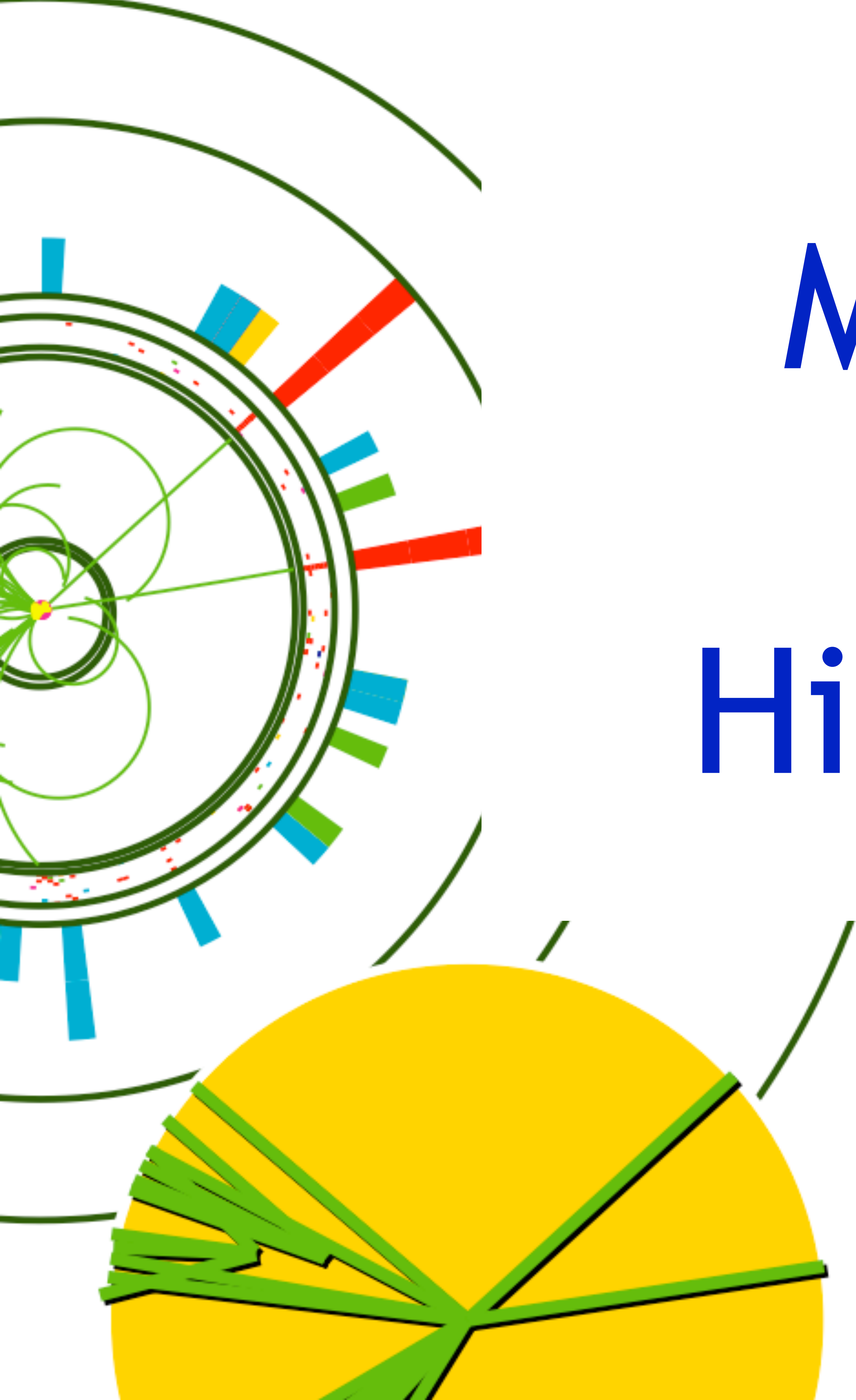


Mysteries of the Higgs Boson

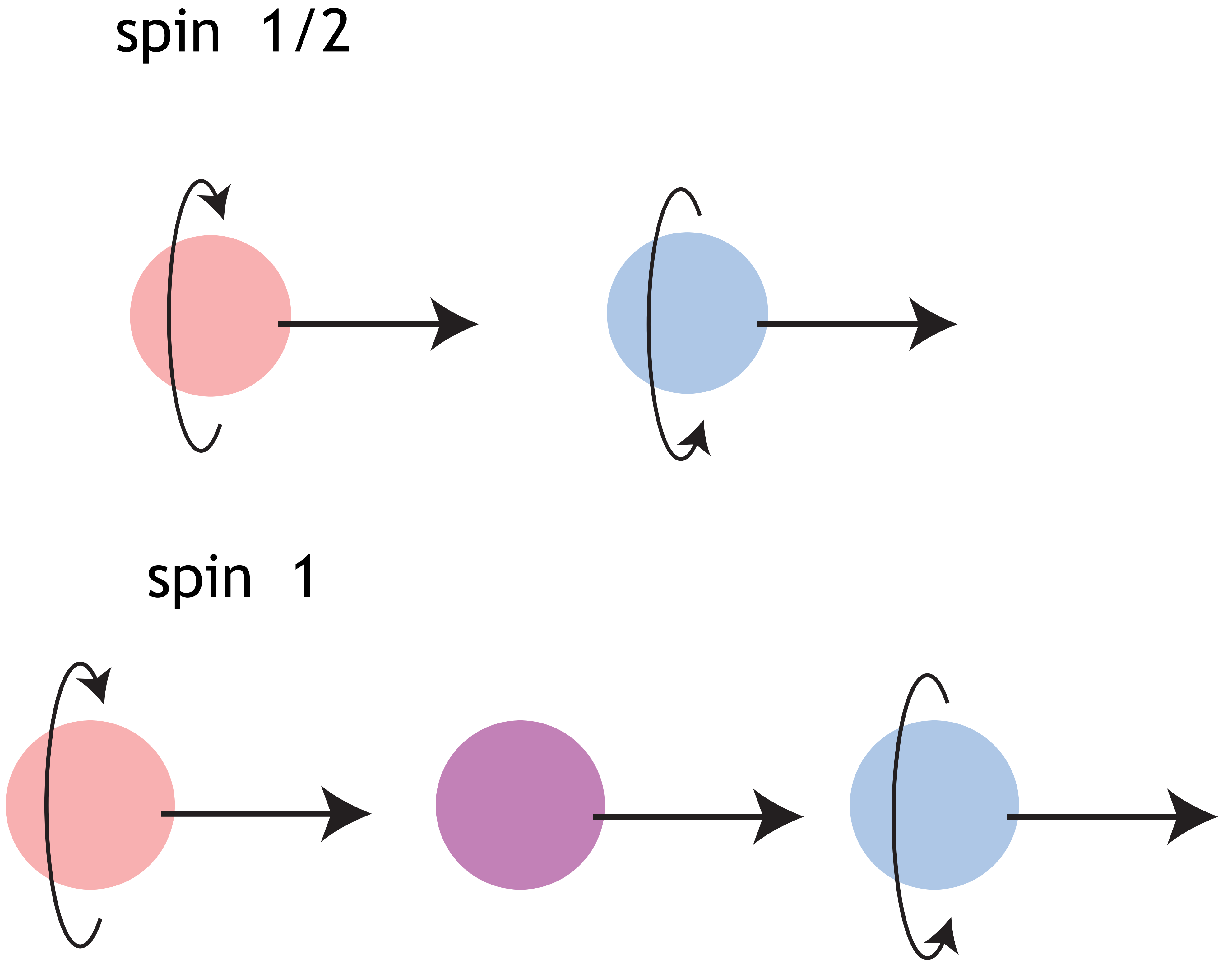
M. E. Peskin
September 2017

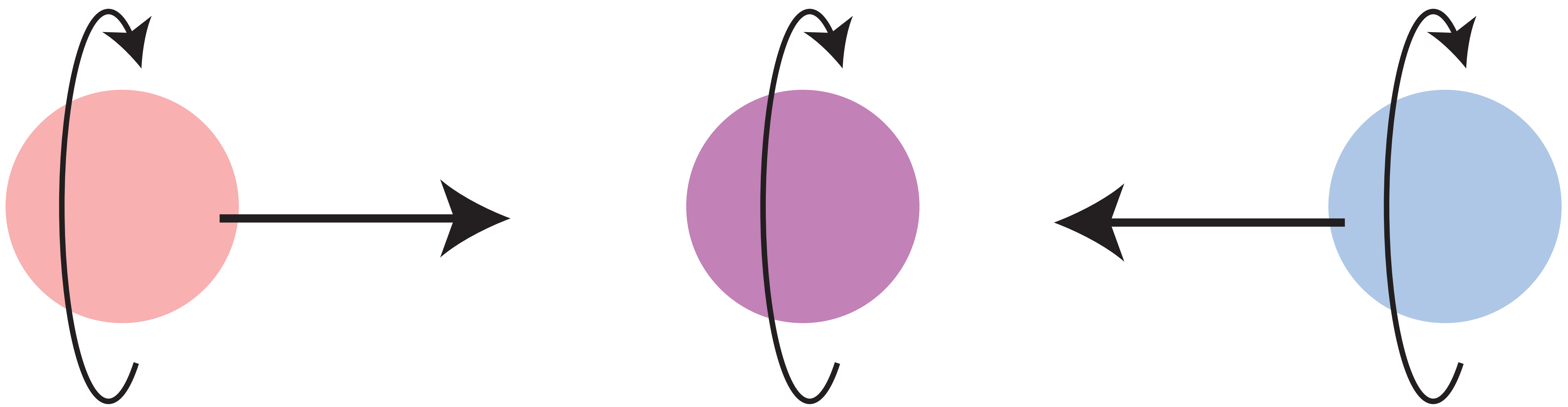
What is the Higgs boson ?

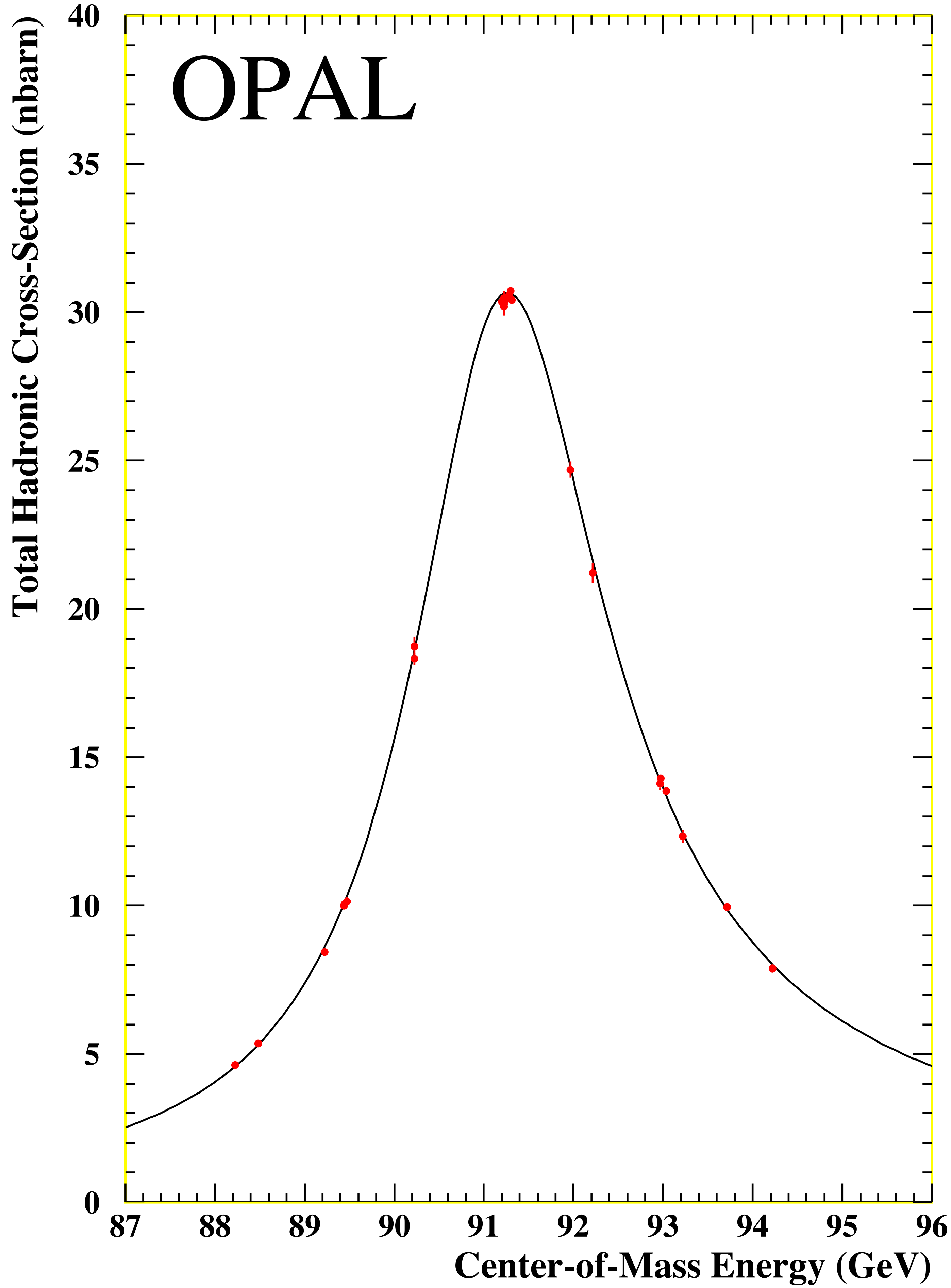
an essential ingredient in the "Standard Model" of elementary particle physics,

without which elementary particles (quarks, leptons, W and Z bosons) cannot have mass.


SMALL
PEQUENA

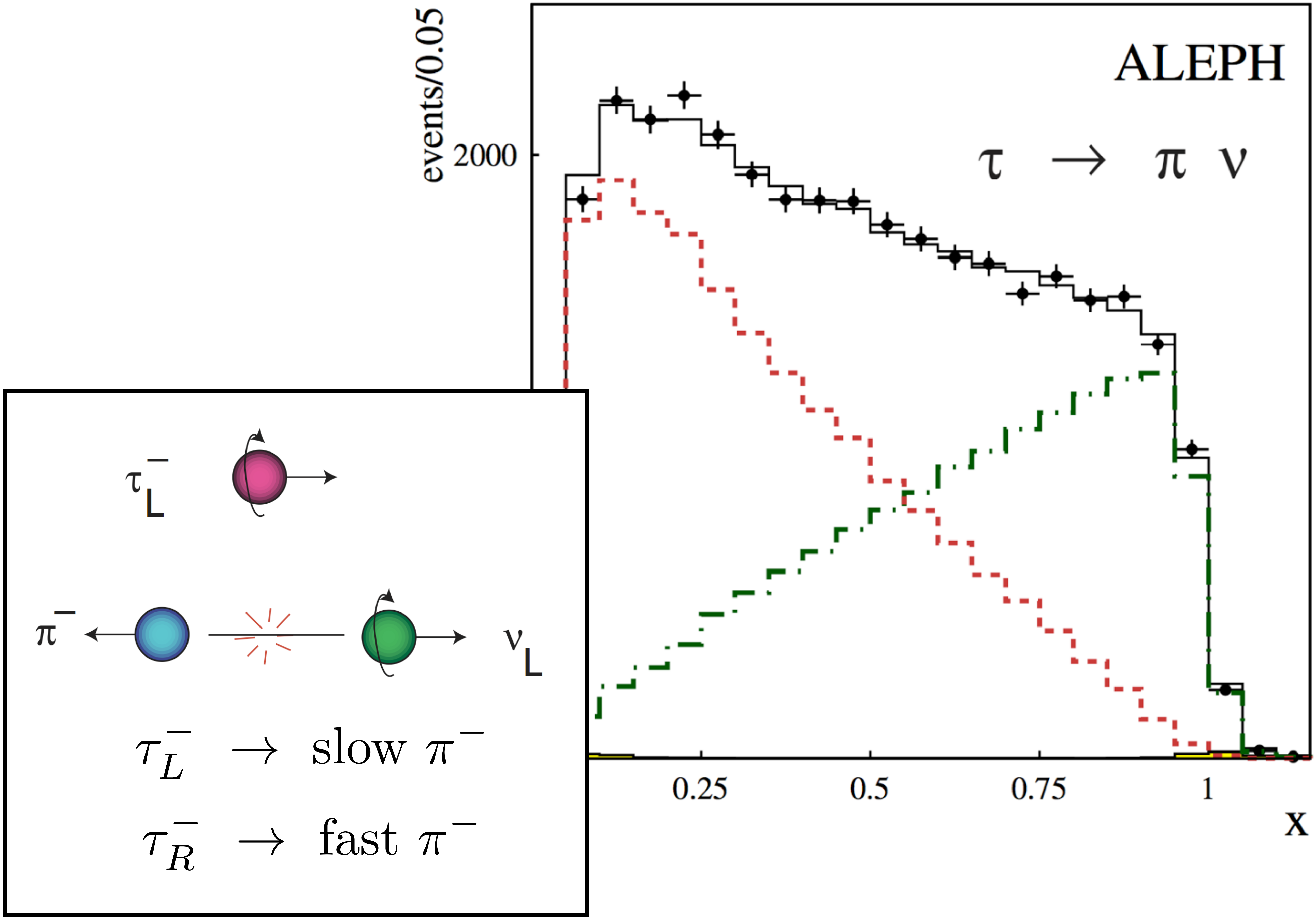

spin 1/2
spin 1





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)

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



All of these results

weak interactions mediated by massive spin-1 bosons

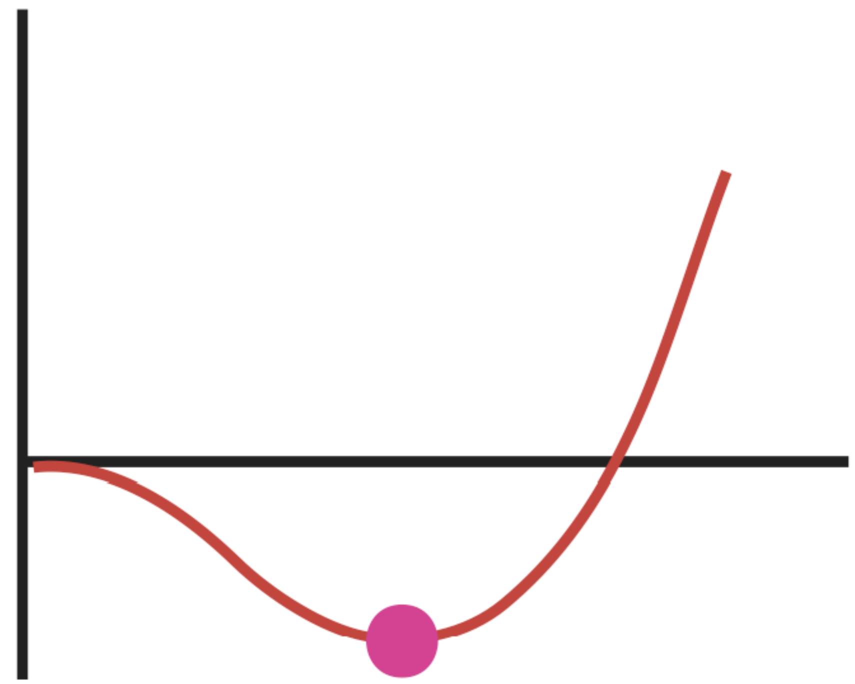
left-right asymmetric couplings to quarks and leptons

are described with high precision by the weak interaction theory of Glashow, Salam, and Weinberg,

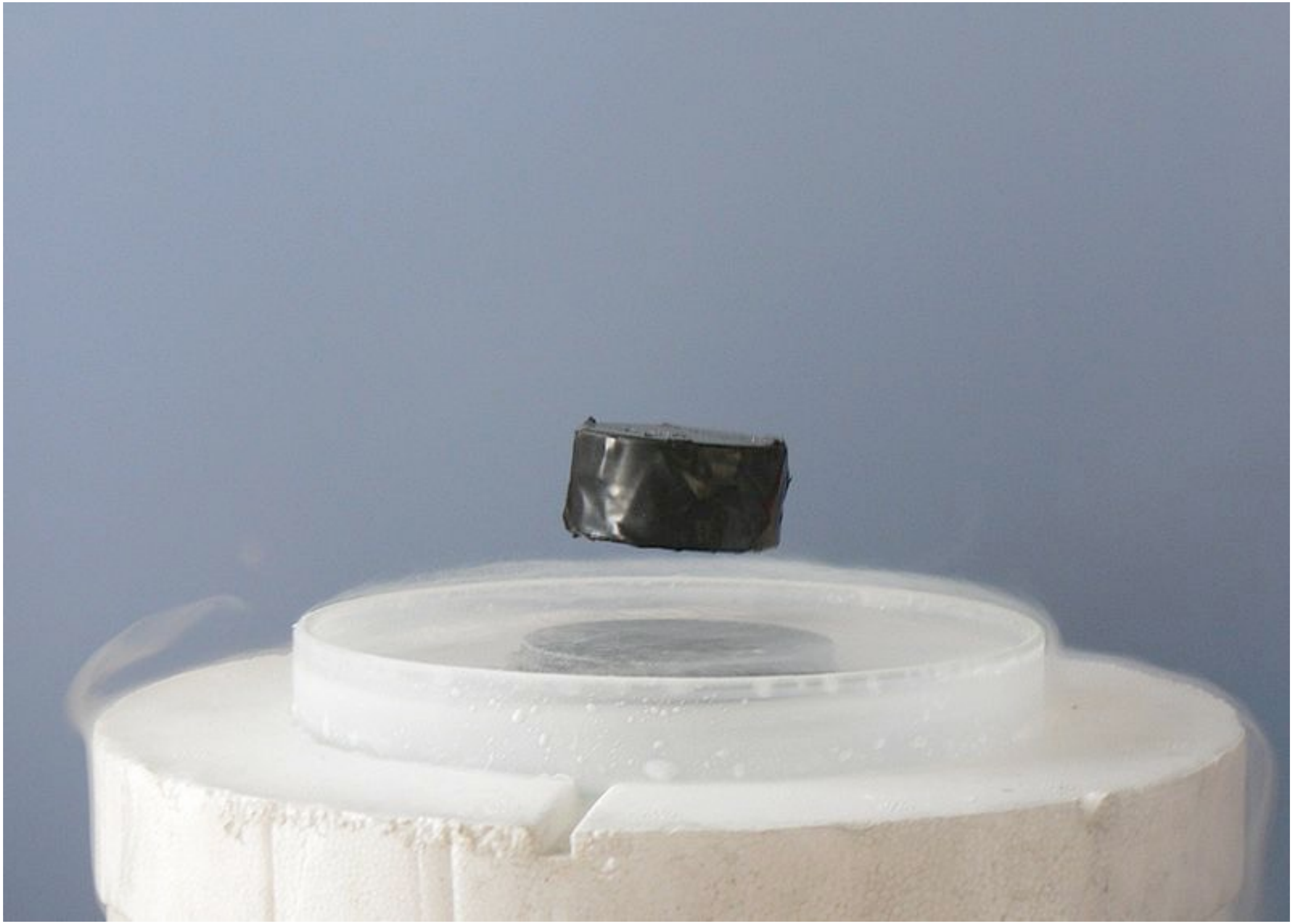
now called simply the “Standard Model”.

solution: (Weinberg, Salam)

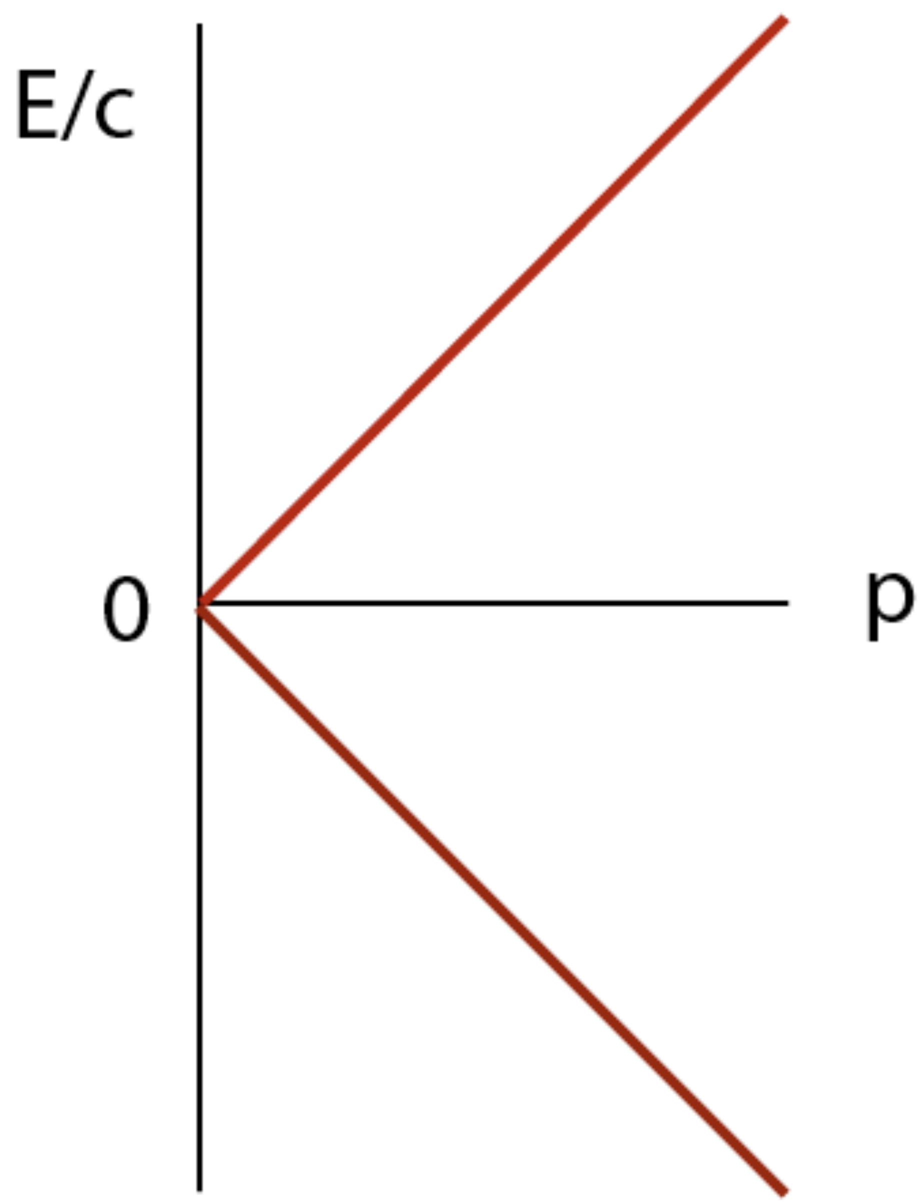
A condensate of the “Higgs field” fills space. Its coupling to particles can flip the weak interaction quantum numbers.



Larger masses come from larger couplings to this field.

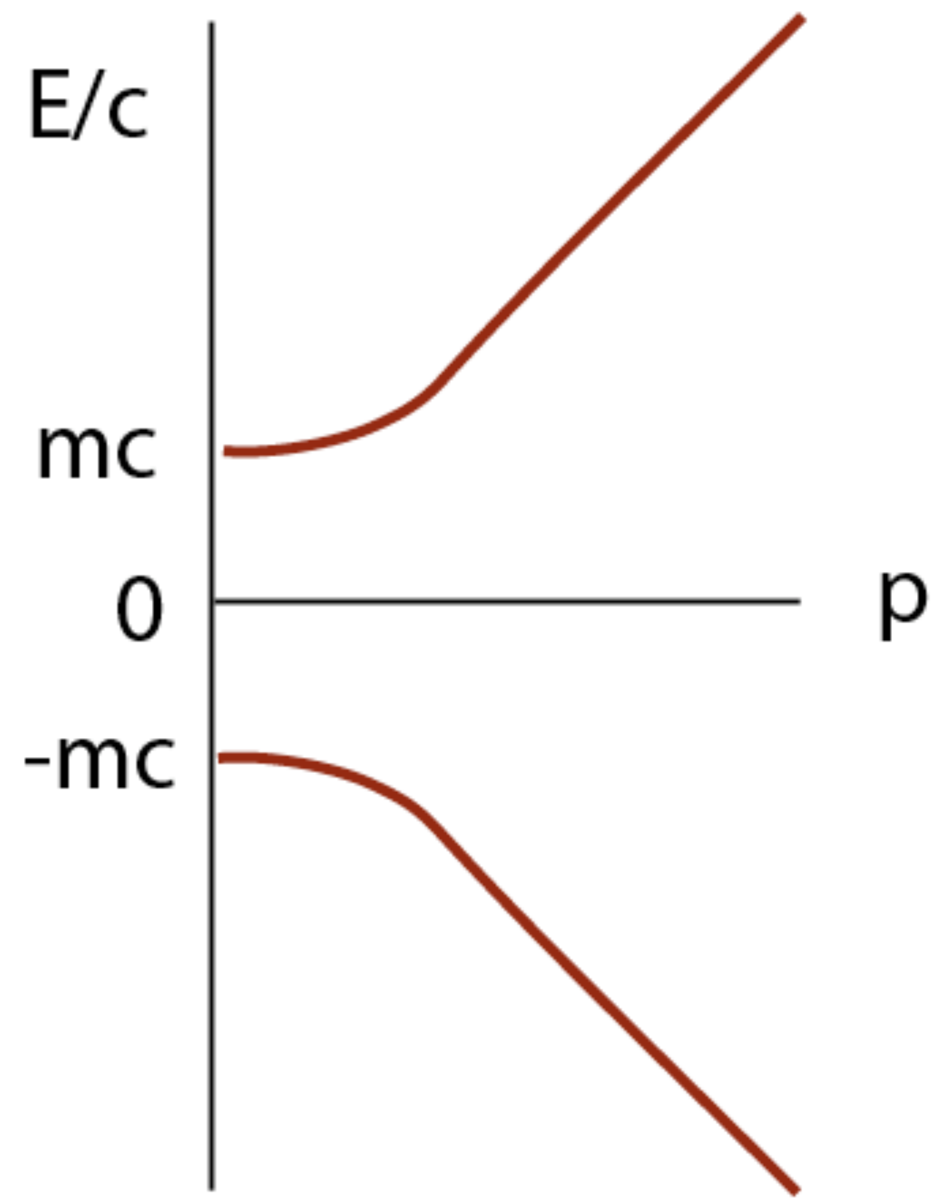


zero mass



$$E = pc$$

massive



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

The field responsible for the symmetry breaking of the W, Z interactions is a complete mystery. We give it a name -- the Higgs field -- but this does not make it less mysterious.

We would like to know:

Does the Higgs field exist ?

Why does this field have a spontaneously broken symmetry ?

Does the Higgs field have partners, or even a Higgs spectroscopy ?

The mysteries of the Higgs boson are linked to other mysteries of particle physics.

One of the most important is the spectrum of quark and lepton masses.

e	0.00051	d	0.0048	u	0.0023
μ	0.106	s	0.095	c	1.28
τ	1.777	b	4.18	t	$173.$

(masses in GeV; $m_p = 0.938\ \mathrm{GeV}$)

In particular, $m_u/m_t = 1 \ / \ 100,000$

The origin of this ratio is the ratio of couplings of these particles to the Higgs boson.

Which is the anomaly ? Is t exceptionally heavy, or is u exceptionally light ?

One way to prove that the Higgs field exists is to find its quantum excitation, the Higgs boson.

This particle has the property that it couples to each quark, lepton, and vector boson proportionally to the mass of that particle.

A very heavy Higgs boson would decay primarily into pairs of W and Z bosons.

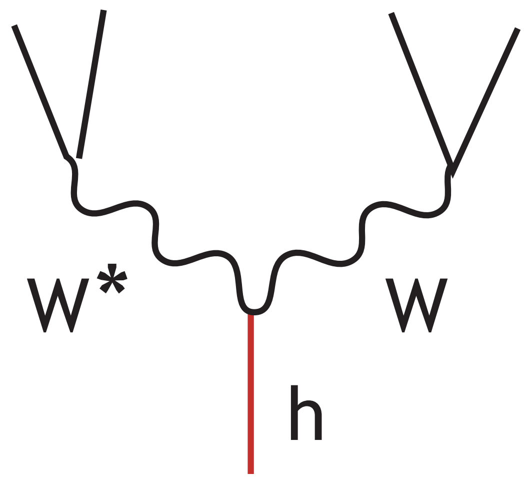
This Higgs production and decay process has been searched for intensively, and excluded.

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

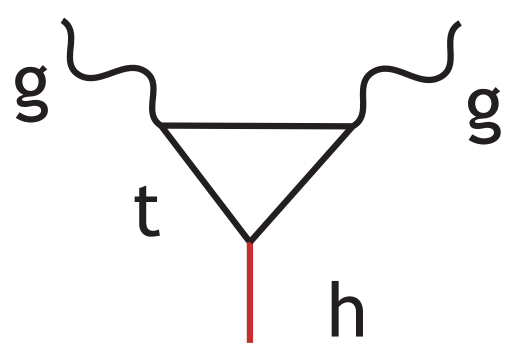
decay to off-shell W, Z

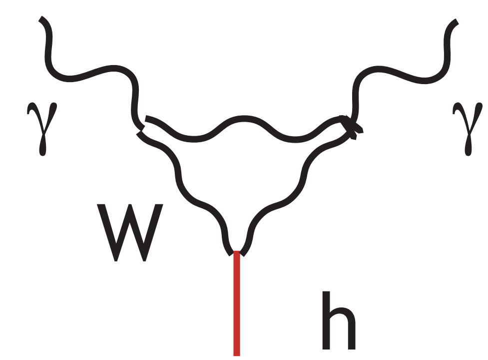


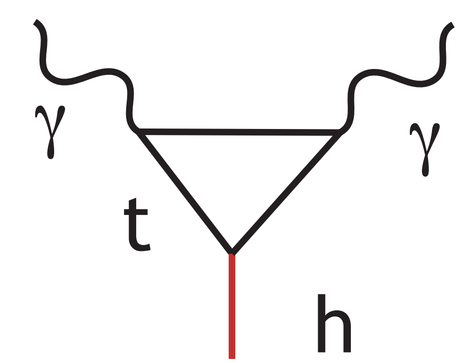
$$h^0 \to WW^*,\ ZZ^*$$

decays through t, W loop diagrams

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







For a Higgs boson of mass 125 GeV, the prediction for the total width is $\Gamma_h = 4.1 \text{ MeV}$.

The branching fractions are predicted to be

$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

Many decay modes of the Higgs will eventually be visible, and measurable.

In the "Standard Model" with only a Higgs scalar field, these predictions are fixed once the Higgs mass is known.

F. Gianotti: "Thank you, Nature."

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 experiments, all we have available to collide are light particles

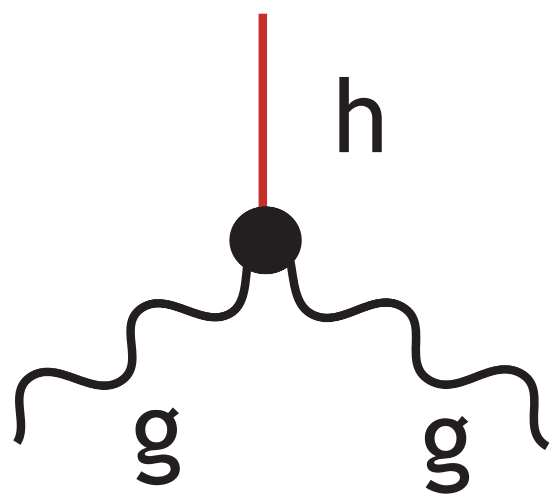
$$e\ ,u,\ d,\ g$$

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

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

A possible strategy is to create very high energy proton-proton collisions.

Gluons in the wavefunction of the proton can react through the higher-order ggh coupling to create the Higgs boson as a resonance.



The rate of this reaction is 2×10^{-10} of the total rate for proton-proton collisions.

Also, there is a problem to recognize the Higgs boson when it is produced.

This is not straightforward in the most prominent decay modes

$$h \to b\bar{b}\ ,\ \ gg\ , WW^*$$

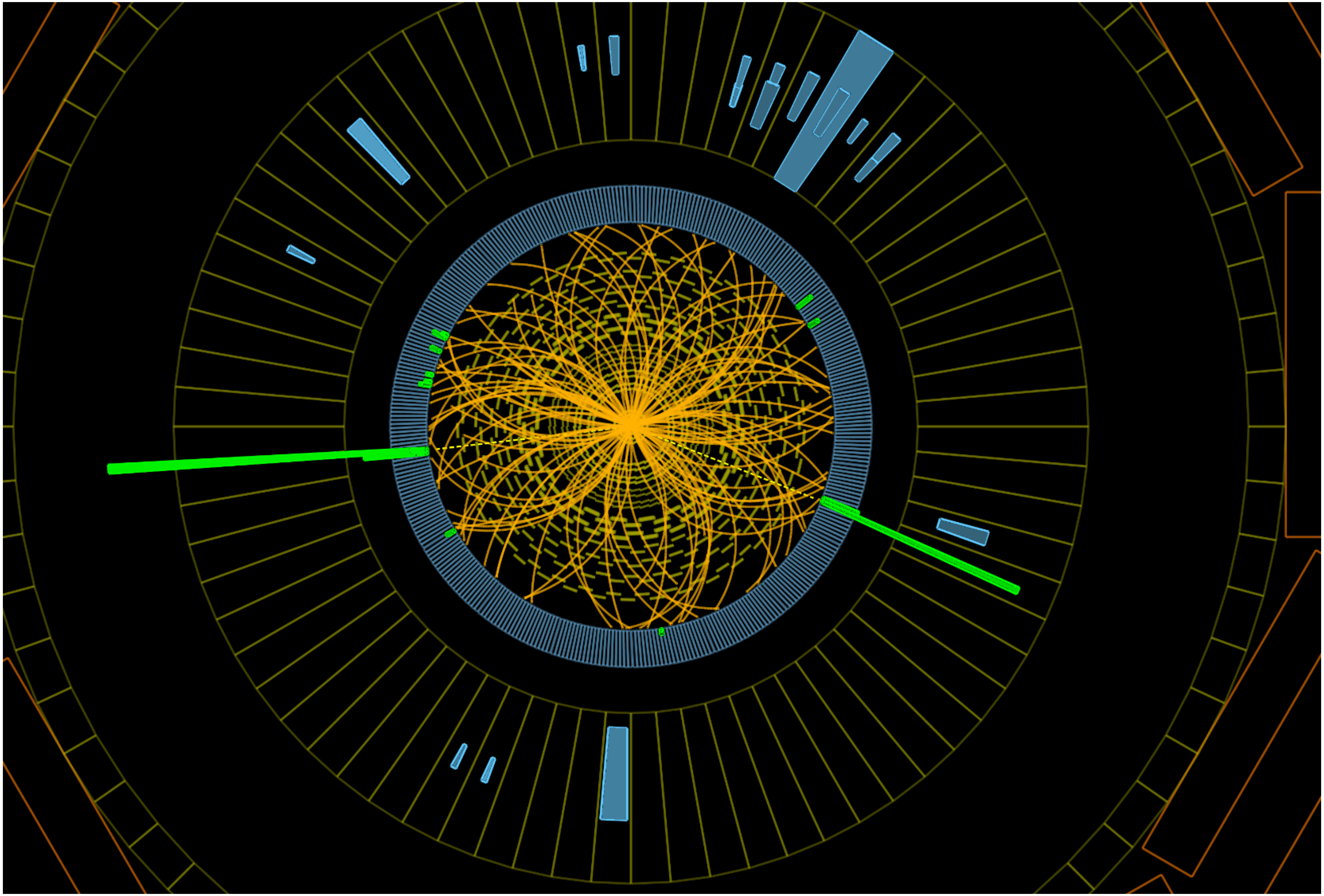
In a two modes, the Higgs boson appears as a true resonance

$$h \to \gamma\gamma\ ,\ \ ZZ^* \to 4\ell$$

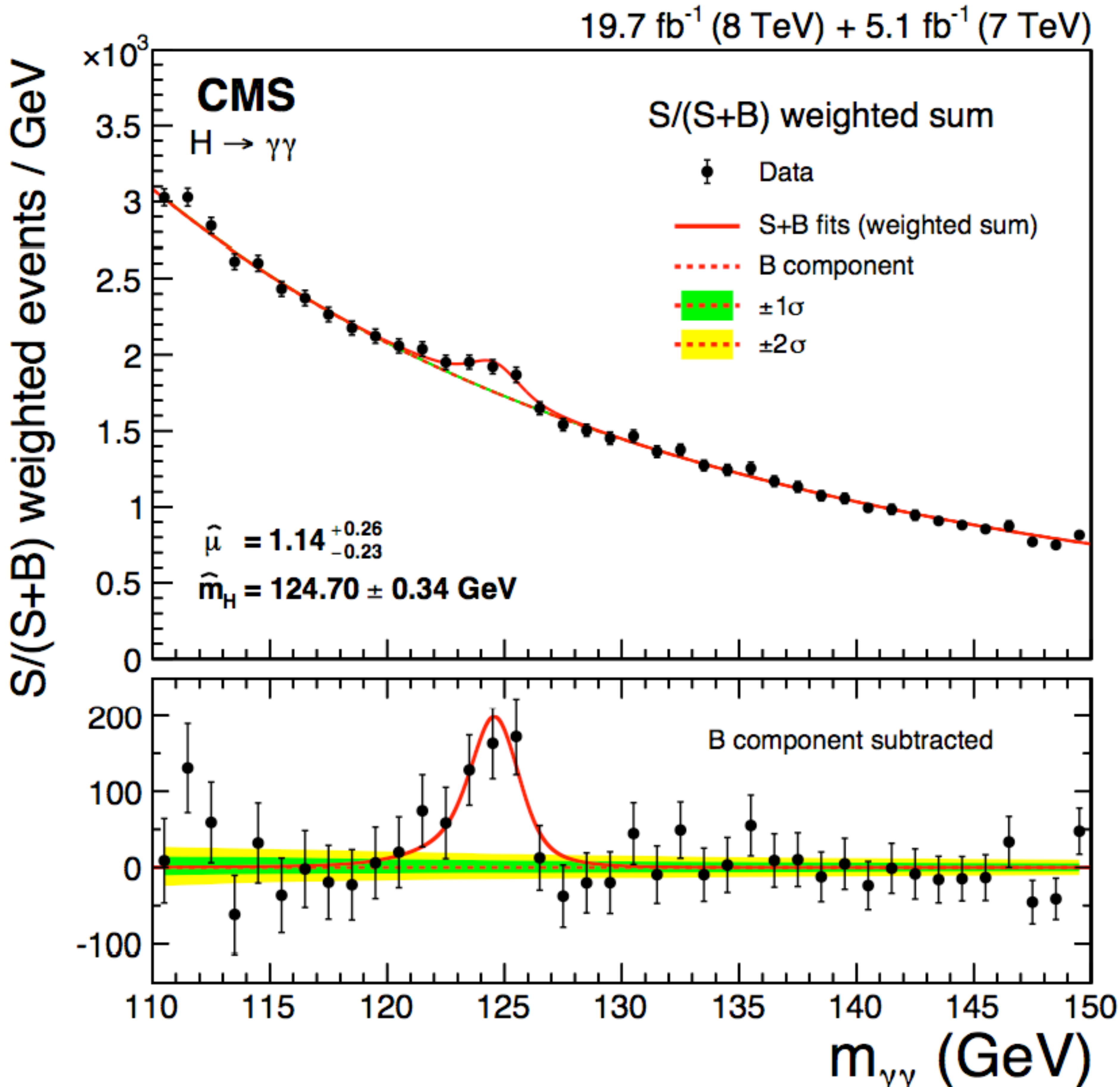
but, recall,

$$BR(h \to \gamma\gamma) = 2 \times 10^{-3}$$

so this decay appears in 1 in 2×10^{12} pp collisions.



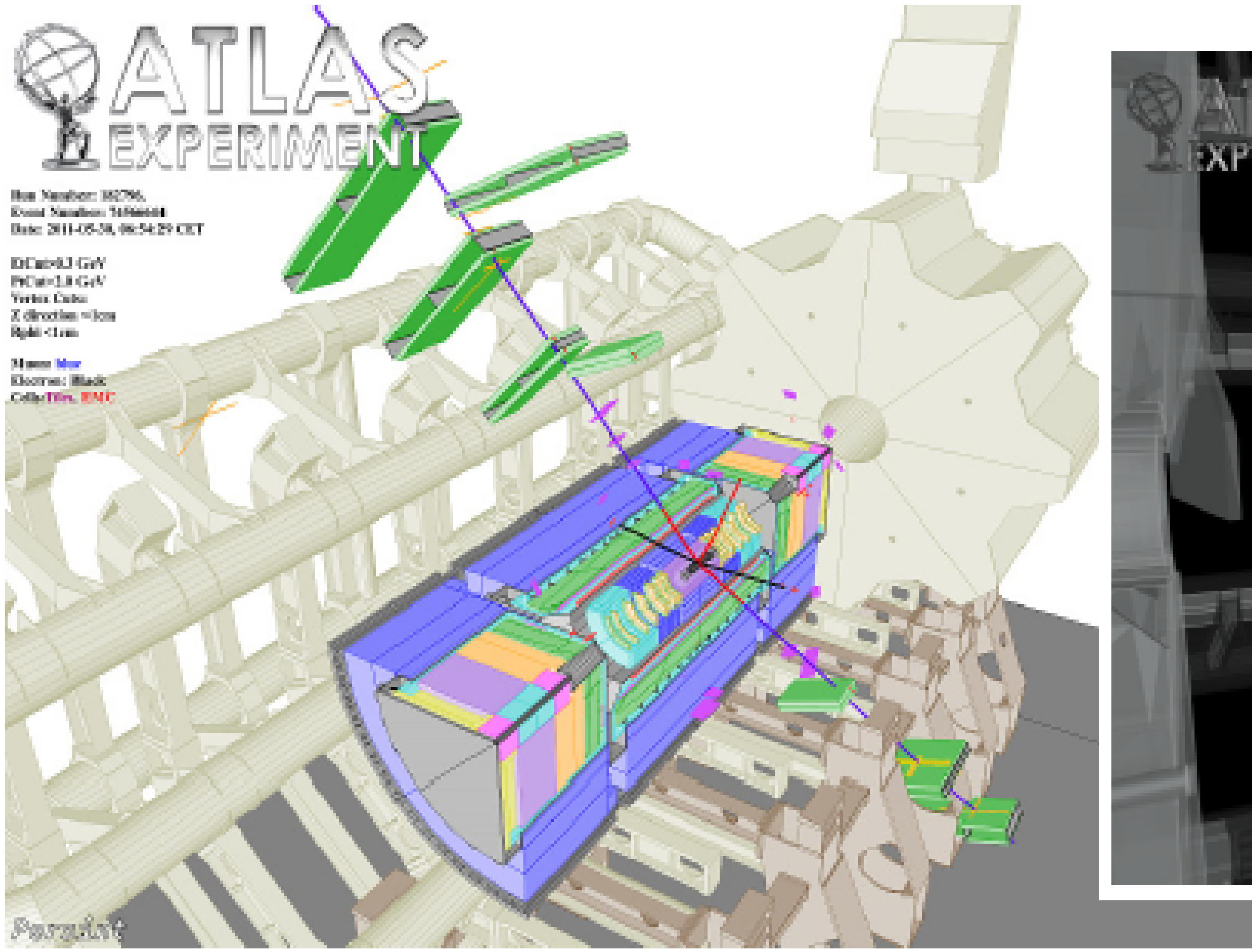
CMS

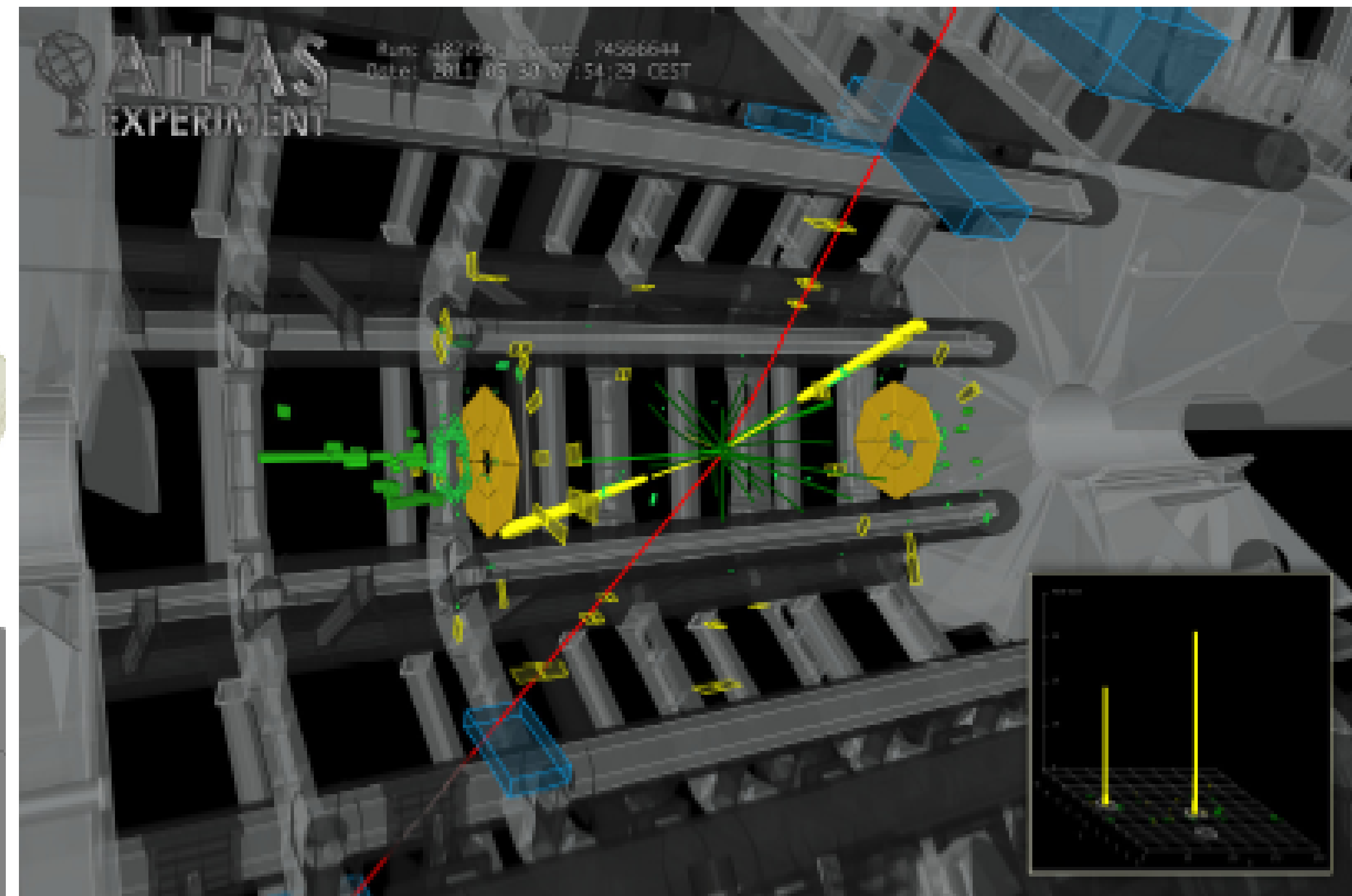


19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
$\hat{\mu} = 1.14^{+0.26}_{-0.23}$
$\hat{m}_H = 124.70 \pm 0.34$ GeV
S/(S+B) weighted events / GeV
×10^3
B component subtracted
$m_{\gamma\gamma}$ (GeV)

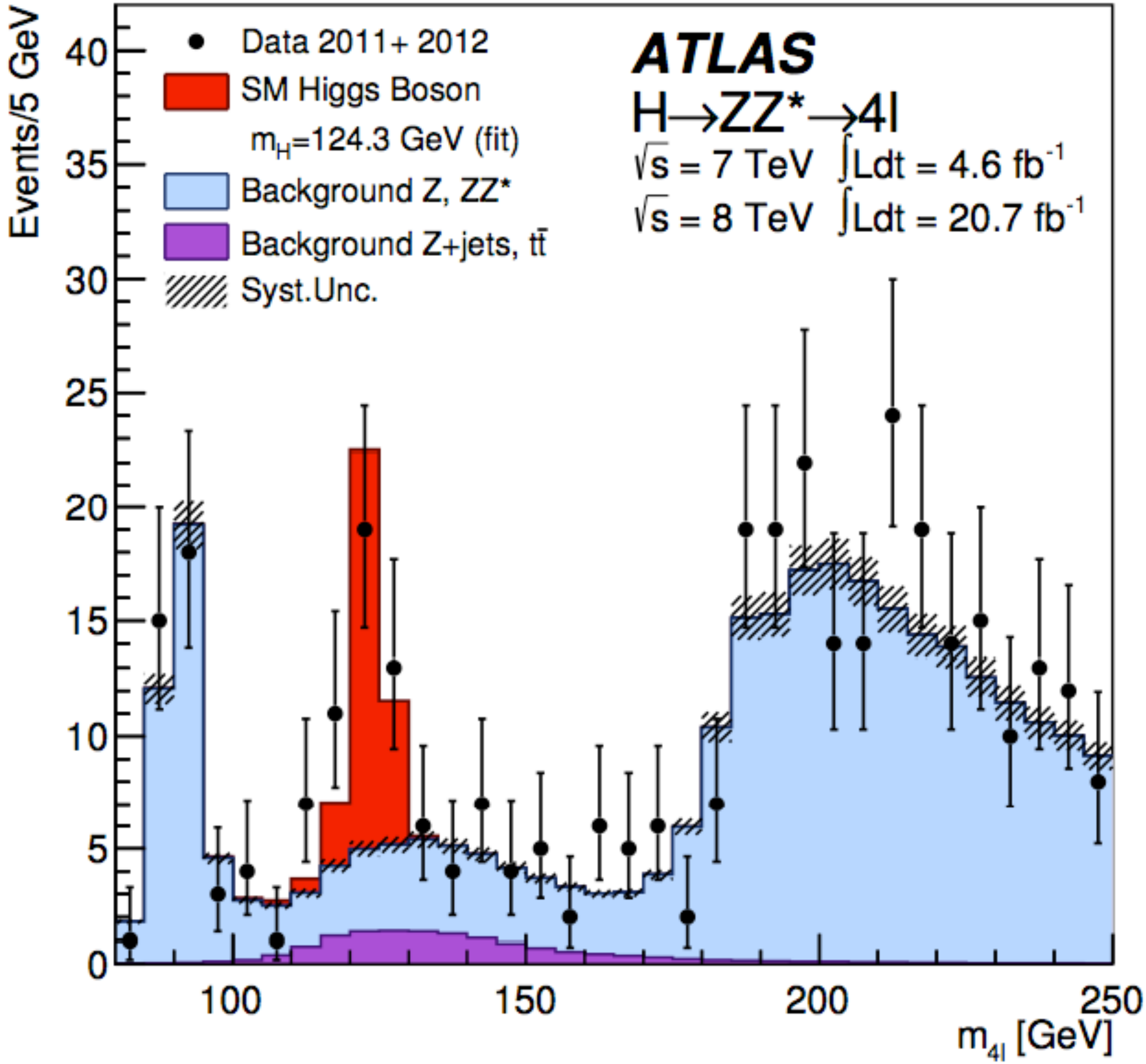
ATLAS candidate

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





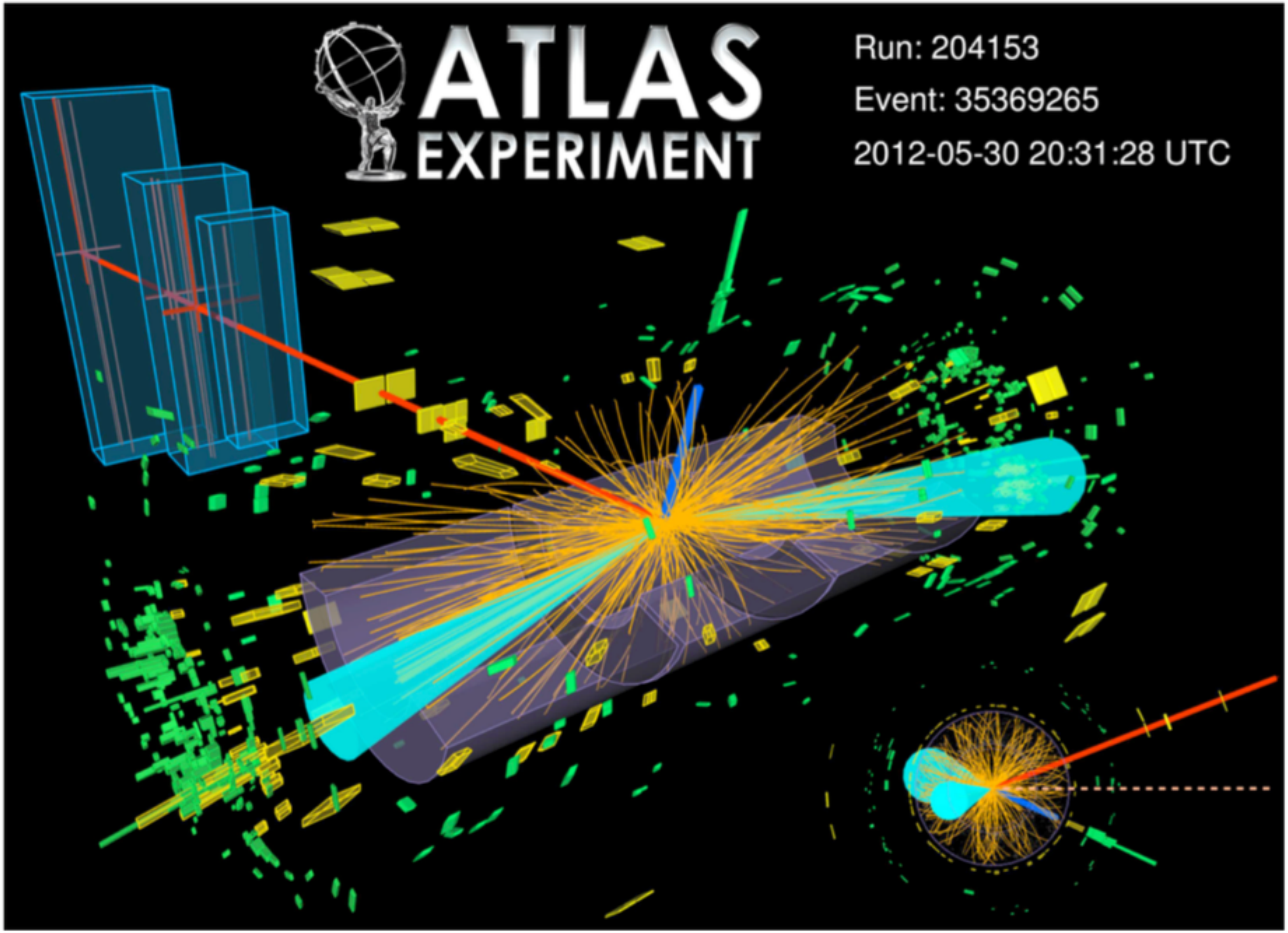
m(4l) = 124.3 GeV



Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, $t\bar{t}$
Syst.Unc.
ATLAS
$H\rightarrow ZZ^*\rightarrow 4l$
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
Events/5 GeV
m_{4l} [GeV]
0
5
10
15
20
25
30
35
40
100
150
200
250

Tests of qualitative properties predicted for the Higgs boson:

γγ decay mode	✔	
ZZ decay mode	✔	
WW decay mode	✔	
$\tau^+\tau^-$ decay mode	✔	
bb decay mode	✔	(2017!)
tt coupling	indirectly, through gg	
spin-parity 0+	✔	


ATLAS
EXPERIMENT
Run: 204153
Event: 35369265
2012-05-30 20:31:28 UTC

So far, so good.

But the reality of the Higgs boson brings us back to the question from which we started:

Generation of mass for quarks, leptons, and W, Z bosons requires the breaking of a fundamental symmetry in the theory.

What actually breaks this symmetry ? What is the underlying order parameter ?

Why is the symmetry broken ? What causes the potential function with asymmetric minima ?

The Standard Model give a simple but completely unacceptable answer to these questions:

There is a scalar field φ , and the symmetry breaking is the result of $\langle\varphi\rangle \neq 0$.

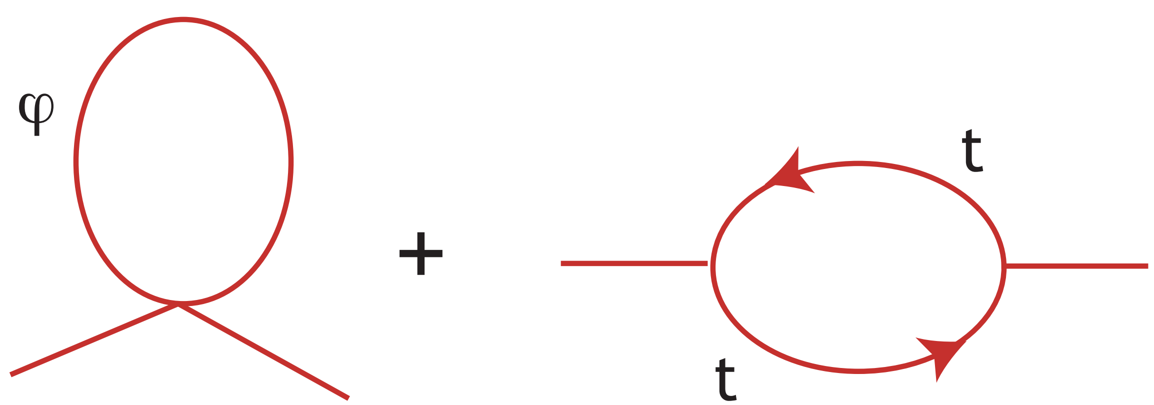
φ has a simple potential postulated to be

$$V(\varphi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

The symmetry is broken because $\mu^2 < 0$.

We get into deeper and deeper trouble if we take the idea of a fundamental scalar field too seriously.

If we compute the first quantum corrections to this picture, we find



$$\mu^2 = \mu^2_{\rm bare} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

Even if the scalar field theory is an effective low-energy theory, there must be new particles whose loop diagrams cancel these at high energy.

There is a strong analogy to the theory of superconductivity.

We have the Landau-Ginzburg theory of weak interaction symmetry breaking, but we do not have the BCS theory.

In fact, we do not know what particles play the role of the electrons in the BCS theory. Almost certainly, these particles have not yet been discovered.

I consider this a great opportunity to learn about new fundamental laws of physics.

In condensed matter physics, phase transitions occur for reasons that are usually not obvious, but instead involve fascinating physical mechanisms.

Why not also in particle physics ?

Here is a first try at such a theory:

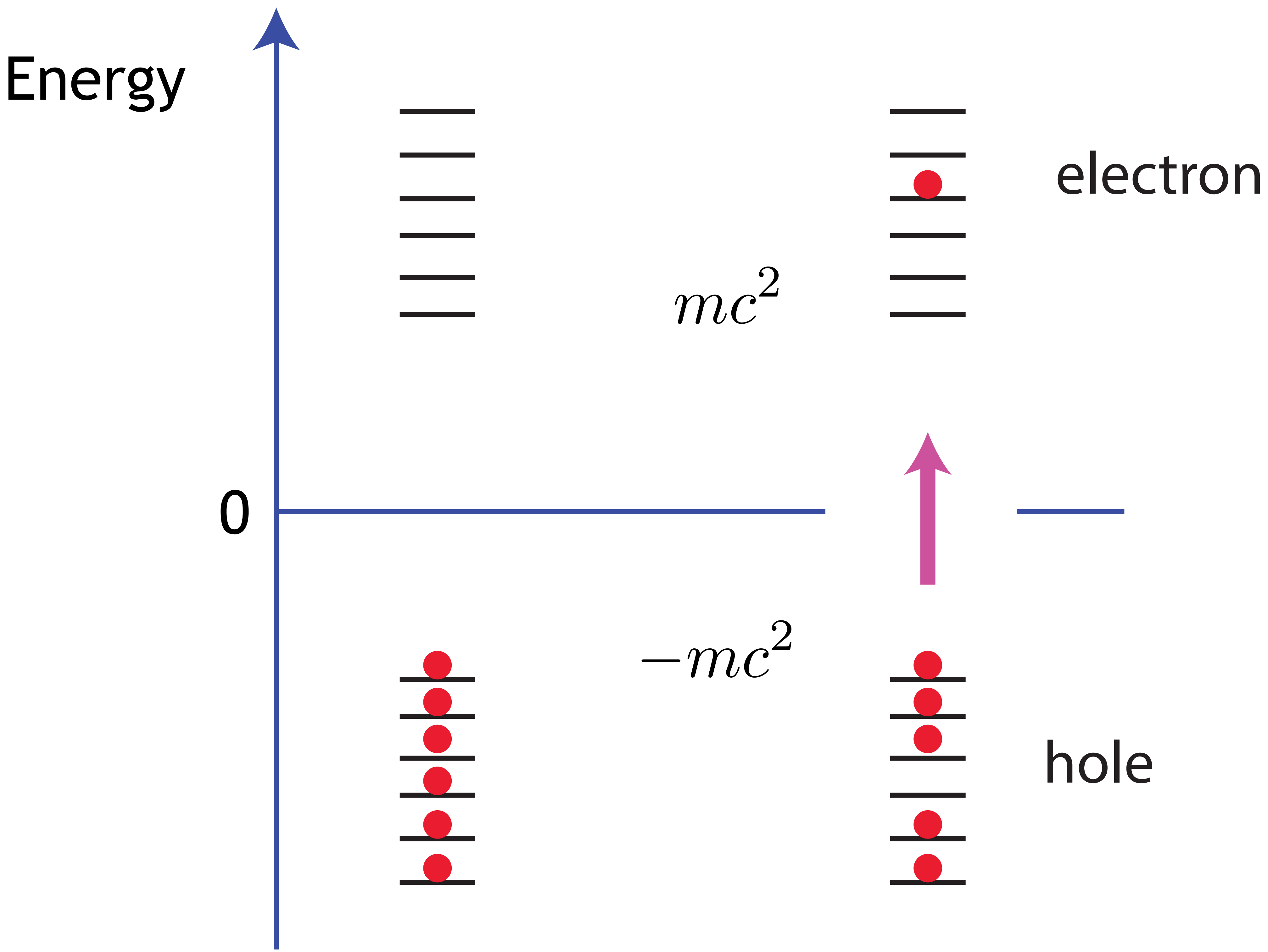
Introduce a Higgs scalar field, and couple top quarks to it. At this level, the top quark is massless.

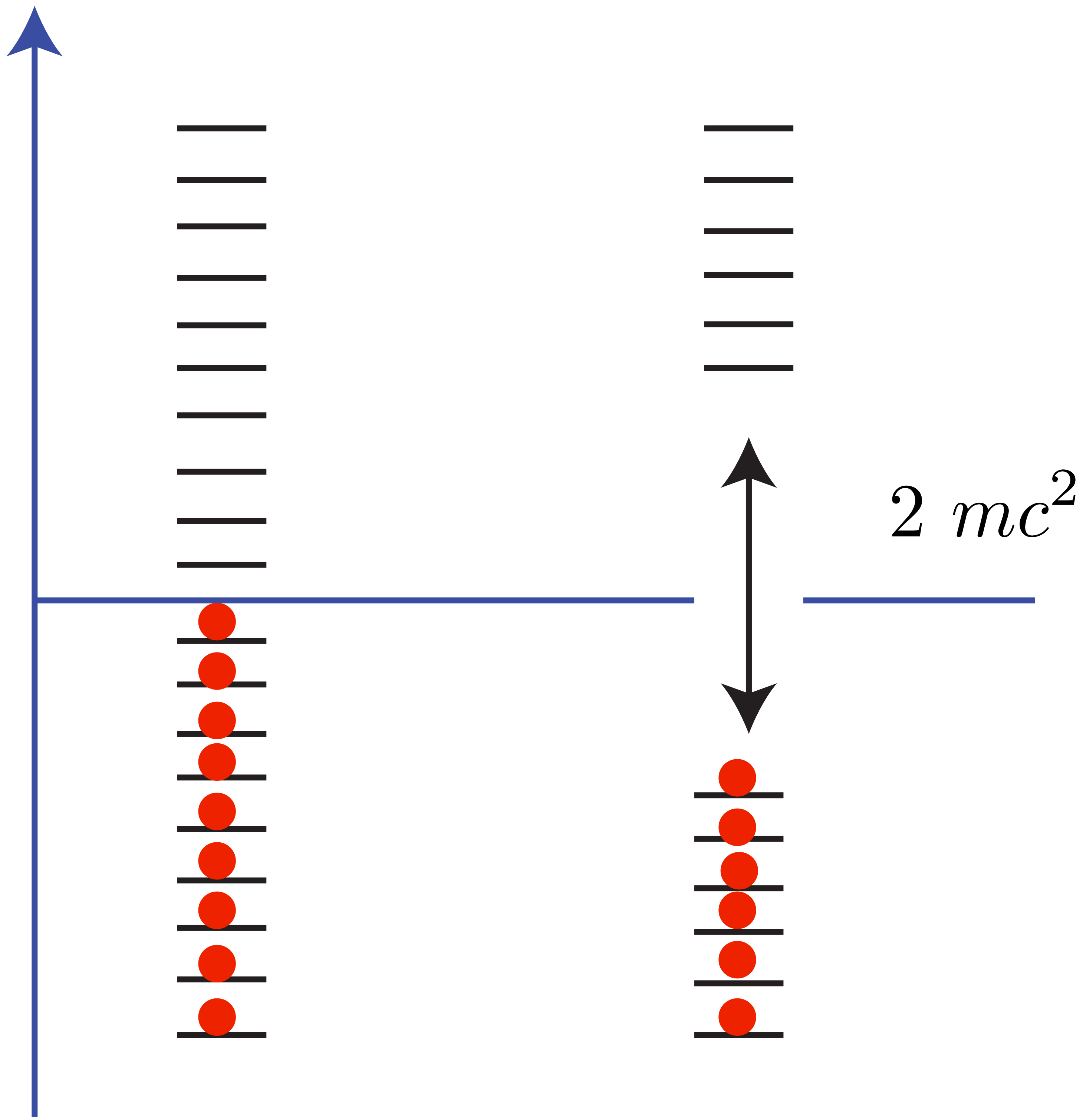
Give the Higgs field a potential energy that is neutral between

$$\langle \varphi \rangle = 0 \quad \text{and} \quad \langle \varphi \rangle \neq 0$$

Then, I claim, there is an effect that drives the Higgs field to nonzero values.

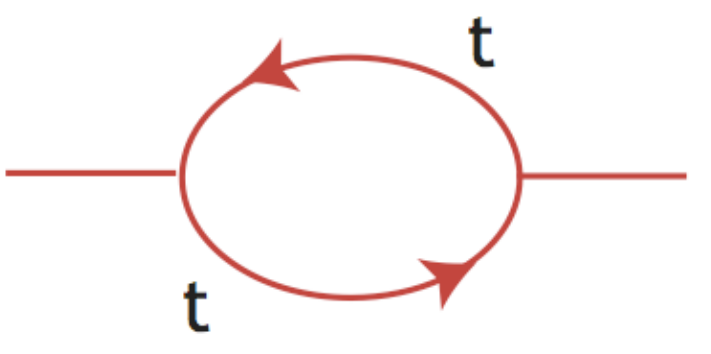
This comes from the physics of the Dirac sea.




$2\ mc^2$

The problem is that the formation of a mass gap does not stabilize at a fixed value. As we make the gap larger, the energy continues to decreases indefinitely. This is an instability of the vacuum

We have seen this problem already. It is the negative infinity of the diagram:



So, to make sense of this calculation, we need a framework in which the Higgs field is not a simple scalar field but, rather, has more structure. Here are some of the solutions proposed:

1.

The Higgs field is a bound state of fermions, like the scalar field of the Landau-Ginzburg theory. This solution is called "technicolor".

This approach necessarily leads to a large mass for the scalar bound state. The discovery of the Higgs boson as a resonance at 125 GeV - which is a small value on the relevant scale - eliminates this class of models.

2.

The Higgs field is a scalar field, but a symmetry forbids it from acquiring mass. When the symmetry is broken, the mass correction can be finite.

The most successful theory along this line is called "supersymmetry". In this theory, there is a new scalar particle that is the partner of each quark and lepton. In particular, there is a scalar top quark that balances the vacuum energy of the massive top quark.

It can be shown that radiative corrections involving the scalar top quark mass term produce a finite negative correction to μ^2.

3.

The Higgs field can be composite, but not an ordinary bound state. Instead, it is a Goldstone boson resulting from spontaneous breaking of a new symmetry at very short distances. A Goldstone boson naturally has zero mass.

However, if the symmetry was not perfect, a small correction can give a mass to the Goldstone boson. Typically, corrections due to the top quark and its heavy partners (which necessarily appear in the theory) give negative corrections to μ^2.

The most obvious way to search for clues to the mechanism of weak interaction symmetry breaking is to search for new particles at high energy.

This search is now pursued intensely at the CERN Large Hadron Collider.

These searches involve fascinating strategies, but that is the subject of another colloquium. In any case, the LHC has not discovered any new particles of these types yet.

Another way is to look in more detail at the properties of the Higgs boson. Surely, there, we can find clues to its origin.

It would seem that is should not be difficult to determine whether the Higgs sector contains one field or many, elementary or composite.

However, there is a barrier:

the “Decoupling Theorem” of Howard Haber

If the Higgs sector contains one light boson of mass

$$m_h = 125 \text{ GeV}$$

and many heavy particles with minimum mass M,

the light boson has properties that agree with the SM predictions up to corrections of order

$$m_h^2 \,/\, M^2$$

Proof:

Integrate out the heavy fields. The result is the SM. But, in the SM, the couplings of the Higgs boson are fixed. The corrections to this picture come from dimension 6 quantum field theory operators.

Implication:

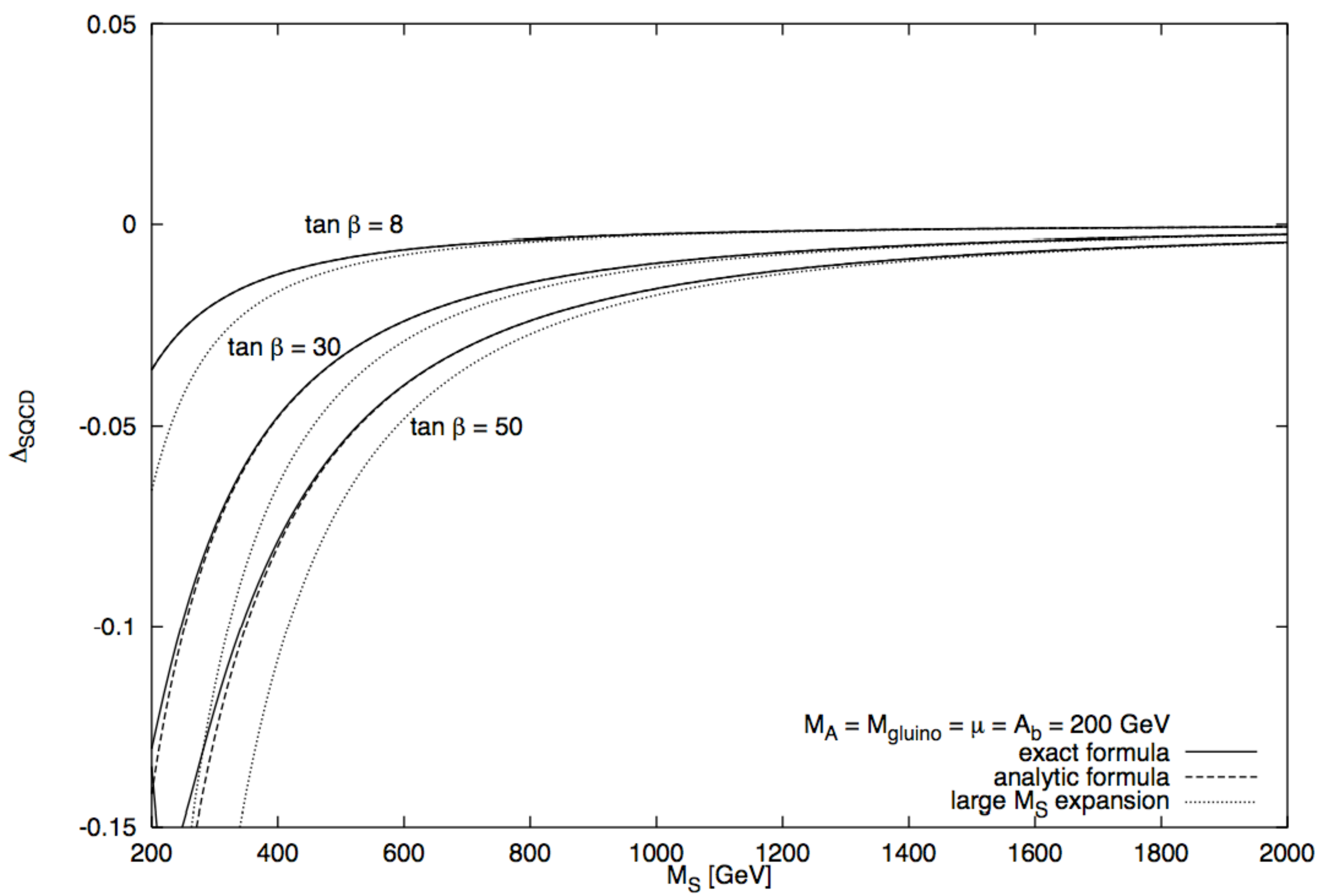
In most models of an extended Higgs sector or other new particles, the corrections to the Higgs couplings are at the few-% level. Precision measurement is needed to see these corrections.

However:

The pattern of corrections is different in different schemes for new physics models. There is much to learn if we can see this pattern.

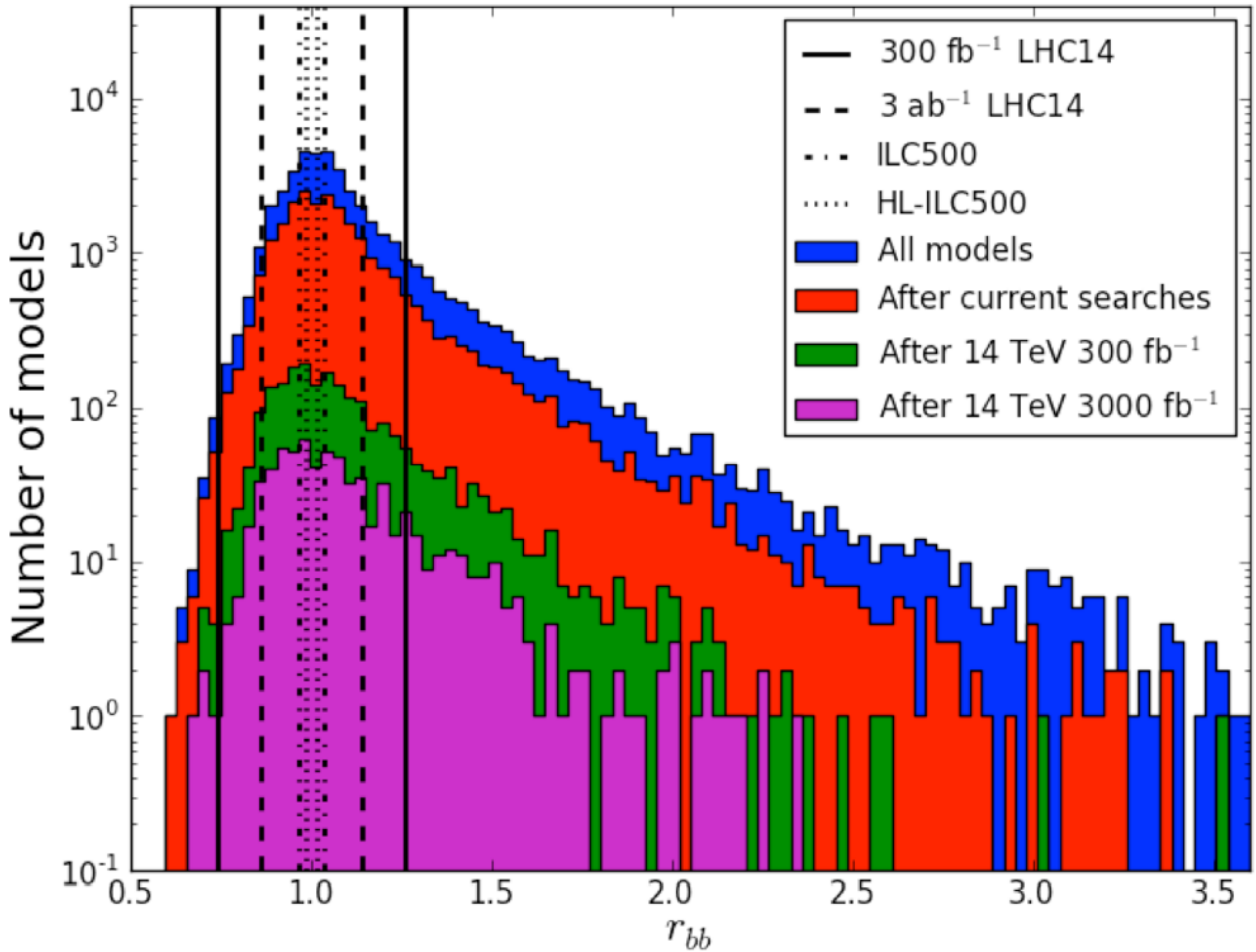
Here are some examples of corrections to the Higgs couplings that appear in specific models of the Higgs potential or Higgs sector:

Supersymmetry is a model with multiple Higgs bosons, plus quantum corrections from top and bottom scalar quarks. Some effects here are sensitive to scalar quarks of extremely high mass.



Haber, Herrero, Logan, Penaranda, Rigolin, Temes

$\Gamma(h \to b\bar{b})$



Cahill-Rowley, Hewett, Ismail, Rizzo

The coupling of the Higgs boson to vector bosons is similarly simple in the SM:

$$g(hVV) = \frac{2m_V^2}{v}$$

Corrections from models with an extended Higgs sector are usually small, since it is the lightest Higgs that has the largest vacuum expectation value.   In SUSY,

$$g(hVV) = 1 + \mathcal{O}(\frac{m_Z^4}{m_A^4})$$

Still, the hWW and hZZ coupling can obtain corrections from a number of sources outside the SM.

Mixing of the Higgs with a singlet gives corrections

$$g(hVV) \sim \cos\phi \sim (1 - \phi^2/2)$$

These might be most visible in the hVV couplings. Similarly, field strength renormalization of the Higgs can give 1% level corrections (Craig and McCullough).

If the Higgs is a composite Goldstone boson of new strong interactions at 10 TeV, these couplings are corrected by (f ~ 1 TeV)

$$g(hVV) = (1 - v^2/f^2)^{1/2} \approx 1 - v^2/2f^2 \approx 1 - 3\%$$

Then, for example, a new heavy T quark contributes

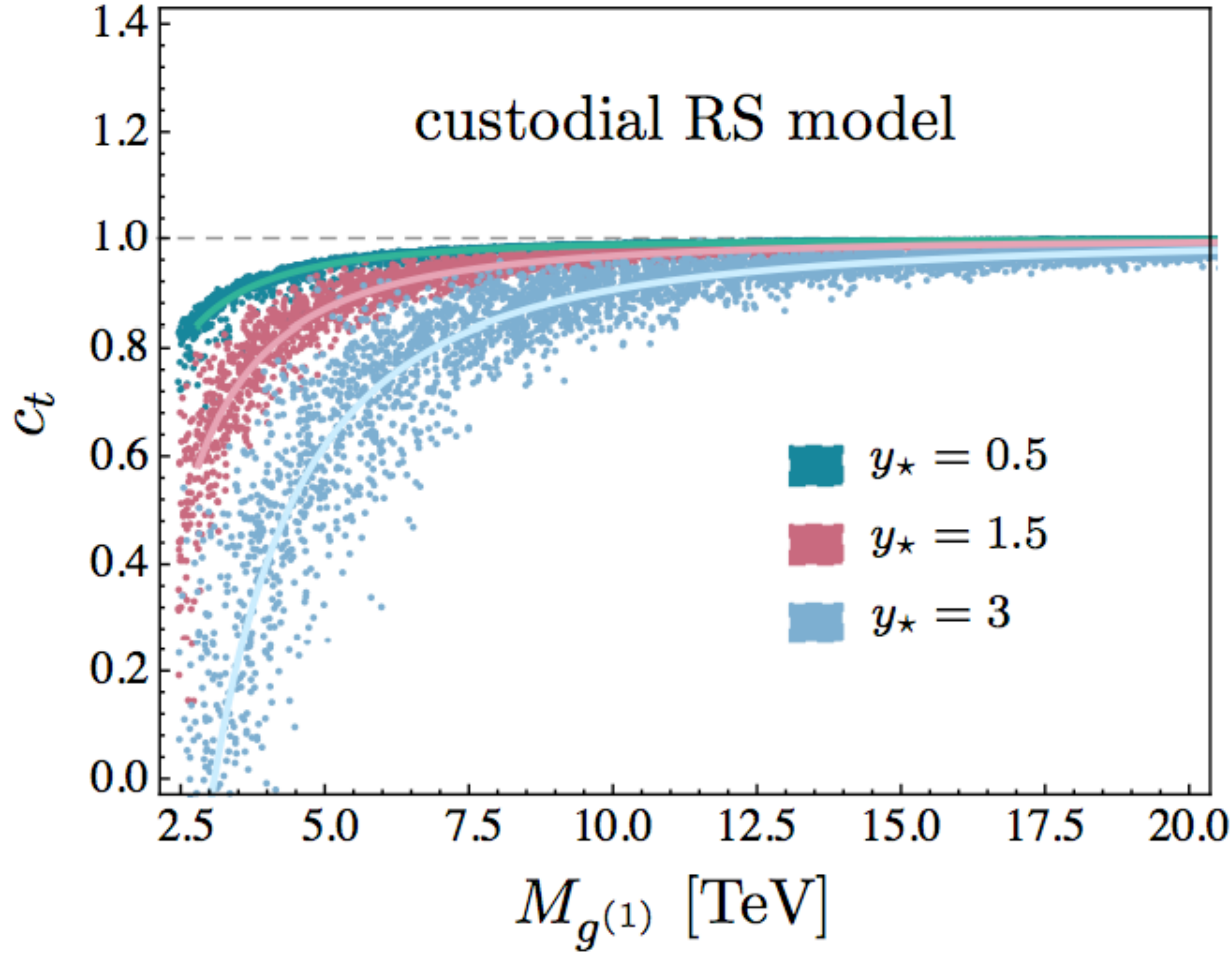
$$g(hgg)/SM = 1 + 2.9\% \left(\frac{1 \text{ TeV}}{m_T}\right)^2$$

$$g(h\gamma\gamma)/SM = 1 - 0.8\% \left(\frac{1 \text{ TeV}}{m_T}\right)^2$$

A complete model will have several new heavy states, and mixing of these with the SM top quark. For example, for the “Littlest Higgs” model

$$g(hgg)/SM = 1 - (5 - 9\%)$$

$$g(h\gamma\gamma)/SM = 1 - (5 - 6\%)$$



Malm, Neubert, Schmell

The study of the deviations from these predictions is guided by the idea that each Higgs coupling has its own personality and is guided by different types of new physics.   This is something of a caricature, but, still, it s is a useful one.

fermion couplings -   multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

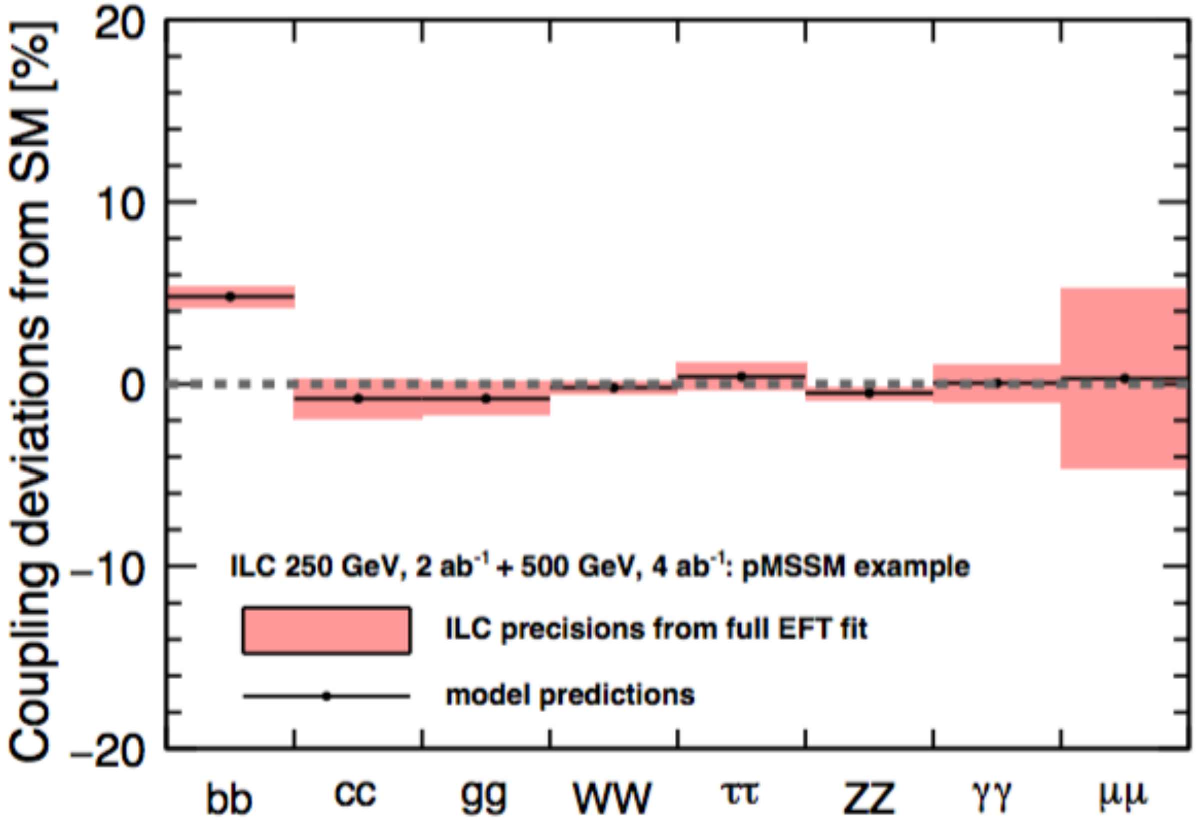
$\gamma\gamma$, gg couplings - heavy top quark partners

tt coupling -   top quark compositeness

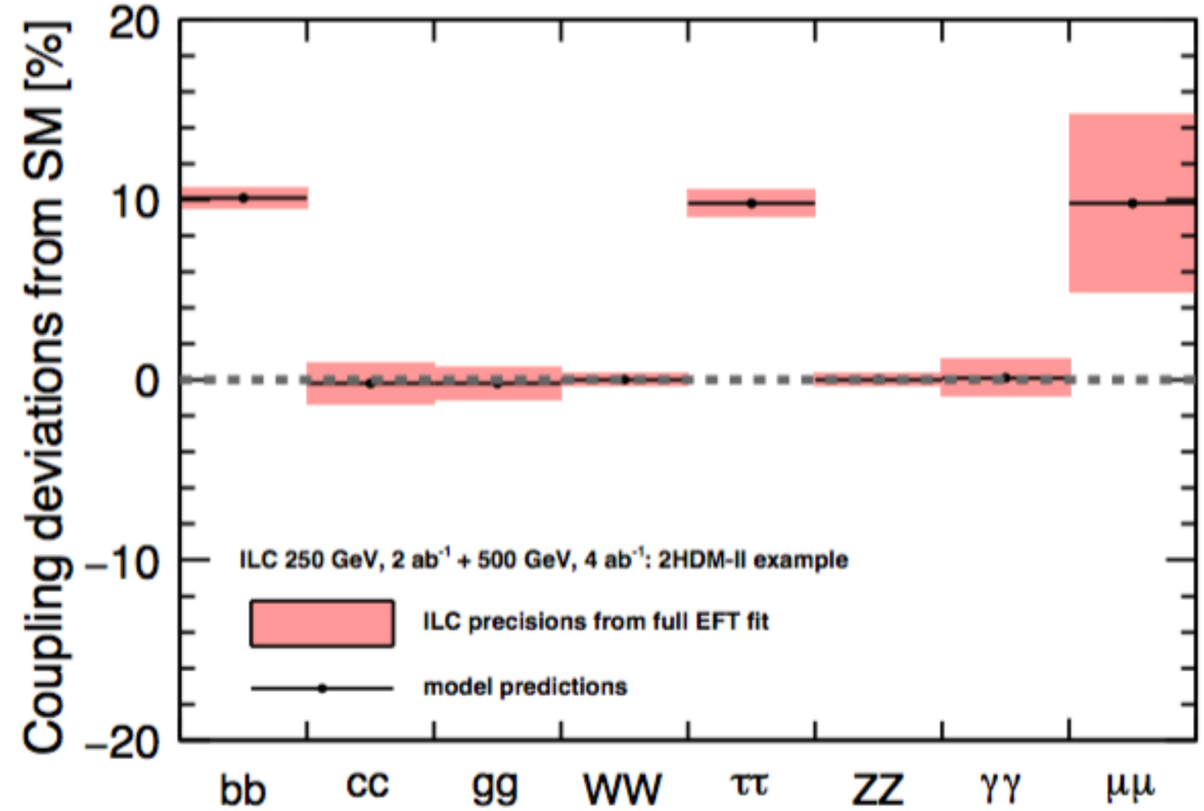
hhh coupling (large deviations) - baryogenesis

From this survey of effects, we see that different models of new particles lead to different patterns of shifts of the Higgs boson couplings:

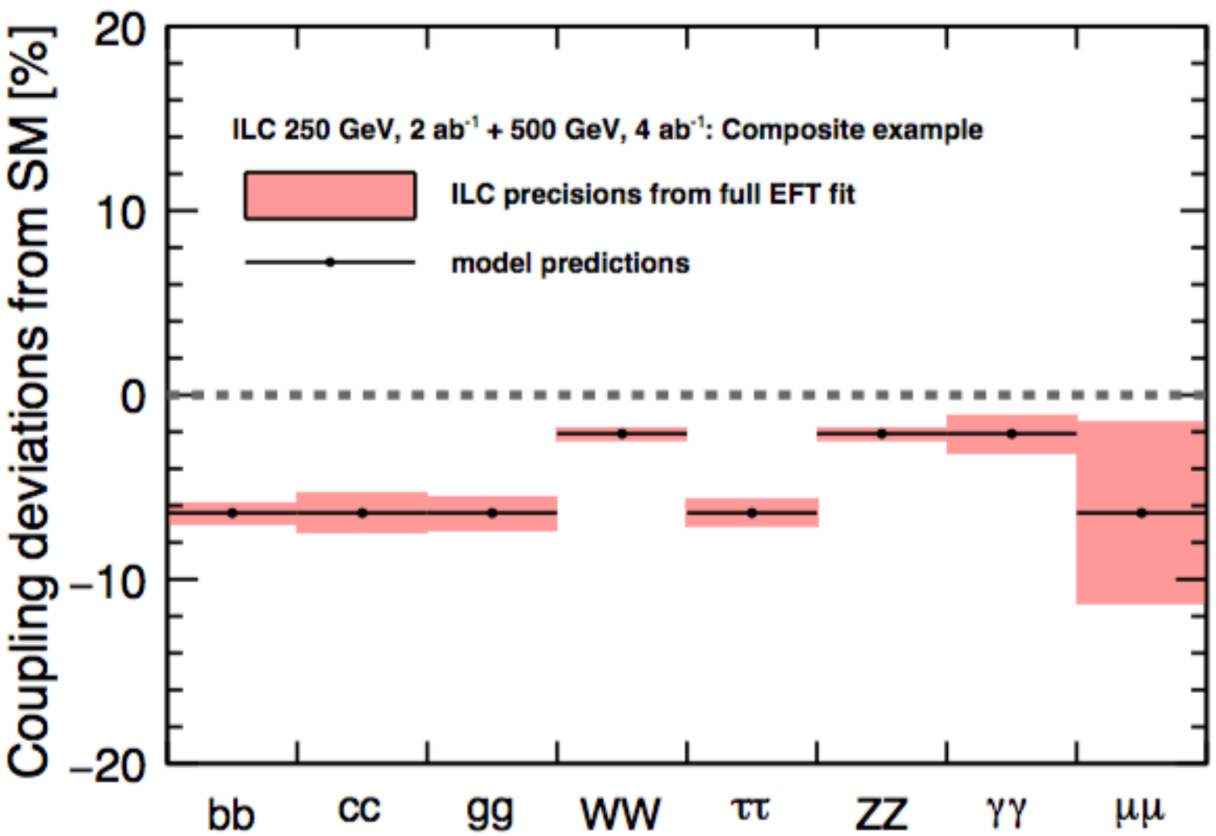
heavy SUSY



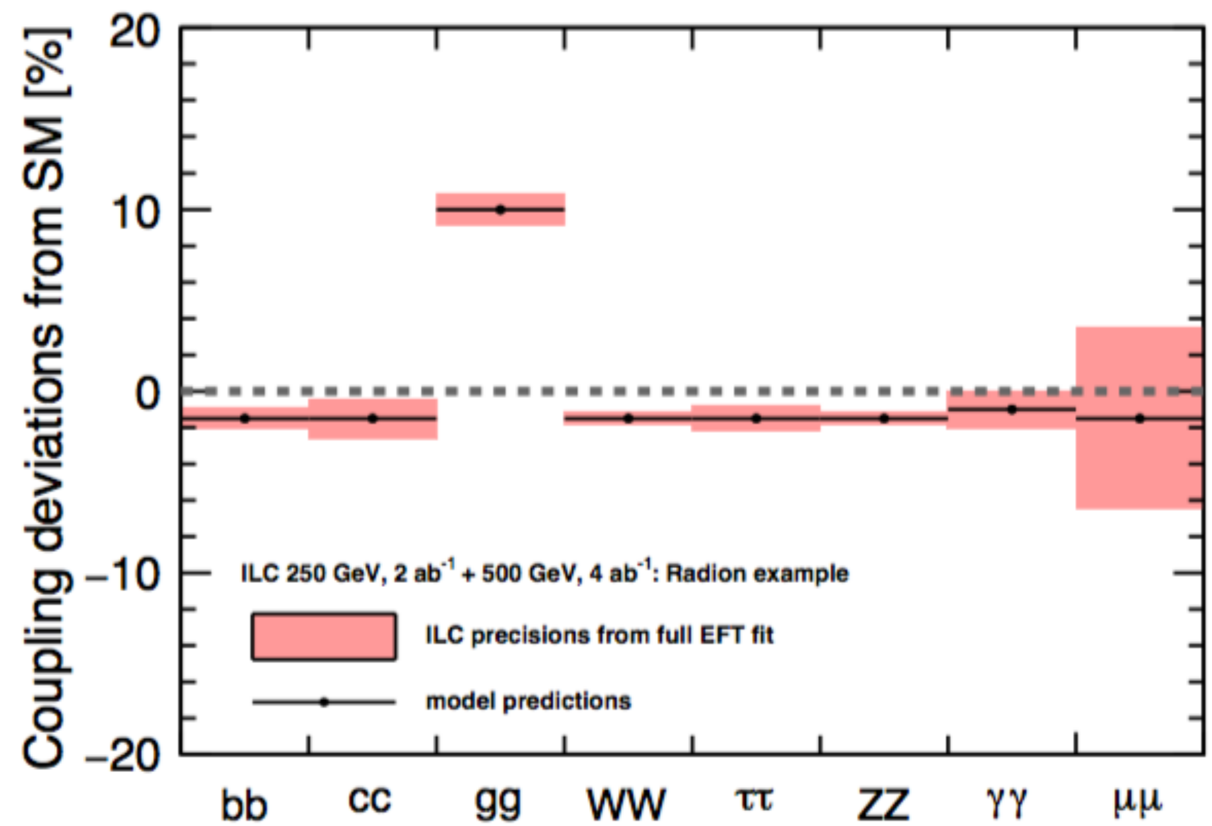
2 Higgs doublet



Composite Higgs



Higgs-Radion mixing



These ideas give strong motivation for a program of precision measurements of the Higgs boson couplings.

The goal should be to measure the individual partial widths to an accuracy of 1%, and better if possible.

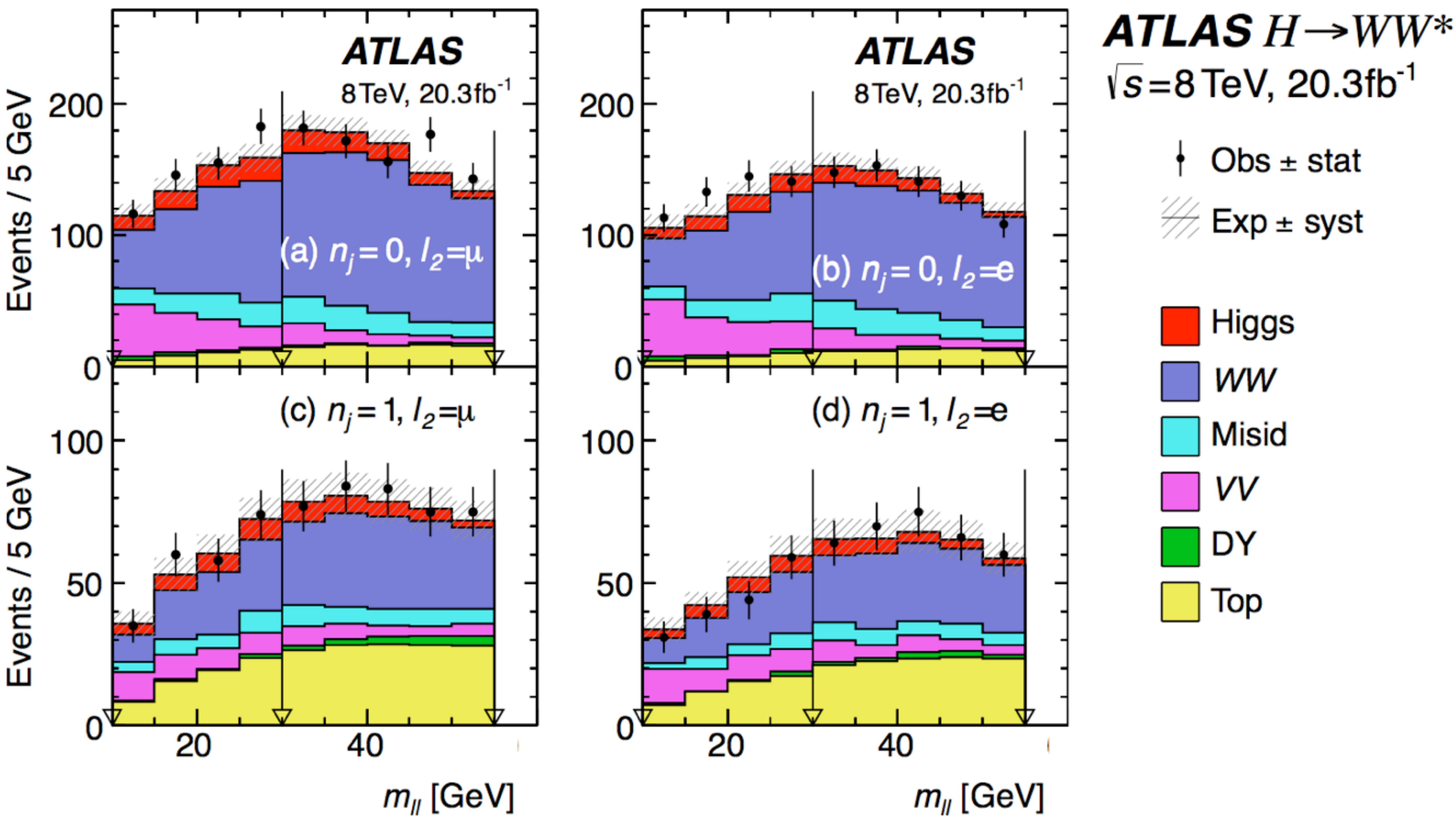
This requires a comprehensive program of measurements of Higgs production and decay processes.

It would be best if the experiments were also highly sensitive to invisible and exotic Higgs decays, which might contribute to Γ_h and also signal new physics in their own right.

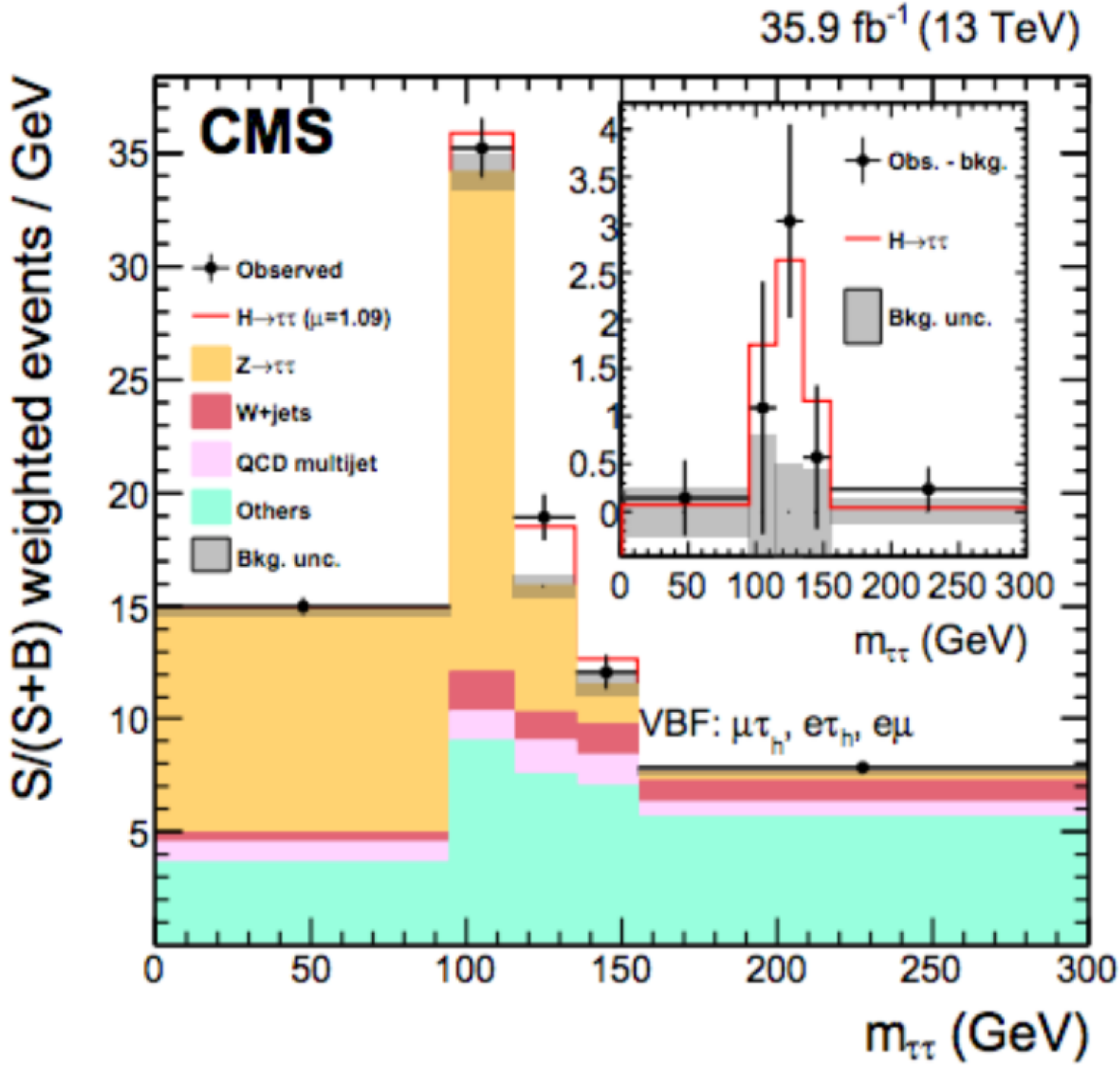
We will learn much about the Higgs boson from its study at the LHC over the next 20 years.

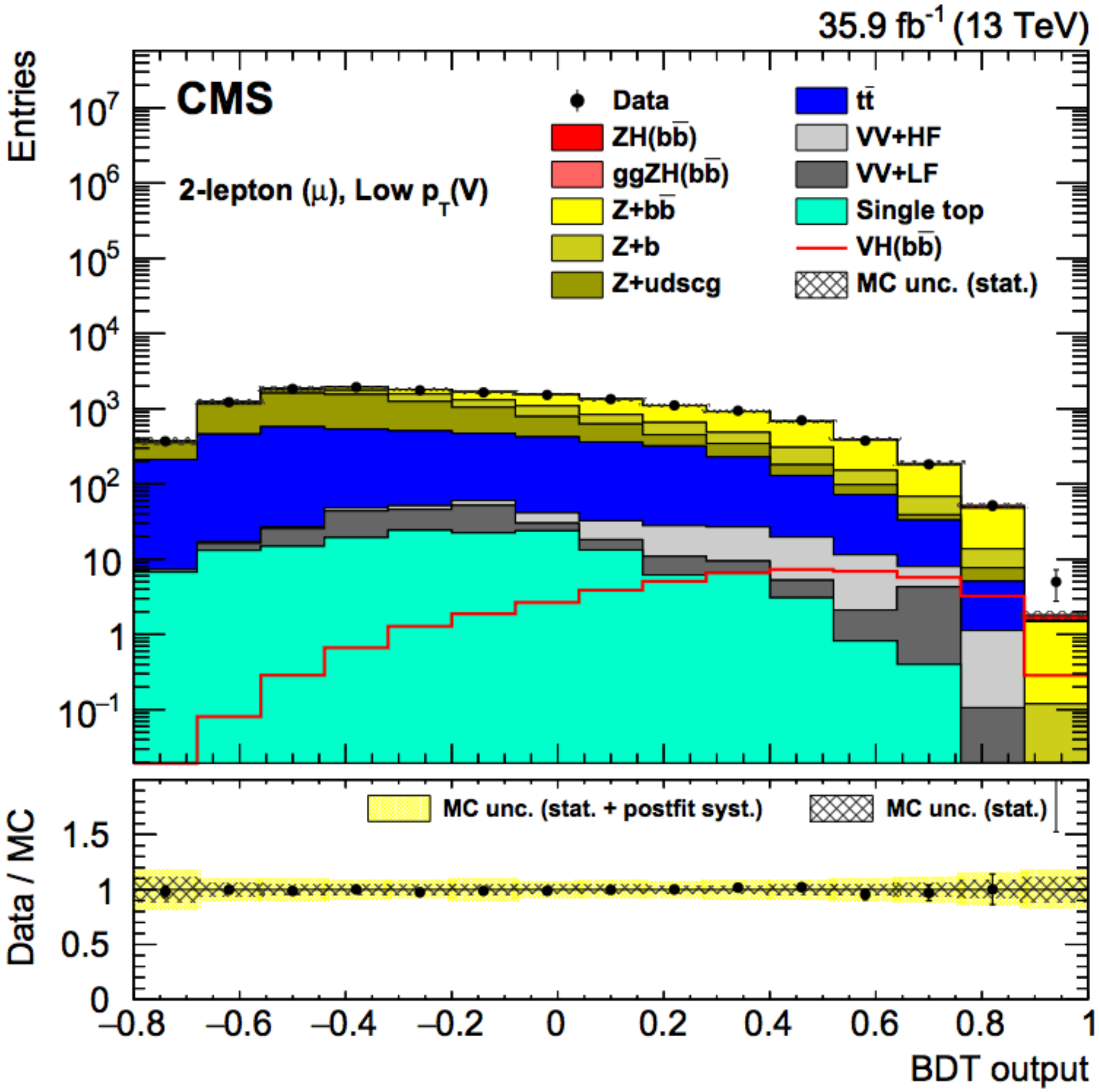
However, the LHC cannot fulfill the goals of the program I have outlined.

The most important reasons for this are made clear by looking at the current evidence for the Higgs boson in its various decay channels.

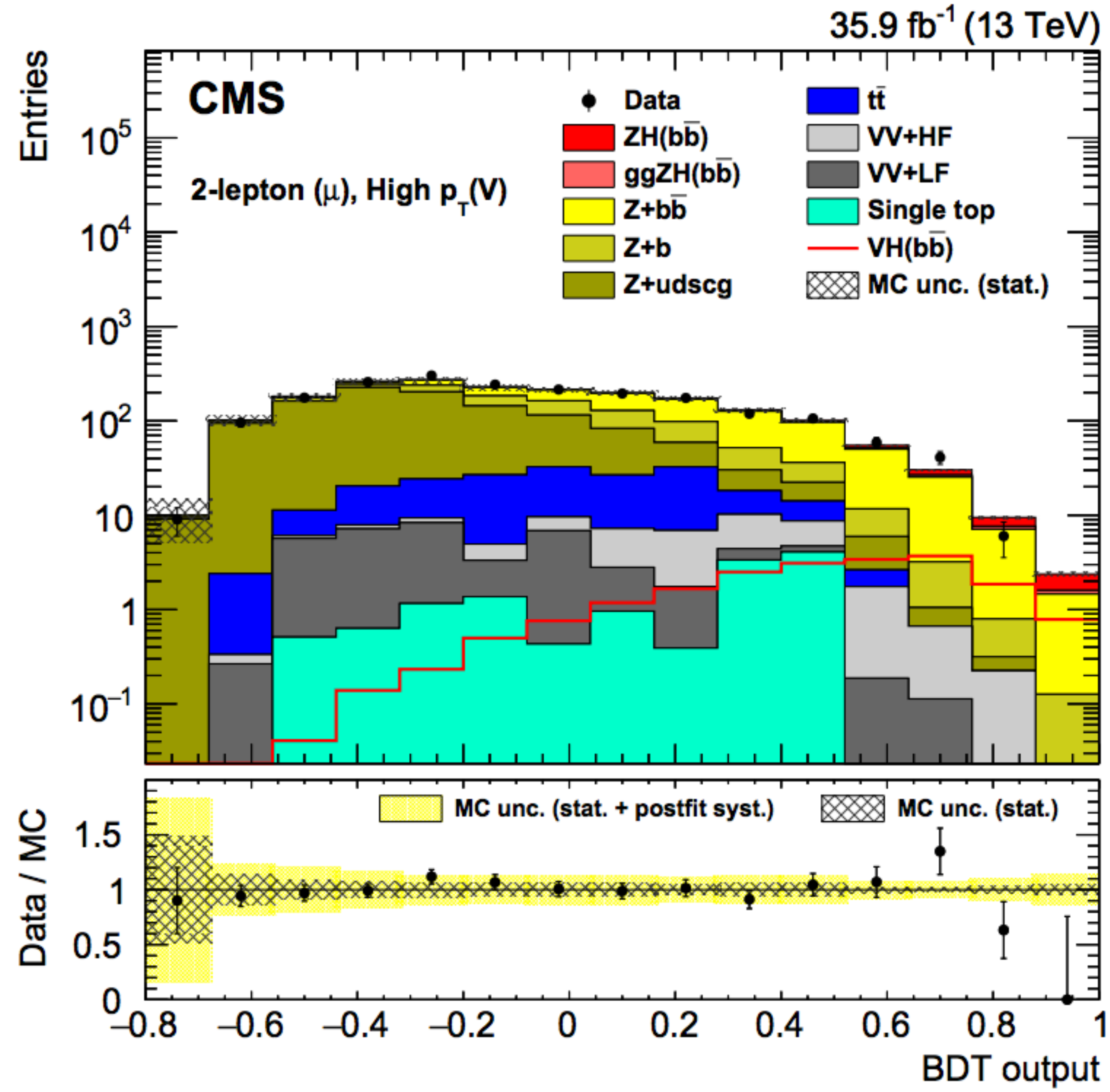


ATLAS
8 TeV, 20.3 fb-1
(a) nj = 0, l2=μ
(b) nj = 0, l2=e
(c) nj = 1, l2=μ
(d) nj = 1, l2=e
Events / 5 GeV
mll [GeV]
ATLAS H→WW*
√s=8 TeV, 20.3fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top


35.9 fb^{-1} (13 TeV)
CMS
Observed
H→ττ (μ=1.09)
Z→ττ
W+jets
QCD multijet
Others
Bkg. unc.
VBF: $\mu\tau_h$, $e\tau_h$, $e\mu$
S/(S+B) weighted events / GeV
$m_{\tau\tau}$ (GeV)
Obs. - bkg.
H→ττ
Bkg. unc.
$m_{\tau\tau}$ (GeV)



low pT

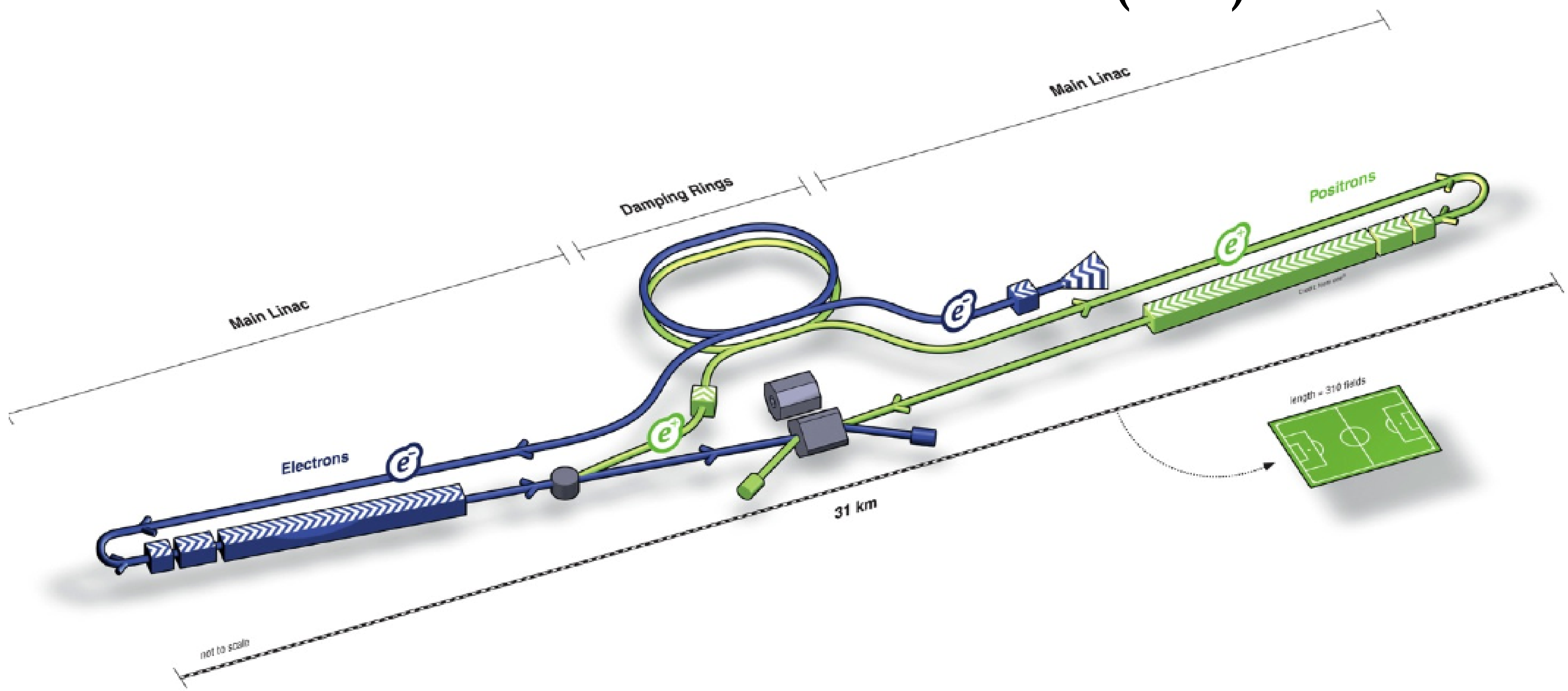


high pT

CMS boosted decision tree

There is a proposed accelerator capable of meeting the goals of a precision Higgs measurement program. It is studied thoroughly, designed at the level its Technical Design Report, and ready for construction.

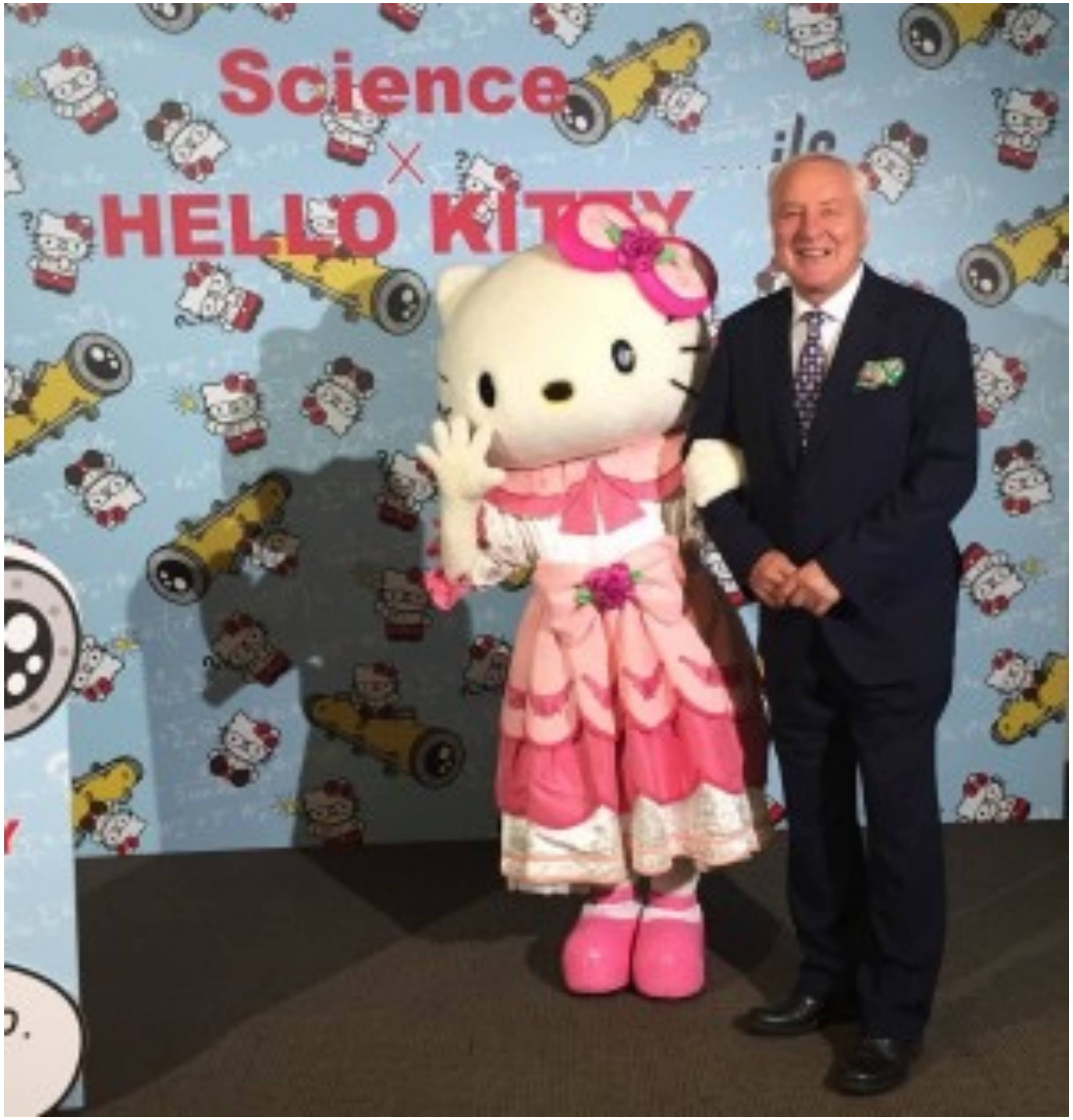
This is the International Linear Collider (ILC).



Kitakami Mountain Range

photo: Richard Ruiz

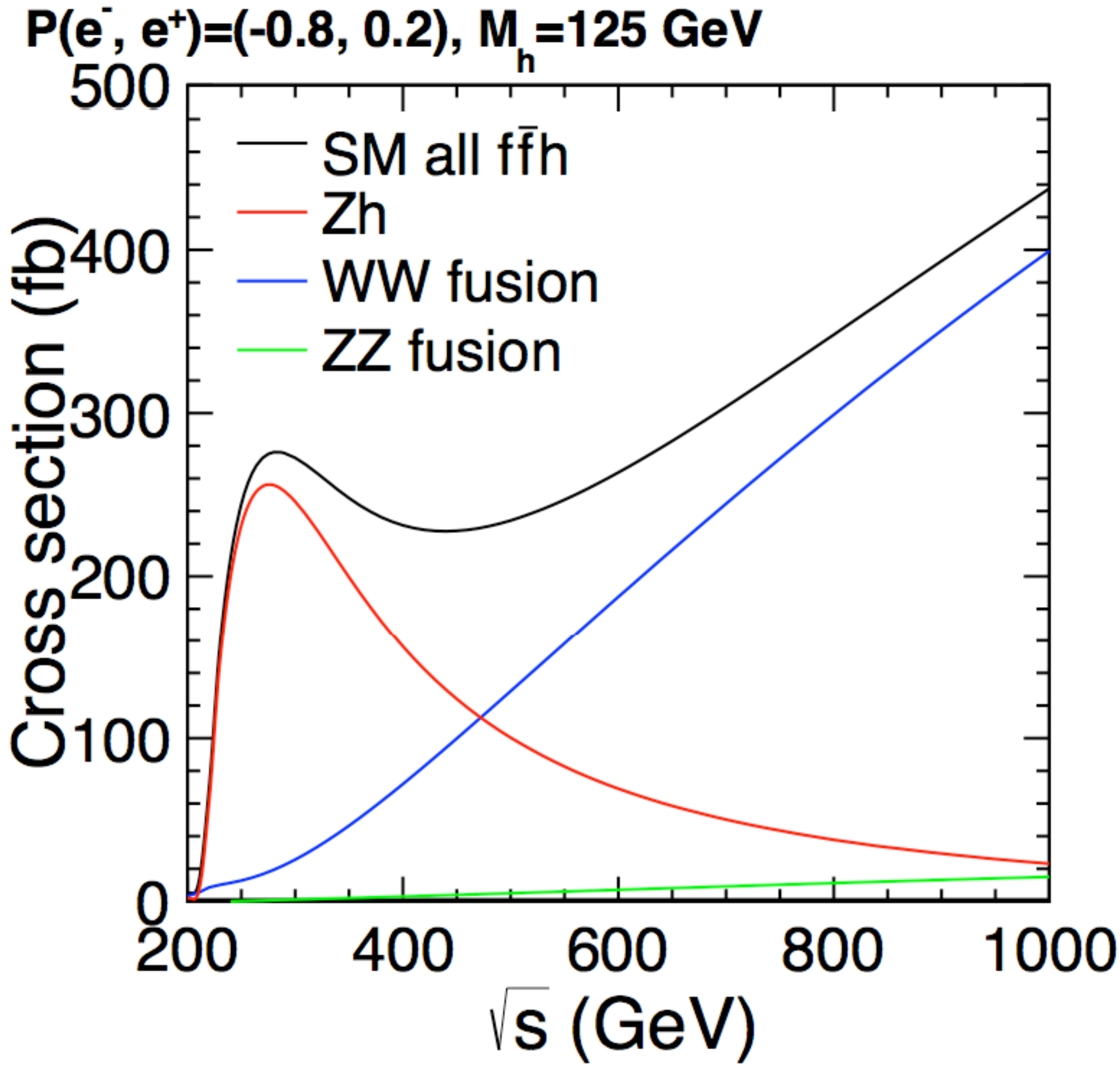
meeting of Lyn Evans and Prime Minister Abe, March 2013
L to R: Murayama, Koshiba, Evans, Abe, Kanemura



ILC partnership with Hello Kitty

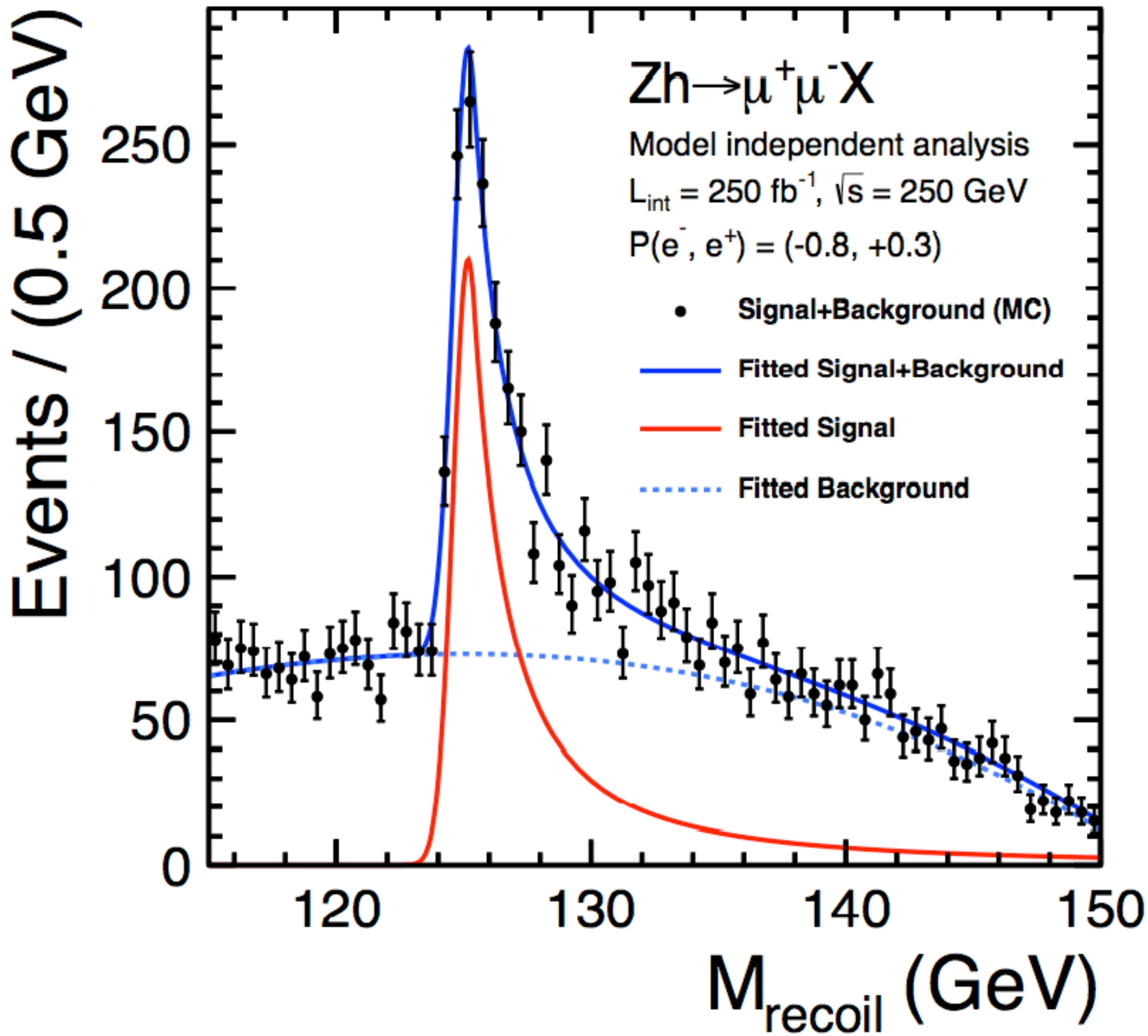
Somewhere on the road to Morioka:

Here are a few snapshots from the physics expectations for the ILC.



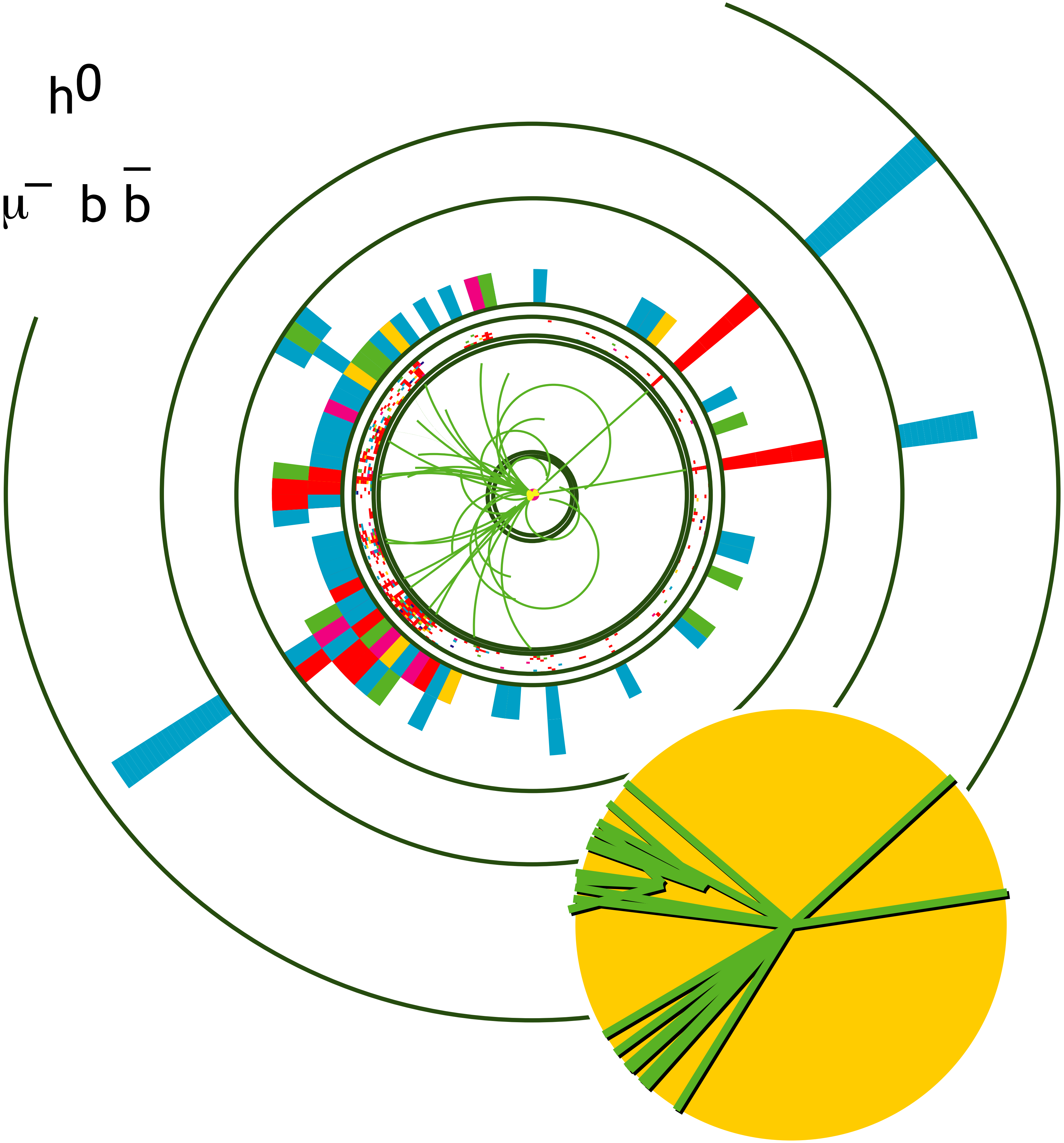
P(e-, e+)=(-0.8, 0.2), M_h=125 GeV
SM all ff̄h
Zh
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
√s (GeV)

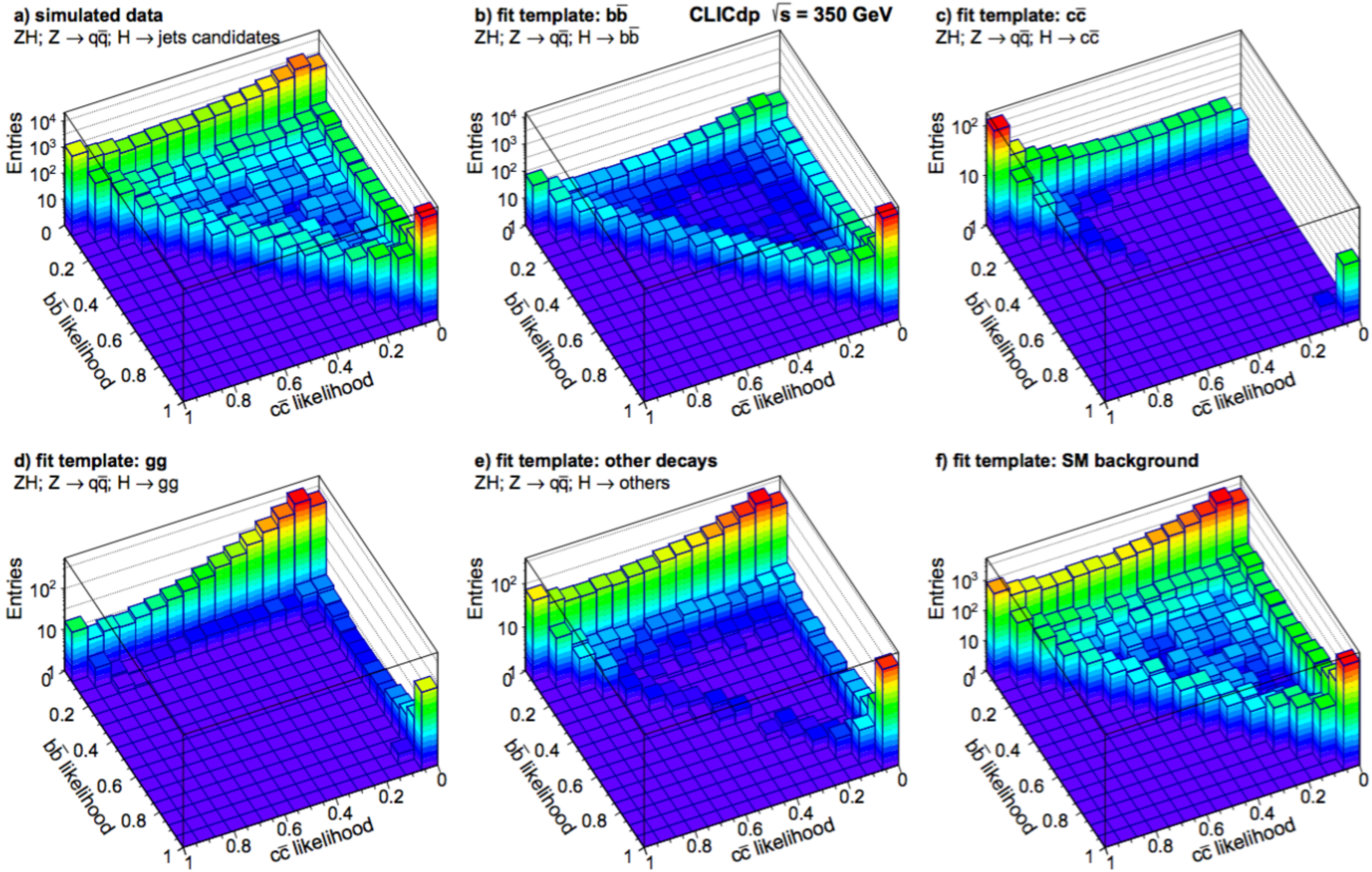
m_h to 15 MeV using a recoil technique



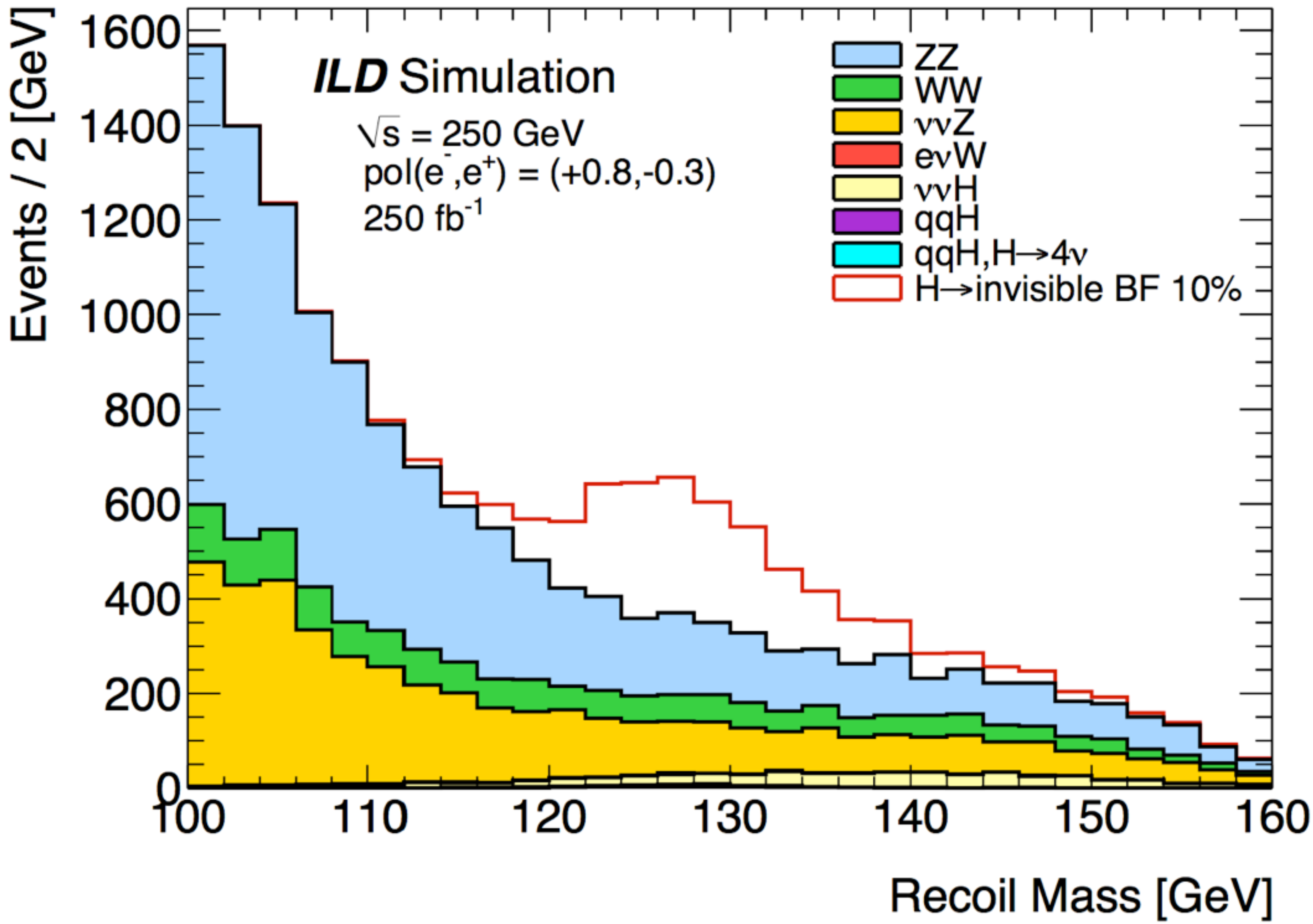
$e^+e^- \to Z^0 \quad h^0$

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

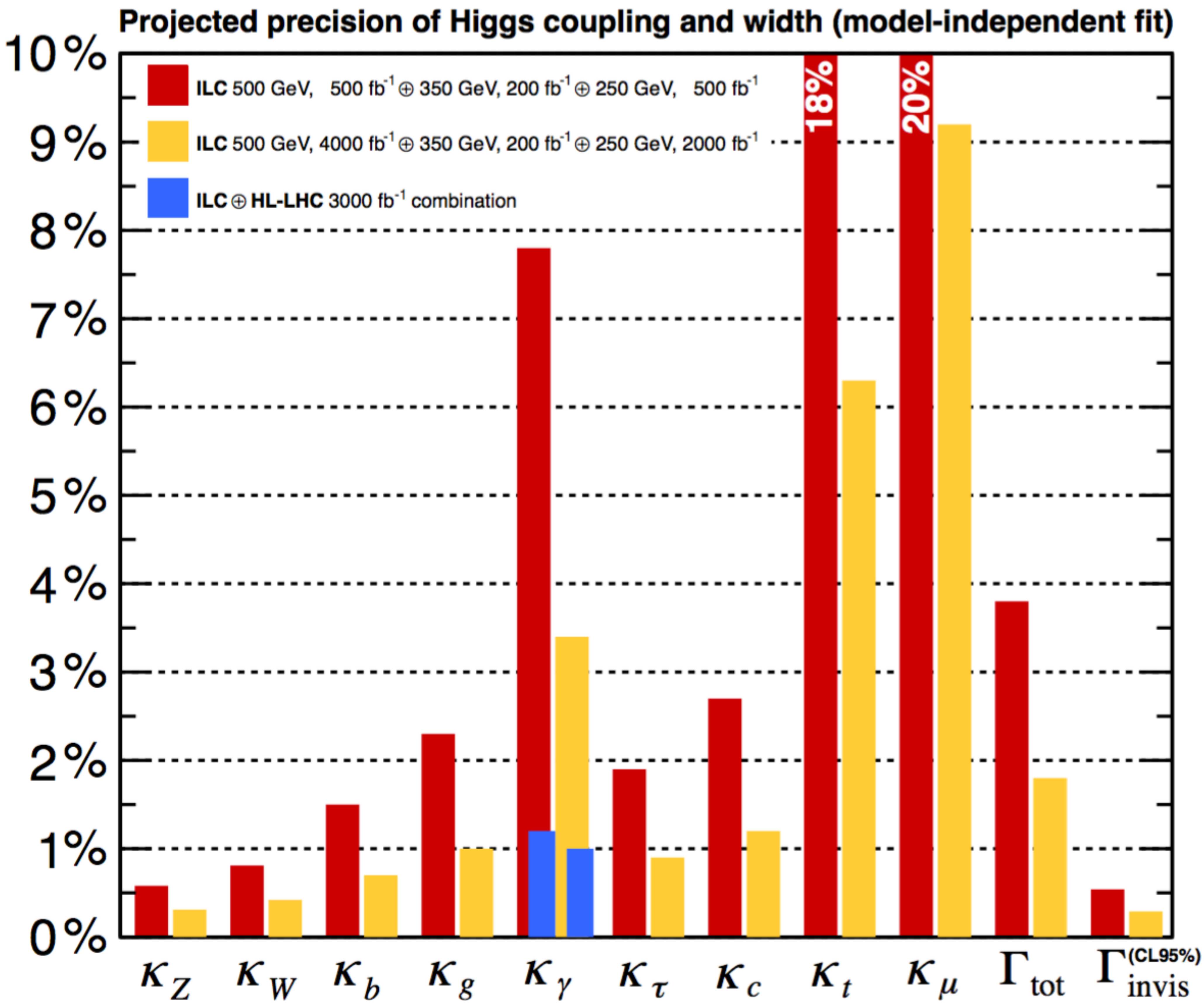




2016 CLIC study



ILD Simulation
$\sqrt{s}$ = 250 GeV
pol(e$^-$,e$^+$) = (+0.8,-0.3)
250 fb^{-1}
ZZ
WW
ννZ
eνW
ννH
qqH
qqH,H→4ν
H→invisible BF 10%
Events / 2 [GeV]
Recoil Mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
100
110
120
130
140
150
160



Projected precision of Higgs coupling and width (model-independent fit)
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
ILC 500 GeV, 500 fb^{-1} ⊕ 350 GeV, 200 fb^{-1} ⊕ 250 GeV, 500 fb^{-1}
ILC 500 GeV, 4000 fb^{-1} ⊕ 350 GeV, 200 fb^{-1} ⊕ 250 GeV, 2000 fb^{-1}
ILC ⊕ HL-LHC 3000 fb^{-1} combination
18%
20%
κ_Z
κ_W
κ_b
κ_g
κ_γ
κ_τ
κ_c
κ_t
κ_μ
Γ_{tot}
$\Gamma_{invis}^{(CL95\%)}$

The Higgs boson has many secrets that are still hidden.
But it is within our power to find them out.

The precision study of the Higgs boson will be one of the next great adventures in particle physics.