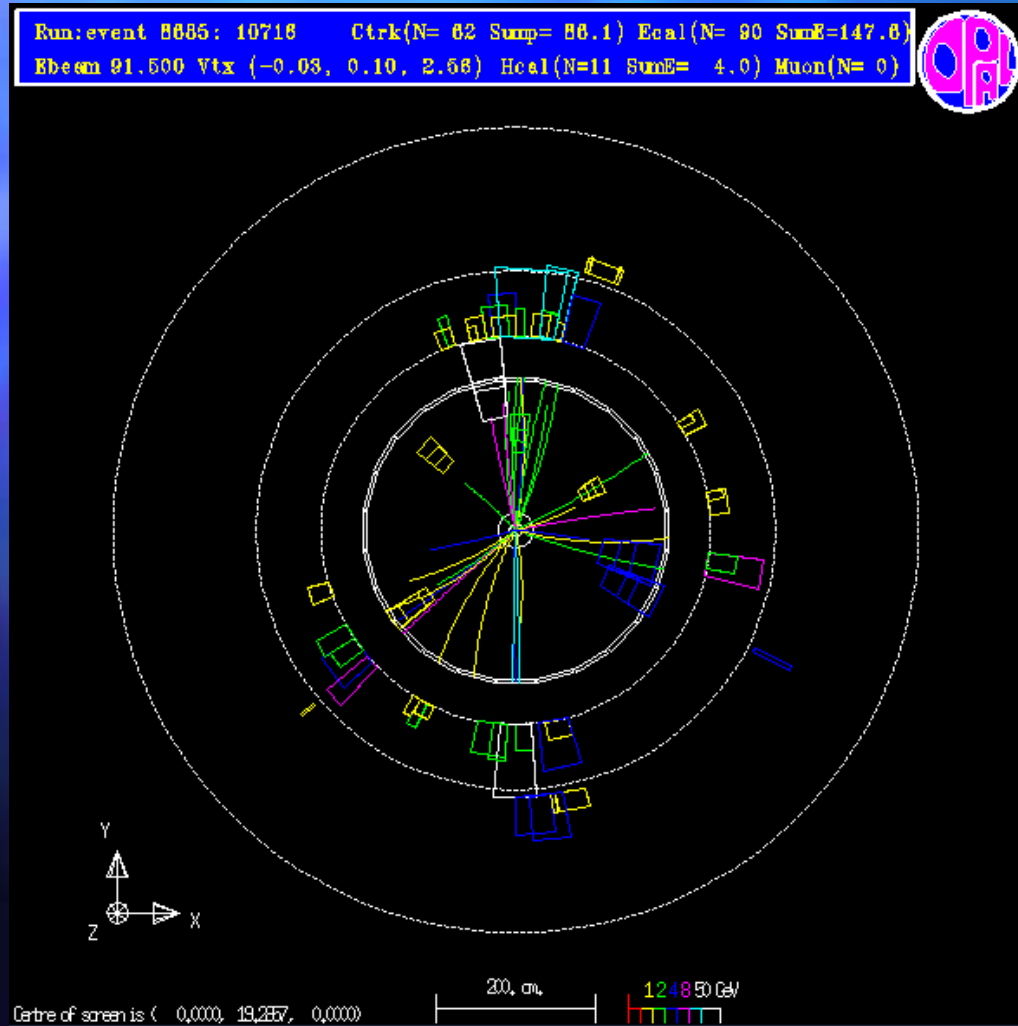
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

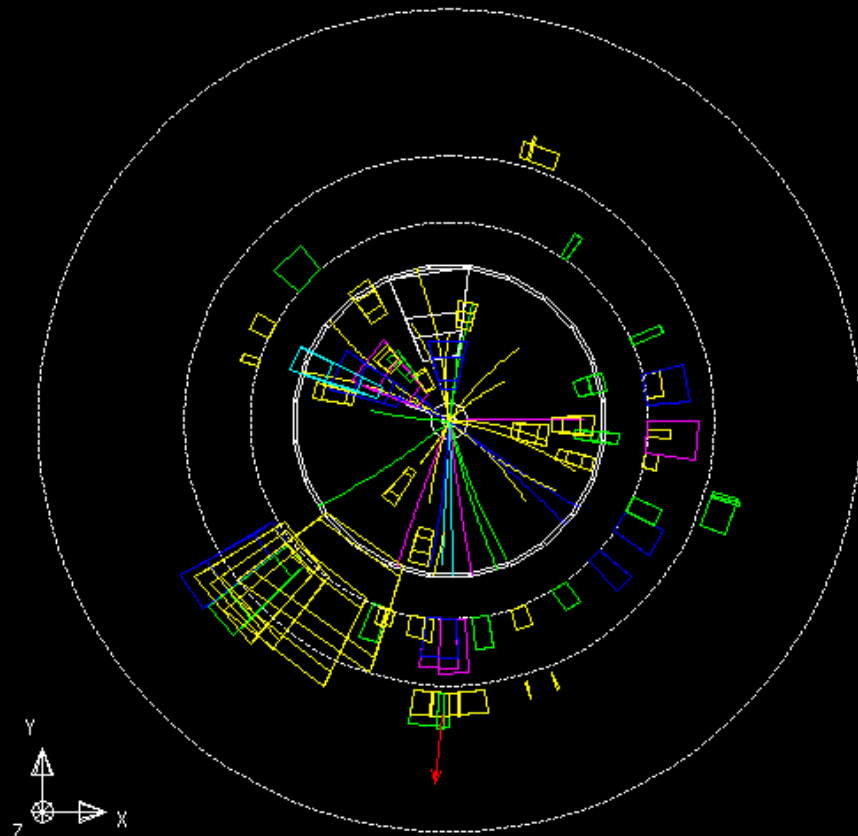
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

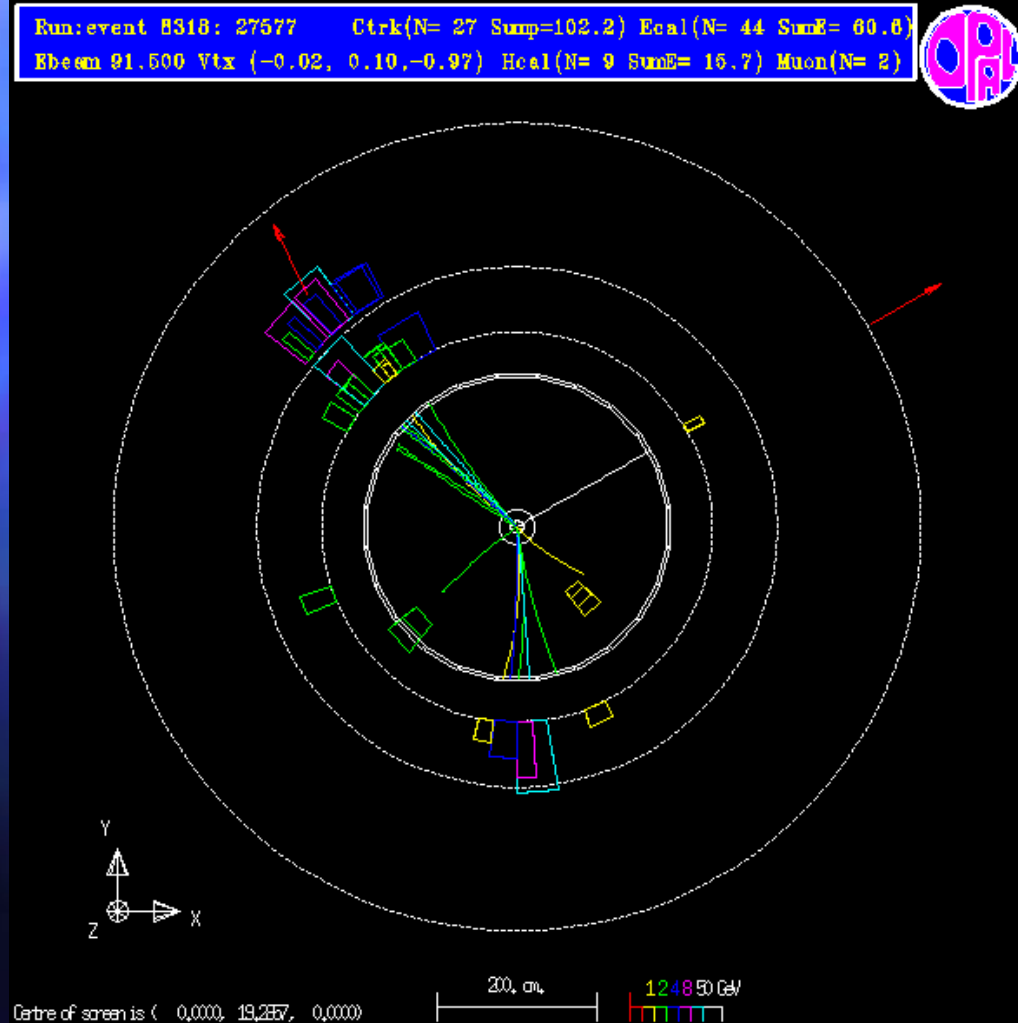
Run:event 8757: 47778 Ctrk(N= 91 Sump= 74.1) Ecal(N= 95 SumE= 99.5)
Ebeam 91.500 Vtx (-0.01, 0.10, -1.81) Hcal(N=23 SumE= 24.5) Muon(N= 1)



Centre of screen is (0.000, 19.287, 0.000) 200 cm 124850 GeV

What sort of WW decay is this?

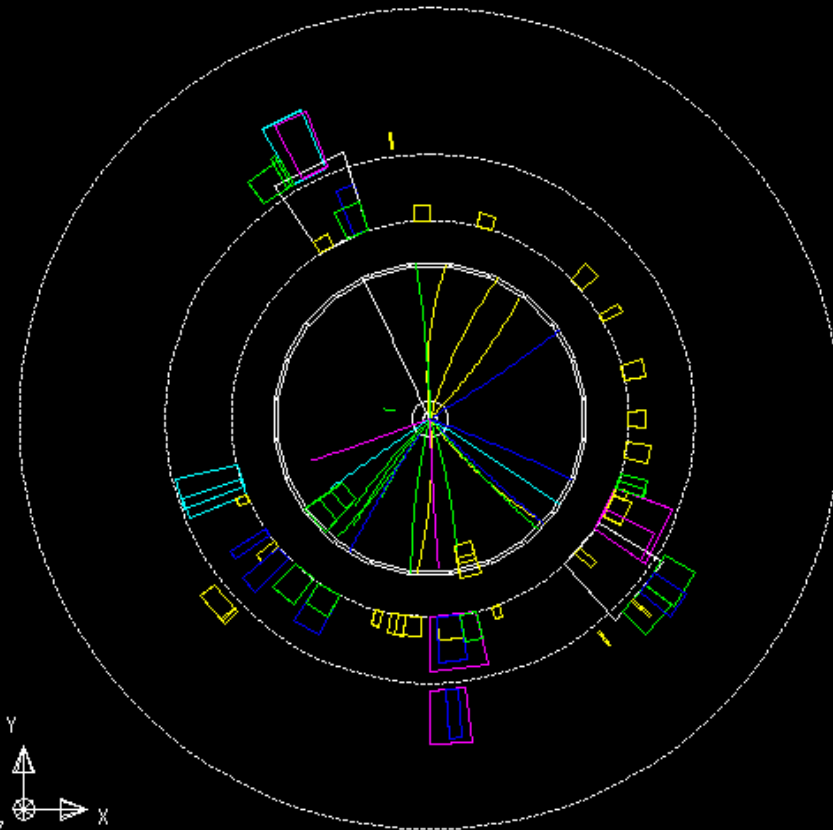
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

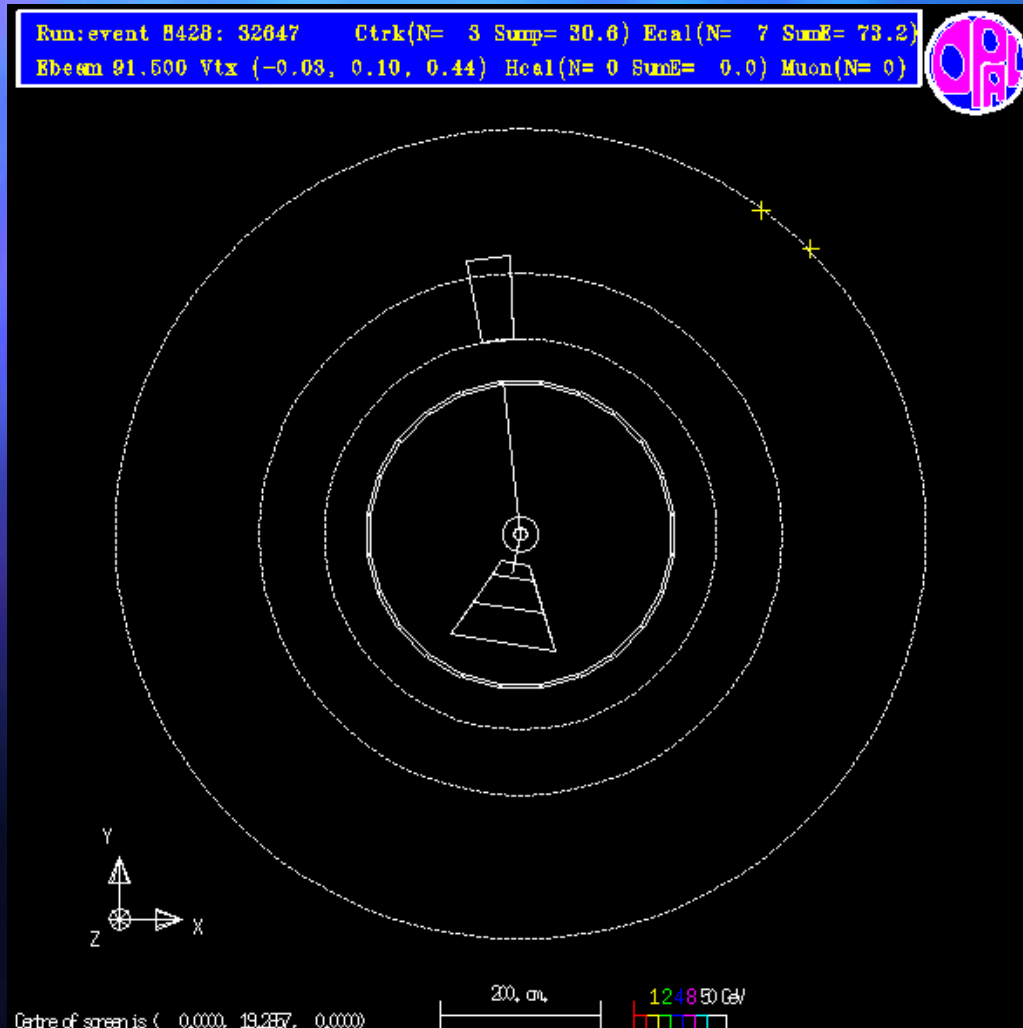
Run: event 8798: 8788 Ctrk(N= 70 Sump= 83.8) Ecal(N= 80 SumE=130.4)
Ebeam 91.000 Vtx (-0.04, 0.09, -1.71) Hcal(N=16 SumE= 20.0) Muon(N= 0)

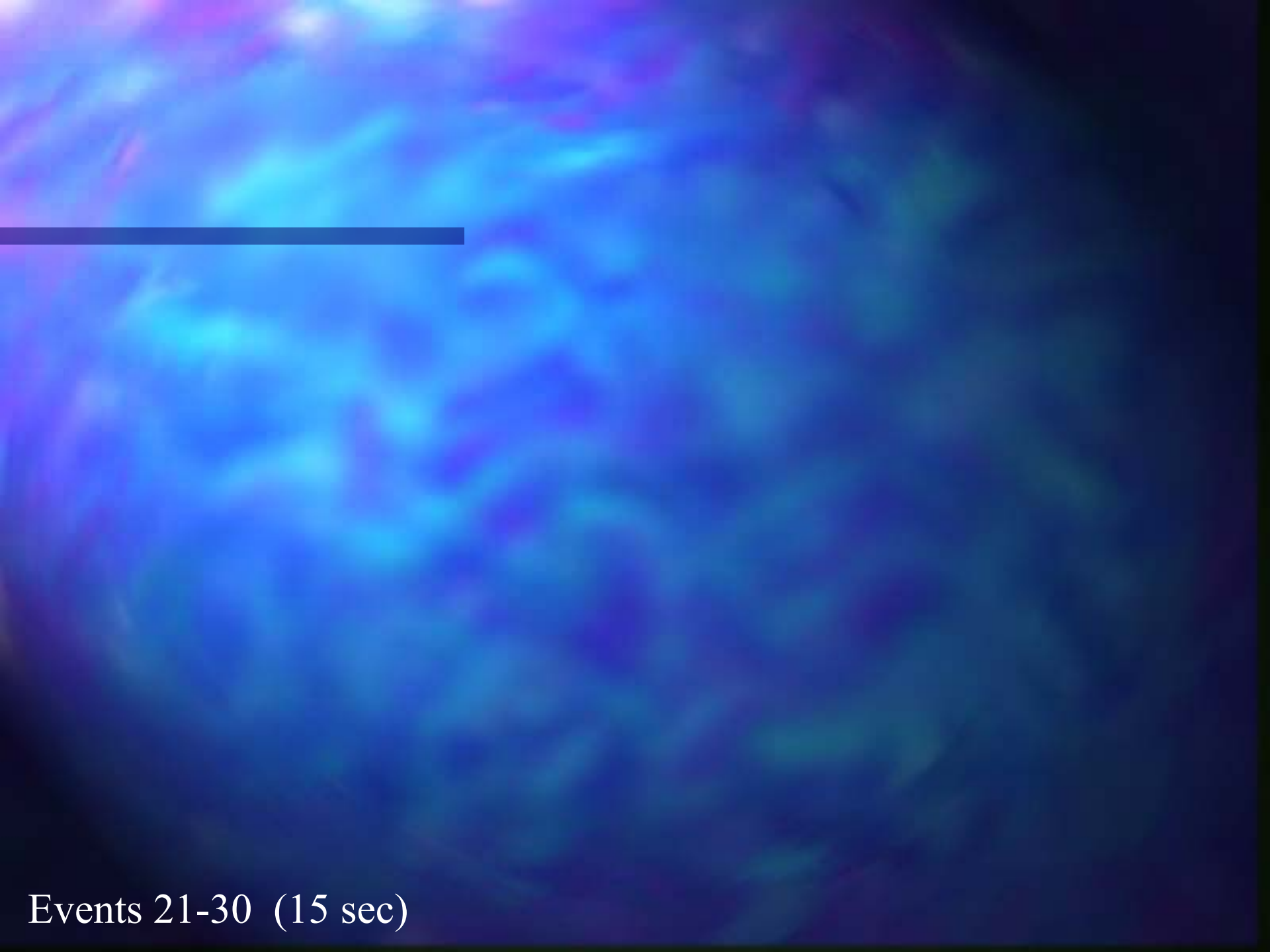


Centre of screen is (0.000, 19.257, 0.000) 200 cm 124.850 GeV

What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

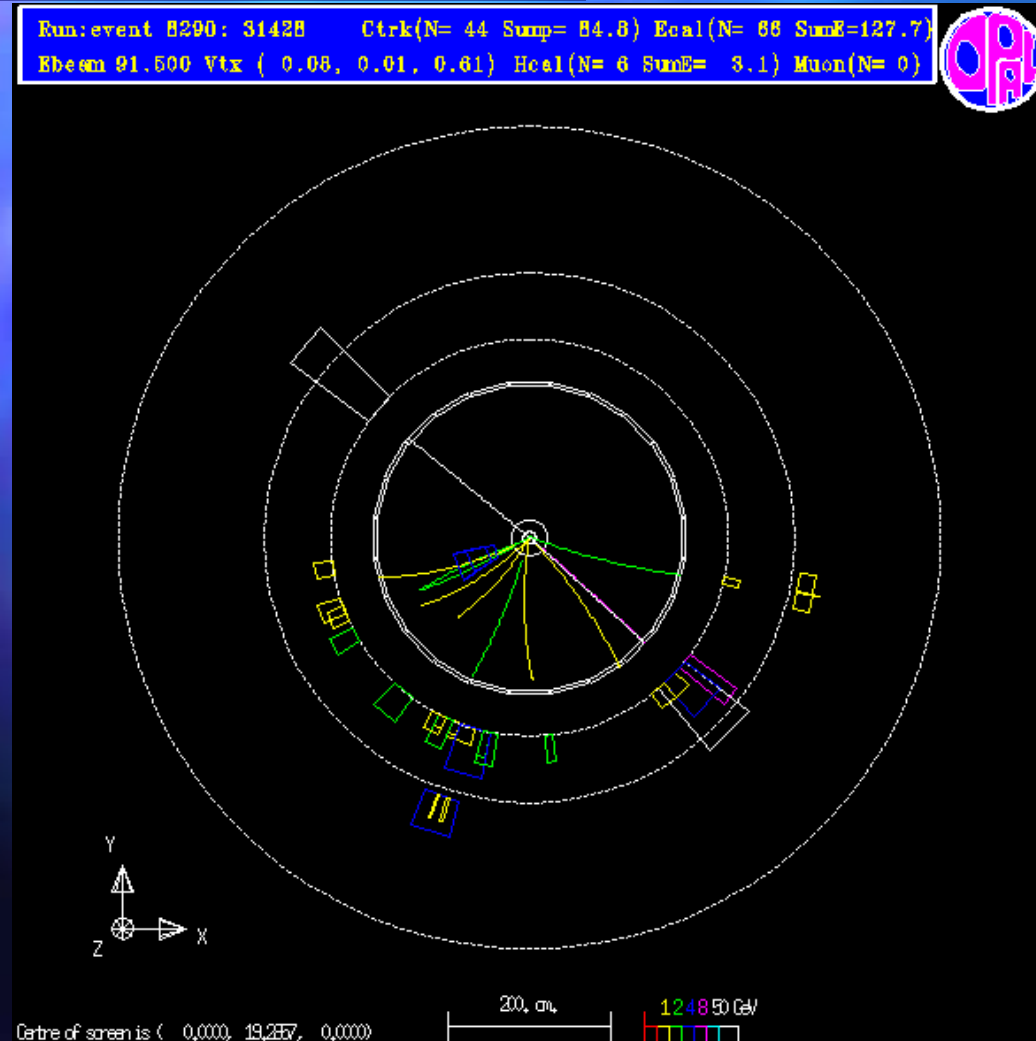




Events 21-30 (15 sec)

What sort of WW decay is this?

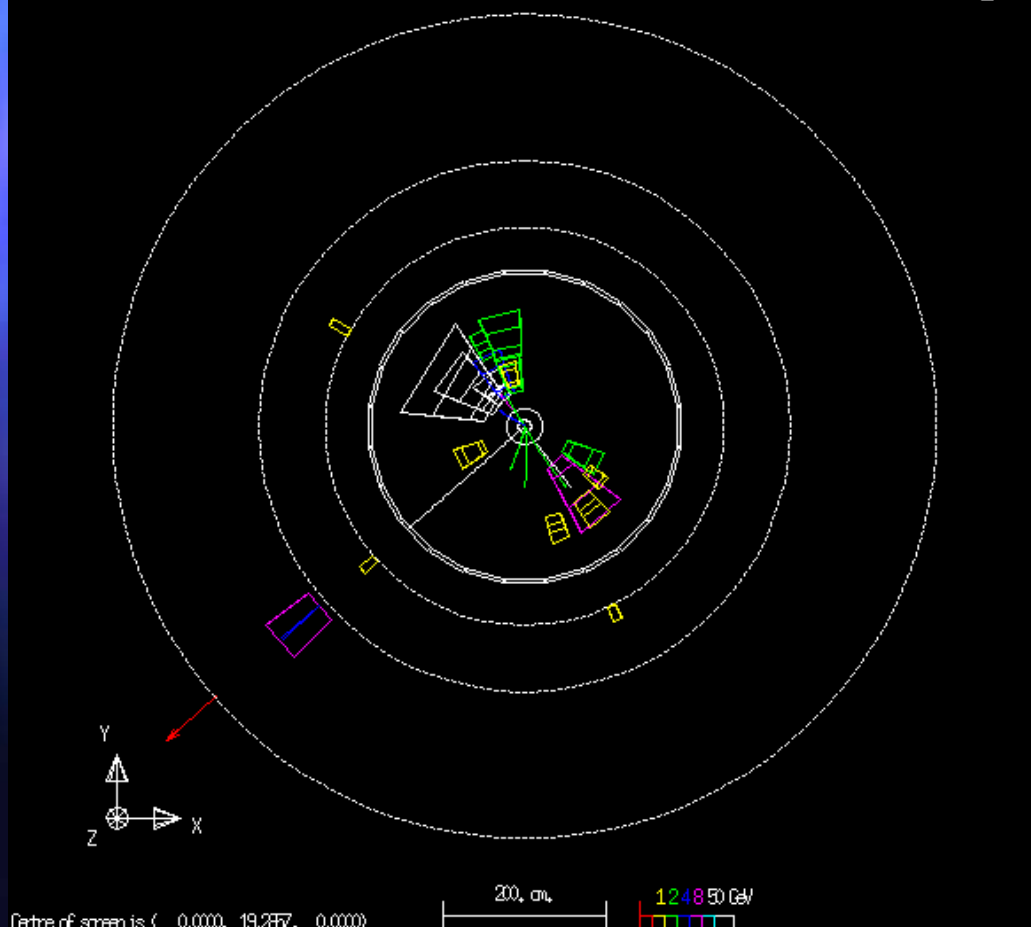
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

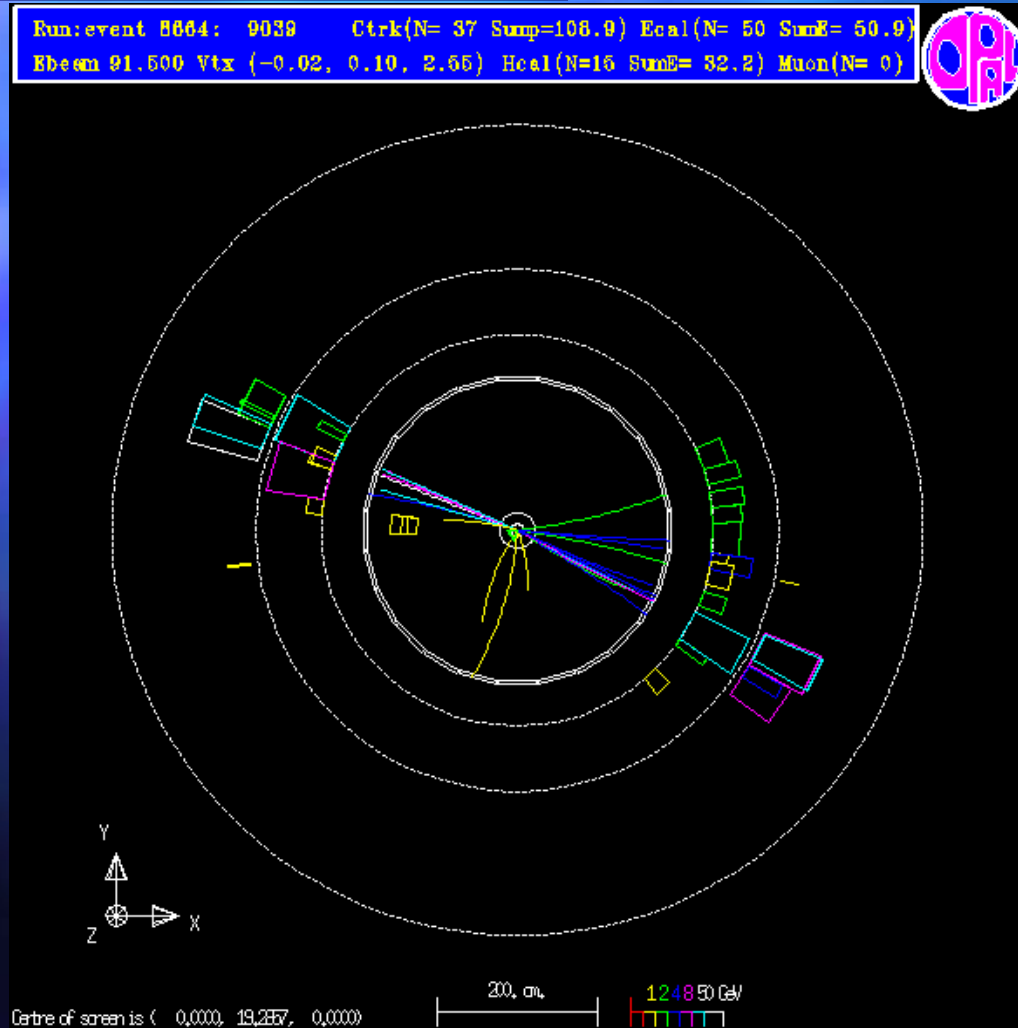
1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run: event 8551: 30188 Ctrk(N= 24 SumP=****) Ecal(N= 27 SumE= 62.1)
Ebeam 91.500 Vtx (0.01, 0.13, -0.03) Hcal(N= 8 SumE= 34.4) Muon(N= 1)



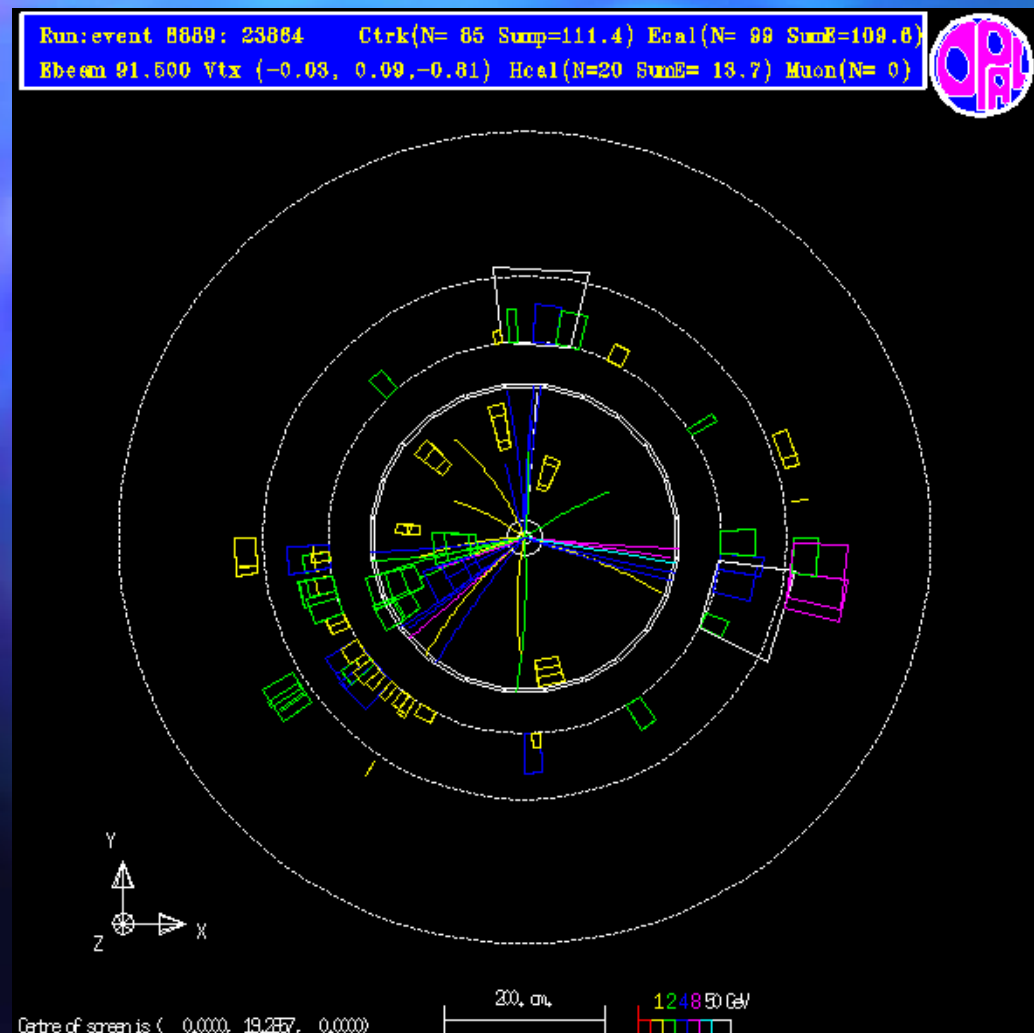
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



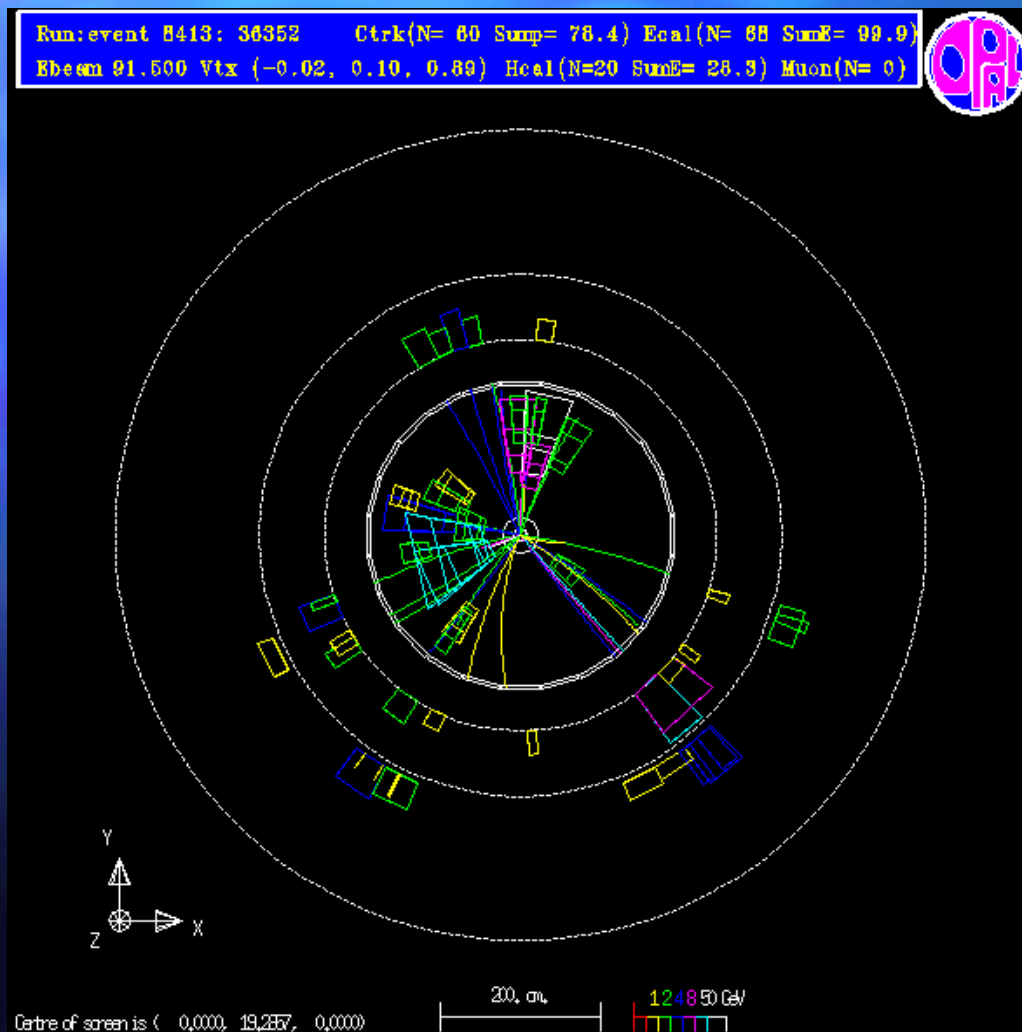
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



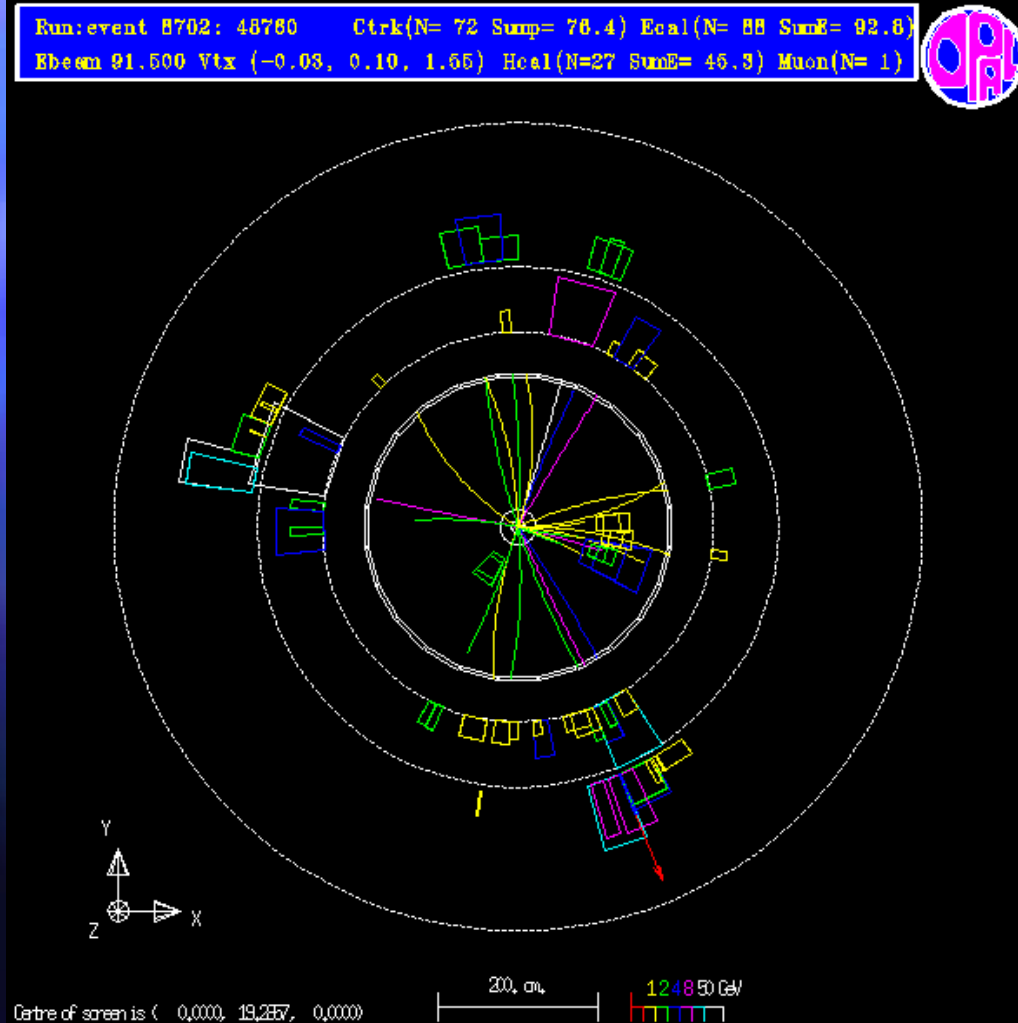
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



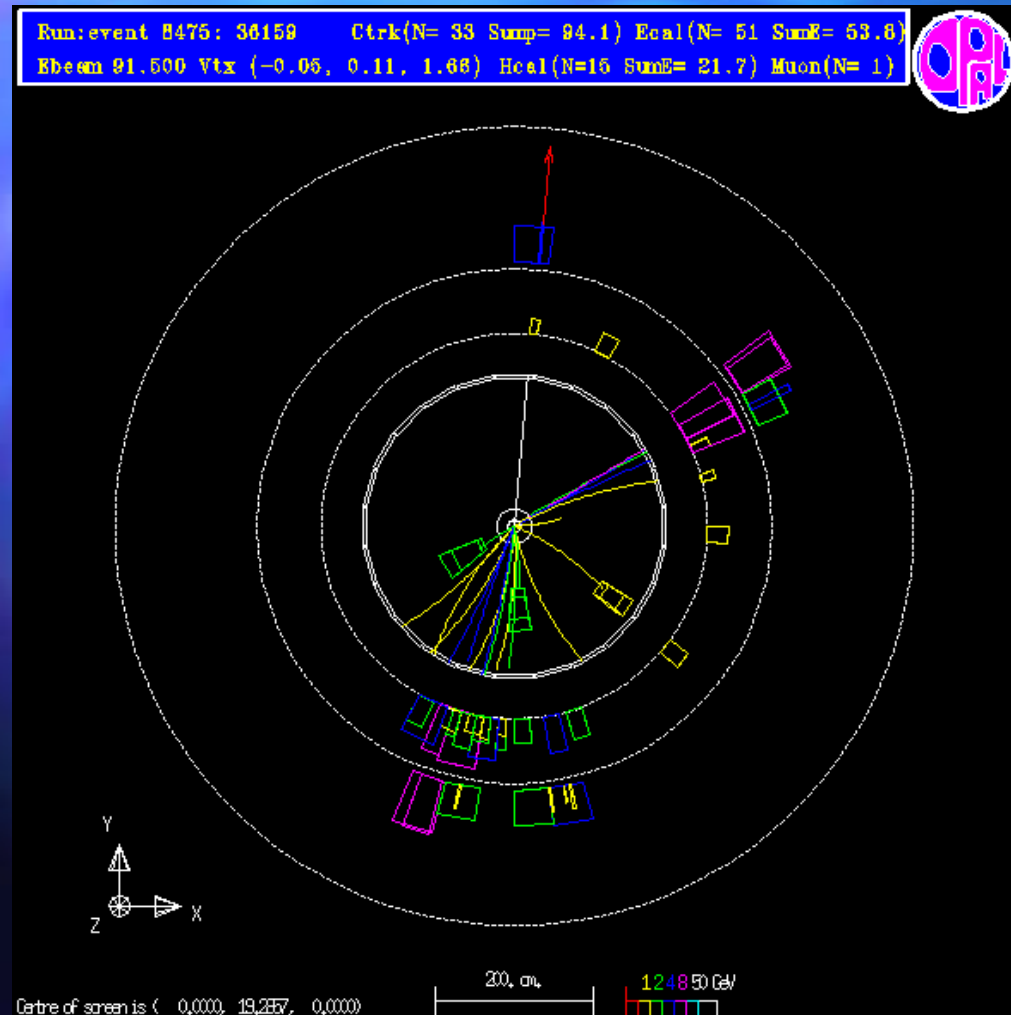
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



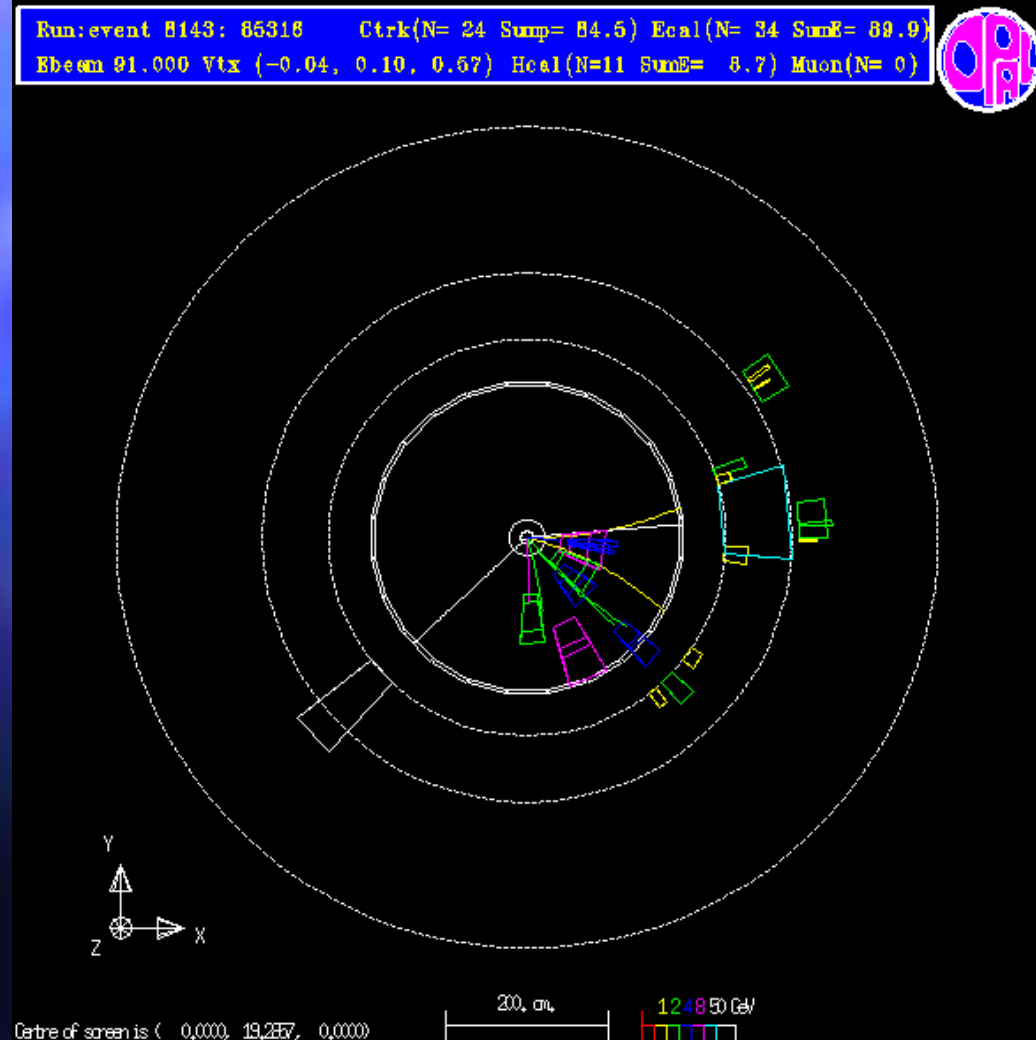
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



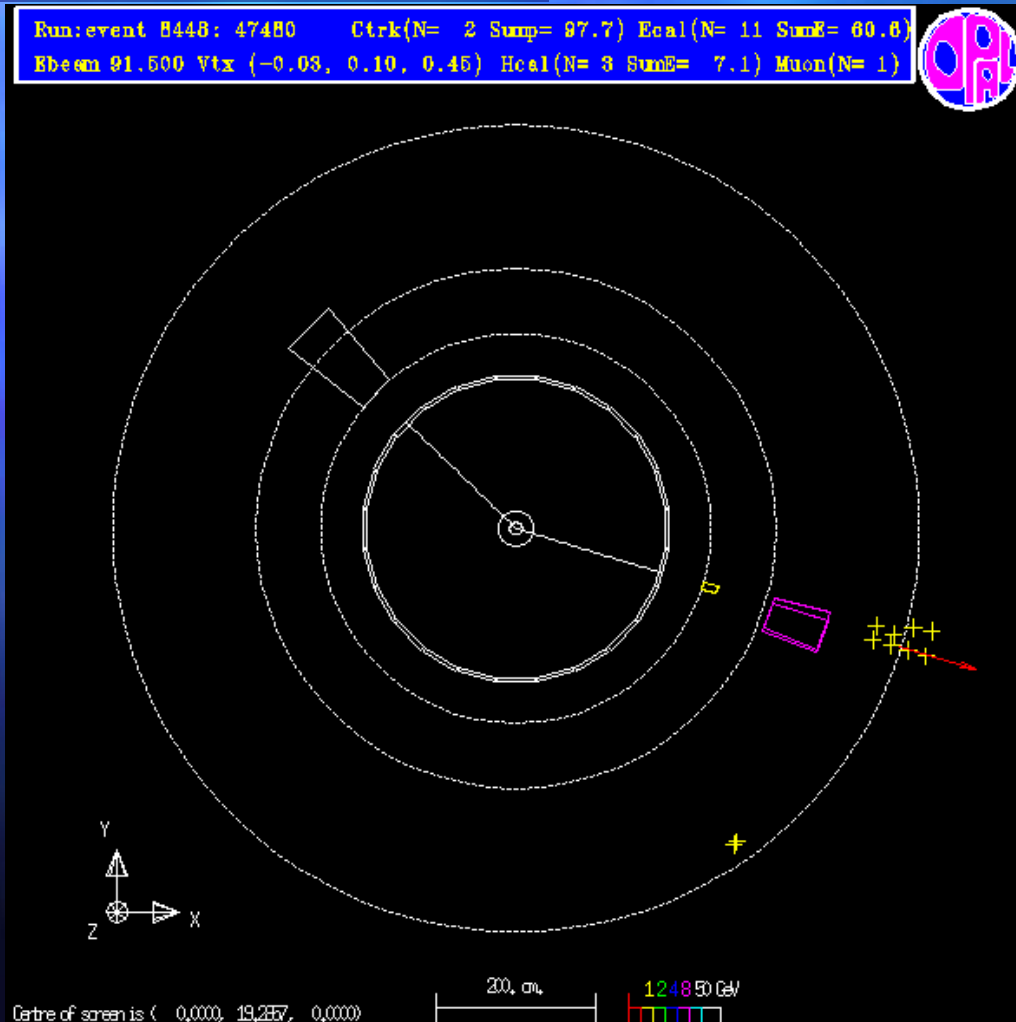
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



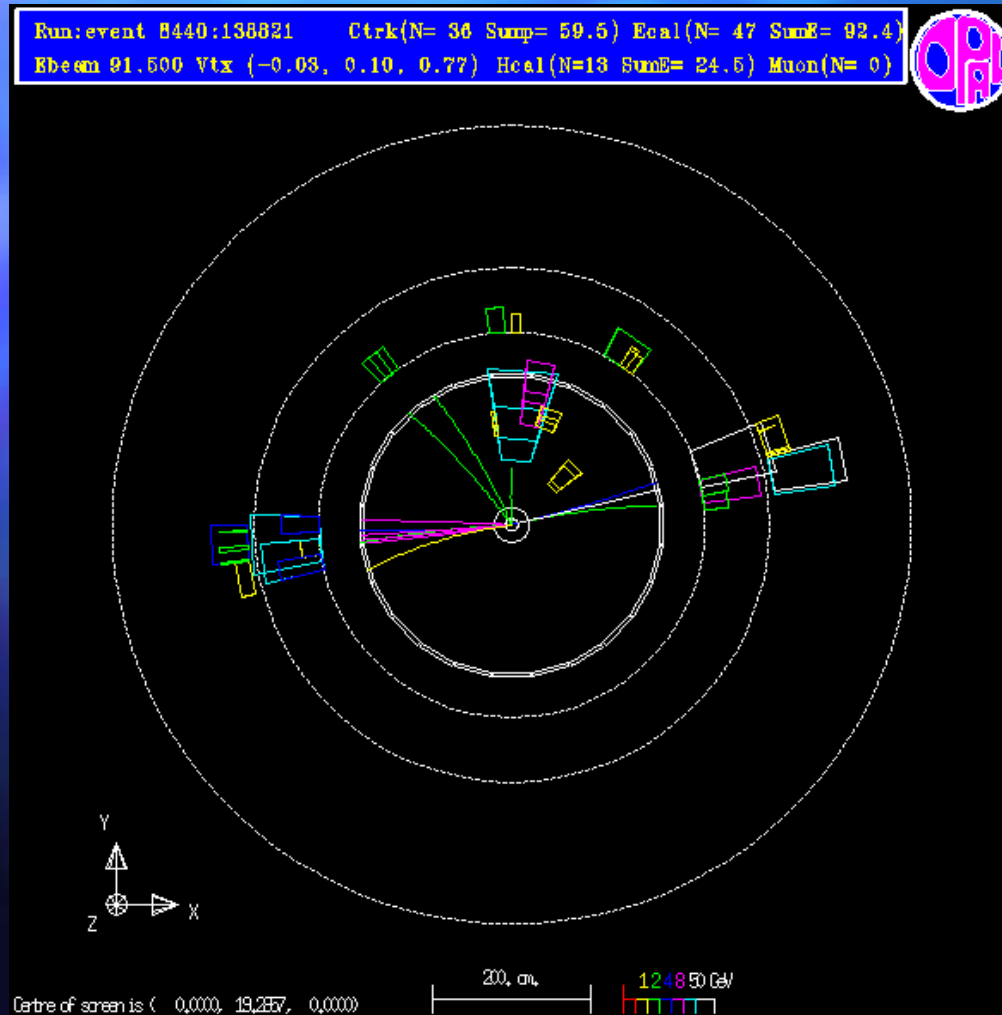
What sort of WW decay is this?

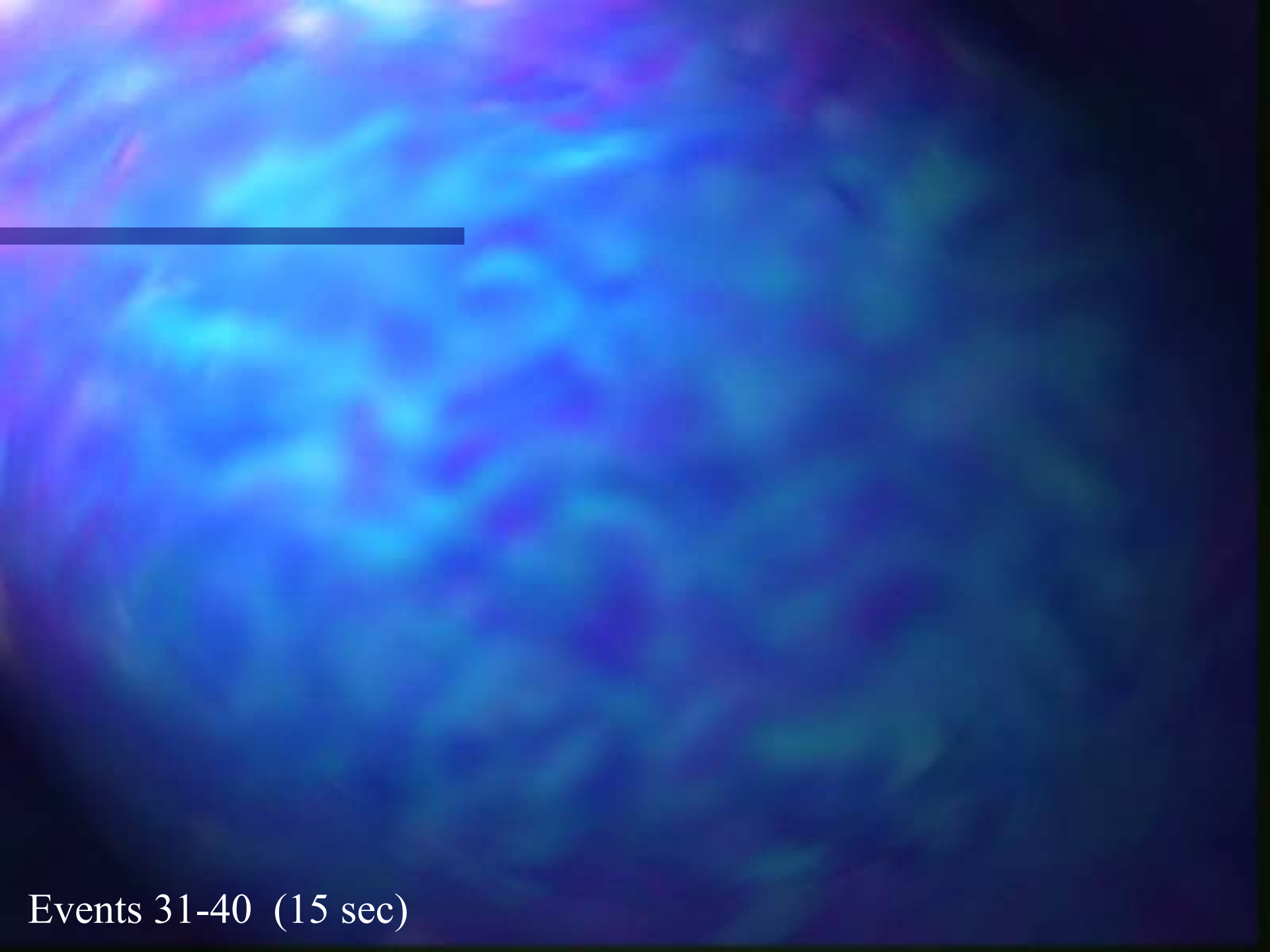
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

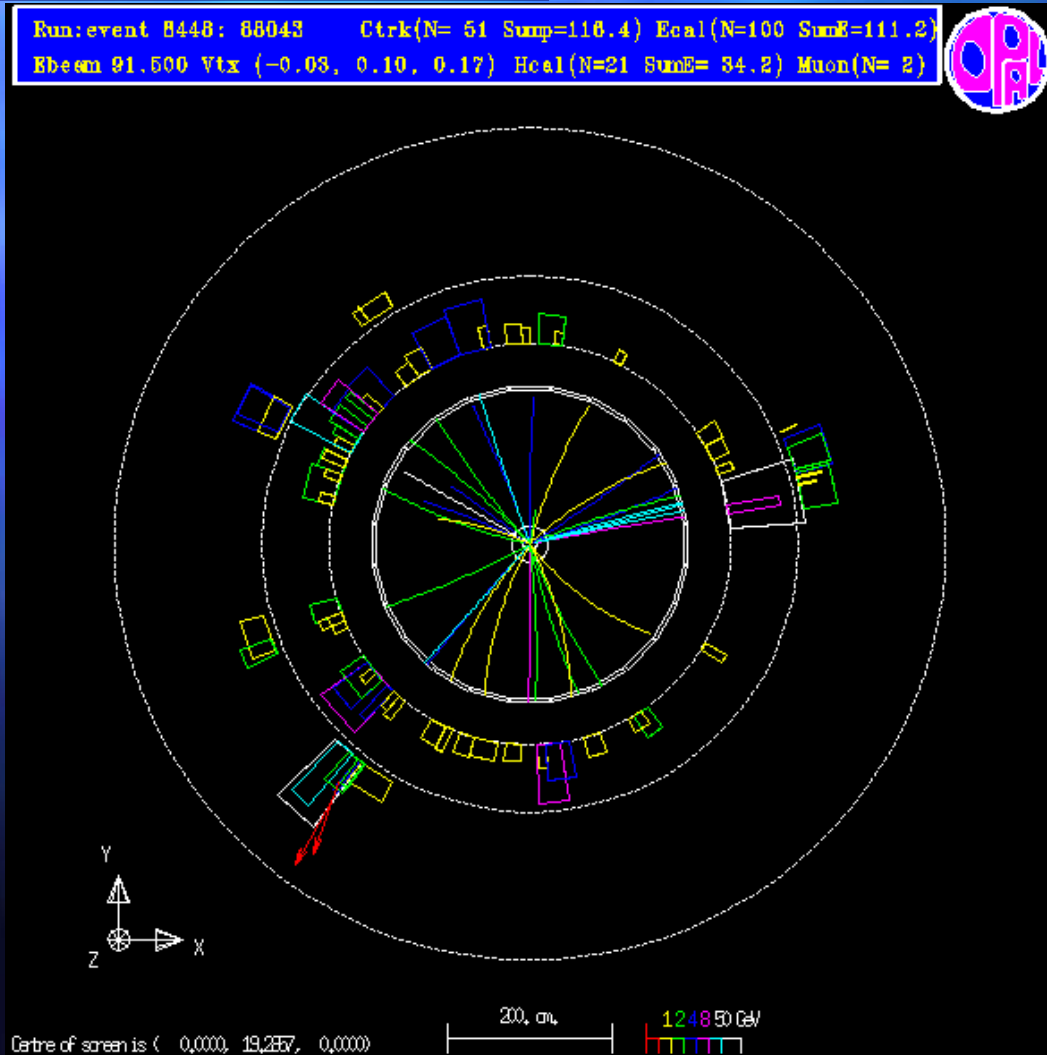




Events 31-40 (15 sec)

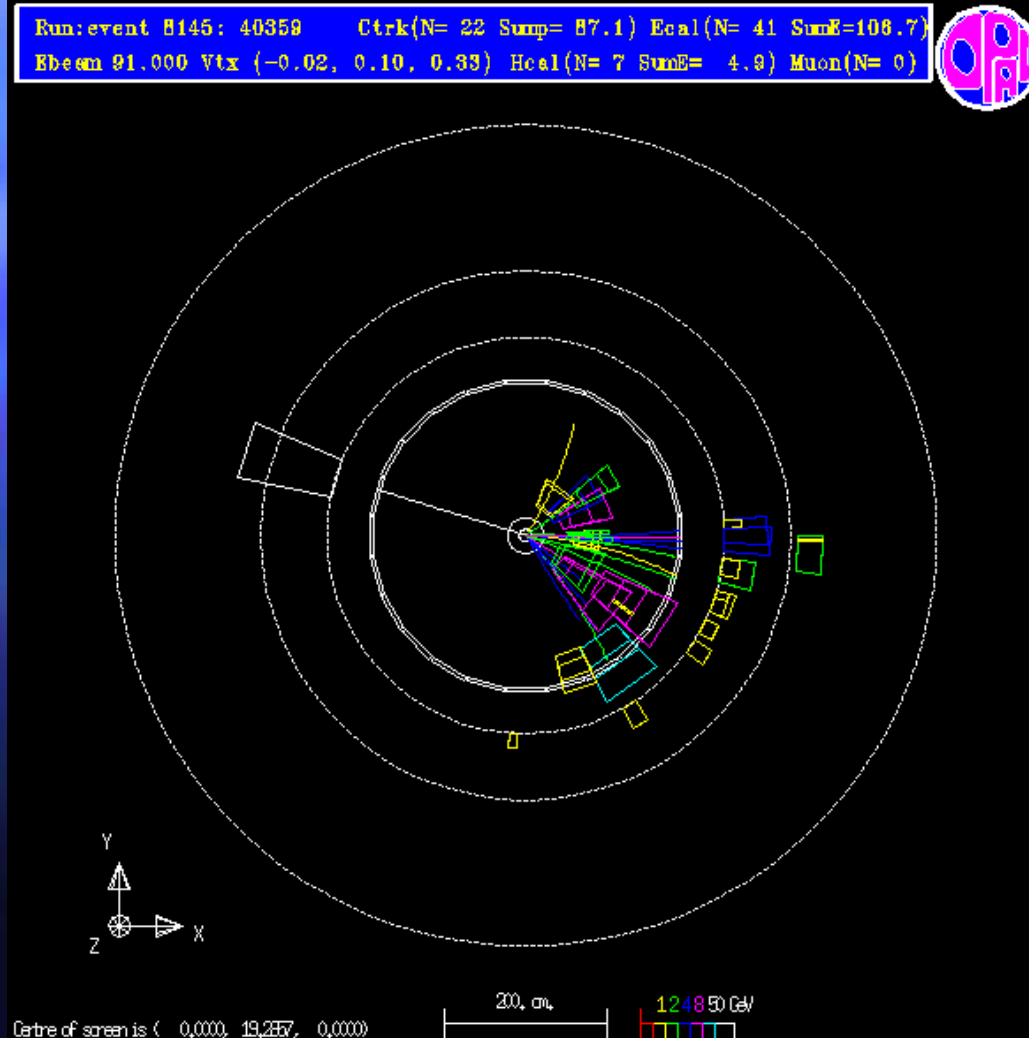
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



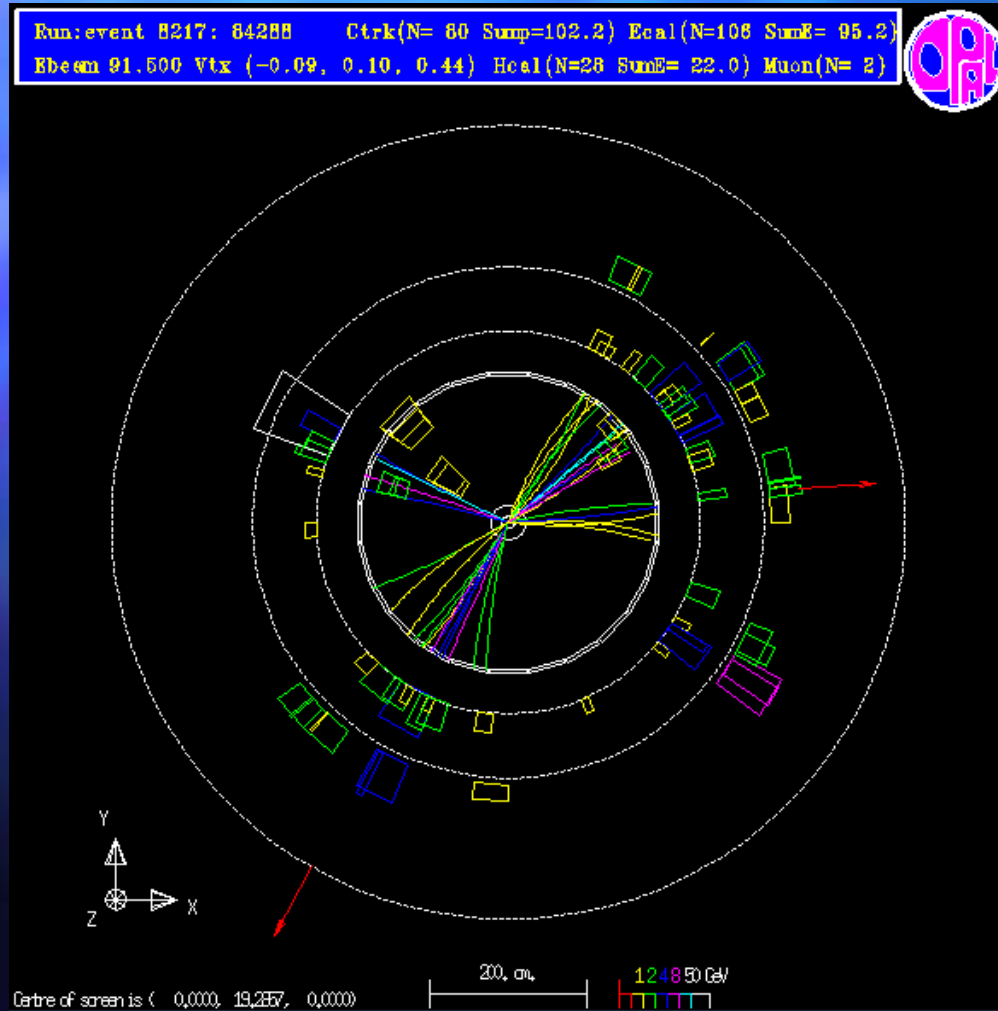
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

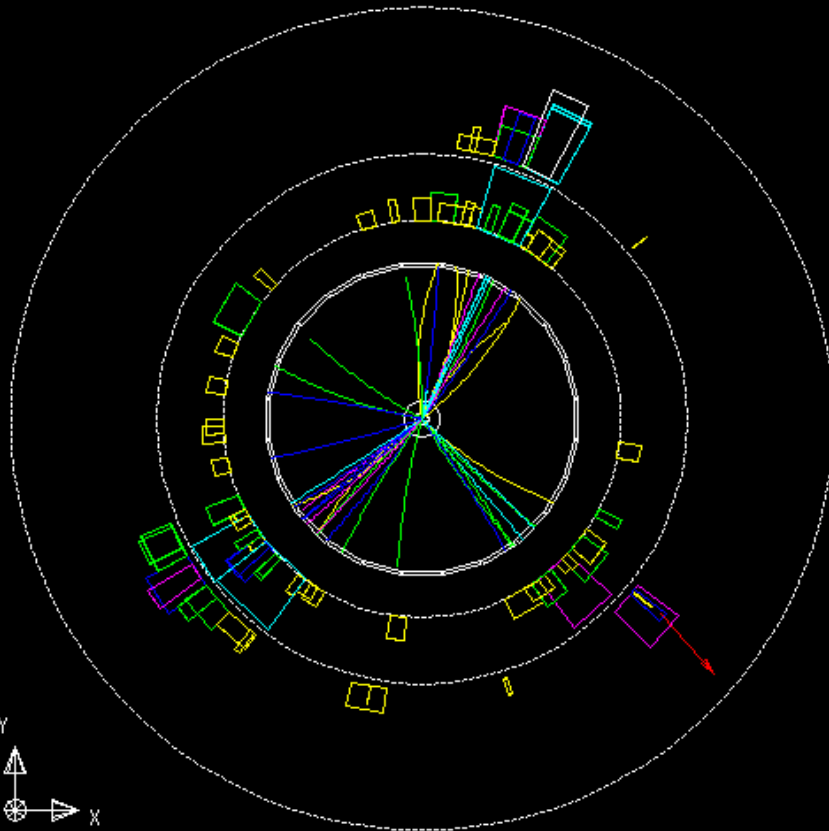
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

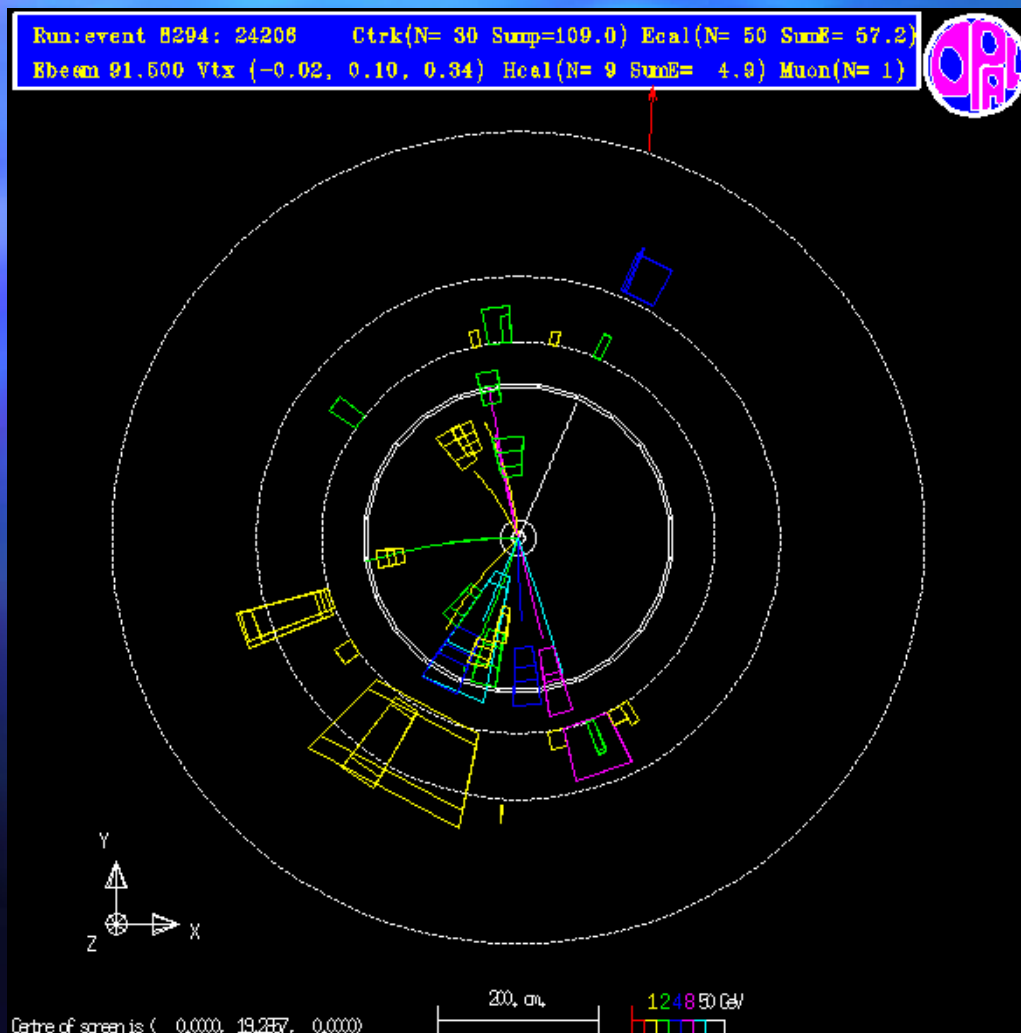
Run: event 8742: 45805 Ctrk(N= 61 Sump=183.4) Ecal(N= 83 SumE= 88.4)
Ebeam 91.500 Vtx (-0.08, 0.10, -1.38) Hcal(N=28 SumE= 42.9) Muon(N= 1)



Centre of screen is (0.000, 19.287, 0.000)

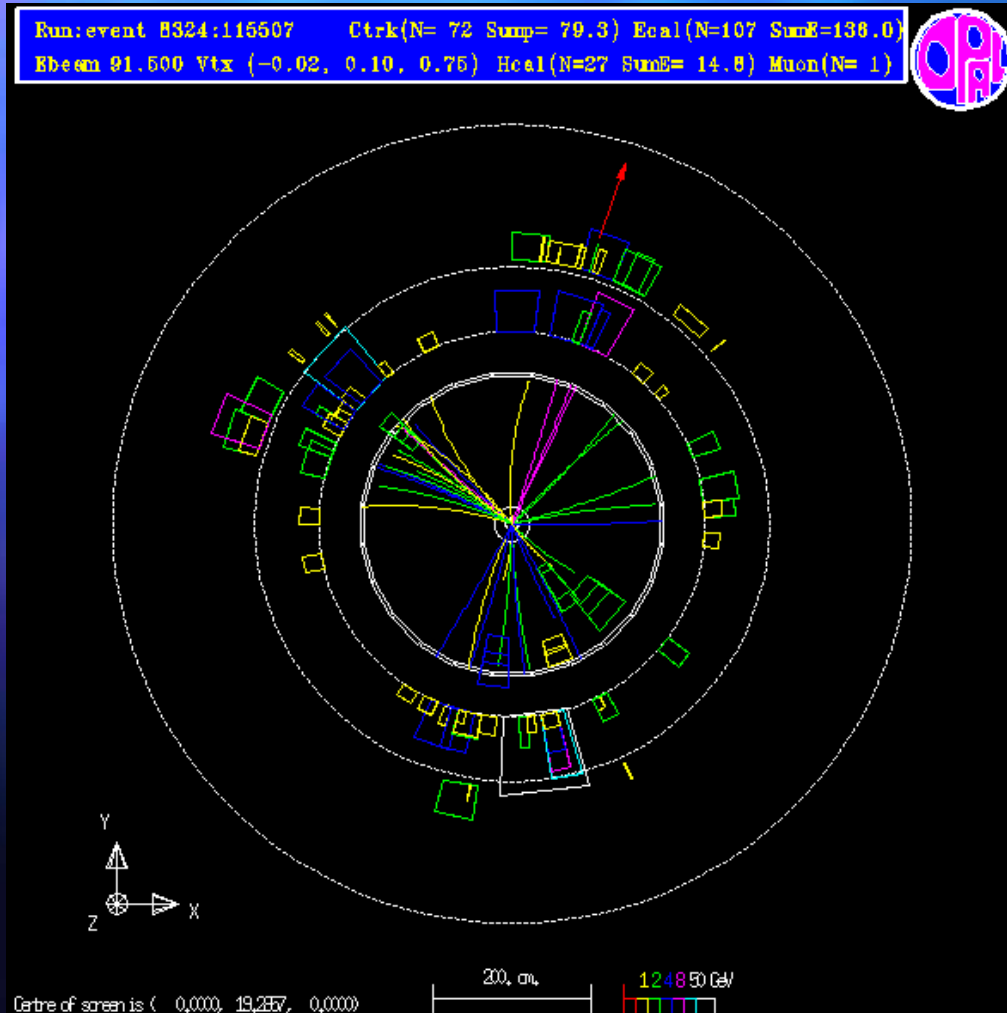
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



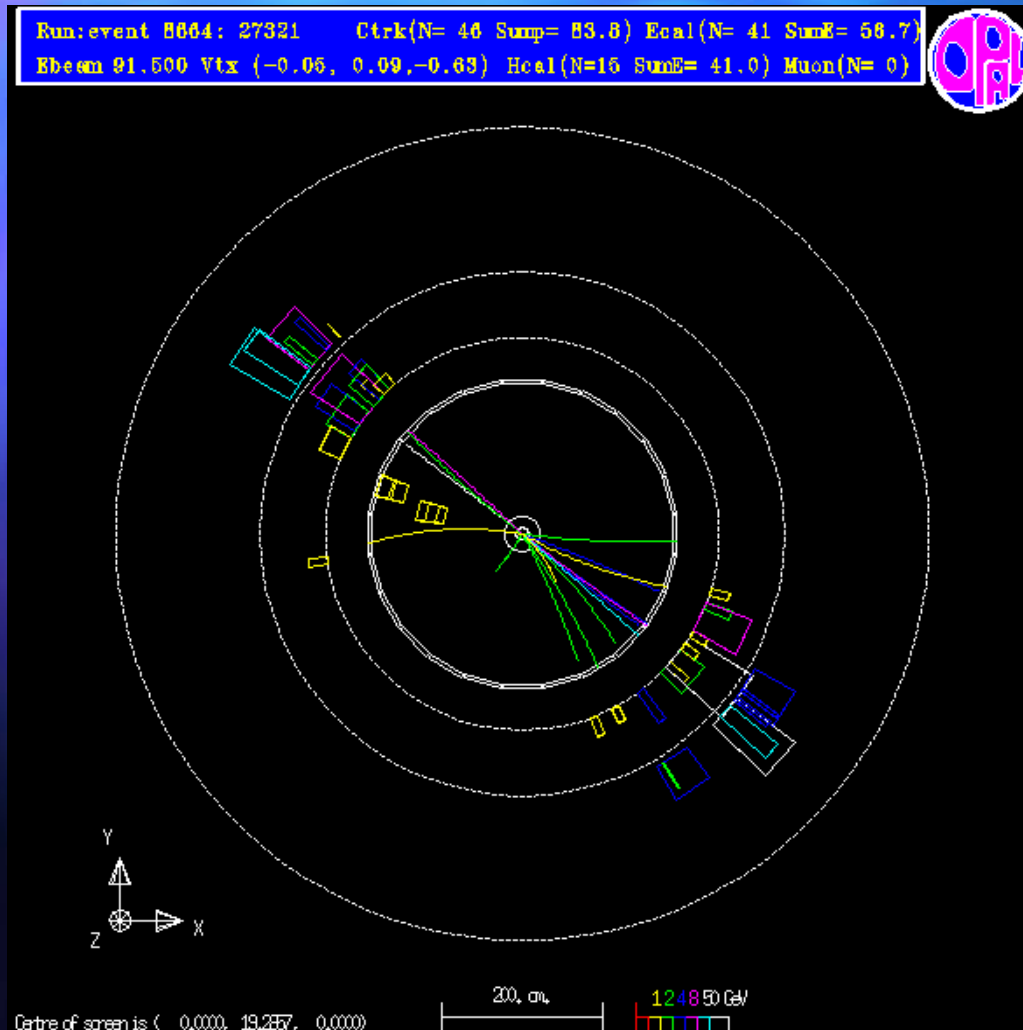
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



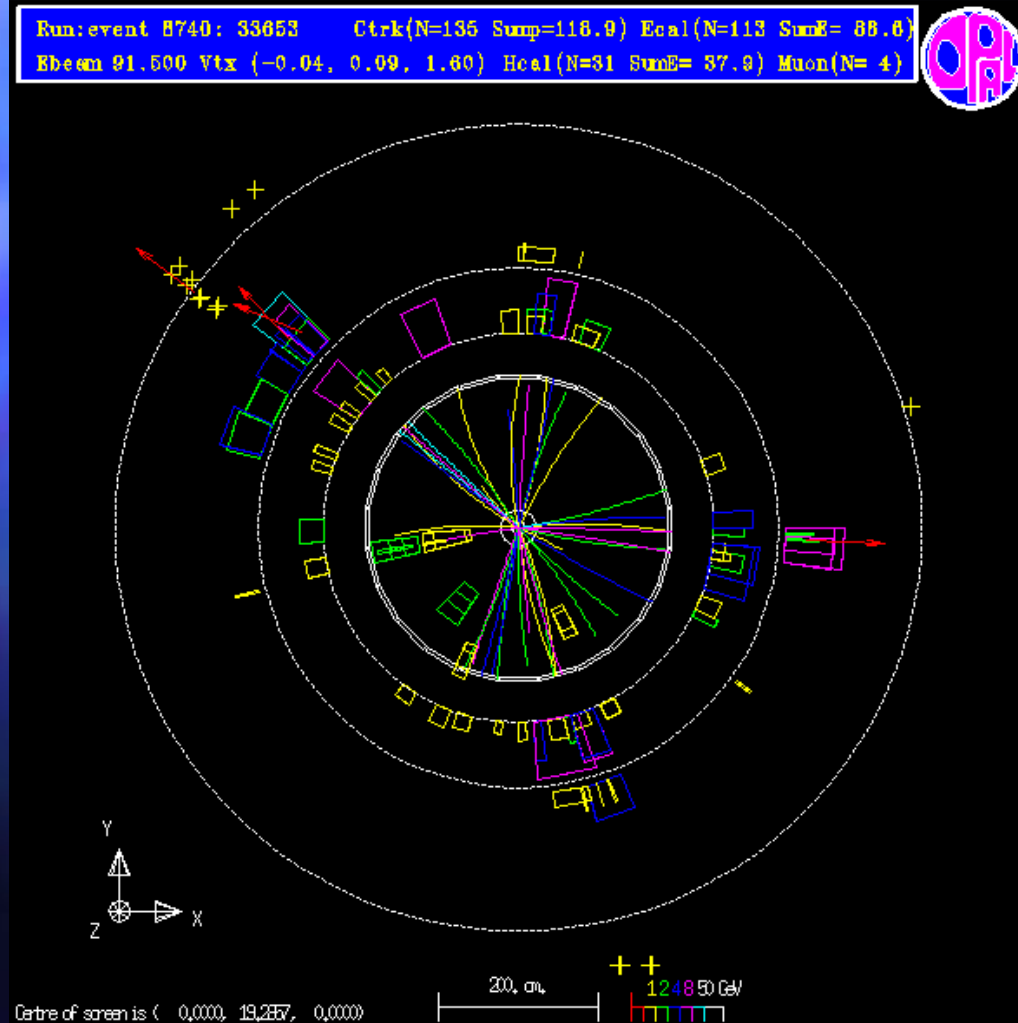
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



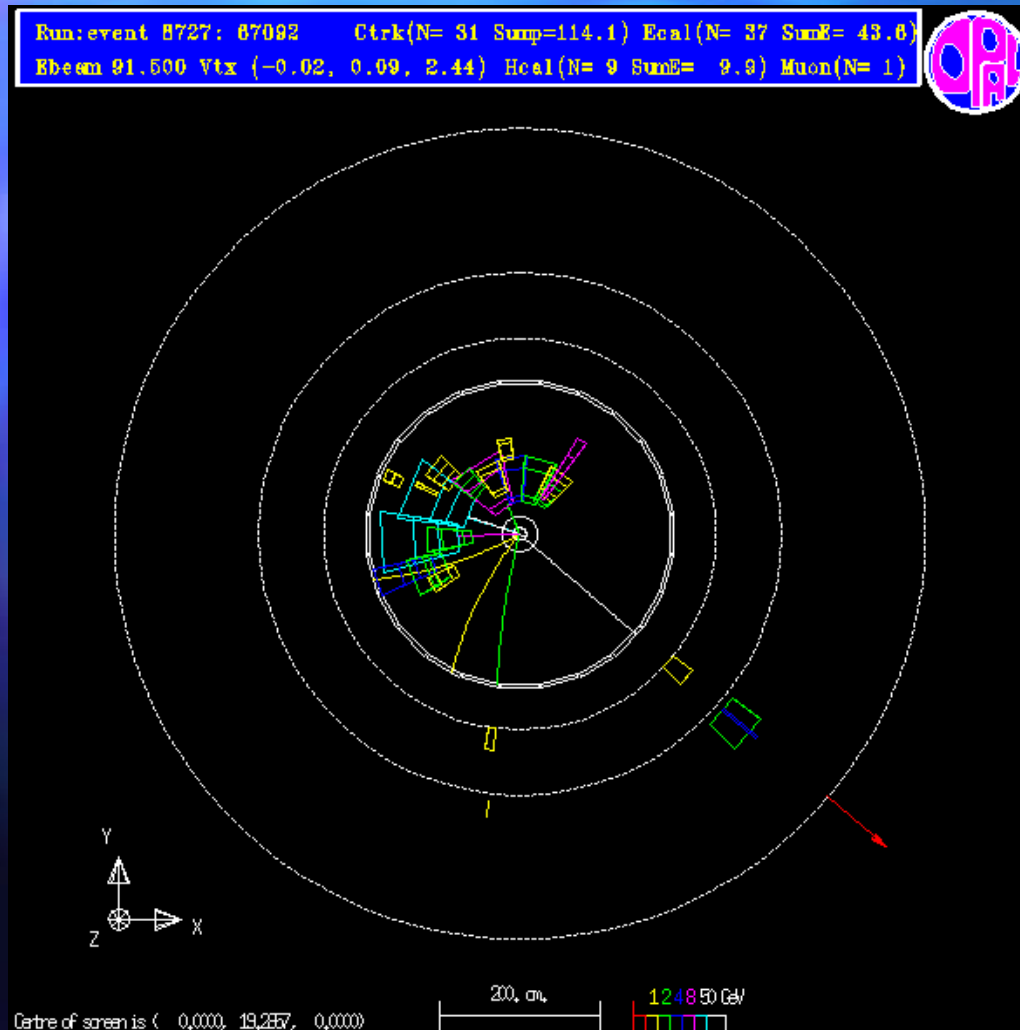
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



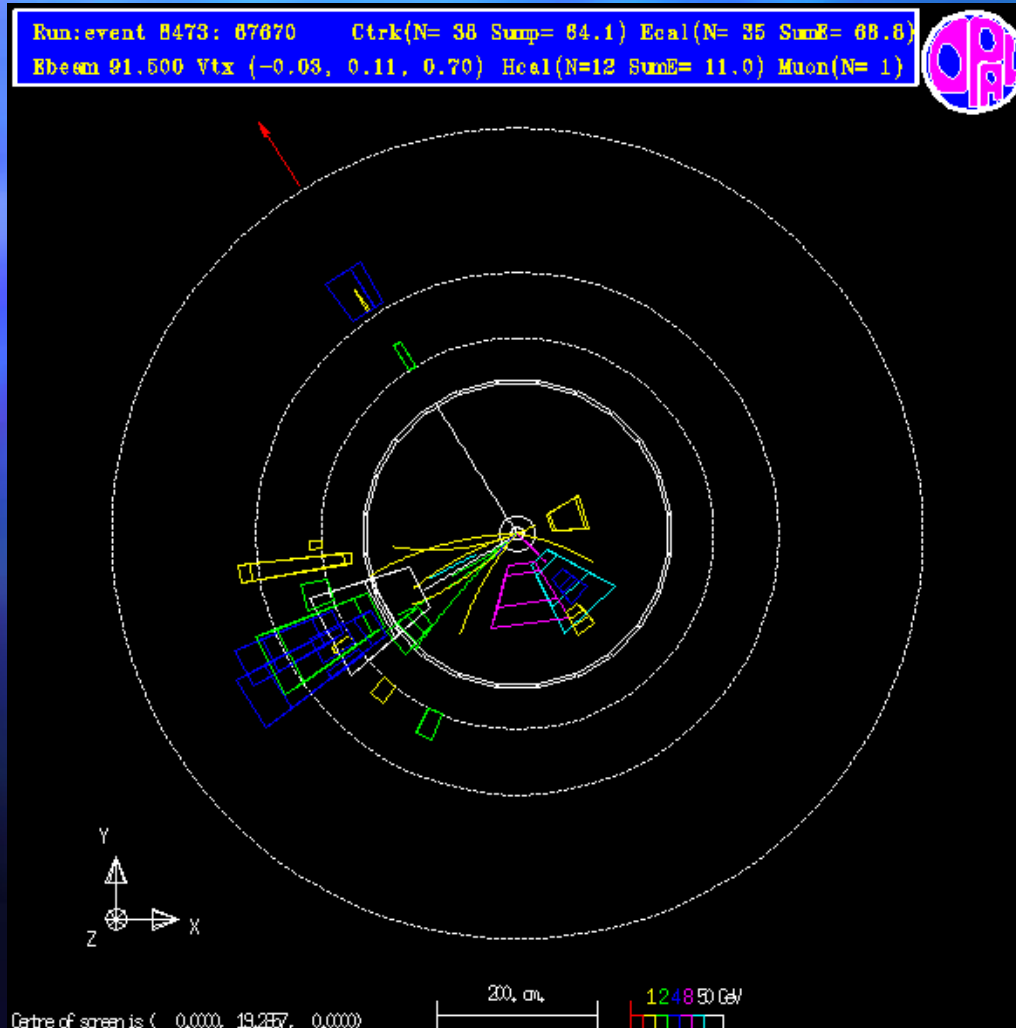
What sort of WW decay is this?

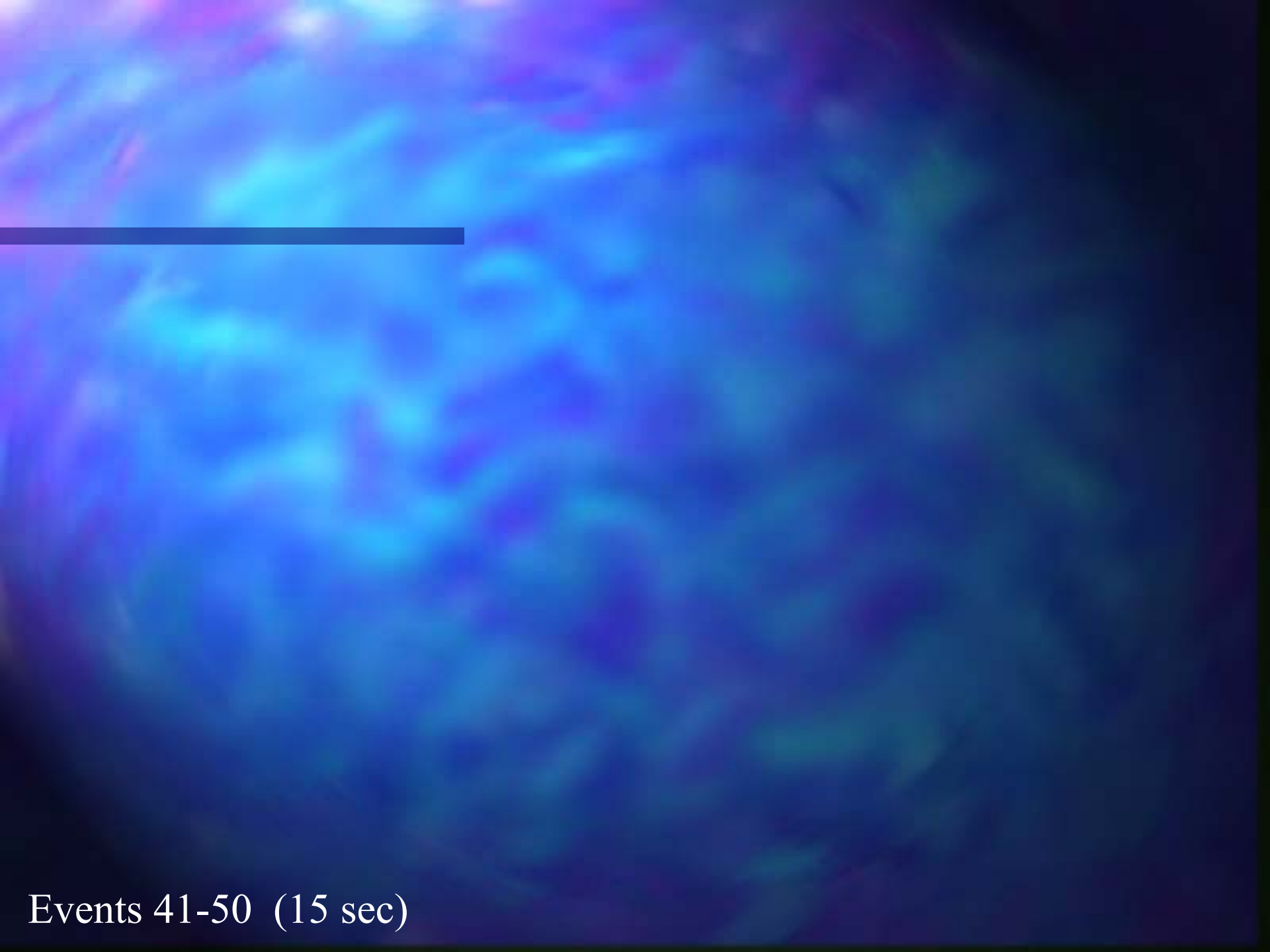
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



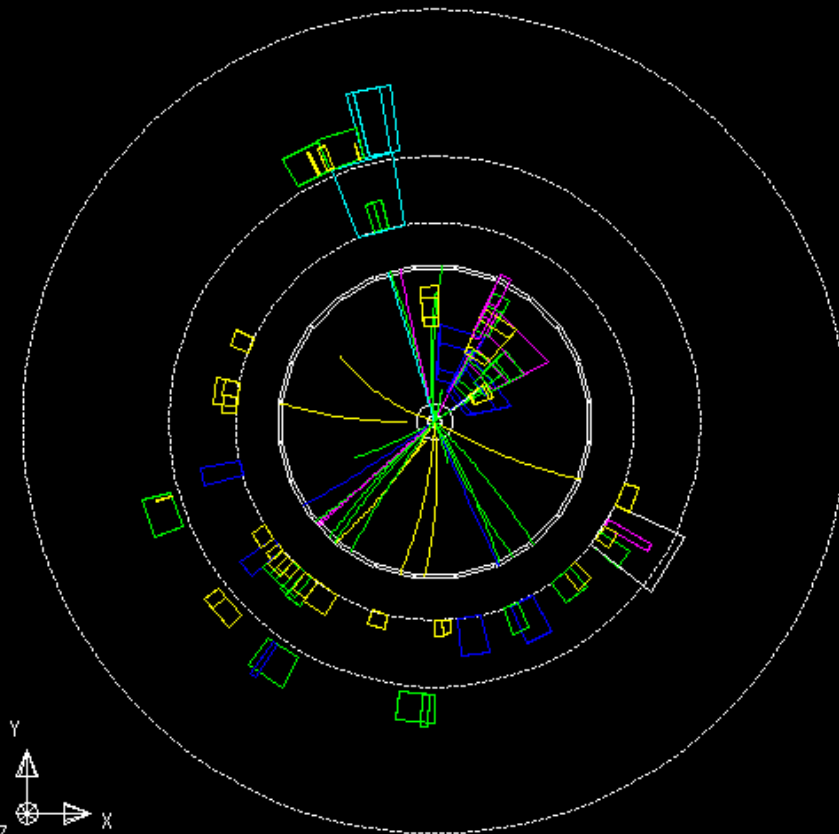


Events 41-50 (15 sec)

What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run: event 8698: 28998 Ctrk(N= 79 Sump= 81.7) Ecal(N= 82 SumE= 94.8)
Ebeam 91.500 Vtx (-0.02, 0.10, -0.33) Hcal(N=19 SumE= 27.1) Muon(N= 0)



Centre of screen is (0.000, 19.257, 0.000)

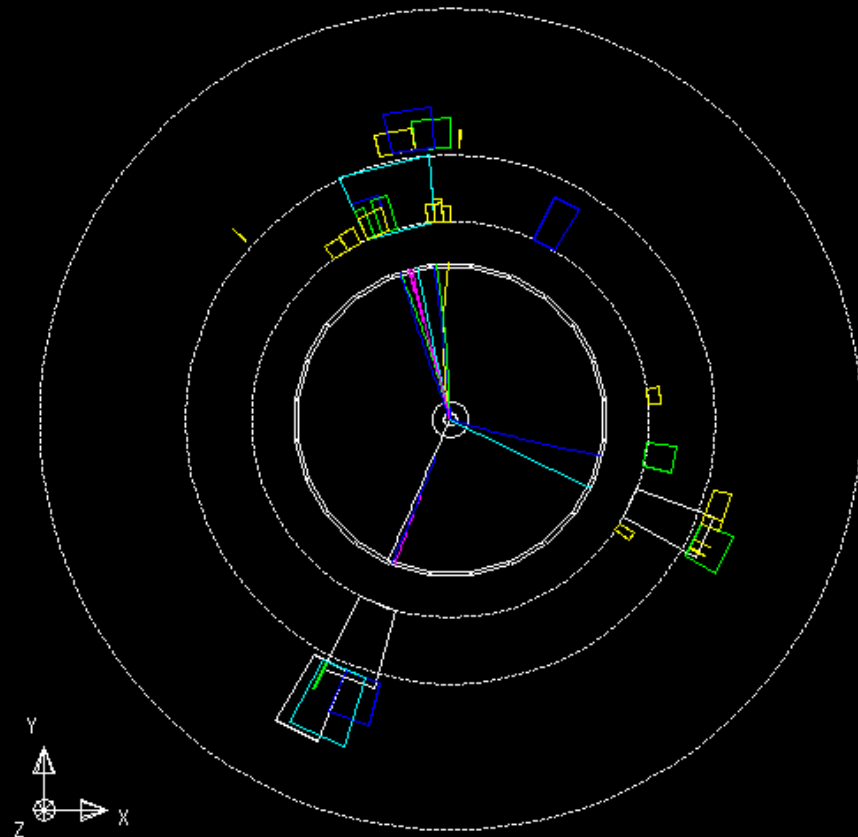
200. cm

124850 GeV

What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run: event 8470: 69013 Ctrk(N= 30 Sump= 81.7) Ecal(N= 44 SumE= 88.8)
Ebeam 91.500 Vtx (-0.01, 0.10, 0.84) Hcal(N=17 SumE= 28.1) Muon(N= 0)



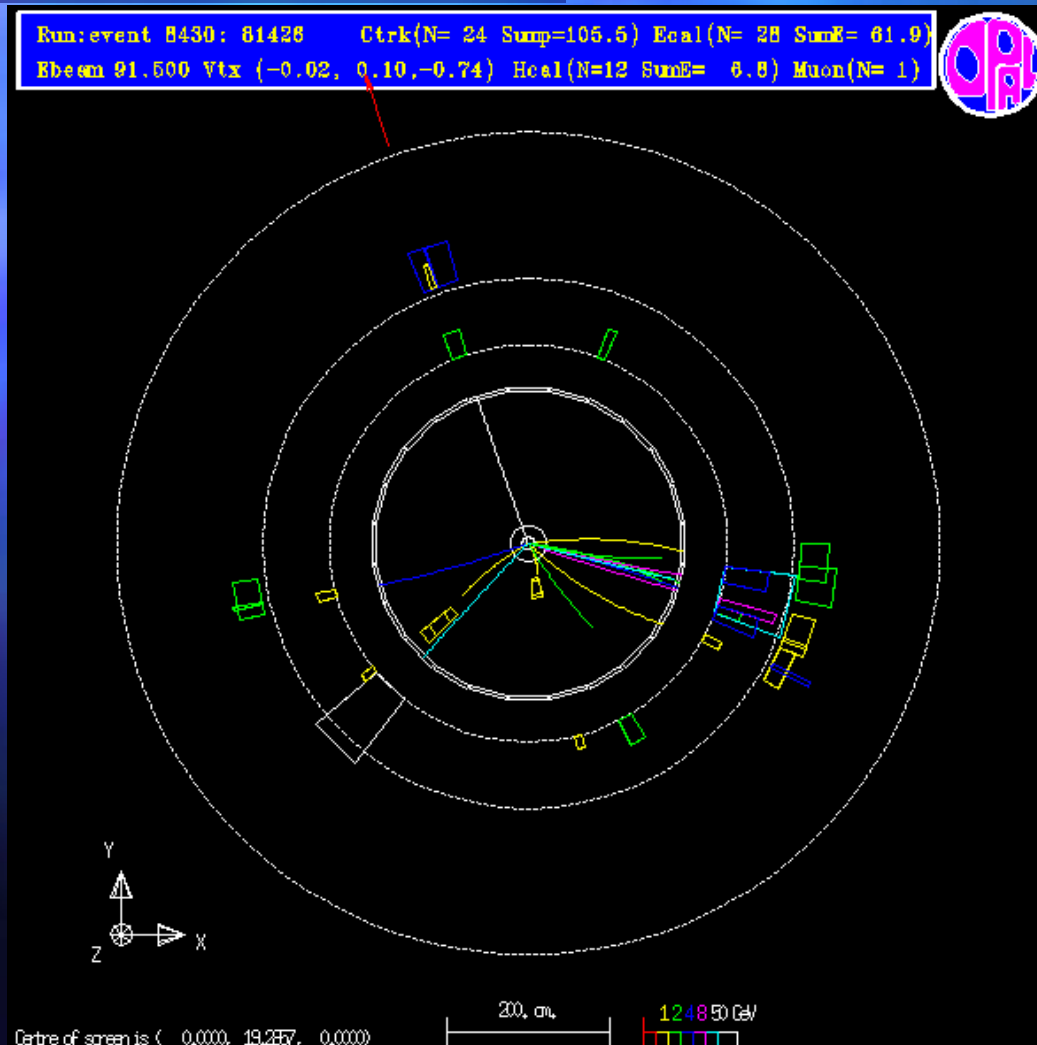
Centre of screen is (0.000, 19.287, 0.000)

200 cm

124850 GeV

What sort of WW decay is this?

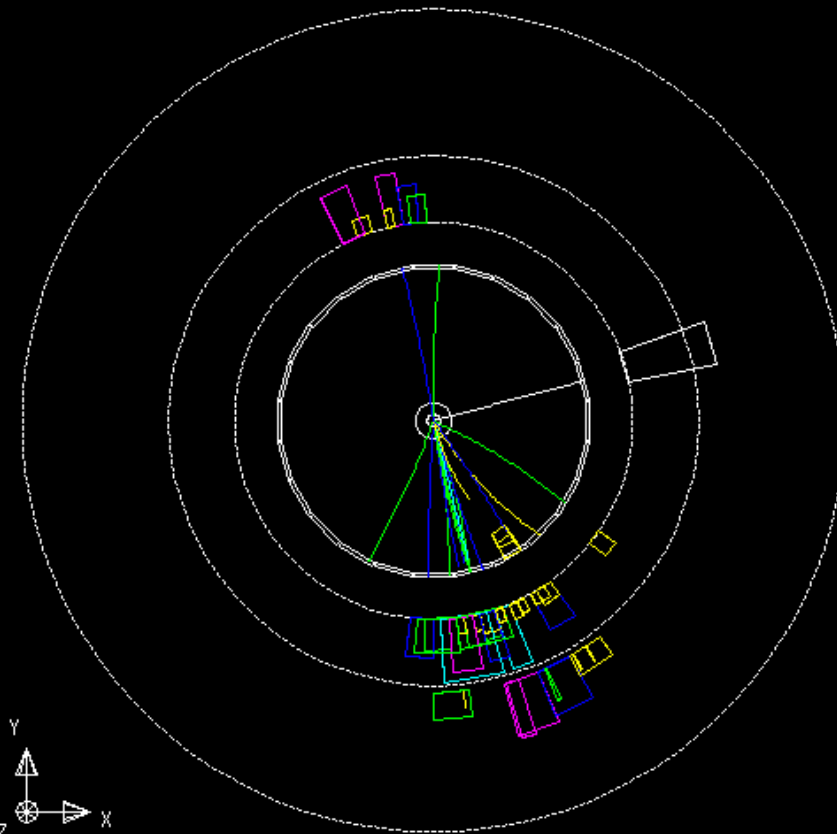
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run: event 8723: 24453 Ctrk(N= 34 Sump= 88.2) Ecal(N= 58 SumE=109.5)
Ebeam 91.500 Vtx (-0.06, 0.10, -4.11) Hcal(N=10 SumE= 11.3) Muon(N= 1)



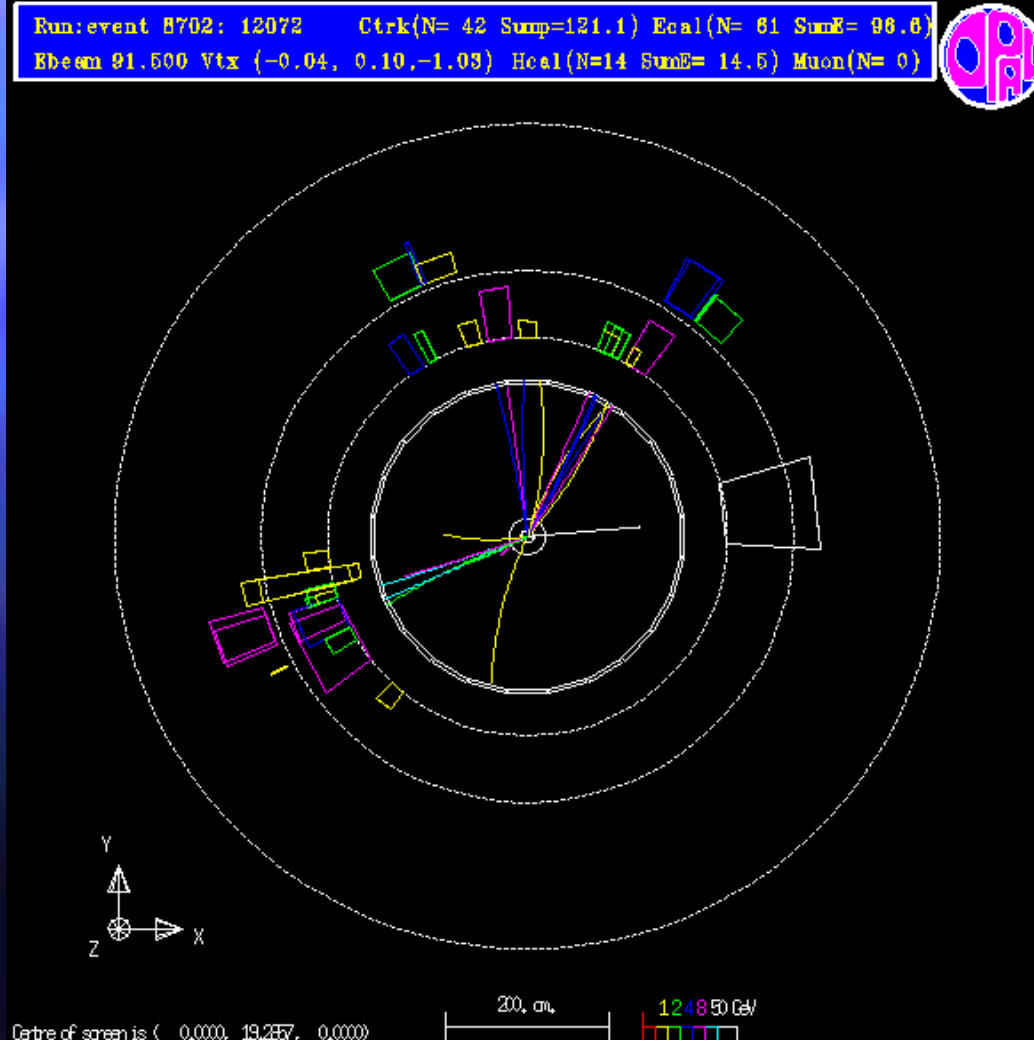
Centre of screen is (0.0000, 19.2857, 0.0000)

200. cm

124850 GeV

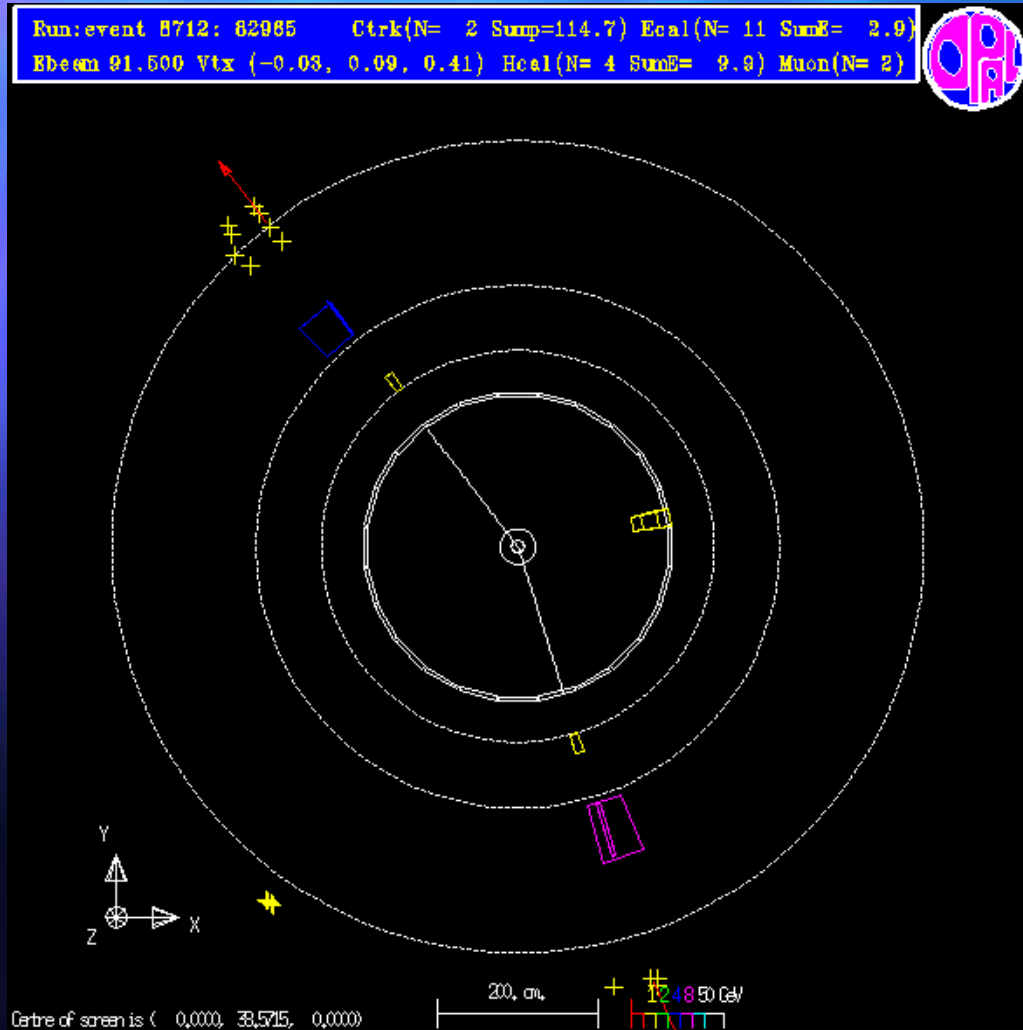
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

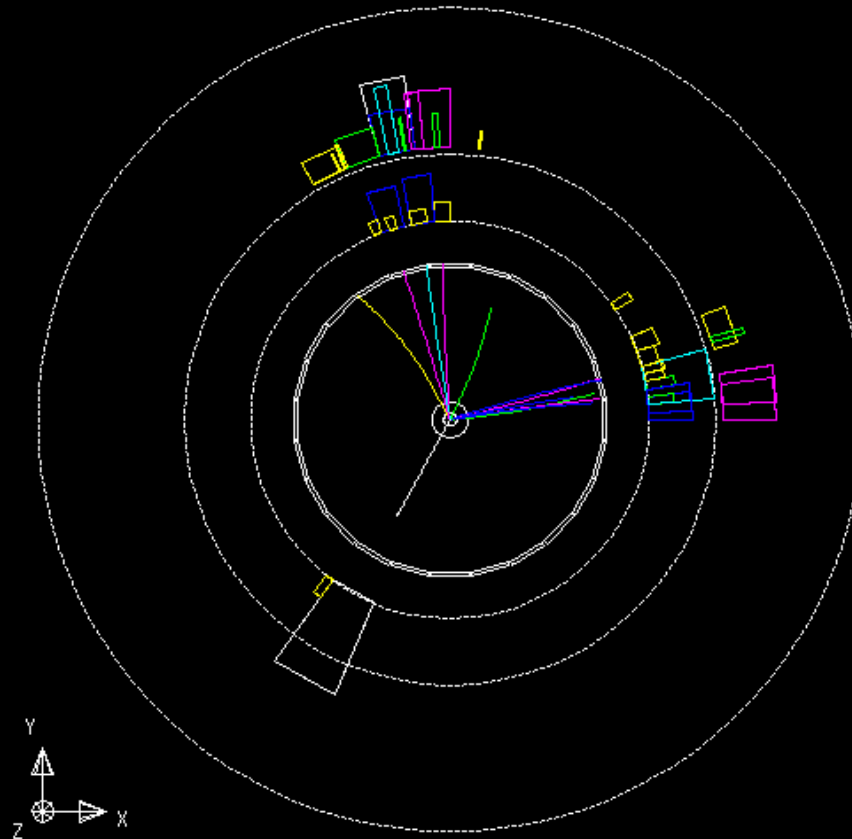
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run:event 8523: 65027 Ctrk(N= 17 SumP=118.1) Ecal(N= 38 SumE=107.8)
Ebeam 91.500 Vtx (-0.04, 0.10, 0.49) Hcal(N=18 SumE= 35.2) Muon(N= 0)



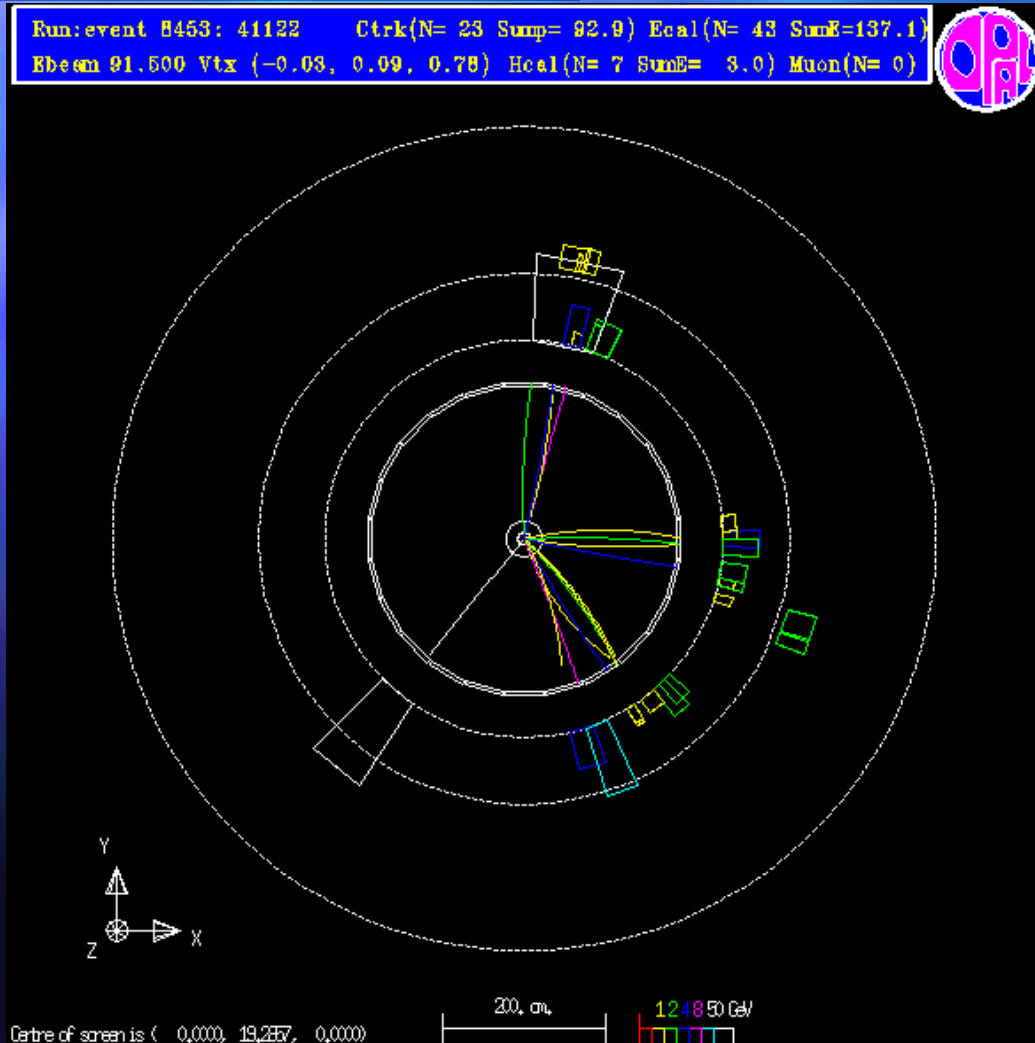
Centre of screen is (0.000, 19.287, 0.000)

200 cm

124850 GeV

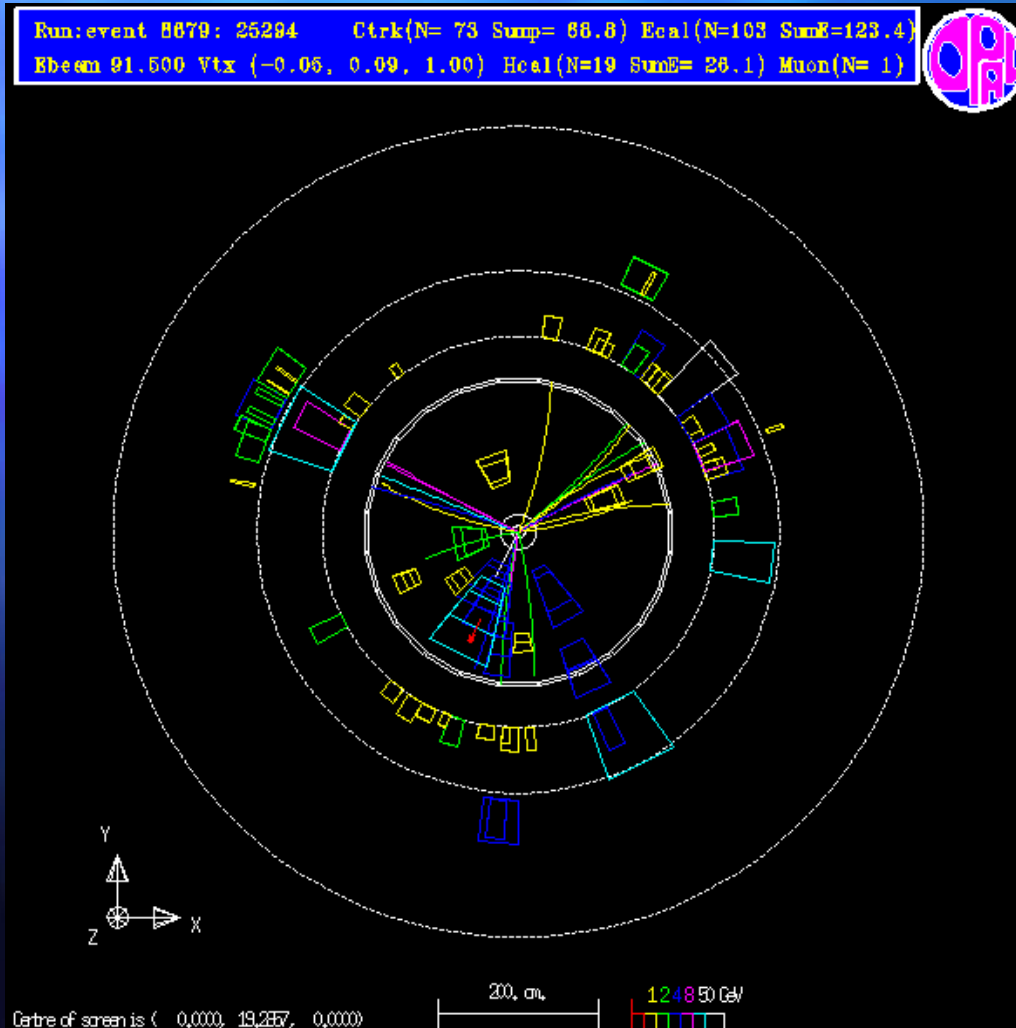
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



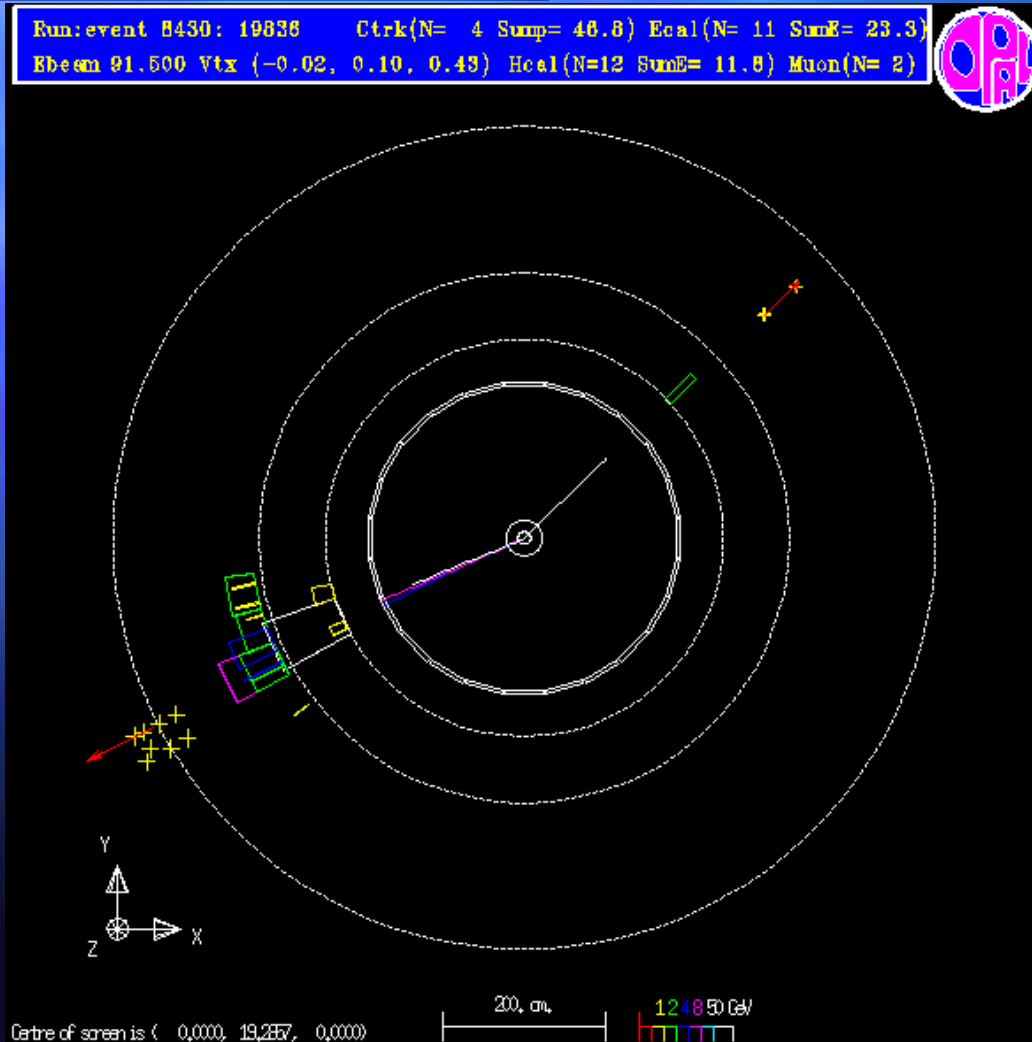
What sort of WW decay is this?

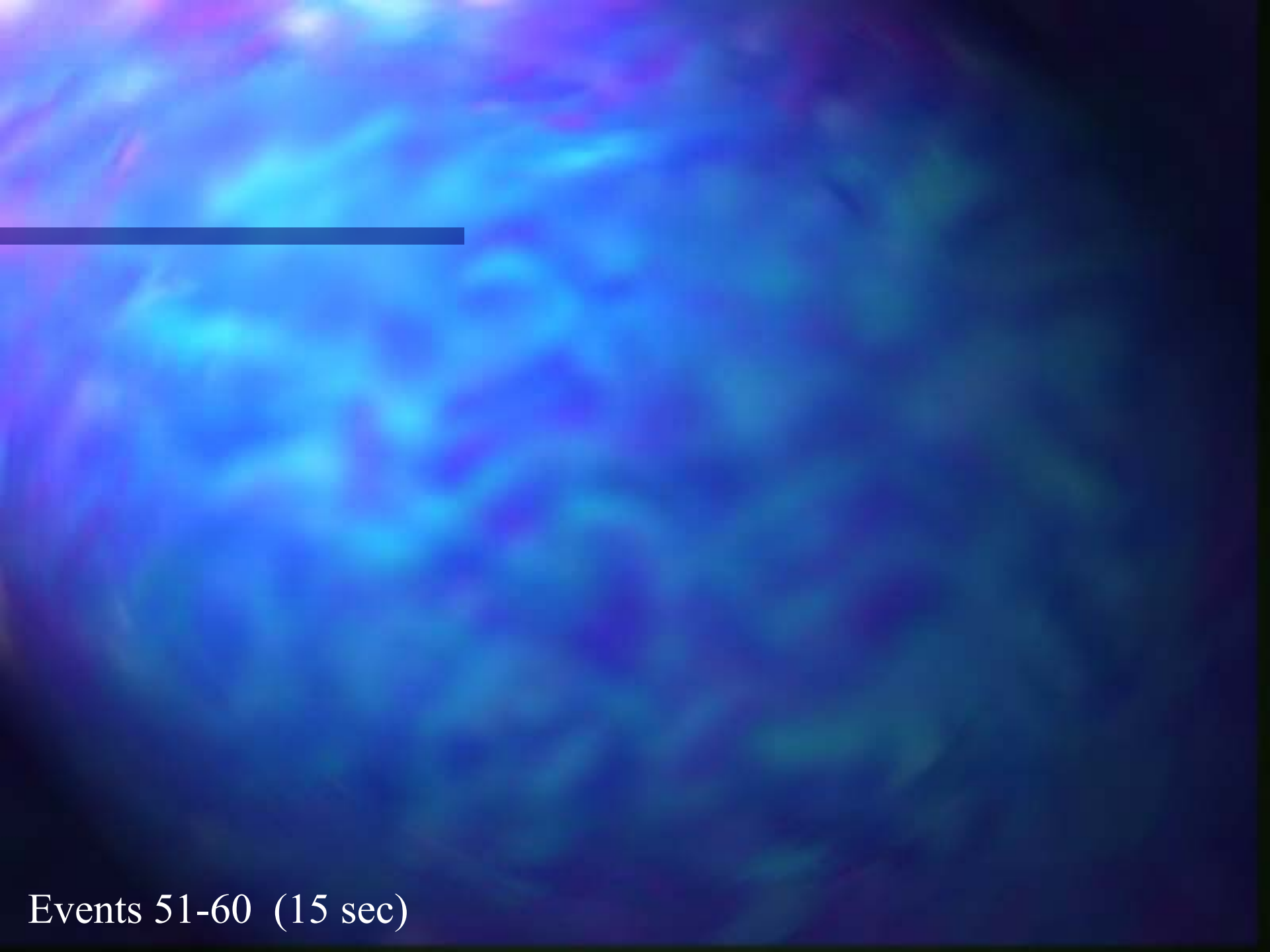
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



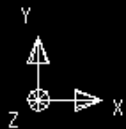
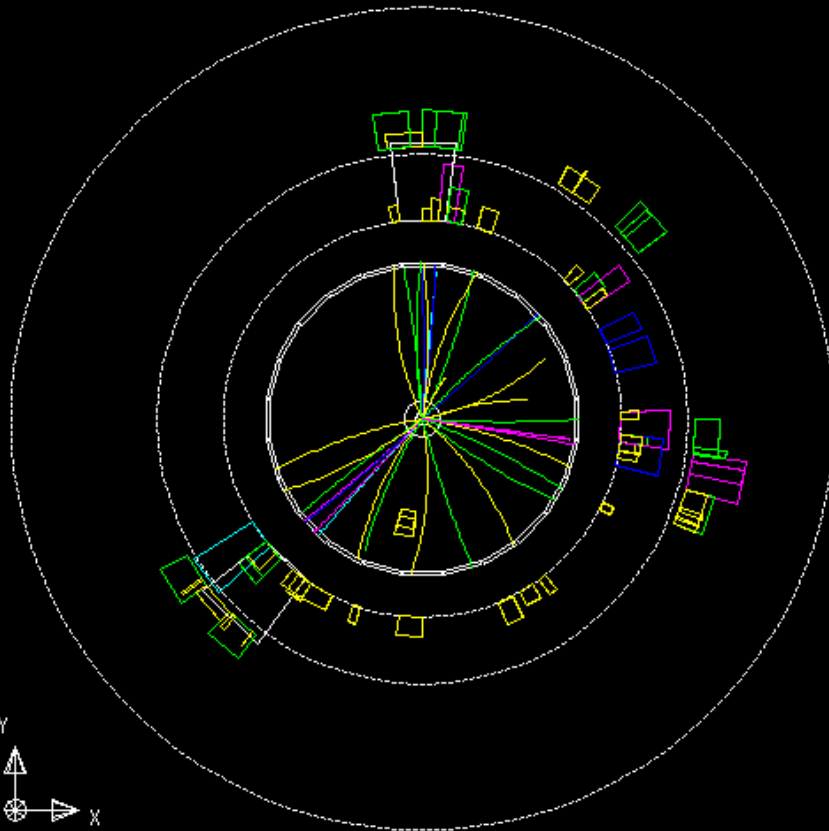


Events 51-60 (15 sec)

What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run:event 8468: 48025 Ctrk(N= 68 Sump= 89.3) Ecal(N= 81 SumE=113.4)
Ebeam 91.500 Vtx (-0.08, 0.10, -0.11) Hcal(N=26 SumE= 18.7) Muon(N= 0)



Centre of screen is (0.000, 19.287, 0.000)

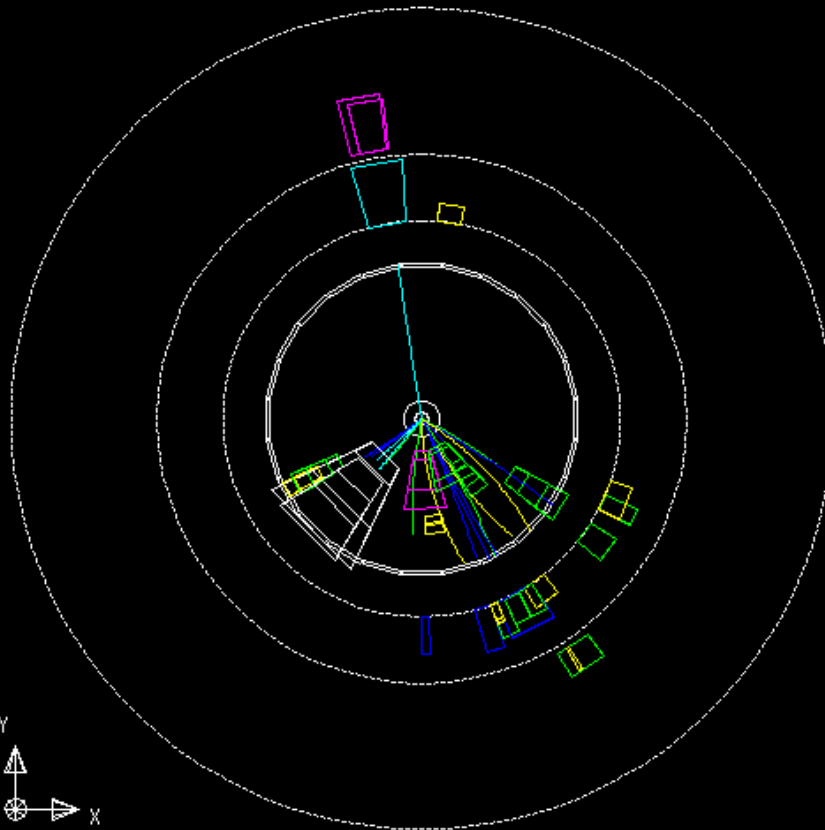
200 cm

124850 GeV

What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run: event 8875: 7120 Ctrk(N= 40 Sump= 80.5) Ecal(N= 51 SumE= 62.4)
Ebeam 91.500 Vtx (0.00, 0.10, 1.30) Hcal(N= 9 SumE= 28.2) Muon(N= 0)



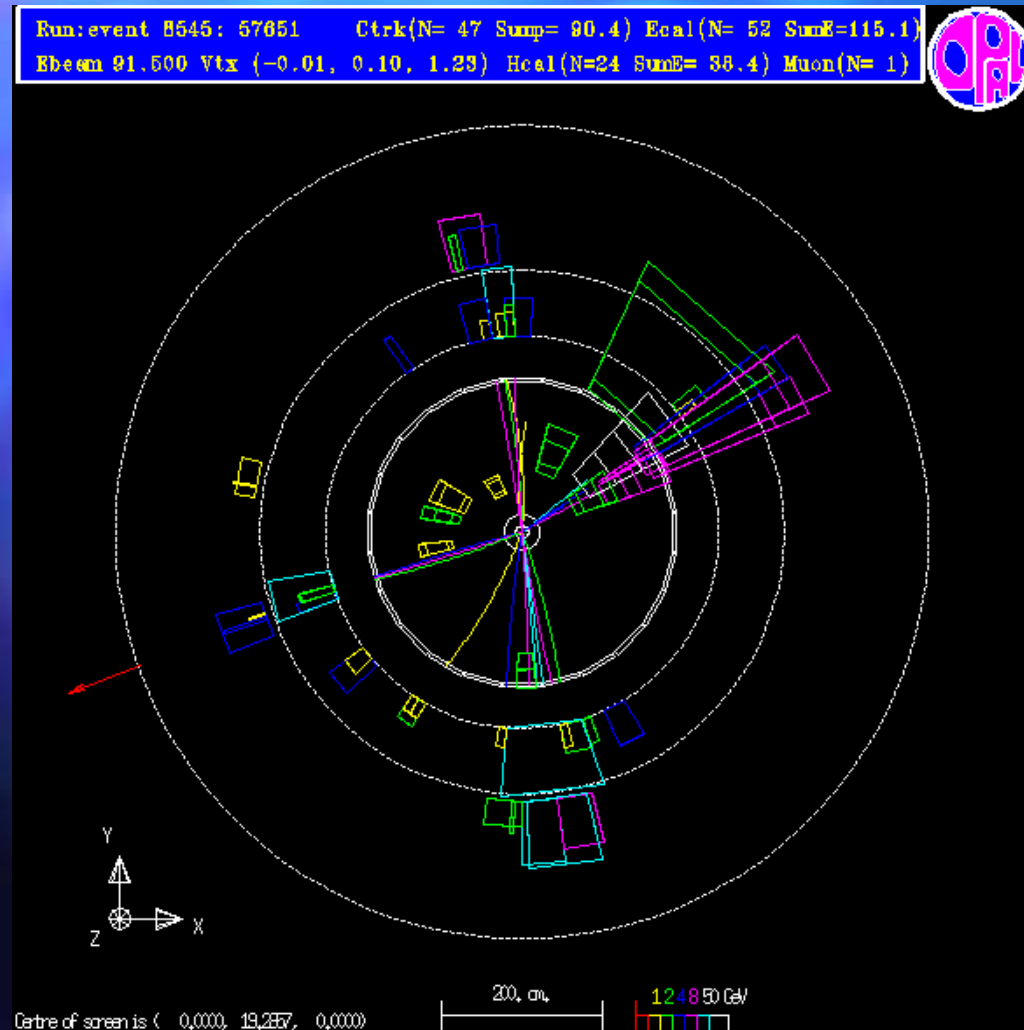
Centre of screen is (0.000, 19.287, 0.000)

200 cm

124850 GeV

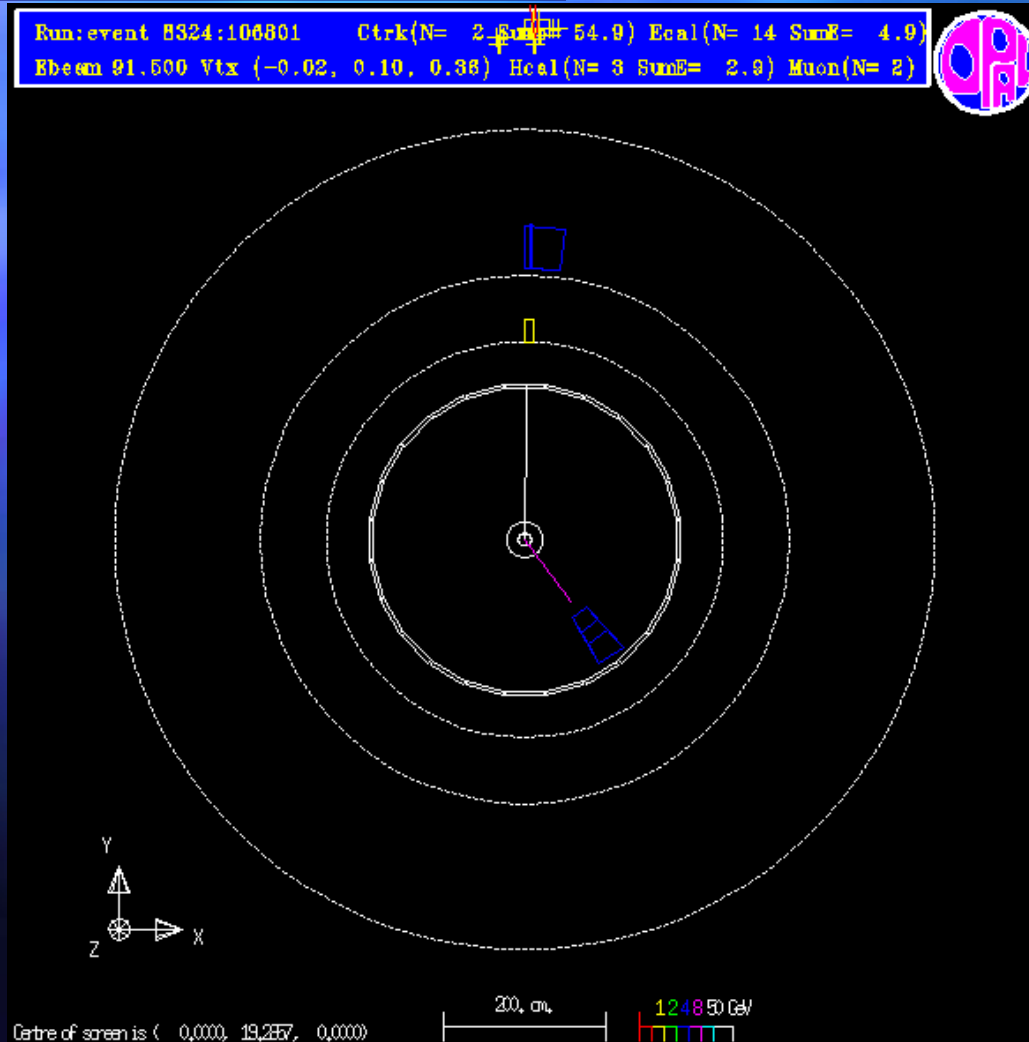
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

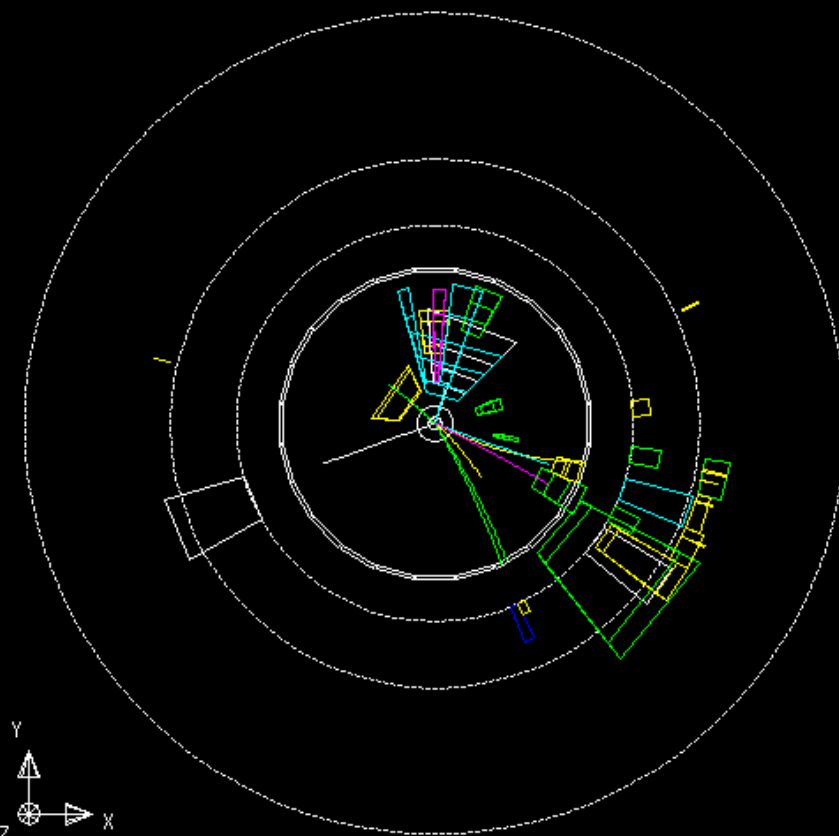
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run: event 8298: 16149 Ctrk(N= 21 SumP= 58.9) Ecal(N= 47 SumE=117.3)
Ebeam 91.500 Vtx (-0.03, 0.10, 0.69) Hcal(N=18 SumE= 33.4) Muon(N= 0)



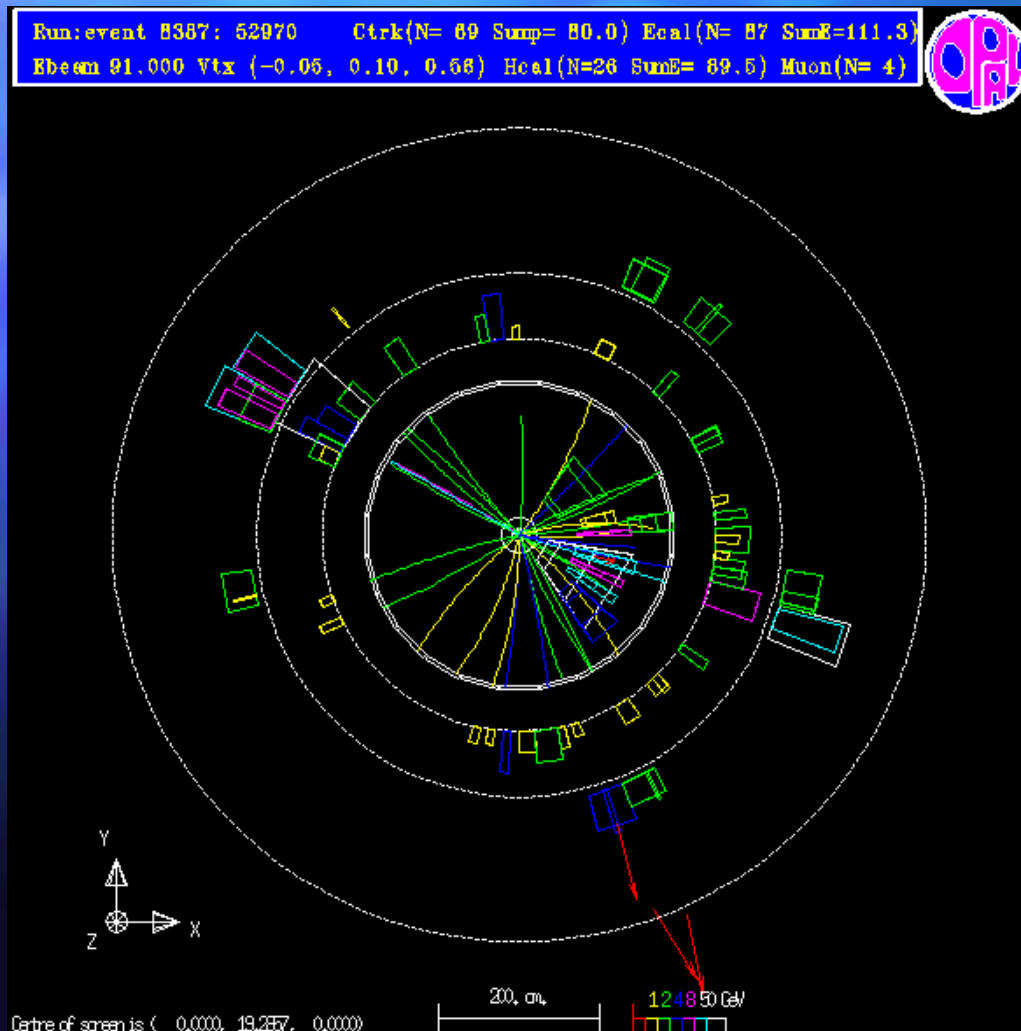
Centre of screen is (0.000, 19.287, 0.000)

200 cm

124850 GeV

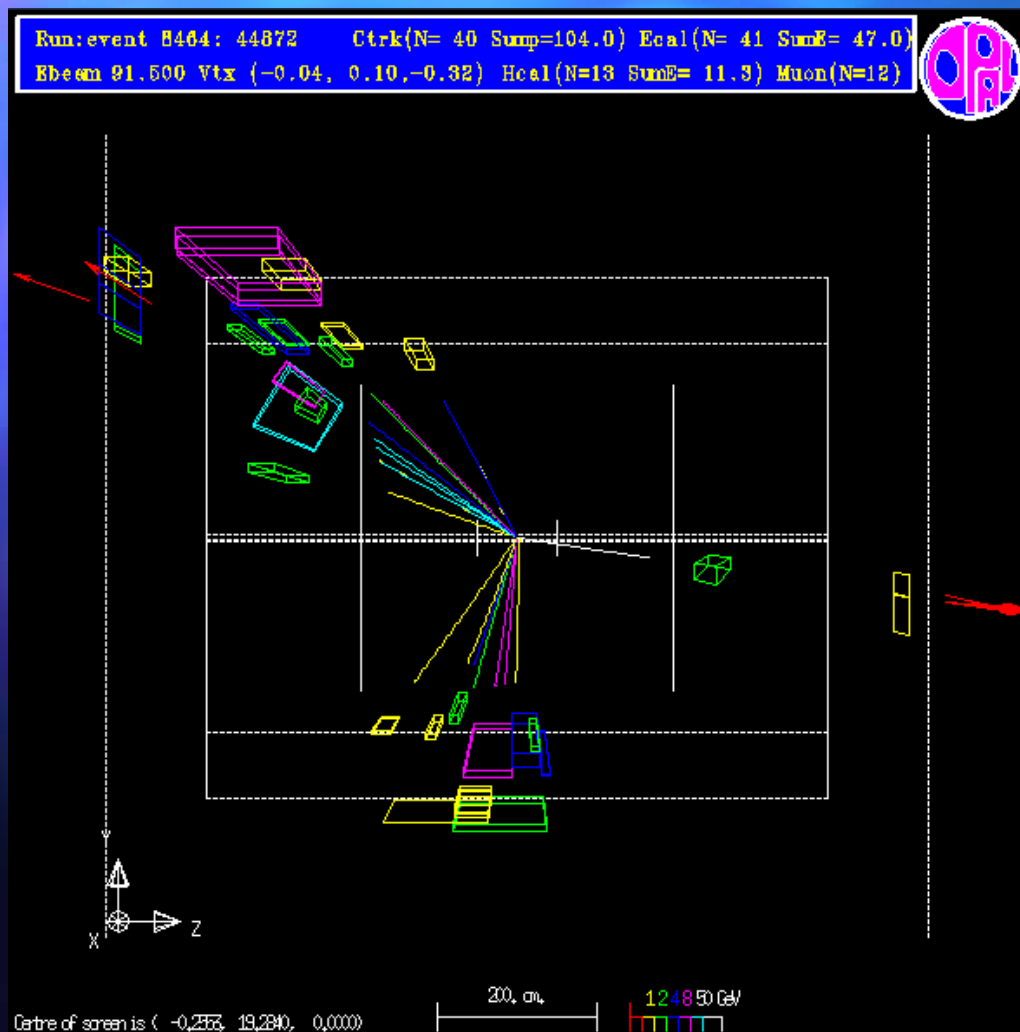
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



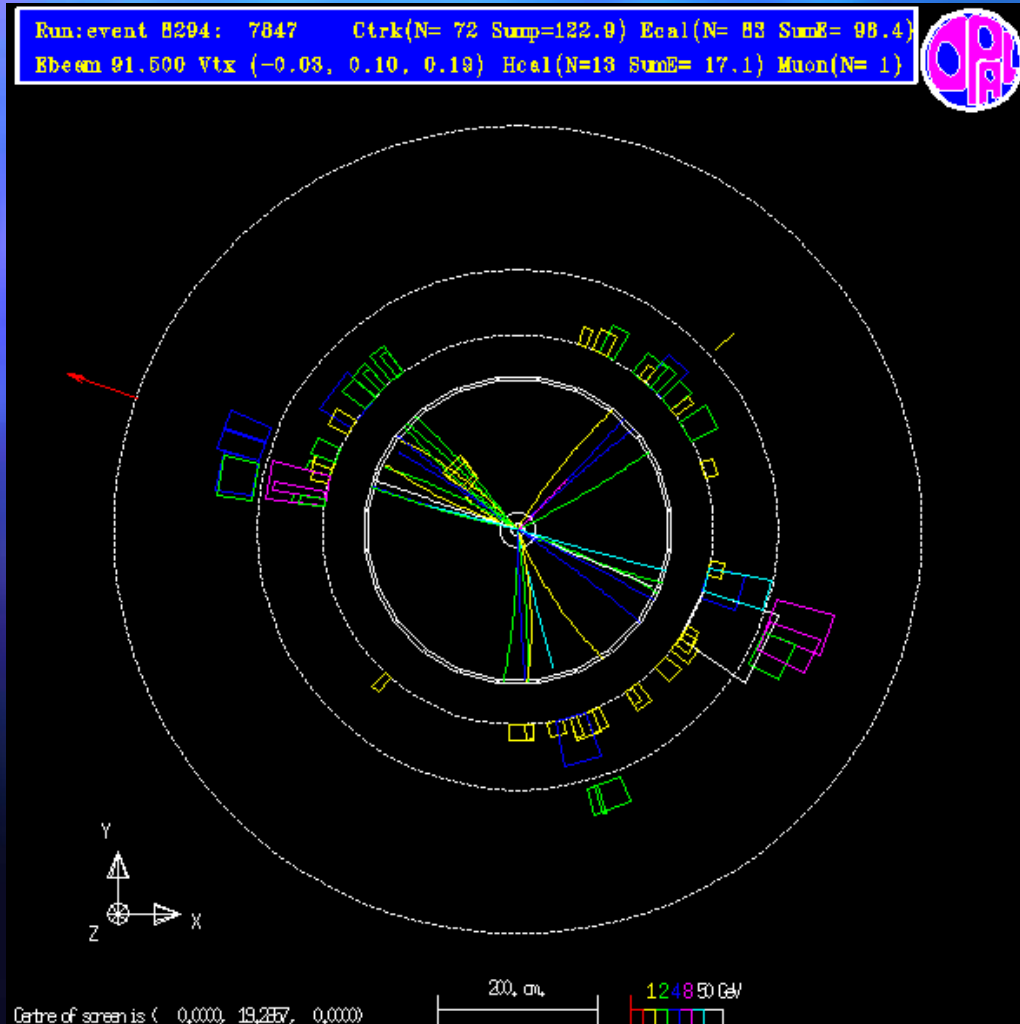
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



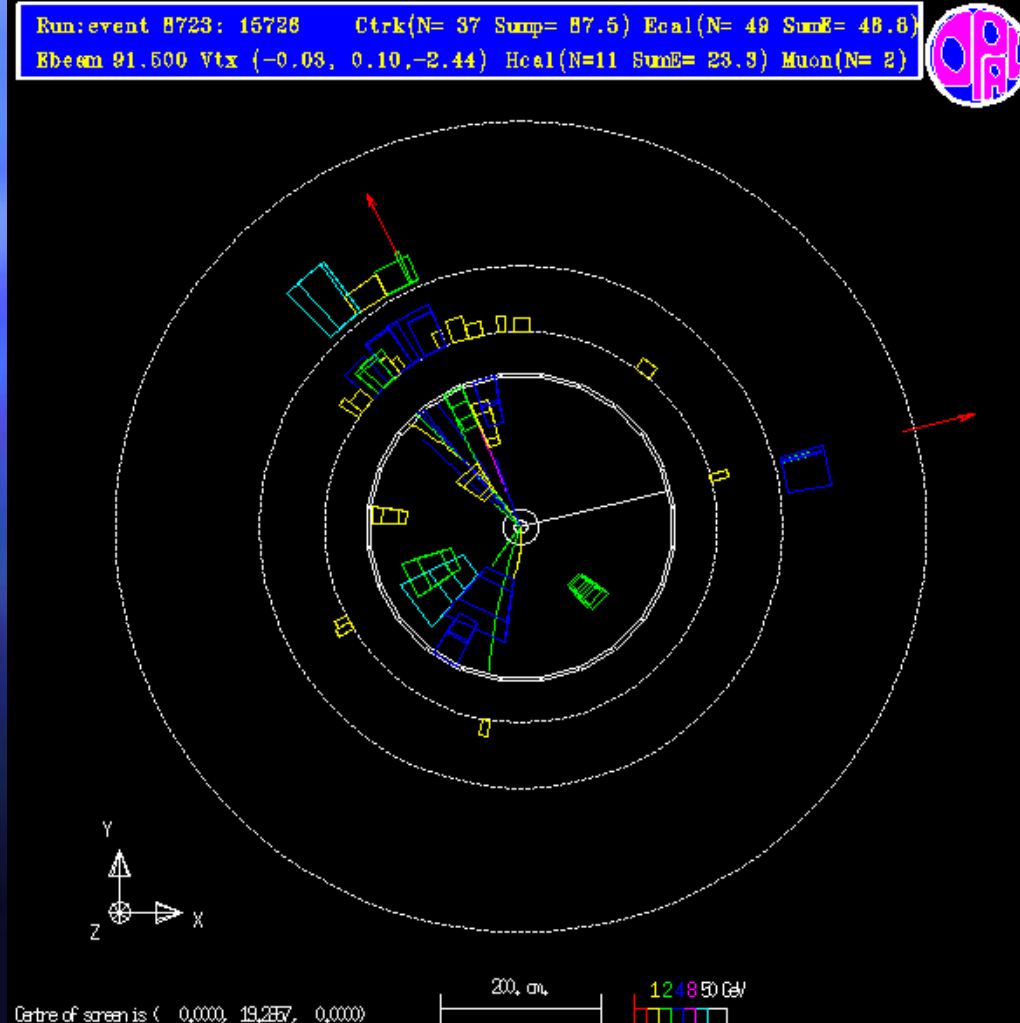
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



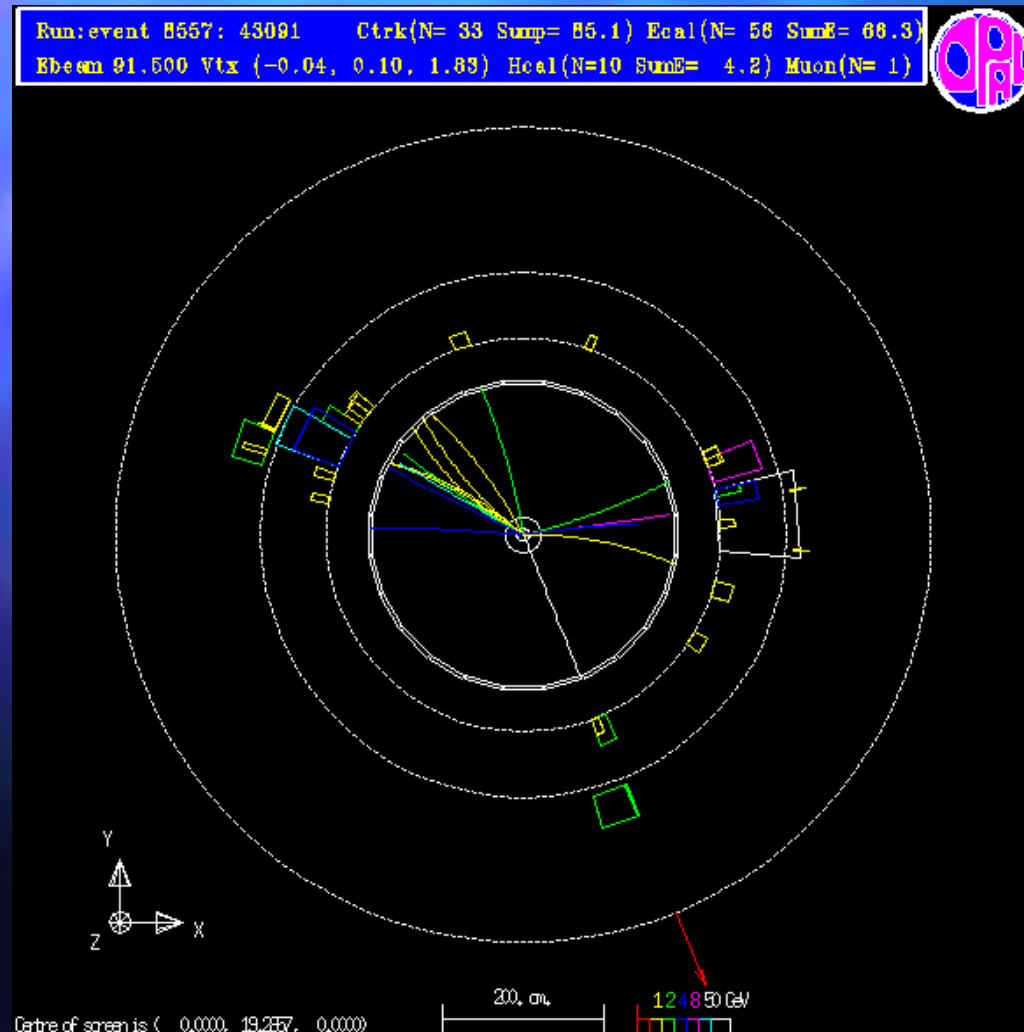
What sort of WW decay is this?

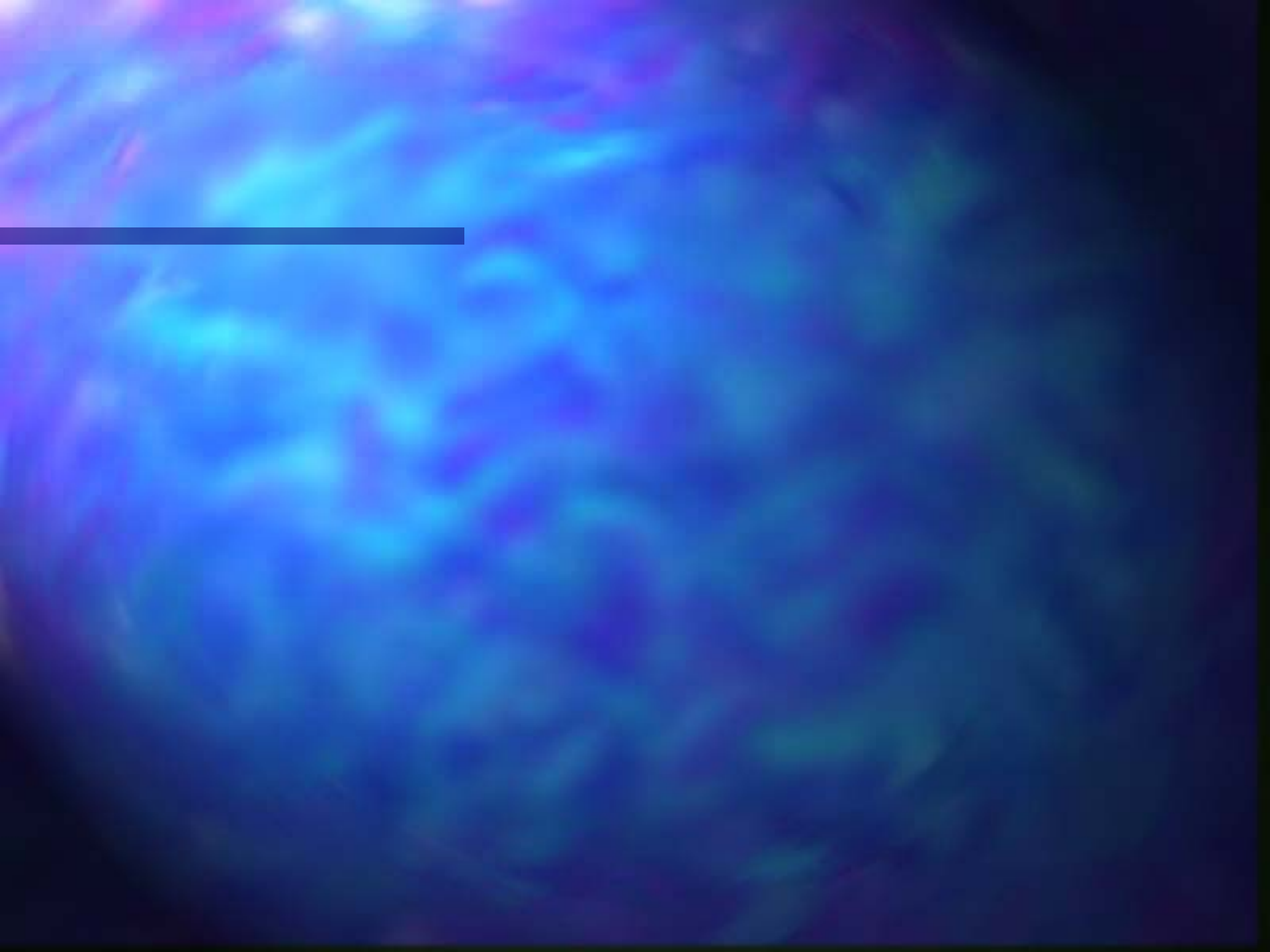
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

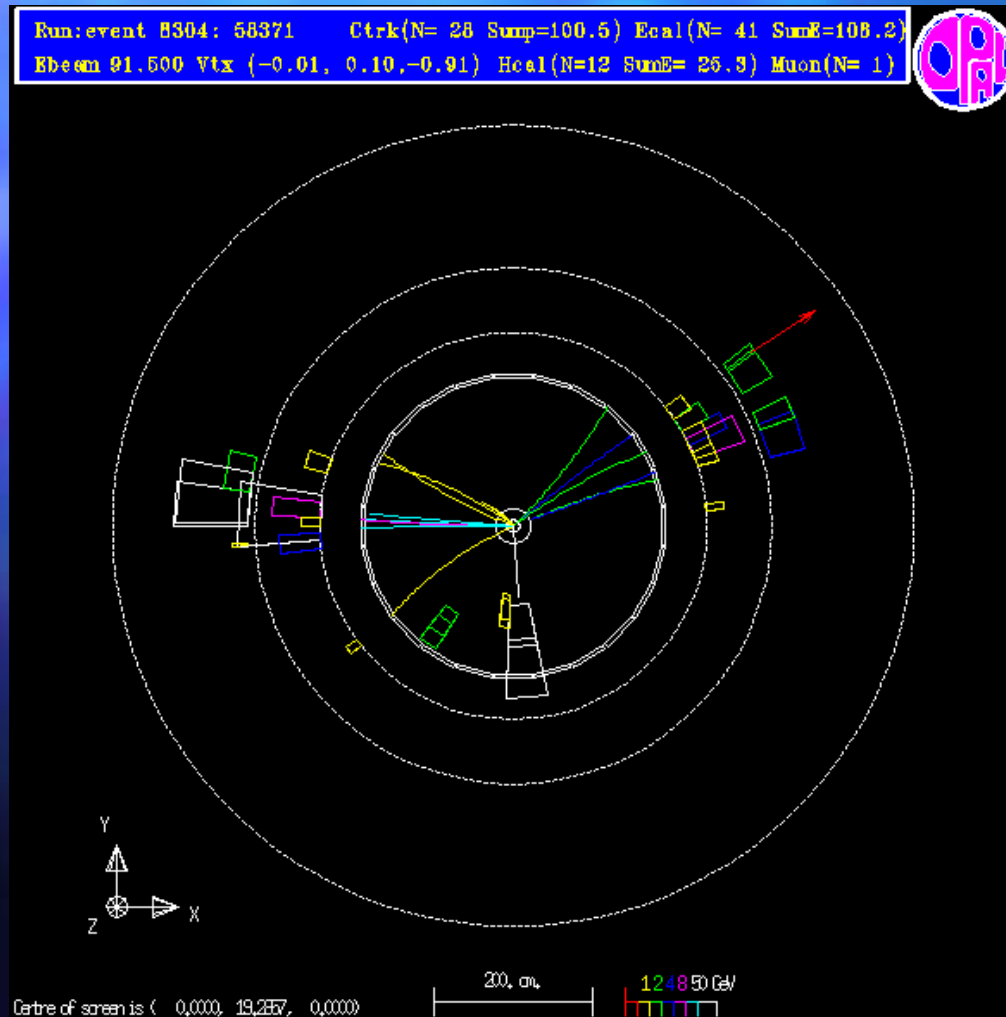
1. Double hadronic decay
2. Mixed
3. Double leptonic decay





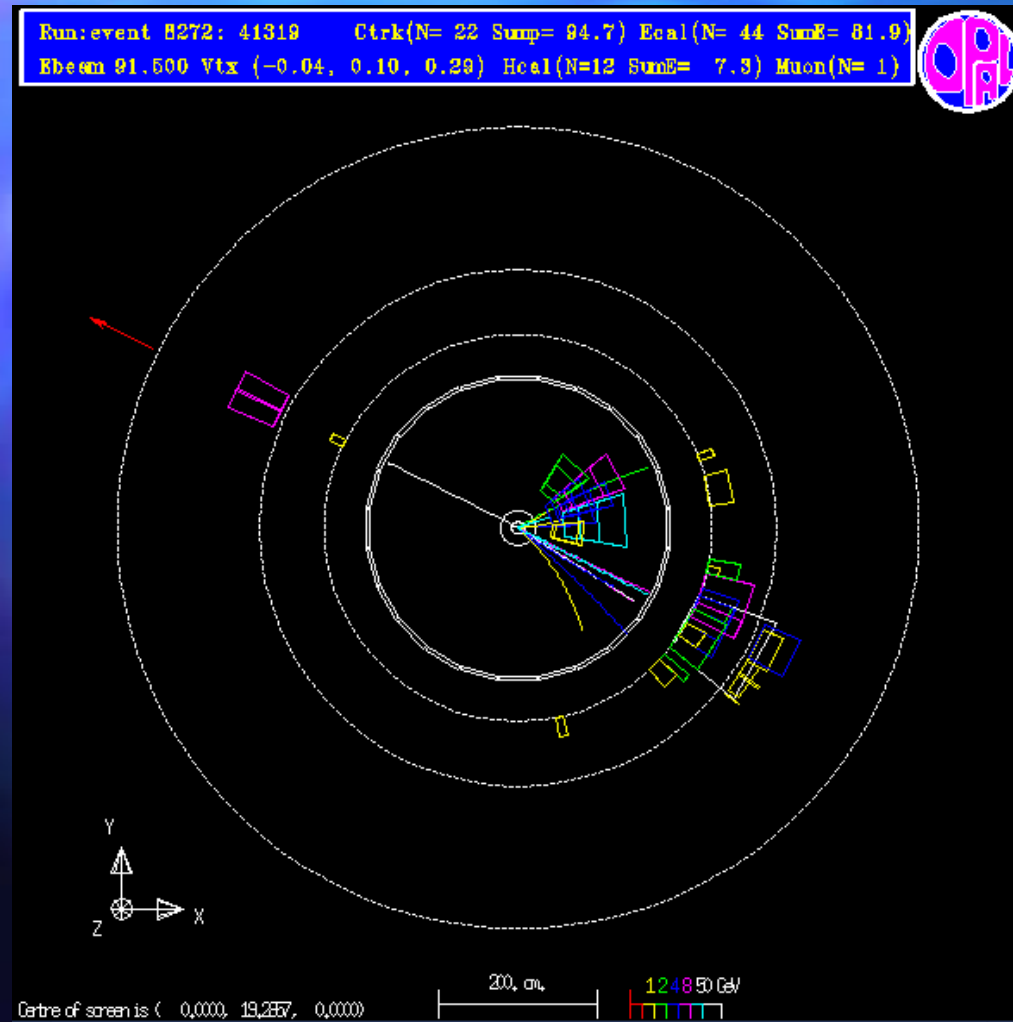
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



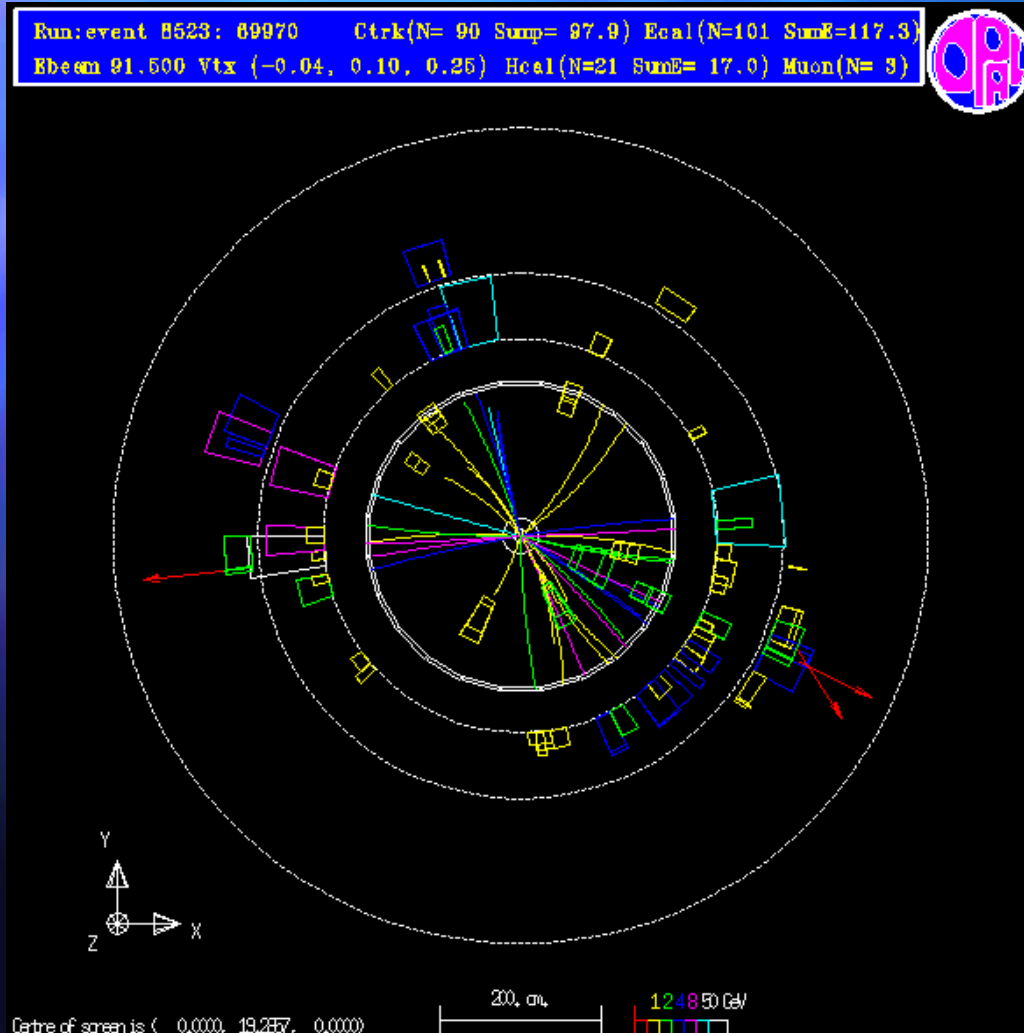
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



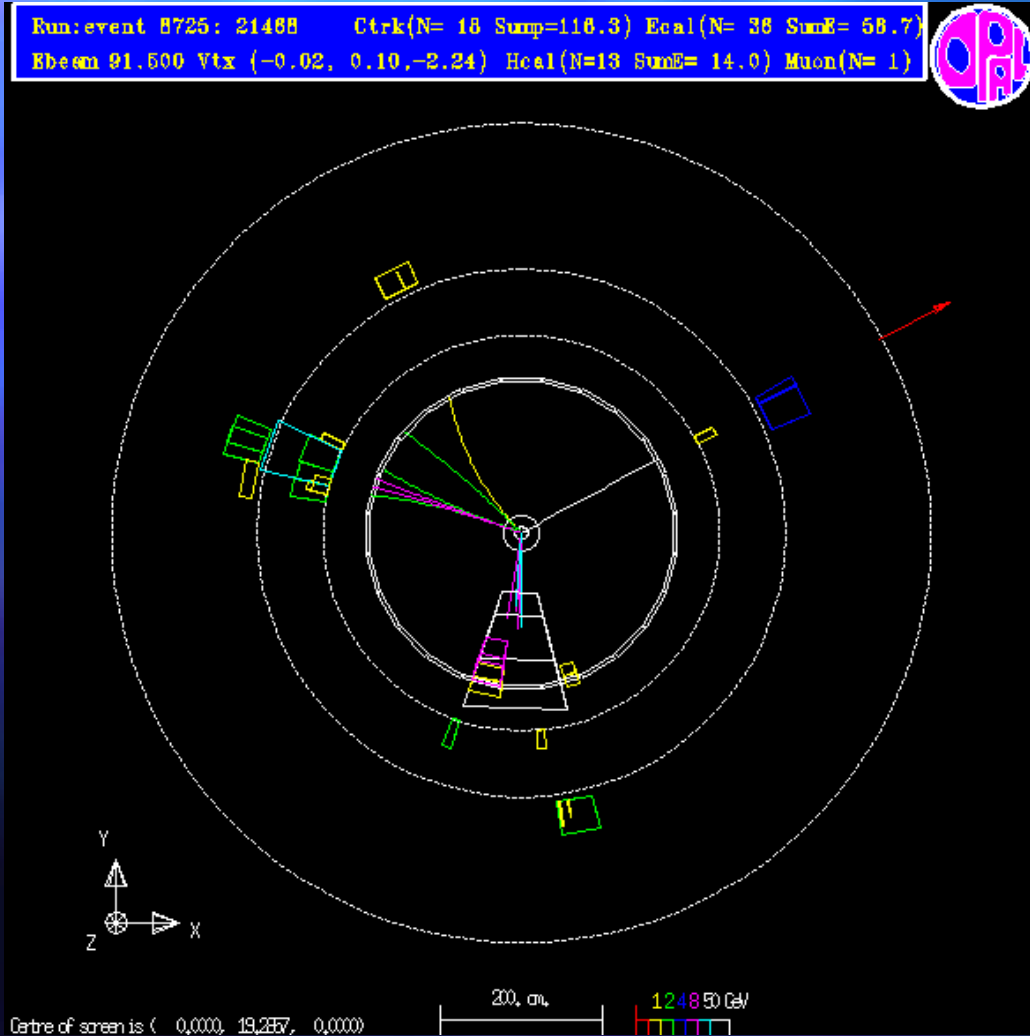
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



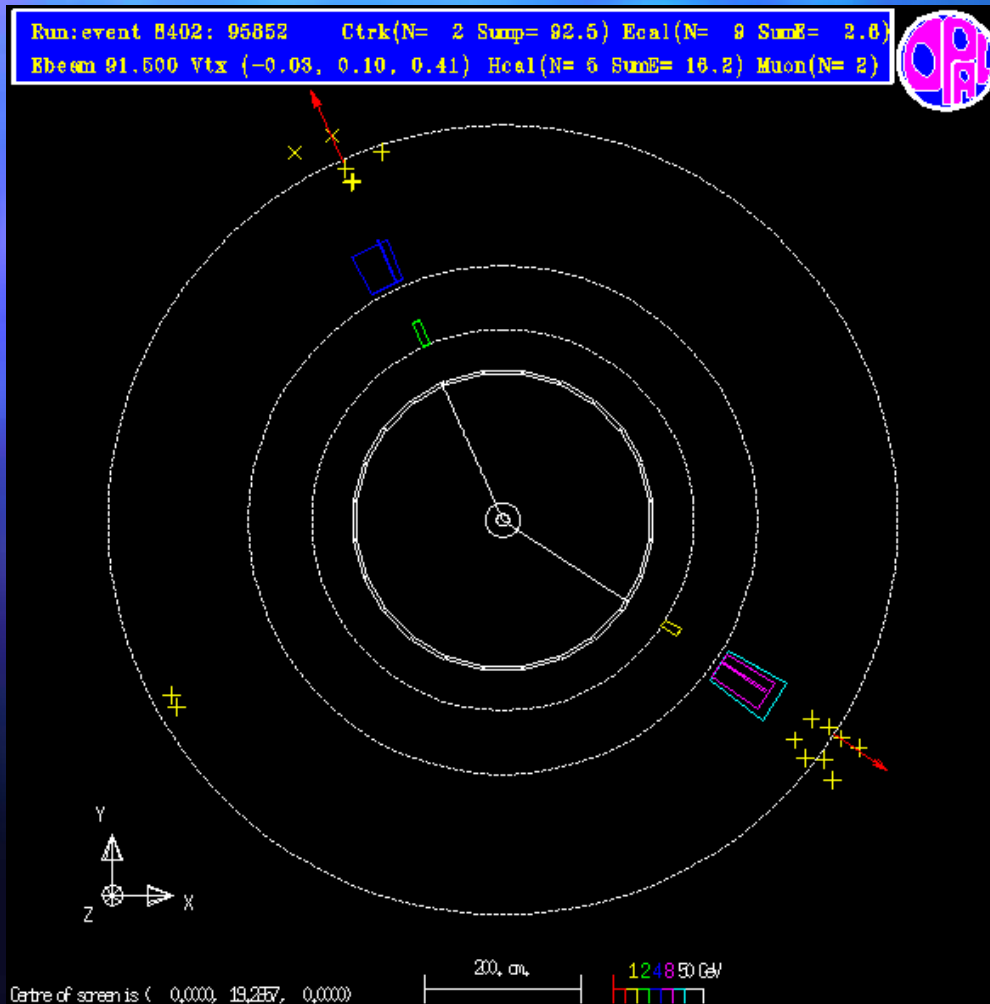
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



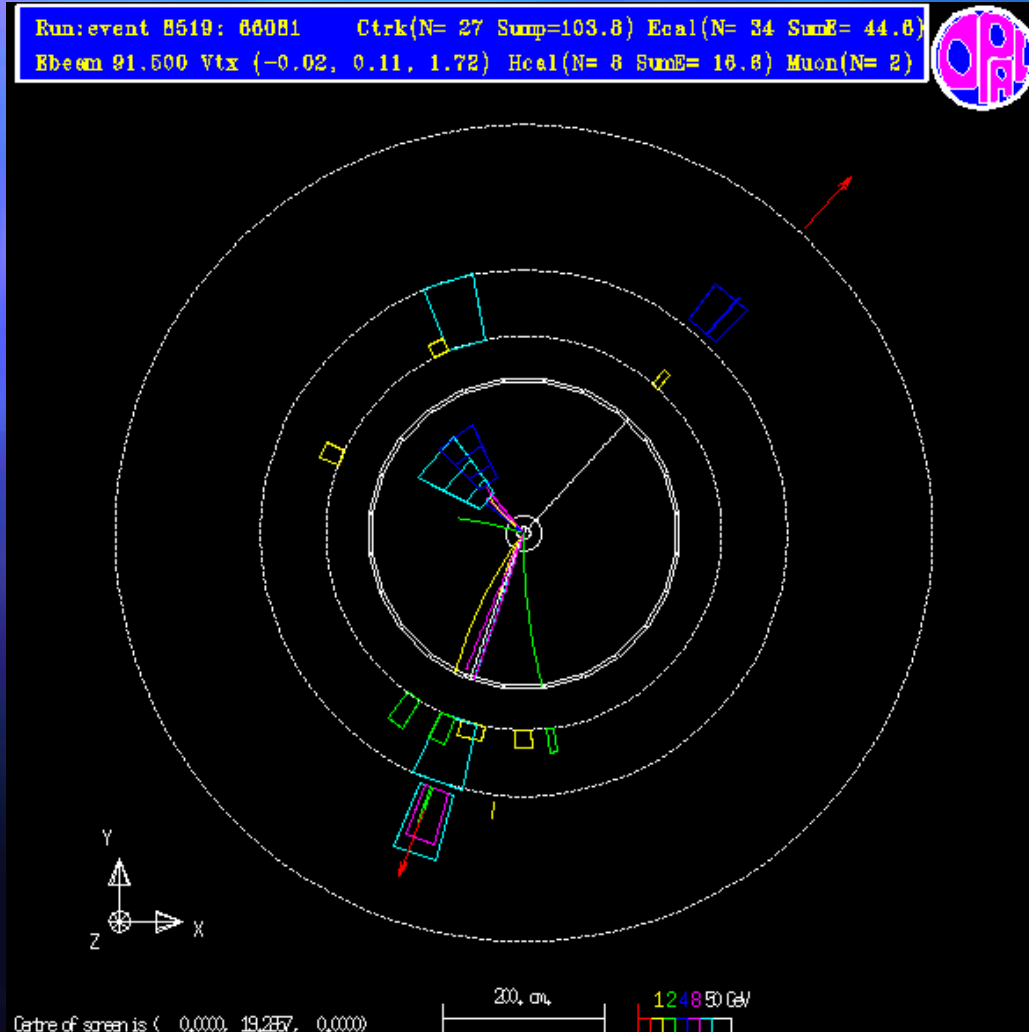
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



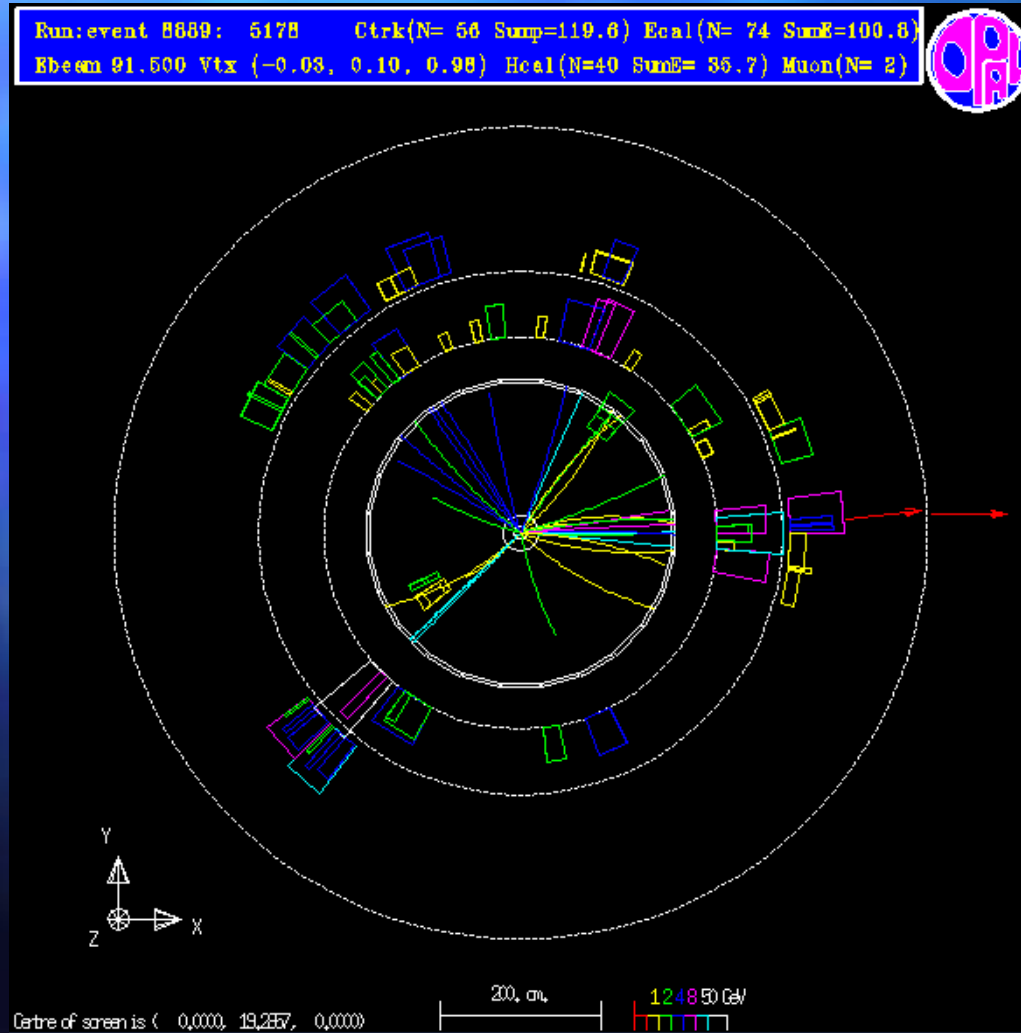
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



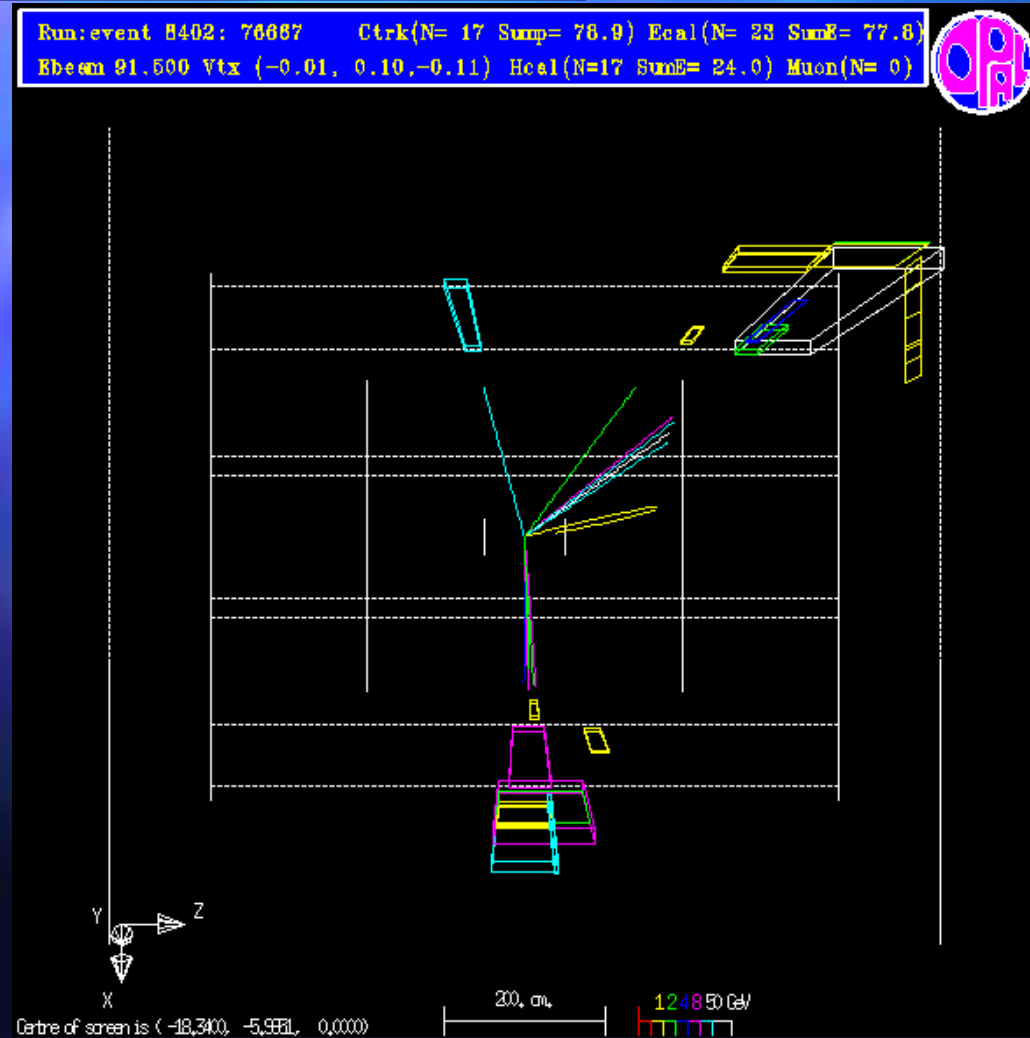
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



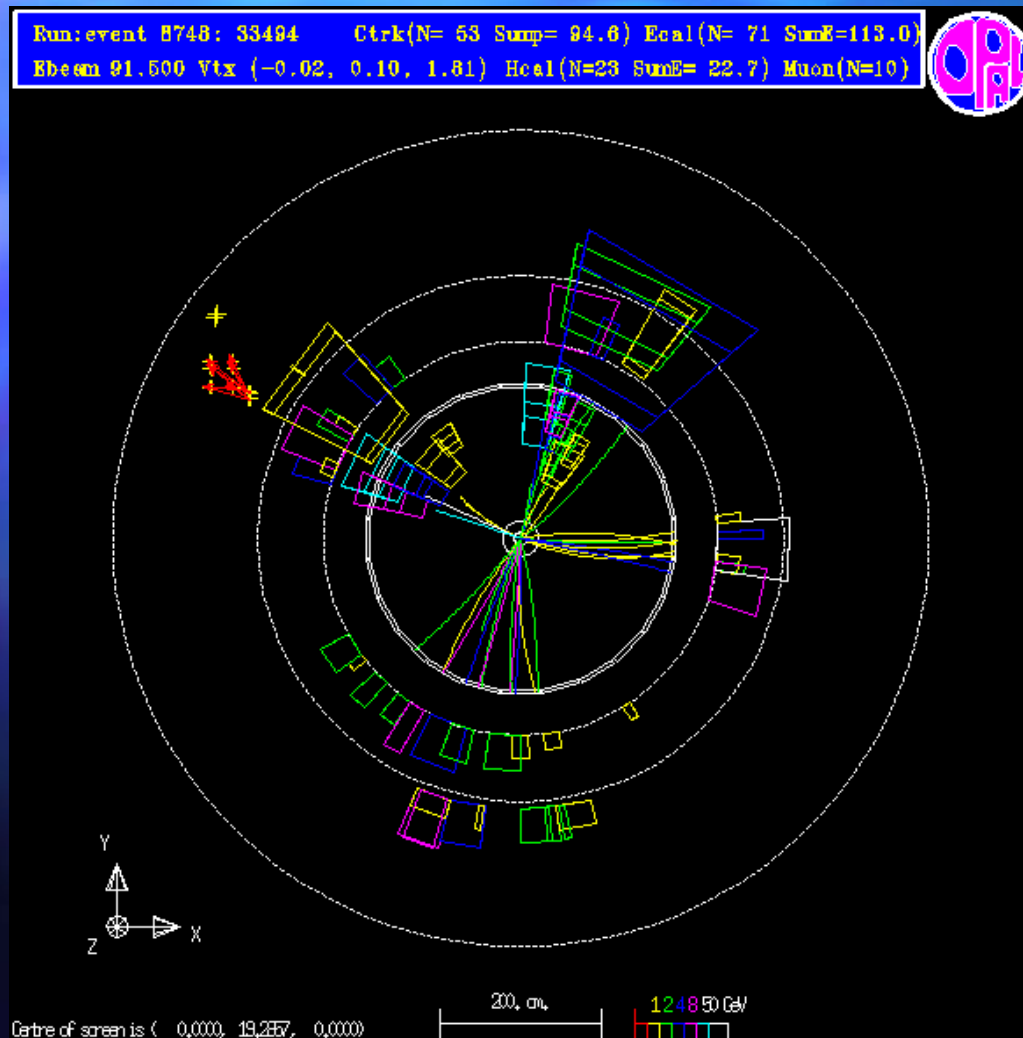
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



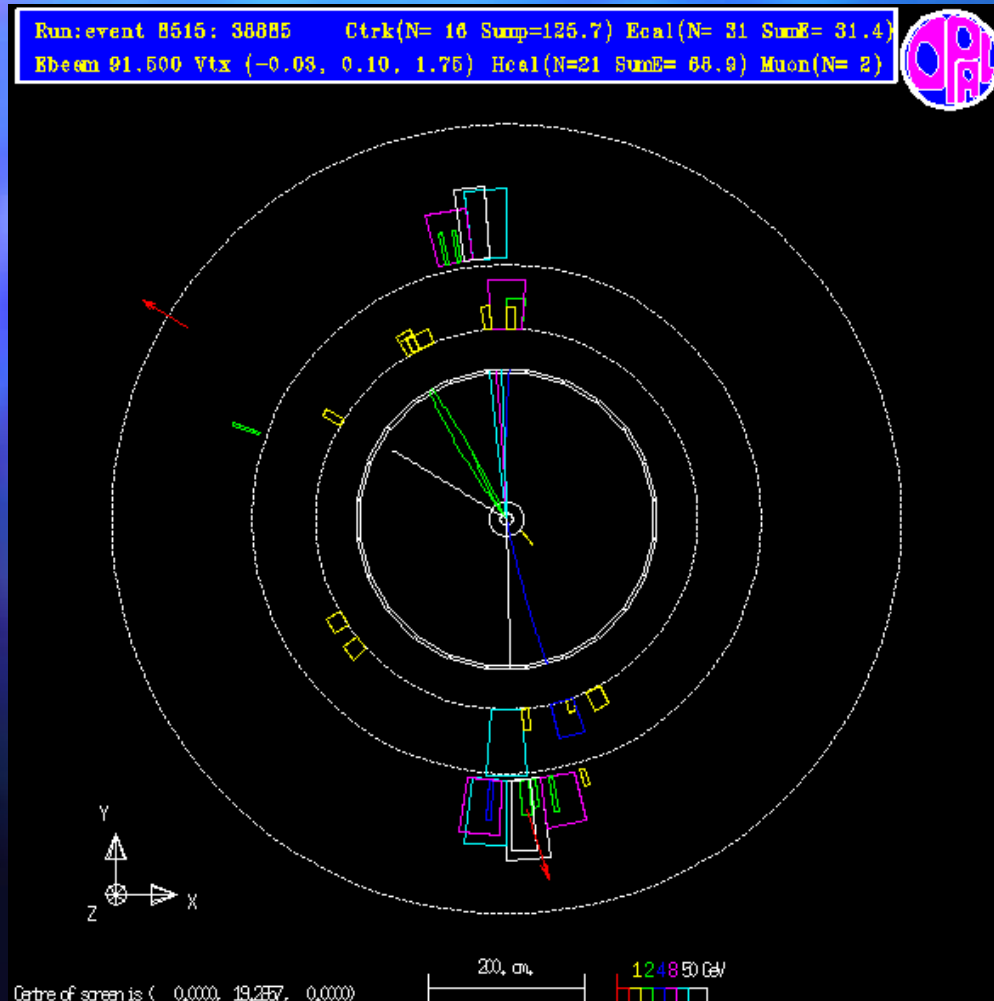
What sort of WW decay is this?

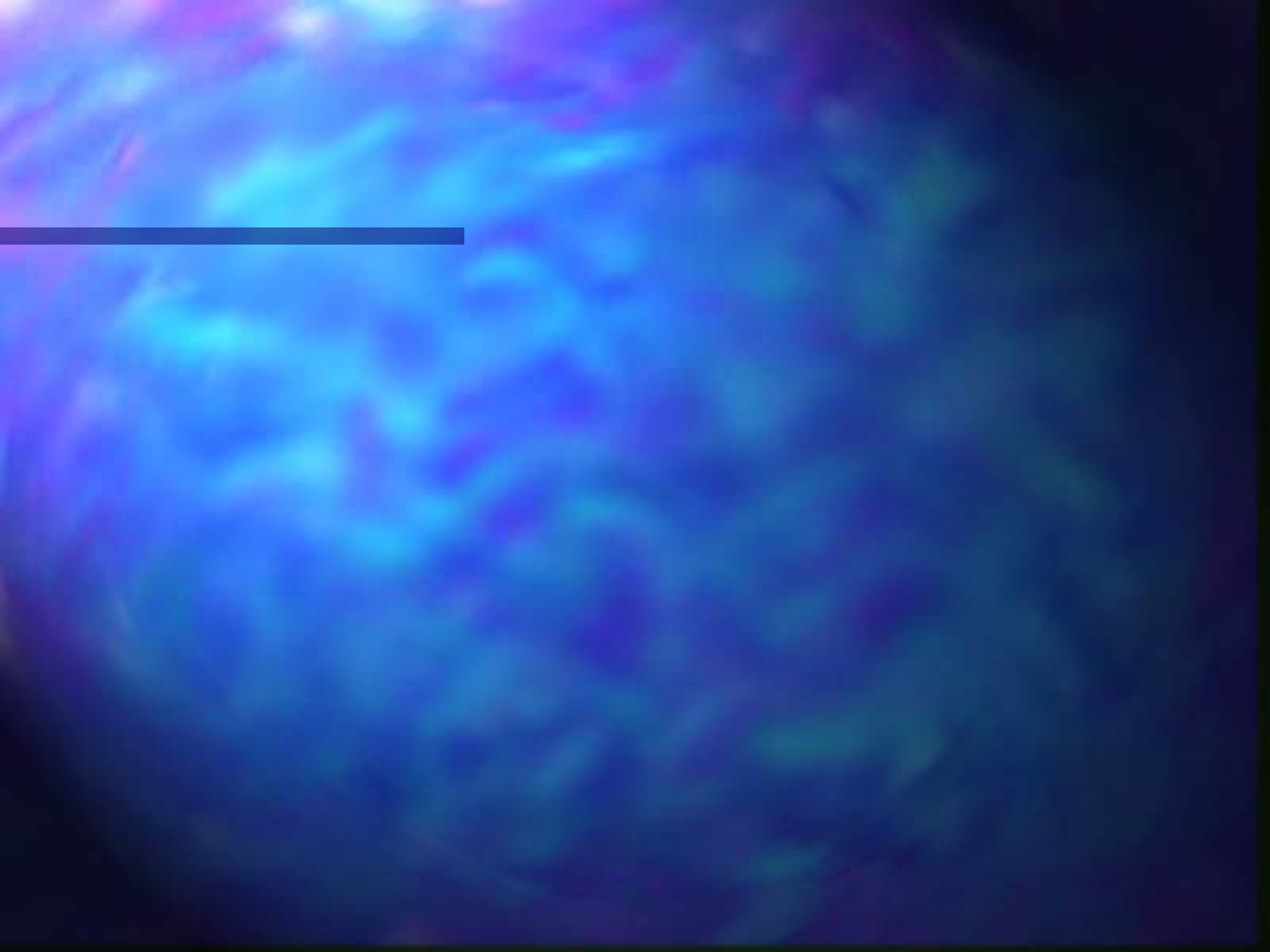
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

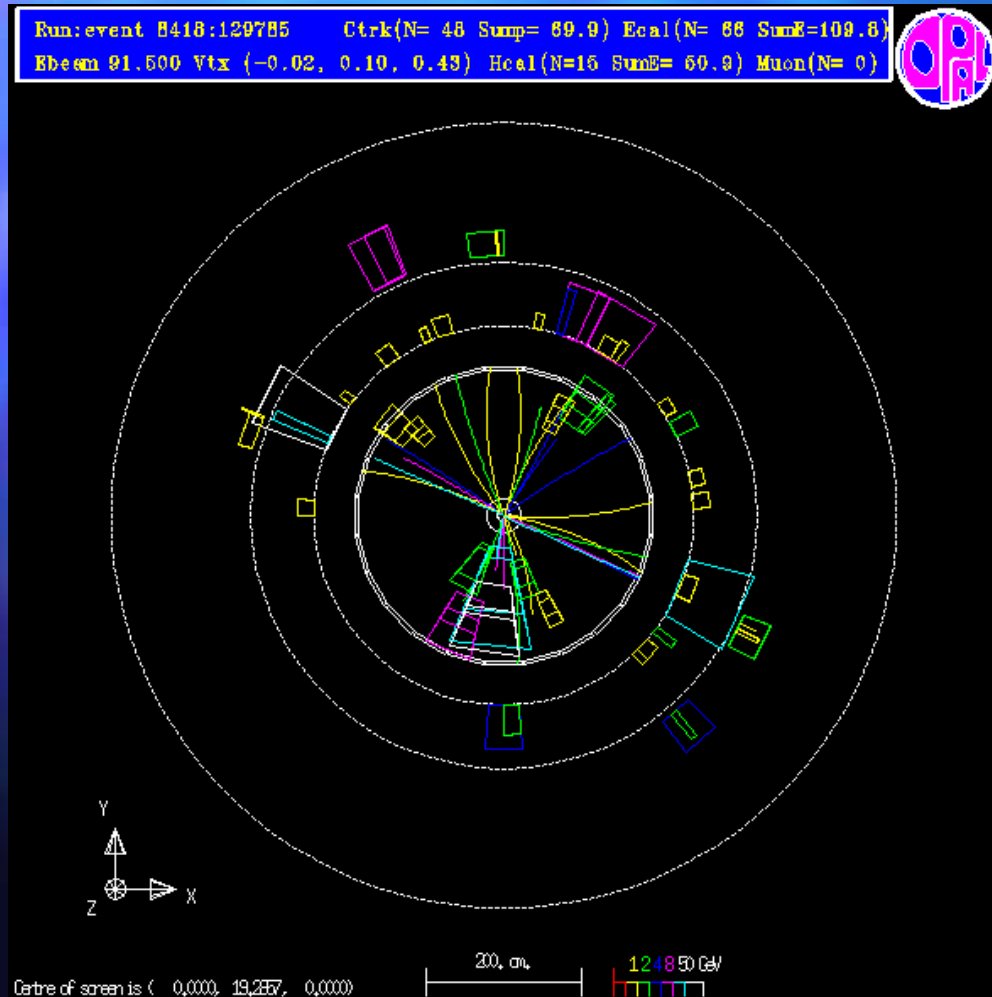
1. Double hadronic decay
2. Mixed
3. Double leptonic decay





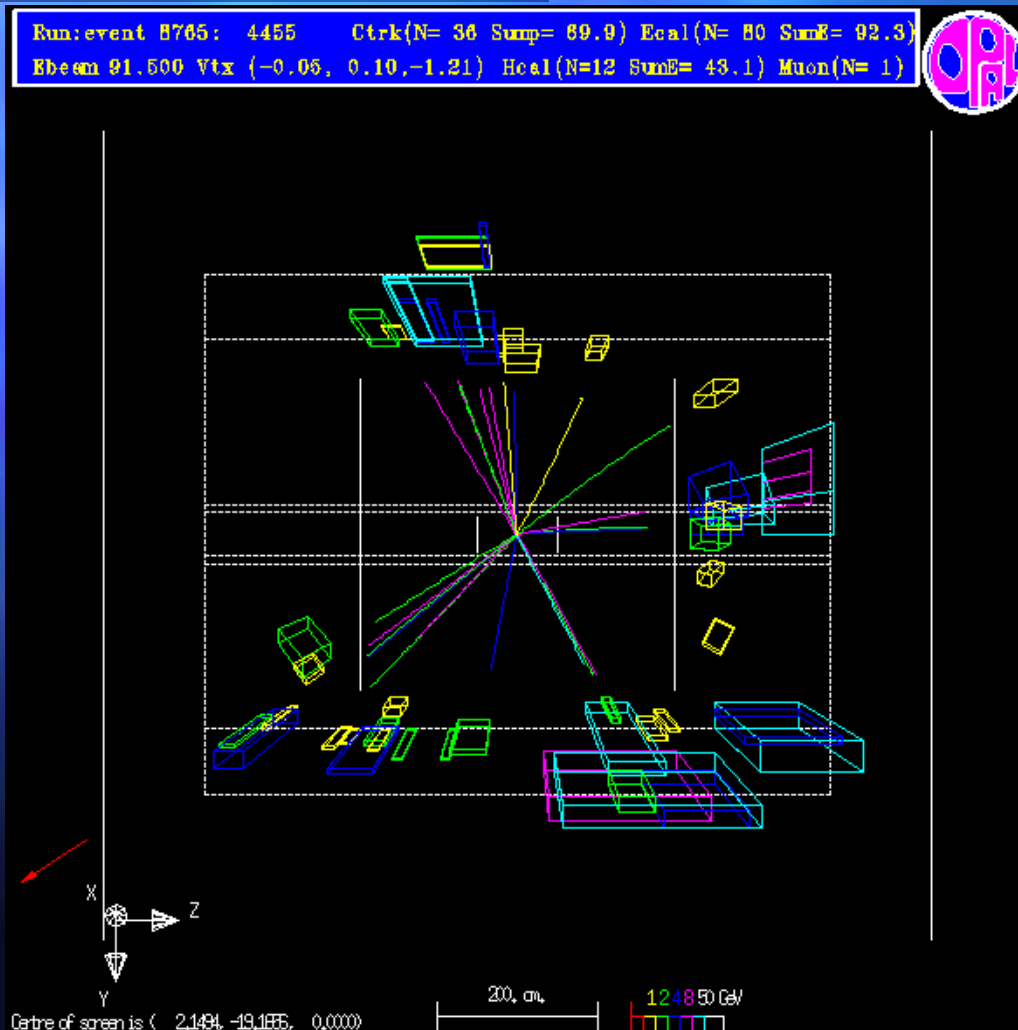
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



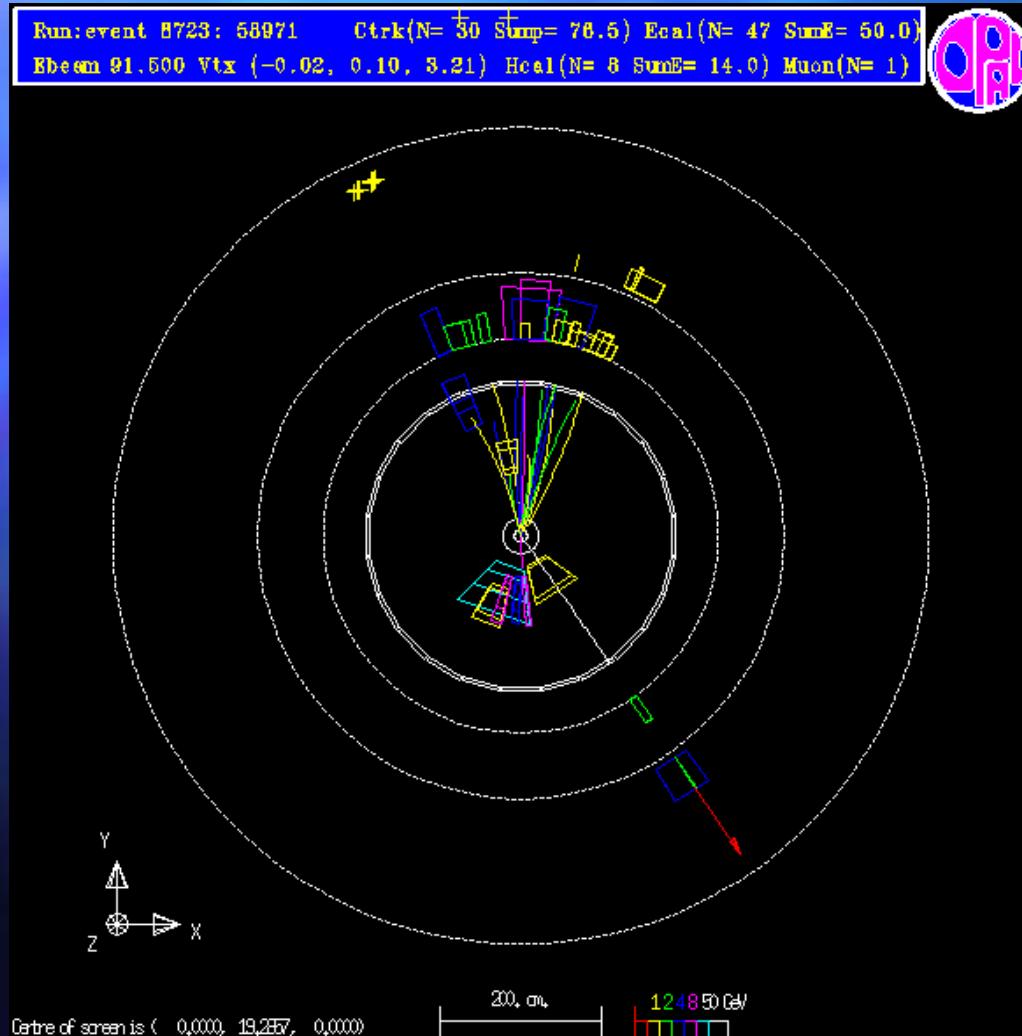
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



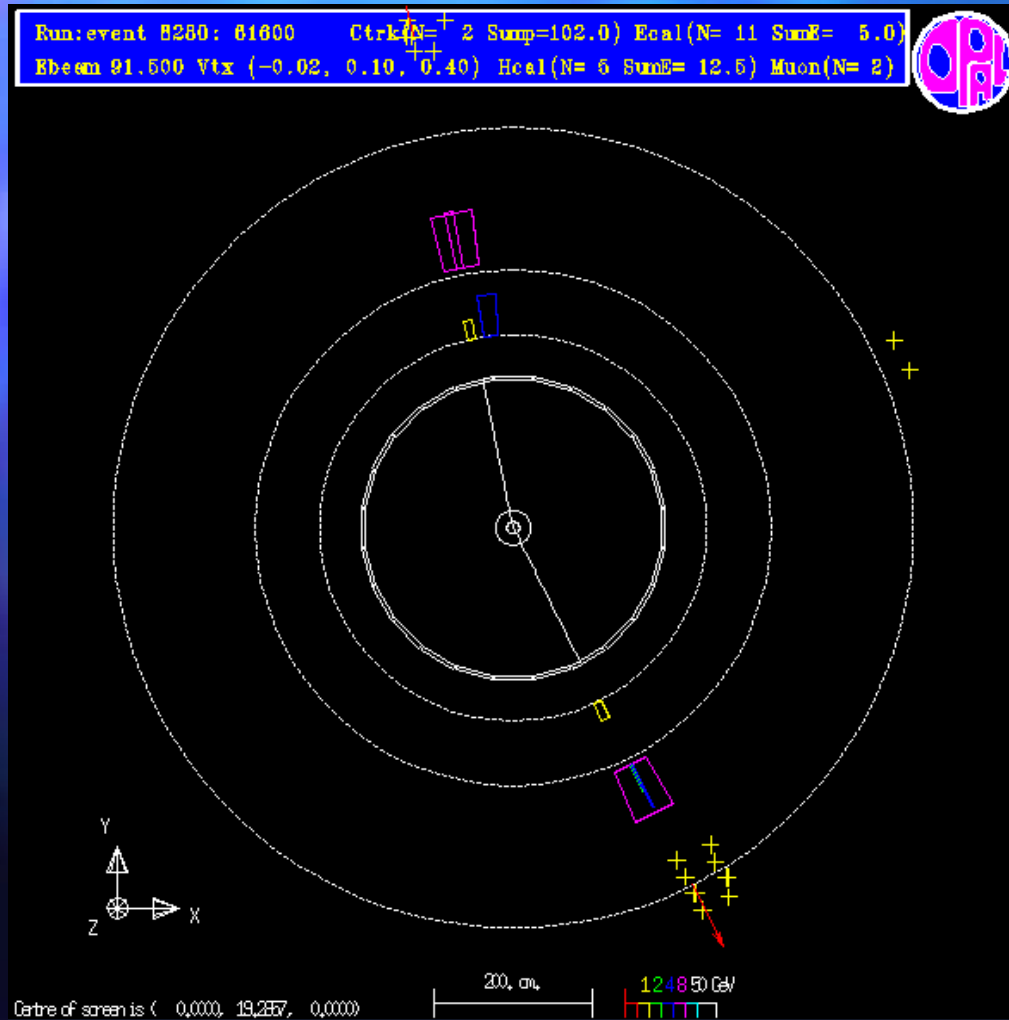
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



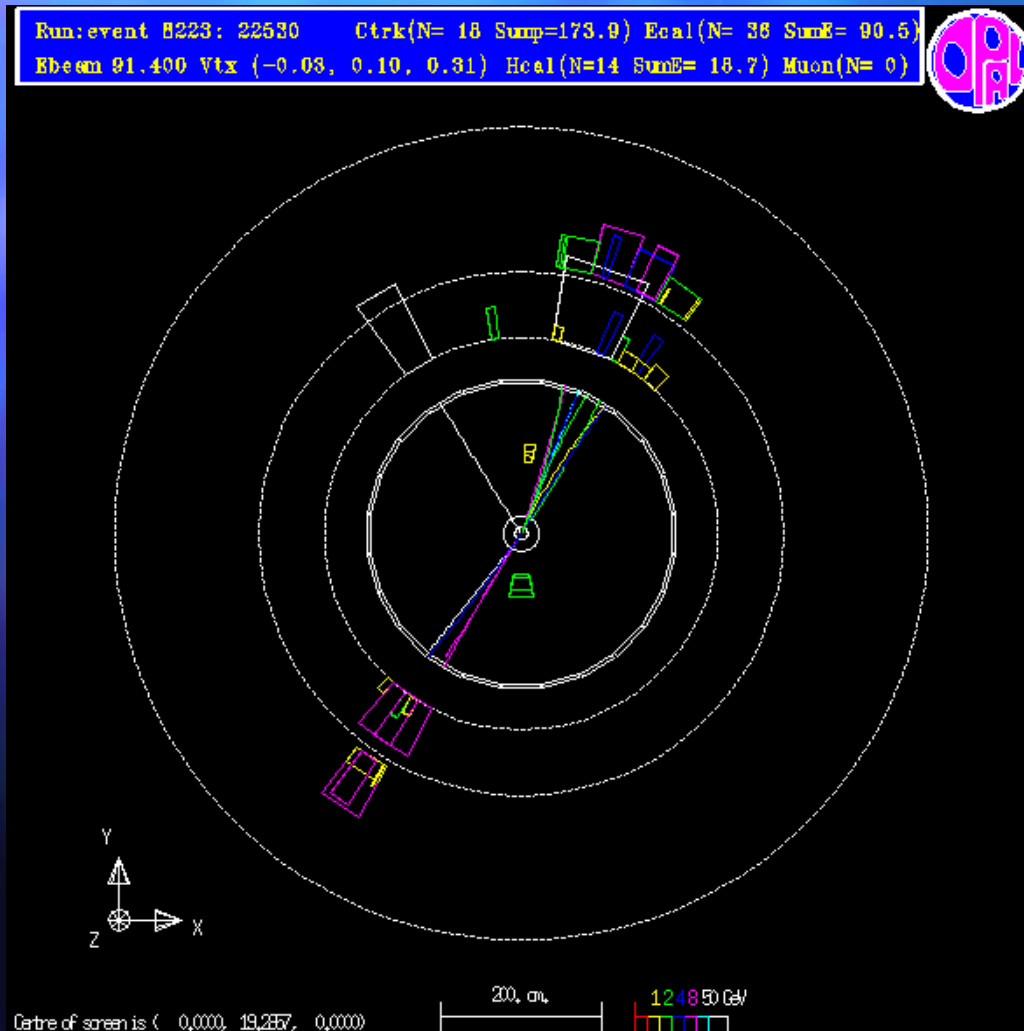
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



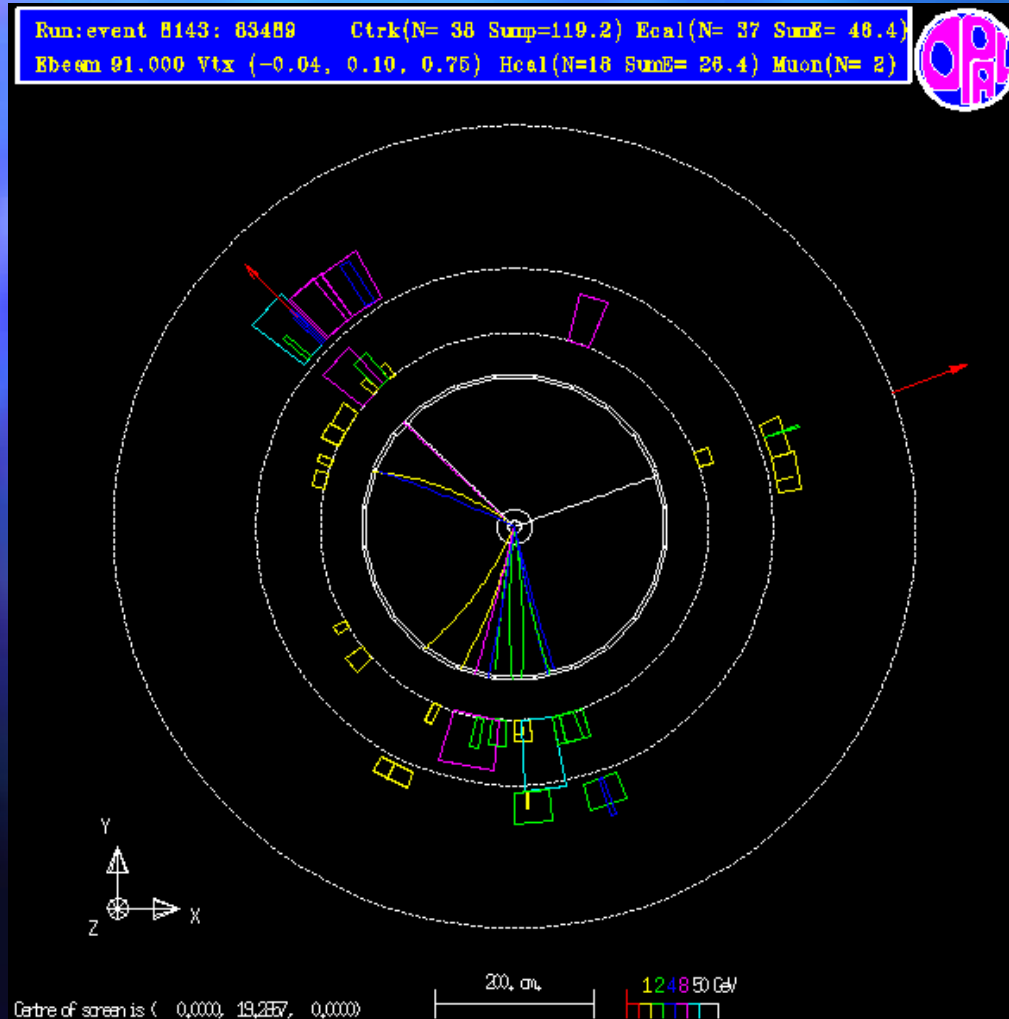
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



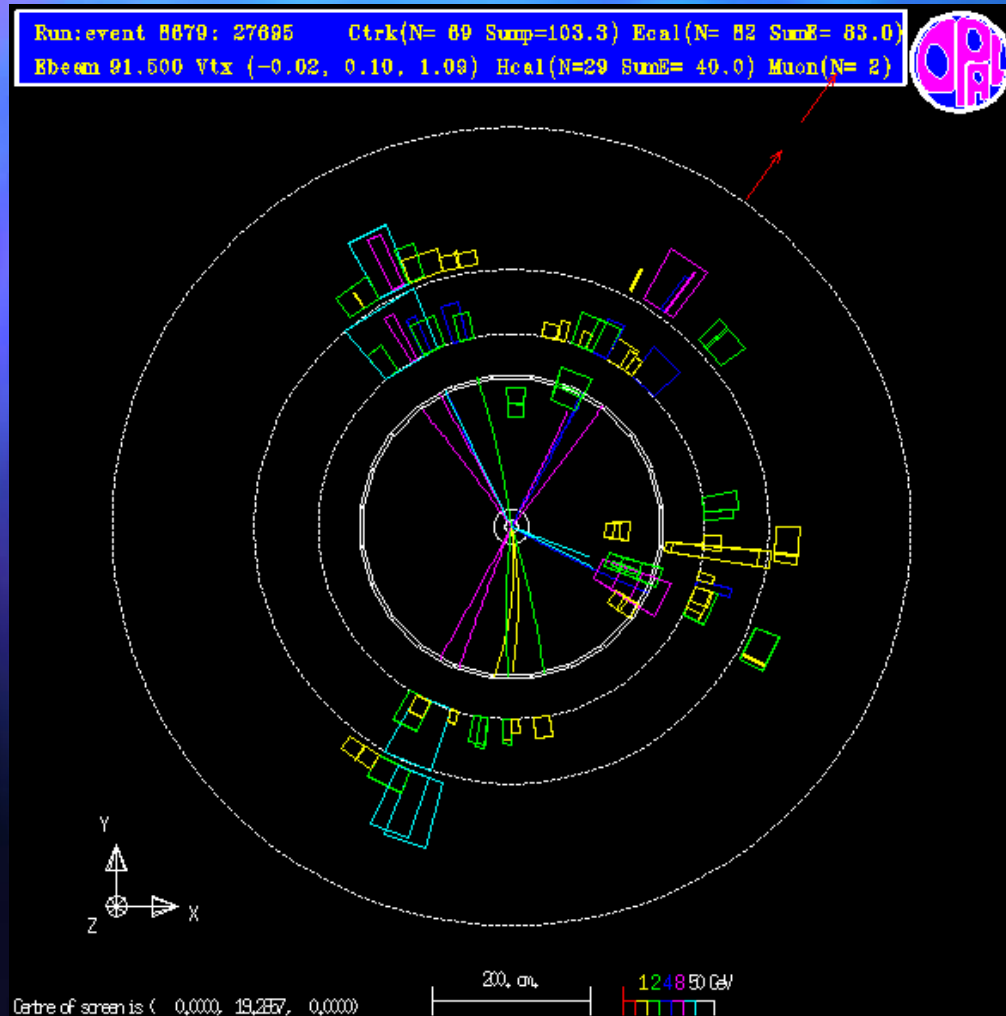
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



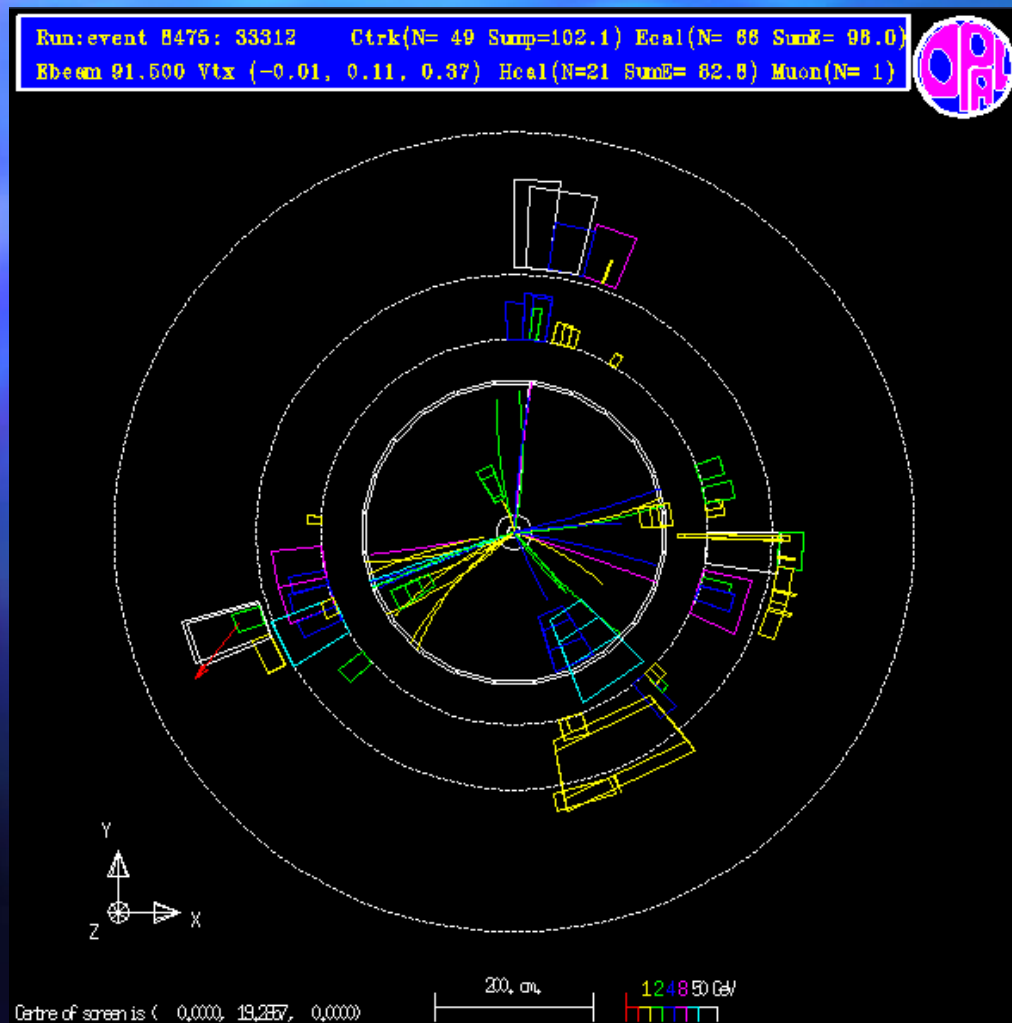
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



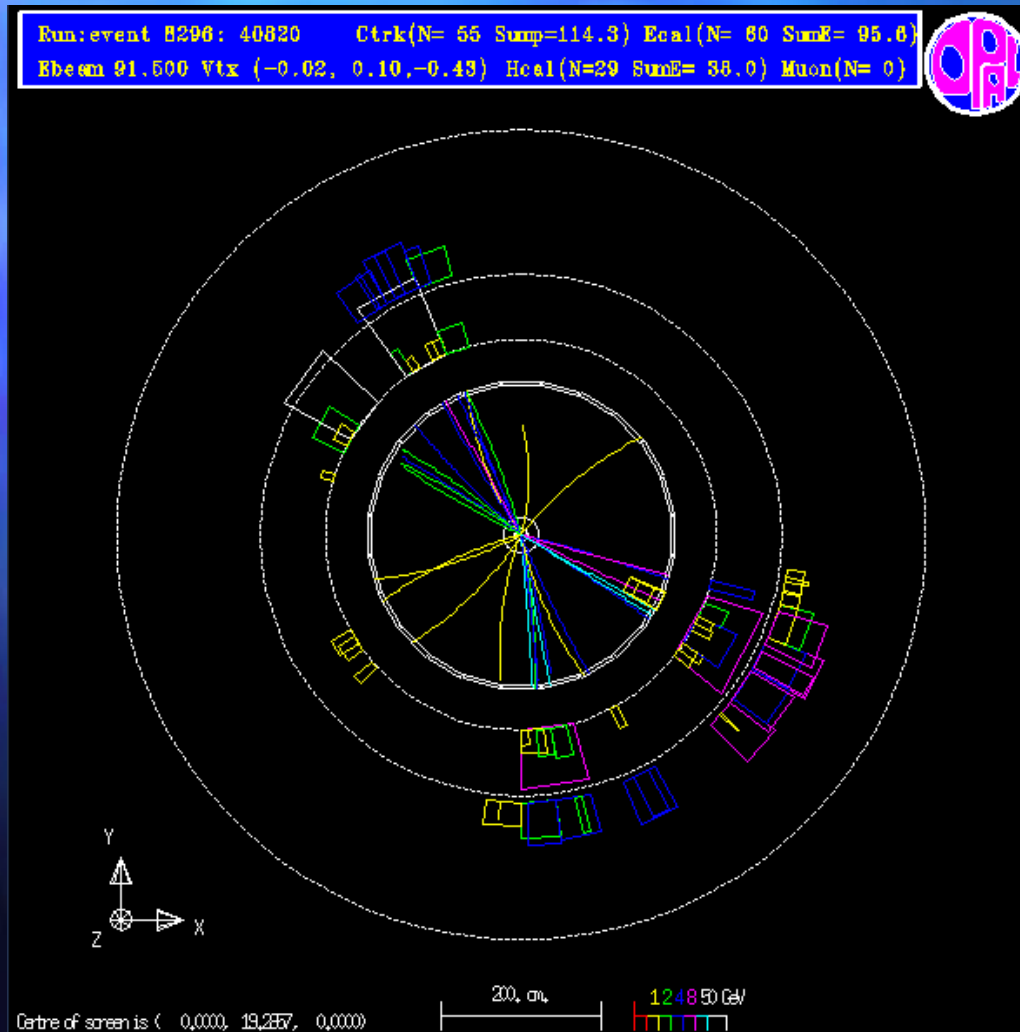
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



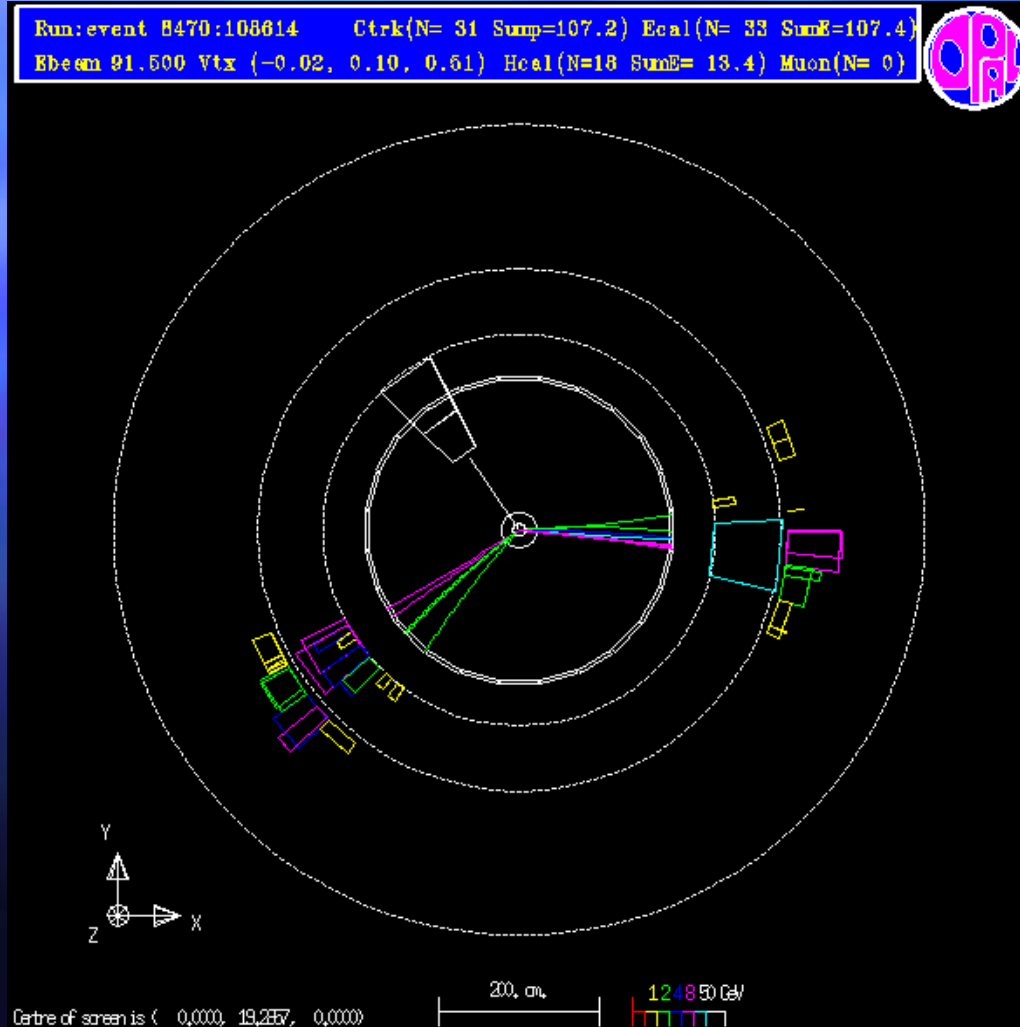
What sort of WW decay is this?

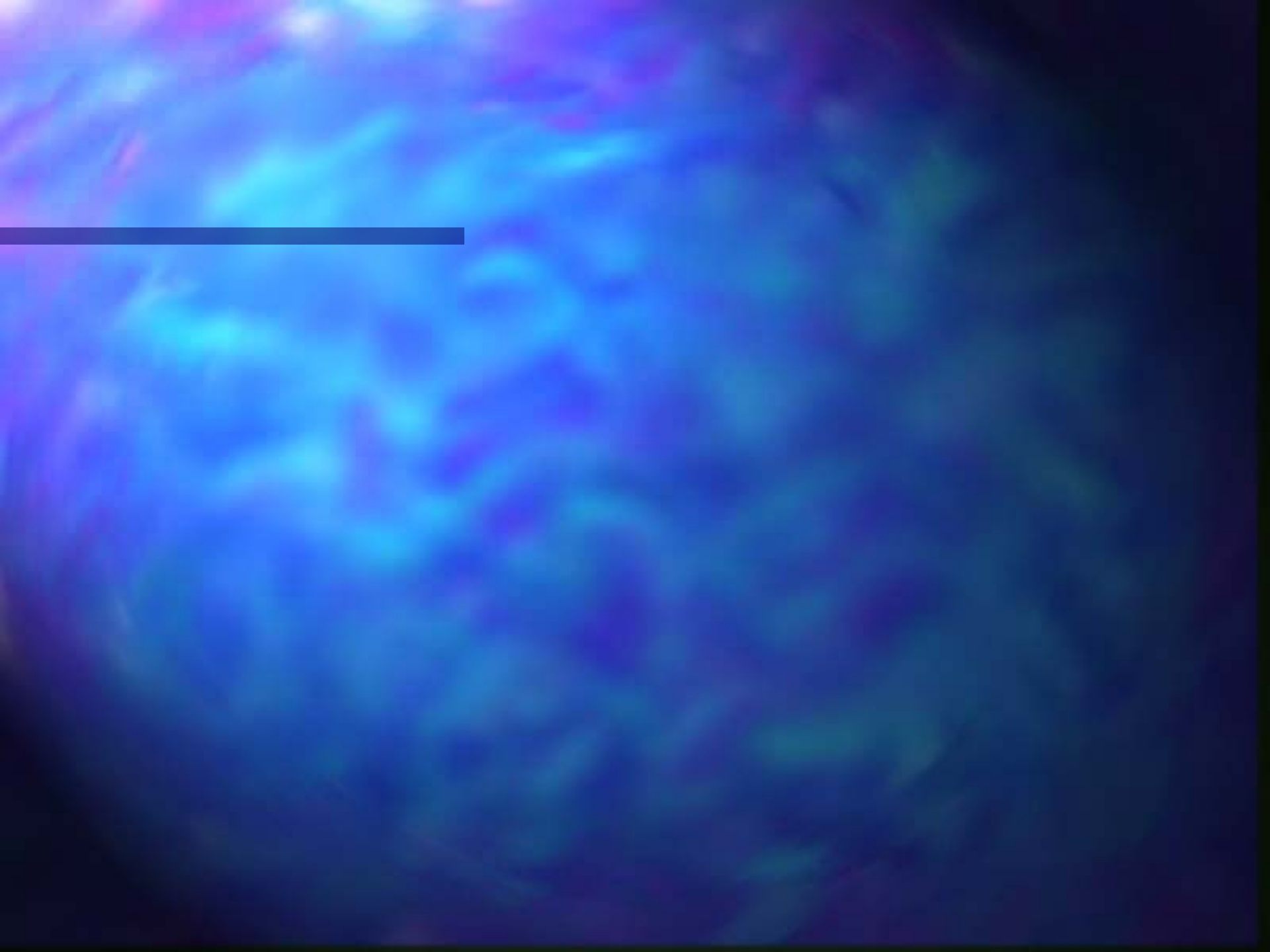
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

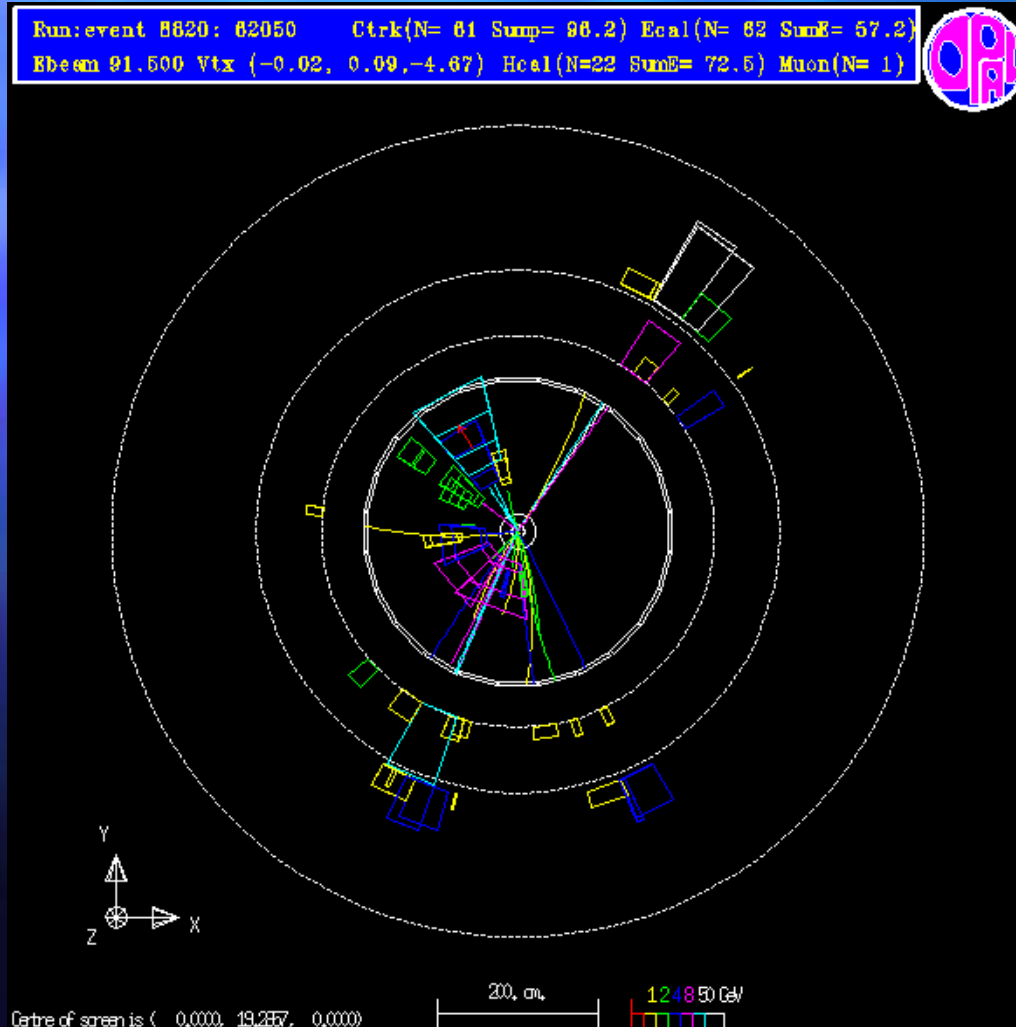
1. Double hadronic decay
2. Mixed
3. Double leptonic decay





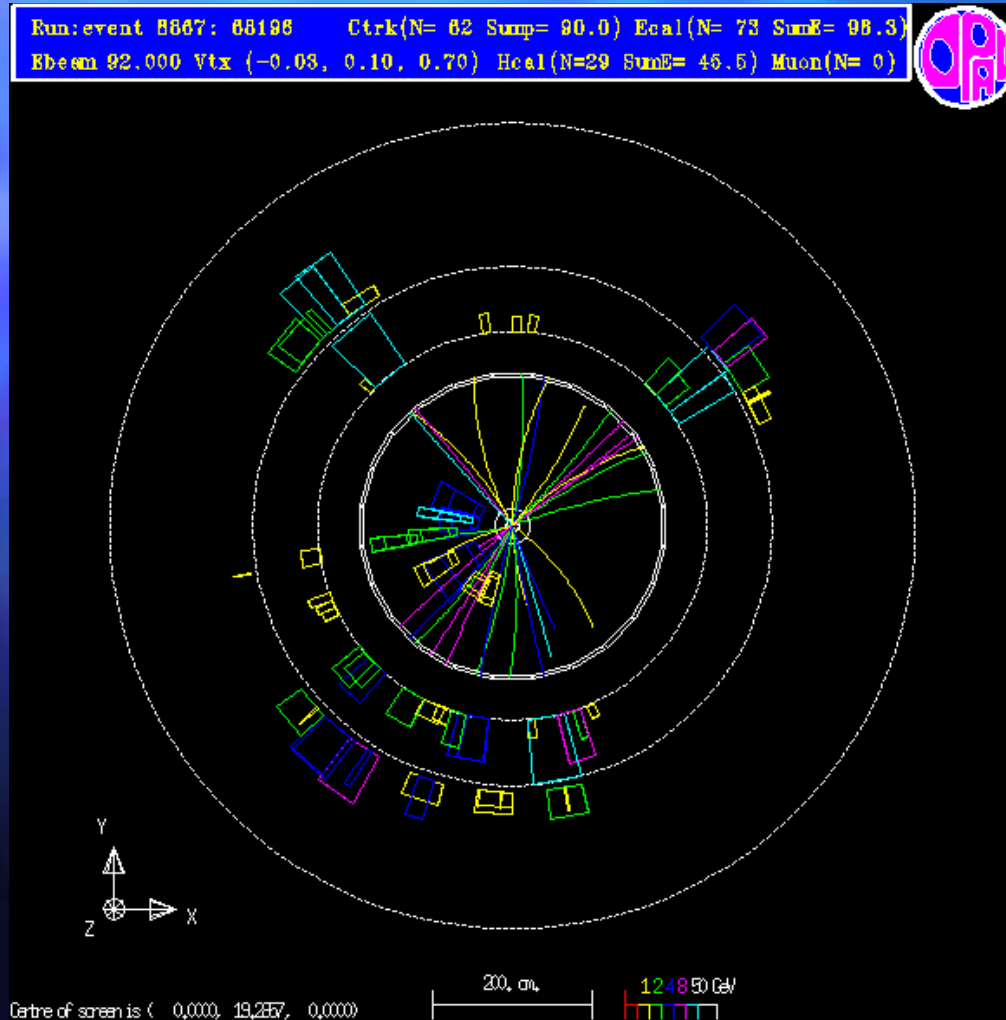
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



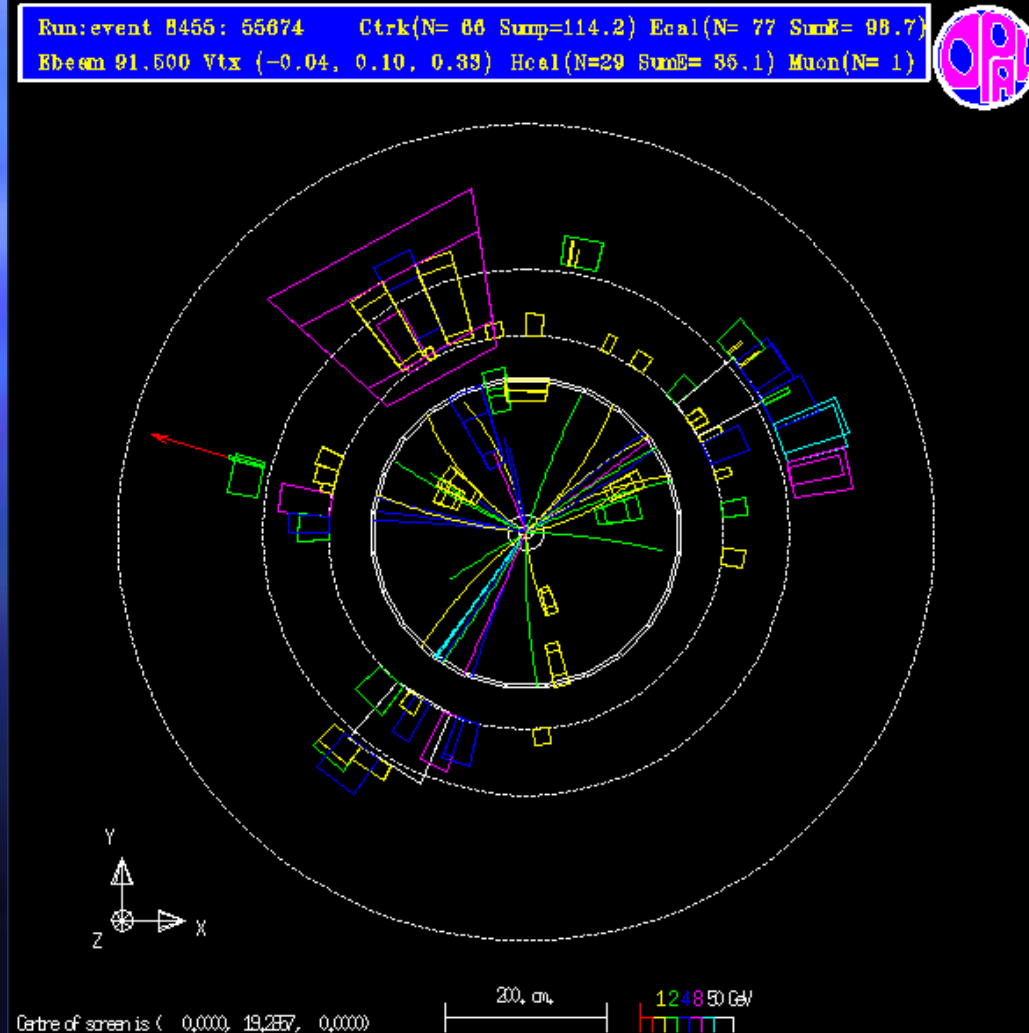
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



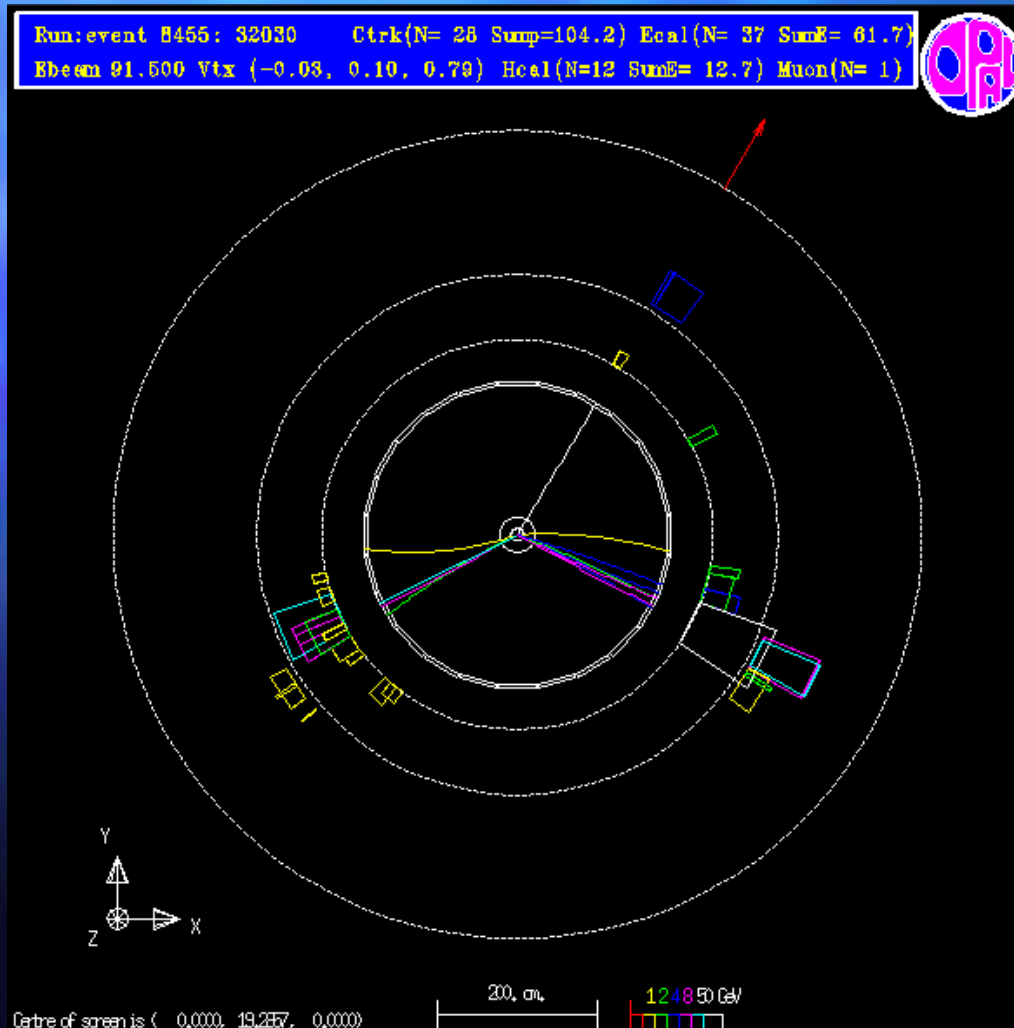
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



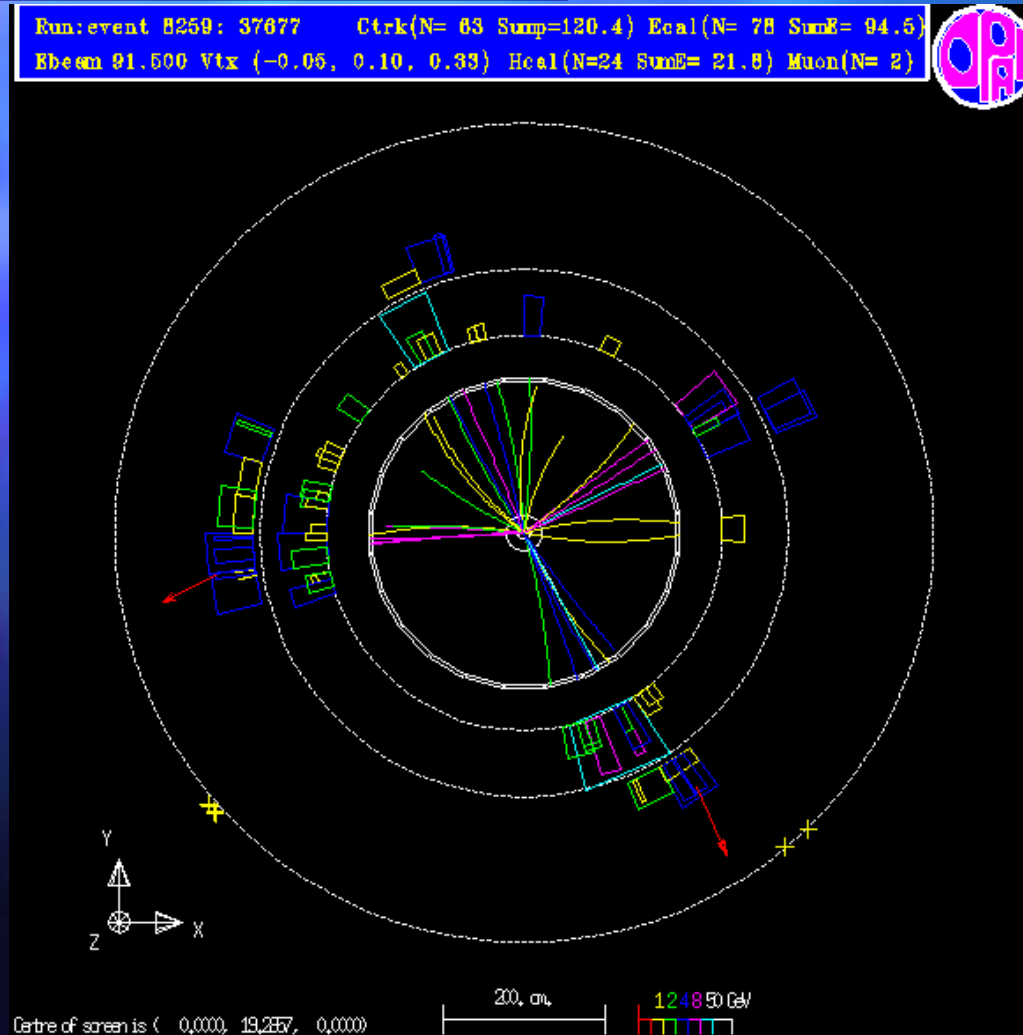
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



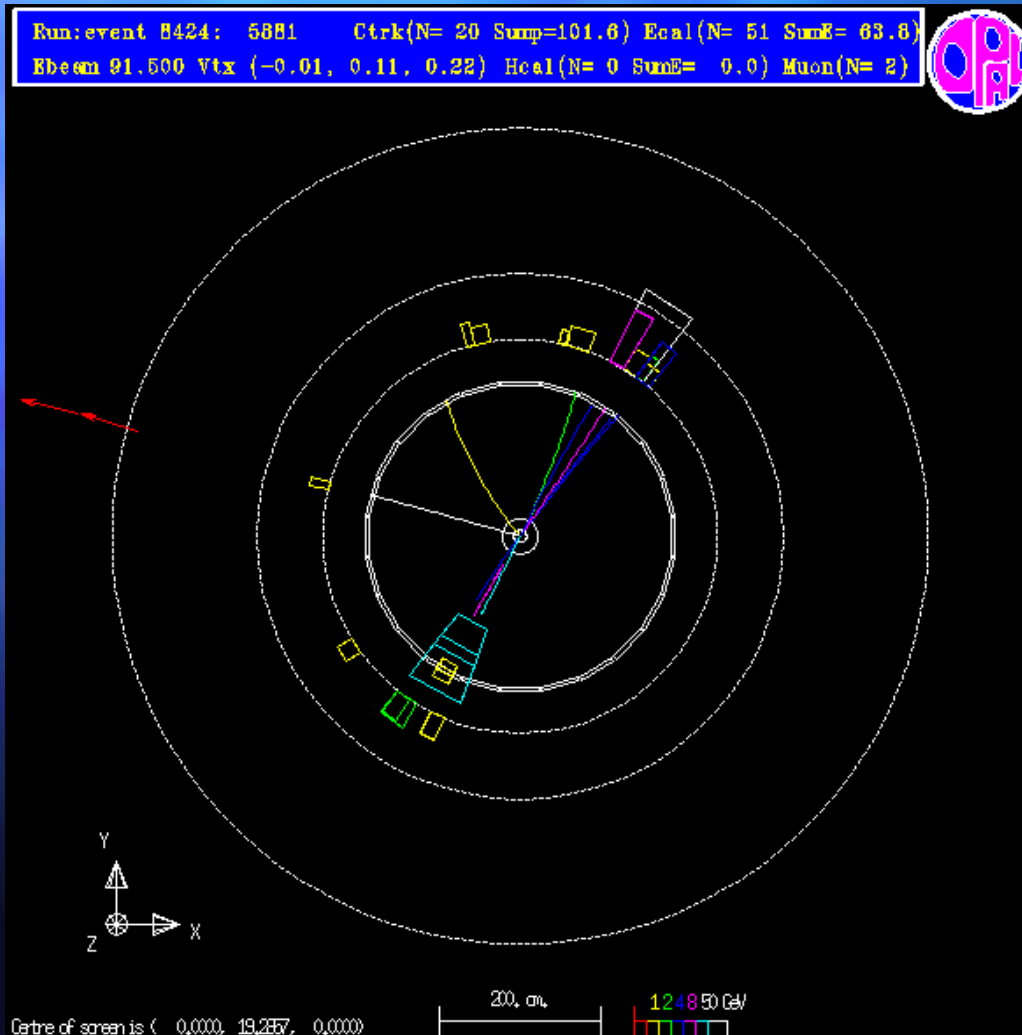
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



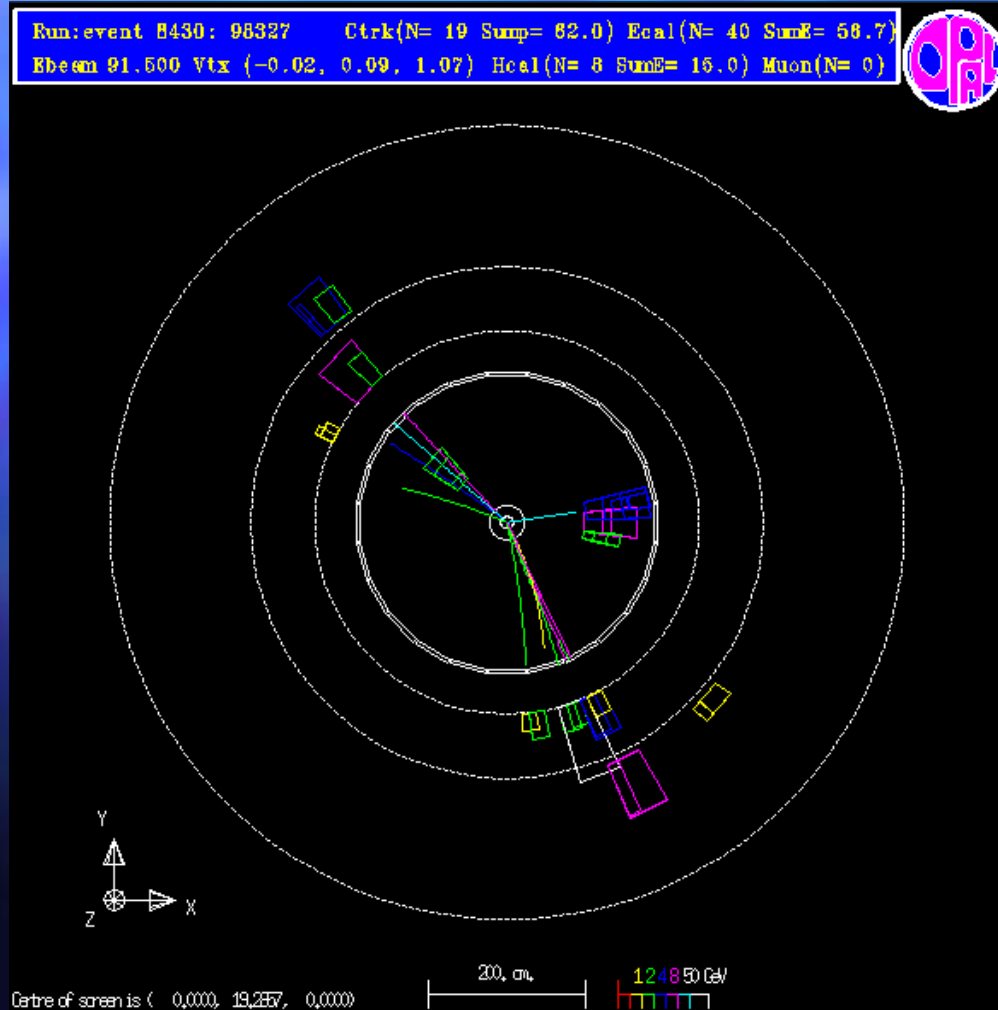
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

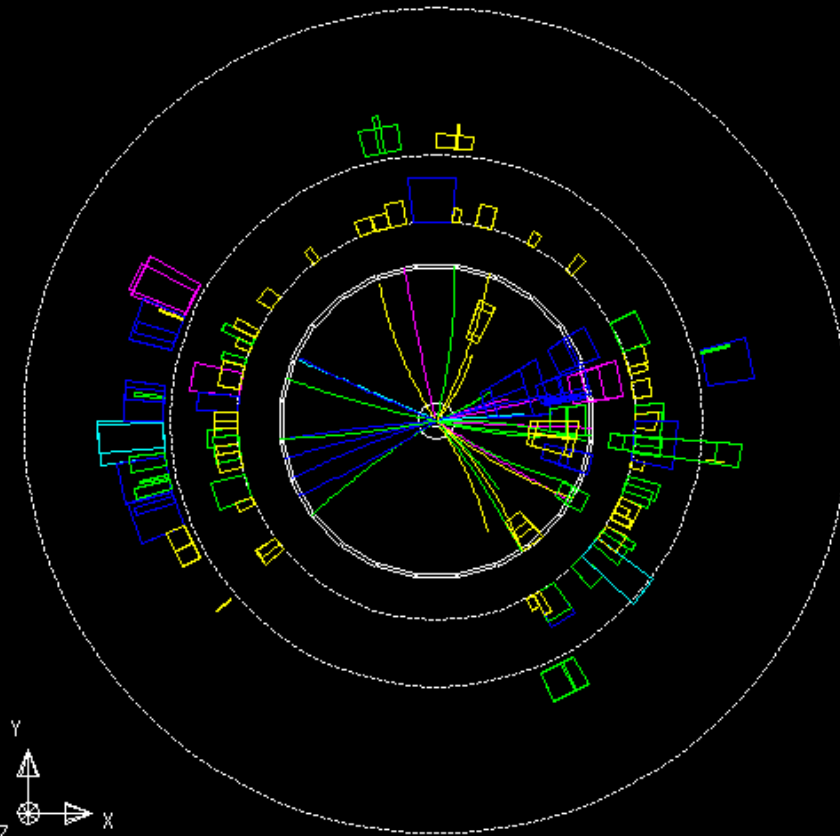
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay

Run:event 8519: 29290 Ctrk(N= 96 SumP= 97.5) Ecal(N=109 SumE=109.5)
Ebeam 91.500 Vtx (-0.05, 0.10, 0.99) Hcal(N=36 SumE= 42.0) Muon(N= 0)



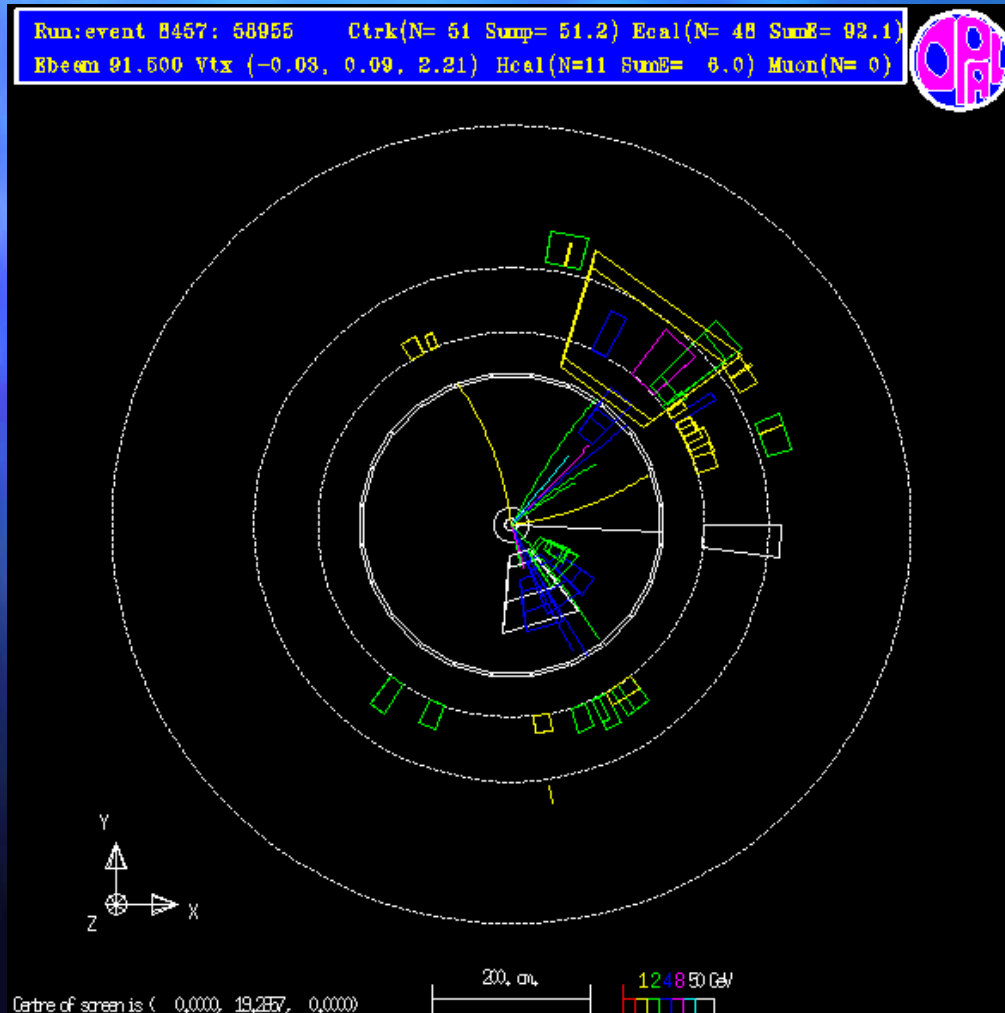
Centre of screen is (0.000, 19.287, 0.000)

200 cm

124850 GeV

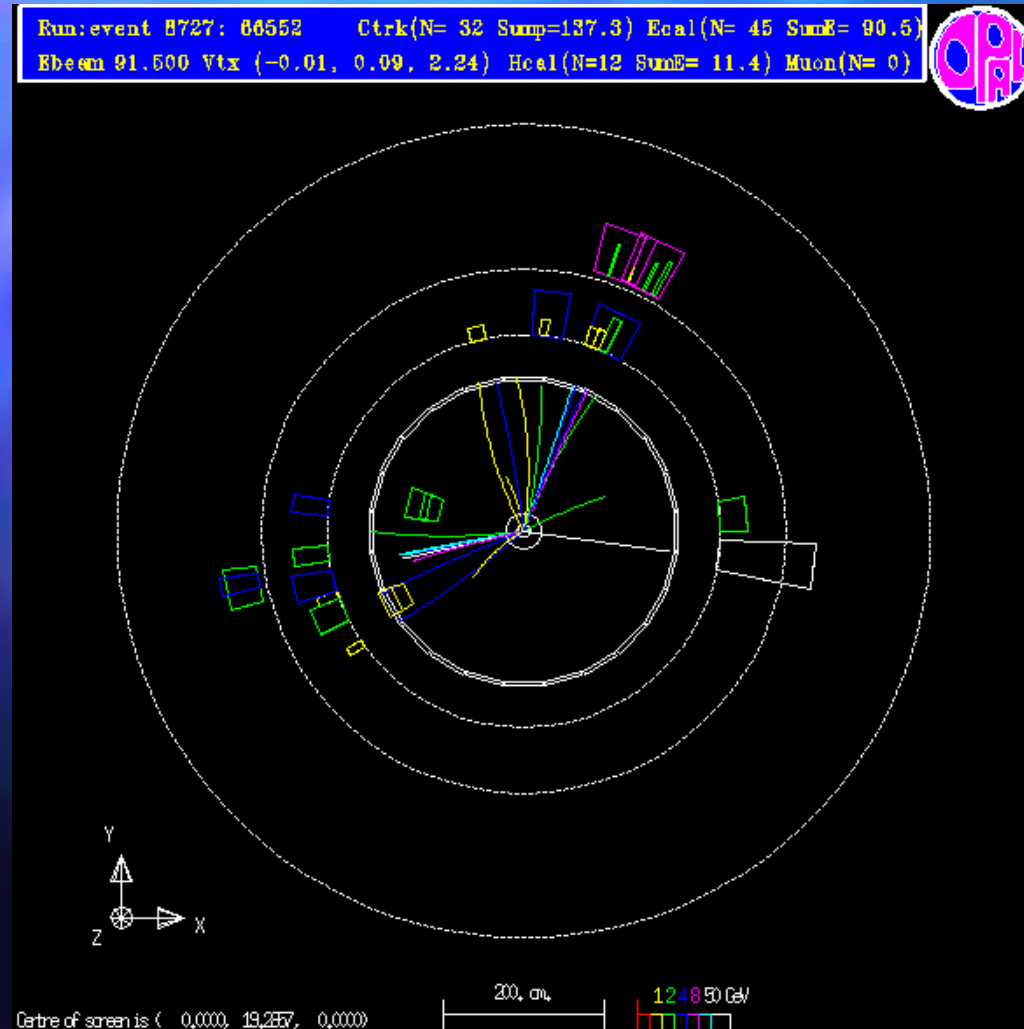
What sort of WW decay is this?

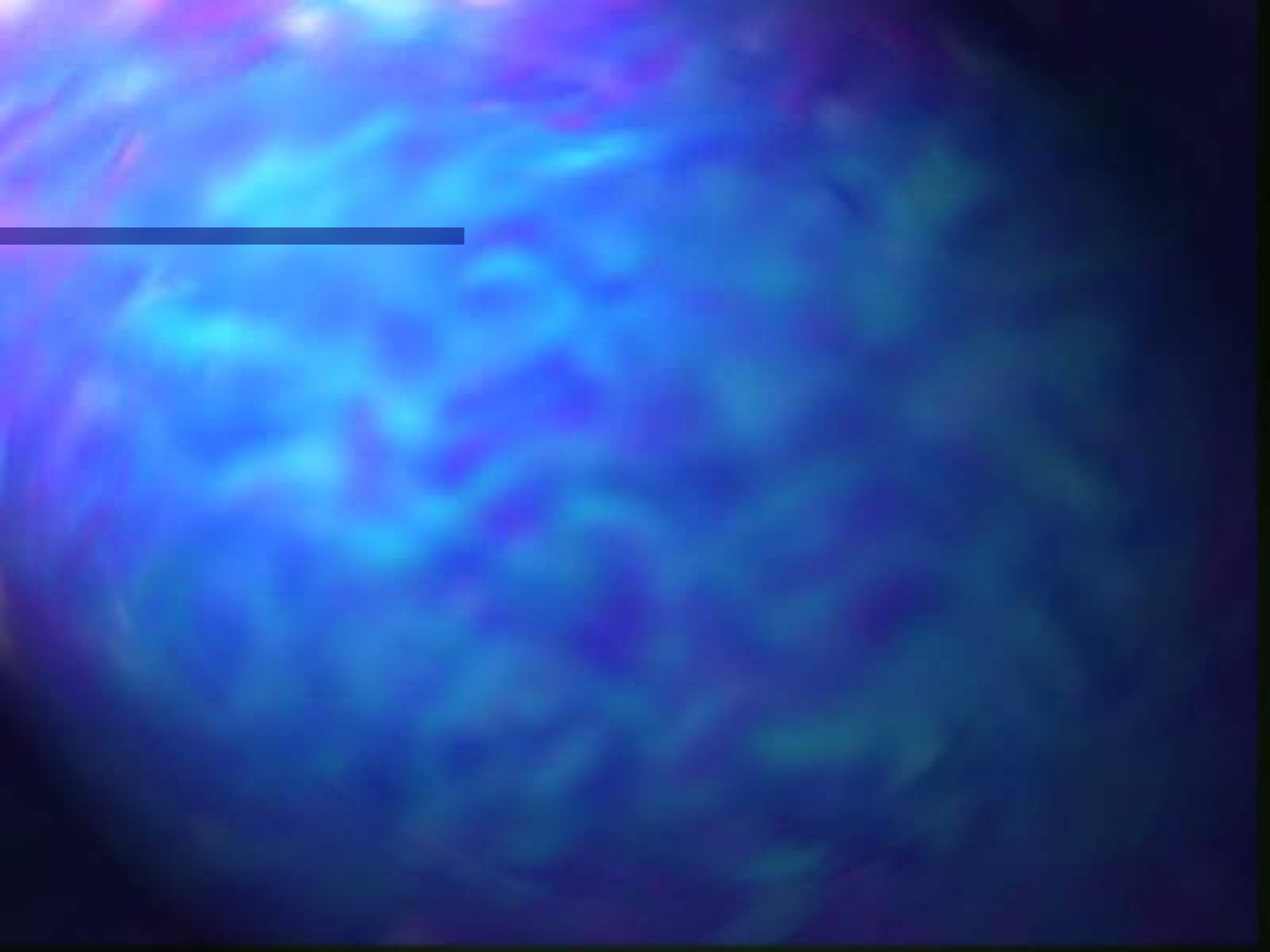
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

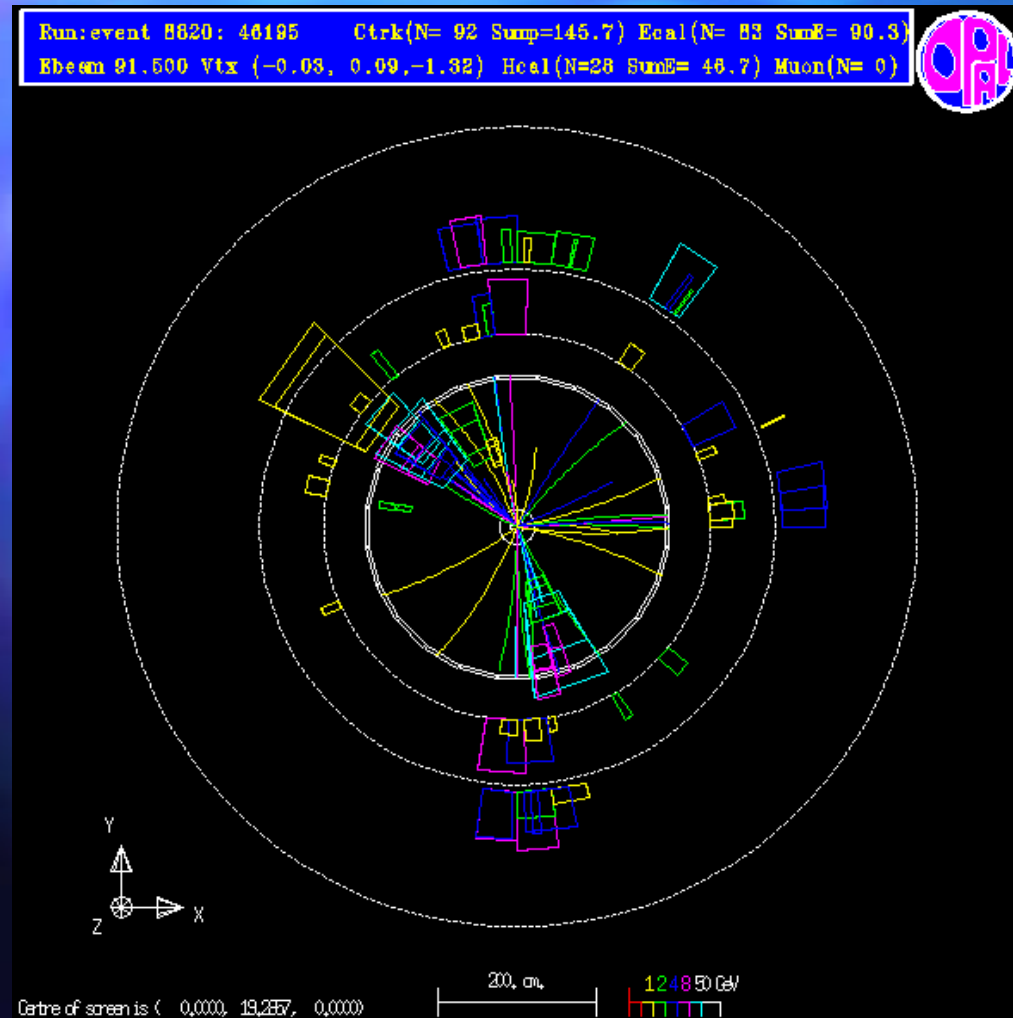
1. Double hadronic decay
2. Mixed
3. Double leptonic decay





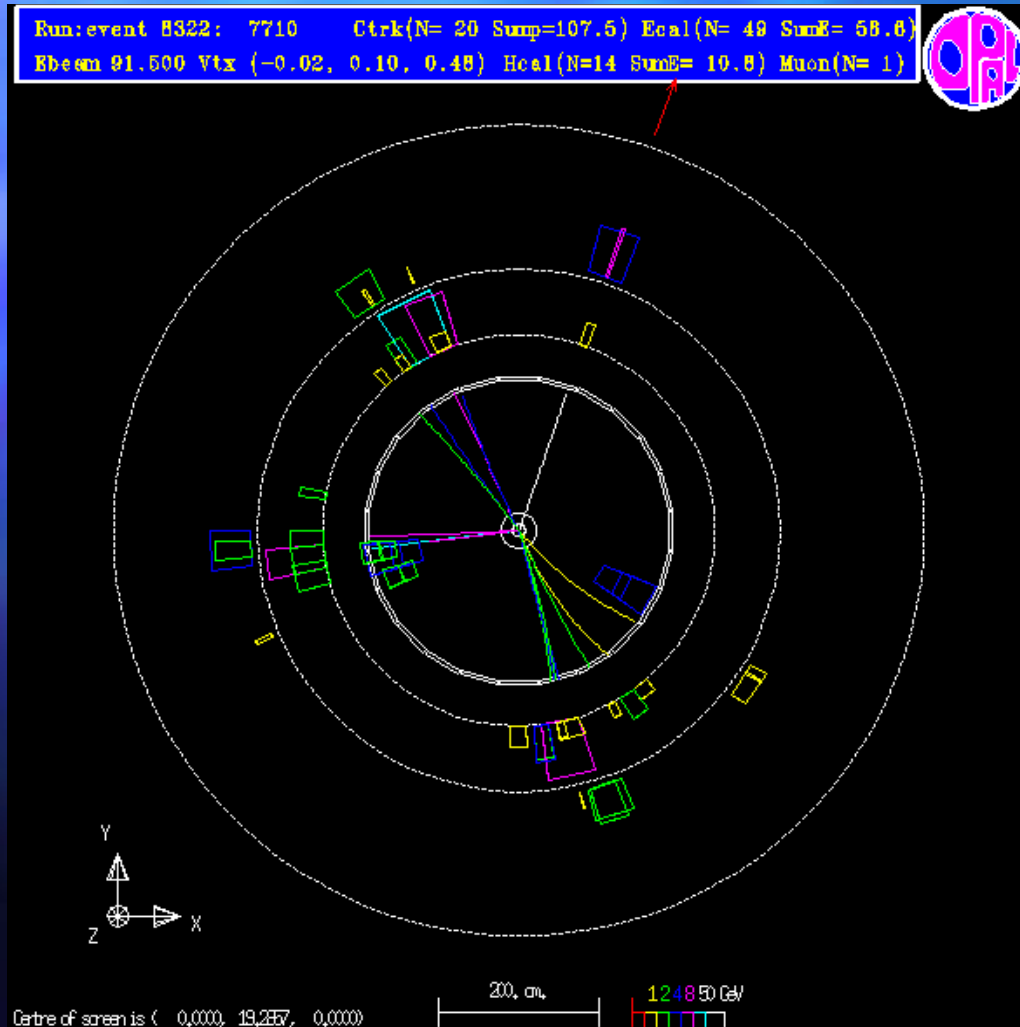
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



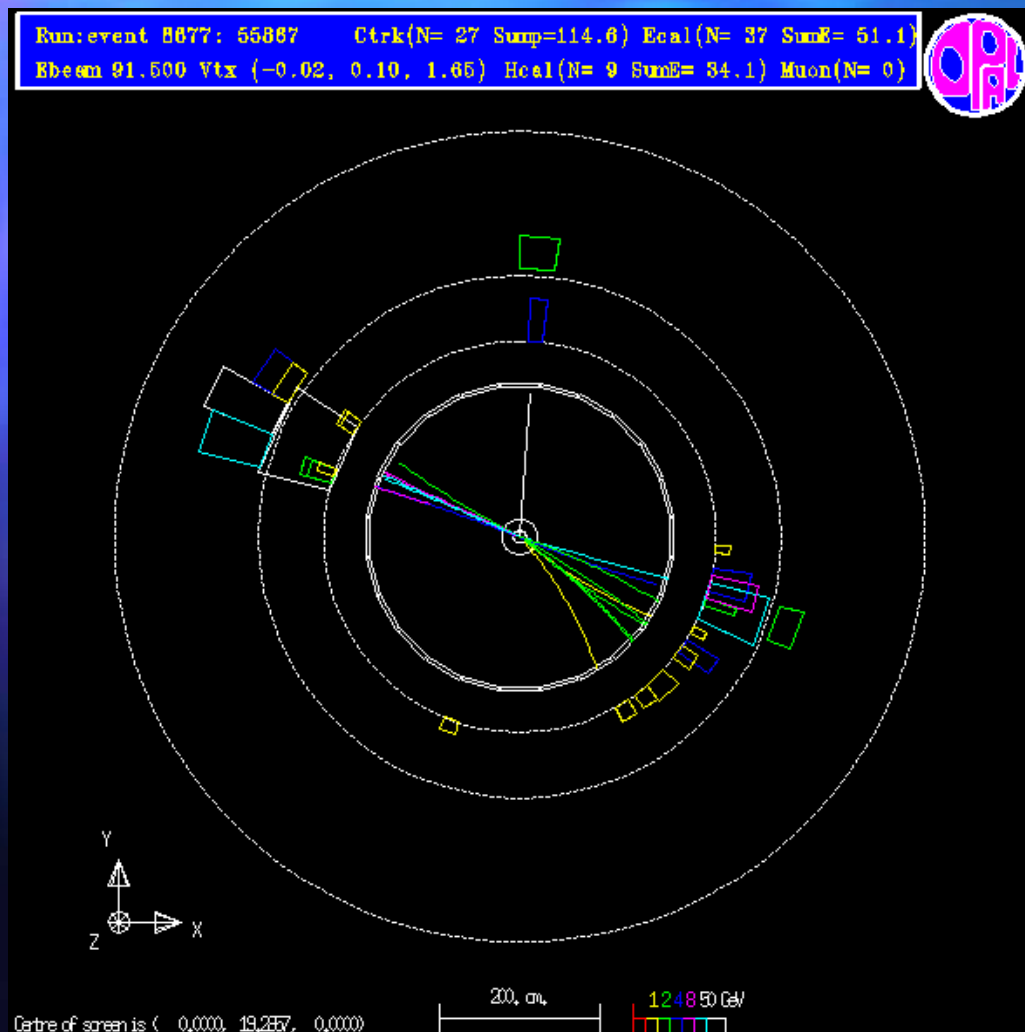
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



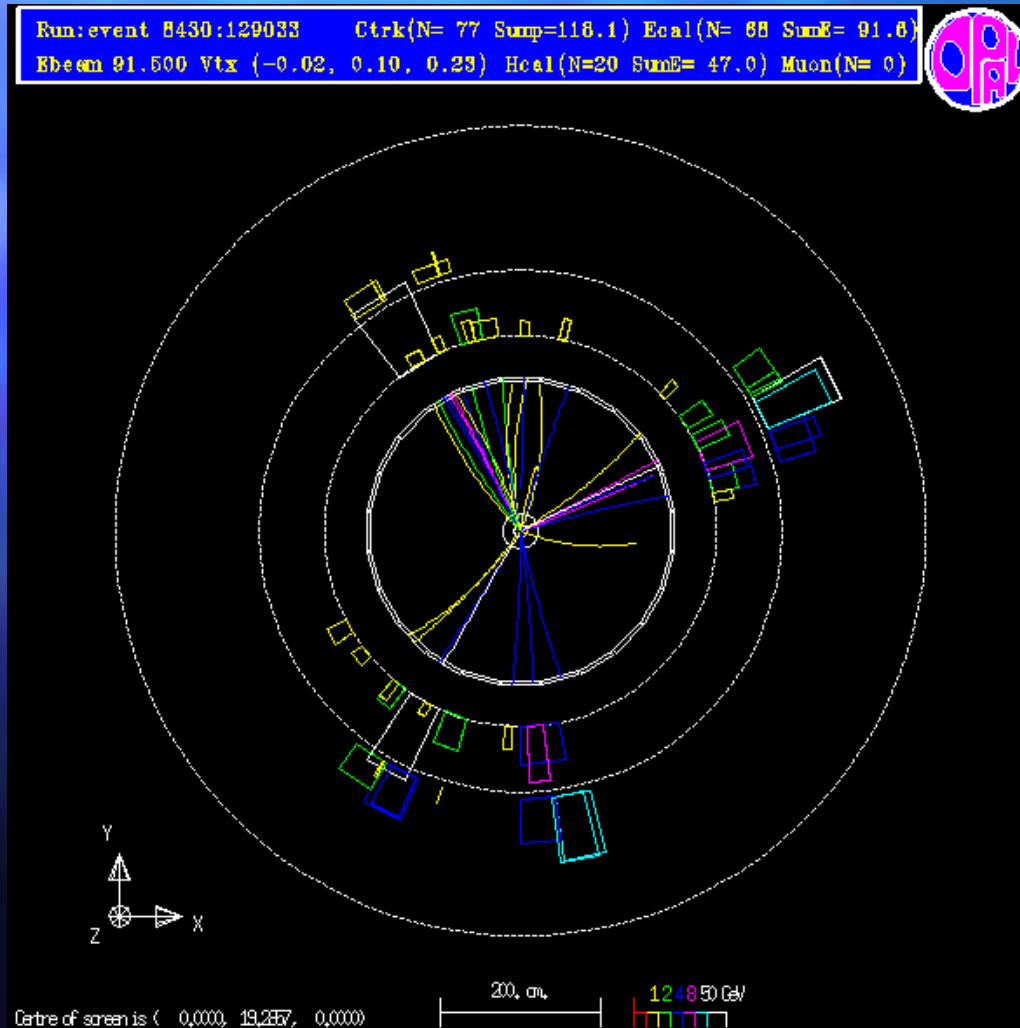
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



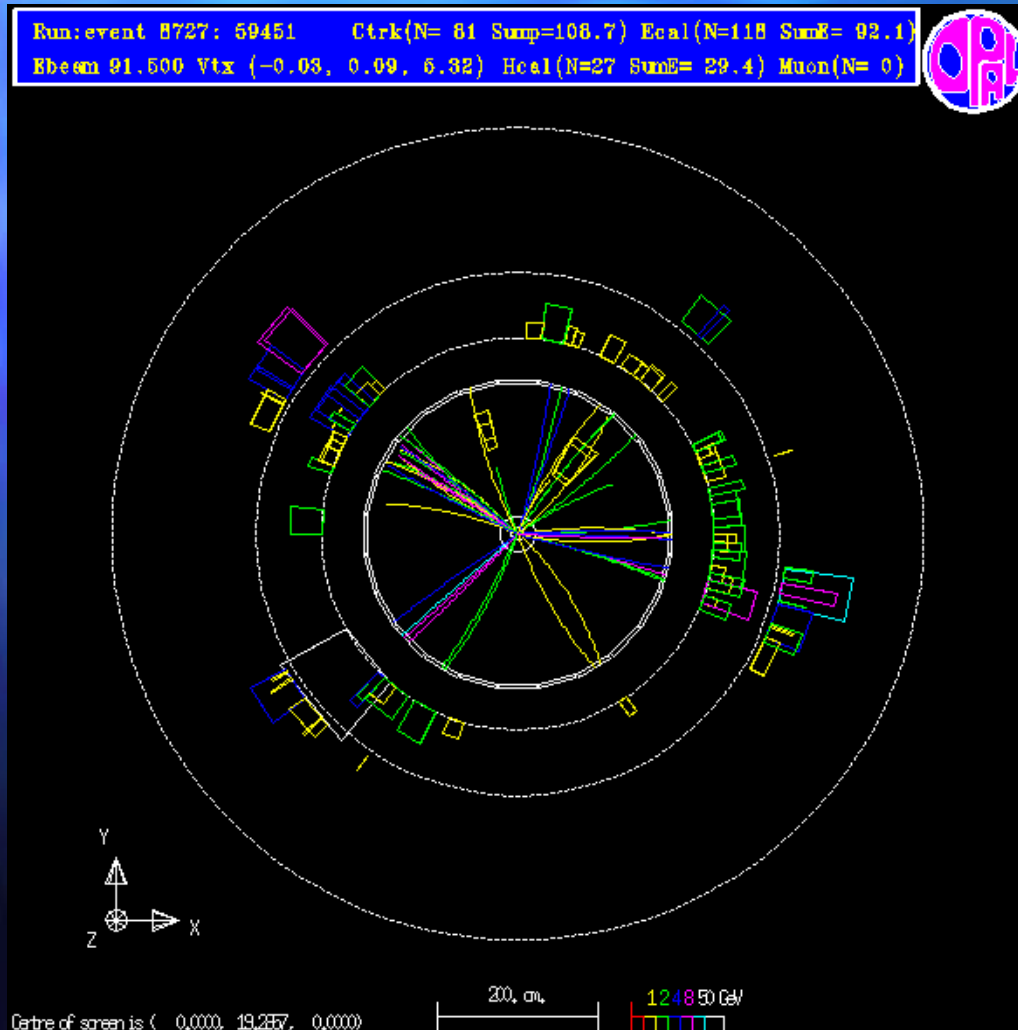
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



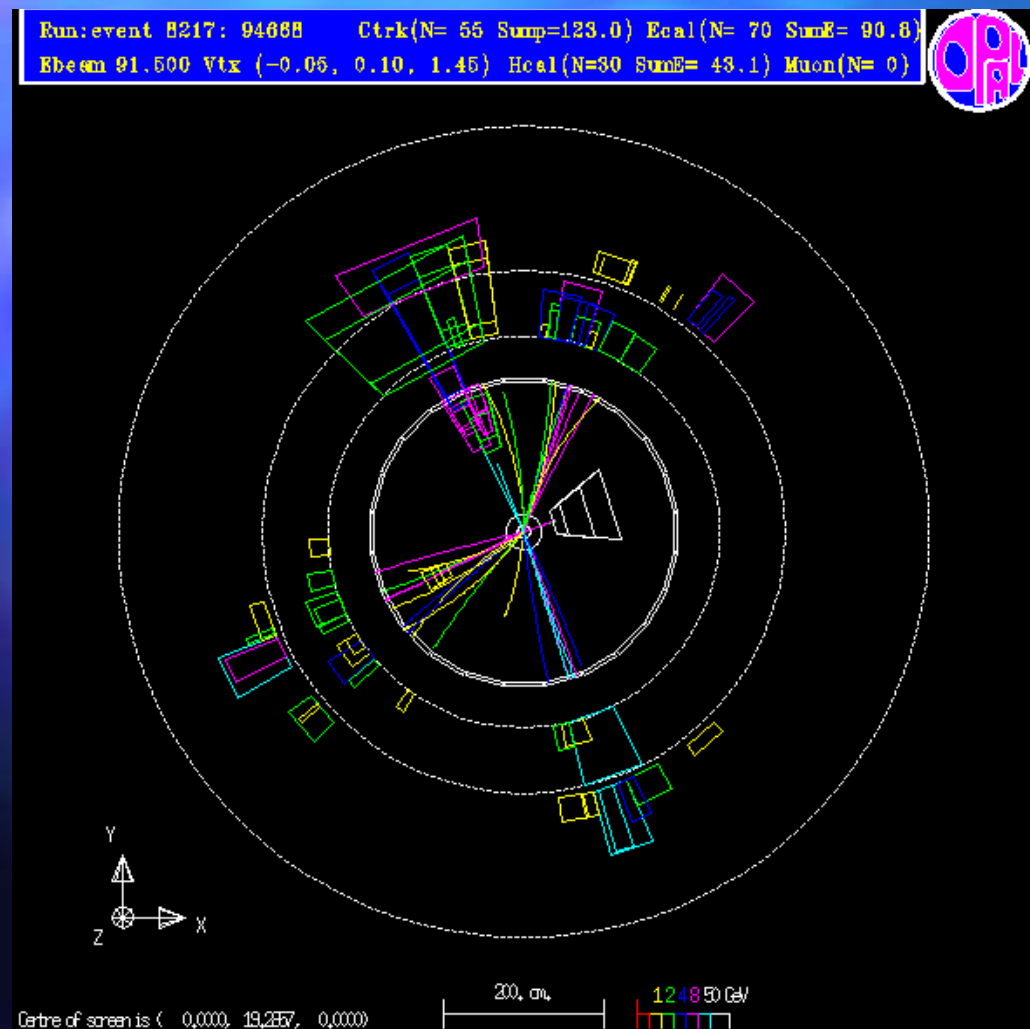
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



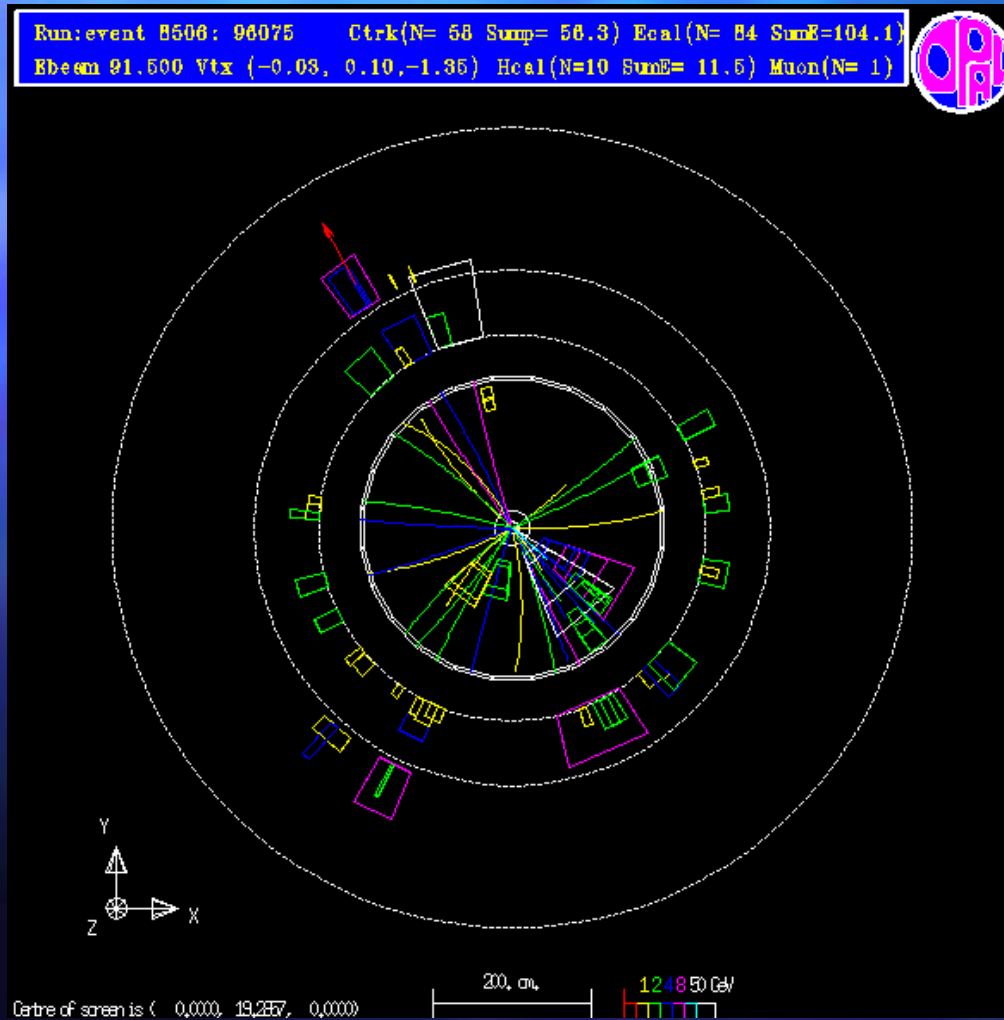
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



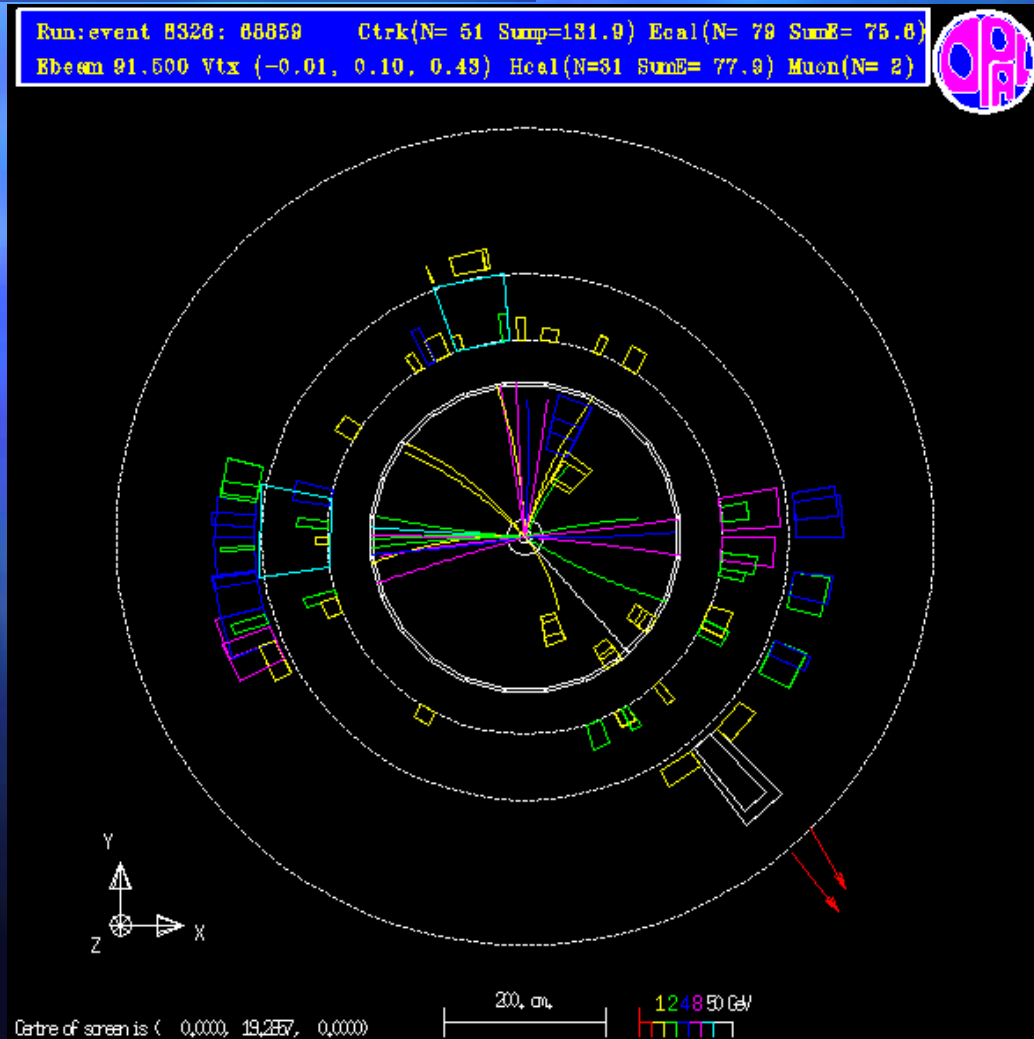
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



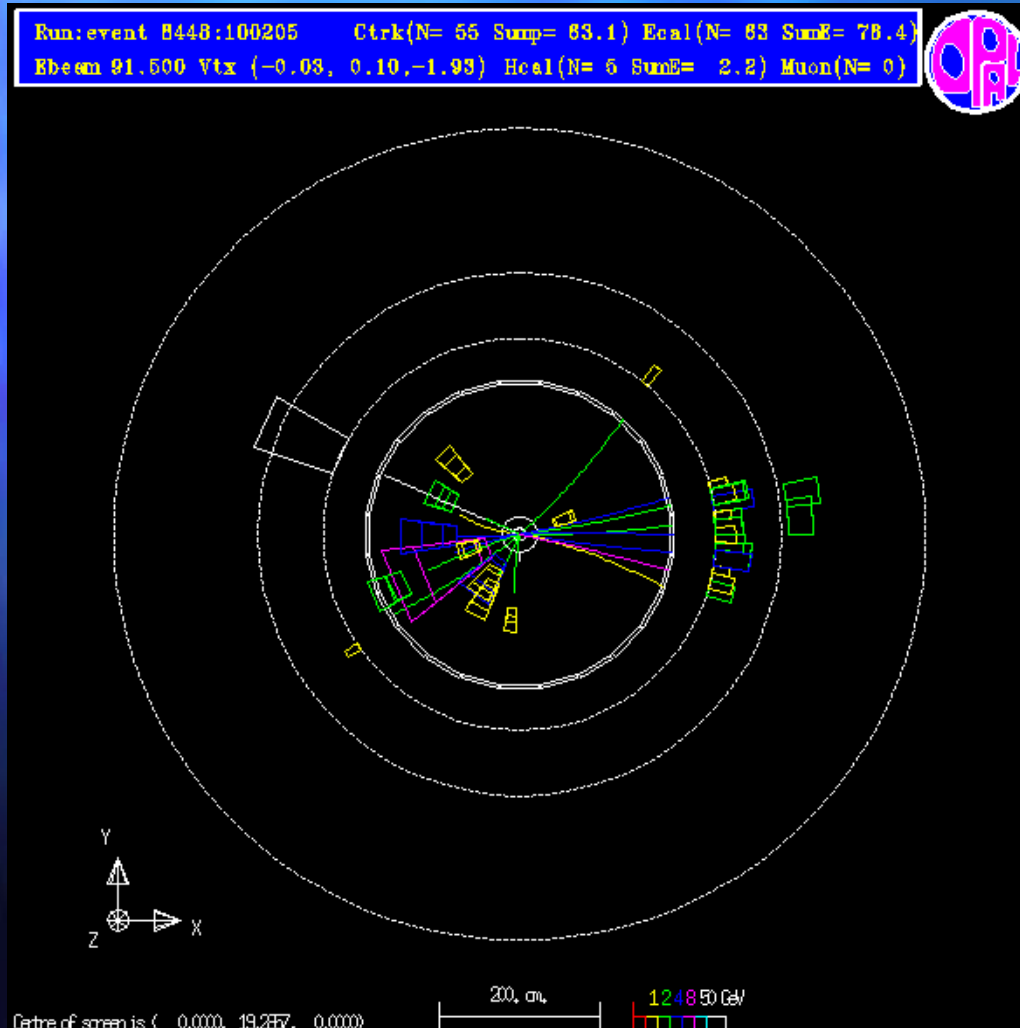
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



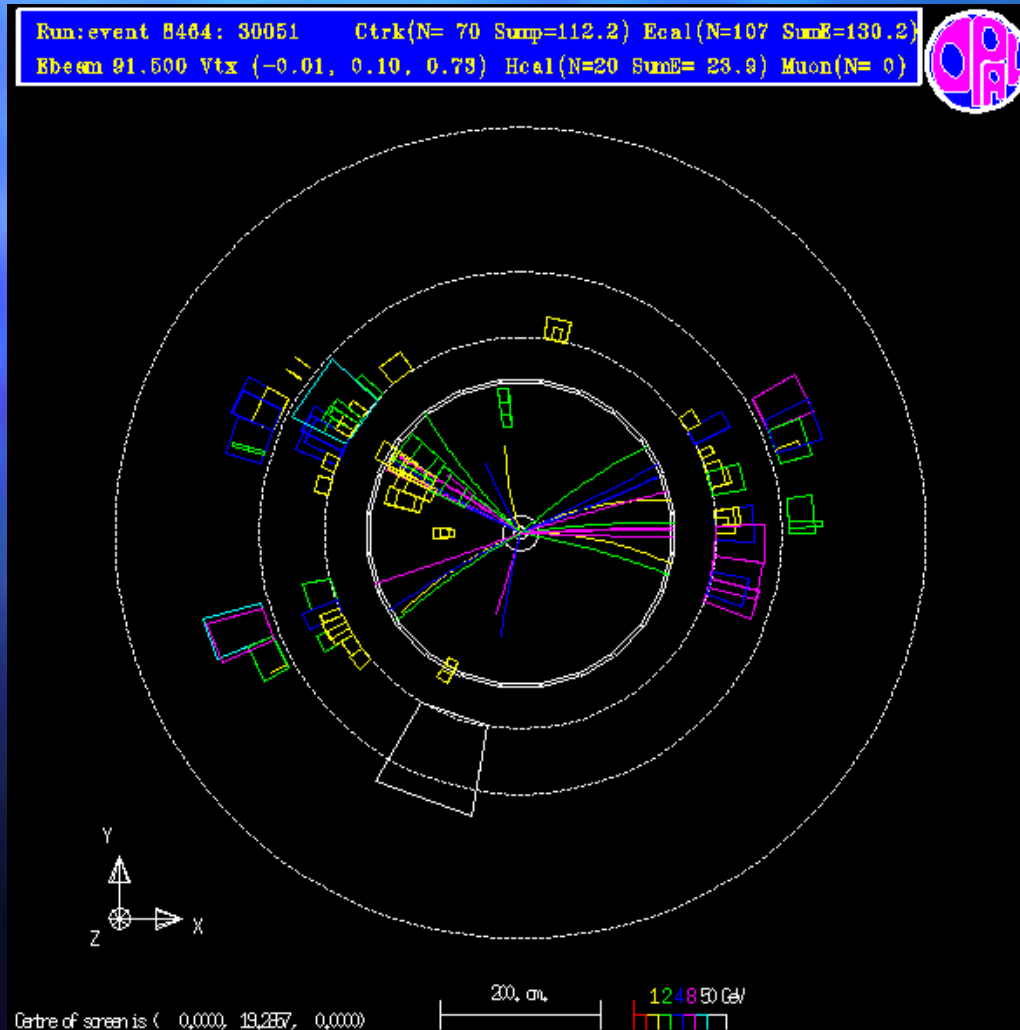
What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

1. Double hadronic decay
2. Mixed
3. Double leptonic decay



Predictions

W⁺W⁻ decay outcomes		W⁺ decay	
		Hadronic (quarks: N)	Leptonic (e/μ/τ: 3)
W⁻ decay	Hadronic (quarks: N)	N ²	3N
	Leptonic (e/μ/τ: 3)	3N	3 ² =9

Probability of a decay type = $\frac{\text{Number of ways it can happen}}{\text{Total number of possible types}}$

$$P(\text{DH}) = N^2 / \text{Total} \quad P(\text{DL}) = 9 / \text{Total} \quad P(\text{M}) = (2 \times 3N) / \text{Total}$$

Results

We know there are three sorts of leptons (e,μ,τ) so there are 9 ways to get double leptonic events

$$DL = 9$$

We saw ?

If there are N quarks we expect N^2 double hadronic events

$$DH = N^2$$

We saw ?

& mixed decays

$$M = 2 \times 3 \times N = 6 N$$

We saw ?

Should observe each decay type according to relative probability

$$N = \frac{6DH}{M}$$

$$N = 3\sqrt{\frac{DH}{DL}}$$

$$N = \frac{3}{2} \frac{M}{DL}$$

We got...

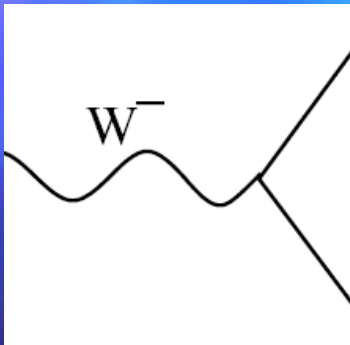
N=?

N=?

N=?

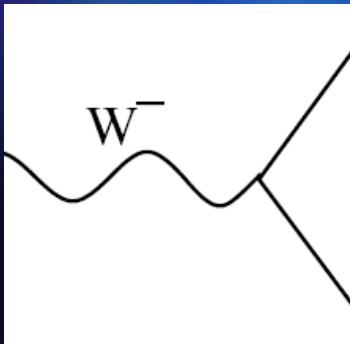
What should we have got?

LEP has enough energy to make four quarks (2 quark decays)



up

down



charm

strange

BUT – there is an additional factor of three because each quark has three different sorts of charges associated with the strong force

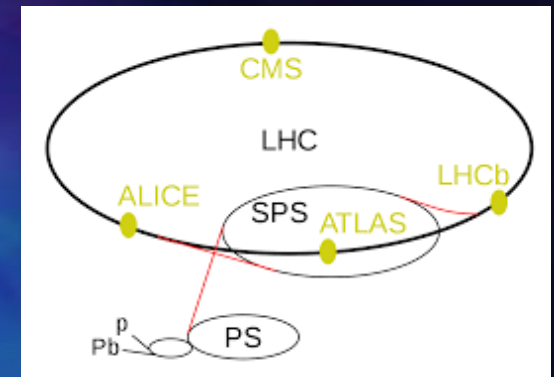
RED

GREEN

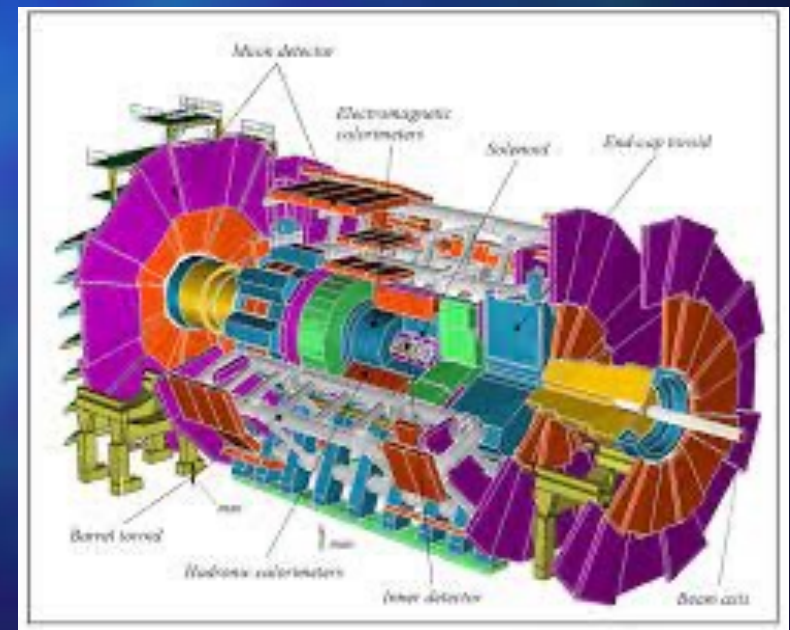
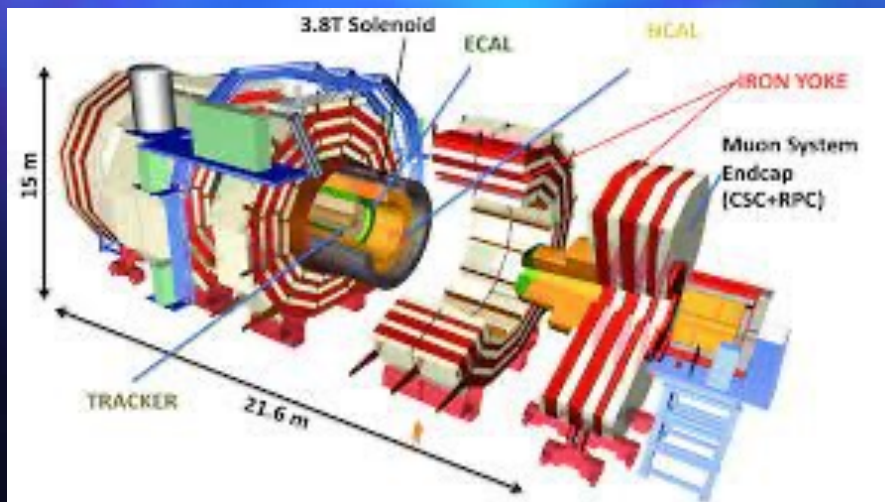
BLUE

$$N = 2 \times 3 = 6$$

State of the art



We used LEP events because they are simple to interpret by eye
Now the Large Hadron Collider (LHC) has been built at CERN in place of LEP, colliding protons instead of e^+e^-

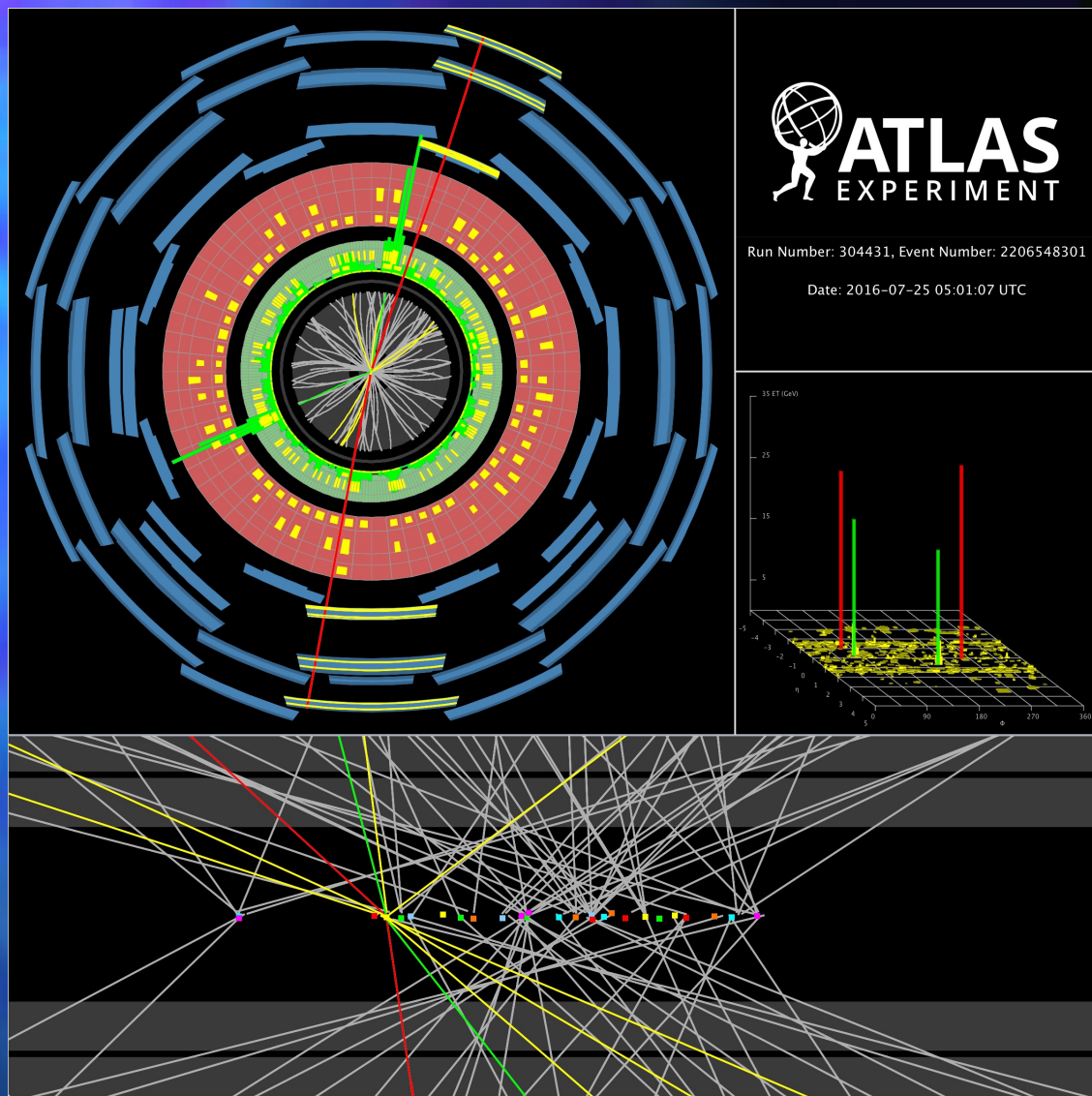


LHC events

Proton-proton collisions
are much “messier”

Multiple interactions
per bunch-crossing,
only one is interesting!

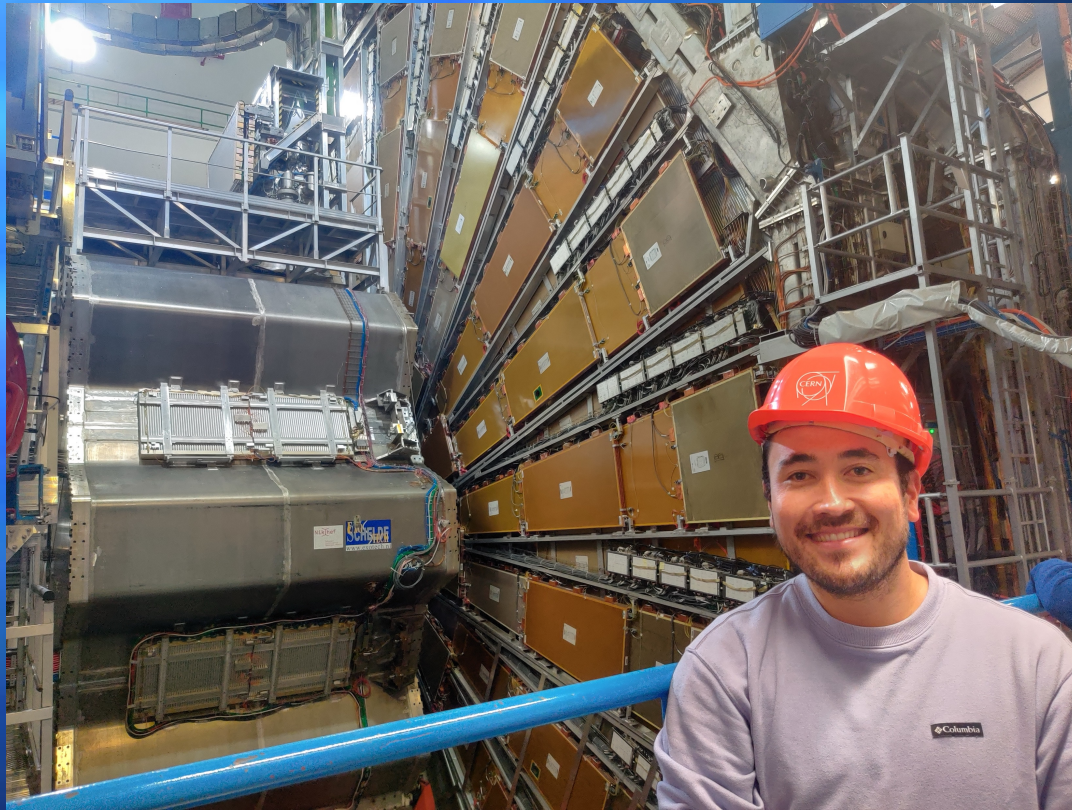
Modern analyses use
complex algorithms &
A.I. to get interesting
physics out!



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayPublicResults>

<https://opendata.cern.ch/visualise/events/cms>

Thanks & hope you enjoyed it!



Visiting the ATLAS detector cavern, Nov. 2023

Ken's results from last night

We know there are three sorts of leptons (e,μ,τ) so there are 9 ways to get double leptonic events

$$DL = 9$$

Ken saw 13

If there are N quarks we expect N^2 double hadronic events

$$DH = N^2$$

Ken saw 48

& mixed decays

$$M = 2 \times 3 \times N = 6 N$$

Ken saw 41

Should observe each decay type according to relative probability

$$N = \frac{6DH}{M}$$

$$N = 3\sqrt{\frac{DH}{DL}}$$

$$N = \frac{3}{2} \frac{M}{DL}$$

Ken got...

$$N=7.0$$

$$N=5.8$$

$$N=4.7$$