The Higgs Boson and Electroweak Symmetry Breaking

1. Minimal Standard Model

M. E. Peskin
Chiemsee School
September 2014

The Higgs boson has an odd position in the Standard Model of particle physics.

On one hand, it is required. The Standard Model cannot describe our world without spontaneous breaking of its symmetry. The Higgs field gives a simple description of that symmetry breaking.

On the other hand, it is mysterious. The Higgs field does not explain the required spontaneous symmetry breaking; it merely parametrizes it. To find explanations, we have to look deeper.

In these lectures, I will describe some aspects of the Higgs boson and the physics of electroweak symmetry breaking.

1. Properties of the Standard Model Higgs Boson

2. Decays of the Higgs Boson

3. Models of Electroweak Symmetry Breaking

The Standard Model is an odd mixture of apparently fundamental and more phenomenological ingredients.

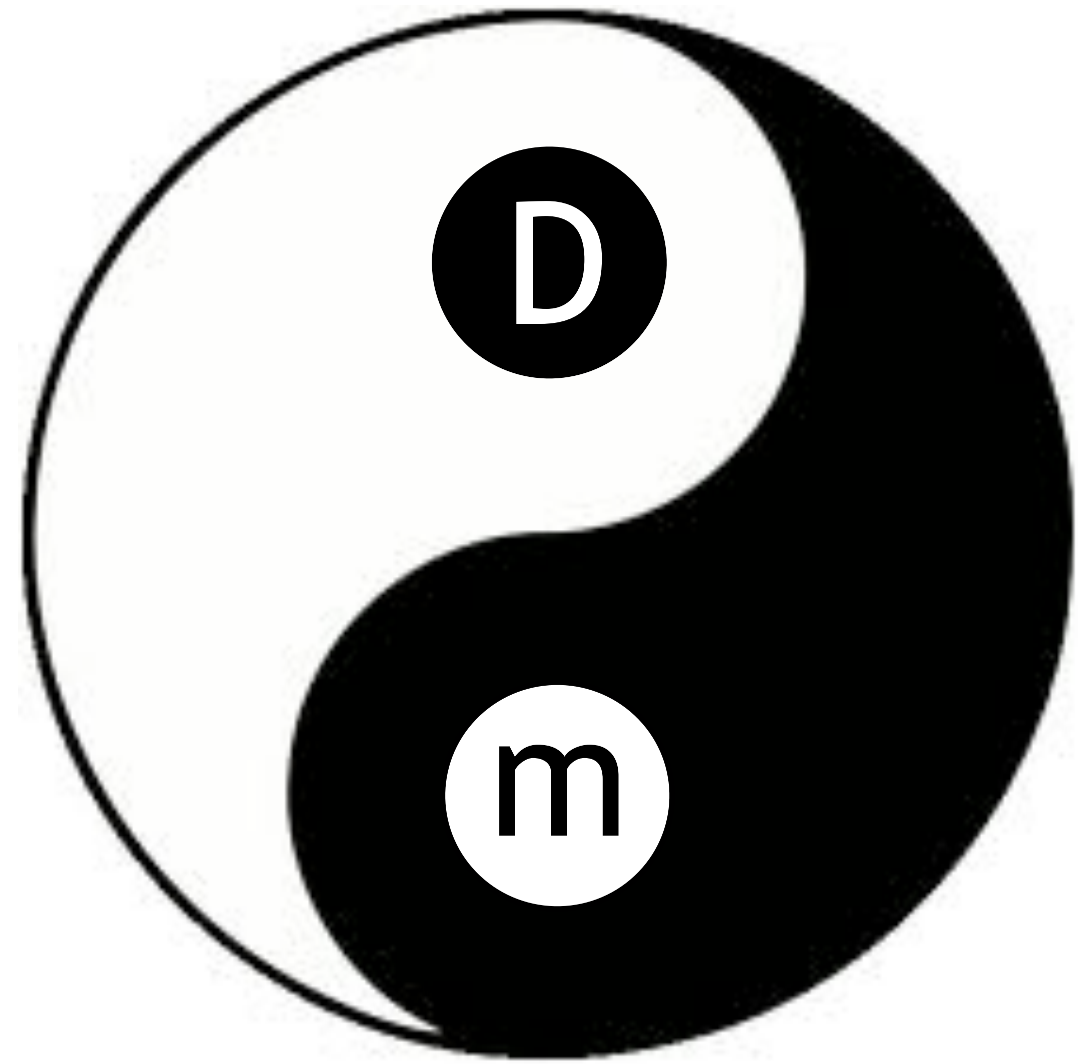
The Lagrangian is

$$\mathcal{L} = -\frac{1}{4}\sum_a (F^a_{\mu\nu})^2 + \overline{f}(i \not{D}) f$$
$$+|D_\mu \varphi|^2 - V(\varphi) - Y^{ij}\overline{f}_{iL} \cdot \varphi f_{jR} - h.c.$$

The first line is very simple. Its structure is entirely determined by gauge invariance. It contains 3 parameters - 1 parameter if you believe in grand unification.

The second line contains the terms associated with the Higgs field. All remaining parameters of the SM are buried here.

In a lecture at the 1981 Lepton-Photon Conference, Lev Okun described this structure with the symbol:



He also emphasized that the search for and study of the Higgs boson was "problem #1" in particle physics.

The Higgs boson is now discovered, but I would like to convince you that his statement is still true today.

It would be good if we could reformulate the Standard Model in such a way that all of the couplings could come from gauge principles. However, this is not possible.

Fermion masses come from mixing of more fundamental 2-component massless fermion states.

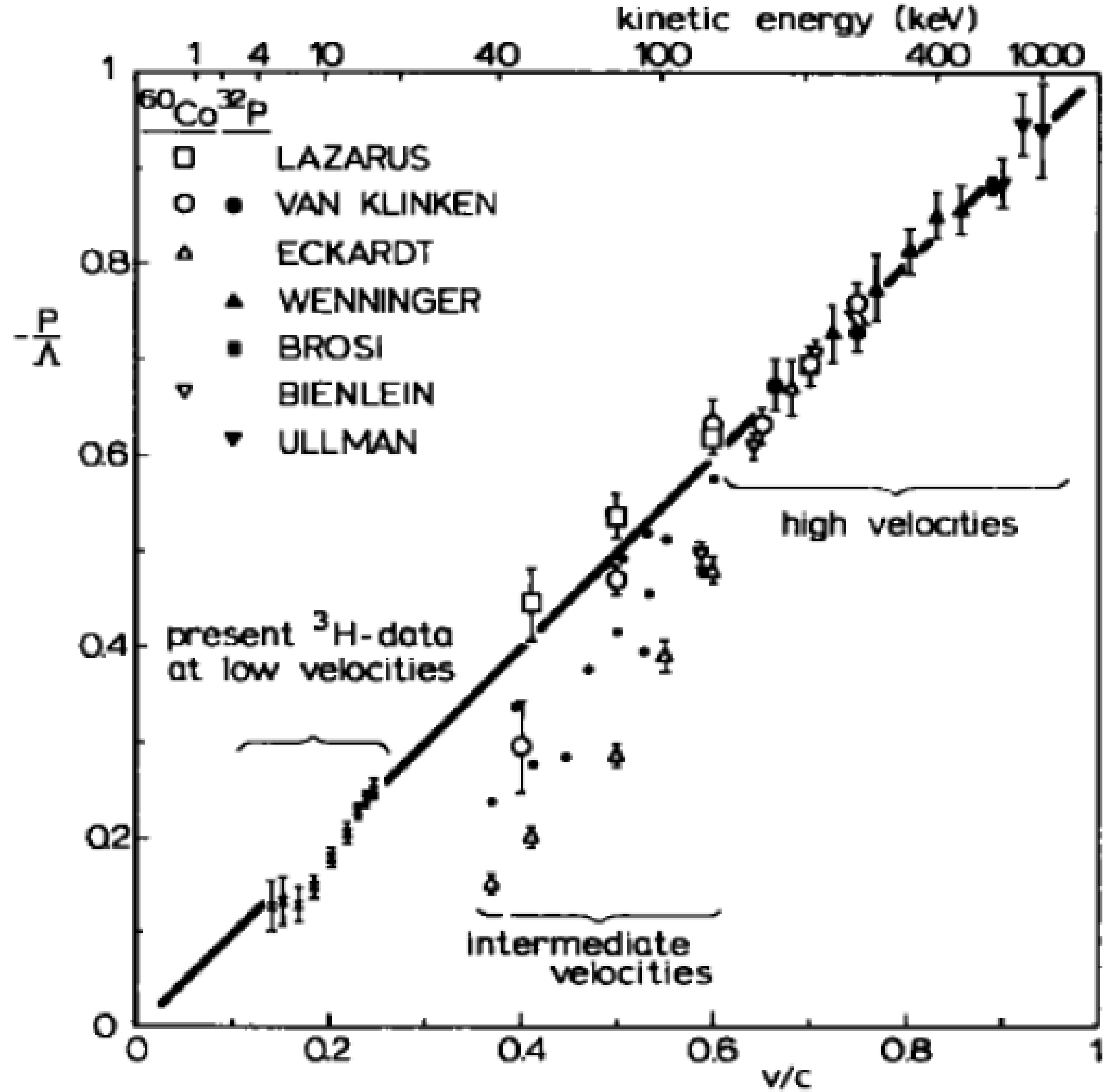
$$-m_{ij}\overline{f}_{iL}f_{jR}$$

If the fermion states that must mix have different quantum numbers under the gauge group, this coupling can only arise from spontaneous symmetry breaking.

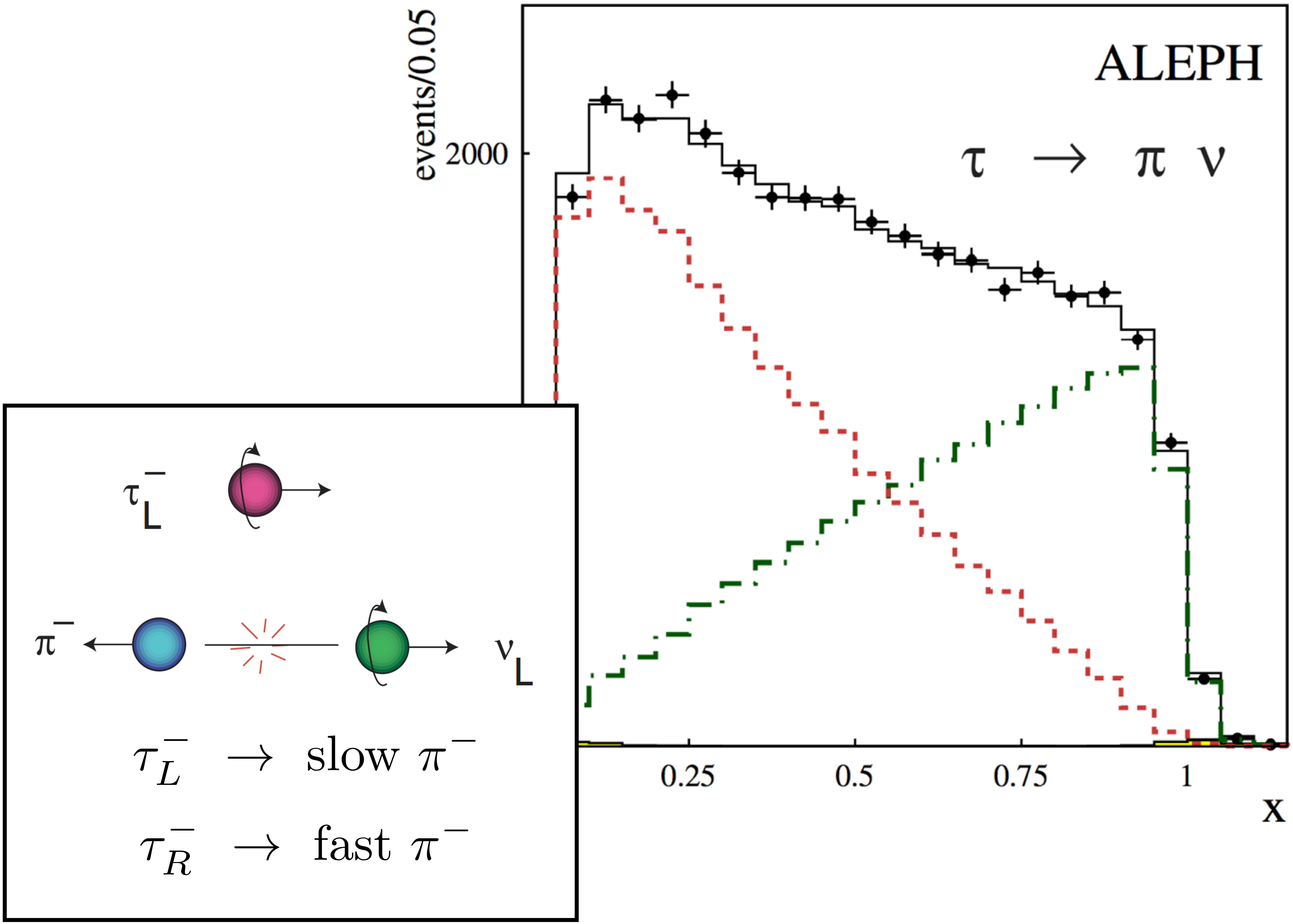
Gauge boson masses can only arise from spontaneous symmetry breaking.

In principle, the gauge group of nature could just allow masses for the quarks and leptons. However, that is not the universe we live in. The SU(2)xU(1) group has different quantum numbers for the left- and right-handed quark and leptons that must mix to give fermion masses.

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

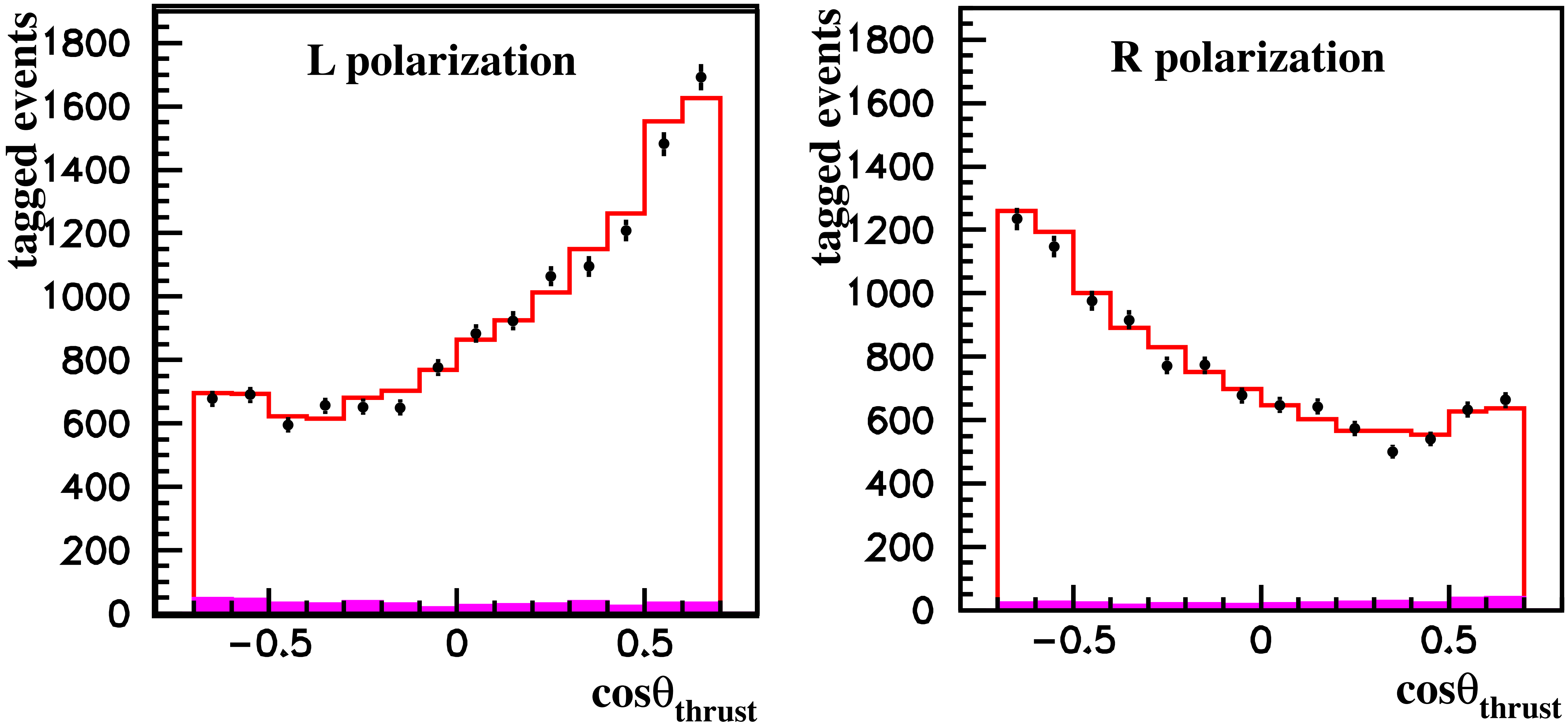


Koks and van Klinken



events/0.05
2000
ALEPH
τ → π ν
0.25
0.5
0.75
1
x
τ_L^-
π^-
ν_L
$\tau_L^- \rightarrow$ slow π^-
$\tau_R^- \rightarrow$ fast π^-

$$e^+e^- \to b\bar{b}$$



SLD

As for the importance of the Higgs for gauge boson masses, my favorite example occurs in the decays of the top quark.

The top quark decays by $t \to W^+ b$. The interaction Lagrangian is

$$\Delta\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(\frac{1-\gamma^5}{2})tW_\mu$$

It is easy to compute the decay rates to W states of definite (Left, Right, longitudinal) polarization:

$$\Gamma(t \to W_L^+ b) = \frac{\alpha_w}{8}(m_t)(1 - m_W^2/m_t^2)^2$$

$$\Gamma(t \to W_R^+ b) = 0$$

$$\Gamma(t \to W_0^+ b) = \frac{\alpha_w}{16}(m_t^3/m_W^2)(1 - m_W^2/m_t^2)^2$$

The longitudinal polarization state is enhanced. Why?

First, the longitudinal polarization vector is weirdly large. For a W moving the 3 direction:

$$\epsilon_0^\mu(\vec{p}=0) = (0,0,0,1)$$
$$\epsilon_0^\mu(\vec{p}=p\hat{3}) = (\frac{p}{m_W}, 0, 0, \frac{E_p}{m_W}) \approx \frac{p^\mu}{m_W}$$

Now dot this with the quark matrix element. The left-handed current is not conserved, due to quark masses:

$$\frac{g}{\sqrt{2}}\overline{u}(k')\gamma^\mu(\frac{1-\gamma^5}{2})\, u(k)\epsilon_{0\mu} \approx \frac{g}{\sqrt{2}}\overline{u}(k')\frac{k-k'}{m_W}(\frac{1-\gamma^5}{2})u(k)$$
$$\approx \frac{g}{\sqrt{2}}\overline{u}(k')(\frac{1+\gamma^5}{2})\frac{k}{m_W}\, u(k)$$
$$\approx \frac{g}{\sqrt{2}}\overline{u}(k')(\frac{1+\gamma^5}{2})\frac{m_t}{m_W}\, u(k)$$

Actually, since $m_W = \frac{gv}{2}$ and $m_t = \frac{y_t v}{\sqrt{2}}$, $\frac{g}{\sqrt{2}} \frac{m_t}{m_W} = y_t$

the final expression is:

$$y_t \, u(k')(\frac{1+\gamma^5}{2})u(k)$$

which is exactly the amplitude for t decay by

$$t \to \pi^+ b$$

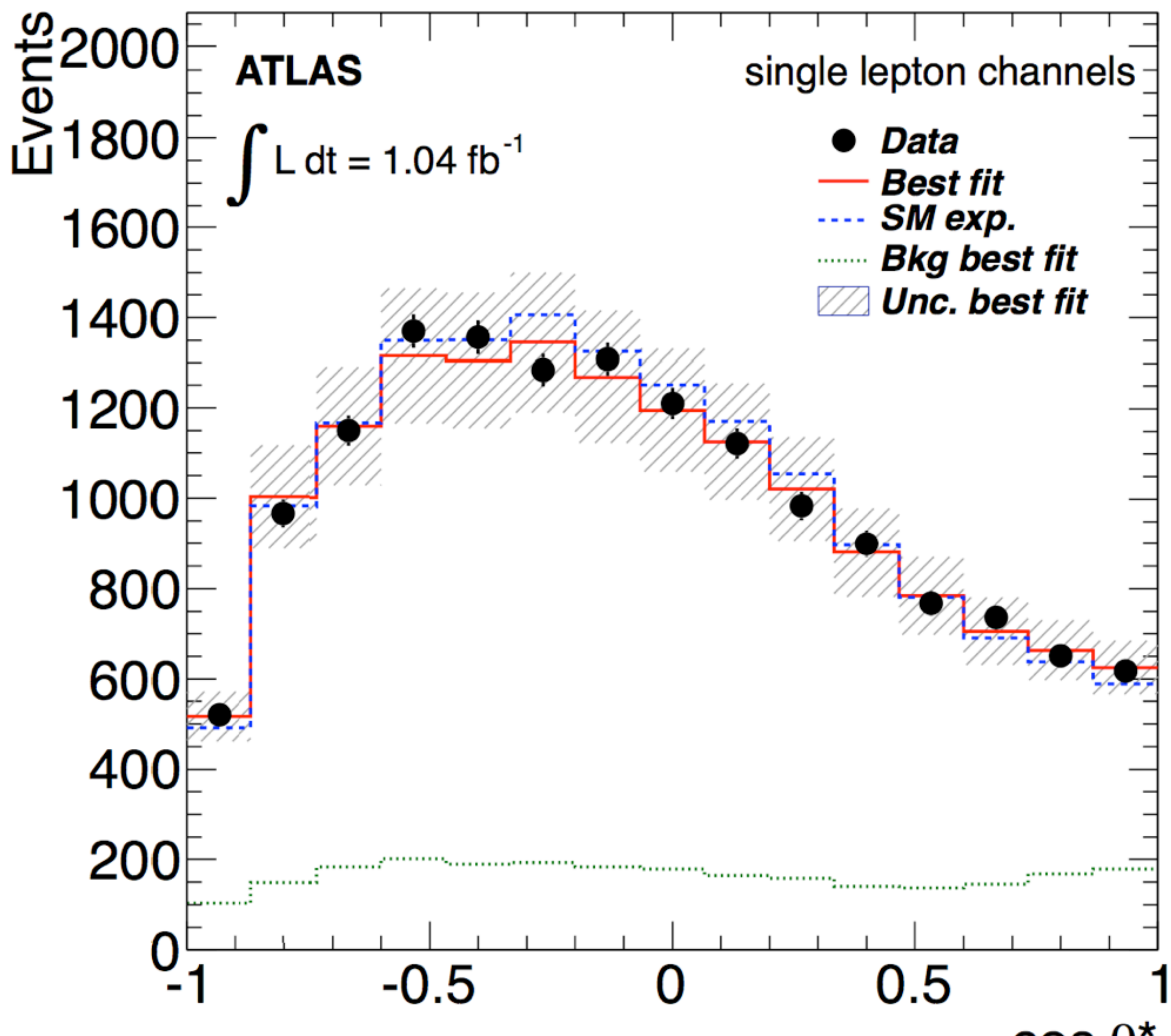
where π^+ is the Goldstone boson in the Higgs multiplet.

The Higgs boson (and spontaneous symmetry breaking) is appearing here whether we asked for it or not.

This analysis gives an experimental prediction:

$$\frac{\Gamma(W_0^+)}{\Gamma(\mathrm{all})} = \frac{m_t^2/m_W^2}{m_t^2/m_W^2 + 2} = 70\%$$

The W polarizations in top decays can be measured using the decay distributions of the W's in fully reconstructed top pair events.

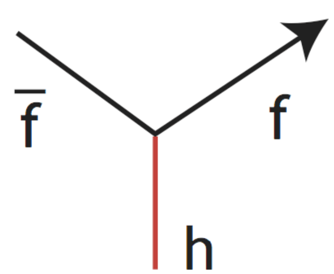


The couplings of the Standard Model Higgs boson to the various SM particles are extremely simple.

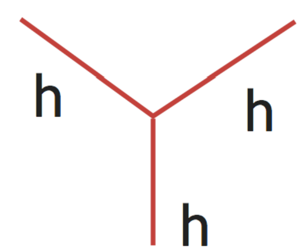
To work them out, note only that all SM particle masses are proportional to the Higgs vev, v, and that the Higgs field appears only in the form

$$(v + h) = v(1 + \frac{h}{v})$$

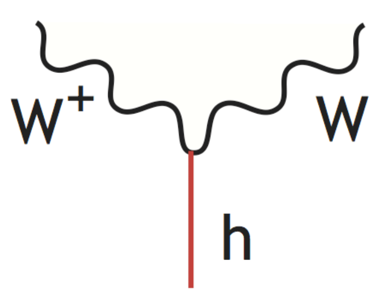
Then



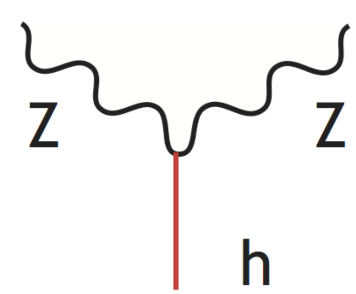
$$= -i\frac{m_f}{v}$$



$$= -3i\frac{m_h^2}{v}$$



$$= 2i\frac{m_W^2}{v}g_{\mu\nu}$$



$$= 2i\frac{m_Z^2}{v}g_{\mu\nu}$$

It is often useful to realize that the Higgs vev v is the only scale in the SM. The Higgs, shifting the overall mass scale, can be thought of as a dilaton. We will use this point of view in the next lecture.

Next, I will briefly review the decay and production modes for the Higgs boson. I will give a more detailed discussion of Higgs decays in the next lecture.

If the Higgs boson of the SM were very heavy, it would decay almost every time to the heaviest SM particles:

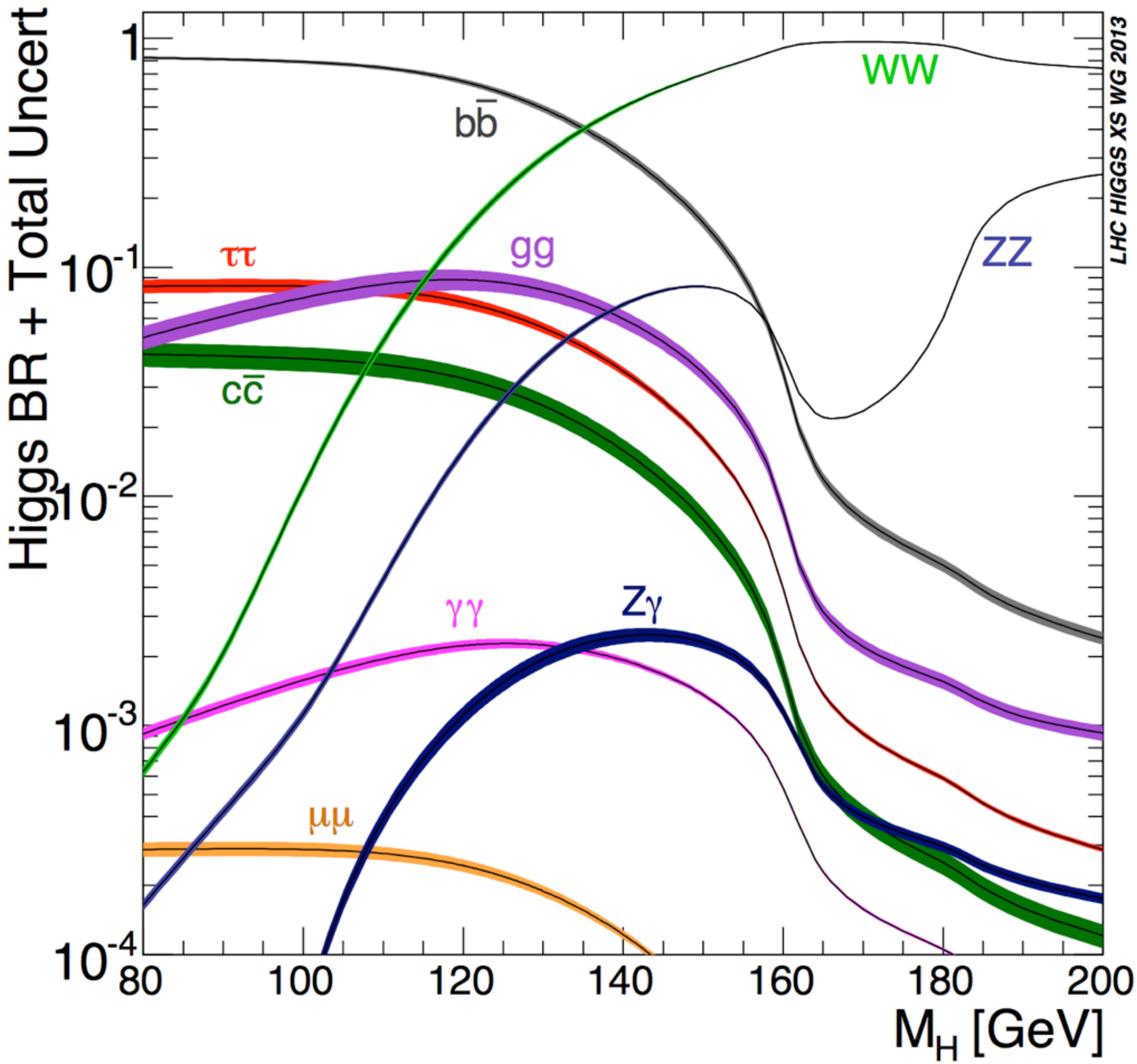
$$h \to W^+W^-, Z^0Z^0, t\bar{t}$$

It turns out that the decays to W and Z always dominate, due to enhancement of the decays to longitudinal polarization states.

However, the real Higgs boson at 126 GeV is not kinematically allowed to decay to these particles.

Then the dominant decays are to the next heaviest SM particles b and τ , with contributions also from decays to off-shell W and Z bosons, and from decays that occur only at the loop level: $h \to gg, \gamma\gamma, Z\gamma$.

We now know the Higgs mass, but still it is instructive to understand the pattern of Higgs decays as a function of mass.



Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
$b\bar{b}$
WW
ZZ
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
$\mu\mu$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]

For a Higgs boson of mass 126 GeV, the prediction for the total width is $\Gamma_h = 4.3\ \mathrm{MeV}$

The branching fractions are predicted to be

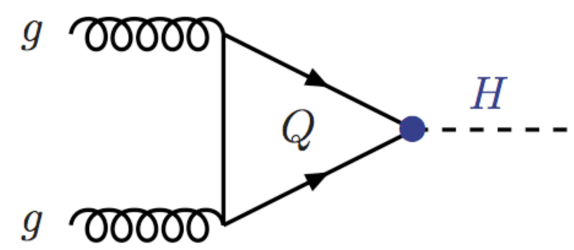
$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

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

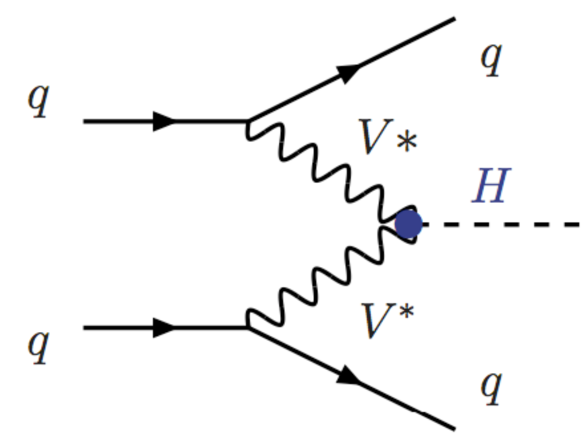
F. Gianotti: "Thank you, Nature."

The important production modes for the Higgs boson at hadron colliders are:

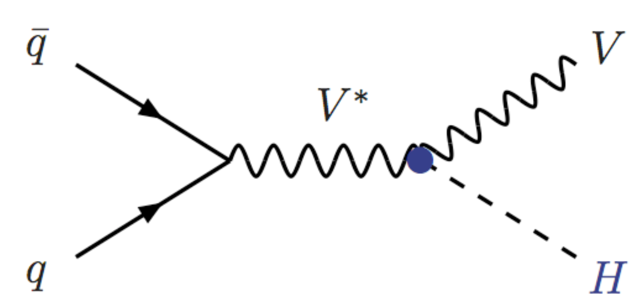
gluon-gluon fusion



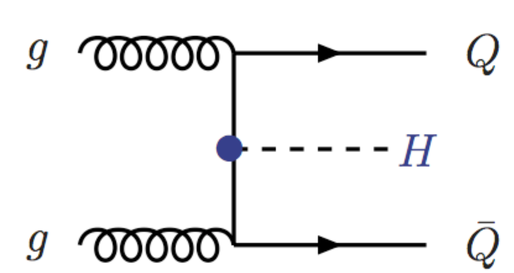
vector boson fusion

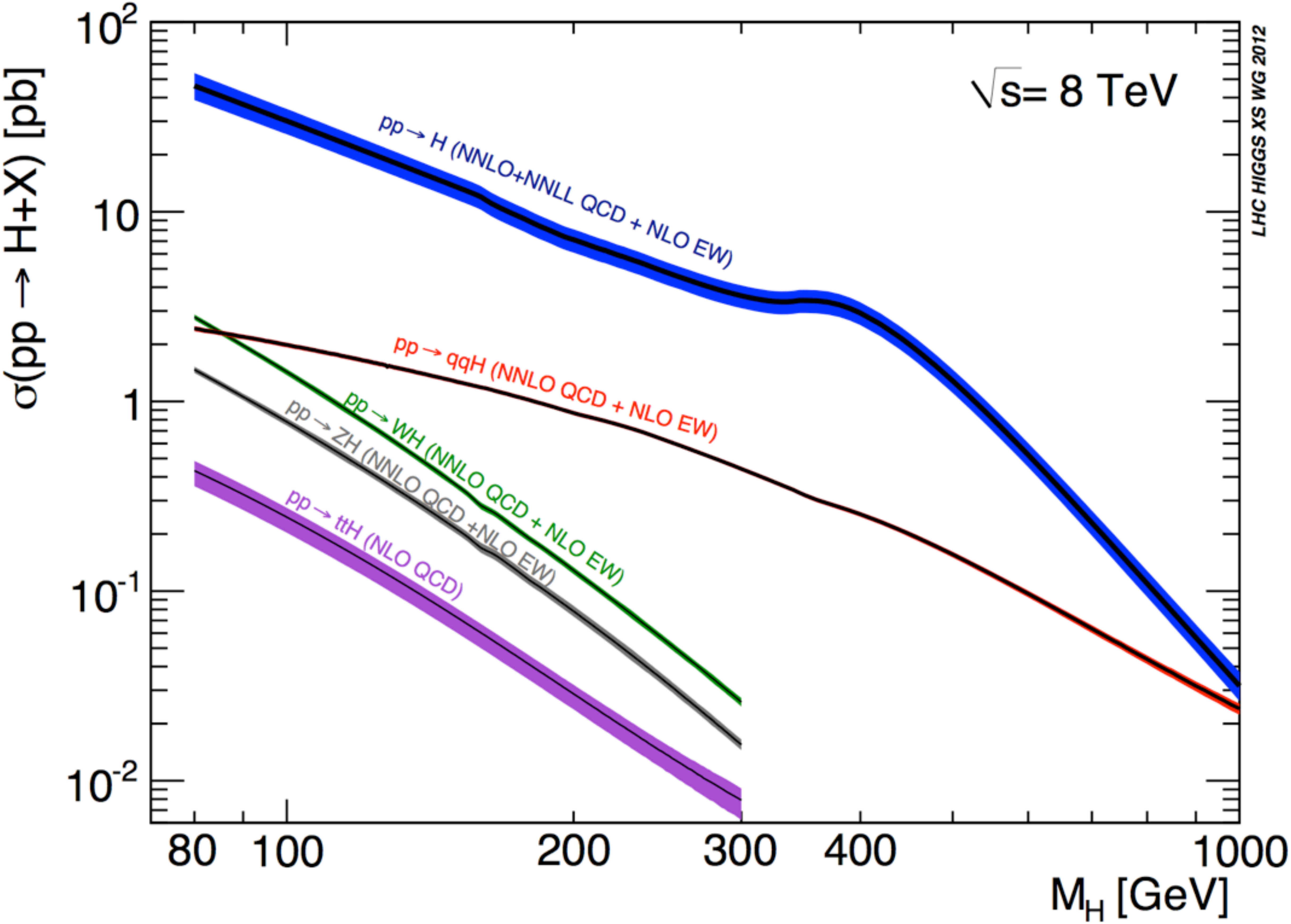


"Higgsstrahlung" associated production w. W, Z



associated production with top





$\sqrt{s}$= 8 TeV
LHC HIGGS XS WG 2012
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
σ(pp → H+X) [pb]
10^2
10
1
10^{-1}
10^{-2}
80
100
200
300
400
1000
M_H [GeV]

These four reactions have different advantages for the precision study of Higgs decays:

gluon-gluon fusion:

highest cross section, access to rare decays

WW fusion:

tagged Higgs decays, access to invisible and exotic modes

smallest theoretical error on production cross section

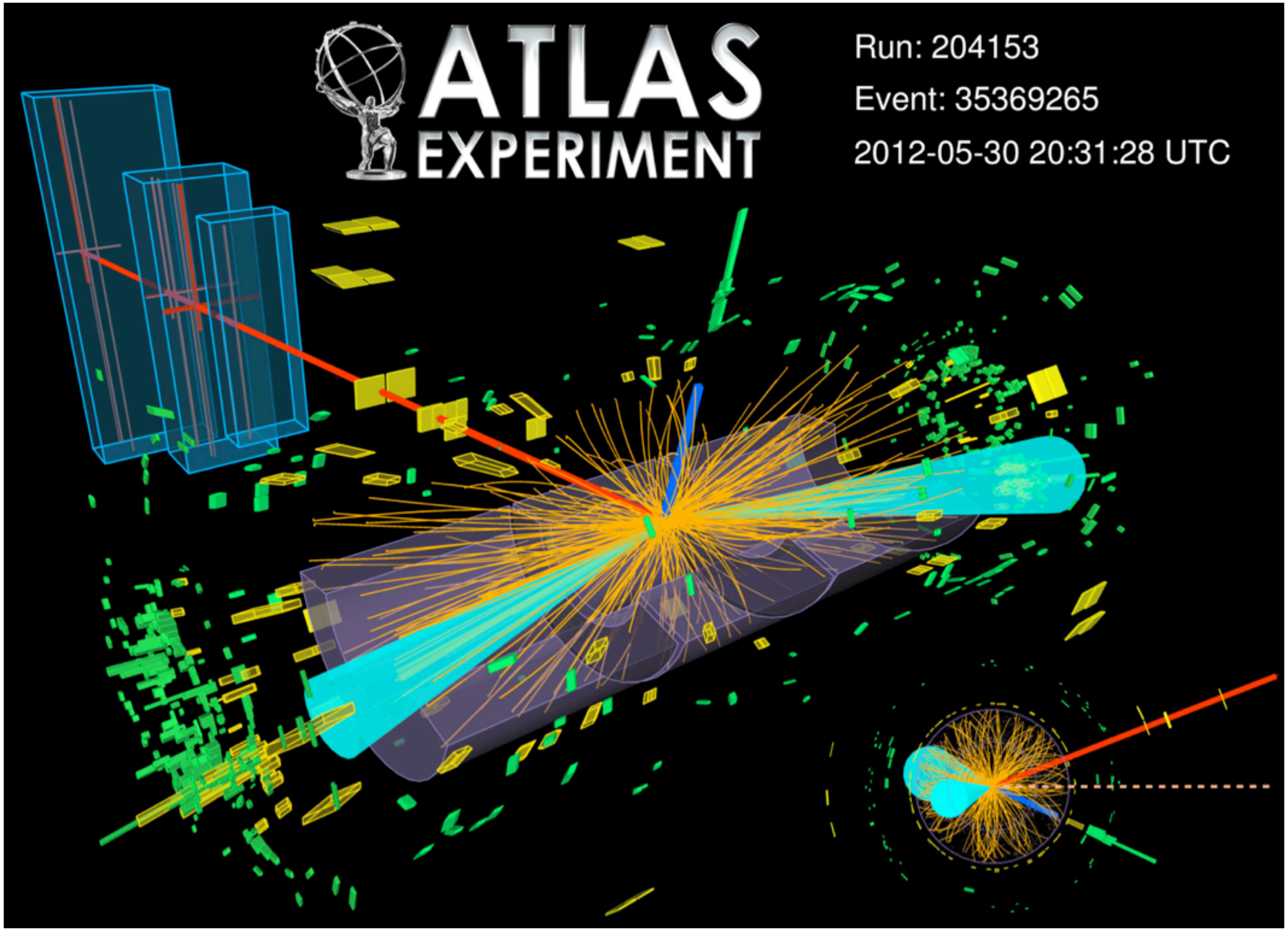
Higgsstrahlung:

tagged Higgs decays

boosted Higgs, for the study of $b\bar{b}$ decay

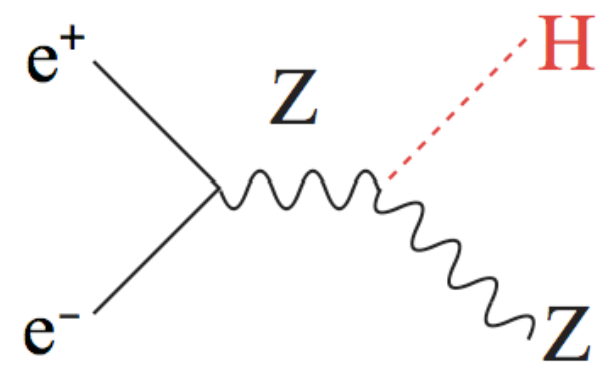
associated production with top:

access to the Higgs coupling to top

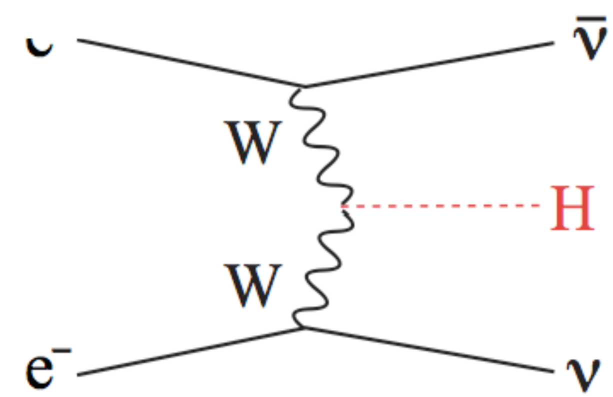

ATLAS
EXPERIMENT
Run: 204153
Event: 35369265
2012-05-30 20:31:28 UTC

The important production modes for the Higgs boson at e^+e^- colliders are:

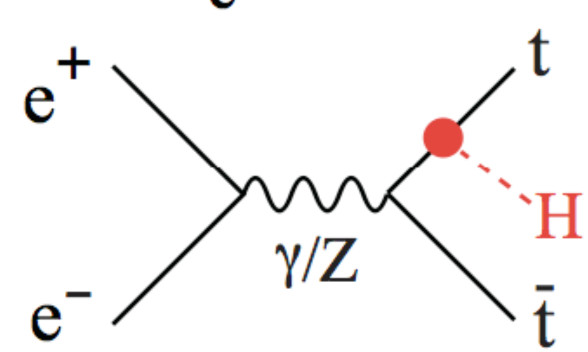
Higgsstrahlung



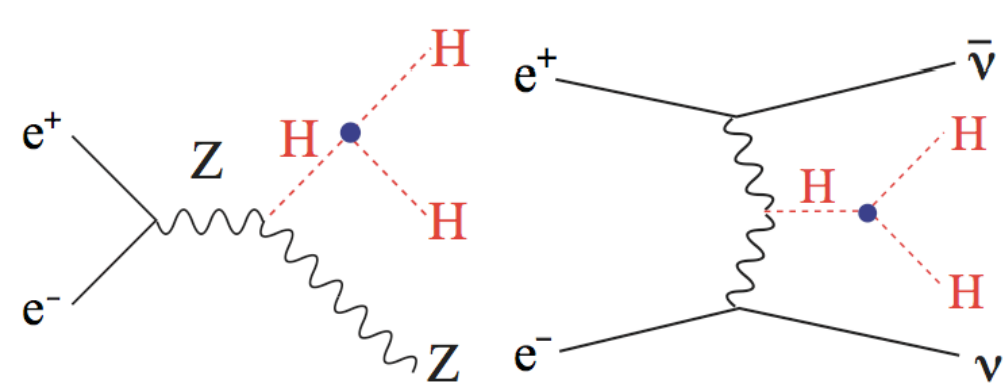
vector boson fusion

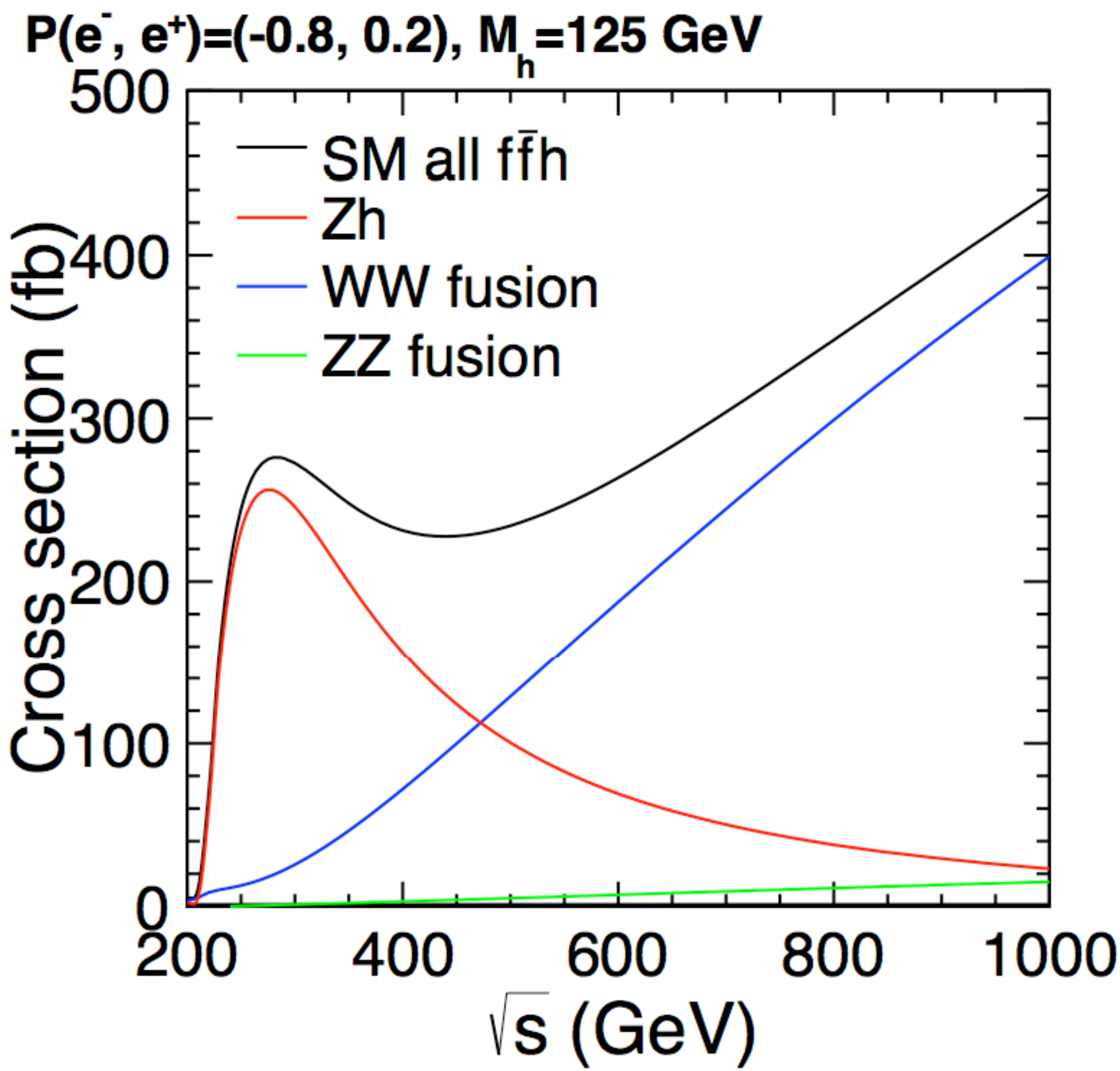


associated production with top



Higgs pair production





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

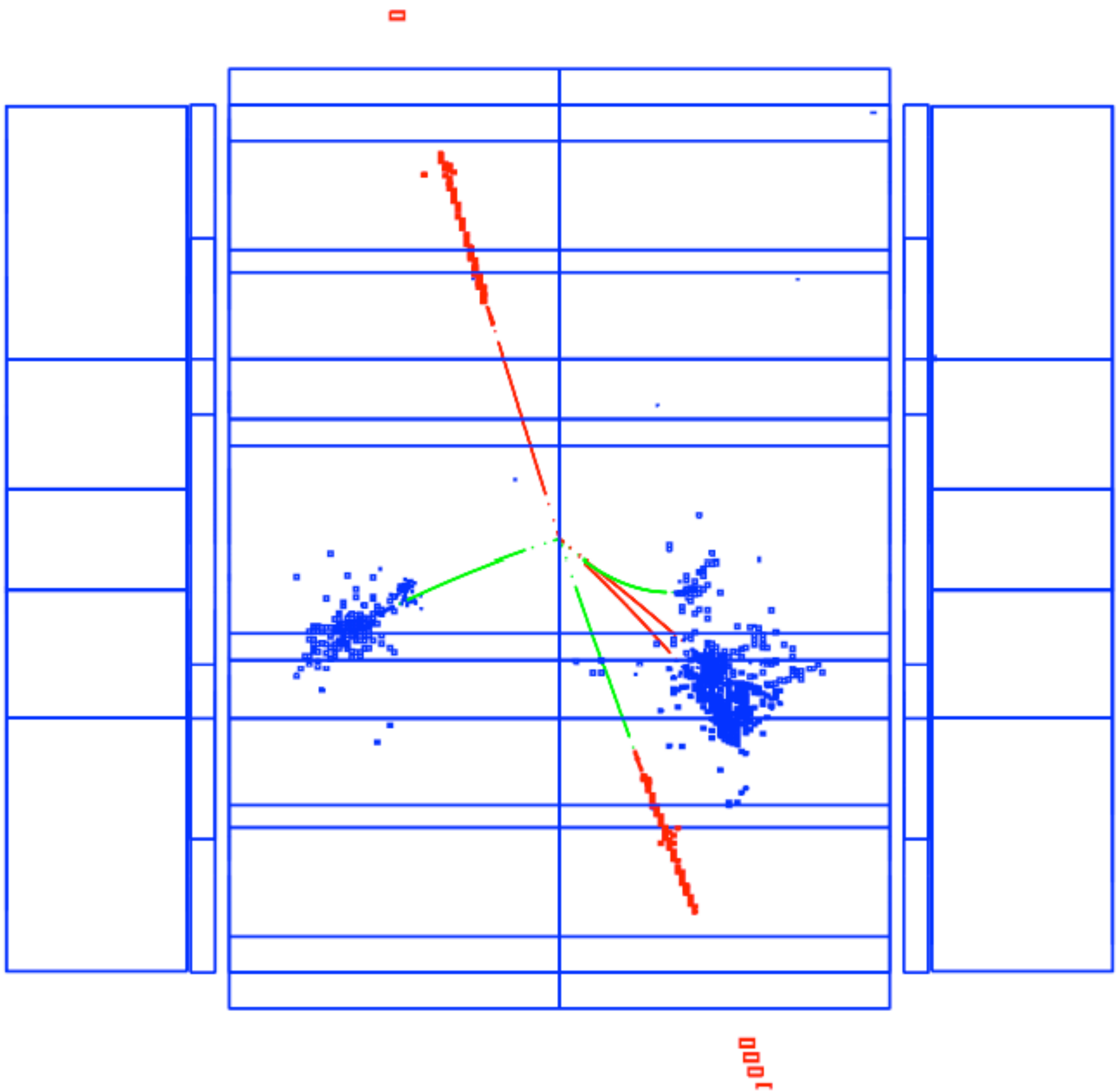
These four reactions have different advantages for the precision study of Higgs decays:

Higgsstrahlung:
- available at the lowest CM energy
- tagged Higgs decay, access to invisible and exotic modes
- direct measurement of the ZZh coupling

WW fusion:
- precision normalization of Higgs couplings

associated production with top:
- access to the Higgs coupling to top

Higgs pair production:
- access to the Higgs self-coupling



ILD simulation

Finally, we come to the question of whether the SM gives a complete theory of the Higgs boson, or whether nature provides an extended or more complex Higgs sector.

At the moment, we do not know. No extended Higgs states have been discovered so far, but there is a long way to go. Effects of complex Higgs sectors on the rates of Higgs processes tend to be small, as I will discuss in the next lecture.

However, there are two properties of the SM Higgs sector that are quite unique. Whether they are "features" or "bugs" is not clear. I will describe them now.

The first property of the SM Higgs sector is “natural flavor and CP conservation”.

Ideally, we might write the couplings of the Higgs field as between specific flavors, e.g.,

$$y_b \overline{Q} \cdot \varphi b_R$$

However, this is not necessary. Can we allow the most general coupling of Higgs fields and quark and lepton fields? This is

$$\Delta\mathcal{L} = -Y_\ell^{ij} \overline{L}_i \cdot \varphi e_{Rj} - Y_d^{ij} \overline{Q}_i \cdot \varphi d_{Rj} - Y_u^{ij} \overline{Q}_{ia} \epsilon_{ab} \varphi_b u_{Rj} - h.c.$$

where the Y are general complex 3x3 matrices, with i,j running over 3 generations. This manifestly has large flavor and CP violation through Higgs boson couplings.

However, we can change our basis for quarks and leptons, and redefine flavor and CP, to improve this situation.

A general 3x3 complex matrix can be represented as

$$Y = U_L y U_R^\dagger$$

with two (in general, different) unitary matrices and a real positive diagonal matrix. In the lepton sector, we can redefine

$$L \to U_L L \ , \quad e_R \to U_R e_R$$

The U matrices cancel out of the kinetic terms and gauge couplings and disappear without a trace. The resulting Higgs coupling is

$$\mathcal{L} = -y_i \overline{L}_i \cdot \varphi e_{Ri} \quad i = e, \mu, \tau$$

The SM, then, has NO lepton flavor violation. Neutrino mass terms will induce small flavor violations.

In the quark sector, the story is not quite as simple. We need separate redefinitions,

$$d_L \to U_L^{(d)} d_L \ , \quad d_R \to U_R^{(d)} d_R$$
$$u_L \to U_L^{(u)} u_L \ , \quad d_R \to U_R^{(u)} u_R$$

This reduces the Higgs couplings to a diagonal form

$$\mathcal{L} = -y_{di} \overline{L}_i \cdot \varphi d_{Ri} - y_{ui} \overline{Q}_{ia} \epsilon_{ab} u_{Ri}$$

The U matrices cancel out of the kinetic terms and the Z and γ gauge couplings. The the W couplings are modified by a matrix

$$U_L^{(u)\dagger} U_L^{(d)} = V_{CKM}$$

This is the CKM matrix. In the SM, the only source of flavor and CP violation the quark sector is the CKM matrix.

One qualification is necessary for the story on the previous slide. The overall phase of the quark mass matrix cannot be removed, because a needed symmetry is broken by the axial vector anomaly. To remove this phase, which contributes to the neutron electric dipole moment, additional particles or symmetries need to be added to the SM. The simplest solution is to add a very light, weakly coupled particle called the axion.

Supersymmetry (to be described in the 3rd lecture) also gives natural flavor and CP conservation. SUSY models contain two Higgs doublets and have a Yukawa structure

$$\Delta\mathcal{L} = -Y_\ell^{ij}\overline{L}_i \cdot \varphi_d e_{Rj} - Y_d^{ij}\overline{Q}_i \cdot \varphi_d d_{Rj} - Y_u^{ij}\overline{Q}_{ia} \cdot \varphi_u - h.c.$$

The same simplifications as above apply. However, SUSY potentially introduces many new sources of flavor and CP violation. Controlling these is a major constraint on SUSY model-building.

Other theories with multiple Higgs bosons produce new sources of flavor violation unless care is taken that these should be suppressed or canceling.

The other exceptional feature of the Higgs field of the SM is that it leads to an unstable vacuum state.

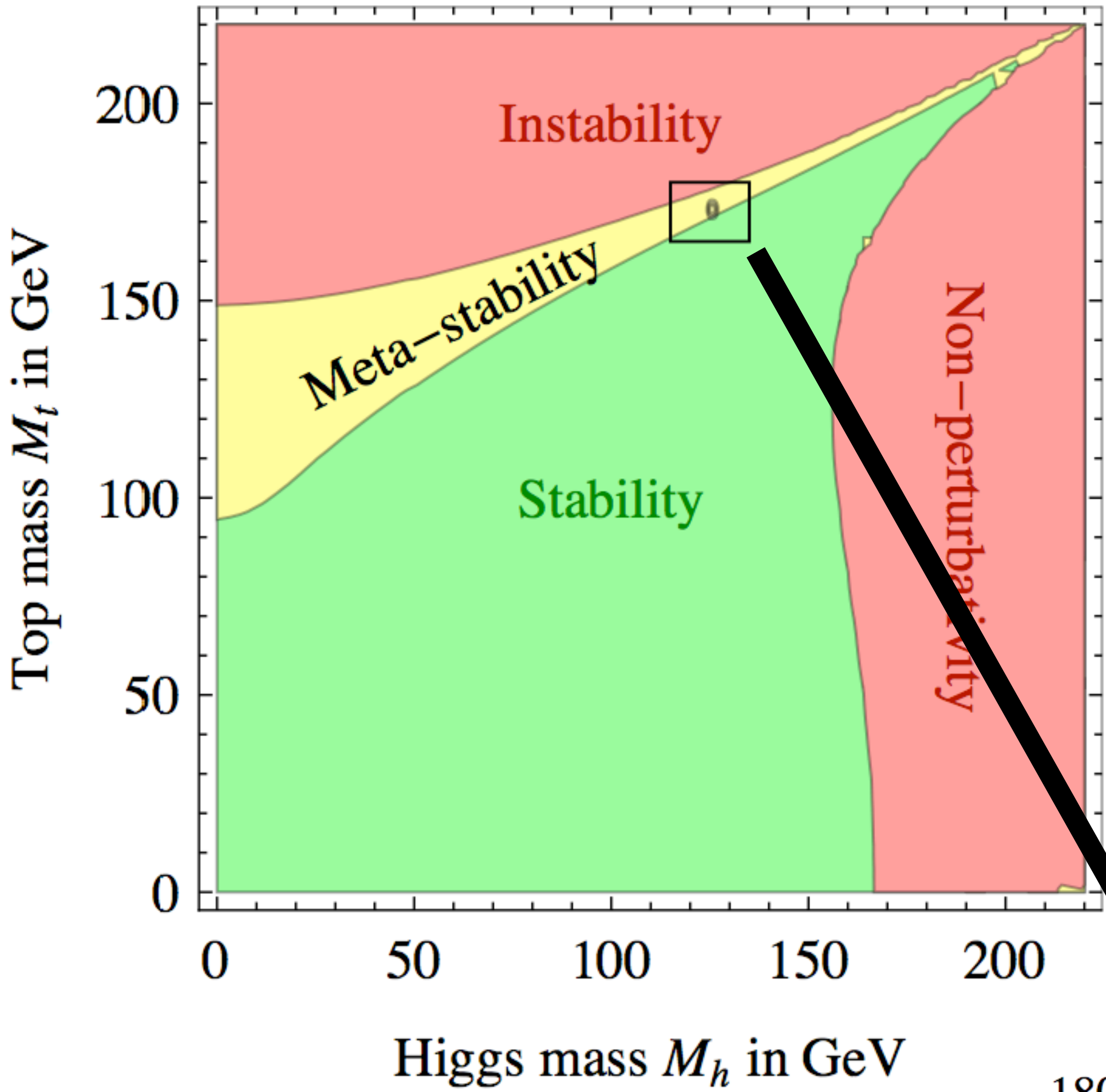
If the SM is correct, we now know all of its parameters, and we can extrapolate them to very high energy scales. The renormalization group equation for the Higgs quartic coupling has the form

$$\frac{d}{d\log Q}\lambda = \frac{3}{2\pi^2}\left[\lambda^2 - \frac{1}{32}\lambda_t^4 + \cdots\right]$$

For the actual Higgs and top quark masses, the second term dominates and the Higgs coupling eventually becomes negative. This gives an instability

$$\Delta\mathcal{L} \sim -|\lambda(\varphi)| \cdot |\varphi|^4$$

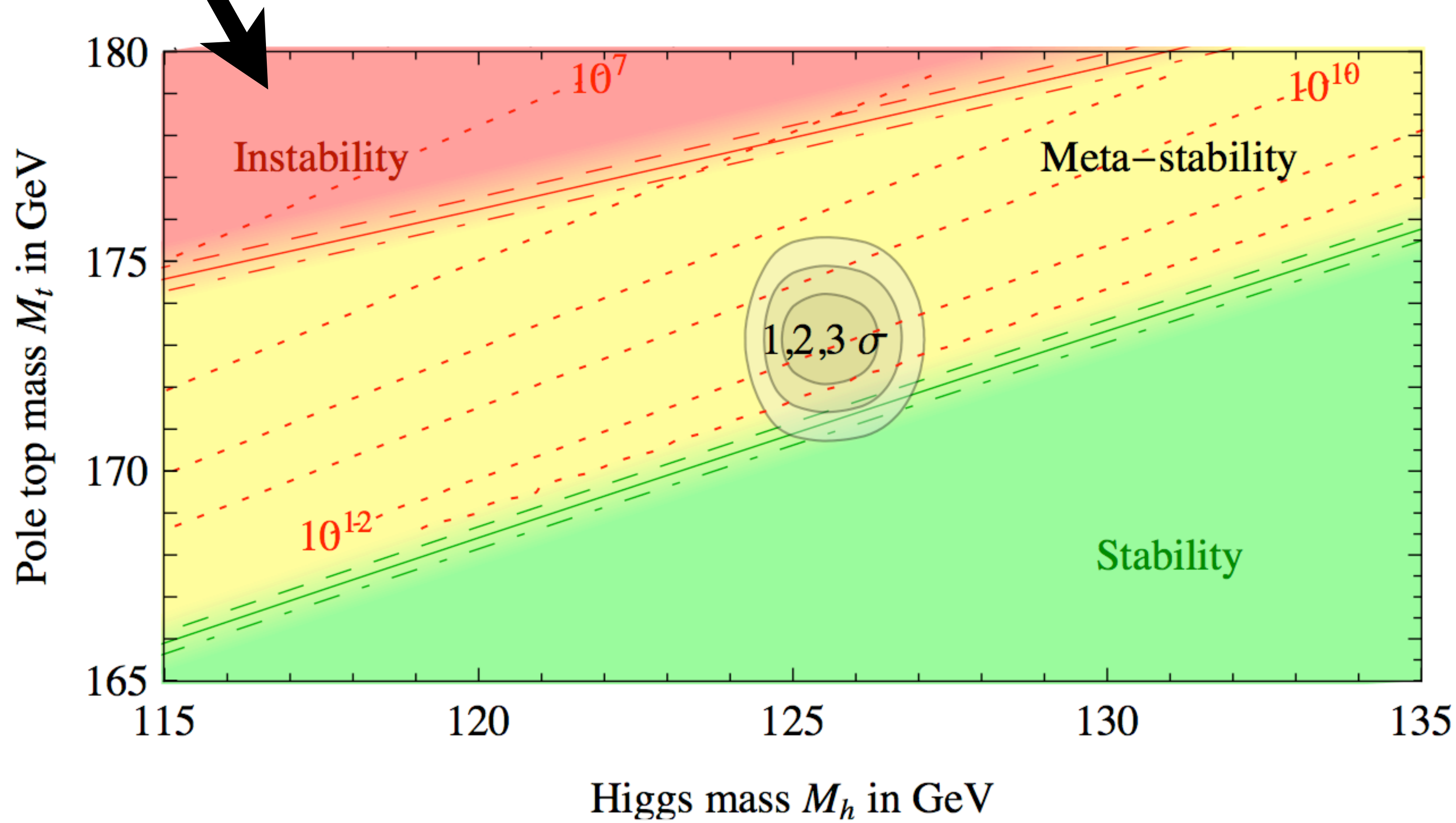
Eventually, the vacuum tunnels to a very deep minimum with a very large value of $\langle\varphi\rangle$.



Our universe seems to be at an exceptional point in the parameter space of the SM.

Is it a clue, or a red herring ?

Degrassi et al.



With this introduction, we will look in the next lecture into the prospects for precision measurement of the Higgs boson couplings.