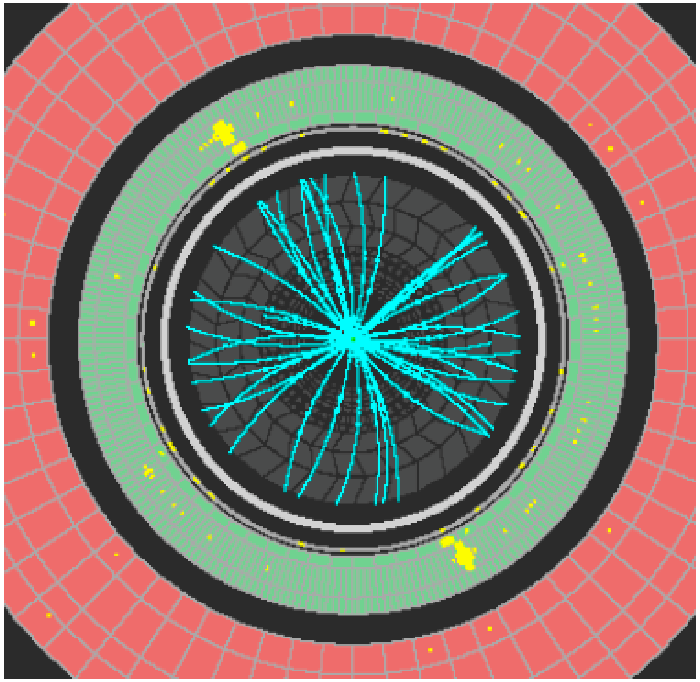
Higgs Boson:

Expectation Meets Reality



M. E. Peskin
Sept. 2012

For more than 40 years, particle physicists have been searching for a particle called the Higgs boson.

On July 4, 2012, the ATLAS and CMS experiments announced the discovery of a particle with many properties of this long-awaited boson.

This discovery set off a world-wide media frenzy, which still continues.

New Scientist CultureLab   August 30

"Newton's apple, the elusive Higgs particle discovered just weeks ago, and the world's best-known paraplegic, physicist Stephen Hawking, lit up last night's dazzling opening ceremony for the London Paralympic Games."

The Higgs is also known as the God Particle. It is also called the Holy Grail of particle physics.

The Higgs is said to be the origin of mass. It is not obvious that anything is needed to cause things to be massive.

Many people say that the discovery of the Higgs is important who do not actually understand what the Higgs particle is.

You may be one of them.

If so, in this lecture, I will explain it all to you.

I will begin with the question of what mass is and why it needs to be generated.

I will then put the answers into the context of our current knowledge of elementary particle physics.

We begin with the question, what is mass ?

There are two types of mass in physics:

Gravitational mass: $F = -mg$

Inertial mass: $ma = F$

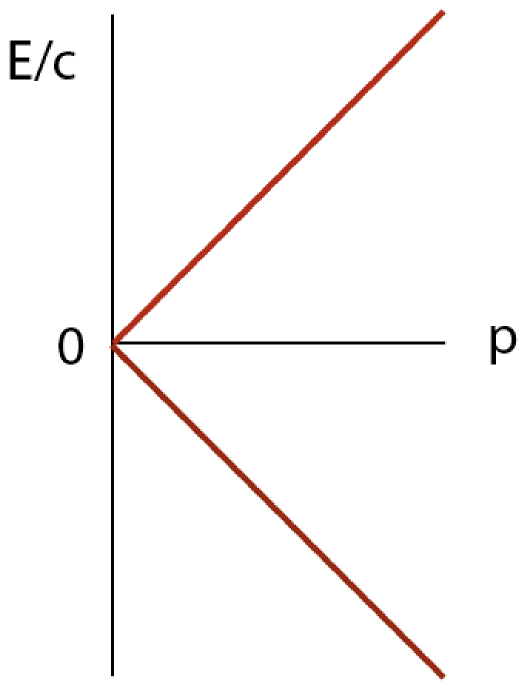
In his theory of general relativity, Einstein explained why gravitational mass equal inertial mass. Space is curved, and each particle follows its shortest path in the absence of other forces.

It is inertial mass that is more primitive.

Neither equation on the previous slide is covariant under special relativity. Relativity makes the story more complicated.

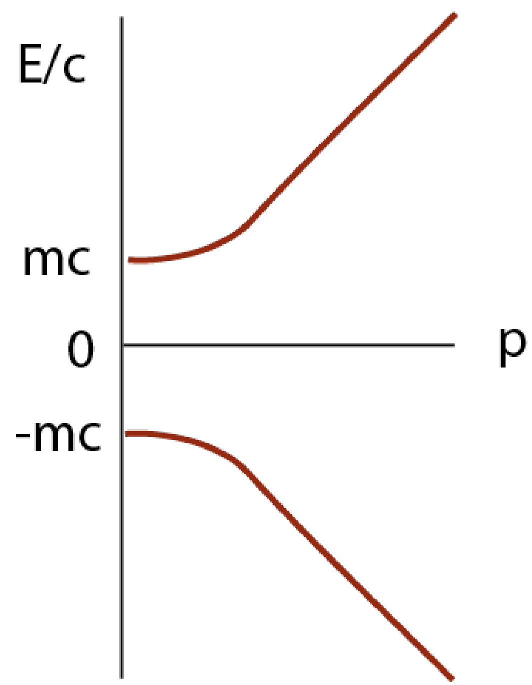
In special relativity, every particle must have an antiparticle. The energy-momentum relation of the particle and antiparticle has the form:

zero mass



$$E = pc$$

massive



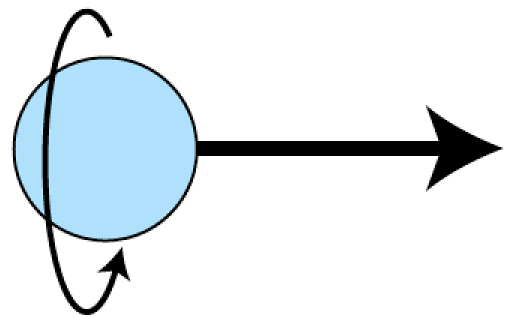
$$E = \sqrt{(pc)^2 + (mc^2)^2}$$

This looks like level-crossing or mixing of states in quantum mechanics.

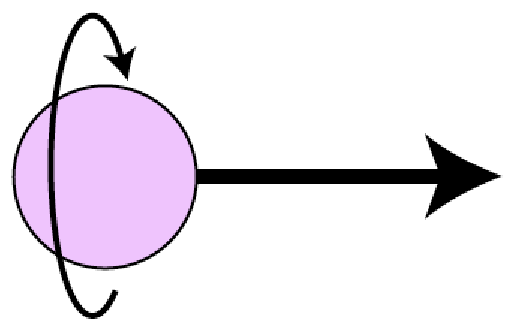
Indeed, in relativistic particle theory, we go from massless to massive particles by mixing quantum states.

What are the states that mix ?

The simplest representations of special relativity have the form of a massless particle with spin J oriented along, or opposite to, the direction of motion



and an antiparticle, which is also massless:



Notice that the antiparticle has the opposite spin.

These are the materials we have to work with.

If the spin is zero, there is no barrier to mixing these states. Then the massless particle can freely become massive.

This is also reflected in the field equations. The massless

$$\mathcal{L} = \frac{1}{2}(\partial^\mu \varphi)^2$$

and massive Klein-Gordon equations

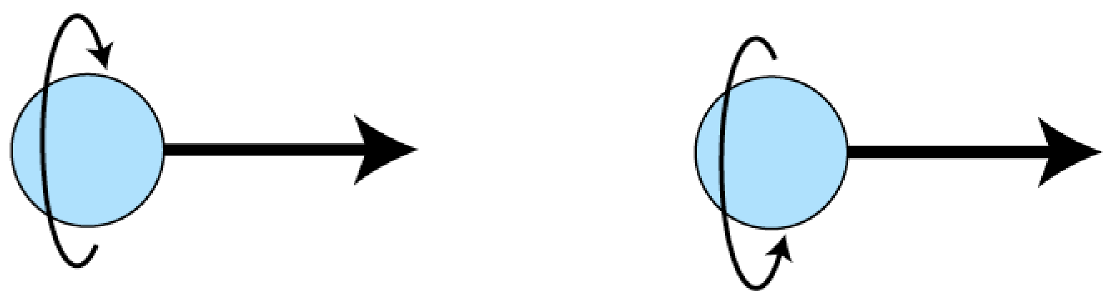
$$\mathcal{L} = \frac{1}{2}(\partial \varphi)^2 - \frac{1}{2} m^2 \varphi^2$$

are hardly different.

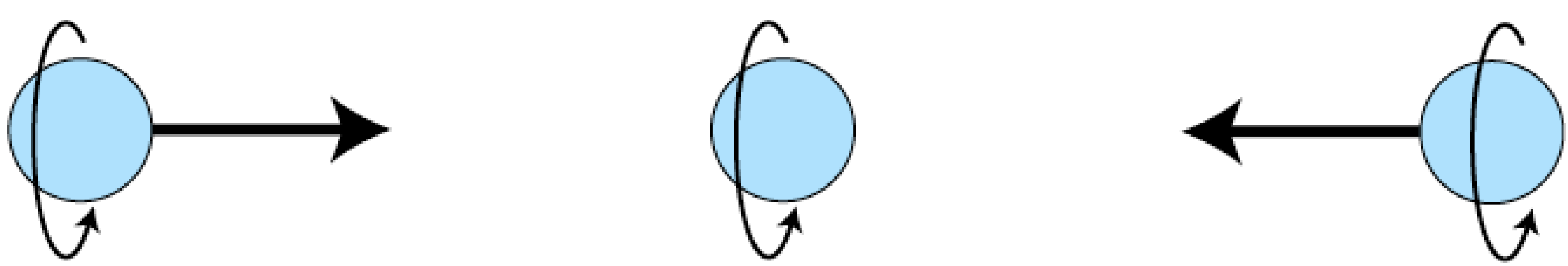
If the spin is nonzero, the story is more complicated.

Consider, for example, spin 1/2. What states must mix to go from a massless particle to a massive particle ?

In the massless case, there are two different particles, with spin +1/2 and -1/2 along the direction of motion.



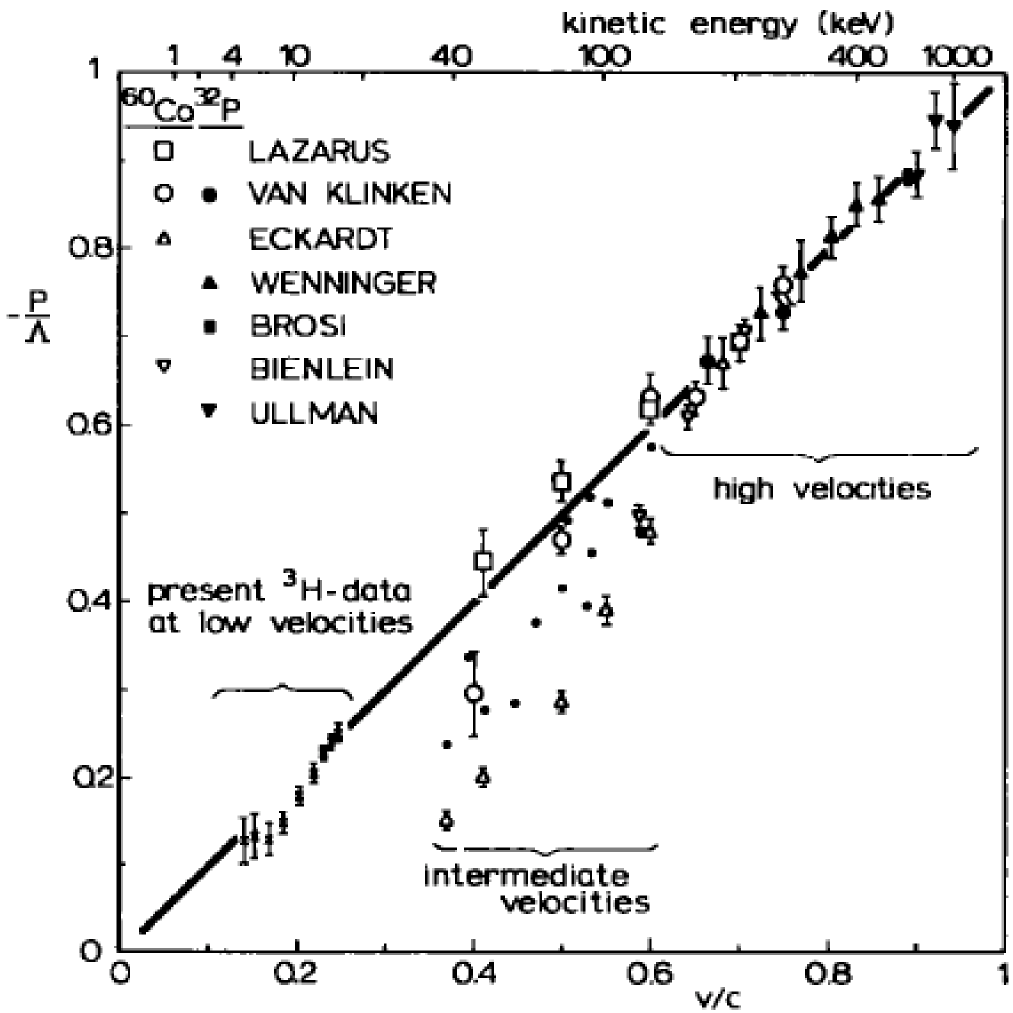
In the massive case, these states are connected by Lorentz boosts. So they must combine into a single particle.



You might think that there should be no barrier to this mixing.

You are wrong.

The weak interactions, the interactions that mediate radioactive decay, treat left- and right-handed leptons and quarks differently.



The difference is expressed by assigning different quantum numbers to these particles.

We have a detailed theory of the weak interactions in which the forces are carried by three massive particles with J = 1:

$$W^+, \ W^-, \ Z^0$$

whose fields obey equations similar to Maxwell's equations.

The theory is easiest to describe if we ignore the masses of these bosons and of the quarks and leptons.

Then the theory has an isospin symmetry, with multiplets similar to spin multiplets. The left-handed quarks and leptons are assigned to isospin 1/2, the right-handed quarks and leptons to isospin 0.

$$I = \frac{1}{2} \ : \ \begin{pmatrix} \nu \\ e \end{pmatrix}_L , \ \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad I = 0 \ : \ e^-_R \ , \ u_R \ , \ d_R$$

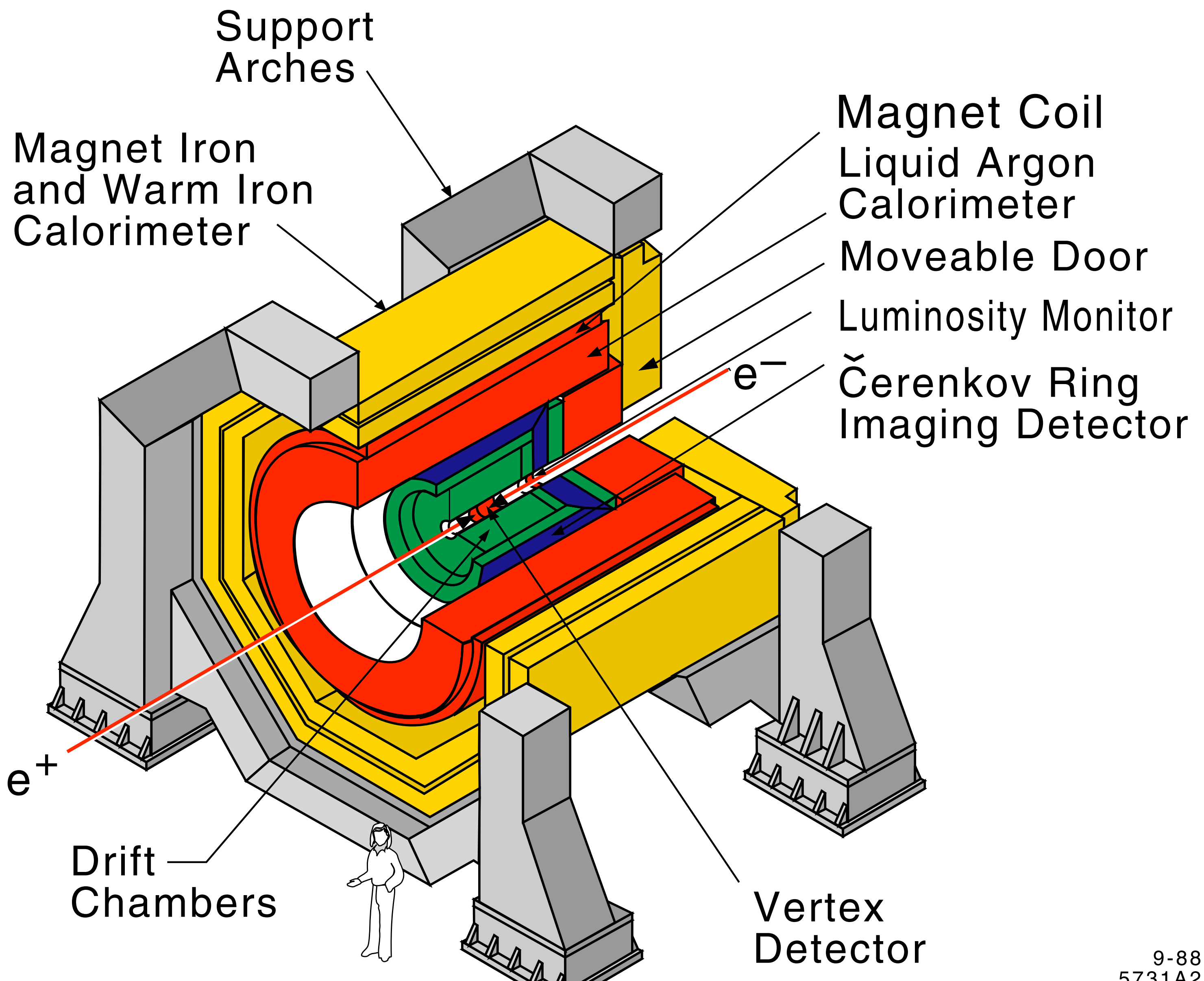
The W bosons couple only to left-handed species. This explains the parity violation of the weak interactions. The Z boson couples to the charge

$$Q_Z = I^3 - s_w^2 Q$$

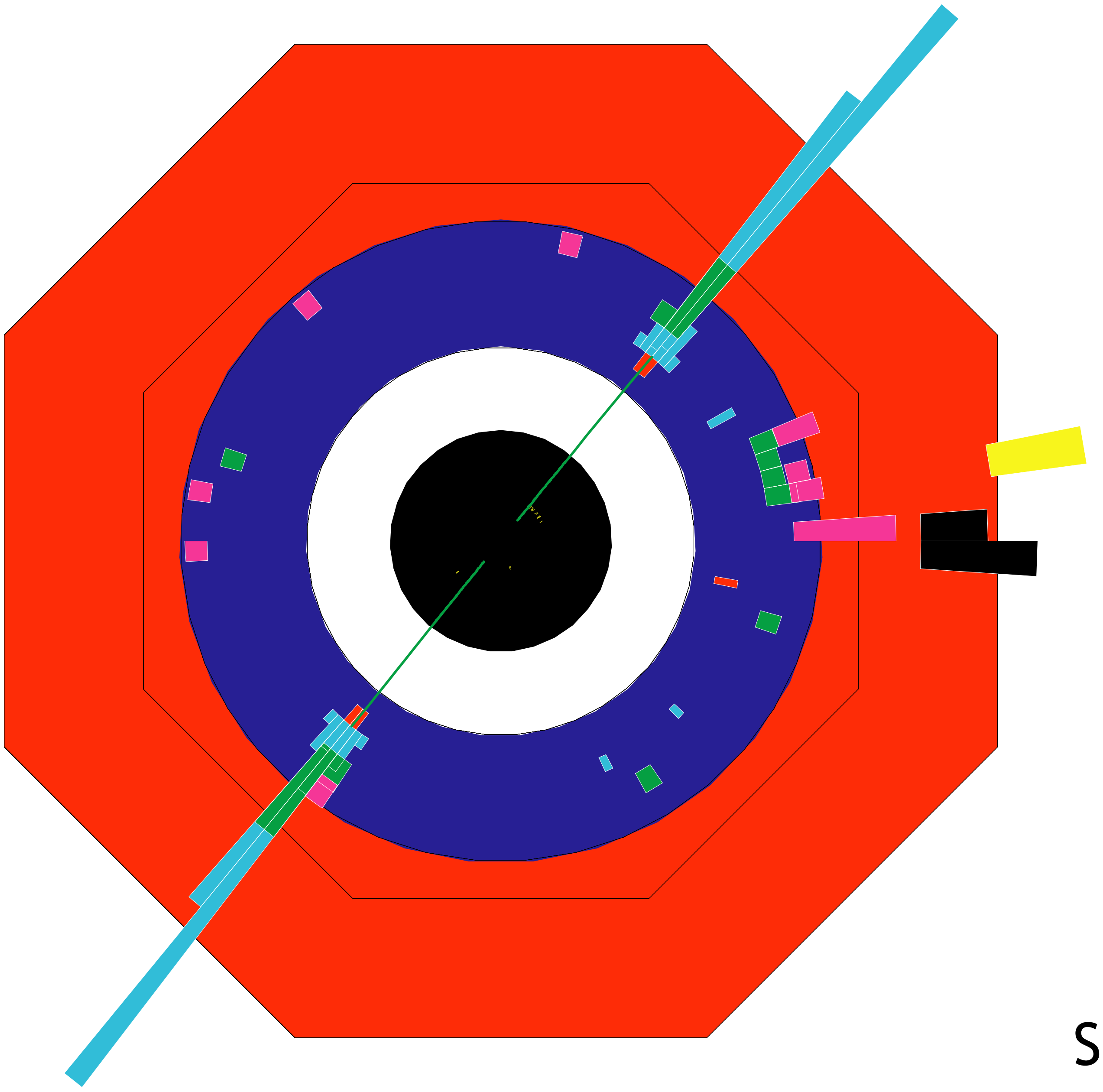
This is very odd. The left- and right-handed states have different charges and would be forbidden to mix. Are we really sure that these assignments are correct ?

To present the evidence, I need to discuss a little about elementary particle experimentation.

SLD

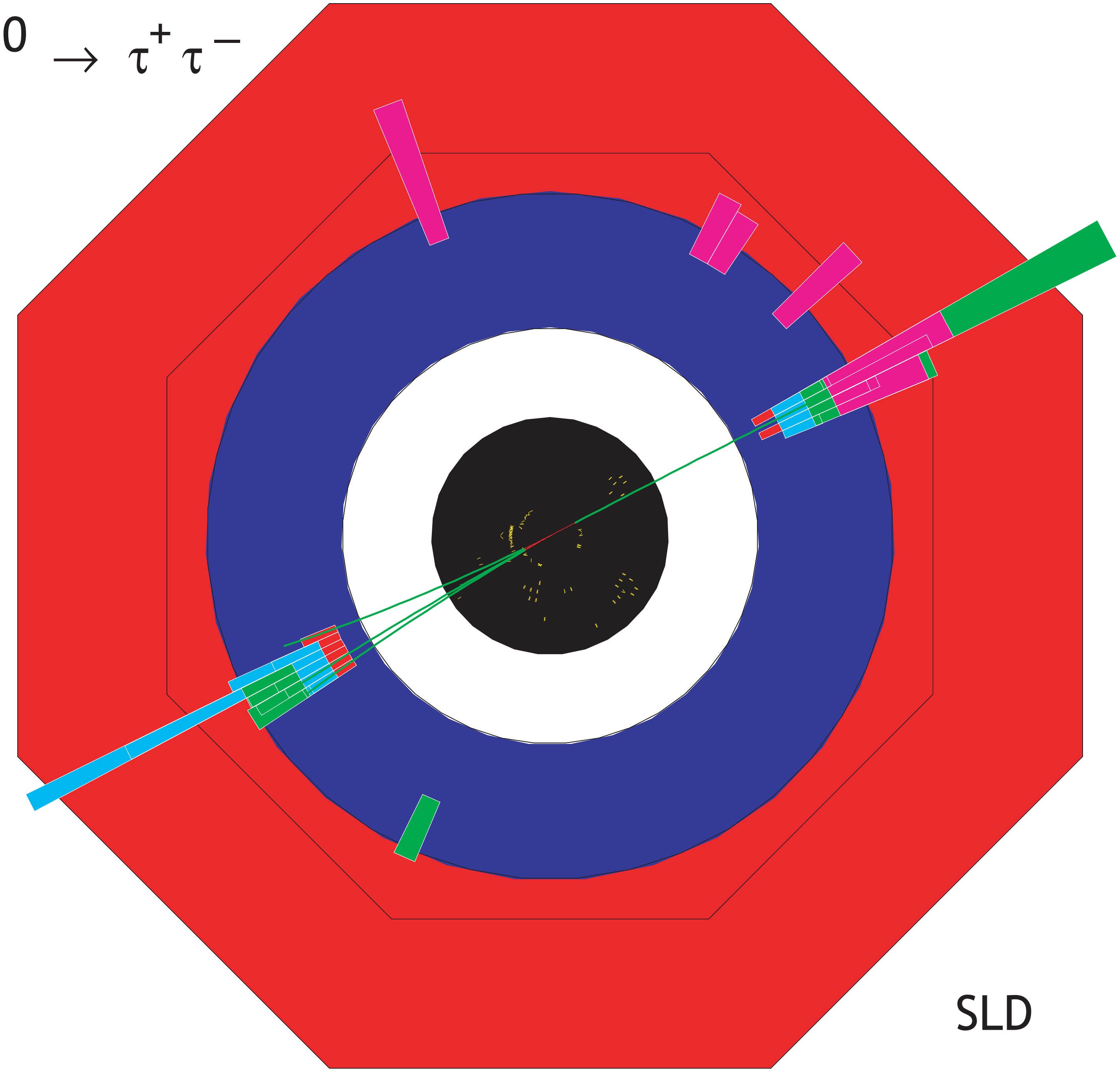

Support
Arches
Magnet Iron
and Warm Iron
Calorimeter
Magnet Coil
Liquid Argon
Calorimeter
Moveable Door
Luminosity Monitor
Čerenkov Ring
Imaging Detector
e−
e+
Drift
Chambers
Vertex
Detector
9-88
5731A2

$e^+e^- \to Z^0 \to e^+e^-$

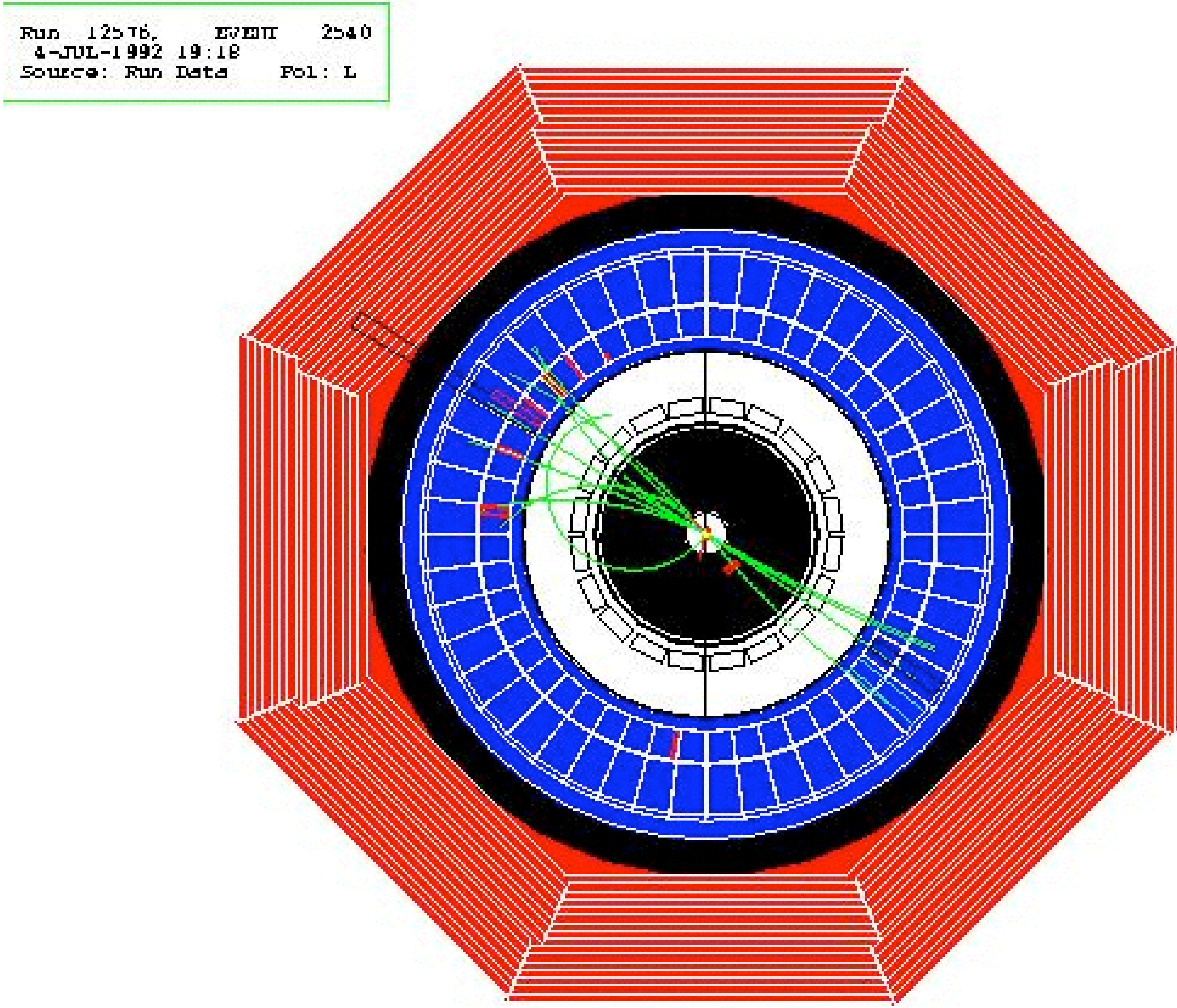


SLD

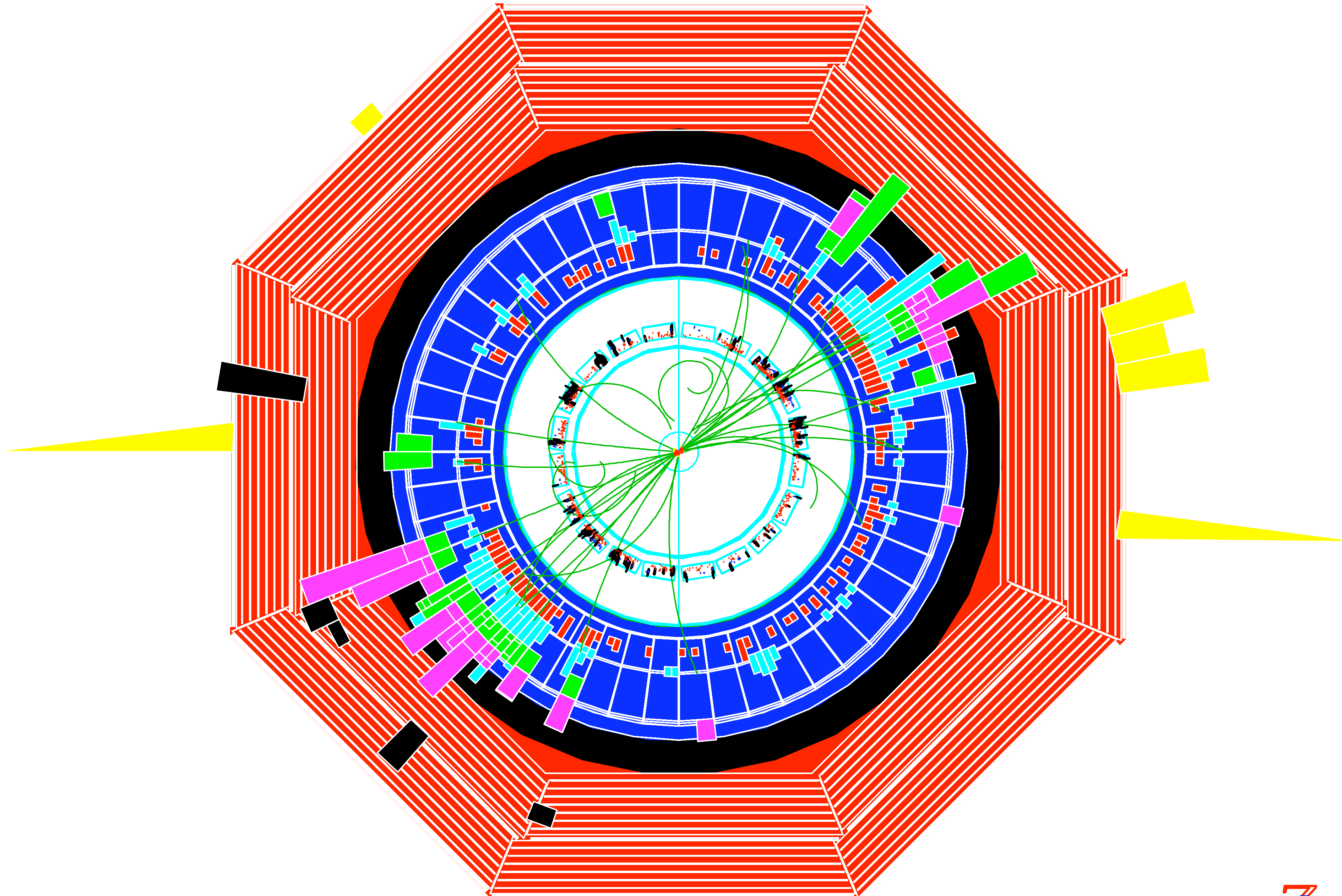
$e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$

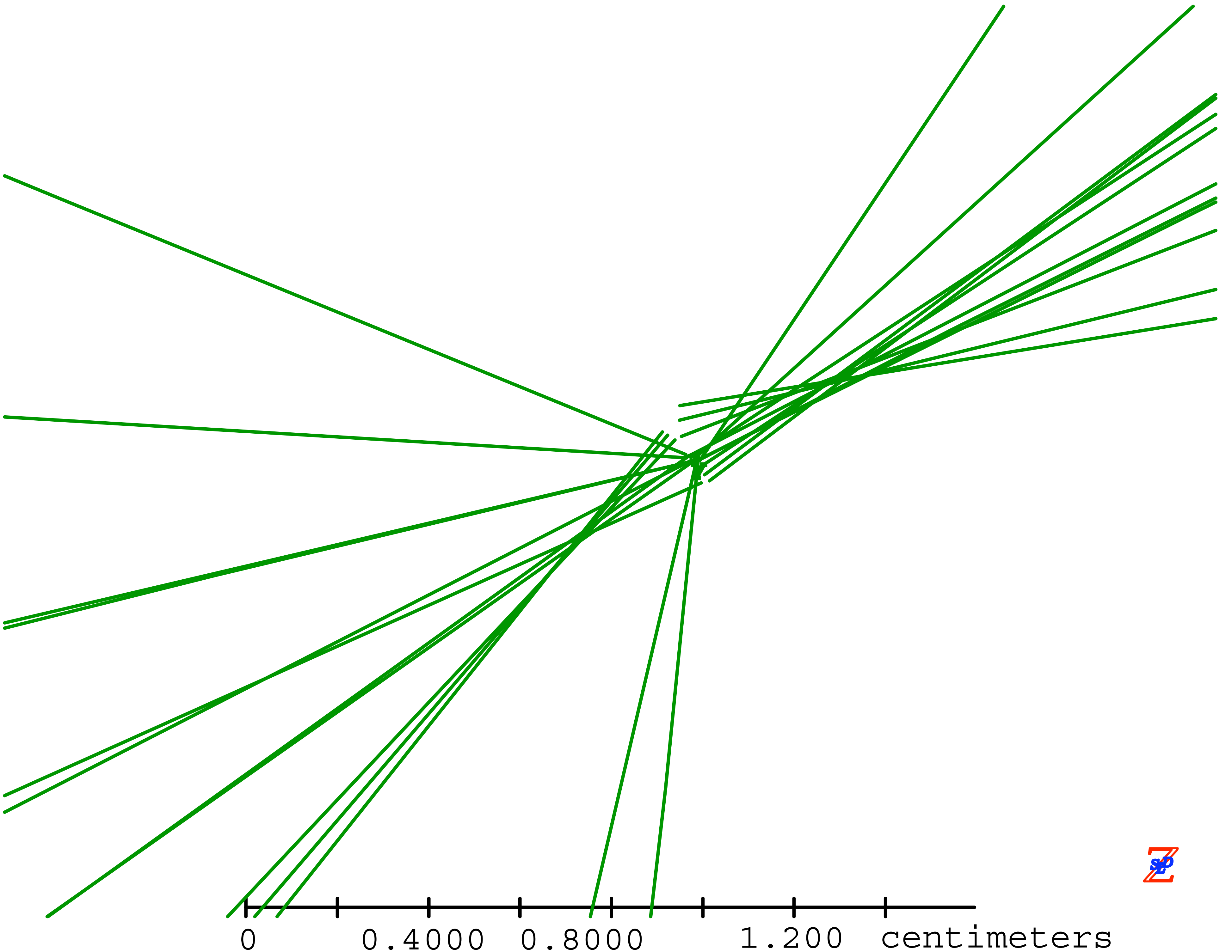


SLD



SLD




0
0.4000
0.8000
1.200
centimeters

We can test the charge assignments by makings millions of Z bosons in the lab and watching their decays one by one.

This was actually done in the 1990's in experiments in e^+e^- annihilation at CERN and SLAC.

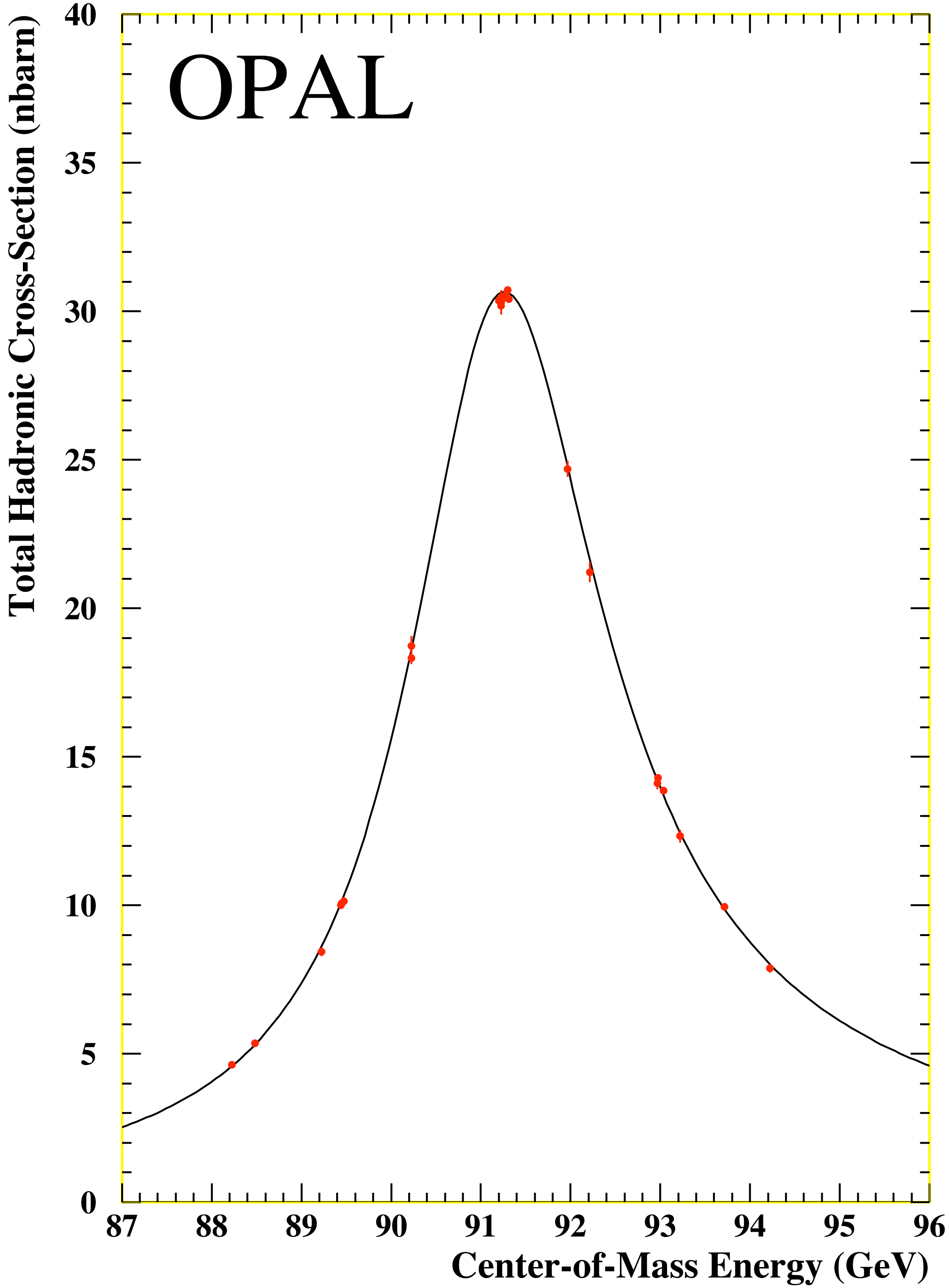
The Z charges determine

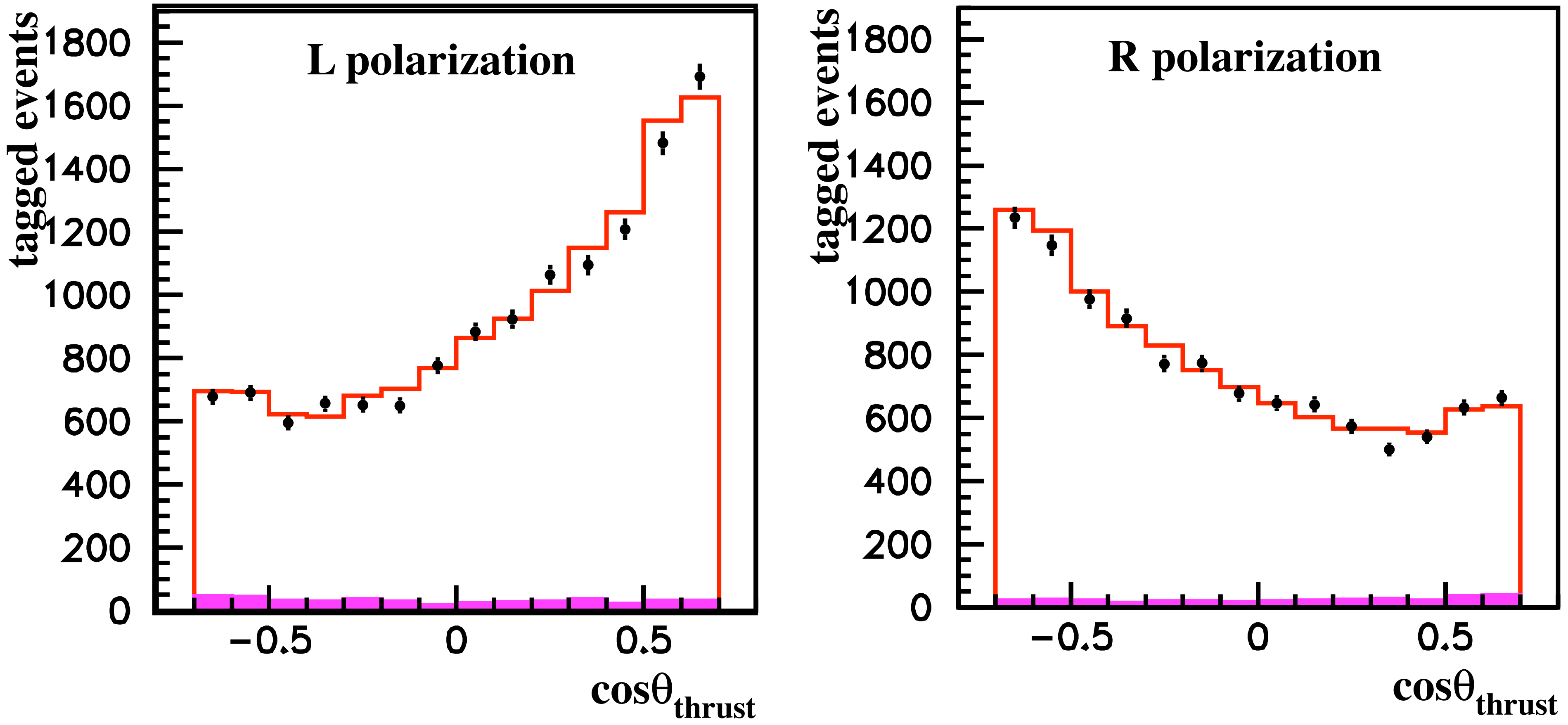
the total width and branching ratios of the Z

$$\Gamma_Z = \frac{\alpha m_Z}{12 c_w^2 s_w^2} \sum_f N_f (Q_{ZL}^2 + Q_{ZR}^2)_f$$

the spin asymmetries of Z decays

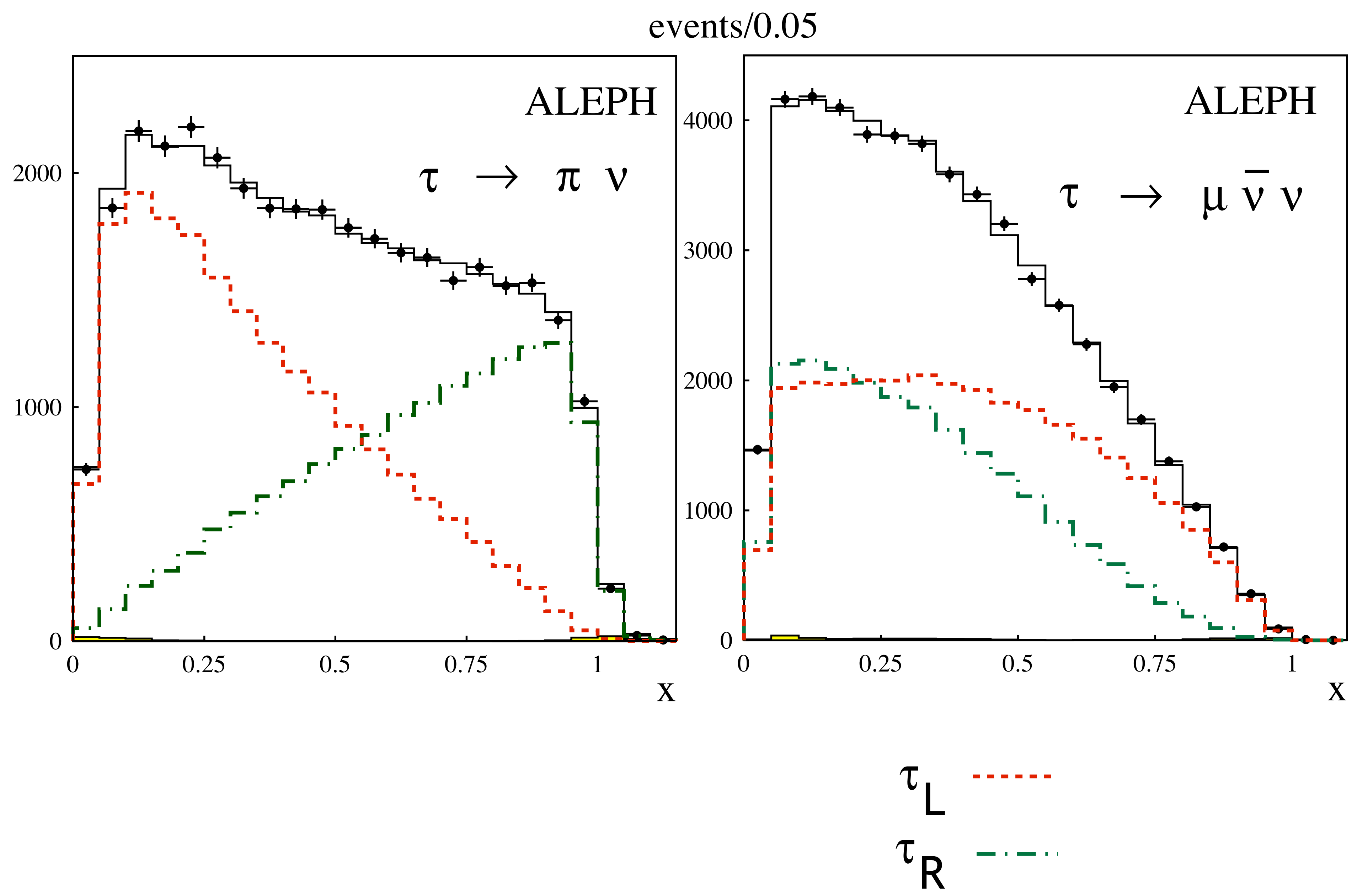
$$A_f = \left. \frac{Q_{ZL}^2 - Q_{ZR}^2}{Q_{ZL}^2 + Q_{ZR}^2} \right|_f$$


OPAL
Total Hadronic Cross-Section (nbarn)
0
5
10
15
20
25
30
35
40
87
88
89
90
91
92
93
94
95
96
Center-of-Mass Energy (GeV)



$A_b = 0.94$ at the Z^0

SLD



events/0.05
ALEPH
τ → π ν
2000
1000
0
0
0.25
0.5
0.75
1
x
ALEPH
τ → μ ν̄ ν
4000
3000
2000
1000
0
0
0.25
0.5
0.75
1
x
τL
τR

A precision experiment at SLAC also measured the asymmetry for producing the Z from polarized electrons.

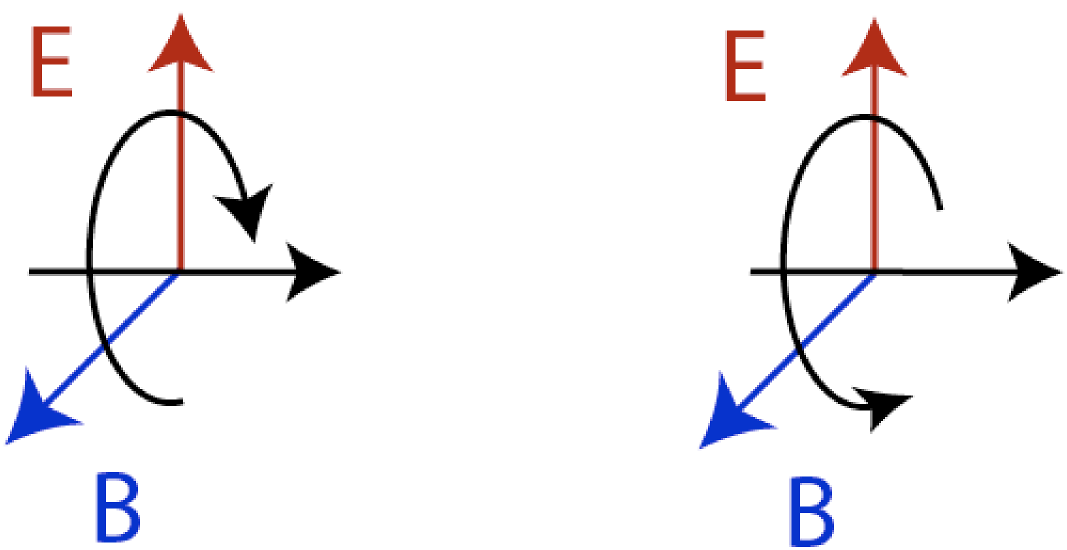
$$A_e = 0.1514 \pm 0.0022$$

So it is very, very clear that electrons and all other fermions have different charges with respect to (W^+, W^-, Z) between the left-handed particles and the right-handed particles.

And, there is another problem with the weak interaction theory.

Not only are mass terms for quarks and leptons forbidden, but also masses for $W^+,\ W^-,\ Z^0$ are forbidden.

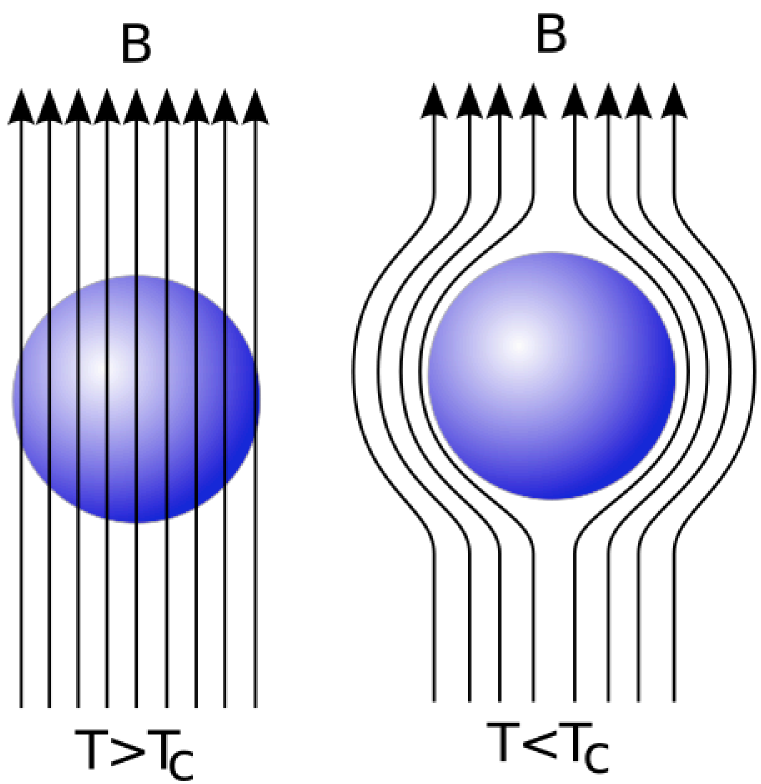
These particles must be massless for the same reason that Maxwell's equations require the photon to be massless.

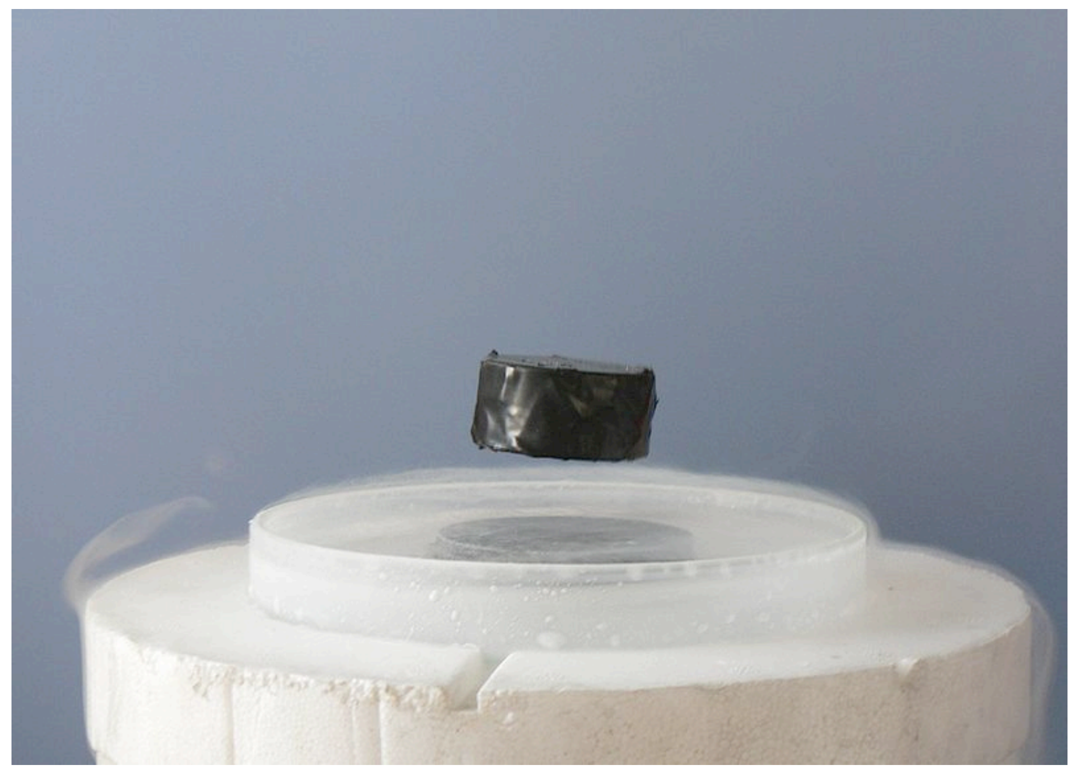


There is one circumstance in Nature in which the photon gets a mass.

In a superconductor, magnetic fields are excluded, or, rather, fall off exponentially in the interior. This is the Meissner effect.

That is exactly the effect of adding a mass term to Maxwell's equations.





In a superconductor, electron pairs $(e^- e^-)$ condense into a superfluid. Electric charge is no longer conserved. A supercurrent flow can correct any imbalance of charge.

The quanta of the supercurrent are phonons. If there were no electromagnetism, these would be massless quantum excitations of the superconducting material.

The supercurrent screeens out magnetic fields. At the quantum level, this is a mixing of the photons and the phonons, producing a mass in Maxwell's equations.

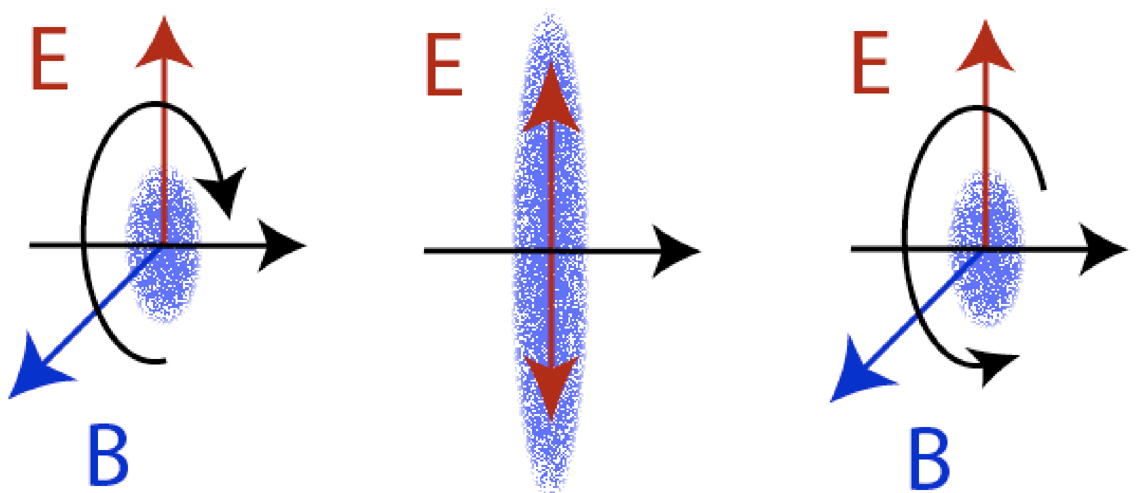
The presence of the phonons solves another problems of state mixing.

A massless photon has only two polarization states, left- and right- circular polarization $\vec{p} \cdot \vec{J} = \pm 1$

However, a massive J = 1 particle, in its rest frame, must have three quantum states: $J^3 = -1, 0, +1$

Mixing with the phonon supplies the needed third state.

In a superconductor, the photons eat the phonon and become a single massless particle:



Nambu and, later, Anderson, demonstrated this mechanism using the BCS theory of superconductivity.

Later, Higgs, Brout, Englert, Hagen, Guralnick, and Kibble demonstrated that this mechanism generates a mass for a vector boson in a way completely consistent with special relativity. The mechanism has become known as the Higgs mechanism.

In fact, this is the only way that a relativistic spin 1 particle can get a mass. I will illustrate this later in the lecture.

We can apply this to the theory of weak interactions.

The big question is, what replaces the electron pair condensate ?

This condensate must extend everywhere through the vacuum of space.

I will avoid answering this question.

Instead, for the moment, I will adopt the simplest possible model, due to Weinberg and Salam:

Glashow, Salam, Weinberg

Postulate a complex-valued scalar field with I = 1/2:

$$\varphi = \begin{pmatrix} \pi^+ \\ \phi^0 \end{pmatrix}$$

By some mechanism, let ϕ^0 acquire a value v everywhere in space. This v is the order parameter for symmetry breaking.

$$\langle \phi^0 \rangle = \frac{1}{\sqrt{2}} v$$

Write $\phi^0 = \frac{1}{\sqrt{2}}(v + h + i\pi^0)$

The fields $\pi^+, \ \pi^-, \ \pi^0$ are eaten by $W^+, \ W^-, \ Z^0$. We obtain the correct masses if v = 246 GeV. The field $h(x)$ is left over.

This model predicts the relation $m_W^2/m_Z^2 = 1 - s_w^2$ which is well satisfied experimentally.

The field φ has exactly the right structure to solve the problem of giving masses to the quarks and leptons. For example, the charges add up correctly to allow a term

$$\lambda(\overline{\nu}\ \overline{e})_L \cdot \begin{pmatrix} \pi^+ \\ \phi^0 \end{pmatrix}\ e_R$$

When ϕ^0 gets its nonzero value, this becomes a mass term for the electron

$$\frac{1}{\sqrt{2}}\lambda v \overline{e}_L\ e_R + h.c.$$

The field h also couples to the electron by

$$\frac{1}{\sqrt{2}}\lambda\ h\ \overline{e}_L\ e_R + h.c. = (m_e/v)\ h\ \overline{e}e$$

In a similar way, the couplings of h to each particle is exactly proportional to the mass of that particle.

The quantum of the field h is the Higgs boson.

It couples to every quark, lepton, and gauge boson proportionally to the mass of that particle.

This structure requires the quantum excitation h. The discovery of that excitation would be the definitive proof of this theory.

We can now work out what the Higgs boson looks like, and how we can search for it.

Before we do this, I would like to show you some experimental evidence that the W boson gets its mass from the Higgs mechanism.

The heaviest quark is the top quark, with a mass of 172 GeV.

Top quarks are produced in pairs, and decay according to

$$t \to bW^+ \to bq\overline{q} \quad \text{or} \quad b\ell^+\nu$$
$$\bar{t} \to \overline{b}W^- \to \overline{b}q\overline{q} \quad \text{or} \quad \overline{b}\ell^-\overline{\nu}$$

These events are quite characteristic. They have been studied at the Fermilab Tevatron and, now, at the CERN Large Hadron Collider (LHC).

e + 4 jet event

40758_44414

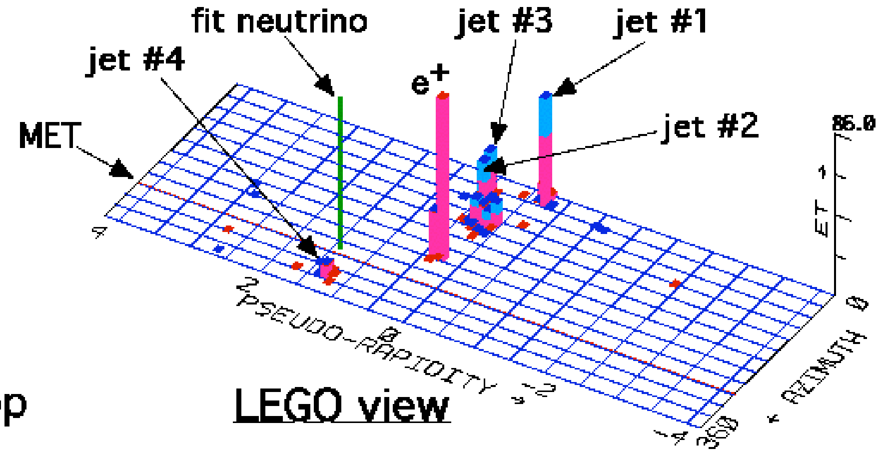
24-September, 1992

TWO jets tagged by SVX

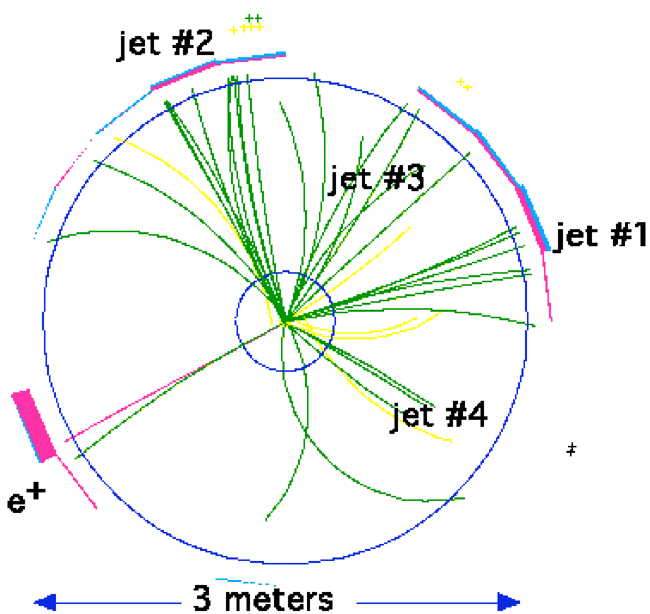
fit top mass is 170 +- 10 GeV

e^+, Missing E_t, jet #4 from top

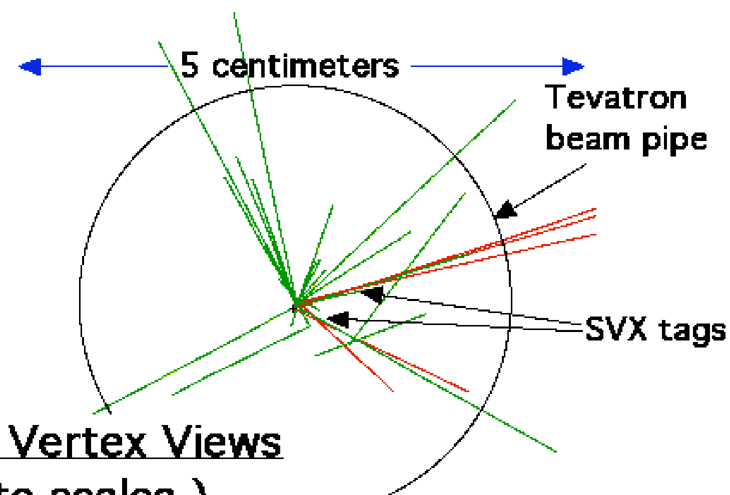
jets 1,2,3 from top (2&3 from W)



LEGO view

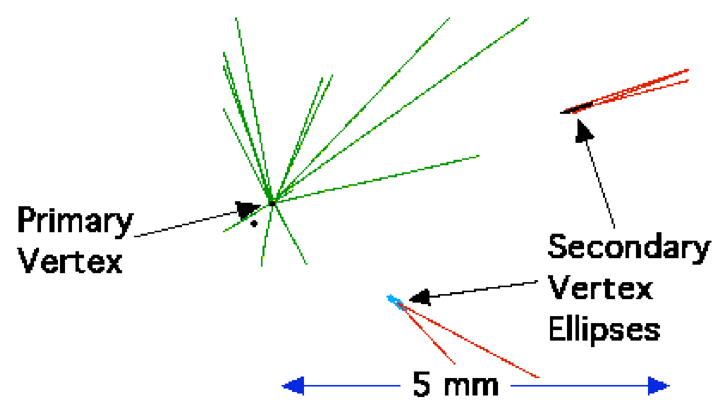


Tracking View

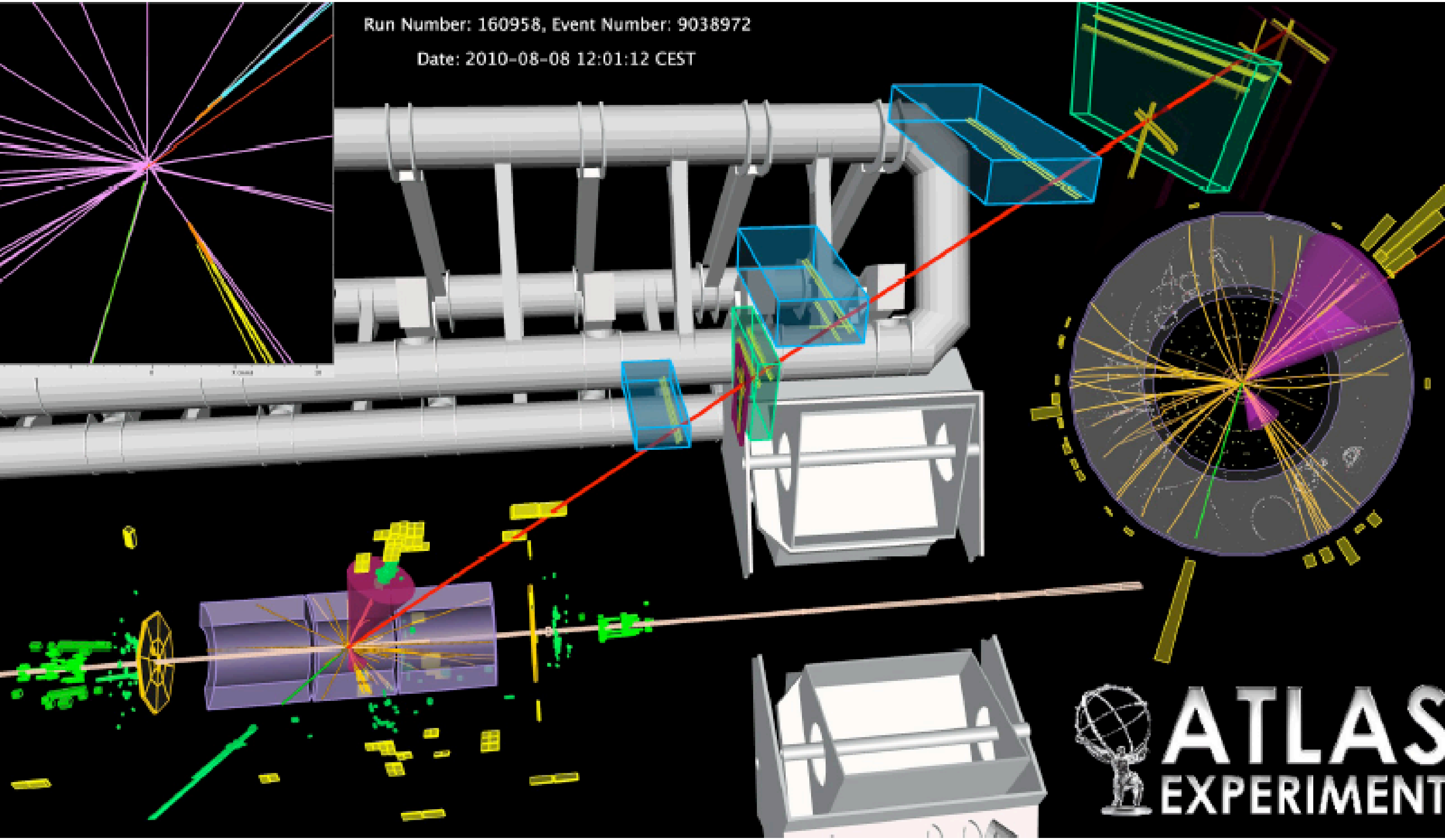


Two Vertex Views

(note scales)



CDF



ATLAS t tbar candidate in e + μ + 2 jets

An interesting question is, what is the polarization of the W boson emitted in t decay ?

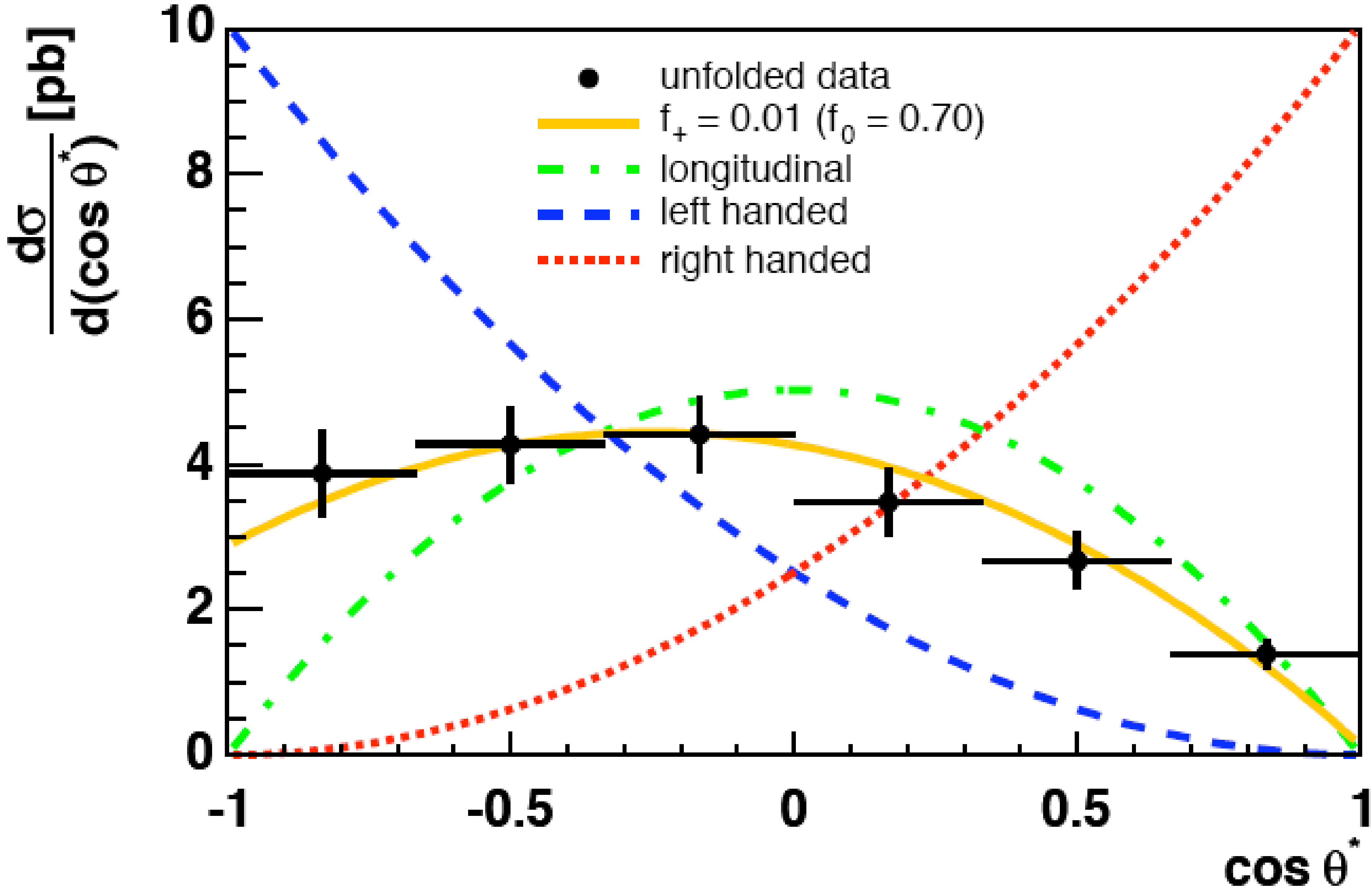
For reference, the strengths of the various couplings involved are

electromagnetic coupling	$e^2/4\pi\hbar c = 1/137.$
weak interaction coupling	$g^2/4\pi\hbar c = 1/29.6$
Higgs coupling to top	$\lambda_t^2/4\pi\hbar c = 1/12.7$

If the Higgs mechanism is correct and the J=0 polarization state of W is really part of the Higgs field, we expect

$$\frac{\Gamma(t \to bW_0)}{\Gamma(t \to bW_T)} = 2.4$$

This ratio can be measured from the angular distribution of the lepton in the subsequent W decay.



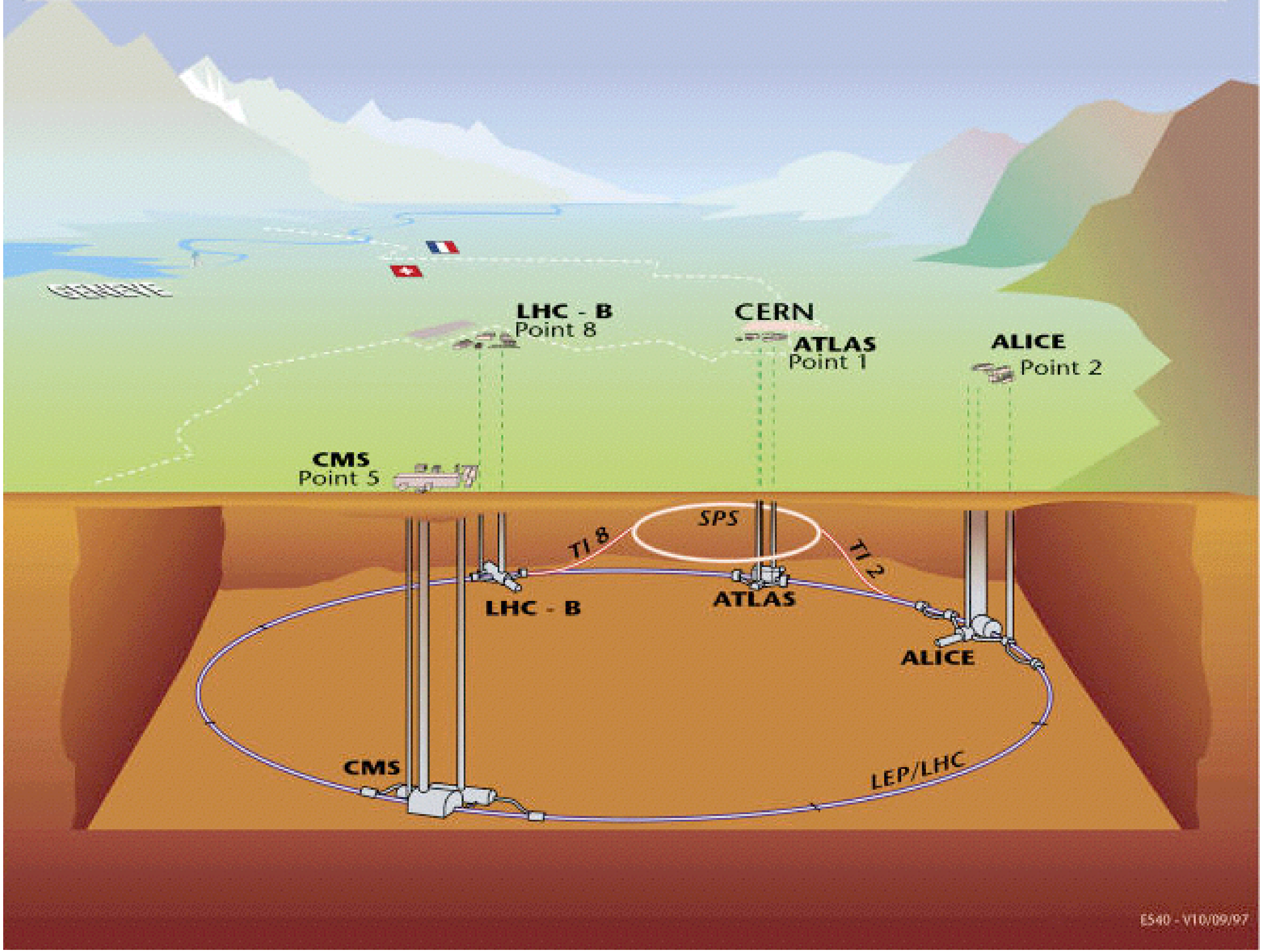
CDF experiment

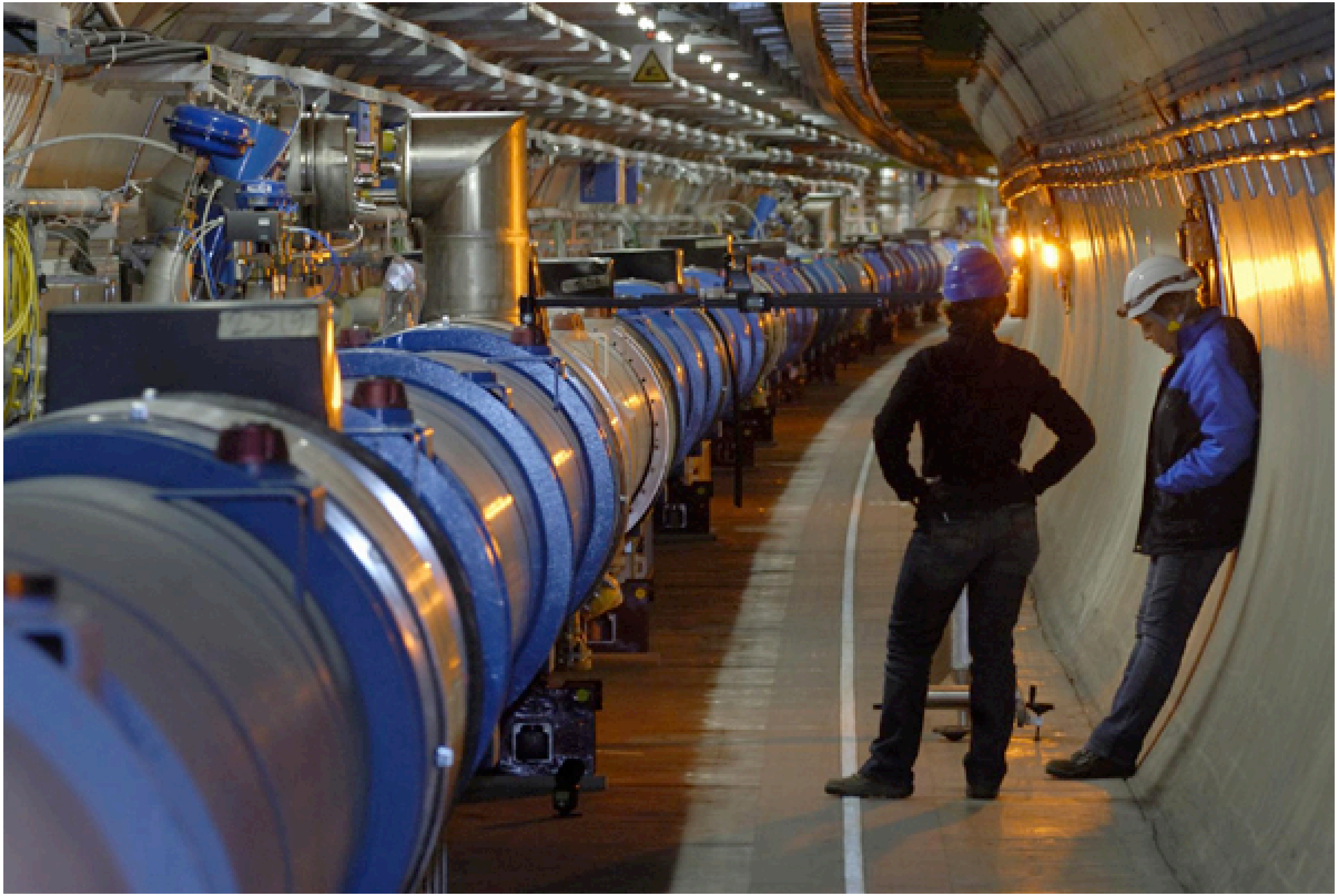
Now we turn to the search for the Higgs boson.

This search requires very high energy, both to produce the Higgs particle and to recognize its decays.

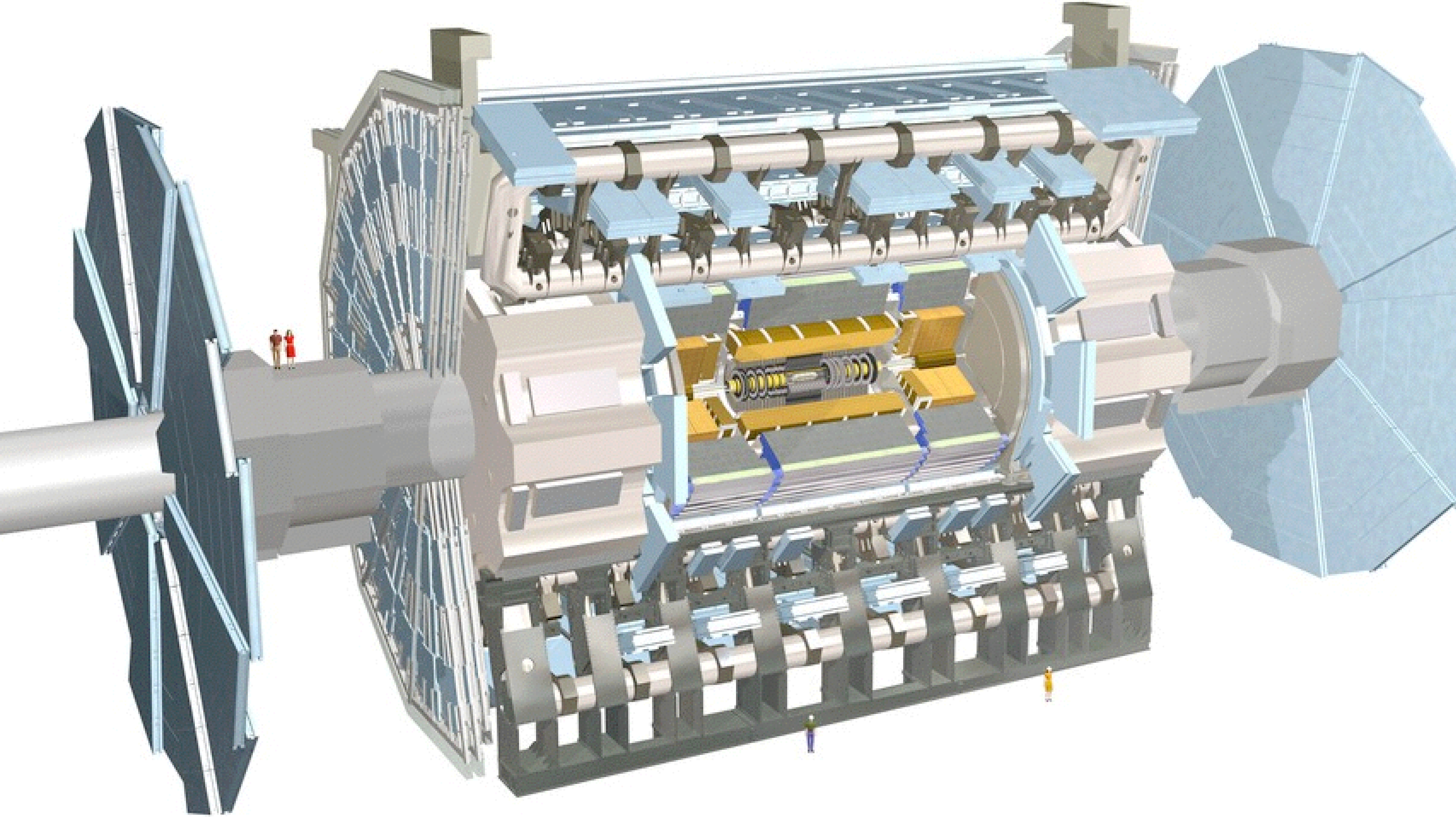
To achieve this, the laboratory CERN in Geneva, Switzerland constructed a mammoth particle accelerator, the Large Hadron Collider.

Overall view of the LHC experiments.





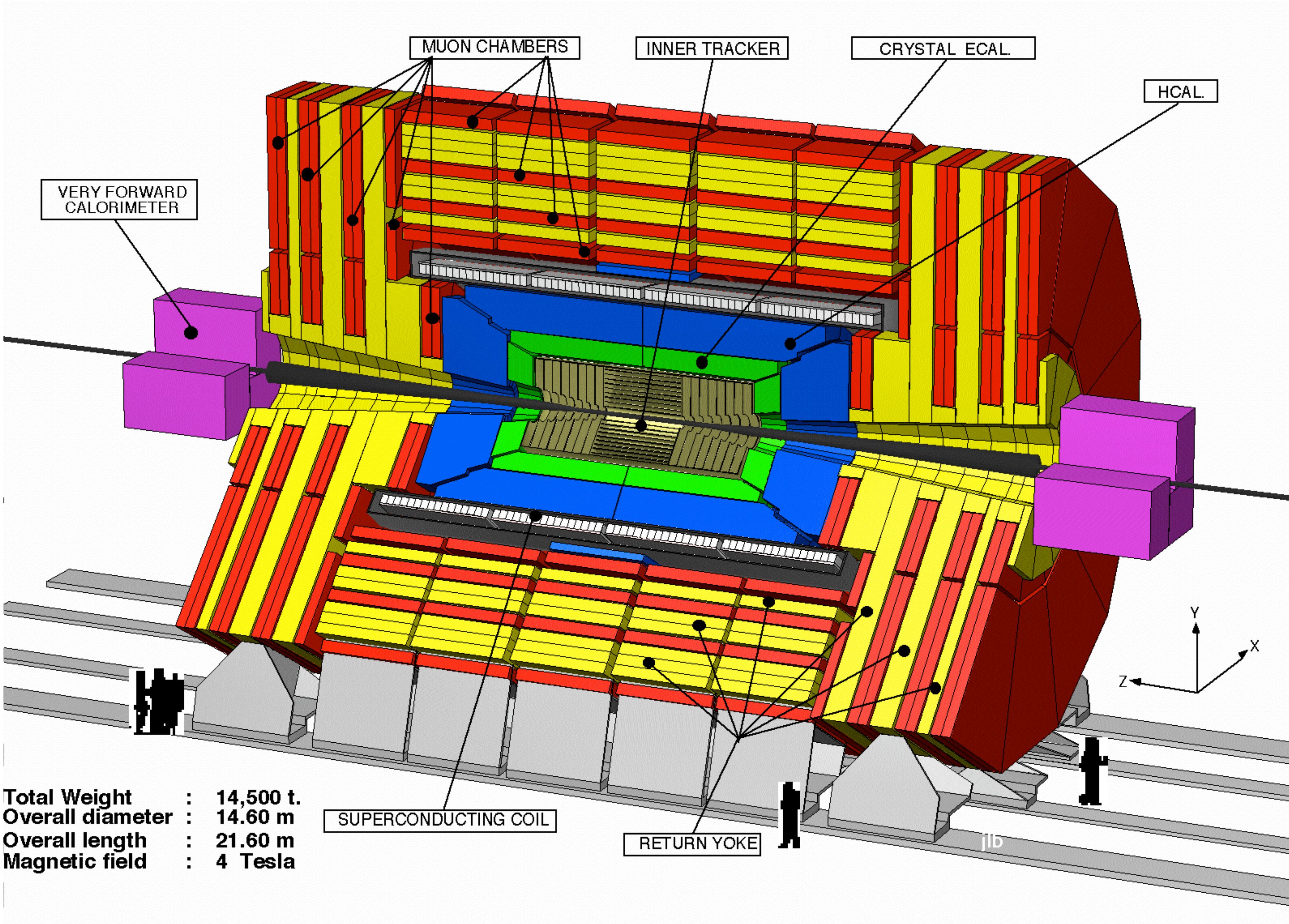
CERN

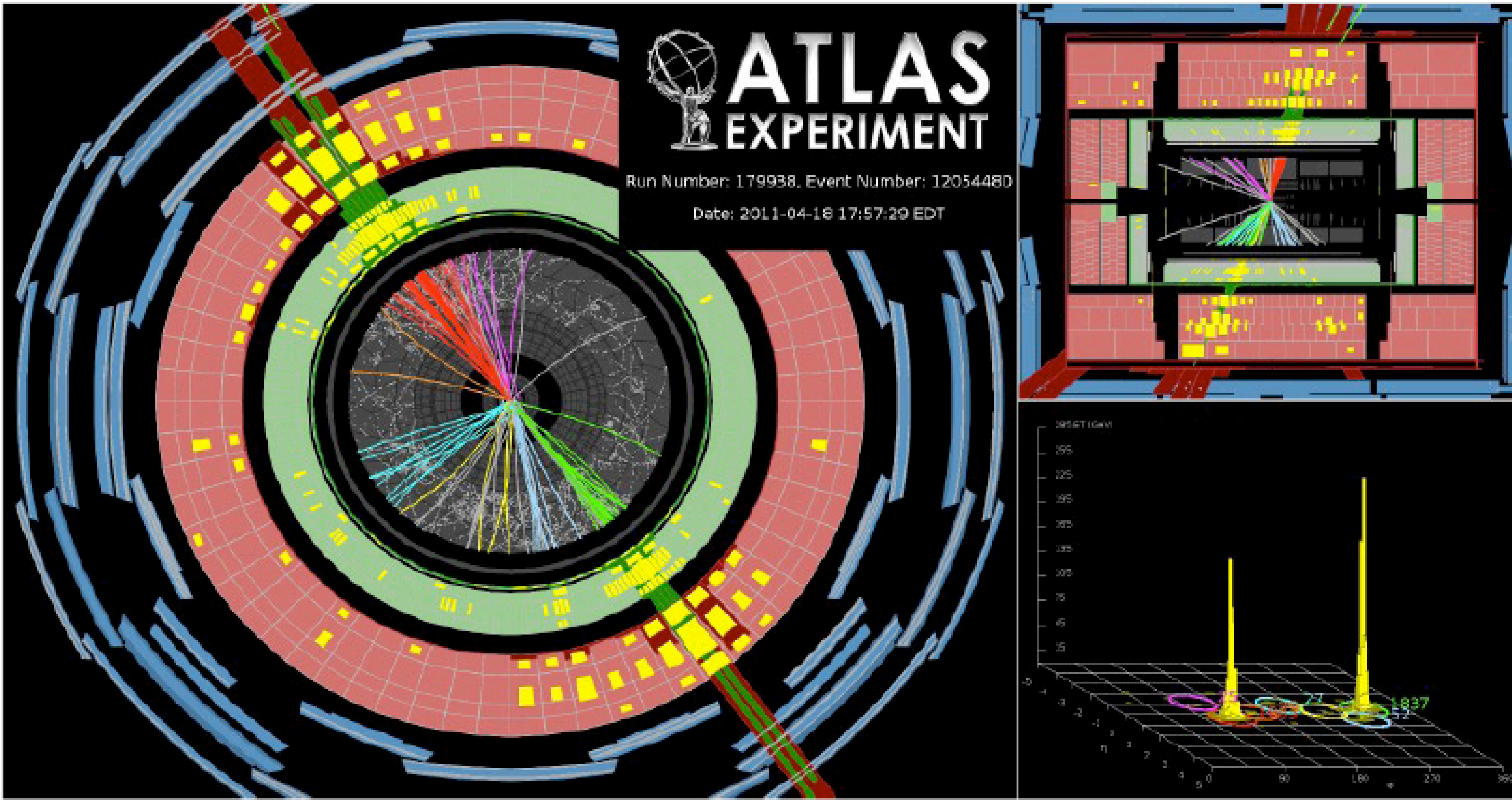


the ATLAS experiment

arrival of a superconducting muon toroid at CERN

A Compact Solenoidal Detector for LHC





m(jet-jet) = 4.0 TeV　　**Missing E_T = 100 GeV**

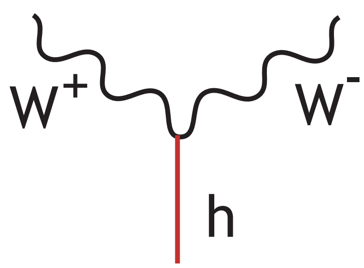
To understand how to recognize a Higgs boson, we must review its possible decay modes.

The Higgs couples to each particle according to mass. Thus, it will decay into the heaviest particles available.

If $m_h > 2m_W = 160\ \text{GeV}$, the dominant decays will be

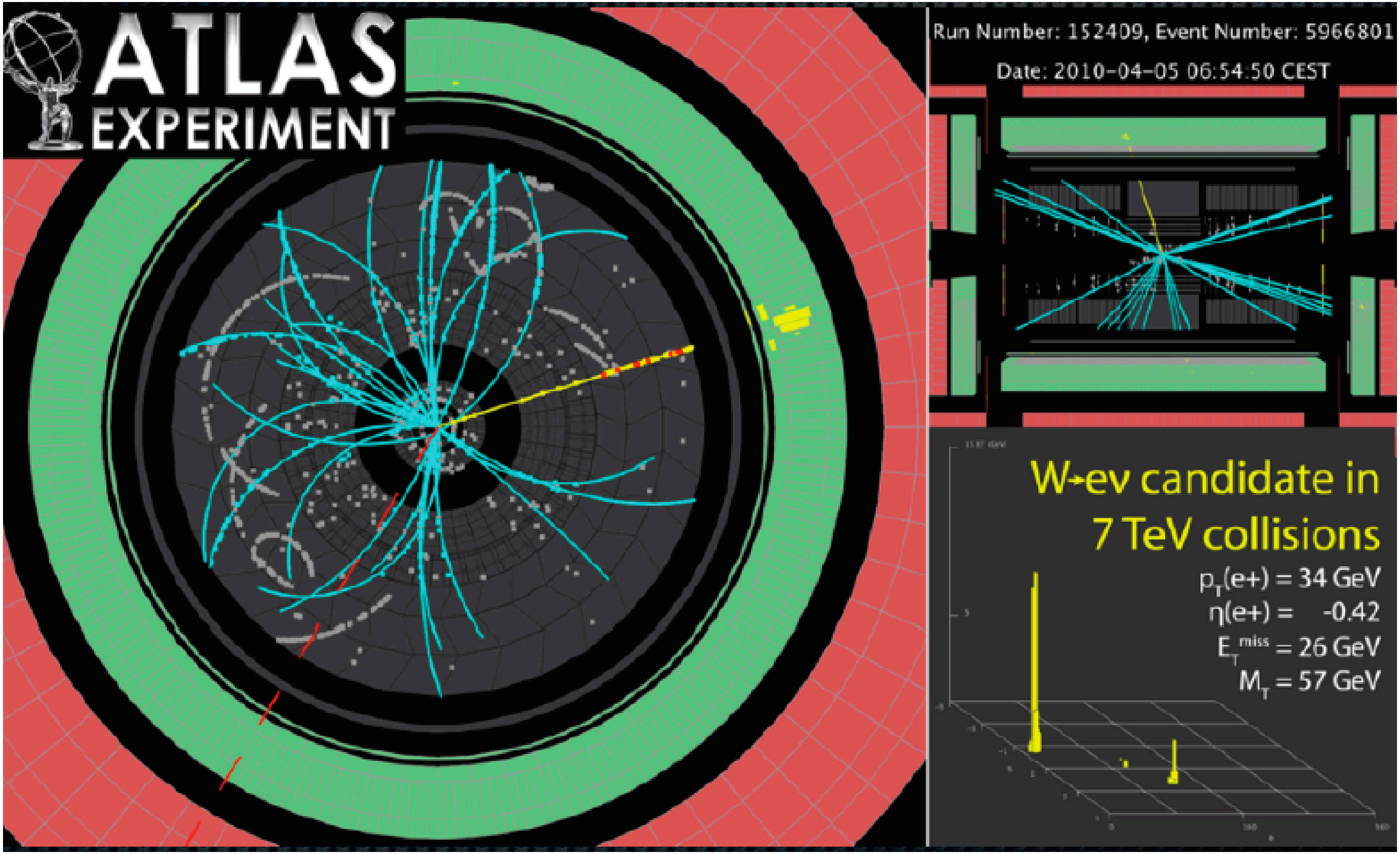
$$h^0 \to W^+W^-,\ Z^0Z^0$$

These are characteristic decays, easy to recognize even when Higgs production is a rare process, as it is at the LHC.

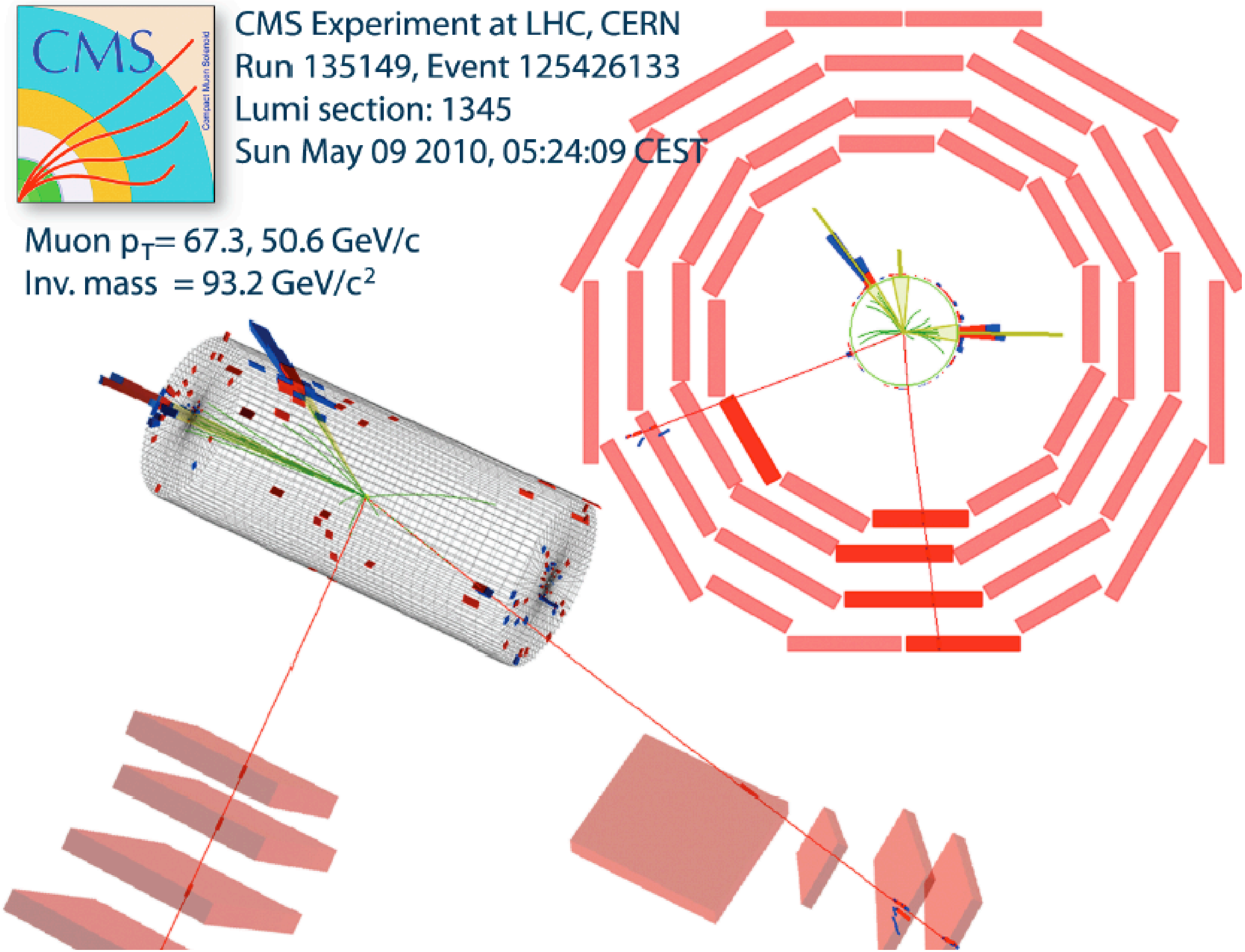


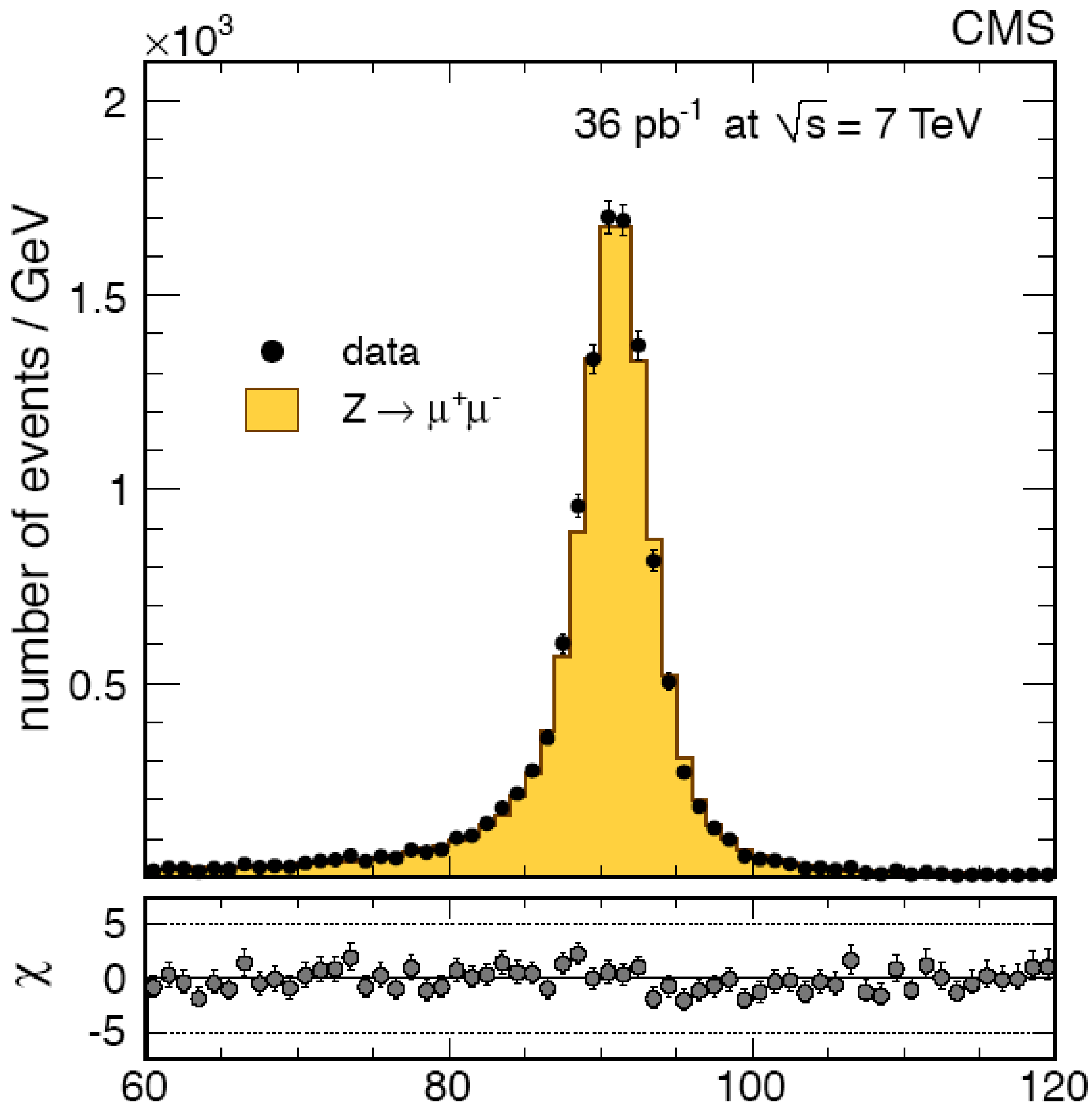
At the LHC, we recognize W and Z bosons through their decays to leptons.

$$\begin{aligned} W^+ &\to e^+\nu,\ \mu^+\nu \\ Z^0 &\to e^+e^-,\ \mu^+\mu^- \end{aligned}$$

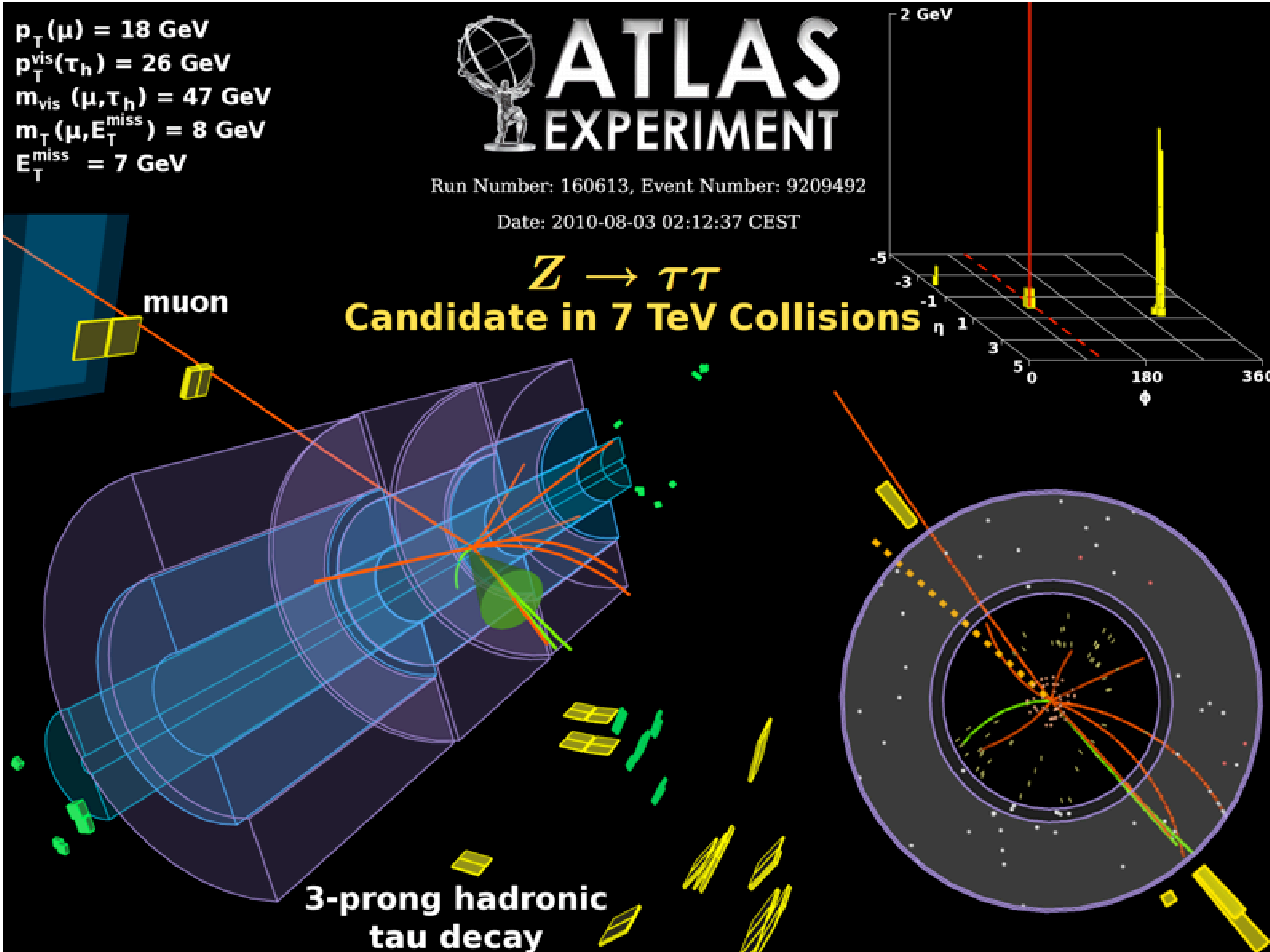


ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
pT(e+) = 34 GeV
η(e+) = -0.42
ET miss = 26 GeV
MT = 57 GeV


CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2



$$Mc^2 = \sqrt{(E_+ + E_-)^2 - (\vec{p}_+ + \vec{p}_-)^2 c^2}$$



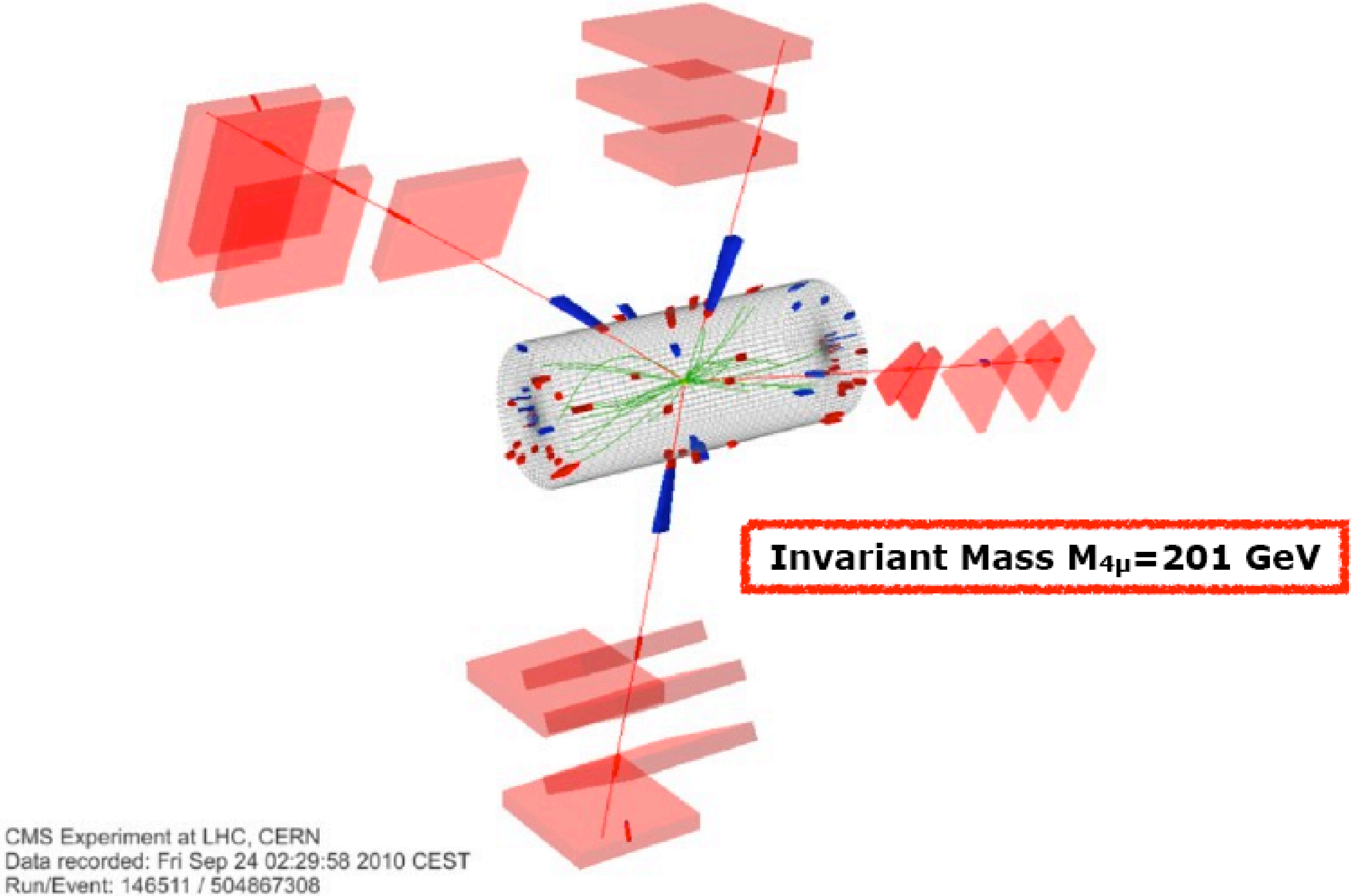
$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
$m_{vis}(\mu,\tau_h)$ = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \to \tau\tau$
Candidate in 7 TeV Collisions
2 GeV
η
φ
muon
3-prong hadronic
tau decay

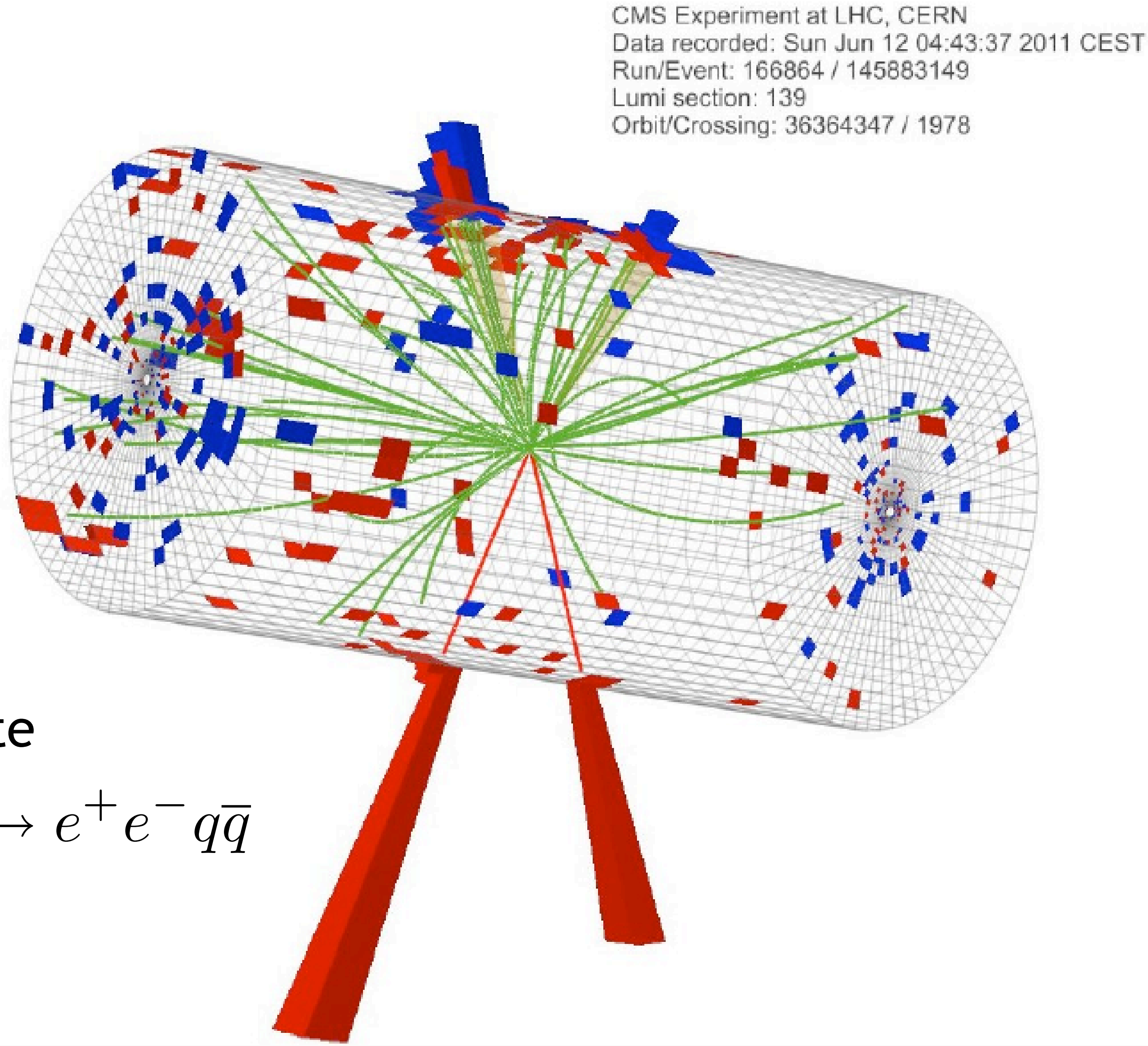
The Higgs then would appear as a resonance in the pair-production of these objects.

Direct W, Z pair production

$$q\overline{q} \to W^+W^-,\ Z^0Z^0$$

forms a background to Higgs production and decay.


Invariant Mass $M_{4\mu}$=201 GeV
CMS Experiment at LHC, CERN
Data recorded: Fri Sep 24 02:29:58 2010 CEST
Run/Event: 146511 / 504867308



candidate

$$h^0 \rightarrow Z^0 Z^0 \rightarrow e^+ e^- q\bar{q}$$

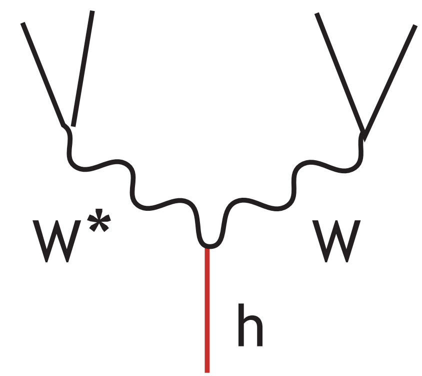
In fact, the rates of $W^+W^-,\ Z^0Z^0$ production are consistent with background and exclude such a heavy Higgs.

For a lighter Higgs, the dominant decays are to the heaviest available quark, the b quark, and the heaviest available lepton, the τ lepton.

$$h^0 \to b\bar{b}\ , \quad h^0 \to \tau^+\tau^-$$

Other higher-order processes compete with these, including

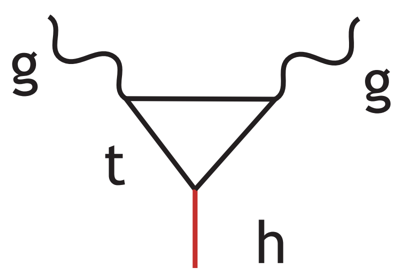
decay to off-shell W, Z

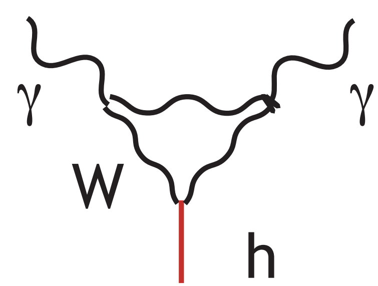


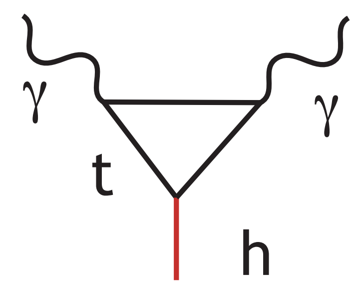
$$h^0 \to WW^*,\ ZZ^*$$

decays through t, W loop diagrams

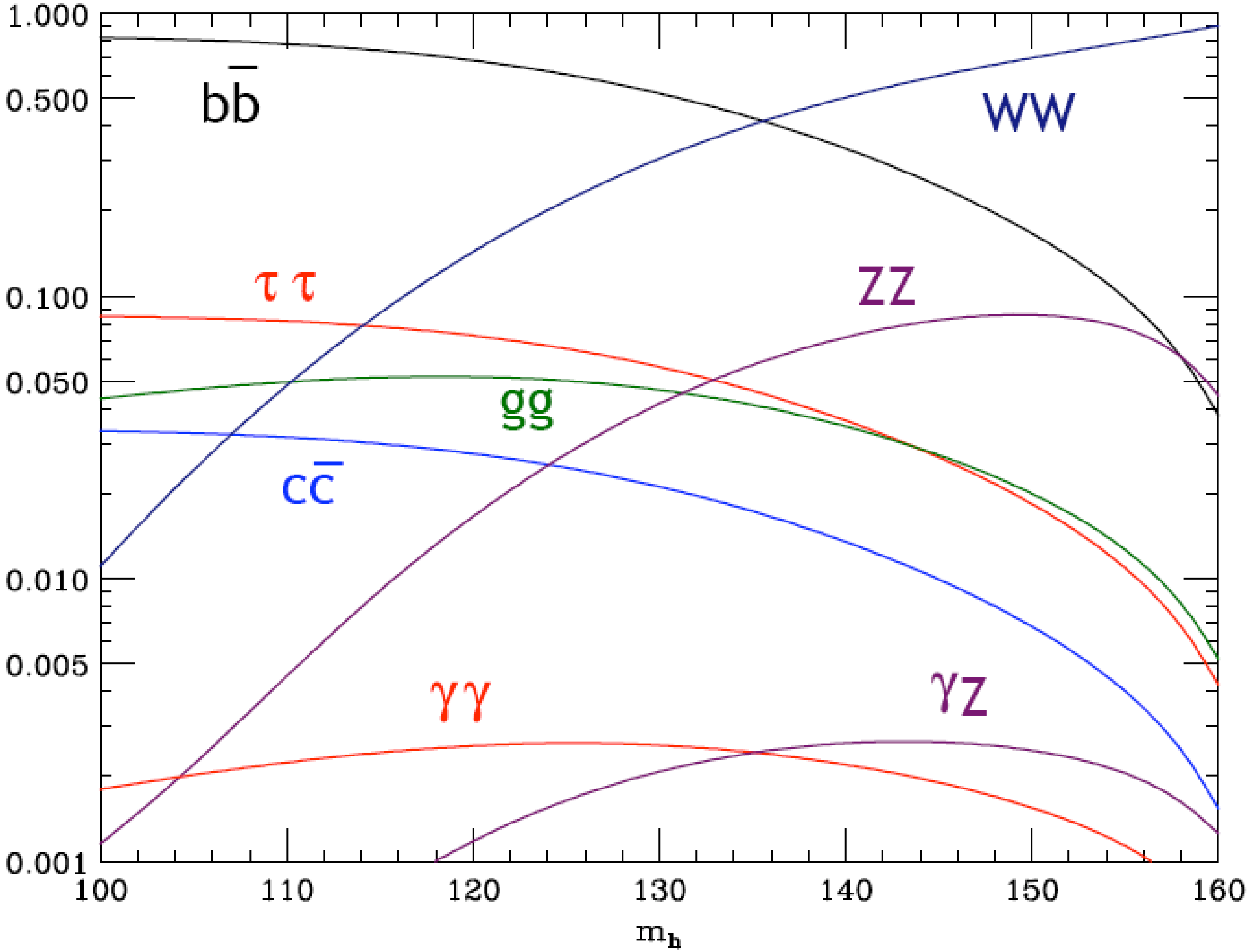
$$h^0 \to gg,\ \gamma\gamma,\ \gamma Z^0$$







We then predict a complex pattern of Higgs decays as a function of the Higgs boson mass.



For example, for a Higgs boson of mass 125 GeV, the predicted branching ratios are:

$$
\begin{array}{ll}
h^0 \to b\bar{b} & 58\% \\
h^0 \to WW^* & 21\% \\
h^0 \to gg & 8.5\% \\
h^0 \to \tau^+\tau^- & 6.4\% \\
h^0 \to ZZ^* & 2.7\% \\
h^0 \to c\bar{c} & 2.6\% \\
h^0 \to \gamma\gamma & 0.22\% \\
h^0 \to \gamma Z & 0.17\%
\end{array}
$$

In principle, the presence of such a large number of decay modes is a good thing. If we can measure all of these decays, we can test many different aspects of the Higgs boson couplings.

Next, how can we produce the Higgs boson in high-energy collider experiments ?

There is a problem.

The Higgs couples strongly only to very massive particles

$$W, \ Z, \ t$$

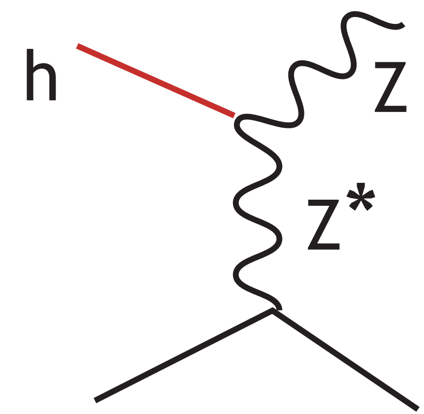
However, there is no technology for colliding these particles. In our experients, all we have available to collide are light particles

$$e \ , u, \ d, \ g$$

To make the Higgs from these particles, we need very clever and exotic reactions.

This is primary reason that the Higgs boson has not been discovered long ago.

At an e^+e^- collider, the best way to produce the Higgs is through the Higgs-strahlung process

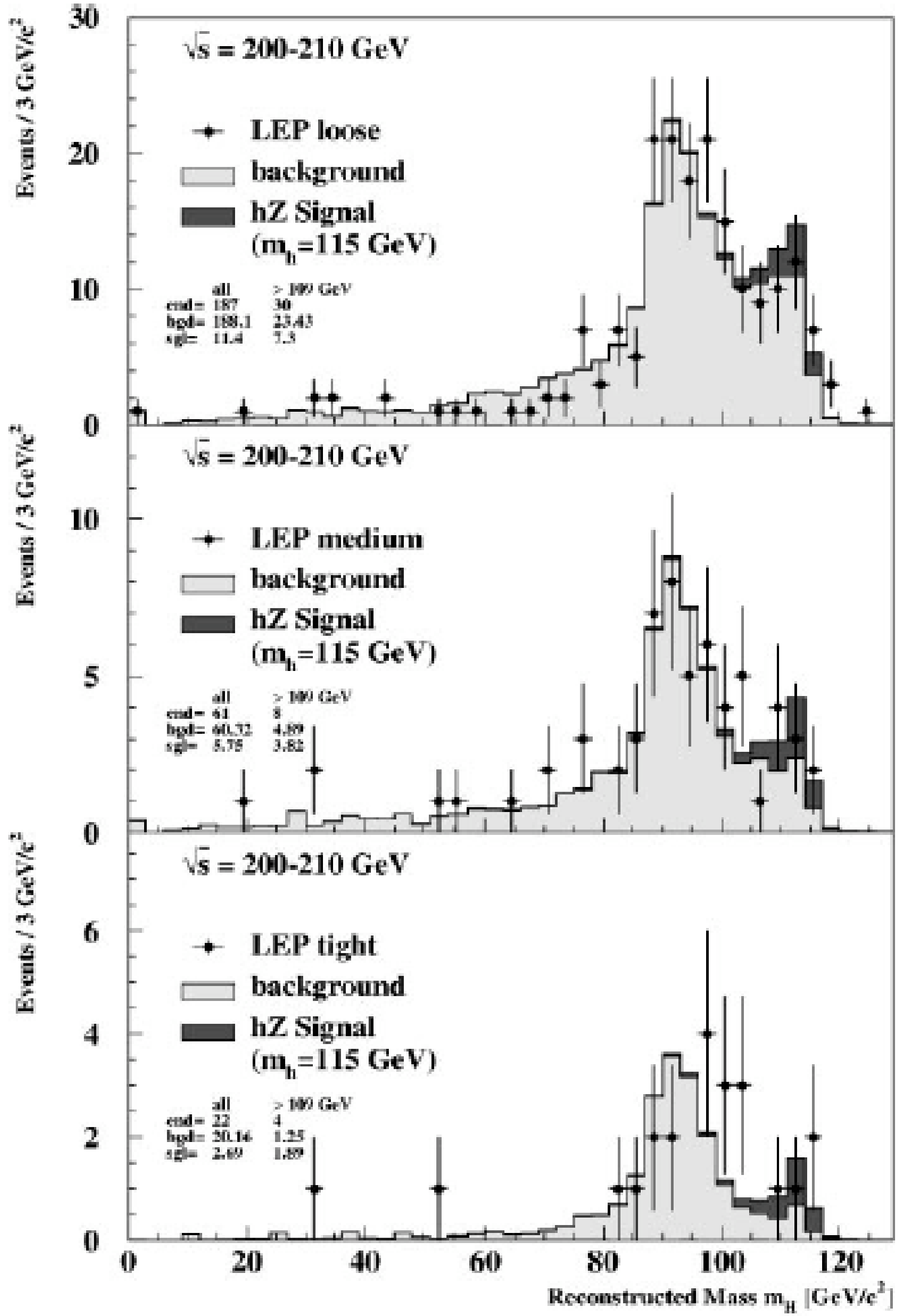


$$e^+e^- \rightarrow Z^* \rightarrow Z + h^0$$

This is an elegant reaction. The Z recoils at a definite energy and tags the Higgs, whatever the Higgs decay mode might be.

In the 1990's, experiments at the LEP collider at CERN searched for this process and found nothing.

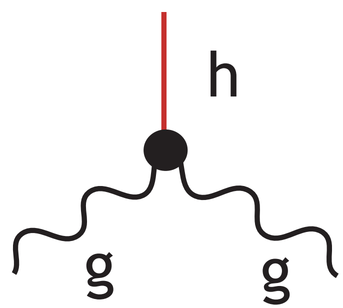
They excluded the Higgs boson up to a mass of 114 GeV.

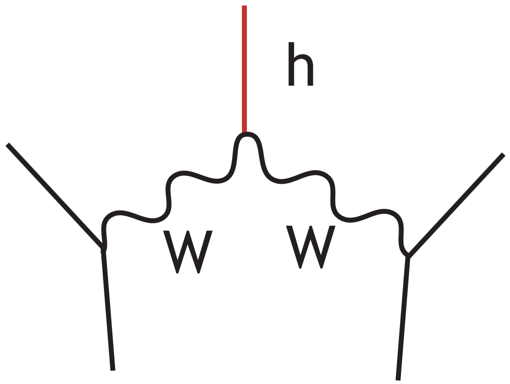


review of Kado and Tully

What about for experiments at the LHC ?

We can take advantage of the fact that the proton is not an elenentary particle. Instead, it is a big bag filled with quarks and gluons. The Higgs decays to gg and $WW,\ ZZ$ can be reversed and used as production modes.





Unfortunately, the rates are very small

$$\sigma(pp \to h^0) = (\ 15\ \mathrm{pb}\ (gg)\ ,\ 1\ \mathrm{pb}\ (WW)\ )$$

to be compared with

$$\sigma(pp \to b\bar{b}\ (125\ \mathrm{GeV})) \sim \mu\mathrm{b}$$

Observing the Higgs boson in the dominant decay channel
is very challenging !

For Higgs discovery at the LHC, the best option is to use the rare decay modes

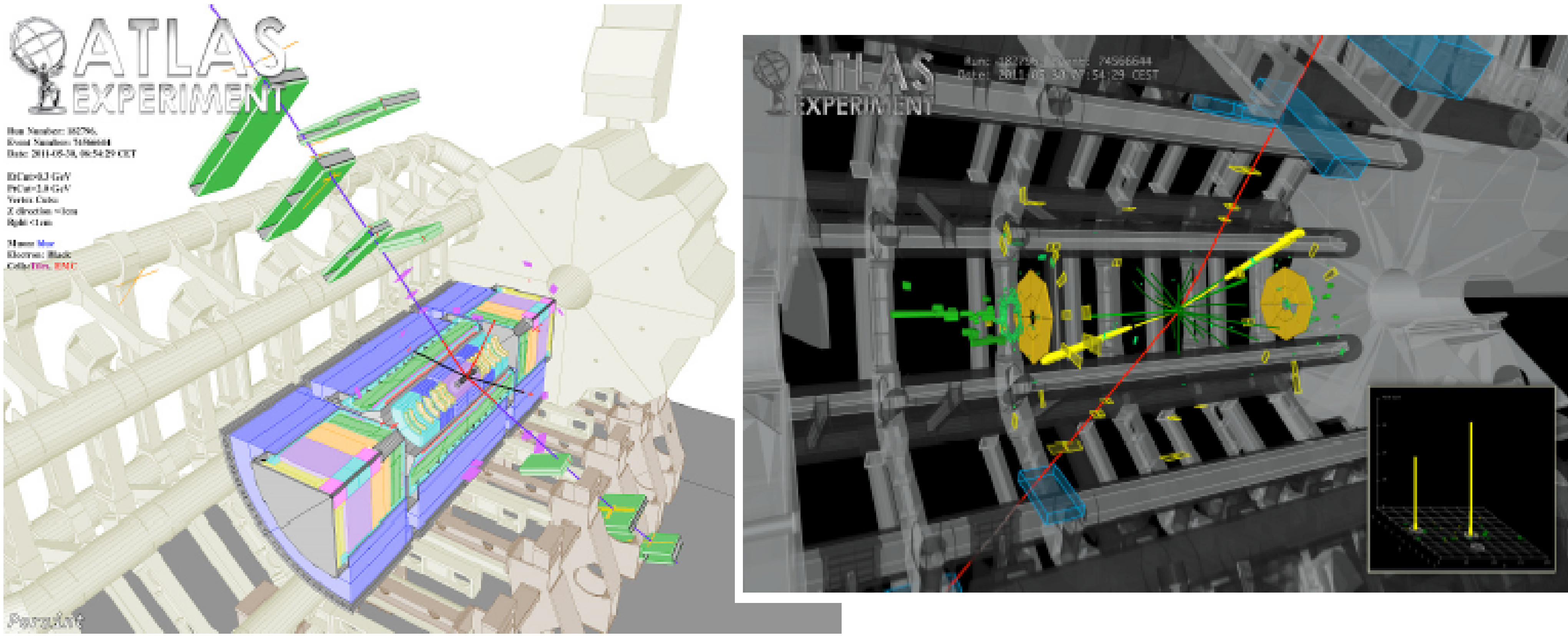
$$\begin{aligned} h^0 &\rightarrow \gamma\gamma & BR = 0.22\% \\ h^0 &\rightarrow ZZ^* \rightarrow 4 \text{ leptons} & BR = 0.16\% \end{aligned}$$

In these channels, the Higgs boson appears as a peak in invariant mass. ATLAS and CMS have good resolution ($\Delta m \sim 2$ GeV).

These channels represent 1 in 2×10^{12} pp collisions.

ATLAS candidate

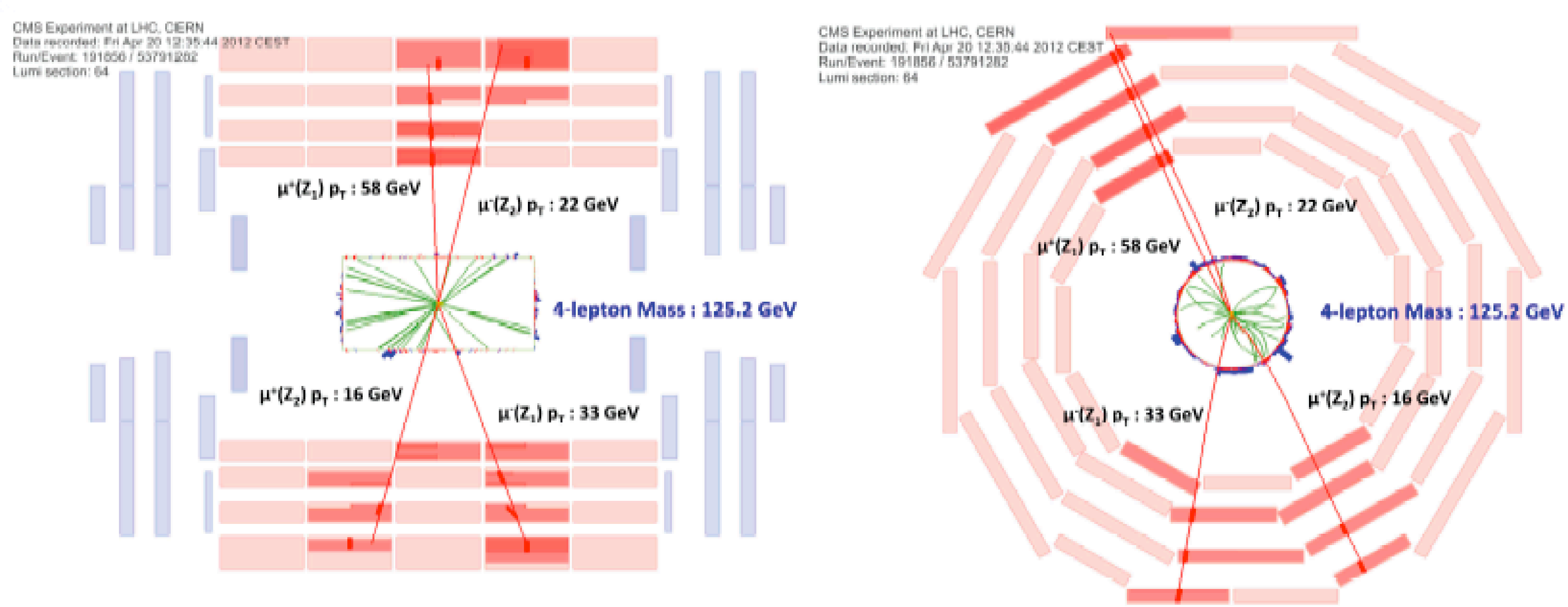
$$h^0 \to Z^0 Z^0 \to \mu^+ \mu^- e^+ e^-$$



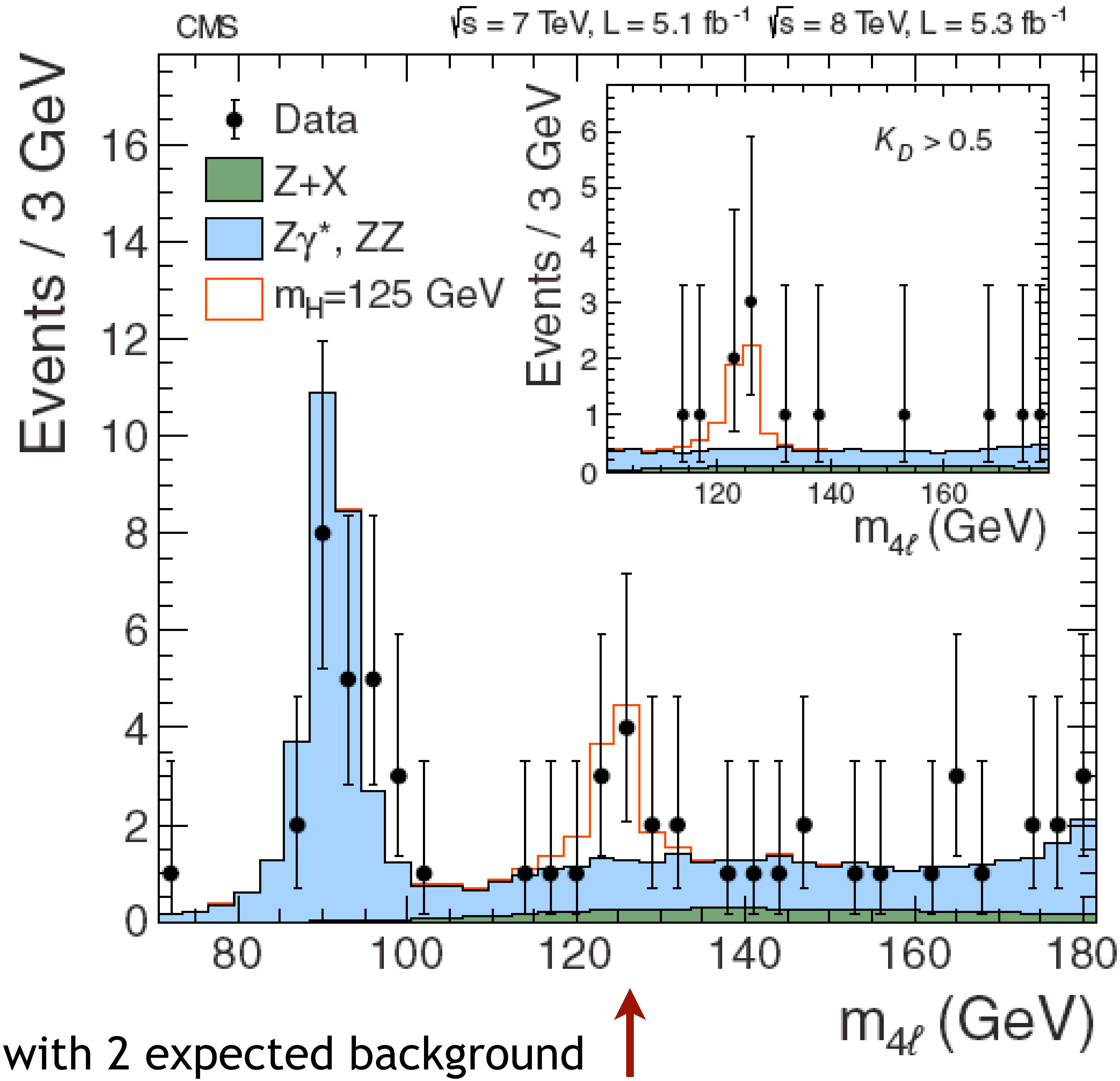
m(4l) = 124.3 GeV

CMS candidate

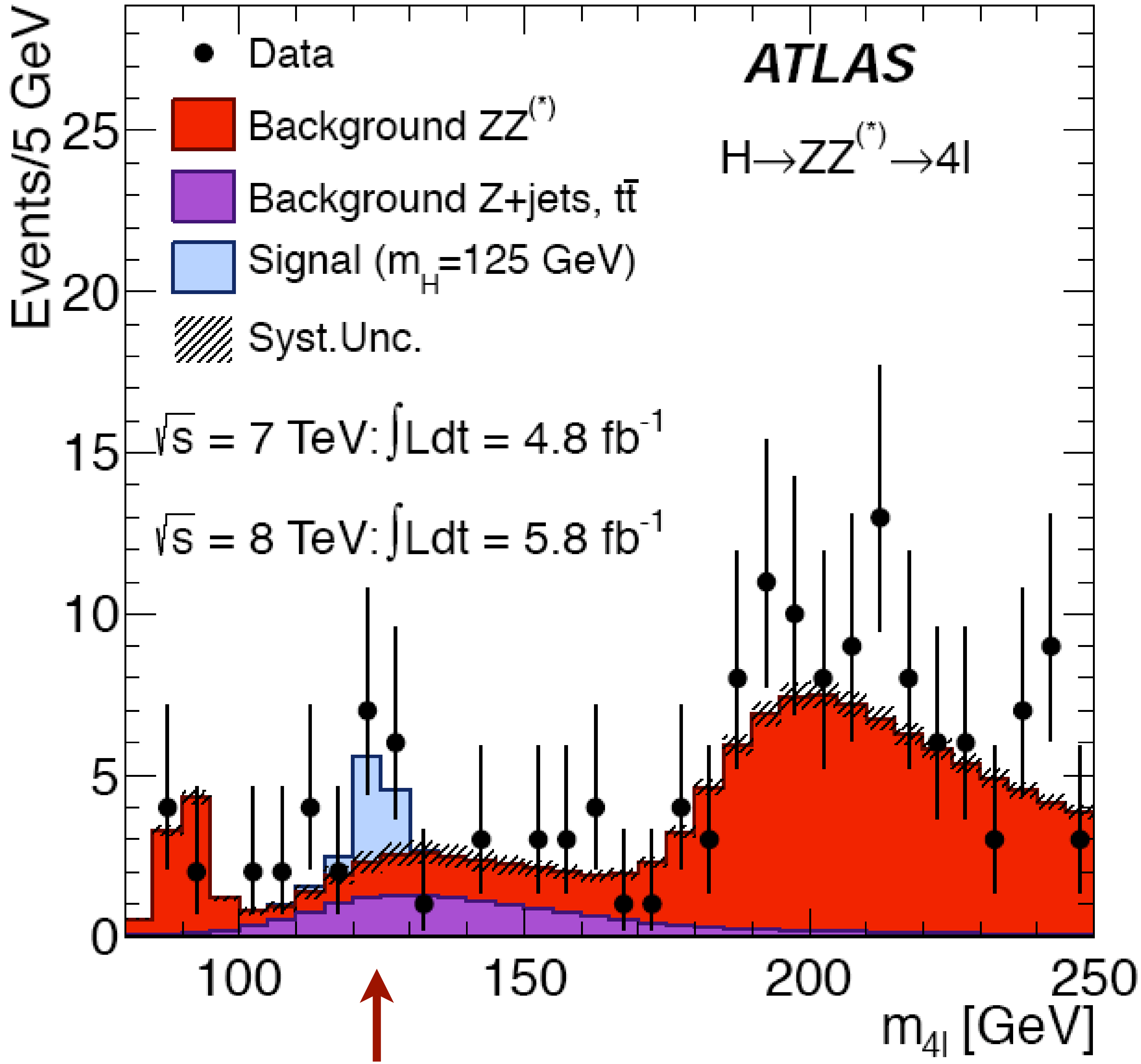
$$h^0 \to Z^0 Z^0 \to \mu^+ \mu^- \mu^+ \mu^-$$



m(4l) = 125.2 GeV

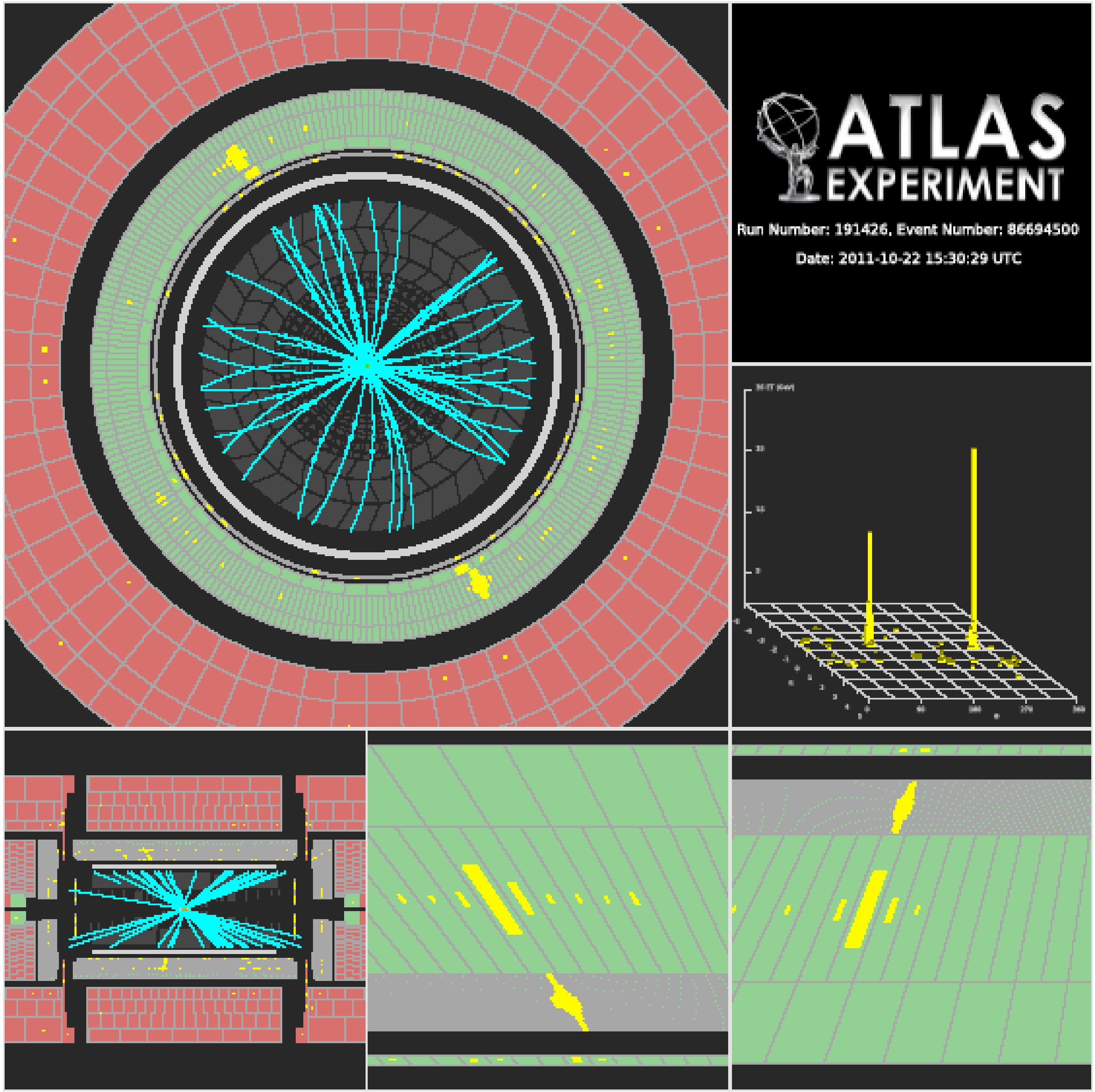


7, with 2 expected background



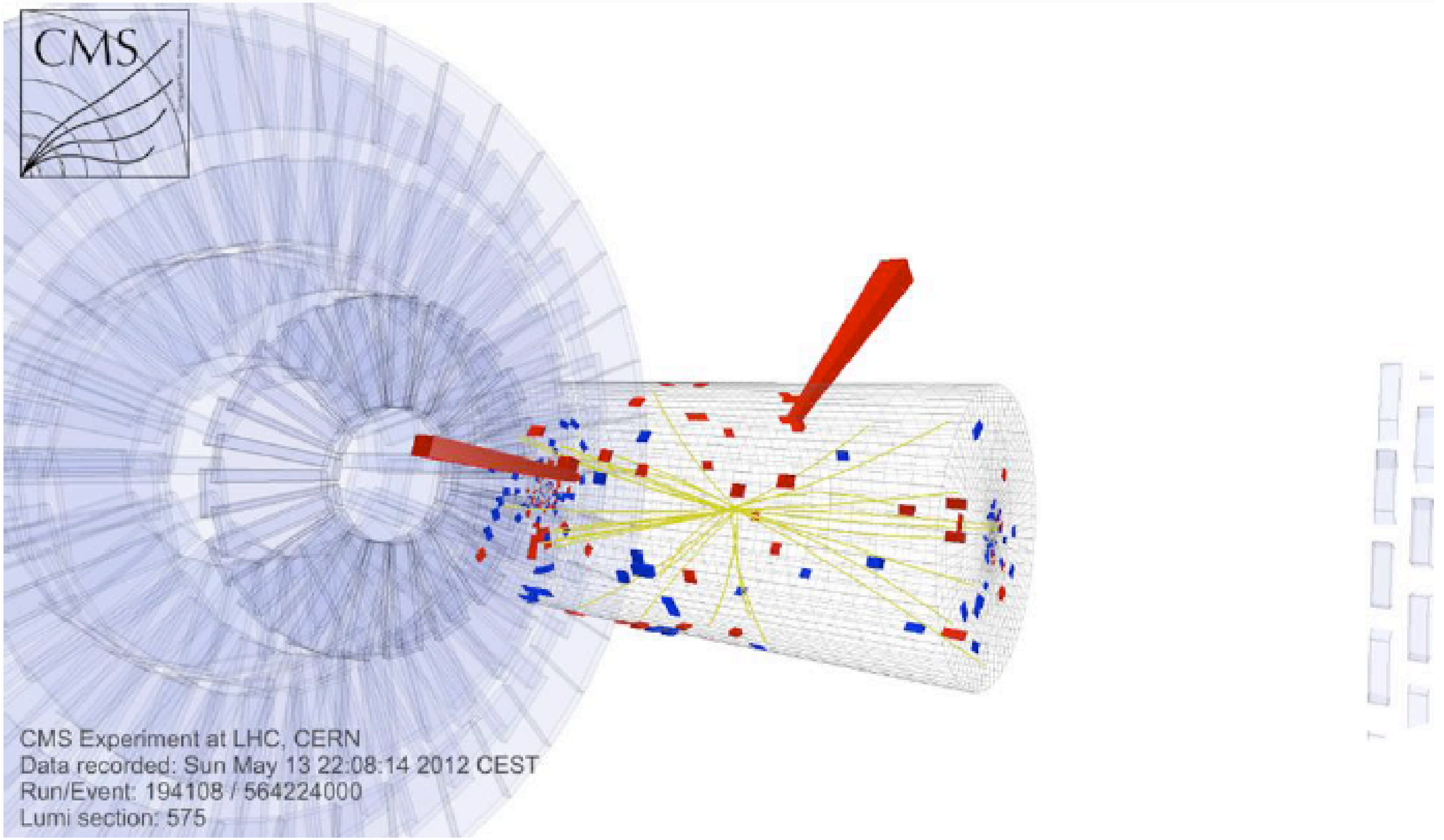
13, with 4 expected background

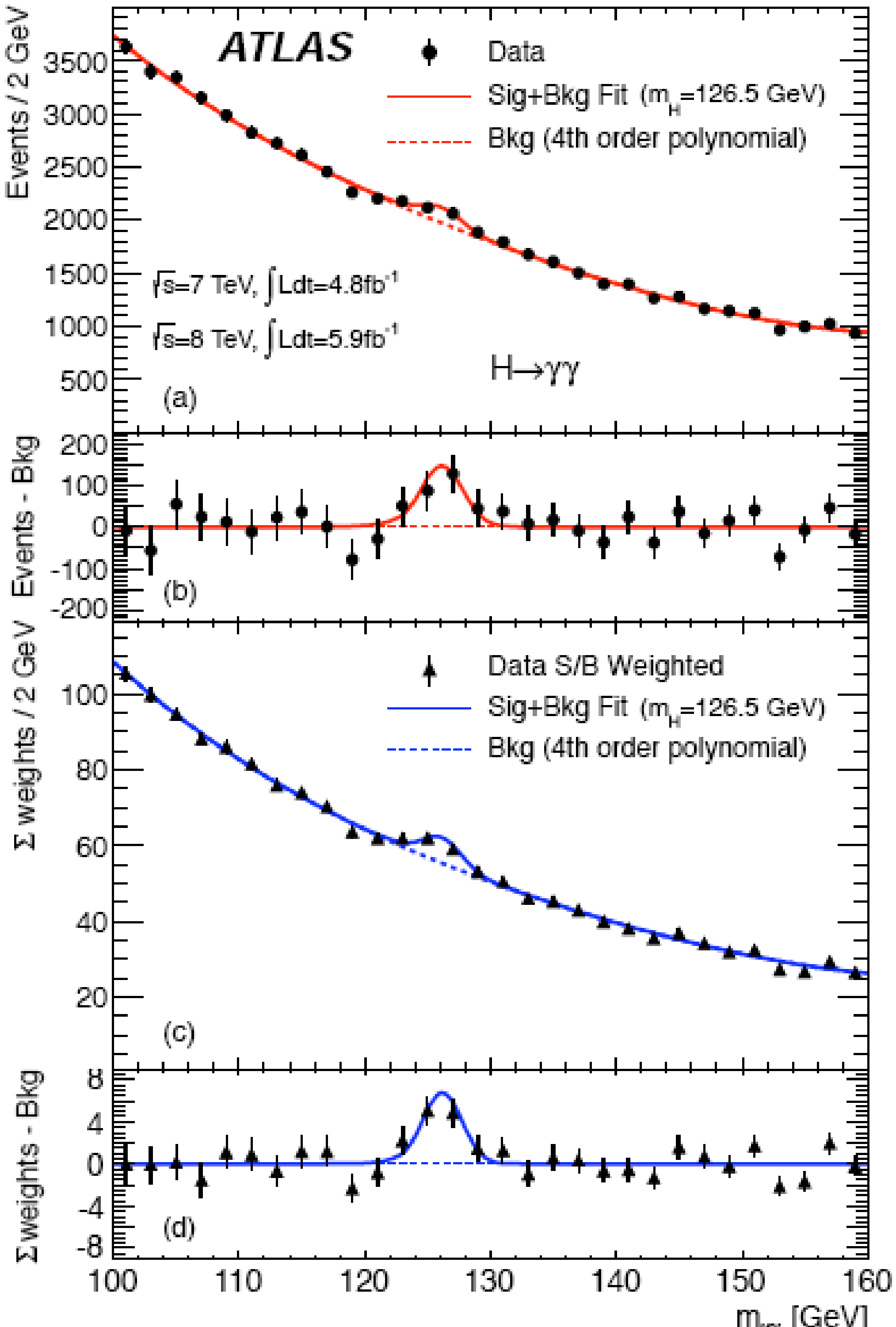
ATLAS candidate $h^0 \to \gamma\gamma$

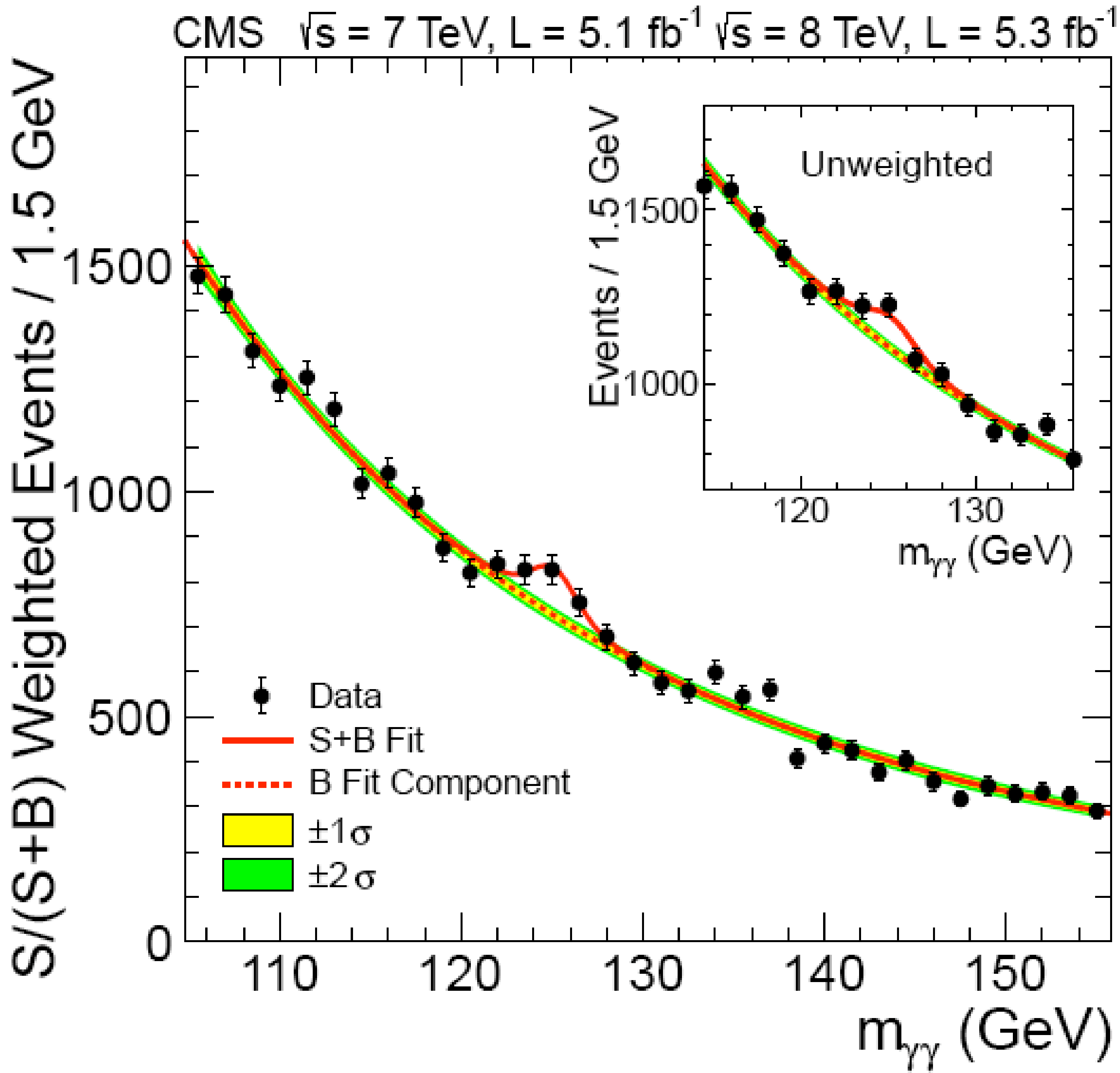


CMS candidate

$$h^0 \to \gamma\gamma$$




ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Events / 2 GeV
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
(a)
Events - Bkg
(b)
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Σ weights / 2 GeV
(c)
Σ weights - Bkg
(d)
m_γγ [GeV]

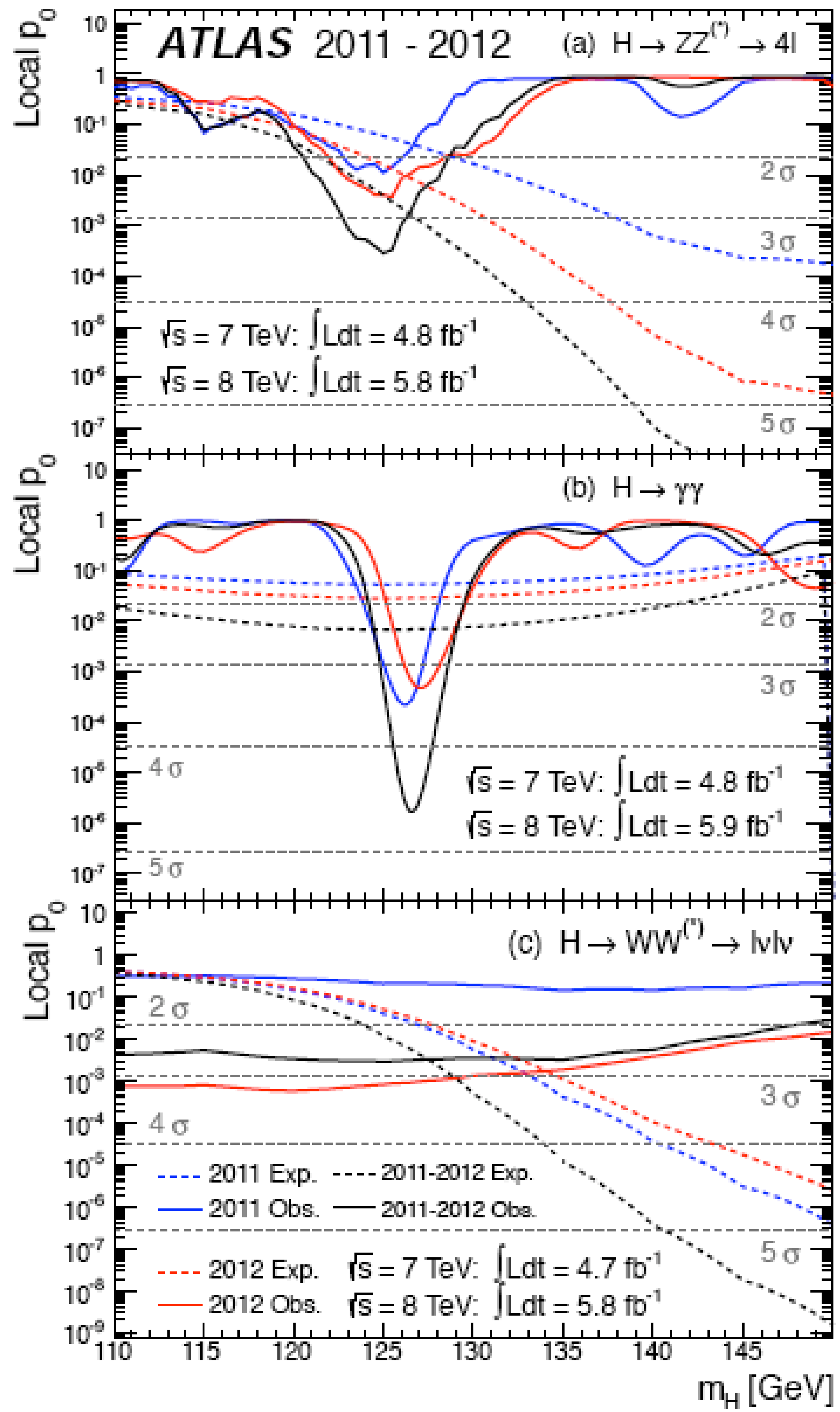


CMS √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 5.3 fb⁻¹
S/(S+B) Weighted Events / 1.5 GeV
0
500
1000
1500
110
120
130
140
150
m_γγ (GeV)
Data
S+B Fit
B Fit Component
±1σ
±2σ
Unweighted
Events / 1.5 GeV
1000
1500
120
130
m_γγ (GeV)

For the ATLAS data, the probability that the apparent resonance is caused by a fluctuation of the background.

blue: 2011 data set
red: 2012 data set
black: combined

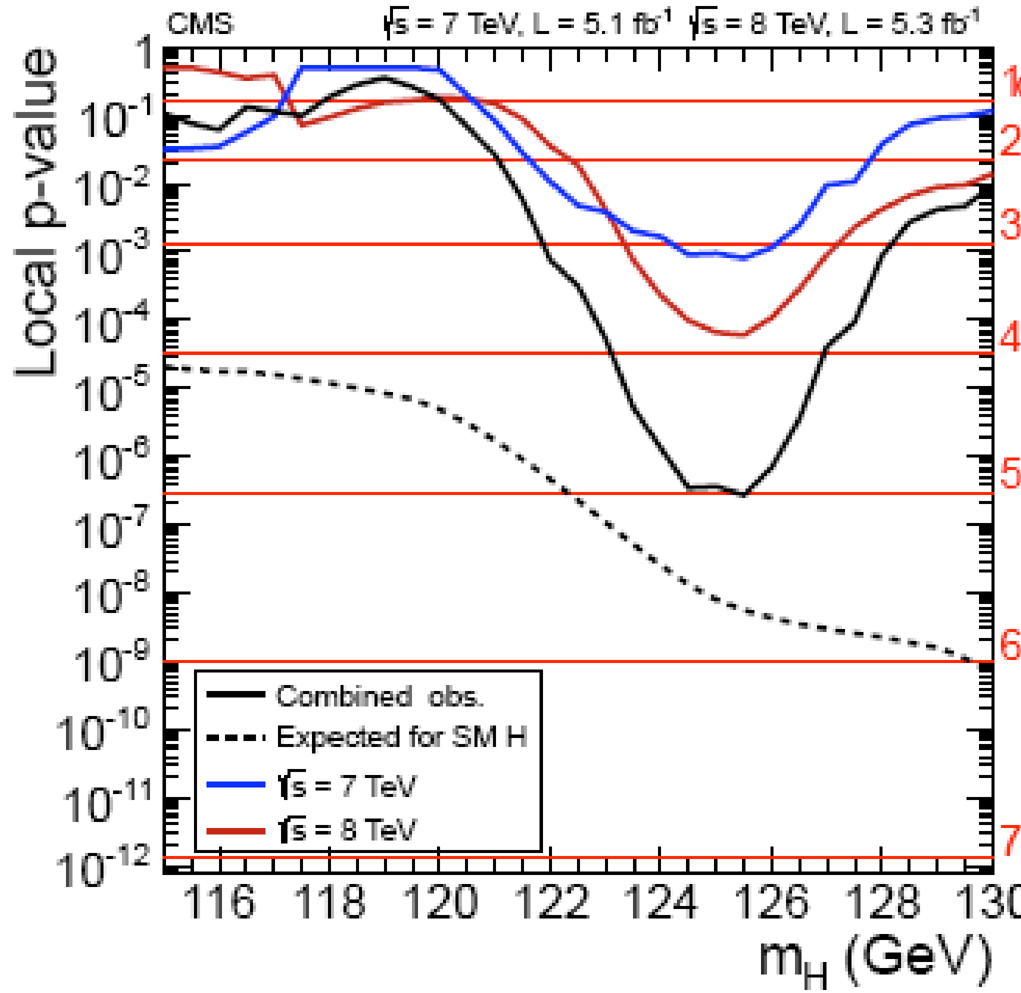
Taking into account the "look-elsewhere effect", the global significance of the set of peaks is 5.1 σ.



For the CMS data, the probability that the apparent resonance is caused by a fluctuation of the background.

blue: 2011 data set
red: 2012 data set
black: combined

Taking into account the "look-elsewhere effect", the global significance of the set of peaks is 4.6 σ.



So, a boson that is at least very much like the Higgs boson has been discovered with a high degree of confidence.

Key properties of the Higgs boson, and their current status in the experiments:

1. Decay to $\gamma\gamma$ ✓
2. Decay to ZZ^* ✓
3. Decay to WW^* ✓
4. Decay to $b\bar{b}$ +
5. Decay to $\tau^+\tau^-$ –
6. Spin 0, parity + +
7. Production in $gg \to h$ ✓
8. Production in $WW, ZZ \to h$ ✓
9. Production in $q\bar{q} \to W, Z + h$ +

The prospects are good that all of these issues will be settled by the end of 2012.

I would like to take a few more minutes to talk about the future.

Earlier in the talk, I put aside the question of what actually forms the Higgs boson condensate.

When the Higgs boson becomes real, this will become an urgent question.   How will we attack it experimentally ?

If the mass of the Higgs boson is indeed near 125 GeV, many Higgs decay modes will be accessible to the LHC experiments. We can expect to see measurements of:

Gluon fusion reactions

$$pp \to h \to \gamma\gamma$$

$$pp \to h \to WW^*, ZZ^*$$

Vector boson fusion reactions

$$pp \to (VBF) + h \to \tau^+\tau^-$$

$$pp \to (VBF) + h \to WW^*, ZZ^*$$

$$pp \to (VBF) + h \to \text{ invisible}$$

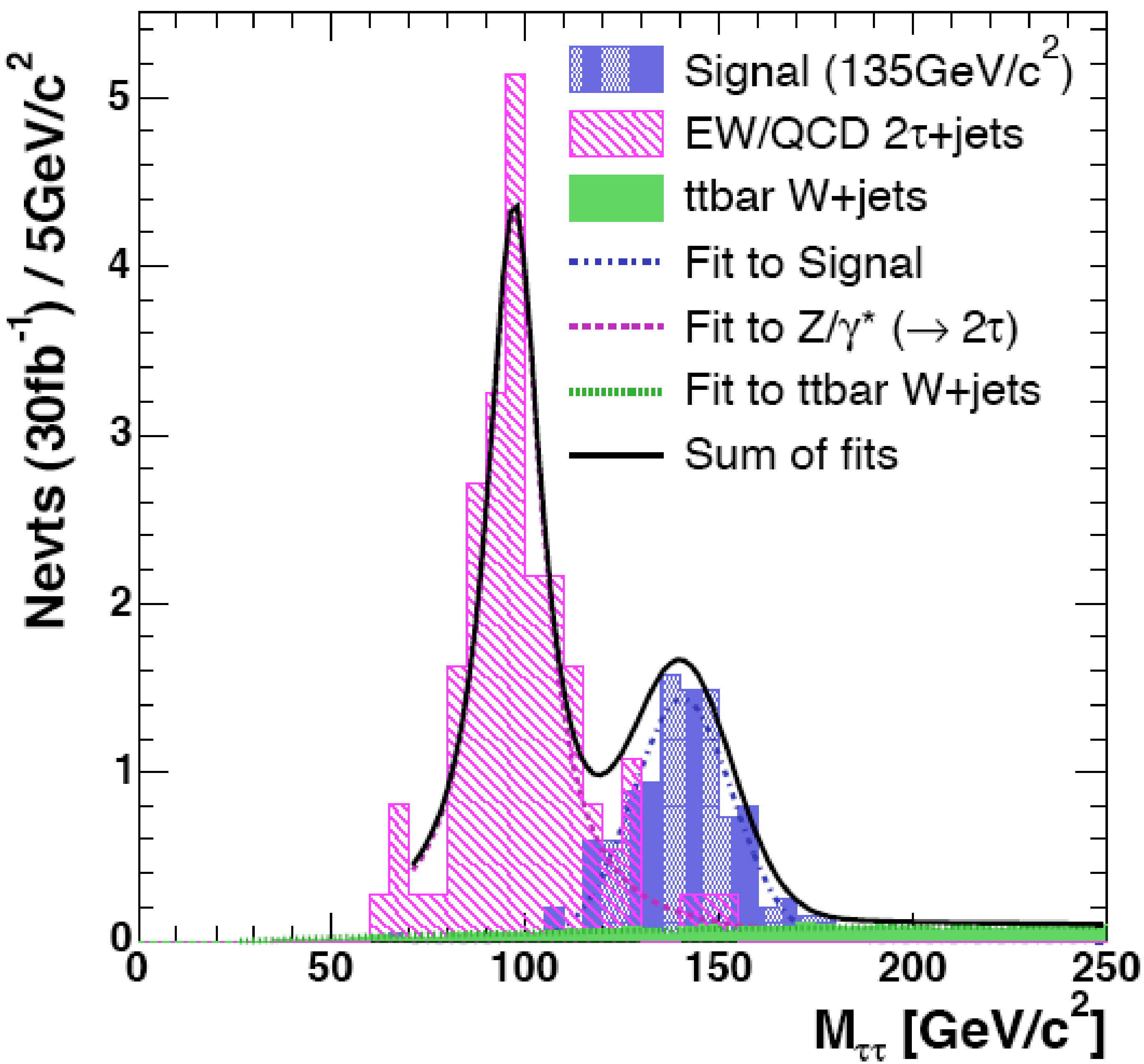
Associated production

$$pp \to (W, Z) + h(\to b\bar{b})$$

$$pp \to t\bar{t} + h(\to b\bar{b})$$

$$h \to \tau^+\tau^-$$

$$m_h = 135 \text{ GeV}$$



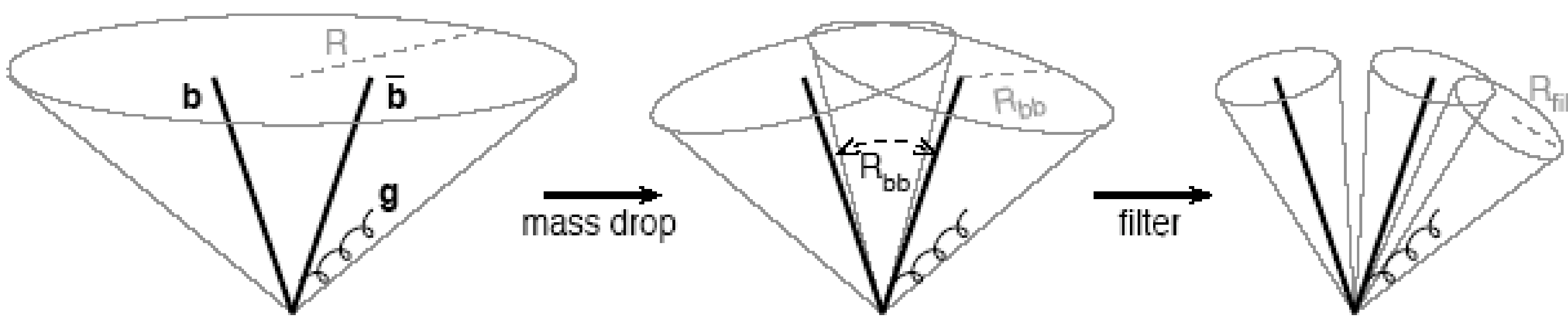
CMS
simulation

A key problem will be to observe the dominant Higgs decay mode $h \to b\overline{b}$.

It is not so obvious that this can be done; remember,

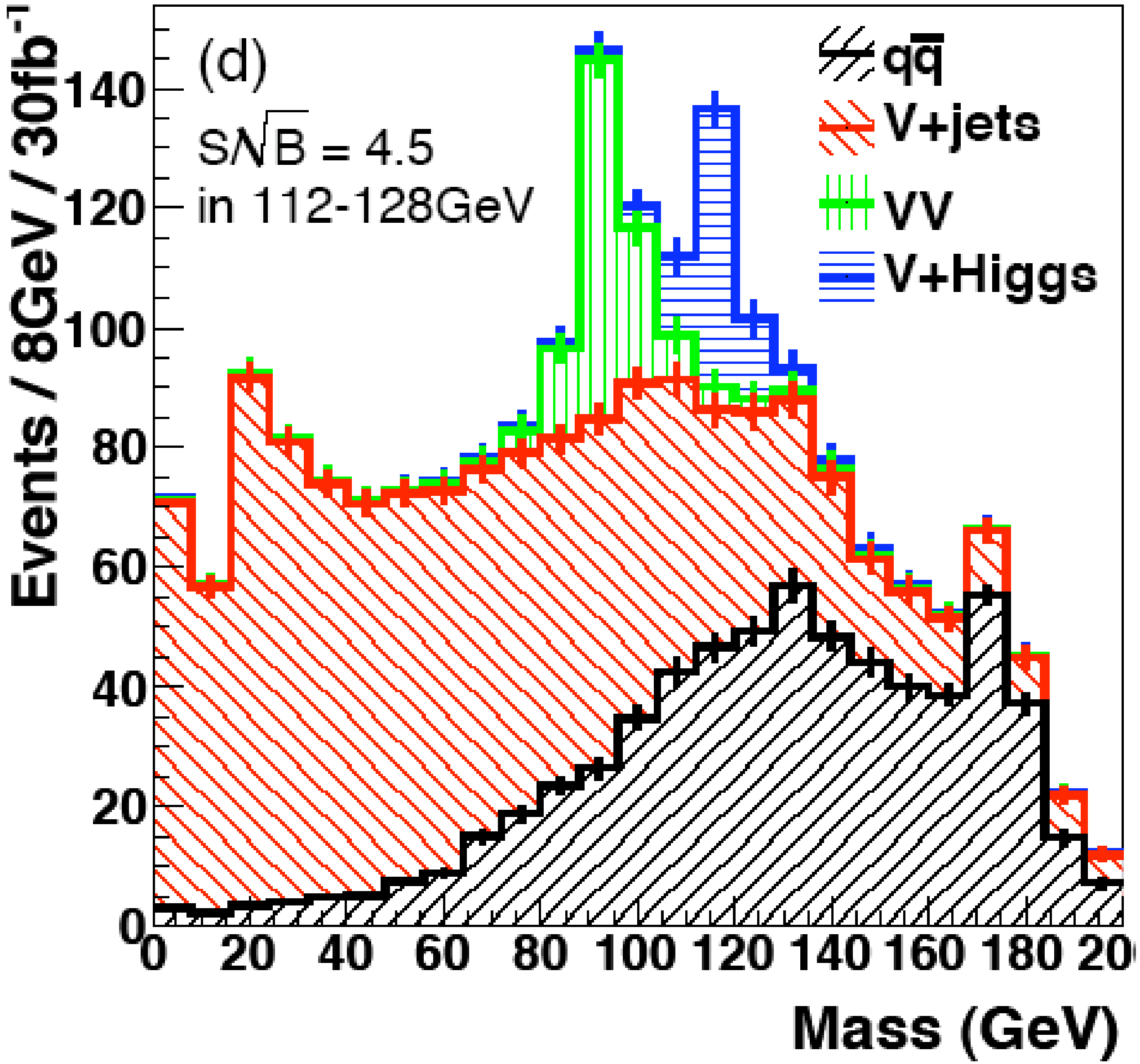
$$\sigma(pp \to h) \sim pb \ , \quad \sigma(pp \to bb(125 \text{ GeV})) \sim \mu b$$

There is a new idea: "boosted Higgs" : Identify h as a high-pT jet with 2-b-subjet substructure. Groom the jets to remove extra radiations, underlying event and pileup.



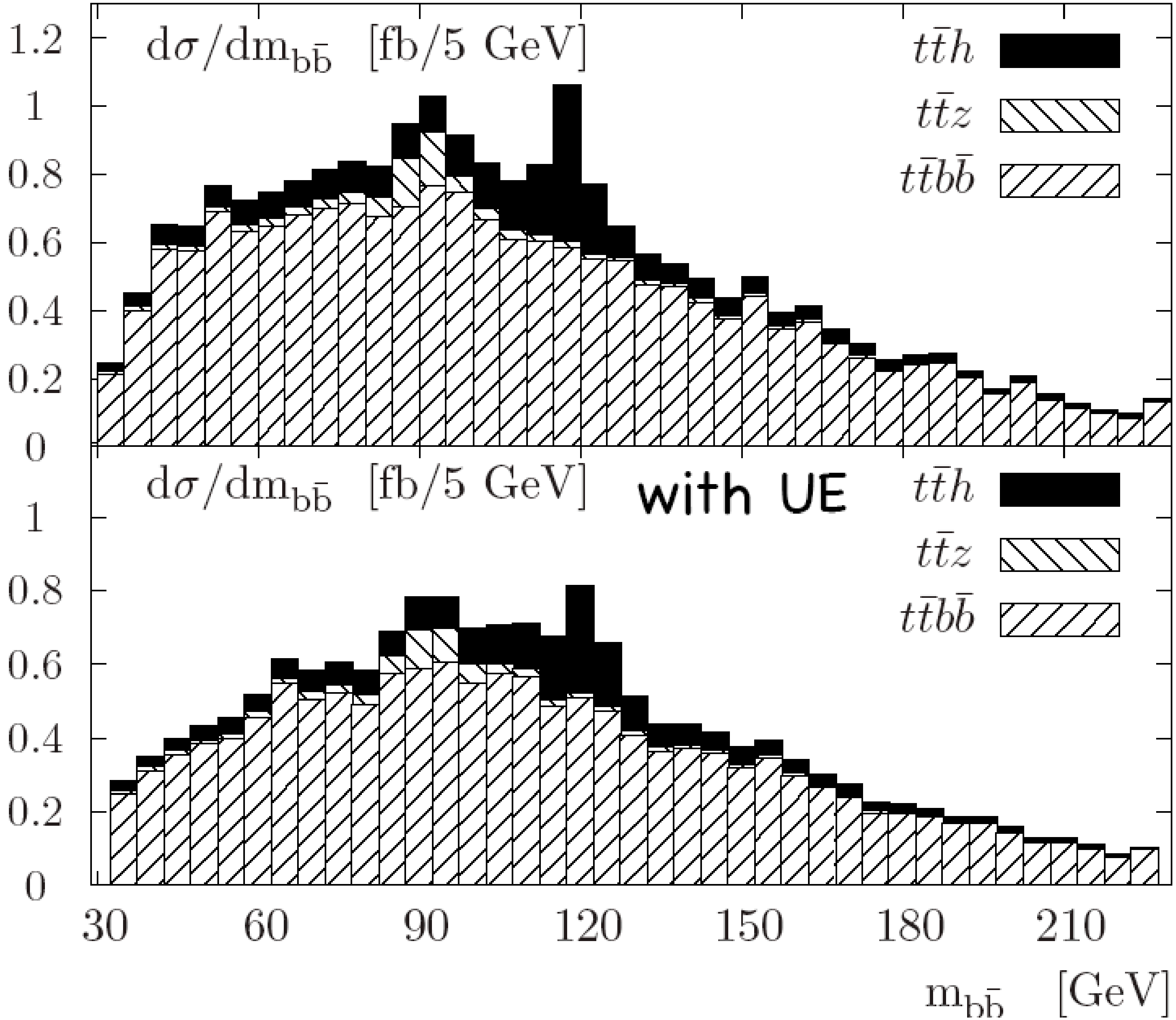
Calibration of this technique is difficult. Probably this will be based on $pp \to Z$ processes seen in parallel analyses.

$pp \to (W, Z) + h$



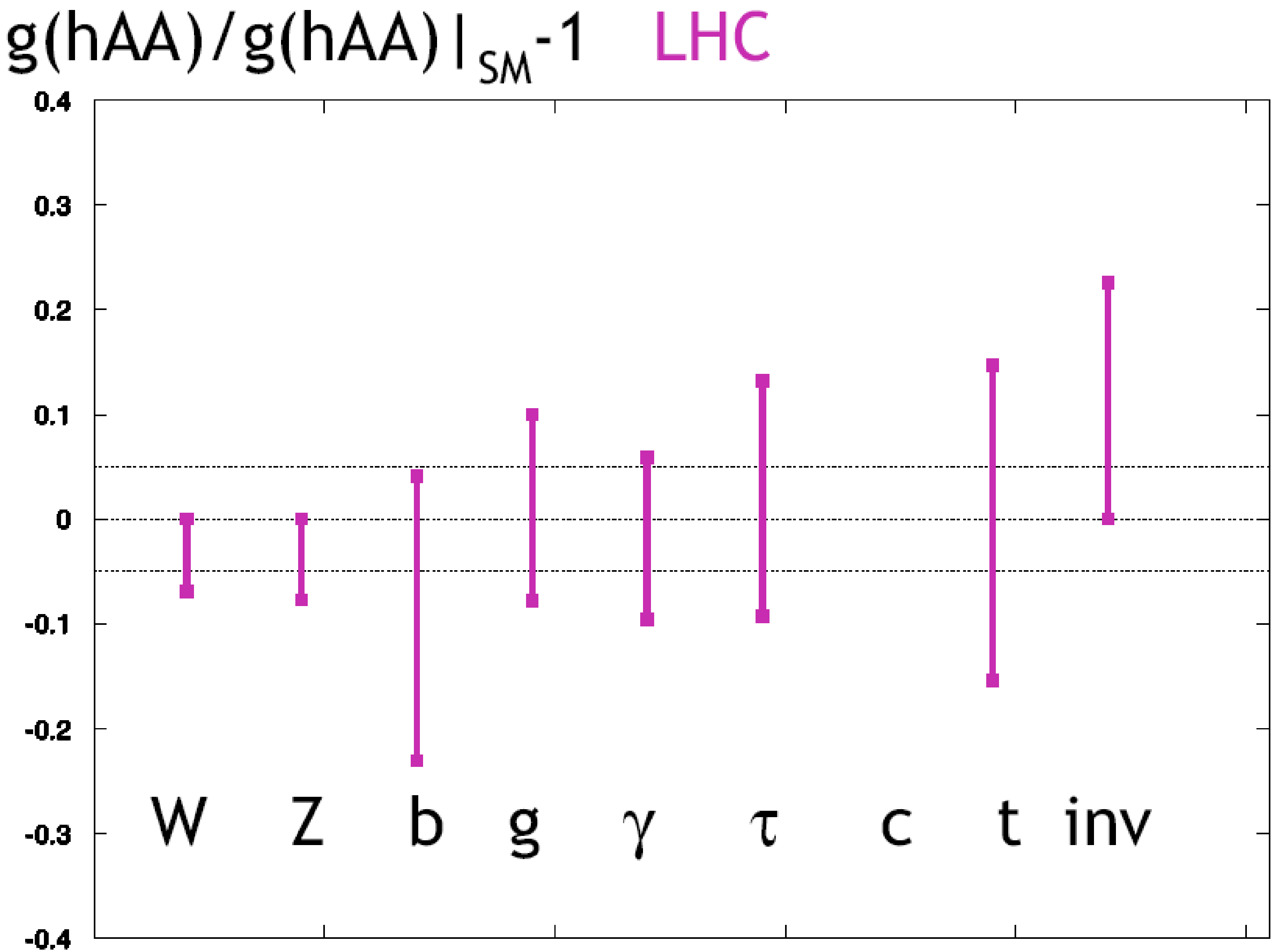
Butterworth, Davison, Rubin, Salam

$pp \to t\bar{t} + h(\to b\bar{b})$



Plehn, Spannowsky, Takeuchi

Here is my esimate of the errors that can ultimately be achieved by ATLAS and CMS in testing the agreement of the Higgs boson couplings with the predictions of the simple scalar field model.



Unfortunately, this not good enough. Different models for the origin of the Higgs condensate predict differences from the simplest model that are smaller than 10%.

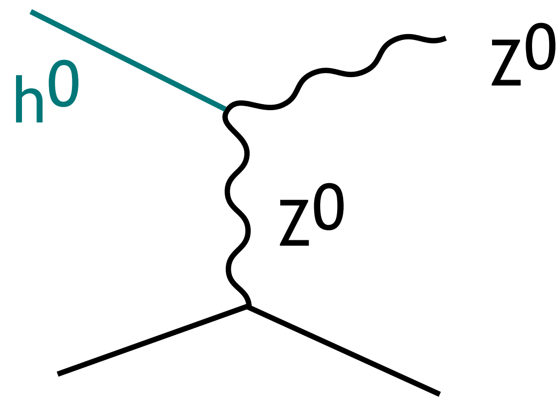
What we really need is a Higgs factory with the following properties:

Higgs boson production is 1%, not 10^{-10} of the total rate.

Decays of Higgs to quarks are manifest as mass peaks.

Higgs boson decays are tagged, allowing precision measurement of branching ratios, even for invisible modes.

To achieve this, we need to study the Higgs in e^+e^- annihilation, using the Higgs-strahlung reaction

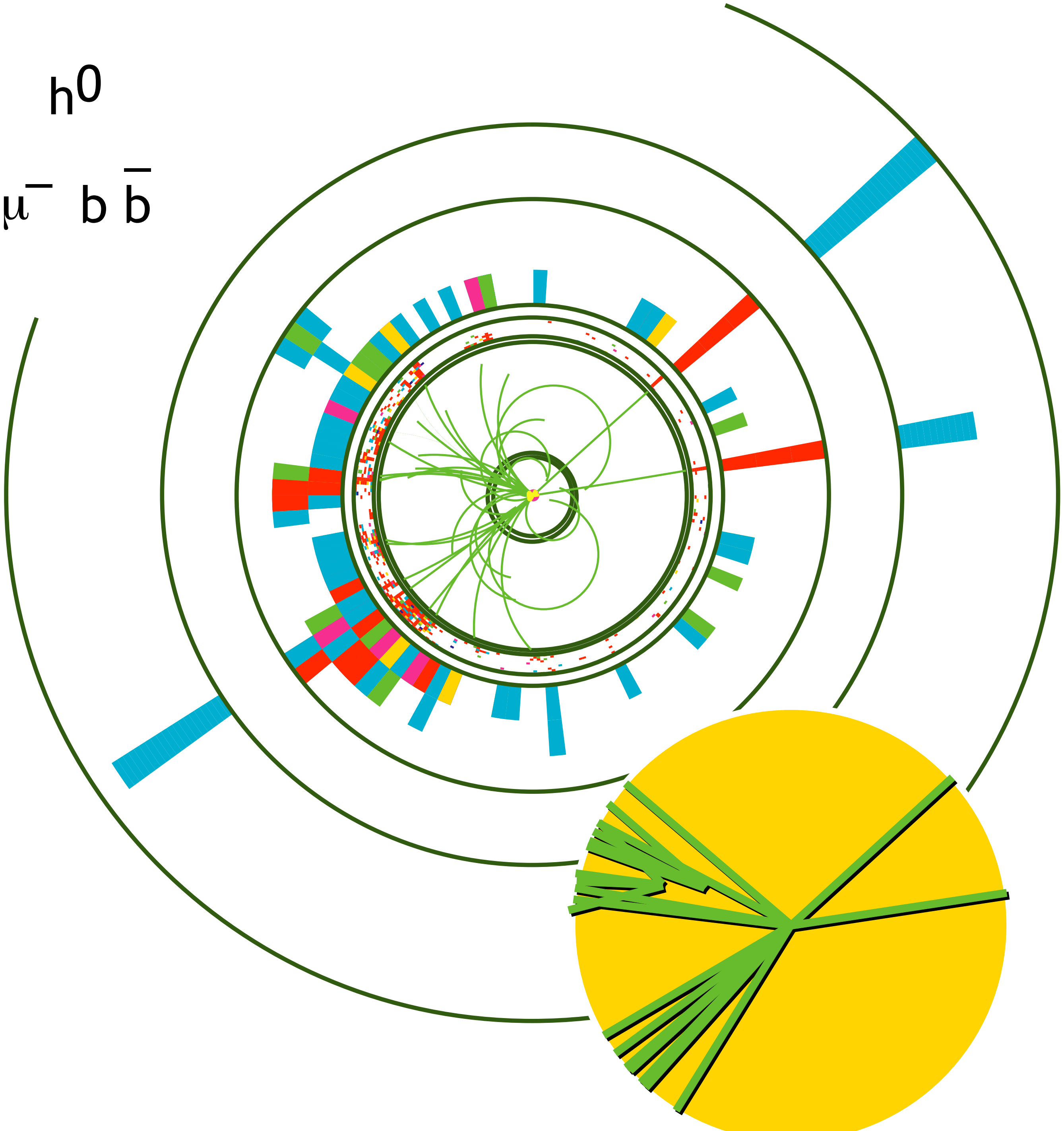


There is a newly available technology, that of electron-positron linear colliders (International Linear Collider).

Here are a few glimpses of the prospects for ILC experiments on the Higgs boson.

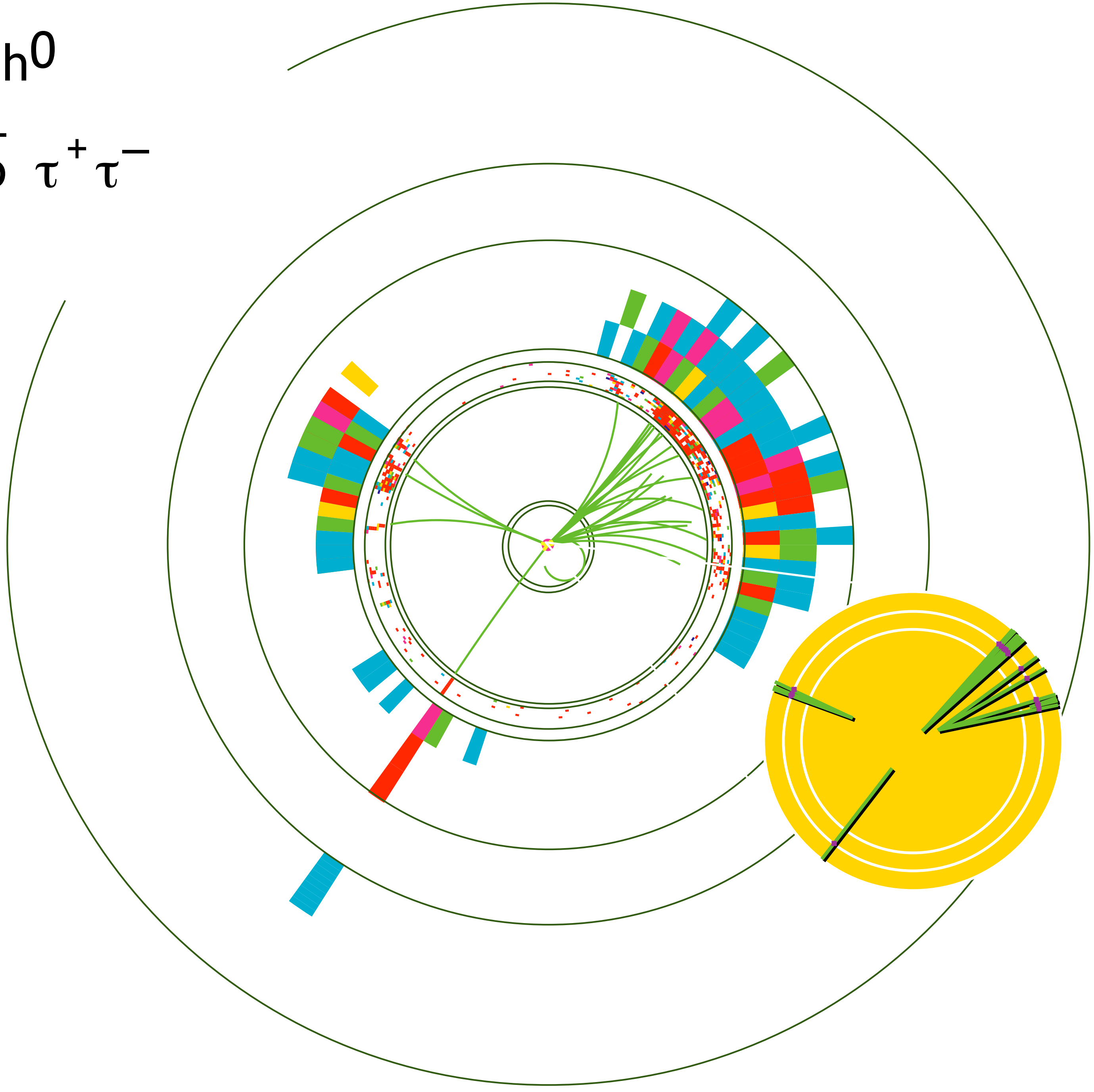
$e^+e^- \to Z^0 \ h^0$

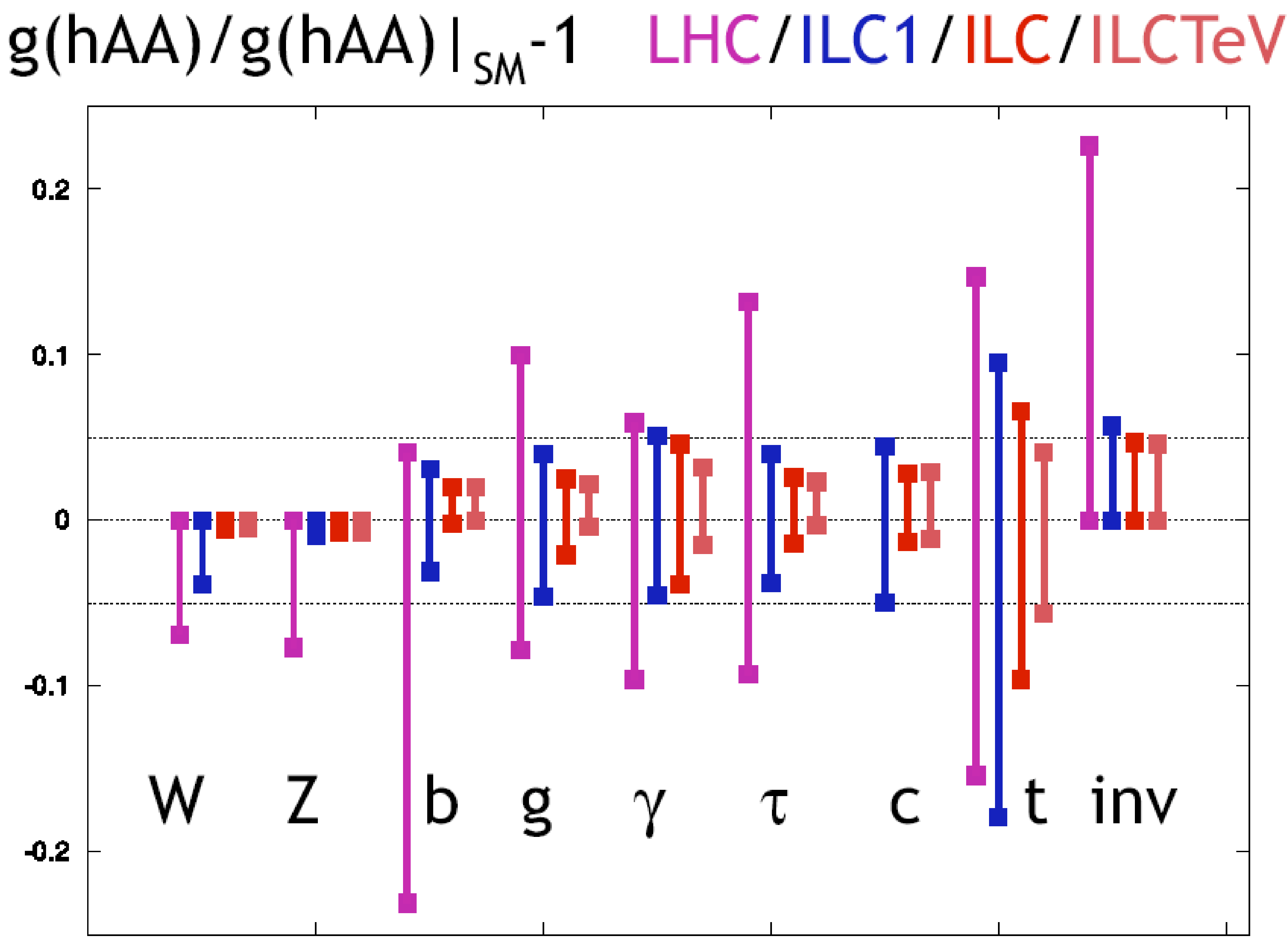
$\to \mu^+\mu^- \ b\,\bar{b}$



$e^+e^- \rightarrow Z^0\ h^0$

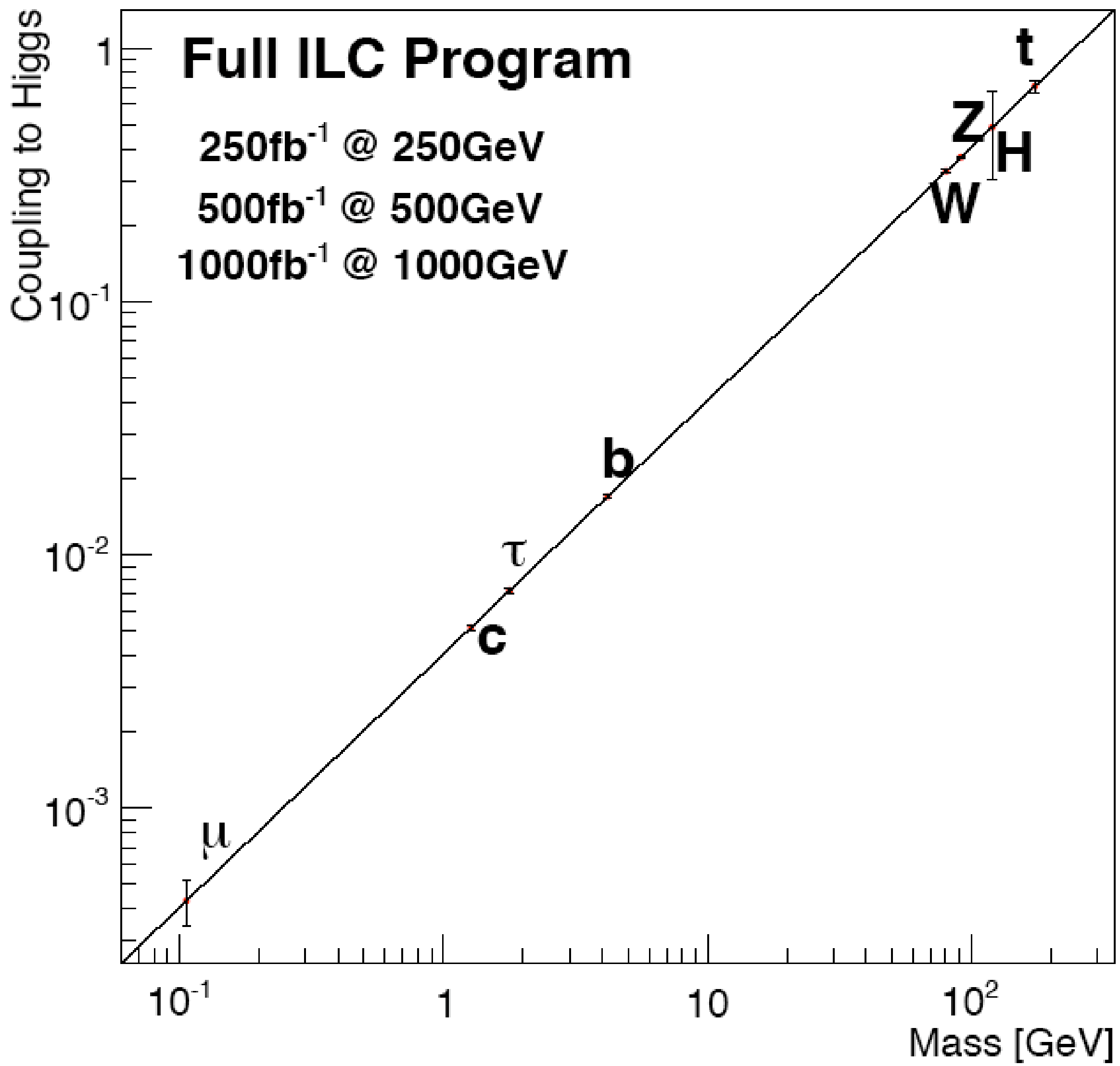
$\rightarrow b\,\bar{b}\ \tau^+\tau^-$





g(hAA)/g(hAA)|SM-1
LHC/ILC1/ILC/ILCTeV
0.2
0.1
0
-0.1
-0.2
W
Z
b
g
γ
τ
c
t
inv

If the simple scalar Higgs model is correct, the Higgs couplings to each particle is proportional to its mass. We can test this hypothesis to high accuracy.



ILC DBD - K. Fujii

The Higgs boson has arrived.

It is meeting its expectations -- so far.

This is the start of a new line of scientific study.

There is much beautiful Higgs physics still ahead.

from the Borowitz Report in the New Yorker: July 3, 2012

an interview with the Higgs boson

O.K., be honest, and no false modesty here: Is there anything the Higgs boson can't do?

A: Honest answer? I want to be considered the Michael Jordan of subatomic particles. By that I mean, Michael Jordan might not have been the most physically gifted player in the history of the N.B.A., but nobody worked harder at his game than he did. That's what I'm all about. Whether it's giving mass to matter, breaking electroweak symmetry, or explaining the origin of the universe and whatnot, I believe I can do it all.