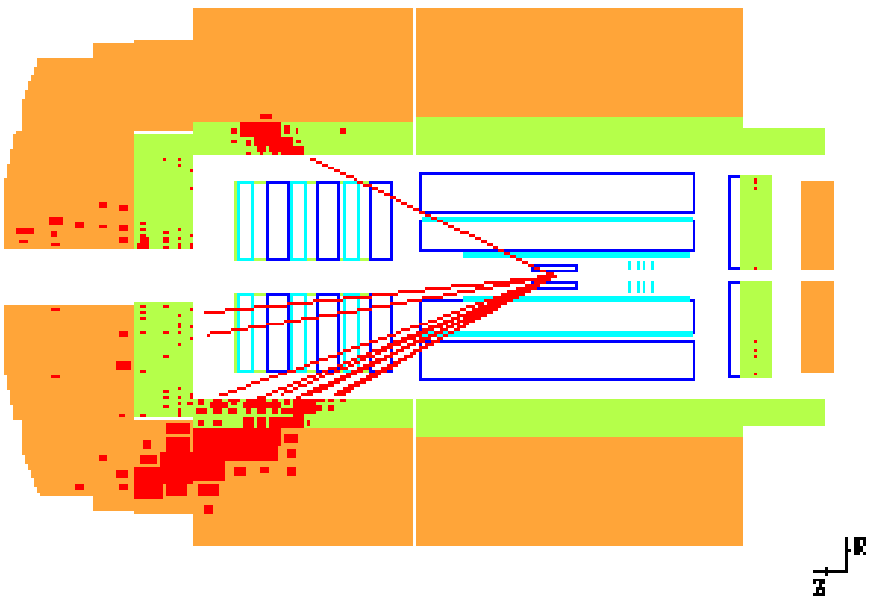
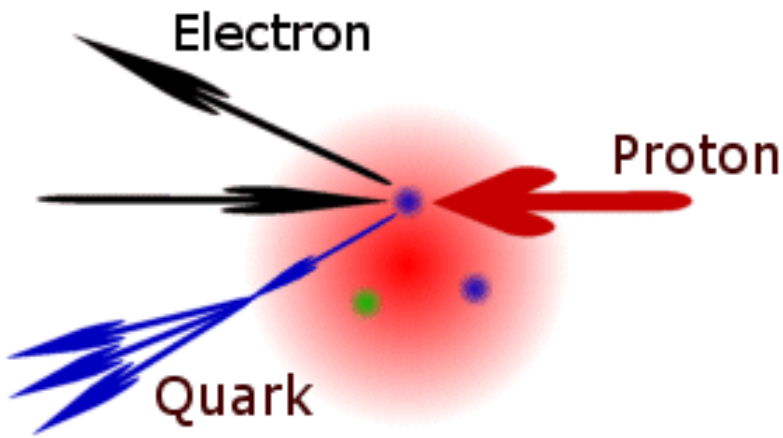
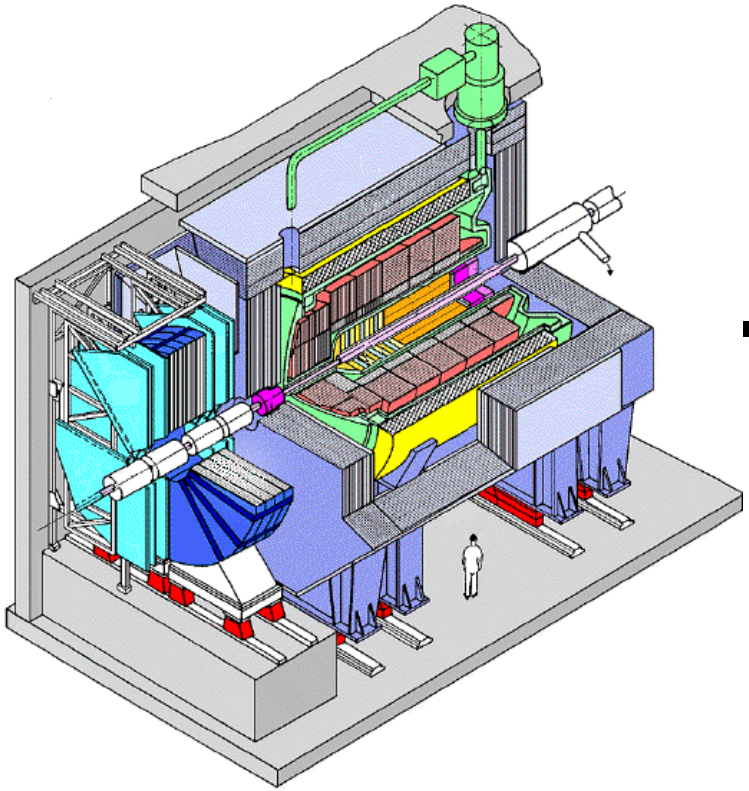
HERA e-p scattering events observed in the H1Detector

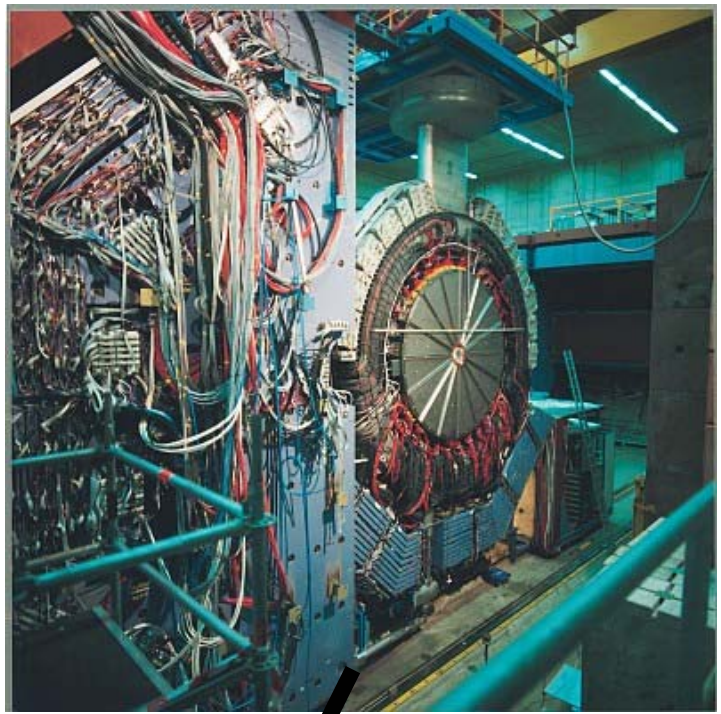


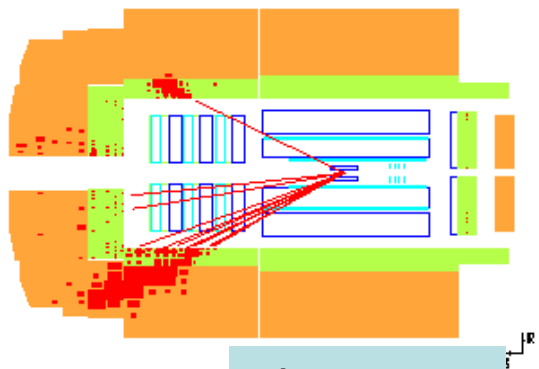


The idea

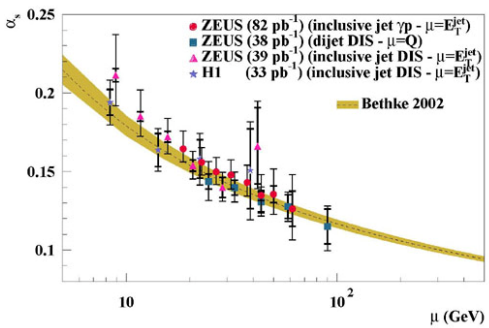


The realisation



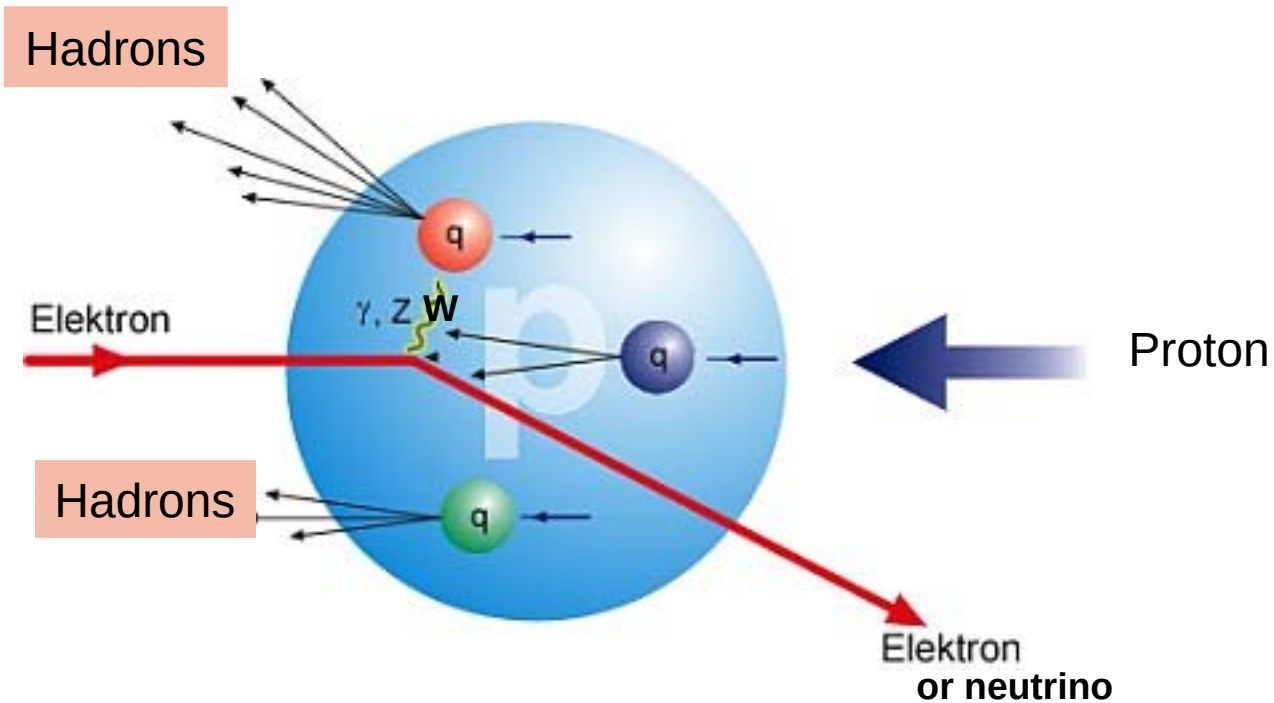


The events

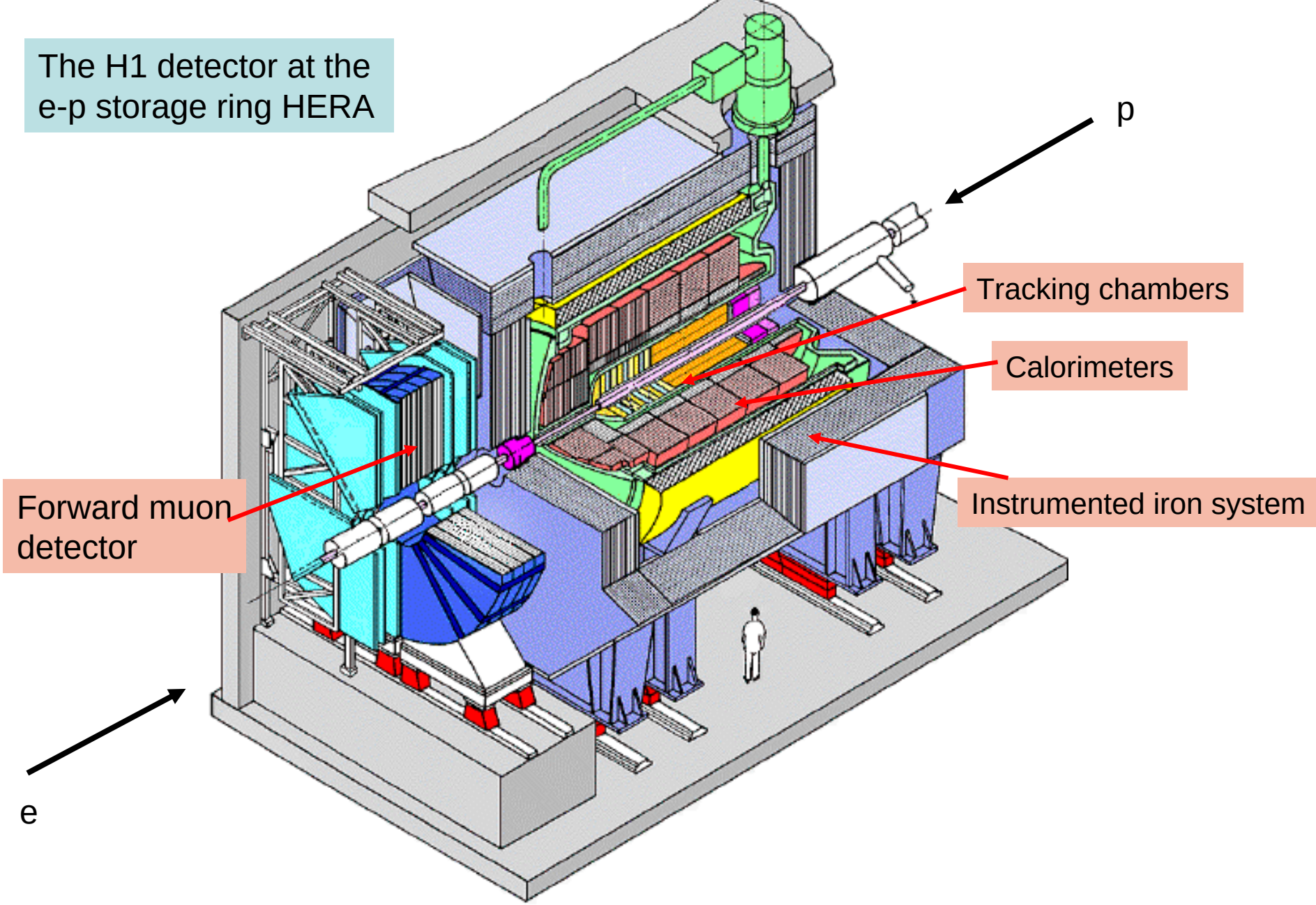


The Physics

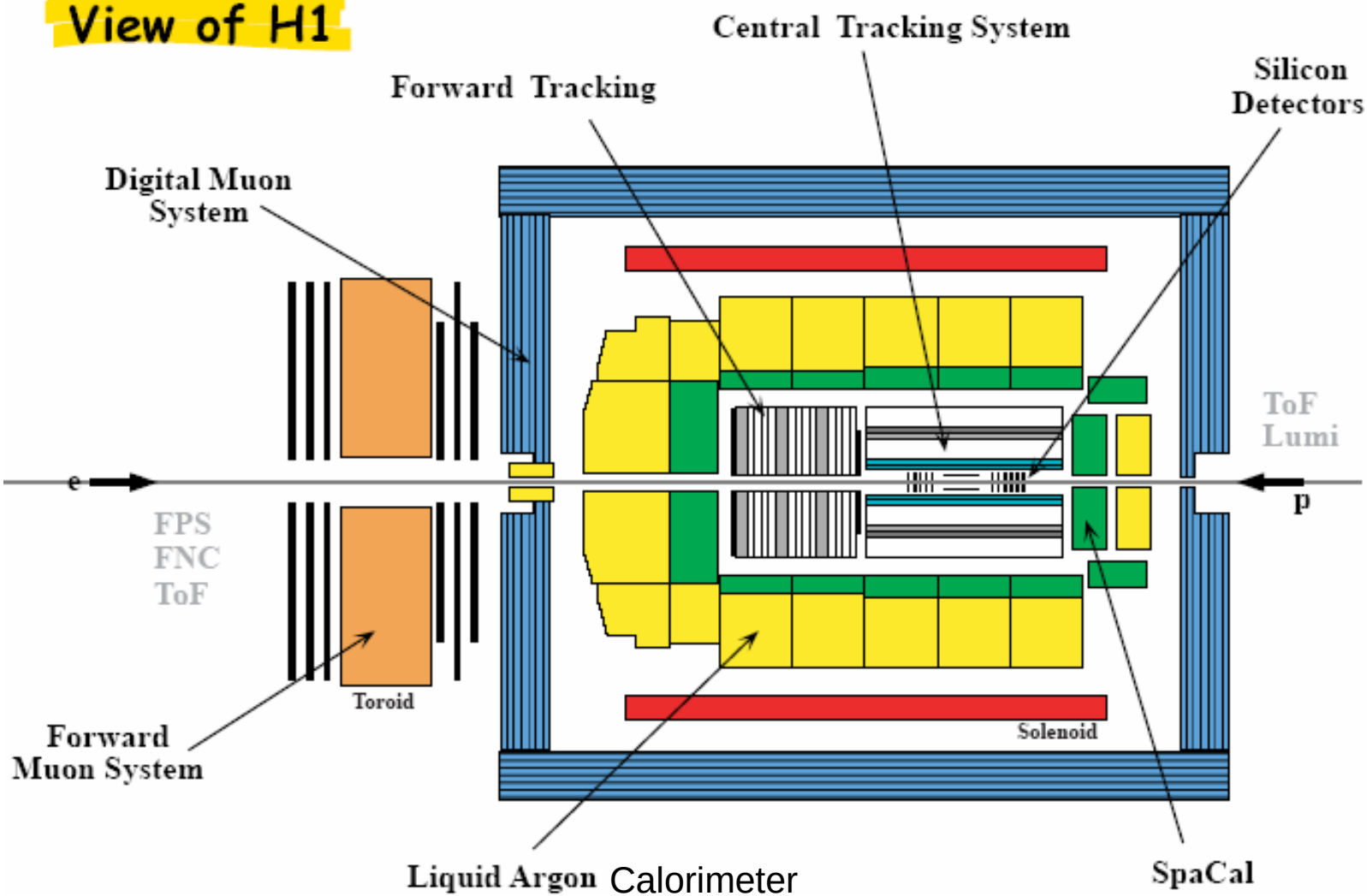
What we think what happens, when we scatter electrons on protons at HERA



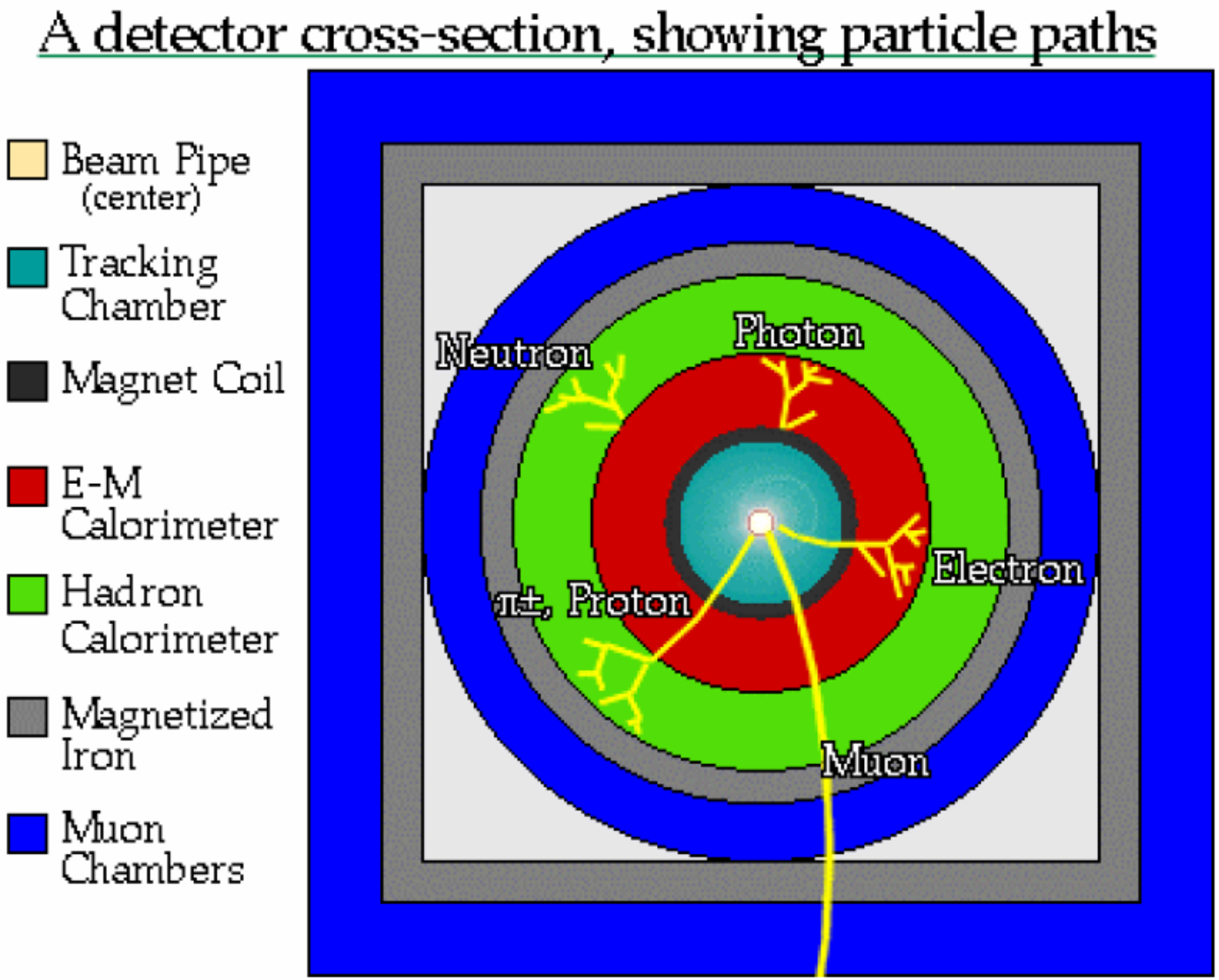
The H1 detector at the e-p storage ring HERA



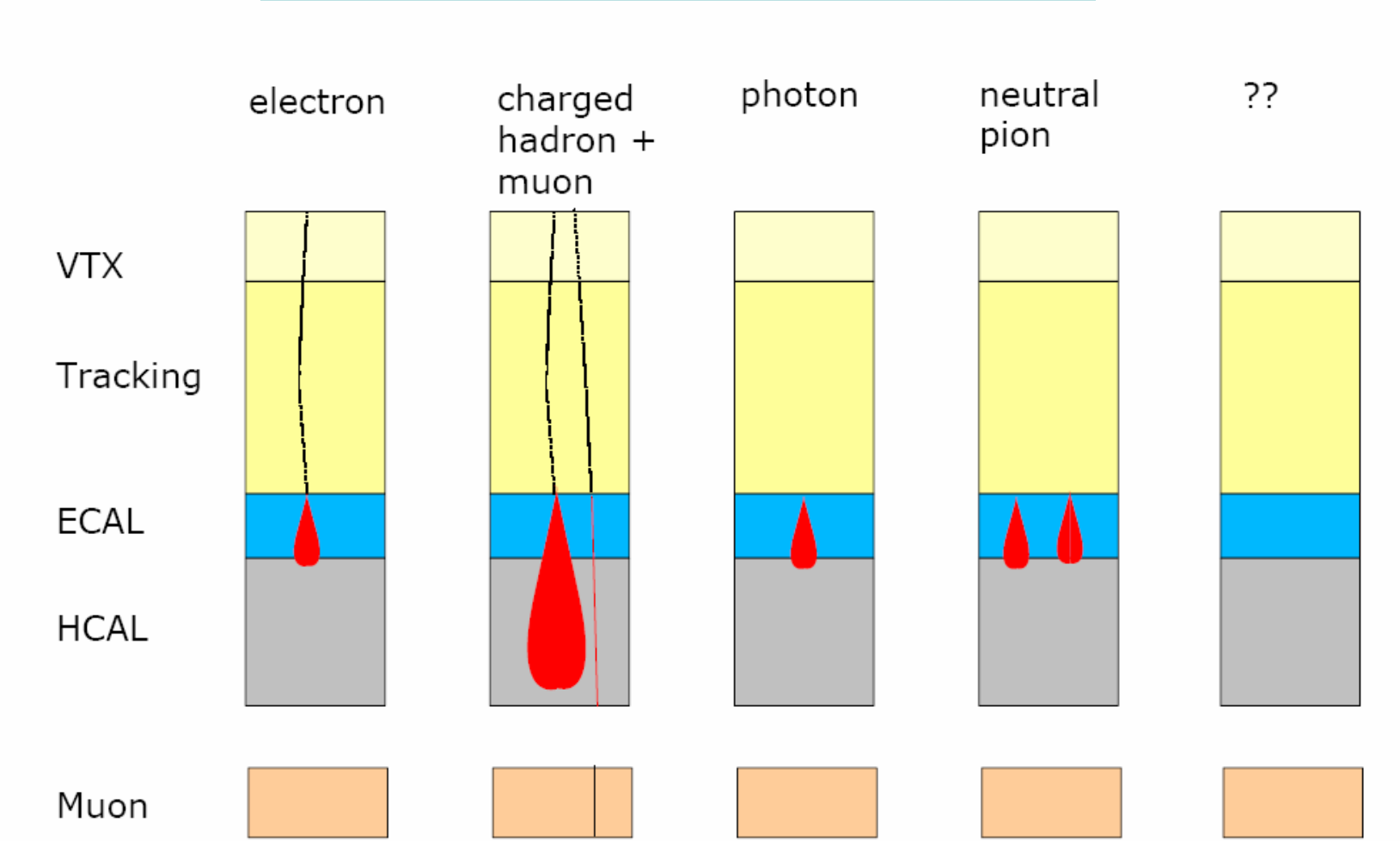
Schematic View of H1



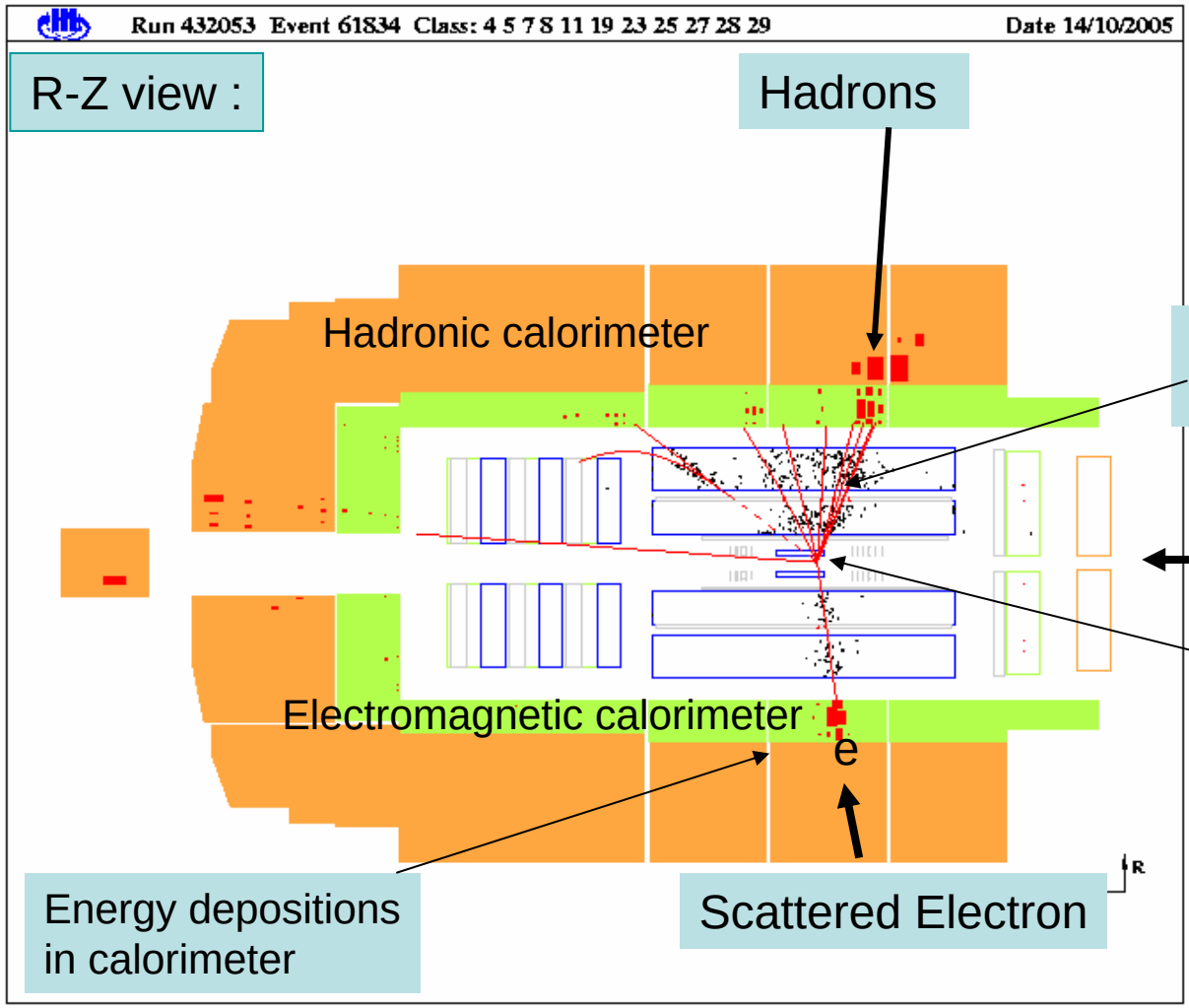
Principle of particle identification



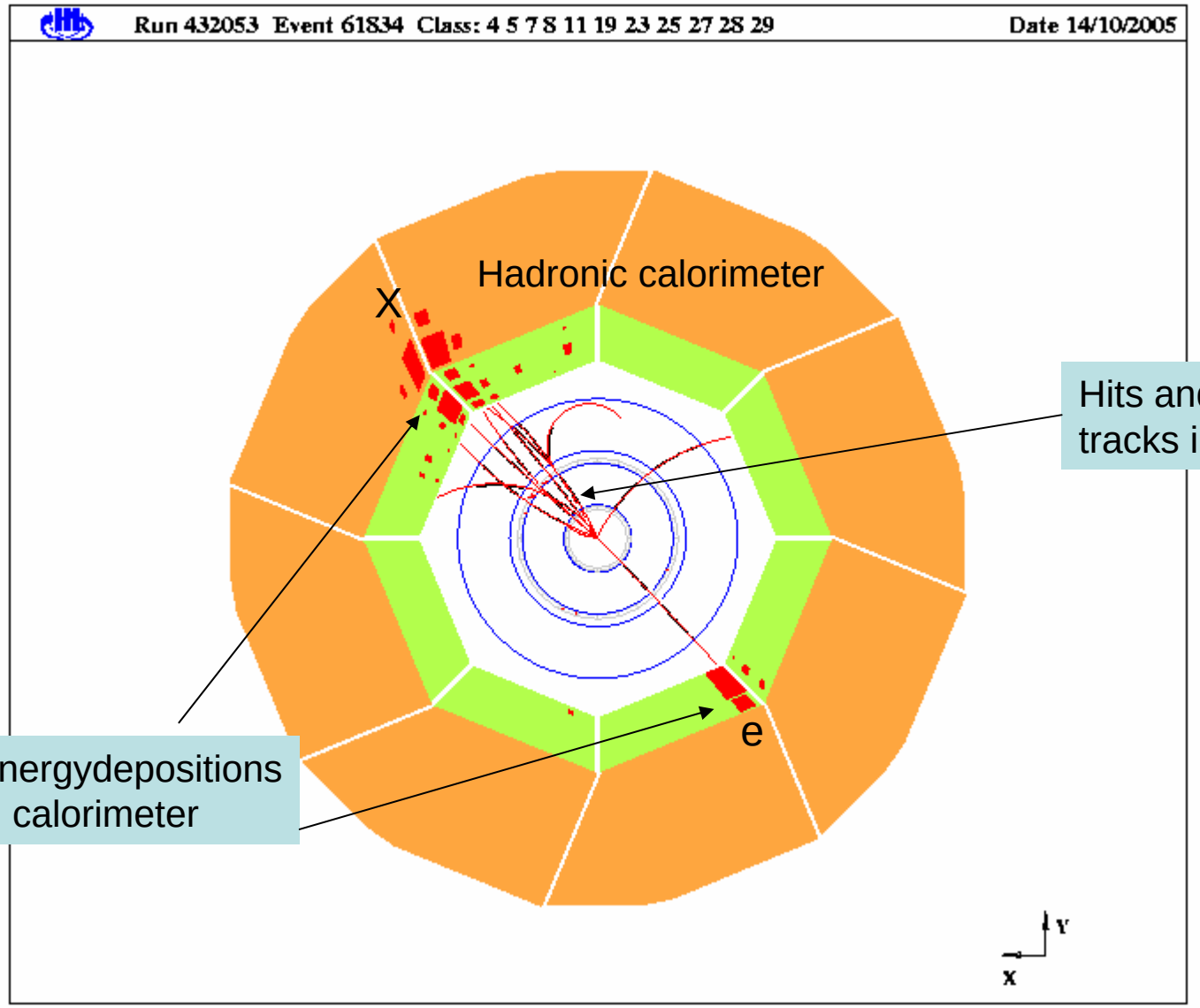
Principle of particle identification



An event display : What do we see ?



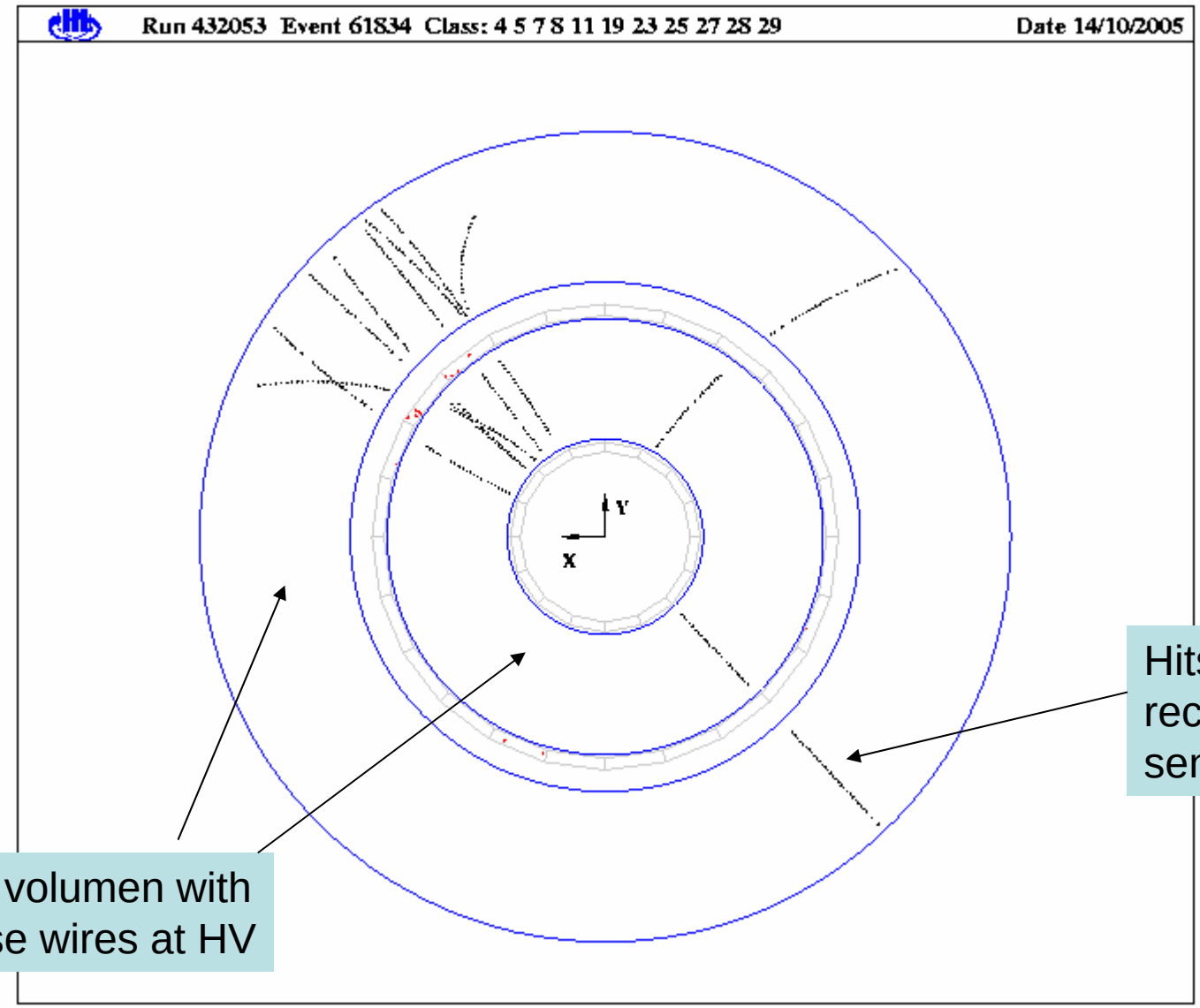
Same event in radial view : $ep \rightarrow e' X$



Hits and reconstructed tracks in tracker

Energydepositions in calorimeter

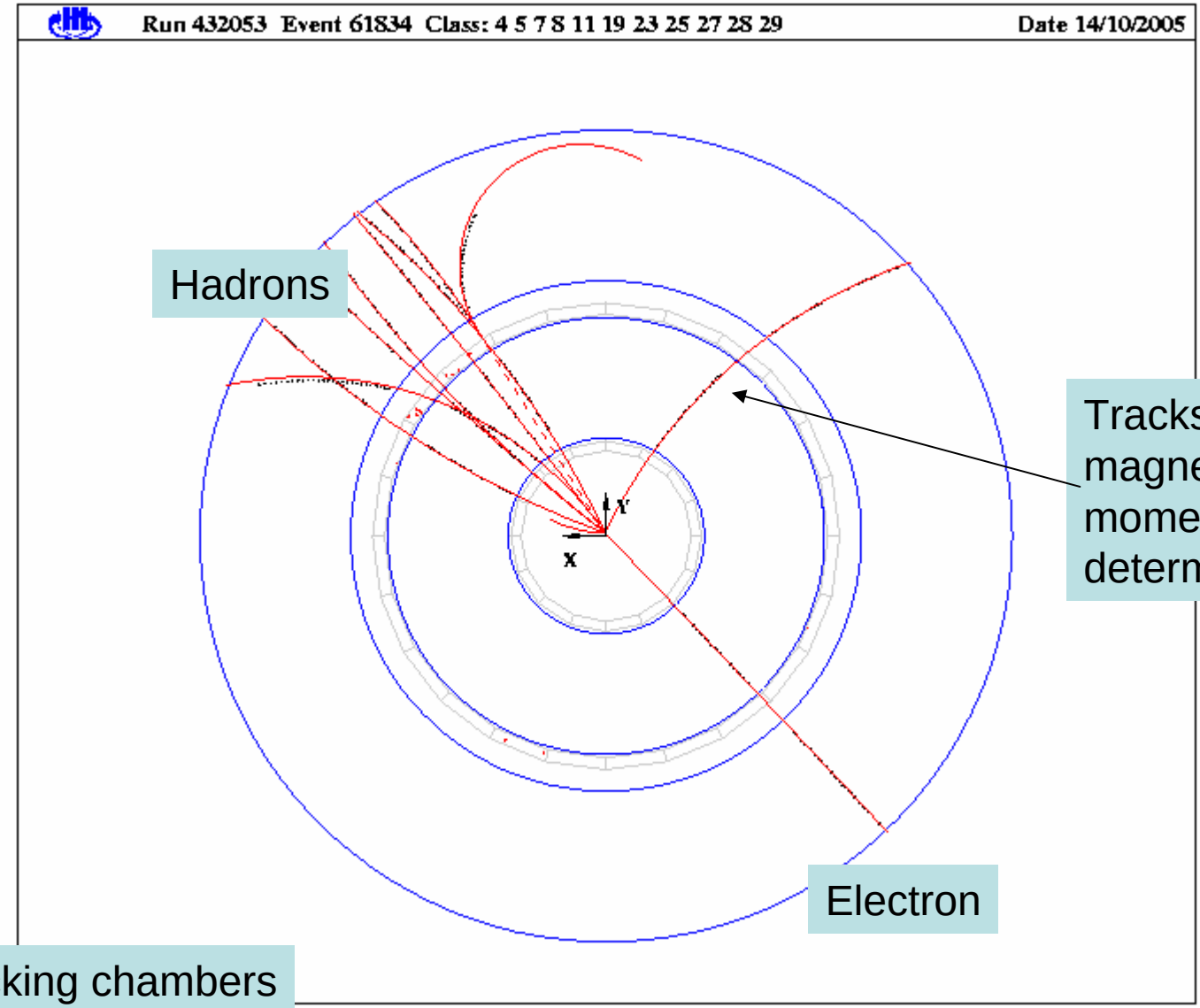
The hits (fired wires) in the tracking chambers



Hits = Signals recorded on sense wires

Gas volumen with sense wires at HV

..and the result of the pattern recognition program trying to combine the hits to tracks (red lines) :



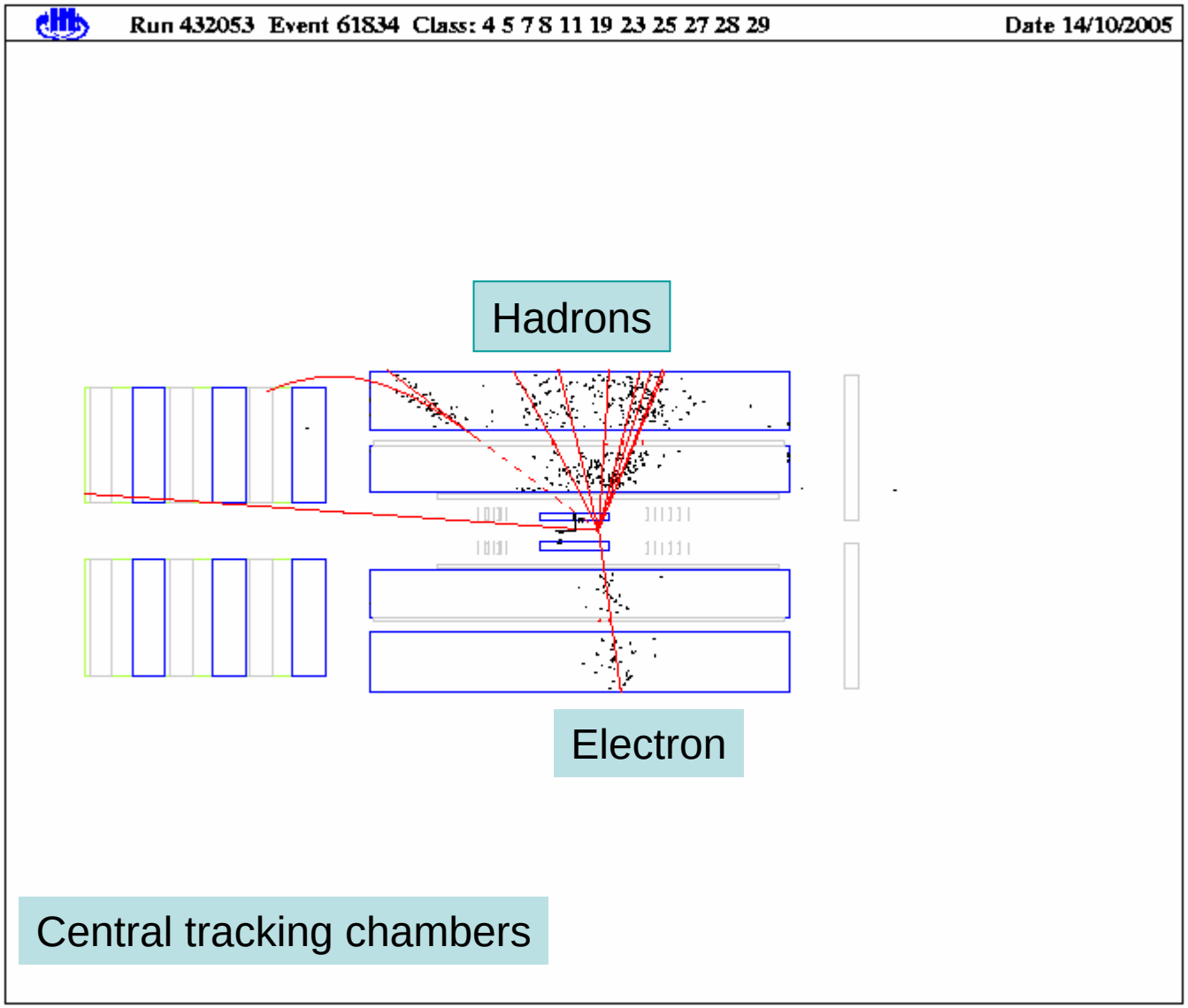
Hadrons

Tracks bend in magnetic field : momentum determination

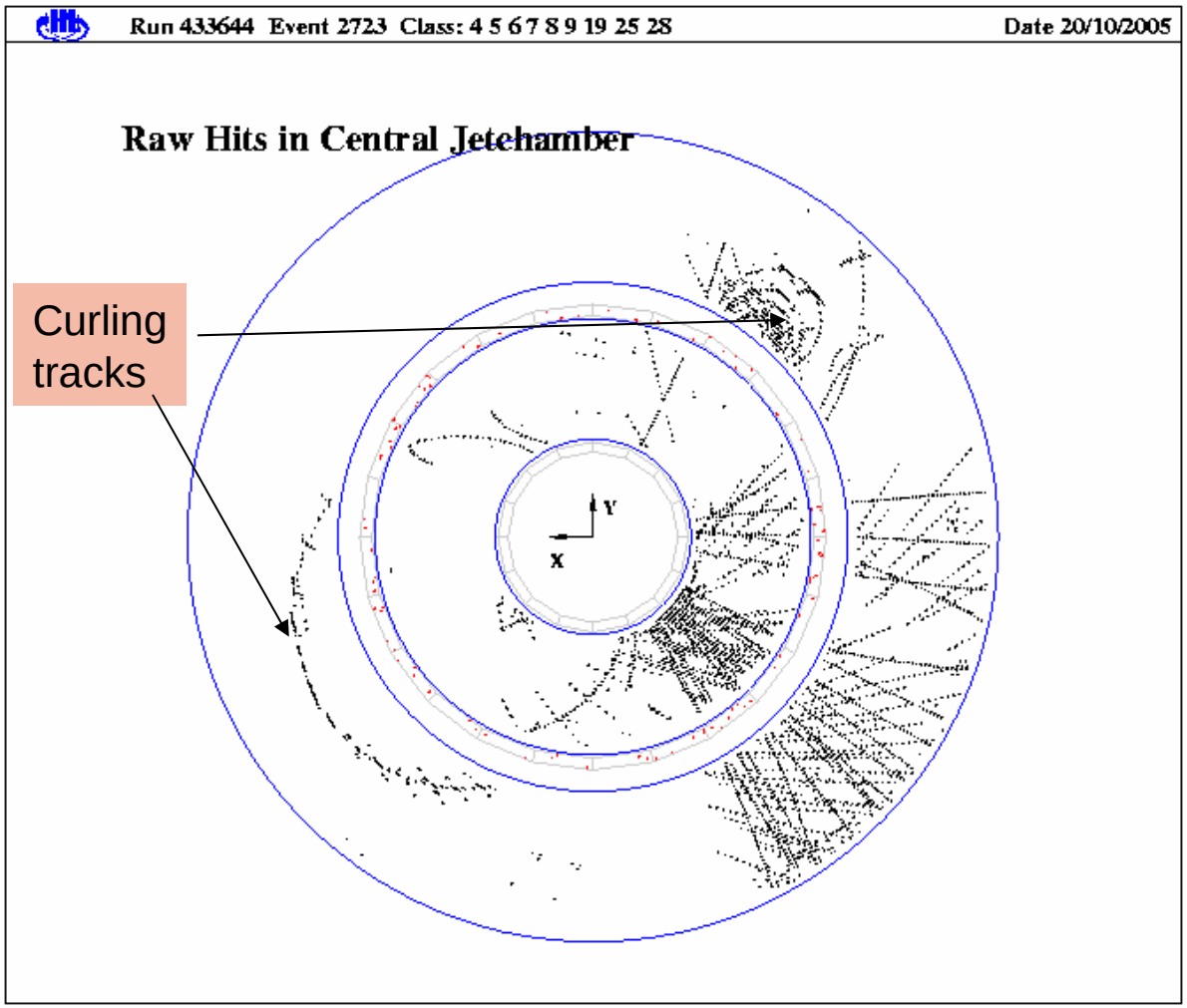
Electron

Central tracking chambers

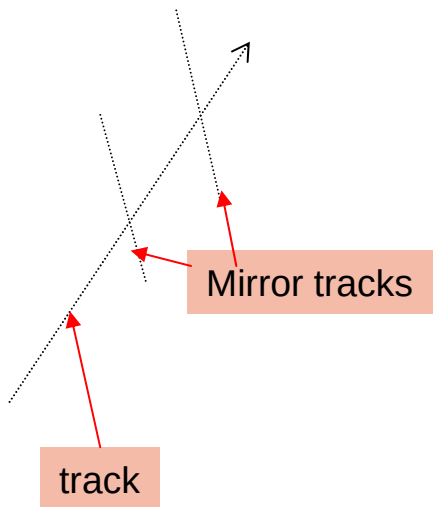
.. and the same procedure in R-Z view :



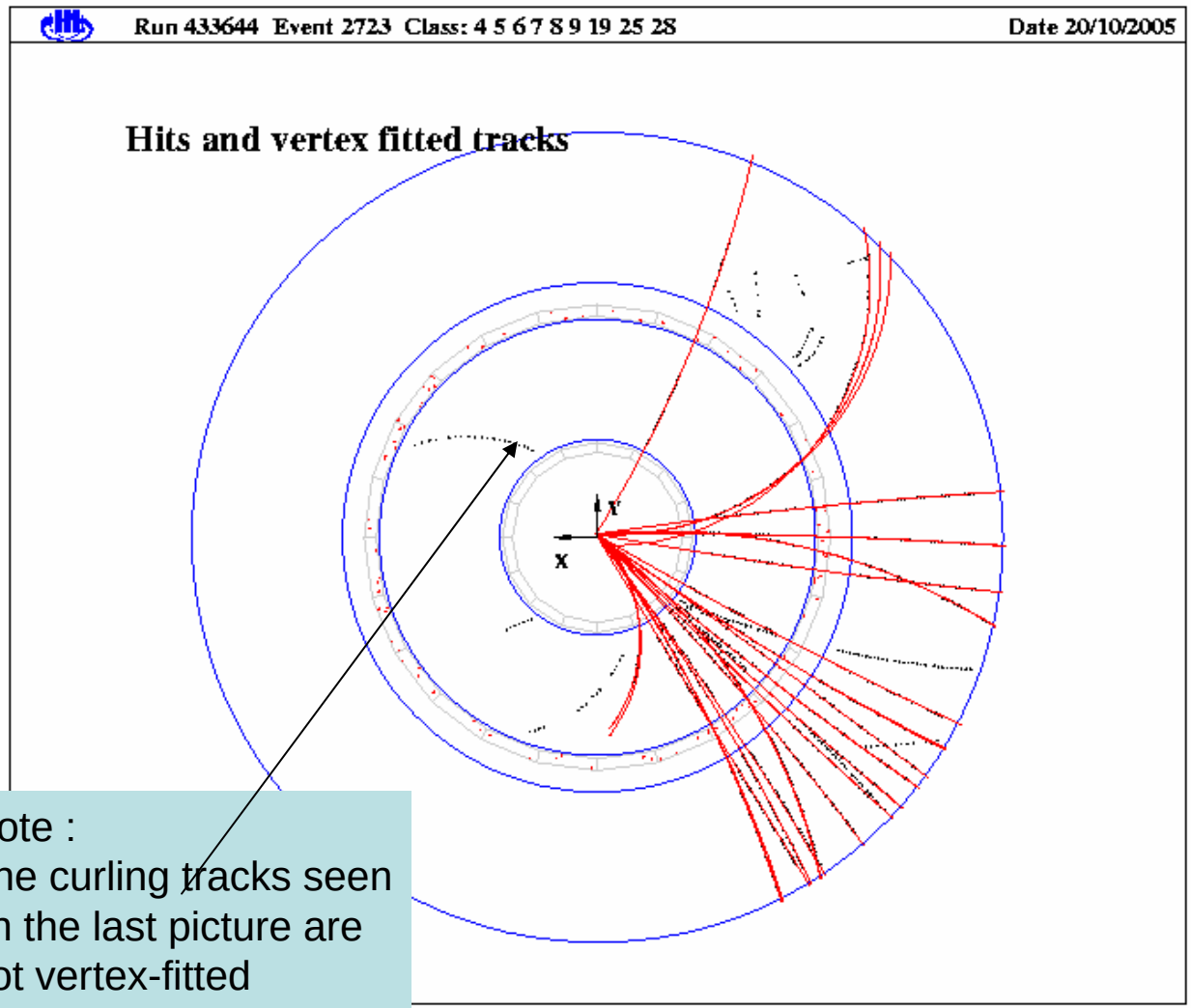
another event :



Here you see the CJC hits including the ‘mirror hits’ (ambiguity not resolved)



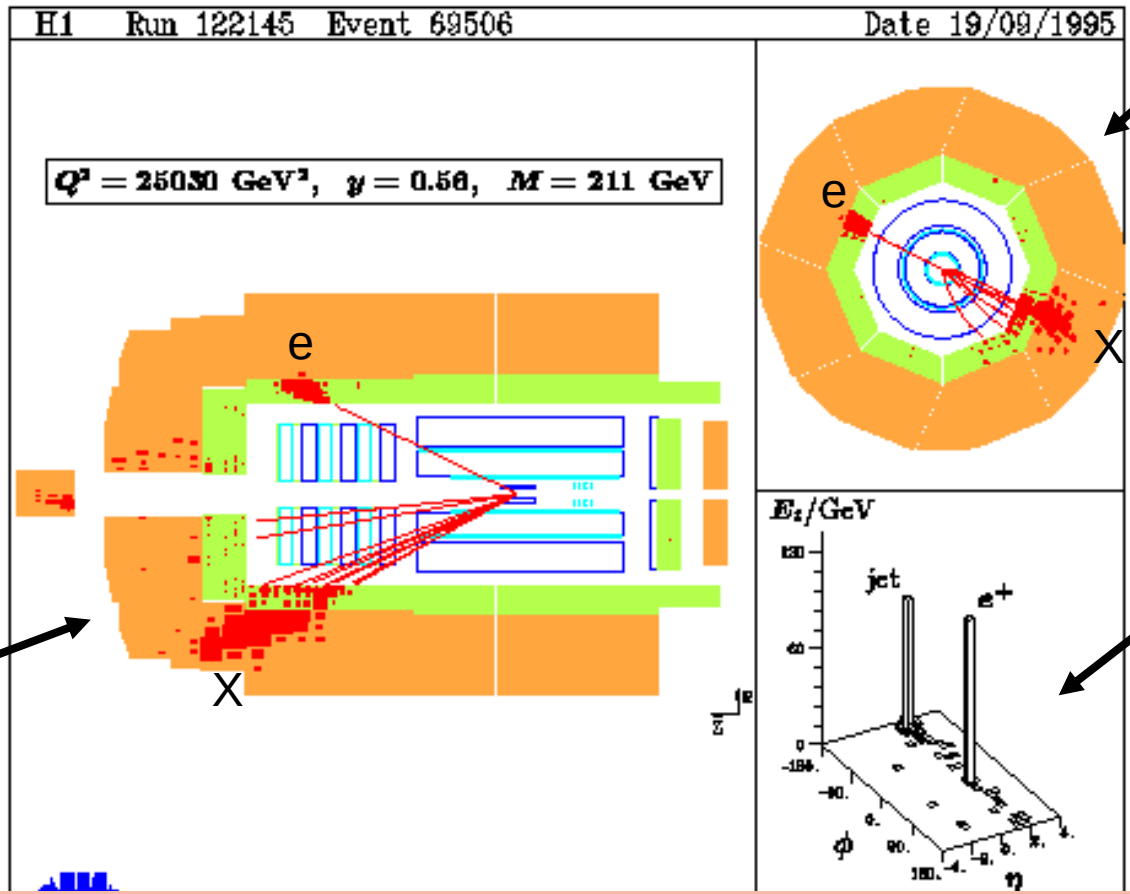
and here the tracks found by the pattern regognition program successfully fitted to the event vertex



Note :
The curling tracks seen on the last picture are not vertex-fitted

Event : Combined view (R-z, R-Phi , calorimeter energies)

$ep \rightarrow e' X$



Transverse view (R-Phi)

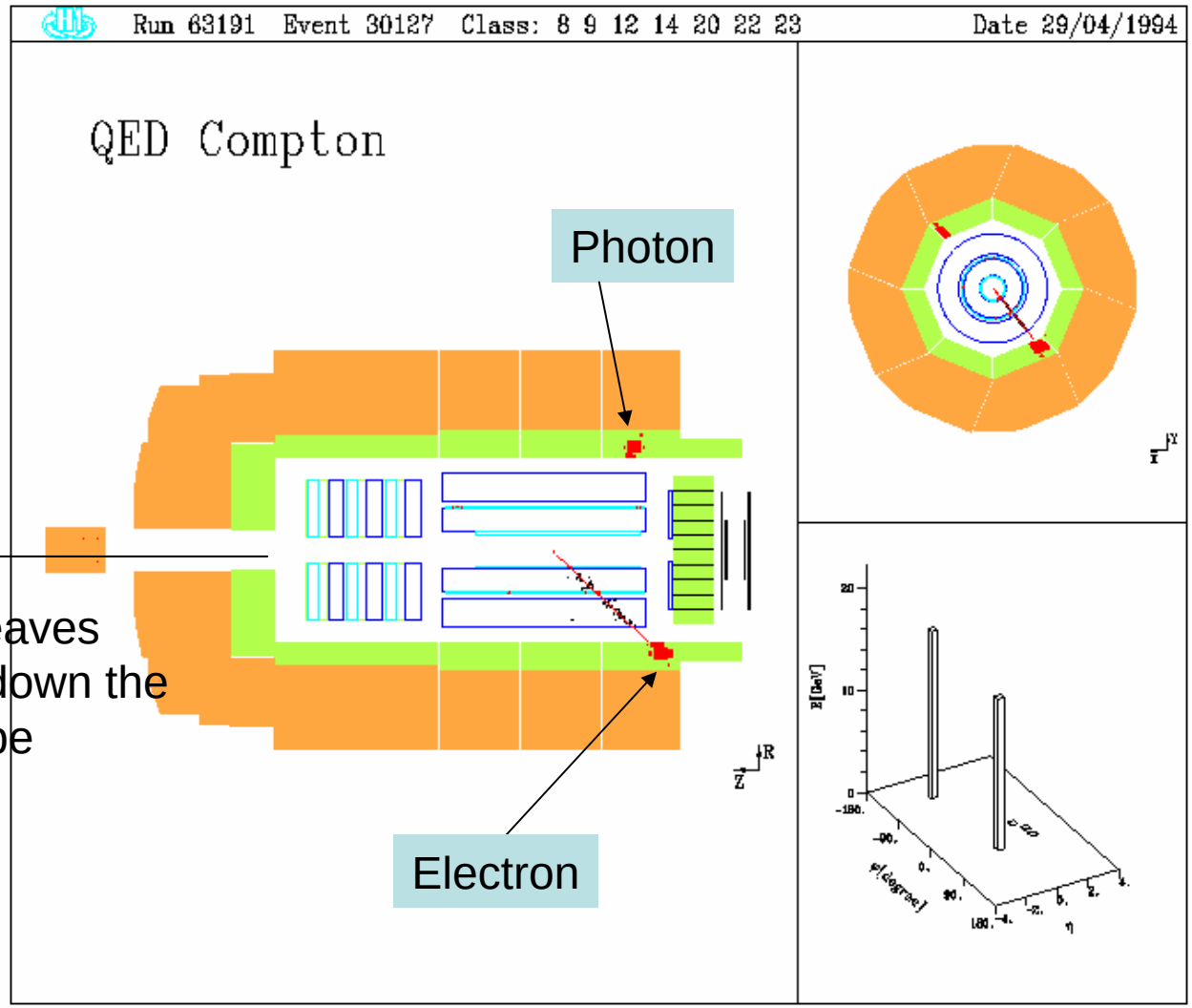
Calorimeter energies

Side view (R-z)

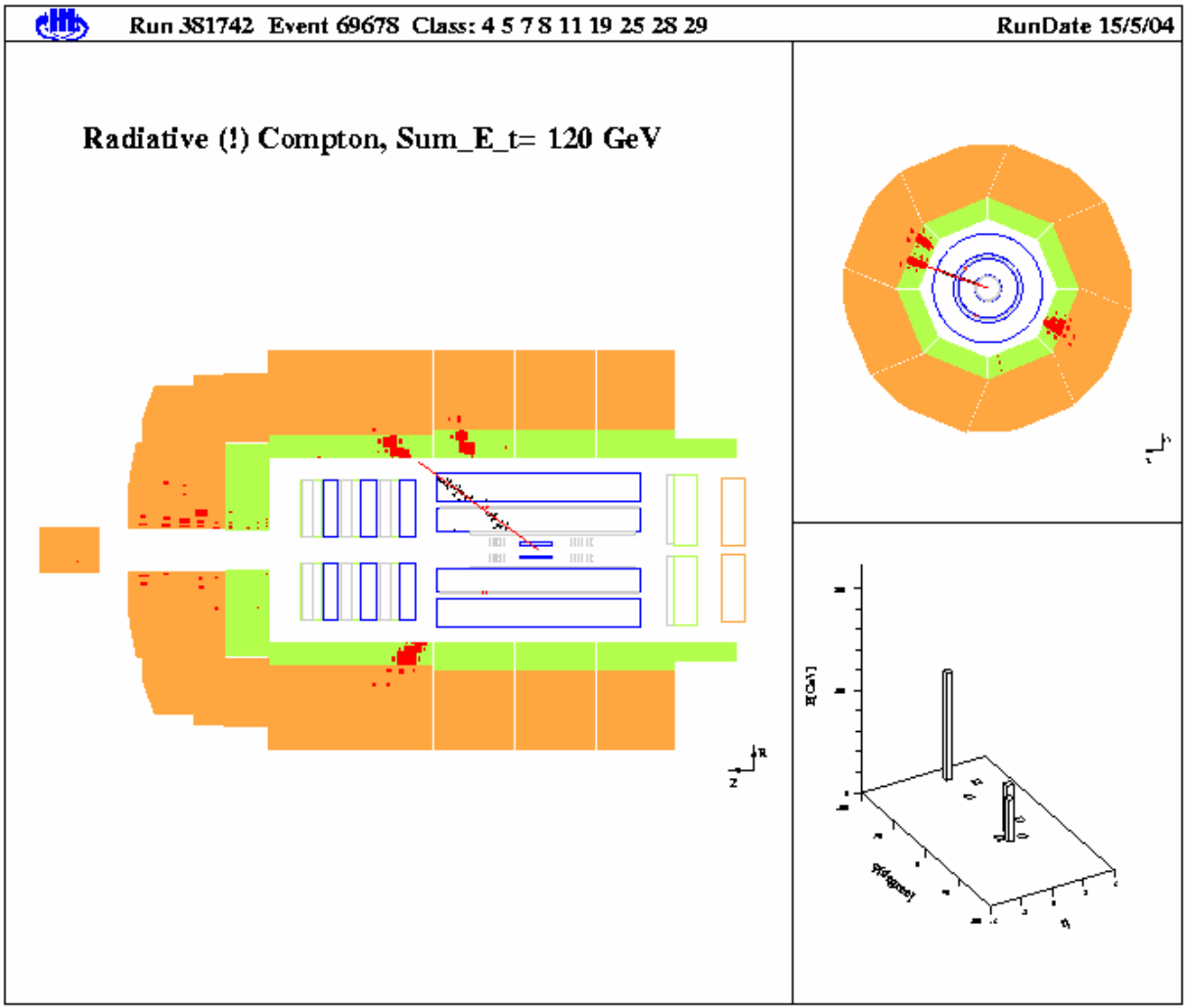
Electron and hadronic system X balanced in transverse momentum

A very simple event :

$$ep \rightarrow e\gamma(p)$$



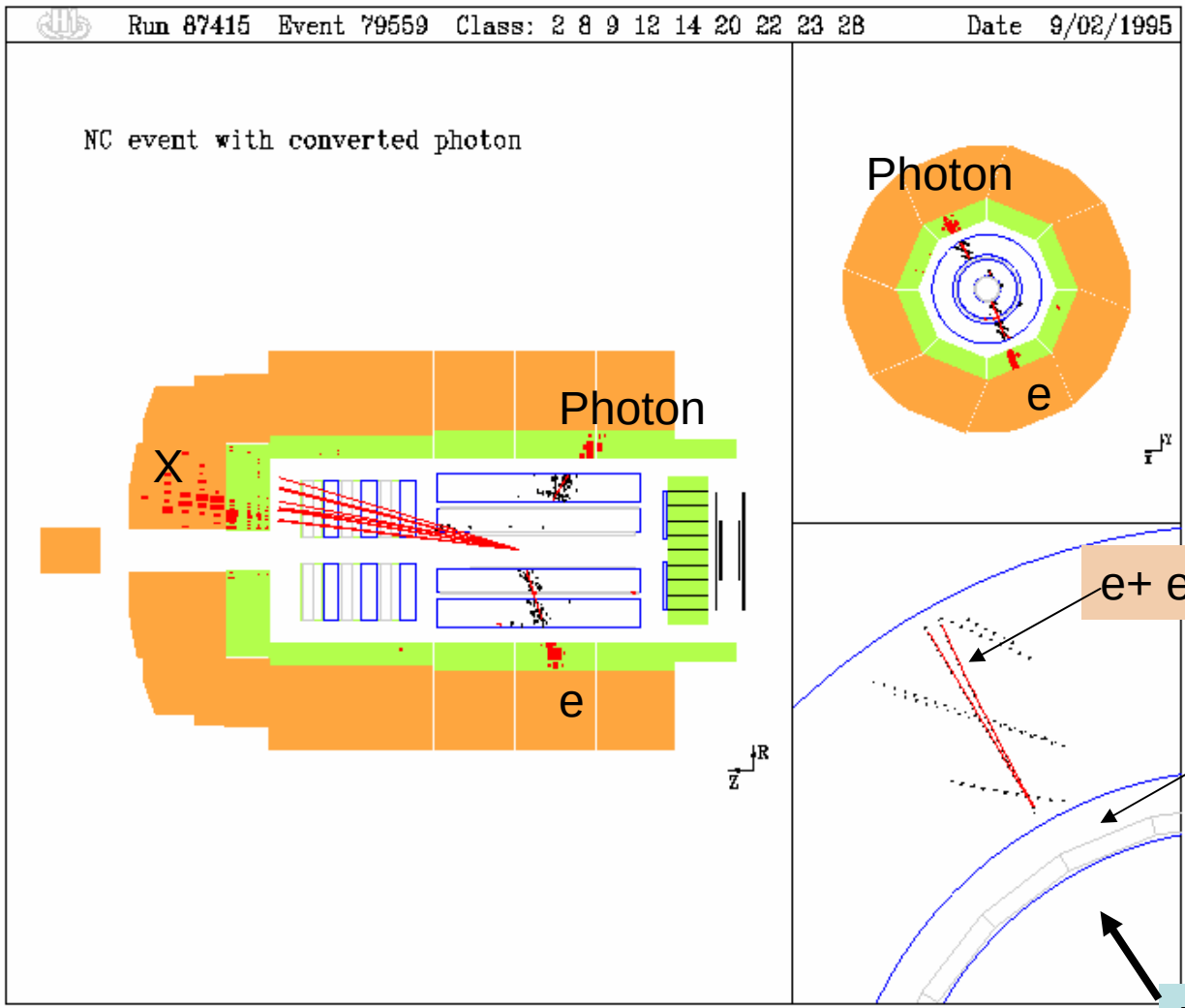
Here an electron and two photons are recorded



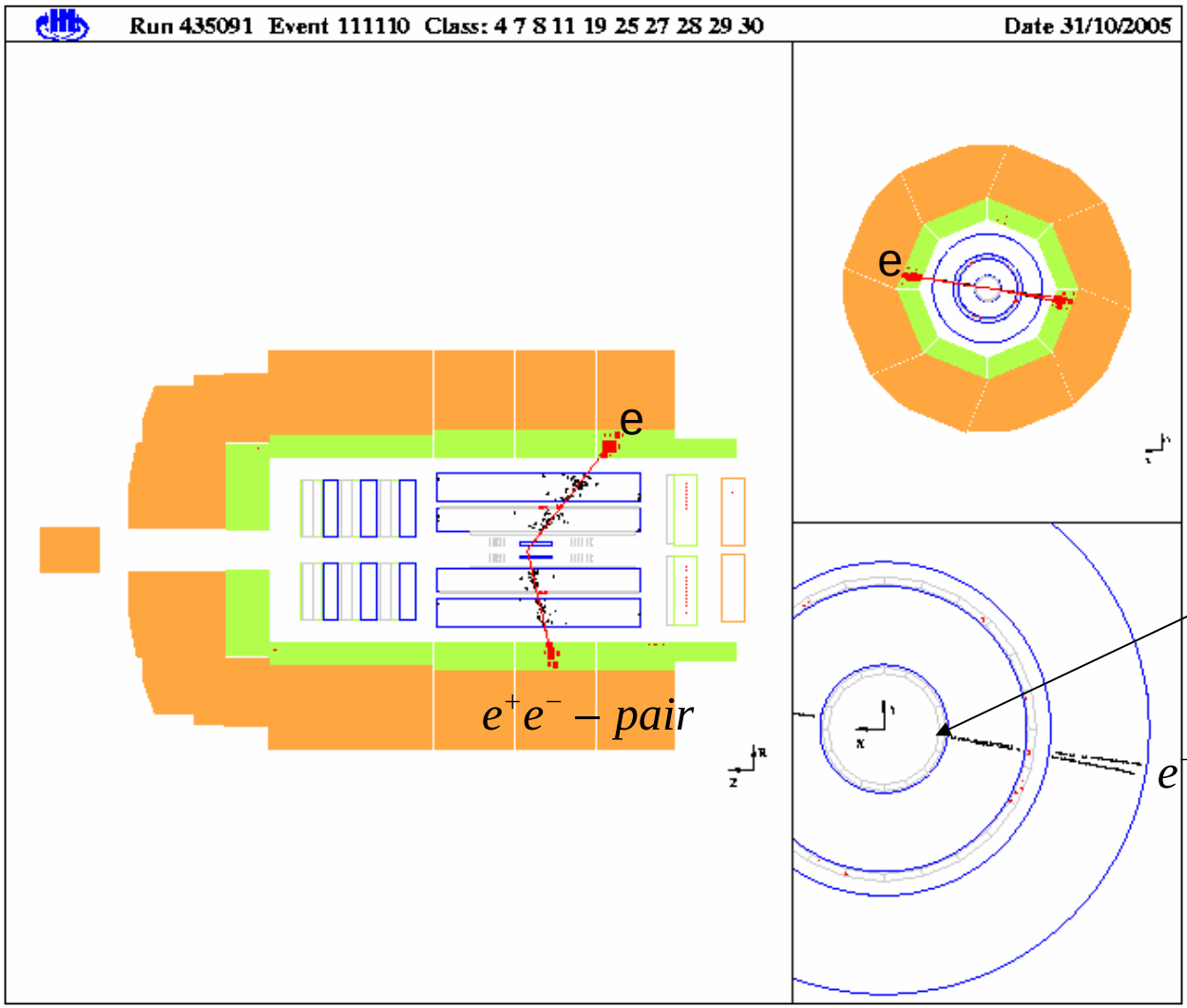
Electrons ‘easily’ radiate photons

Photons tend to convert to e+ e- pairs in material

$$ep \rightarrow e\gamma X \ldots\ldots \gamma \rightarrow e^+e^-$$



This looks like a di-electron, but is not.
A photon converted to a small angle e+ e- pair within the beam pipe

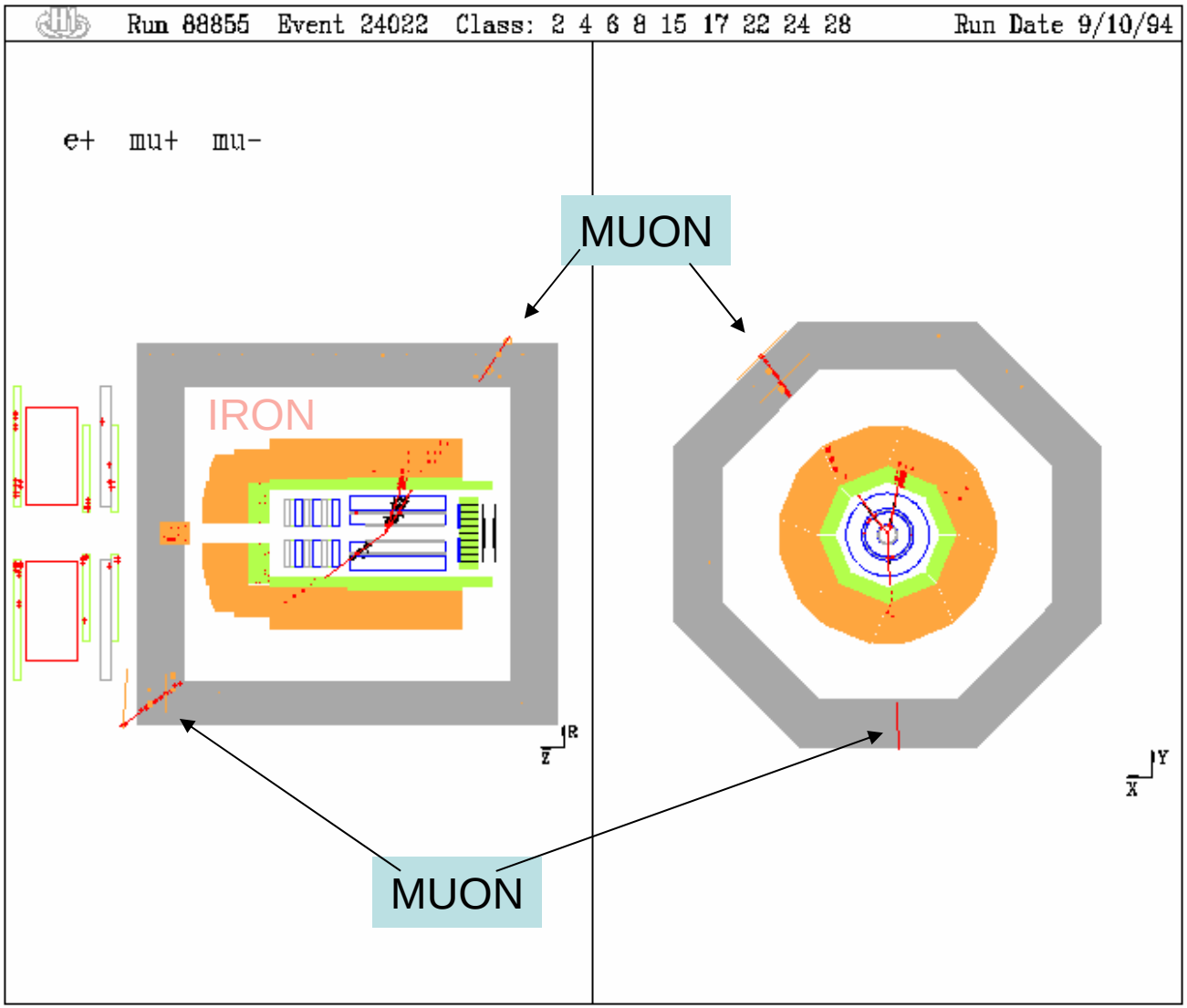


$$ep \to e\gamma(p)$$

$$\gamma \to e^+e^-$$

Another ‘simple’ event : A elastic dimuon production

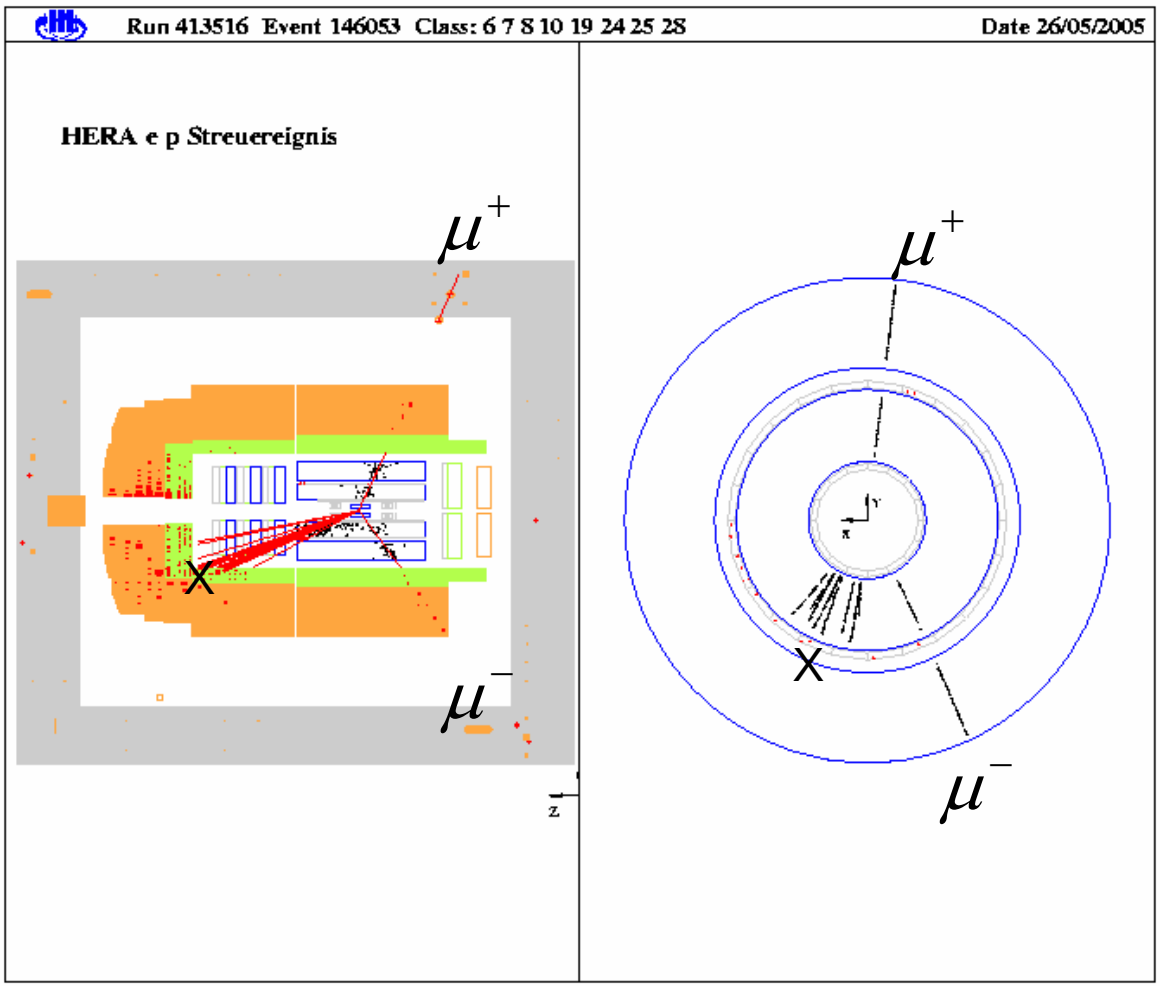
$$ep \to e\mu^+\mu^-(p)$$



Muons penetrate thick materials !

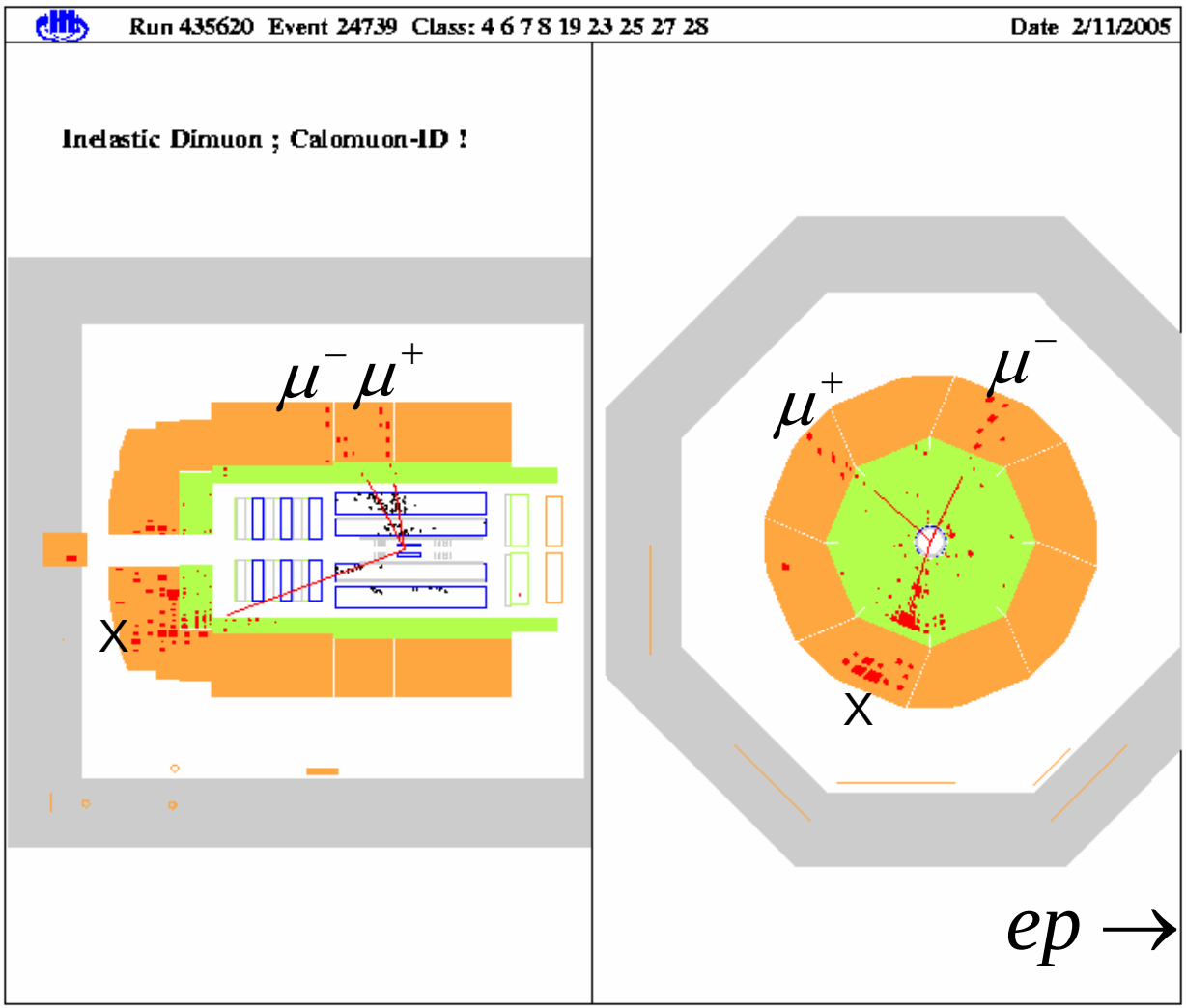
An inelastic dimuon production without visible scattered electron

$$ep \to (e)\mu^+\mu^- X$$



Another inelastic dimuon production without visible scattered electron

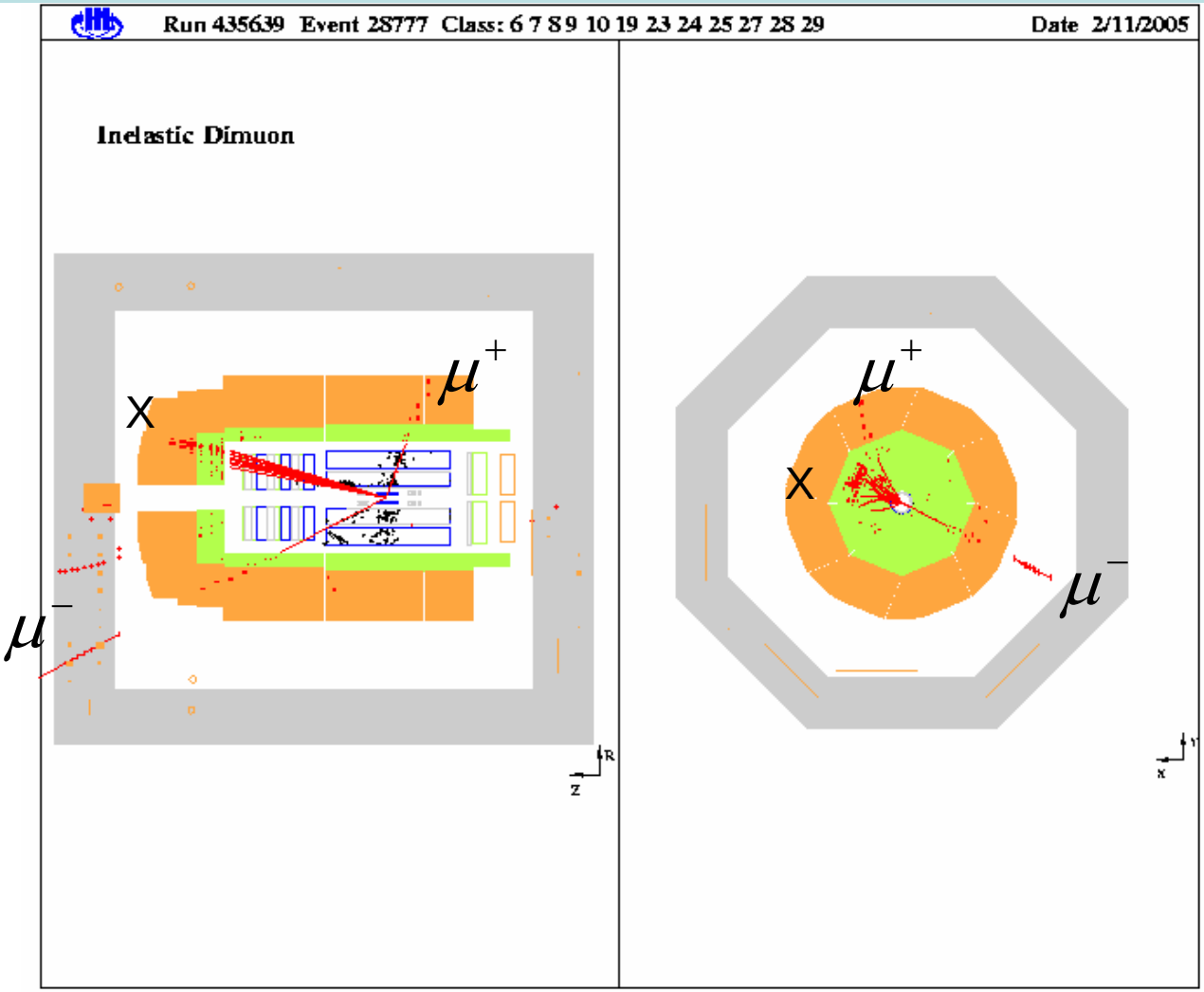
The muons are low energetic and don't read the iron,they are 'mips' in calorimeter



$$ep \rightarrow (e)\mu^+\mu^- X$$

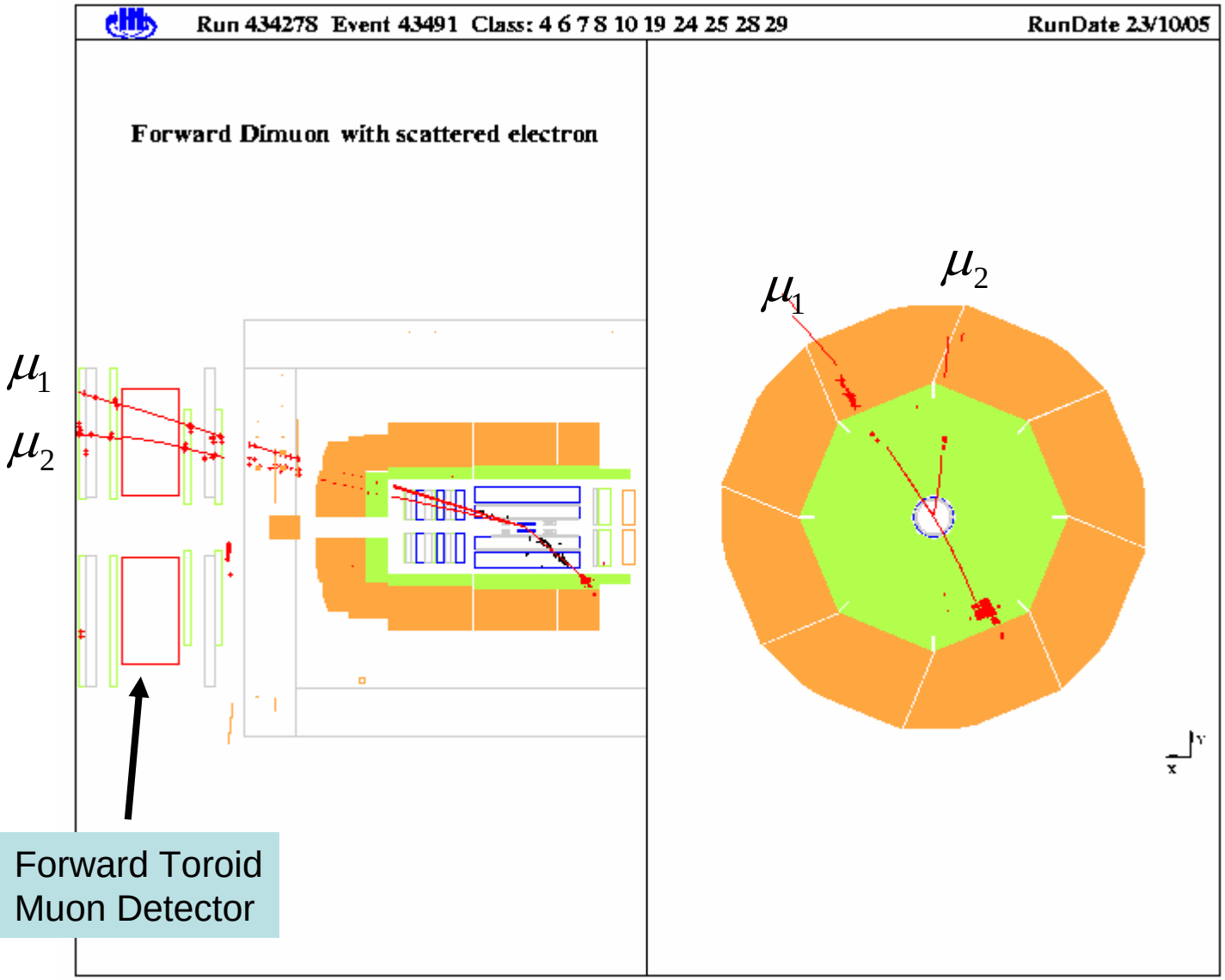
Another inelastic dimuon production without visible scattered electron

One muon identified in calorimeter, the other in the iron system

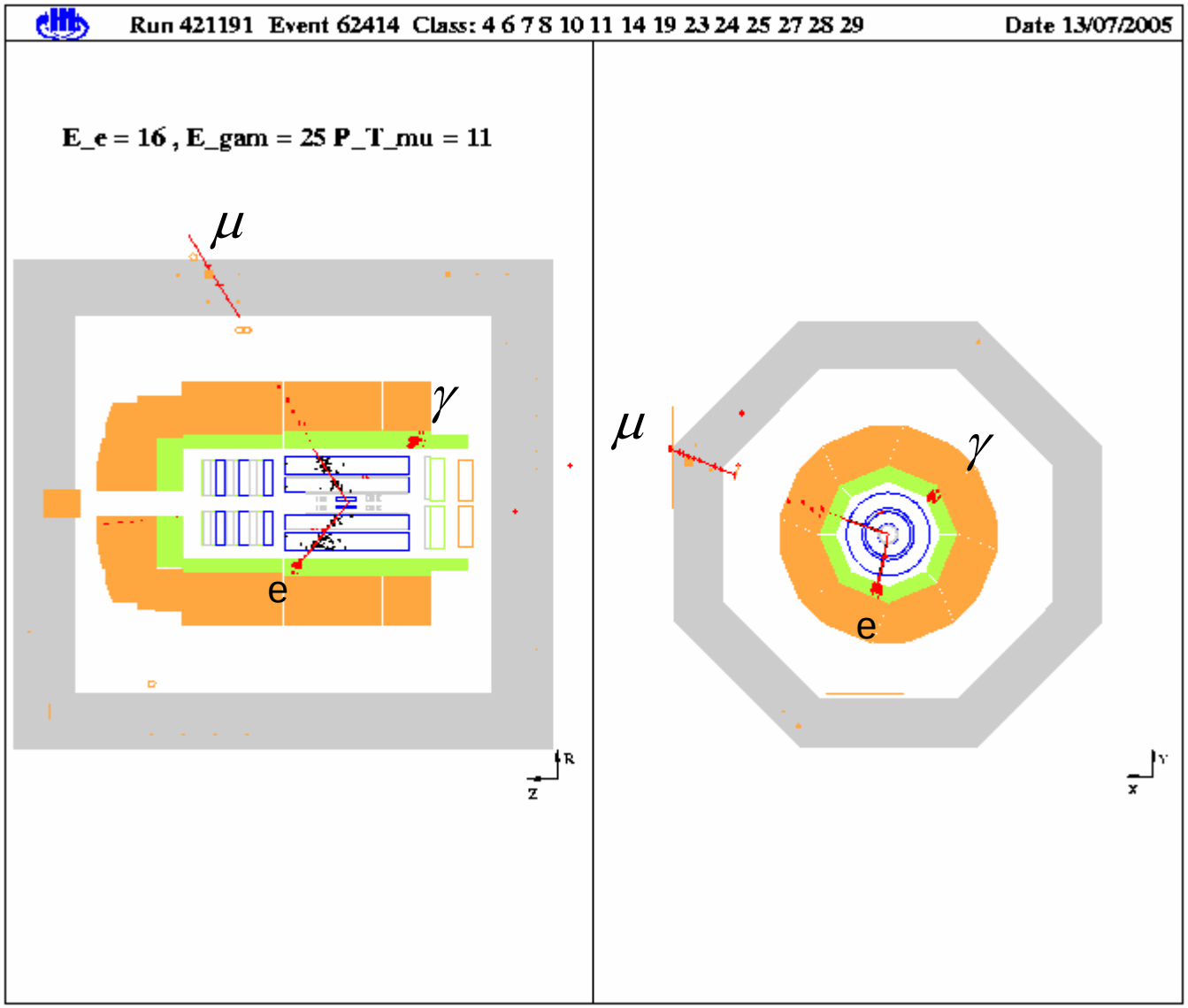


$$ep \to (e)\mu^+\mu^- X$$

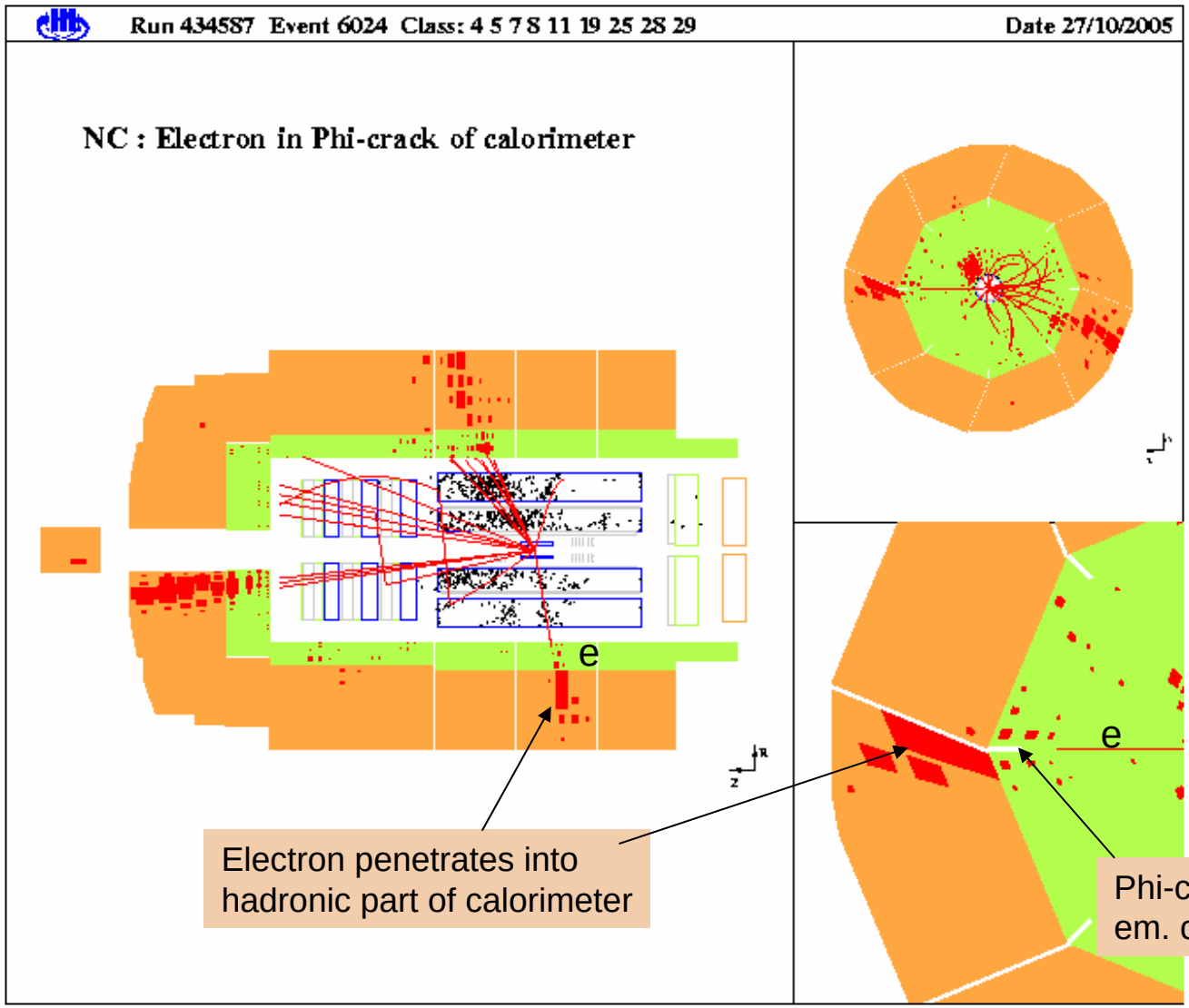
In the ‘forward direction’ muons are measured by the ‘Forward Toroid Muon Detector’



Here it is very visible how electron, muon and photon are distinguished



No detector is perfect : Here the scattered electron enters a nonsensitive region (Phi-crack) of the electromagnetic calorimeter

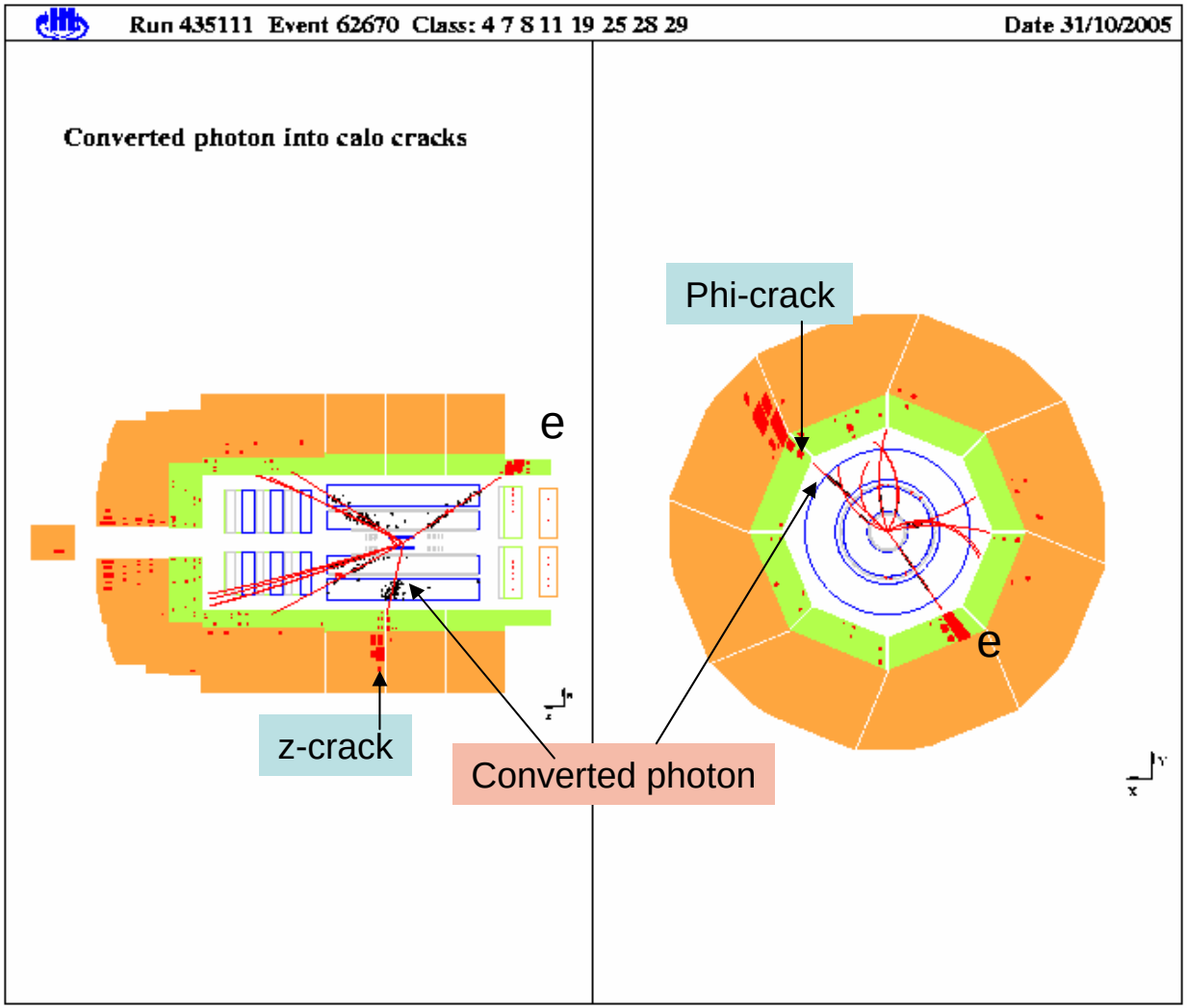


Such an effect has to be recognized in the physics analysis !

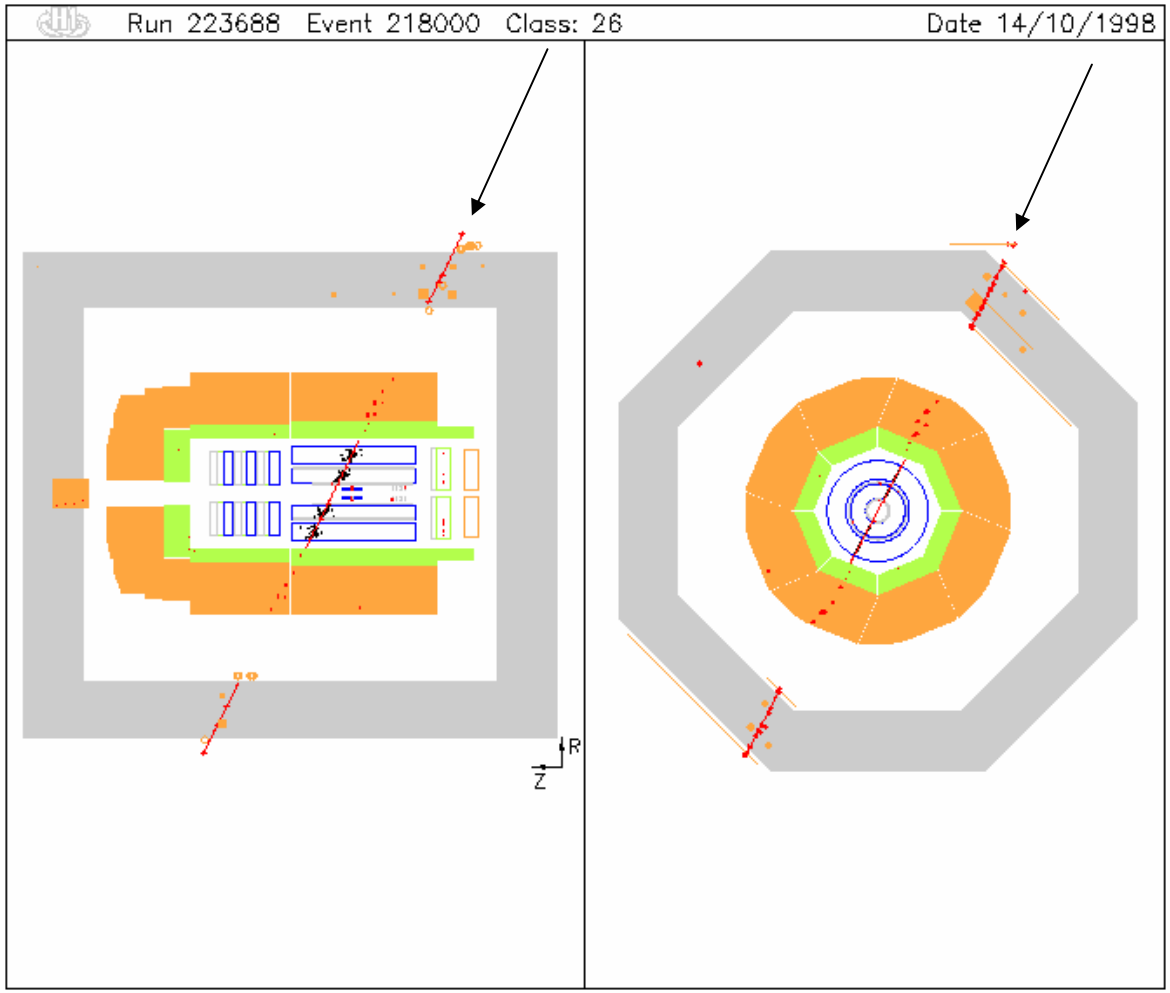
Here a photon converts and the e+ e- pair enters an insensitive region of the em. calorimeter (z- and Phi-cracks)

$$ep \to e\gamma X$$

$$\gamma \to e^+e^-$$

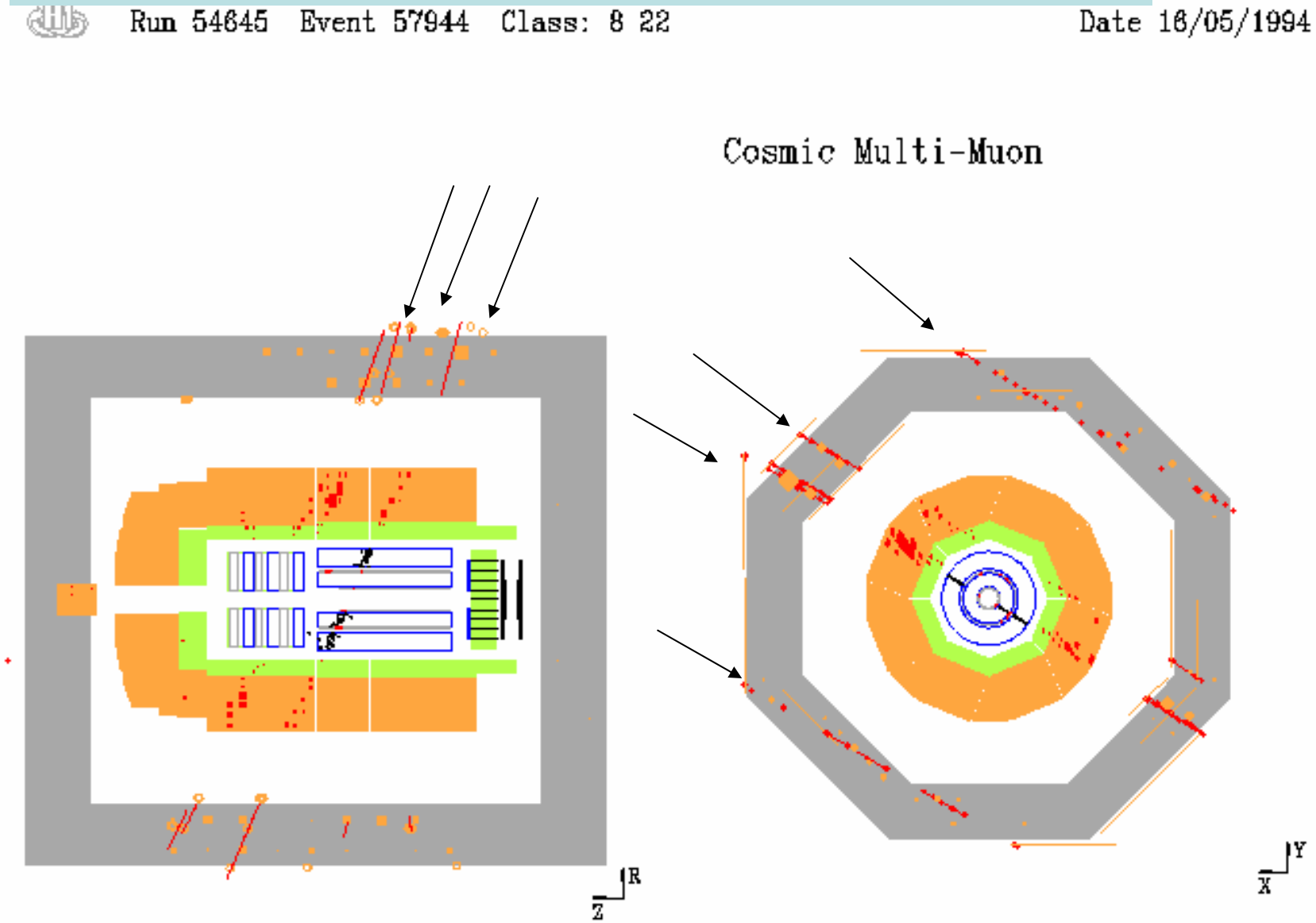


Muons also come from the sky ……

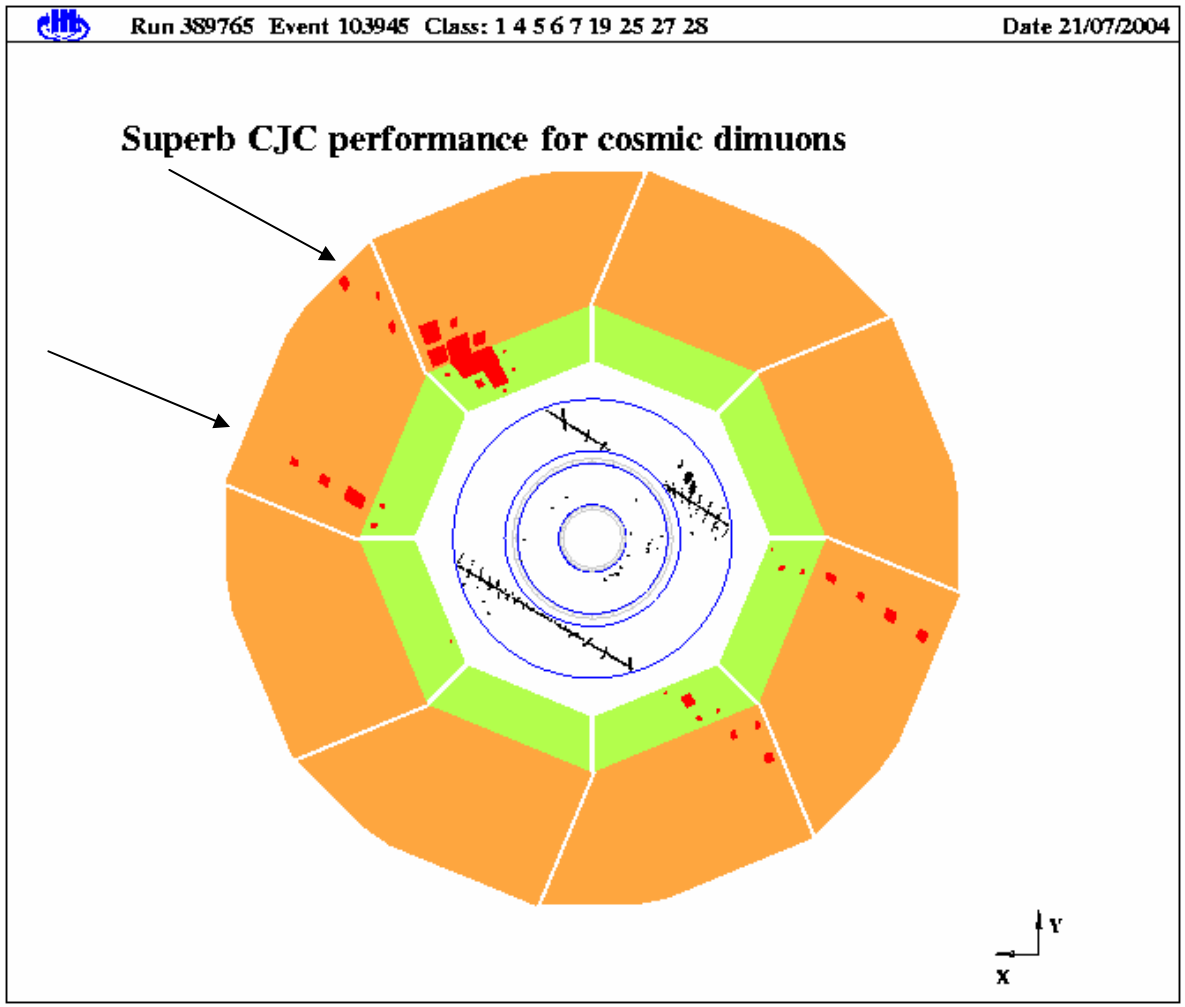


This is BACKGROUND, which we do not like !

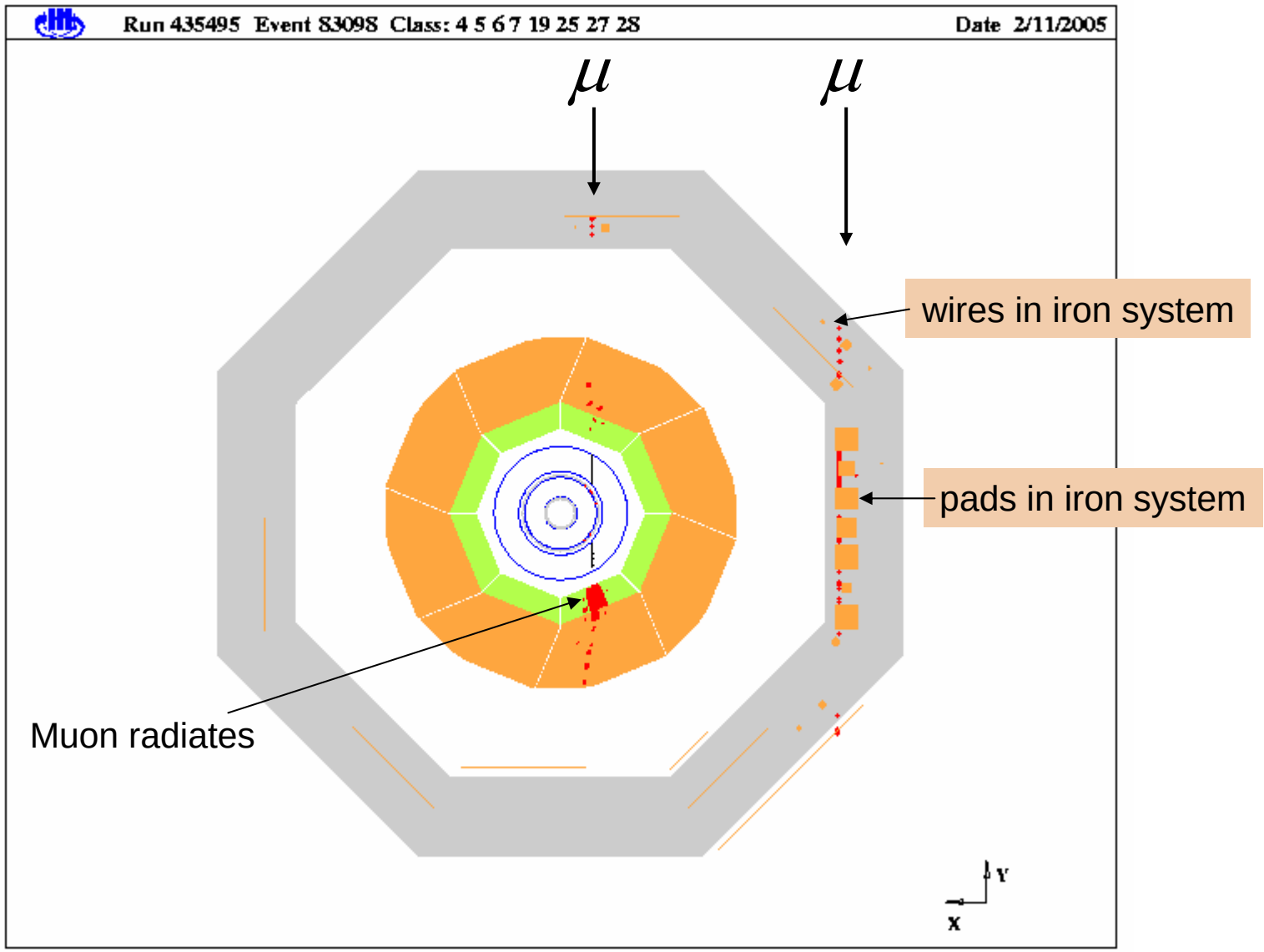
Interaction of cosmic primaries create showers in the atmosphere, and multimuons reach us here



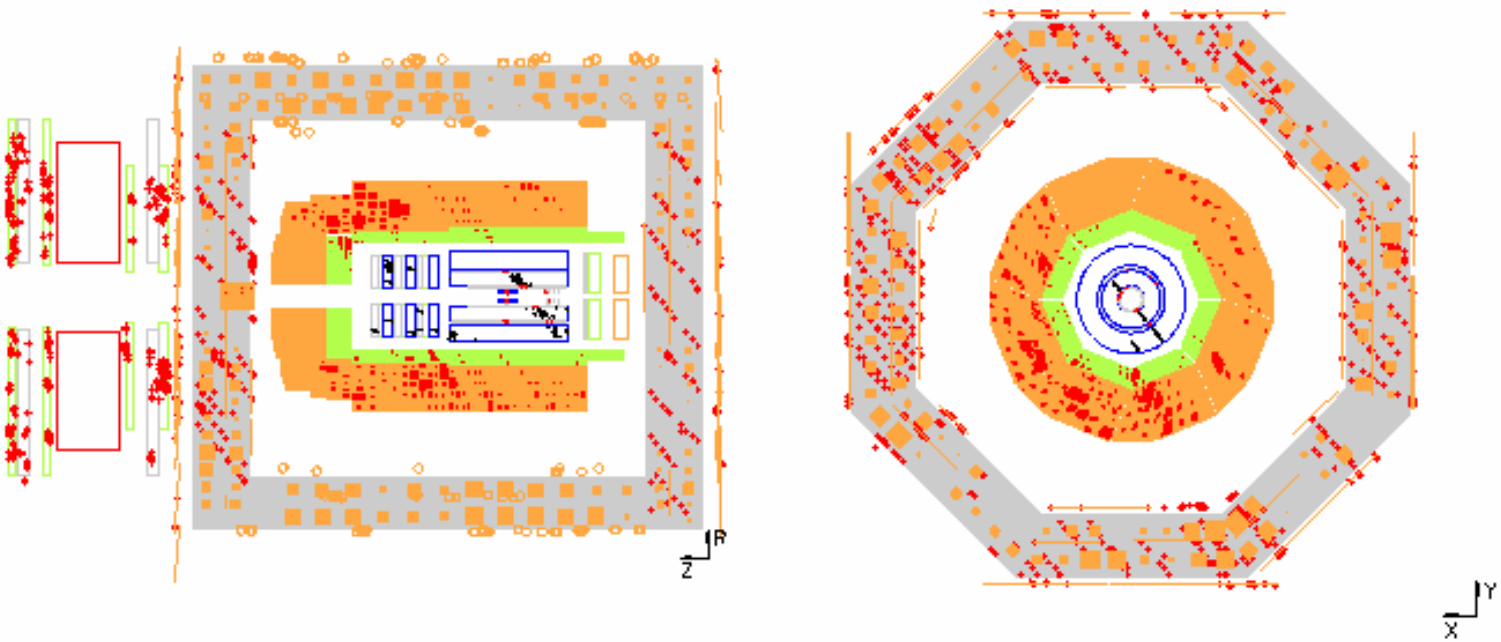
Cosmic dimuon seen in calorimeter and central track detector



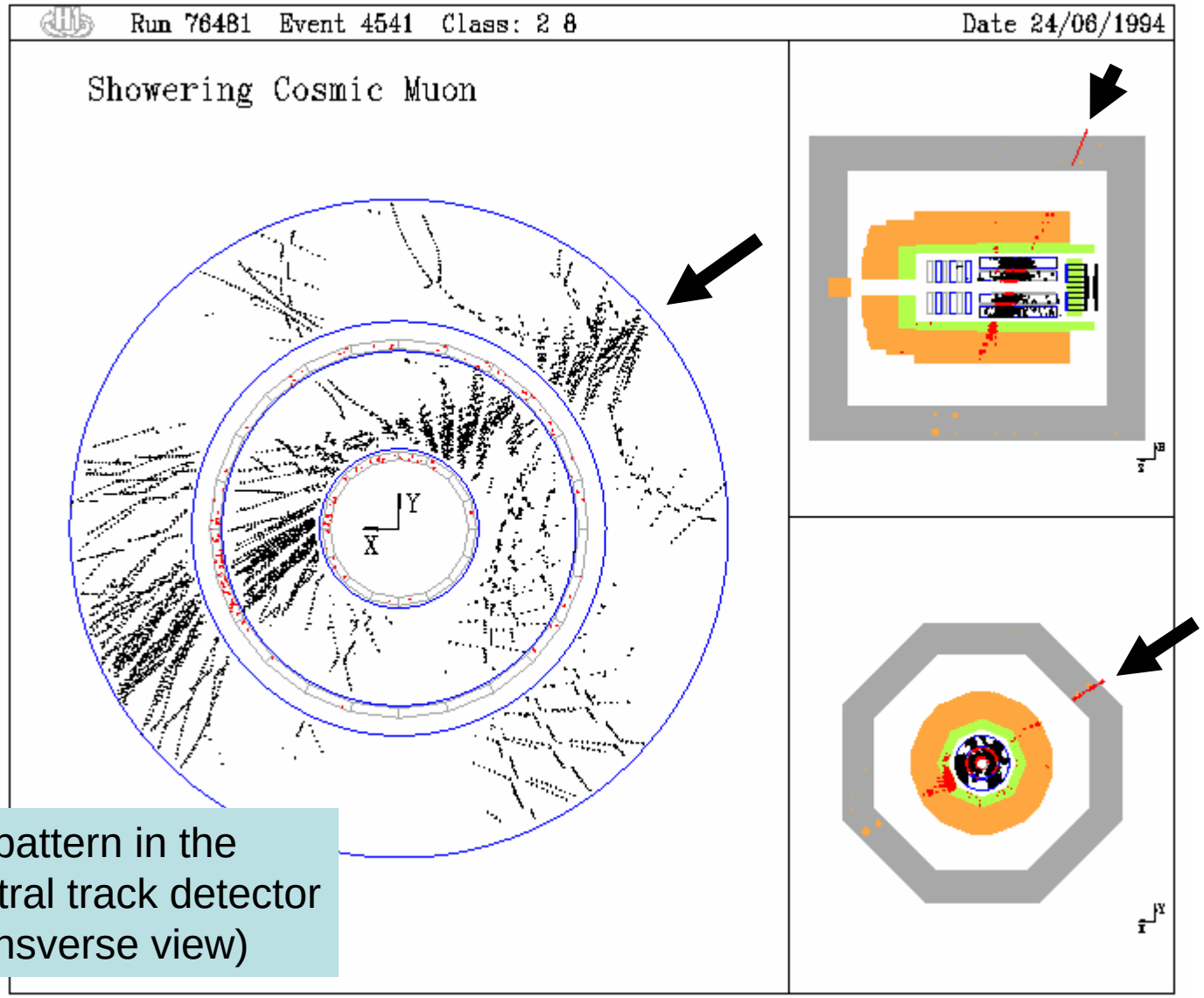
Another cosmic dimuon …



…and it can be even more fierce ….

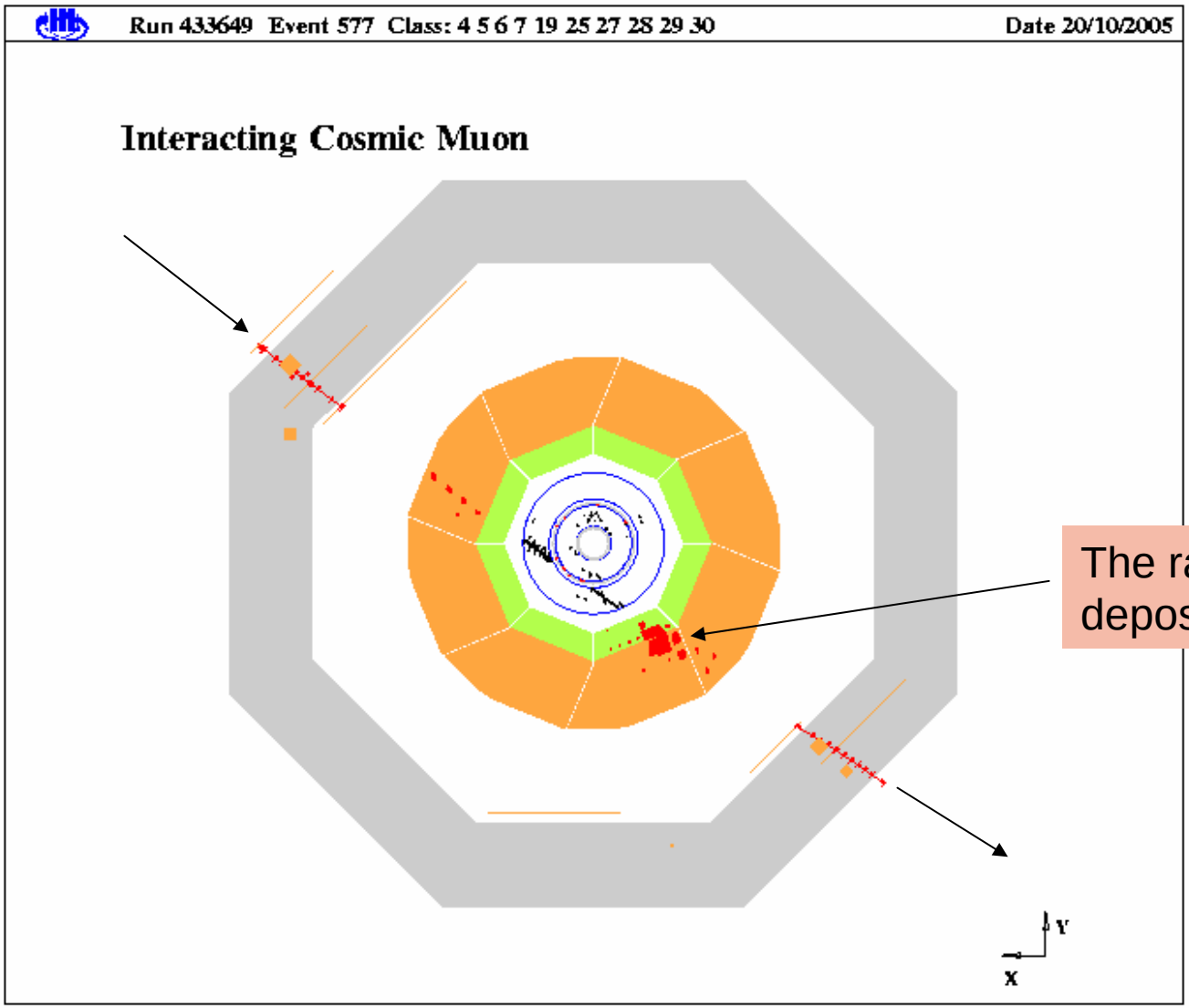


Muons interact rarely, but they do



Hit pattern in the central track detector (transverse view)

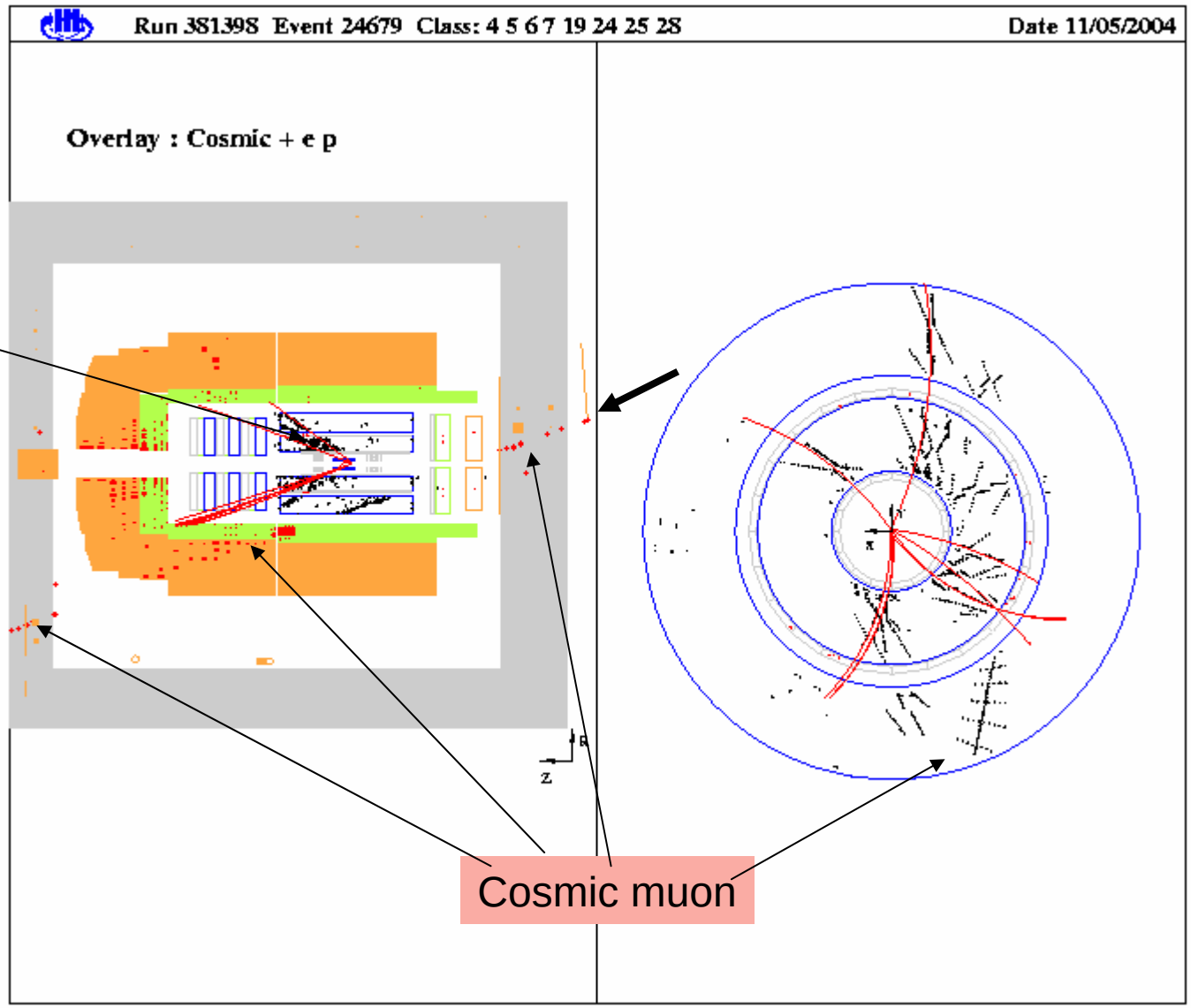
Here a cosmic muon radiates a photon which gets absorbed in the calorimeter. The muon then exits the detector.



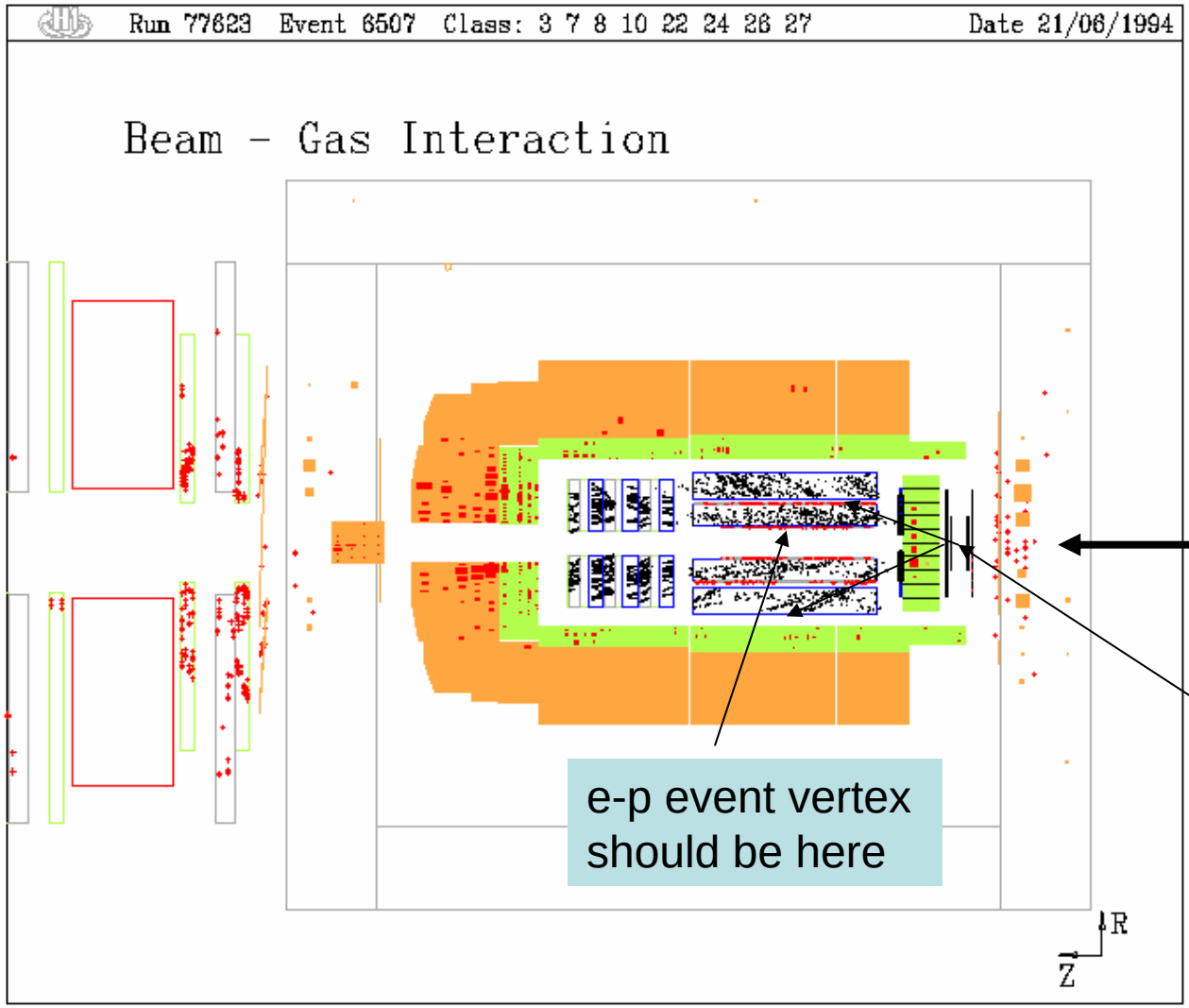
The radiated energy deposition

A HERA ep event overlayed with a cosmic muon

Such an effect has to be recognized in the physics analysis !



There is not only background from cosmics but also from the Proton beam interacting with the restgas

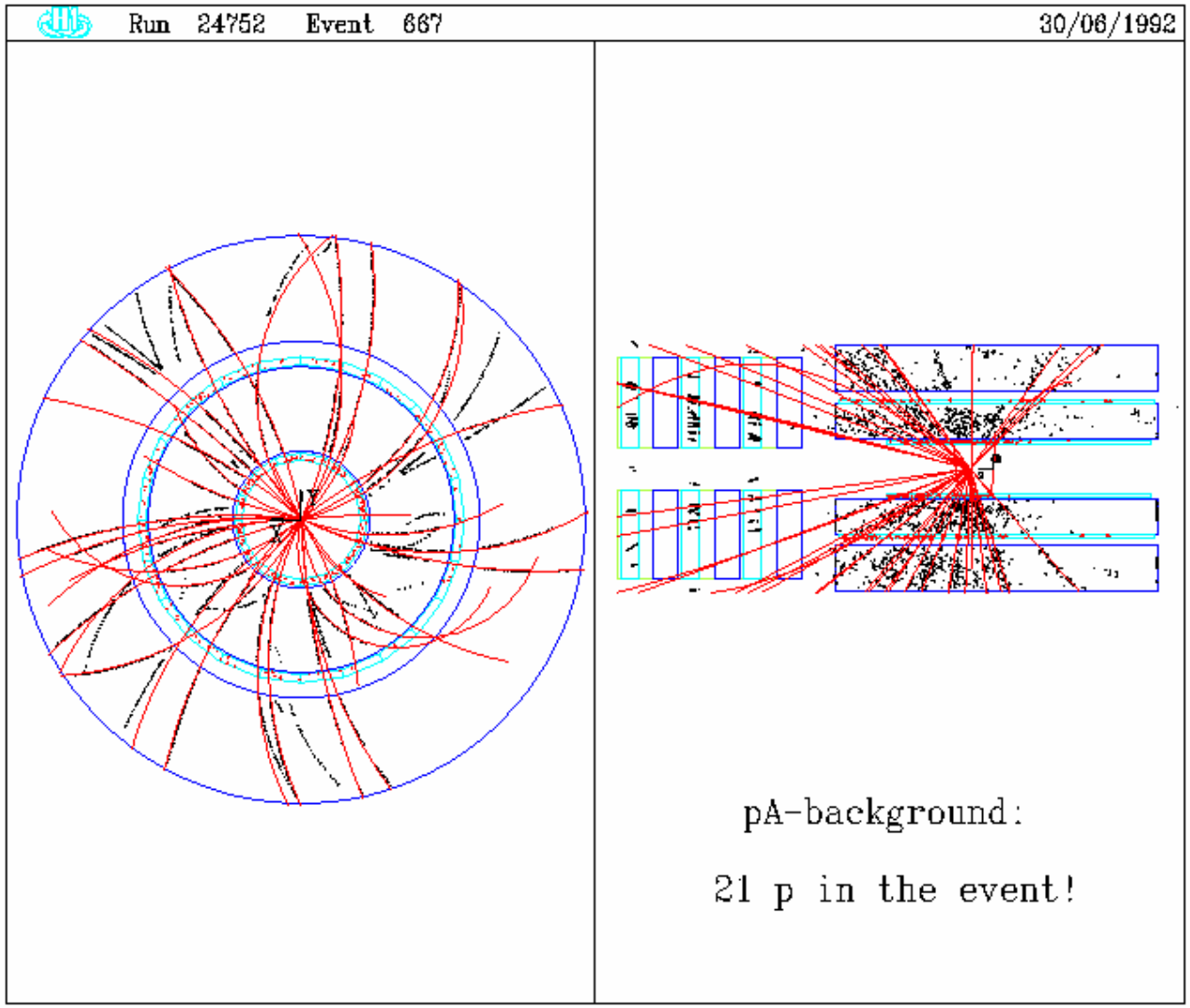


P - beam

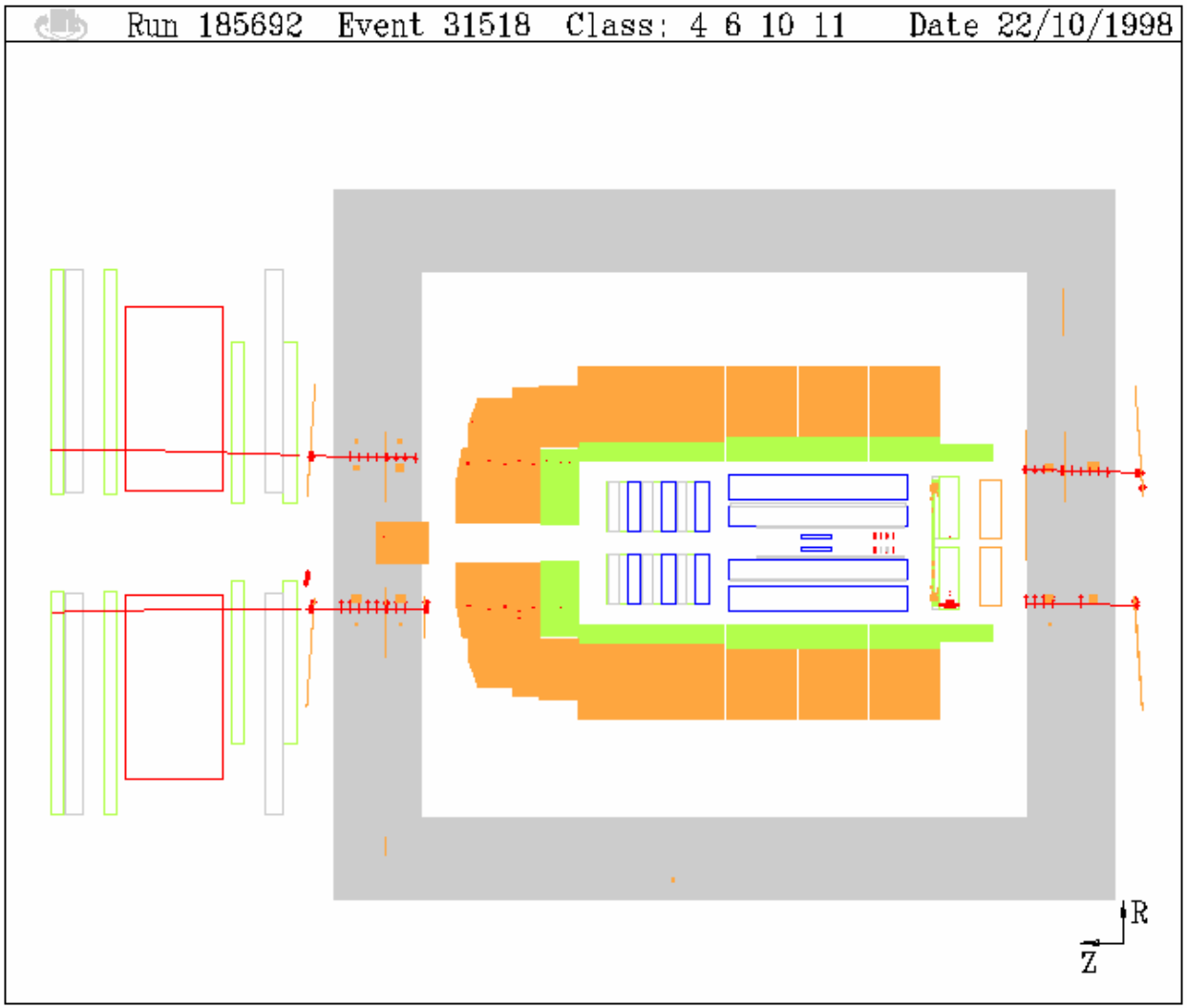
e-p event vertex should be here

Event vertex is here

Scattering of the HERA-proton on a nucleus of the restgas.
The nucleus dissociates into lots of protons (positive tracks) and neutrons



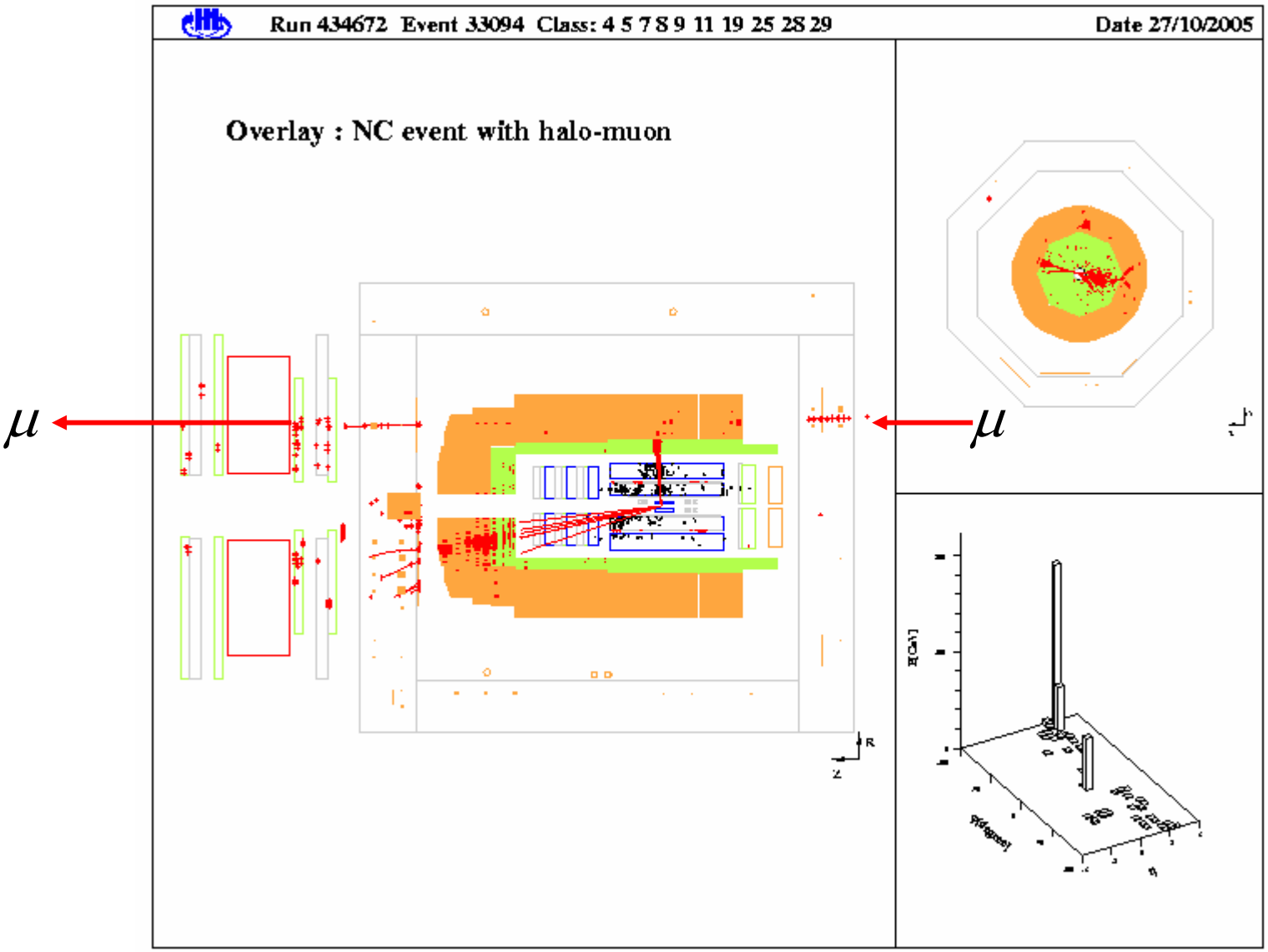
Another kind of beam-related background :
Protons lost in the ring create showers and muons from decaying pions accompany the beam and may be visible in the detector



Beamhalo muons

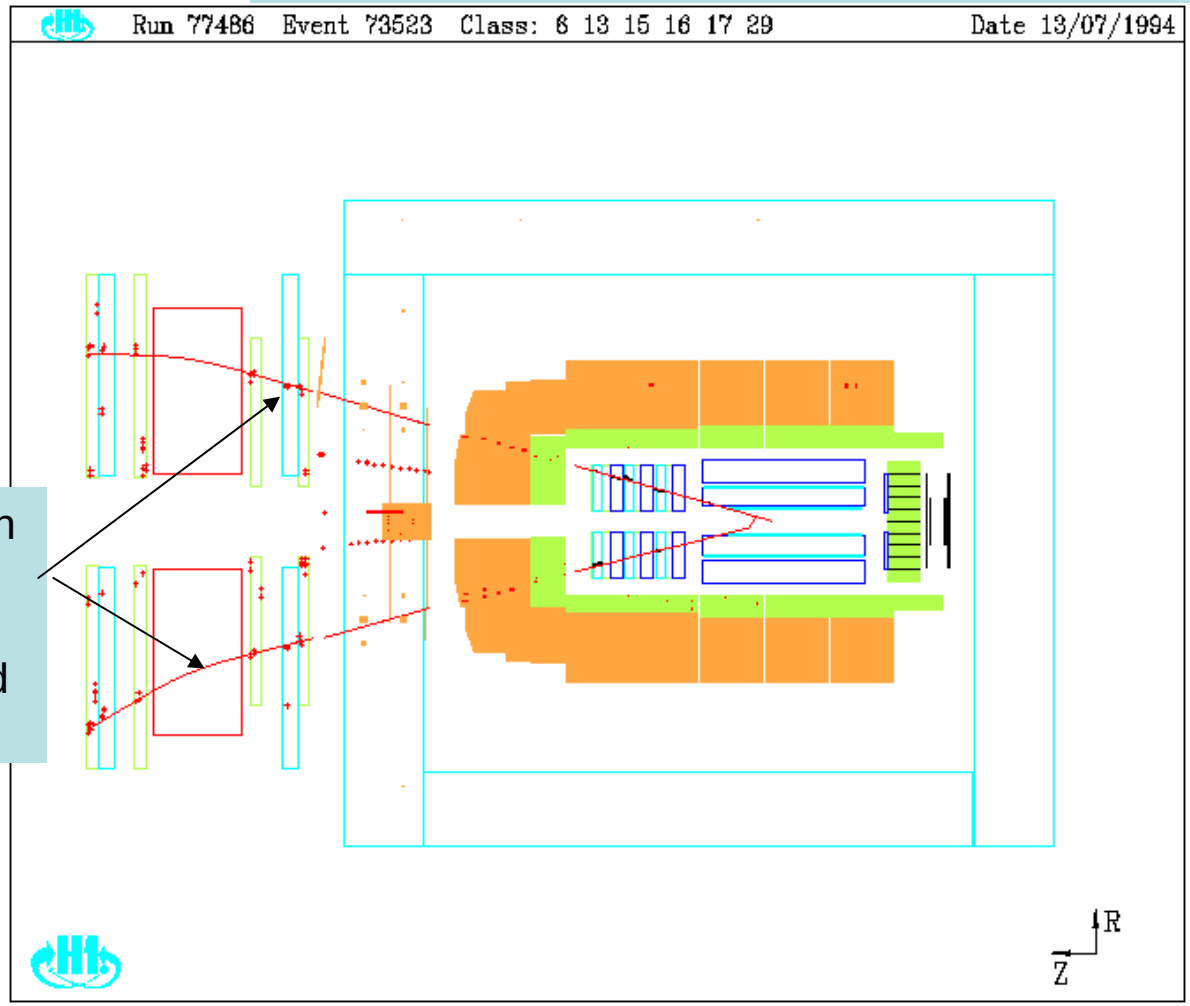
Here a NC event is overlayed by a beam halo muon

Such an effect has to be recognized in the physics analysis !



Back to HERA -e-p scattering events :
A very forward Dimuon event

These muons are decay products of the famous J/Psi particle

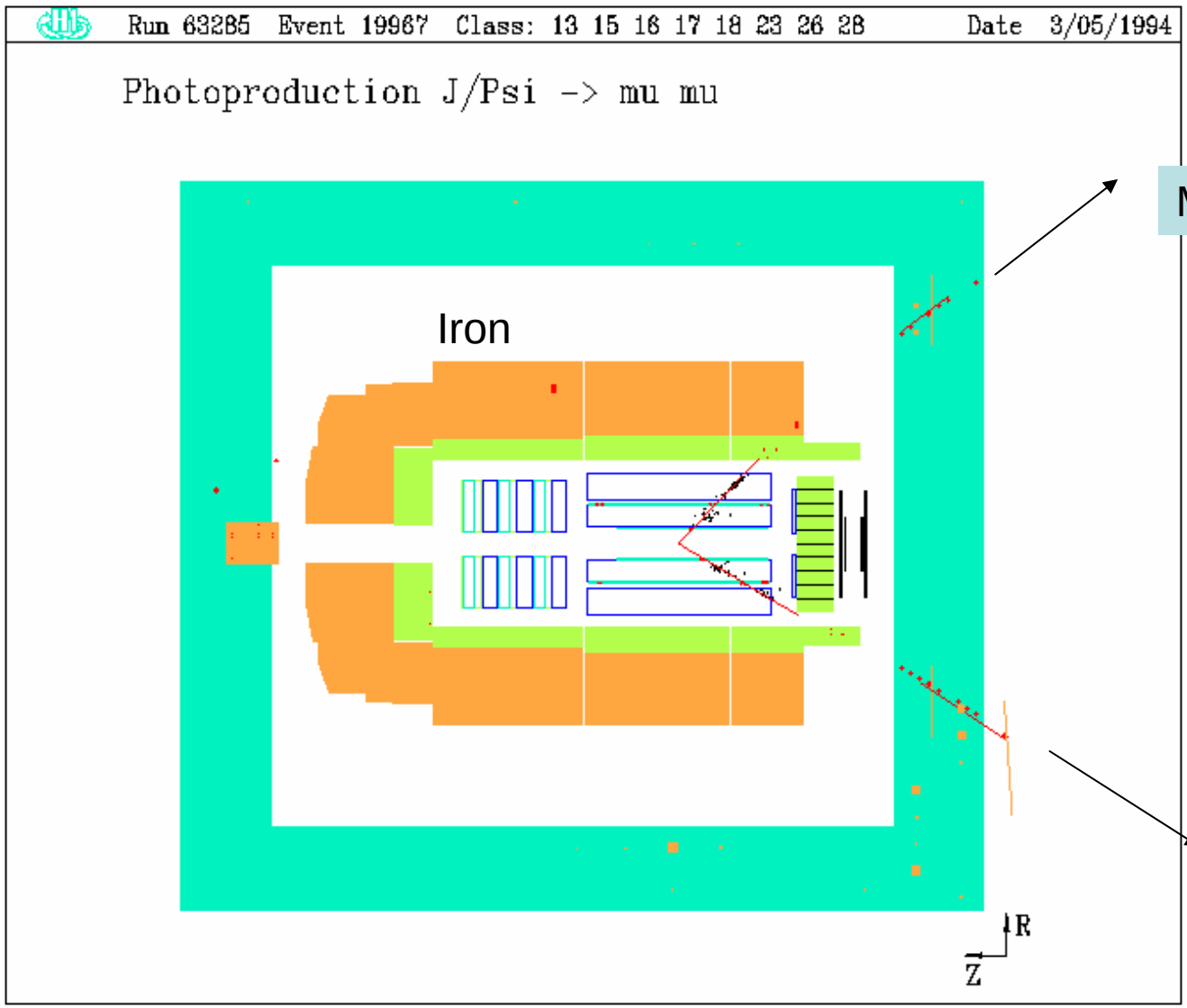


Muons bent in the magnetic field of the forward toroid magnet

$$ep \rightarrow (e)(p)J/\Psi$$

$$J/\Psi \rightarrow \mu^+\mu^-$$

Another event where the J/Psi particle decays into two muons (this time 'backward')



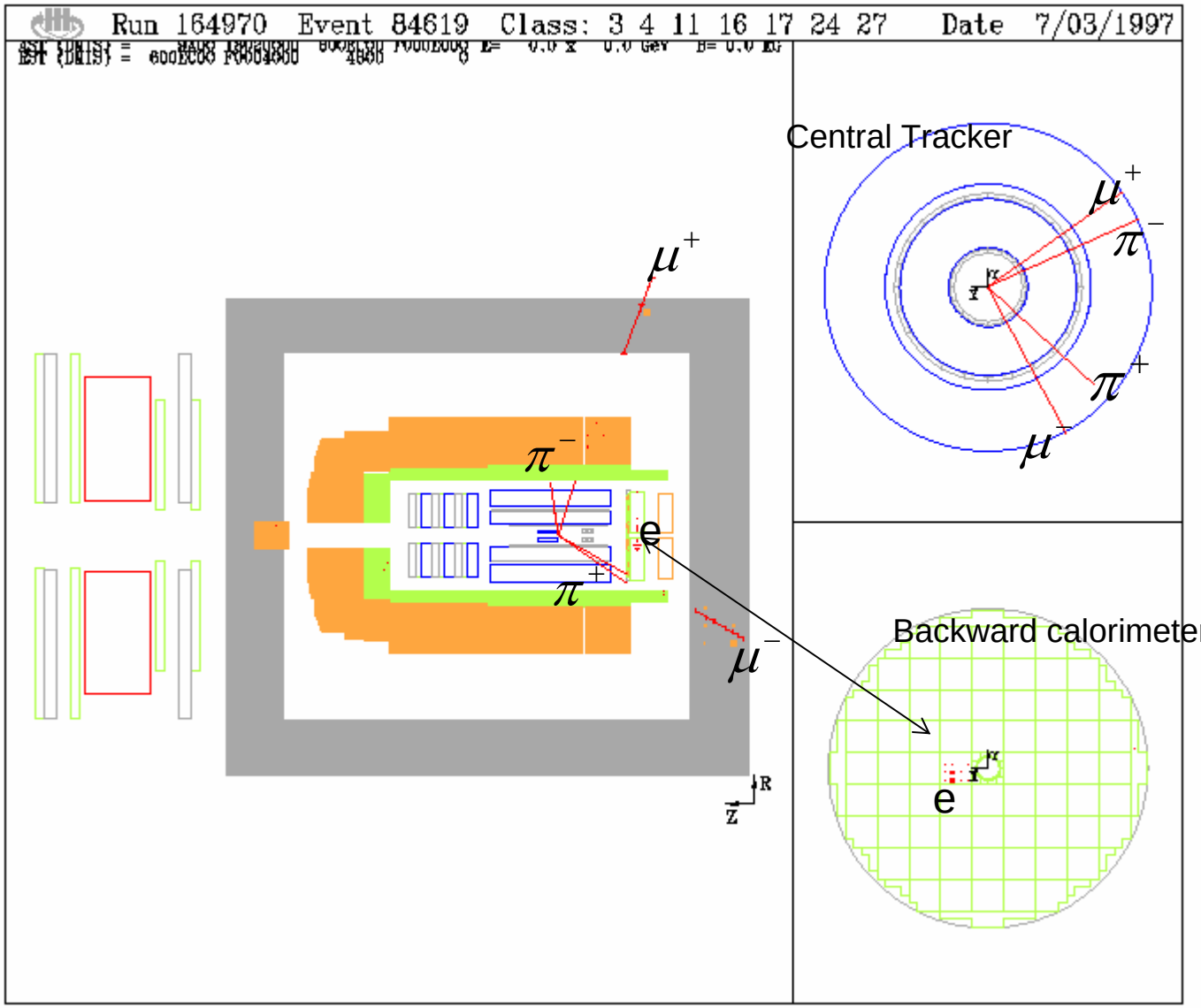
Muon

Muon

$$ep \to (e)(p)J/\Psi$$

$$J/\Psi \to \mu^+\mu^-$$

The J/Ψ particle has a sister the Ψ'

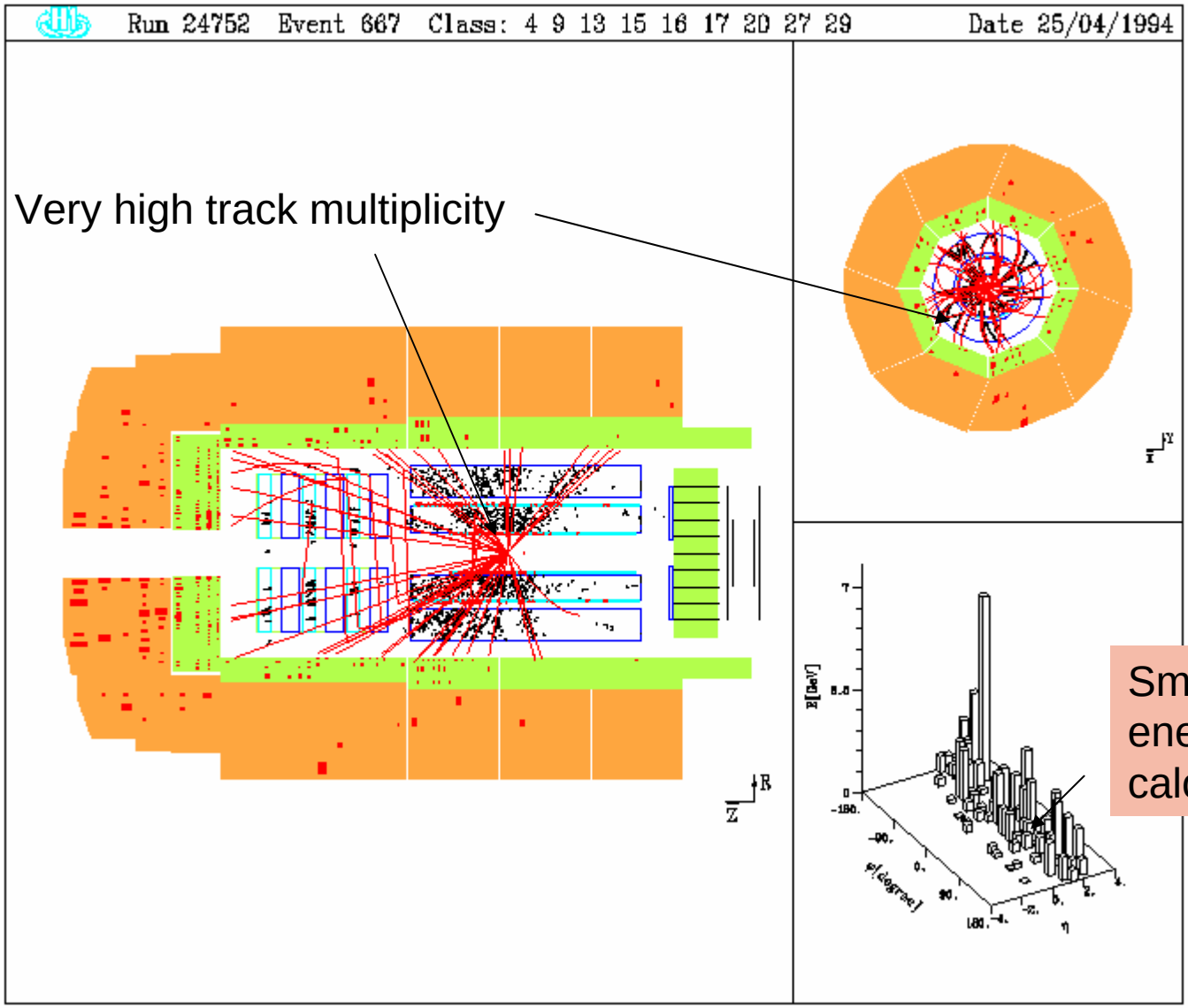


$$ep \to e(p)\Psi'$$

$$\Psi' \to \Psi \pi^+ \pi^-$$

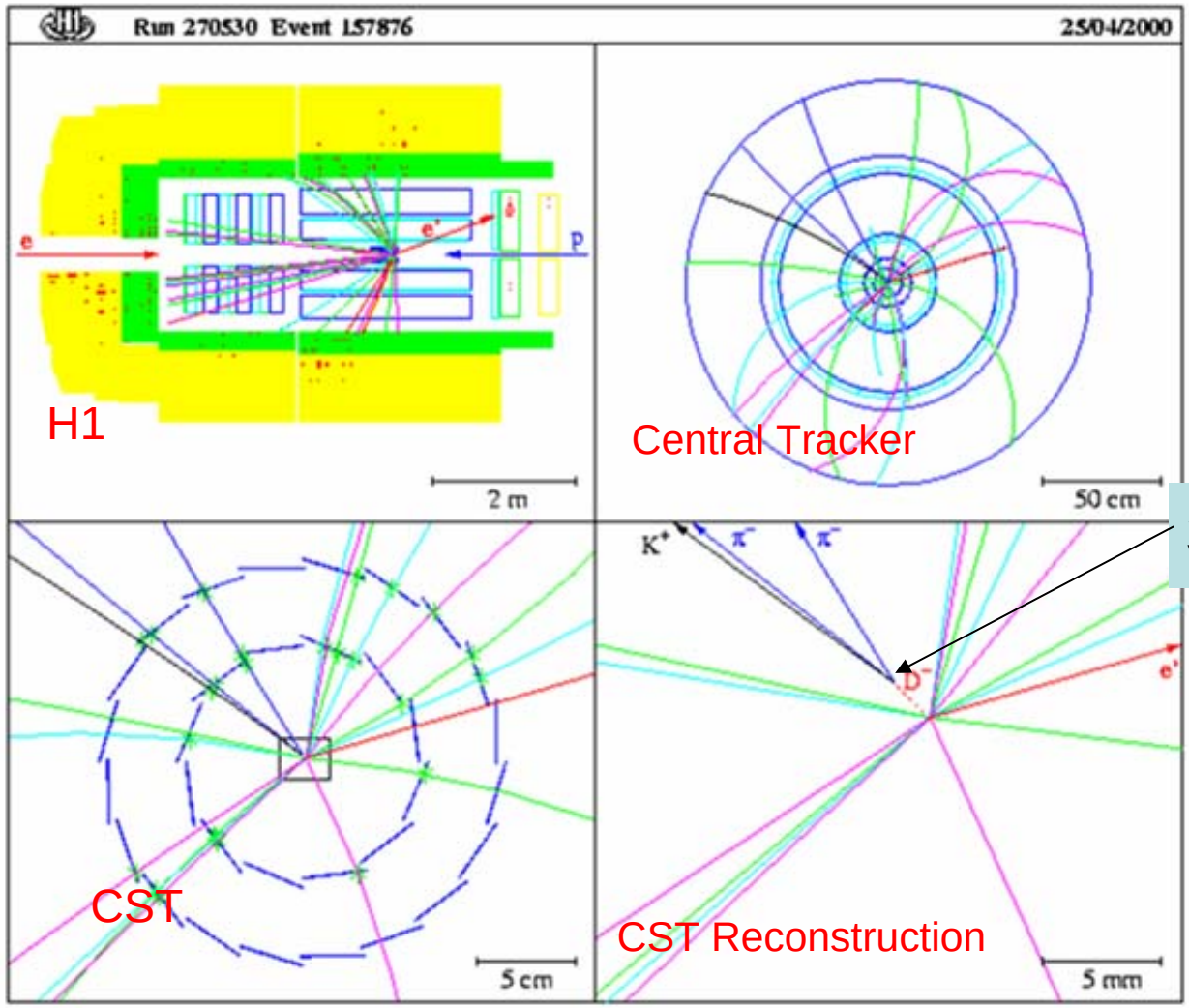
$$\Psi \to \mu^+ \mu^-$$

Most events are much more complicated :

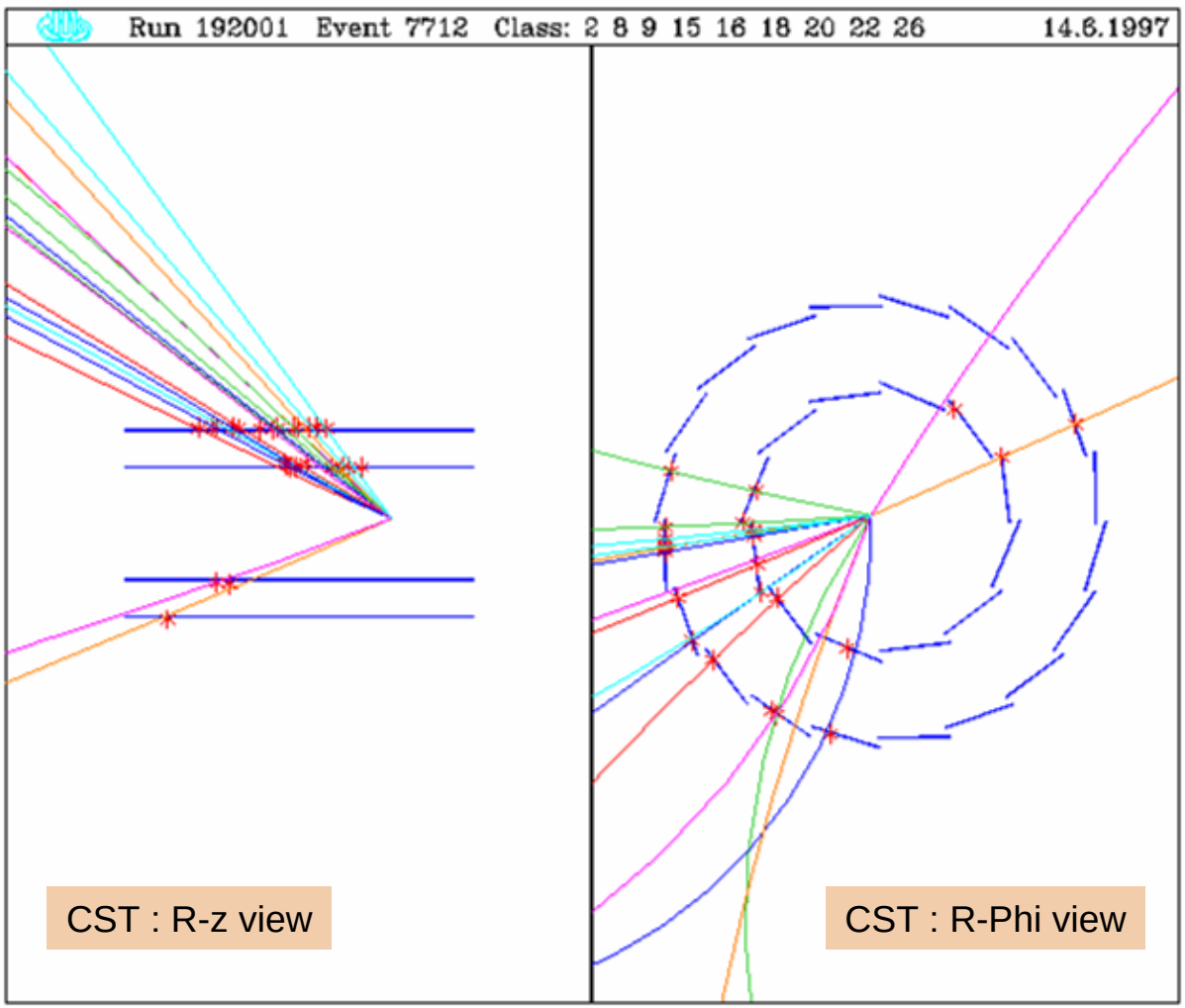


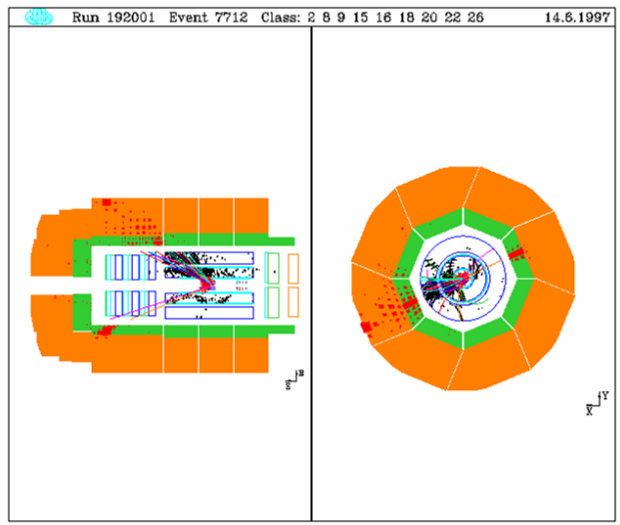
The Central Silicon Detector (CST) measures hits very precisely (10 micrometer). search for secondary vertices of heavy quark (charm,bottom) decays :

Zoom in ….

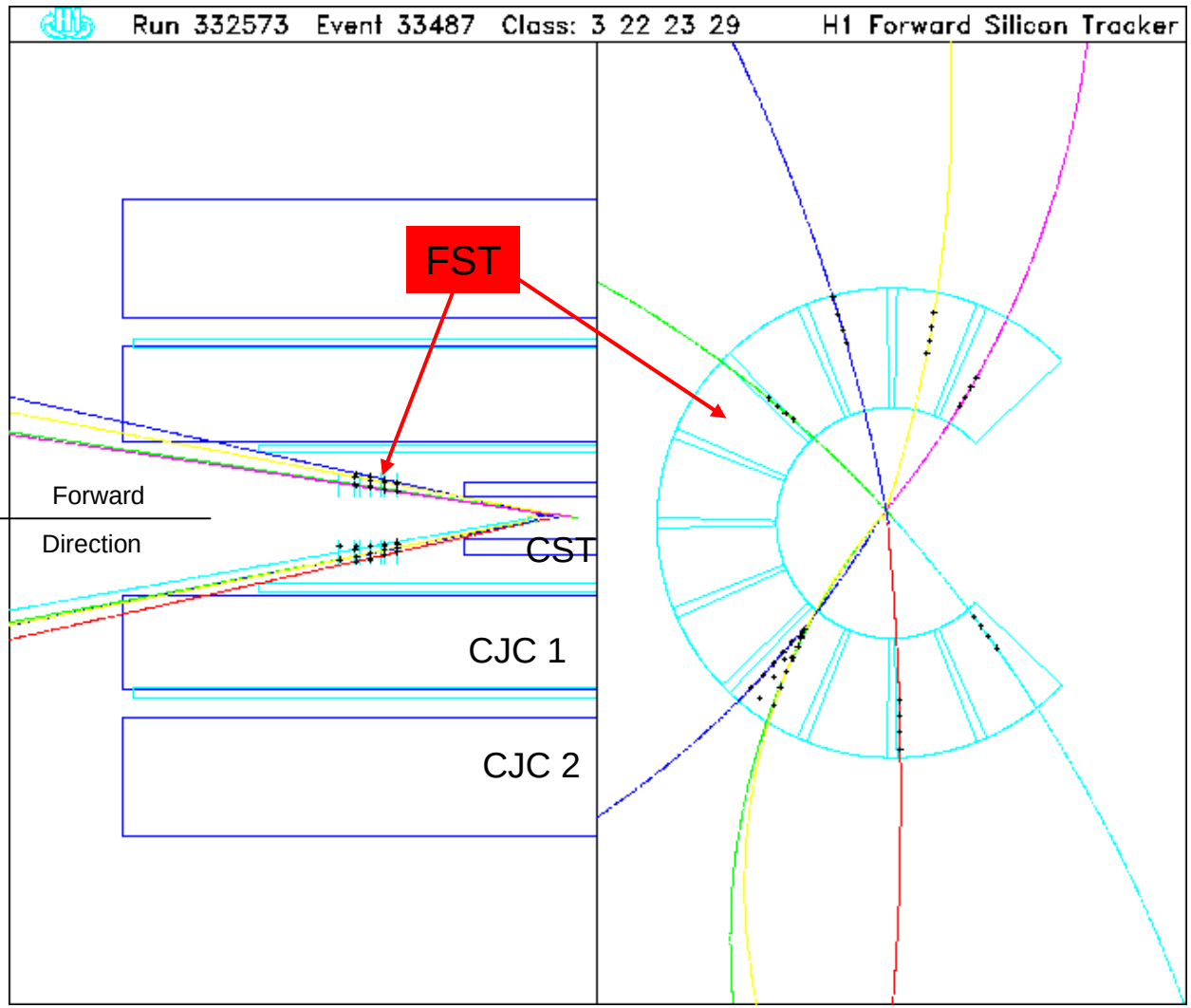


Another event with detailed track measurement in the CST



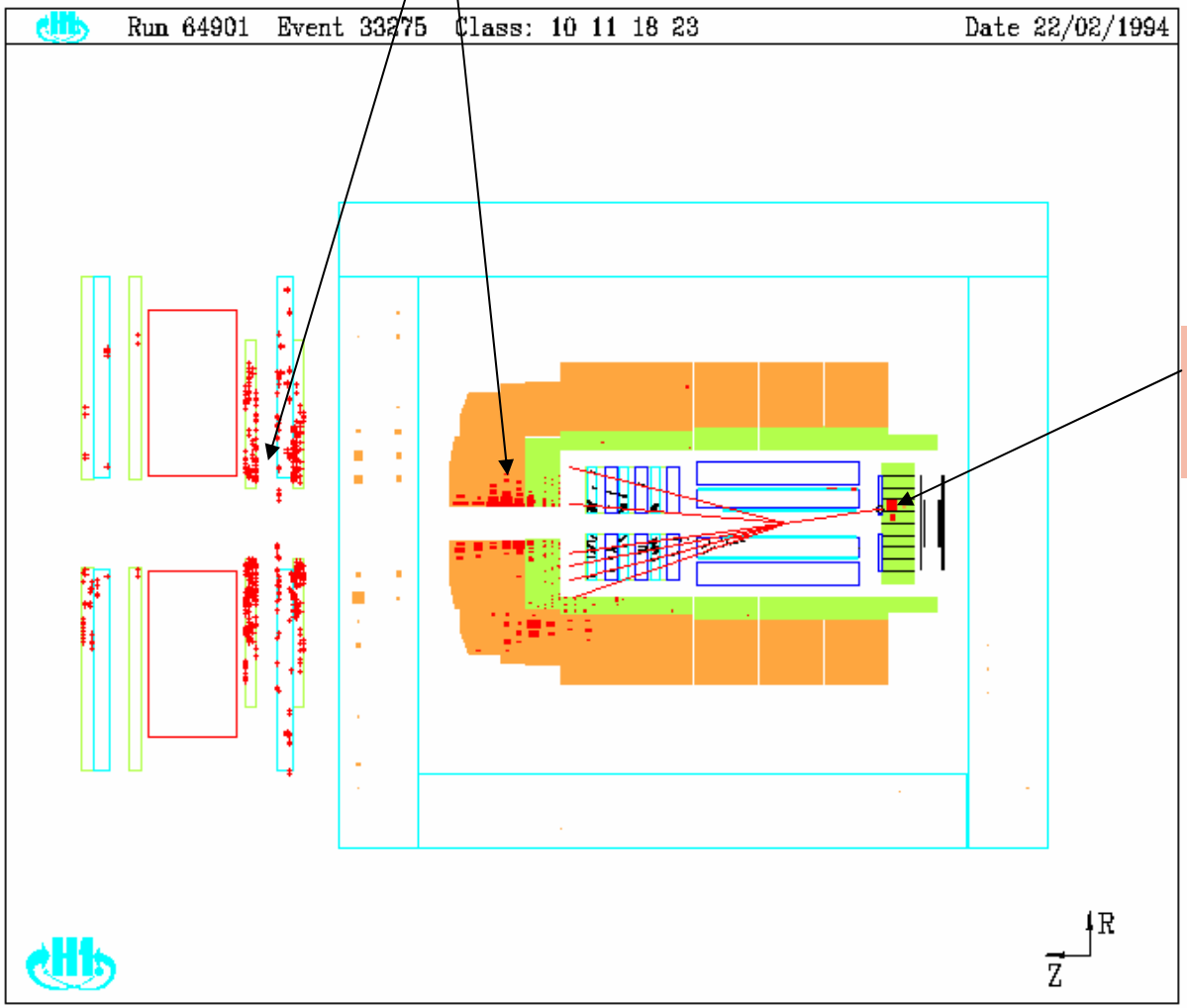


Tracks seen in the Forward Silicon Track Detector (FST)



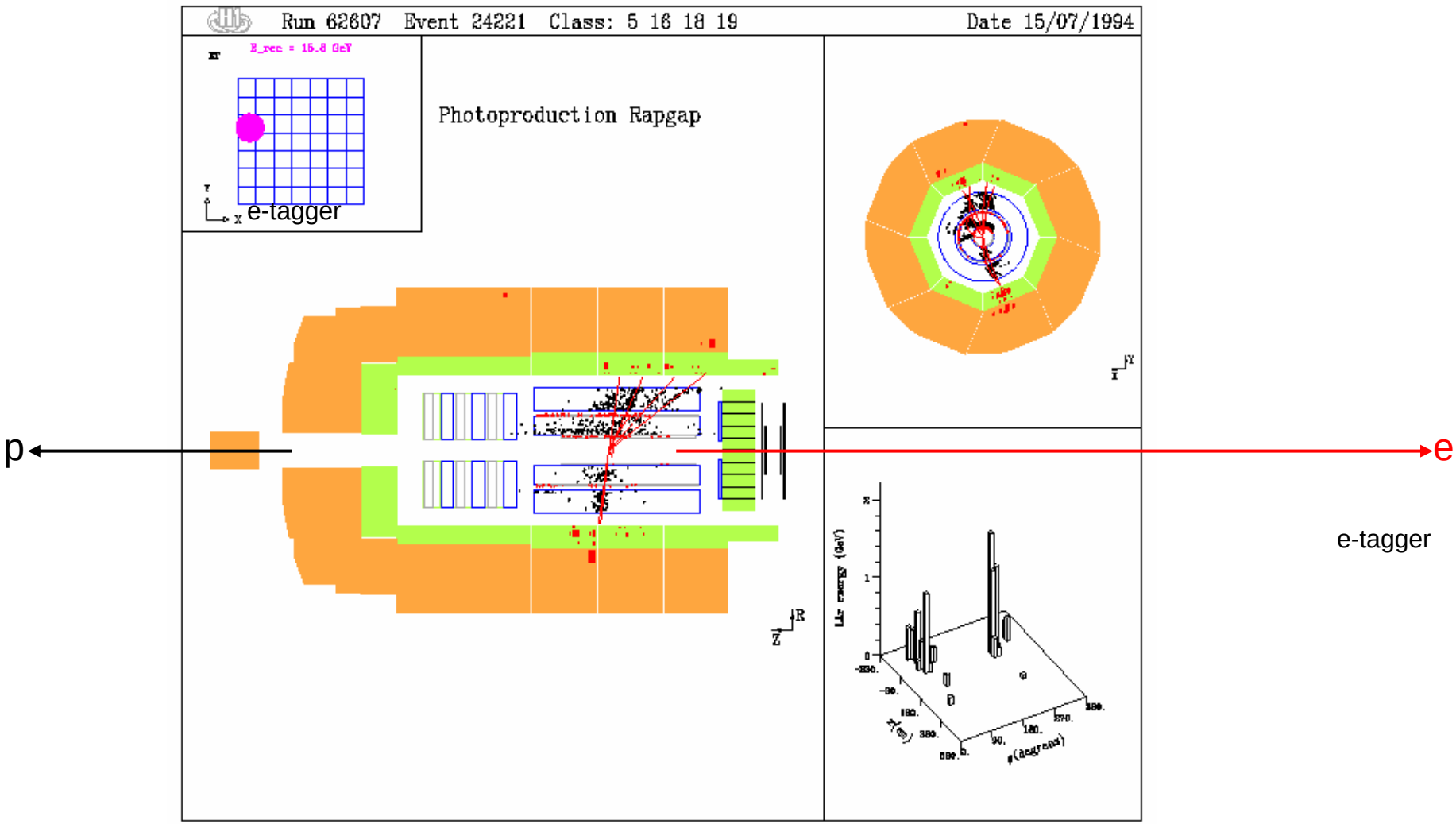
The FST allows to cover very small forward angles

Often there is activity in forward direction around the beam pipe : that are the ‘left overs’ of the ‘broken’ proton

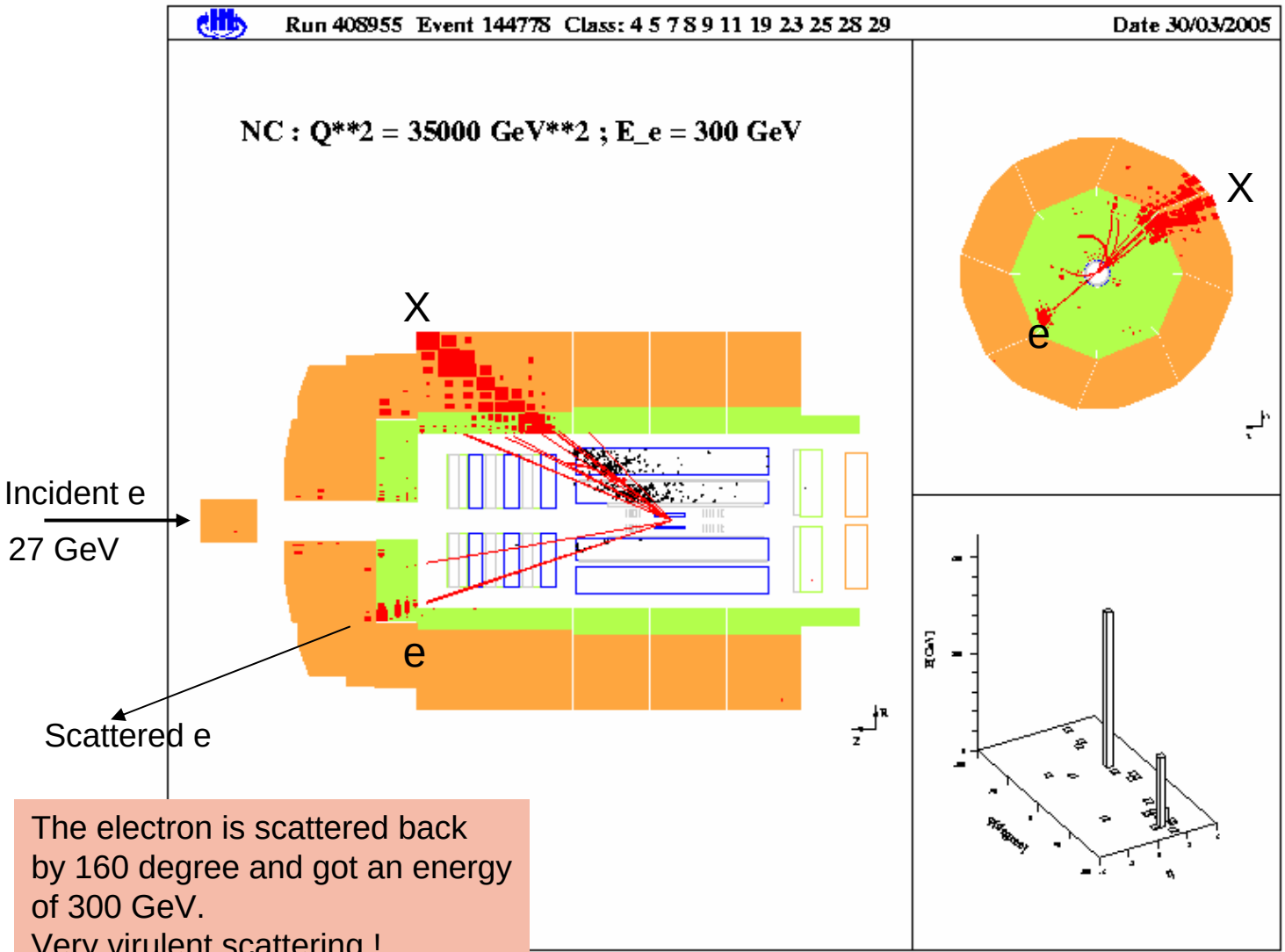


Electron scattered under small angle into backward calorimeter

But in 10% of all cases there is no forward activity :
the proton stays intact, and disappears down the beam pipe



Back to the Deep-Inelastic-Electron-Proton-Scattering (DIS) $ep \rightarrow e' X$



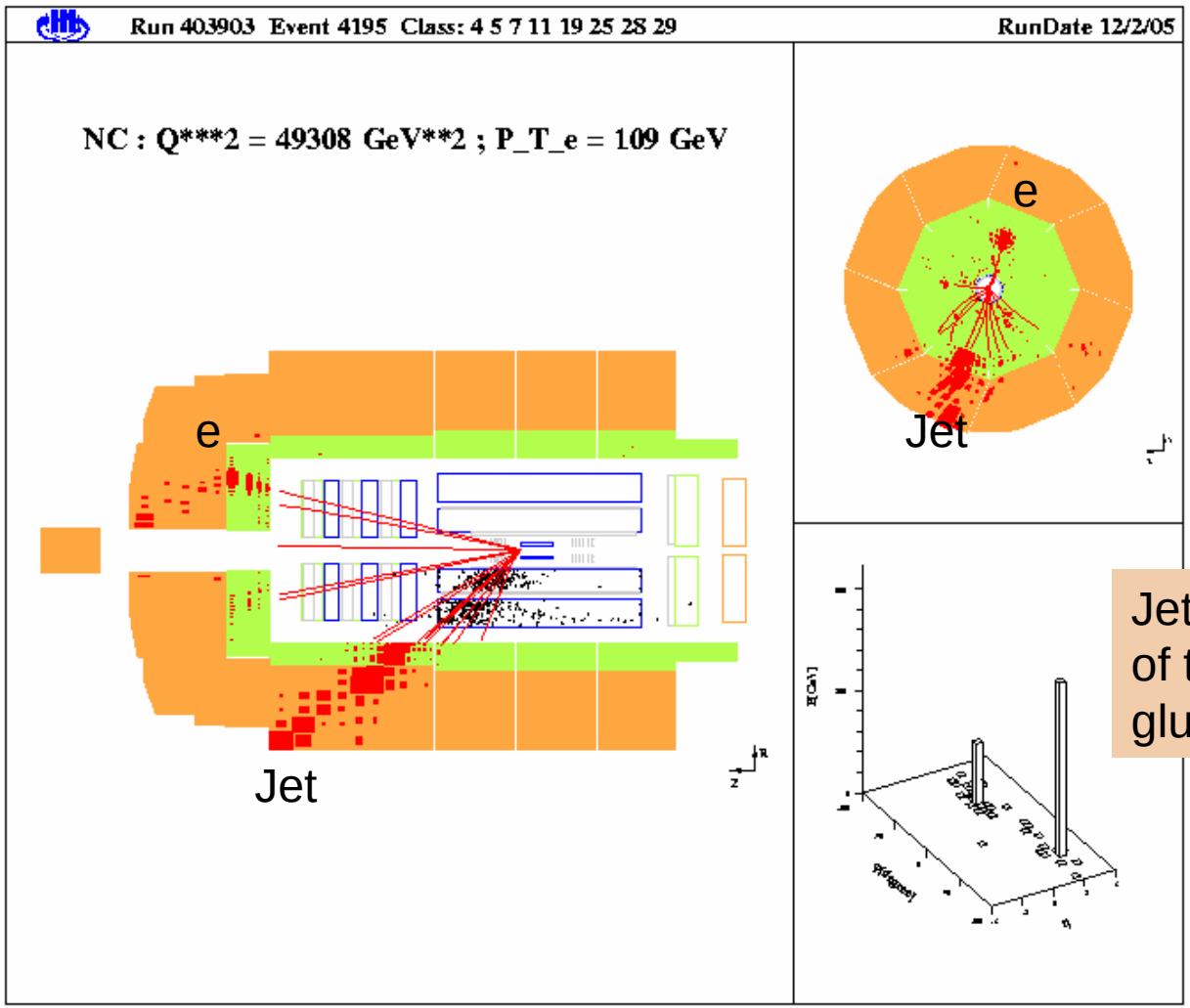
The electron is scattered back by 160 degree and got an energy of 300 GeV.
Very virulent scattering !

.and here its even more virulent.

$$ep \rightarrow e' X$$

The squared momentum transfer is $Q^2 \approx 50000 GeV^2$, this corresponds to a space resolution of

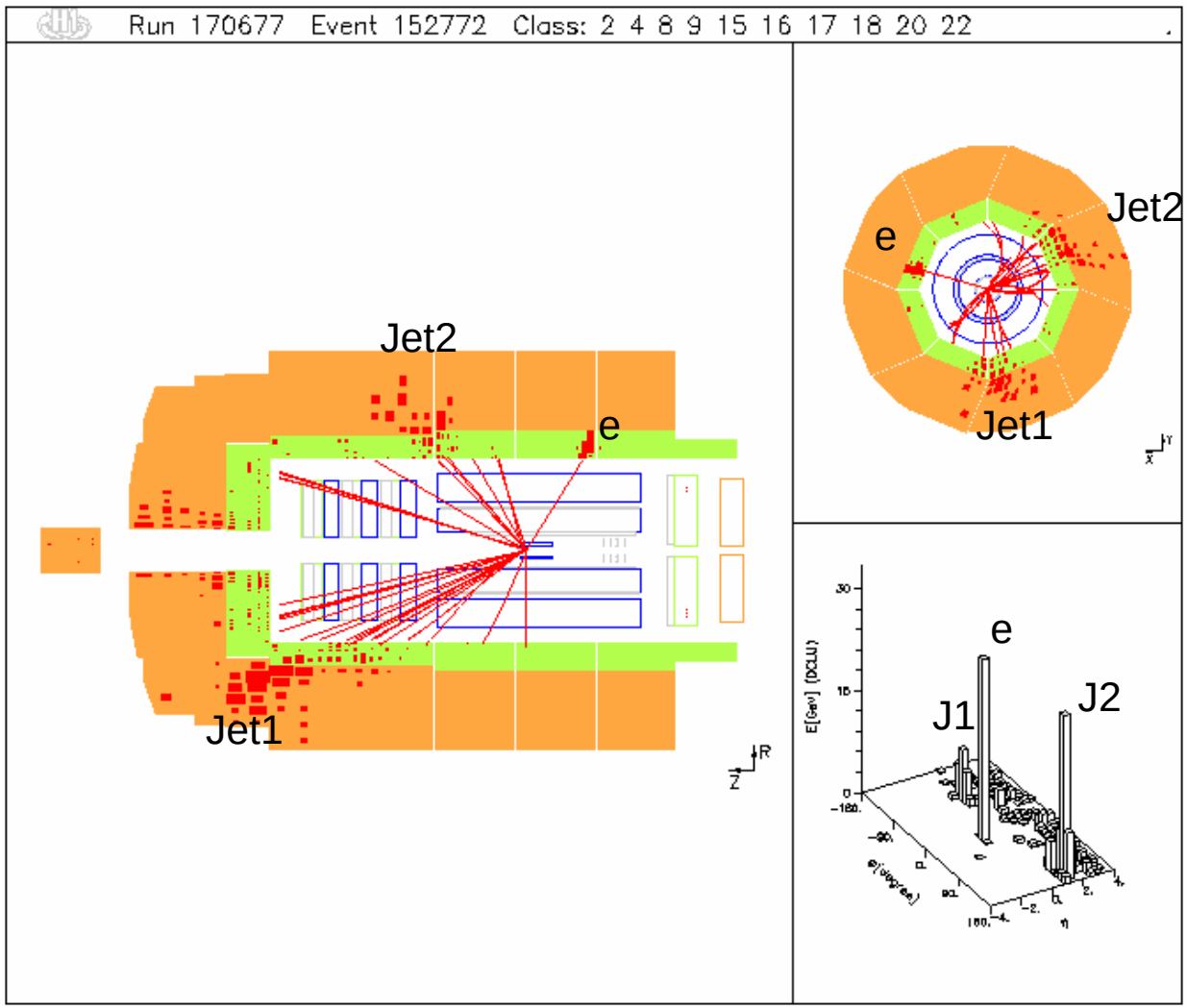
$$\Delta x \approx 10^{-18} m$$



Notice :
The hadronic system X is a well collimated bundle of particles. This is called JET

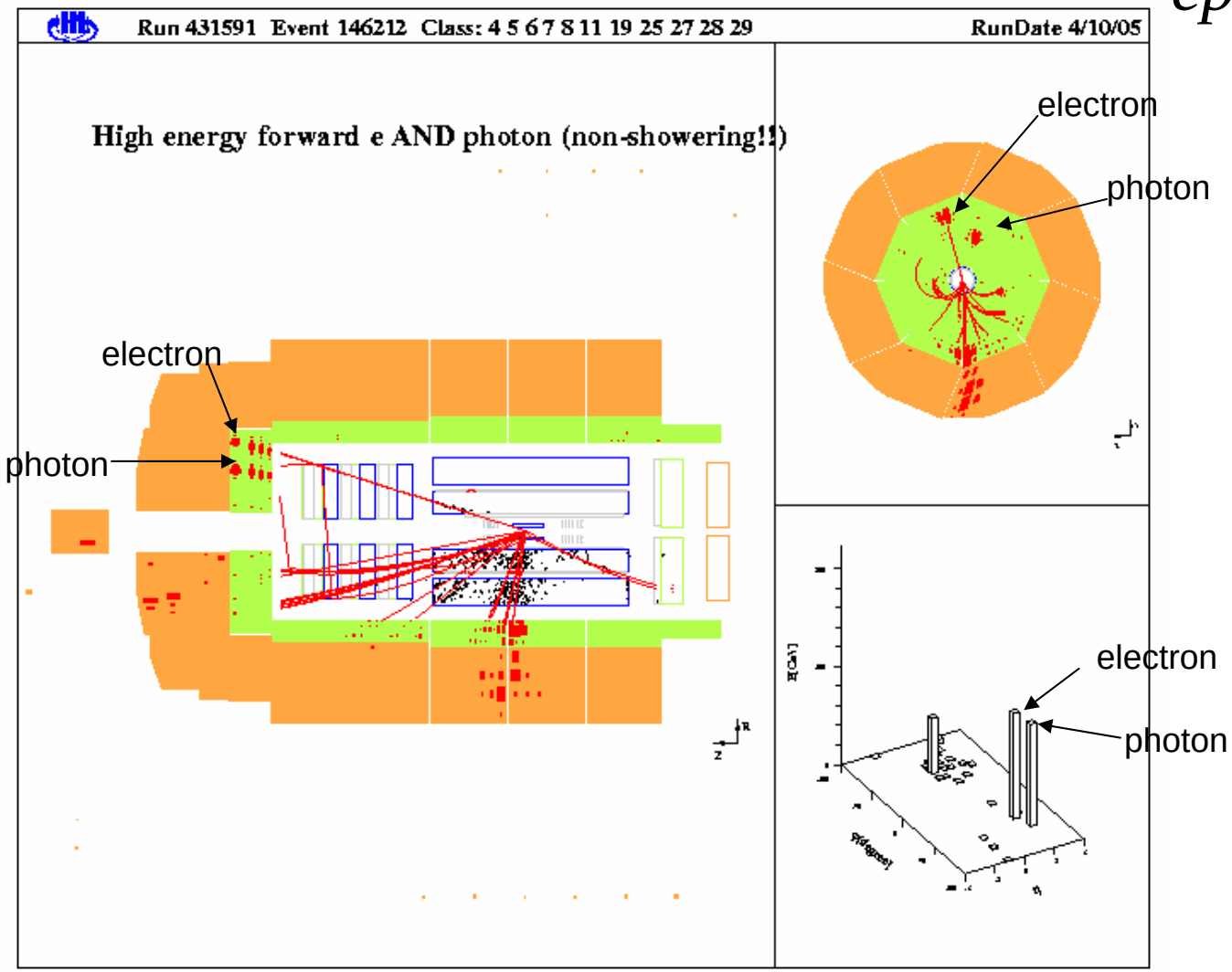
Jets are the ‘footprints’ of the quarks and gluons

A NC-DIS event with two jets $ep \rightarrow e' Jet_1 Jet_2$

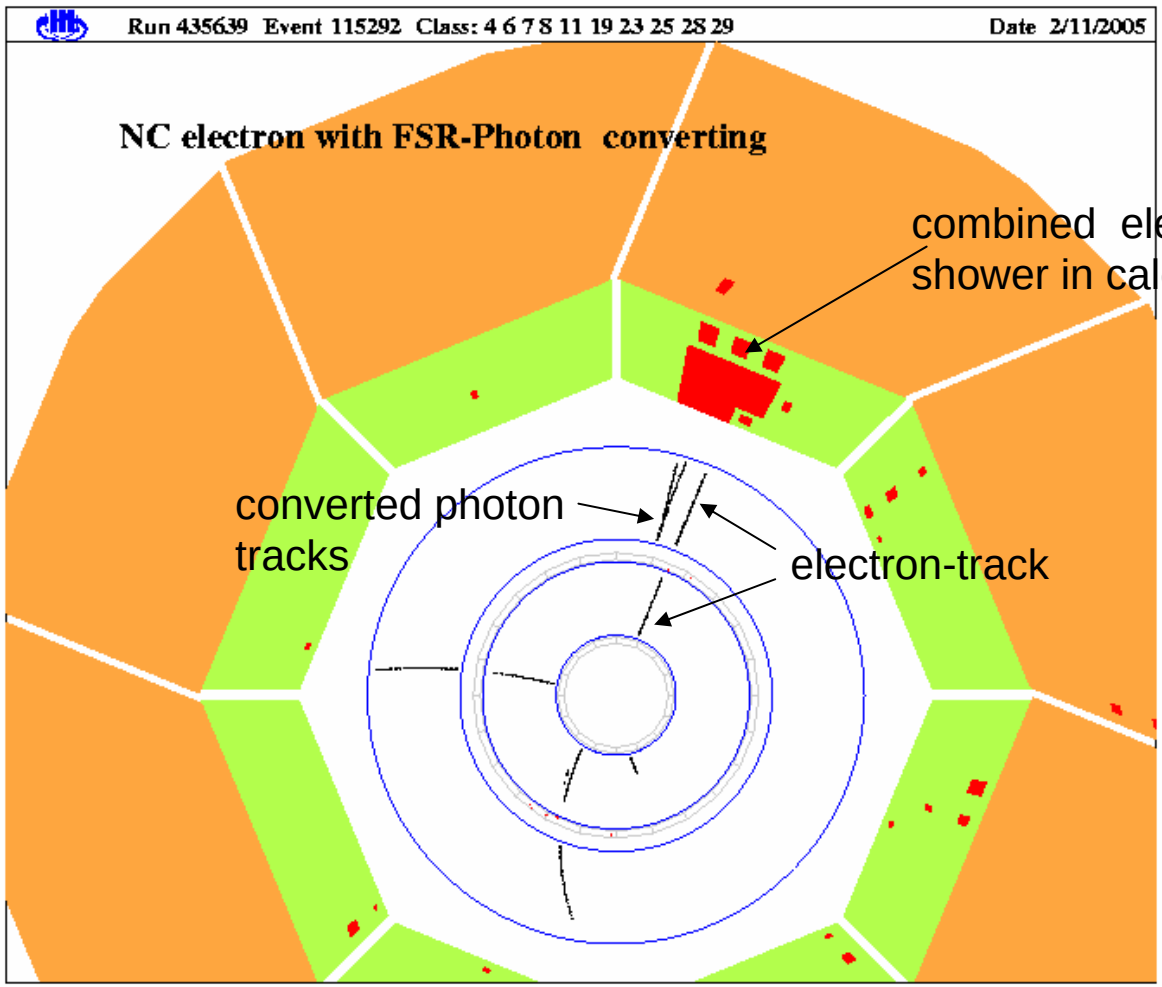


Here the ‘forward scattered’ electron radiates a very energetic photon

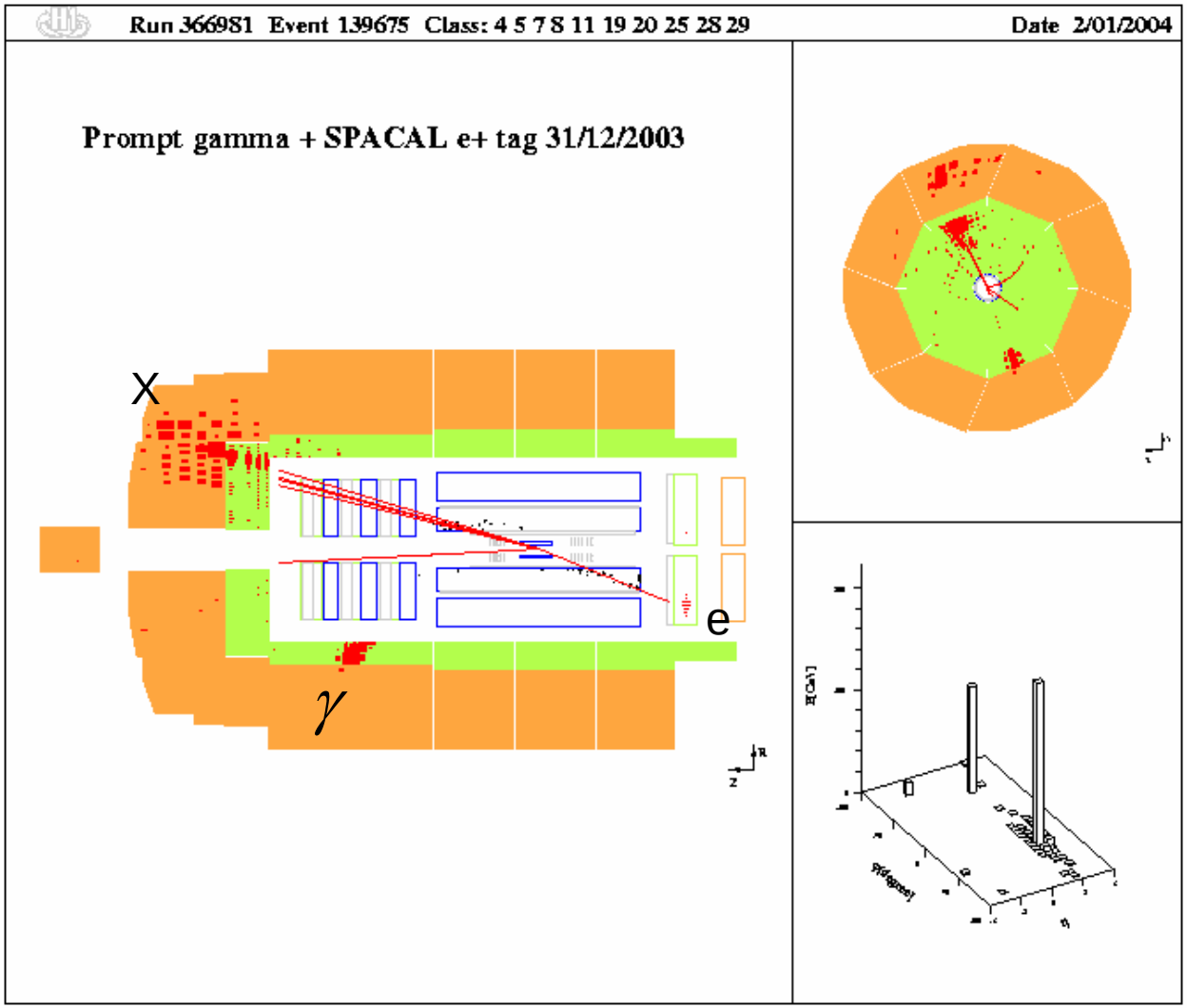
$$ep \to e' X \gamma$$



In general the photon is ‘near’ to the electron. Here both created a single electromagnetic shower in the calorimeter, but can be resolved in the tracker

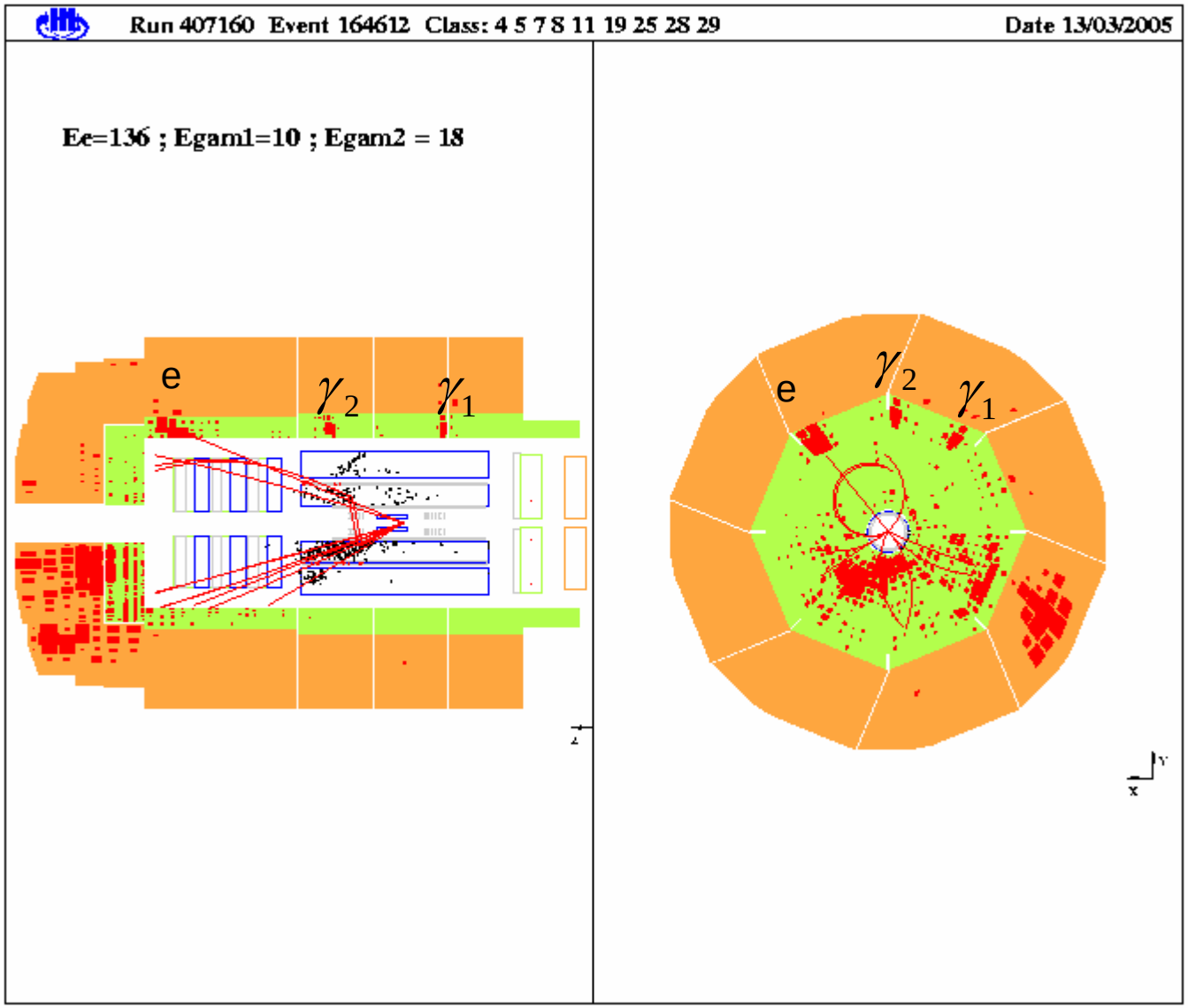


Another $ep \to e' X \gamma$ event, but here the scatted electron and photon are far apart



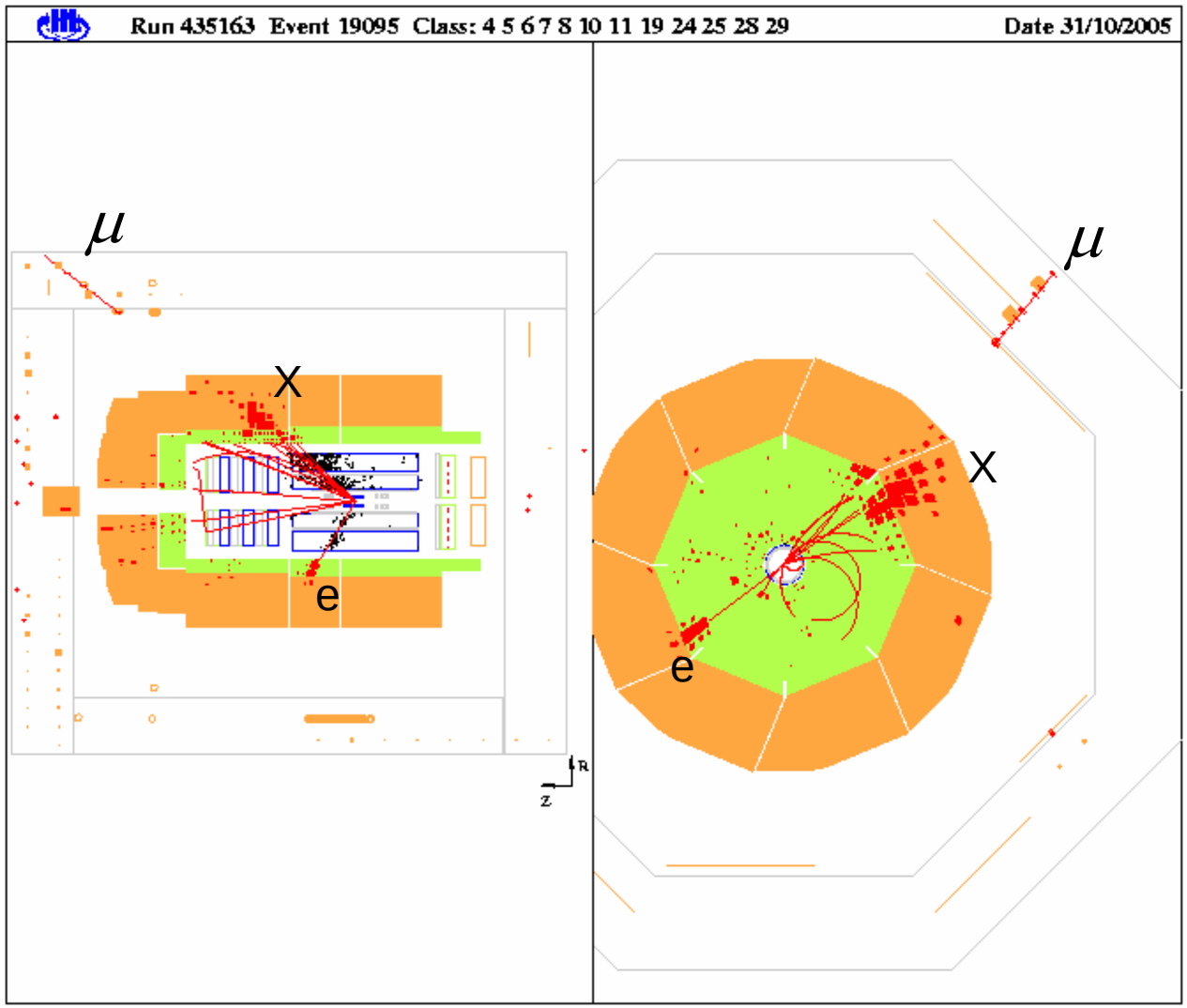
It is likely that here the photon is of hadronic origin (prompt photon)

There is also a chance that two photons are radiated : $ep \rightarrow e' X \gamma_1 \gamma_2$



In this NC event a muon is produced within the hadronic final state X

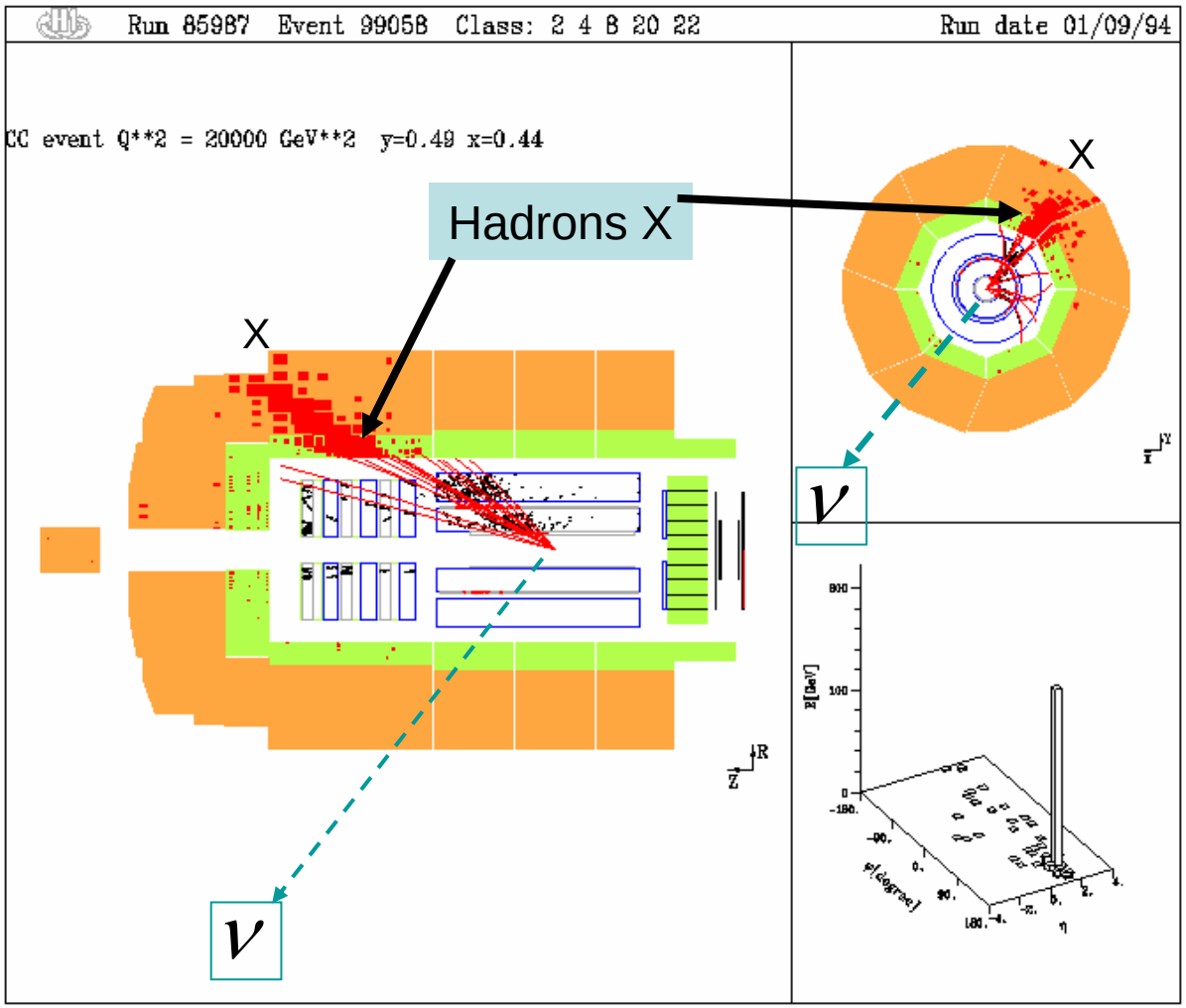
$$ep \to e' X \mu$$



A new event class : In this event the hadrons X are NOT balanced by an electron !

$ep \rightarrow \nu X$

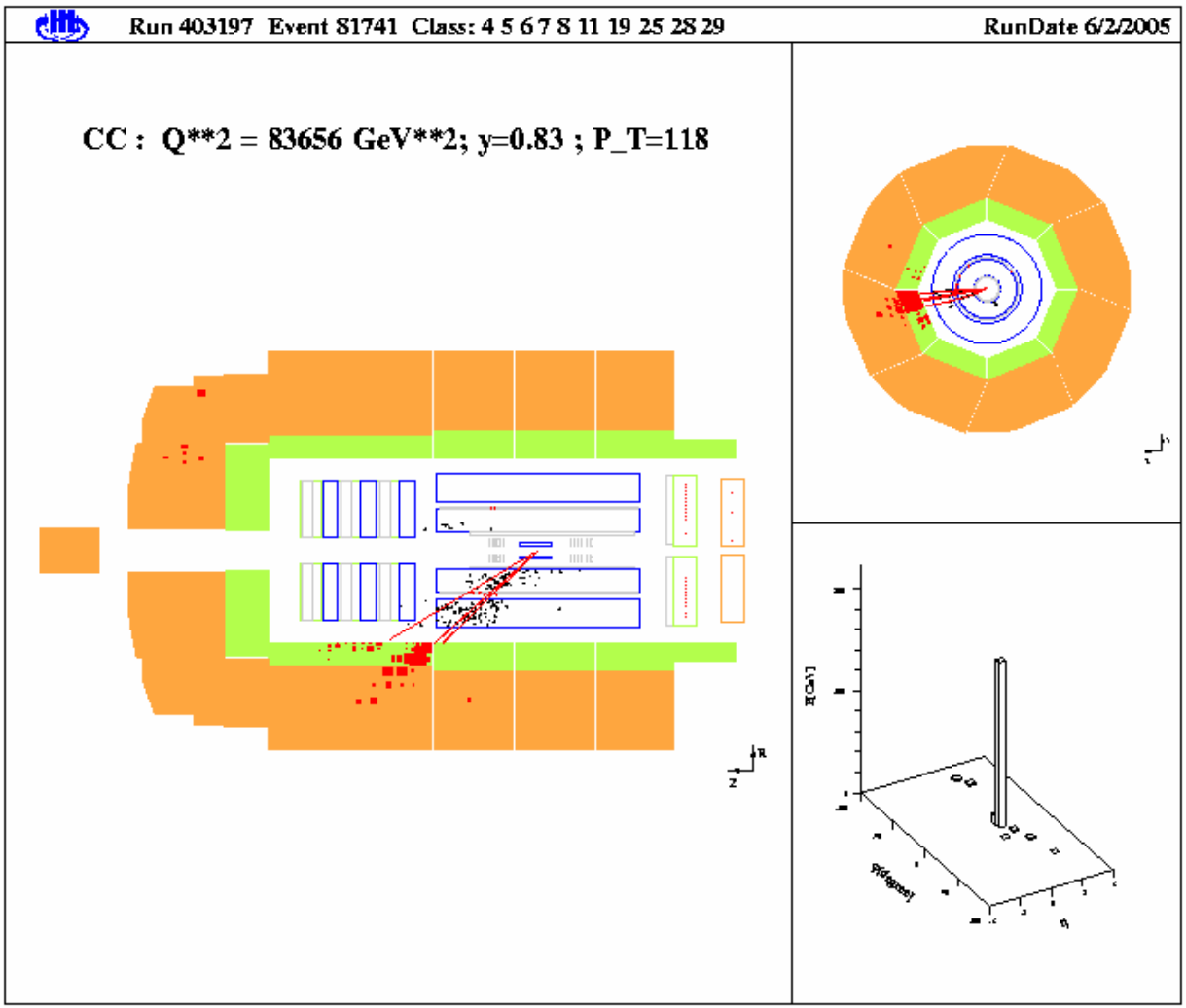
The Neutrino does not leave a trace in the detector



This is a different type of DIS event
It is pure weak interaction.

It is a Charged Current (CC) event

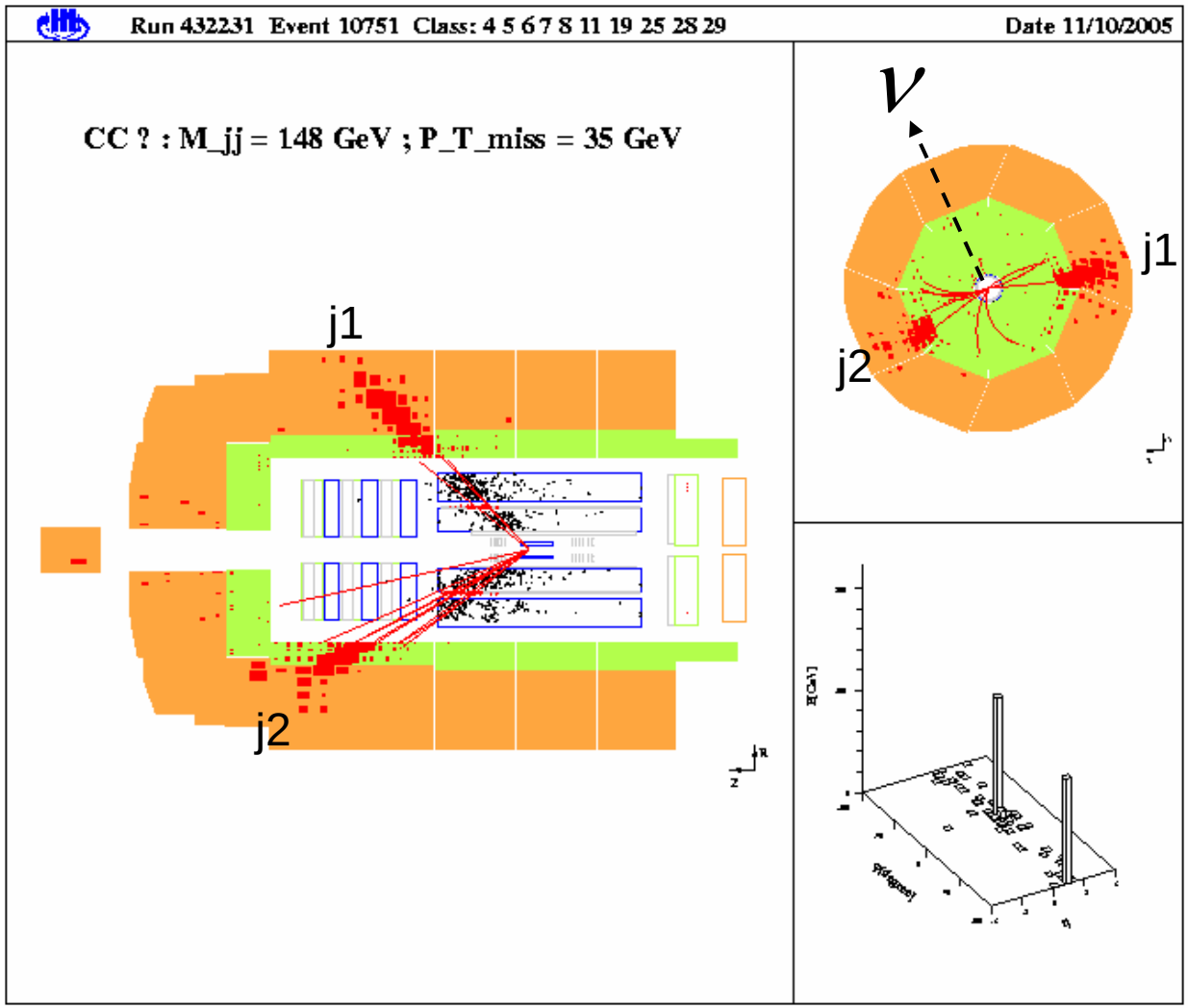
The CC event with the highest recorded transverse momentum Q^2



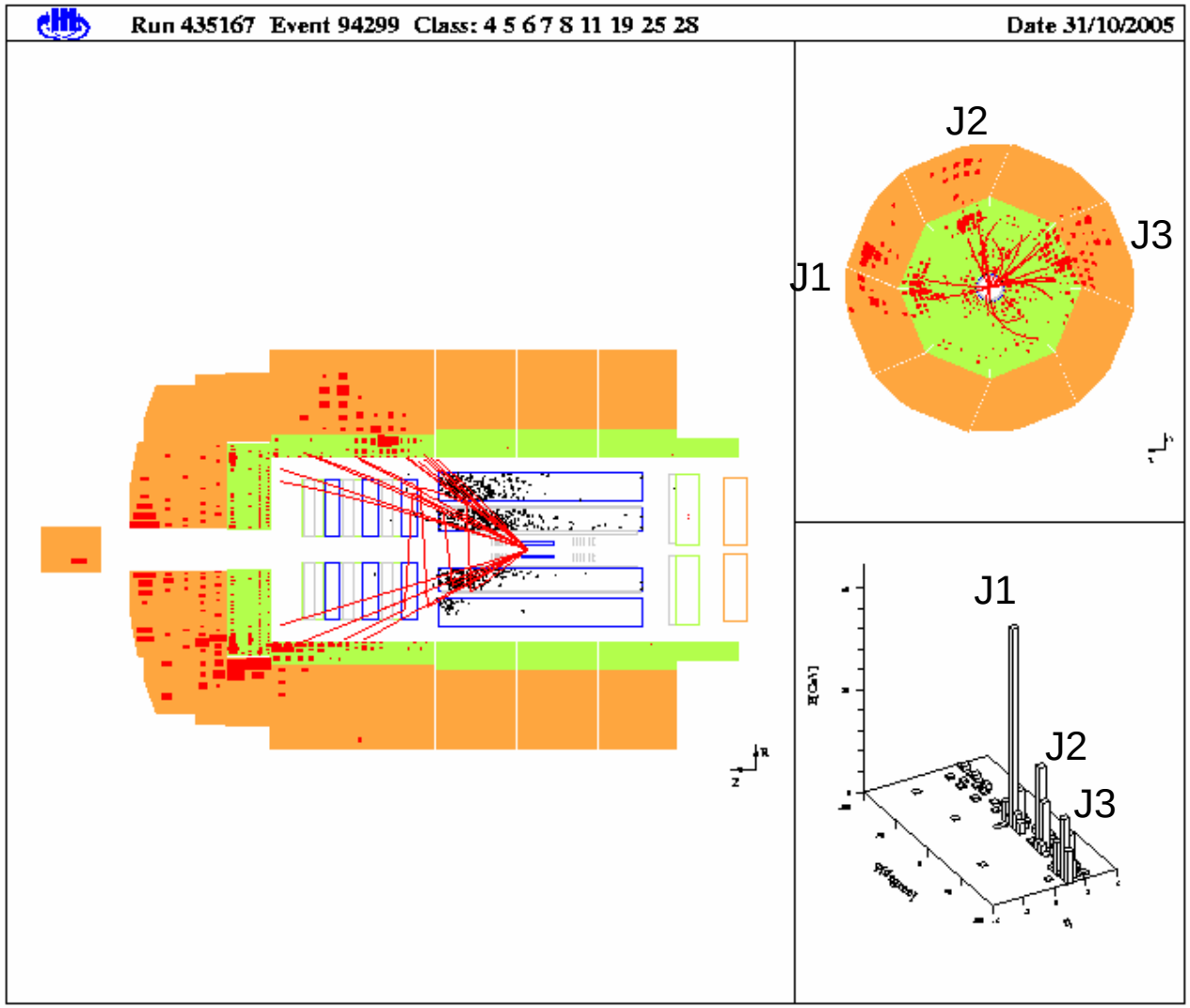
$$ep \to \nu X$$

The quark on which the electron scattered had nearly all of the proton momentum

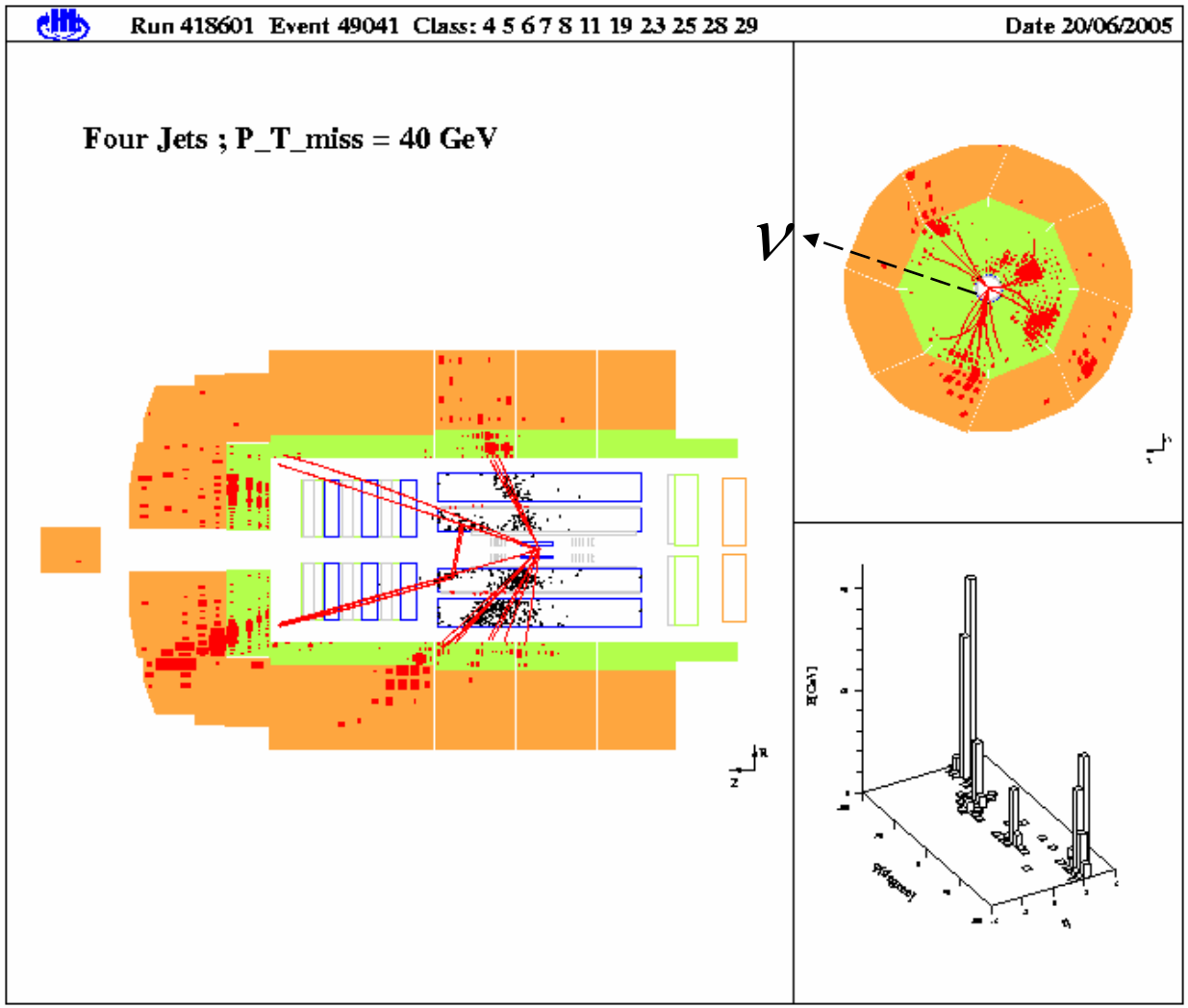
This is a CC event with a pronounced two-jet structure $ep \to \nu j_1 j_2$



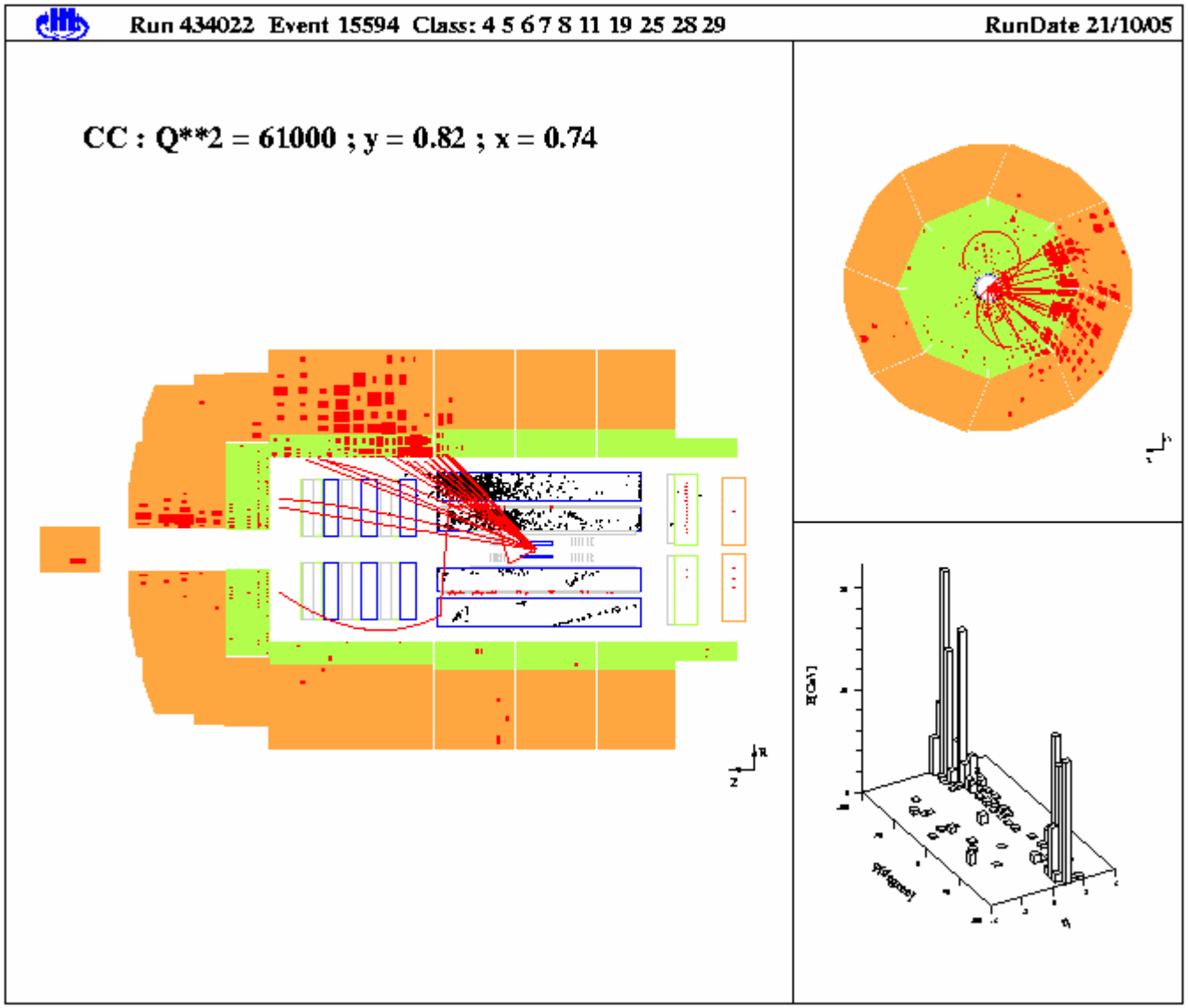
CC event with three jets



Also CC events exhibit multijet structures

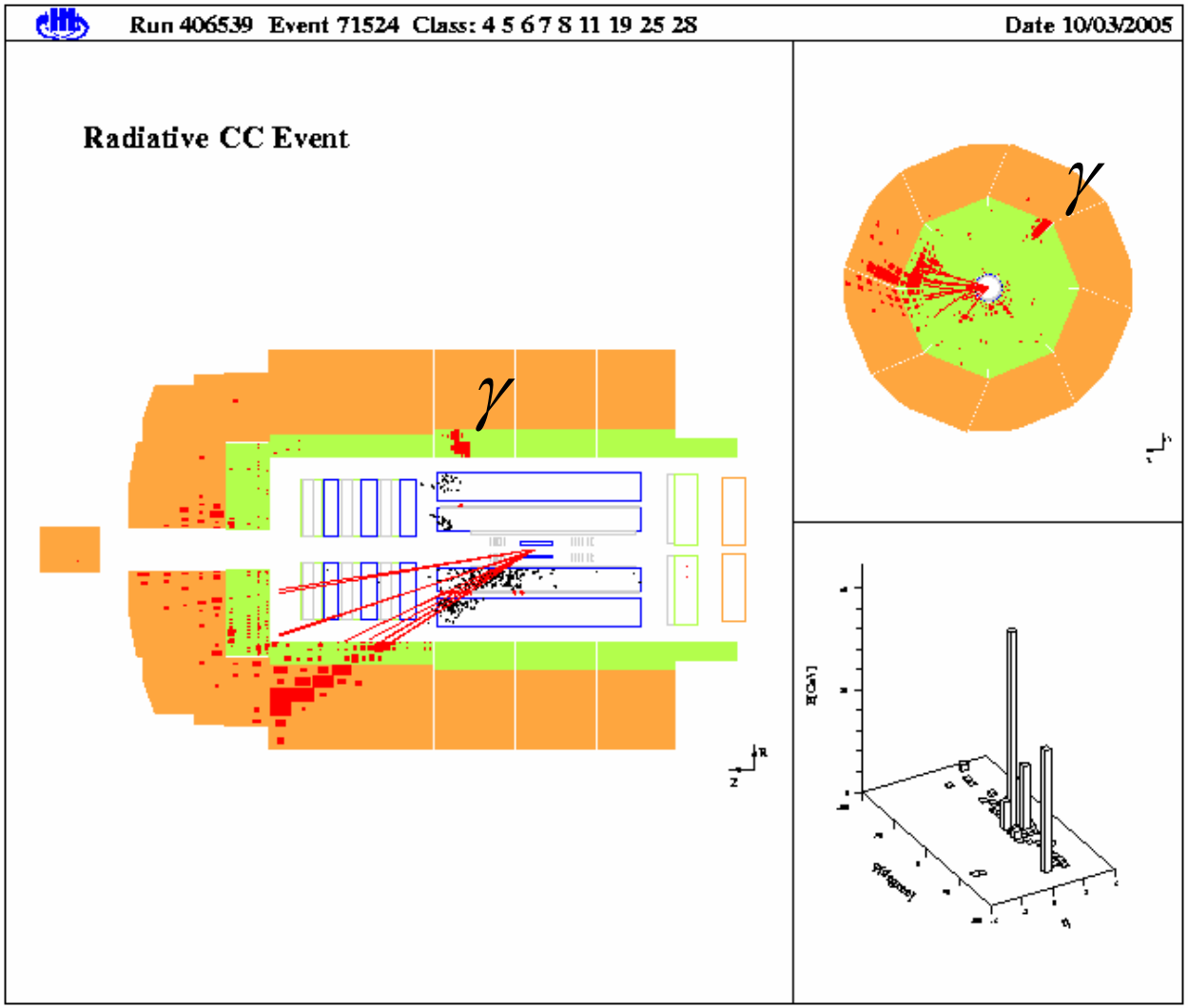


In this CC event the ‘Jet’ is very broad

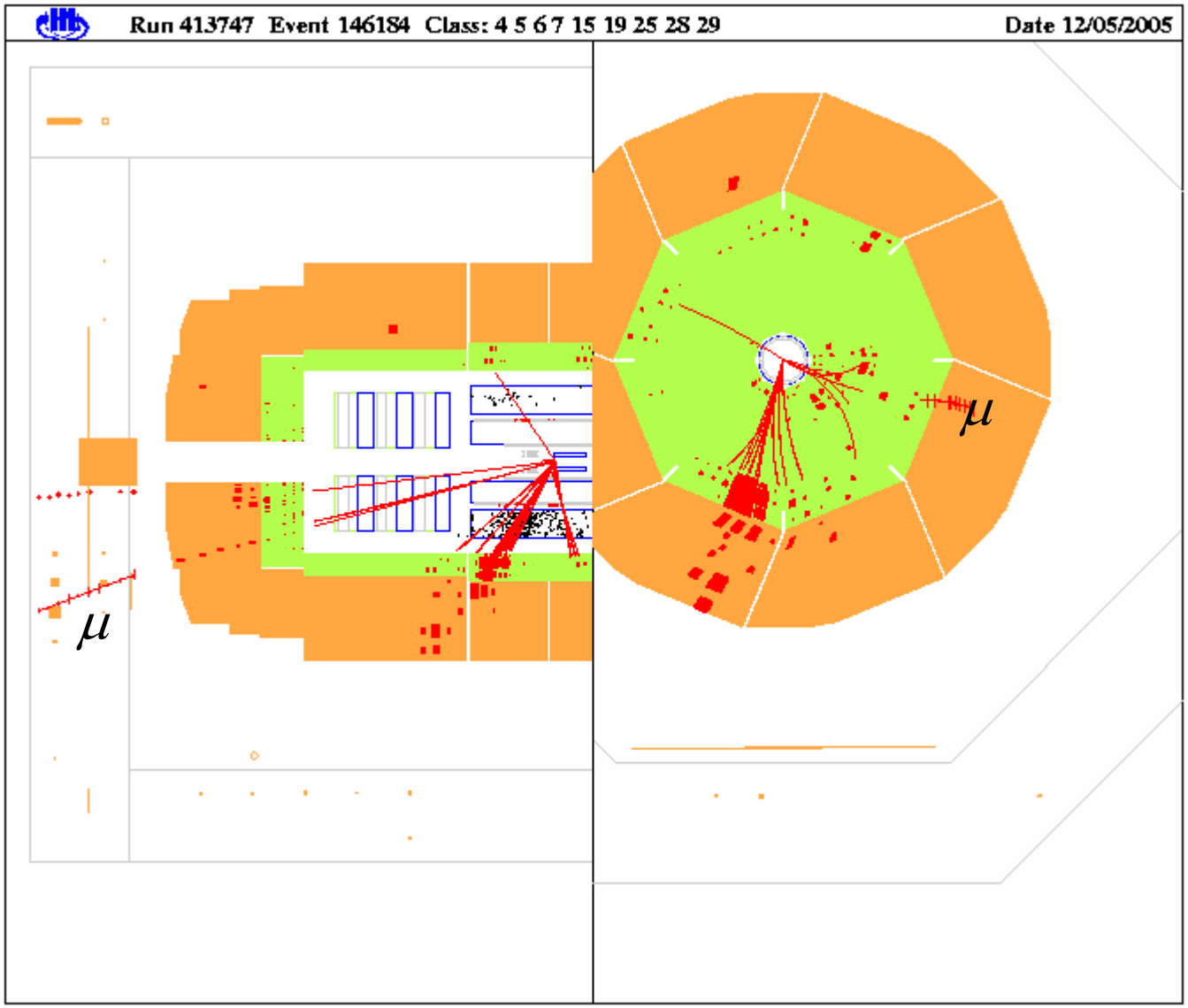


A CC event with a photon radiated from the incident electron

$$ep \to \nu\gamma X$$

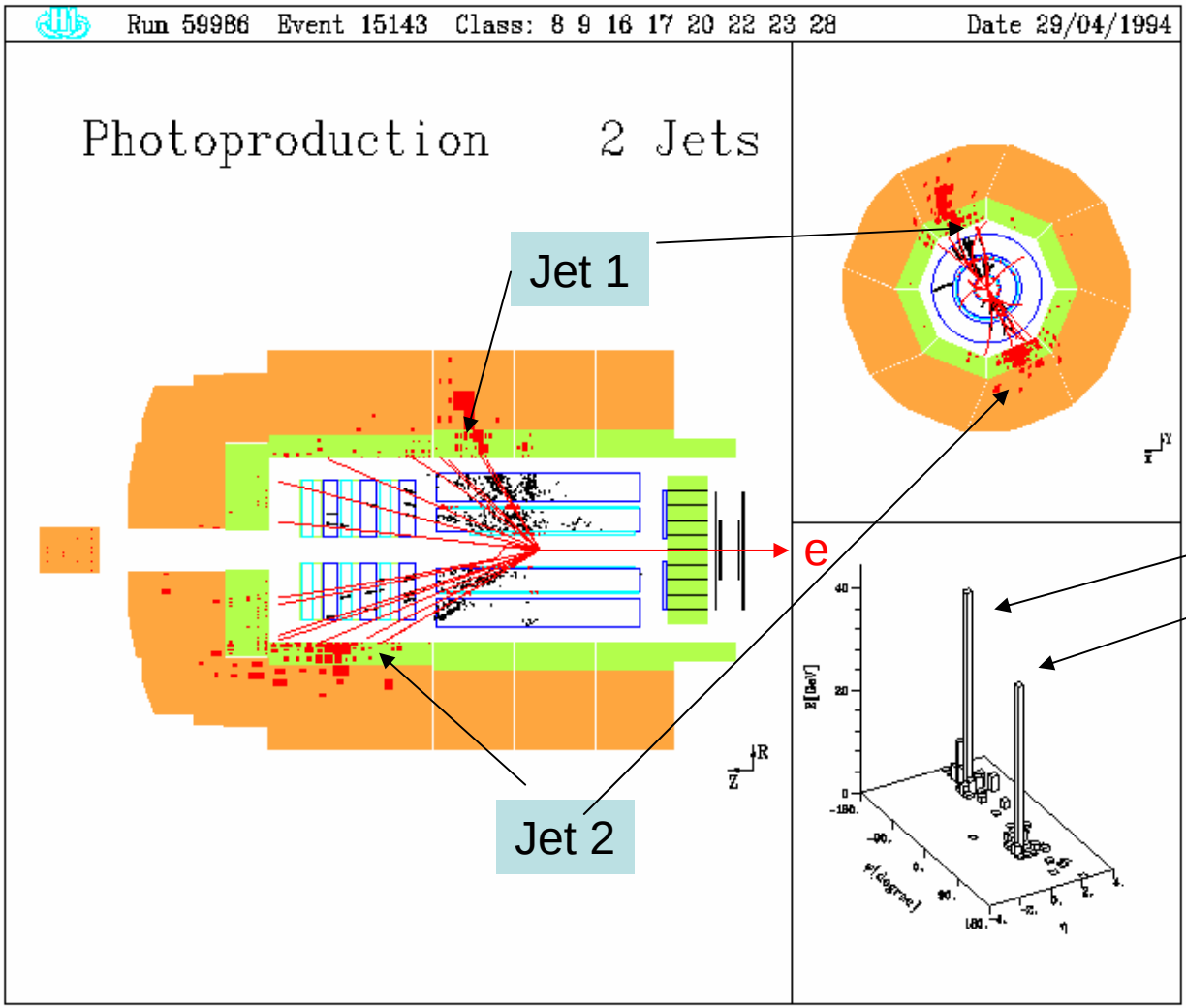


This CC event shows a muon separated from the jet

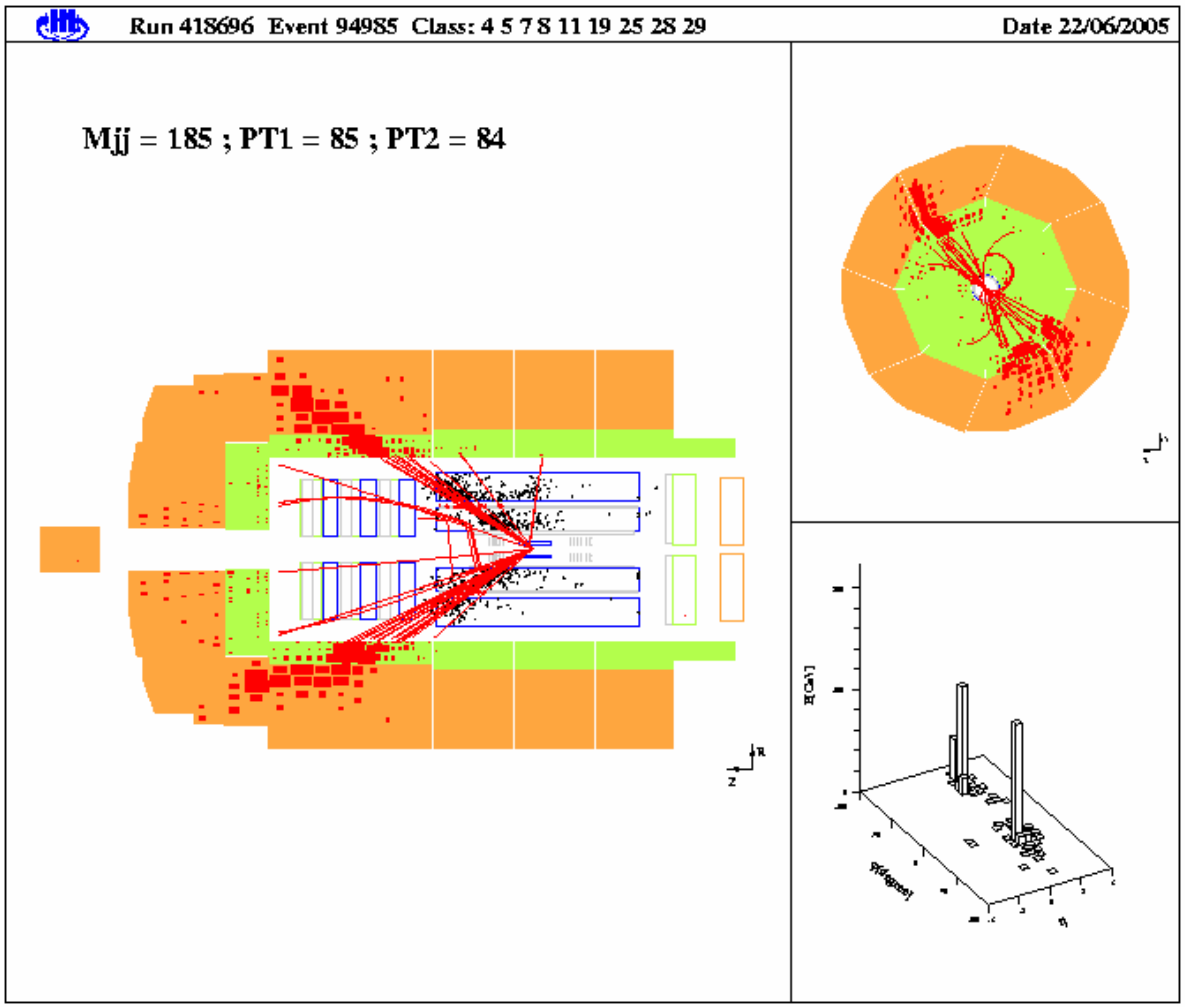


This could be a muon produced in the semileptonic decay of a charm quark

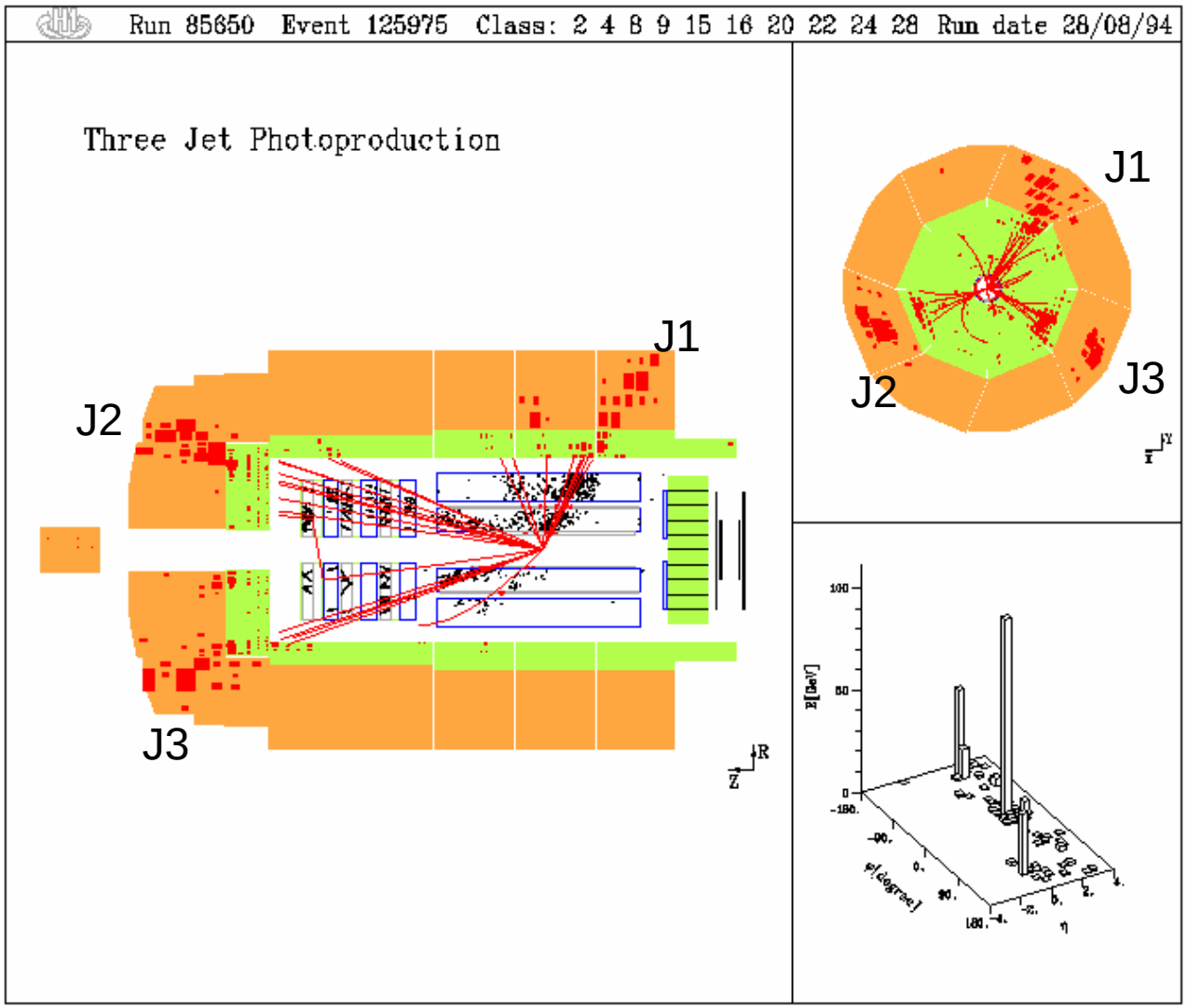
Another event class : ‘Photoproduction’
Here two jets are visible, but the scattered electron is not recorded, it leaves the detector under very small scattering angle



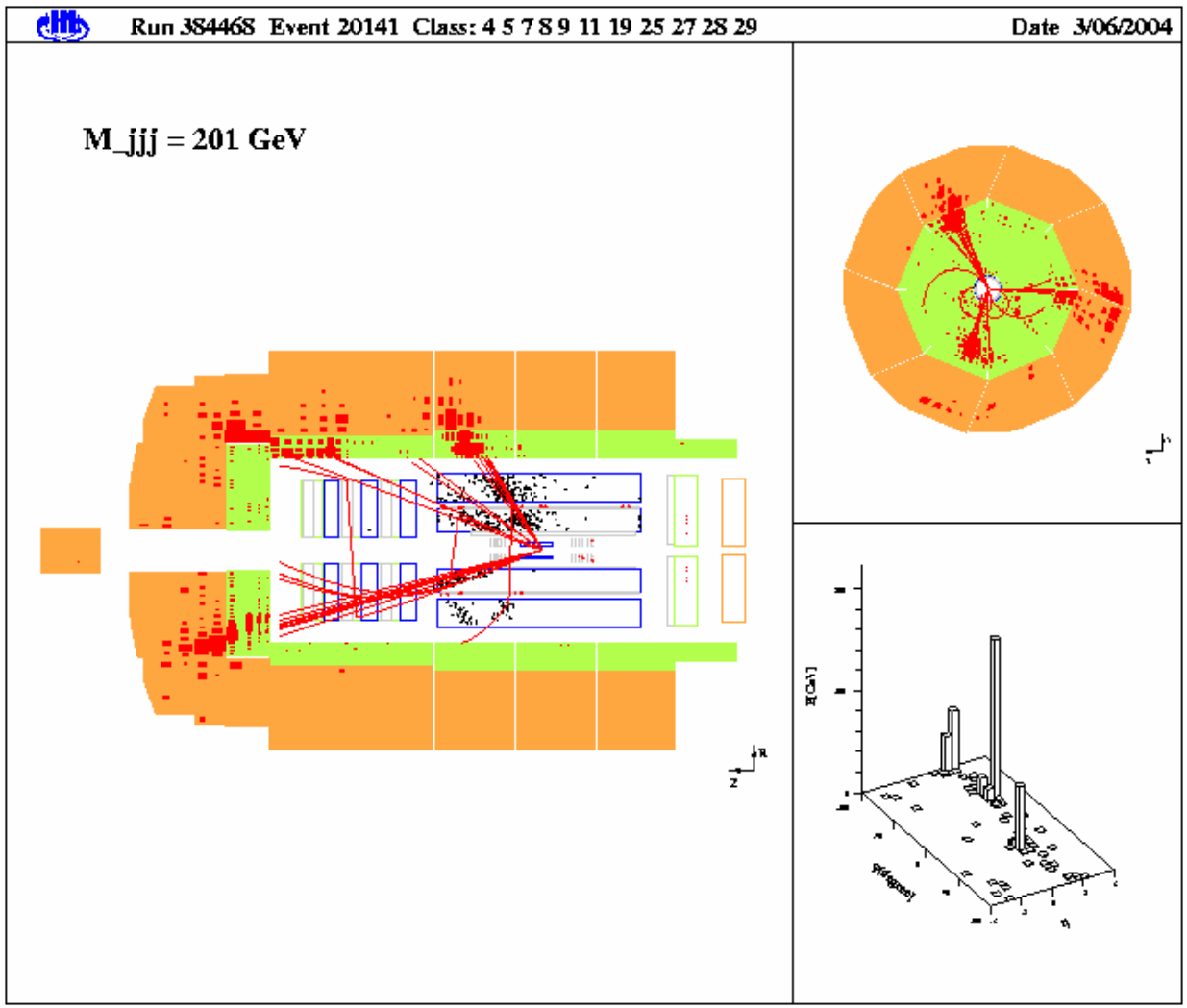
A dijet event with very high dijet-mass



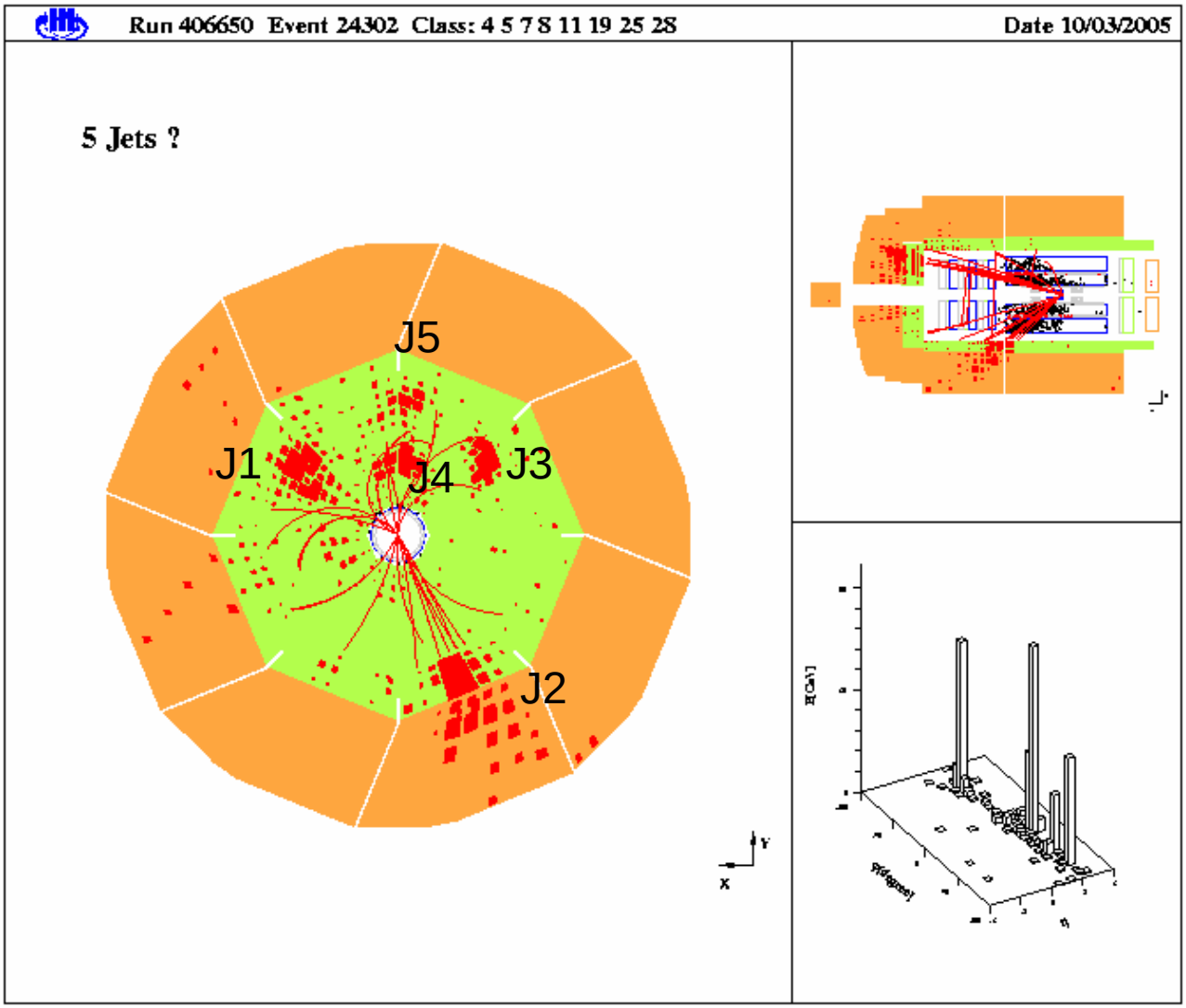
Here a THREE-JET-EVENT



A very high three-jet mass

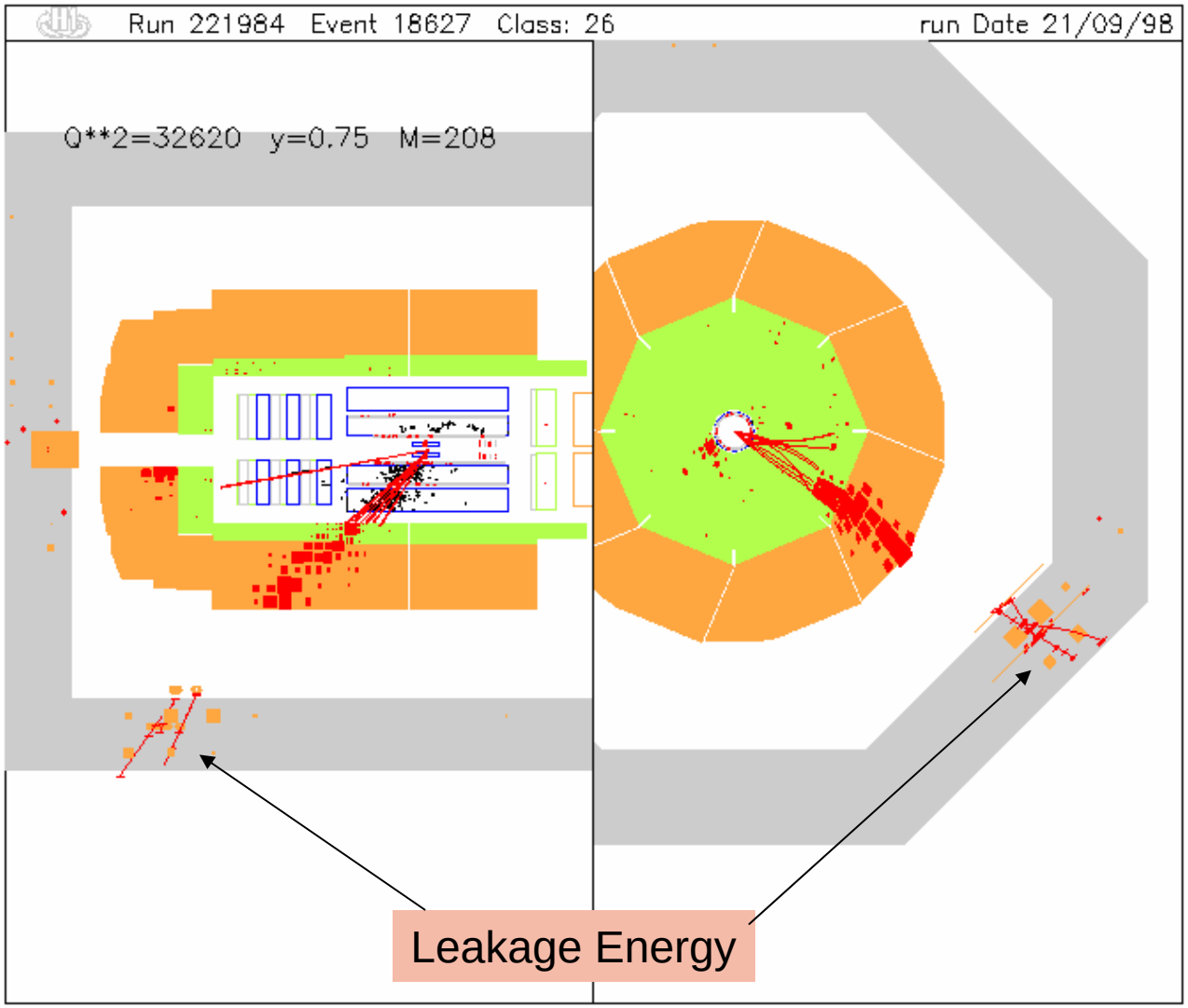


Here 5 jets are visible, there is no limit in the number.

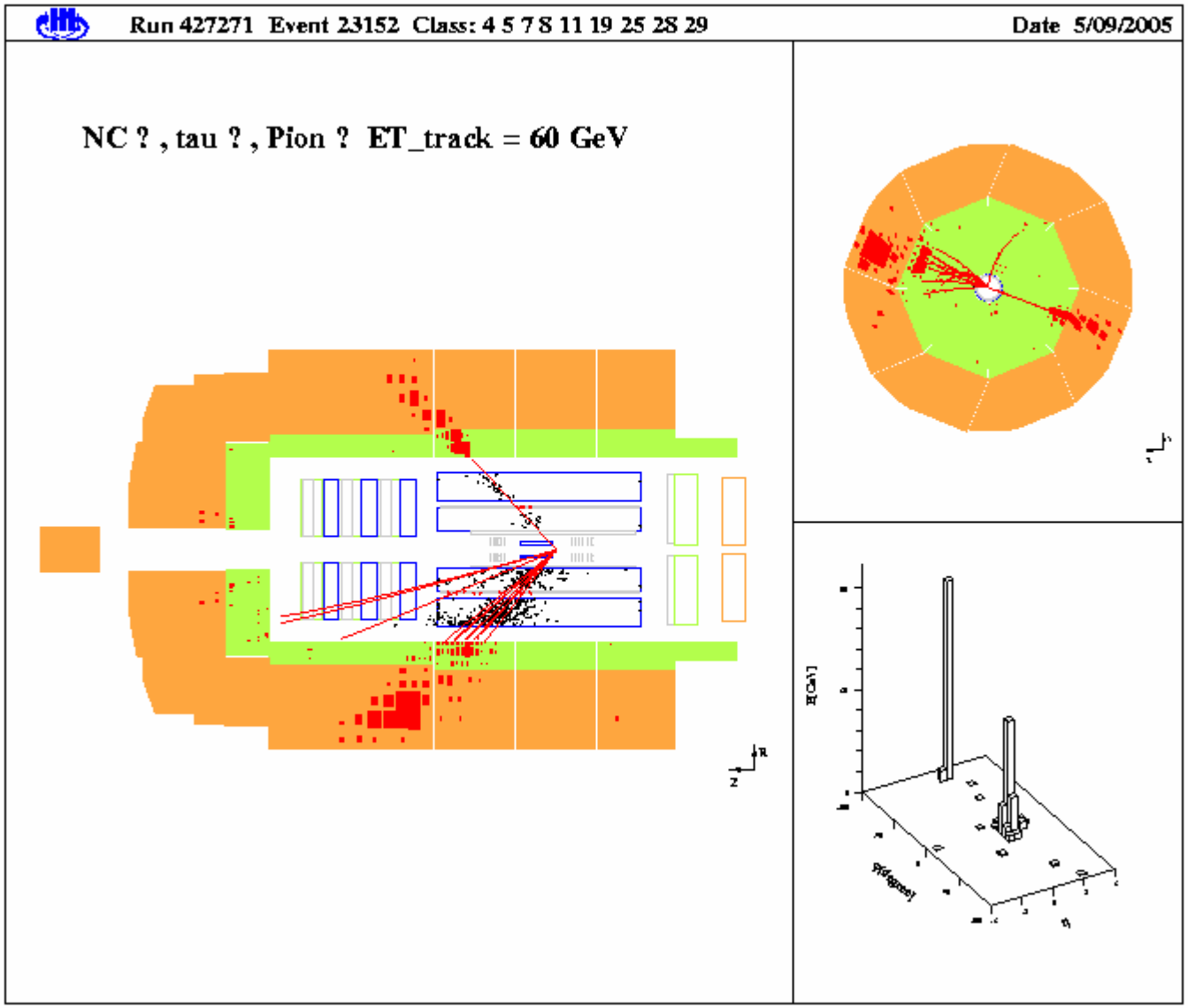


Quarks radiate gluons, which in turn may radiate gluons or produce quark-antiquark pairs.
All turn (if energetic enough) to visible jet structures

The jets can be so energetic that they are not absorbed in the main calorimeter but leak out into the instrumented iron yoke.



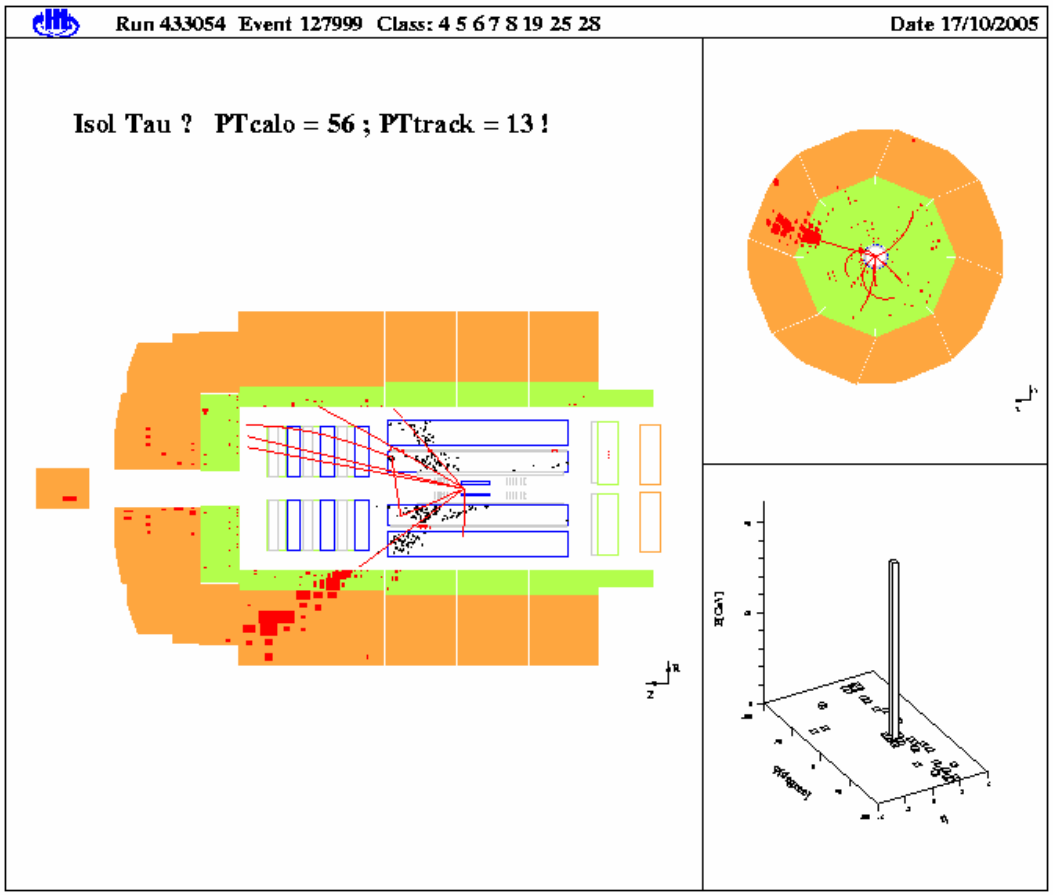
It happens that a jet is associated to only a single charged particle



Explanation :
-statistical
fluctuation ?
-physics reason
Tau –Lepton ?

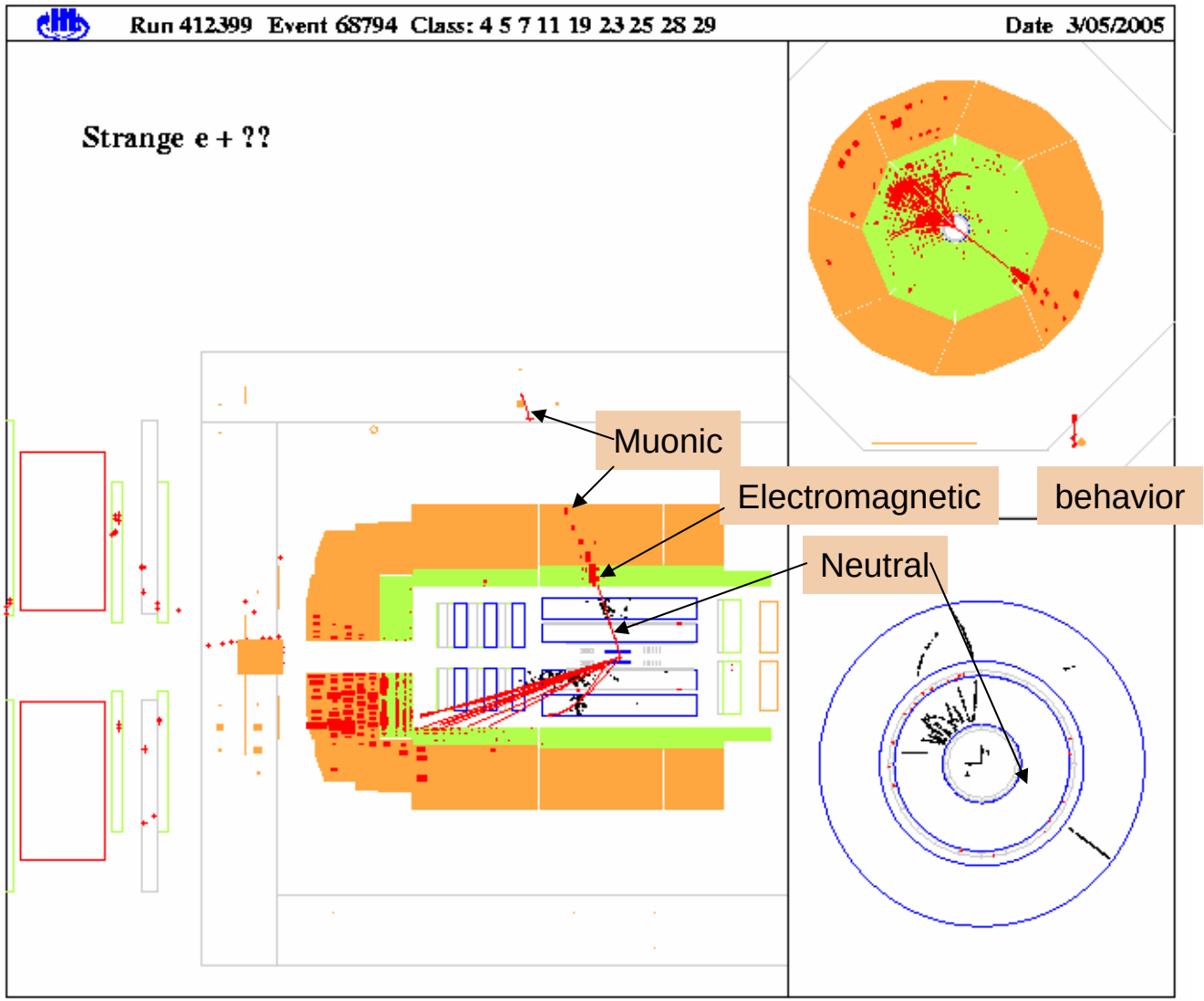
$$\tau \rightarrow \pi \nu$$

We also record events with an unbalanced jet associated to a single particle.



Are these events with isolated tau-mesons and missing transverse momentum ?

Sometimes strange features show up :

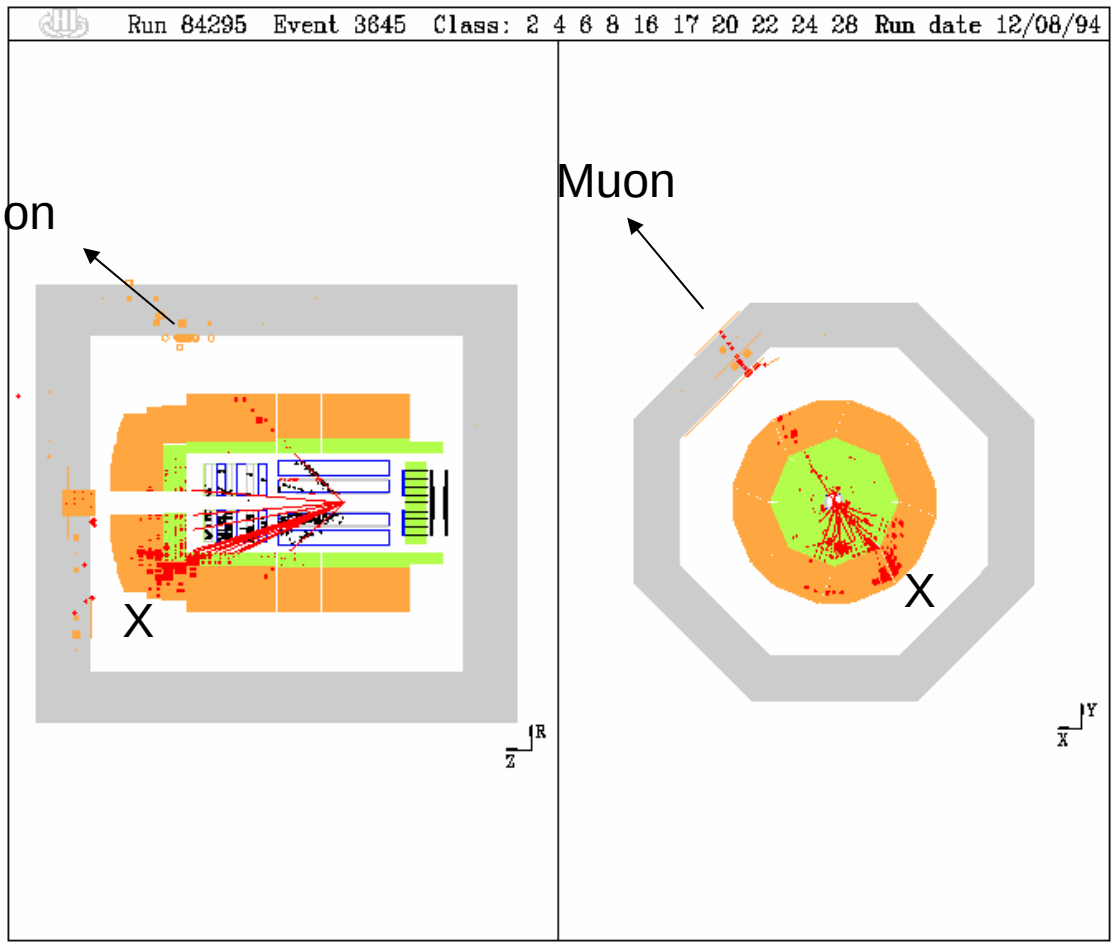


Explanation ??

The most exciting issue : Are there new phenomema, we don't expect ?

We have seen $ep \rightarrow e' X$ DIS - events

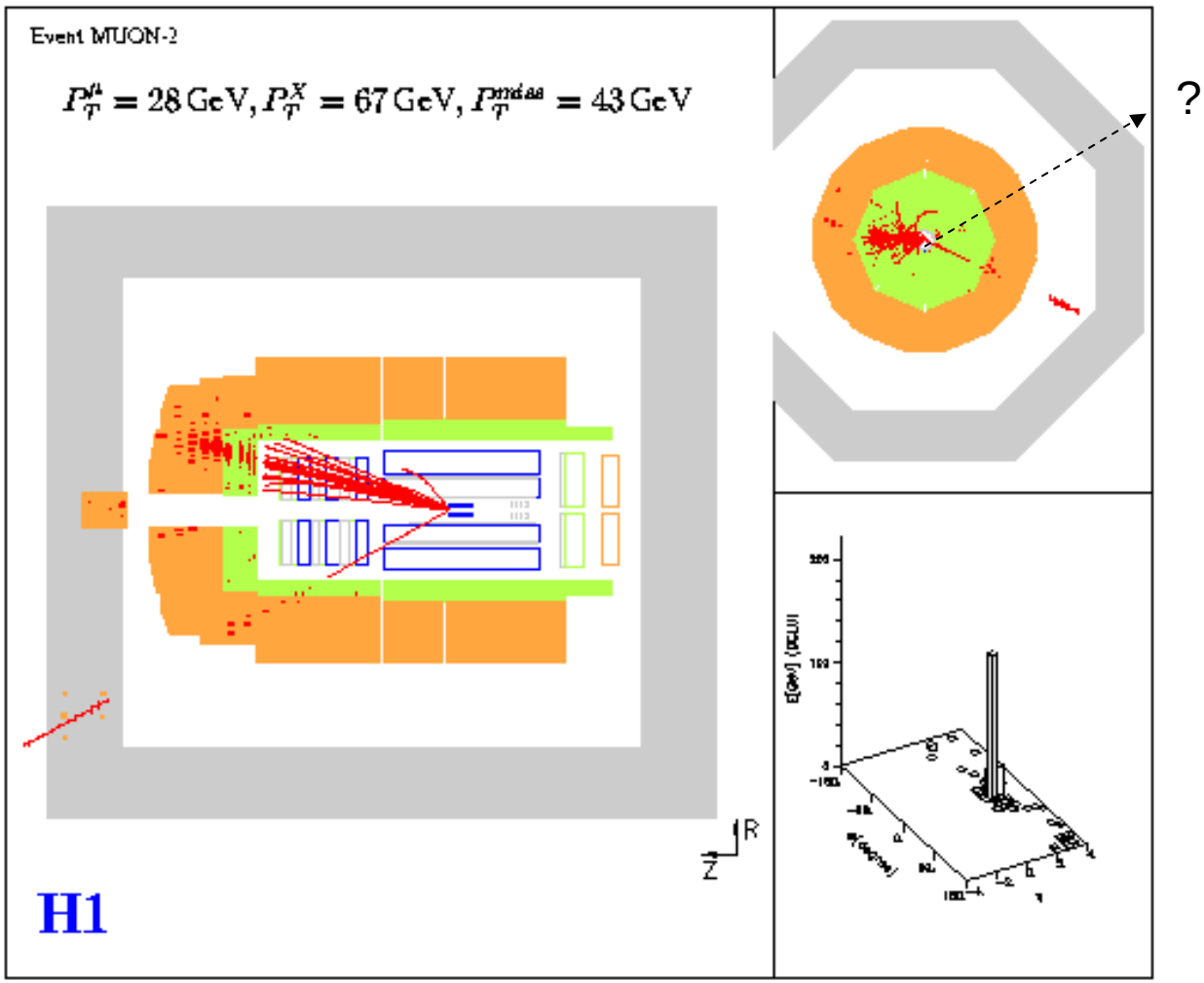
But this looks like $ep \rightarrow \mu X$ (As such forbidden in HEP Standard Model)



Fluctuating background
or
sign of new physics ?

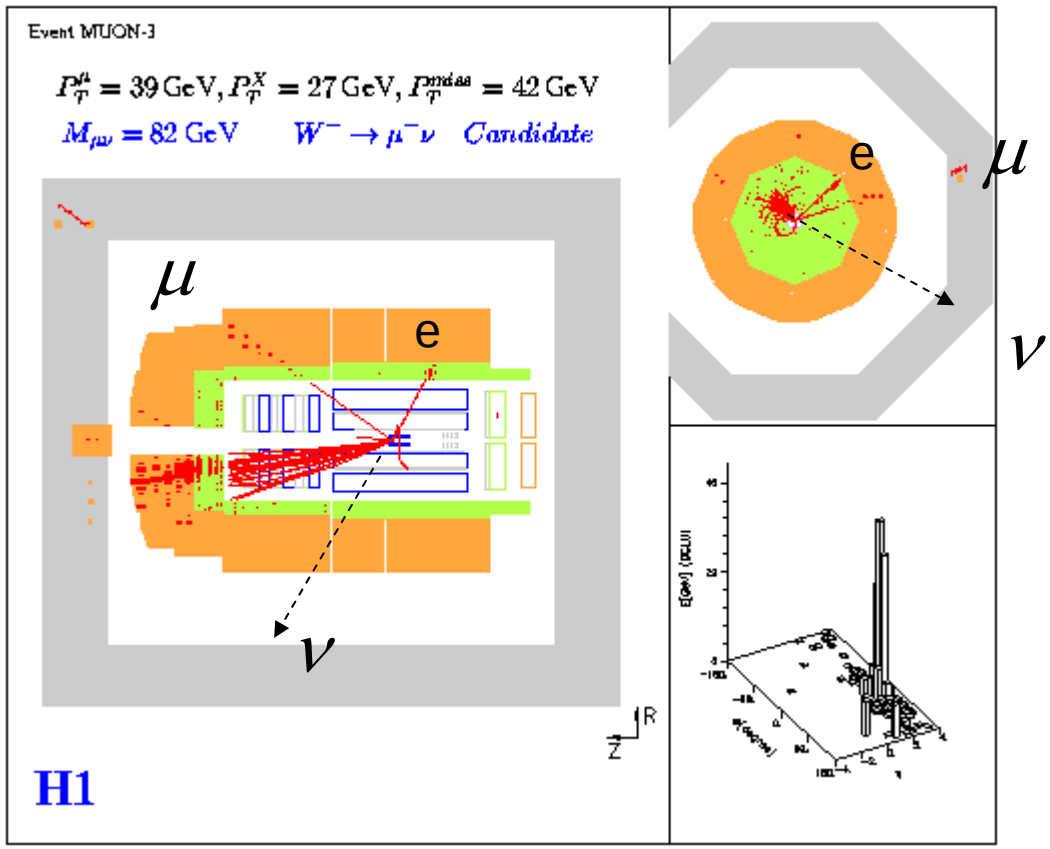
A similar event, but here muon and hadronic jet are not back-to-back : clear evidence for unobserved particle (neutrino ?)

$$e^+p \rightarrow \mu^+X$$



Similar event, but here also the scattered electron is visible.
This allows to reconstruct the invariant mass of the muon-neutrino-system.
It turns out to be 82 GeV. That's close to the W mass.

$$e^+p \to e^+\mu^-X$$

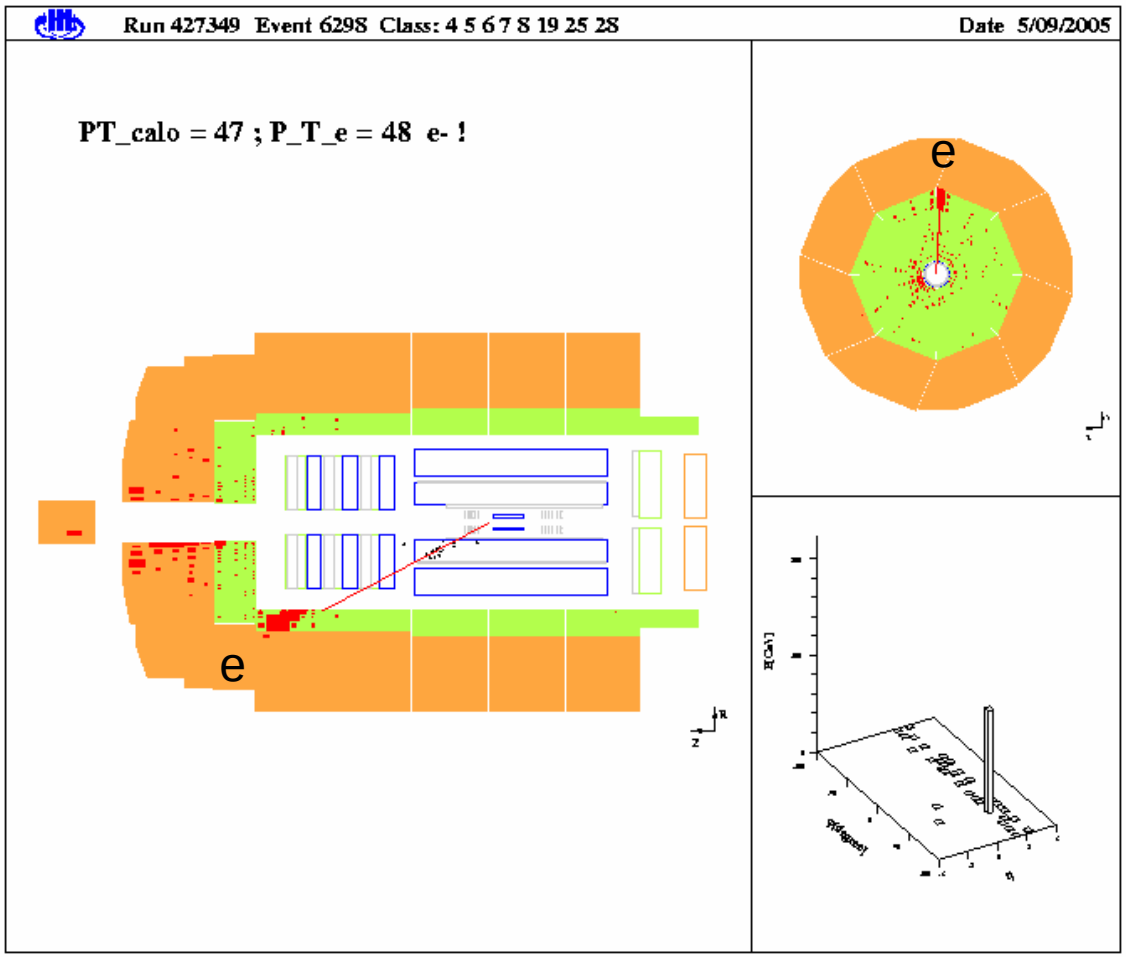


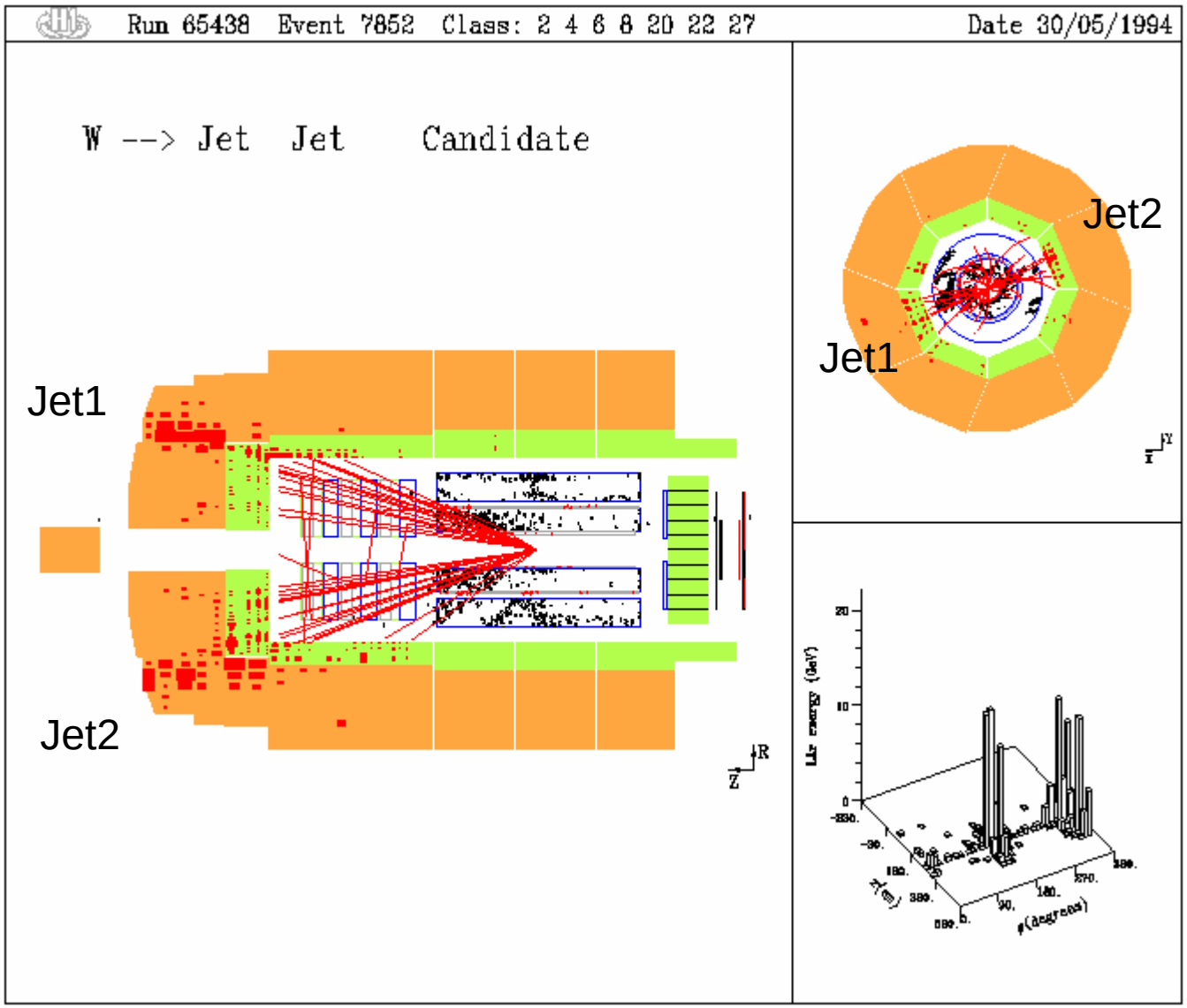
$$ep \to eXW.....W \to \mu\nu$$

H1 sees more events than expected from this reaction. New physics ?

Here only an unbalanced electron is visible. This topology is predominantly expected for

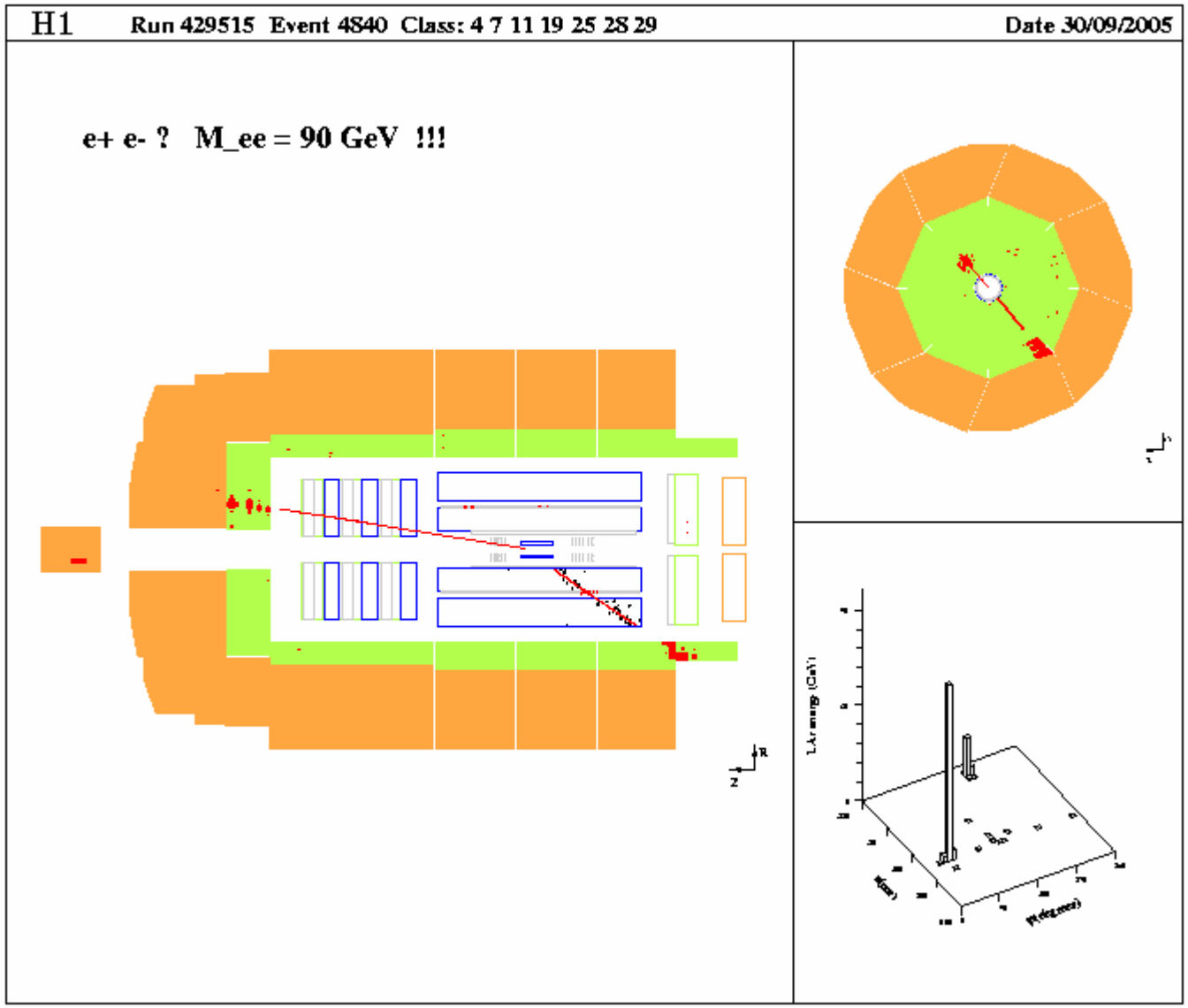
$$ep \rightarrow (e)(X)W.....W \rightarrow e\nu$$





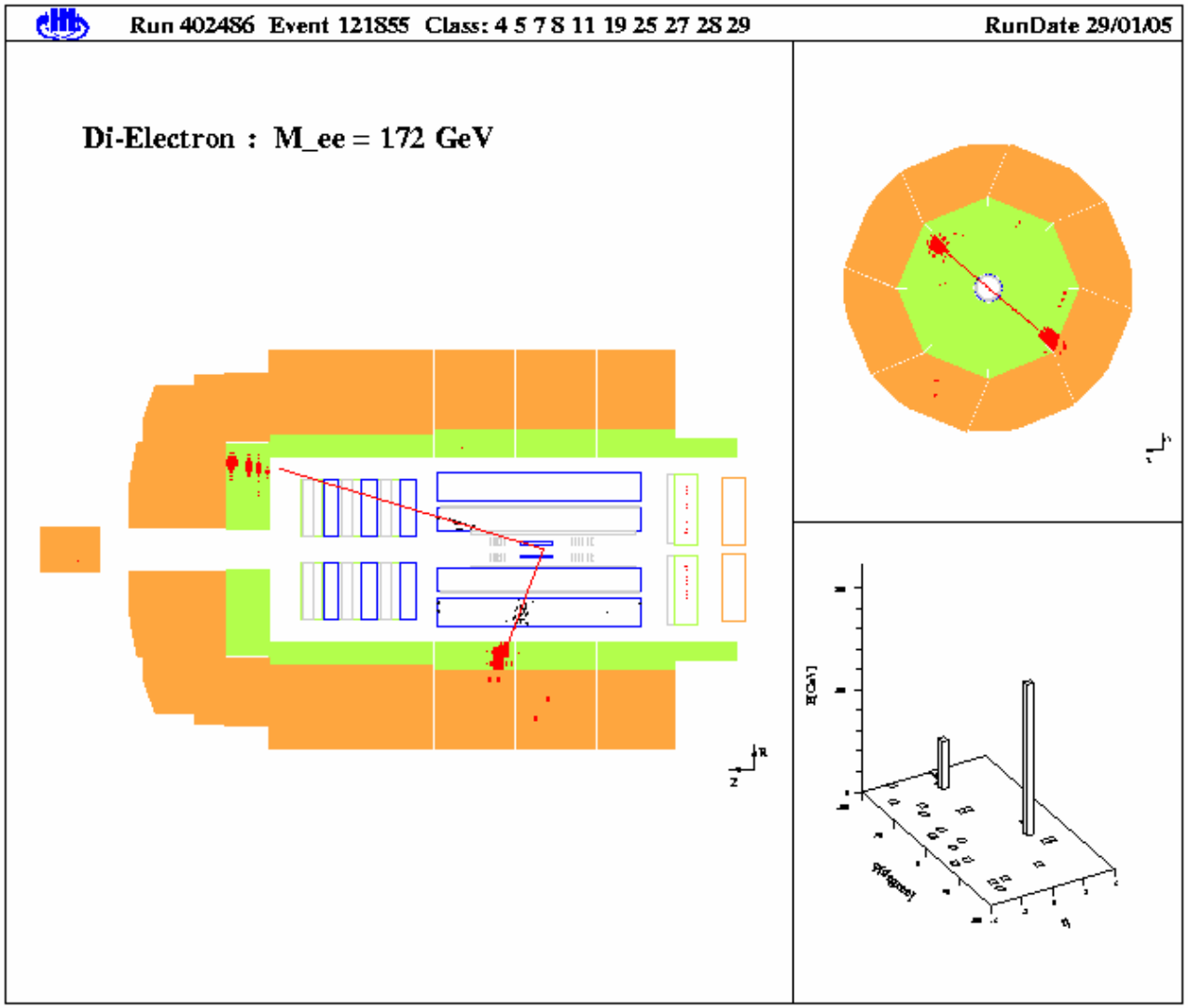
The W decays also into quark-antiquark producing two jets.
The jet-jet-mass is 80 GeV, just the known W-mass.

The W particle has a sister, the Z , of 90 GeV mass, decaying into lepton pairs

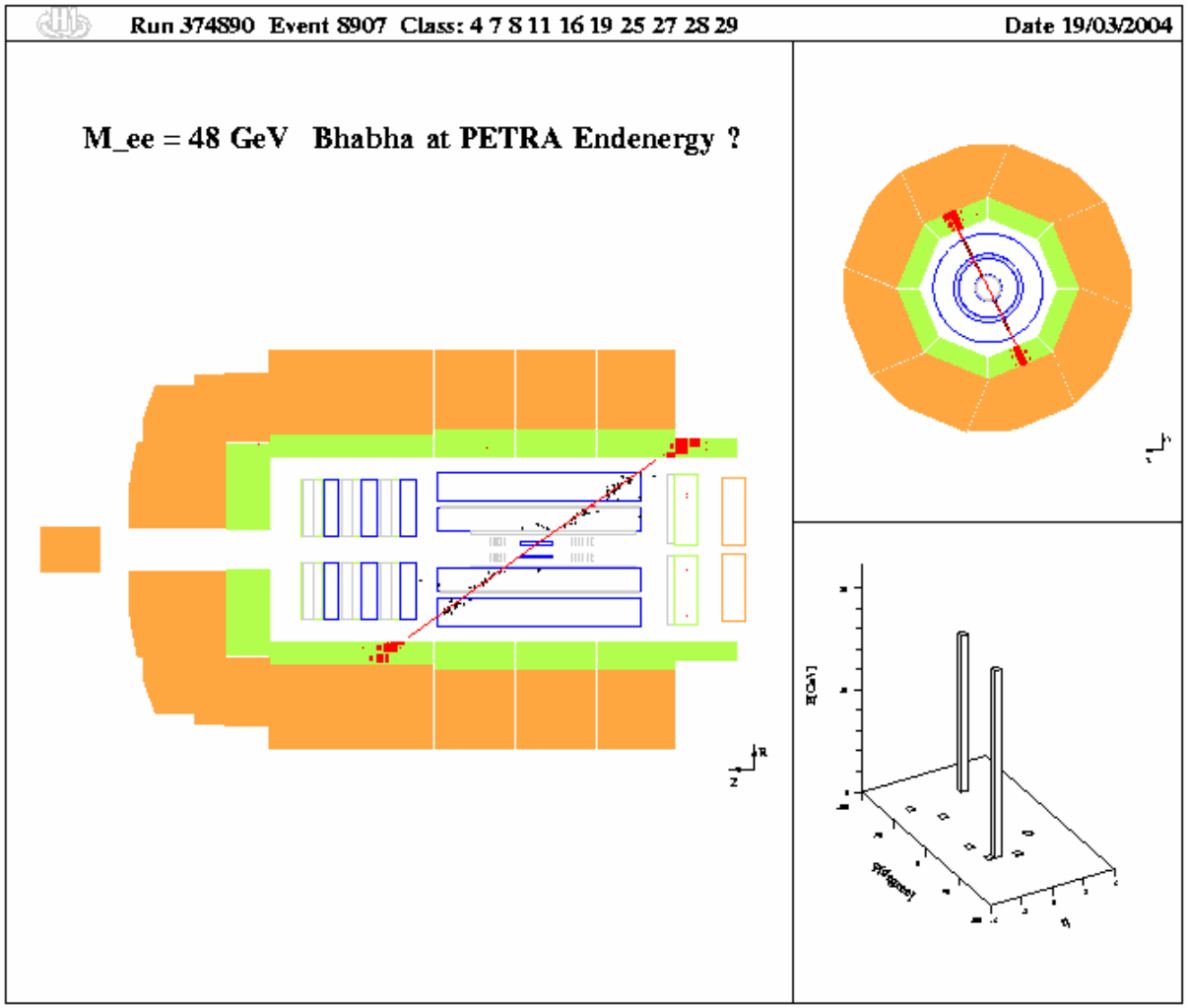


$$Z_0 \rightarrow e^+ e^-$$

In this event an even more massive e+ e- pair ….. : What physics is that ?

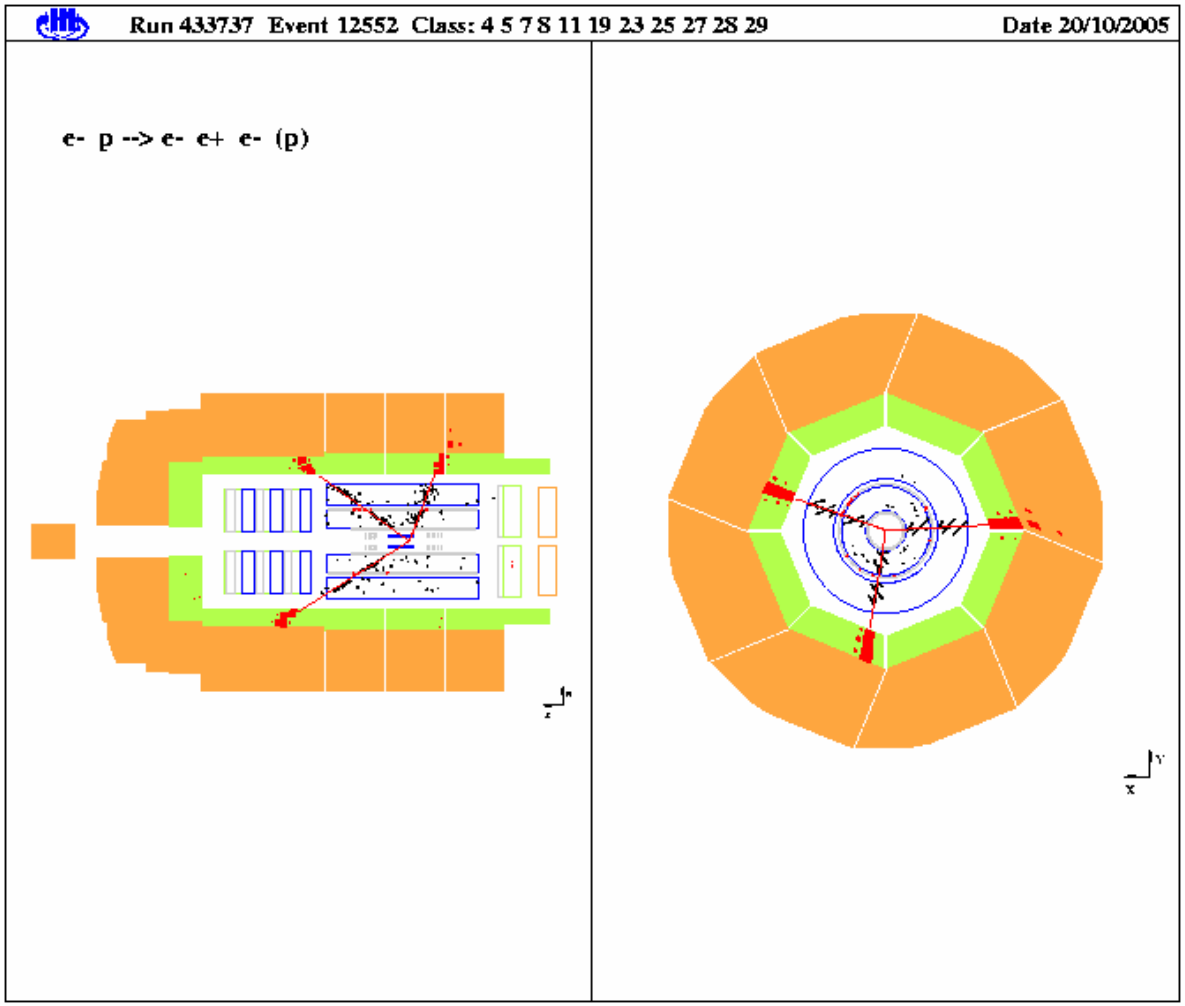


A collinear electron pair



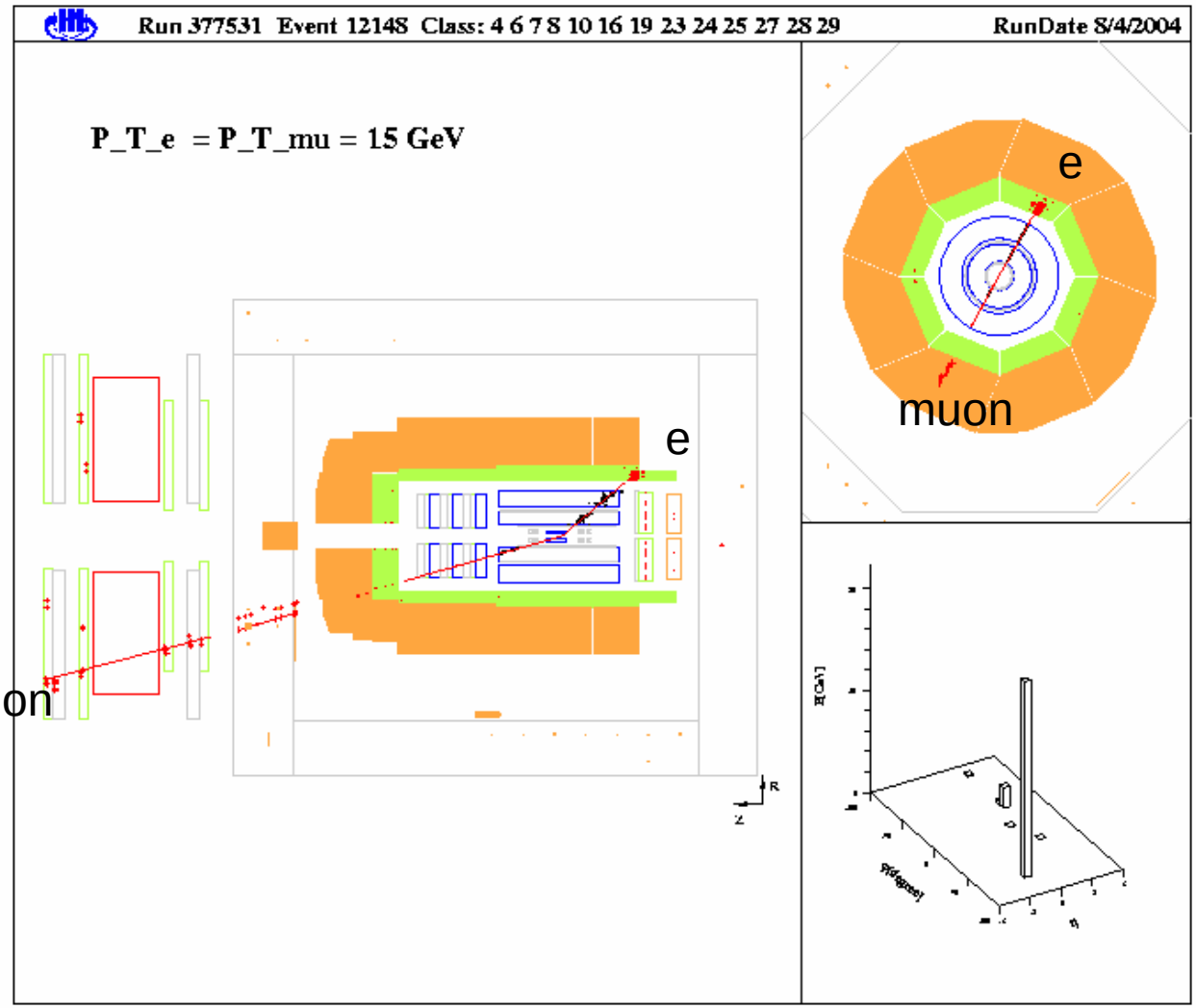
Such events we were used to see at the electron-positron collider PETRA

Here a positron and 2 electrons are recorded. Presumably the scattered electron and a pair created in the interaction

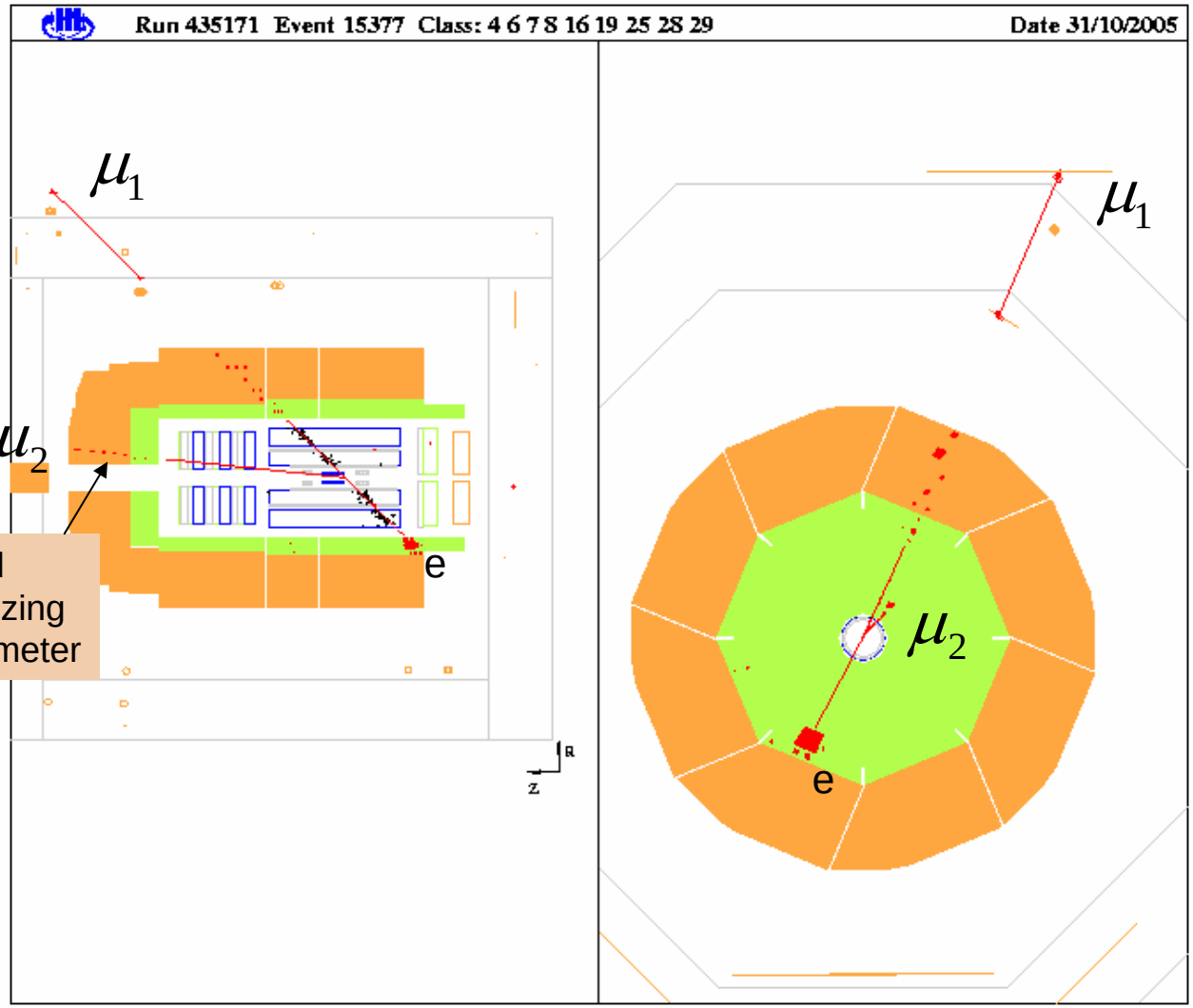


Note :
All ‘electrons’ are well confined in the electromagnetic part (green) of the calorimeter

There are also dilepton events with different lepton types : Electron and muon



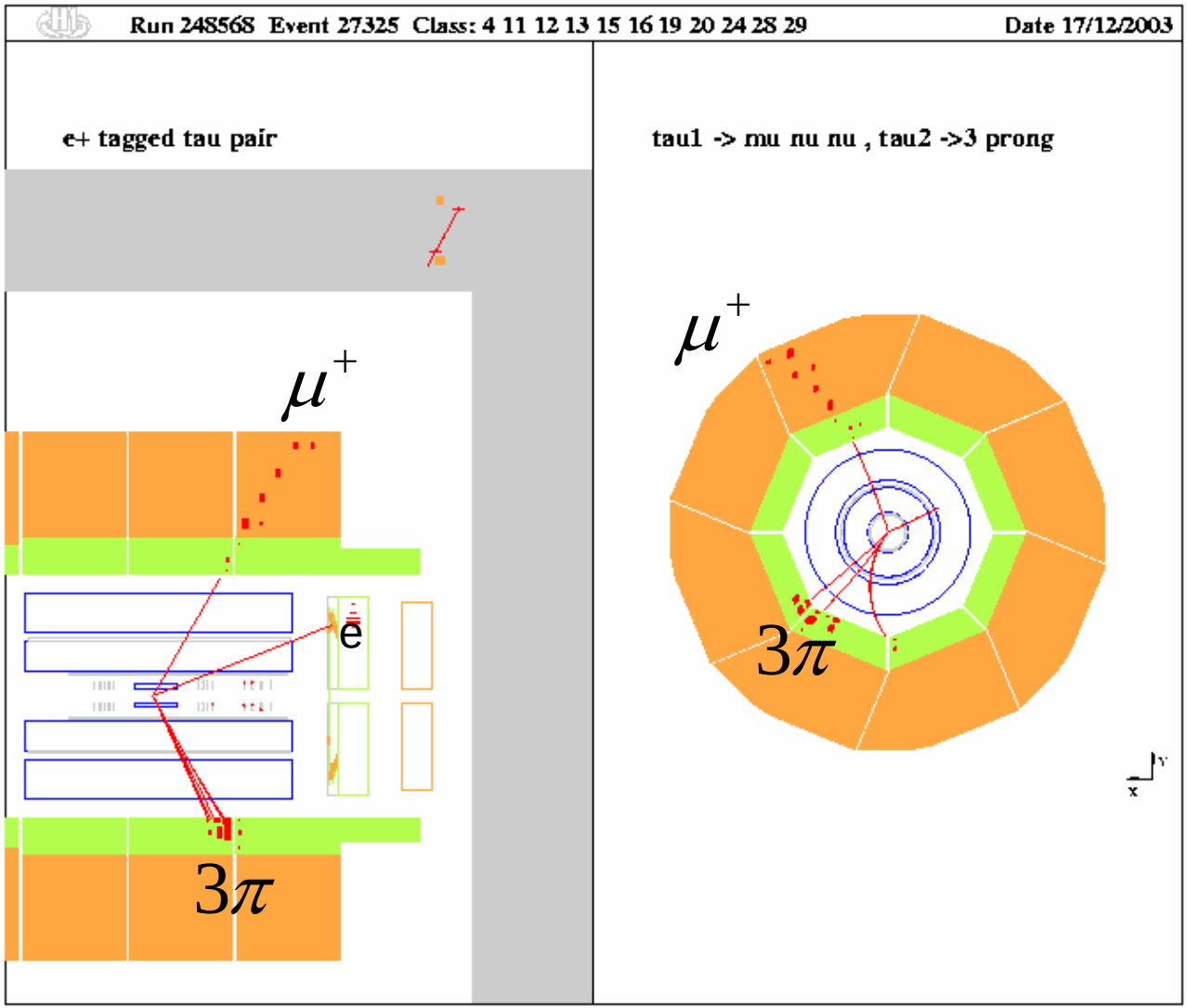
Here it is evident that a pair of muons is produced



Muon2 identified as minimum ionizing particle in calorimeter

A pair of tau-mesons with the scattered electron

$$ep \to e(p)\tau^+\tau^-$$



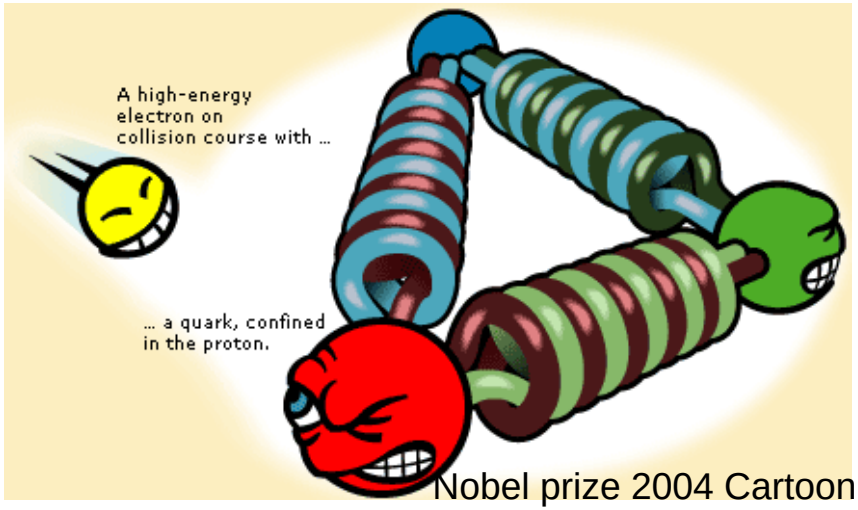
$$\tau^+ \to \mu^+\nu$$

$$\tau^- \to \pi^-\pi^+\pi^-\nu$$

Summary

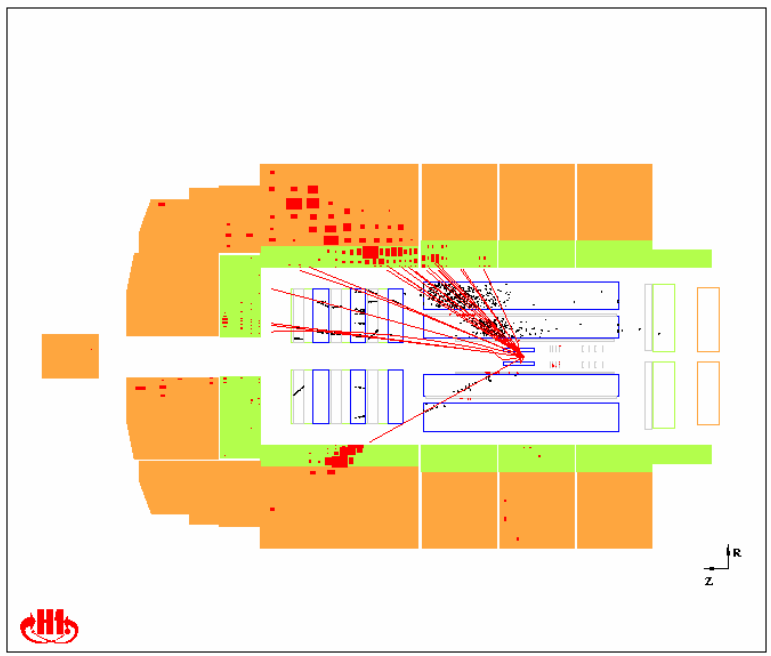
The Method:

e p scattering



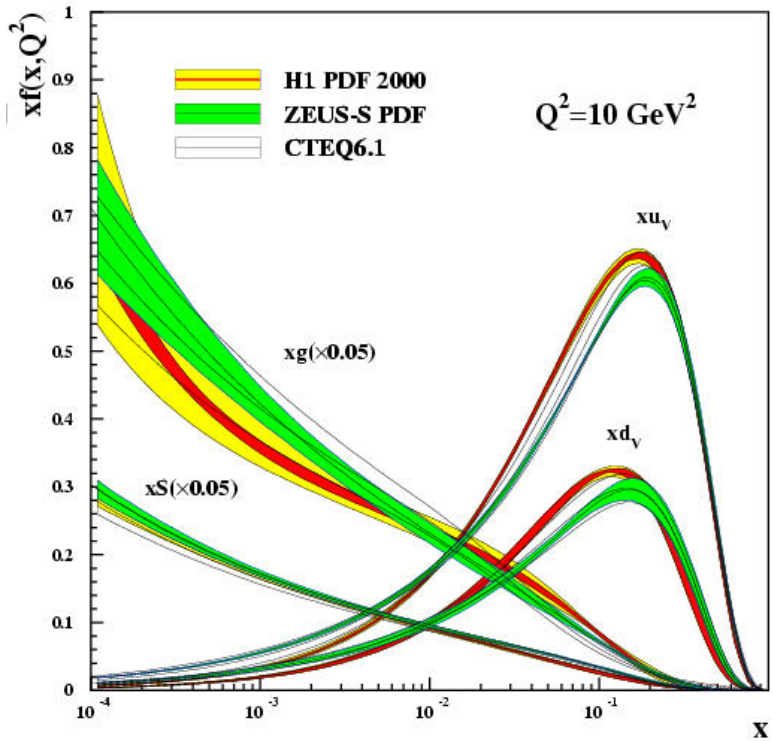
Nobel prize 2004 Cartoon

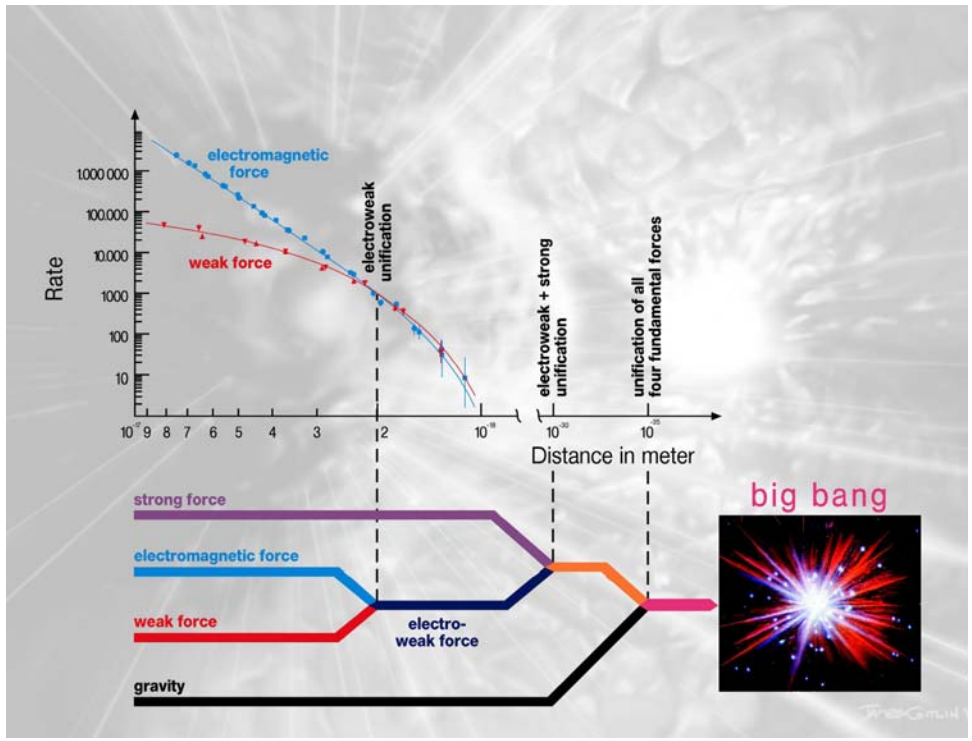
The Data



Physics Results

examples :



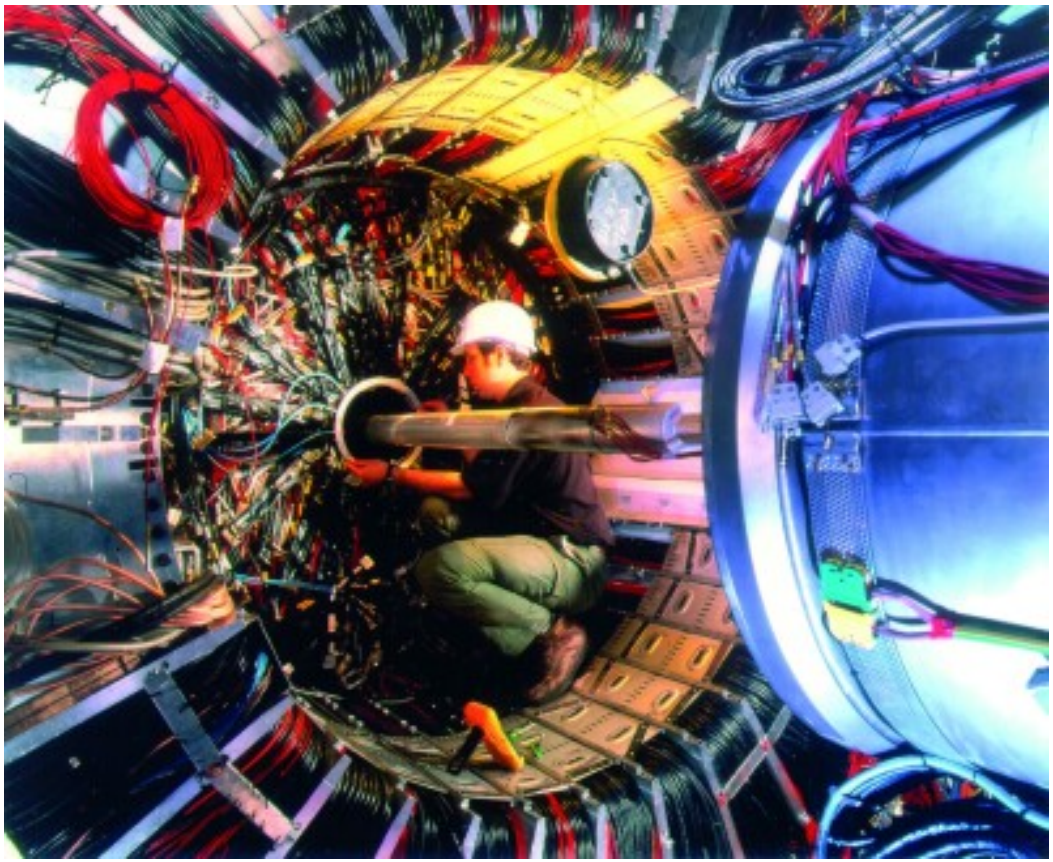


Protonstructure : Quarks and Gluons

Electroweak Unification

..and many more …..

All this became possible thanks to the work of the H1 members……



Work at the innermost parts of the H1 detector

Some members of the H1 Collaboration

…and thanks to HERA….

.. the worlds most powerful microscope $\Delta x \approx 10^{-18}\, m$