Secrets of the Higgs Boson

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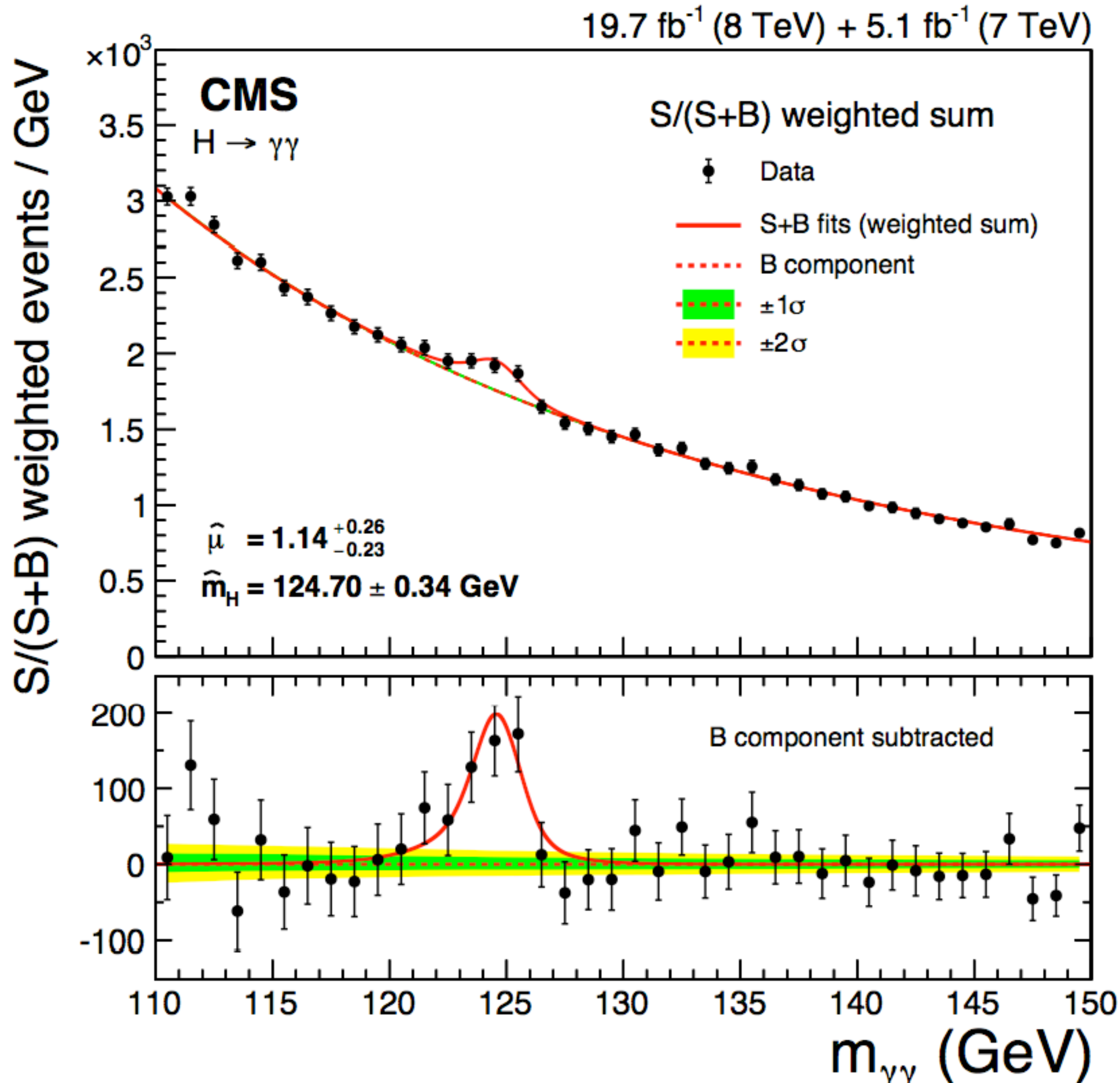
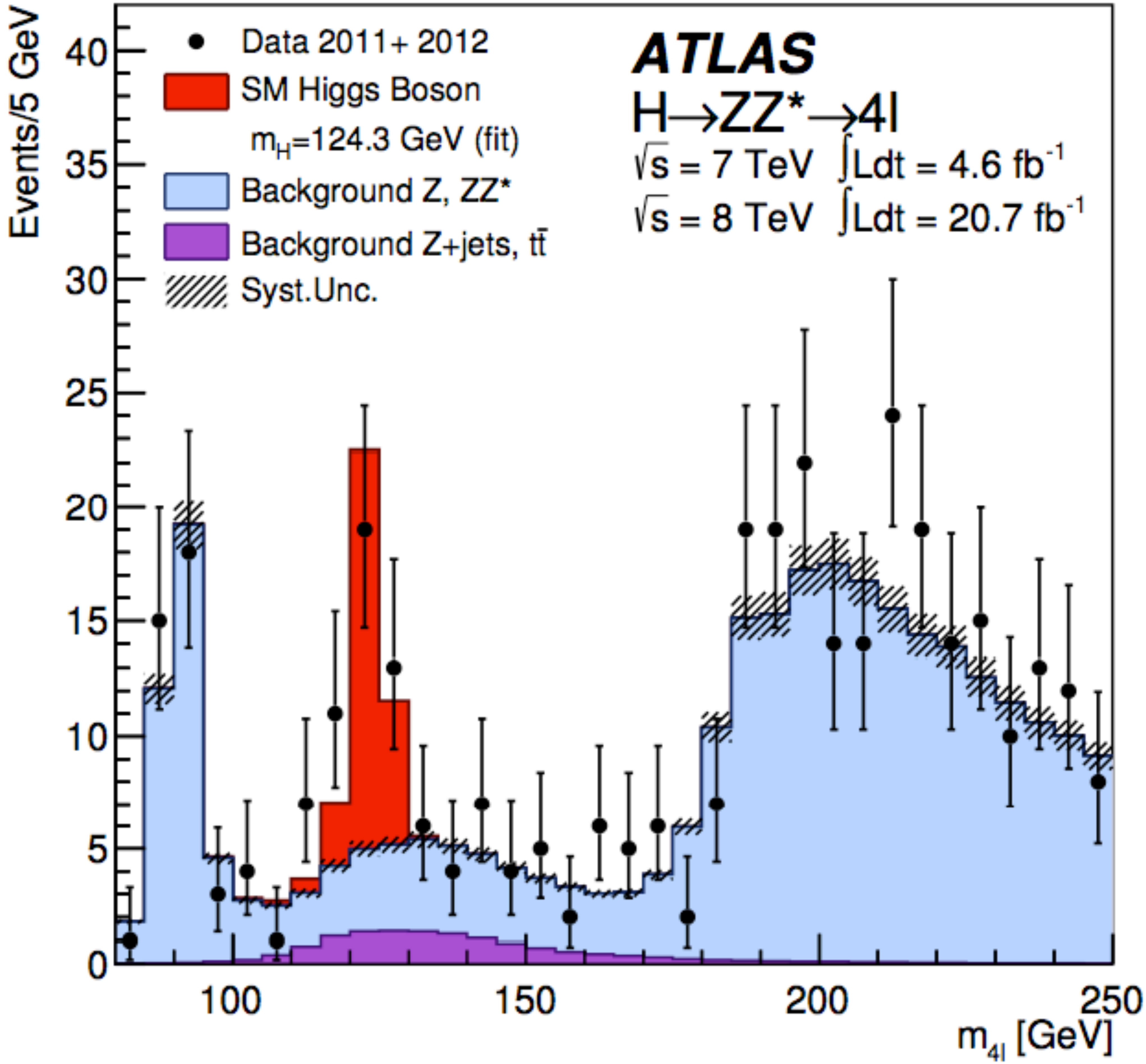
February 2015

Only four years ago, in the fall of 2011, it was a popular theme for discussion among particle physicists that the Higgs boson did not exist.

Searches at the LHC had eliminated most of allowed range for the Higgs boson mass. Only a small corner remained in which the Higgs could hide.

Today, the situation could not be more different.


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
μ̂ = 1.14 +0.26 −0.23
m̂H = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
×10³
B component subtracted
mγγ (GeV)



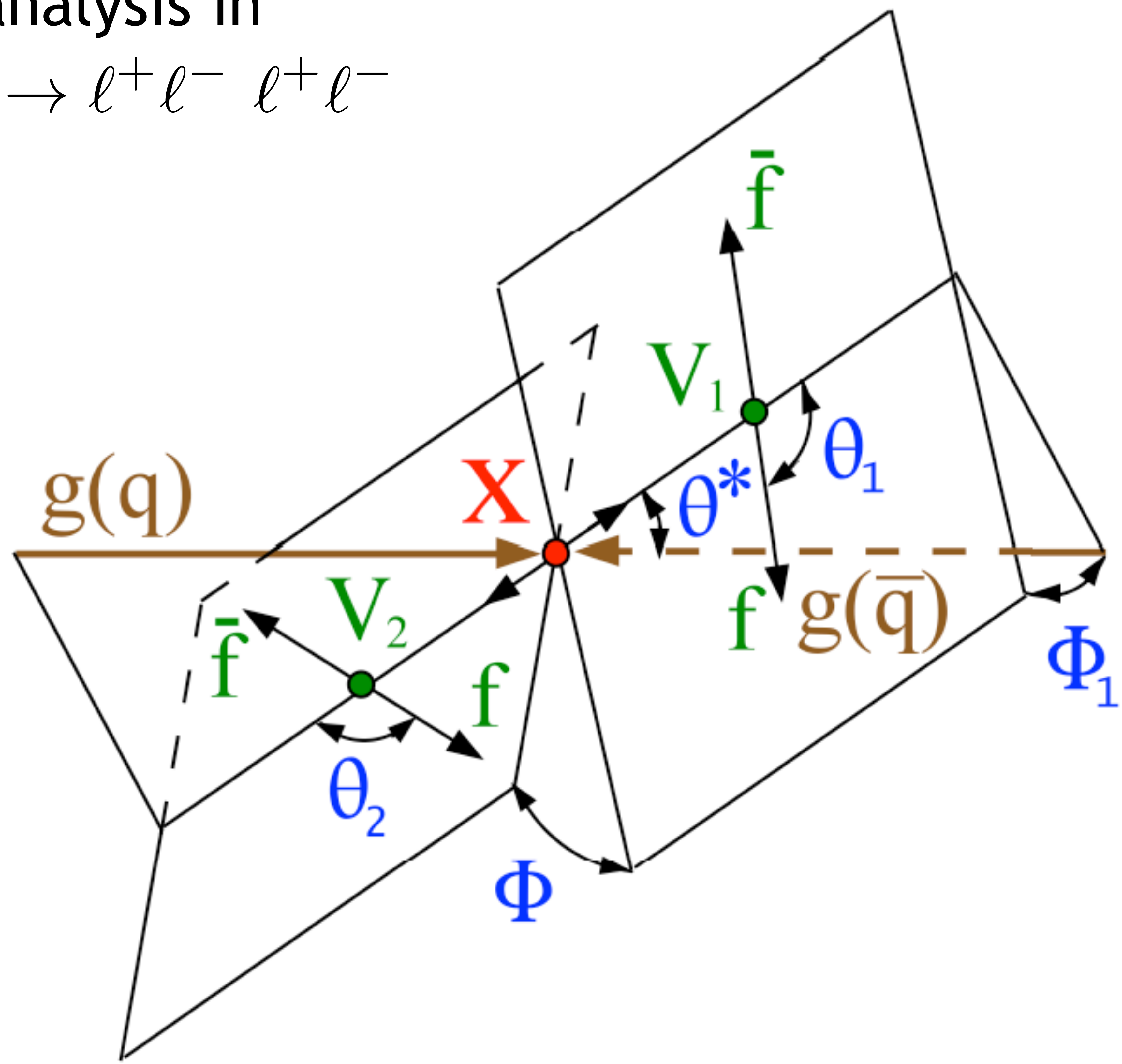
Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, $t\bar{t}$
Syst.Unc.
ATLAS
$H \rightarrow ZZ^* \rightarrow 4l$
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
Events/5 GeV
m_{4l} [GeV]
0
5
10
15
20
25
30
35
40
100
150
200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

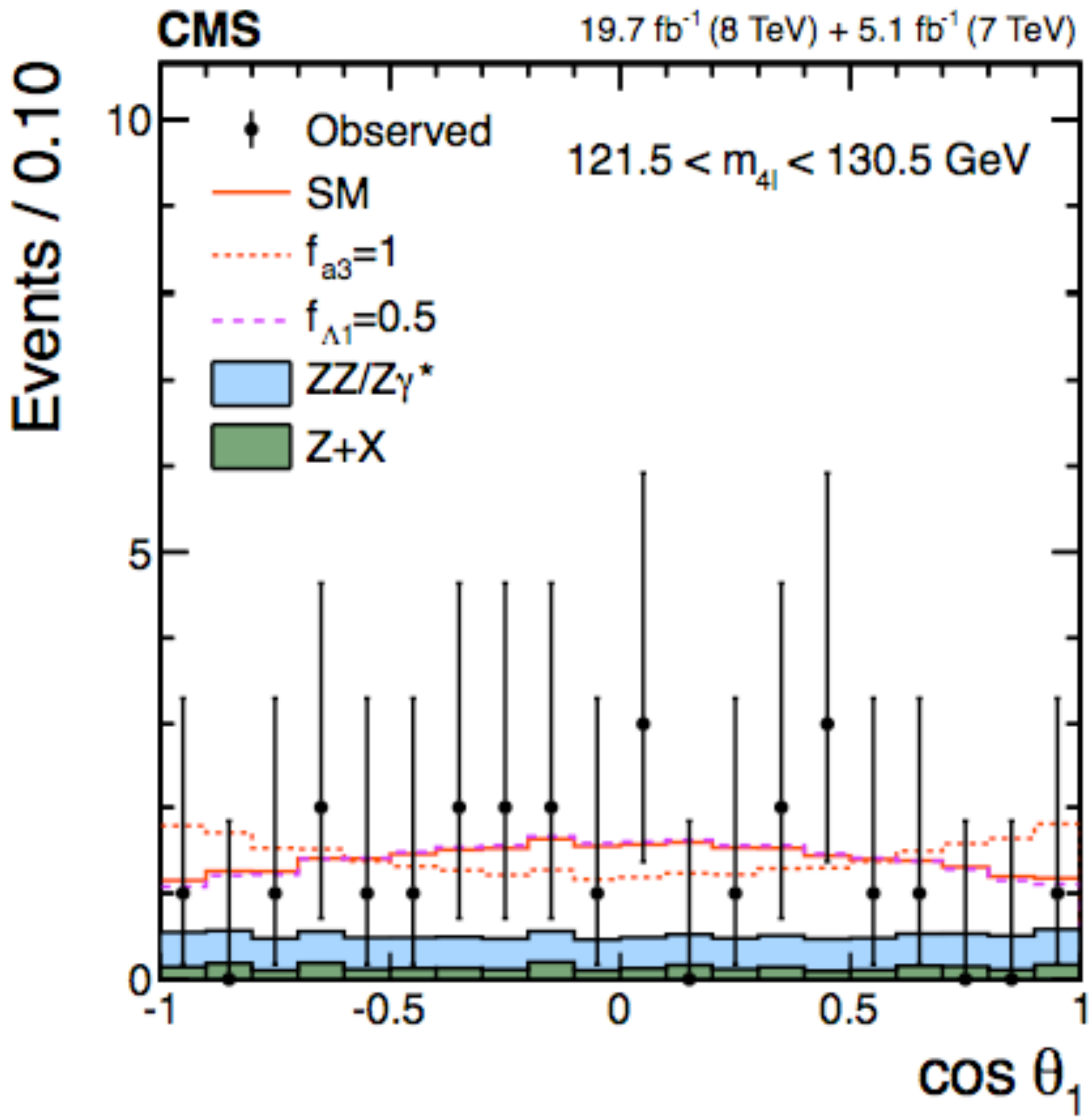
Tests of qualitative properties predicted for the Higgs boson:

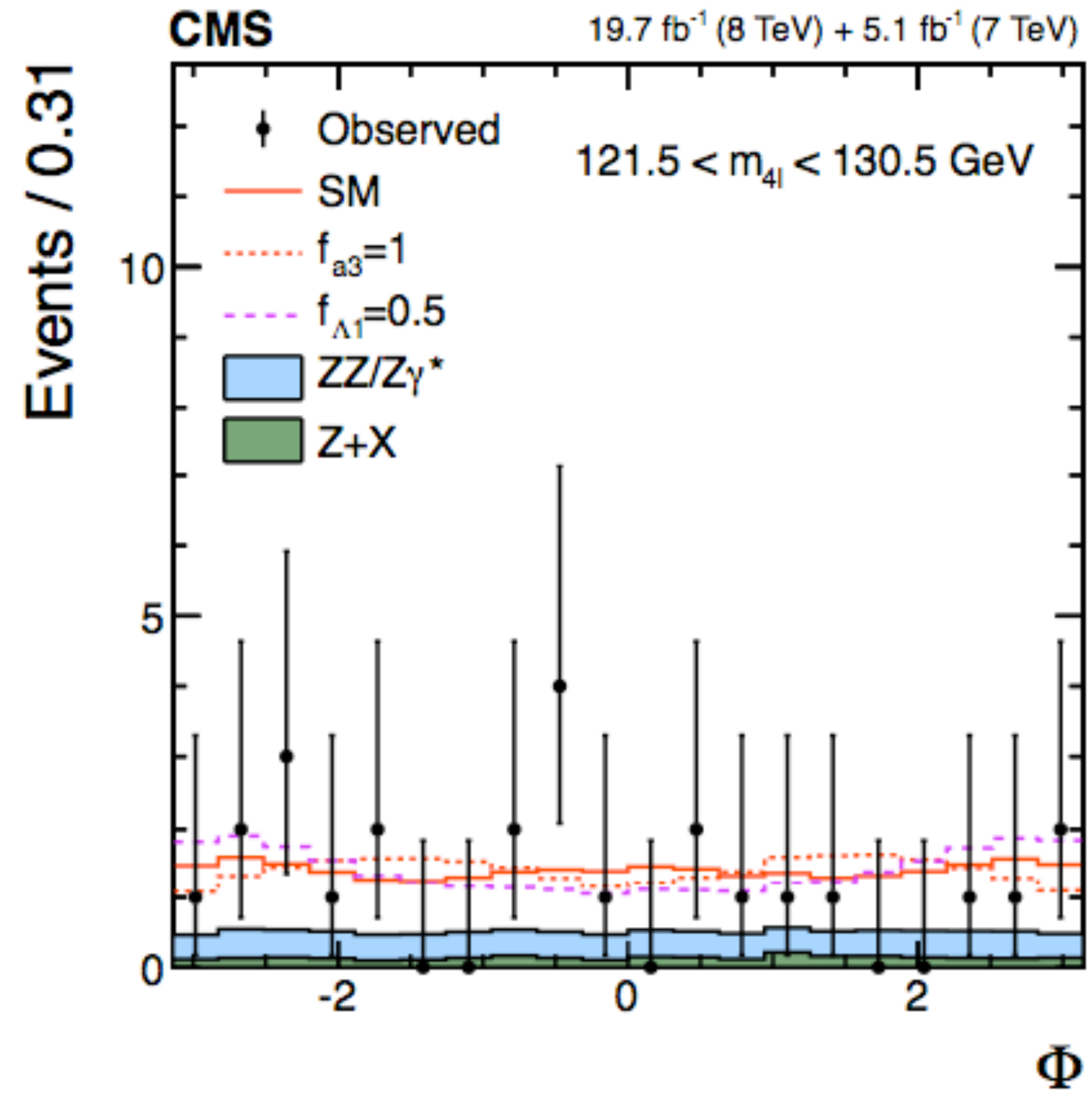
$\gamma\gamma$ decay mode	✔
ZZ decay mode	✔
WW decay mode	✔
$\tau^+\tau^-$ decay mode	✔
bb decay mode	preliminary
tt coupling	indirectly, through gg
spin-parity 0+	✔

variables for the CMS spin analysis in

$$h \to ZZ^* \to \ell^+\ell^- \ \ell^+\ell^-$$





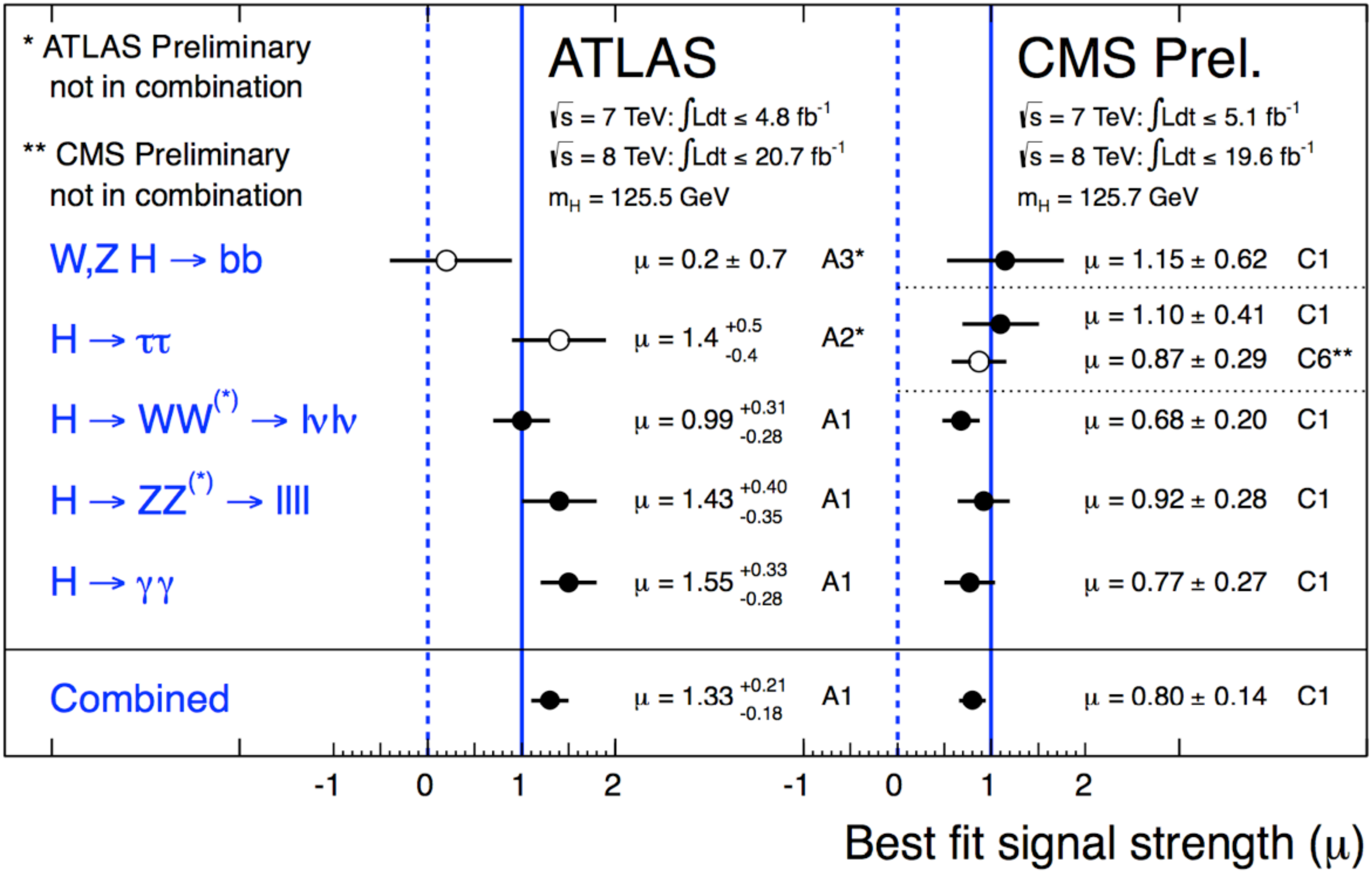


preference for Z to be longitudinally polarized

preference for Z decay planes to be parallel

The quantitative measure for used today for Higgs coupling values is the “signal strength”

$$\mu(A, B) = \frac{\sigma(A\overline{A} \to h) BR(h \to B\overline{B})}{(\text{SM expectation})}$$



PDG summary 2014

Today, received opinion in high-energy physics goes to the other extreme. The Higgs boson is discovered, it is Standard-Model-like, and its story is closed.

My view of the current situation is rather different.

The Higgs boson is required by the Standard Model, and it important to have its existence confirmed. Viewed at low precision, the Higgs boson must meet the simplest expectations. Only when we reach a required higher level of precision does the picture of the Higgs boson become richer and more instructive.

The picture is similar to that of the cosmic microwave background. This phenomenon is required by Big Bang cosmology, and its features are determined to the level of parts in 100,000.

However, measurement of those deviations reveals significant information about cosmology.

For the Higgs, we have to ask the same questions:

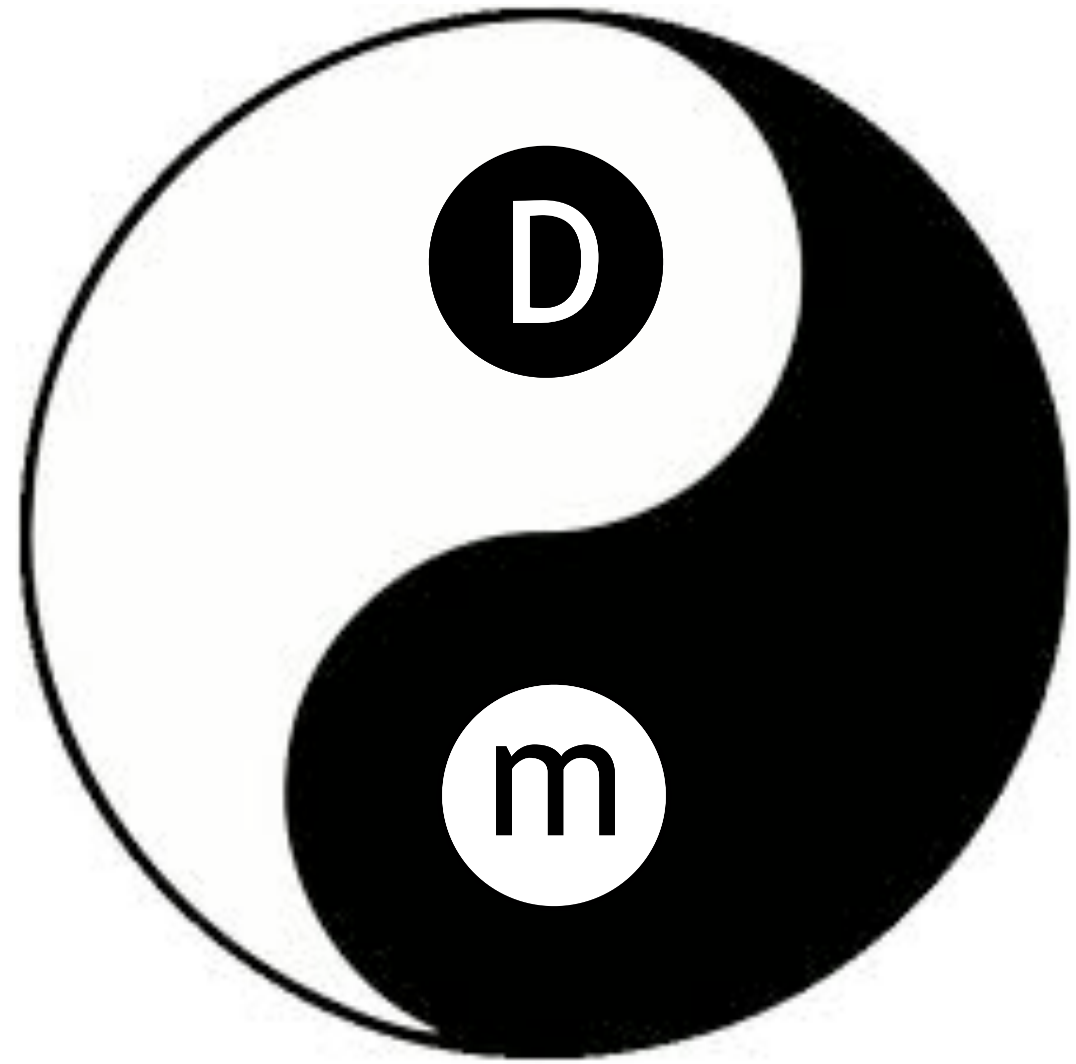
What can we potentially learn, and how closely do we need to measure to uncover this information ?

Today, we do not know whether electroweak spontaneous symmetry breaking is due to a single scalar field or to a more complicated, even strongly interacting, sector.

We do understand that this is a central -- in my opinion, the central -- question today in particle physics.

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

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

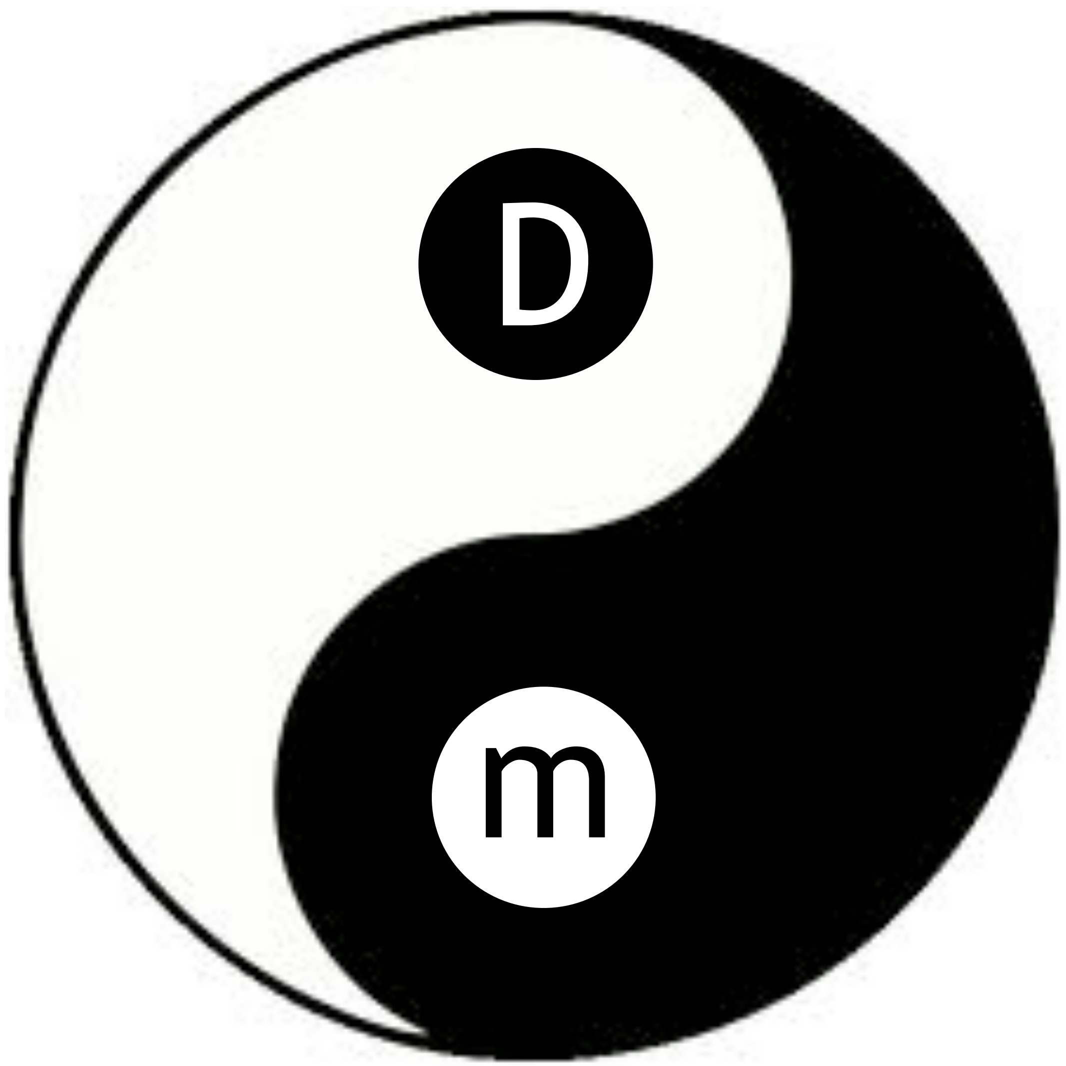


Half of the Standard Model is governed by the gauge principle, which gives us a tight structure and perfect knowledge.

About the other hand, we are ignorant.

Gauge principle / Vacuum structure

Maxwell's equations
Quantum numbers
Parity violation
W, Z boson
Asymptotic freedom



W, Z mass
Quark masses and mixings
CP violation

L, B violation

Dark energy

Standard Model is all-powerful

Dark matter ?

Standard Model is impotent

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, plus a set of operators of minimum dimension 6.

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.

Given the mass of the Higgs boson, the Standard Model makes a precise set of predictions for the couplings. These should be considered as reference values for precision measurements.

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

$b\bar{b}$	58%	$\tau^+\tau^-$	6.3%	$\gamma\gamma$	0.23%
WW^*	21%	$c\bar{c}$	2.9%	γZ	0.15%
gg	8.6%	ZZ^*	2.6%	$\mu^+\mu^-$	0.02%

Many decay modes of the Higgs will eventually be visible, and measurable. F. Gianotti: “Thank you, Nature.”

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, a useful one.

fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

γγ, gg couplings - heavy vectorlike particles

tt coupling - top compositeness

hhh coupling (large deviations) - baryogenesis

In a model with two Higgs doublets, the physical states are mixtures of the two fields

mixing angle
$$\begin{array}{llll} \alpha: & h^0, H^0 & & \tan\beta = v_u/v_d \\ \beta: & \pi^0, A^0 & \pi^{\pm}, H^{\pm} & \end{array}$$

Then the coupling modifications are

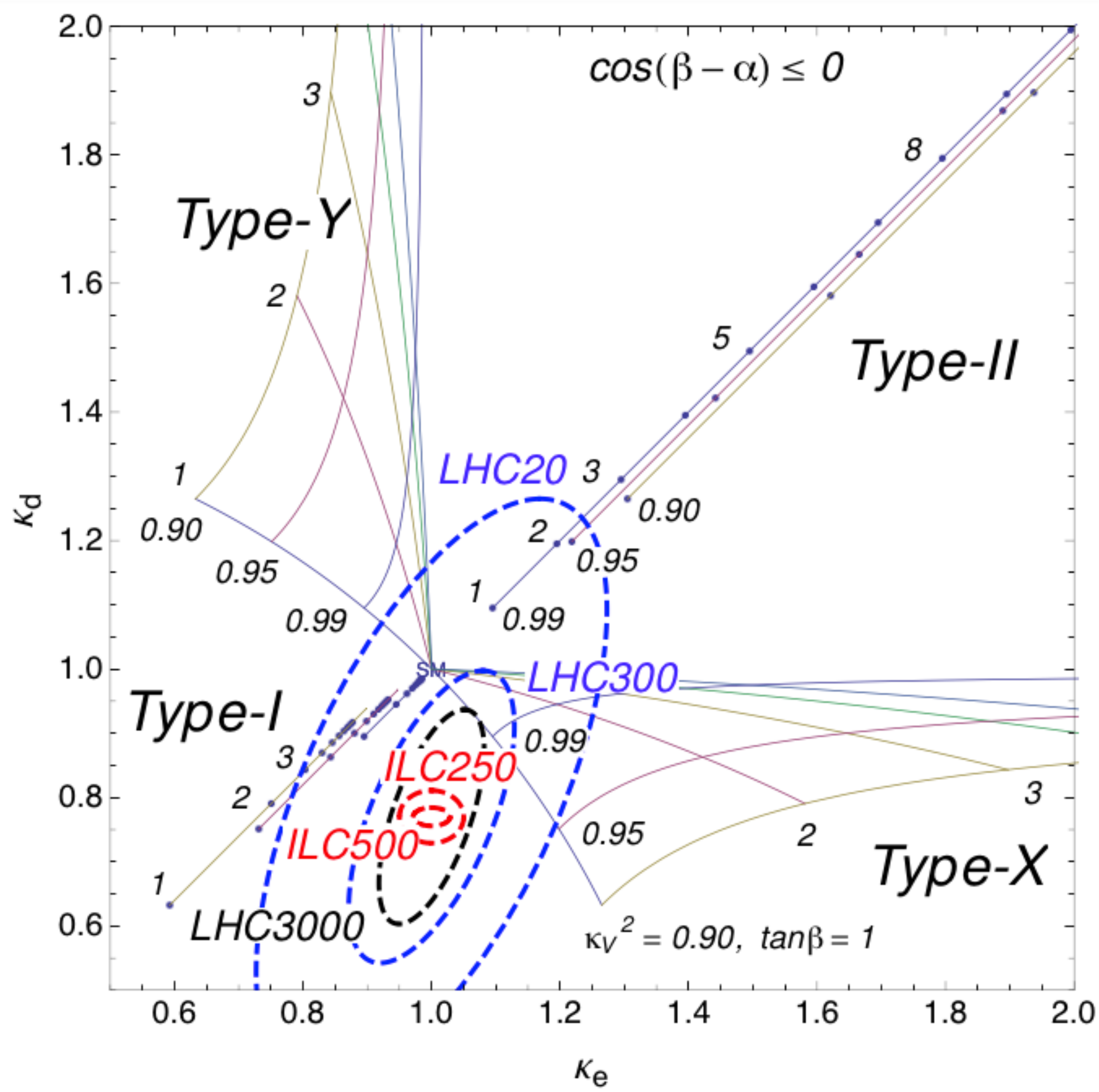
$$g(b\bar{b}) = -\frac{\sin\alpha}{\cos\beta}\frac{m_b}{v} \qquad g(c\bar{c}) = \frac{\cos\alpha}{\sin\beta}\frac{m_c}{v}$$

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

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

so that

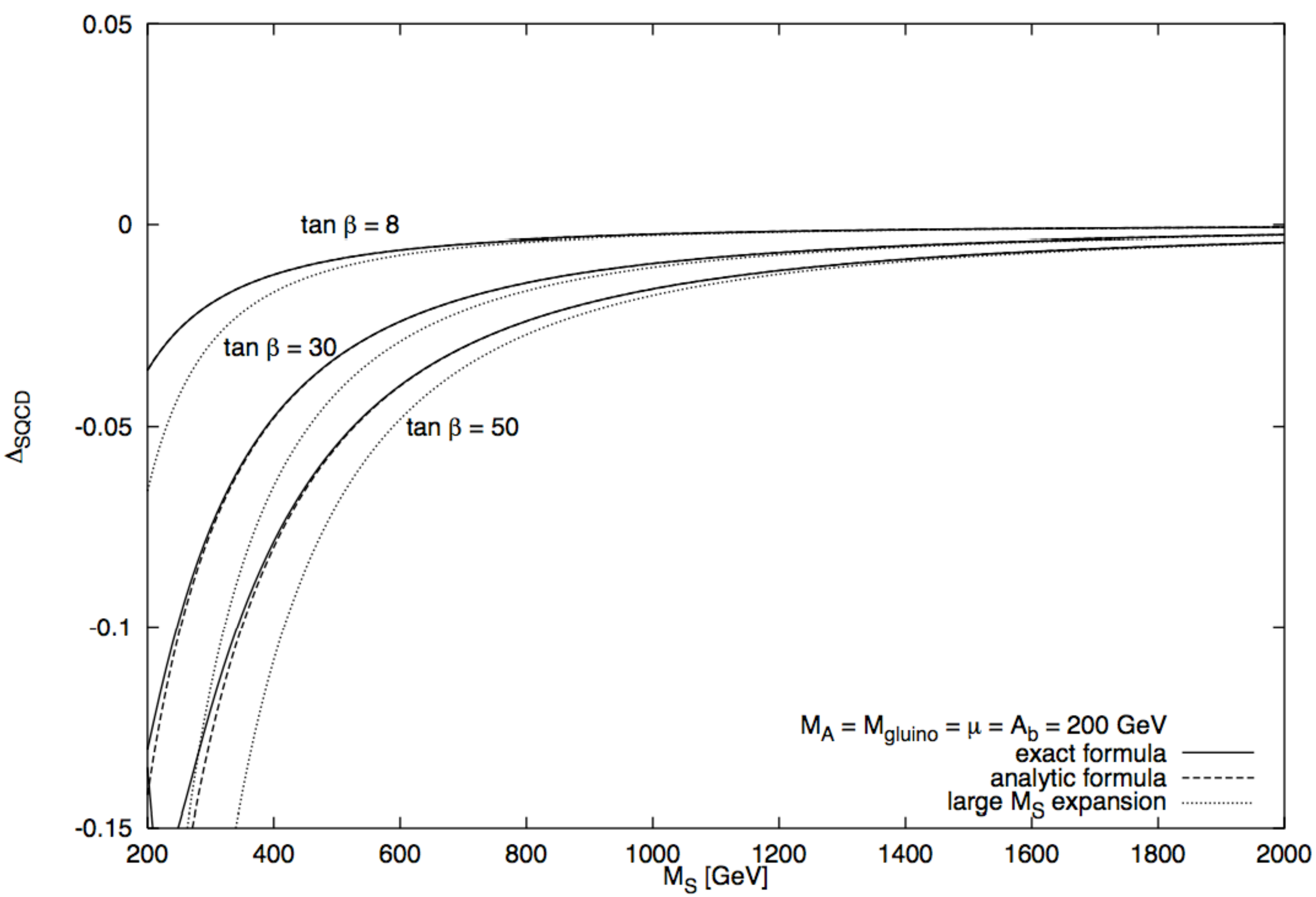
$$\frac{g_{hbb}}{g_{h_{\mathrm{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\mathrm{SM}}\tau\tau}} \simeq 1 + 40\% \left(\frac{200 \text{ GeV}}{m_A}\right)^2$$



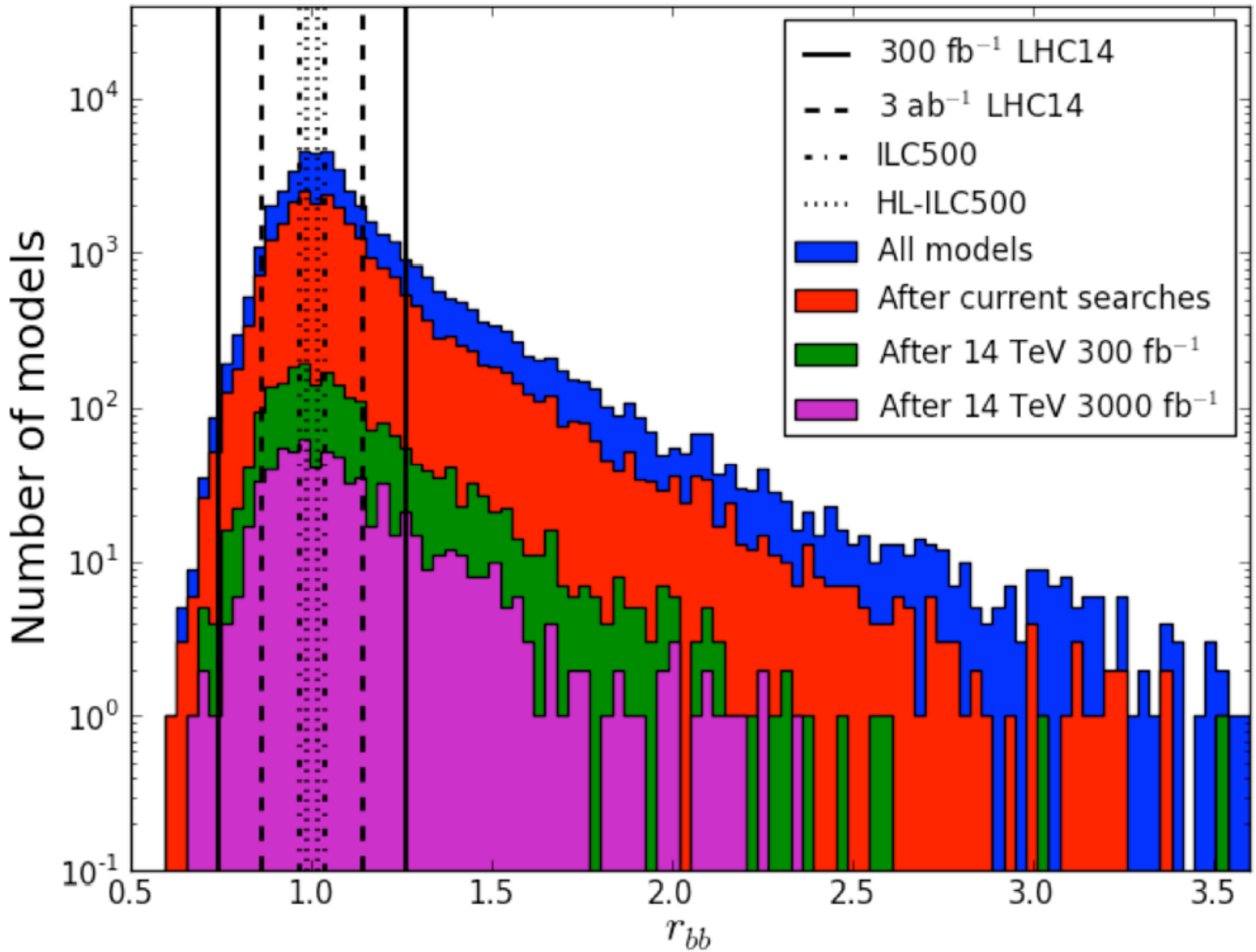
Kanemura, Tsumura, Yagyu, Yokoya

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

Haber, Herrero, Logan, Penaranda, Rigolin, Temes

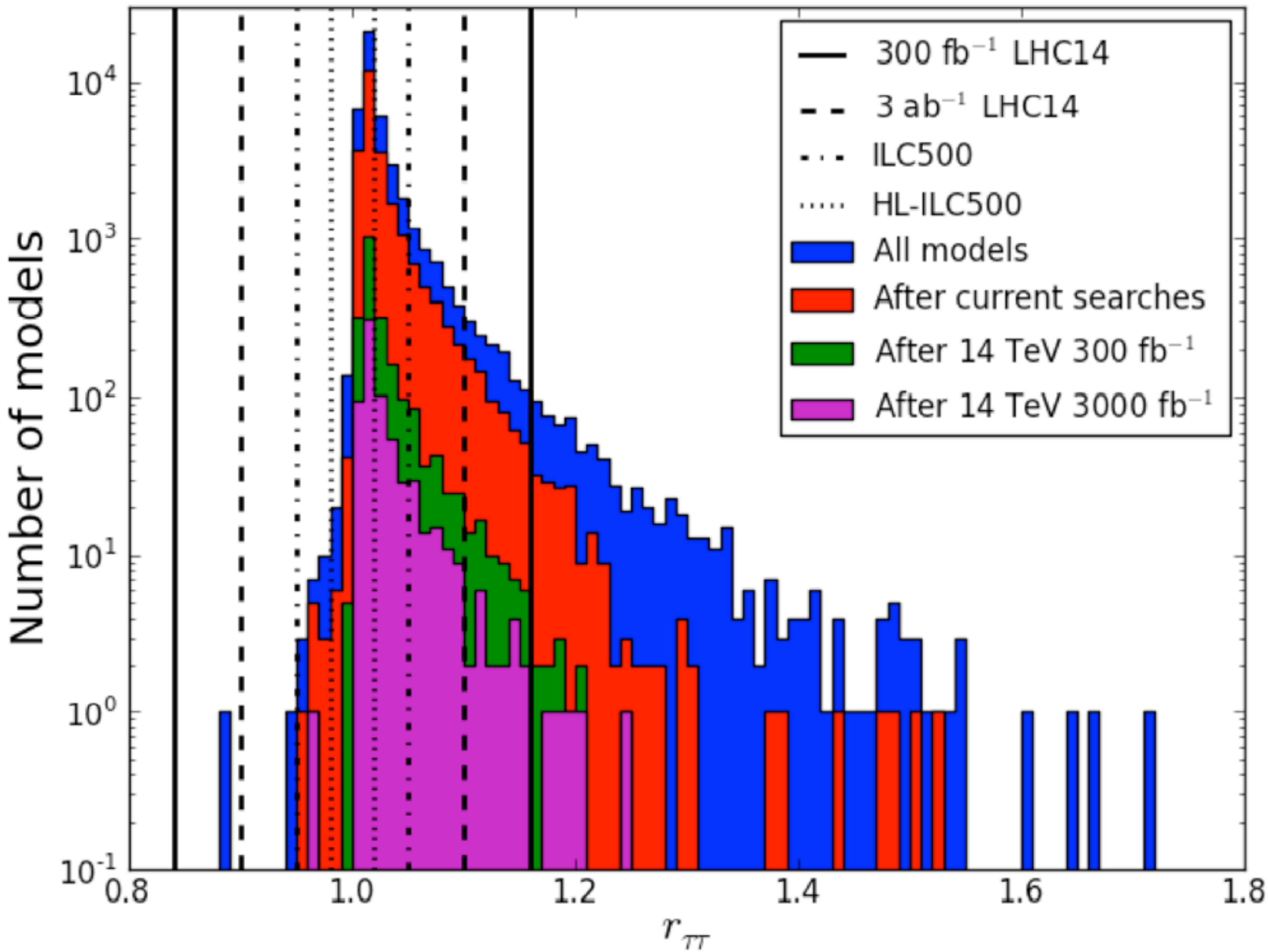


$\Gamma(h \to b\bar{b})$



Cahill-Rowley, Hewett, Ismail, Rizzo

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



Cahill-Rowley, Hewett, Ismail, Rizzo

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).

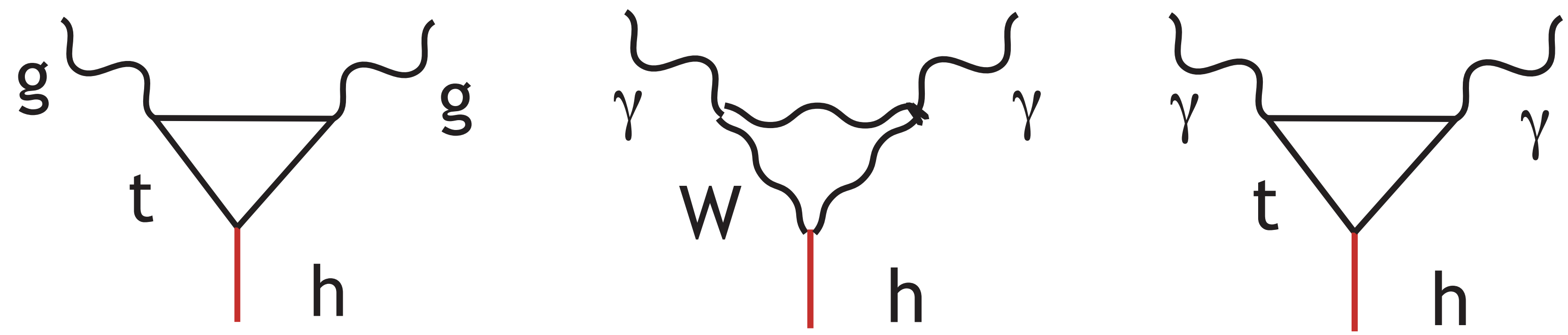
If the Higgs is a composite Goldstone boson, these couplings are corrected by (f ~ 1 TeV)

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

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

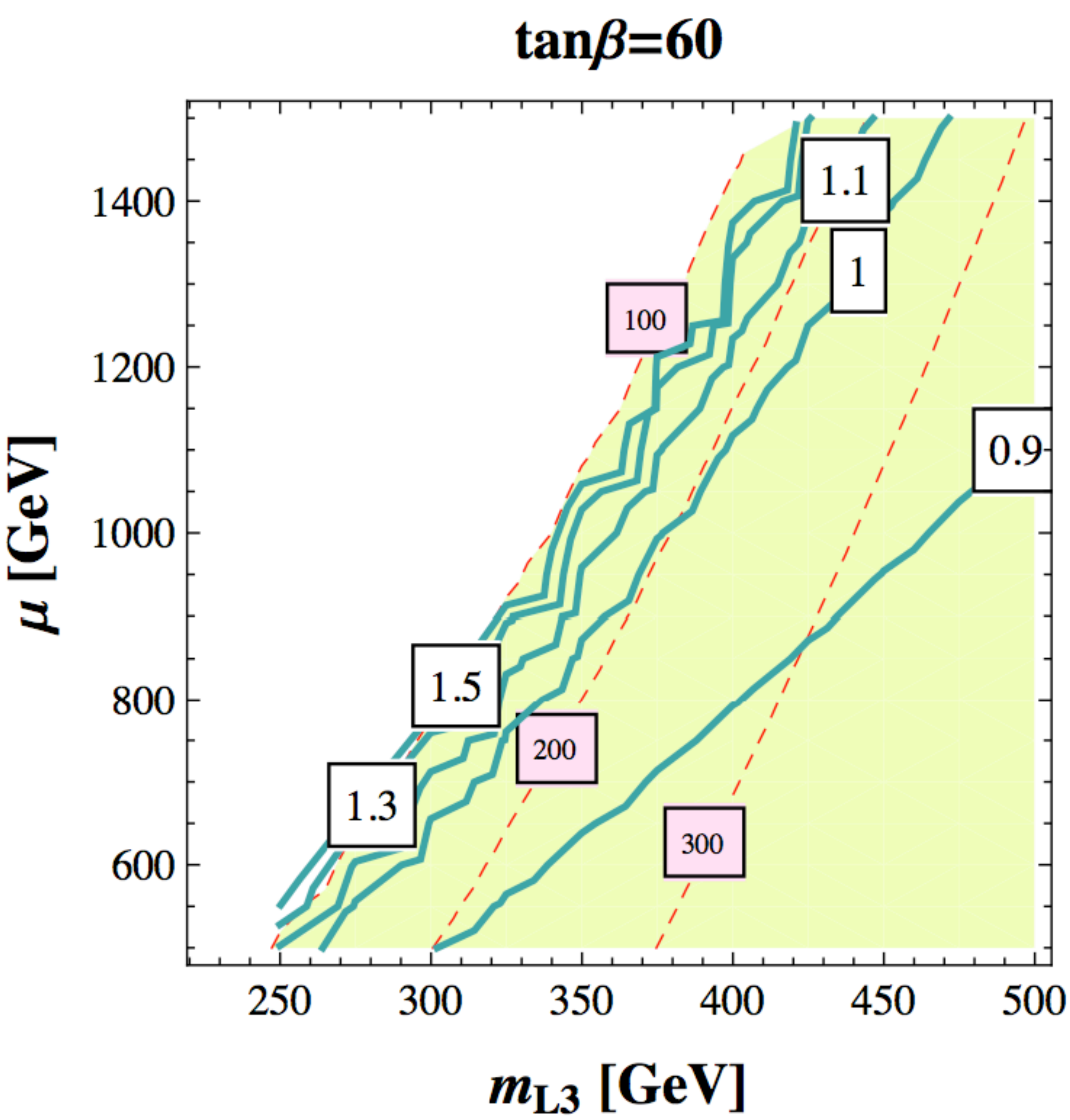
$$g(hgg)/SM = 1 + 2.9\% \big(\frac{1 \text{ TeV}}{m_T}\big)^2$$

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

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

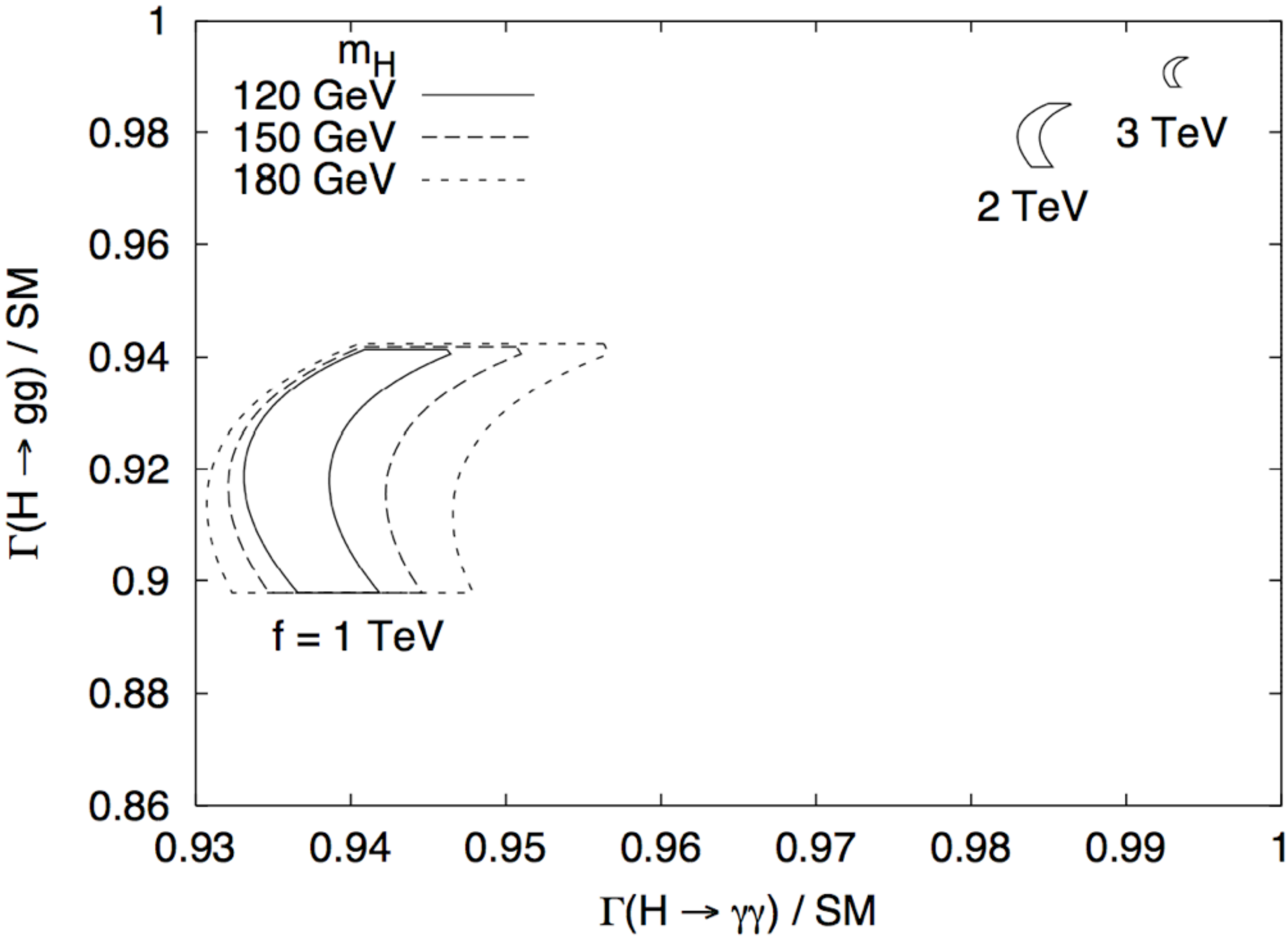
$$g(hgg)/SM = 1 - (5 - 9\%)$$

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



Carena, Gori, Shah, Wagner

Littlest Higgs model

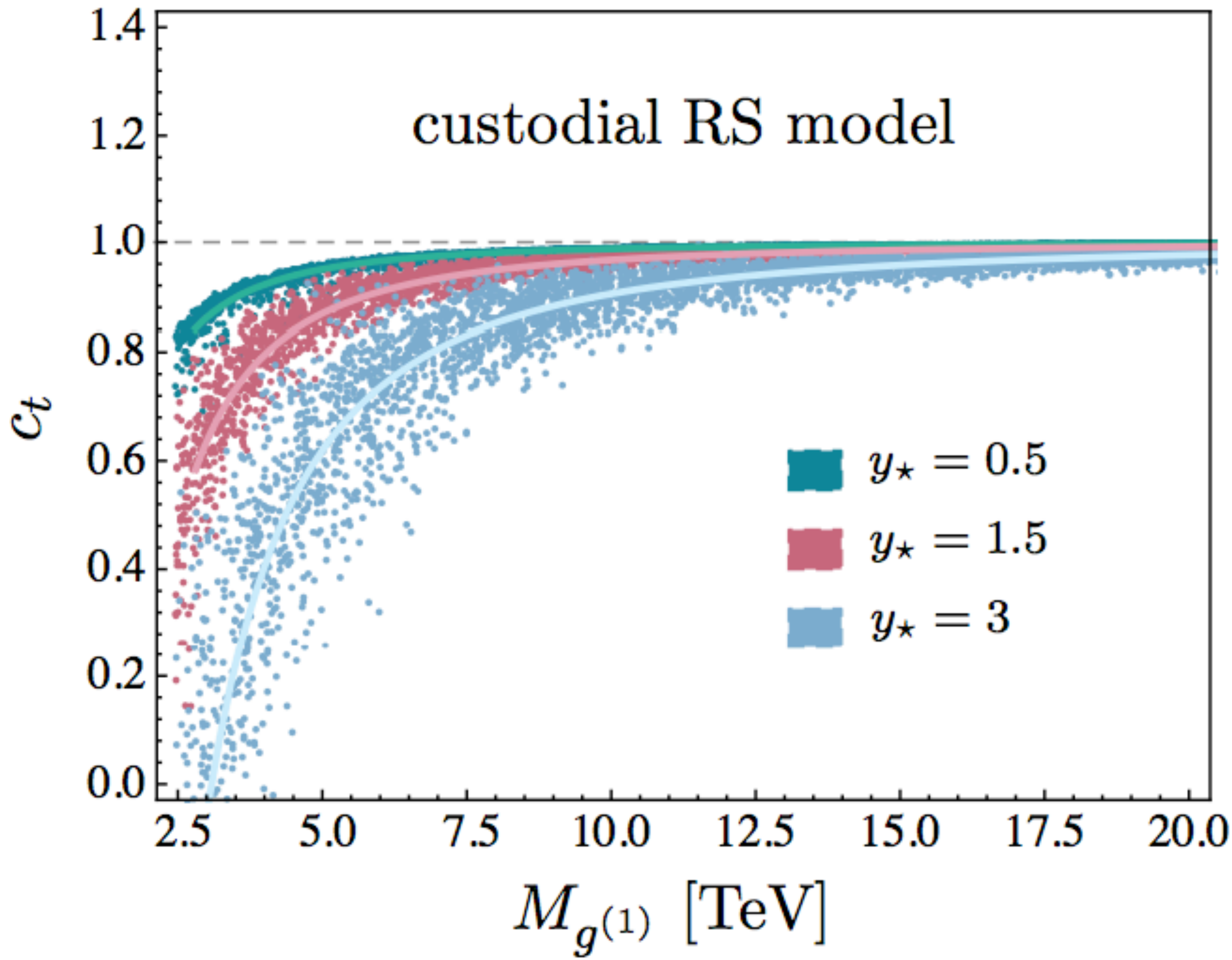


Han, Logan, McElrath, Wang

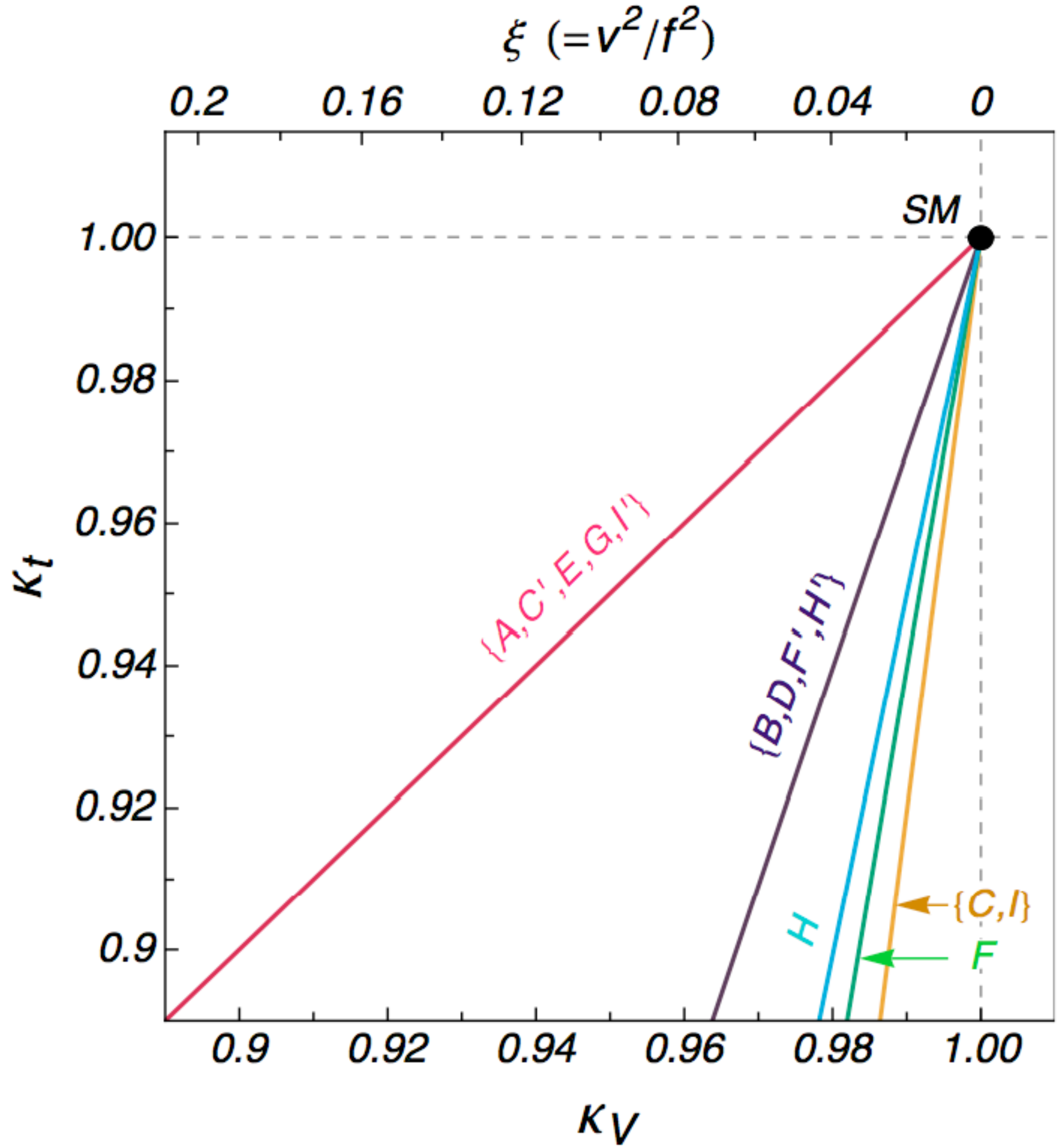
In composite Higgs models, the shifts in the $\gamma\gamma$ and gg partial widths come both from the modification of the top quark coupling and from the contributions of heavy vectorlike particles.

These effects are disentangled by direct measurement of the Higgs coupling to tt.

Substantial effects are expected in models of partial top compositeness, as in Randall-Sundrum models.



Malm, Neubert, Schmell



Kanemura, Kaneta, Machida, Shindou

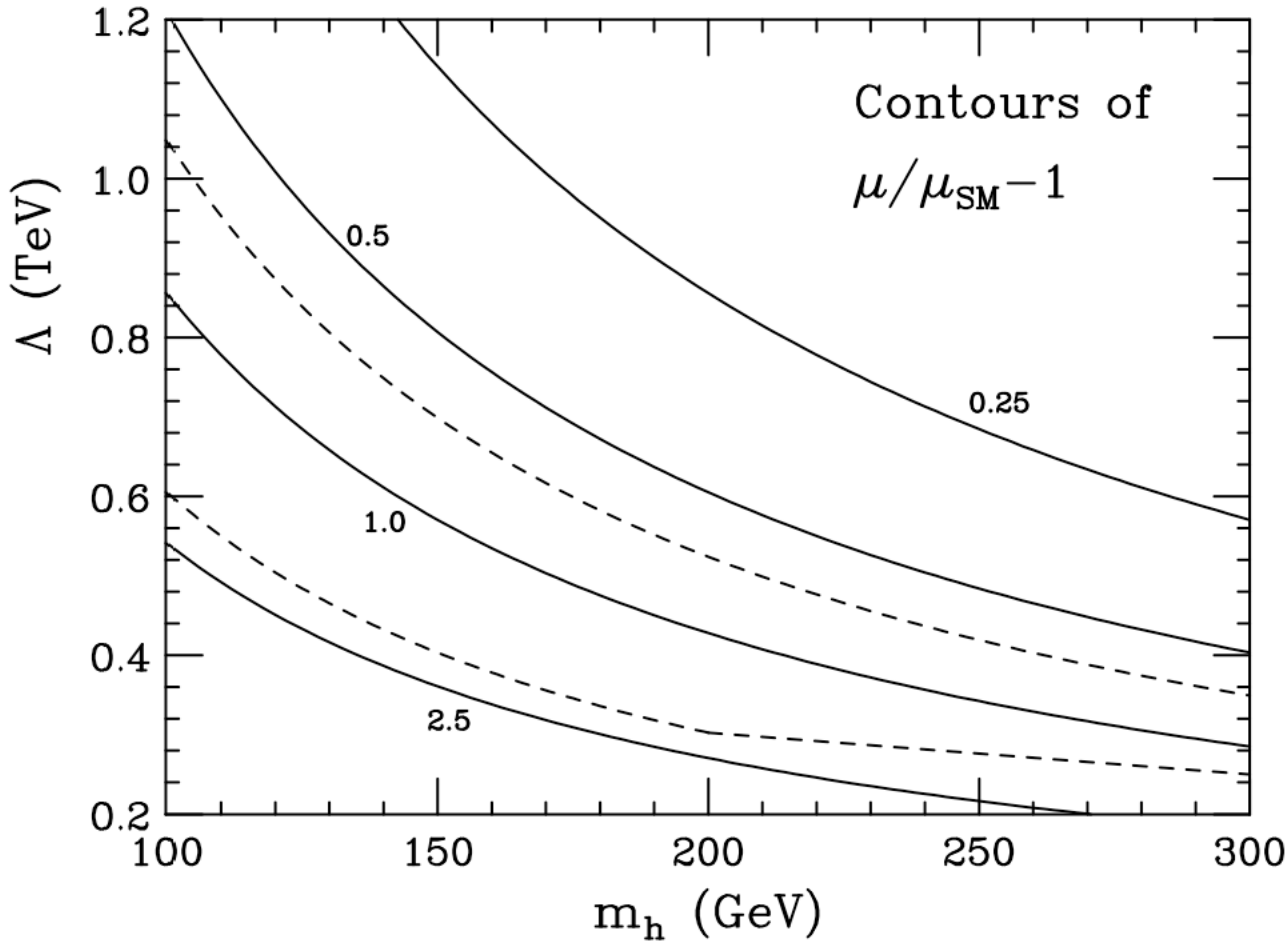
The Higgs self-coupling is a special case in this story.

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

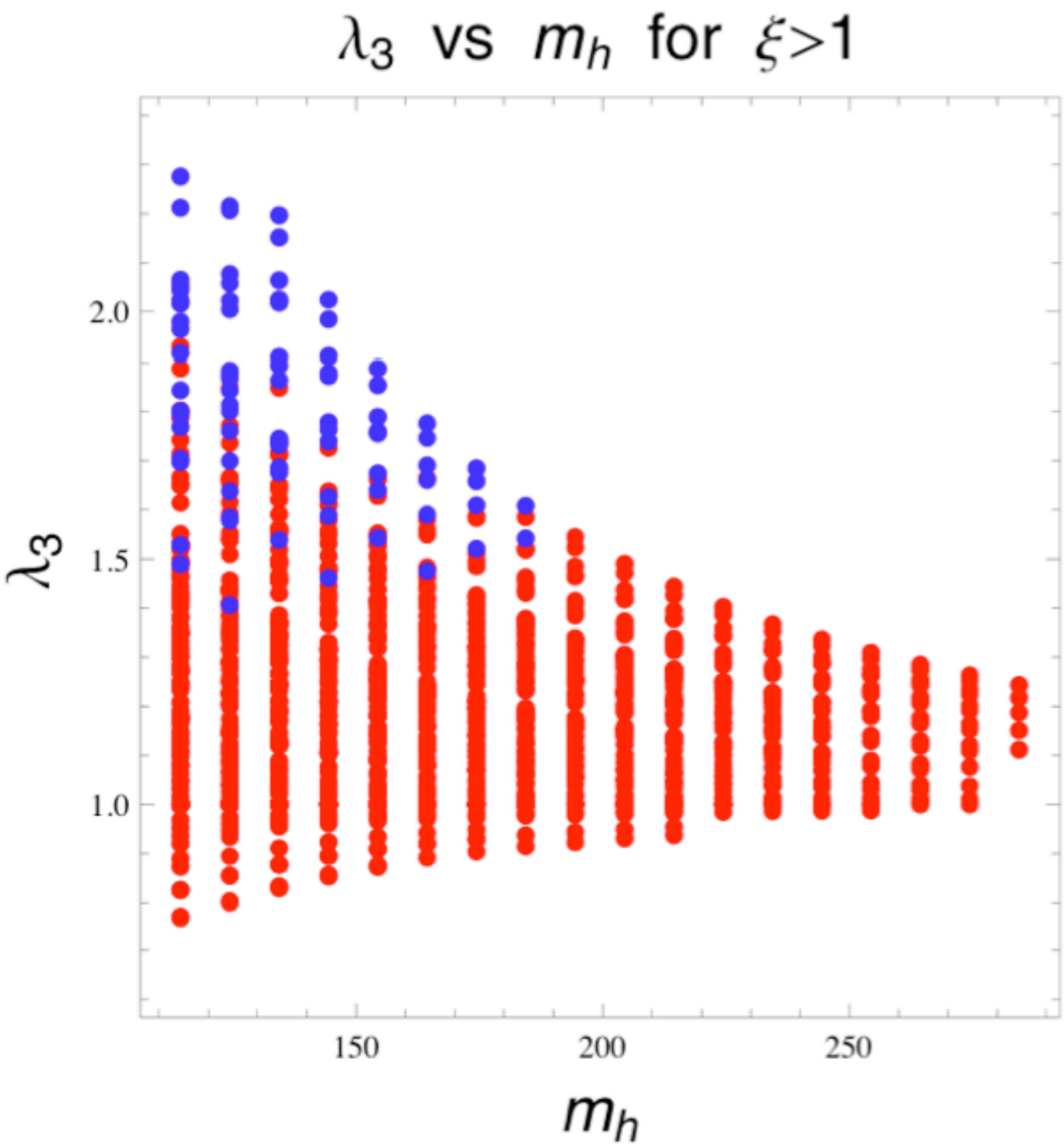
The current expectation for ILC is a 16% measurement with 2000/fb at 1 TeV. Though it is expected that the LHC will have some sensitivity to this coupling, this has not yet been demonstrated (see ATL-PHYS-PUB-2014-019).

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.

contours of fixed hhh coupling



Grojean, Servant, Wells

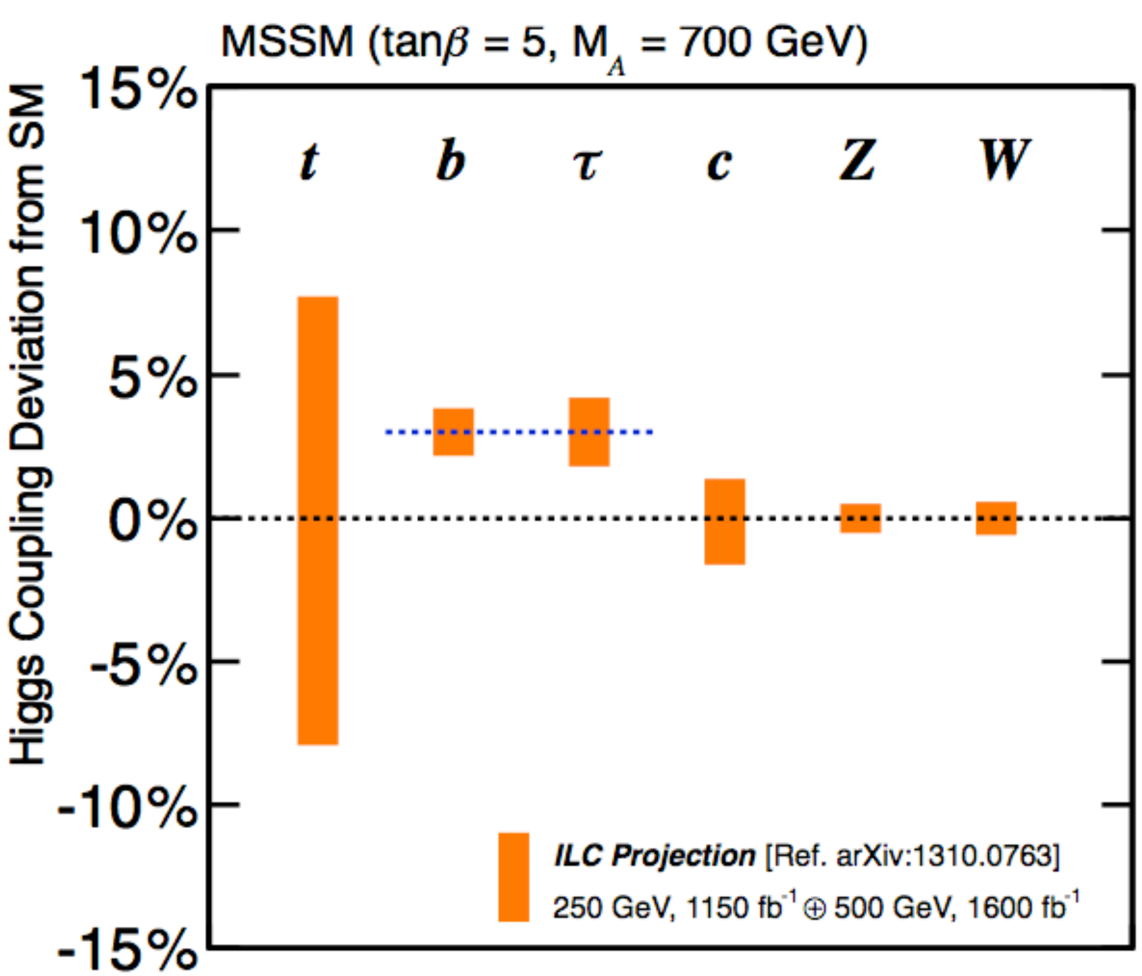


Noble and Perelstein

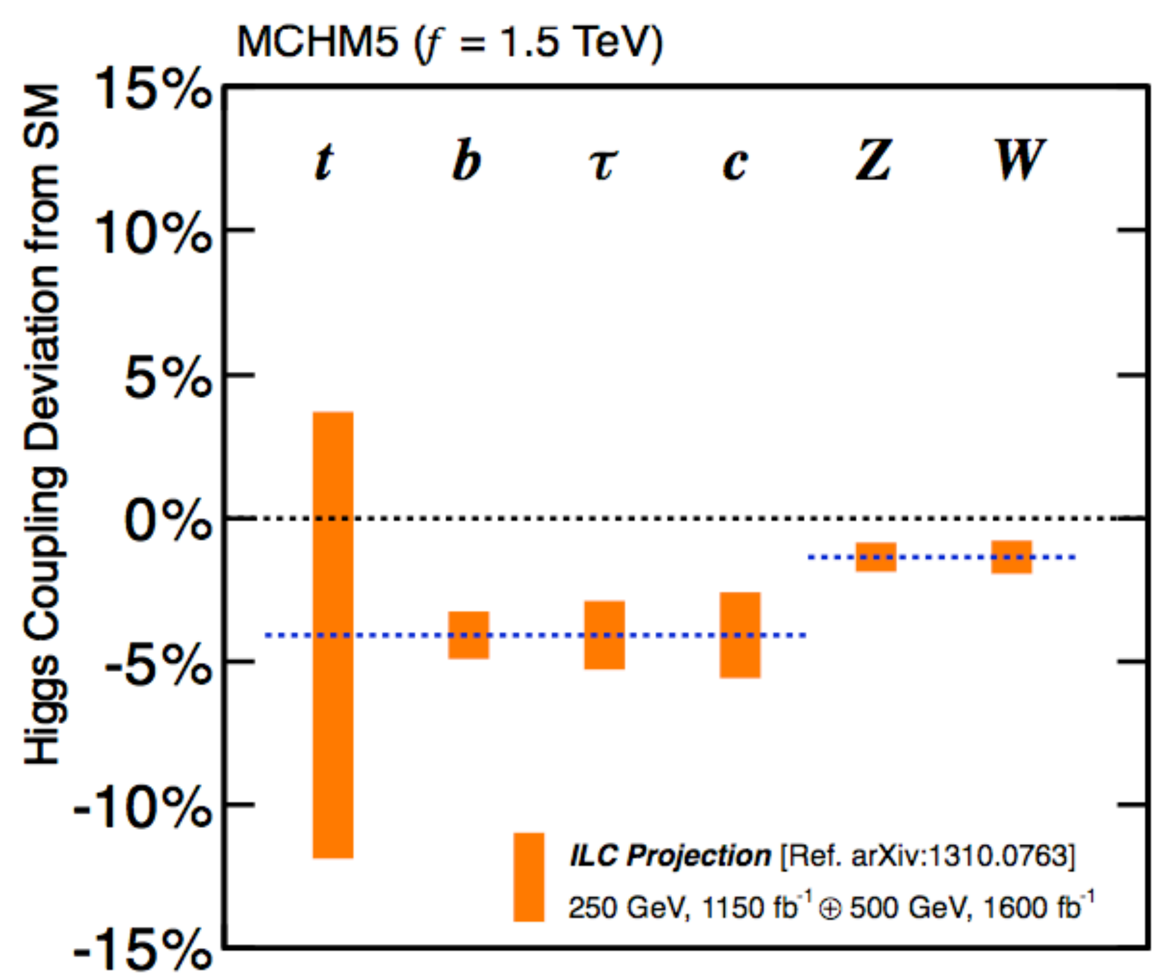
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs



Kanemura, Tsumura, Yagyu, Yokoya

There is one more question on the theory side that we must address:

In order to measure a deviation from the Standard Model expectation, we must be able to compute the Standard Model reference values to better than 1% accuracy. Will this actually be possible ?

This has been questioned in the literature, especially for $\Gamma(h \to b\bar{b})$, for which a very accurate value of the b quark mass is needed.

There are two types of contributions to the theoretical error on SM predictions:

error from uncalculated orders of perturbation theory

error from uncertainty in input parameters (m_b, α_s)

For the errors of the first type, the situation is quite good. These theoretical uncertainties are currently

0.3% for Higgs couplings to quarks
3 % for Higgs couplings to gg
1 % for Higgs couplings to WW, ZZ
1 % for Higgs coupling to $\gamma\gamma$

Among the most impressive theoretical efforts are

Baikov, Chetyrkin, Kuhn: $g(hb\bar{b})$ to $\mathcal{O}(\alpha_s^4)$
Baikov, Chetyrkin,
Schreck and Steinhauser: $g(hgg)$ to $\mathcal{O}(\alpha_s^4)$
Actis, Passarino, Sturm, Uccirati: $g(hgg)$ to $\mathcal{O}(\alpha\alpha_s)$

Improvement of the current results to 0.1% accuracy is possible, but it will require dedicated effort.

For the dependence on input parameters, the situation is easier to quantify. The most important dependences of Higgs coupling predictions are ($\delta_A = \Delta\Gamma(A)/\Gamma(A)$):

$$\delta_b = 1. \cdot \delta m_b(10) \oplus (-0.28) \cdot \delta\alpha_s(m_Z)$$
$$\delta_c = 1. \cdot \delta m_c(3) \oplus (-0.80) \cdot \delta\alpha_s(m_Z)$$
$$\delta_g = 1.2 \cdot \delta\alpha_s(m_Z)$$

We need to know the inputs in this table to the 0.1% level.

Many of the best determinations of these quantities now come from Lattice QCD. Mackenzie, Lepage, and I projected the errors from Lattice QCD ten years into the future and estimated:

	$\delta m_b(10)$	$\delta\alpha_s(m_Z)$	$\delta m_c(3)$	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

relative errors in percent

The partial widths to WW, ZZ also depend strongly on the mass of the Higgs boson:

$$\delta_W = 6.9 \cdot \delta m_h \ , \quad \delta_Z = 7.7 \cdot \delta m_h$$

This is a 0.2% uncertainty for $\Delta m_h = 30 \text{ MeV}$.

This is the primary motivation (in my opinion) for a very accurate Higgs mass measurement.

So, if there is new physics beyond the Standard Model at the TeV scale, we expect to see deviations of the Higgs couplings from their Standard Model expectations at least at the few-percent level.

These deviations will form a pattern that will give us information on the nature of the new physics.

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.

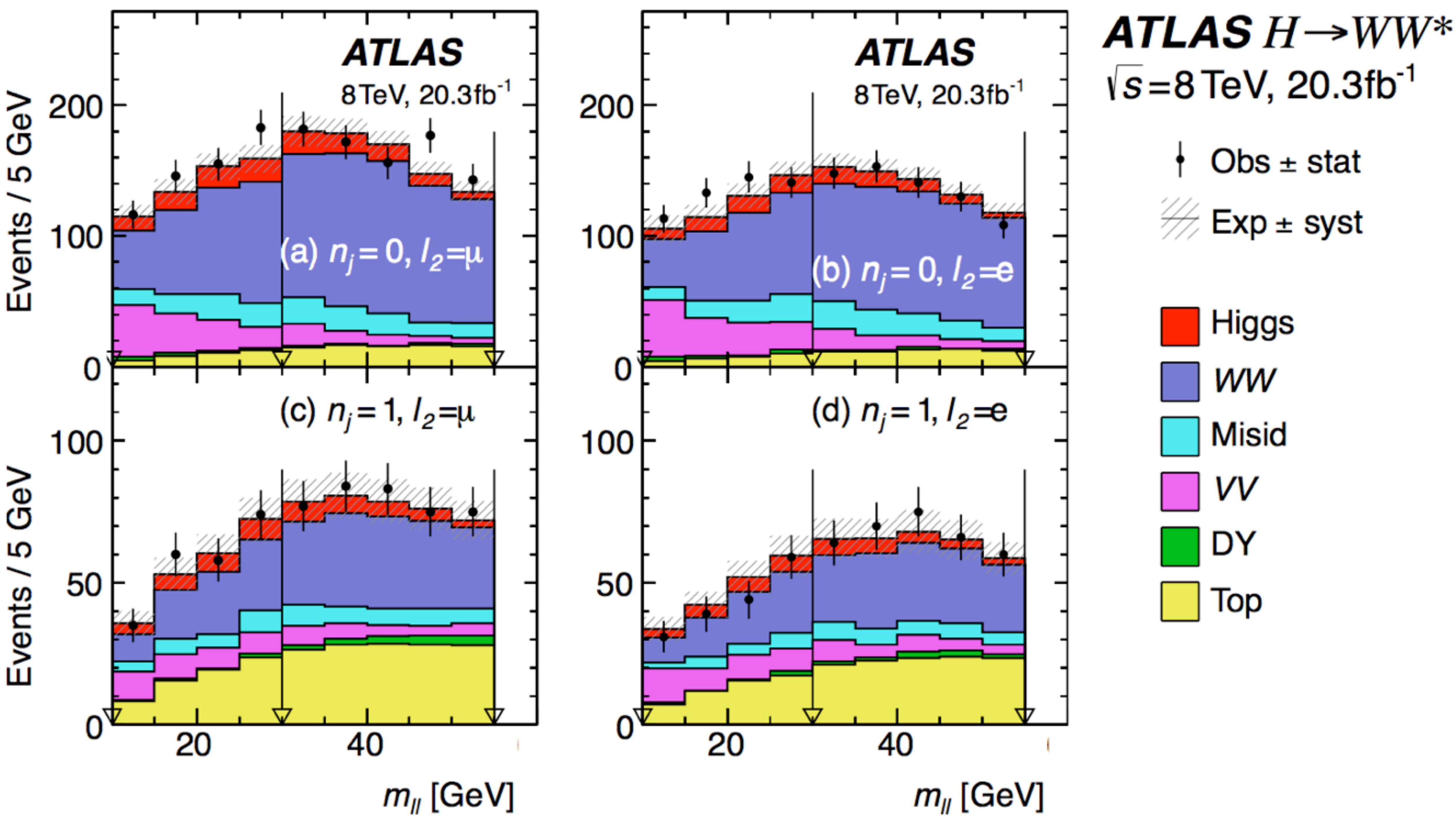
This requires a comprehensive program on Higgs production and decay processes, such that the partial widths can be extracted by a combination of $\mu(A, B)$ and cross section measurements.

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.

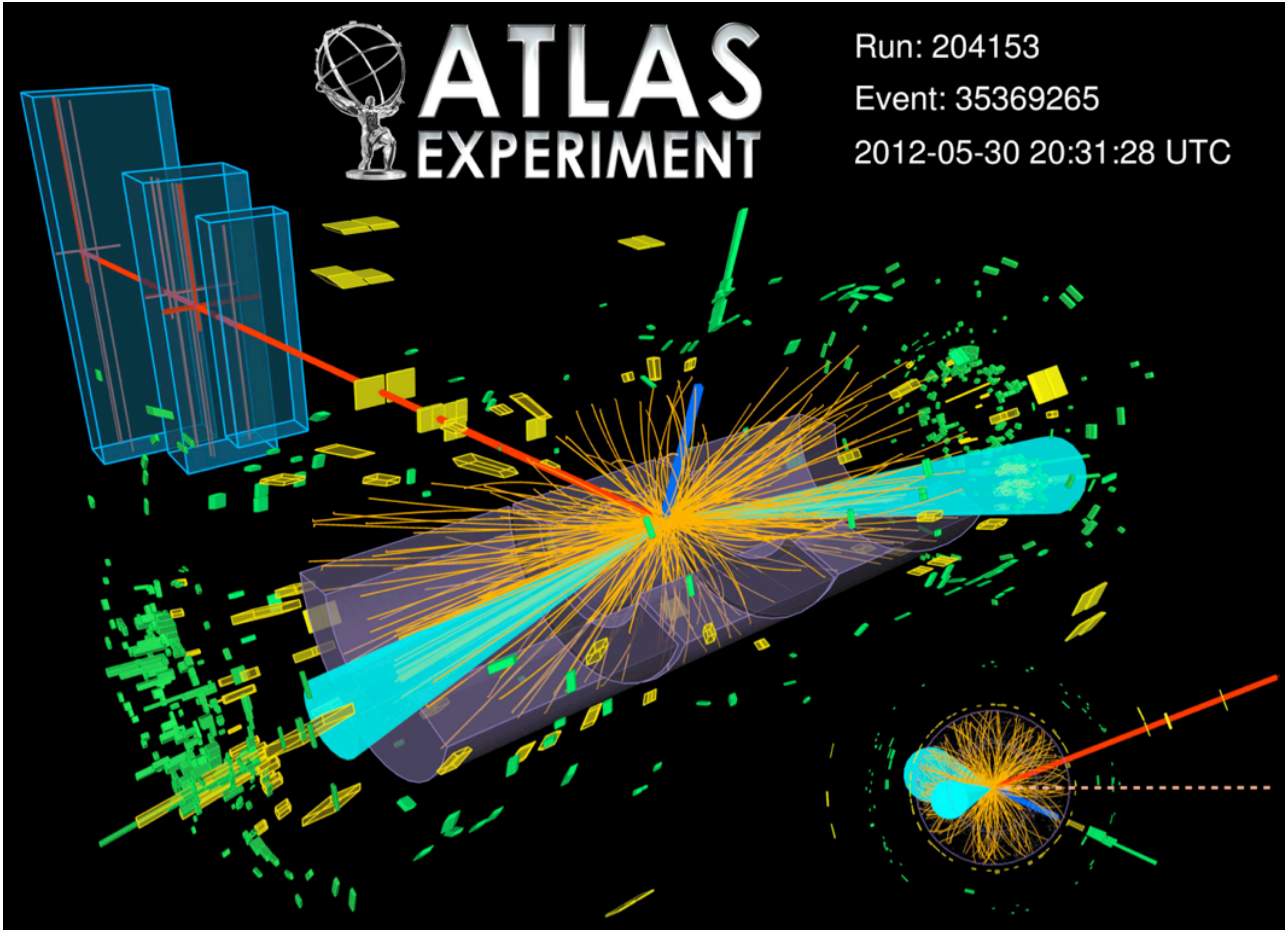
We will learn much about the Higgs boson from its study at the LHC over the next 20 years.

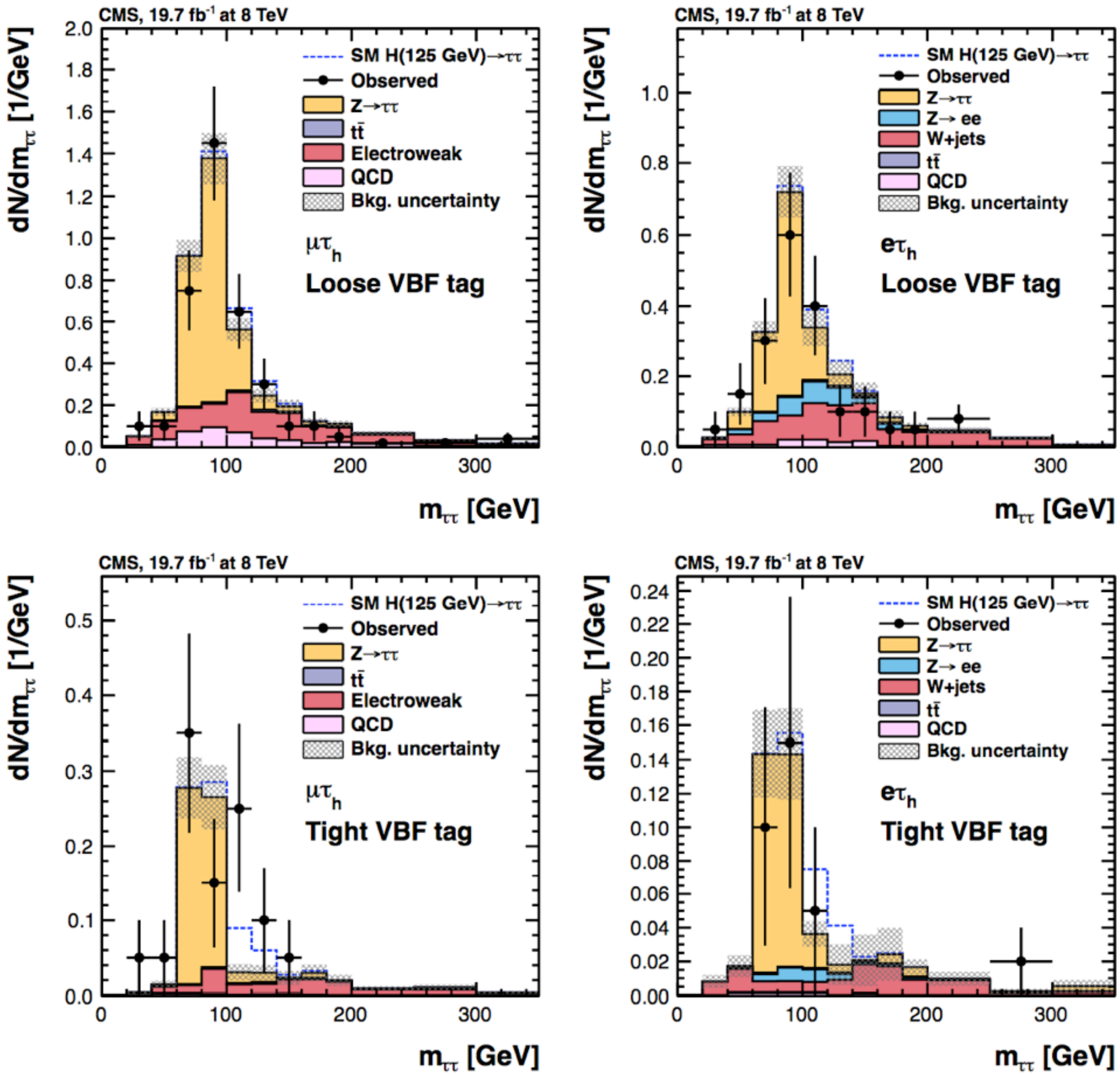
However, the LHC cannot fulfill the goals of the program I have outlined.

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

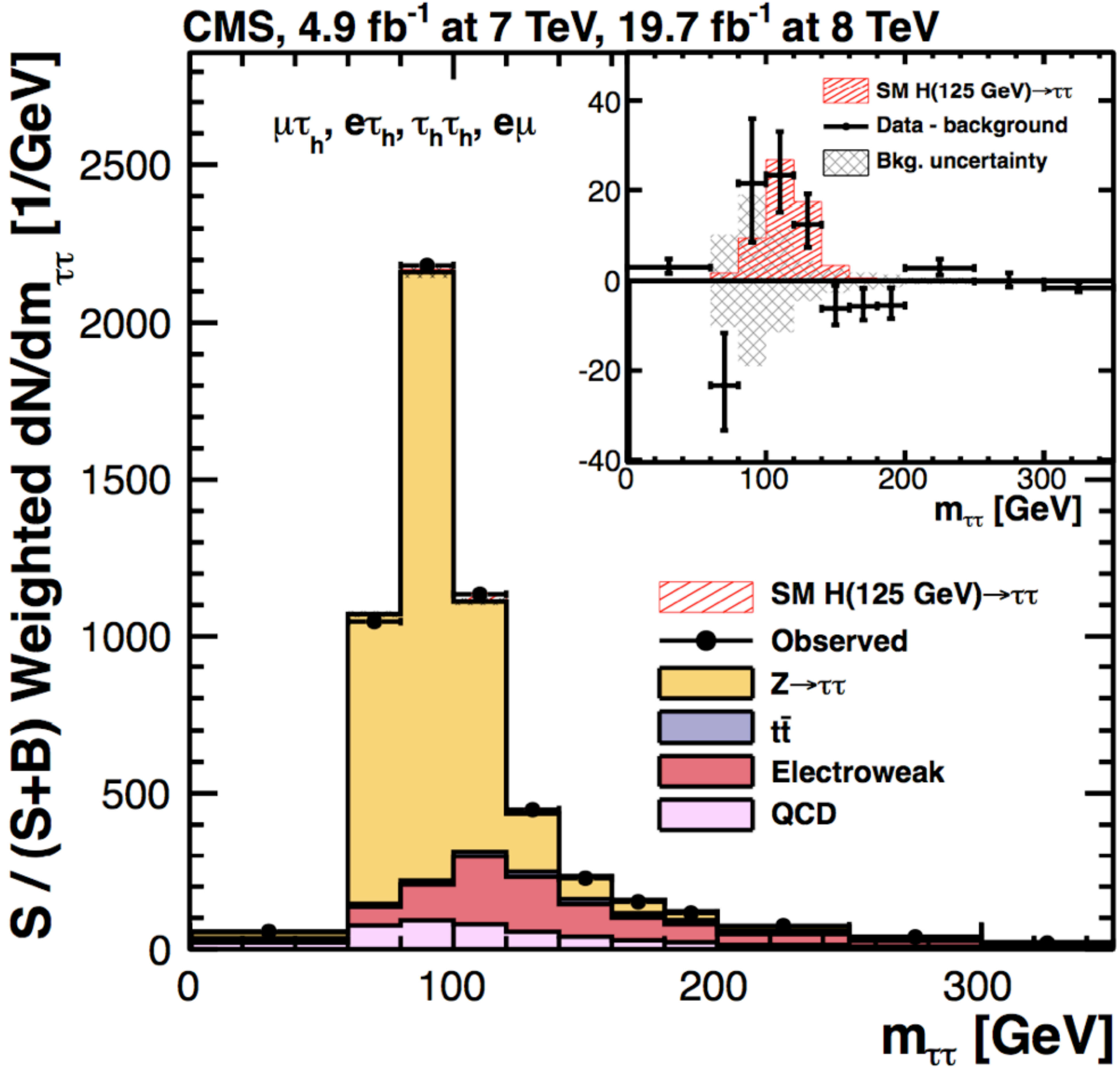


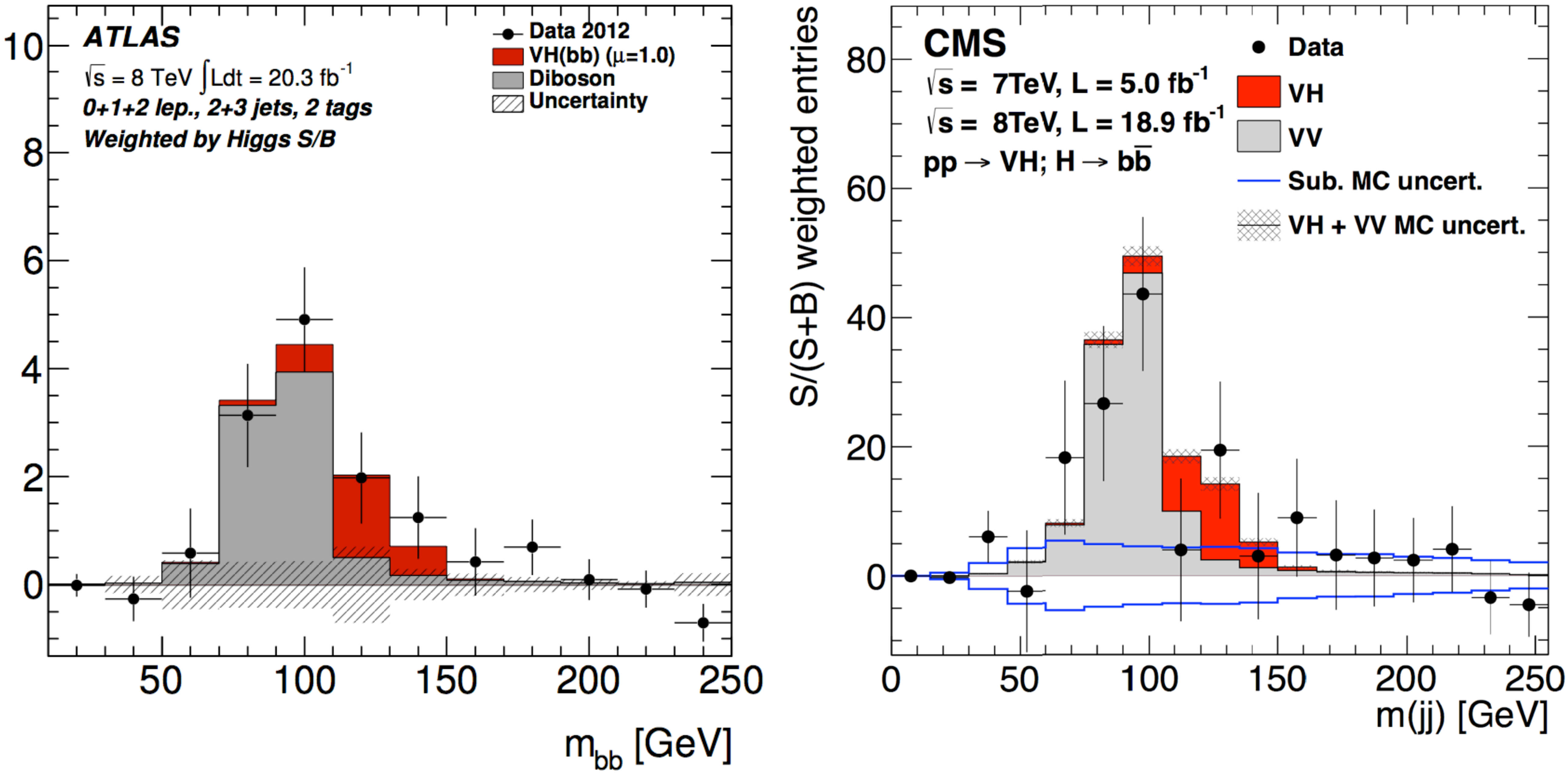
ATLAS
8 TeV, 20.3fb-1
(a) $n_j = 0, l_2 = \mu$
(b) $n_j = 0, l_2 = e$
(c) $n_j = 1, l_2 = \mu$
(d) $n_j = 1, l_2 = e$
Events / 5 GeV
m_{ll} [GeV]
ATLAS $H \rightarrow WW^*$
$\sqrt{s} = 8$ TeV, 20.3fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top


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

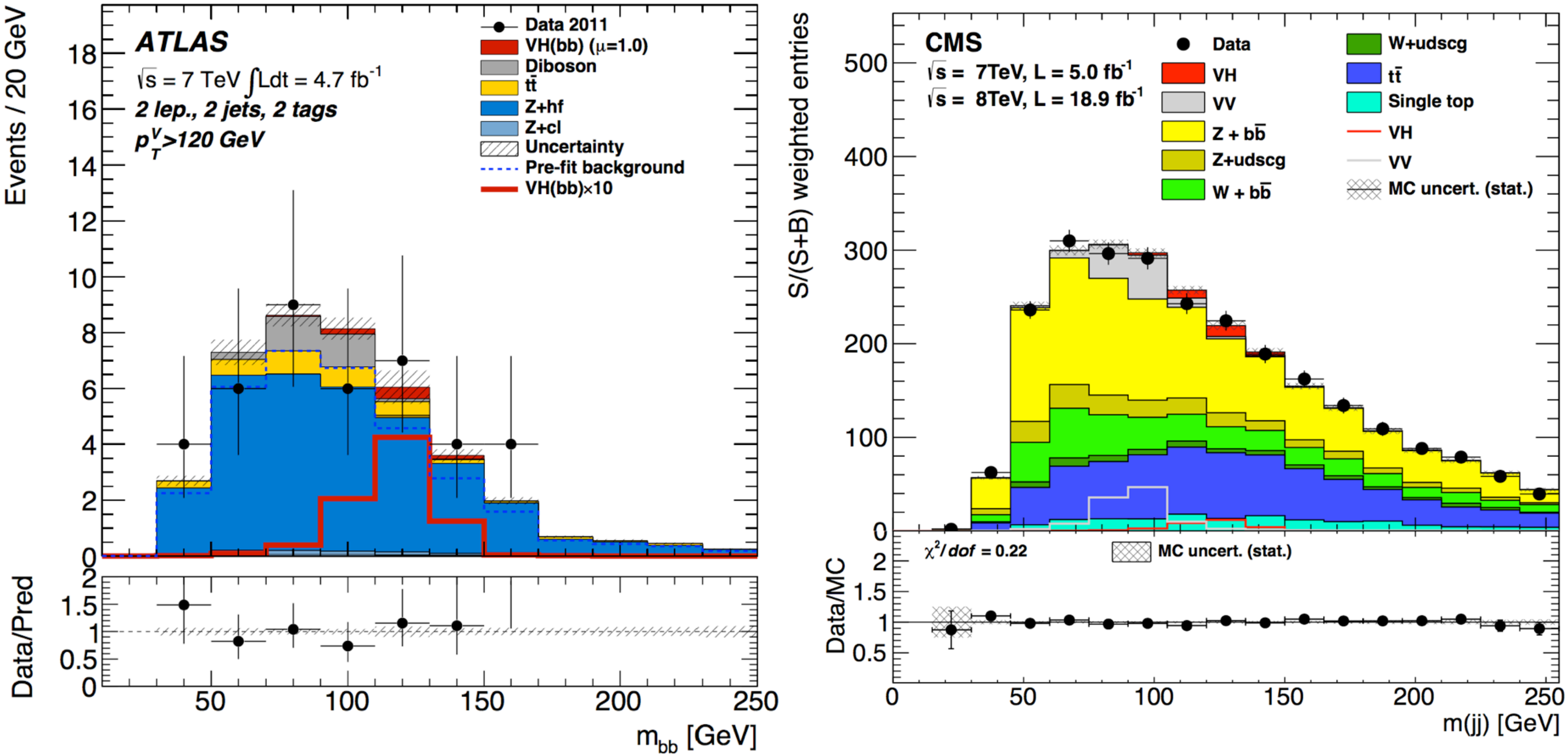


CMS, 19.7 fb-1 at 8 TeV
dN/dmττ [1/GeV]
mττ [GeV]
SM H(125 GeV)→ττ
Observed
Z→ττ
tt̄
Electroweak
QCD
Bkg. uncertainty
μτh
Loose VBF tag
CMS, 19.7 fb-1 at 8 TeV
Z→ ee
W+jets
eτh
Loose VBF tag
μτh
Tight VBF tag
eτh
Tight VBF tag


CMS, 4.9 fb^{-1} at 7 TeV, 19.7 fb^{-1} at 8 TeV
$\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$
S / (S+B) Weighted dN/dm$_{\tau\tau}$ [1/GeV]
m$_{\tau\tau}$ [GeV]
SM H(125 GeV)→ττ
Data - background
Bkg. uncertainty
SM H(125 GeV)→ττ
Observed
Z→ττ
t$\bar{t}$
Electroweak
QCD



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]



ATLAS
$\sqrt{s}$ = 7 TeV $\int$Ldt = 4.7 fb^{-1}
2 lep., 2 jets, 2 tags
p_T^V>120 GeV
Data 2011
VH(bb) (μ=1.0)
Diboson
$t\bar{t}$
Z+hf
Z+cl
Uncertainty
Pre-fit background
VH(bb)×10
Events / 20 GeV
Data/Pred
m_{bb} [GeV]
CMS
$\sqrt{s}$ = 7TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8TeV, L = 18.9 fb^{-1}
Data
VH
VV
Z + $b\bar{b}$
Z+udscg
W + $b\bar{b}$
W+udscg
$t\bar{t}$
Single top
VH
VV
MC uncert. (stat.)
S/(S+B) weighted entries
χ^2/dof = 0.22
MC uncert. (stat.)
Data/MC
m(jj) [GeV]

CMS projections for the measurement accuracy of Higgs couplings at LHC and HL-LHC :

L (fb^{-1})	$H \to \gamma\gamma$	$H \to WW$	$H \to ZZ$	$H \to bb$	$H \to \tau\tau$	$H \to Z\gamma$	$H \to$ inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

CMS assumed that these accuracies are limited mainly by statistics and by theory uncertainties in the total cross sections. However, really, the limiting factor will be the 10:1 ratio of background to signal in the best signal regions.

(For a comparison of CMS and ATLAS projections, see my paper arXiv:1312.4974.)

One important special case should be noted:

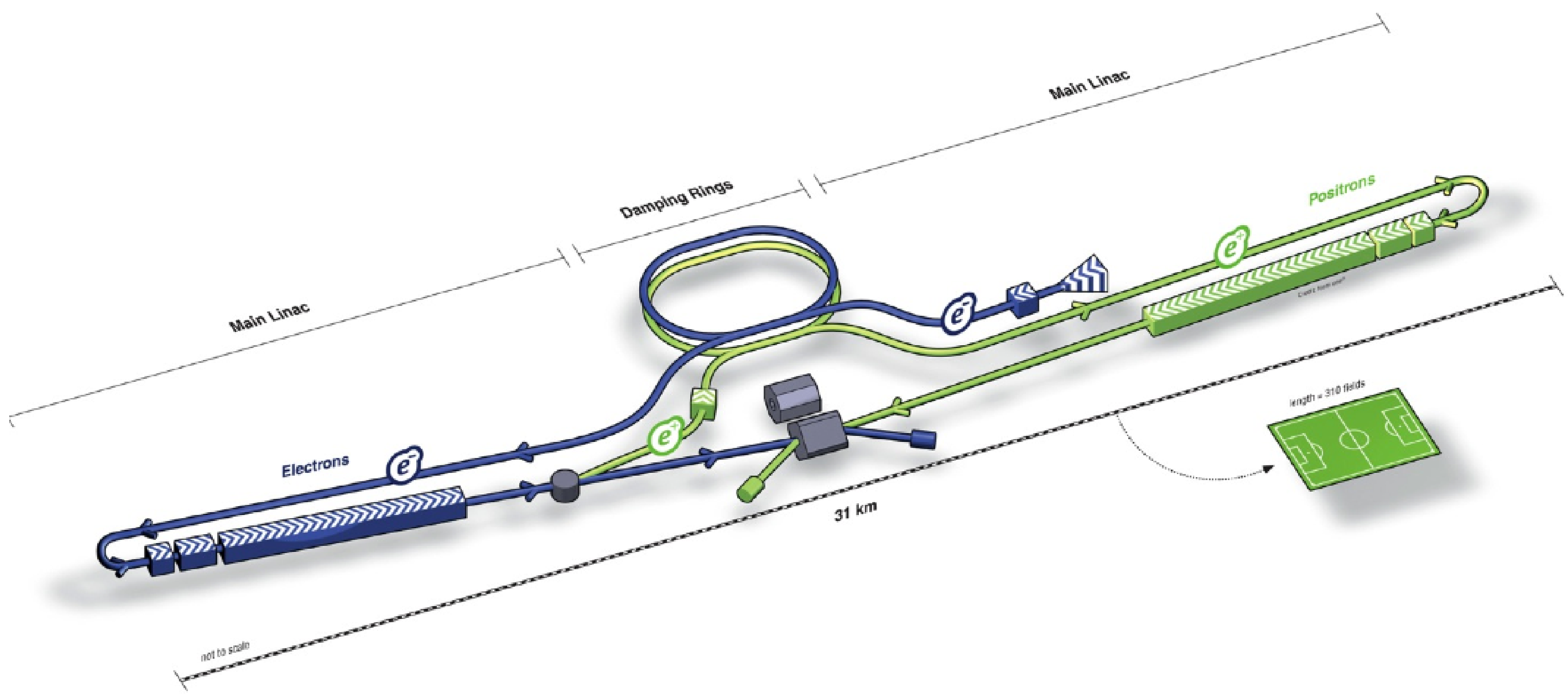
The modes $h \to \gamma\gamma$ and $h \to 4\ell$ are visible in the total cross section, with very similar selections.

It should be possible to design an analysis in which measurement the ratio of the production rates, in the same specified region of η , is independent of the Higgs production cross section and is limited by statistics only.

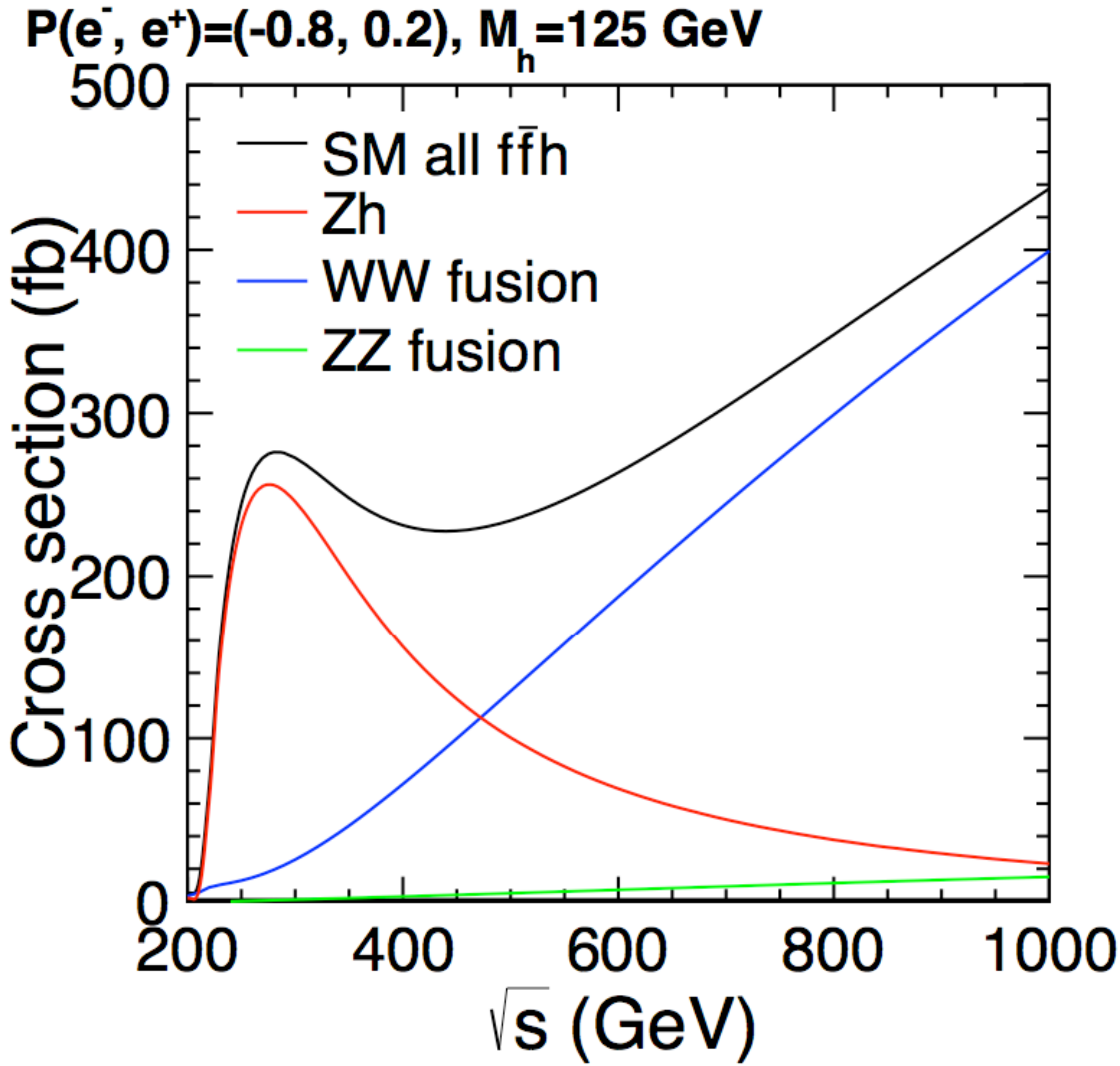
ATLAS estimated the ultimate error on this ratio as 3.6%. This is probably an overestimate. The pure statistics limit (50% efficiency) is about 2% for 3000/fb.

There is a proposed accelerator capable of meeting these goals that is studied thoroughly, designed at the level its TDR, and ready for construction.

This is the International Linear Collider (ILC).

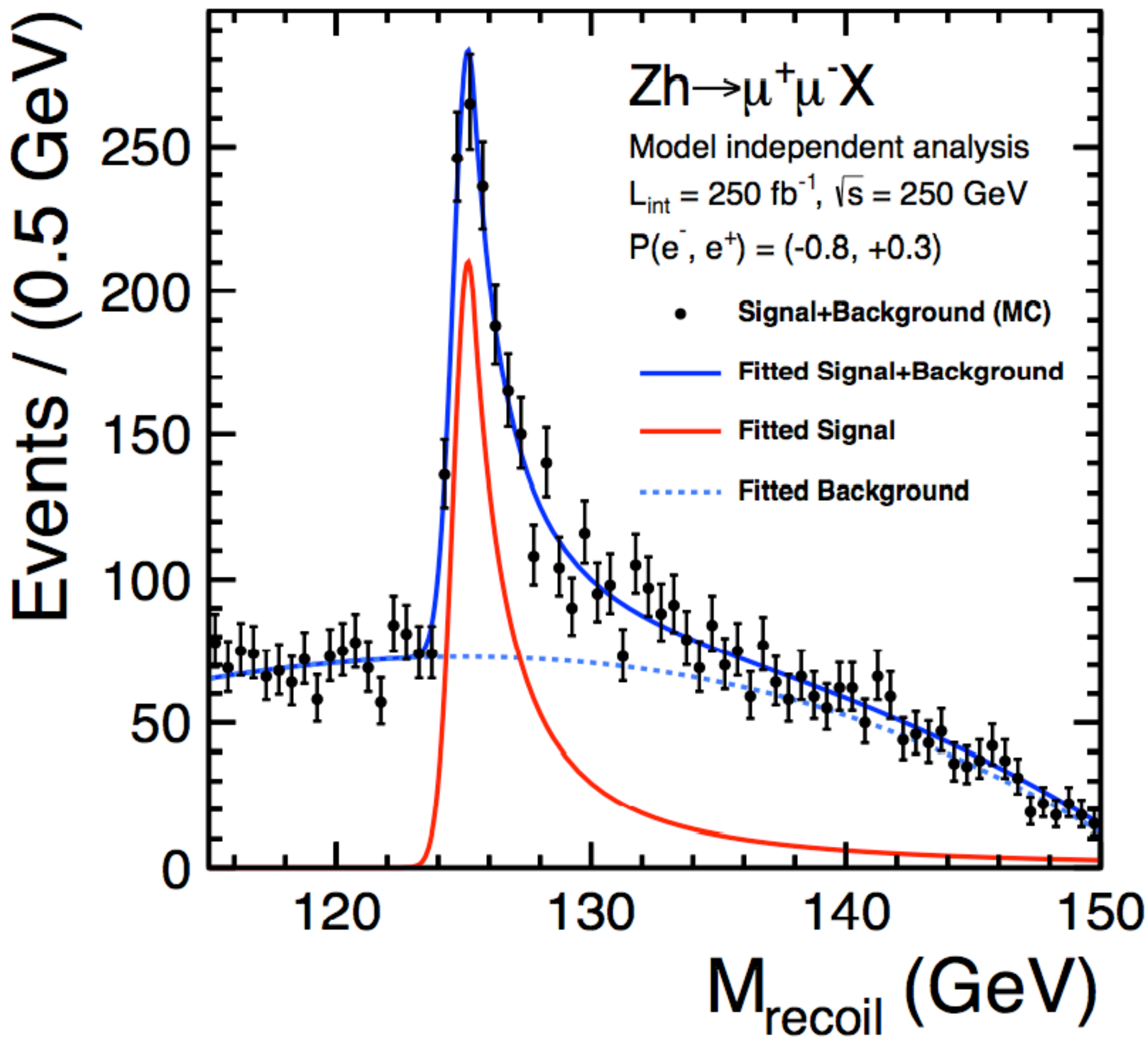


Here are a few snapshots from the physics expectations for the ILC.



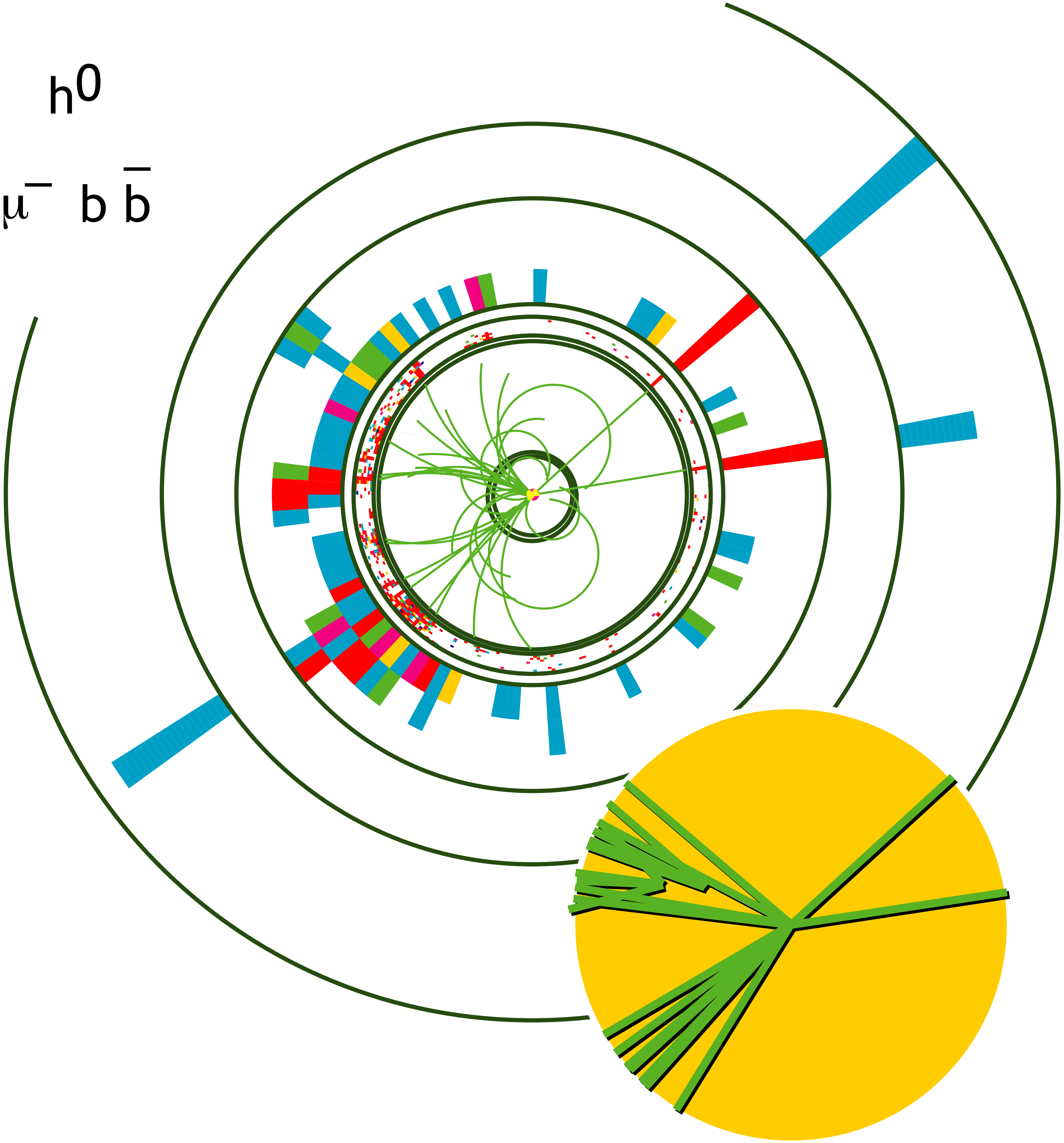
P(e⁻, e⁺)=(-0.8, 0.2), M_h=125 GeV
SM all f f̄ h
Zh
WW fusion
ZZ fusion
Cross section (fb)
500
400
300
200
100
0
200
400
600
800
1000
√s (GeV)

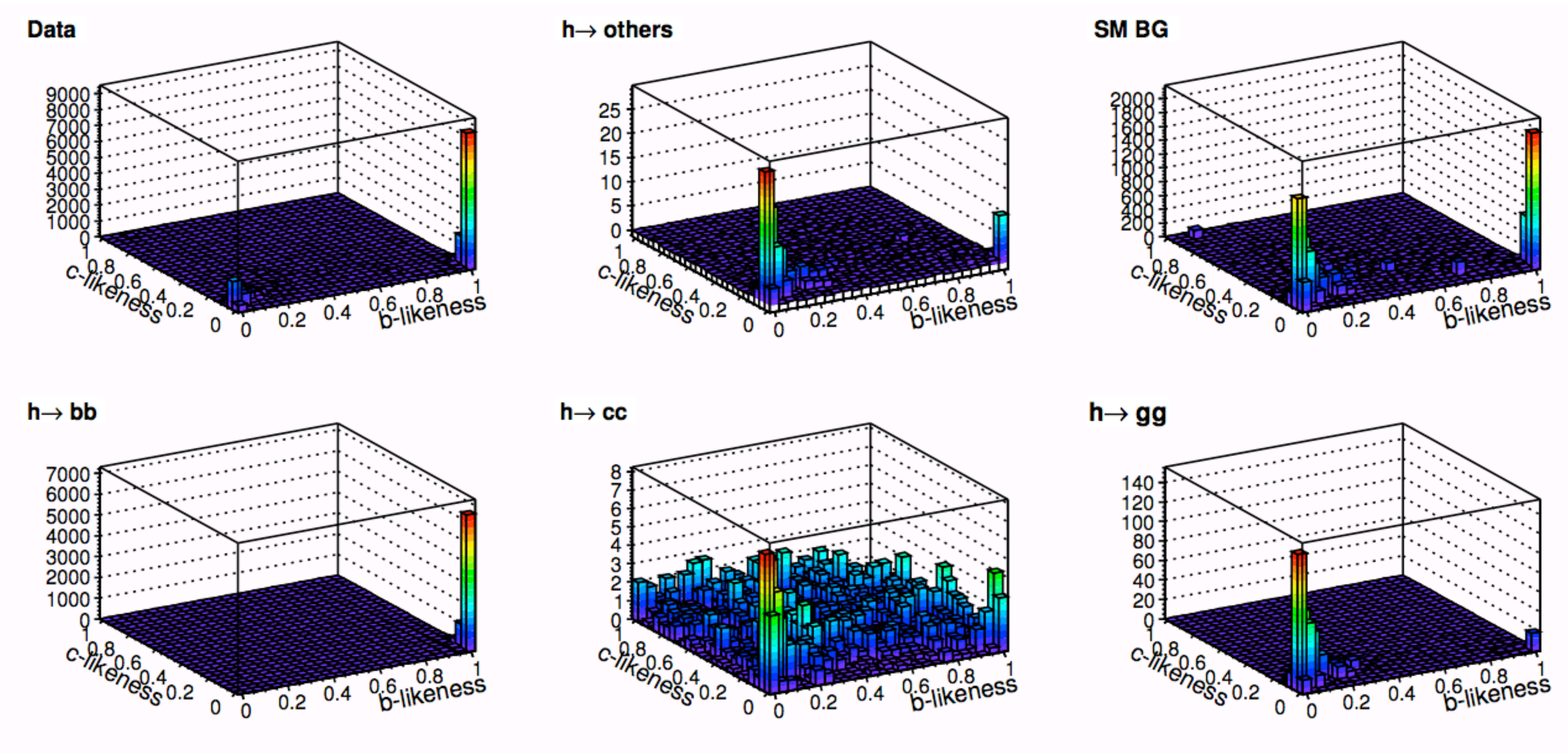
m_h to 30 MeV using a recoil technique



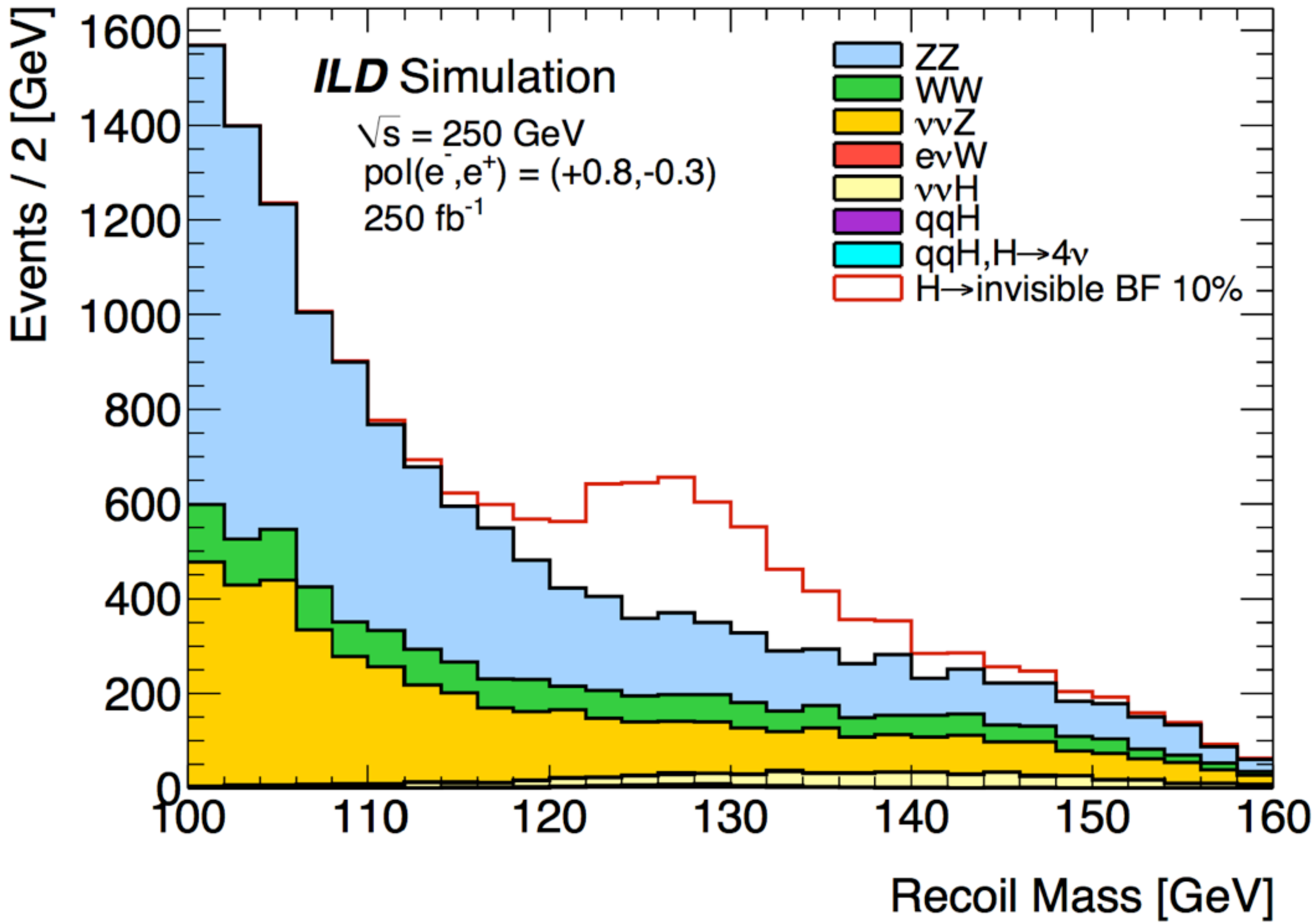
$$e^+e^- \rightarrow Z^0 \quad h^0$$

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

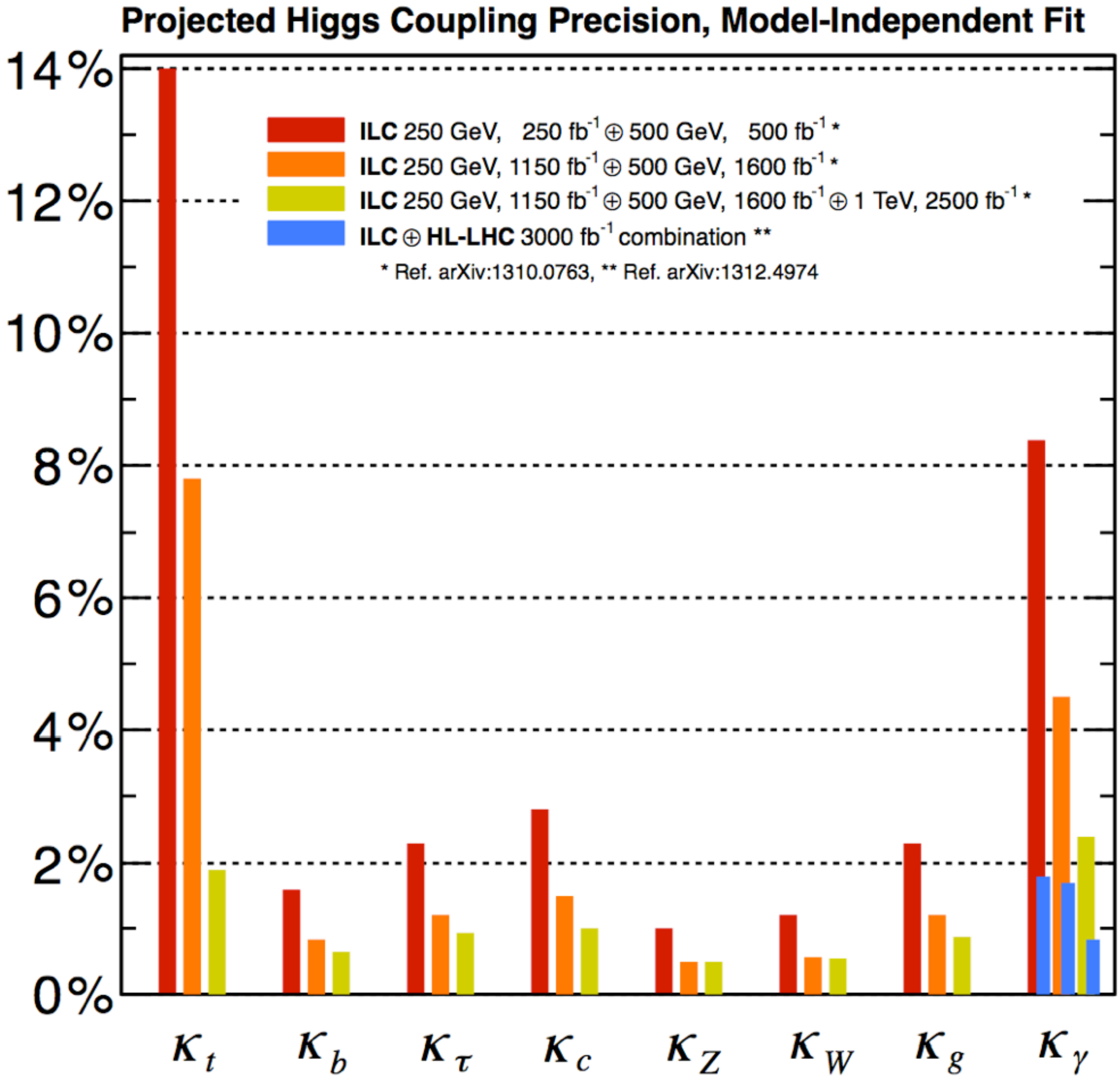




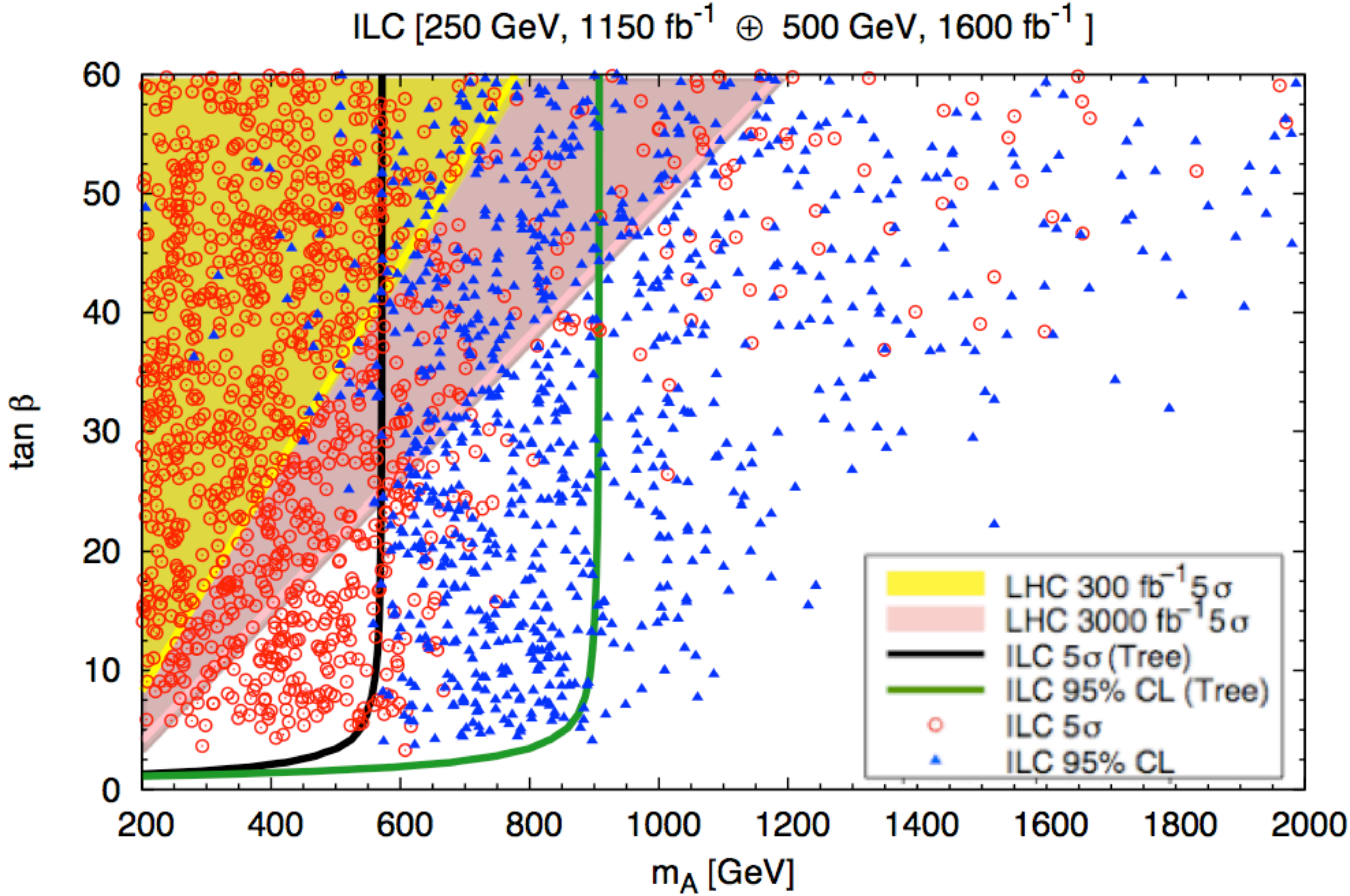
Data
h→ others
SM BG
h→ bb
h→ cc
h→ gg
c-likeness
b-likeness



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 Higgs Coupling Precision, Model-Independent Fit
14%
12%
10%
8%
6%
4%
2%
0%
ILC 250 GeV, 250 fb^{-1} ⊕ 500 GeV, 500 fb^{-1} *
ILC 250 GeV, 1150 fb^{-1} ⊕ 500 GeV, 1600 fb^{-1} *
ILC 250 GeV, 1150 fb^{-1} ⊕ 500 GeV, 1600 fb^{-1} ⊕ 1 TeV, 2500 fb^{-1} *
ILC ⊕ HL-LHC 3000 fb^{-1} combination **
* Ref. arXiv:1310.0763, ** Ref. arXiv:1312.4974
κ_t
κ_b
κ_τ
κ_c
κ_Z
κ_W
κ_g
κ_γ



Kanemura, Kikuchi, Matsui, Taniguchi, Yokoya

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

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