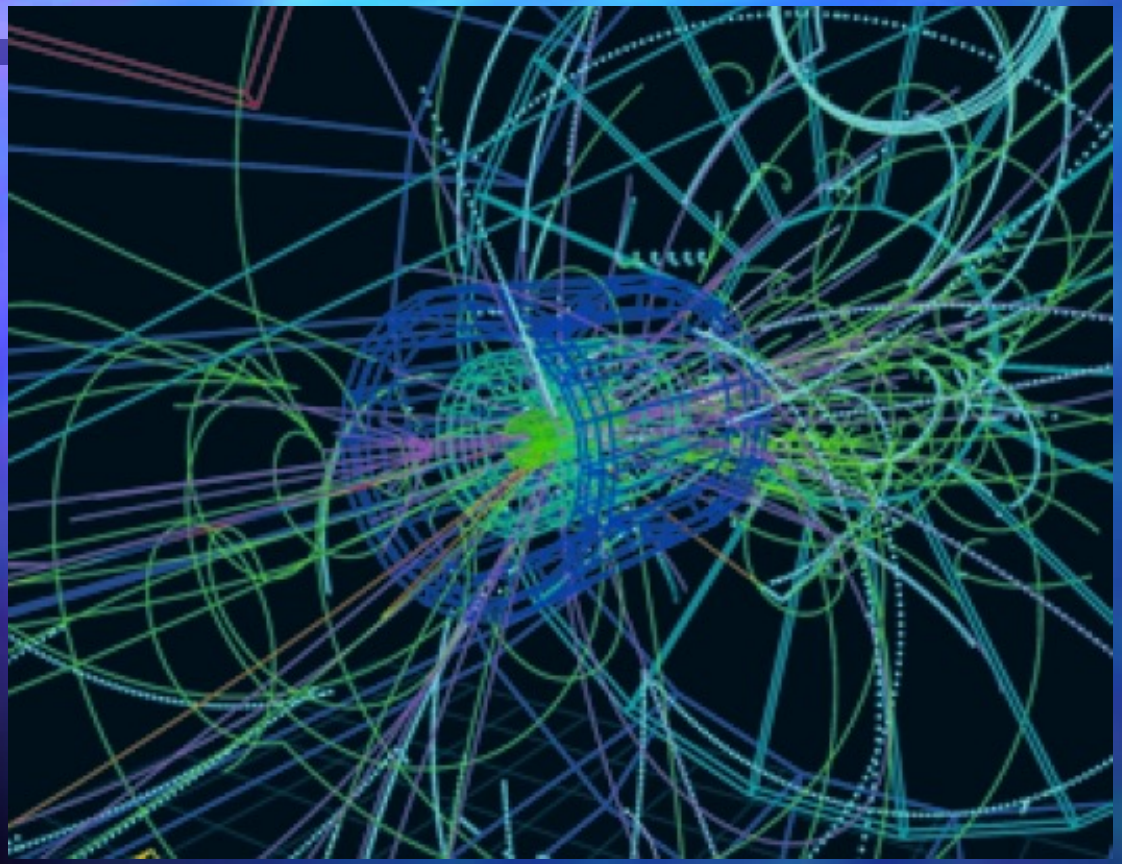
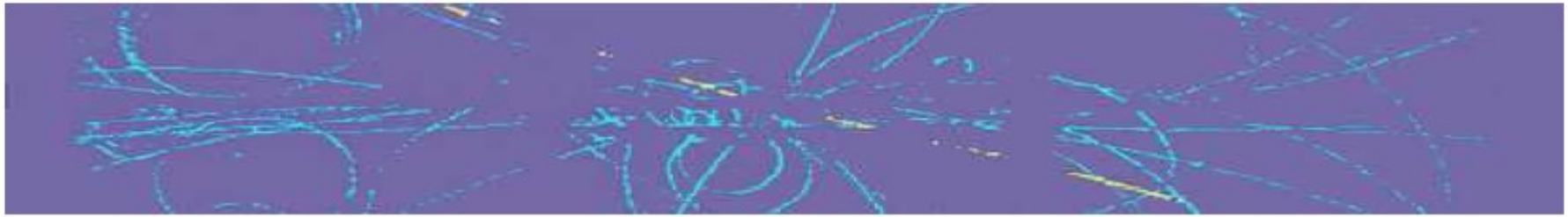
Counting Quarks



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

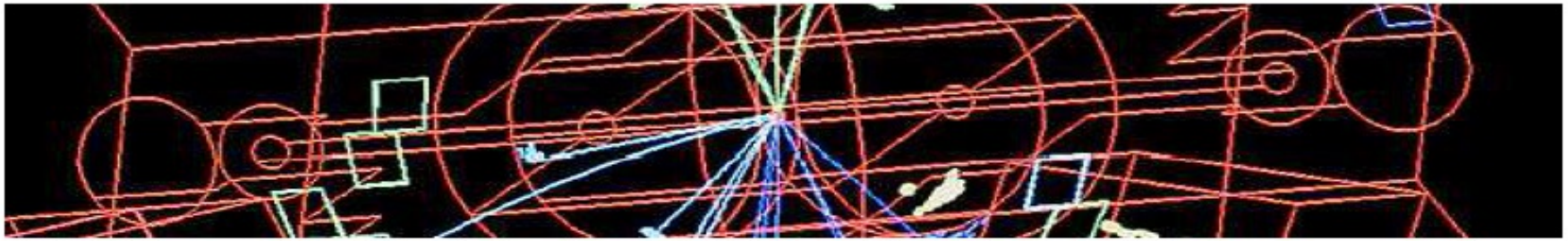
The Particle World



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

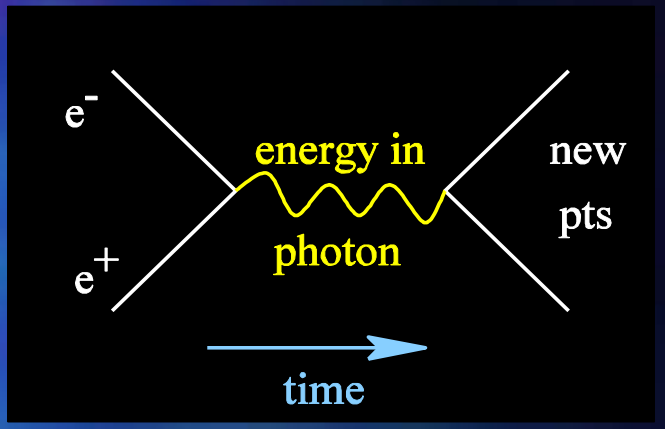
A question to test Vevox

What did you drink with your breakfast this morning?

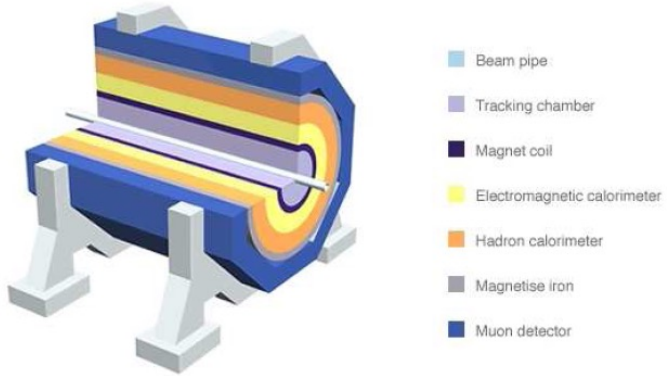
1. Tea
2. Coffee
3. Fruit Juice
4. Water
5. Other
6. Nothing

LEP: the Large Electron Positron Collider

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

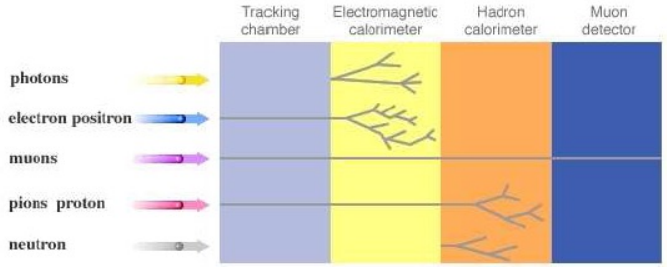


OPAL

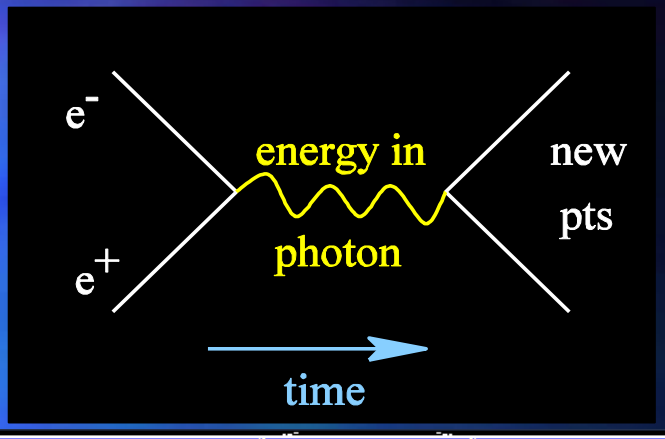


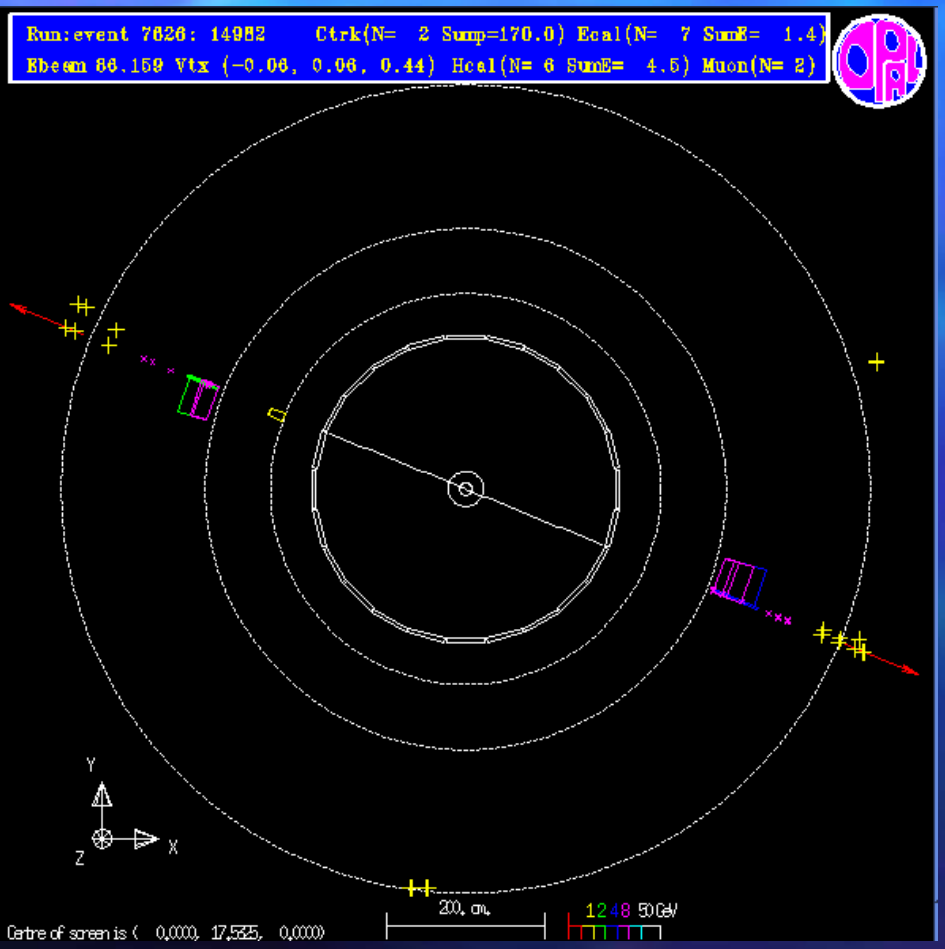
Detector Ingredients

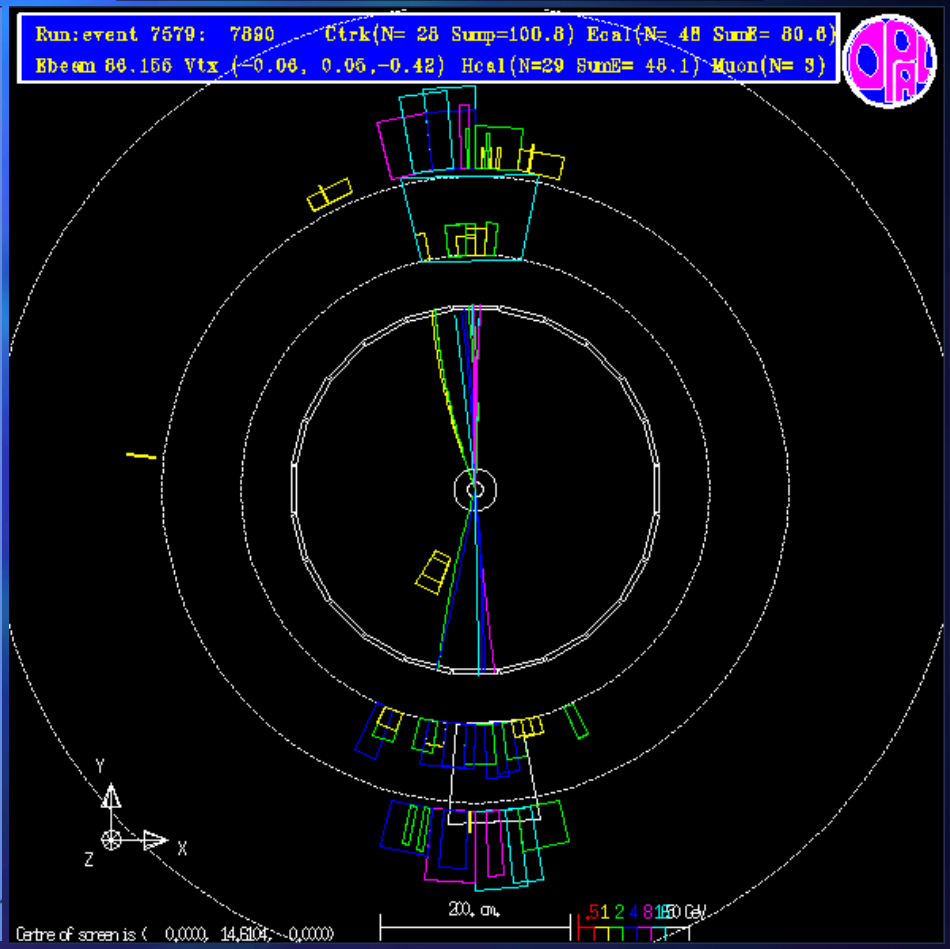
- Tracking chamber: records the tracks of charged particles
- Electromagnetic calorimeter or ecal: measures energy of light particles (electrons, photons) as they interact with electrically charged particles inside matter
- Hadron calorimeter: measures energy of hadrons as they interact with atomic nuclei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



Some Simple Events

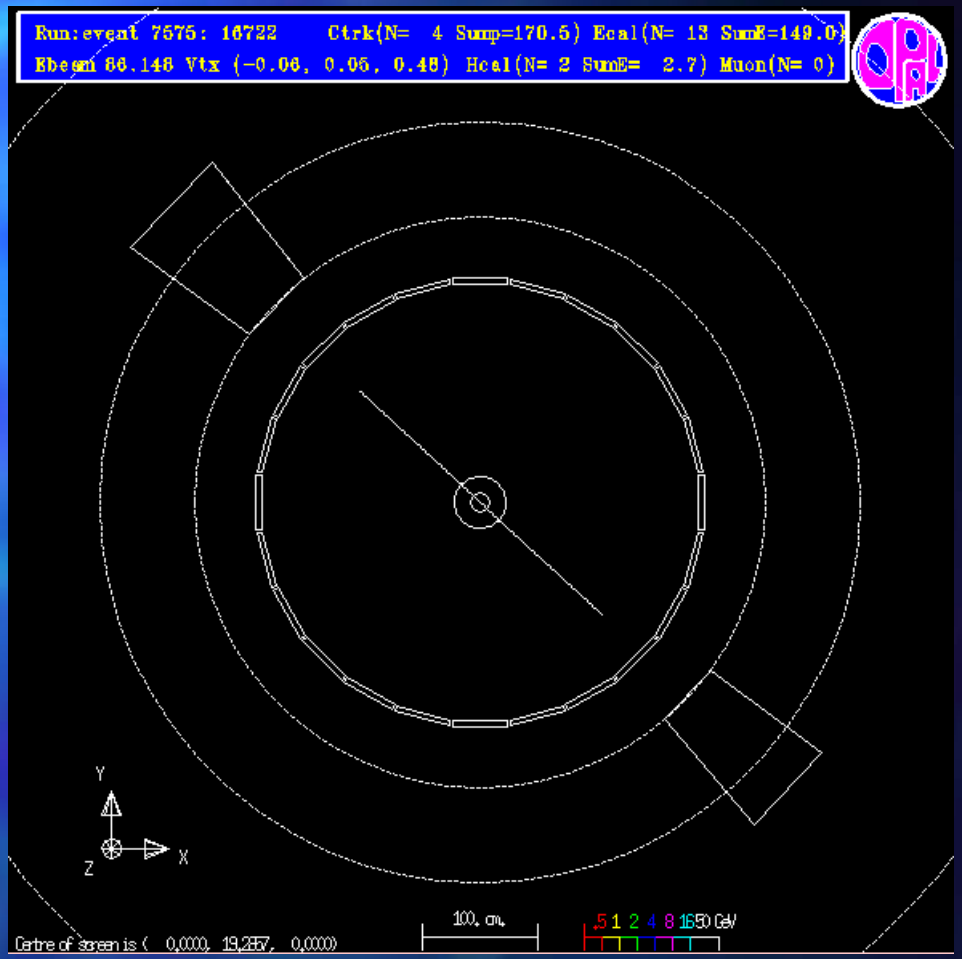






Electrons

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

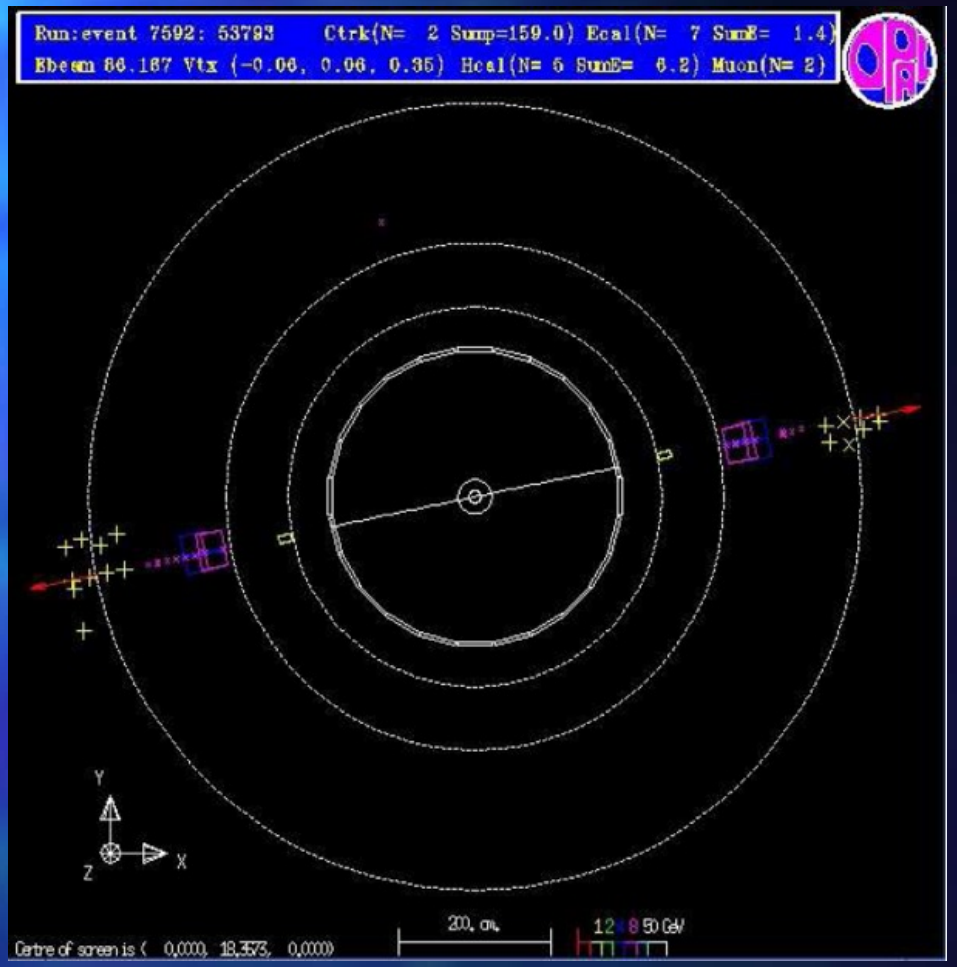
Muons (μ)

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!

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



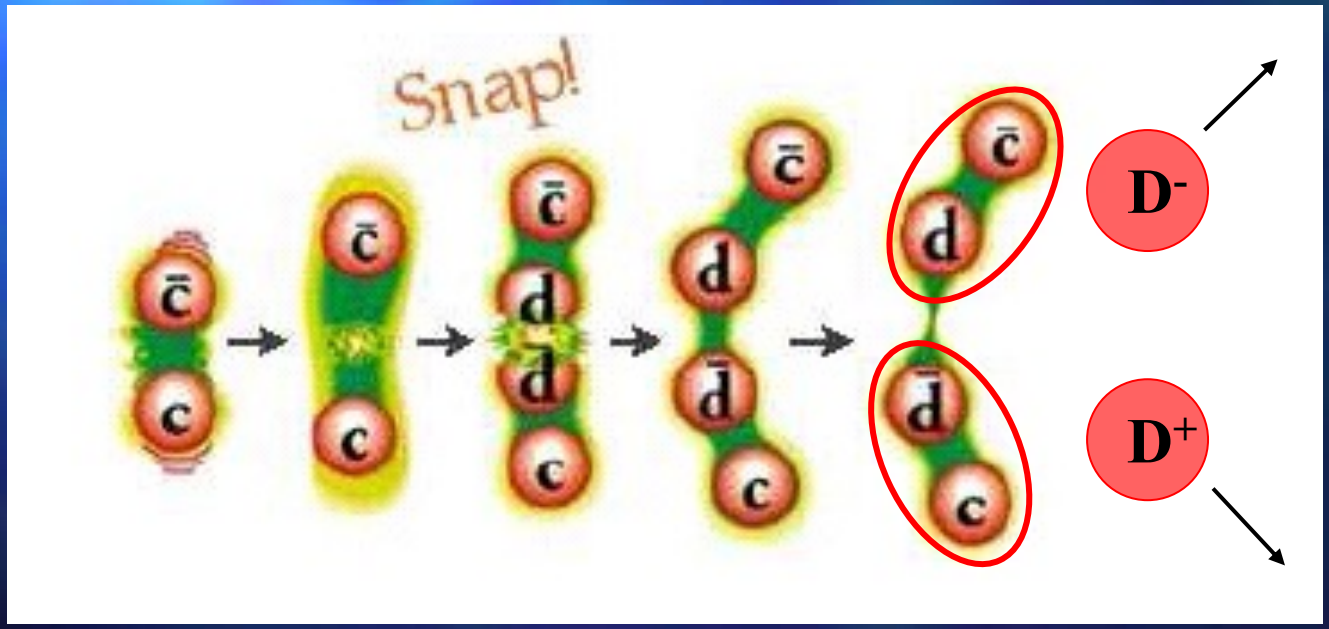
Signature:

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

Strong Nuclear Force

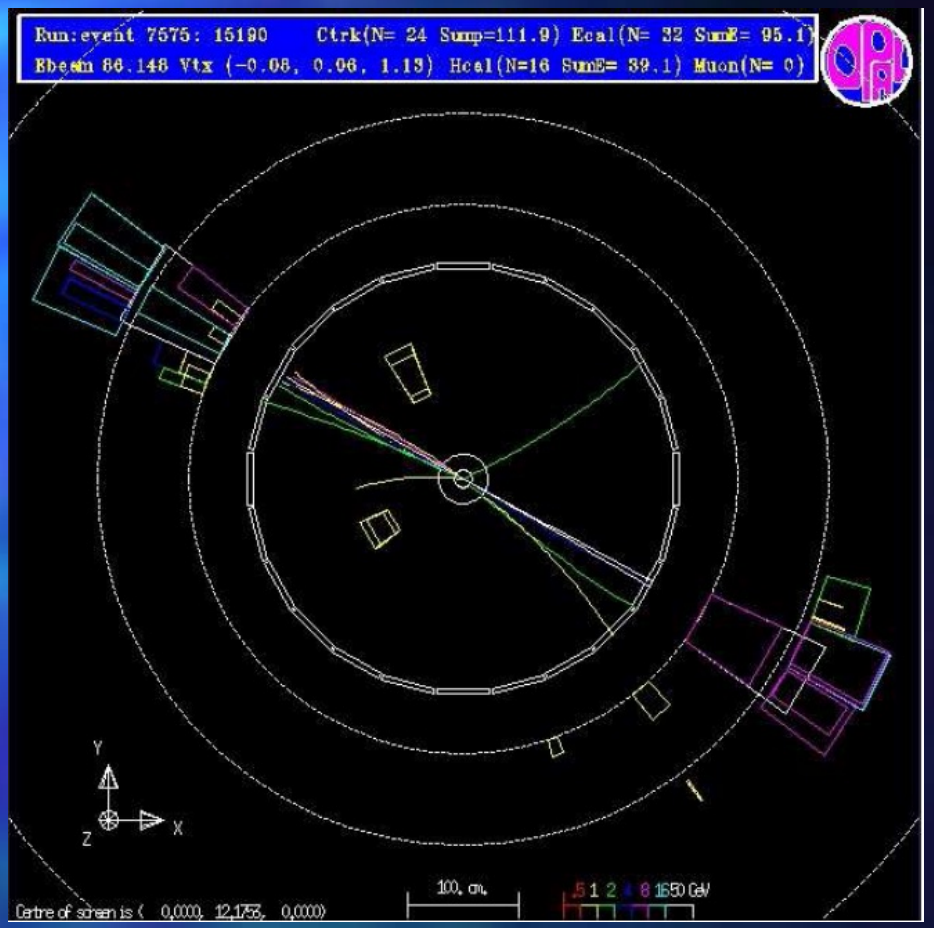
The force between quarks grows with distance !!!!!

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!

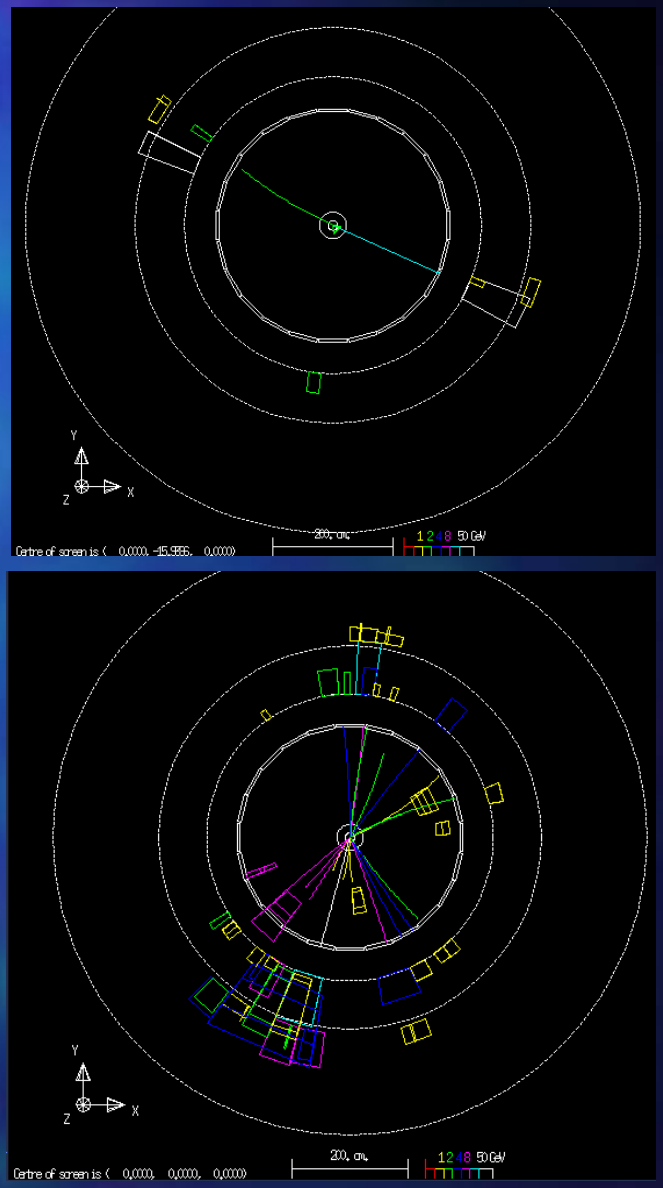
Signature:

a) Electron or muon (will correctly be identified as leptonic decay)

b) 1 or 3 jets (tracks + electromagnetic & hadronic calorimeter hits)

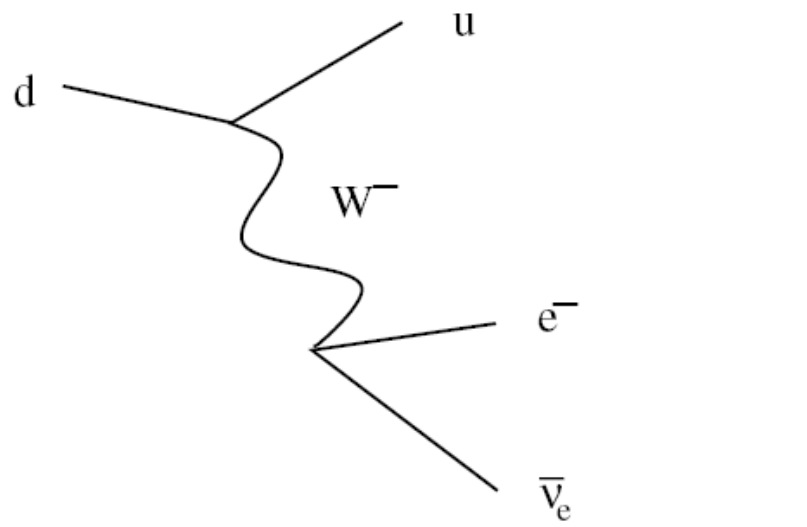
- Difficult to distinguish from jets!

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



The Weak Nuclear Force (Beta Decay)

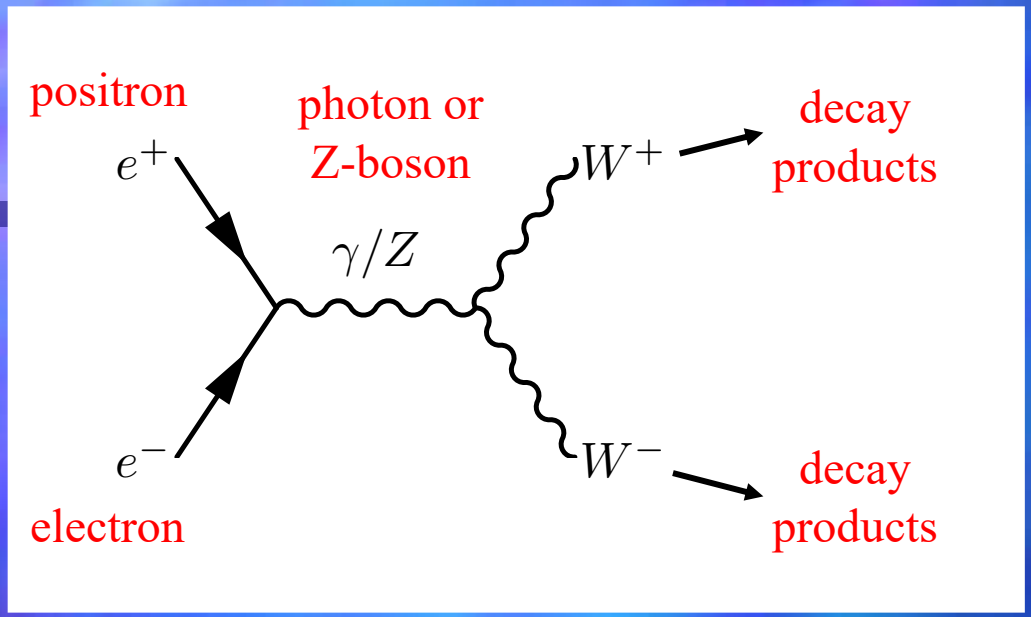
Weak decays, eg β-decay,
$n \rightarrow p + e^- + \bar{\nu}_e$ is understood as decay of a d quark, mediated by a W particle.



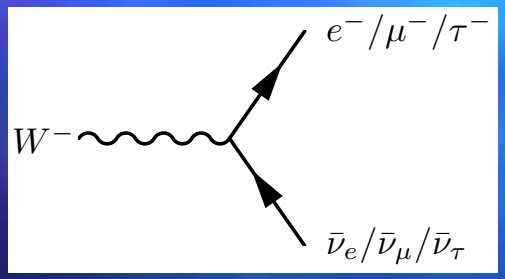
Neutrinos only interact by the weak force – once produced we never see them again (thanks Pauli!)…

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

WW Events at LEP

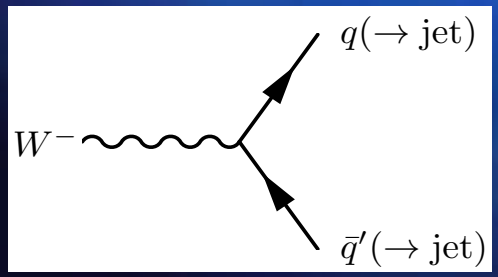


The decays are so fast you'll only see the final products in the detector…



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 ($e/\mu/\tau$)
W^- decay	Hadronic (quarks)	4 jets	2 jets + e, μ or τ
	Leptonic ($e/\mu/\tau$)	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:

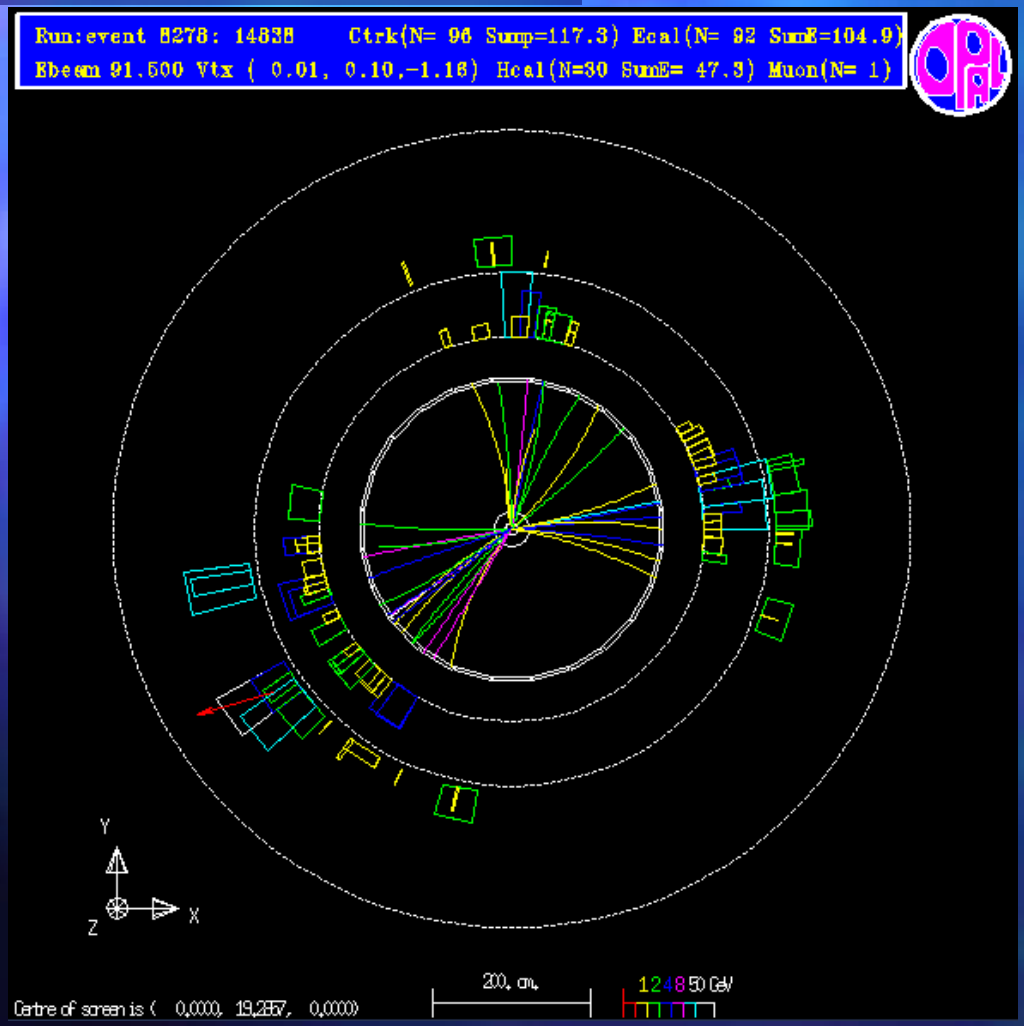
Link to cheatsheet

“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



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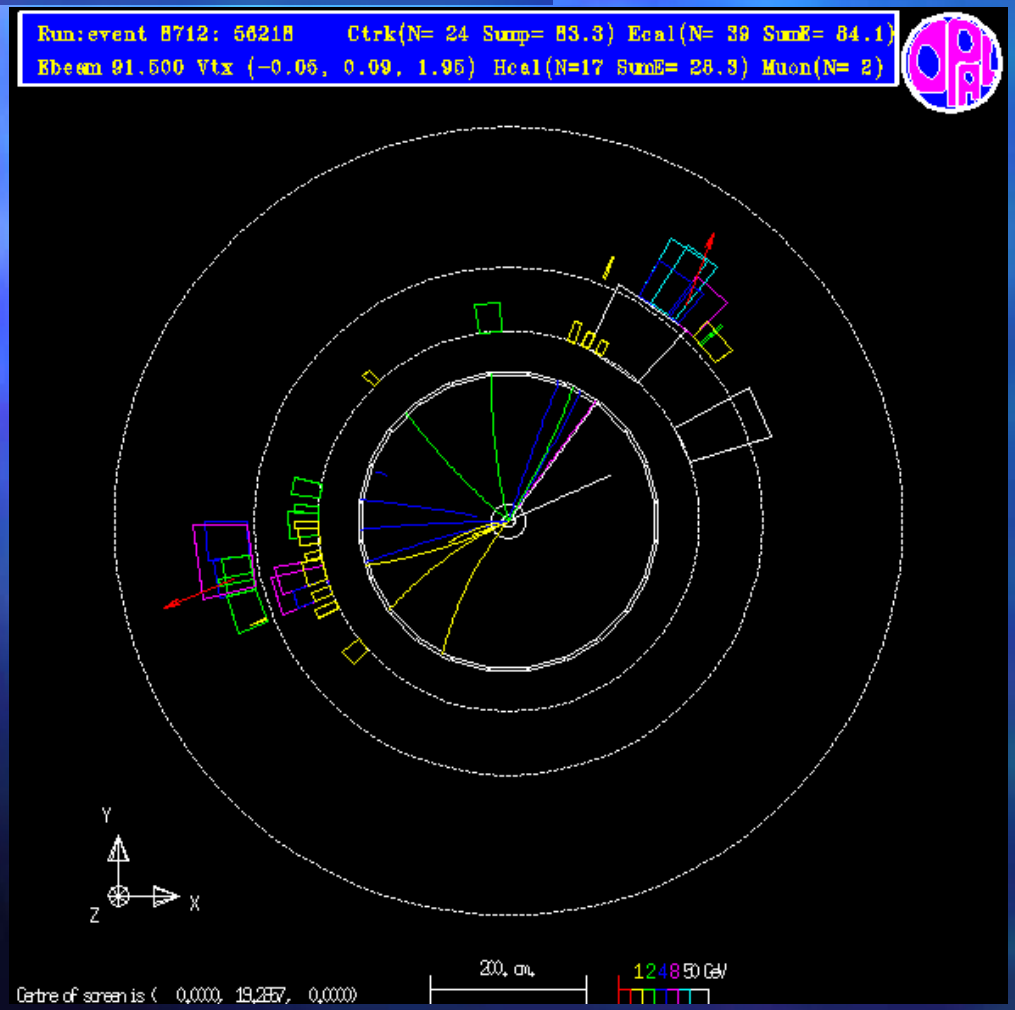

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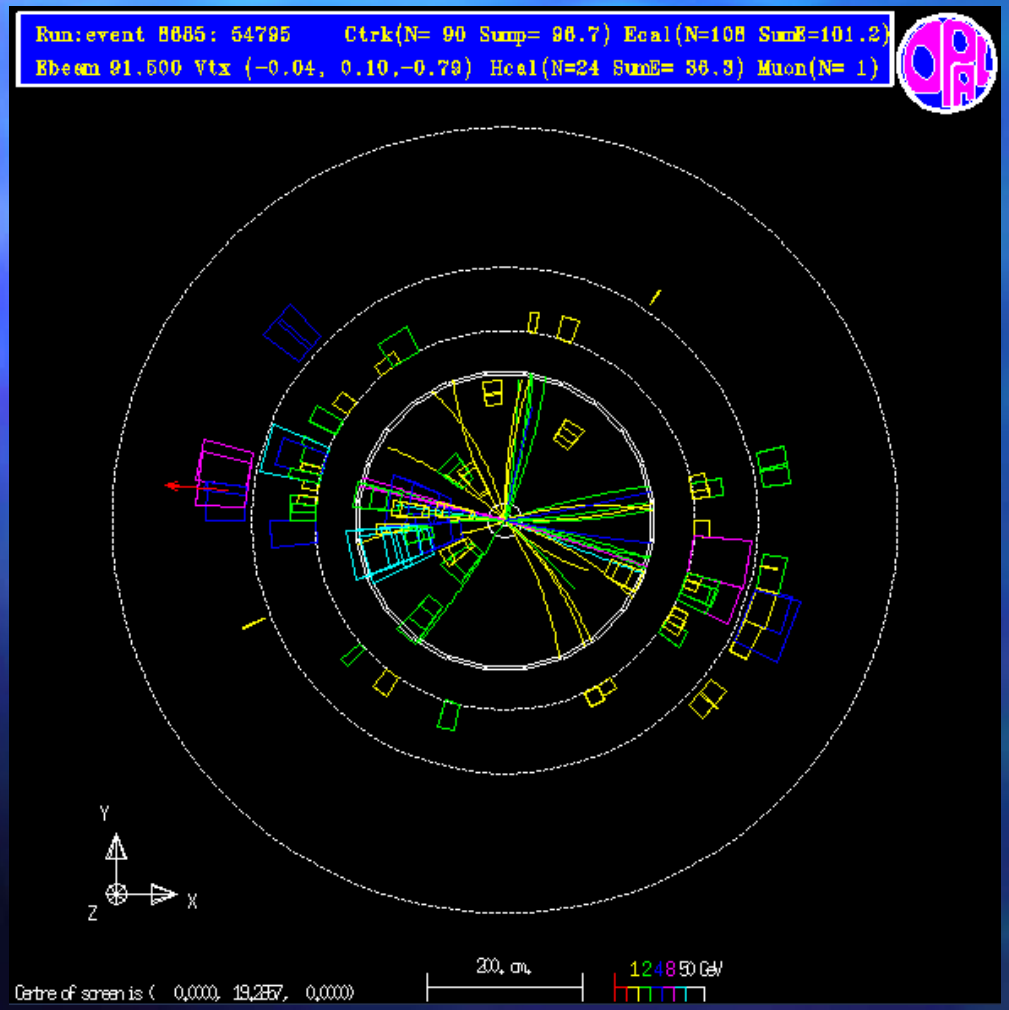

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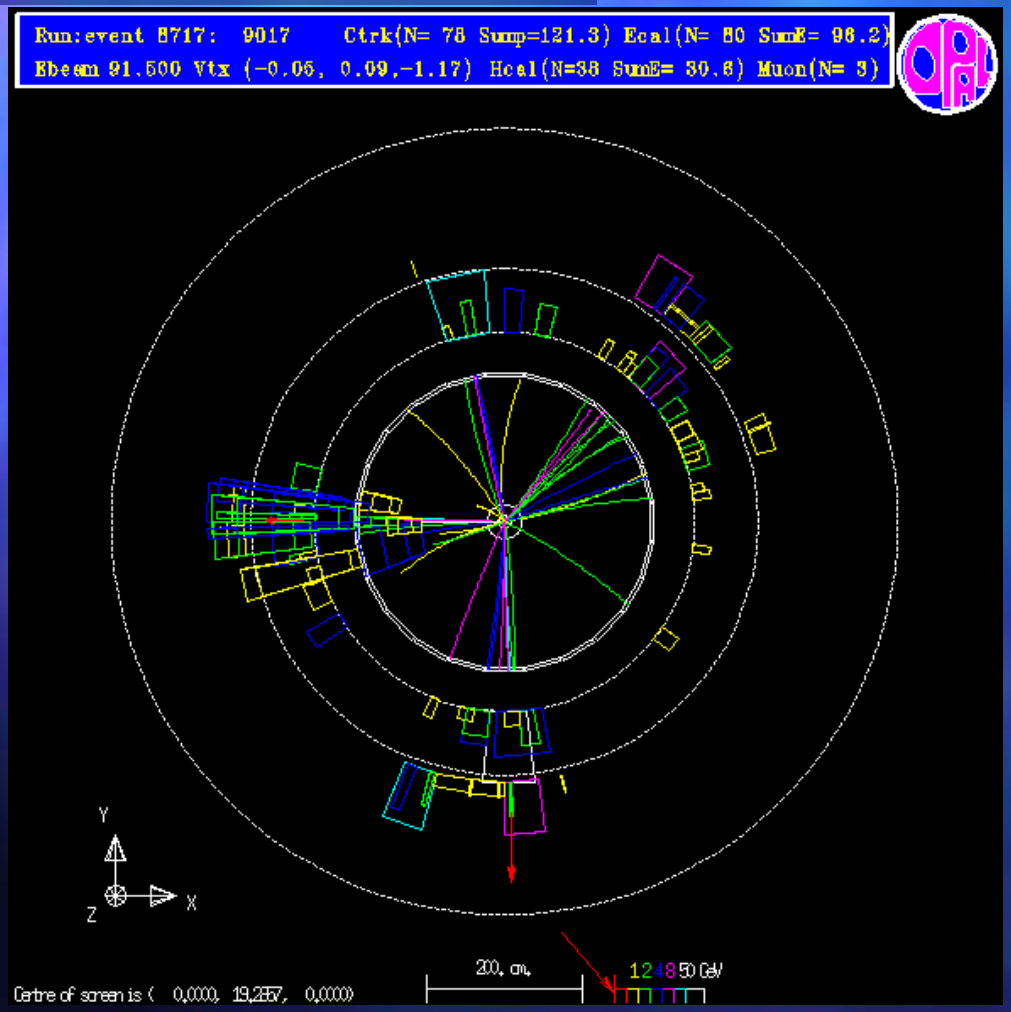

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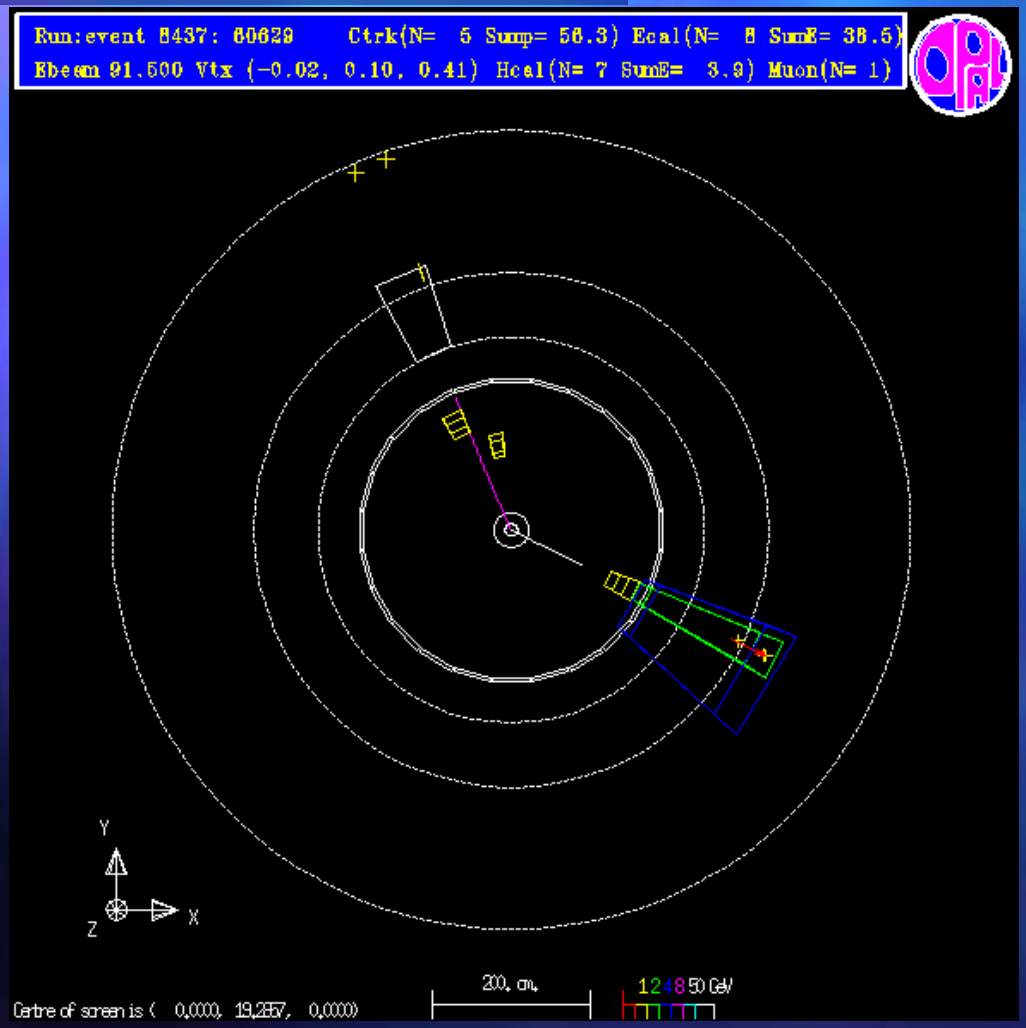

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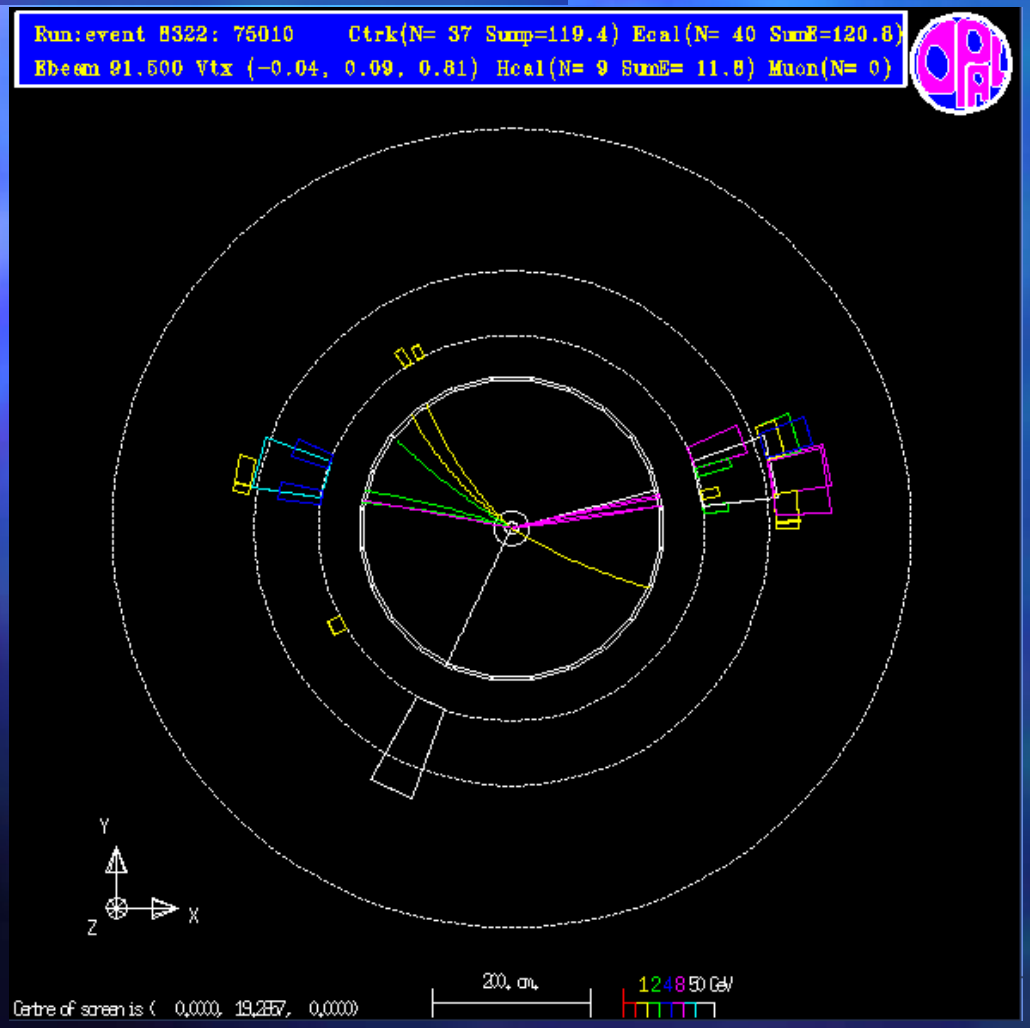

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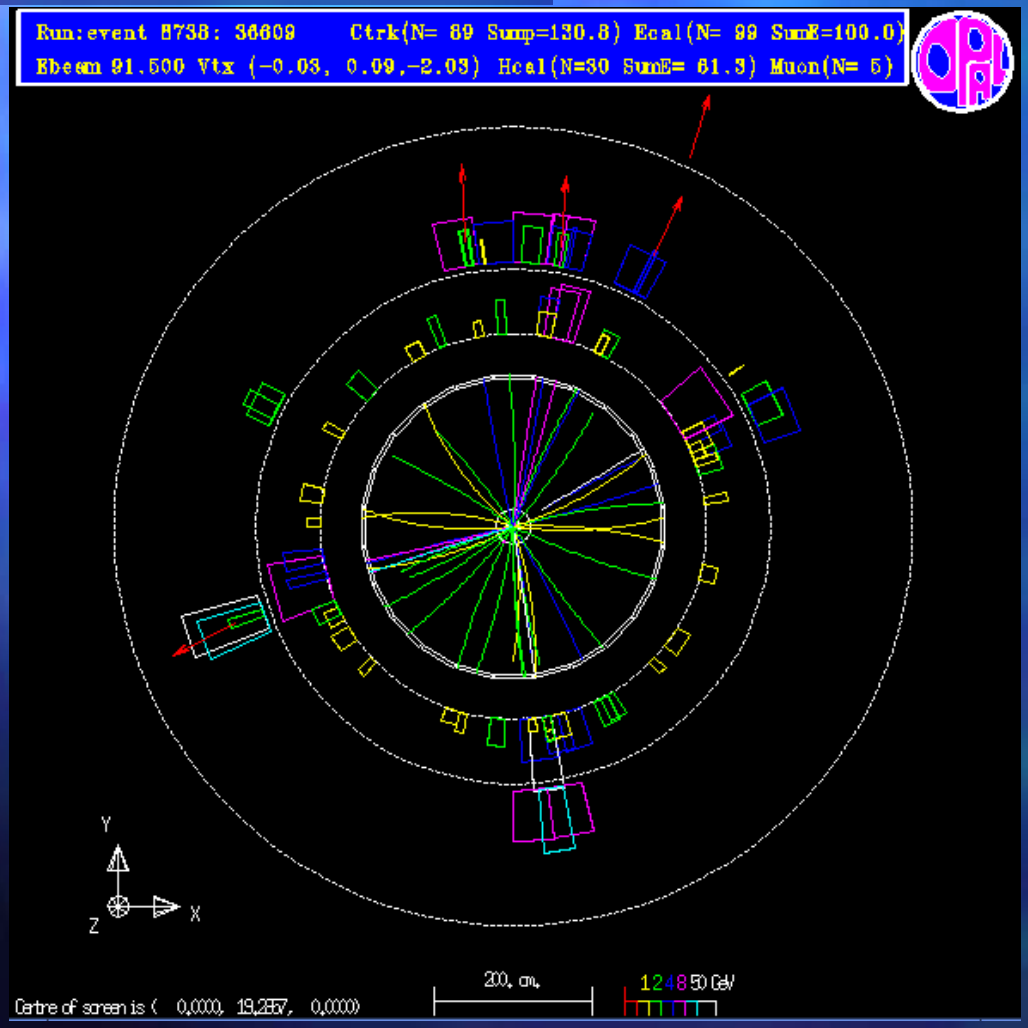

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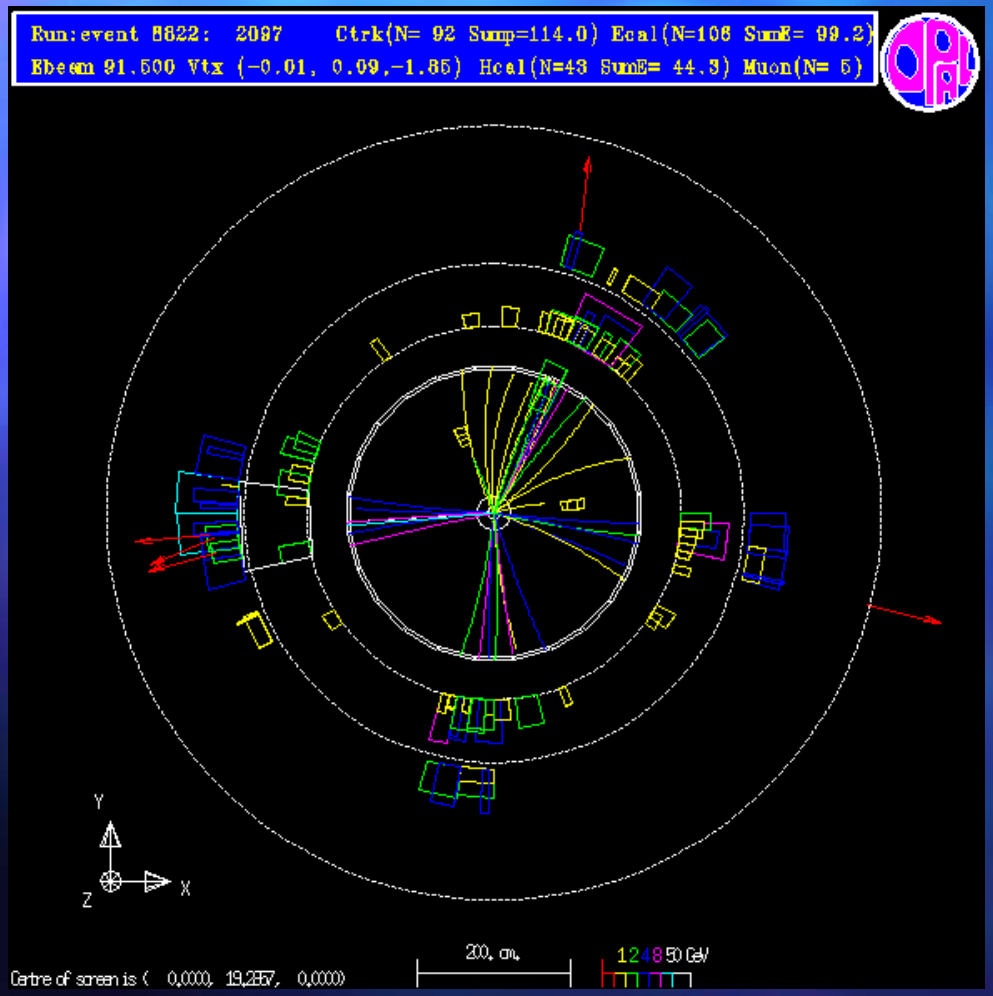

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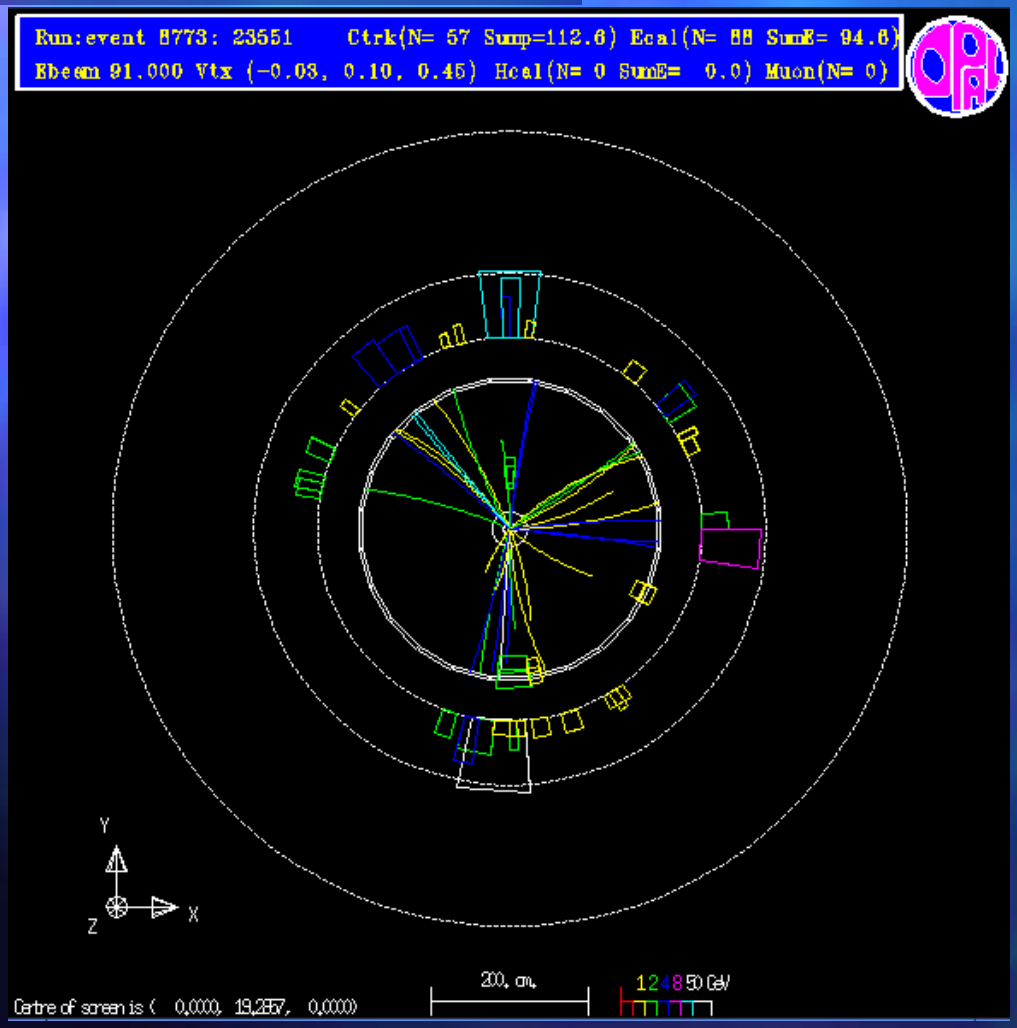

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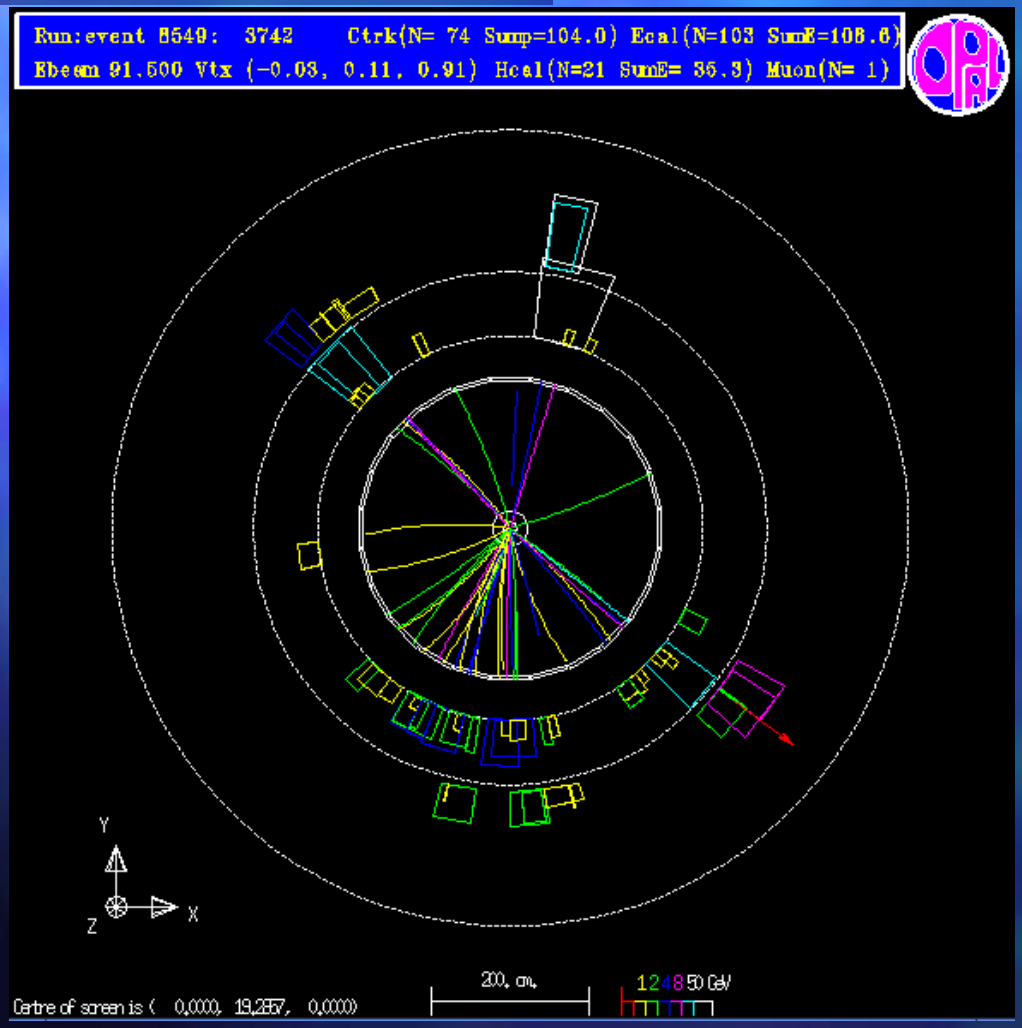

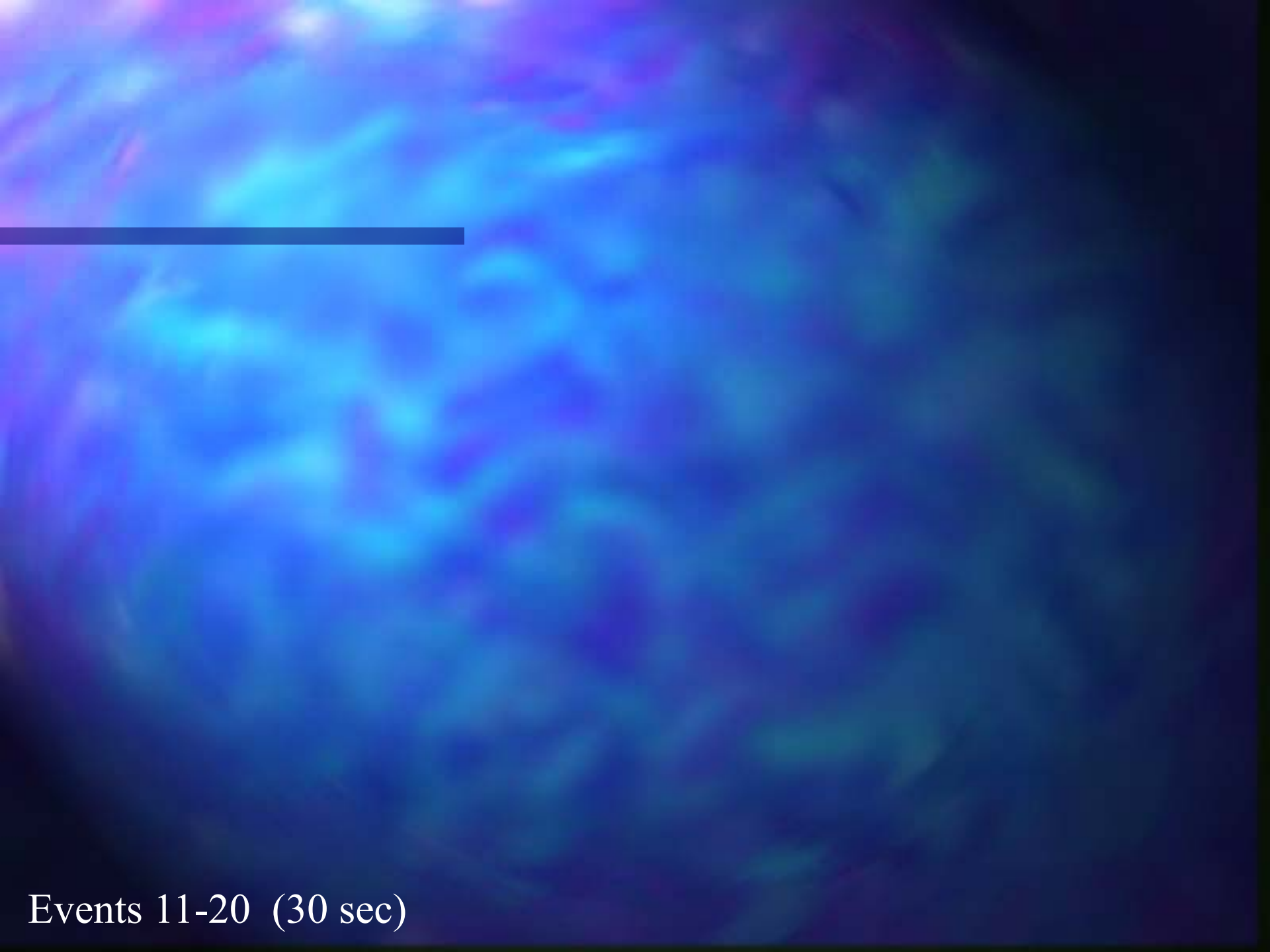
Events 11-20 (30 sec)

What sort of WW decay is this?

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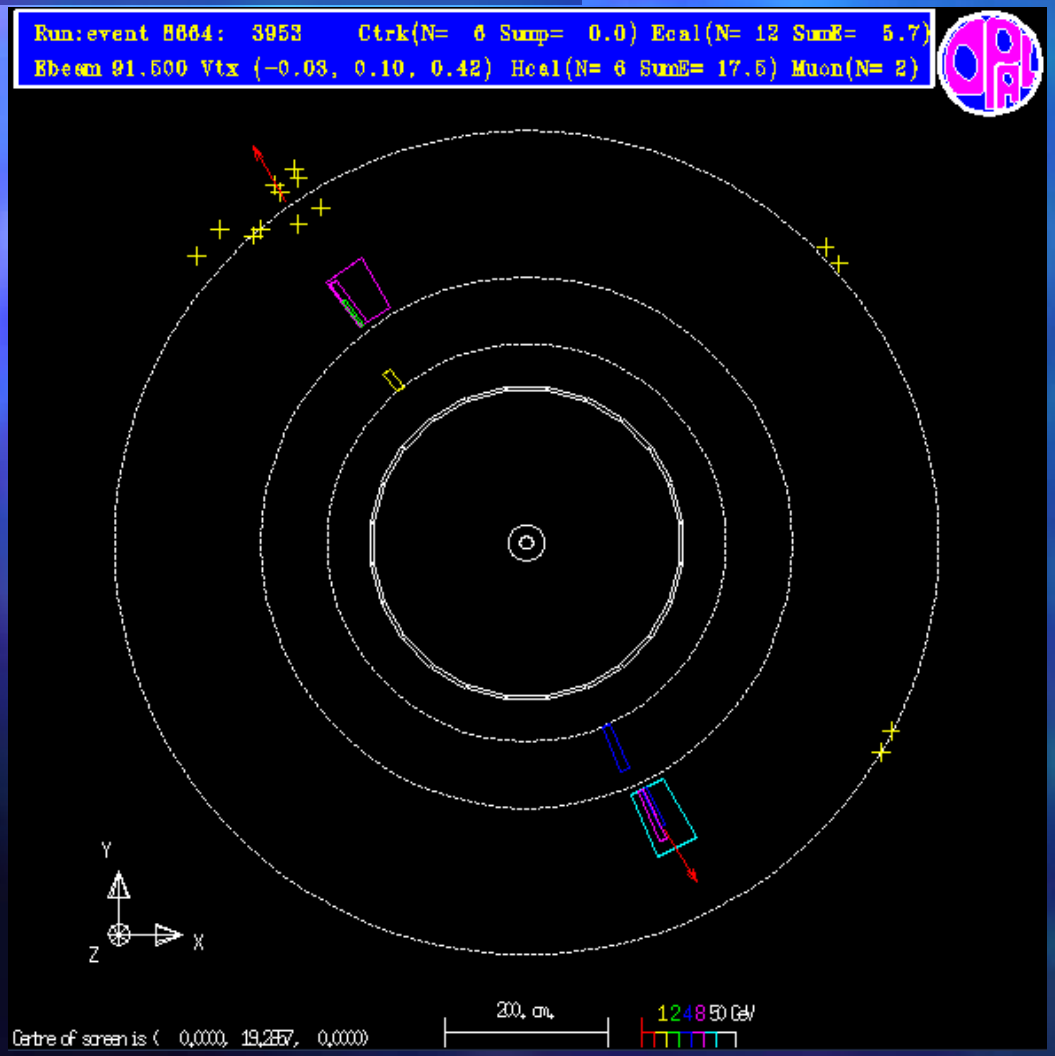

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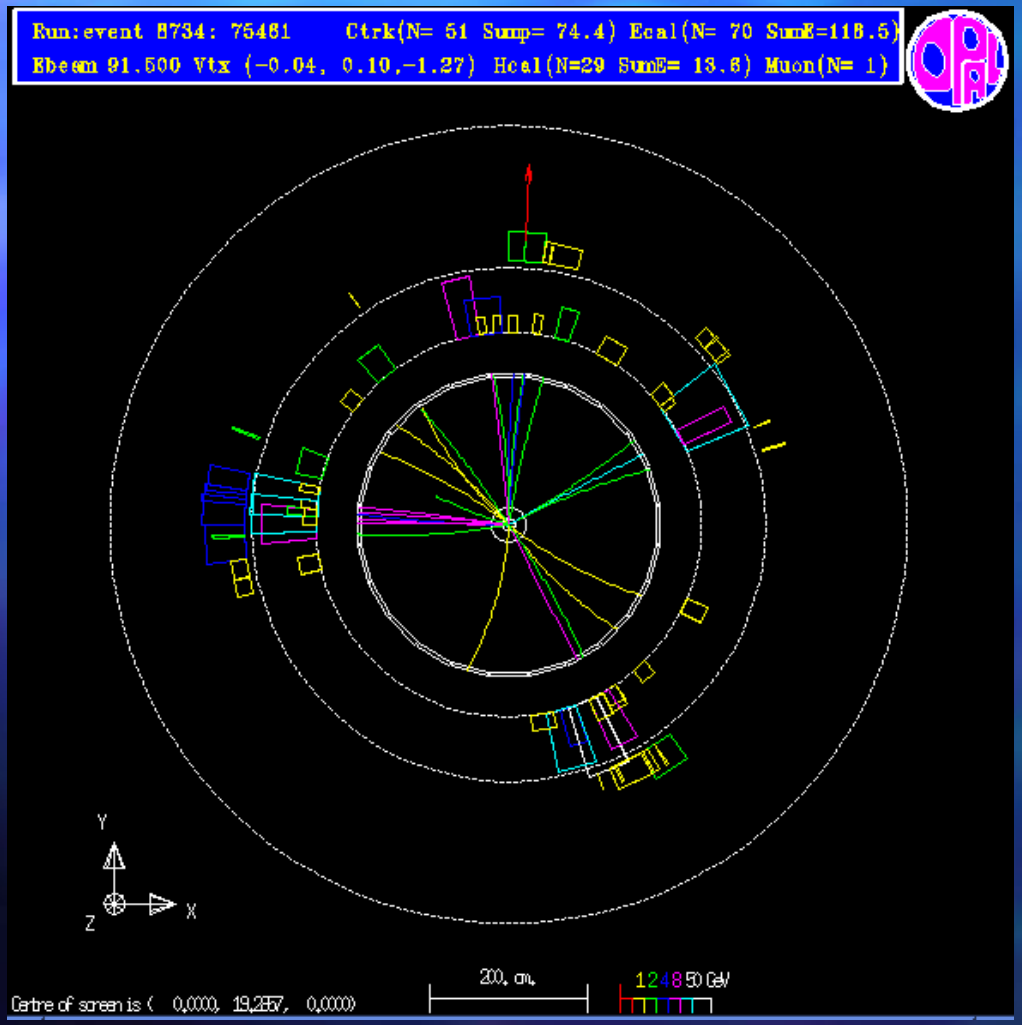

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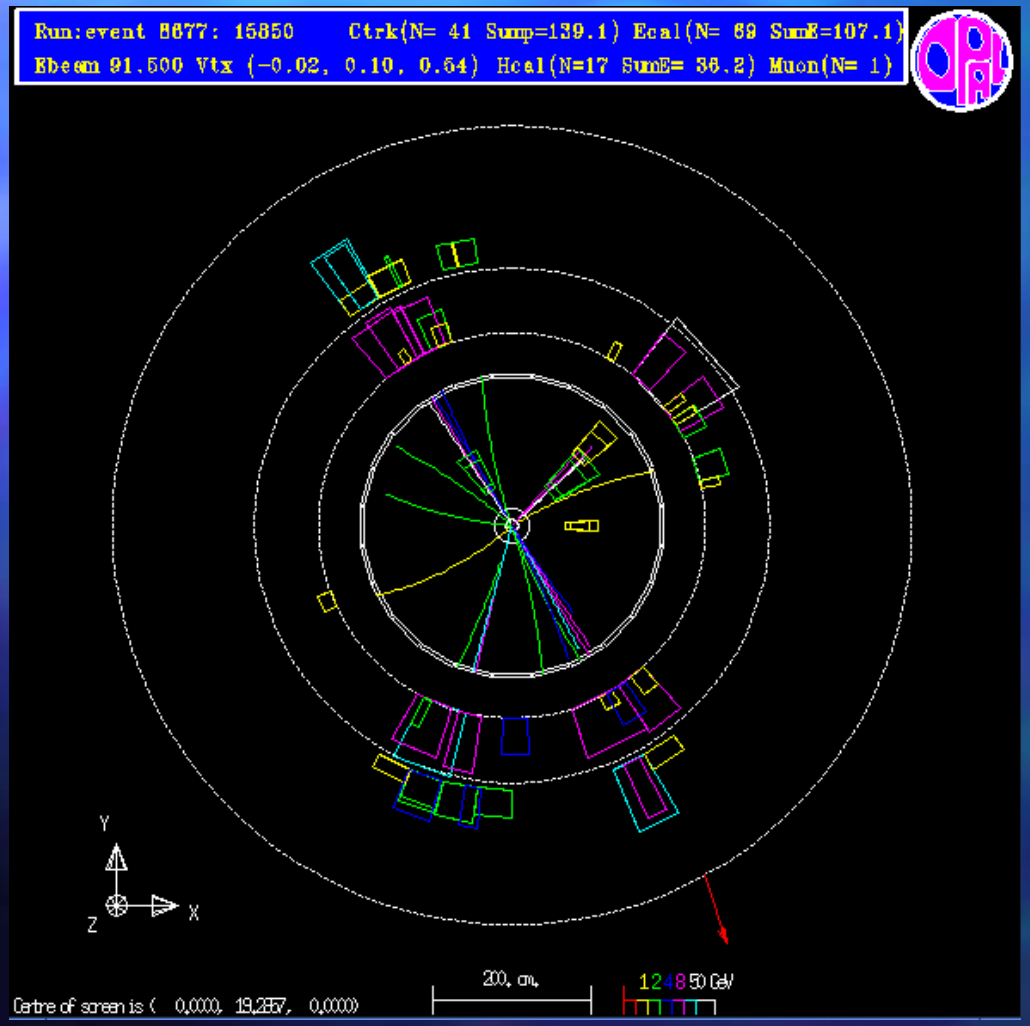

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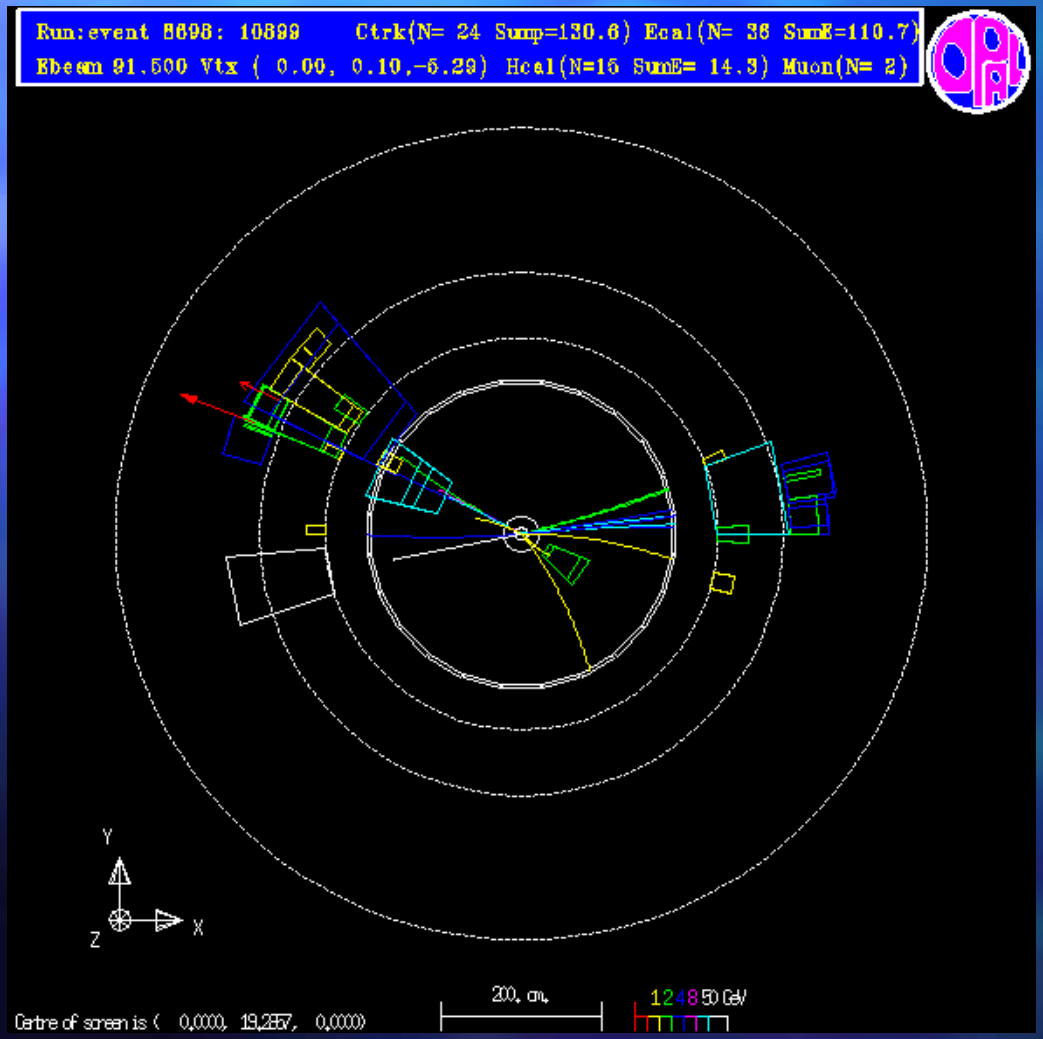

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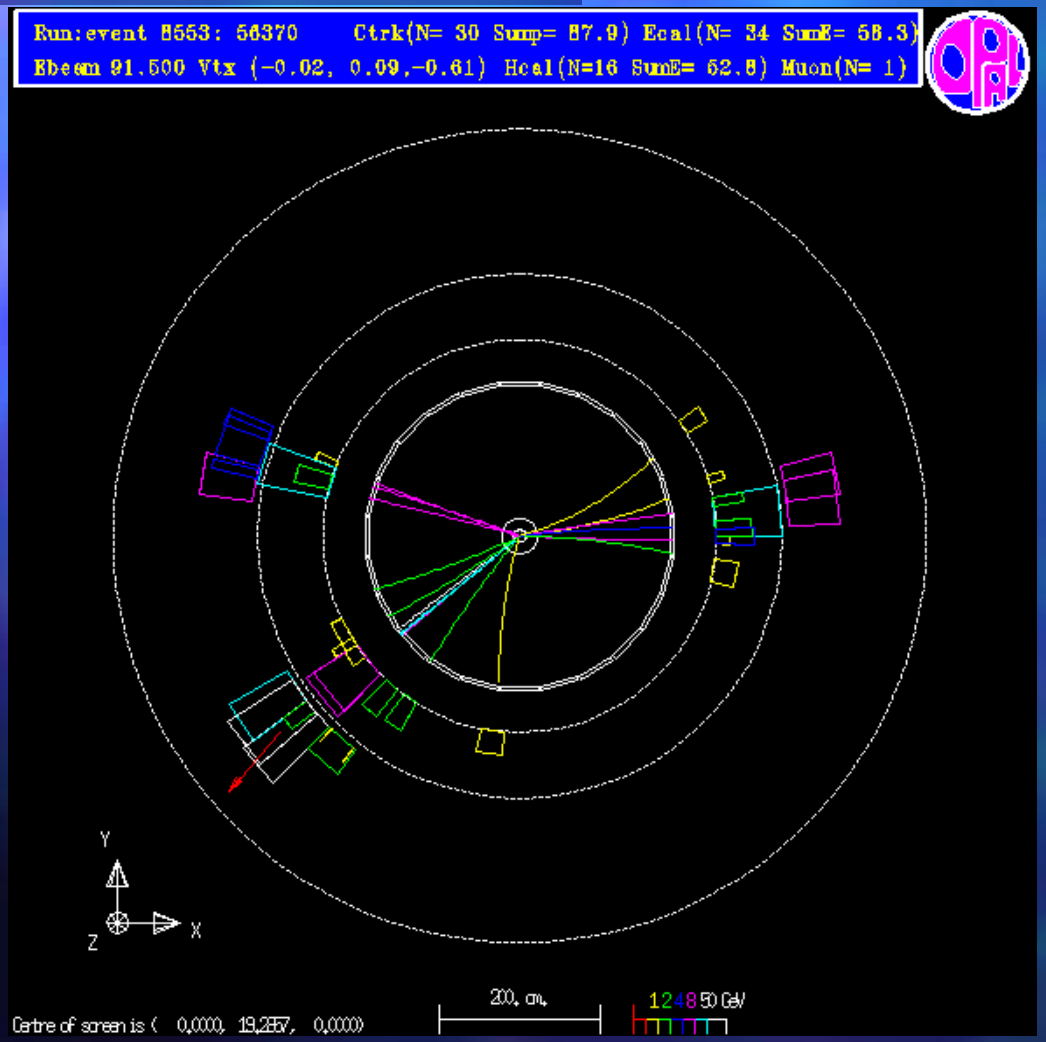

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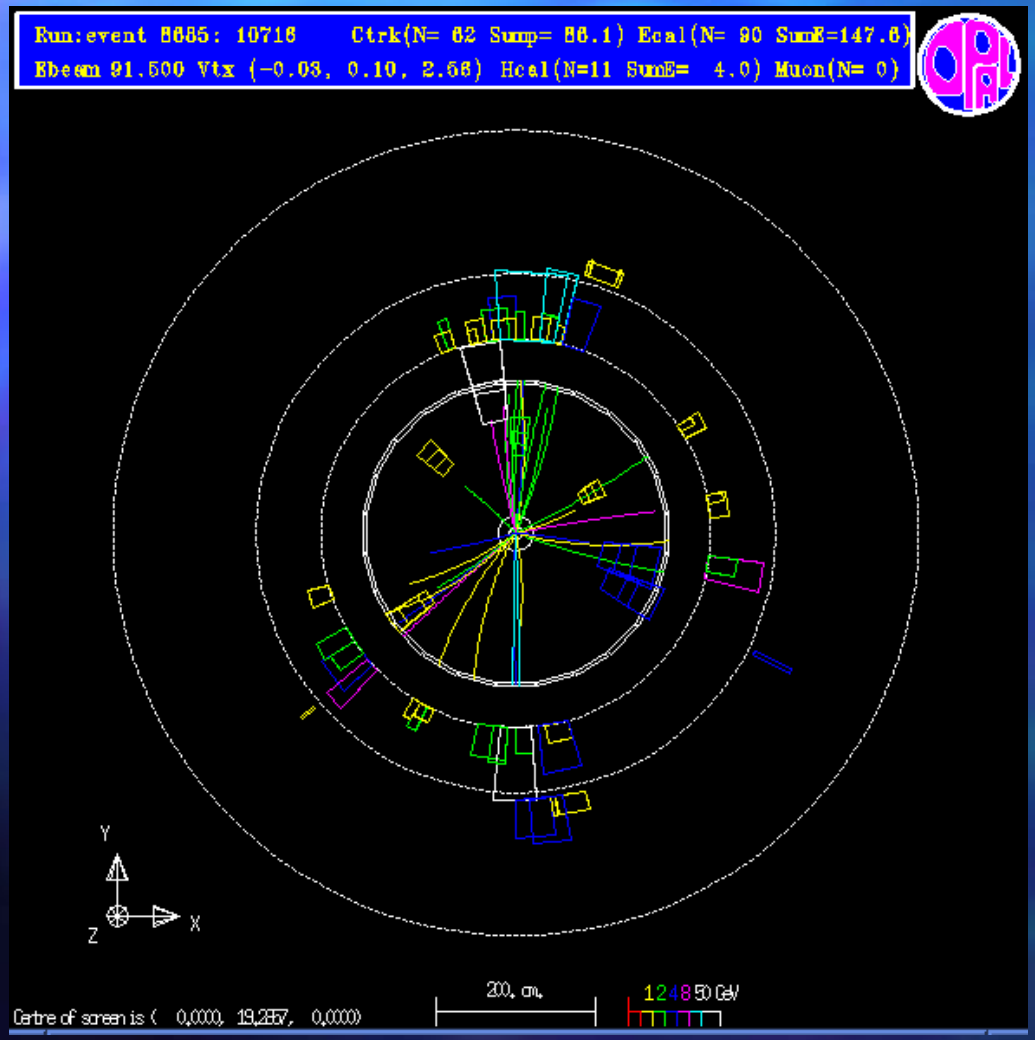

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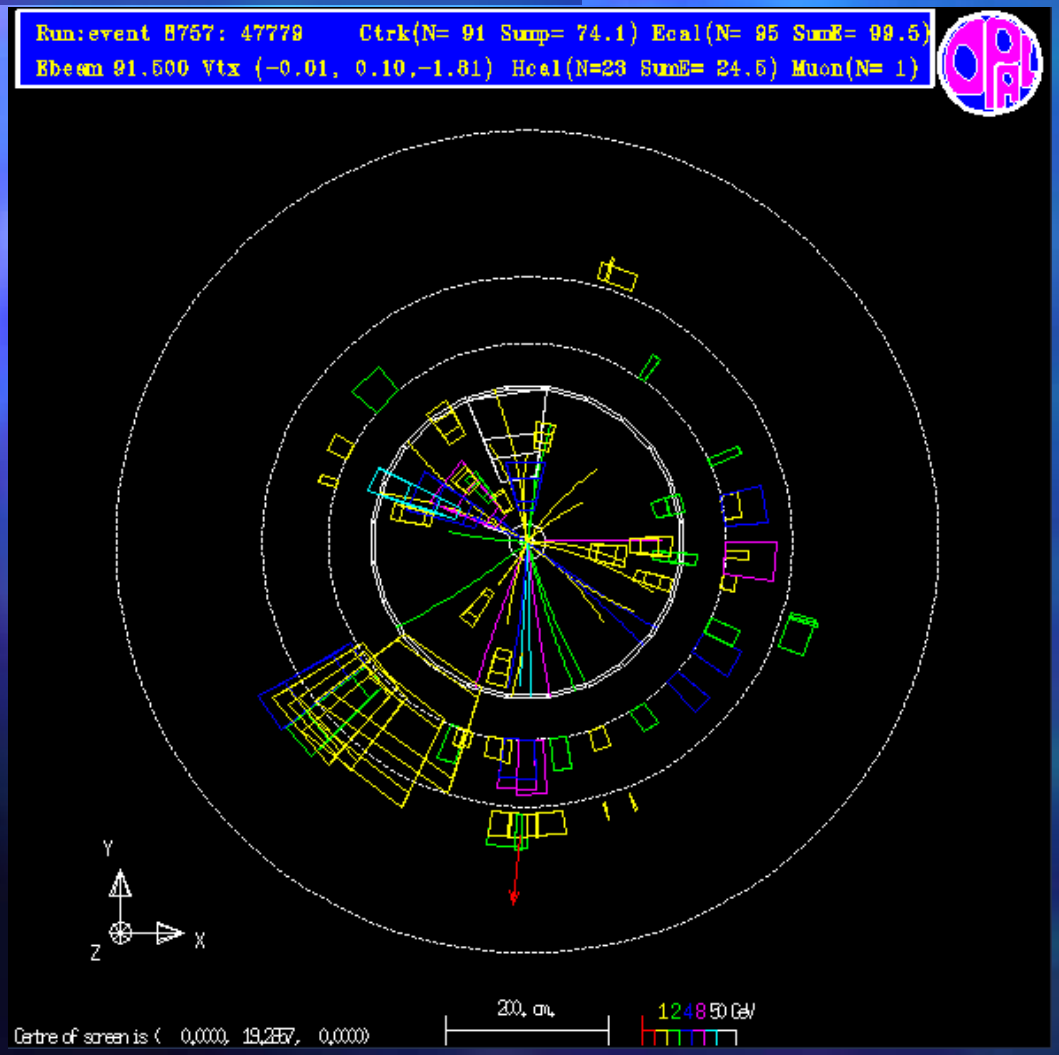

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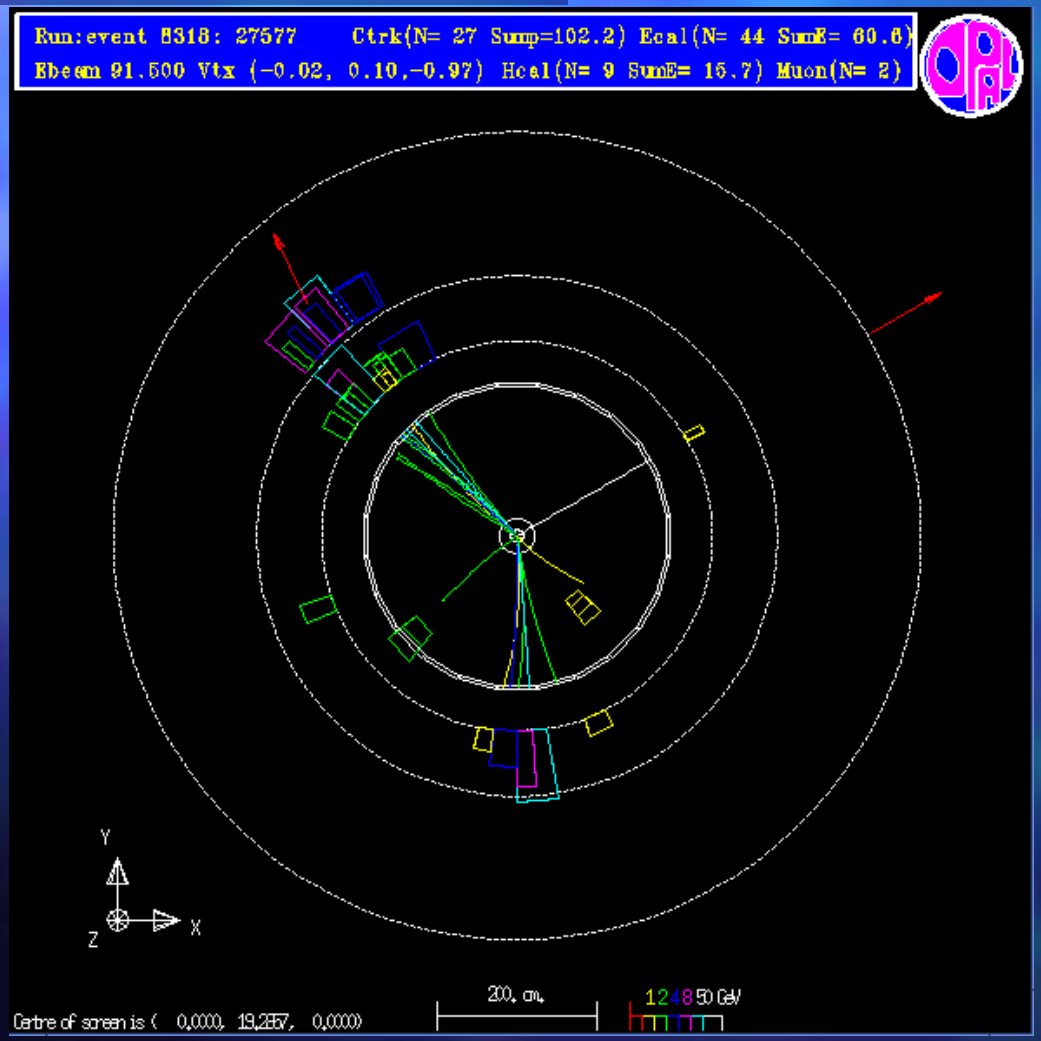

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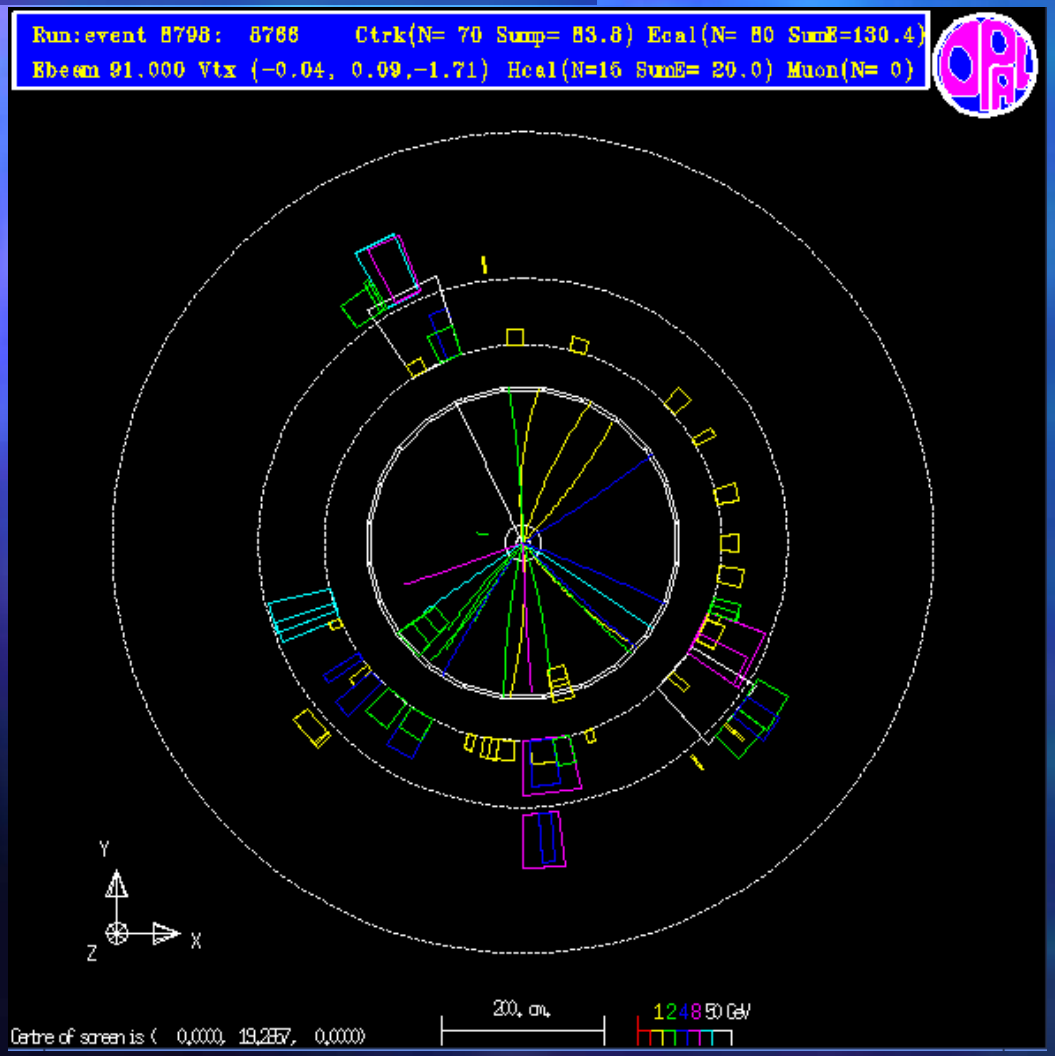

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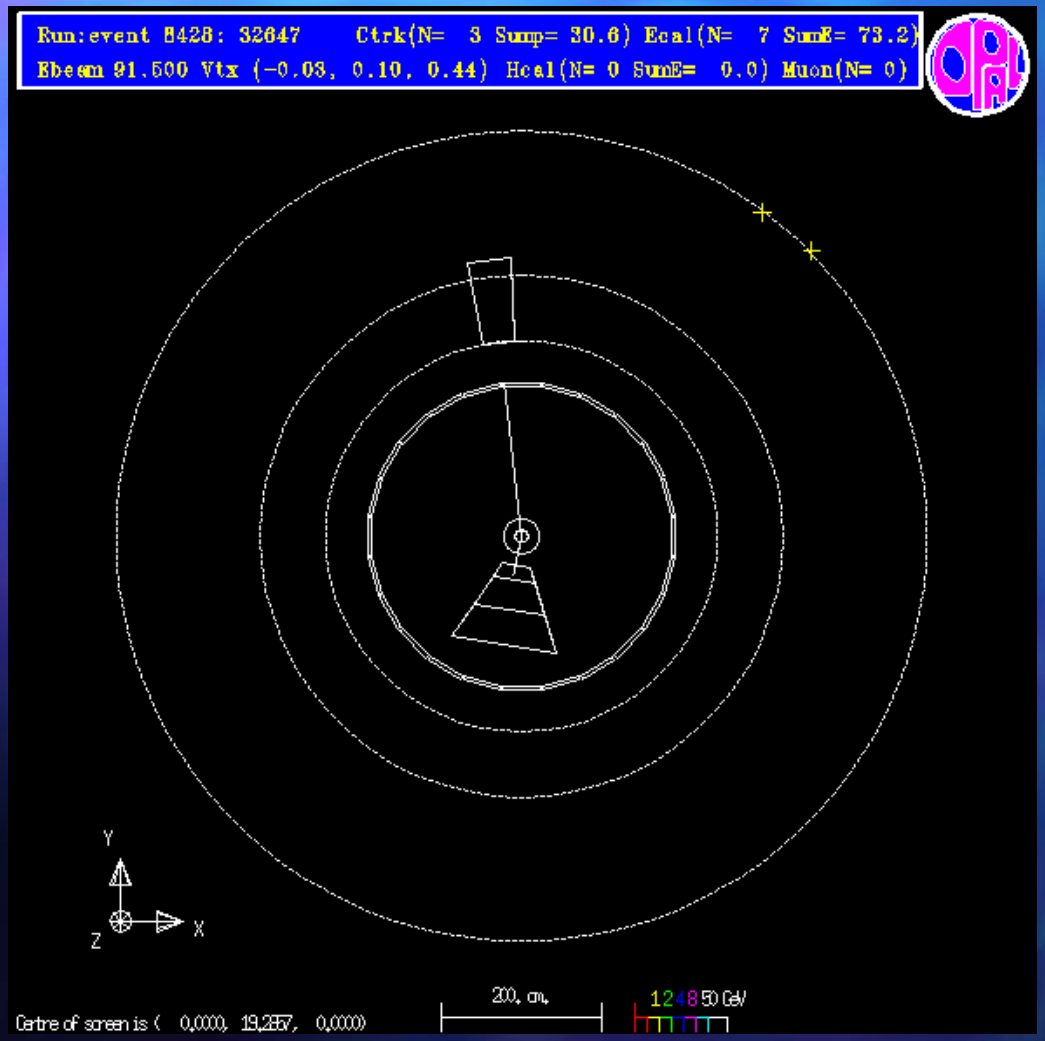

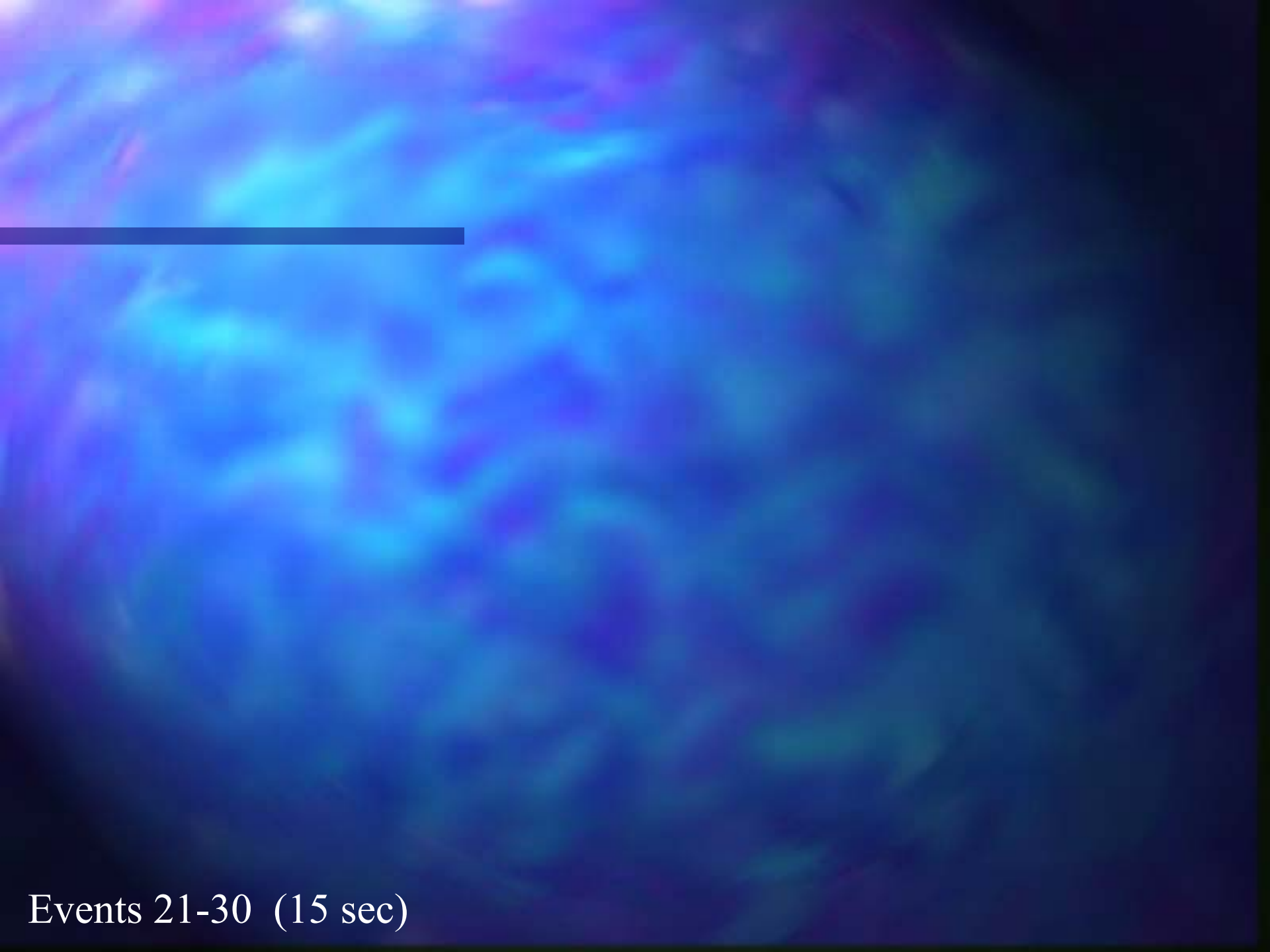
Events 21-30 (15 sec)

What sort of WW decay is this?

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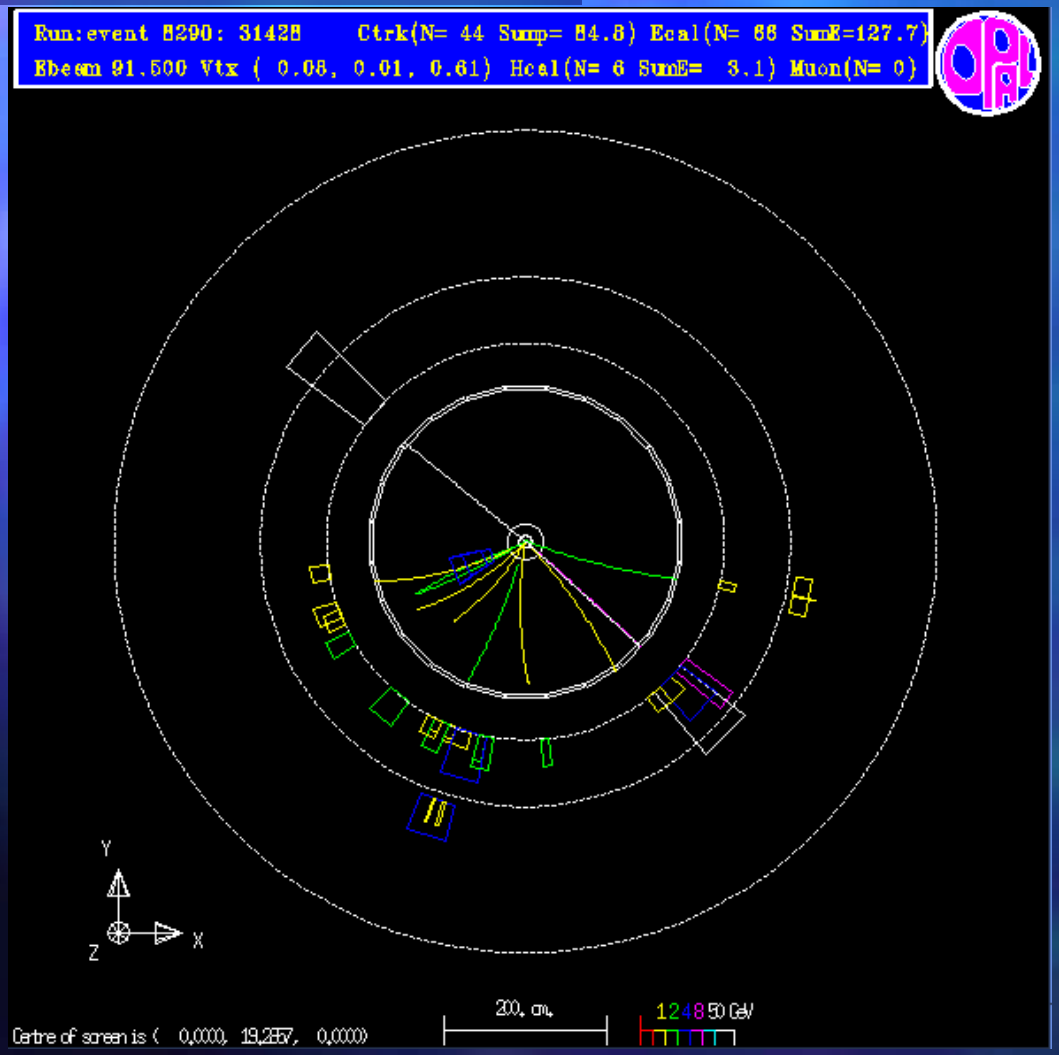

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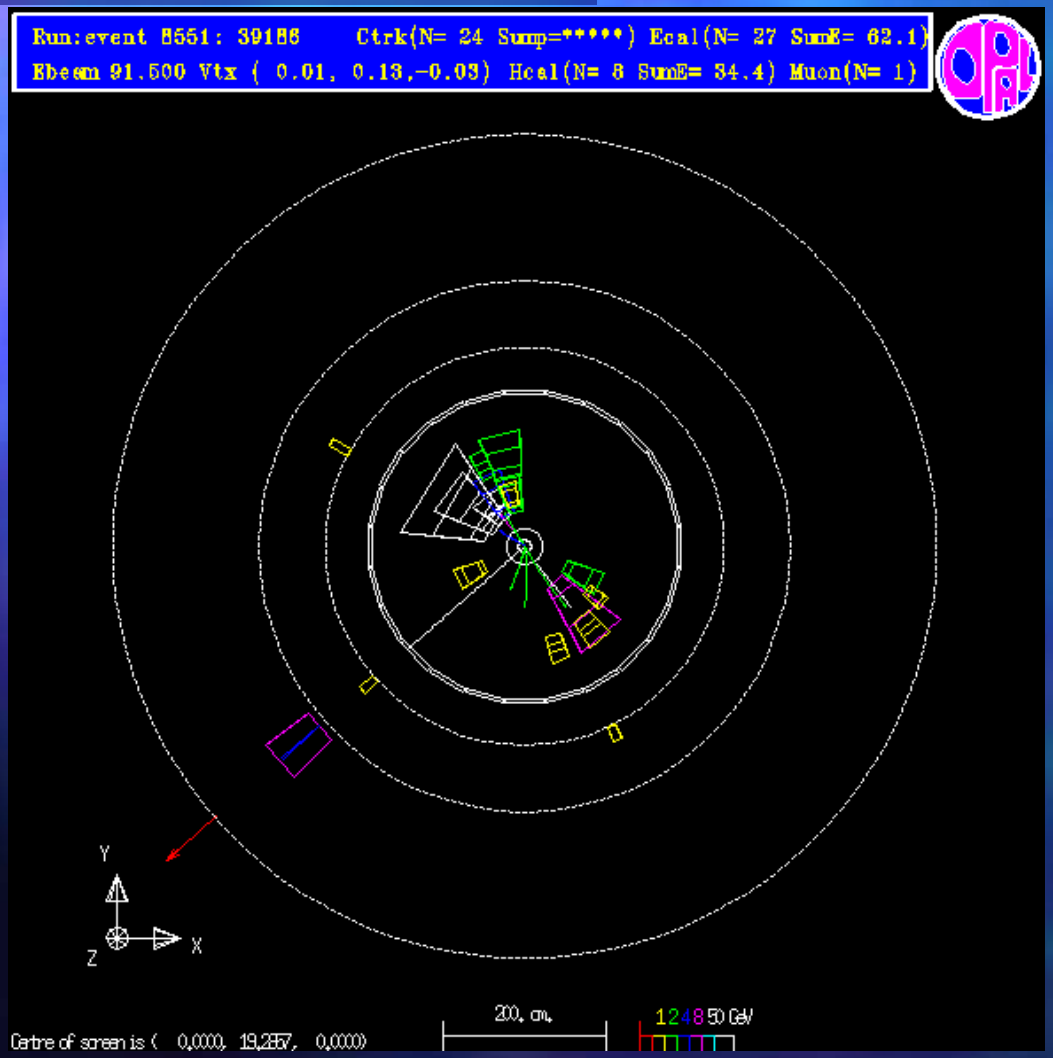

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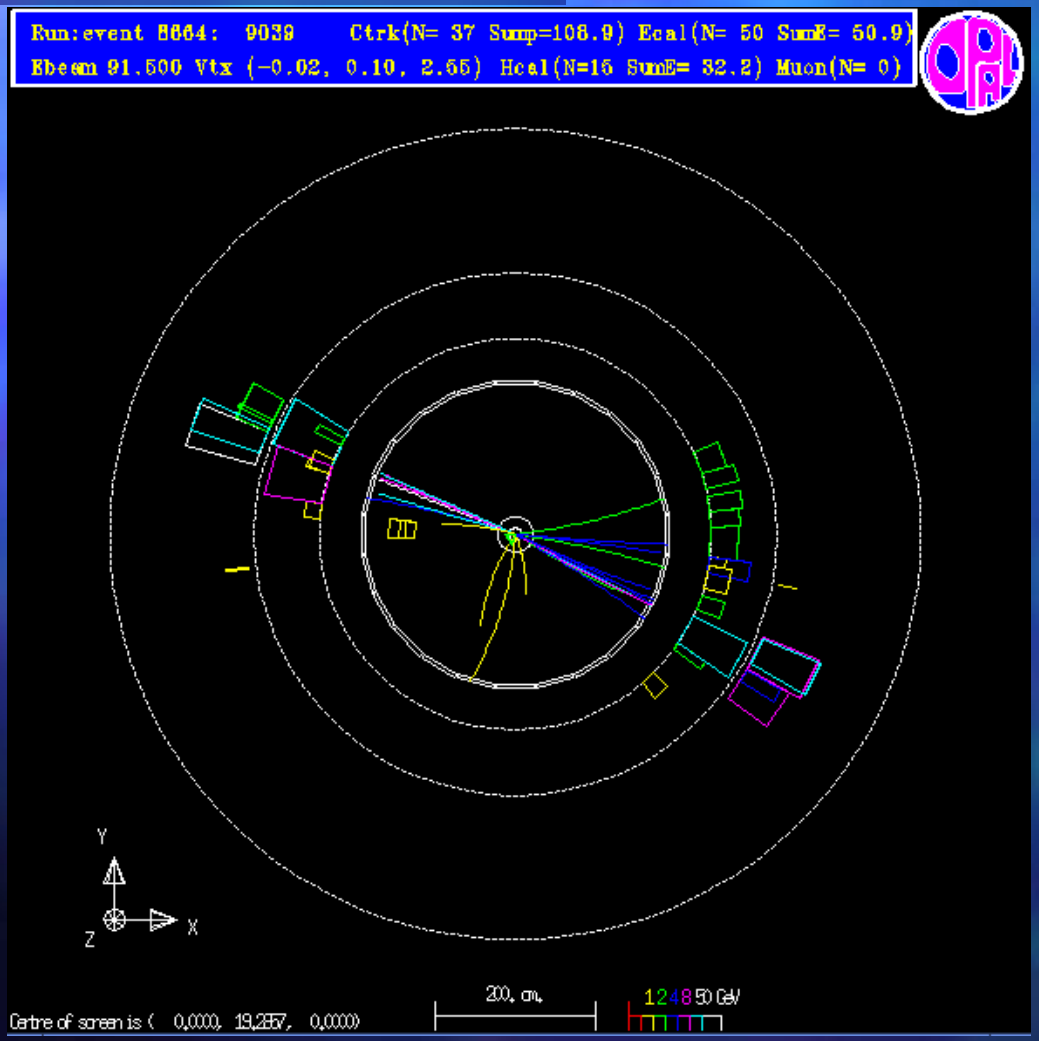

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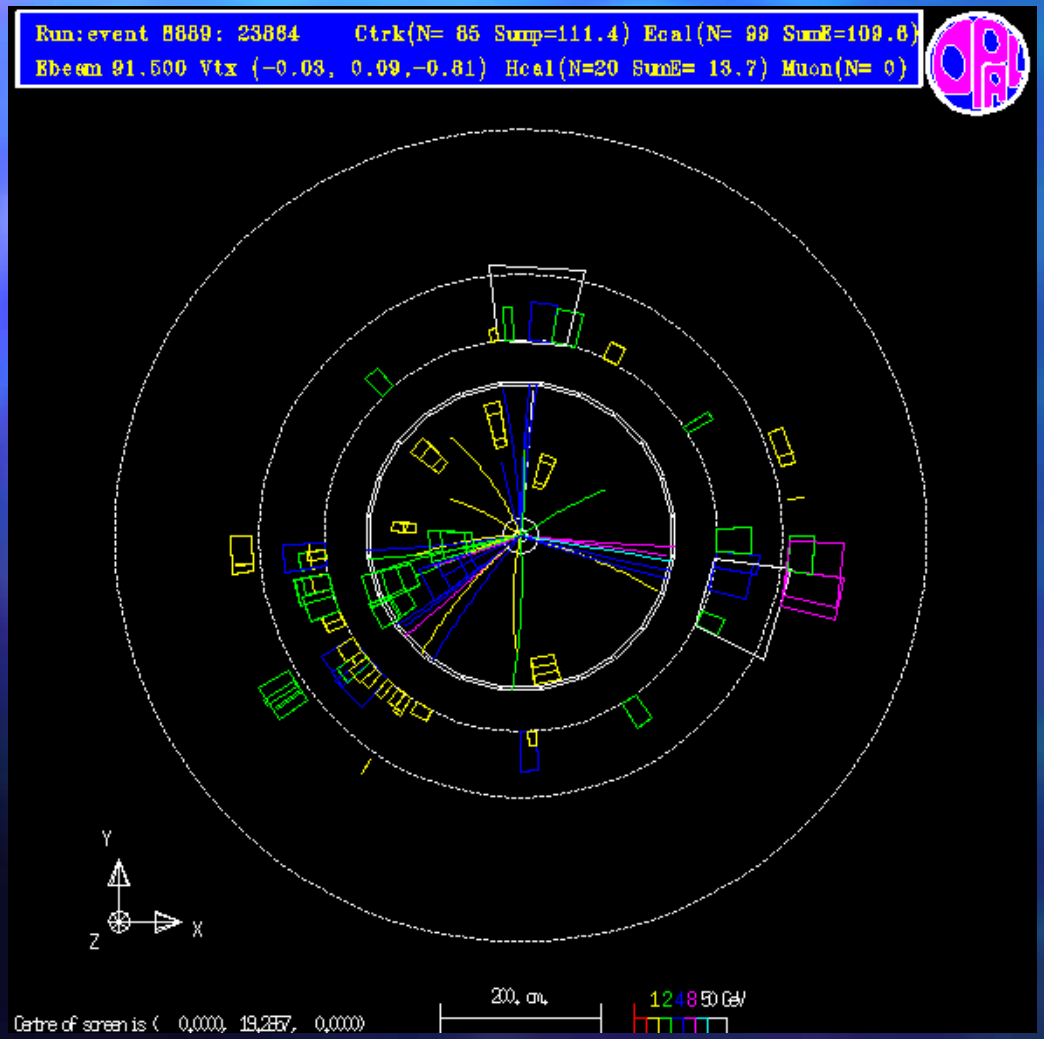

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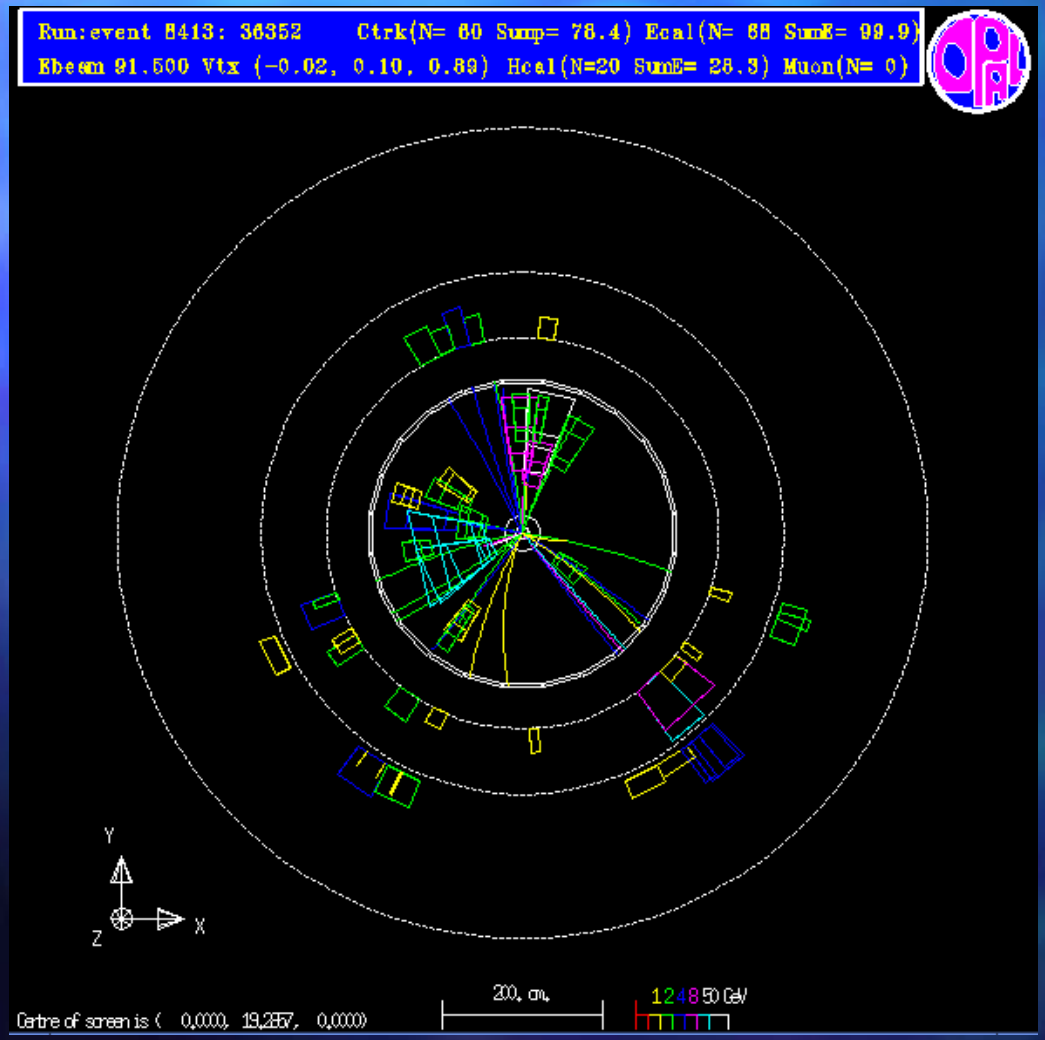

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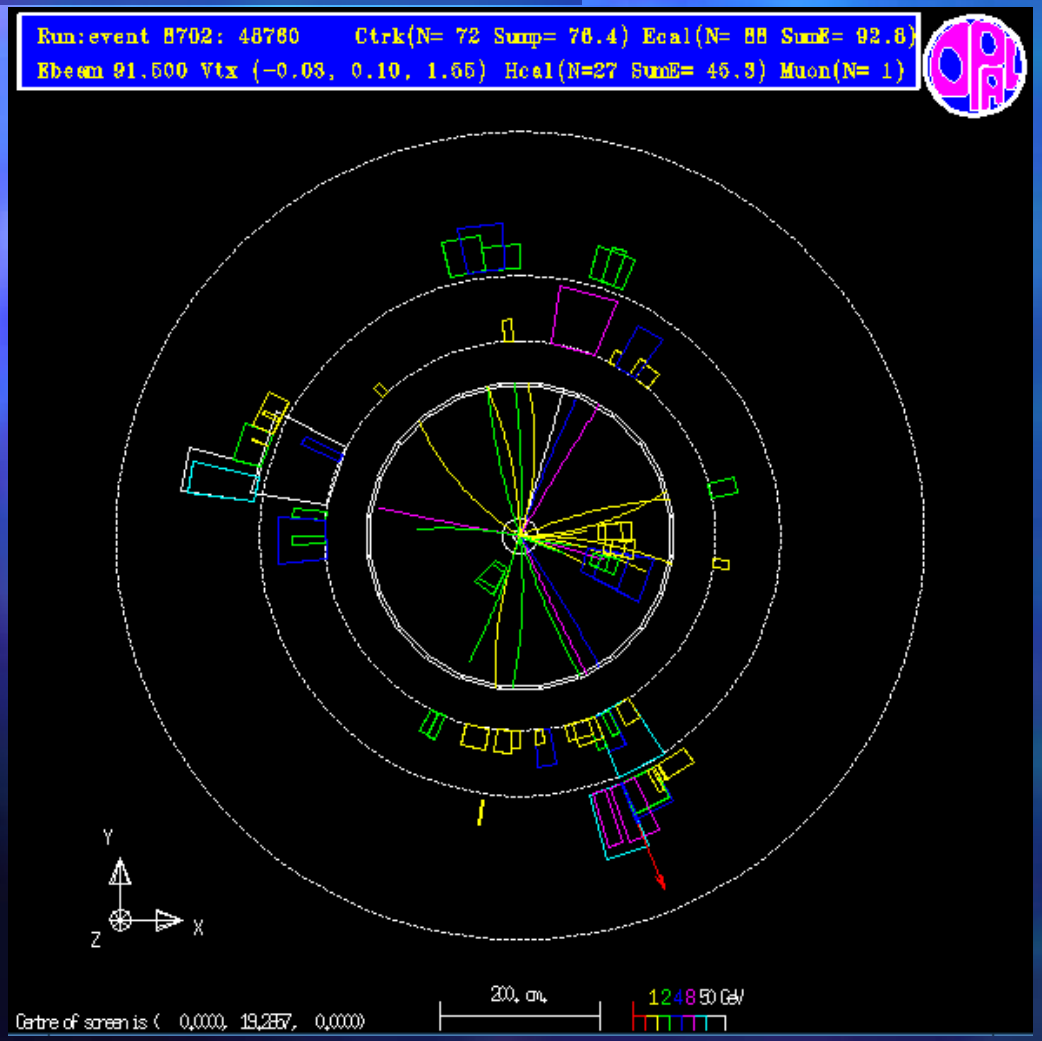

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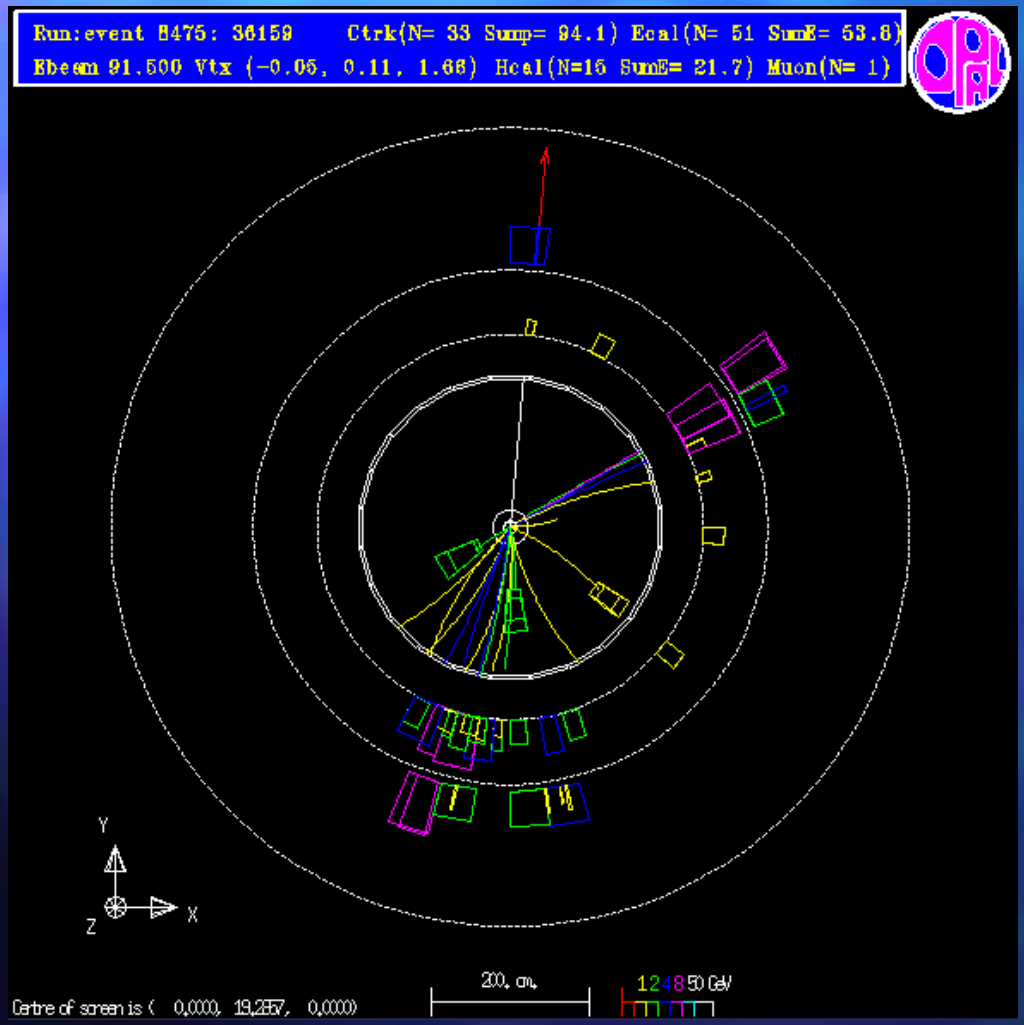

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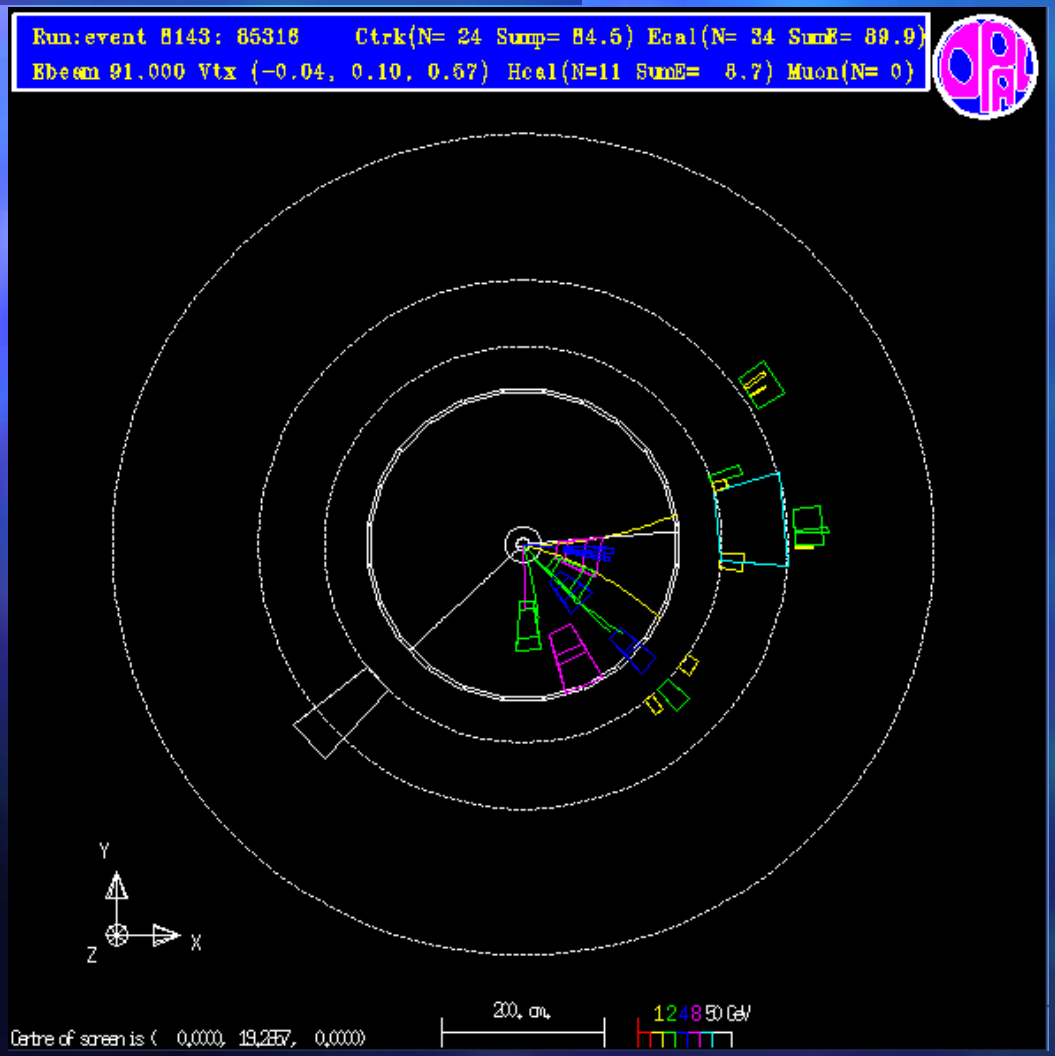
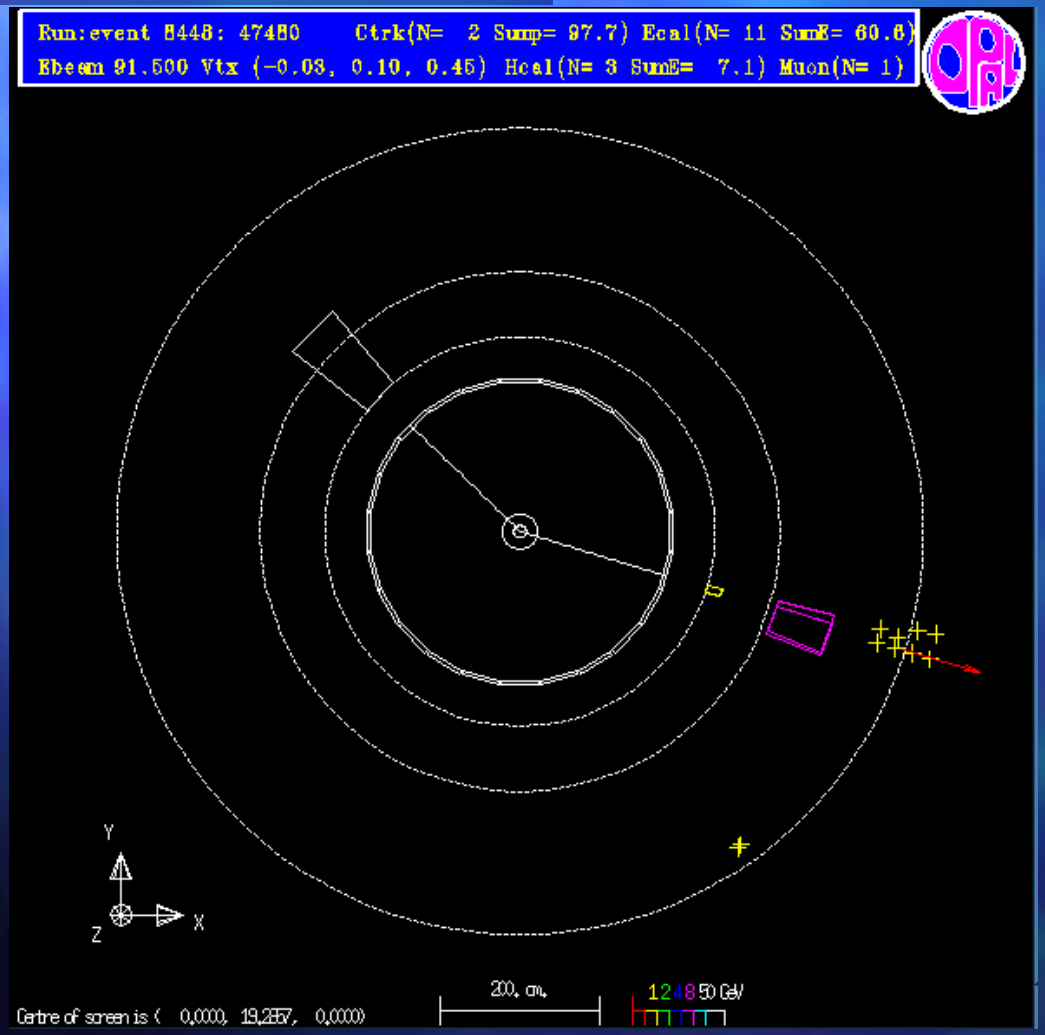
2. Mixed
3. Double leptonic decay



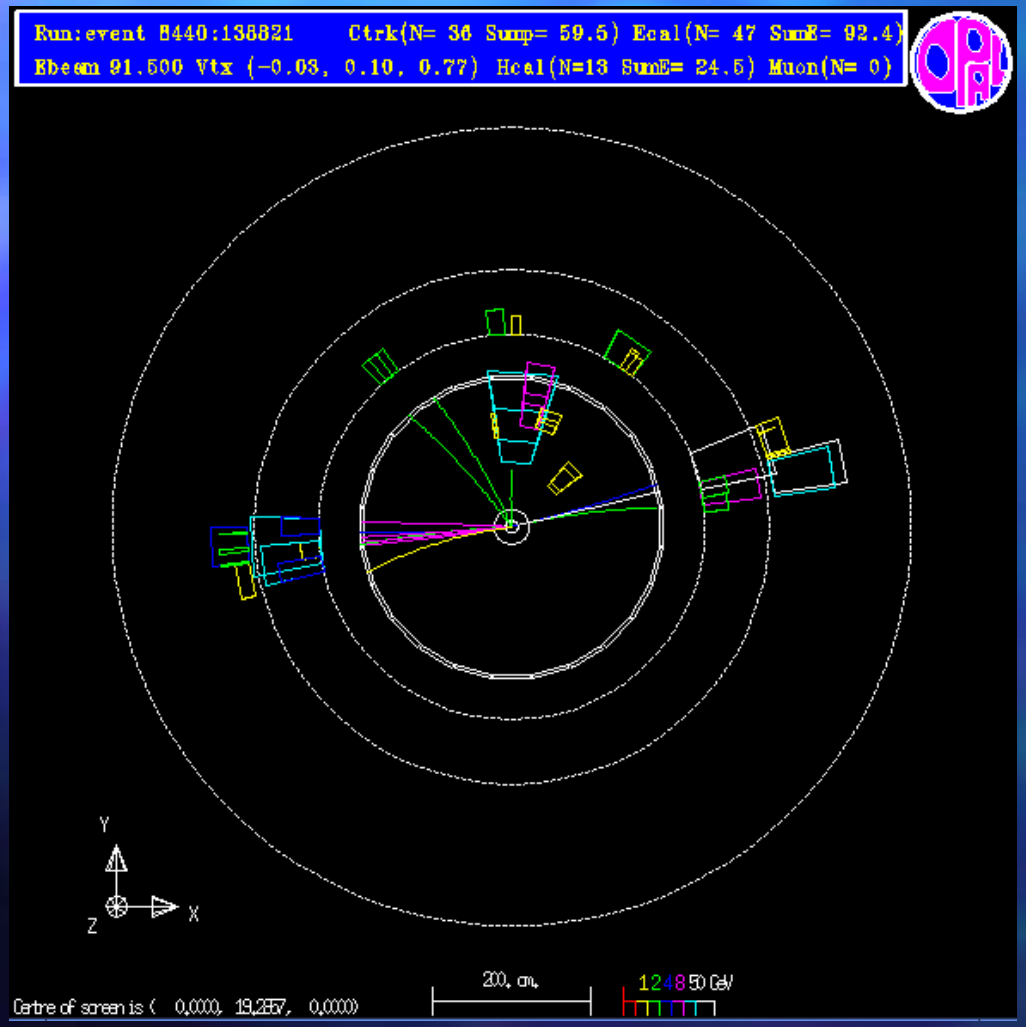
What sort of WW decay is this?

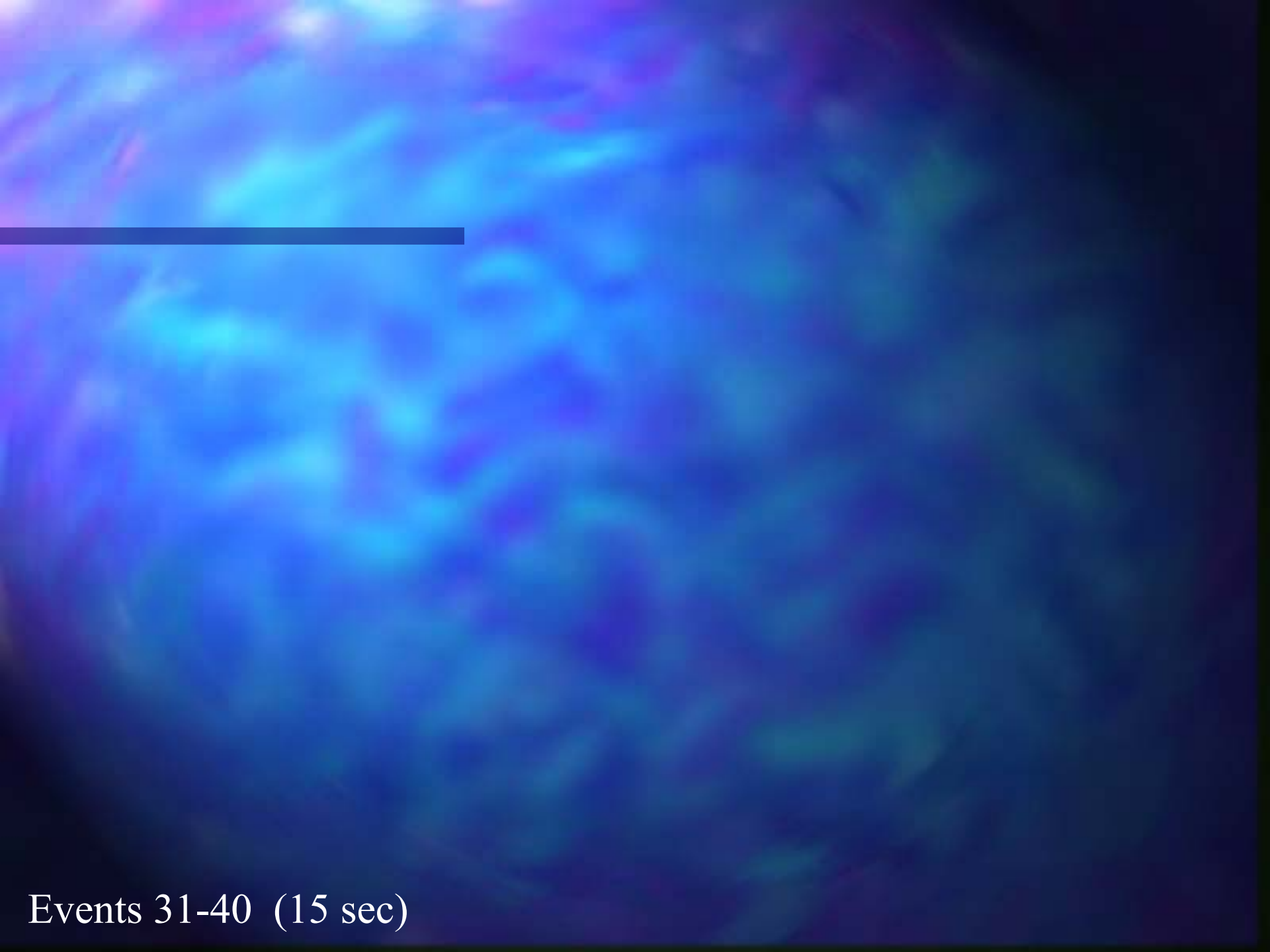
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

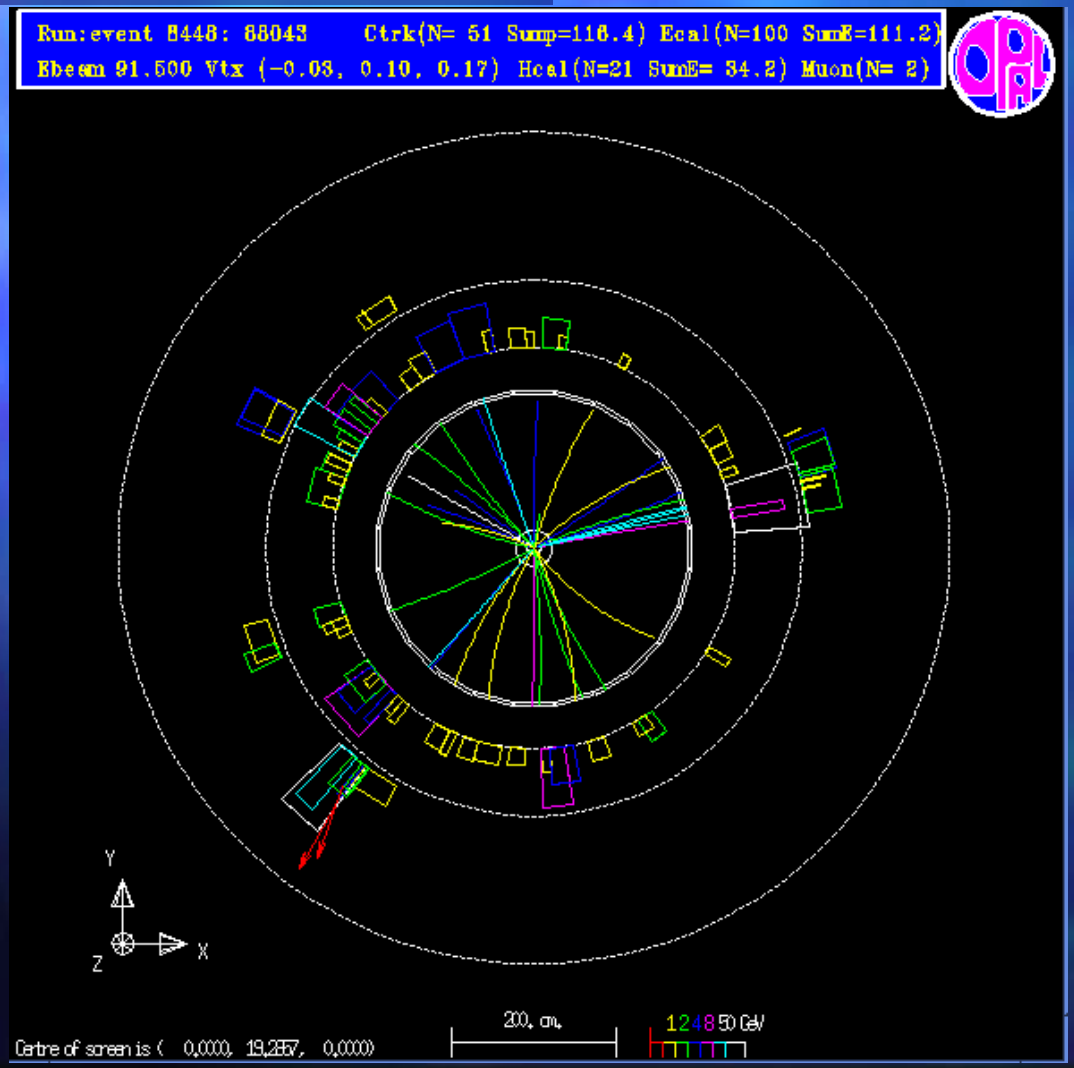
1. Double hadronic decay
2. Mixed
3. Double leptonic decay




Events 31-40 (15 sec)

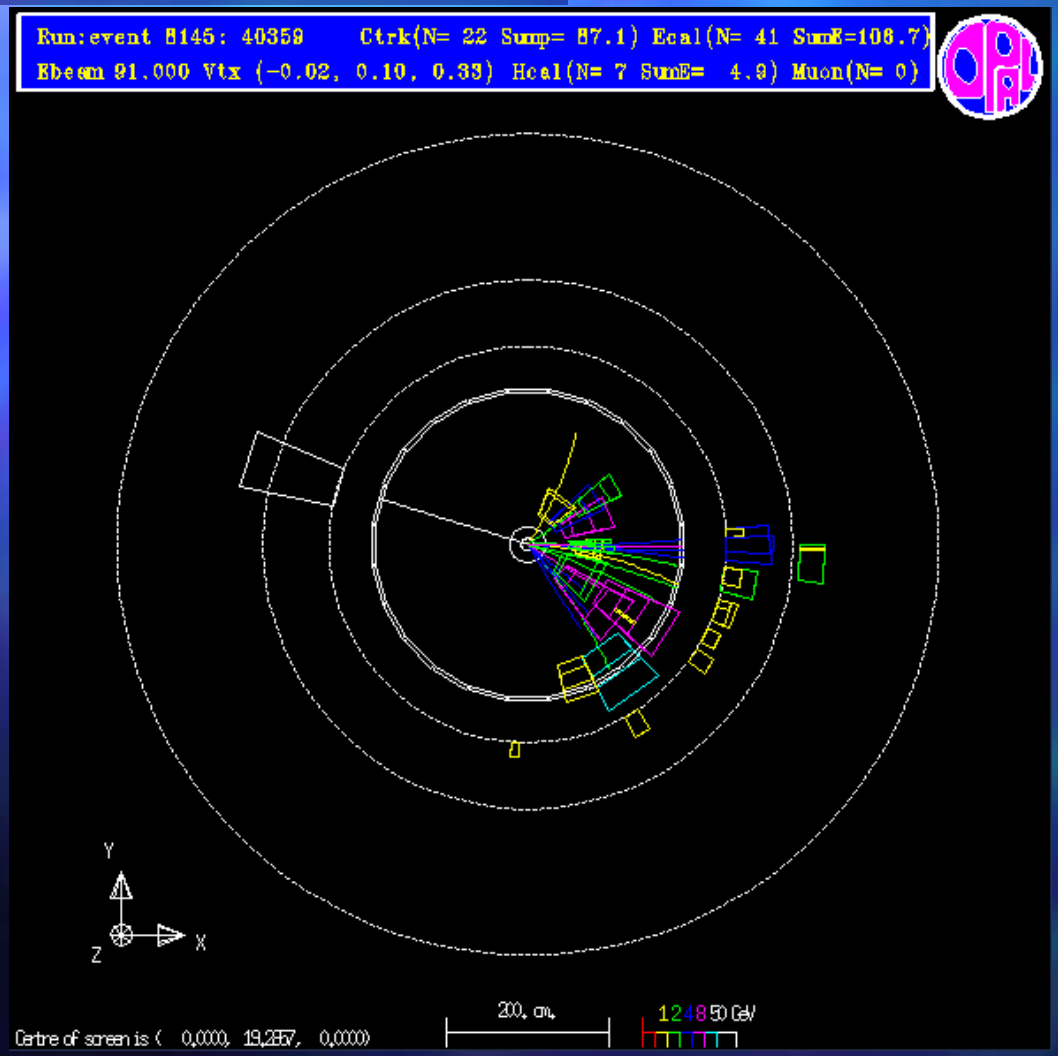
What sort of WW decay is this?

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



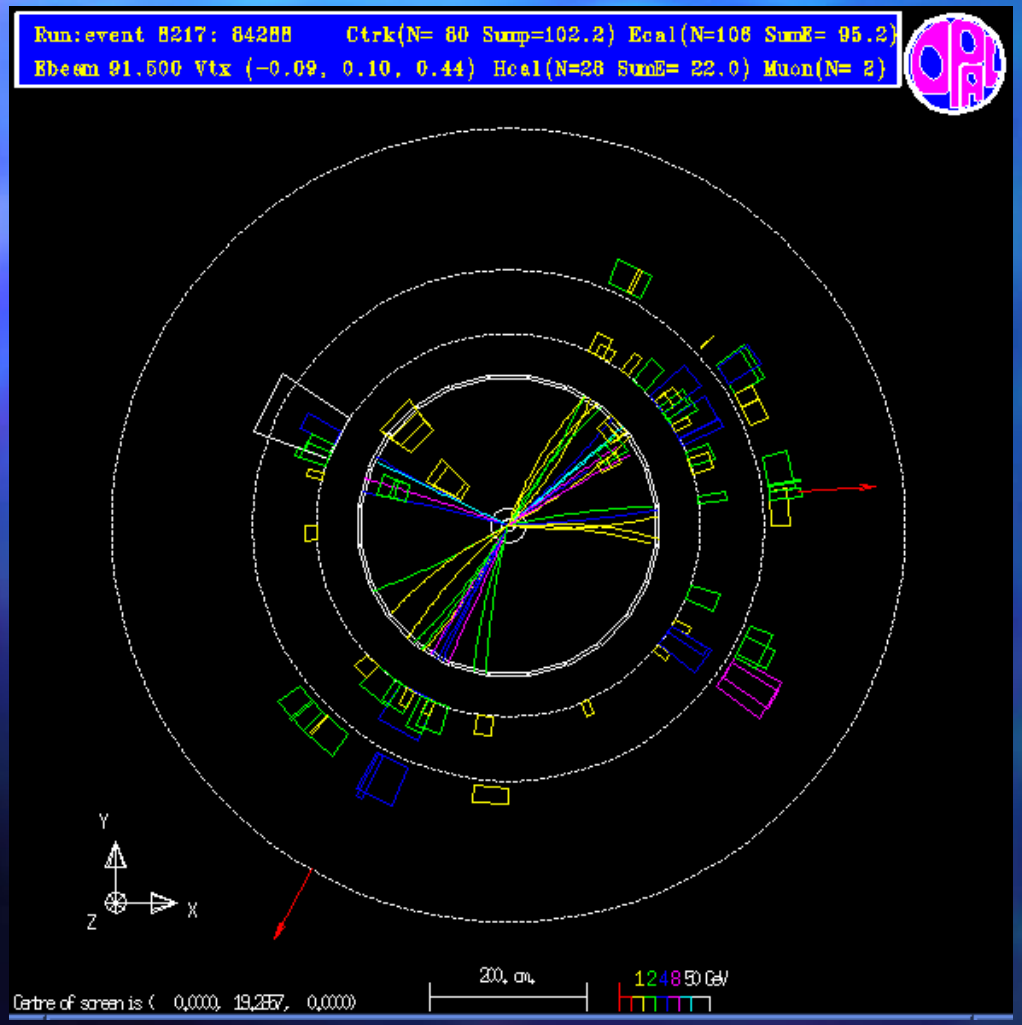
What sort of WW decay is this?

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



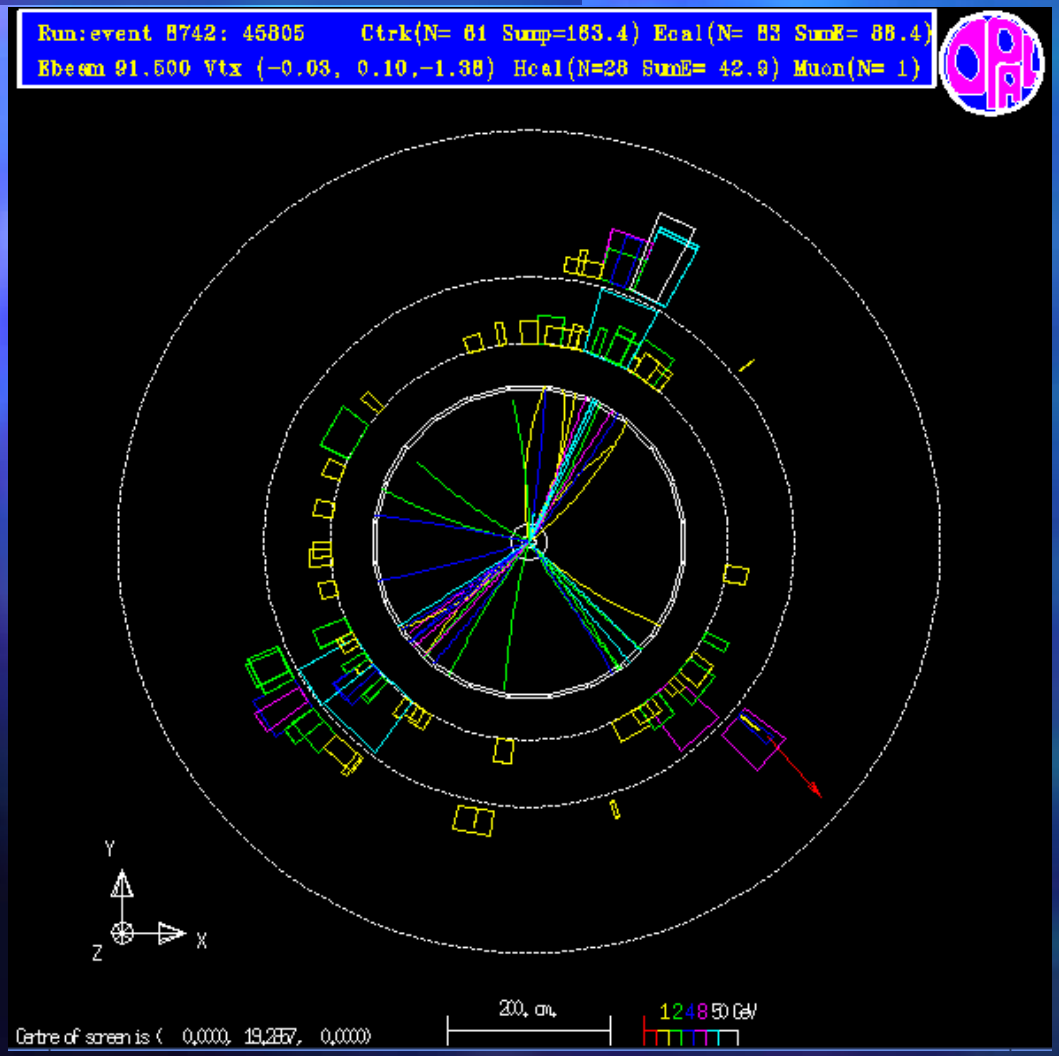
What sort of WW decay is this?

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



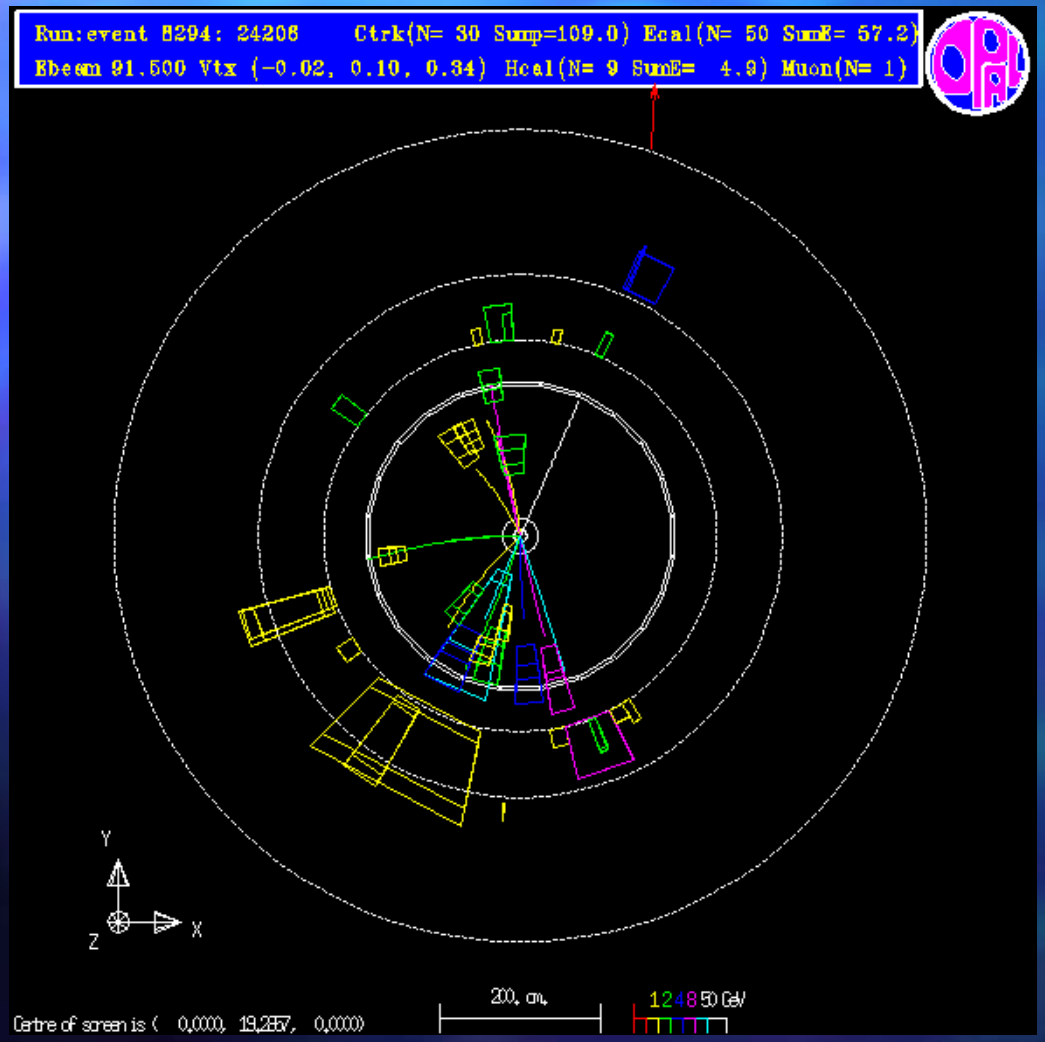
What sort of WW decay is this?

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



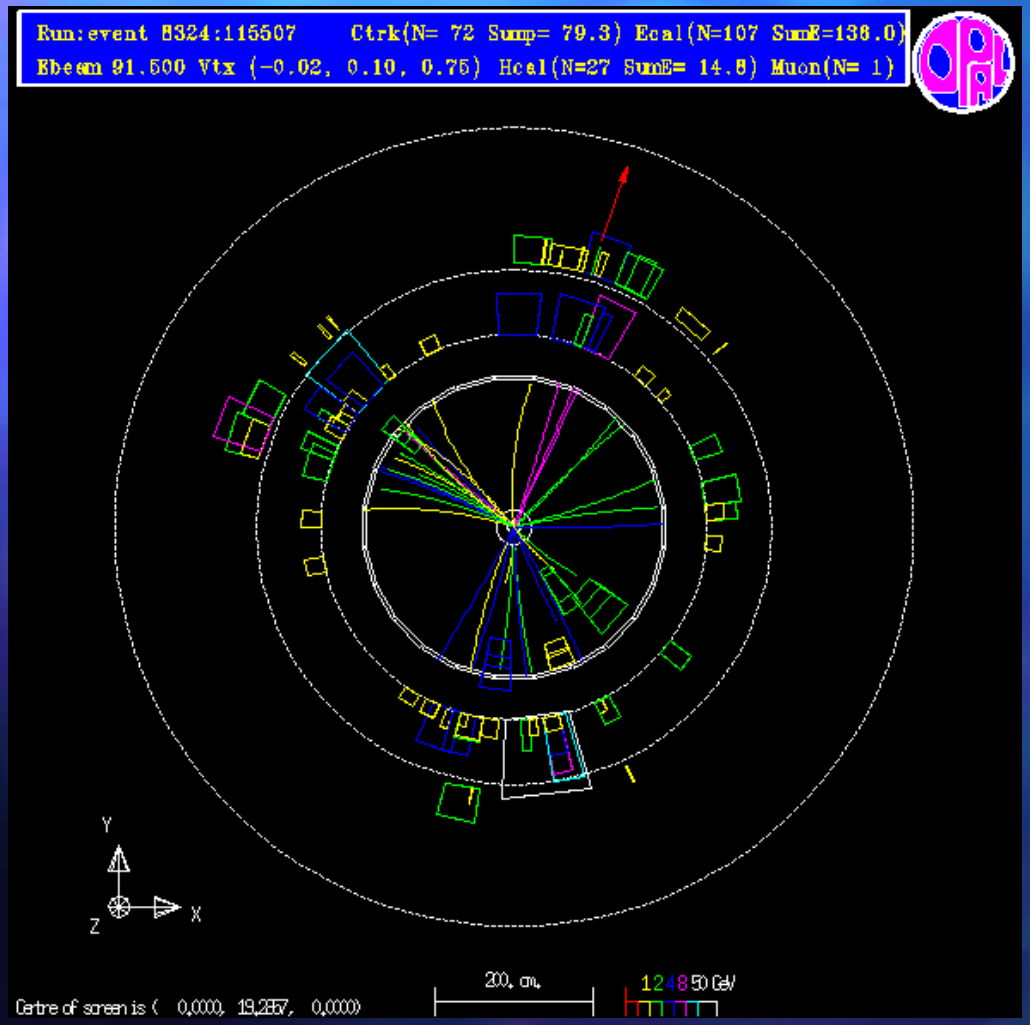
What sort of WW decay is this?

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



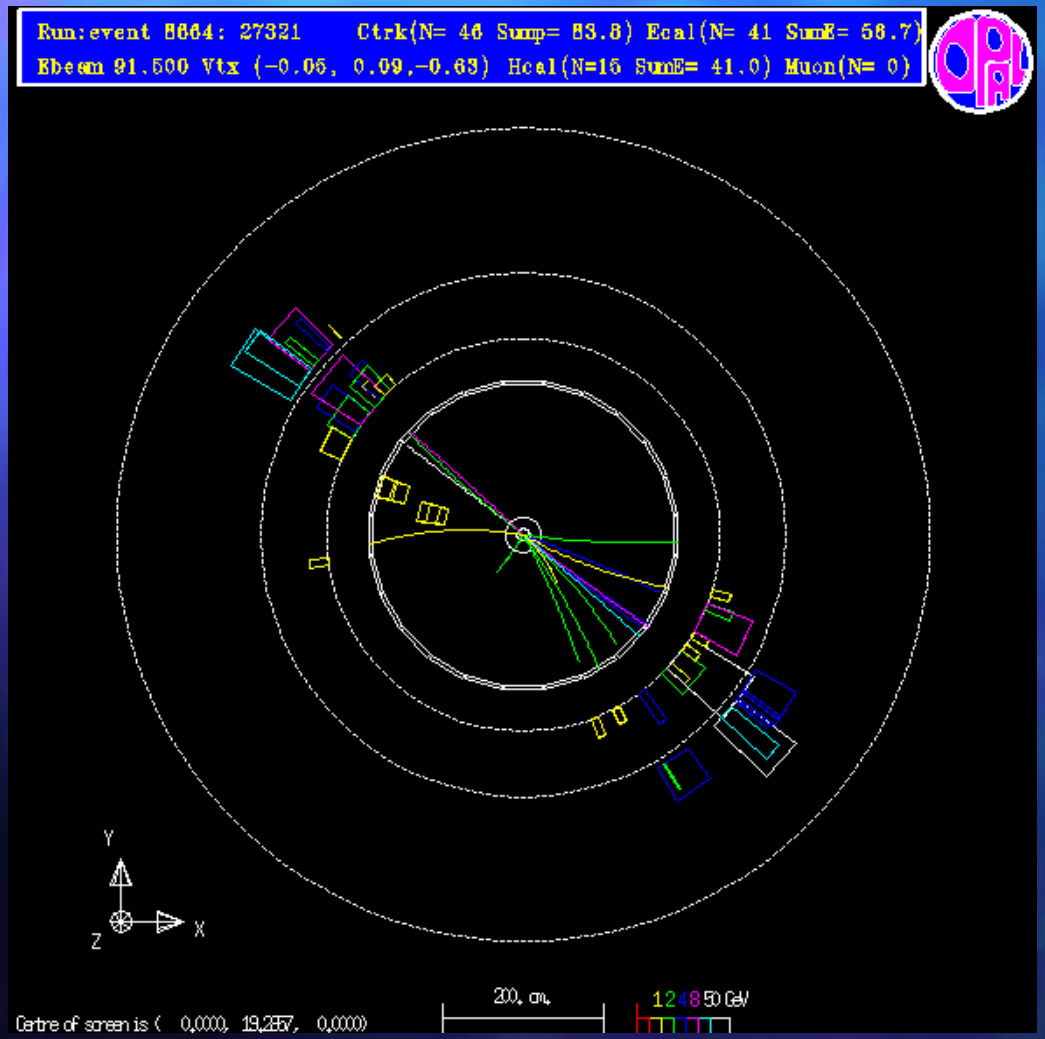
What sort of WW decay is this?

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



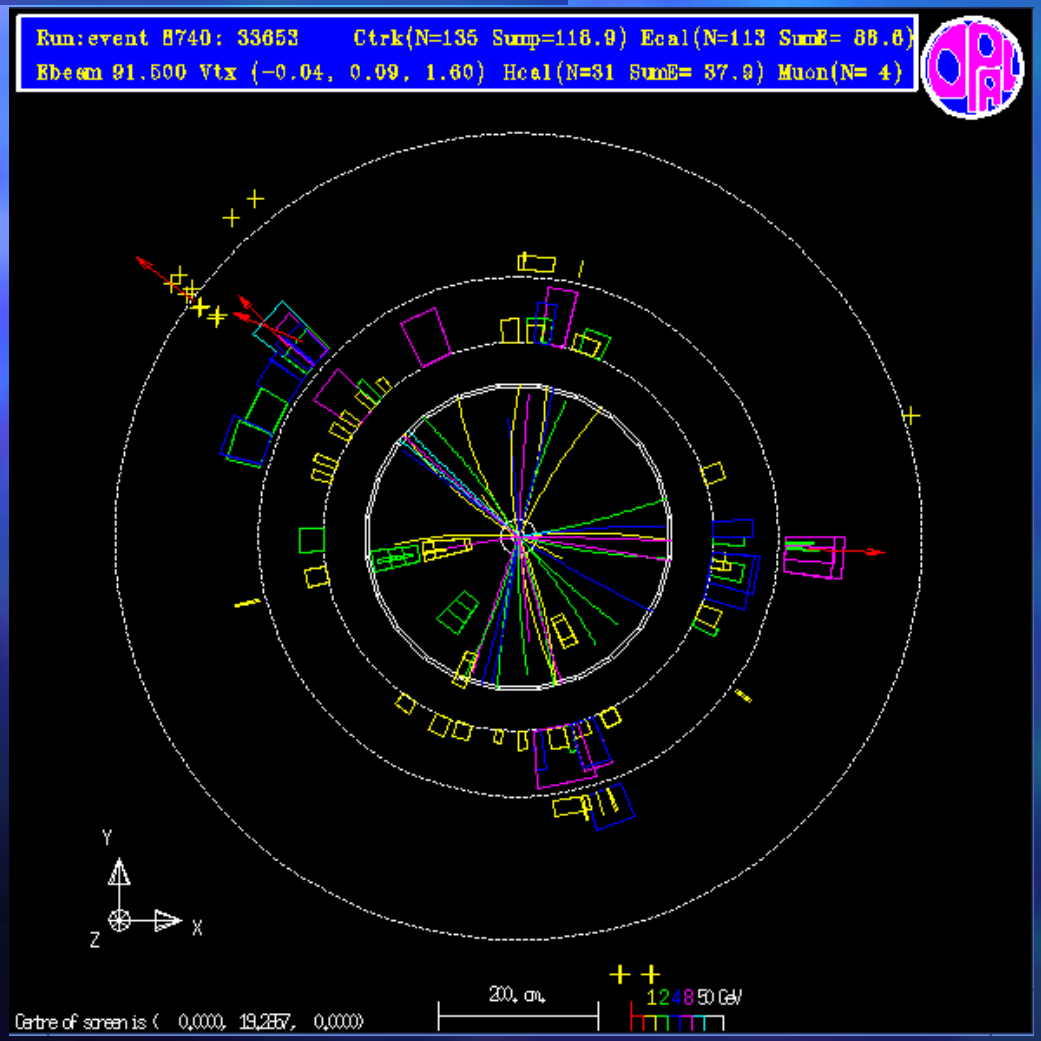
What sort of WW decay is this?

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



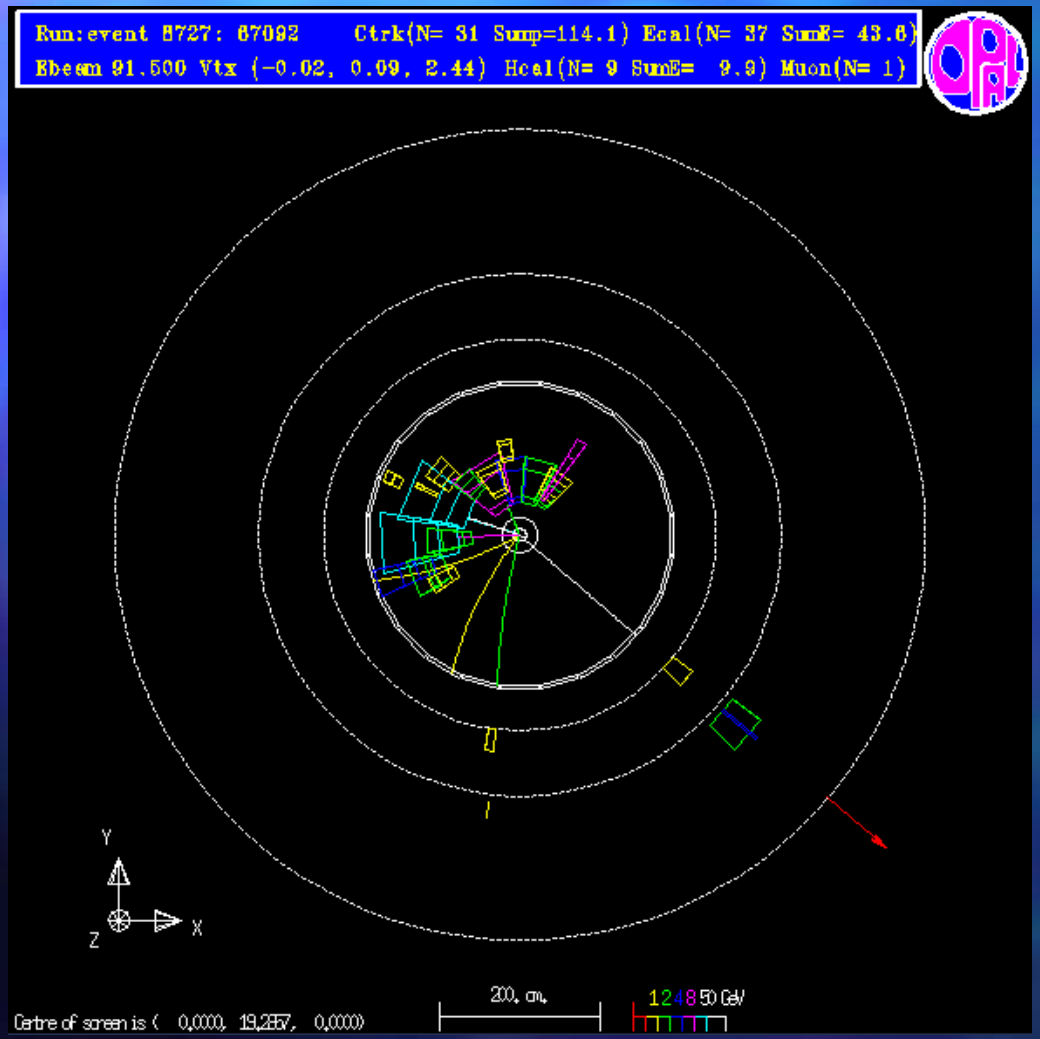
What sort of WW decay is this?

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



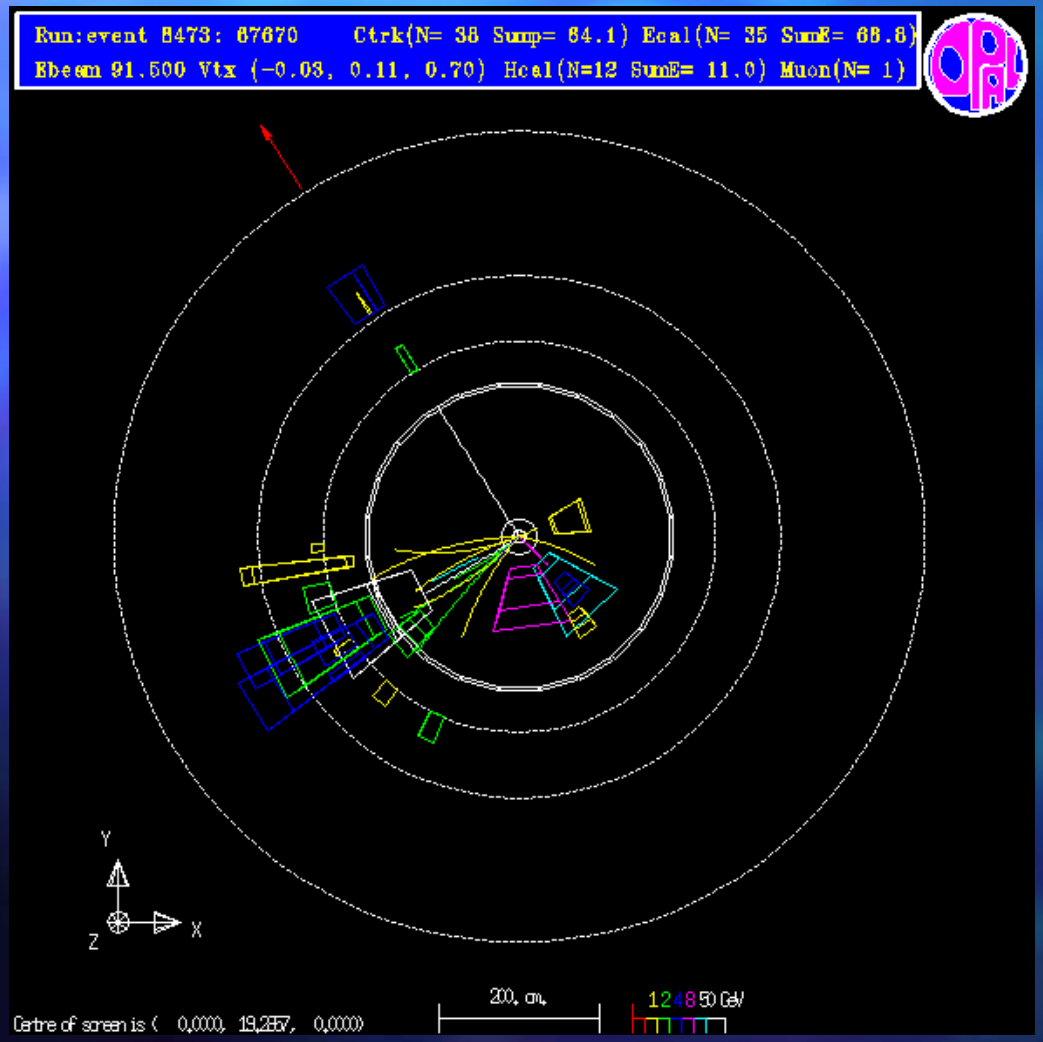
What sort of WW decay is this?

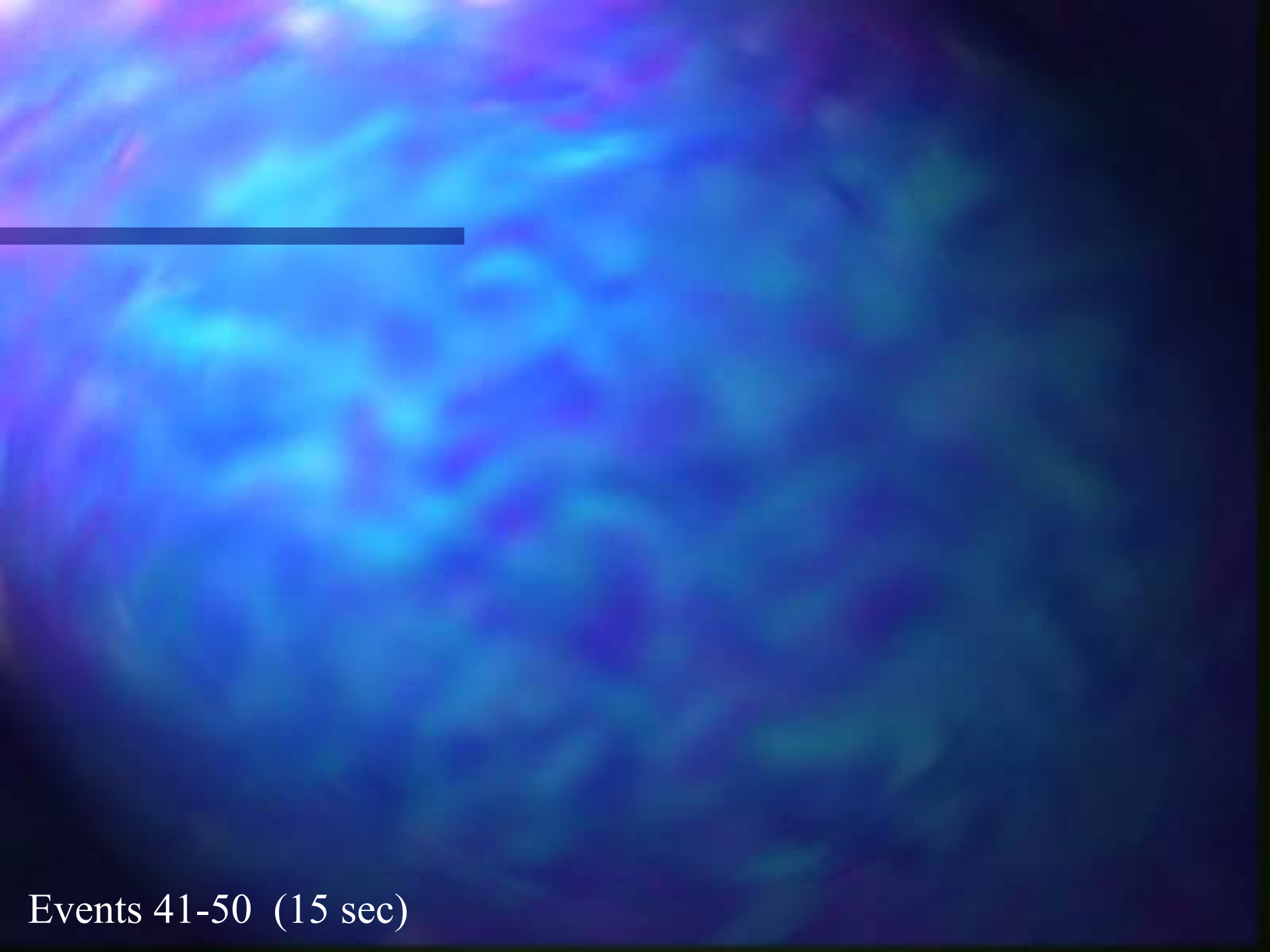
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

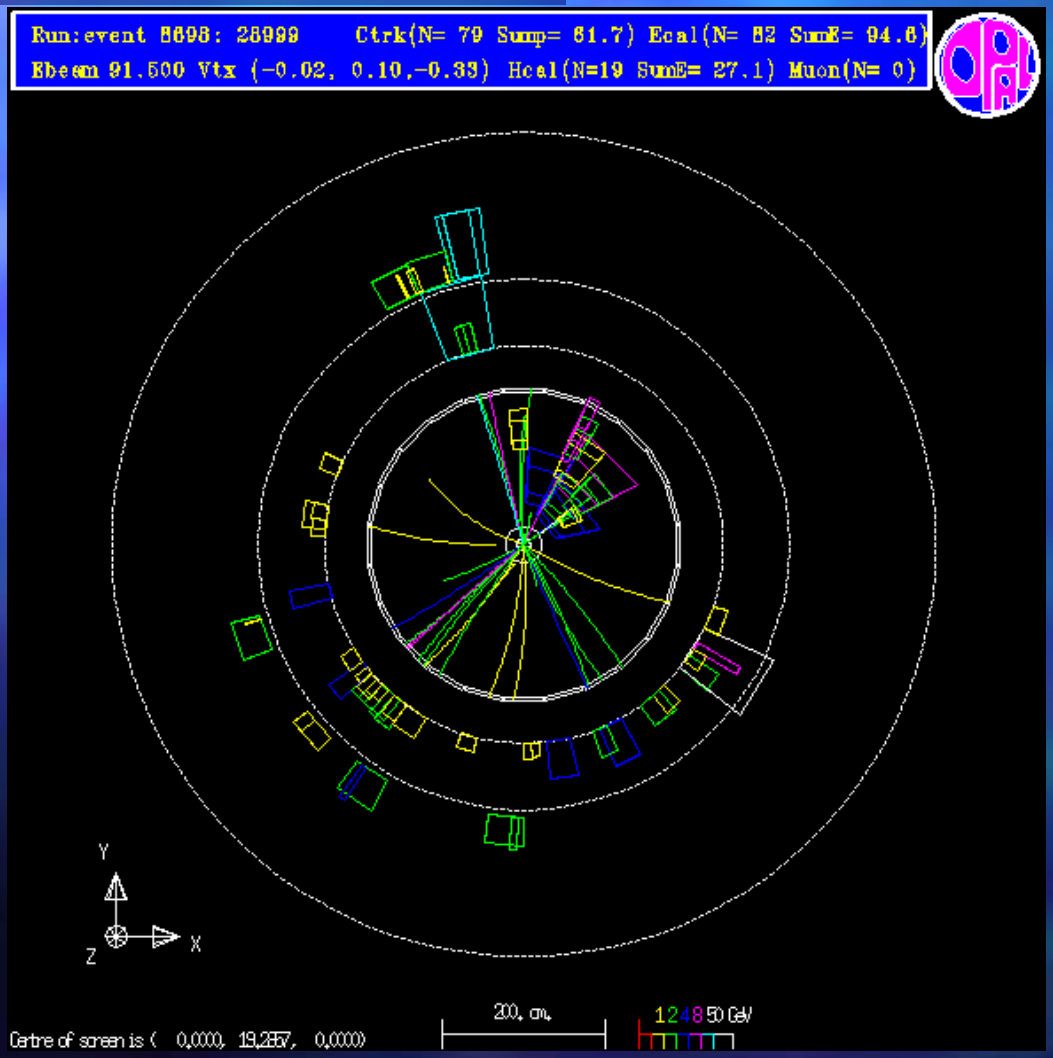
1. Double hadronic decay
2. Mixed
3. Double leptonic decay




Events 41-50 (15 sec)

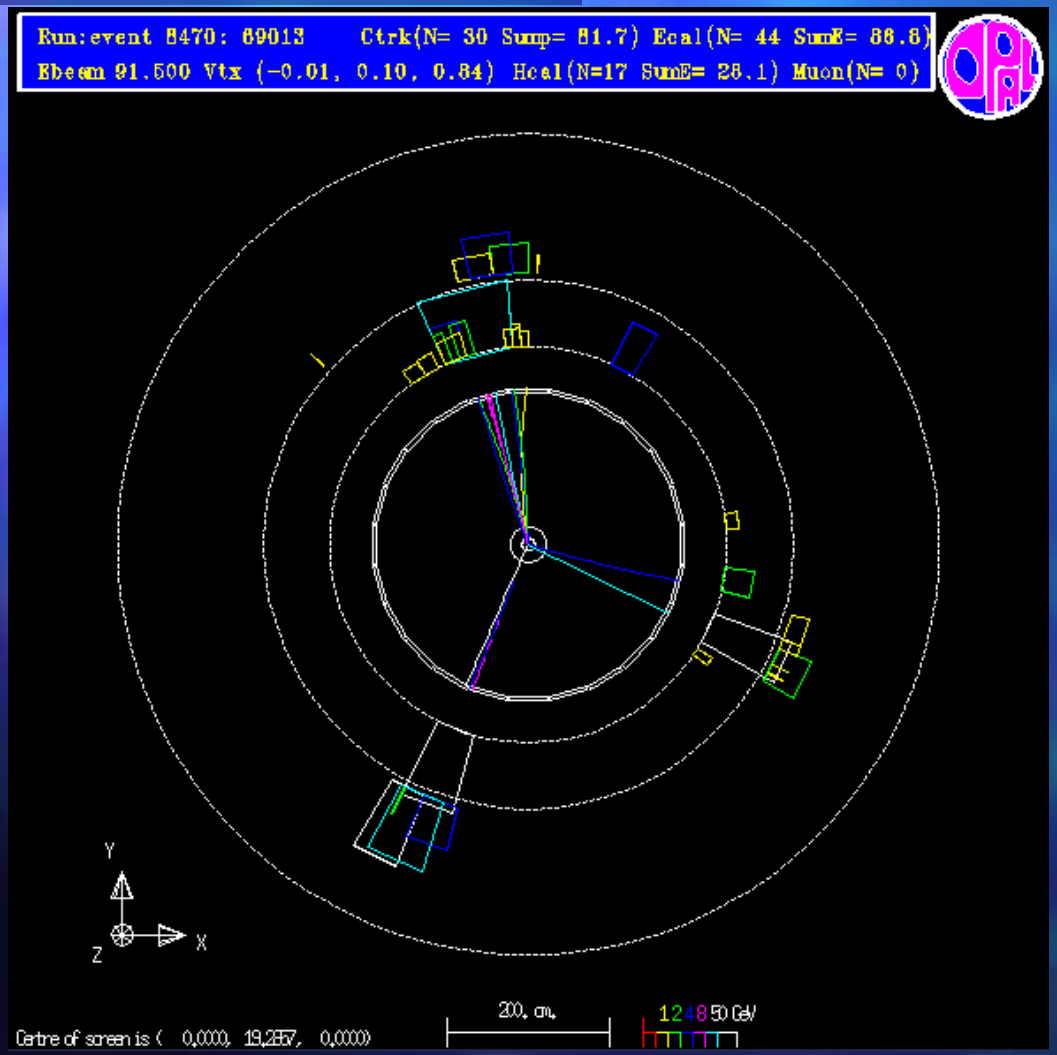
What sort of WW decay is this?

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



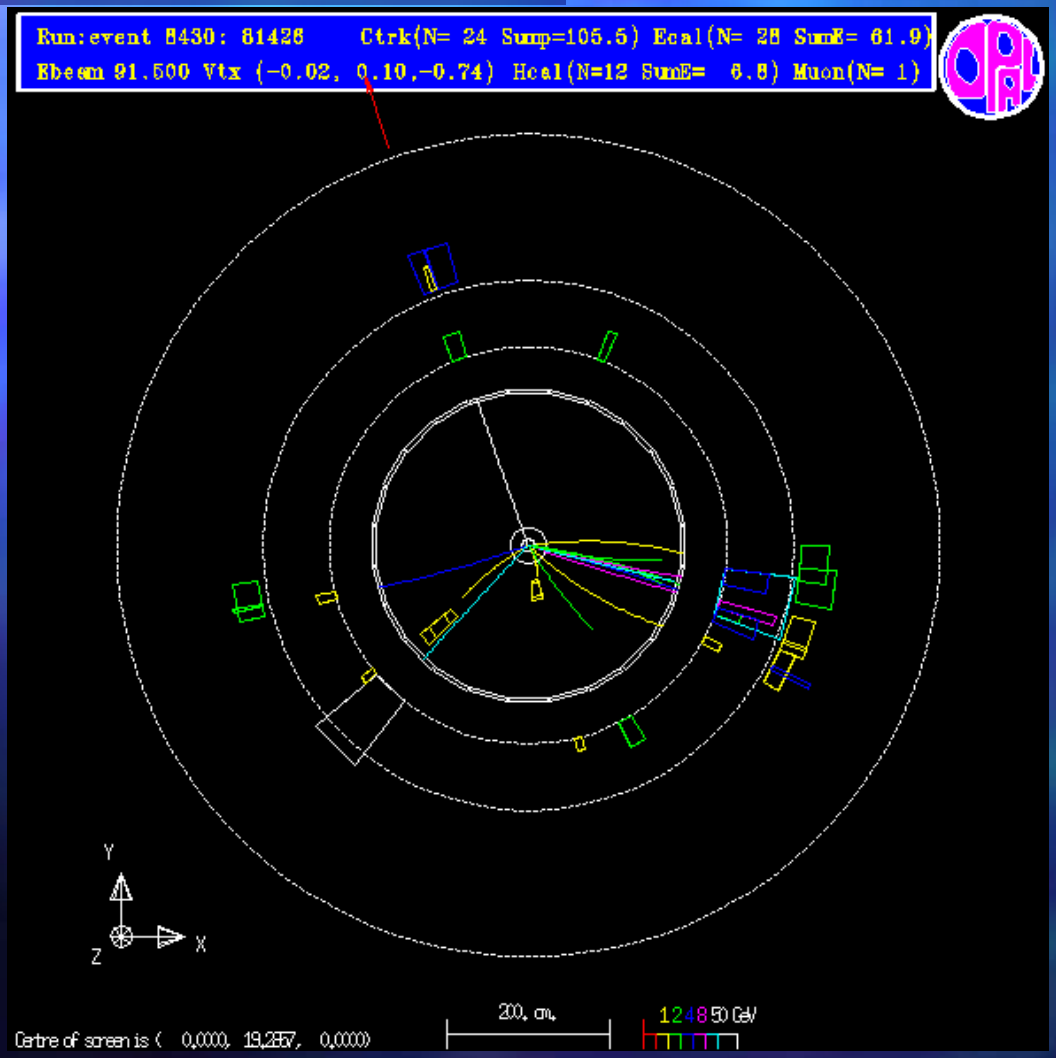
What sort of WW decay is this?

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



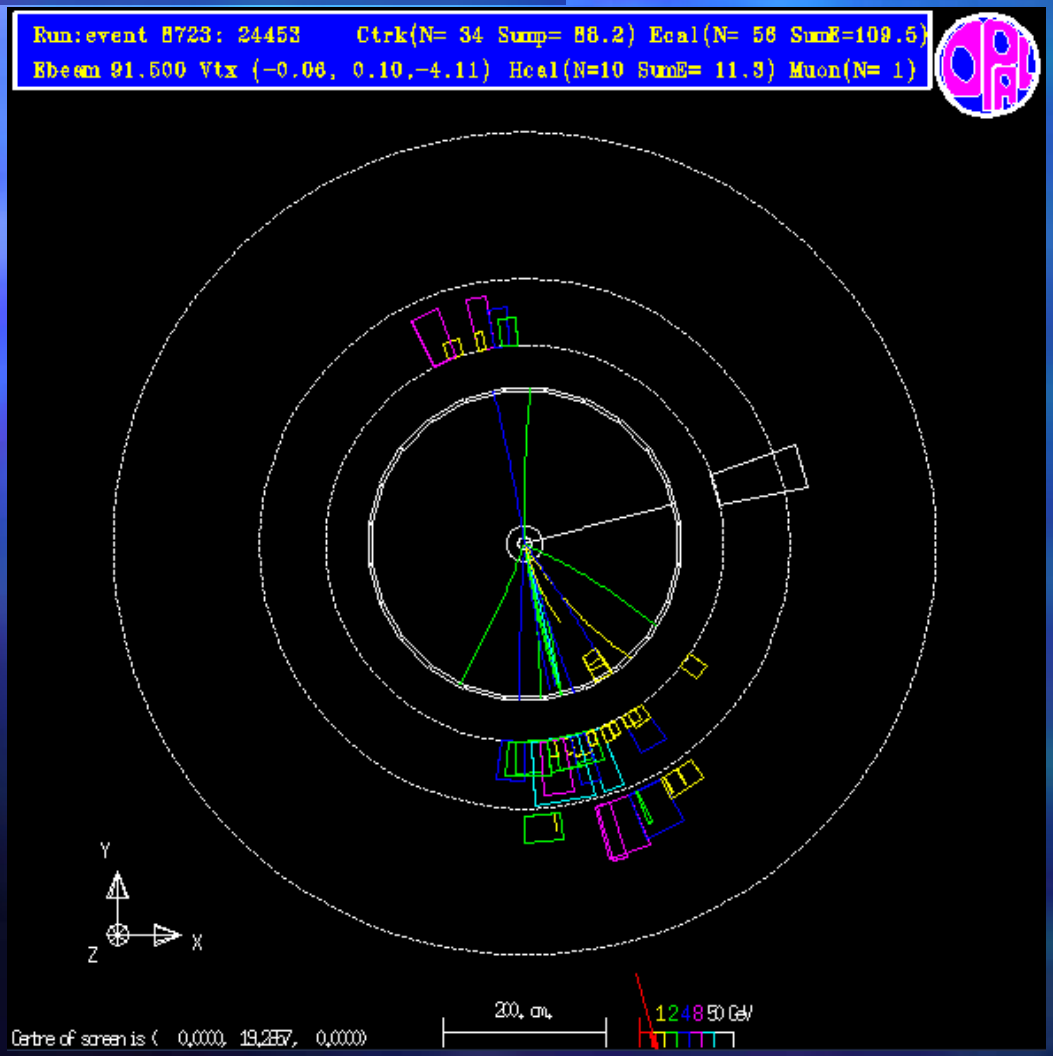
What sort of WW decay is this?

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



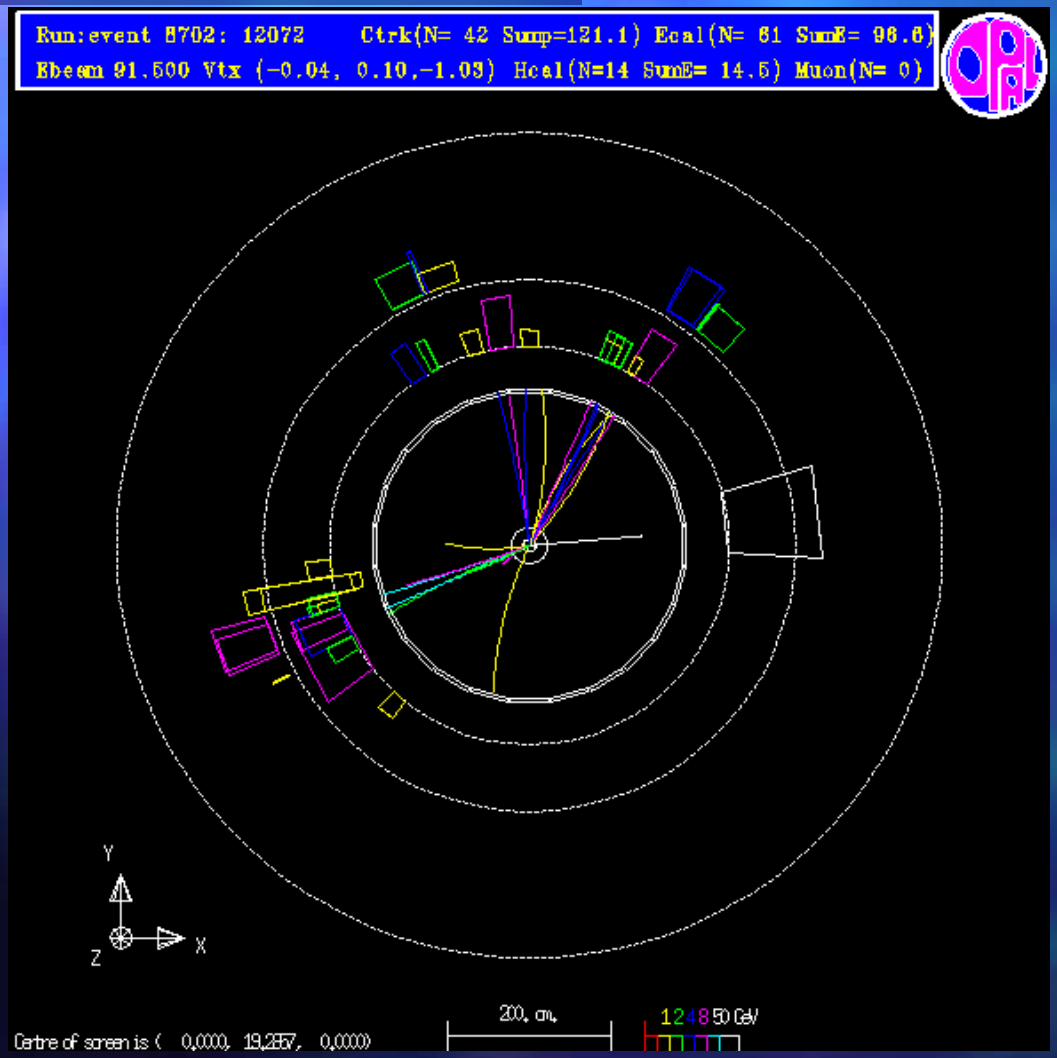
What sort of WW decay is this?

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



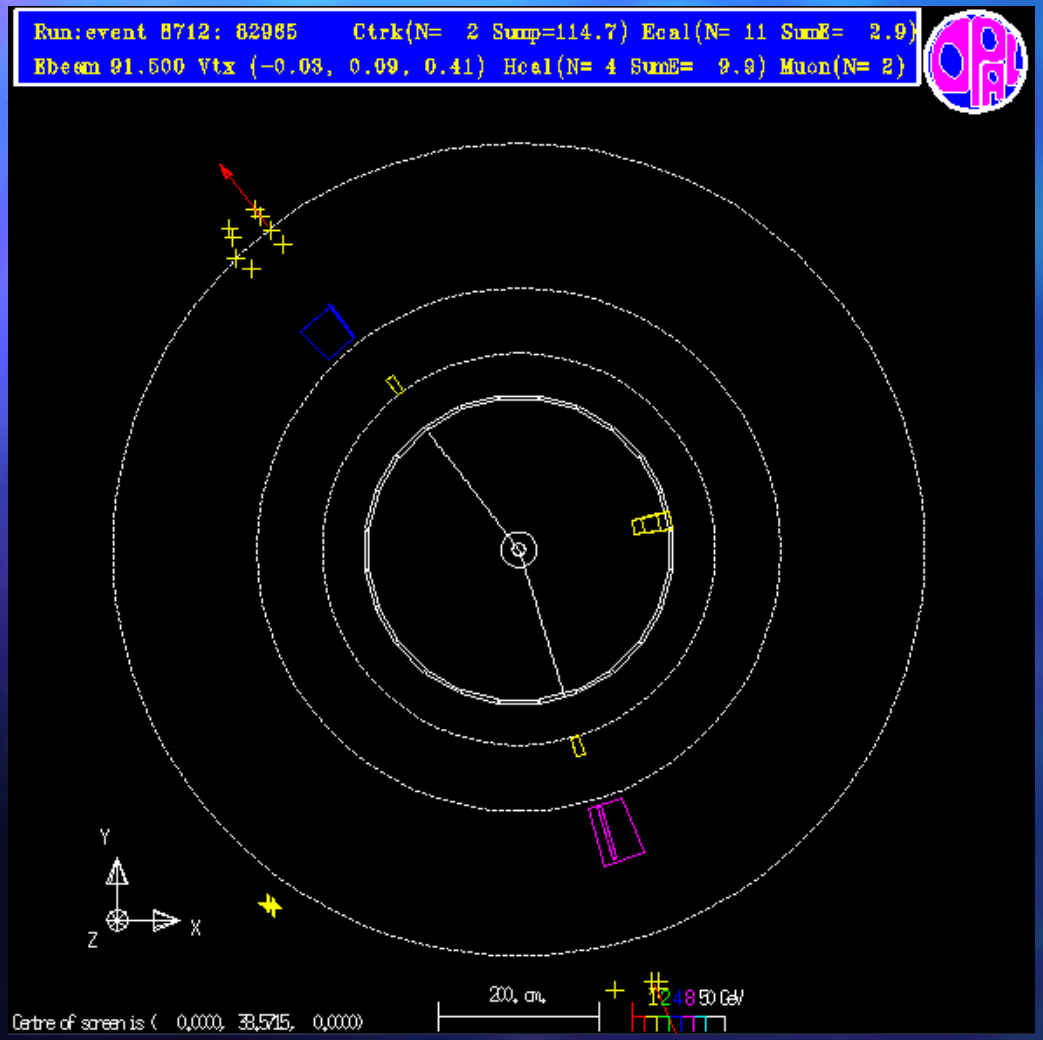
What sort of WW decay is this?

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



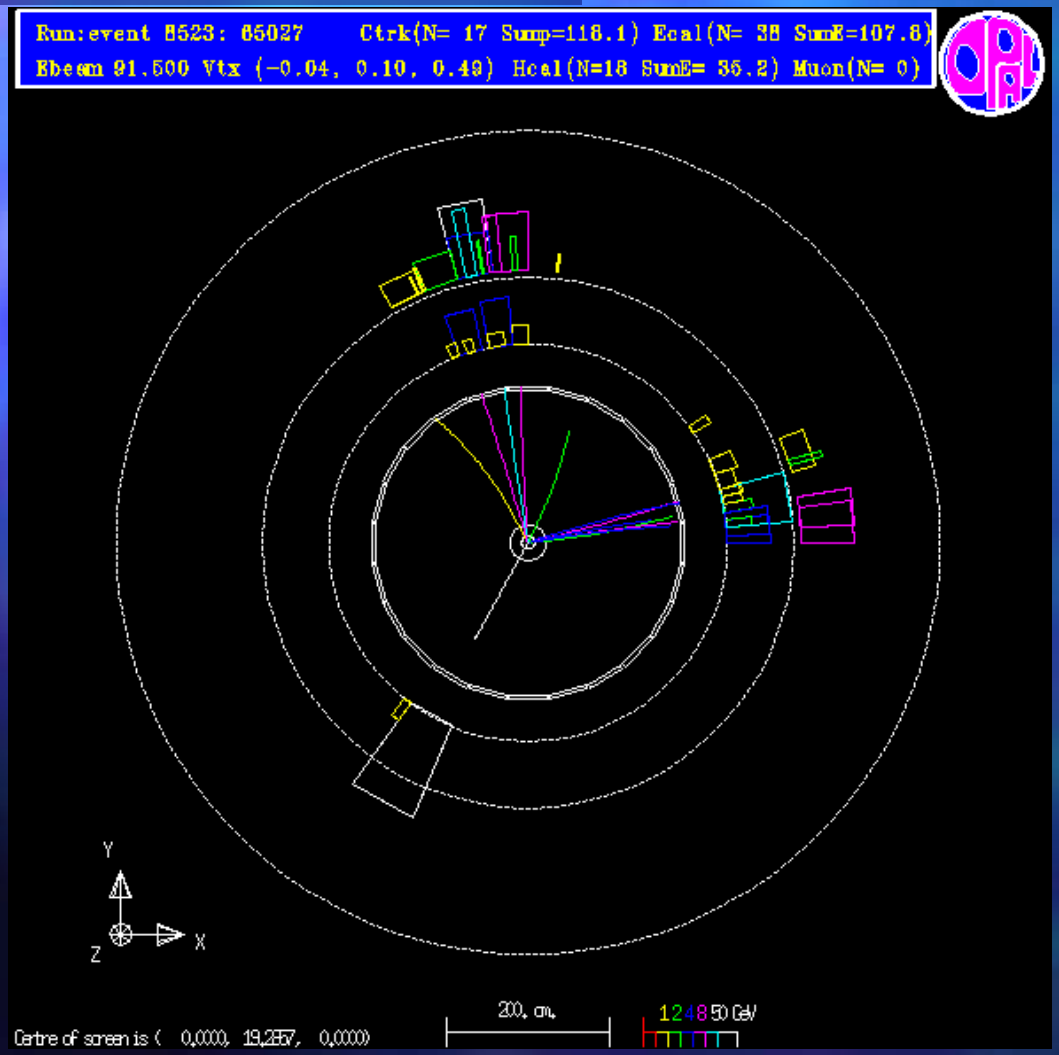
What sort of WW decay is this?

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



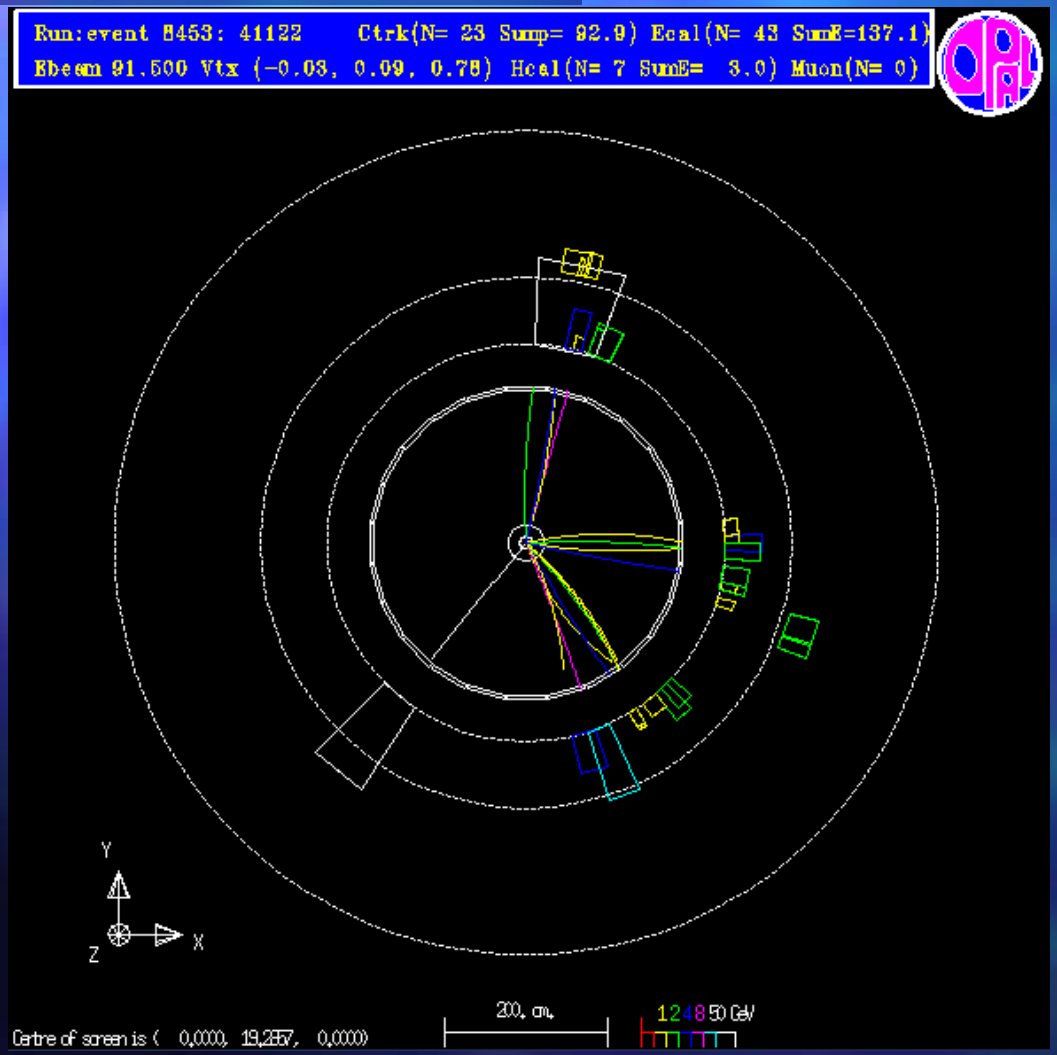
What sort of WW decay is this?

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



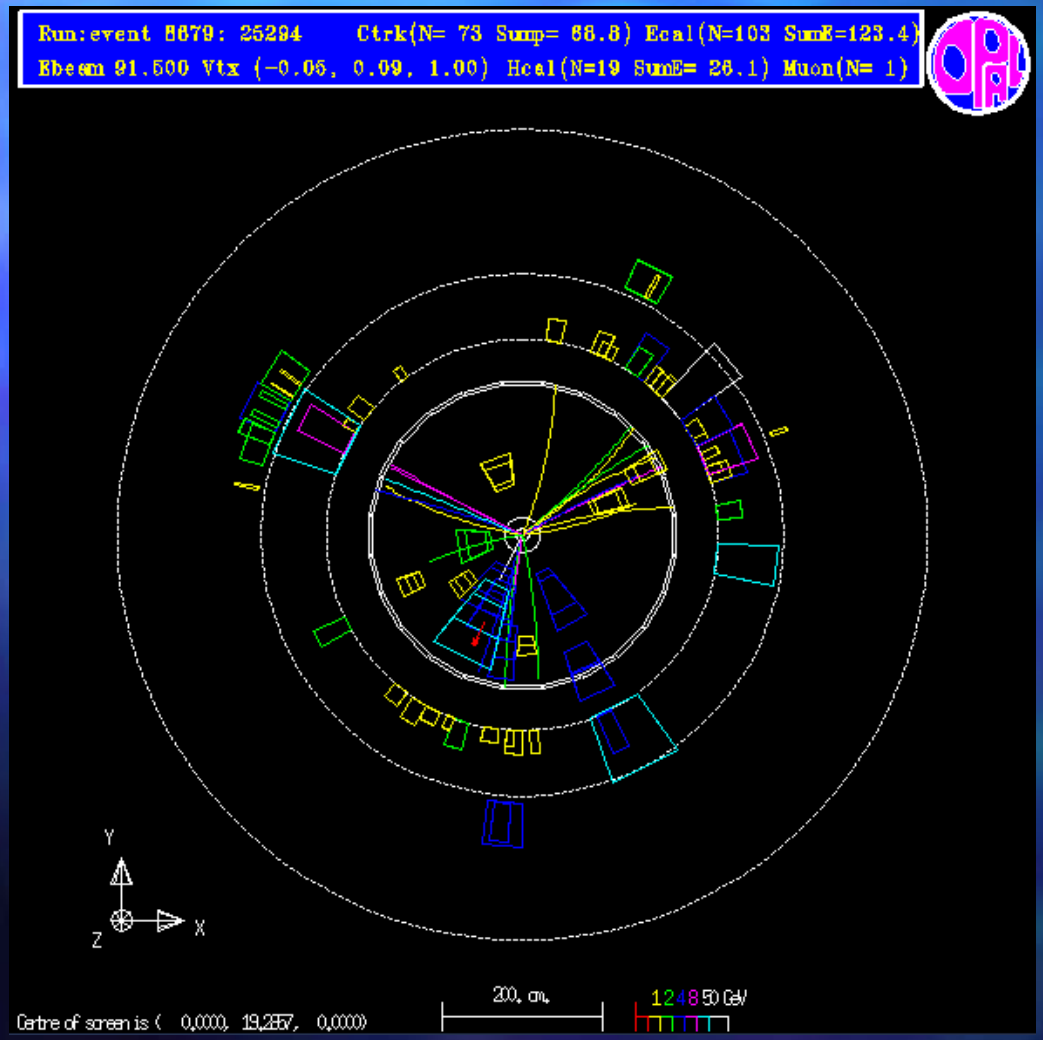
What sort of WW decay is this?

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



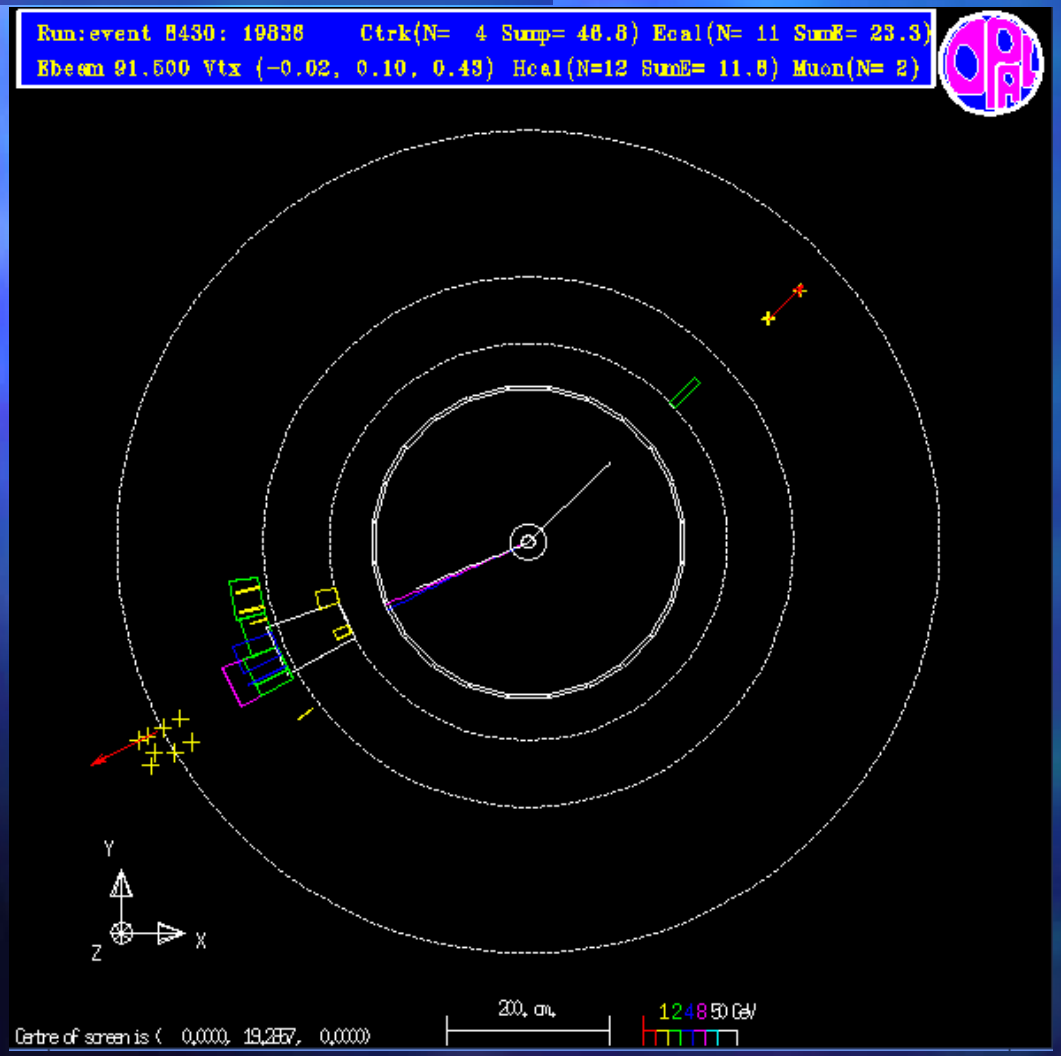
What sort of WW decay is this?

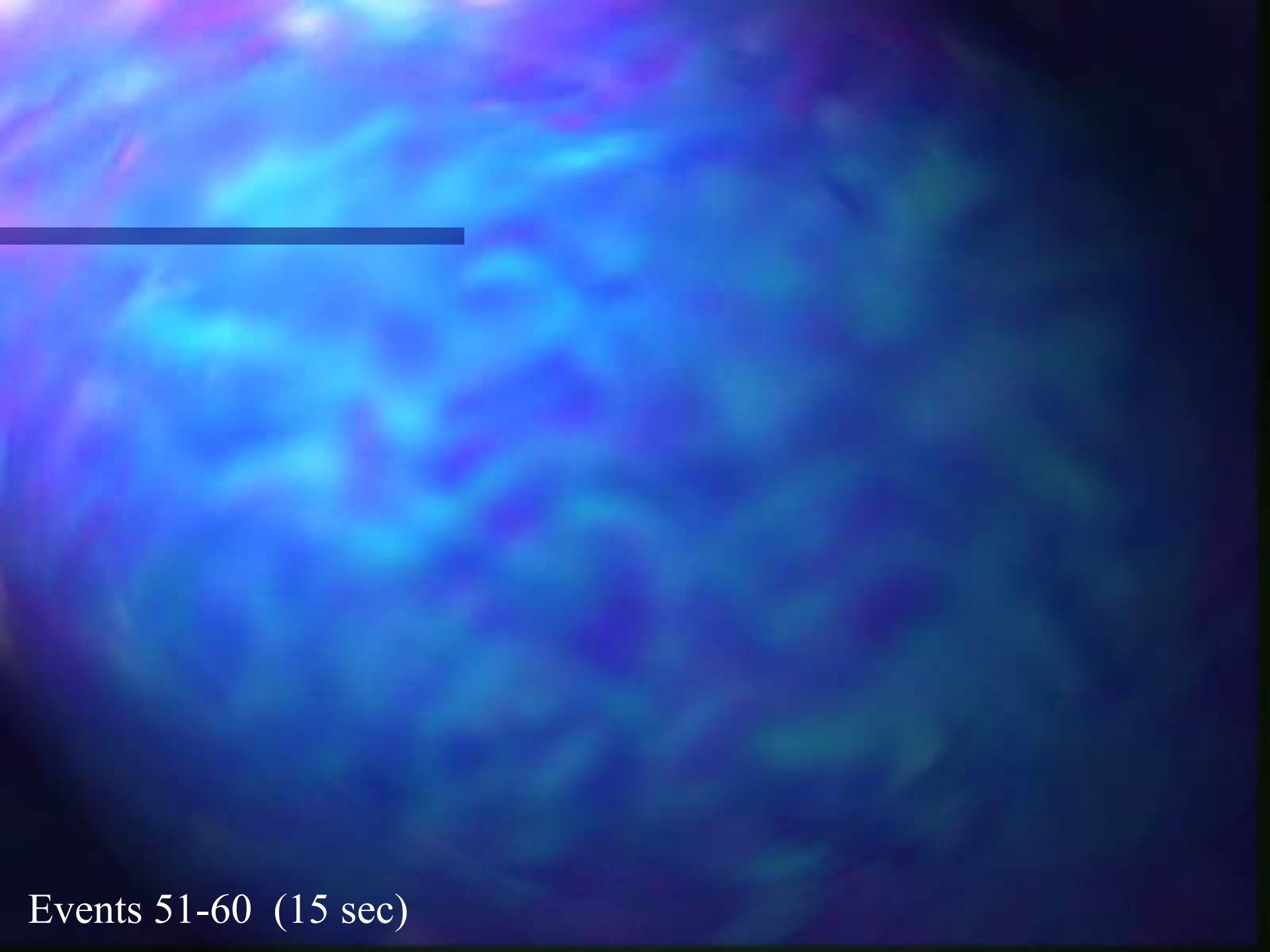
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

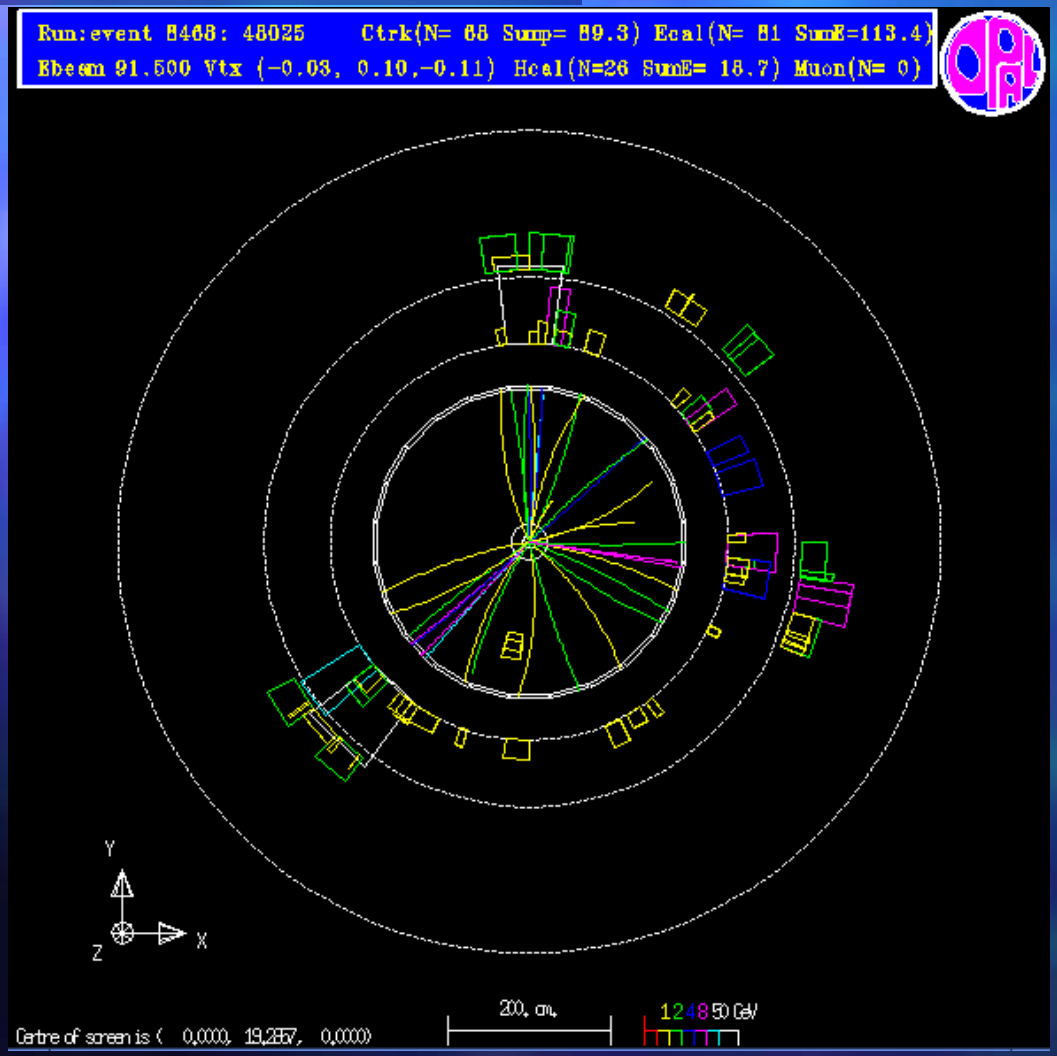
1. Double hadronic decay
2. Mixed
3. Double leptonic decay




Events 51-60 (15 sec)

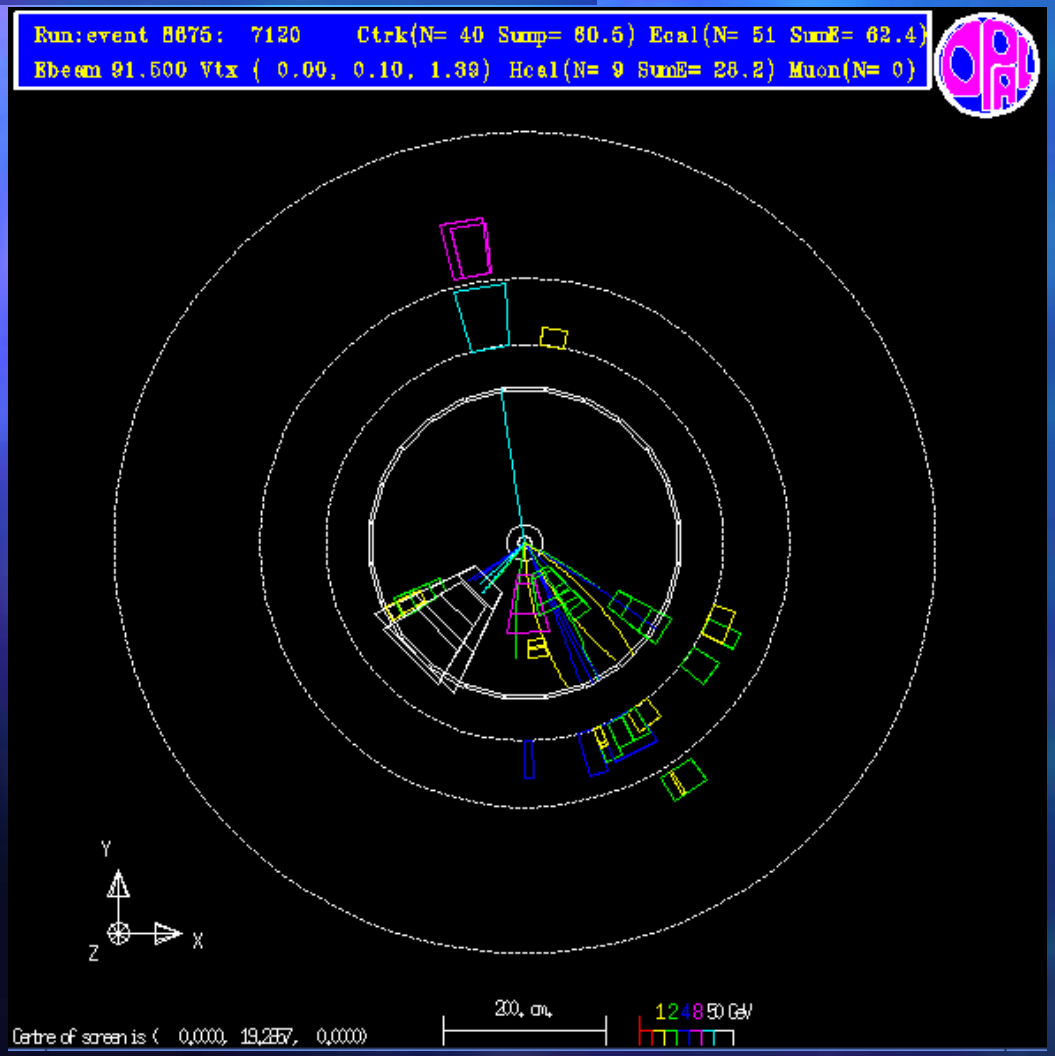
What sort of WW decay is this?

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



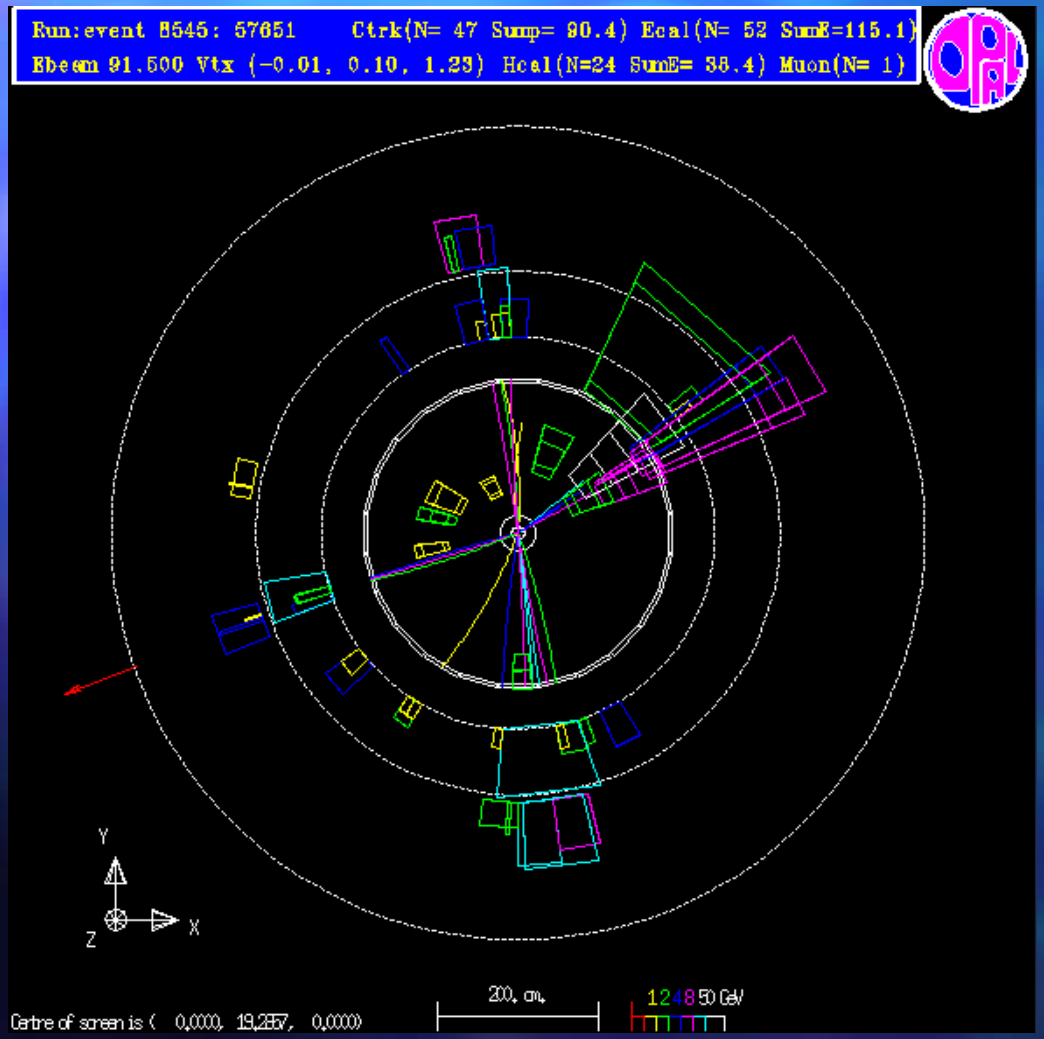
What sort of WW decay is this?

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



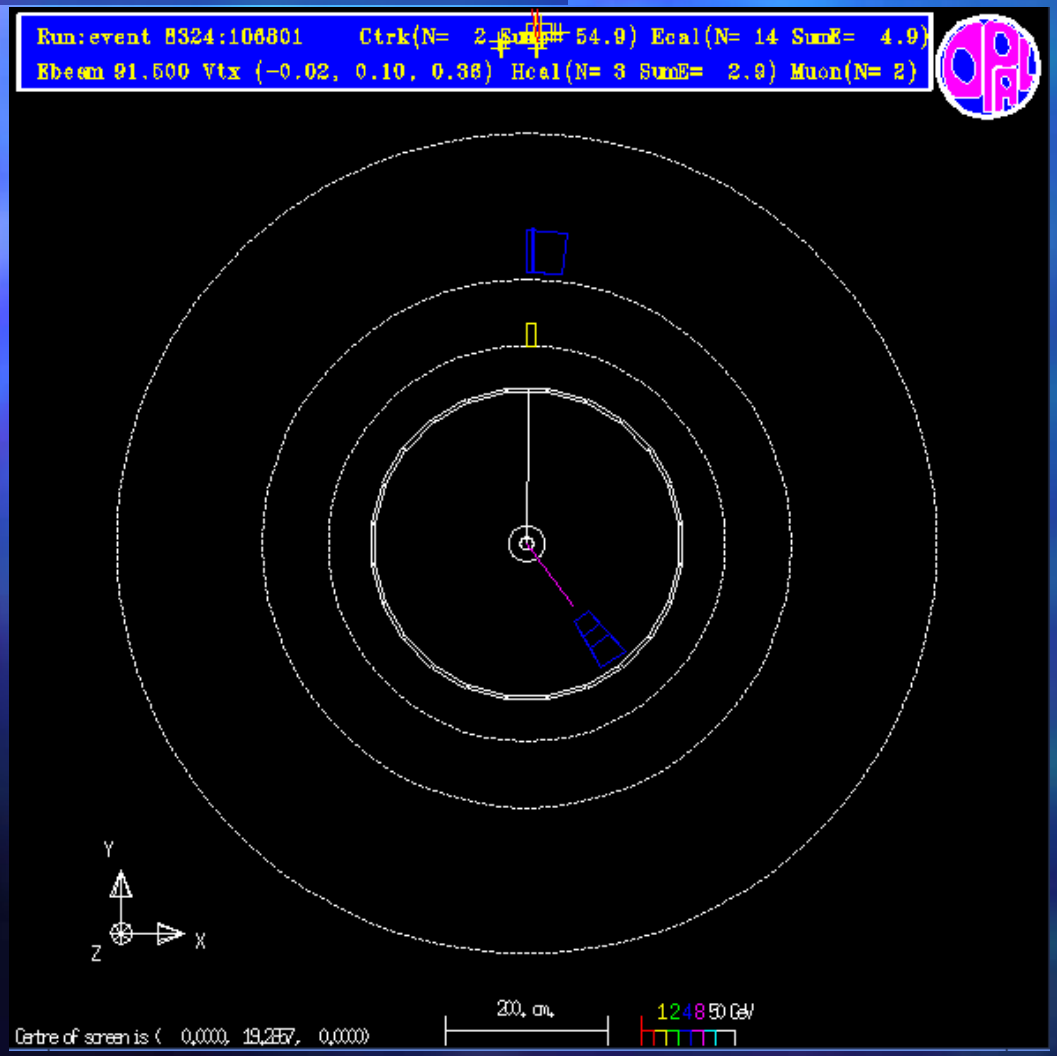
What sort of WW decay is this?

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



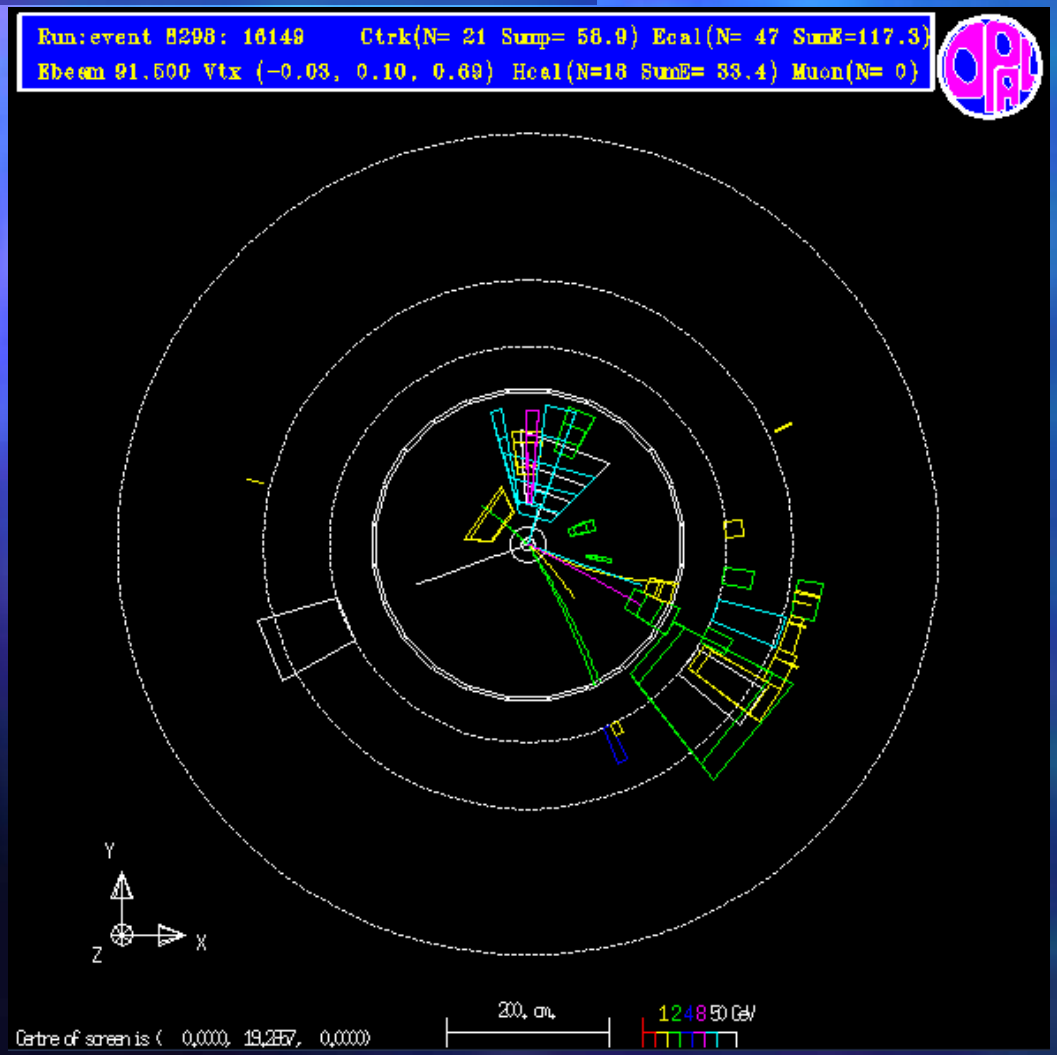
What sort of WW decay is this?

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



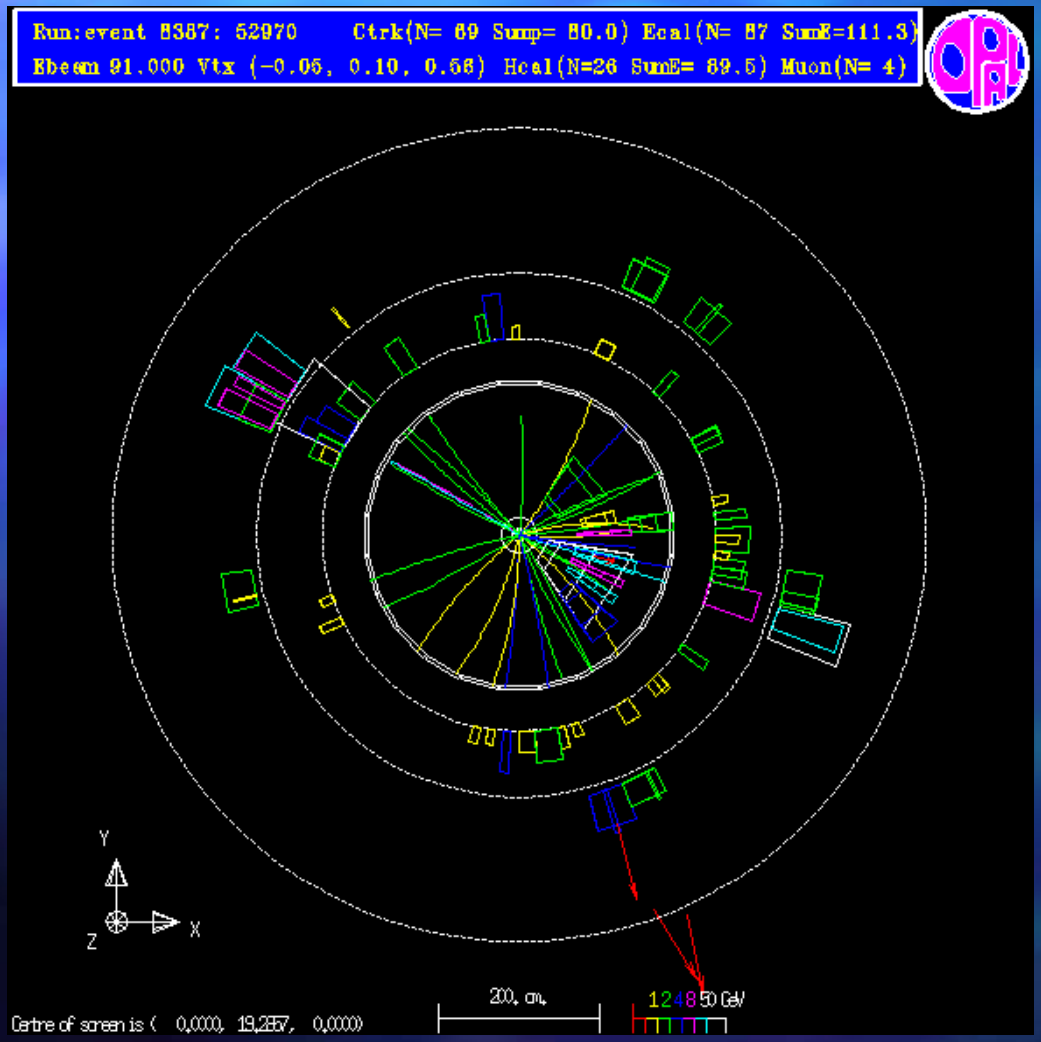
What sort of WW decay is this?

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



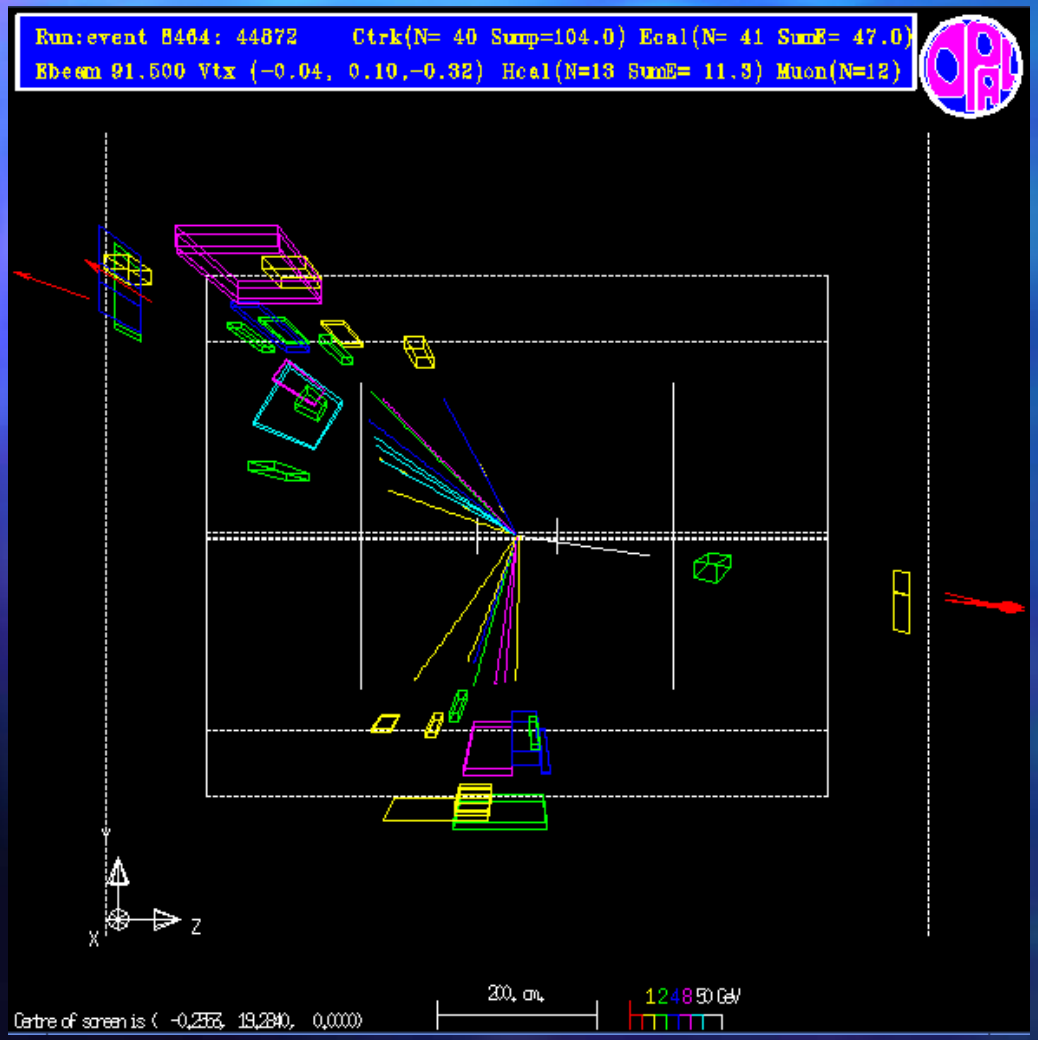
What sort of WW decay is this?

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



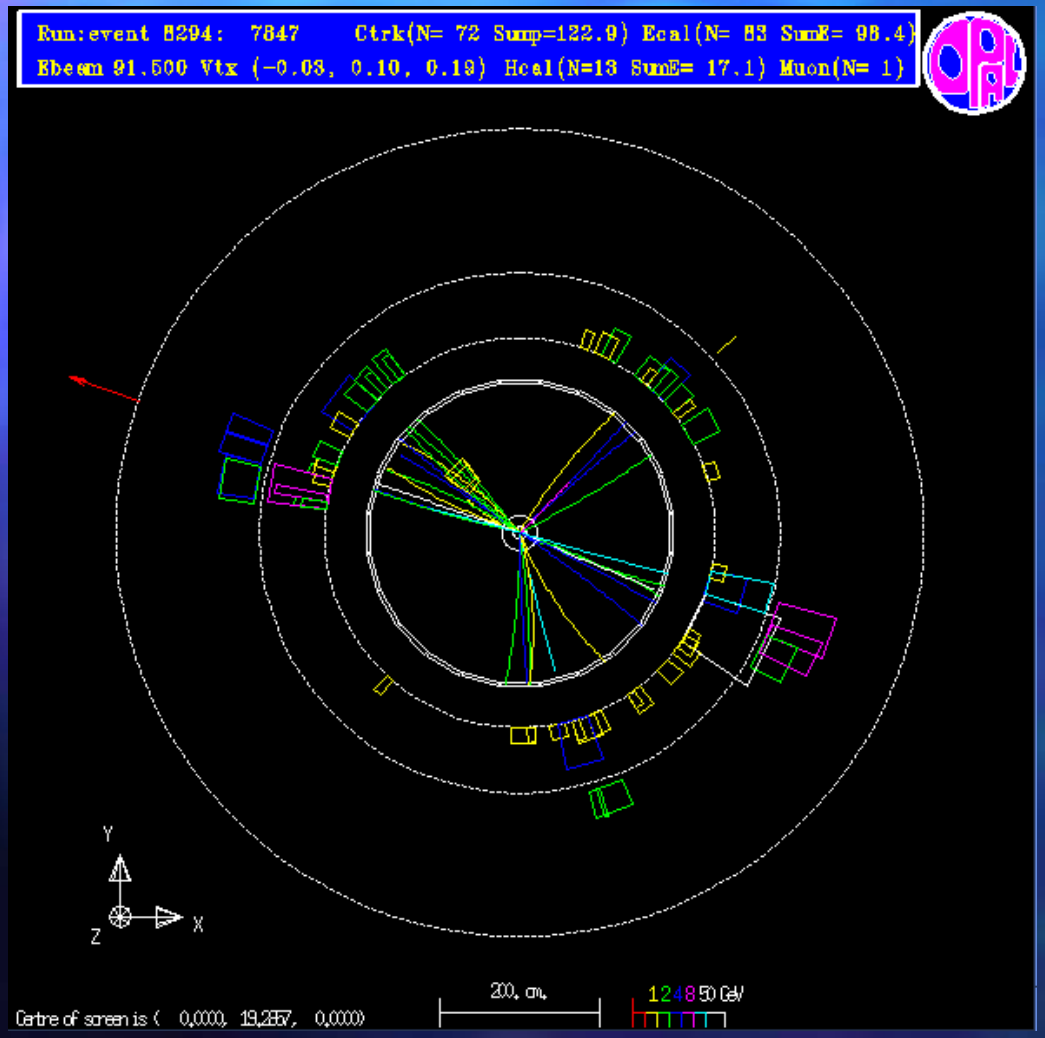
What sort of WW decay is this?

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



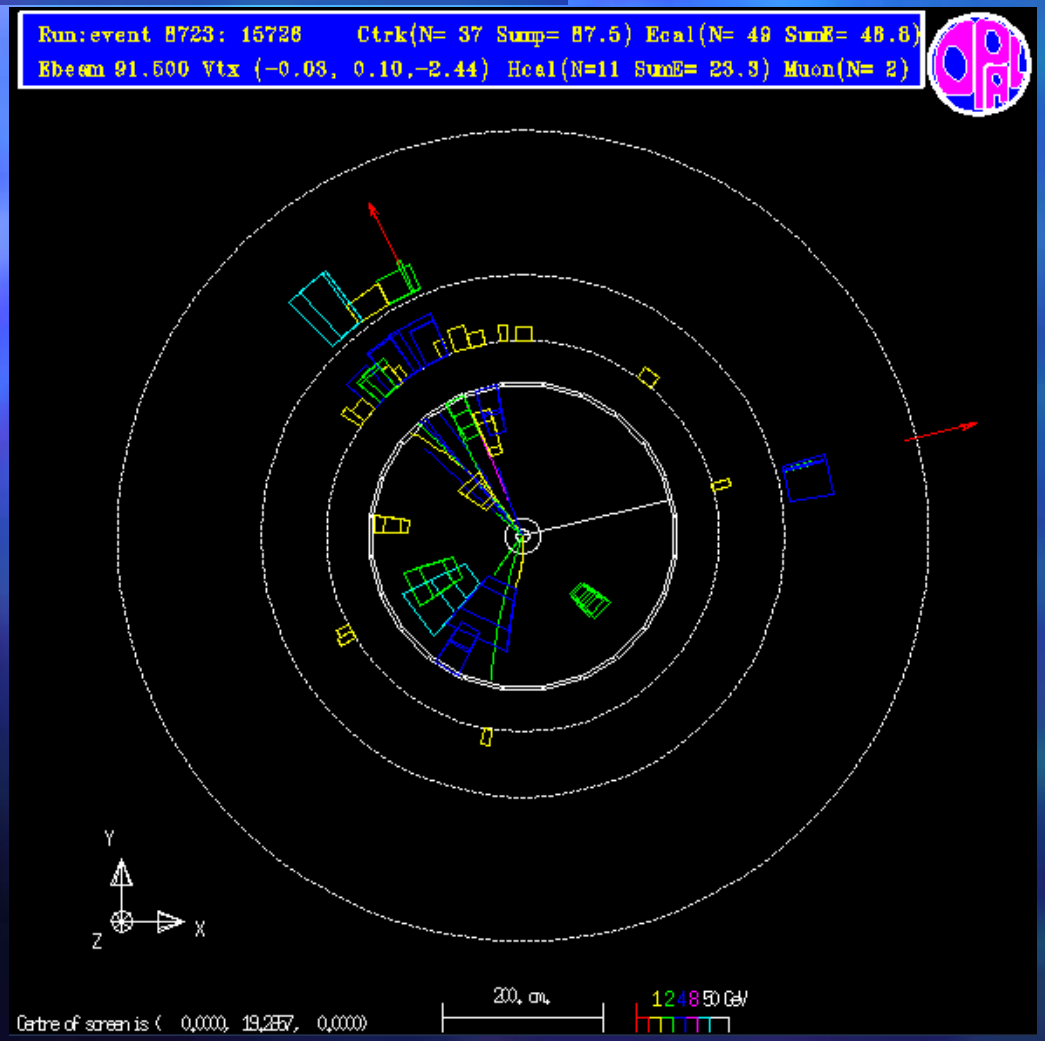
What sort of WW decay is this?

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



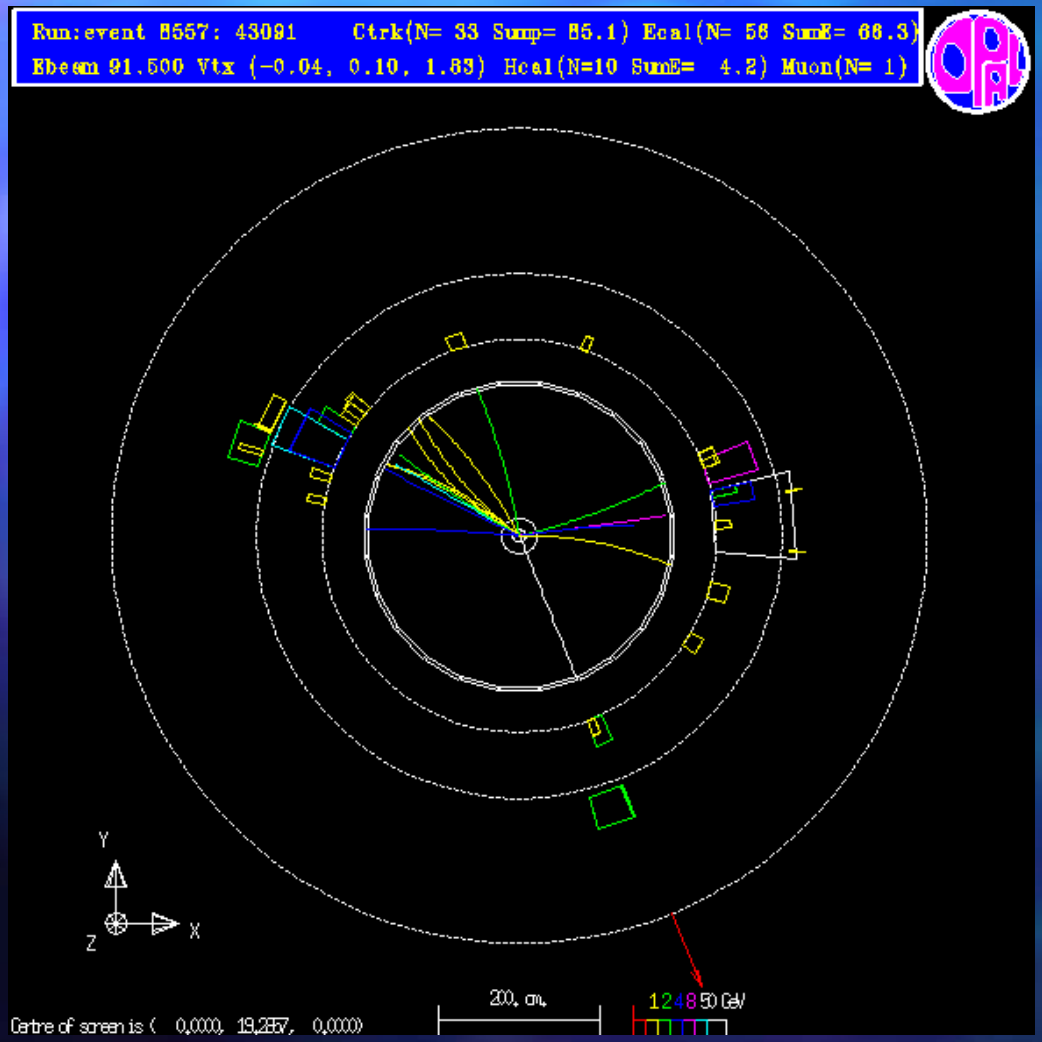
What sort of WW decay is this?

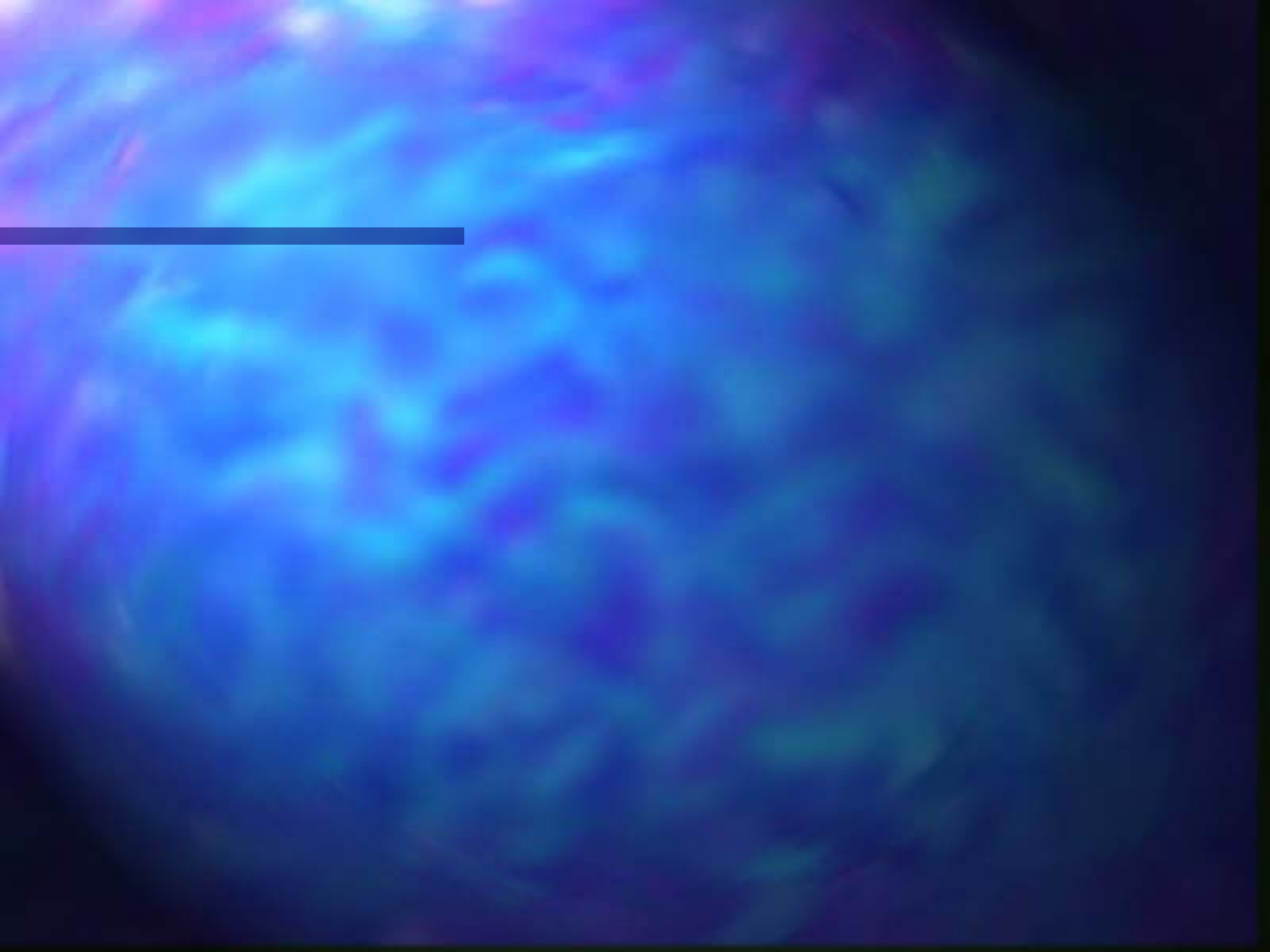
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

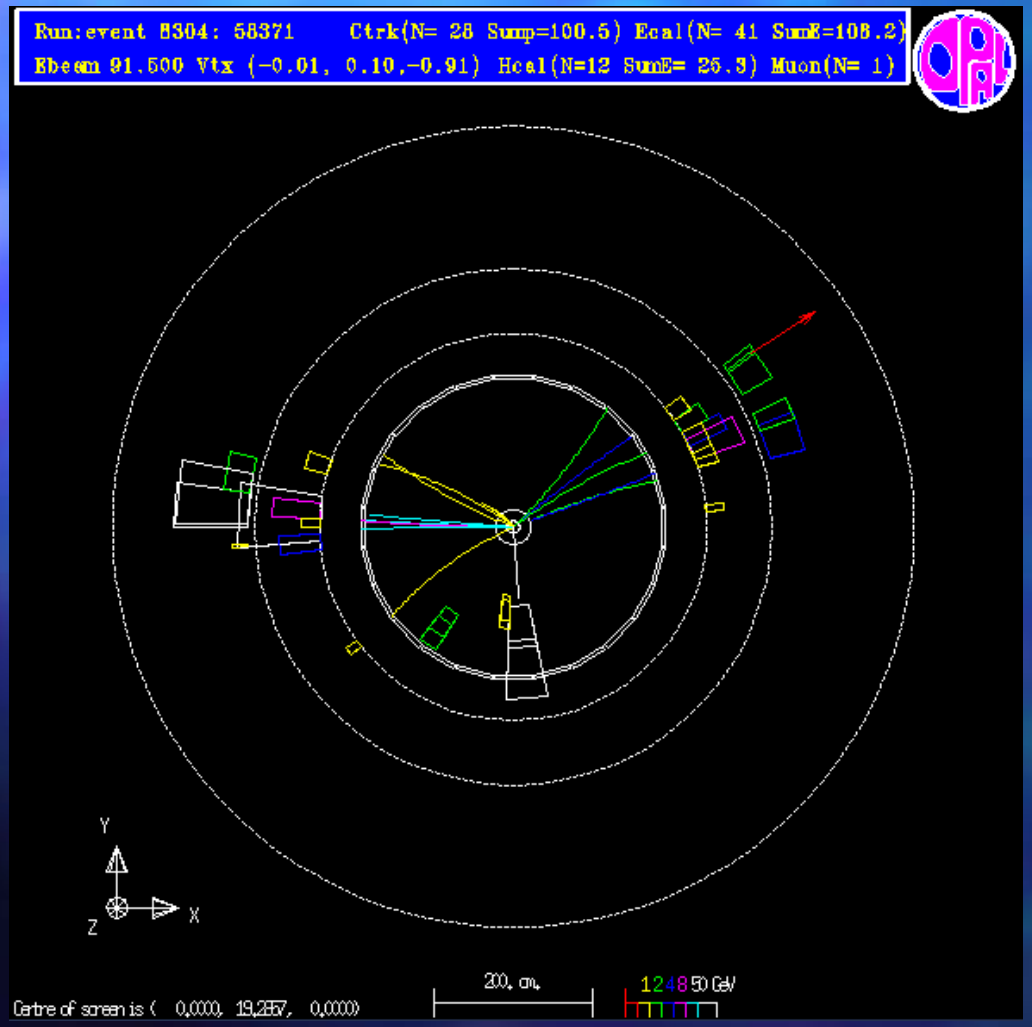
1. Double hadronic decay
2. Mixed
3. Double leptonic decay





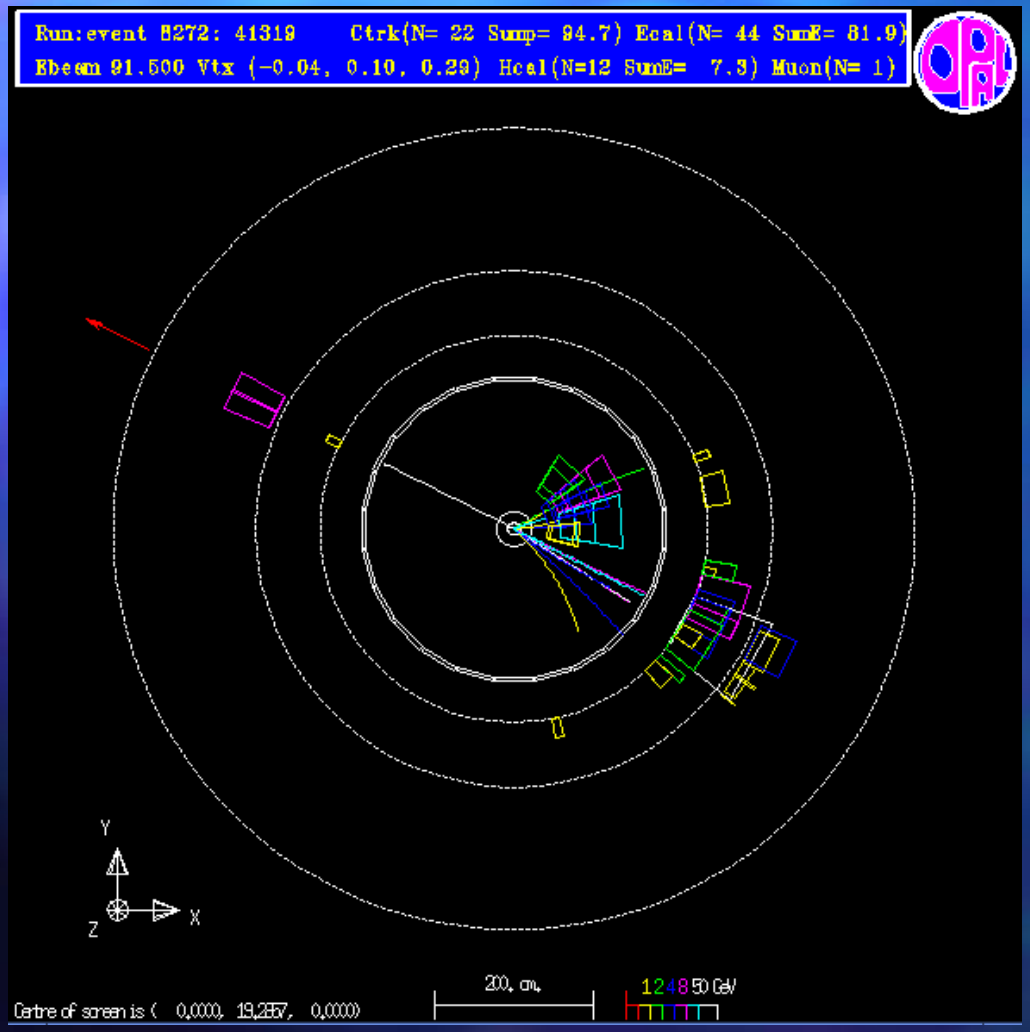
What sort of WW decay is this?

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



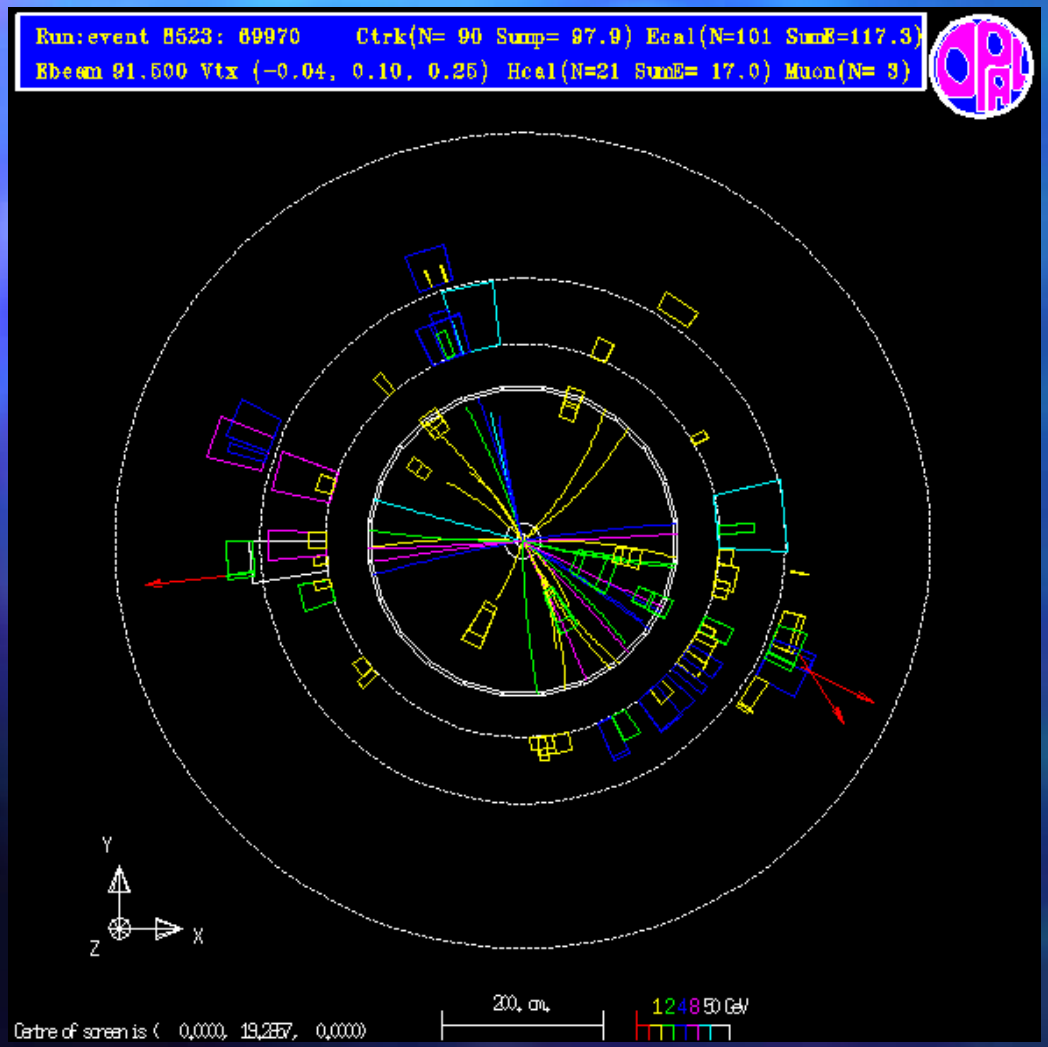
What sort of WW decay is this?

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



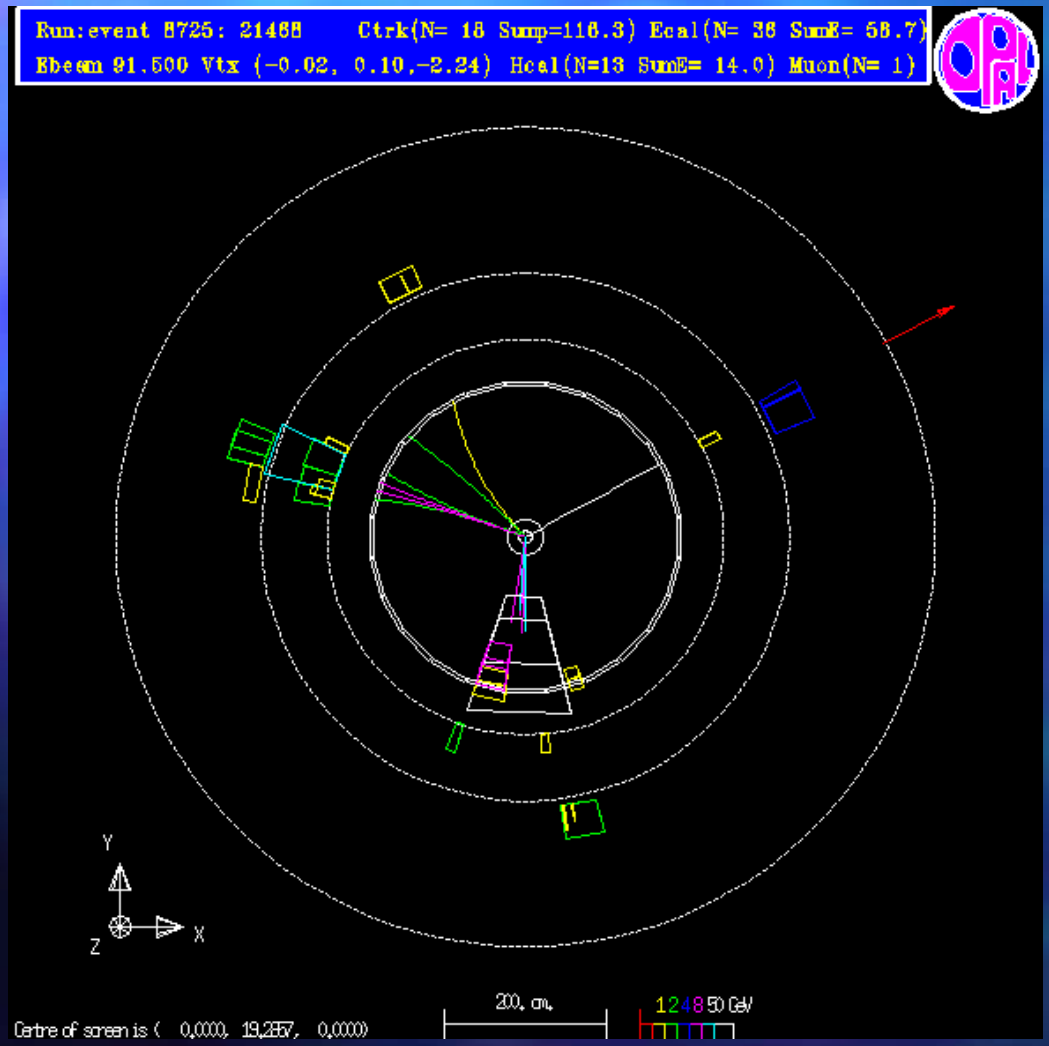
What sort of WW decay is this?

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



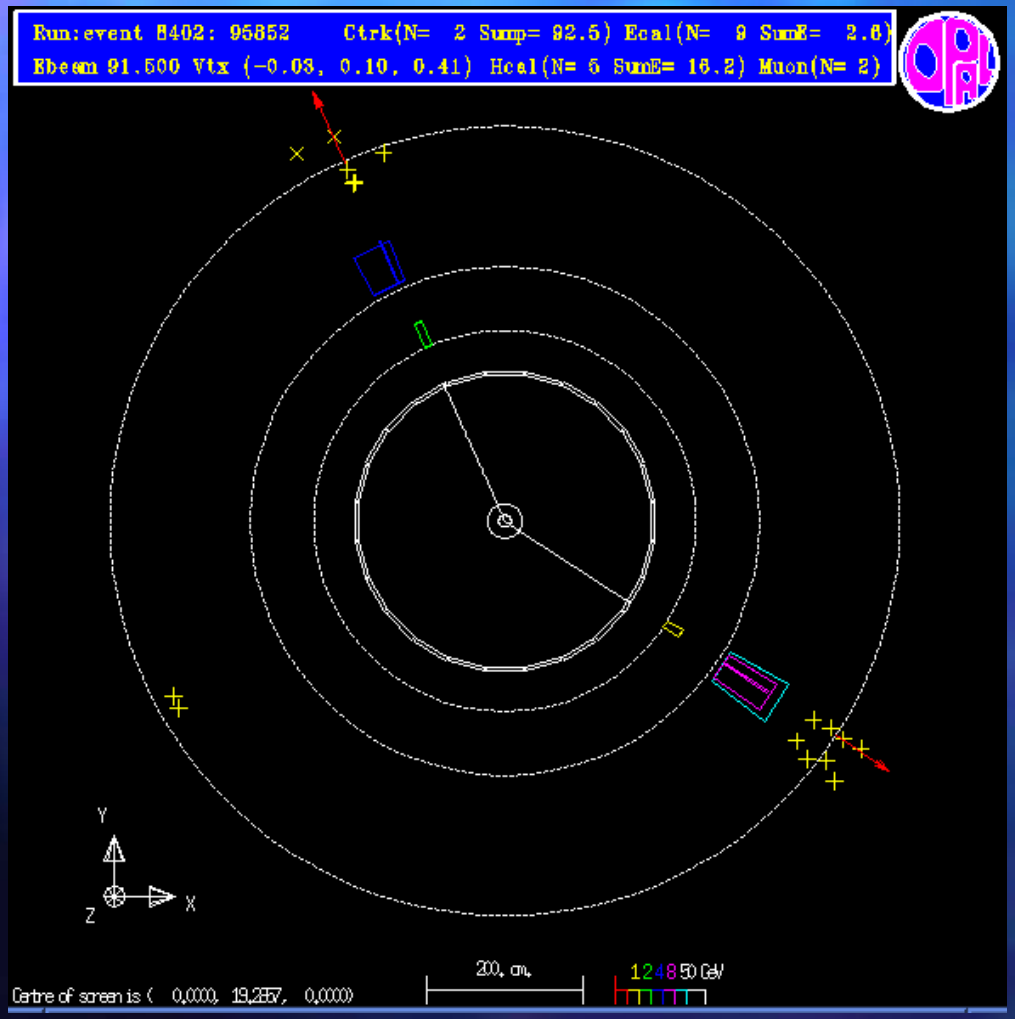
What sort of WW decay is this?

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



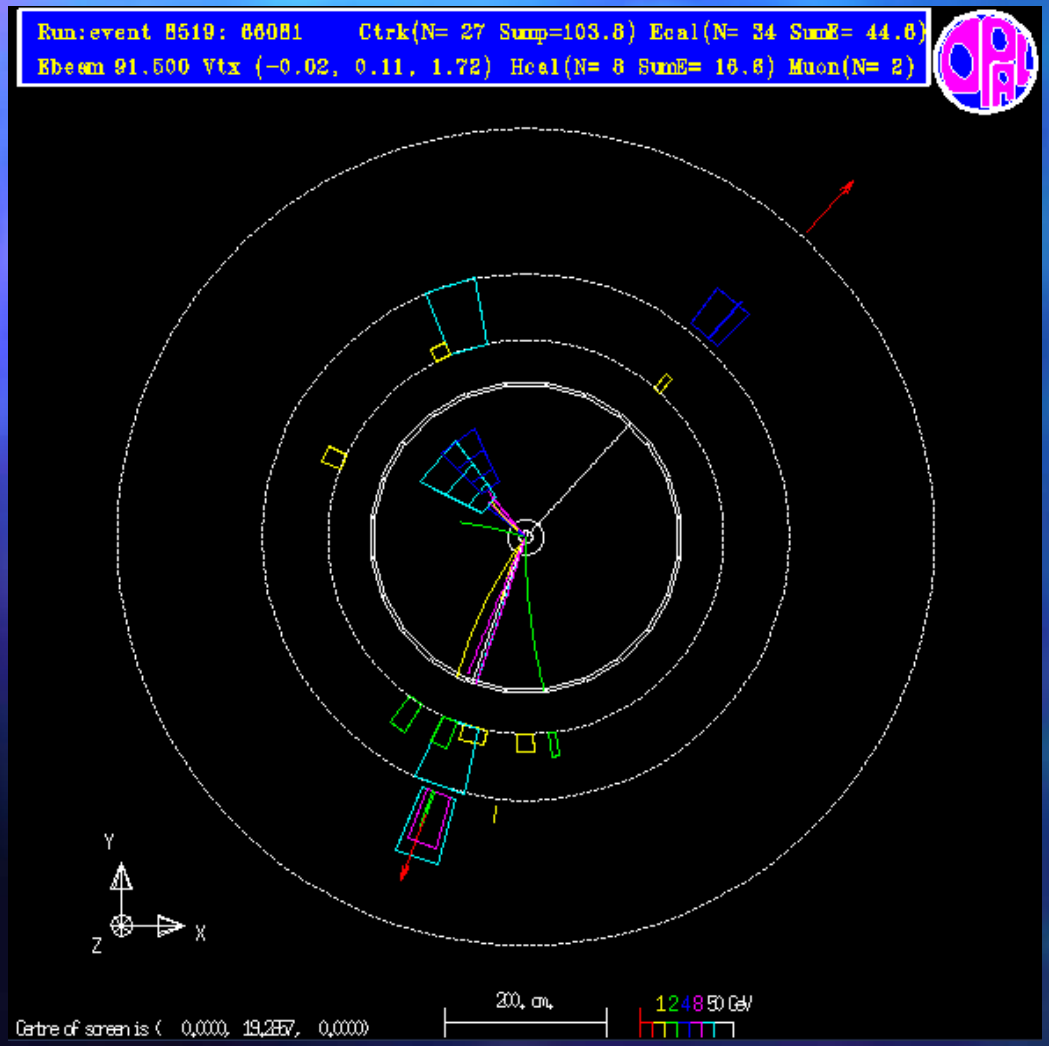
What sort of WW decay is this?

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



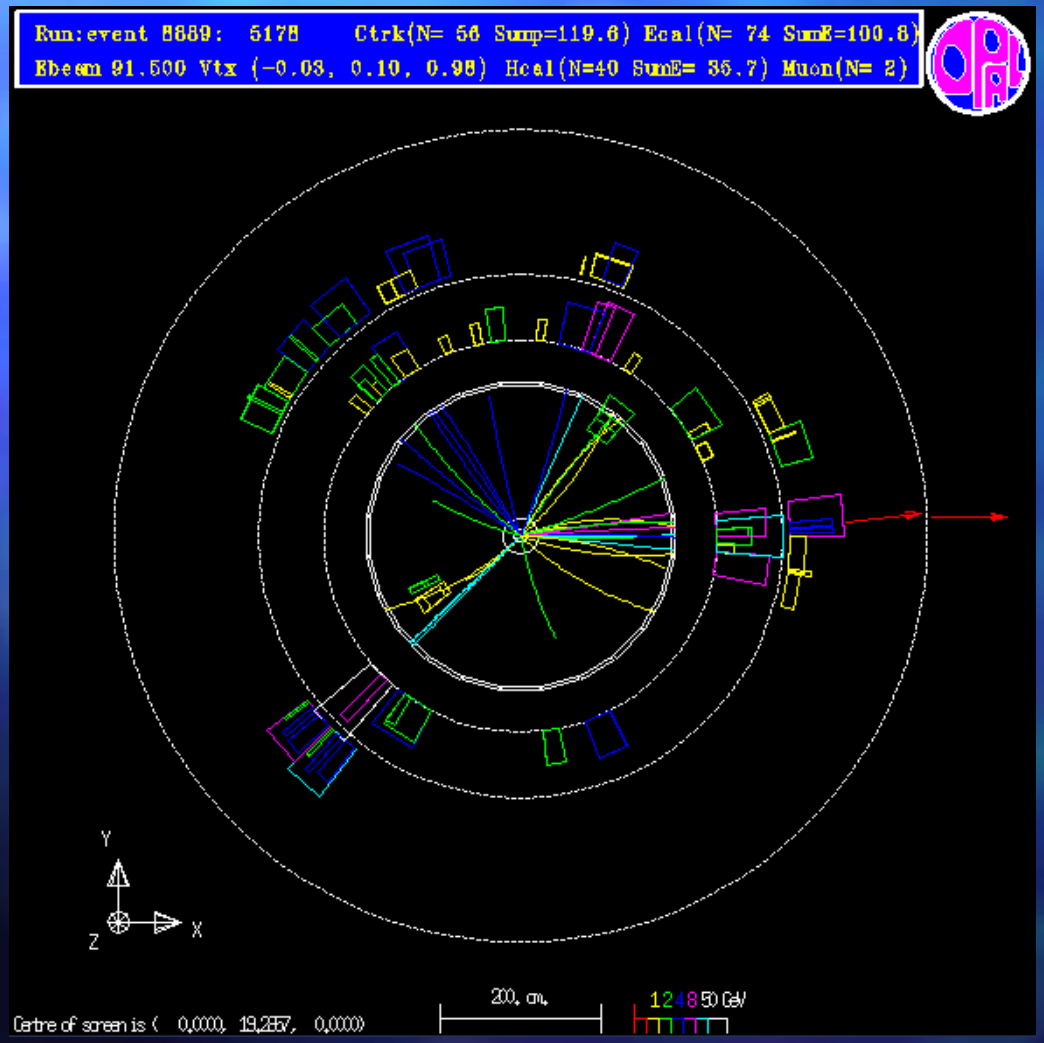
What sort of WW decay is this?

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



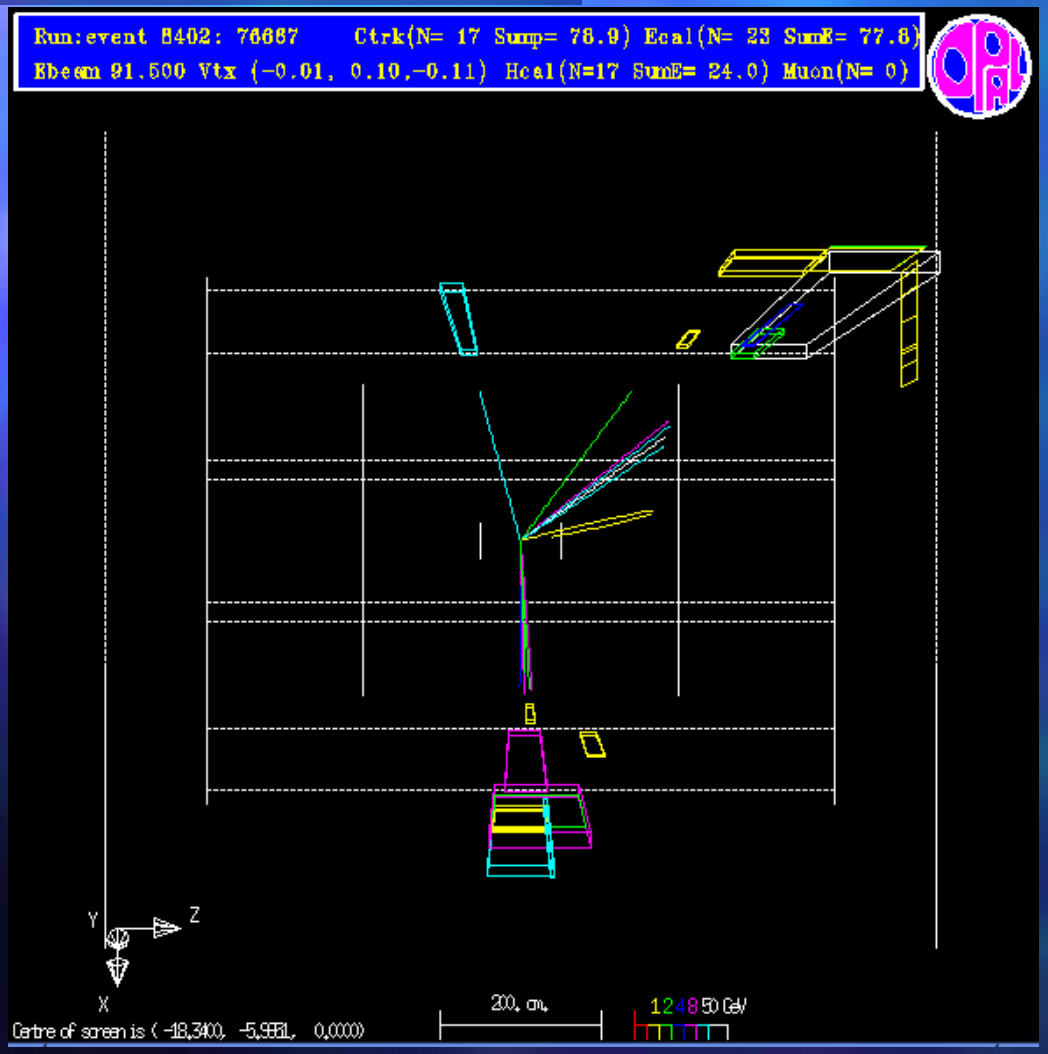
What sort of WW decay is this?

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



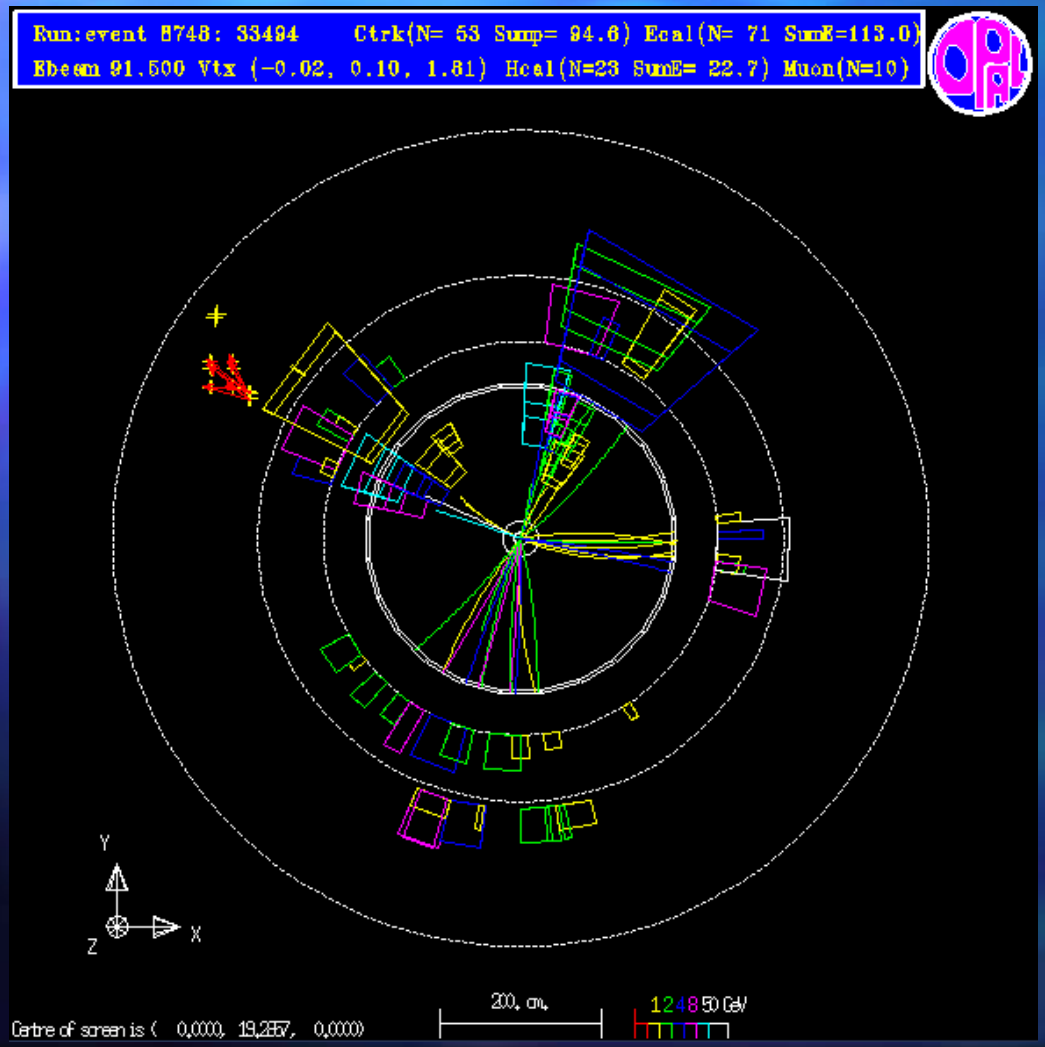
What sort of WW decay is this?

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



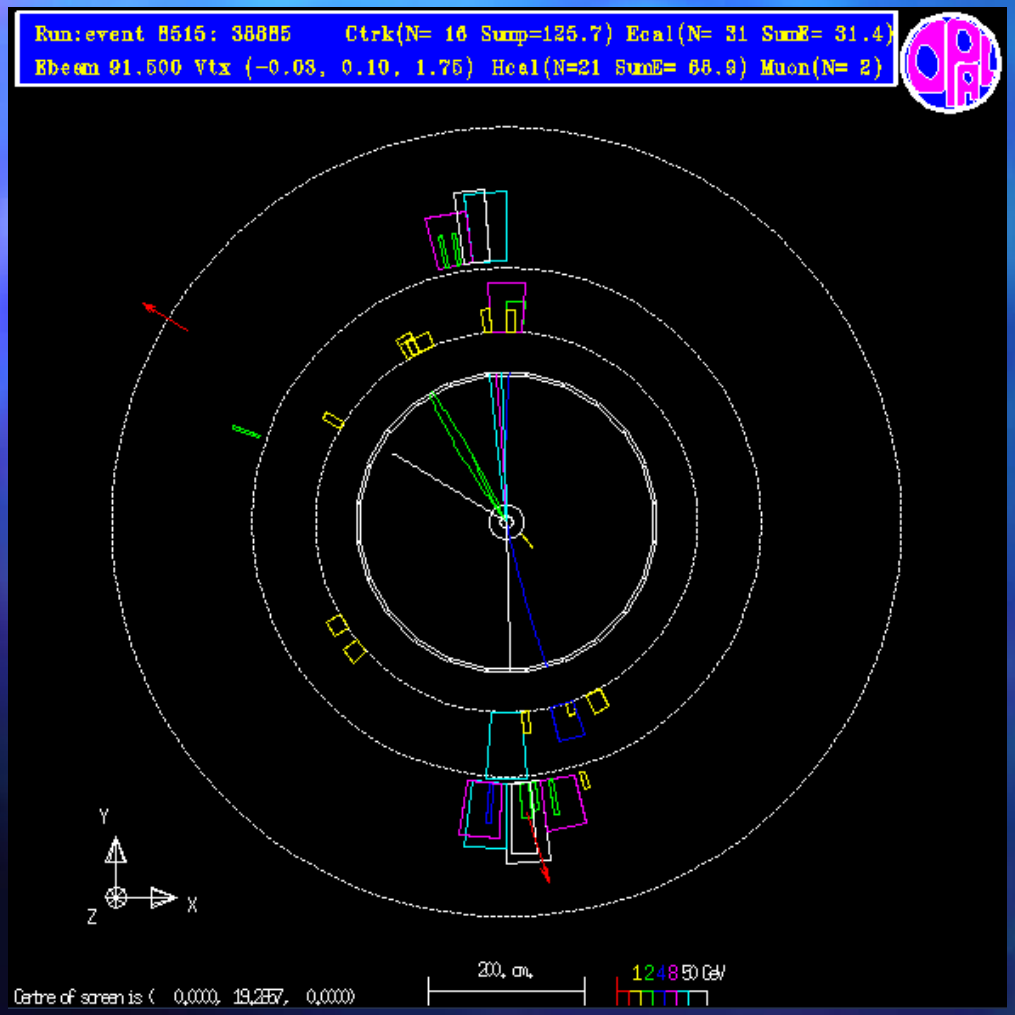
What sort of WW decay is this?

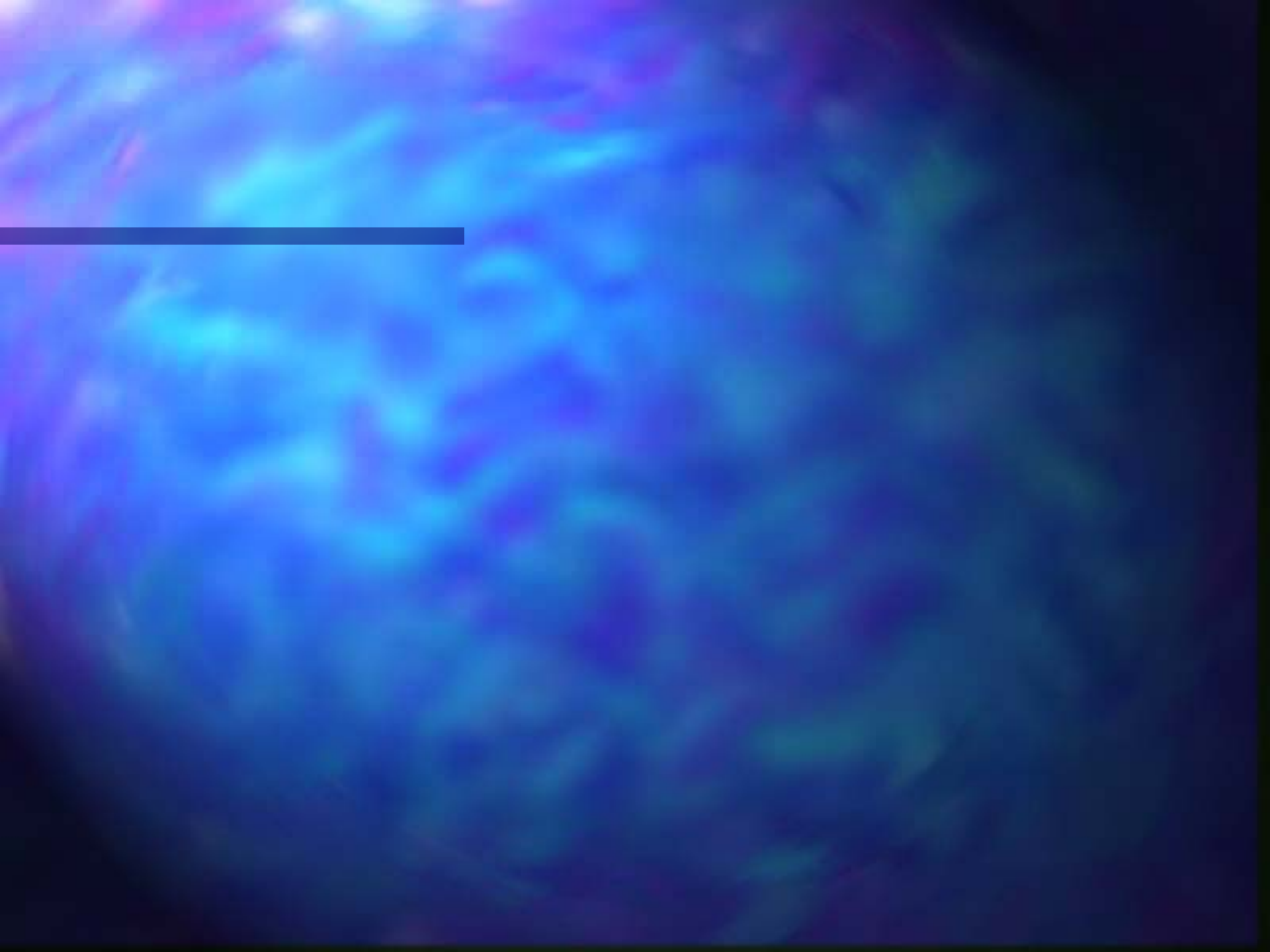
1. Double hadronic decay
2. Mixed
3. Double leptonic decay



What sort of WW decay is this?

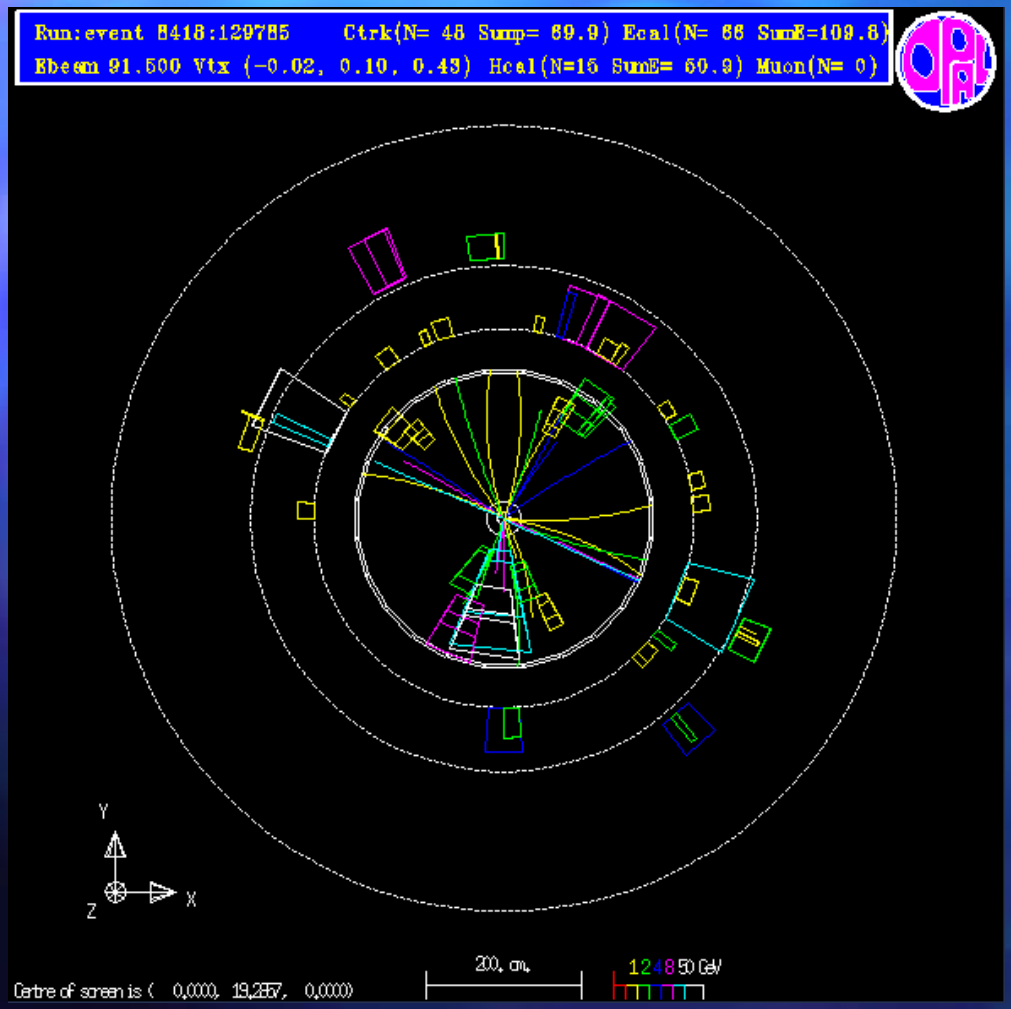
1. Double hadronic decay
2. Mixed
3. Double leptonic decay





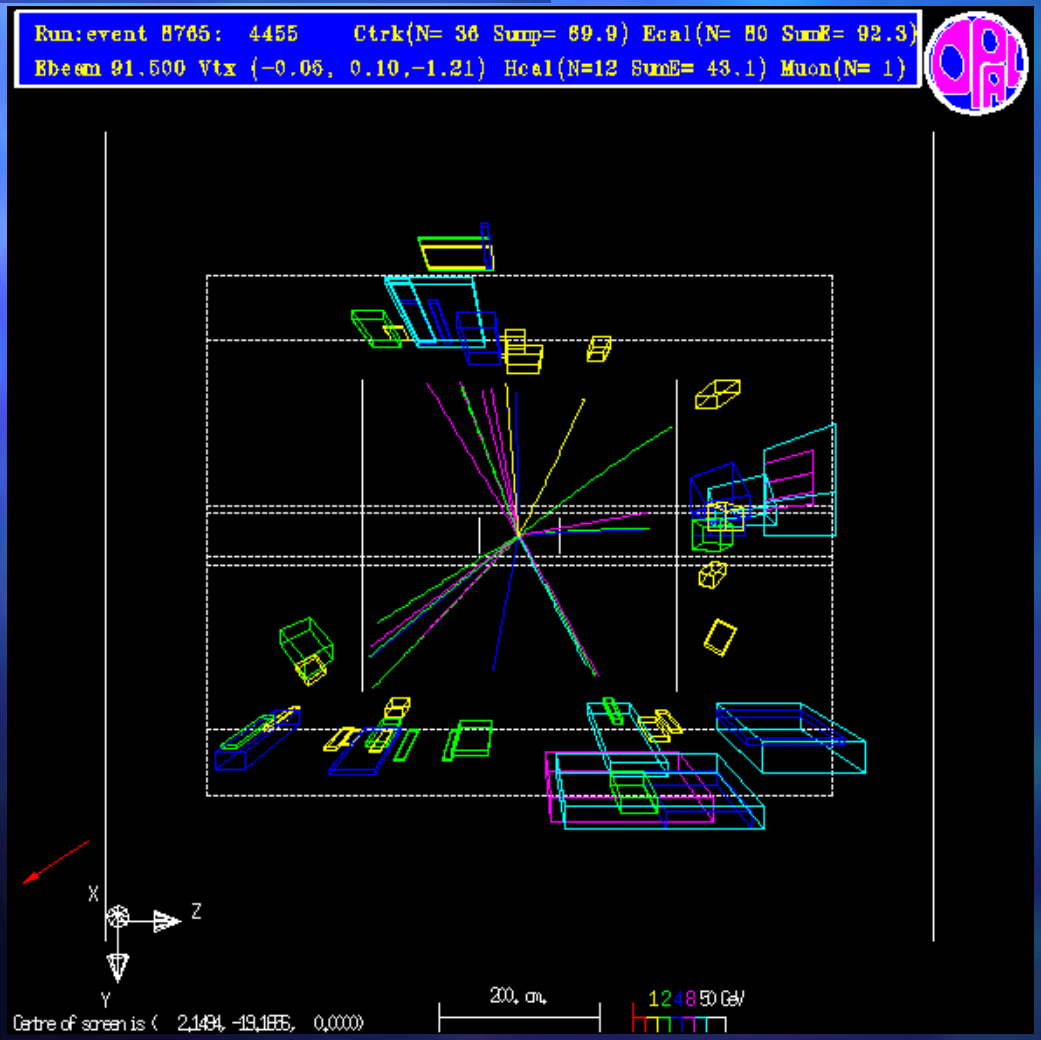
What sort of WW decay is this?

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



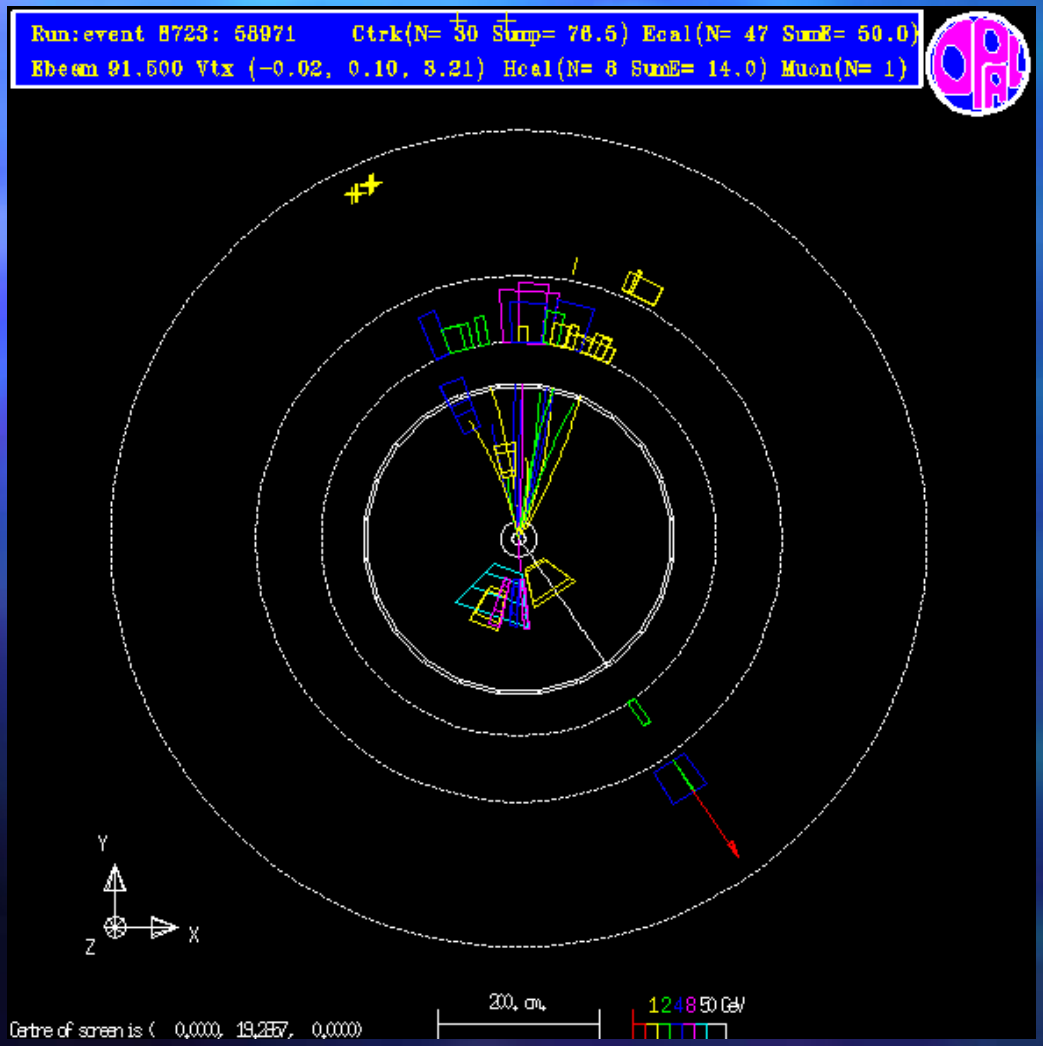
What sort of WW decay is this?

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



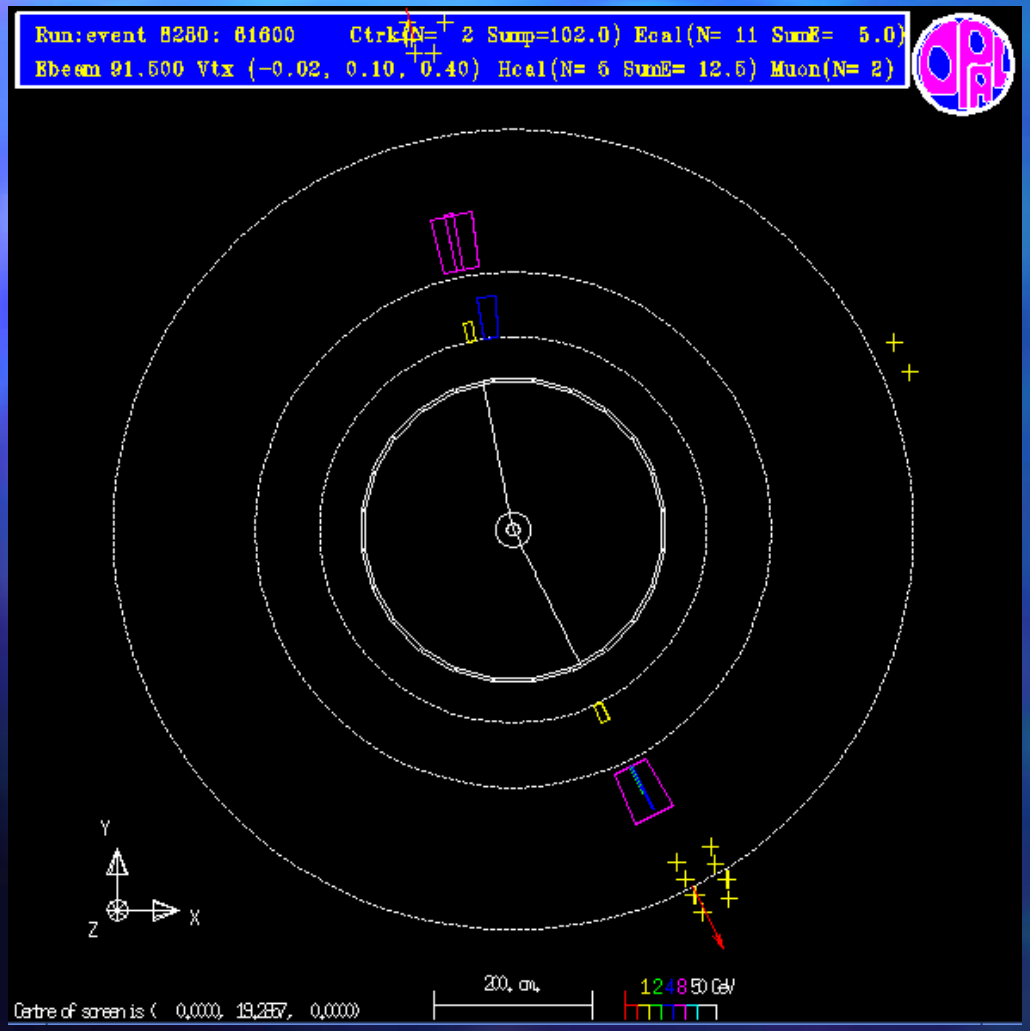
What sort of WW decay is this?

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



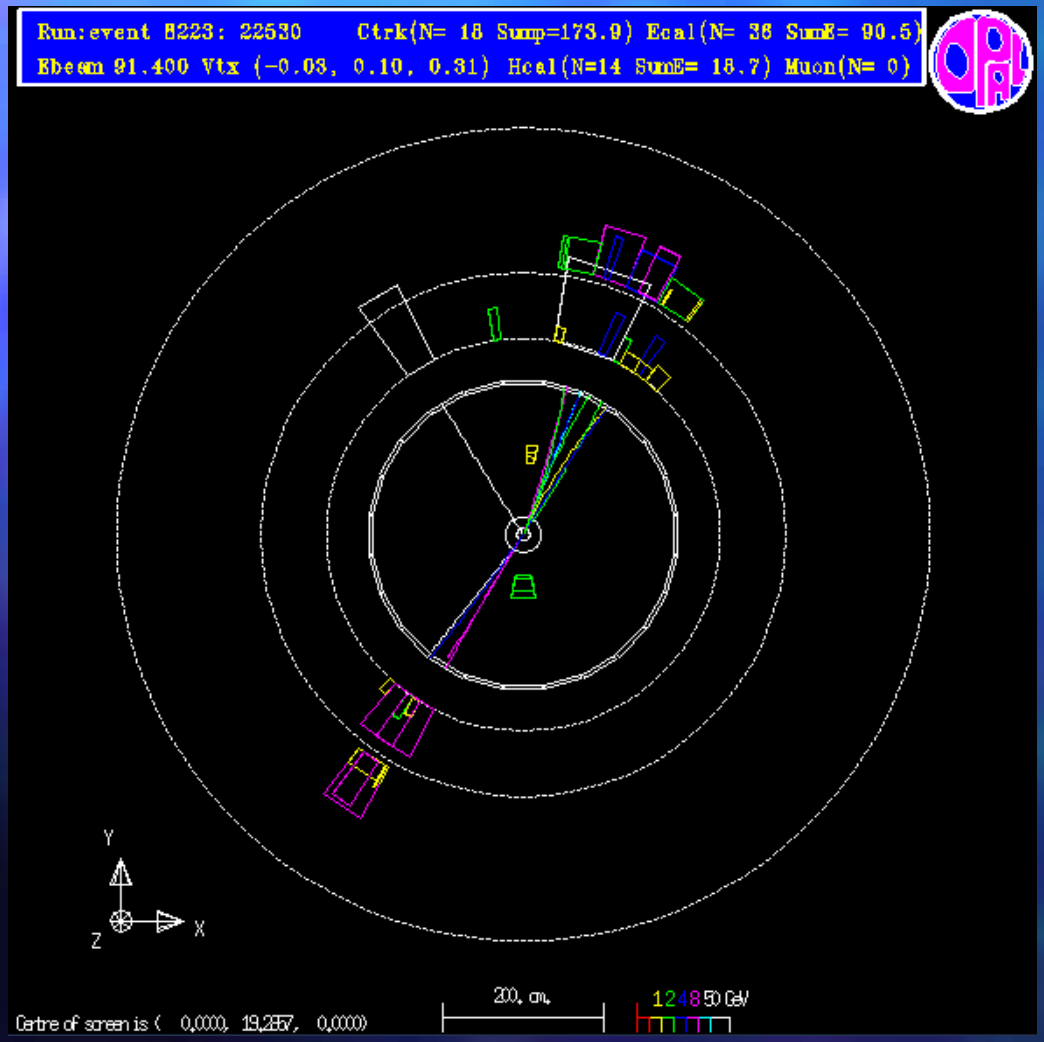
What sort of WW decay is this?

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



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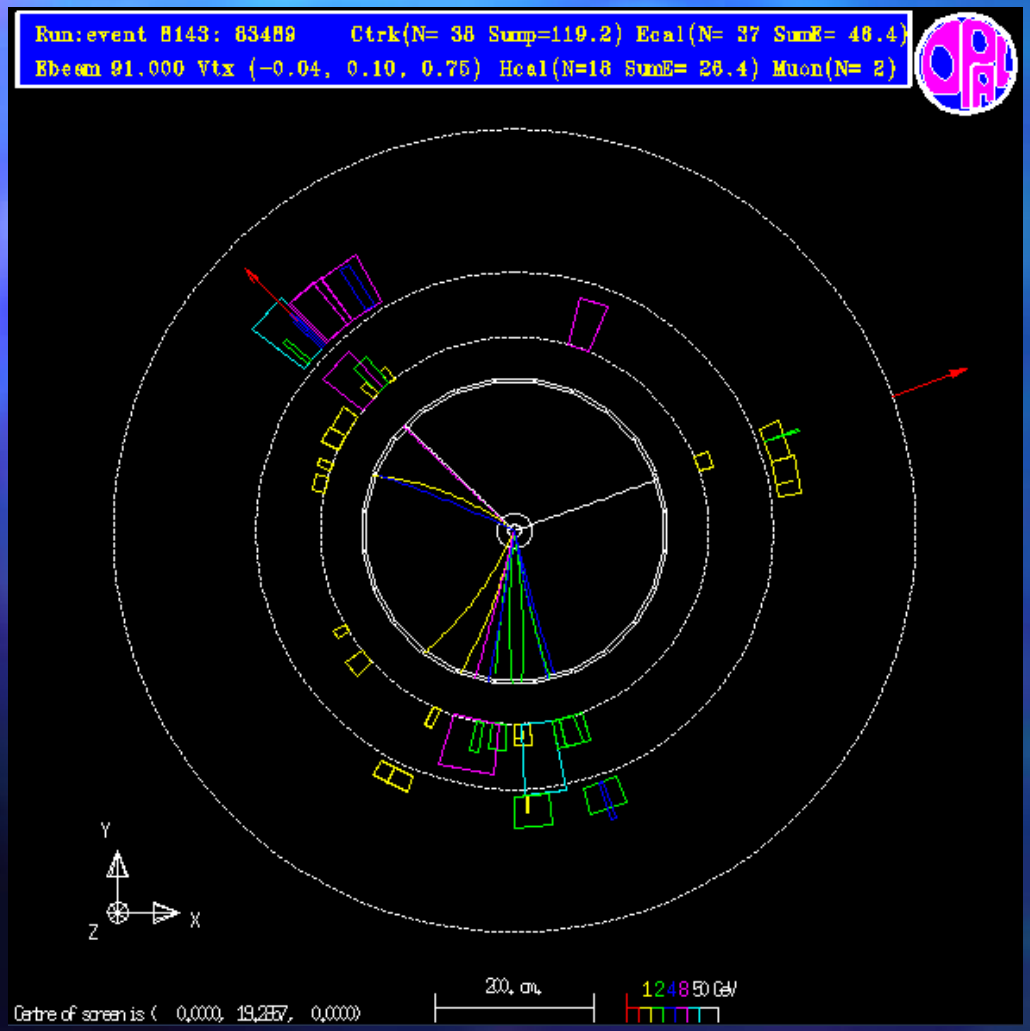

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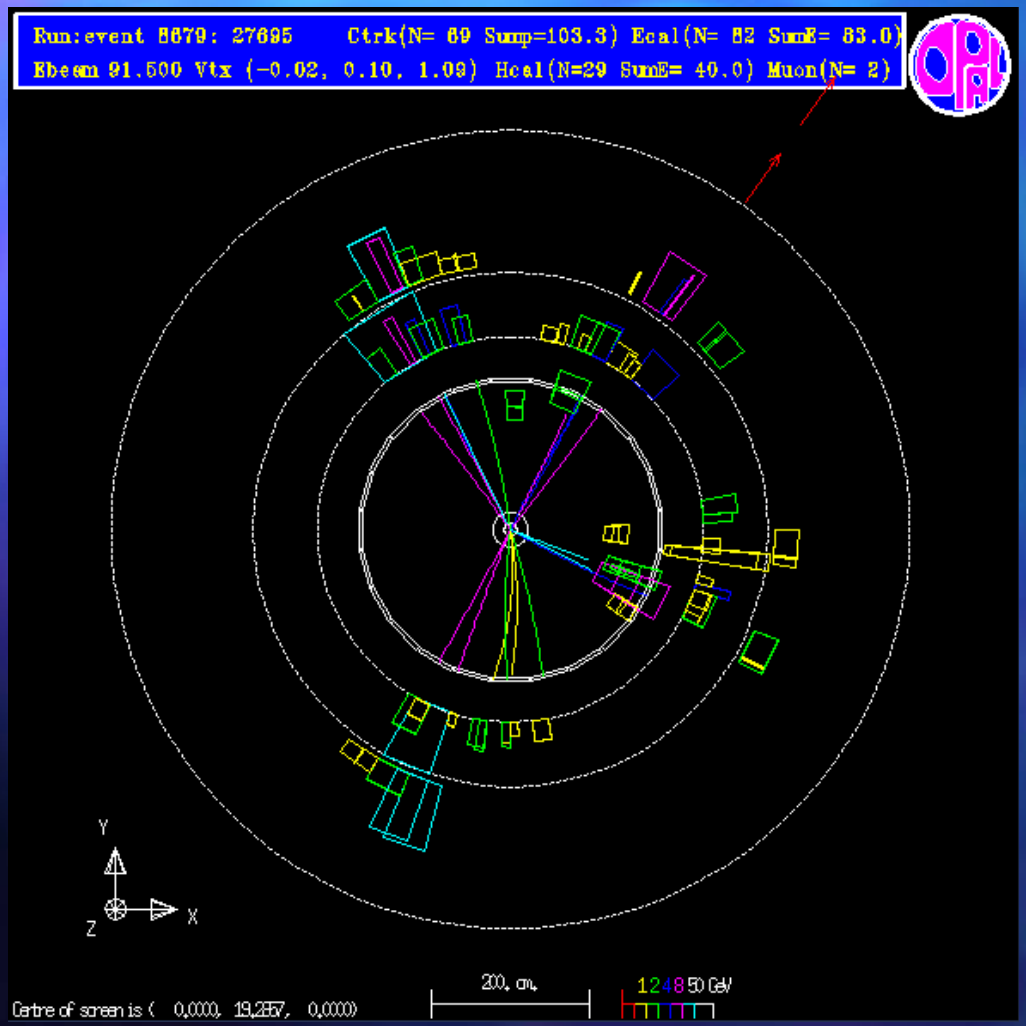

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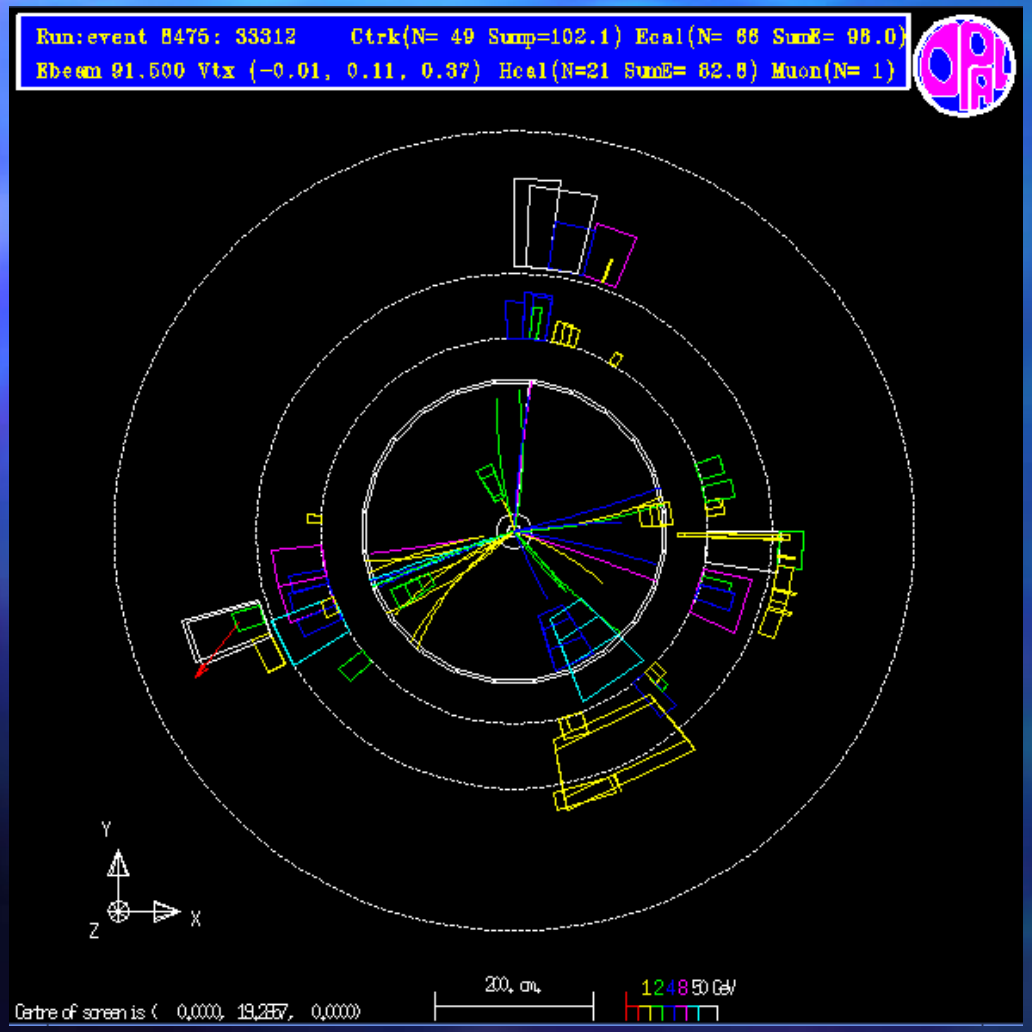

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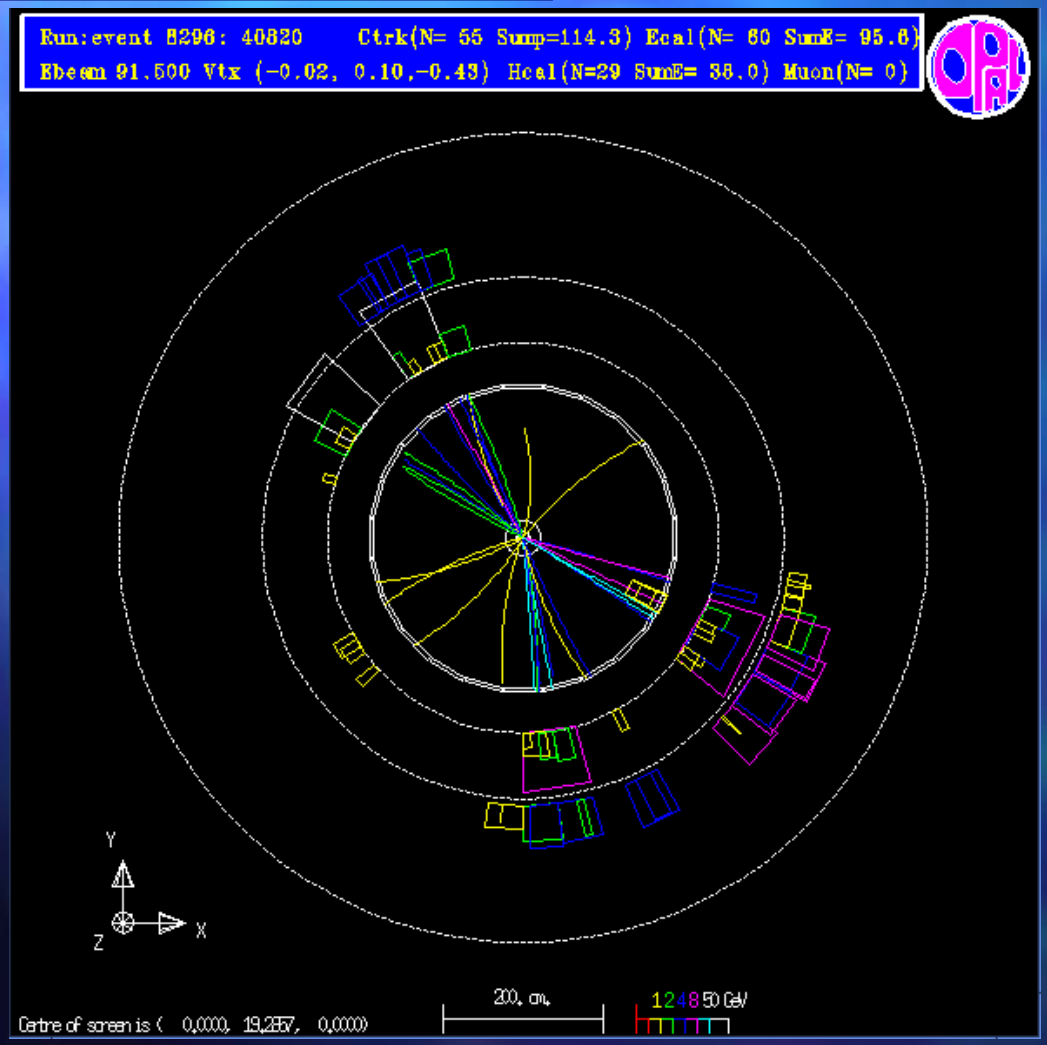

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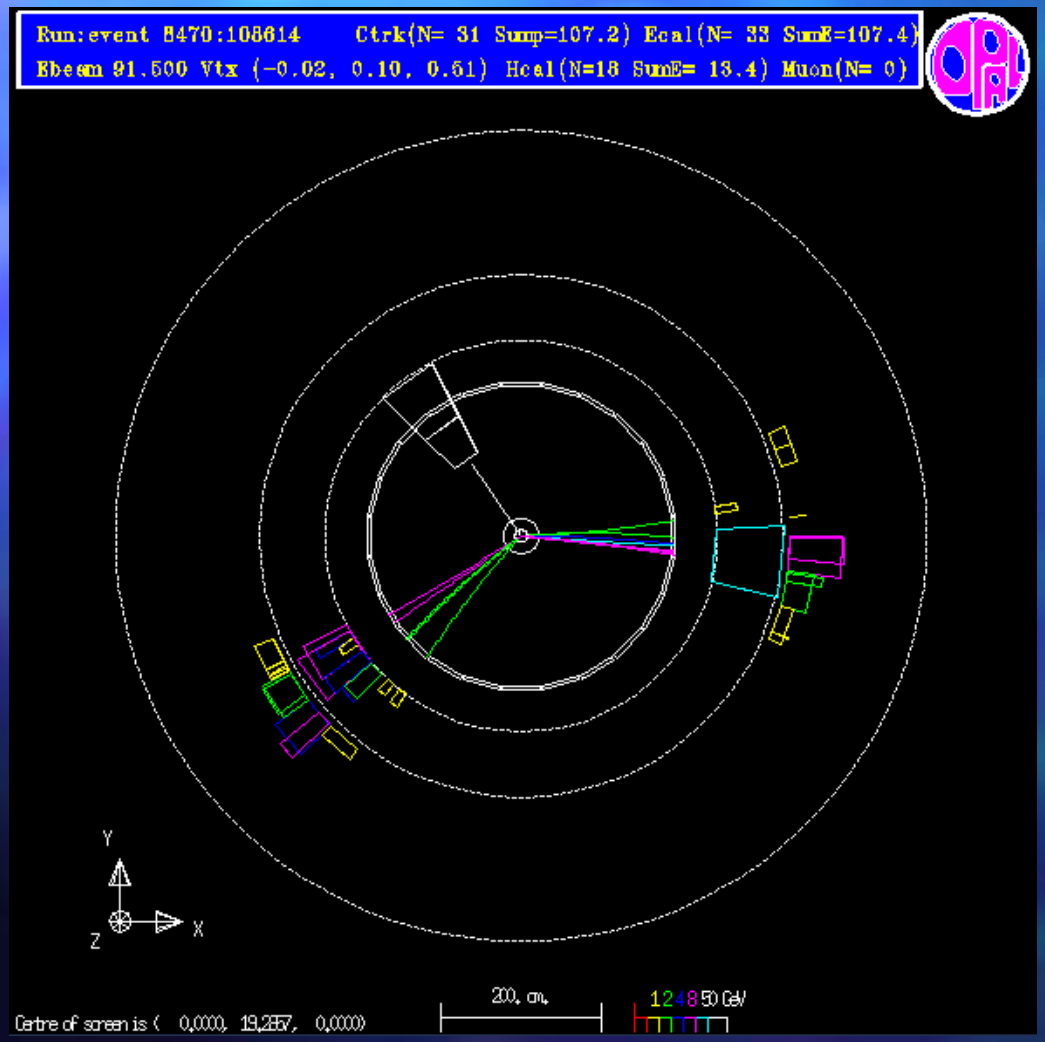

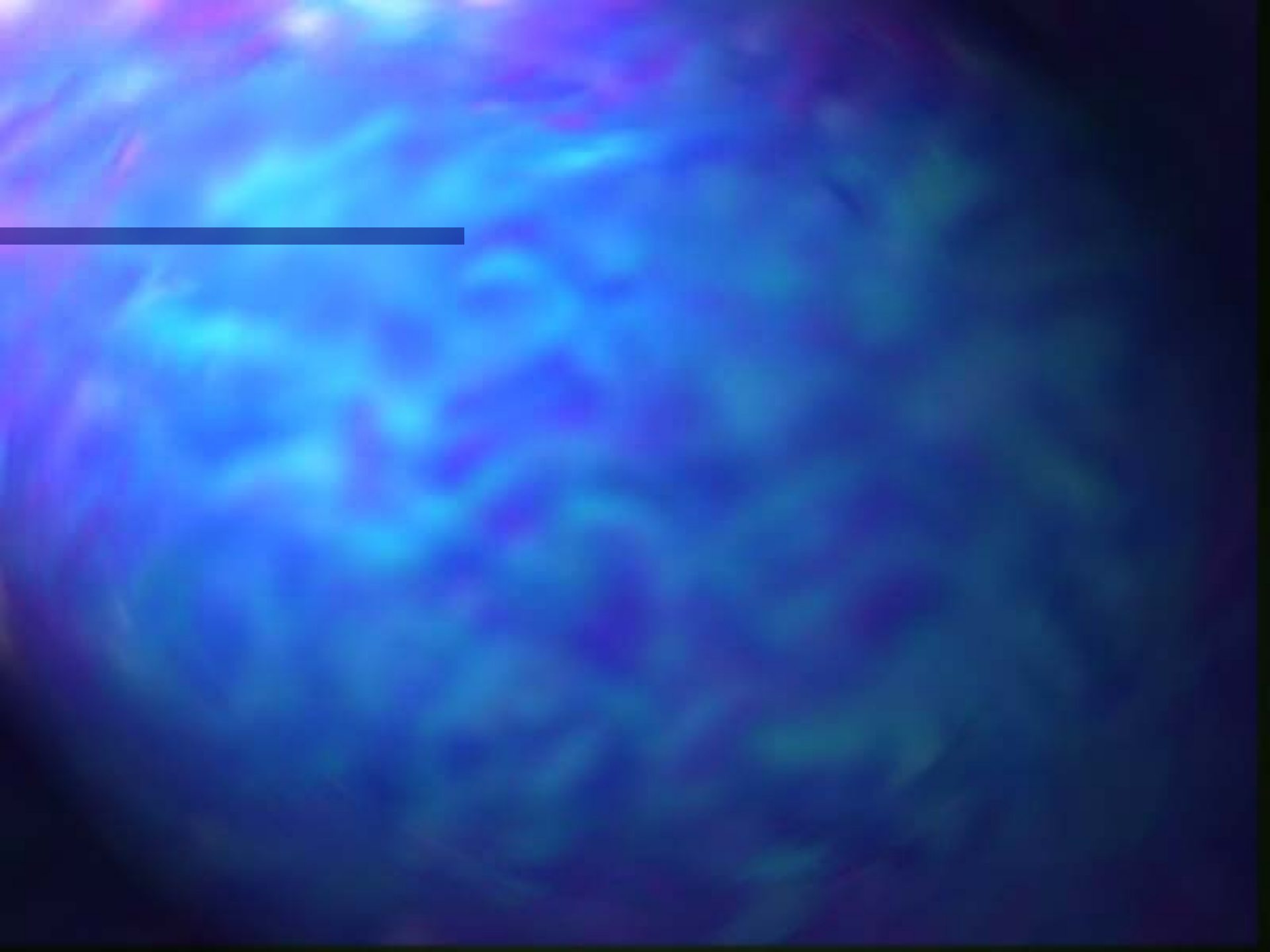

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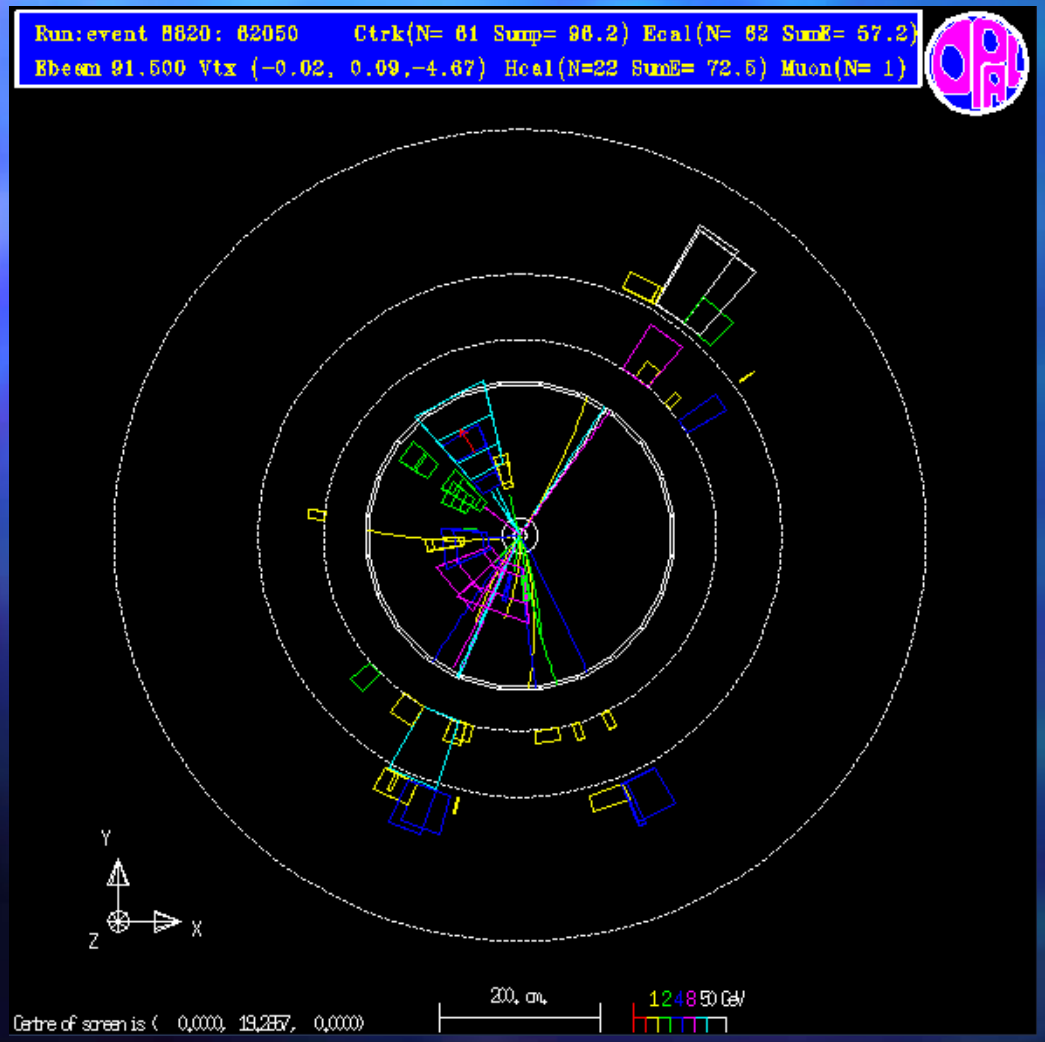

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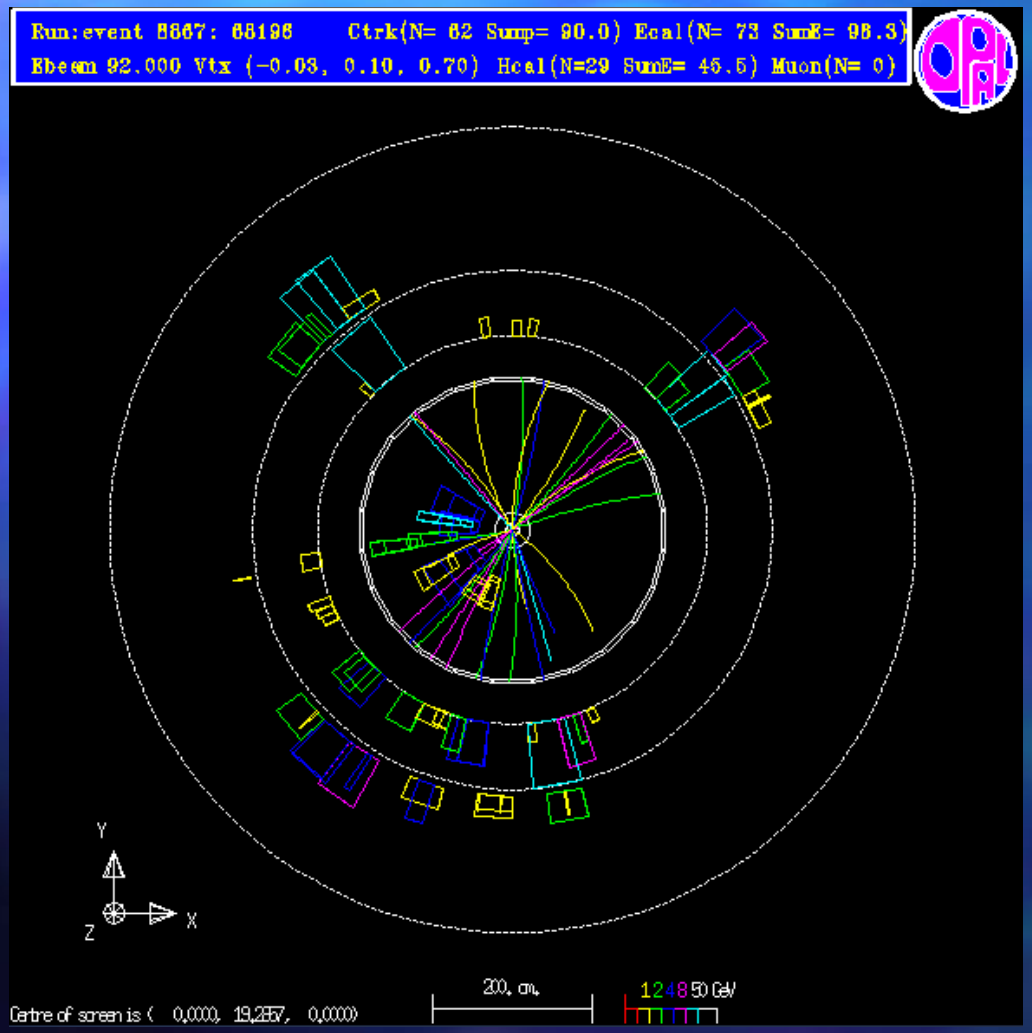

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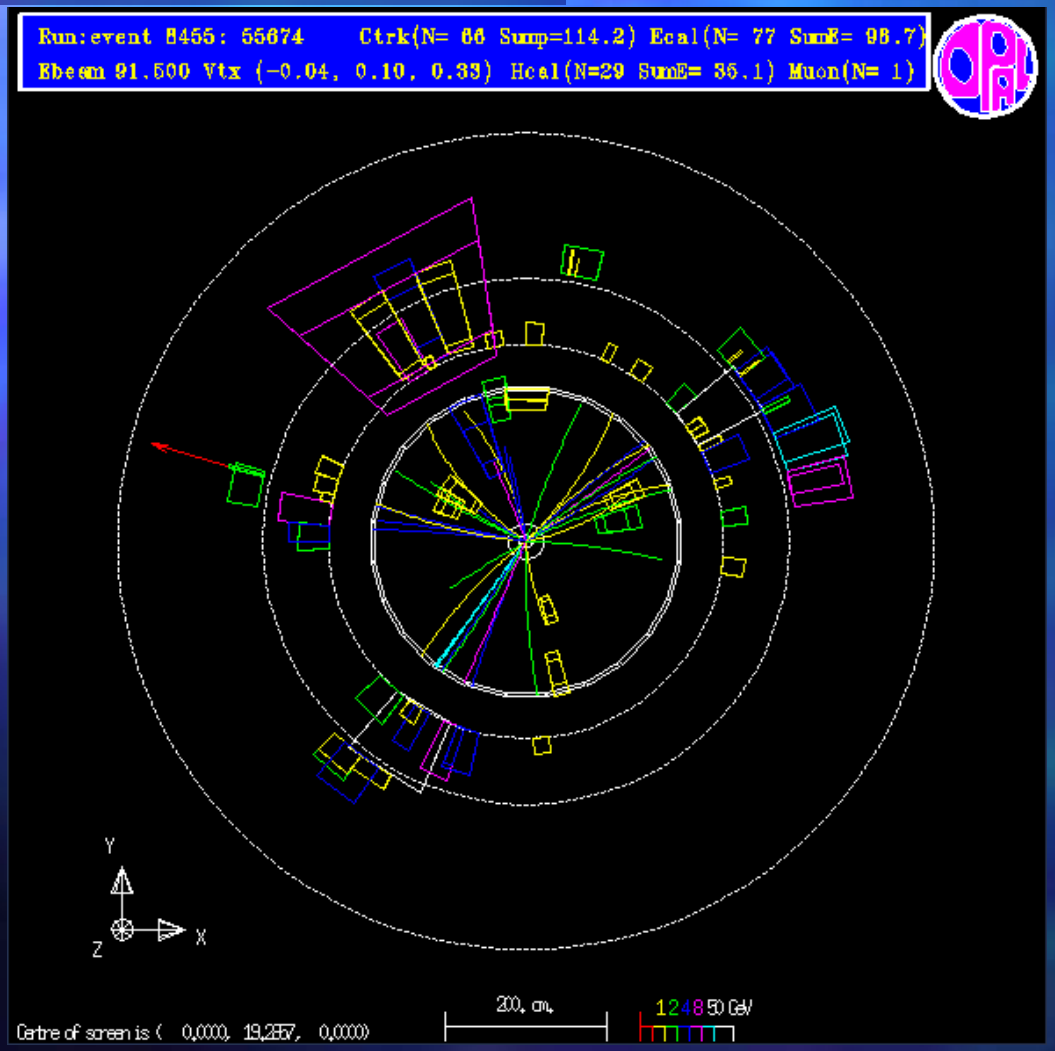

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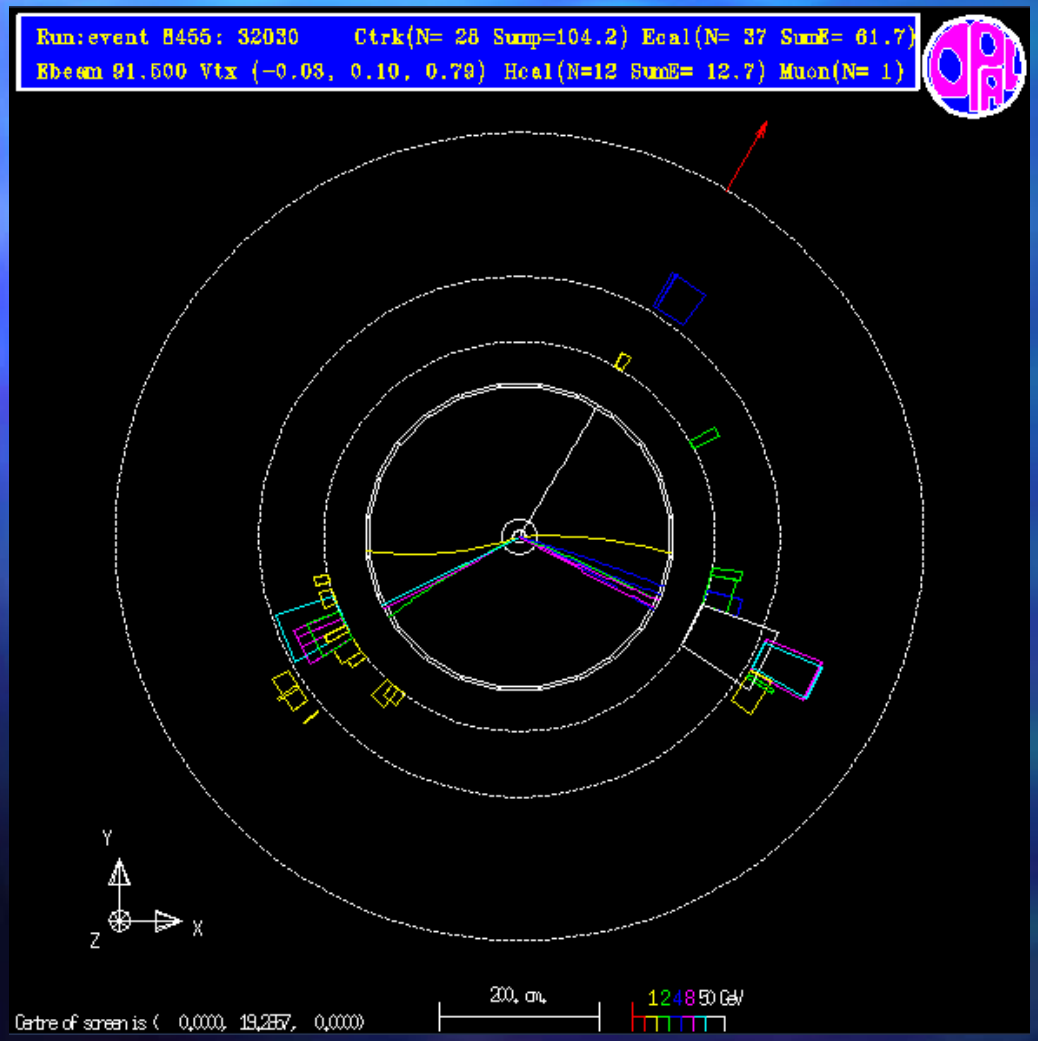

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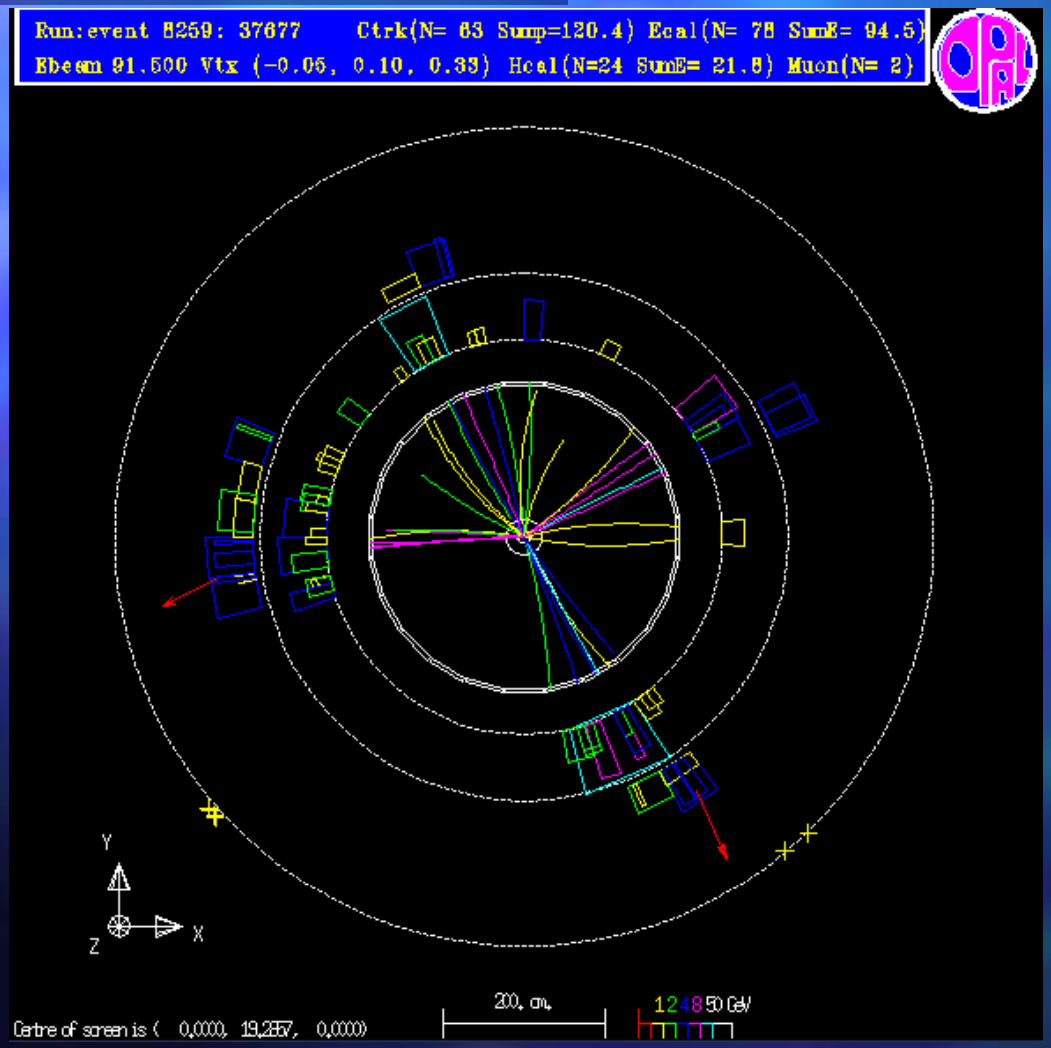

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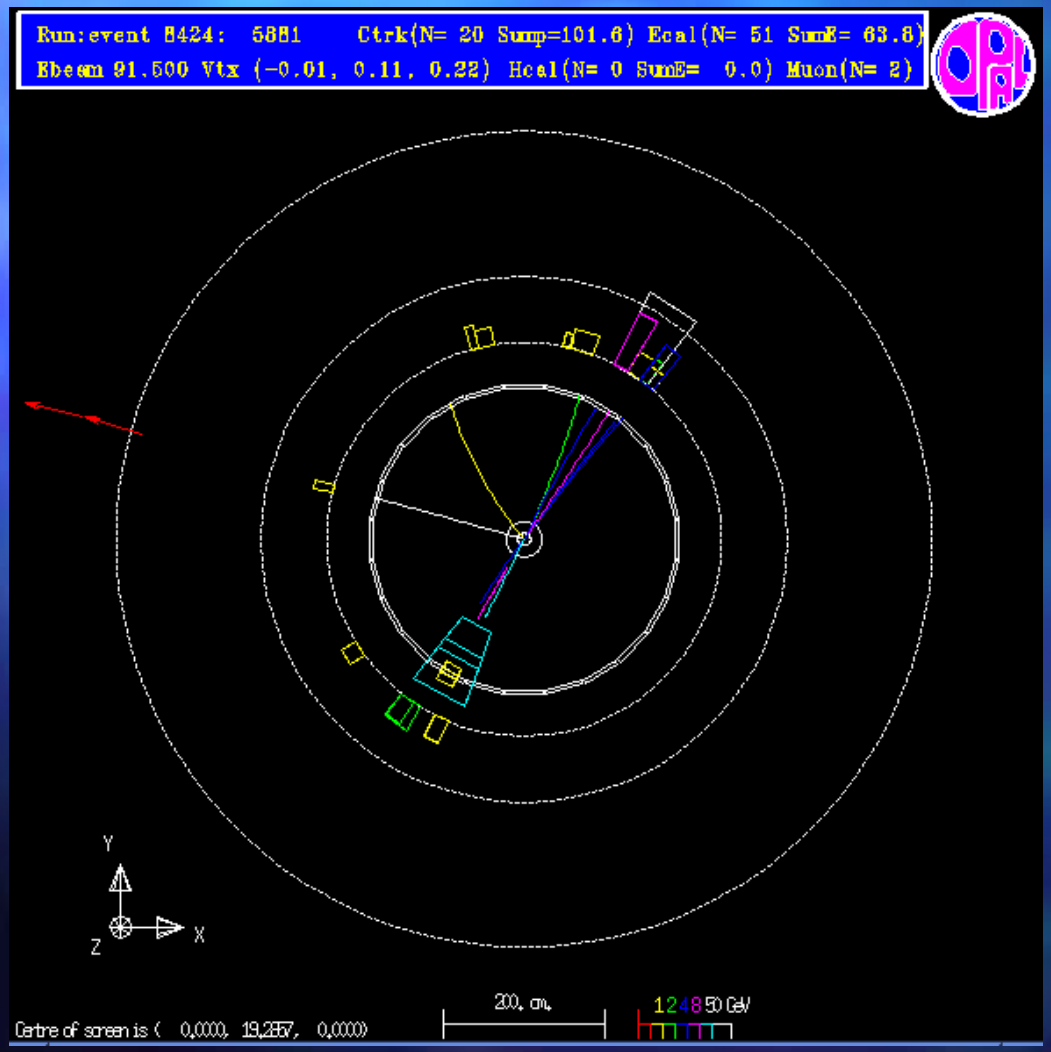

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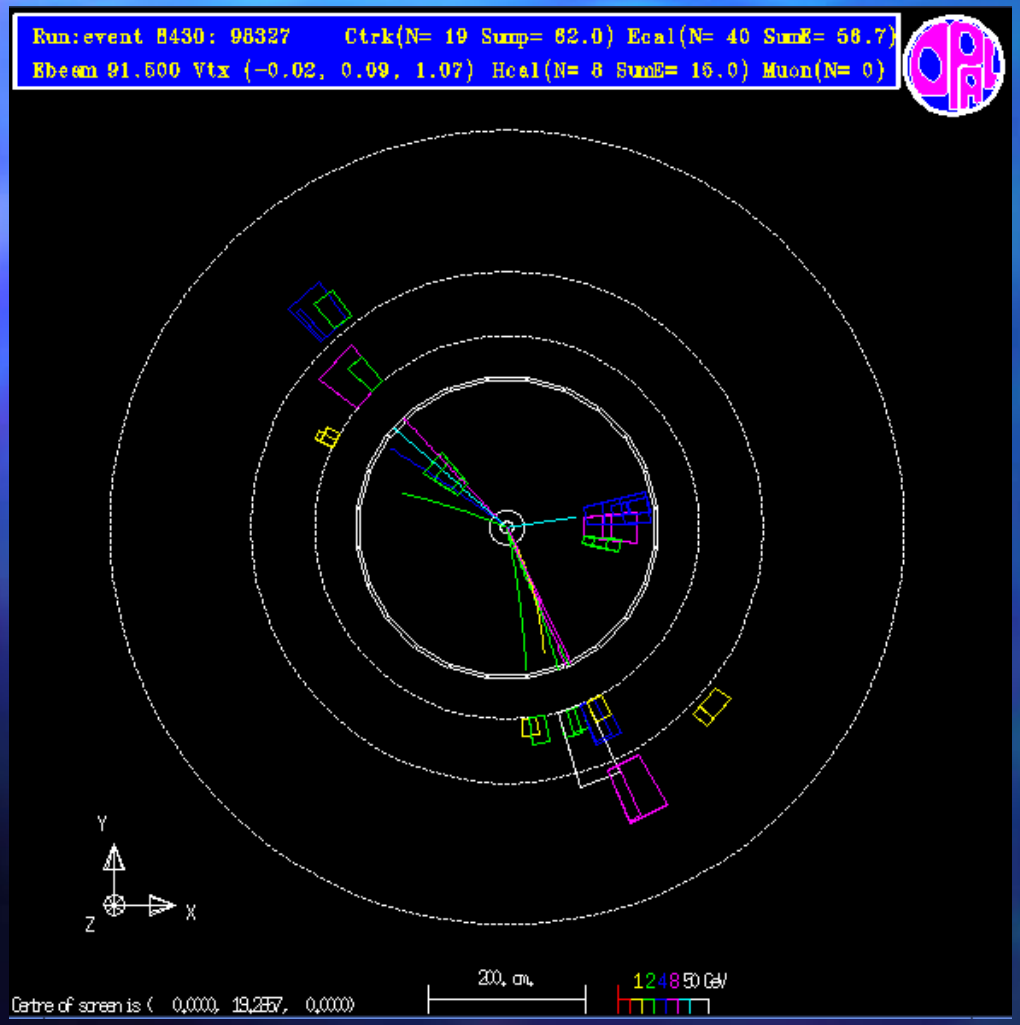

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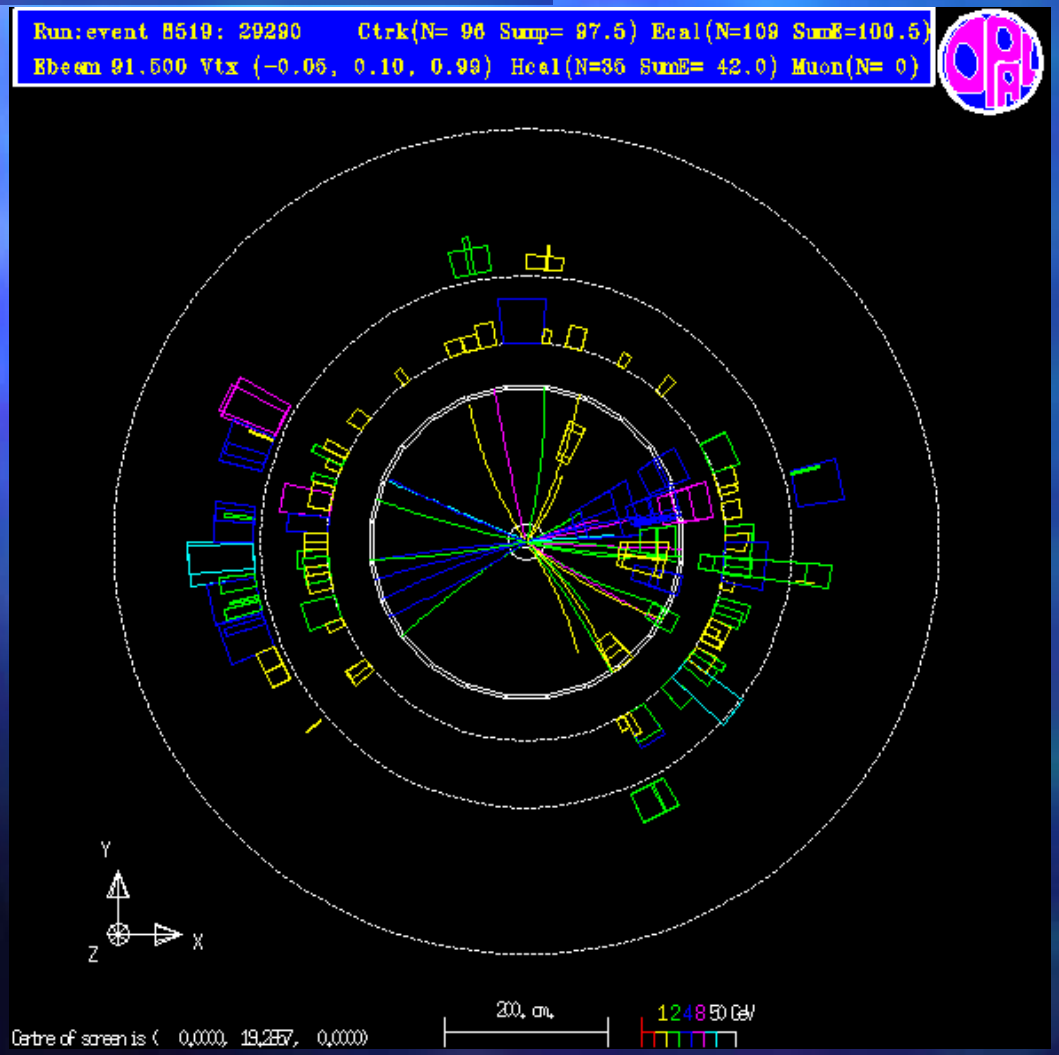

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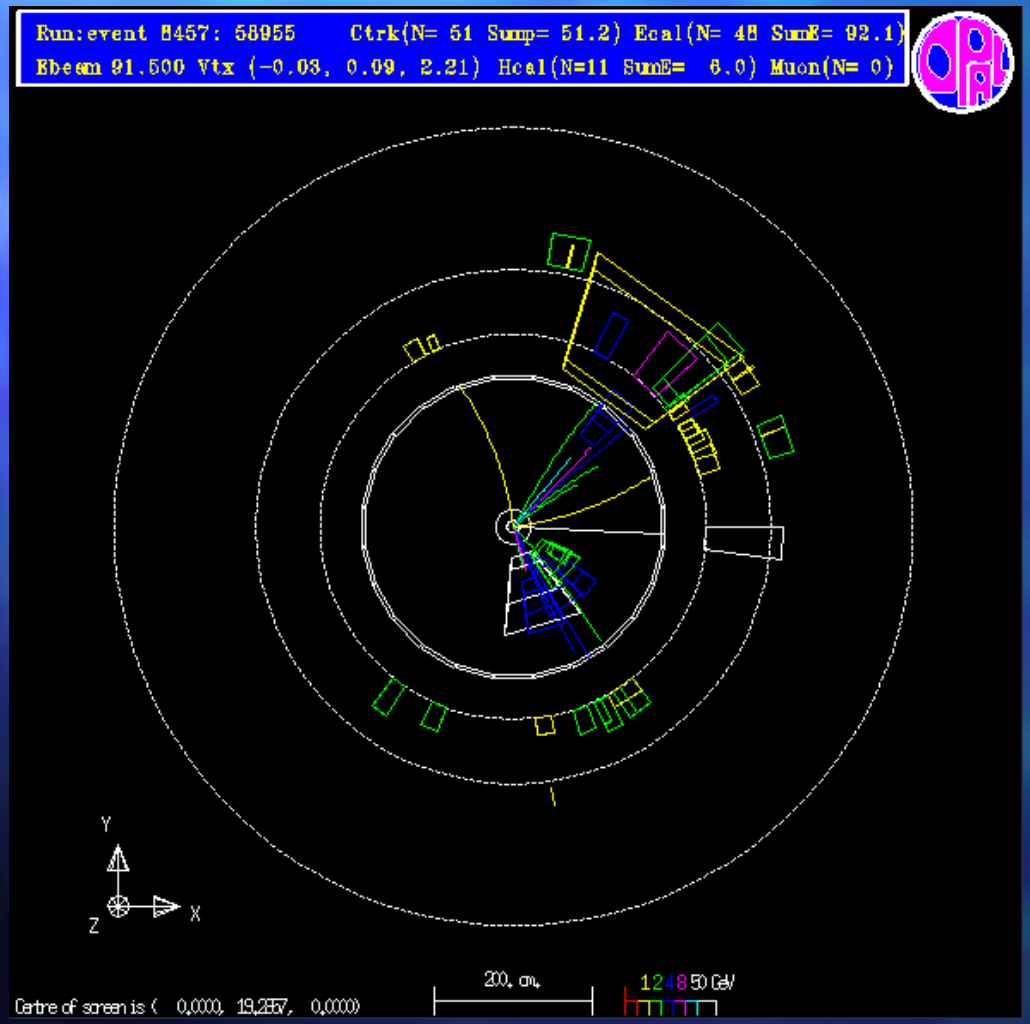

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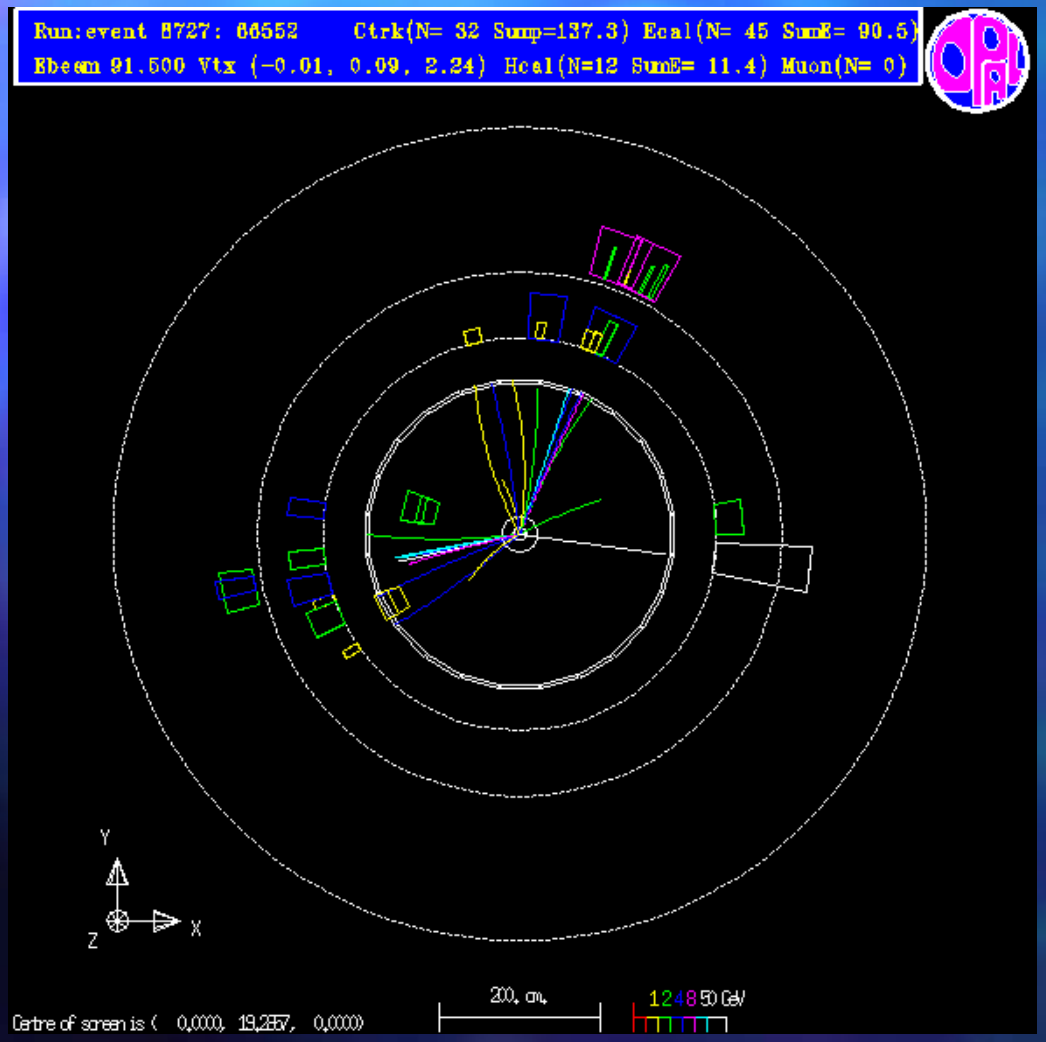

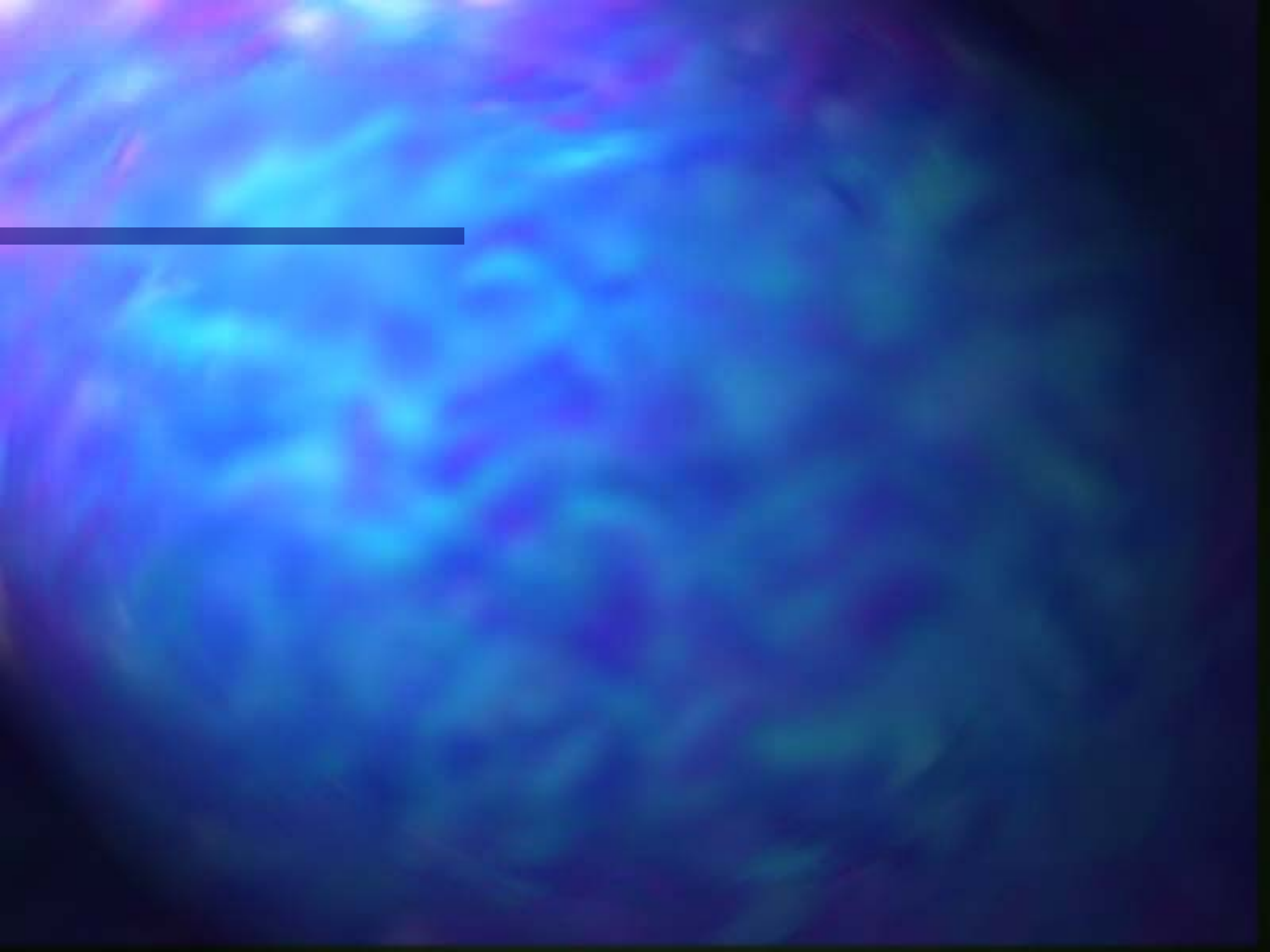

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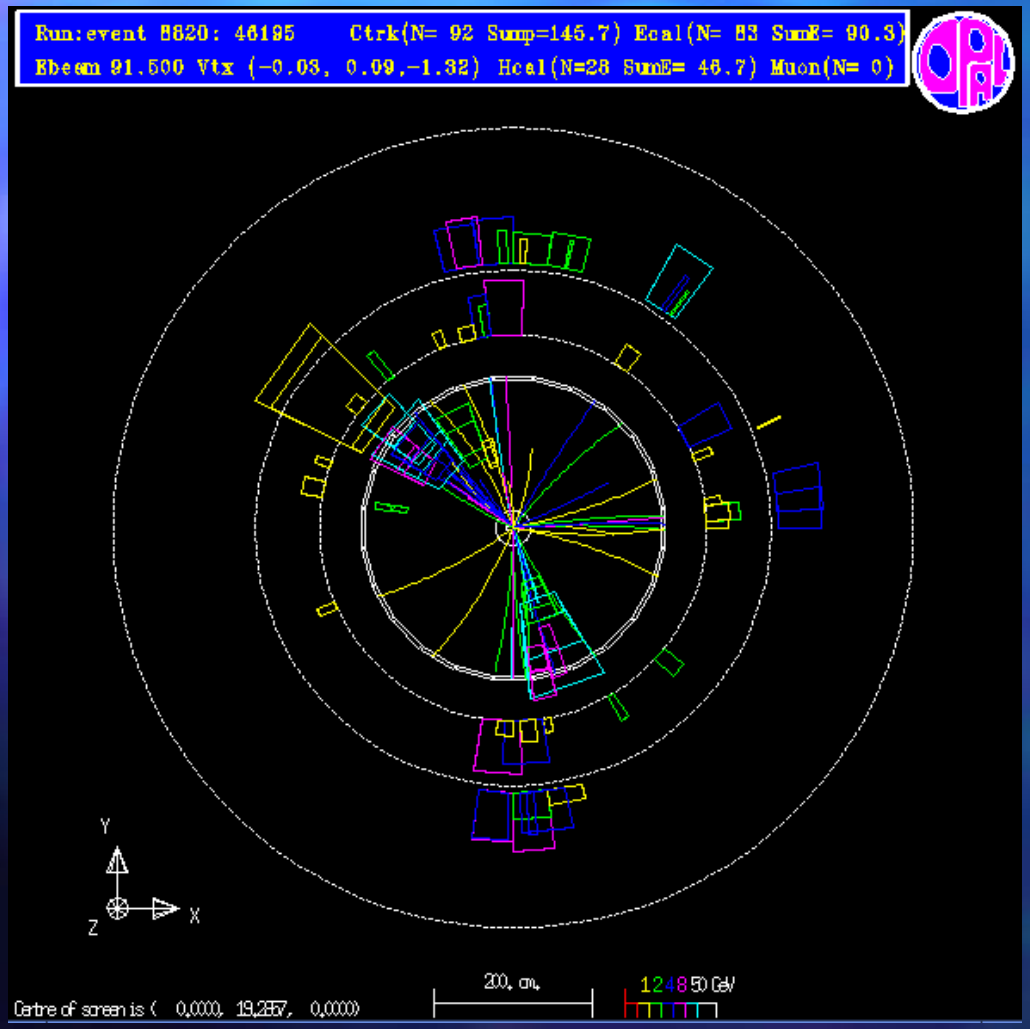

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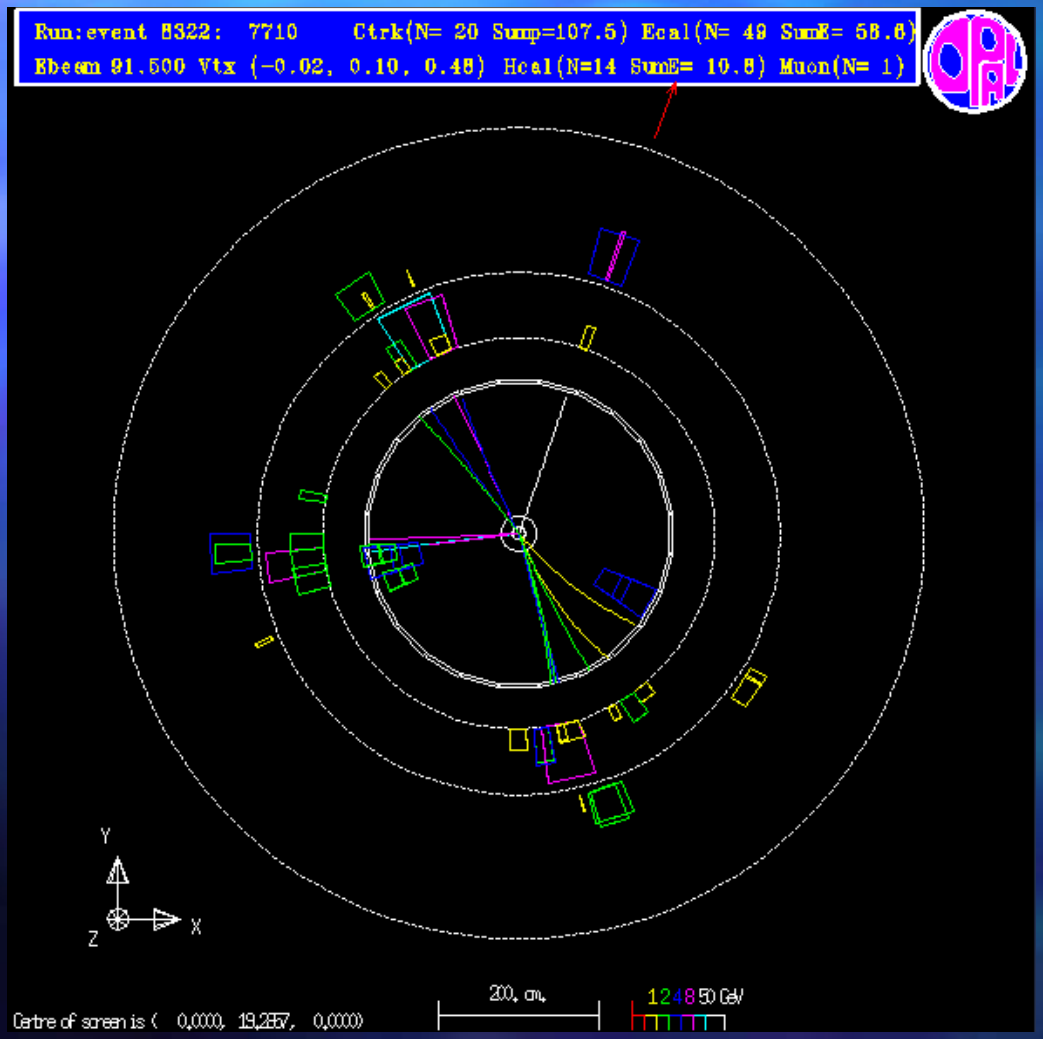

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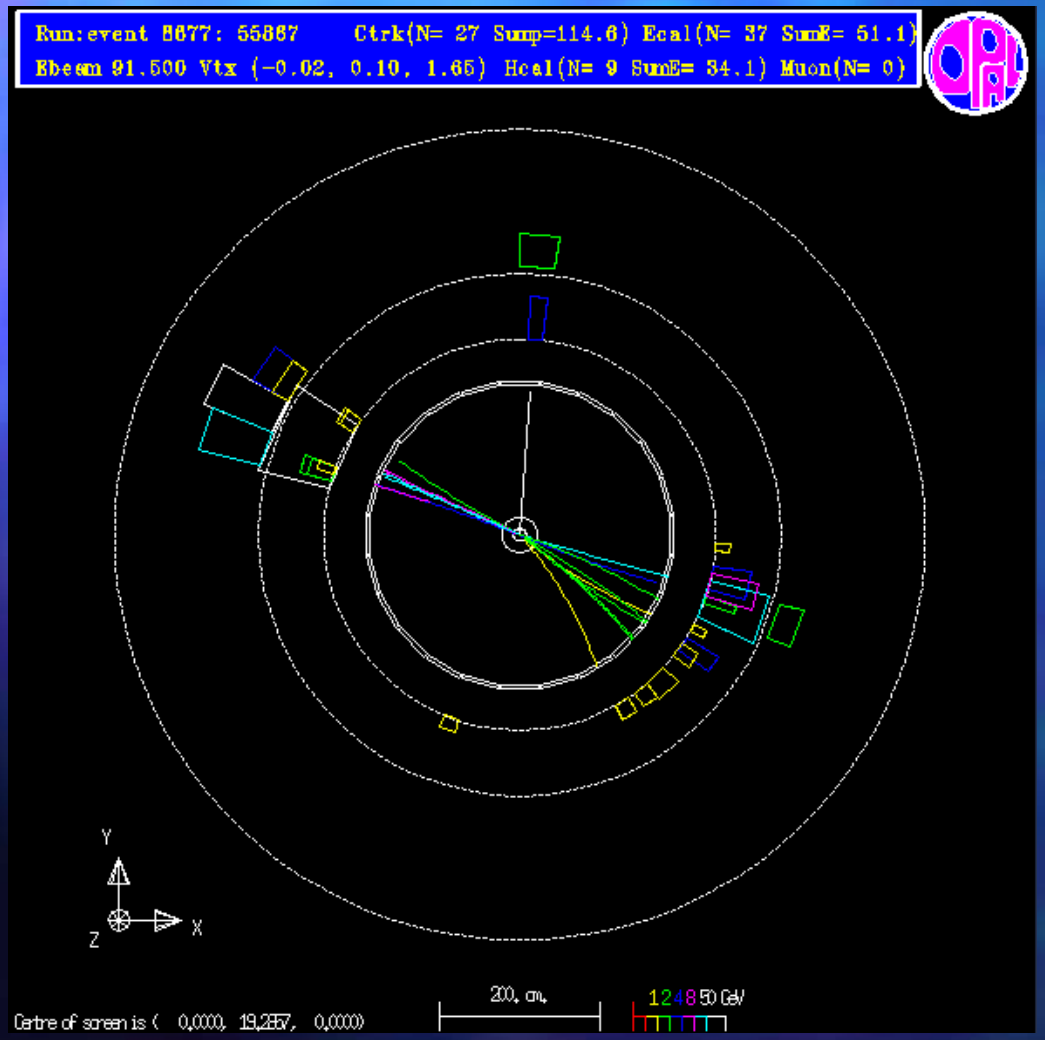

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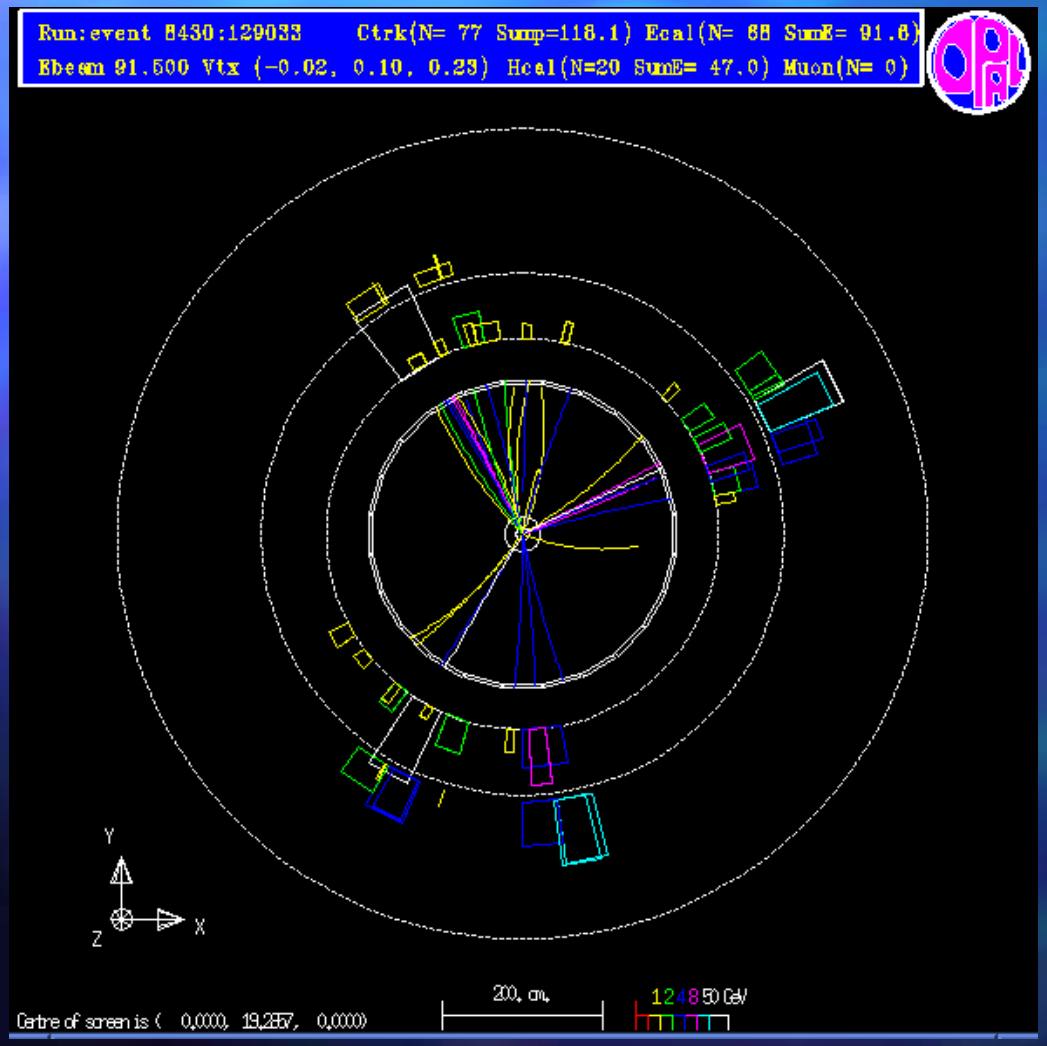

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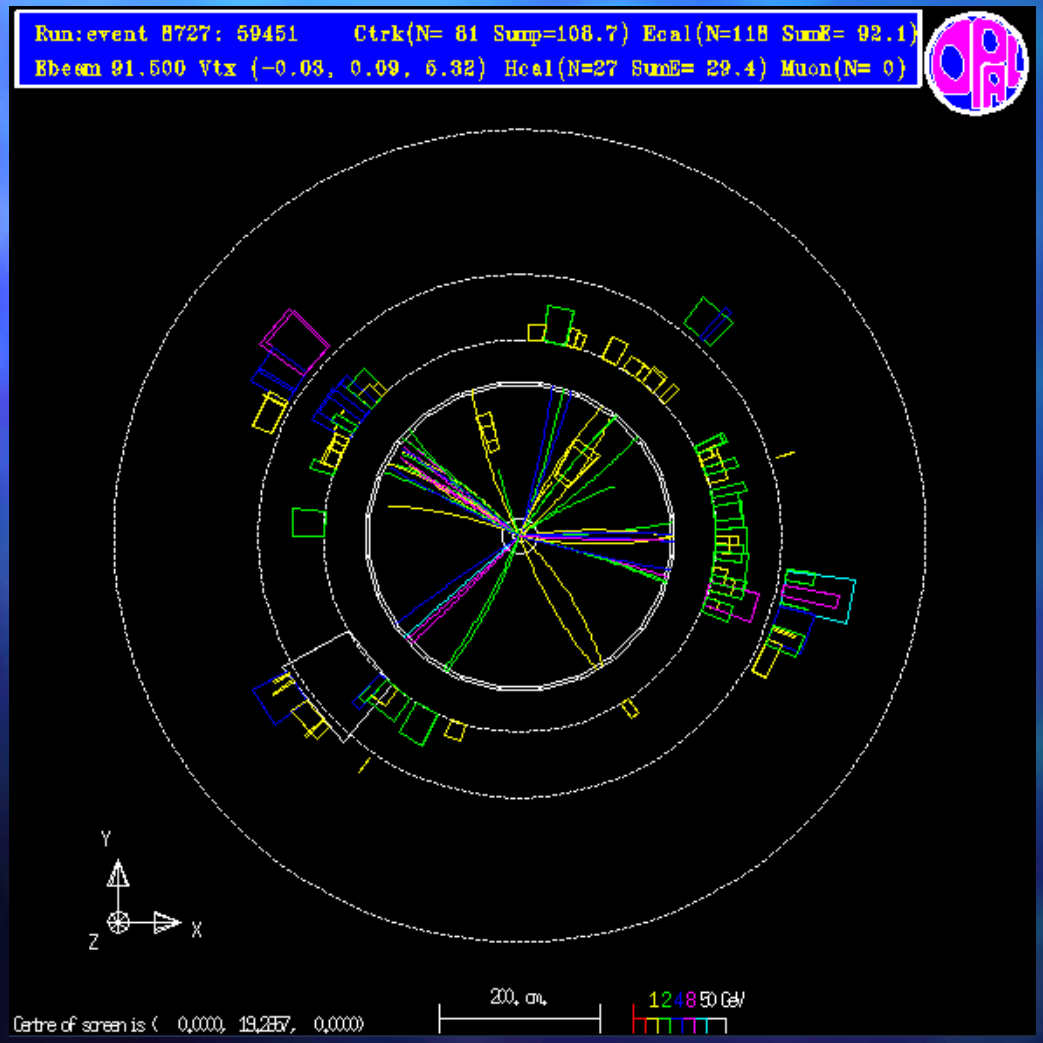

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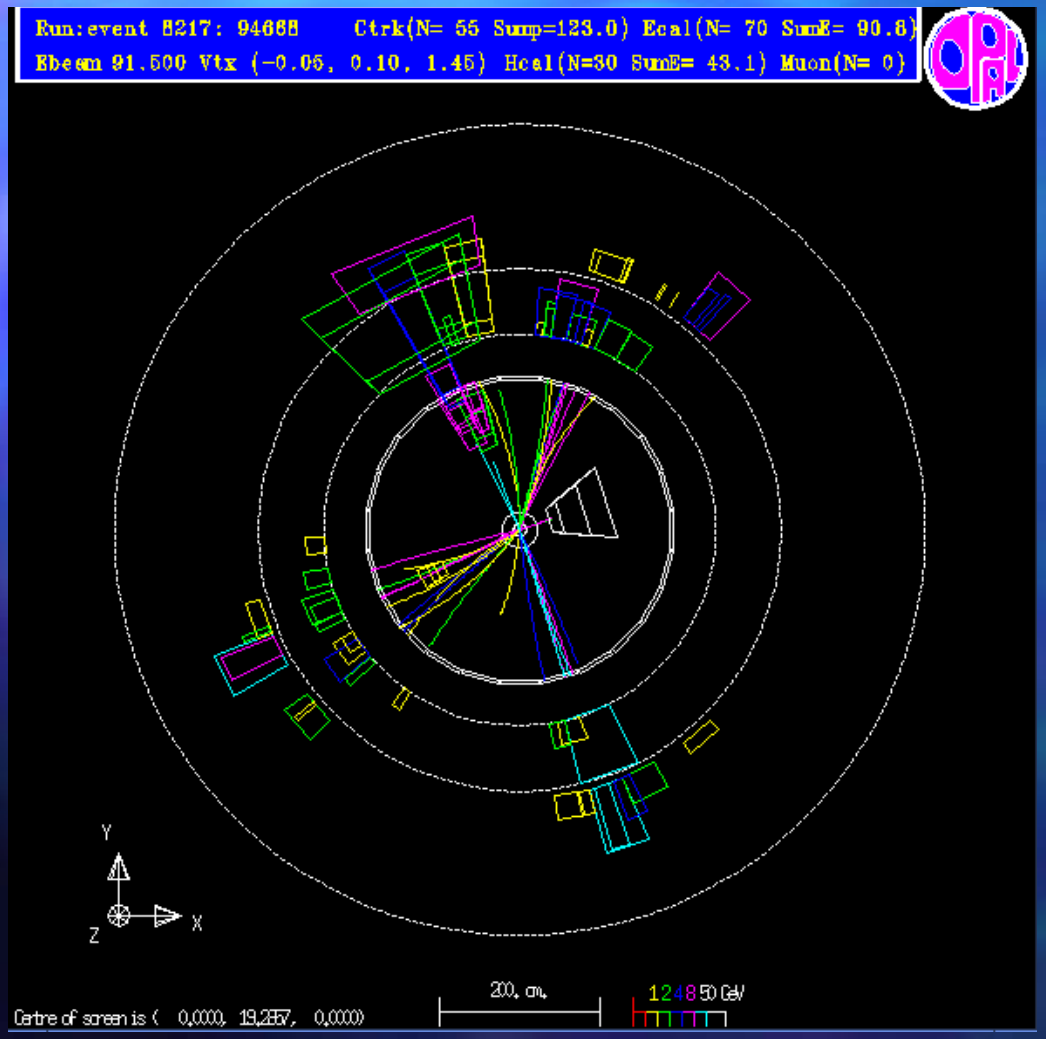

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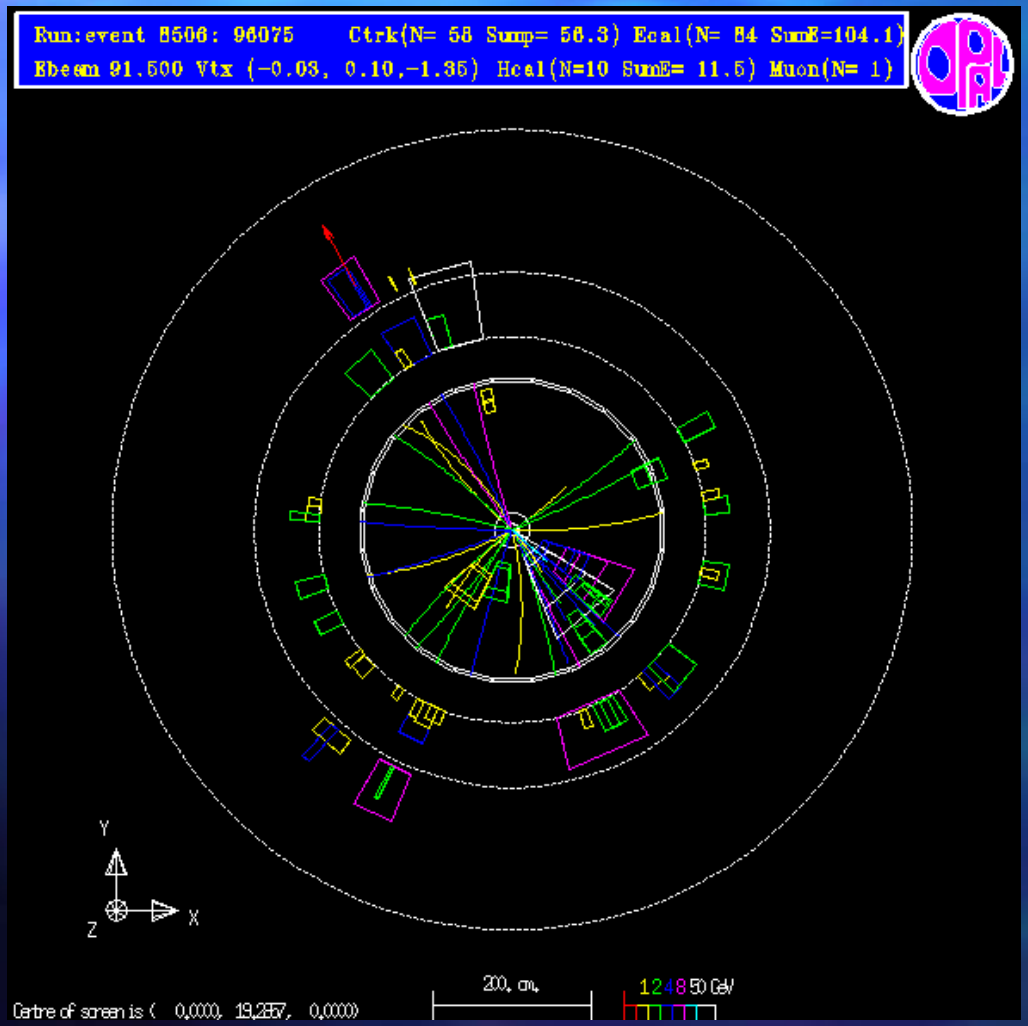

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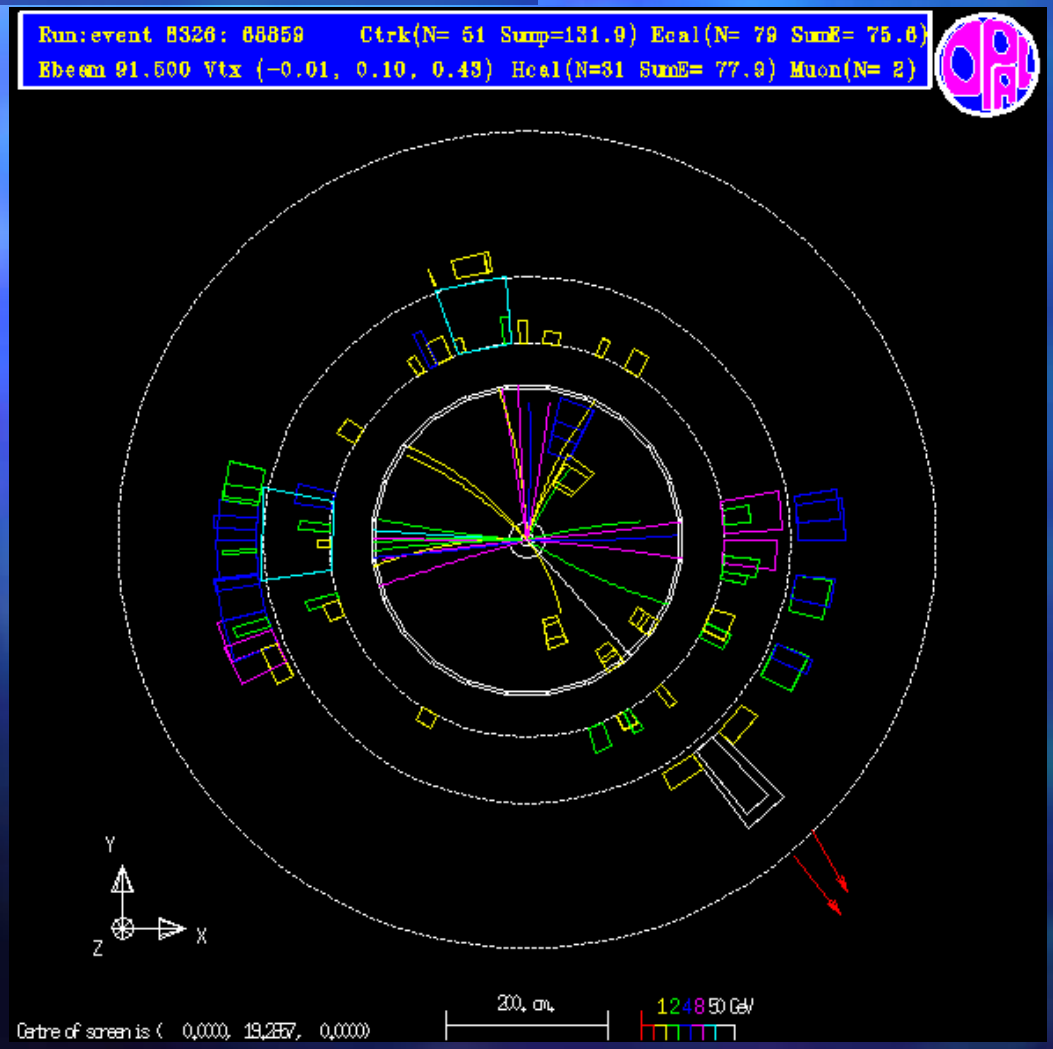

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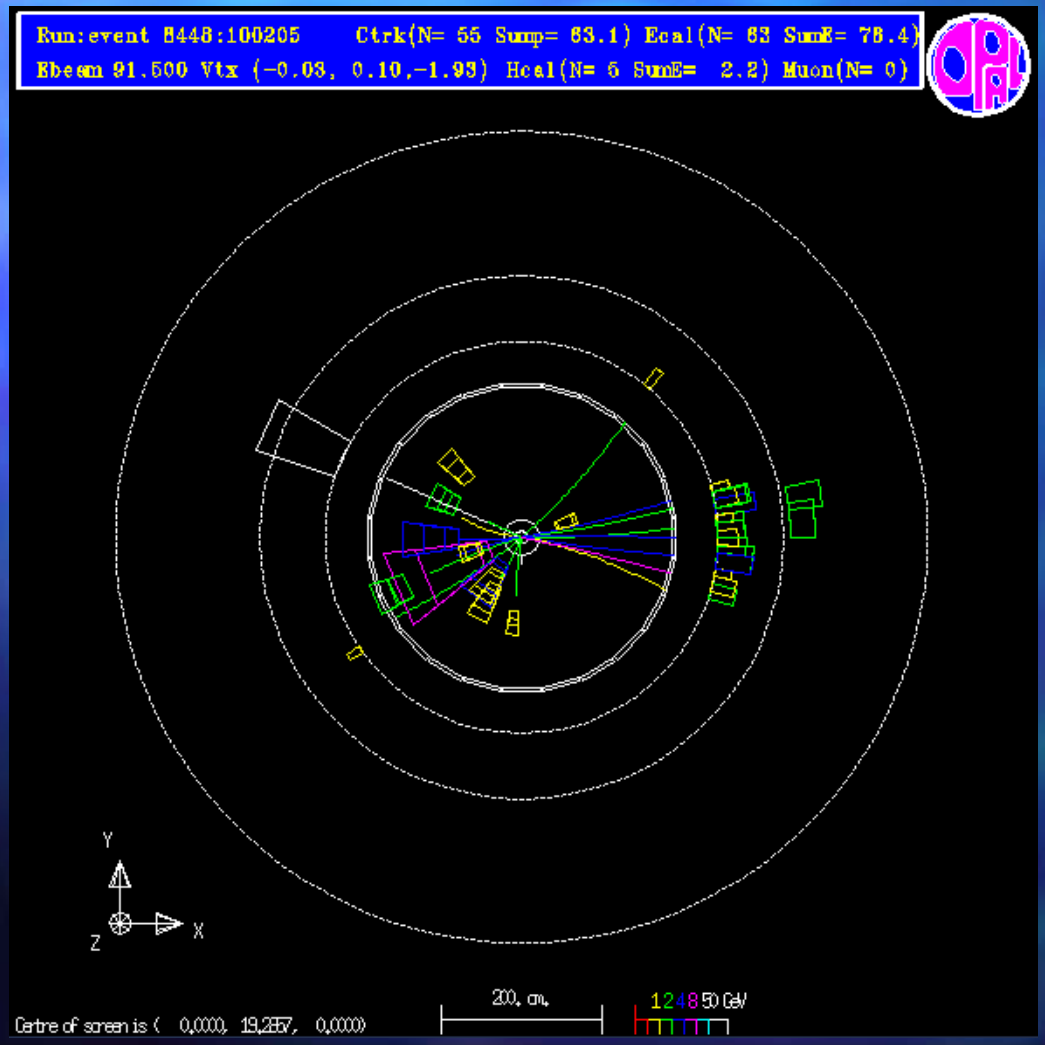

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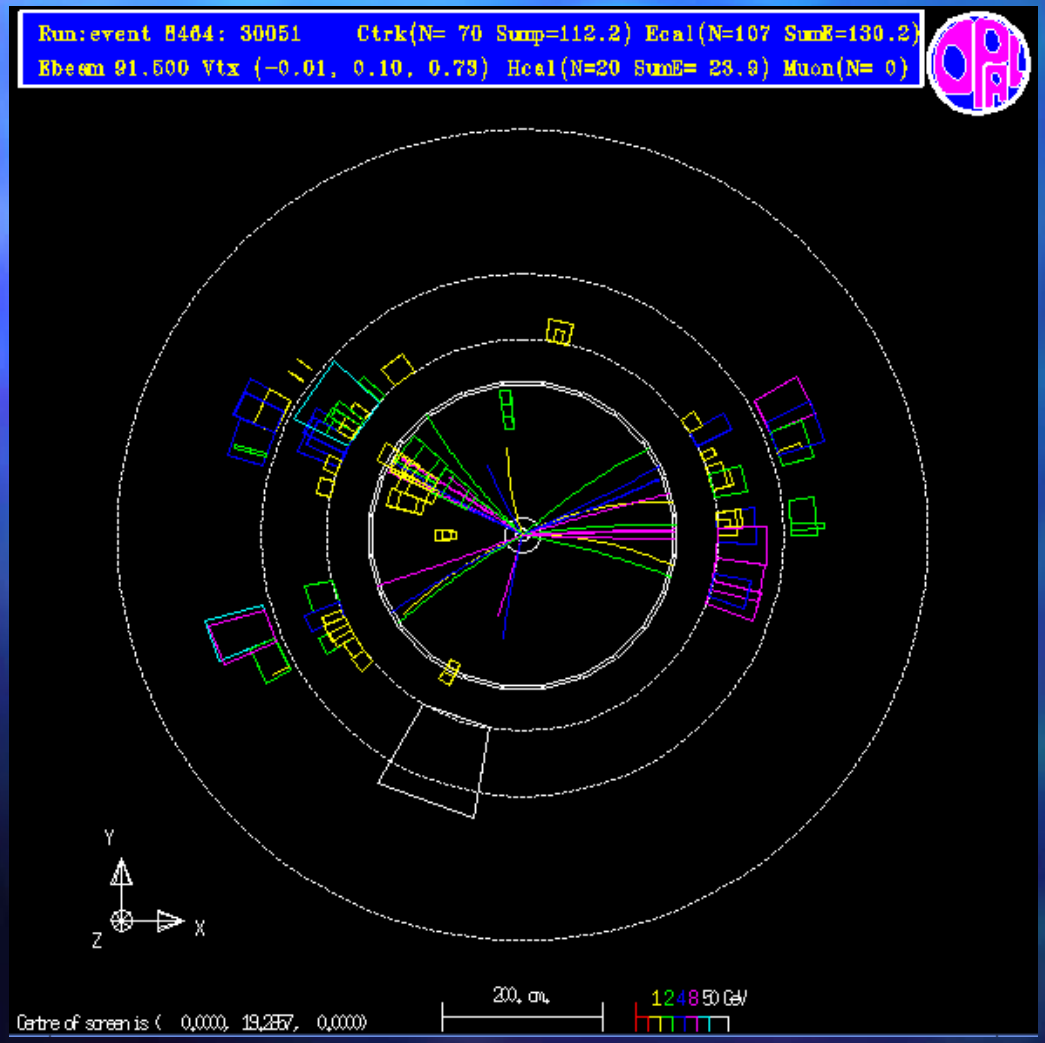


Predictions

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	$3^2=9$

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

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

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 x 3 x N = 6 N We saw ?

Should observe each decay type according to relative probability

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

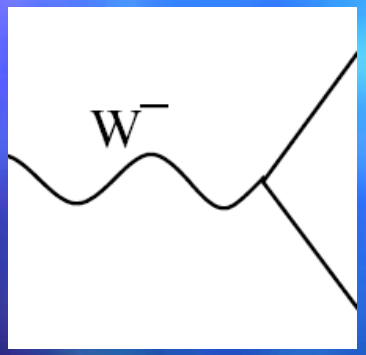
$$N = 3\sqrt{\frac{DH}{DL}}$$

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

We got… N=? N=? N=?

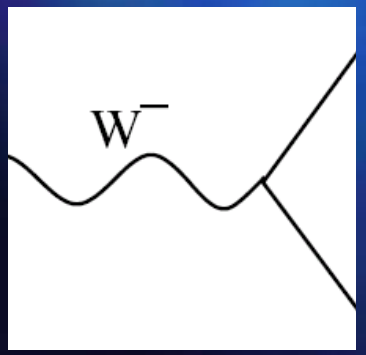
What should we have got?

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

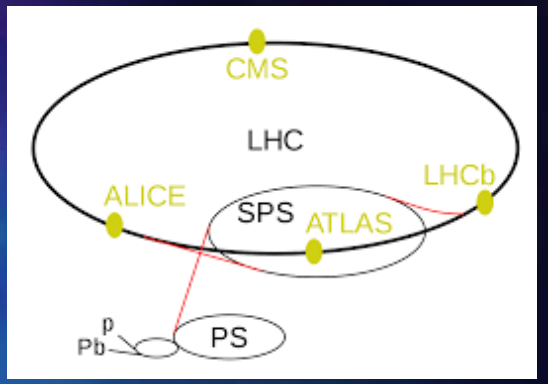
RED

GREEN

BLUE

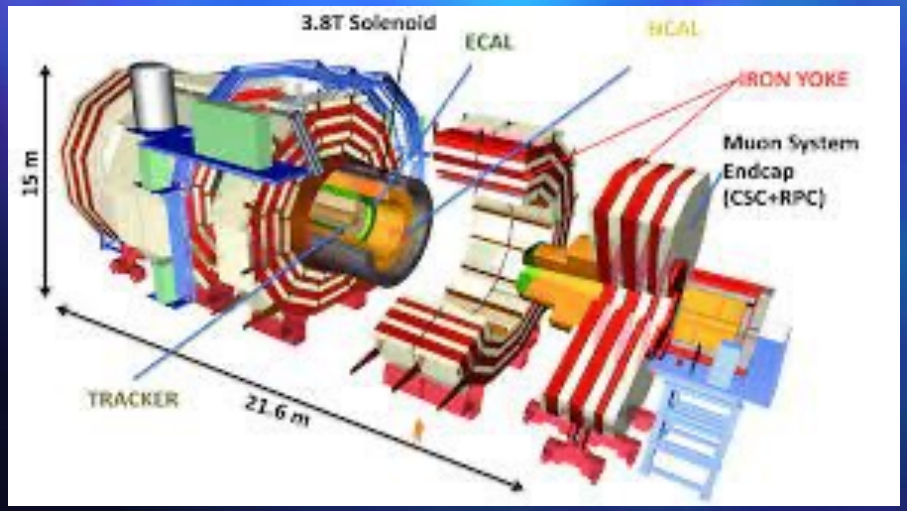
N = 2 x 3 = 6

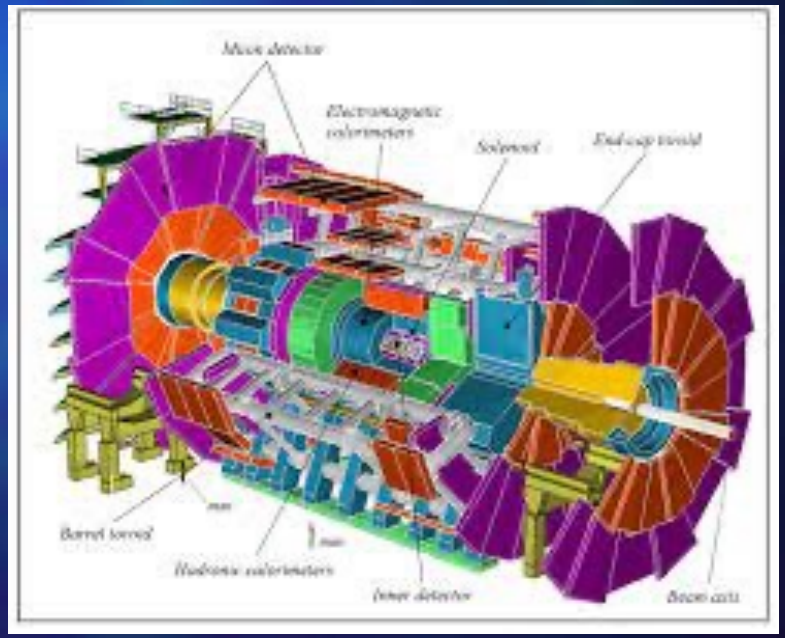
State of the art



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^-





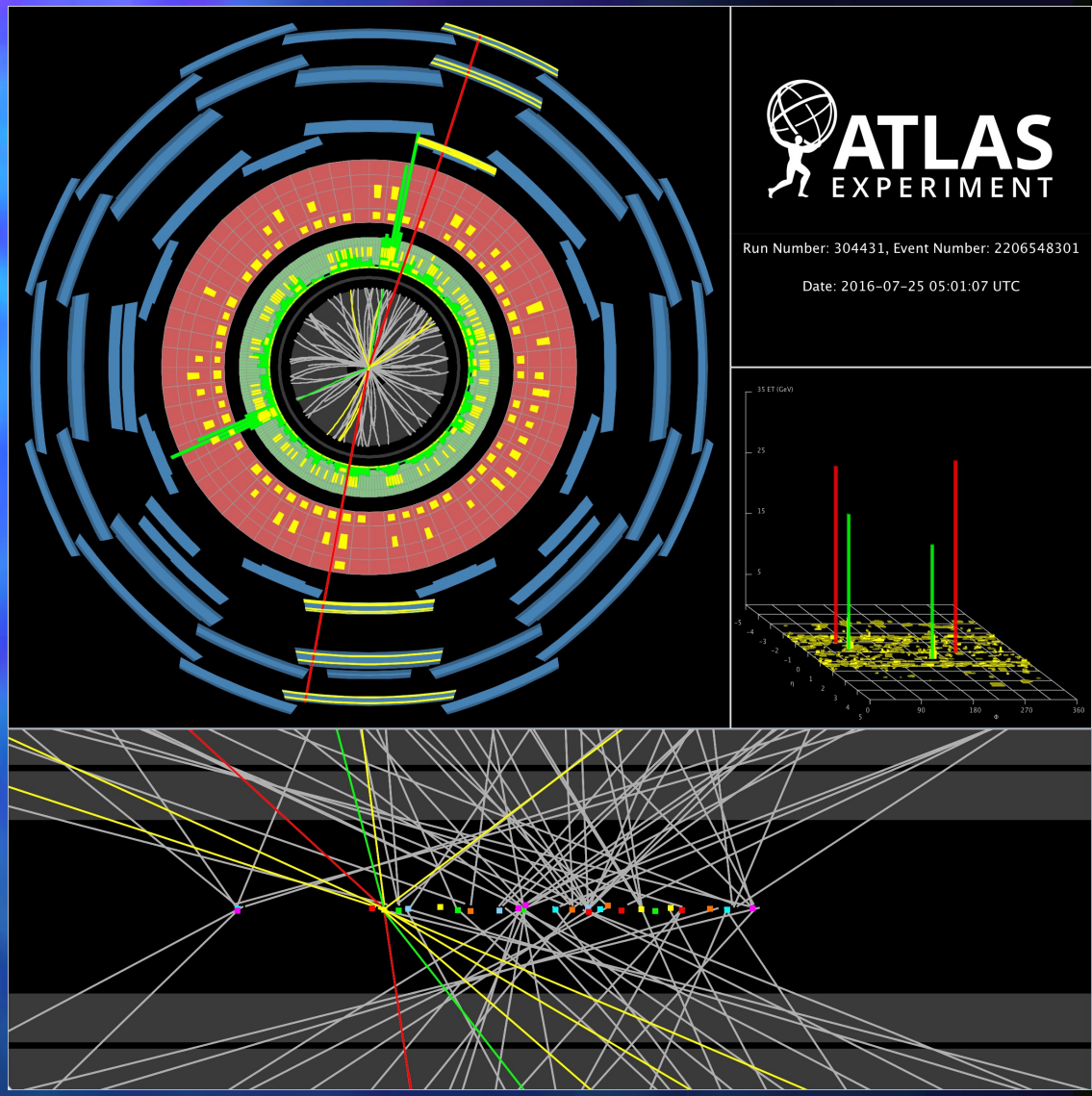
LHC events

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!

Higgs boson event decaying into $e^+e^-\mu^+\mu^-$



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 x 3 x 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