Topics in Electroweak Symmetry Breaking

3. Precision study of the Higgs boson

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In this lecture, I will discuss the precision study of the Higgs boson as a probe for new physics beyond the Standard Model.

The Higgs boson was discovered only in 2012, after many years of search. At the moment, its interactions are known from experiment to about the 20-30% level. And, at this level, the results are in agreement with the predictions of the Standard Model.

On the other hand, as I have argued in the previous lecture, the mechanism of SU(2)xU(1) symmetry breaking is a complete mystery. Behind the apparently simple Higgs boson, a wealth of complexity could be hiding.

Can we see this by more detailed study of the Higgs?

To begin, we should review the predictions of the Standard Model for the properties of the Higgs boson.

The basics of the theory are extremely simple. A general Higgs field configuration can be simplified by a gauge transformation to the form

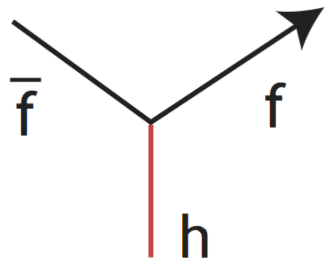
$$\varphi(x) = \exp[-i\alpha^a(x)\sigma^a/2] \begin{pmatrix} 0 \\ (v + h(x))/\sqrt{2} \end{pmatrix}$$

Here v is the vacuum expectation value of the field. From m_W and g, we extract

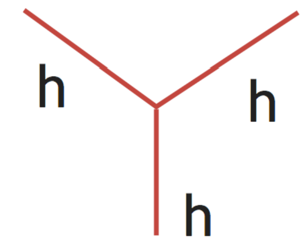
$$v = 250 \text{ GeV}$$

The dynamical part of the field is a single scalar field $h(x)$. The vertices of $h(x)$ are given by shifting v. Thus, the vertices of $h(x)$ are completely determined by known information from the Standard Model.

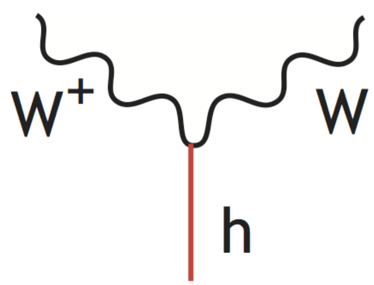
So,



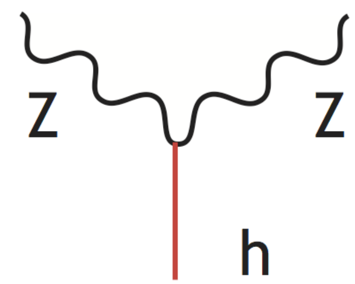
$$= -i\frac{m_f}{v}$$



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



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



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

within the Standard Model, there is no freedom. The decay widths of the Higgs boson will depend on the Higgs boson mass, but, once this is known, these widths can be computed precisely.

These couplings imply that a heavy Higgs boson will decay dominantly by

$$h \to W^+W^- \ , \quad h \to ZZ \ , \quad h \to t\bar{t}$$

The theory of these Higgs boson decays is very simple.

However, by now you all know that the LHC experiments exclude a Standard Model Higgs boson in the mass range where decay to these particles would be permitted. The Higgs resonance found at the LHC has a mass of 125 GeV.

Therefore, all of the actual decays of the Higgs boson are suppressed in some way, by factors

$$\frac{m_f^2}{m_W^2} \ , \quad \frac{\alpha_w}{4\pi} \ , \quad (\frac{\alpha_s}{4\pi})^2$$

However, this means that the theory of Higgs boson decays is very rich, with a large number of decay modes accessible.

Begin with the decays to fermions. The matrix element for Higgs decay to a light fermion is

$$i\mathcal{M}(h \to f_R \overline{f}_R) = -i\frac{m_f}{v} u_R^\dagger v_R = -i\frac{m_f}{v}(2E)$$

Summing over final fermion helicities and integrating over phase space

$$\Gamma(h \to f\overline{f}) = \frac{1}{2m_h}\frac{1}{8\pi}\frac{m_f^2 m_h^2}{v^2} \cdot 2$$

or, using $v^2 = 4m_W^2/g^2$

$$\Gamma(h \to f\overline{f}) = \frac{\alpha_w}{8} m_h \frac{m_f^2}{m_W^2}$$

For final leptons, we can immediately evaluate this:

$$\Gamma(h \to \tau^+\tau^-) = 260 \text{ keV} \qquad \Gamma(h \to \mu^+\mu^-) = 9 \text{ keV}$$

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

For quarks, a few more details must be added.

The mass in this formula should be the $\overline{MS}$ mass evaluated at $Q = m_h$. This is related to the quark mass as usually quoted by

$$m_f(m_h) = m_f(m_f)\left[\frac{\alpha_s(m_h)}{\alpha_s(m_f)}\right]^{4/b_0}(1+\mathcal{O}(\alpha_s))$$

The appropriate values of quark masses (in MeV) are

m_u	m_d	m_s	m_c	m_b
1.5	3	60	700	2800

Also, there is a QCD correction that is larger than the one for e^+e^- annihilation:

$$3(1+\frac{17}{3\pi}\alpha_s(m_h)+\cdots) = 3\cdot 1.24$$

Then, for example,

$$\Gamma(h \to b\bar{b}) = \frac{\alpha_w m_h}{8} \left(\frac{2.8}{m_W}\right)^2 \cdot 3 \cdot (1.24) = 2.4 \text{ MeV}$$

This will turn out to correspond to a BR of 58%. So the total width of the Higgs is about 4.1 MeV, and the other fermion BRs are

$\tau^+\tau^-$	$c\bar{c}$	$s\bar{s}$	$\mu^+\mu^-$
6.3%	3%	0.03%	0.02%

(Did you expect that $BR(\tau^+\tau^-) > BR(c\bar{c})$ despite the color factor 3 ?)

For a heavy Higgs that can decay to W and Z bosons on shell, the decay amplitudes would be

$$i\mathcal{M}(h \to W^+W^-) = i\frac{2m_W^2}{v}\ \epsilon_+^* \cdot \epsilon_-^*$$

$$i\mathcal{M}(h \to ZZ) = i\frac{2m_Z^2}{v}\ \epsilon_1^* \cdot \epsilon_2^*$$

For a very heavy Higgs, there is a further enhancement for the longitudinal polarization states

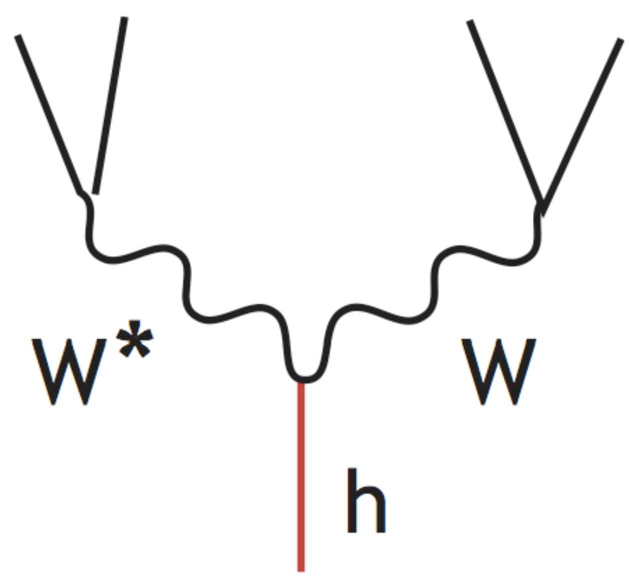
$$\epsilon_1^* \cdot \epsilon_2^* = \frac{k_1 \cdot k_2}{m_Z^2} = \frac{m_h^2}{2m_Z^2}$$

This factor is just

$$\lambda/(g^2 + g'^2)$$

so that the longitudinal Z and W couple like (heavy) Higgs bosons rather than gauge bosons, as predicted by the GBET.

For the actual situation of a 125 GeV Higgs boson, one or both of the Ws or Zs must be off shell. Then the decay is best described as a $h \to 4 \text{ fermion}$ process

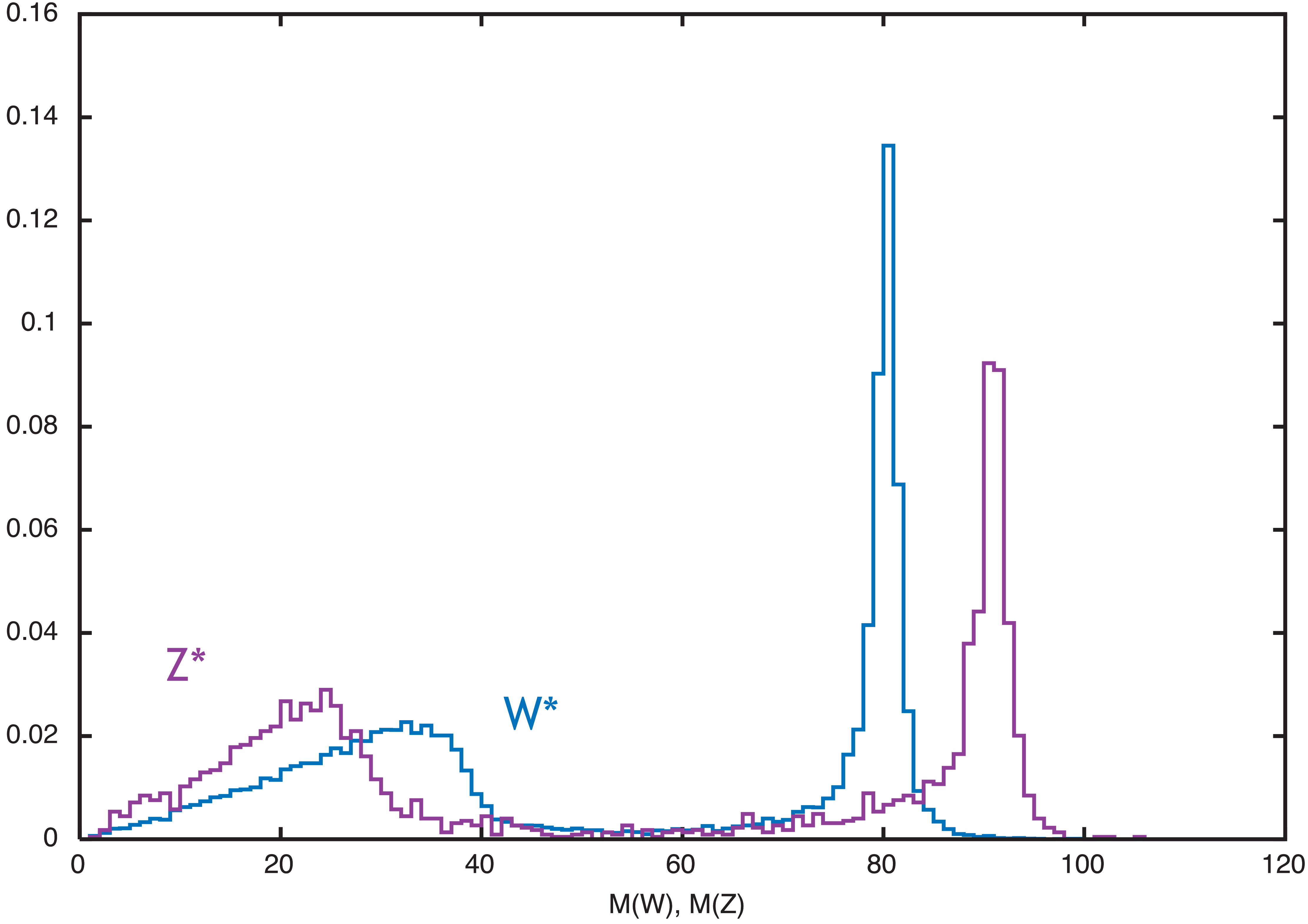


The rate is suppressed by a factor of α_w and by the off-shell W or Z propagator. The result is that the rate is competitive with $b\bar{b}$ for W and a factor 10 smaller for Z.

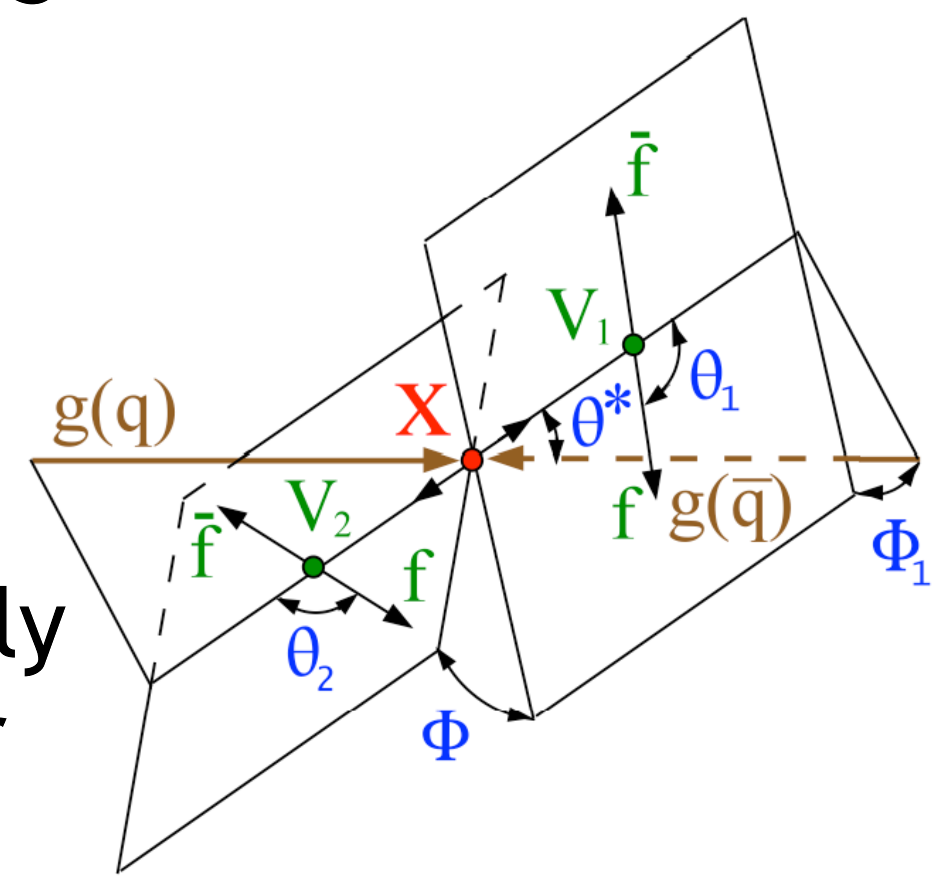
The Standard Model branching fractions are

$$BR(h \to WW^*) = 22\% \qquad BR(h \to ZZ^*) = 2.7\%$$

2-jet mass distributions in h→WW*, ZZ* decays
m(h) = 120 GeV



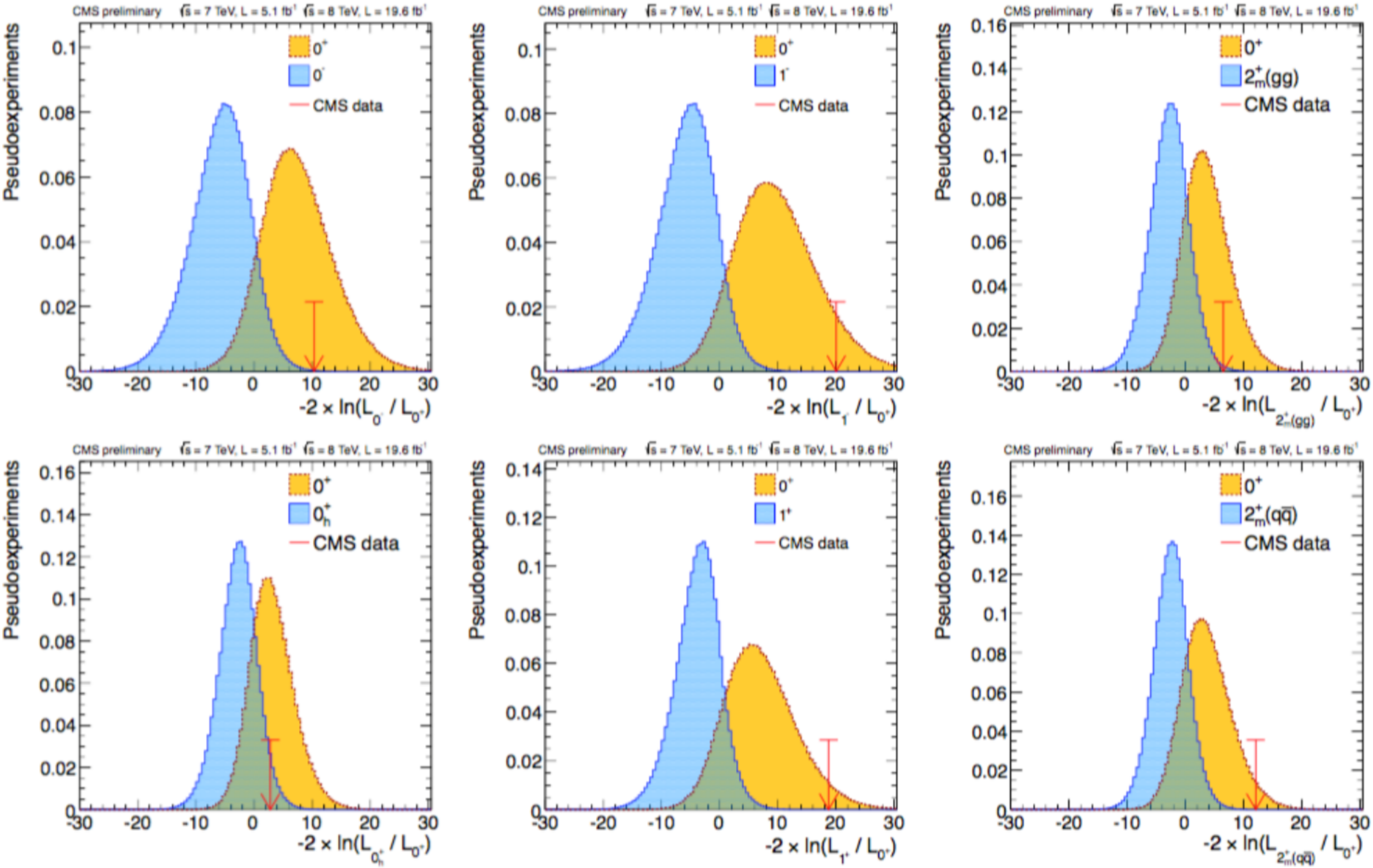
The Higgs decay to ZZ* is exceptionally interesting because it is completely reconstructable when both Zs decay to charged leptons. The angular distribution of the leptons permits a spin analysis.



For the Standard Model amplitude, the two Zs are preferentially longitudinally polarized, and their decay planes are preferentially parallel. This contrasts with other possible assignments

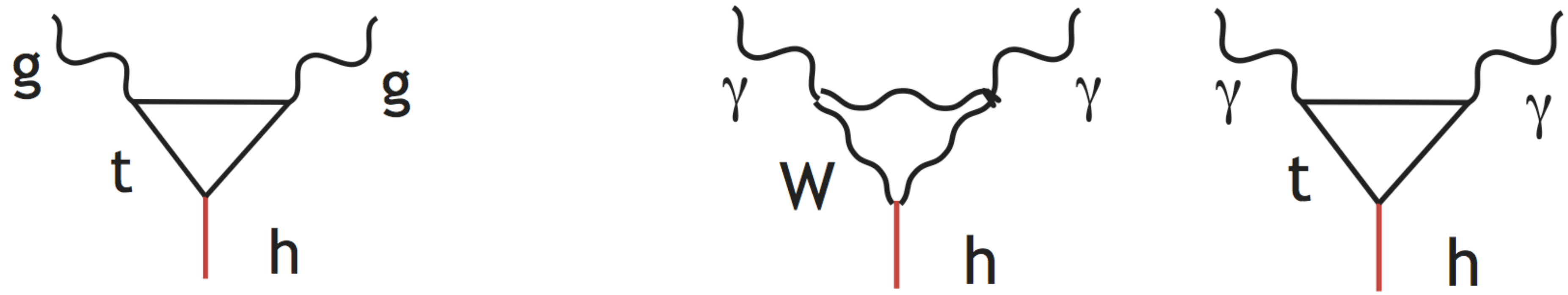
$0^{-} \qquad h\ \epsilon^{\mu\nu\lambda\sigma} Z_{\mu\nu} Z^{\lambda\sigma} \qquad\qquad 0_h^{+} \qquad h\ Z_{\mu\nu} Z^{\mu\nu}$

or assignments to spin 2.



CMS preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
Pseudoexperiments
0+
0-
1-
1+
0h+
2m+(gg)
2m+(qq̄)
CMS data
-2 × ln(L0- / L0+)
-2 × ln(L1- / L0+)
-2 × ln(L2m+(gg) / L0+)
-2 × ln(L0h+ / L0+)
-2 × ln(L1+ / L0+)
-2 × ln(L2m+(qq̄) / L0+)

Finally, there are loop processes that allow the Higgs to decay to massless vector boson states gg and γγ, and to Zγ.



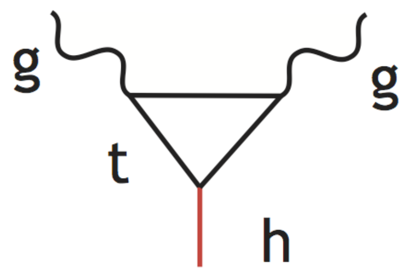
Begin with the hgg vertex. Integrating out the top quark loop gives an effective operator

$$\delta\mathcal{L} = \frac{1}{4} A\ h\ F^a_{\mu\nu} F^{\mu\nu a}$$

where $F^a_{\mu\nu}$ is the QCD field strength and A has dimension $(\mathrm{GeV})^{-1}$. This operator yields the vertex

$$-iA\delta^{ab}(k_1 \cdot k_2 g^{\mu\nu} - k_1^\nu k_2^\mu)$$

For a quark of mass m_f , we might estimate the size of the diagram as



$$\sim \frac{\alpha_s m_f}{v} \cdot \frac{1}{M}$$

where M is the momentum that flows in the loop

$$M \sim \max(m_h, 2m_f)$$

There are two cases: For $2m_f < m_h$, the diagram is suppressed by a factor $2m_f/m_h$. For $2m_f > m_h$, the factors of m_f cancel, and the diagram is at full strength no matter how large m_f is.

So, this diagrams gets large contributions only from those quarks that are too heavy to be decay products of the Higgs. In the Standard Model, this is uniquely the top quark.

To compute the diagram for the top quark, we can start from the top quark QCD vacuum polarization, which has the value

$$i(k^2 g^{\mu\nu} - k^\mu k^\nu)\ \mathrm{tr}[t^a t^b]\ \frac{\alpha_s}{3\pi}\ \log\frac{\Lambda^2}{m_t^2}$$

$$= i(k^2 g^{\mu\nu} - k^\mu k^\nu)\ \delta^{ab}\ \frac{\alpha_s}{6\pi}\ \log\frac{\Lambda^2}{m_t^2}$$

Now introduce a zero momentum Higgs boson by shifting $v \to (v+h)$ where v appears in this expression through

$$m_t^2 = y_t^2 v^2/2$$

The hgg vertex is then

$$i(k^2 g^{\mu\nu} - k^\mu k^\nu)\delta^{ab}\ \frac{\alpha_s}{3\pi}\frac{1}{v}$$

Comparing to our previous expression, we find

$$A = \frac{\alpha_s}{3\pi v} = \frac{g\alpha_s}{6\pi m_W}$$

From this expression, we can compute the partial width $\Gamma(h \to gg)$ in the limit $m_h \ll 4m_t^2$

$$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^2} \frac{m_h^3}{m_W^2}$$

The full expression is

$$\Gamma(h \to gg) = \frac{\alpha_w \alpha_s^2}{72\pi^2} \frac{m_h^3}{m_W^2} \cdot \left| \frac{3}{2}\tau(1 - (\tau - 1)(\sin^{-1} \frac{1}{\sqrt{\tau}})^2) \right|^2$$

where $\tau = 4m_t^2/m_h^2$.

An interesting feature of the argument I have given is that we have related the Higgs coupling to gg to the top quark contribution to the QCD β function. We can use a similar idea to obtain the Higgs coupling to γγ, from the t and W contributions to the QED coupling constant renormalization.

Write the photon vacuum polarization amplitude due to W bosons and top quarks

$$i(k^2 g^{\mu\nu} - k^\mu k^\nu)\frac{\alpha}{4\pi}\Big[\overset{W}{-\frac{22}{3}} + \overset{\pi}{\frac{1}{3}} + \overset{t}{\frac{4}{3}\cdot 3\cdot (\frac{2}{3})^2}\Big] \;\log\frac{\Lambda^2}{v^2}$$

$$= -i(k^2 g^{\mu\nu} - k^\mu k^\nu)\frac{\alpha}{3\pi}\Big[\frac{21}{4} - \frac{4}{3}\Big] \;\log\frac{\Lambda^2}{v^2}$$

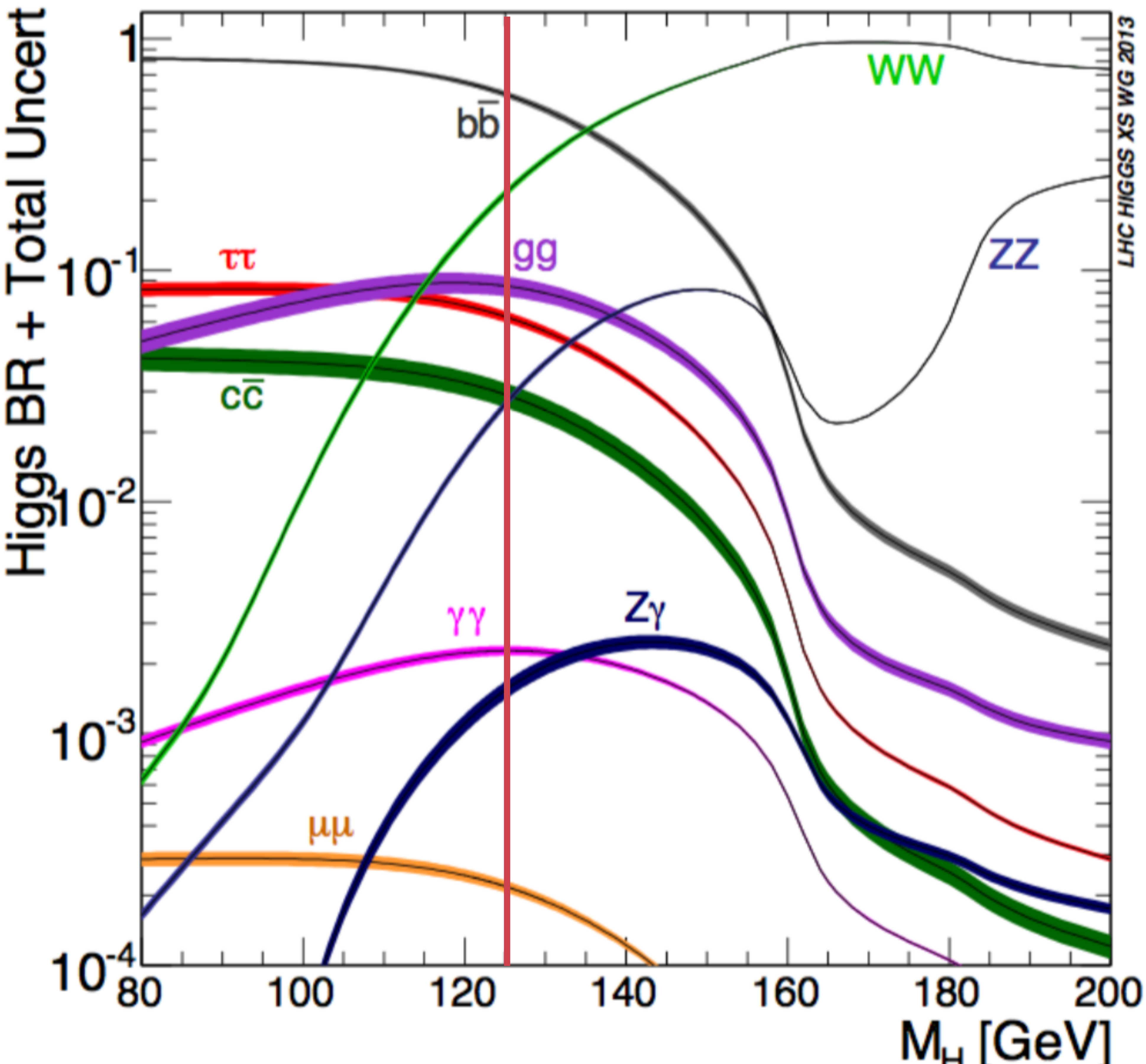
Then, following the same logic, we find in the limit $m_h \ll (2m_W, 2m_t)$

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha_w \alpha^2}{144\pi^2}\frac{m_h^3}{m_W^2}\Big|\frac{21}{4} - \frac{4}{3}\Big|^2$$

Careful evaluation, including QCD corrections to the gluon width, gives the branching ratios

$$BR(h \to gg) = 8.6\% \qquad BR(h \to \gamma\gamma) = 0.23\%$$

We can now put all of the pieces together and graph the Standard Model predictions for the various branching ratios of the Higgs as a function of the Higgs mass.

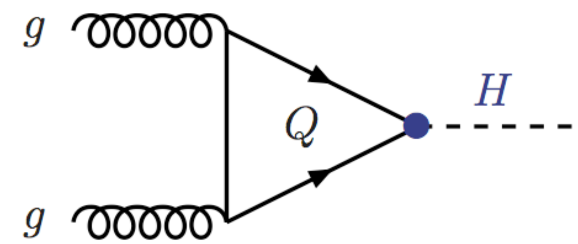


LHC Higgs
XS WG

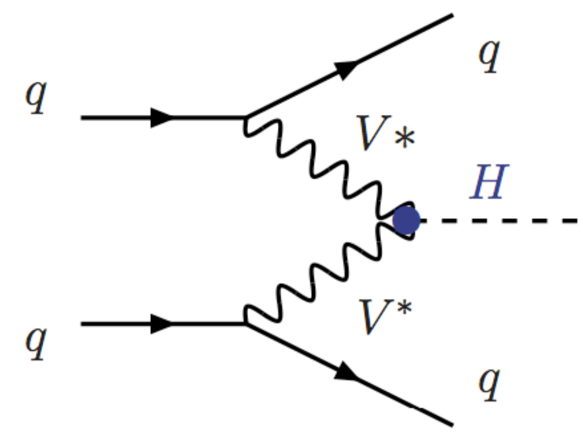
With this introduction to the Standard Model Higgs properties, I can very briefly discuss the study of the Higgs boson at the LHC.

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

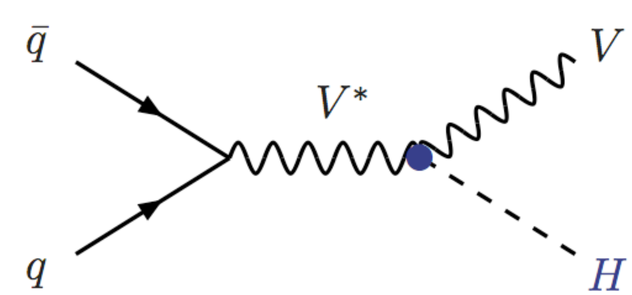
gluon-gluon fusion



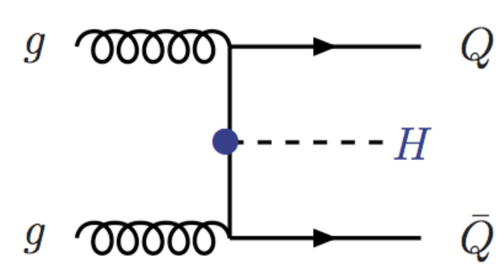
vector boson fusion

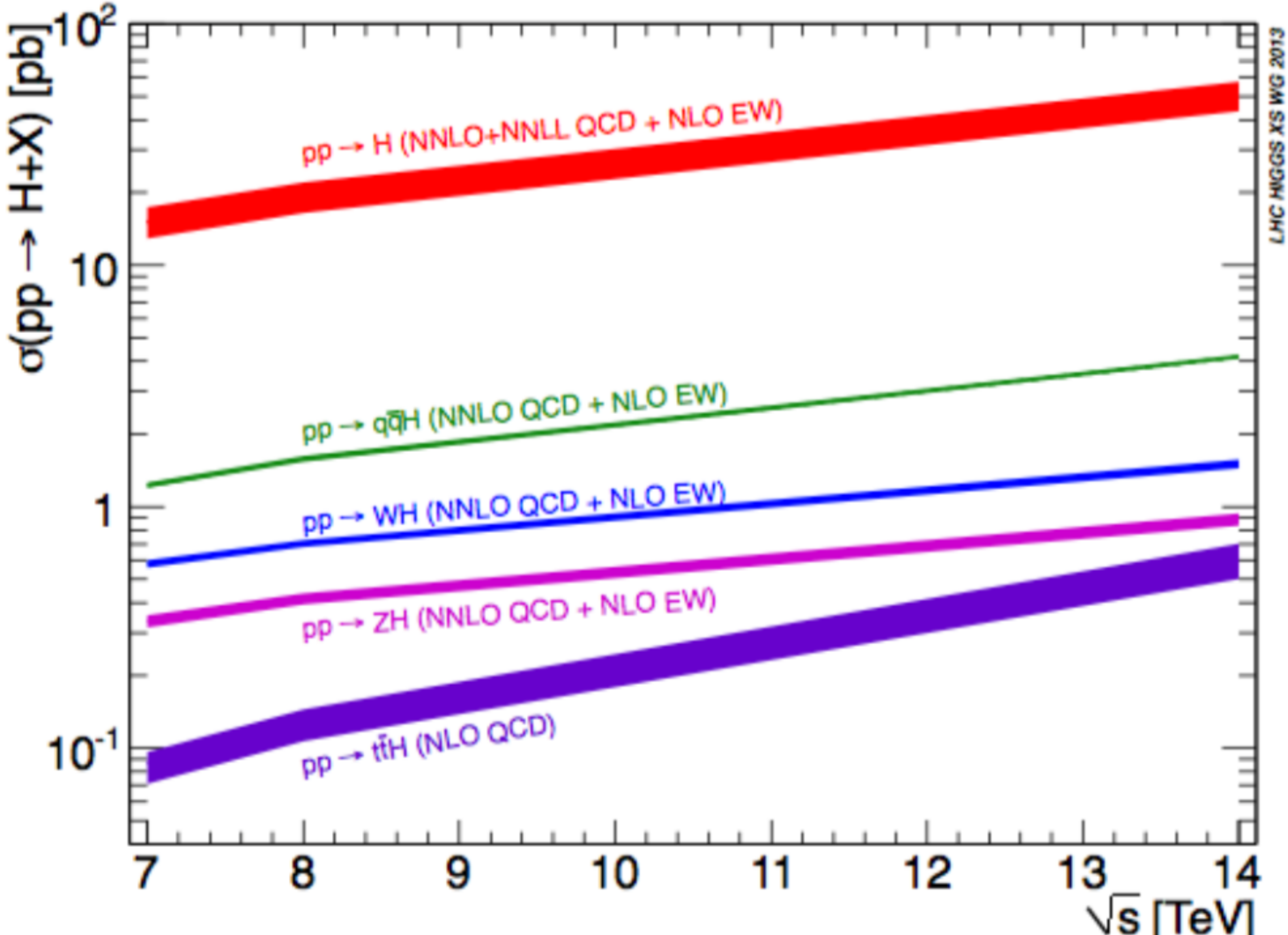


"Higgsstrahlung" associated production w. W, Z



associated production with top





$\sigma(pp \to H+X)$ [pb]
10^2
10
1
10^{-1}
7
8
9
10
11
12
13
14
$\sqrt{s}$ [TeV]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qq̄H (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → tt̄H (NLO QCD)
LHC HIGGS XS WG 2013

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

The original strategy for observing the Higgs boson at the LHC used the characteristic decay modes in which the Higgs could be reconstructed as a resonance,

$$h \to \gamma\gamma \qquad\qquad h \to ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$$

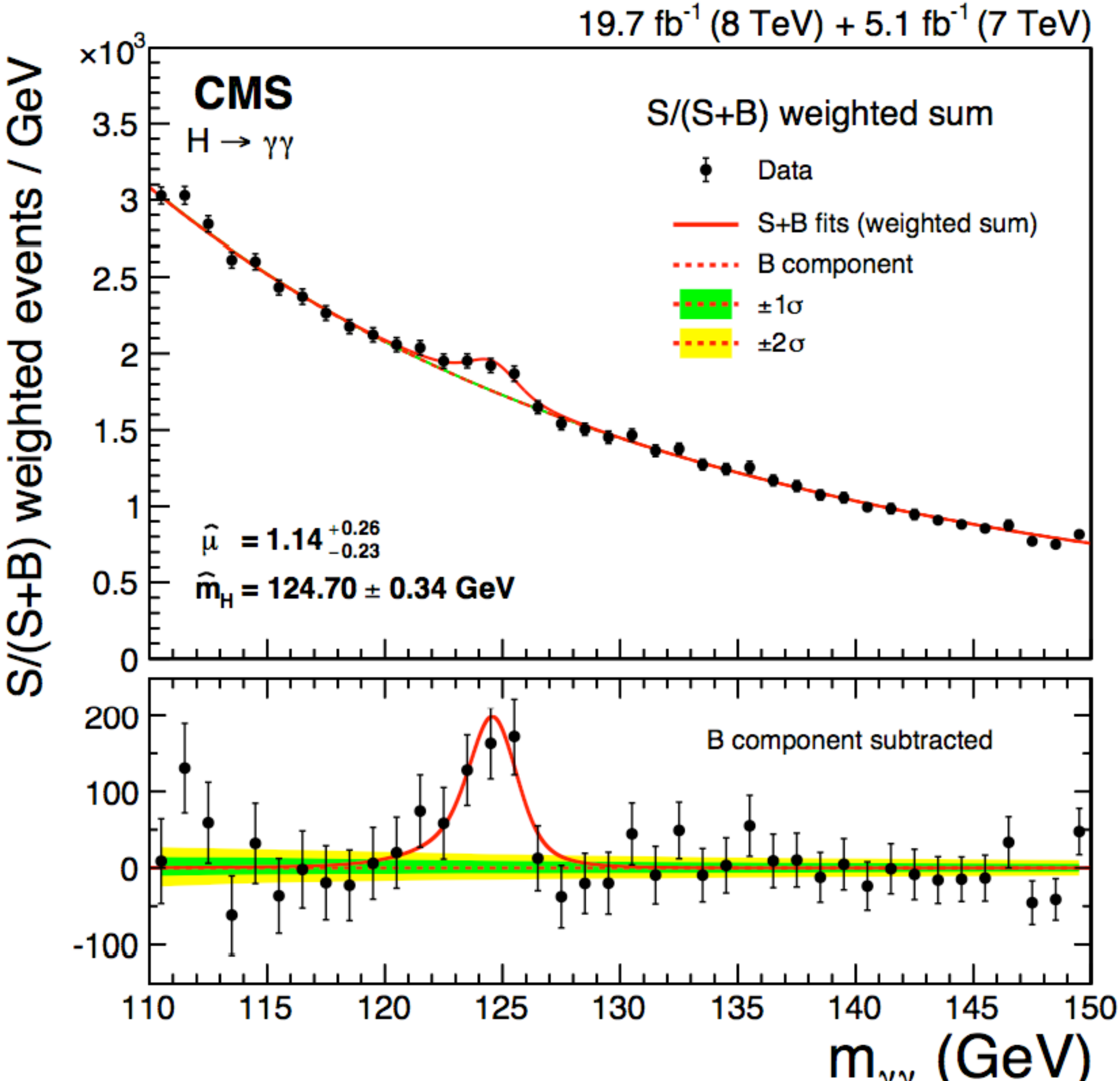
Note that these modes correspond to branching ratios of

0.23% and 0.012%

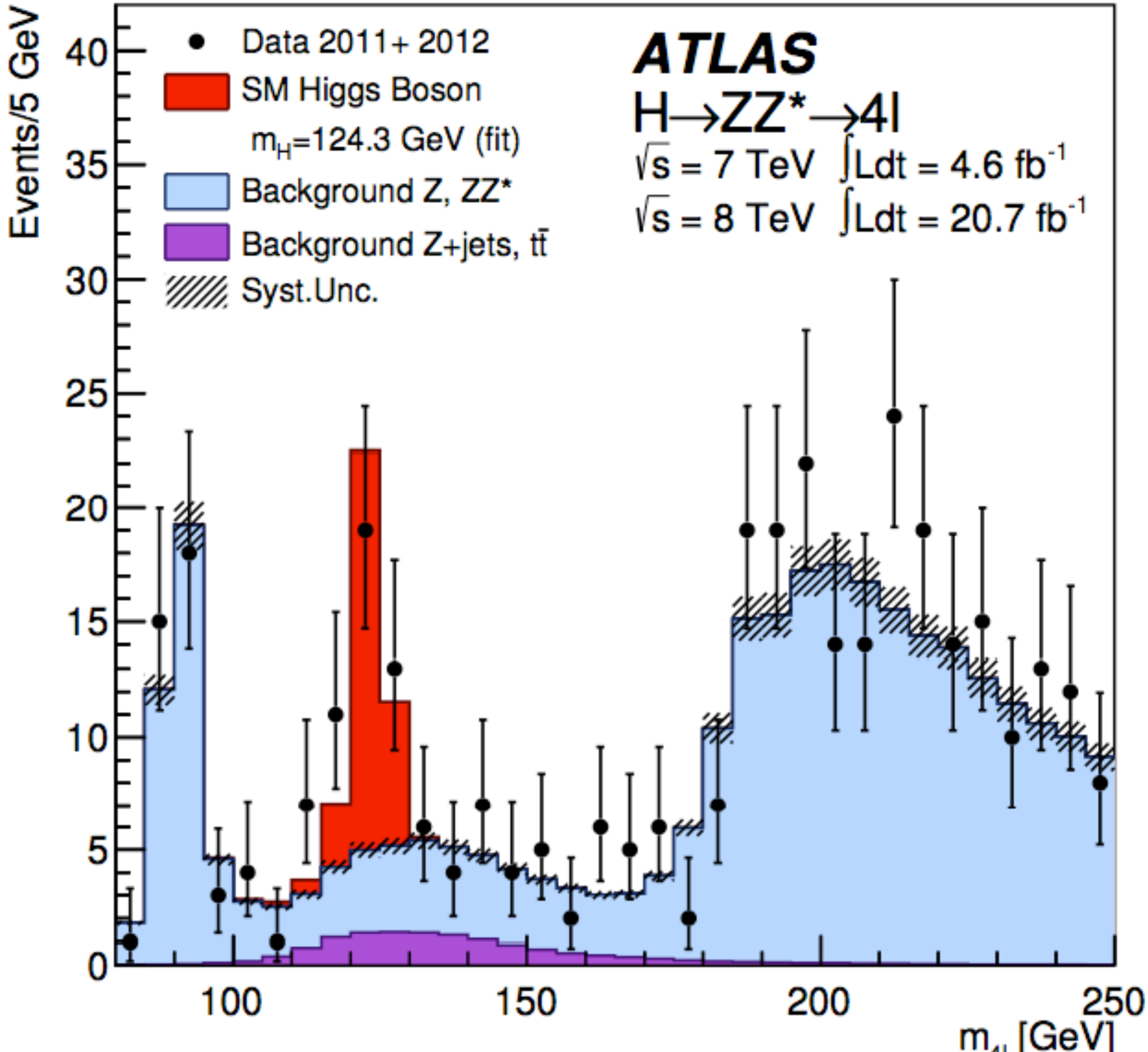
respectively. With a production cross section of about 20 pb, these processes have rates

4×10^{-13} and 2×10^{-14}

of the pp total cross section.



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
×10³
B component subtracted
$m_{\gamma\gamma}$ (GeV)



Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, tt̄
Syst.Unc.
ATLAS
H→ZZ*→4l
√s = 7 TeV ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Events/5 GeV
m_4l [GeV]
0
5
10
15
20
25
30
35
40
100
150
200
250

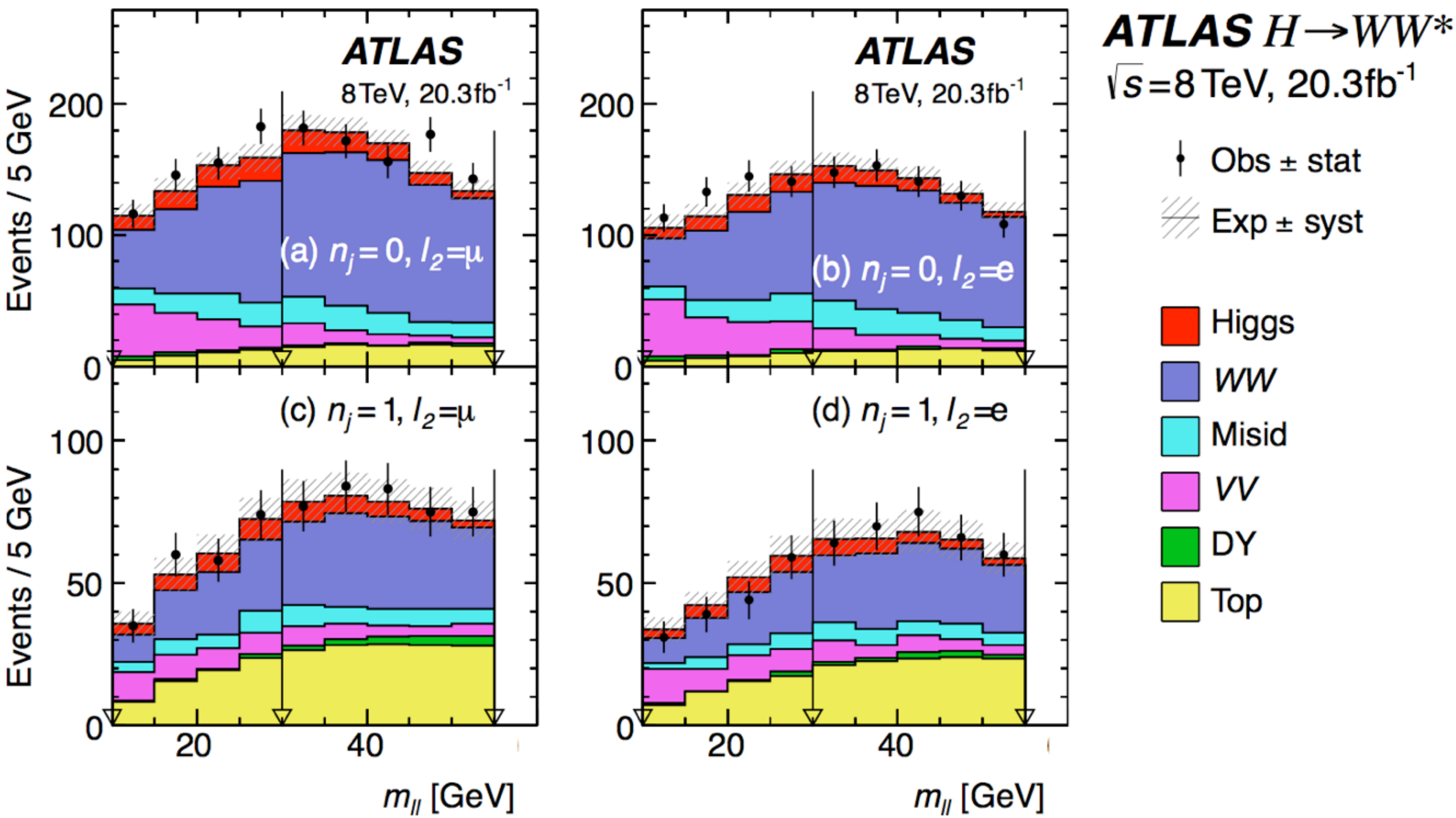
Once we are convinced that the Higgs resonance is actually present at a mass of 125 GeV, we can look for its signatures in other decay modes. These have larger rates, but they produce events that are not obviously distinguishable from other Standard Model reactions.

An example is $pp \to h \to W^+W^- \to \ell^+\ell^-\nu\overline{\nu}$. This is not obviously distinguishable from

$$pp \to W^+W^- \to \ell^+\ell^-\nu\overline{\nu}$$

The signal to background can be enhanced to going to a region where $m(\ell^+\ell^-)$ and the angle between the two leptons are relatively small. It is also necessary to apply a jet veto ($n_j = 0, 1$) to avoid background from

$$pp \to t\bar{t} \to b\bar{b}\ell^+\ell^-\nu\overline{\nu}$$

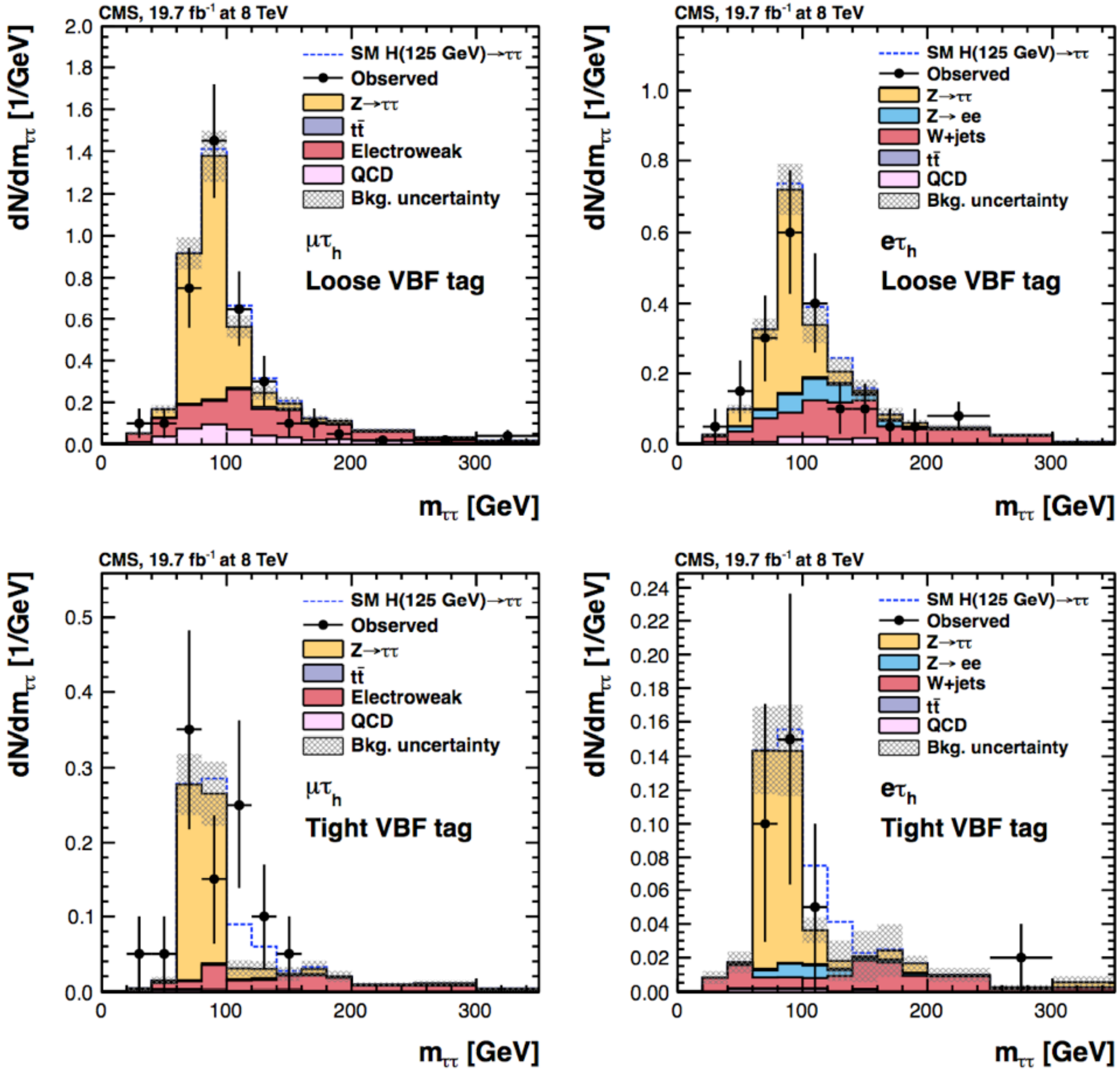


ATLAS
8 TeV, 20.3fb-1
(a) nj = 0, l2=μ
(b) nj = 0, l2=e
(c) nj = 1, l2=μ
(d) nj = 1, l2=e
Events / 5 GeV
mll [GeV]
ATLAS H→WW*
√s=8 TeV, 20.3fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top

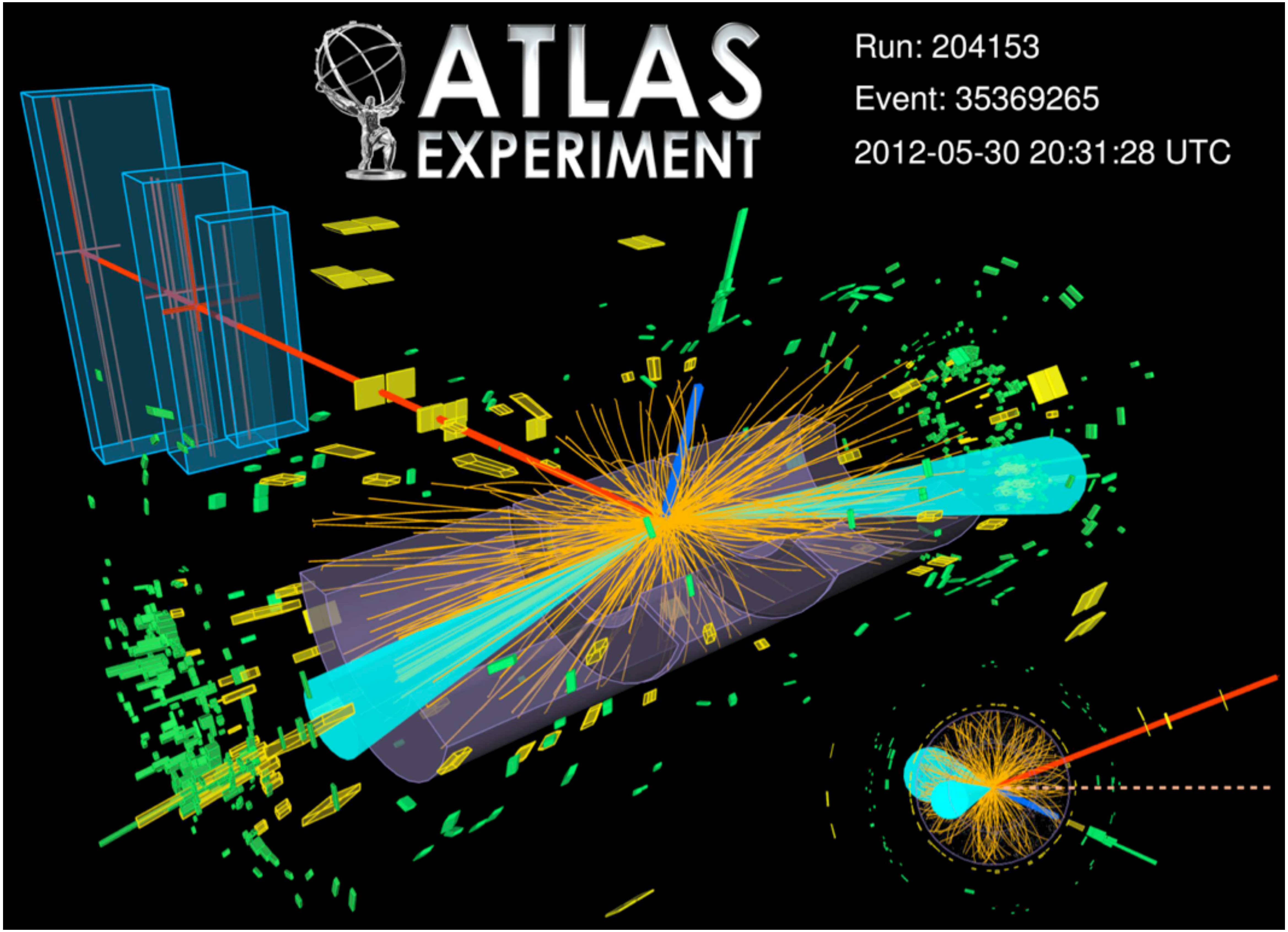
For $pp \to h \to \tau^+\tau^-$, important backgrounds are

$$pp \to Z \to \tau^+\tau^- \qquad\qquad pp \to W^+W^-$$

and QCD reactions where jets fake the τ signature. The strongest analyses use the vector boson fusion signature, with forward jets, to minimize the QCD background.



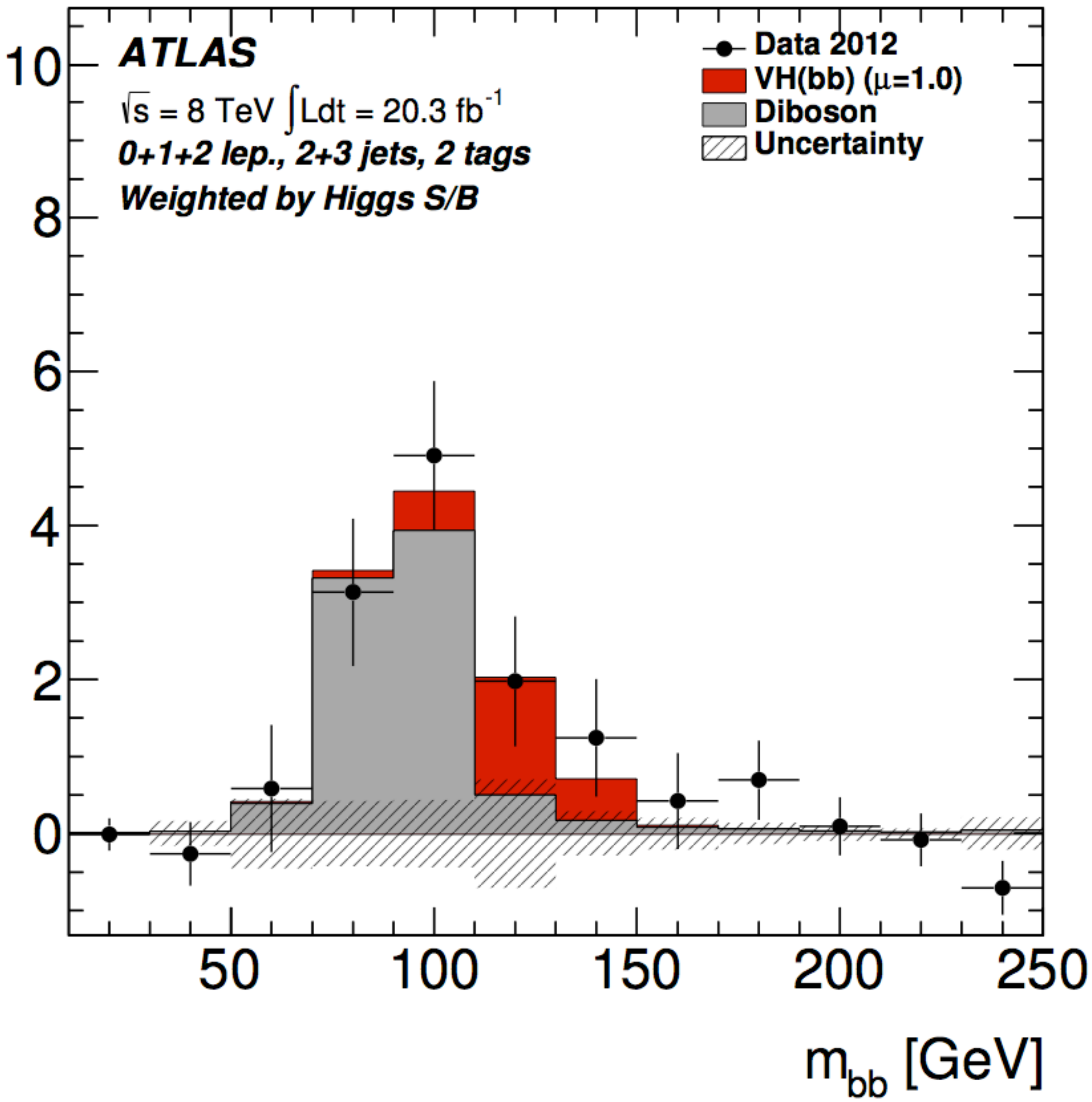
CMS, 19.7 fb^{-1} at 8 TeV
dN/dm$_{\tau\tau}$ [1/GeV]
m$_{\tau\tau}$ [GeV]
SM H(125 GeV)→ττ
Observed
Z→ττ
$t\bar{t}$
Electroweak
QCD
Bkg. uncertainty
μτ$_h$
Loose VBF tag
CMS, 19.7 fb^{-1} at 8 TeV
SM H(125 GeV)→ττ
Observed
Z→ττ
Z→ ee
W+jets
$t\bar{t}$
QCD
Bkg. uncertainty
eτ$_h$
Loose VBF tag
μτ$_h$
Tight VBF tag
eτ$_h$
Tight VBF tag


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

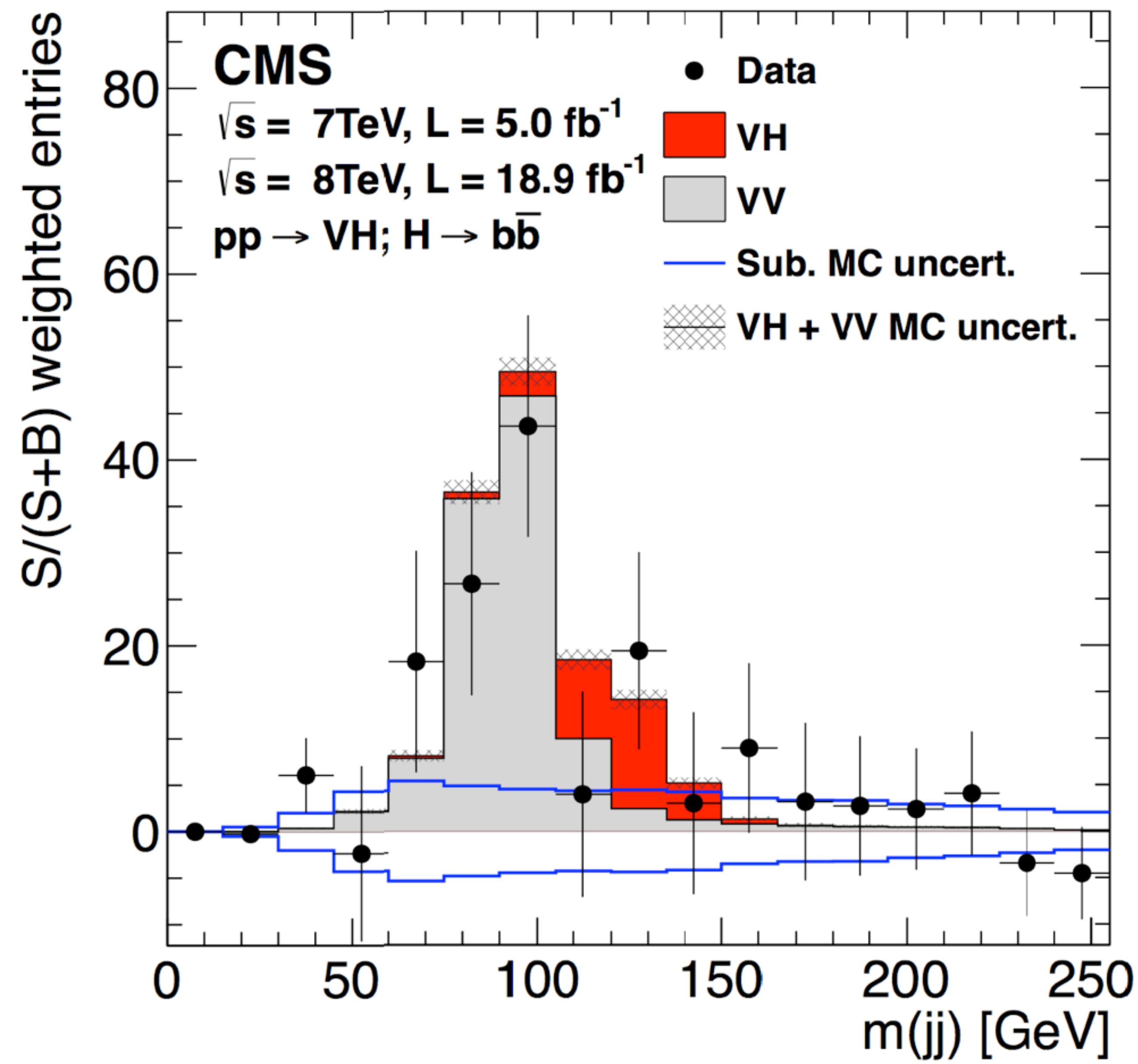
The most challenging of the major modes is the largest one, $h \to b\bar{b}$. Observing this mode in gg production is probably hopeless, since $gg \to b\bar{b}$ with 125 GeV mass jets is about a million times larger. Current analyses use associated production with W or Z. However, the reactions

$$
\begin{aligned}
pp &\to Vh \ , \ h \to b\bar{b} \\
pp &\to VZ \ , \ Z \to b\bar{b} \\
pp &\to Vg \ , \ g \to b\bar{b}
\end{aligned}
$$

are difficult to distinguish. It is thought that this can be done using properties of boosted h, Z, g systems including the jet mass and color flow.

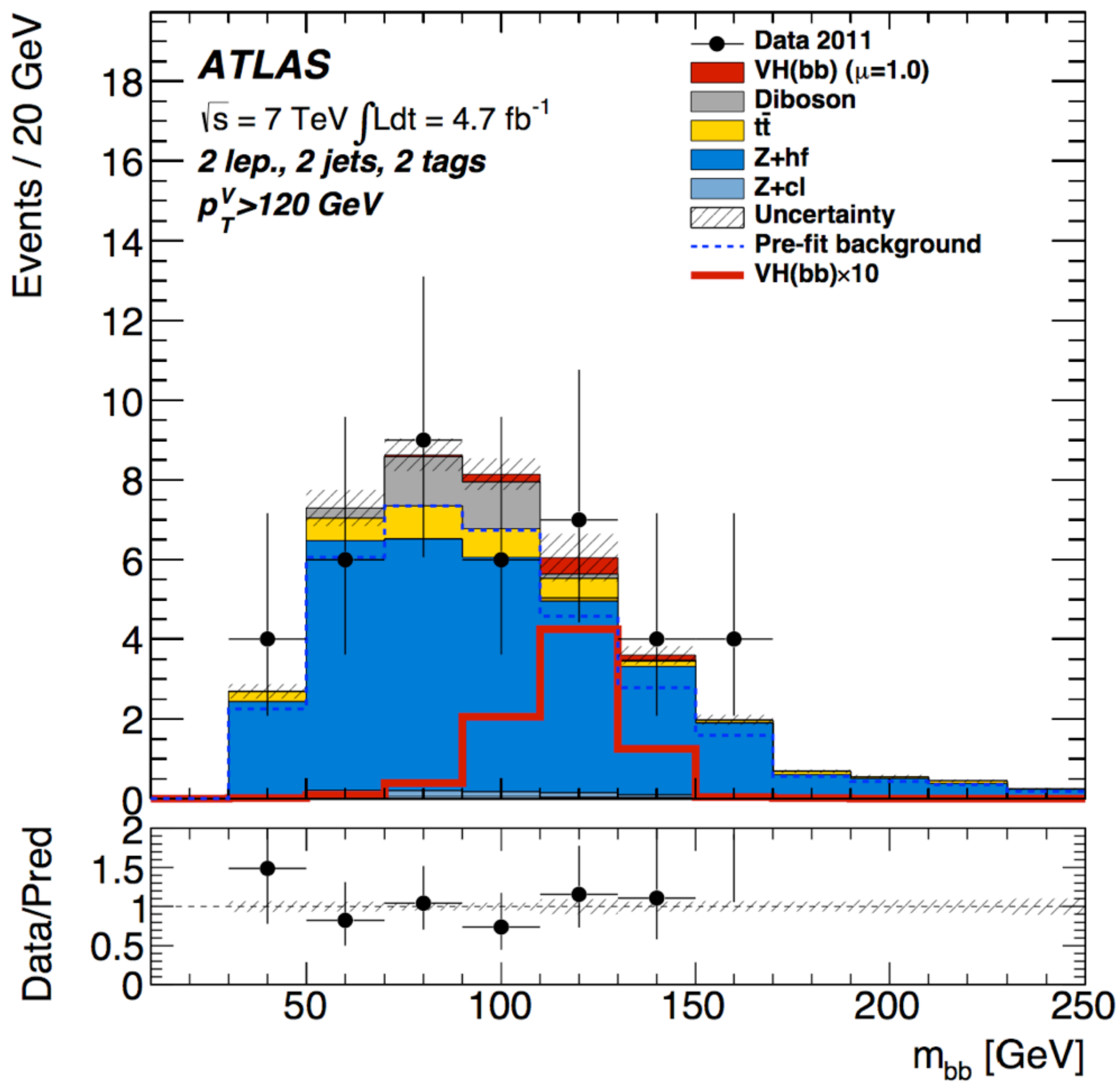


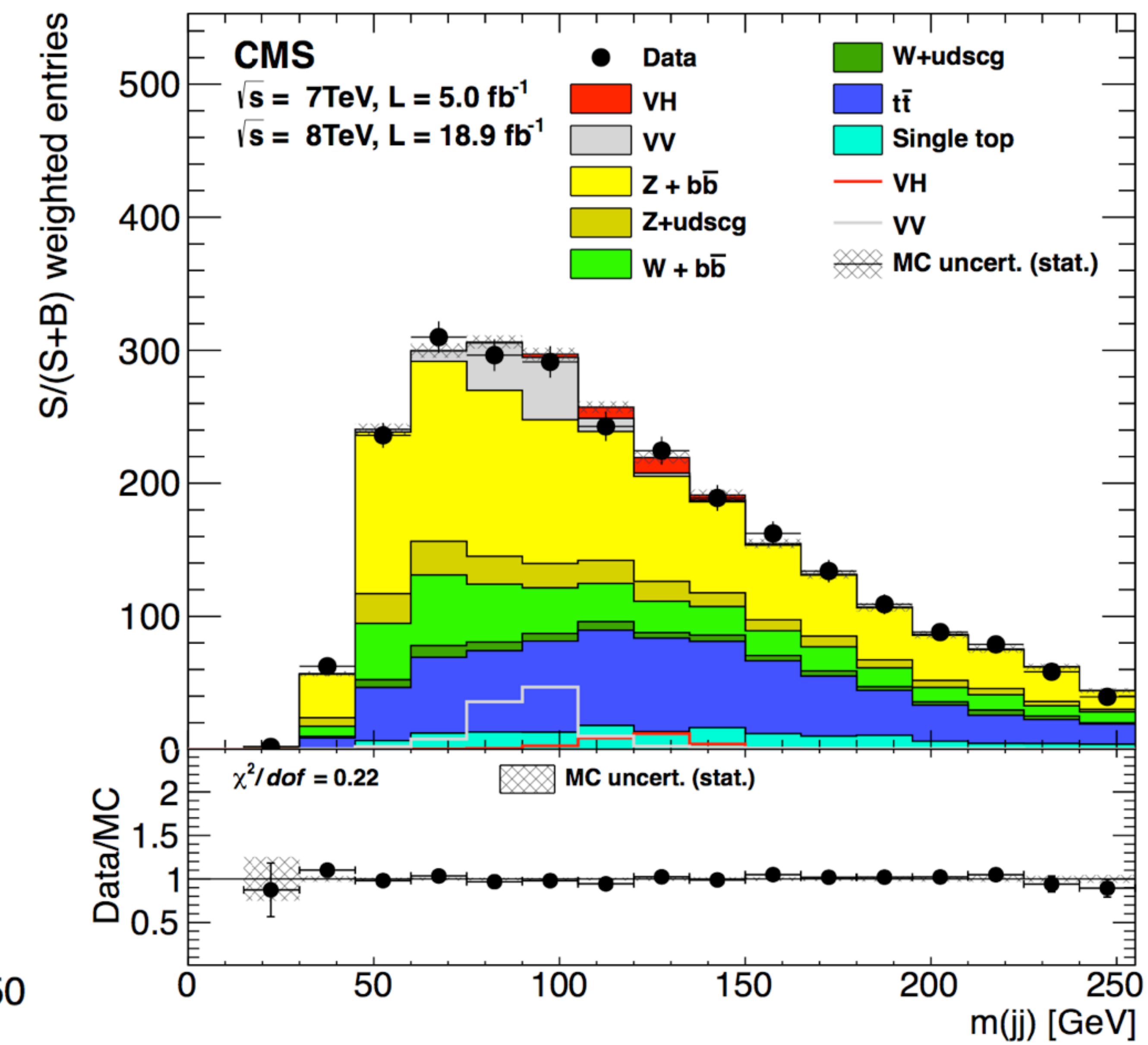
ATLAS
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
0+1+2 lep., 2+3 jets, 2 tags
Weighted by Higgs S/B
Data 2012
VH(bb) (μ=1.0)
Diboson
Uncertainty
m_bb [GeV]



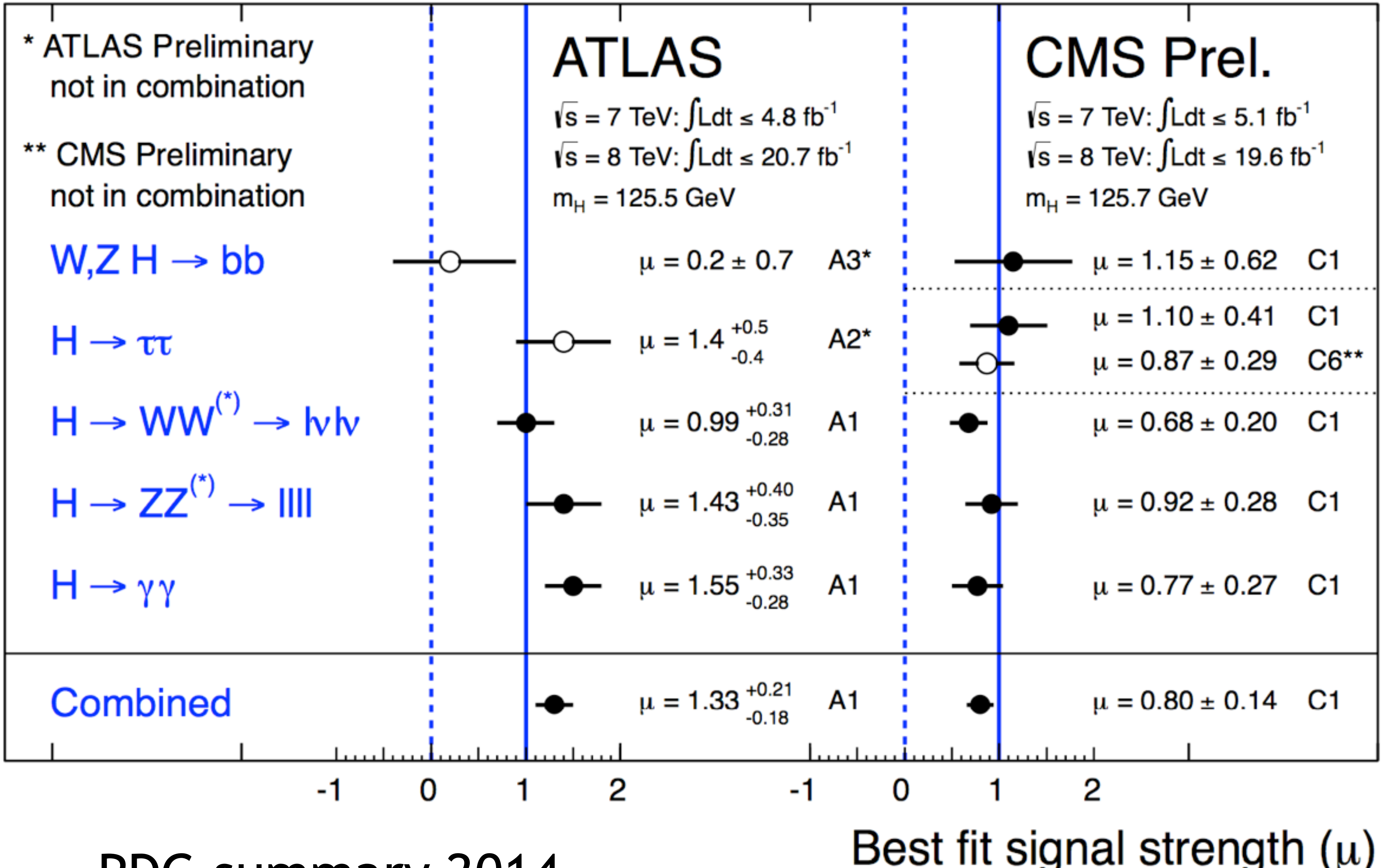
CMS
√s = 7TeV, L = 5.0 fb⁻¹
√s = 8TeV, L = 18.9 fb⁻¹
pp → VH; H → bb̄
Data
VH
VV
Sub. MC uncert.
VH + VV MC uncert.
S/(S+B) weighted entries
m(jj) [GeV]

Here are sample plots from some signal regions that are not background-subtracted.





Here is a summary of Higgs observations from LHC Run 1



PDG summary 2014

Now, what happens when we step outside the context of the Standard Model ?

The Standard Model has some special properties that we would like to preserve in more general models of symmetry breaking.

Look at the vector boson m^2 matrix

$$\begin{pmatrix} g^2 & & & \\ & g^2 & & \\ & & g^2 & -gg' \\ & & -gg' & g'^2 \end{pmatrix} \quad \text{on} \quad \begin{pmatrix} A^1 \\ A^2 \\ A^3 \\ B \end{pmatrix}$$

This has

a zero eigenvalue, leading to $m_A = 0$

an SU(2) symmetry among (A^1, A^2, A^3) leading to
$m_W = m_Z c_w$ ("custodial SU(2)")

Custodial symmetry is an accidental property of the Standard Model.

In the Standard Model, if we write $\varphi = \begin{pmatrix} \varphi^1 + i\varphi^2 \\ \varphi^0 + i\varphi^3 \end{pmatrix}$

the Higgs potential depends only on

$$|\varphi|^2 = (\varphi^0)^2 + (\varphi^1)^2 + (\varphi^2)^2 + (\varphi^3)^2$$

An expectation value for φ^0 preserves the SO(3) symmetry among the other components.

However, there are many other possible Higgs field assignments that also satisfy the requirements:

2- or multiple-Higgs doublet models:

In particular, the fermion-Higgs couplings of the Standard Model can be generalized. Let

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

Then we can give mass to the quarks and leptons with

$$\mathcal{L} = -y_e L_a^\dagger \varphi_{1a} e_R - y_d Q_a^\dagger \varphi_{2a} d_R - y_u Q_a^\dagger \epsilon_{ab} \varphi_{3b} u_R + h.c.$$

where φ_1, φ_2 have $Y = +1/2$, φ_3 has $Y = -1/2$. In the Standard Model, we set $\varphi = \varphi_1 = \varphi_2 = \varphi_3^*$; however, we could as well introduce separate fields. The assignment $\varphi_3^* = \varphi$ is inconsistent with supersymmetry, so in those models we must have at least two Higgs doublets.

Georgi-Machacek model:

Introduce (2I+1) Higgs multiplets in an isospin I representation of SU(2). For example, for I = 1,

$$X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

where the columns have Y = -1, 0, 1, respectively. The model can be arranged to have an SU(2)xSU(2) symmetry, and an expectation value

$$\langle X \rangle = V \cdot \mathbf{1}$$

breaks this down to the diagonal SU(2). We need at least one I = 1/2 multiplet (equivalent to the Standard Higgs) to give mass to fermions. Otherwise, we can add fields with any I.

Technicolor:

Introduce a copy of QCD with two massless flavors (U,D), with the left-handed fields in a weak-interaction SU(2) doublet, and $M_\rho = 2\ TeV$. This model has SU(2)xSU(2) chiral symmetry, broken to the diagonal SU(2) as in ordinary QCD. This breaks SU(2)xU(1). The W mass generated is

$$m_W = \frac{gF_\pi}{2} \quad \text{with} \quad F_\pi = 250\ \mathrm{GeV}$$

(This specific model is excluded by the measurement of S in precision electroweak, and because it contains no light Higgs boson.)

"Little Higgs":

Introduce new strong interactions at 10 TeV with the chiral symmetry SU(4) (e.g. 4 gauge multiplets in a real representation of the gauge group), such that strong interaction will break this spontaneously to SO(4).

This model has 15 - 6 = 9 pion-like Goldstone bosons.

SO(4) = SU(2)xSU(2). The 9 bosons belong to the representations $(0,0) + (0,\frac{1}{2}) + (\frac{1}{2},0) + (\frac{1}{2},\frac{1}{2})$

ie. 1 + 2 + 2 + 4 states

If we gauge the first SU(2), the $(\frac{1}{2},\frac{1}{2})$ multiplet of bosons can be identified with the Higgs field.

So, there are many possible forms for the symmetry-breaking sector, which potentially involve many new fields. But, now that we have discovered the Higgs boson and measured some of its properties, shouldn't these be excluded ?

There is a barrier: Haber's Decoupling Theorem:

If the spectrum of the Higgs sector contains one Higgs boson of mass m_h and all other particles have mass at least M , then the influence of these particles on the properties of the light Higgs boson is proportional to

$$m_h^2/M^2$$

Then the effects of new physics at 1 TeV on the properties of the Higgs are at the percent level.

Proof of the theorem:

Integrate out the heavy fields. This gives a general Lagrangian with the Standard Model field content and SU(2)xU(1) symmetry. But, the Standard model is already the most general renormalizable model meeting these conditions. So (after we have measured the effective Standard Model parameters), the only effects of new fields come from dimension 6 operators, which give effects of size q^2/M^2 .

This is depressing but not hopeless.

In this context, the current 20-30% agreement of the Higgs properties with the predictions of the Standard Model is completely expected.

But, more accurate experiments could potentially show deviations in all of the visible Higgs decay modes.

Begin with 2 Higgs doublet models. In SUSY, e.g., one Higgs φ_d gives mass to e,d, the other φ_u gives mass to u.

Now there are 8 Higgs degrees of freedom, of which 3 are eaten by W,Z. We also add a parameter: $\tan\beta = v_u/v_d$

The physical states are mixtures of the remaining fields fields, with mixing angle

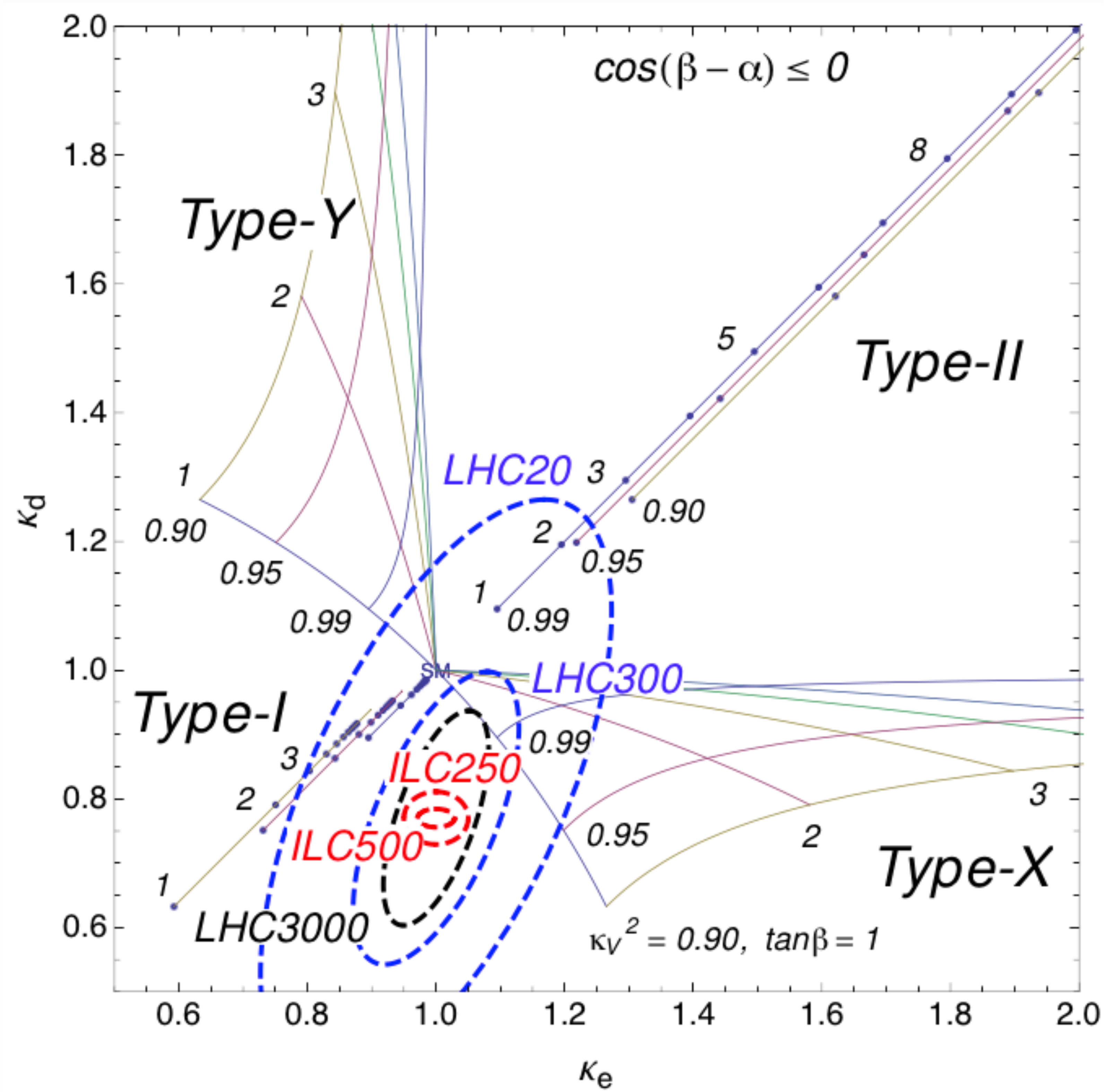
$$\begin{array}{ll} \alpha: & h^0, H^0 \\ \beta: & \pi^0, A^0 \quad \pi^\pm, H^\pm \end{array}$$

Then the coupling modifications are

$$g(b\bar{b}) = -\frac{\sin\alpha}{\cos\beta}\frac{m_b}{v} \qquad g(c\bar{c}) = \frac{\cos\alpha}{\sin\beta}\frac{m_c}{v}$$

In full models such as SUSY, the two angles are not independent. In fact, typically,

$$-\frac{\sin\alpha}{\cos\beta} = 1 + \mathcal{O}\left(\frac{m_Z^2}{m_A^2}\right)$$



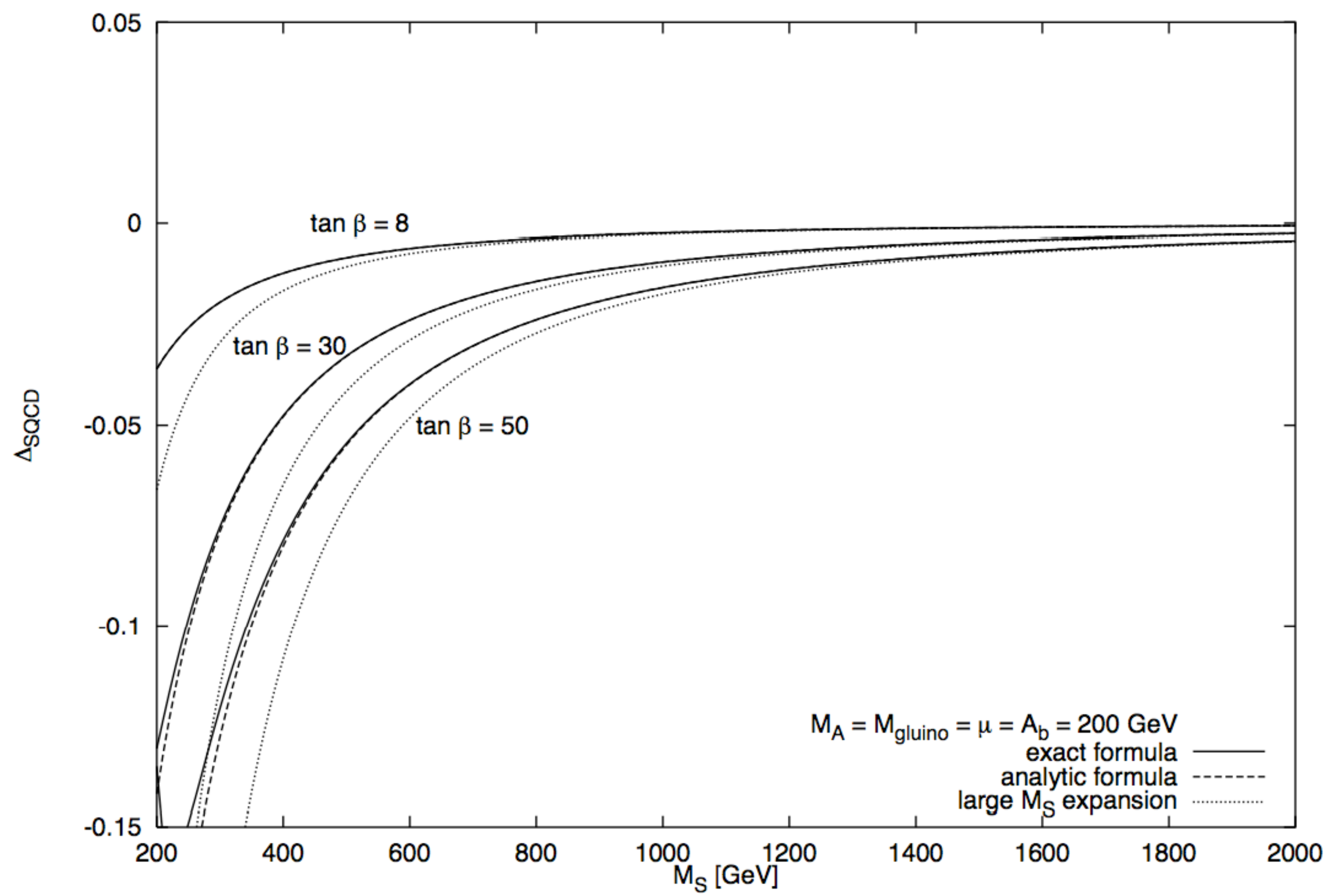
Kanemura, Tsumura, Yagyu, Yokoya

Then, typically, the corrections decrease as the SUSY mass scale becomes larger, for example

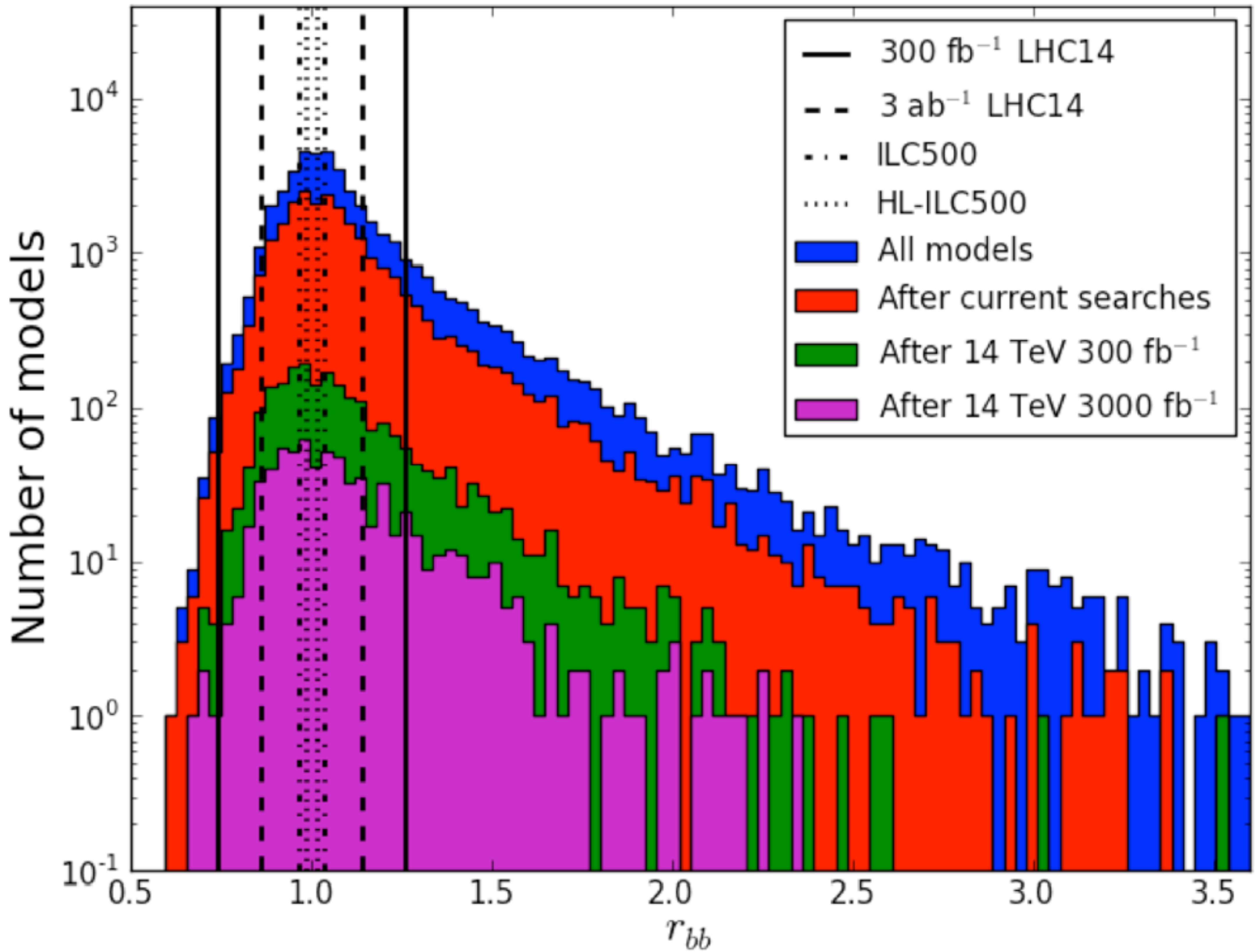
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \text{GeV}}{m_A}\right)^2$$

Loop with b,t squarks and gluinos can also modify this vertex, especially at large tan β.

Haber, Herrero, Logan, Penaranda, Rigolin, Temes

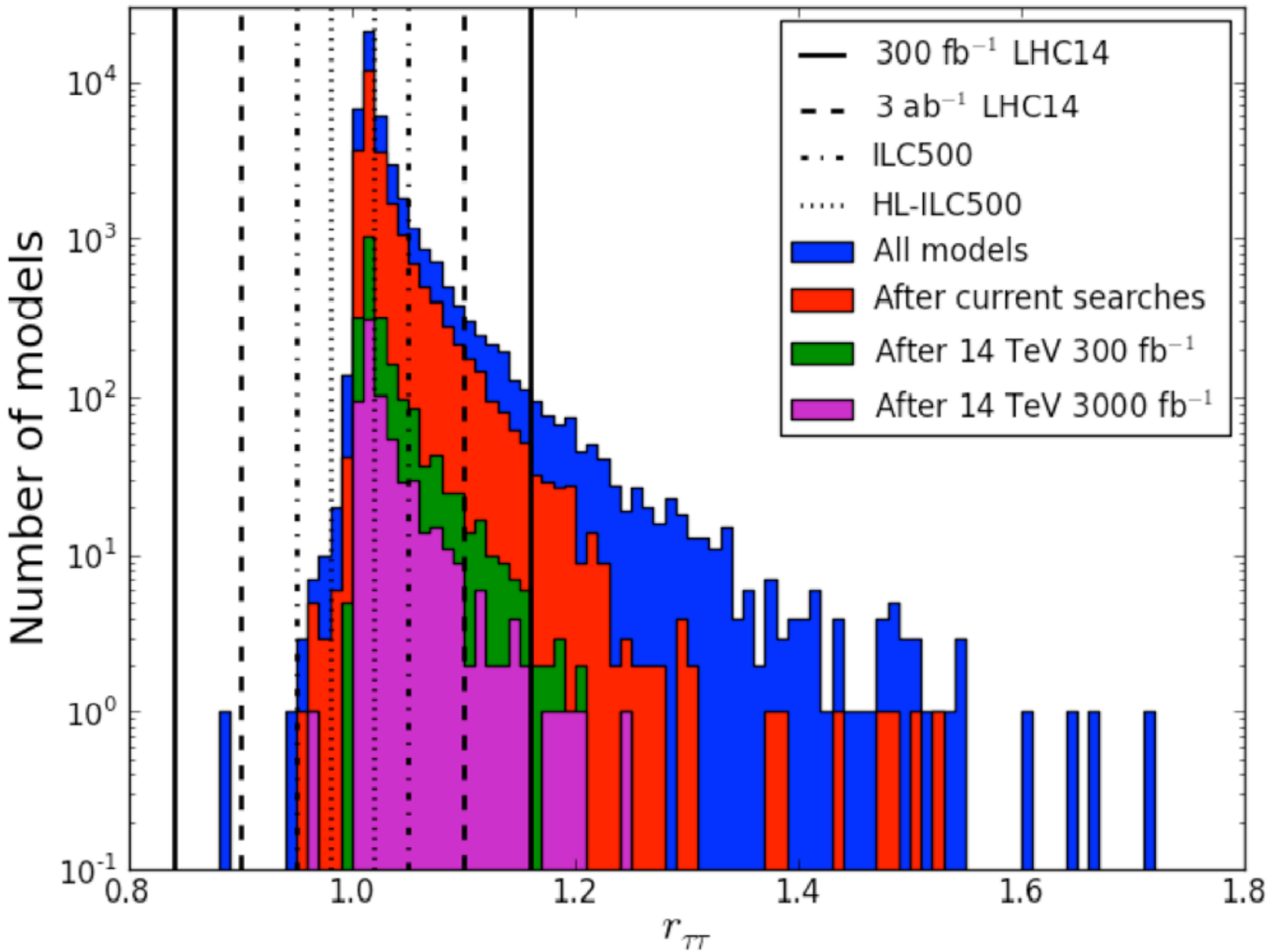


$\Gamma(h \to b\bar{b})$



Cahill-Rowley, Hewett, Ismail, Rizzo

$\Gamma(h \to \tau^+\tau^-)$



Cahill-Rowley, Hewett, Ismail, Rizzo

In 2 Higgs doublet models, corrections to the hVV are usually small. These are proportional to the contribution of each state h, H to the W,Z masses, and h 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).

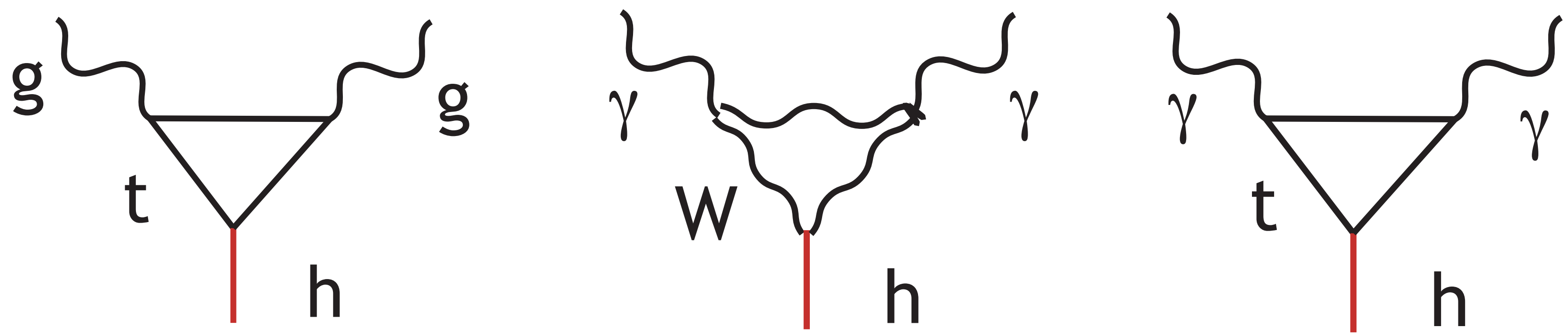
If the Higgs is a composite Goldstone boson, these couplings are corrected by (f ~ 1 TeV)

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

The decays

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

proceed through loop diagrams.



The loops are dominated by heavy particles that the Higgs boson cannot decay to directly.

However, again, decoupling puts a restriction:

Only the heavy particles of the SM, that is, t, W, Z, get 100% of their mass from the Higgs. For BSM particles such as $\widetilde{t}$ or T , the contribution to these loops is proportional to the fraction of their mass that comes from the Higgs vev.

Then, for example, a vectorlike T quark contributes

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

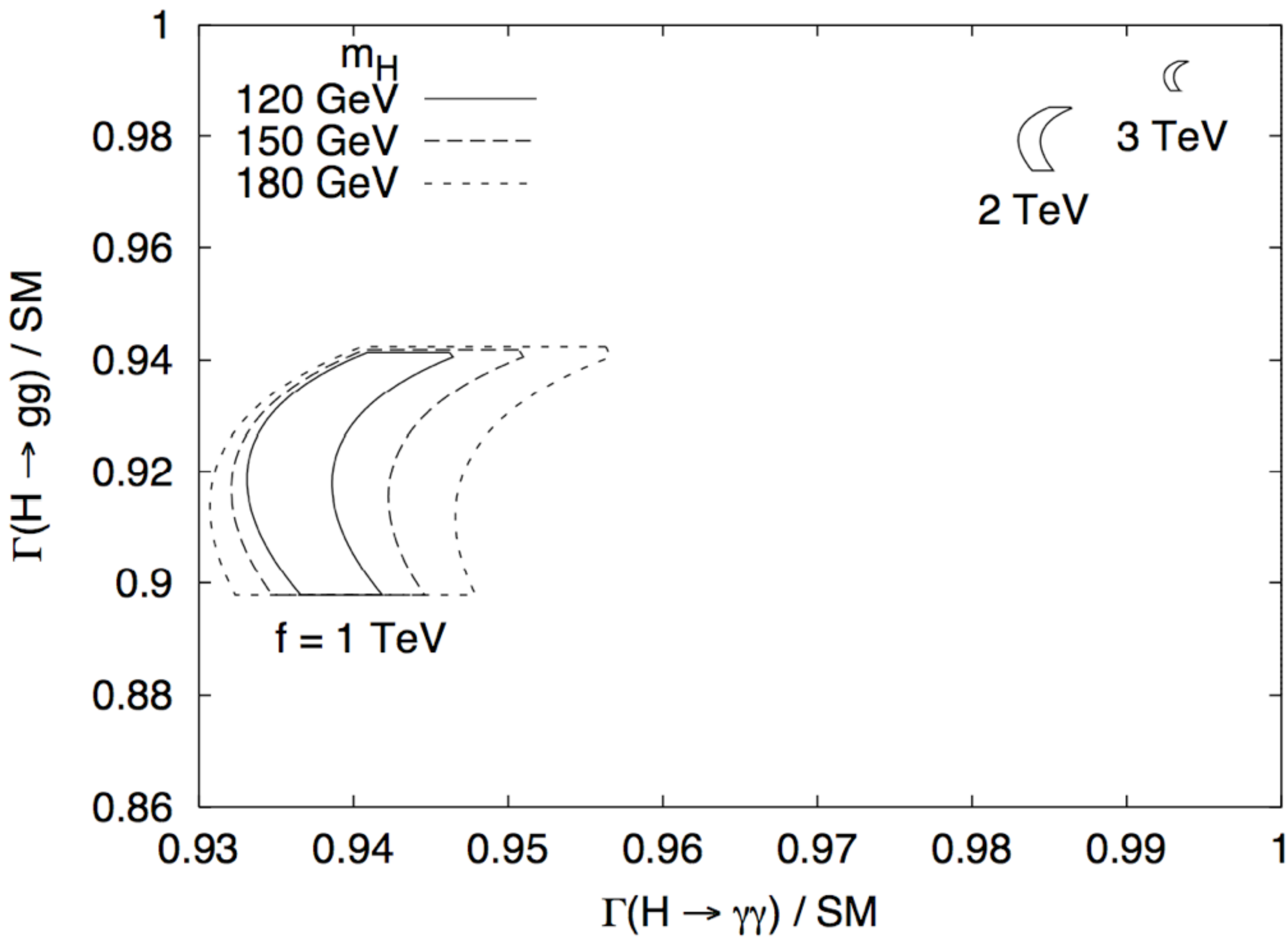
$$g(h\gamma\gamma)/SM = 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

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

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

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

Littlest Higgs model

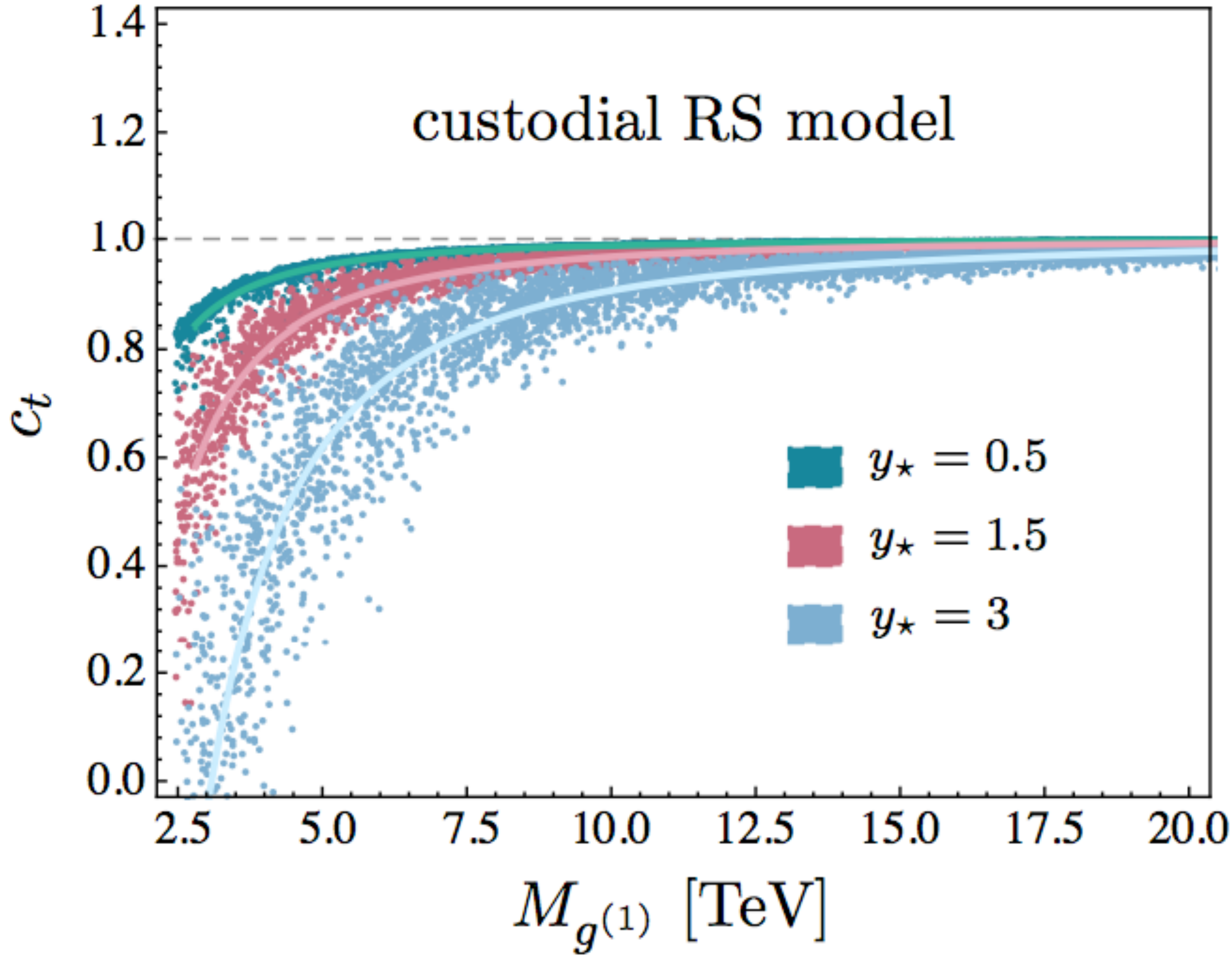


Han, Logan, McElrath, Wang

In composite Higgs models, the shifts in the $\gamma\gamma$ and gg partial widths come both from the modification of the top quark coupling and from the contributions of heavy vectorlike particles.

These effects are disentangled by direct measurement of the Higgs coupling to $t\bar{t}$.

Substantial effects are expected in 5-dimensional models, such as Randall-Sundrum models, especially those that have a special role for the top quark in SU(2)xU(1) symmetry breaking.



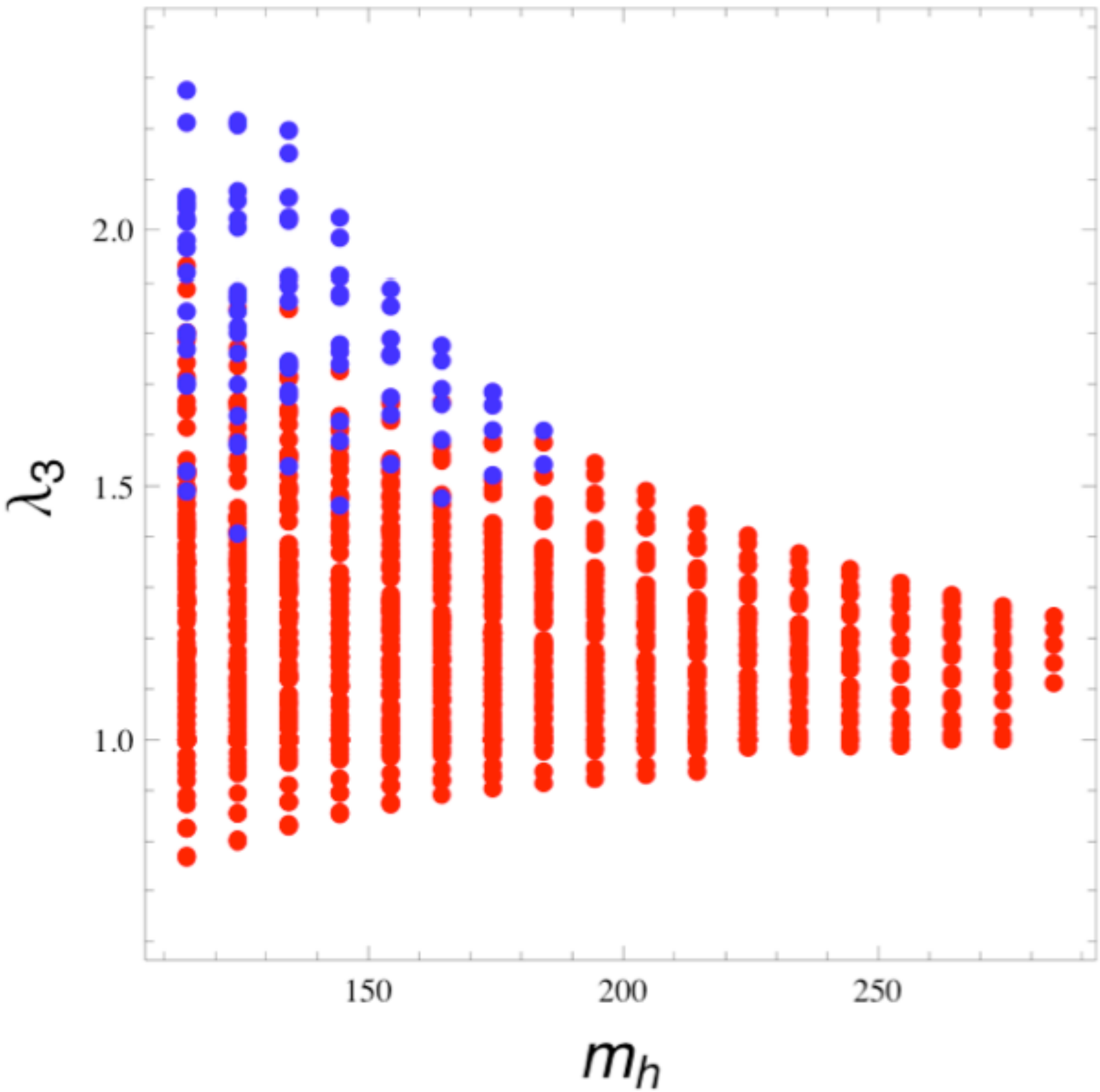
Malm, Neubert, Schmell

The Higgs self-coupling is a special case in this story.

Whereas we can expect the other Higgs couplings to be measured at the percent level, the hhh coupling is much more difficult to access.

However, order-1 deviations in the hhh coupling are expected in some scenarios, in particular, in models of baryogenesis at the electroweak scale. These may be the only models of baryogenesis testable with accelerator data.

λ_3 vs m_h for $\xi>1$



Noble and Perelstein

The result of this survey is 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, a useful one.

fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

γγ, gg couplings - heavy vectorlike particles

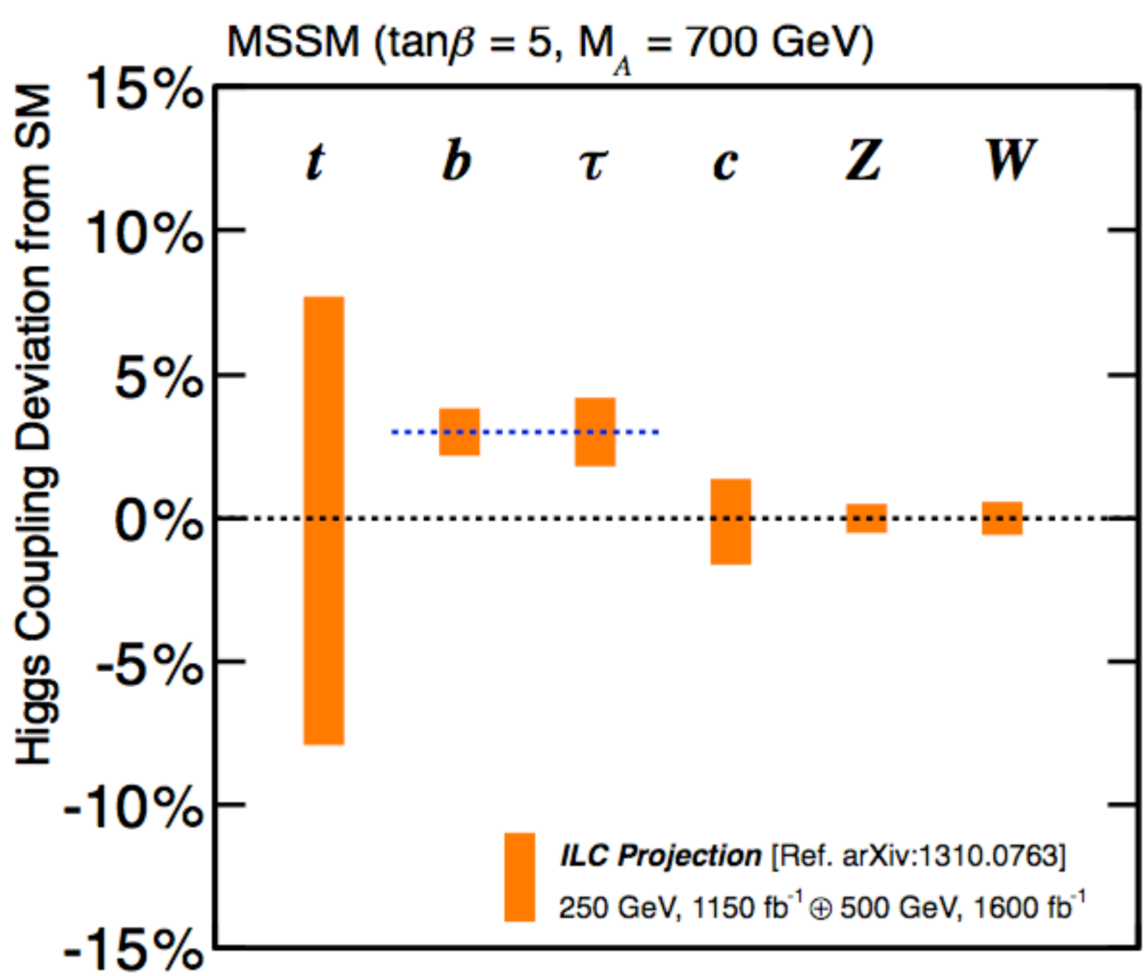
tt coupling - Higgs/top compositeness

hhh coupling (large deviations) - baryogenesis

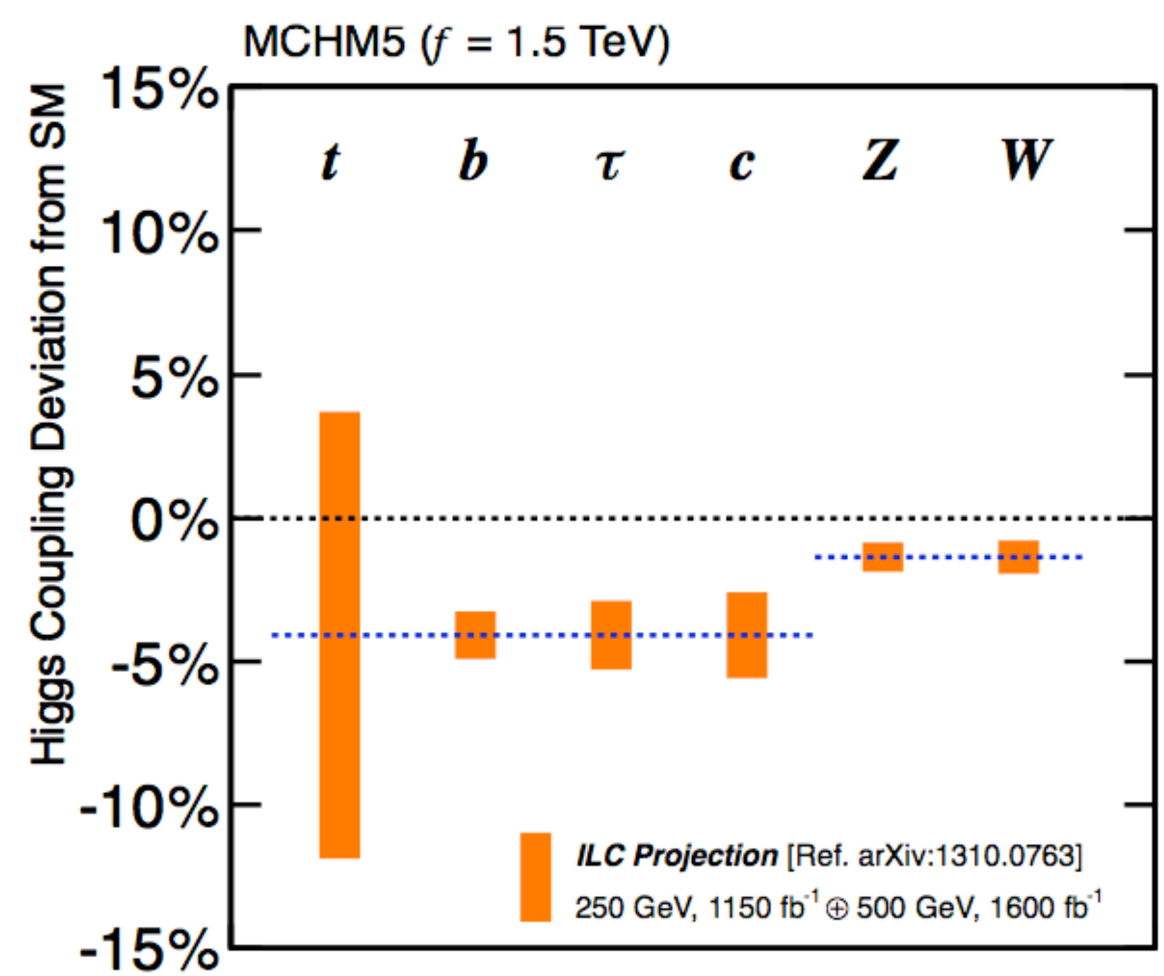
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs

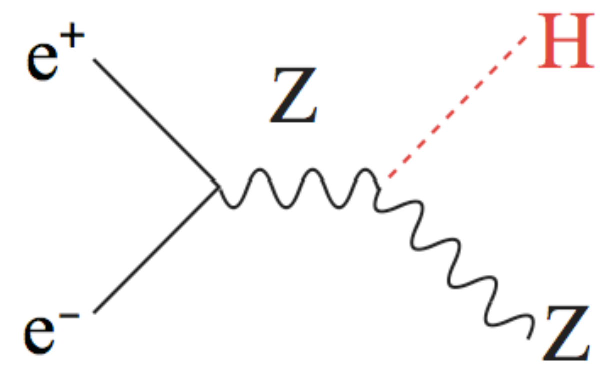


Kanemura, Tsumura, Yagyu, Yokoya

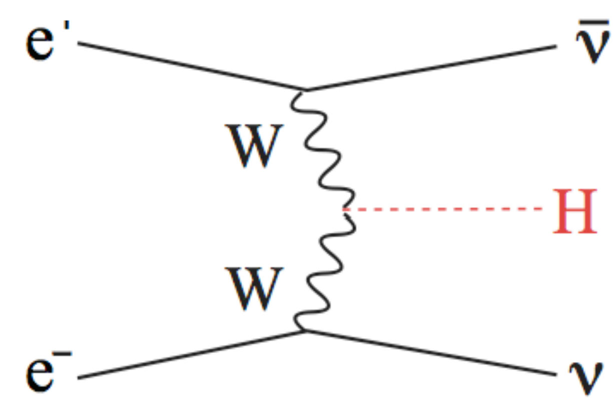
Given the interest of this program and the difficulty of reaching the required levels of precision at the LHC, it is not surprising that there are a number of proposals of new e^+e^- colliders specifically addressing precision Higgs measurements.

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

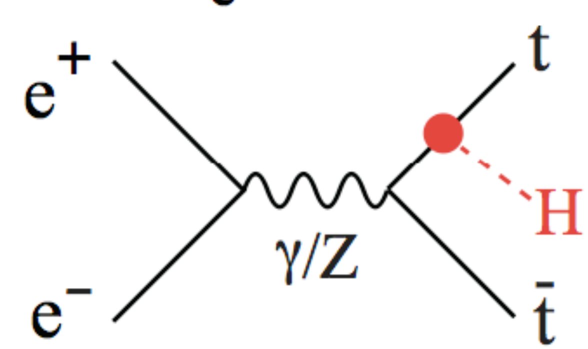
Higgsstrahlung



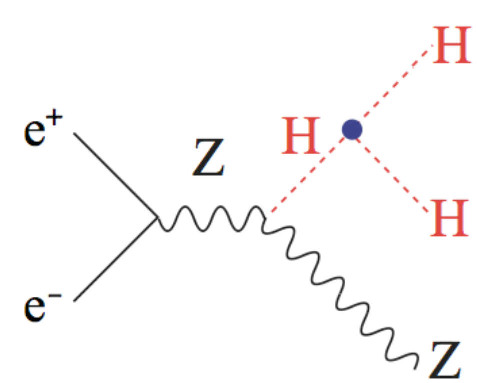
vector boson fusion

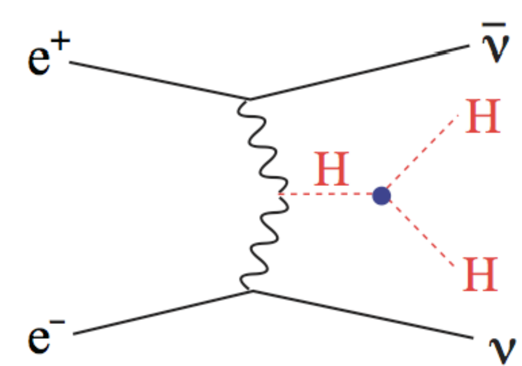


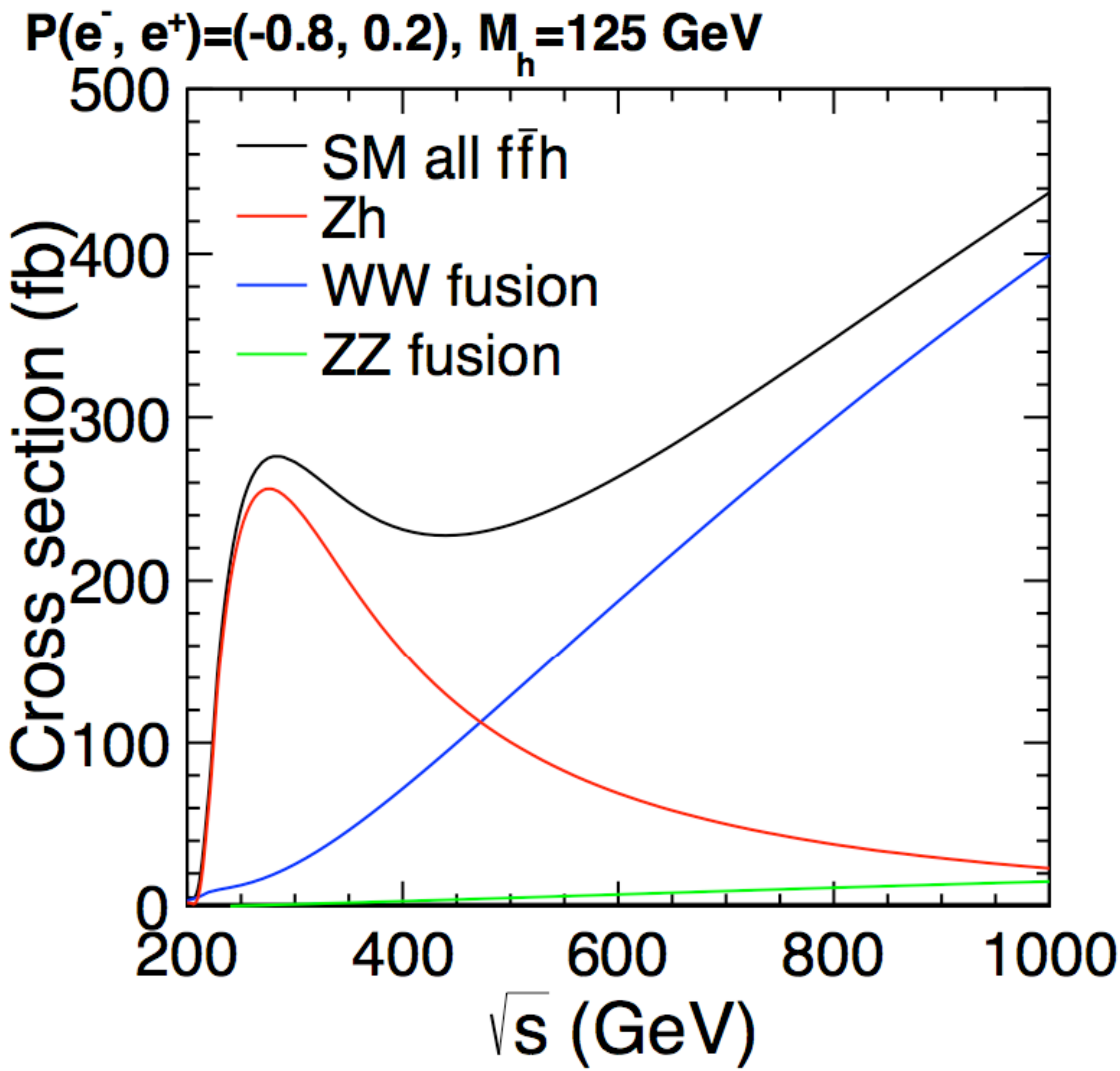
associated production with top



Higgs pair production







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

Before going into the experimental prospects, it is important to say that we also need improved Standard Model theory.   The experimental comparison with the Standard Model can only be as good as the accuracy of the Standard mode predictions.

For this, we need a program of theoretical calculations similar to the program of high precision calculations for the Z experiments.   Particularly important terms missing today are

$\Gamma(h \to b\bar{b})$	complete 2-loop electroweak
$\Gamma(h \to ZZ \to 4f)$	complete 2-loop electroweak
$\Gamma(h \to \gamma\gamma)$	to 3 loops

The precision Higgs program also requires imputs from experiment that need to be known to high precision.

One of these must be determined as a part of the Higgs measurements

$$\Delta(m_h) = 15 \text{ MeV} \to \Delta(g_{hWW}),\ \Delta(g_{hZZ}) \sim 0.1\%$$

Also, the quantities

$$m_b\ ,\ m_c\ ,\ \alpha_s$$

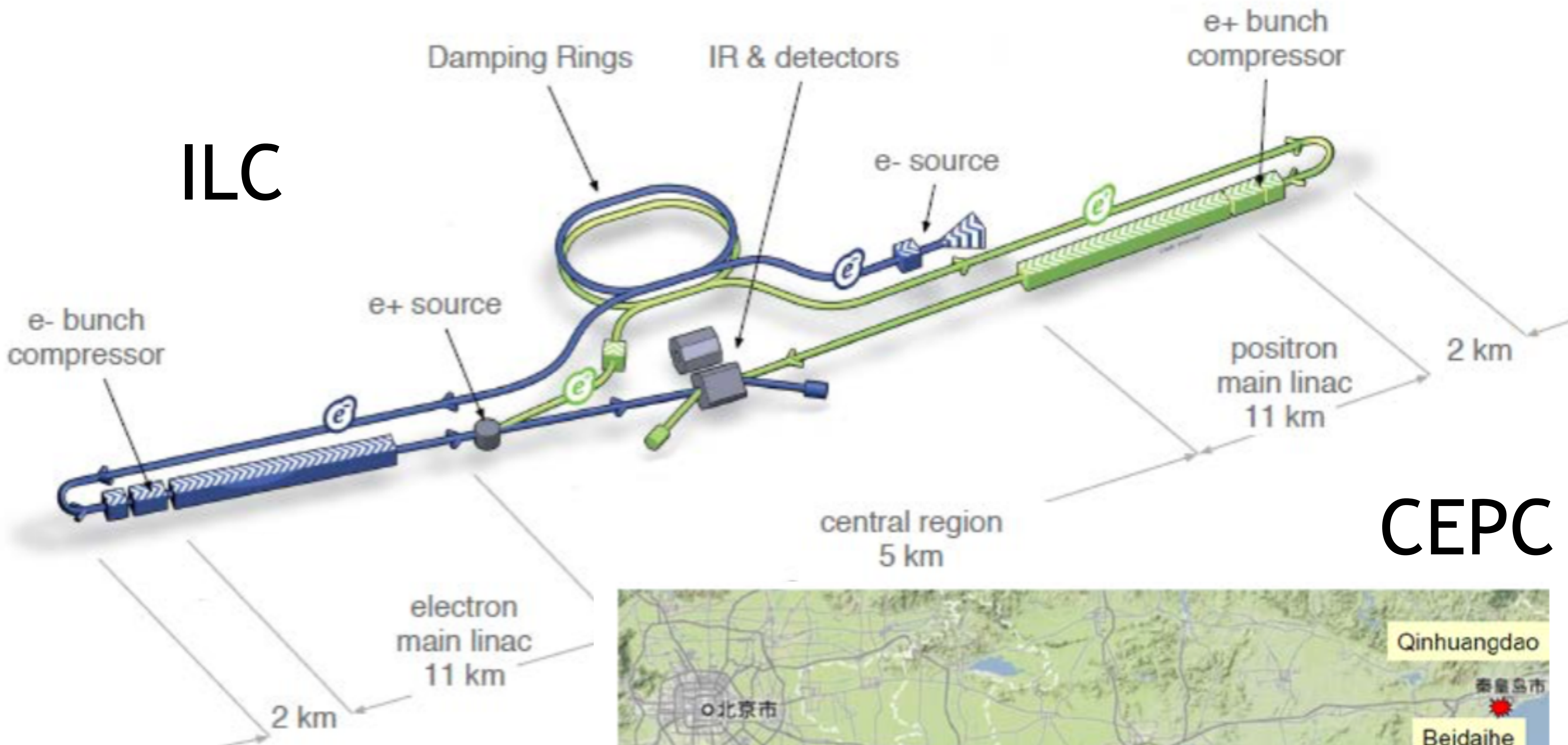
need to be determined accurately from lower energy data.

projection of lattice QCD inputs, from Lepage, Mackenzie, MEP:

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

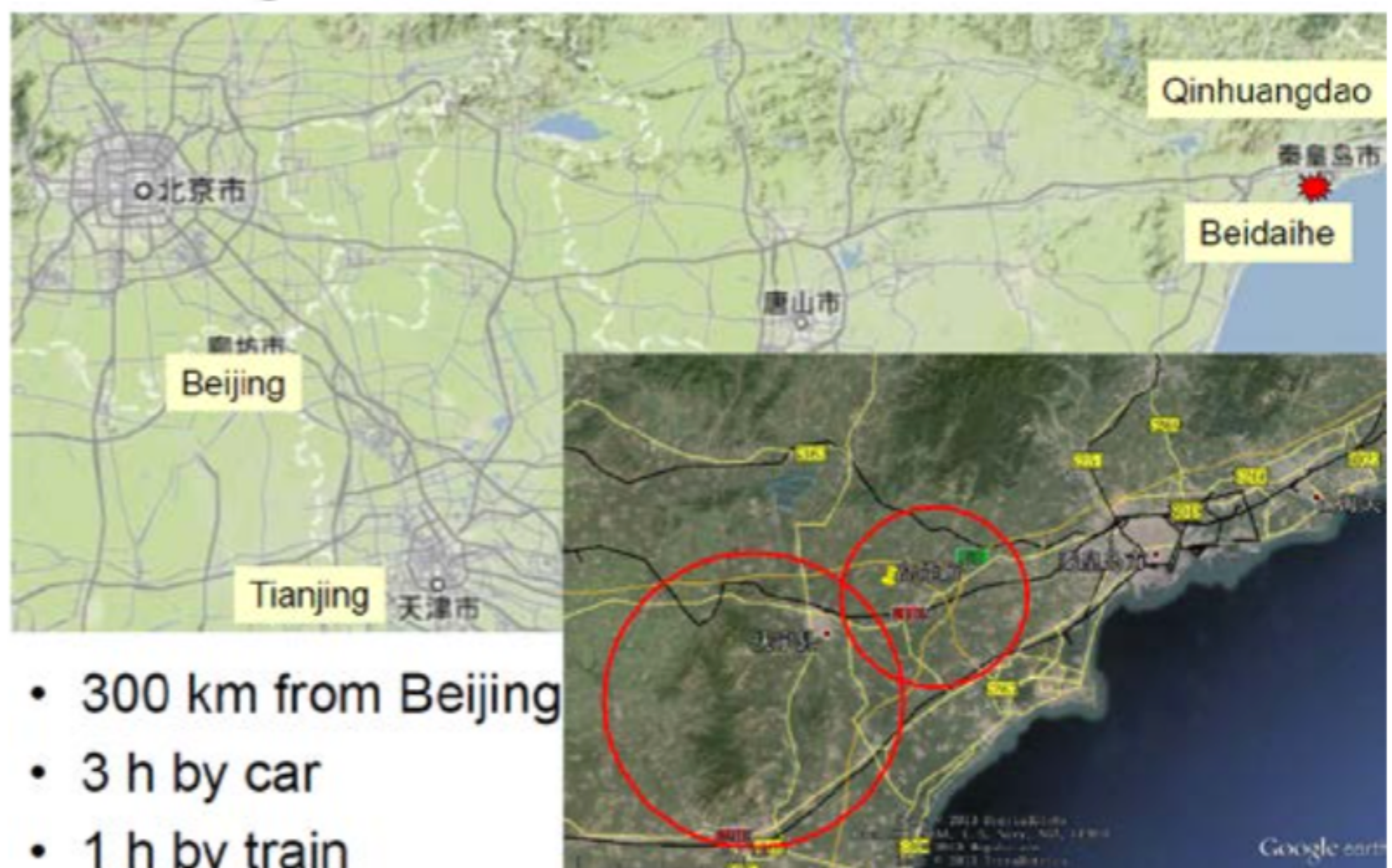
errors in %

ILC

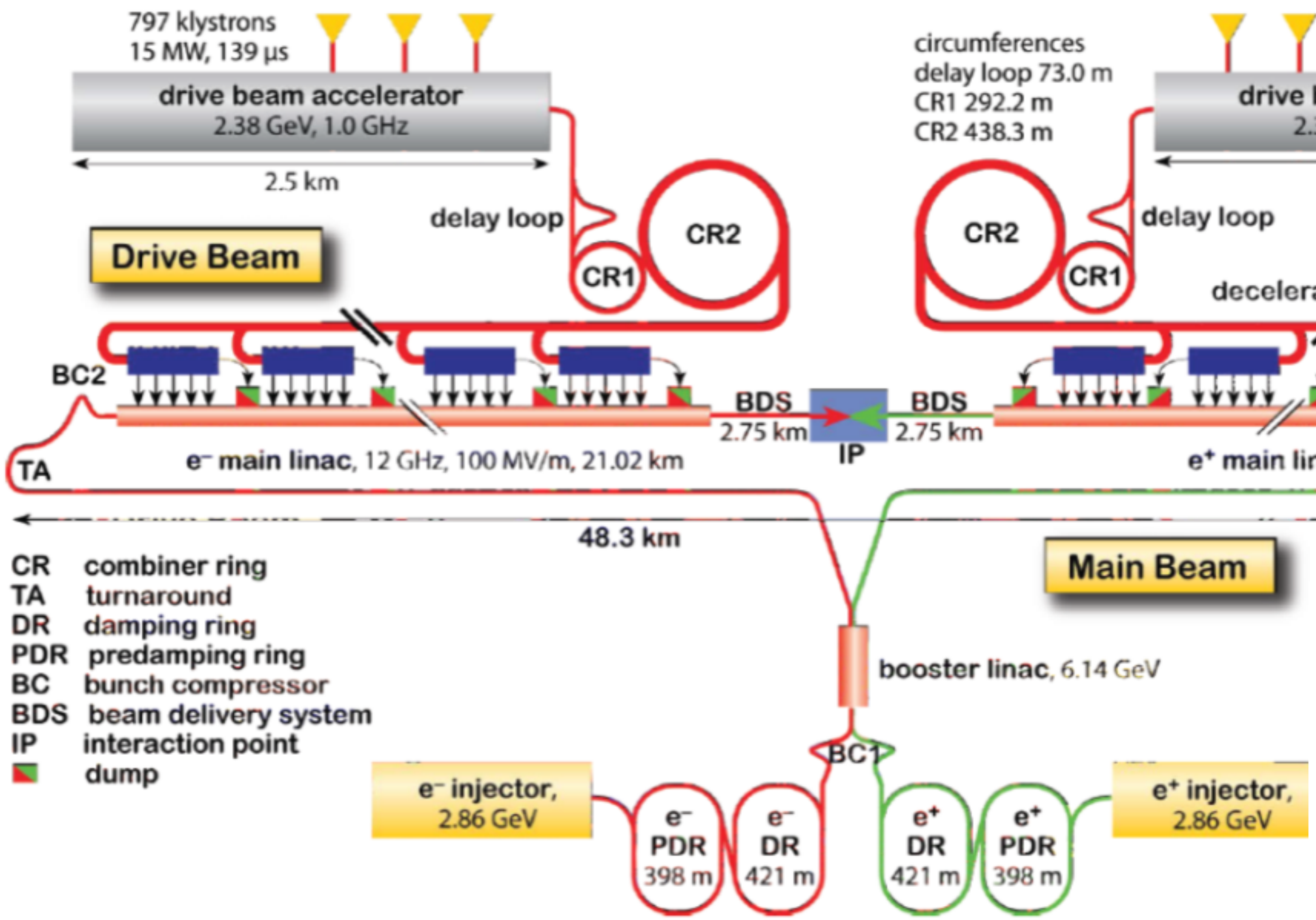


CEPC

new accelerators proposed in Asia

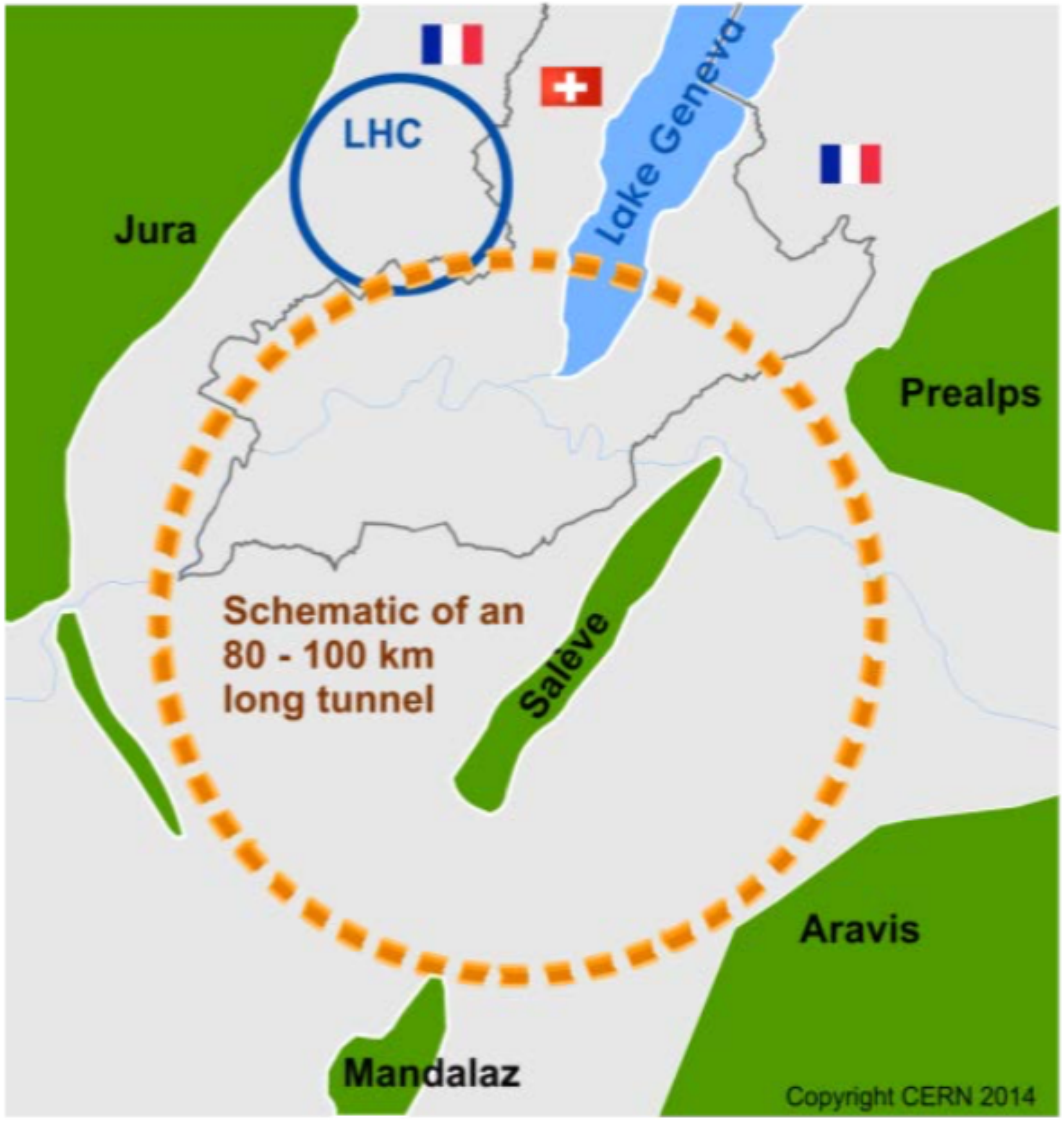


- 300 km from Beijing
- 3 h by car
- 1 h by train



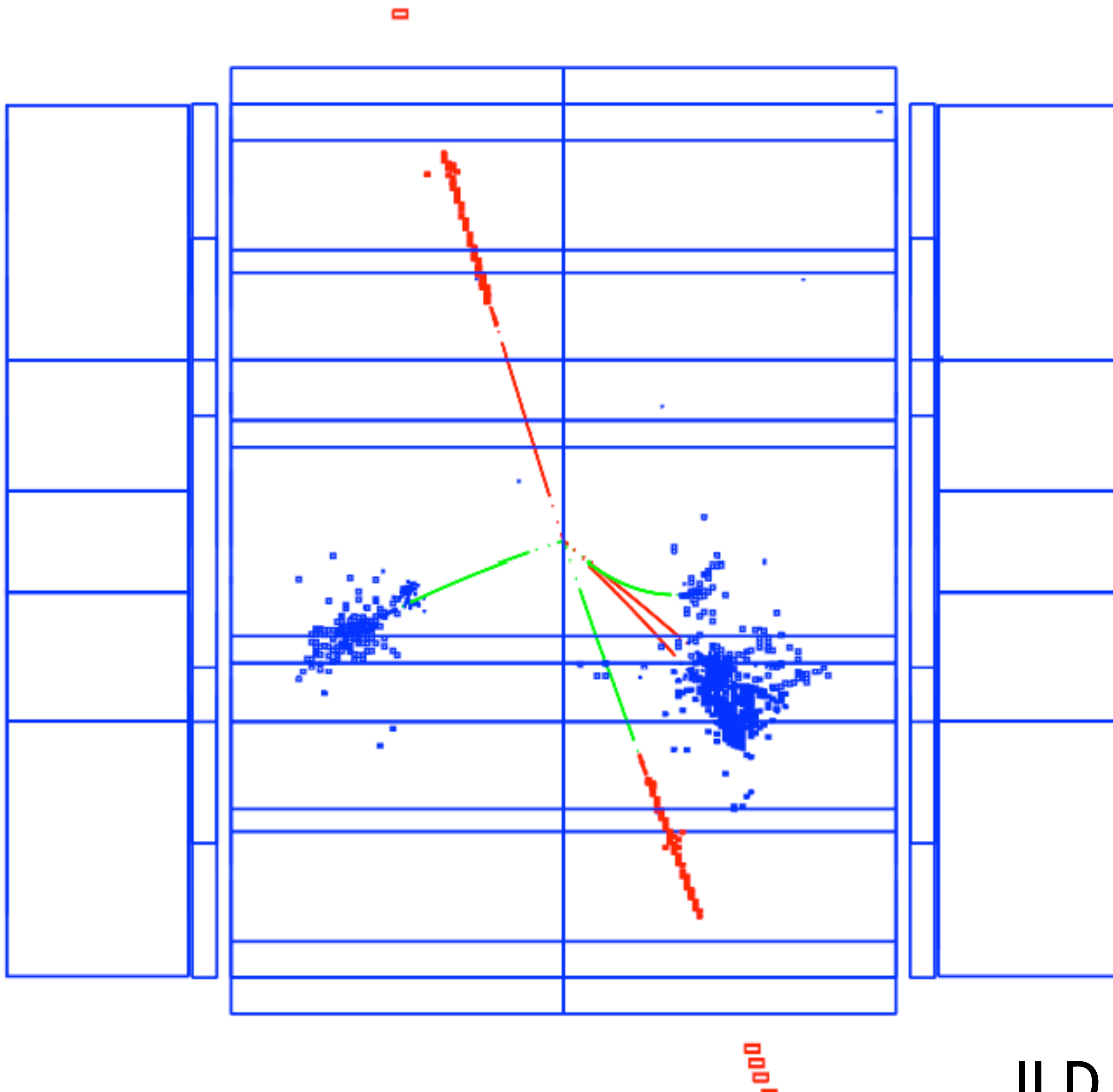
CLIC

FCC-ee



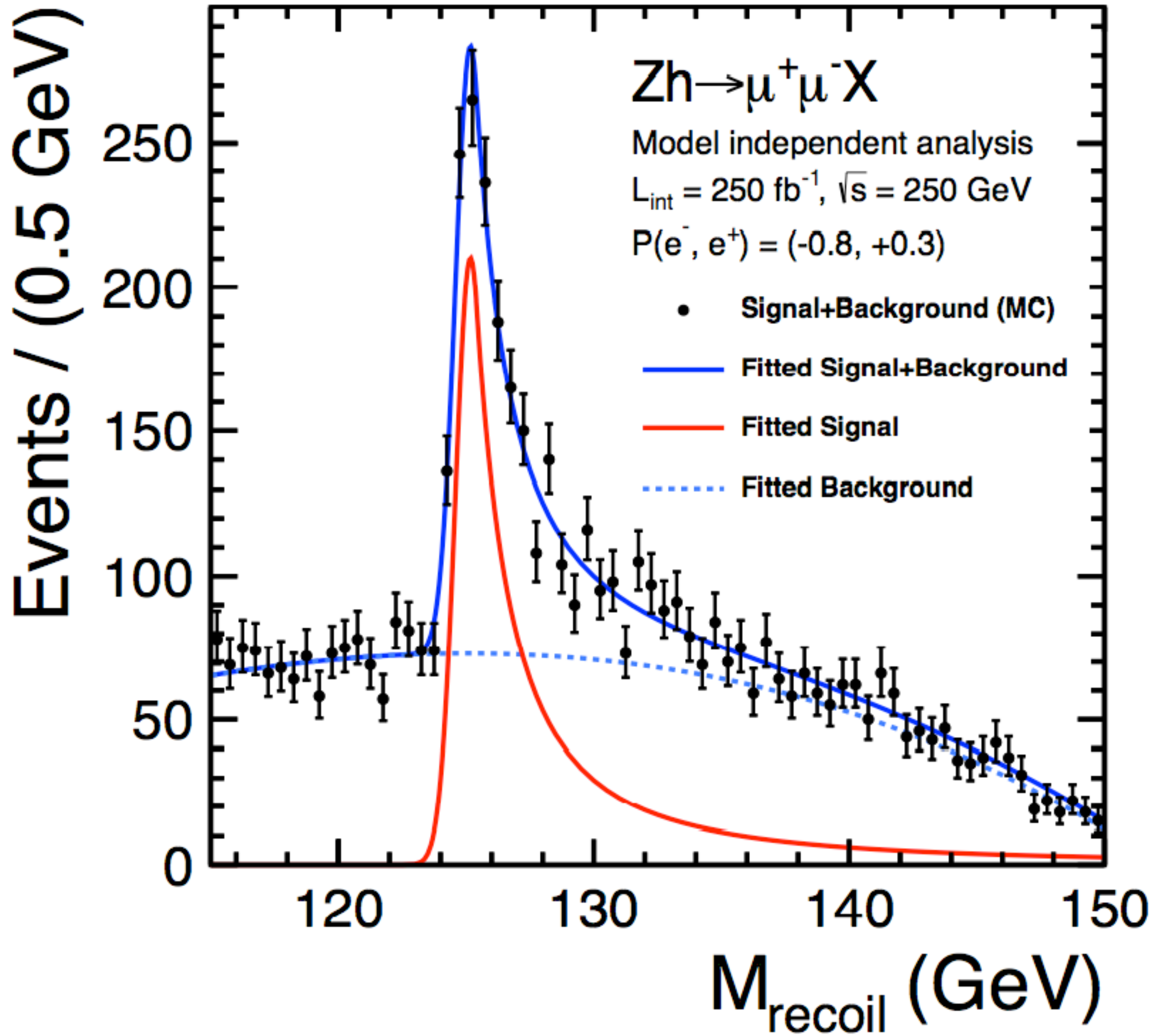
new accelerators proposed for the next CERN project after LHC

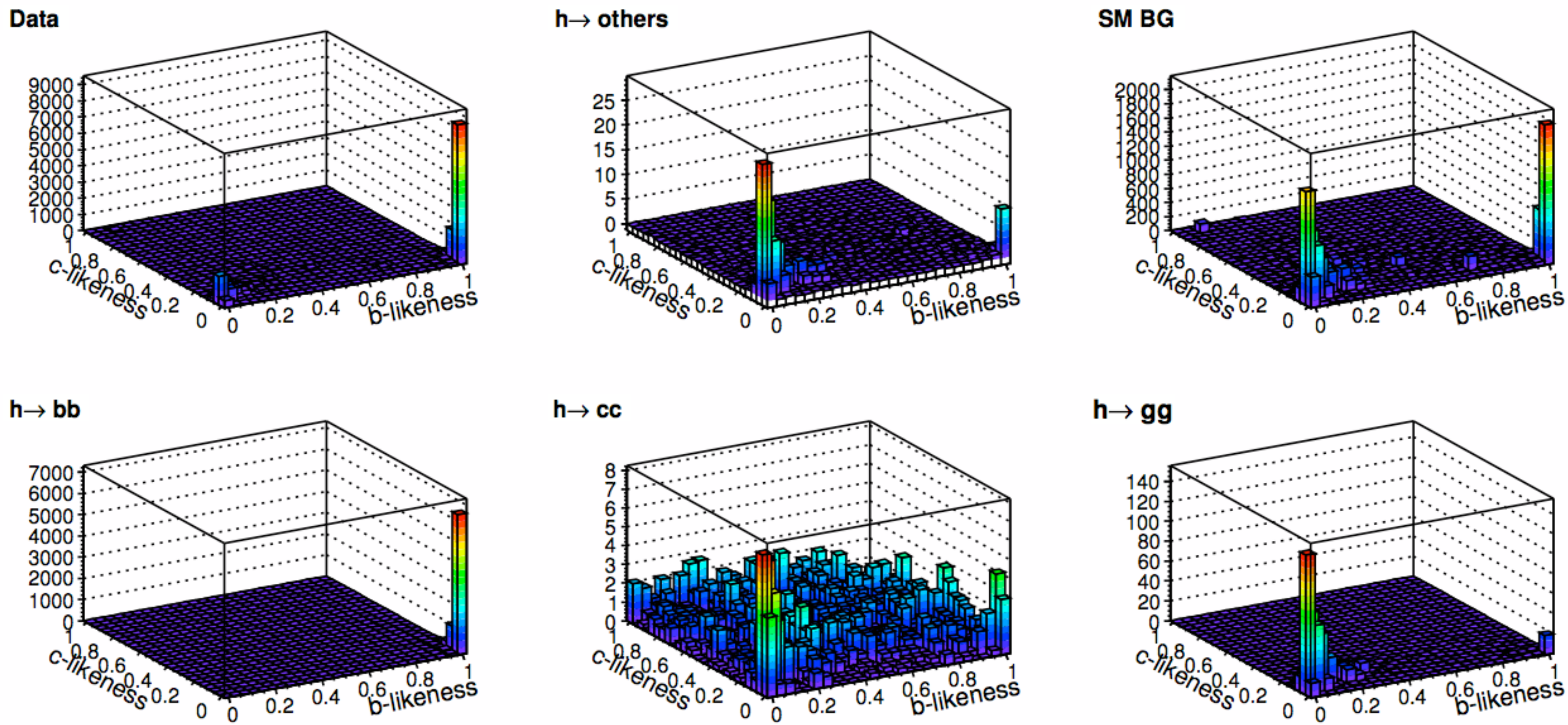
$$e^+e^- \to Zh \to (\mu^+\mu^-)(\tau^+\tau^-)$$



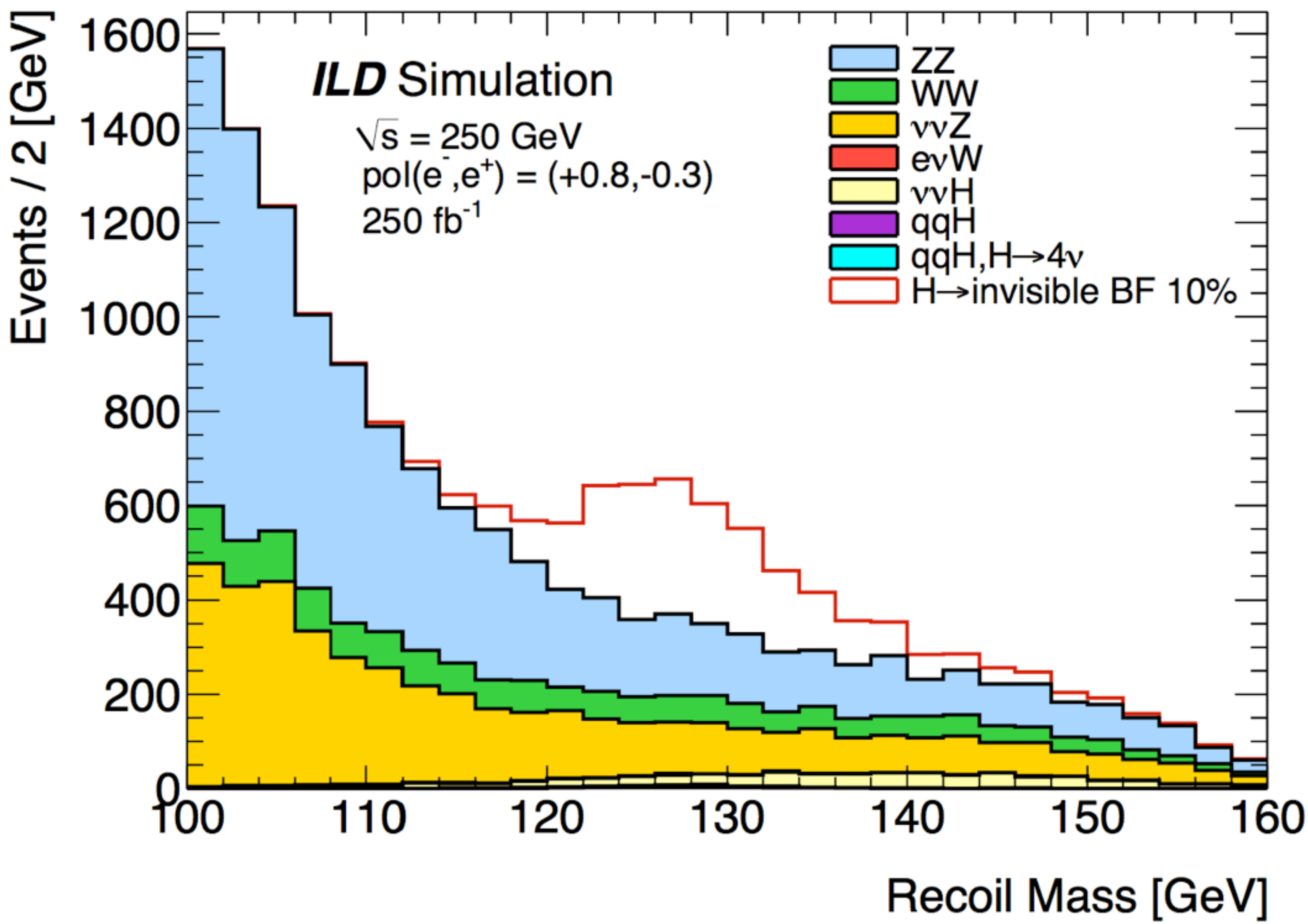
ILD simulation

m_h to 15 MeV using recoil against Z
(corresponds to 0.1% systematic error in g(hWW)

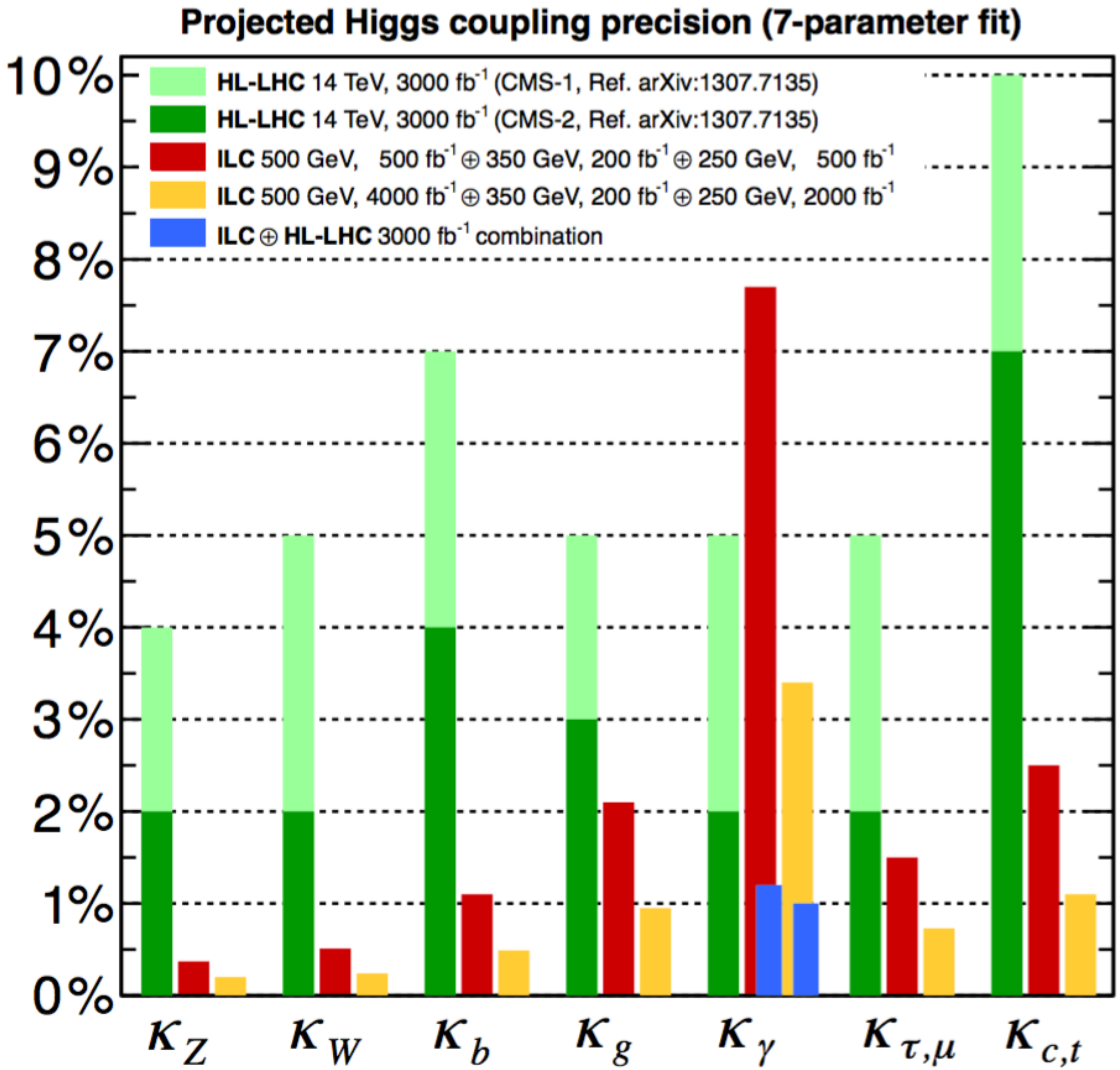




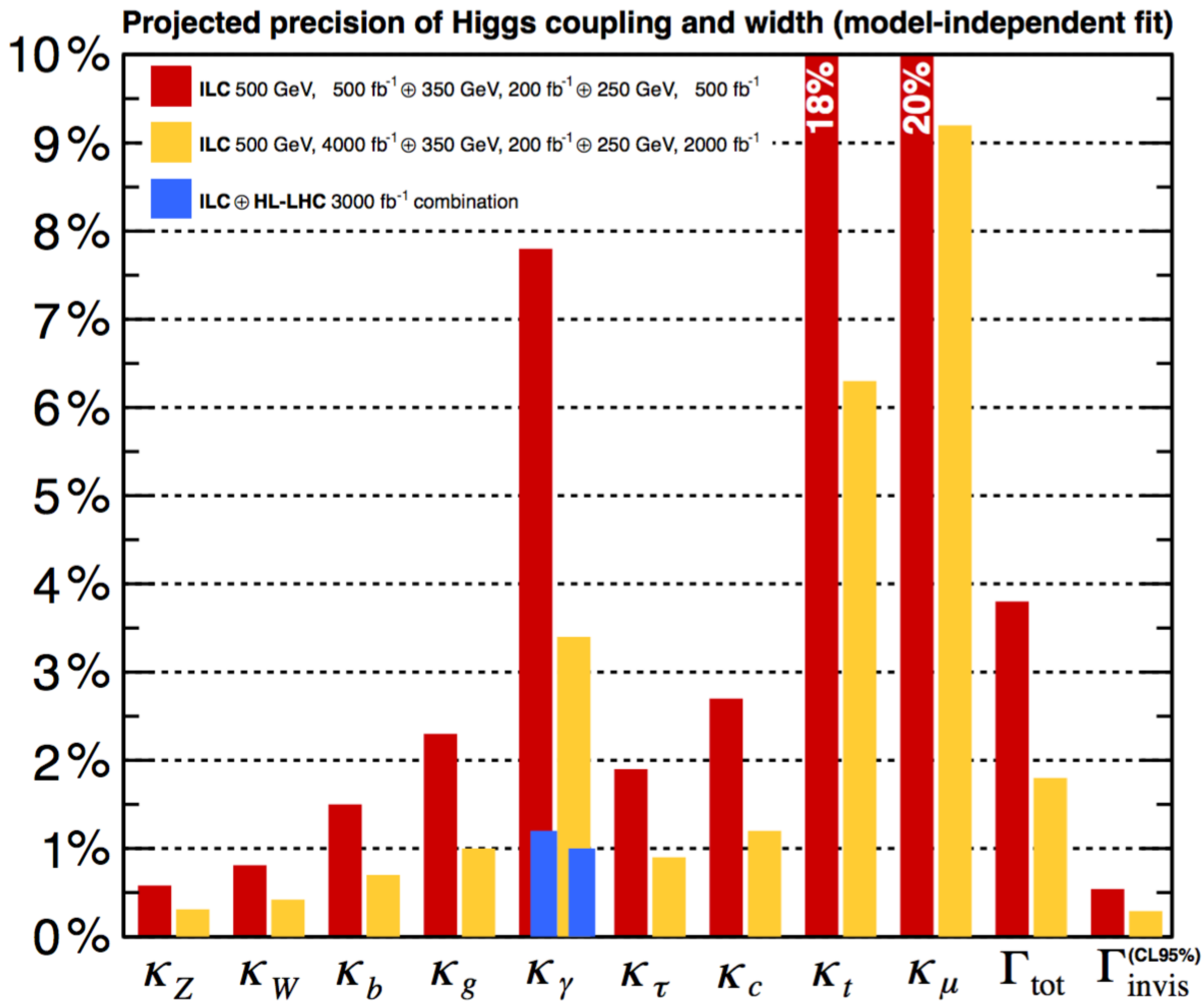
Data
h→ others
SM BG
h→ bb
h→ cc
h→ gg
c-likeness
b-likeness



ILD Simulation
√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



(fit from Snowmass 2013:
to facilitate comparison with LHC)



κt - 3% if ILC can run at 550 GeV

κγ - 1% using LHC γγ/ZZ

A wealth of information will be available if we can study the decays of the Higgs boson with high precision.

This program will certainly establish the role of the Higgs boson, in the way that the precision study of Z has established the SU(2)xU(1) gauge theory.

This program can also give information — not only quantitative but also qualitative — on the nature of new physics beyond the Standard Model. This information will be in many ways orthogonal to what we will learn from particle searches at the LHC.

I look forward to this program as the next great project in the future of particle physics.