LHC physics

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High energy physics

❑High Energy Physics:

- ➢Physics of high energy interactions at the microscopic scale,

- ➢Tries to understand the sub-atomic interactions and features of particles

- ➢It has nothing to do with nuclear physics which is more worthy to be called a high energy science

❑Model:

The successful model describing elementary particle interactions is Standard Model

This model describes particle characteristics and their interactions

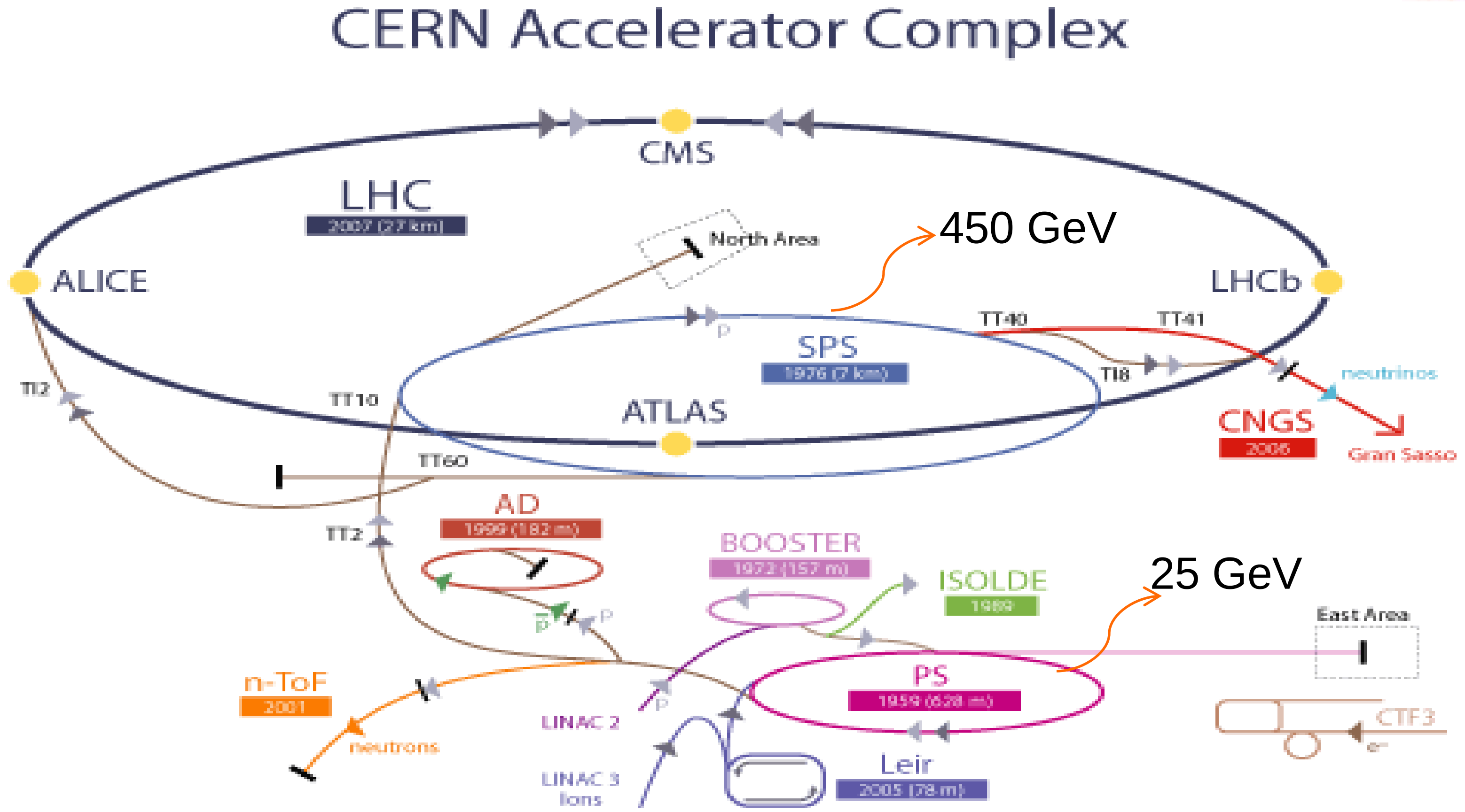
❑Experiments:

- ➢Many experiments at CERN and Fermilab, DESY, …

- ➢In these places many sub-atomic particles were discovered so far

- ➢More exciting news to come out of the LHC experiment …

CERN and LHC complex



❑Protons acceleration involves the following chain :

➢LINAC2 => PS booster => PS (proton synchrotron) => SPS => LHC

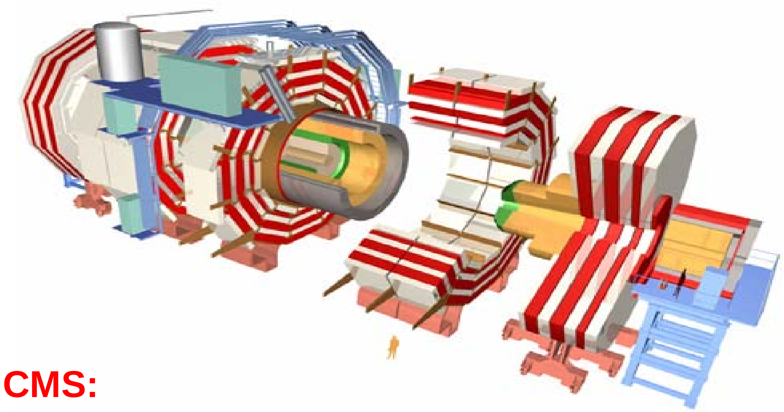
❑Heavy ions acceleration chain :

➢LINAC3 => LEIR => LHC

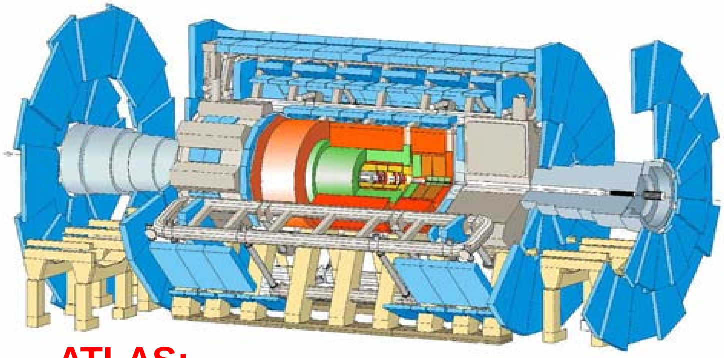
LHC (Large Hadron collider) is not only a collider but also an accelerator

LHC detectors

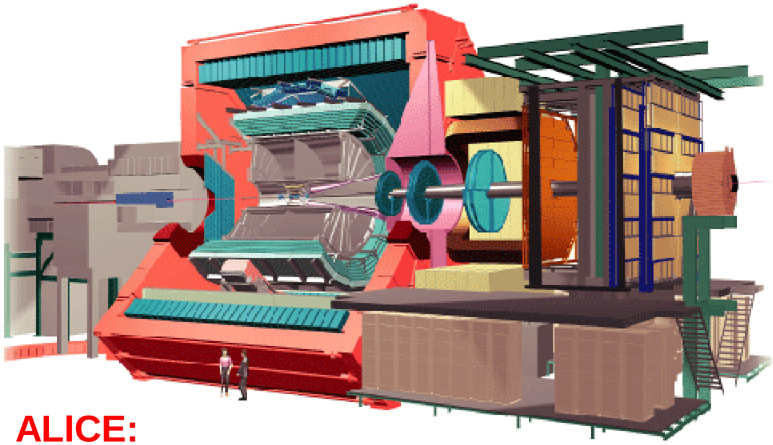
LHC has 4 main detectors:



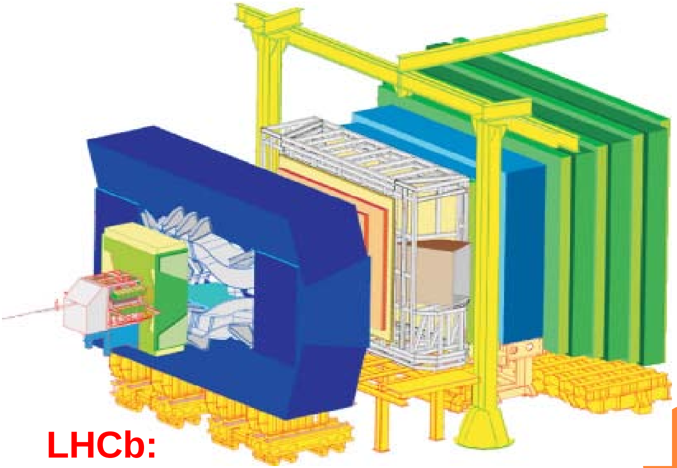
CMS:
Size: 21 m long, 15 m wide and 15 m high.
Weight: 12 500 tonnes
Location: Cessy, France.



ATLAS:
Size: 46 m long, 25 m high and 25 m wide.
Weight: 7000 tonnes
Location: Meyrin, Switzerland.



ALICE:
Size: 26 m long, 16 m high, 16 m wide
Weight: 10 000 tonnes
Location: St Genis-Pouilly, France



LHCb:
Size: 21m long, 10m high and 13m wide
Weight: 5600 tonnes
Location: Ferney-Voltaire, France.

LHC features

❑**The largest machine in the world...**

The LHC circumference is 27 km, with a total of 9300 magnets inside.
All the magnets are filled with nearly 120 tonnes of liquid helium to bring them down to 1.9 K.

❑**The fastest racetrack on the planet...**

Protons will race around the LHC accelerator ring 11 000 times a second, travelling at 99.9999991% the speed of light. About 600 million collisions take place every second.

❑**The emptiest space in the Solar System...**

To avoid colliding with gas molecules inside the accelerator, the beams of particles travel in an ultra-high vacuum . The internal pressure of the LHC is 10^{-13} atm, ten times less than the pressure on the Moon!

❑**The hottest spots in the galaxy, but even colder than outer space...**

When two beams of protons collide, they will generate temperatures more than 100 000 times hotter than the heart of the Sun, concentrated within a minuscule space. By contrast, the 'cryogenic distribution system’ keeps the LHC at a super cool temperature of -271.3°C (1.9 K) – even colder than outer space!

Questions to be answered by LHC

❑**What is mass?**

➢What is the origin of mass and the mass spectrum?

➢The Higgs boson will most likely provide an answer to the above question.

➢First hypothesised in 1964, it has yet to be observed.

➢The ATLAS and CMS experiments are currently searching for this particle.

❑**An invisible problem...**
What is 96% of the universe made of?

➢Everything we see in the Universe is made up of ordinary particles forming 4% of the Universe.

➢The rest are dark matter and dark energy.

➢They are difficult to detect and study, other than through the gravitational forces they exert.

➢In the theory of supersymmetry a dark matter candidate is proposed which is the lightest supersymmetric particle called LSP.

➢This particle is stable since it does not decay to an SM particle.

➢The ATLAS and CMS experiments will look for supersymmetric particles to test this hypothesis.

Questions to be answered by LHC

❑**Why is there no more antimatter?**

➢We live in a world of matter.
➢Where is Antimatter.
➢In the Big Bang, equal amounts of matter and antimatter should have been produced but we only see matter in the universe.
➢What is the origin of this bias?

➢The LHCb experiment will be looking for differences between matter and antimatter to help answer this question.

Questions to be answered by LHC

- **What was matter like within the first second of the Universe’s life?**

- The ordinary matter is made of atoms containing a nucleus composed of protons and neutrons, which in turn are made of quarks bound strongly together by other particles called gluons.

- It seems that during the first microseconds after the Big Bang the Universe contained a very hot and dense mixture of quarks and gluons called quark–gluon plasma.

- The ALICE experiment will use the LHC heavy ion collisions to recreate conditions similar to those just after the Big Bang,
  and in particular to analyse the properties of the quark-gluon plasma.

Questions to be answered by LHC

- ❑**Do extra dimensions of space really exist?**

➢Some theories propose that further hidden dimensions of space may exist; for example, string theory implies that there are additional spatial dimensions yet to be observed.

➢ADD model also predicts several extra dimensions to explain the weakness of gravity.

➢These may become detectable at LHC although no confirmation yet.

An example analysis

❑Consider the Higgs boson decaying through H→WW,

  - ➢The production process is pp →H →WW
  - ➢The first background is pp →WW

❑Question:

  - ➢How can we distinguish between these two processes while the final state looks the same ?

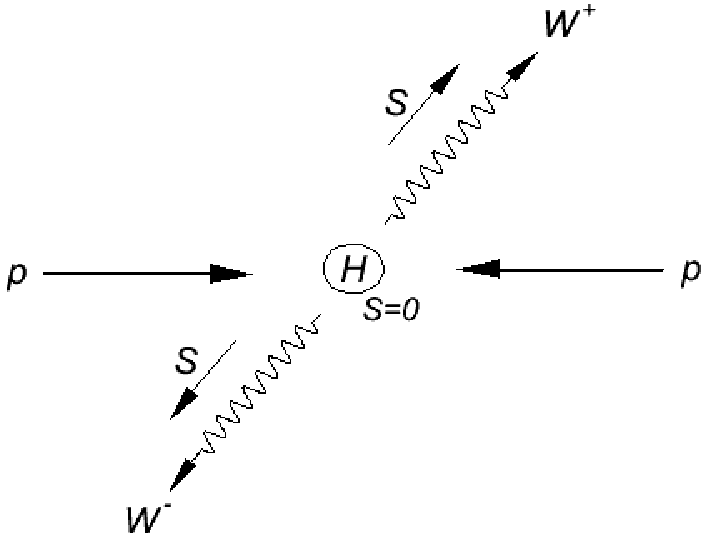
❑Answer:

  - ➢Find kinematic differences between the signal and background and use them by applying kinematic cuts (selection cuts).

An example analysis

- To find differences between pp →H →WW and pp →WW consider the following facts:

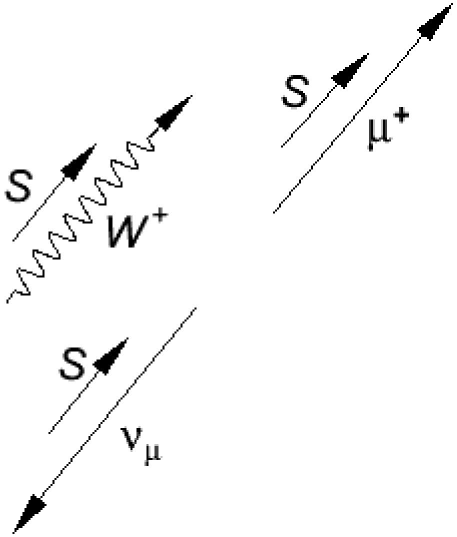
- H is spin-less so W^+ and W^- are both either right-handed or left-handed,

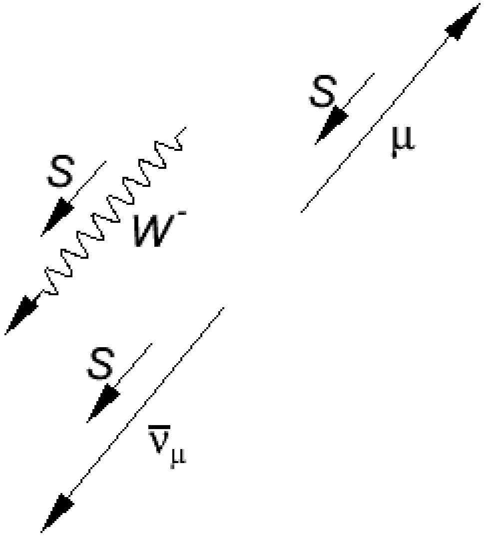


while W bosons from pp →WW have no spin preference.

An example analysis

- Consider the W decays in signal events:





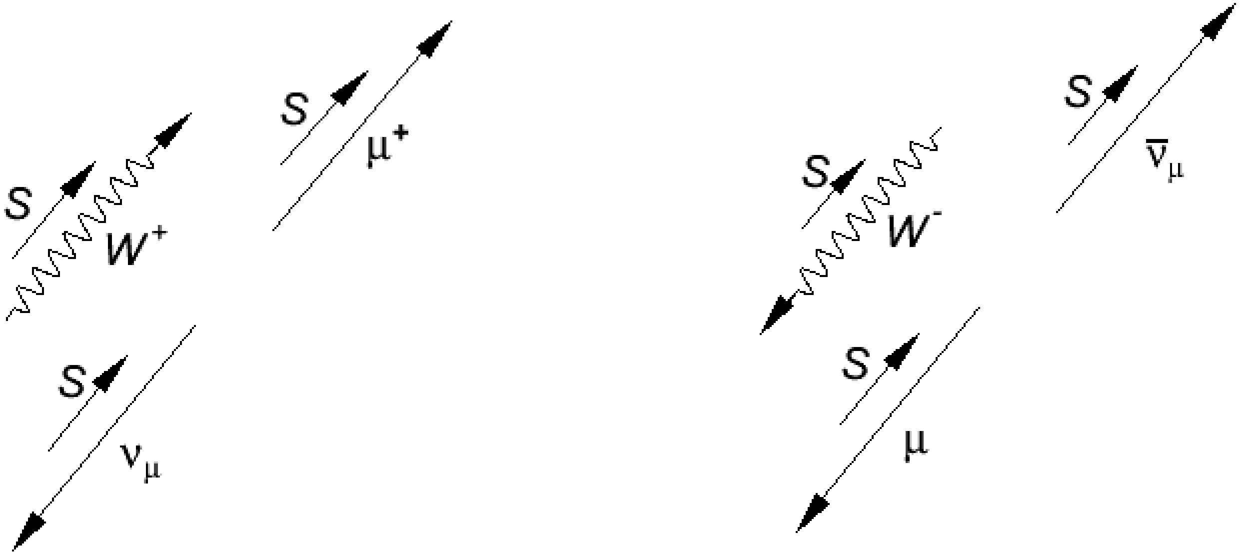
Conclusion: Muons tend to fly in the same direction
Collinear lepton pair
Small $\Delta\phi(\mu_1,\mu_2)$
Small invariant mass of the lepton pair ($M_{\mu\mu}$)

$$M_{\mu\mu} = \sqrt{2E_1E_2(1-\cos\theta)}$$

An example analysis

- The background process pp →WW has no spin orientation preference because colliding protons are not polarized,

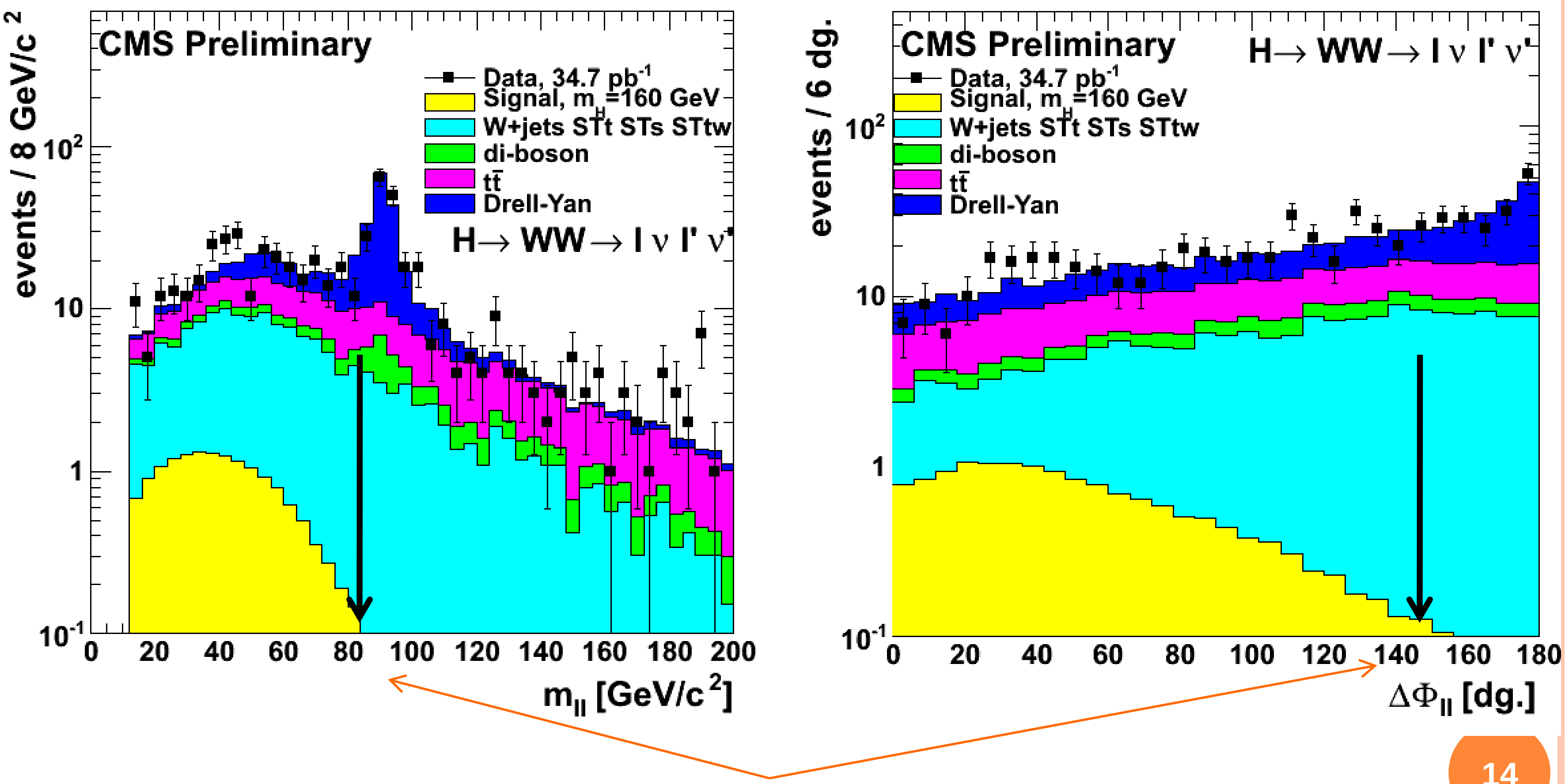
- In some cases they may appear with the same spin configuration as signal but in other cases like the following configuration the situation is opposite:



Conclusion: Muons tend to fly in OPPOSITE directions
non-collinear lepton pair
Large $\Delta\phi(\mu_1,\mu_2)$
Large invariant mass of the lepton pair ($M_{\mu\mu}$)

An example analysis

- To exploit what I said in the previous slides, plot the distributions and cut on the range of kinematic variable which selects signal events most of the time:



Selection cuts used for H->WW->l nu l nu search

Interpretation of results

What we do:

❑Look at kinematic distributions of signal and all background events,

❑Cut on distributions so as to maximize S/B

❑Count number of signal and background events which pass all selection cuts

❑Quote the results in terms of signal significance:

$$Significance = \frac{N_S}{\sqrt{N_B}}$$

❑Quantifies the observed excess(N_S) in units of standard deviations of the background ($\sqrt{N_B}$)

❑Convention : if significance > 5 , discovery is possible

Example of a signal selection

Example : search for a Higgs boson with m(H)=160 GeV

Cut/Sample	H160	WW	tt	WJets
#events	897	43000	157500	31×10^6
HLT eff.	84%	52%	81%	47%
Lepton sel.	28%	4.2%	3%	0.004%
Kin. Presel.	85%	65%	84%	43%
e-mu	49%	49%	49%	61%
CJV	68%	71%	3%	76%
Met	28%	17%	34%	10%
Dphi	93%	54%	33%	75%
Mll	93%	57%	59%	0
Ptmax	83%	97%	38%	0
Ptmin	85%	39%	60%	0
LRHWW	98%	100%	33%	0
LRWW	93%	100%	100%	0
Events at $1 fb^{-1}$	9.1+/-0.3	4.2+/-1.2	0.2+/-0.2	0

Statistical interpretation

Sample/m(H)	130 GeV	150 GeV	160 GeV	170 GeV	200 GeV
Signal	7.06	13.2	9.1	11.1	5.9
Background	24.05	20.5	5.1	5.6	16.4

- With m(H)=160 GeV selection cuts:

- If signal does not exist: 5.1 background events only
- If signal exists: 9.1+5.1 = 14.2 events

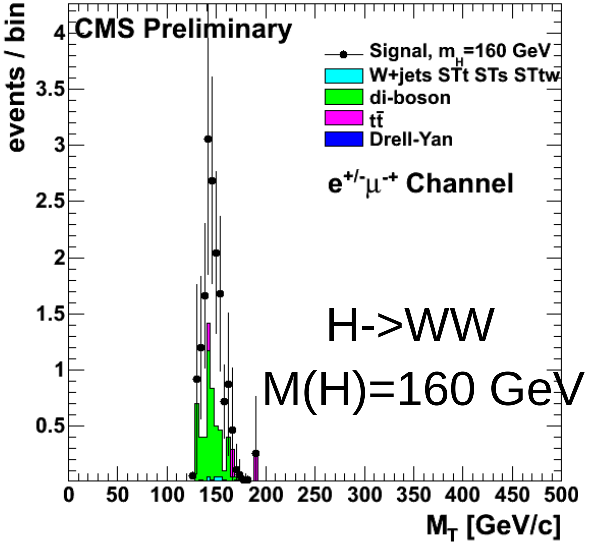
- So in one case 5 events, in another 14 events pass selection cuts

- If signal exists we get 14 events with a signal purity of 64%

- We can never say if a single event is signal or background
- We only look for excess of events over SM background
- Higgs boson mass is measured using a distribution with a finite impurity which is quoted in terms of the Higgs boson mass error

Higgs boson mass reconstruction

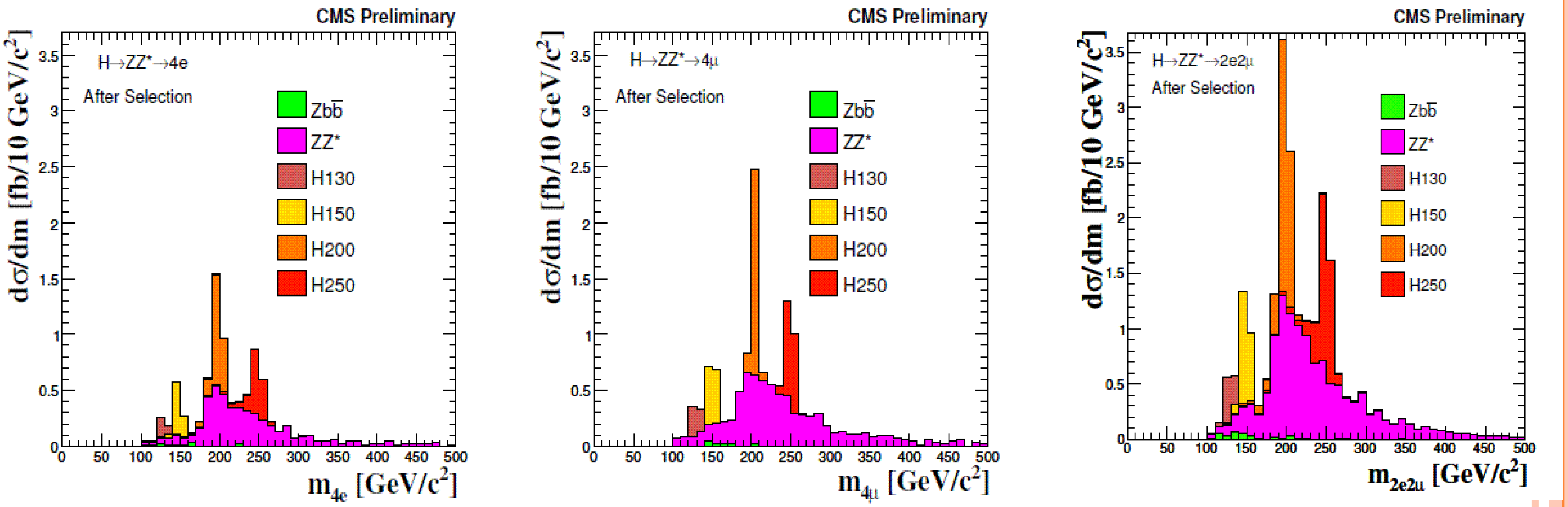
Higgs boson candidate mass distributions can be used to measure the Higgs boson mass



H->WW

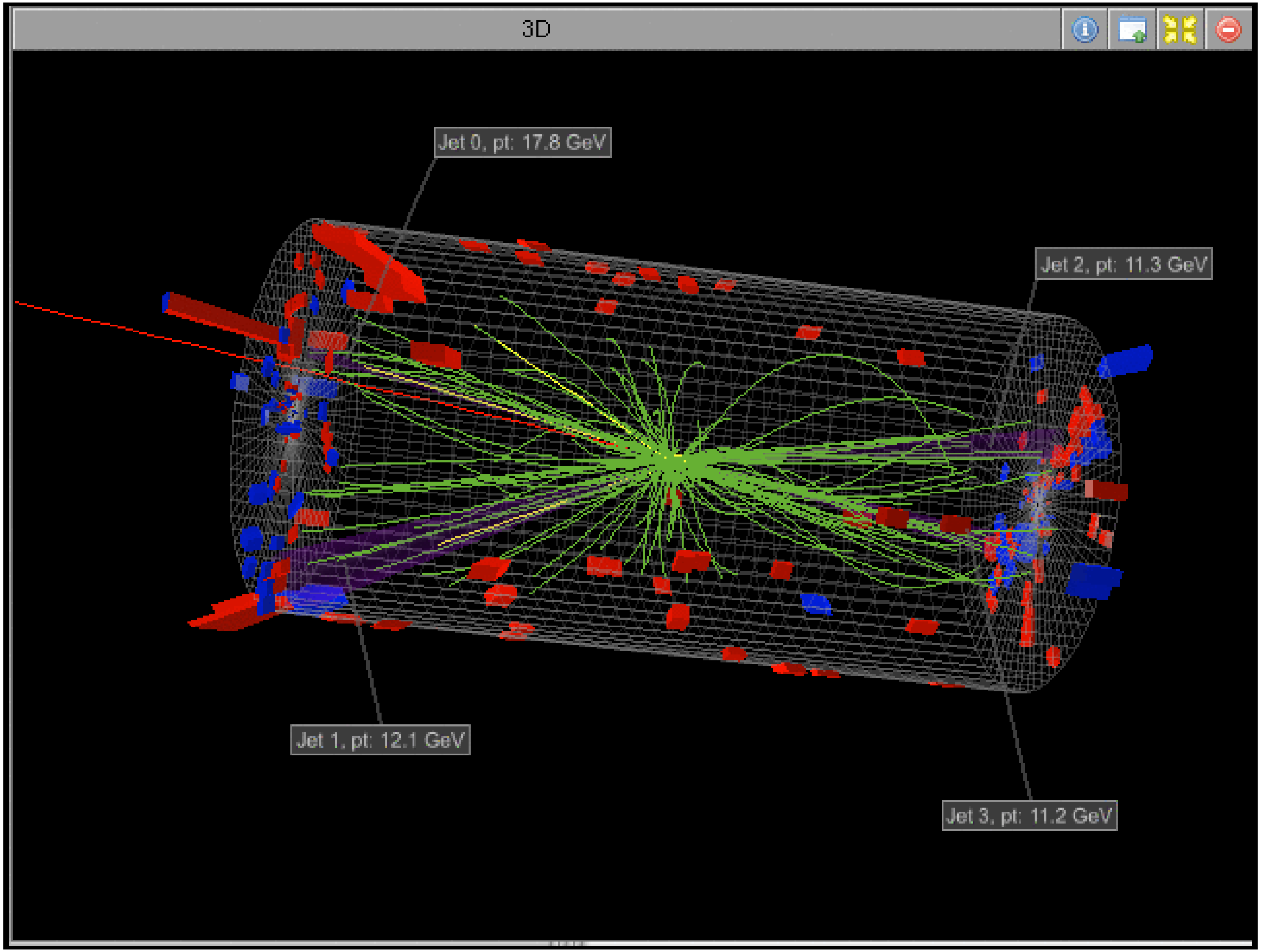
M(H)=160 GeV

e mu nu nu transverse mass



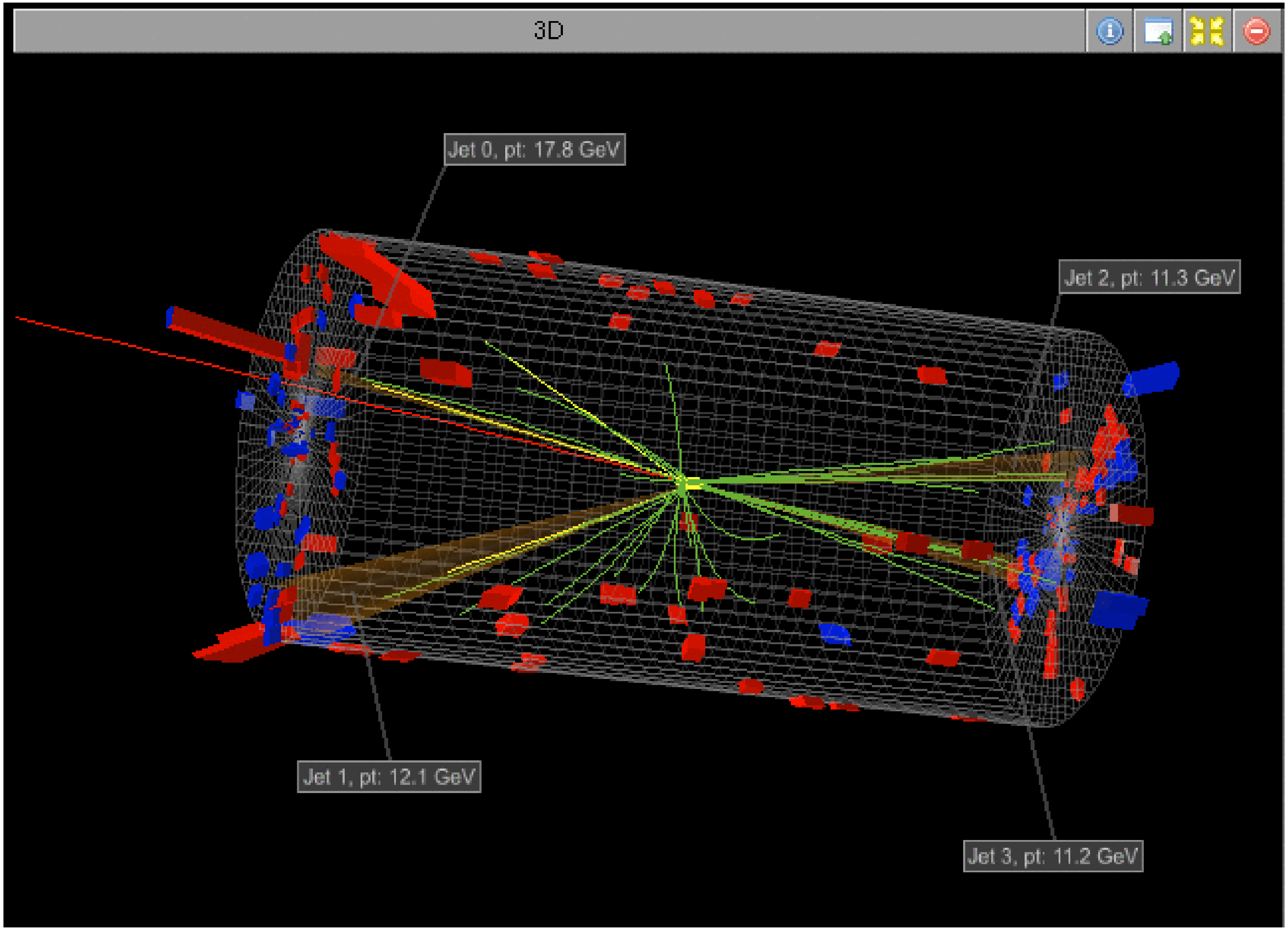
4 lepton invariant mass

Event display example (1)



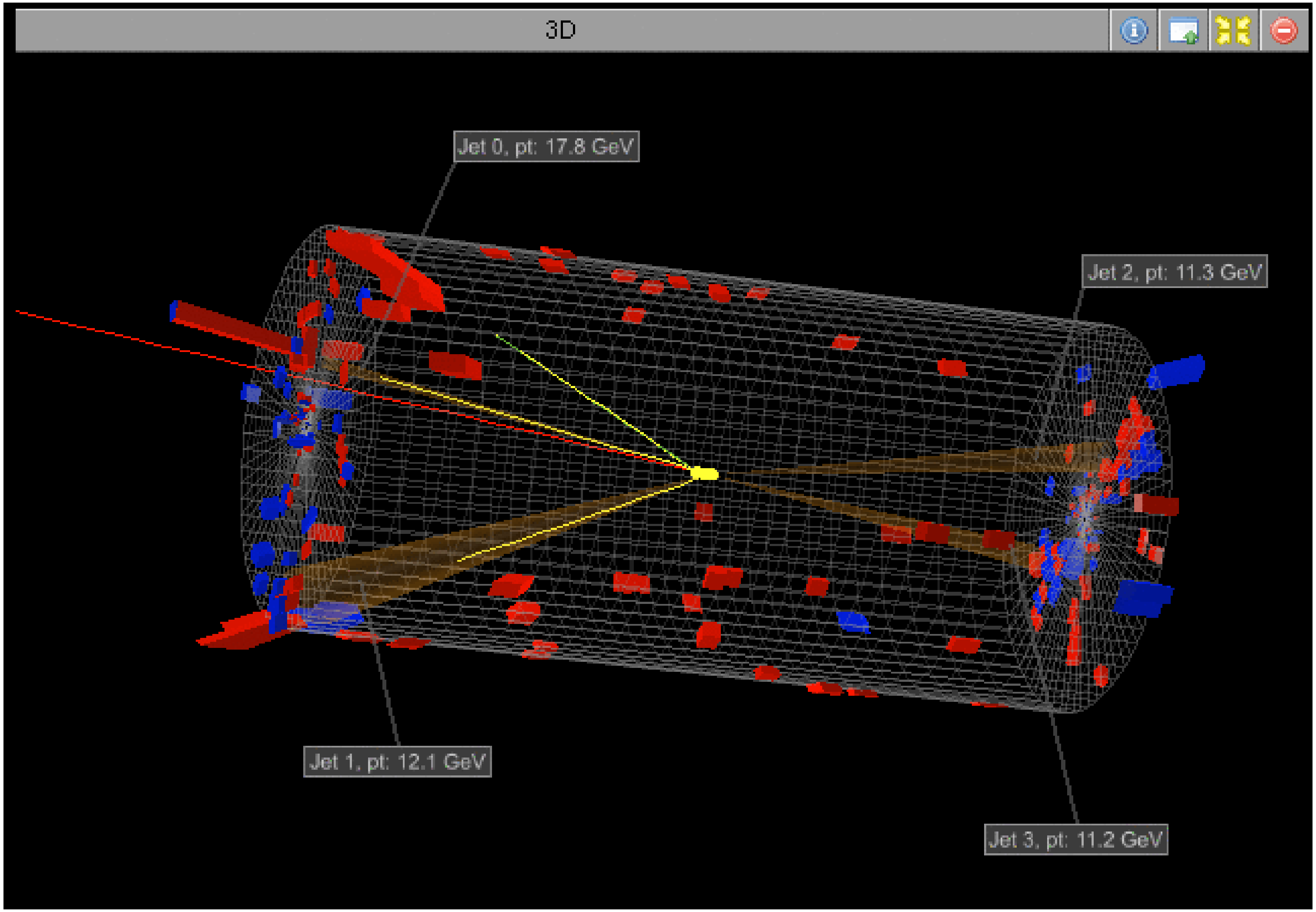
Signal candidate : no cut on p_T of tracks

Event display example (2)



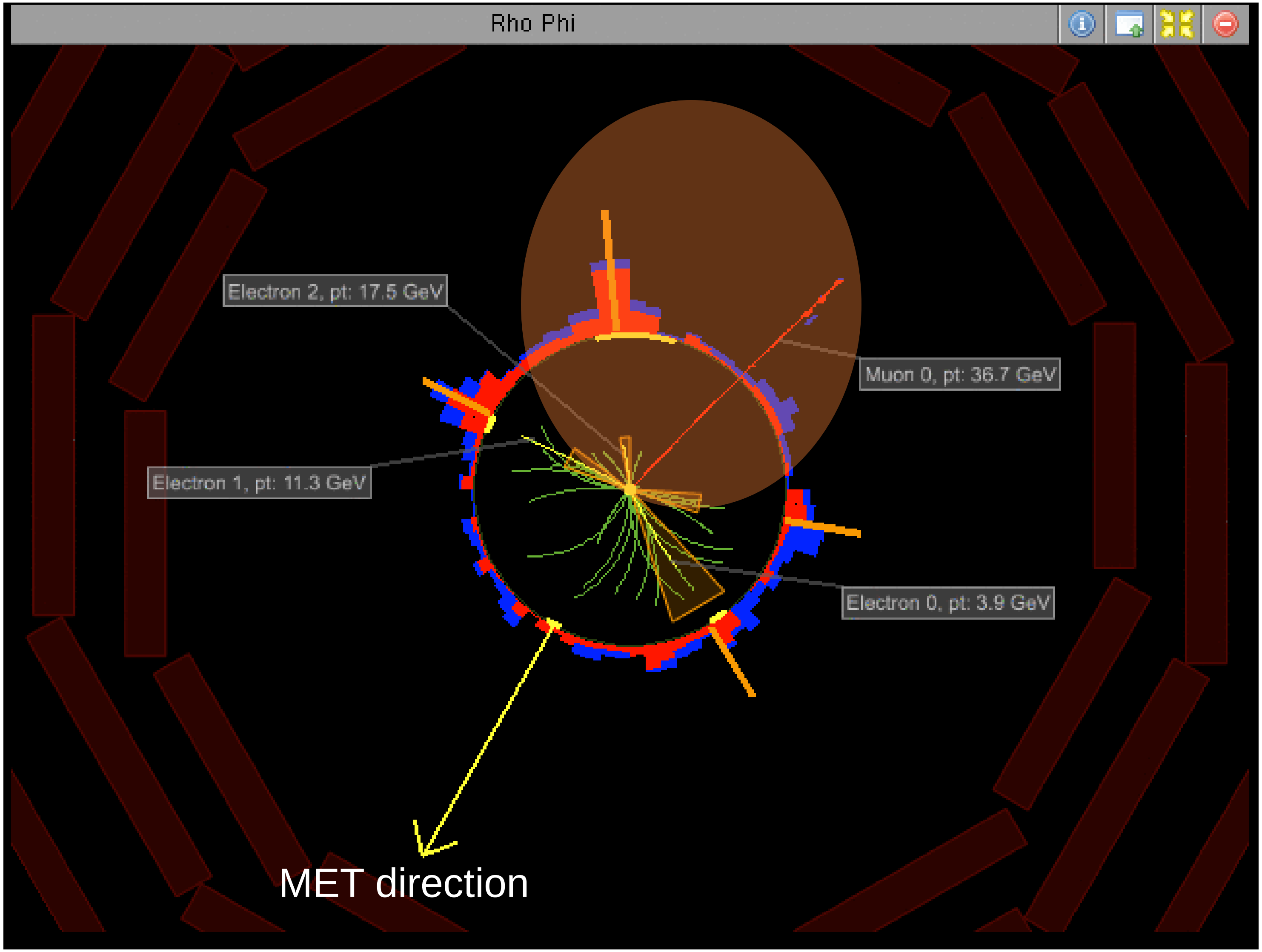
Track $p_T > 1$ GeV

Event display example (3)



Track $p_T > 10$ GeV

Event display example (4)



Conclusions

- ❑The High energy physics is an expensive and challenging science
- ❑Within the type of the work done at CERN and FERMILAB it requires accelerators
- ❑Accelerators need detectors to show particle interactions
- ❑These projects aim at answering several questions which are fundamental to particle physics and cosmology
- ❑LHC is currently running and producing many exciting news everyday
- ❑We need to wait to see what it tells us about the Higgs particle, SUSY, …
- ❑Tomorrow LHC results about Higgs particle …