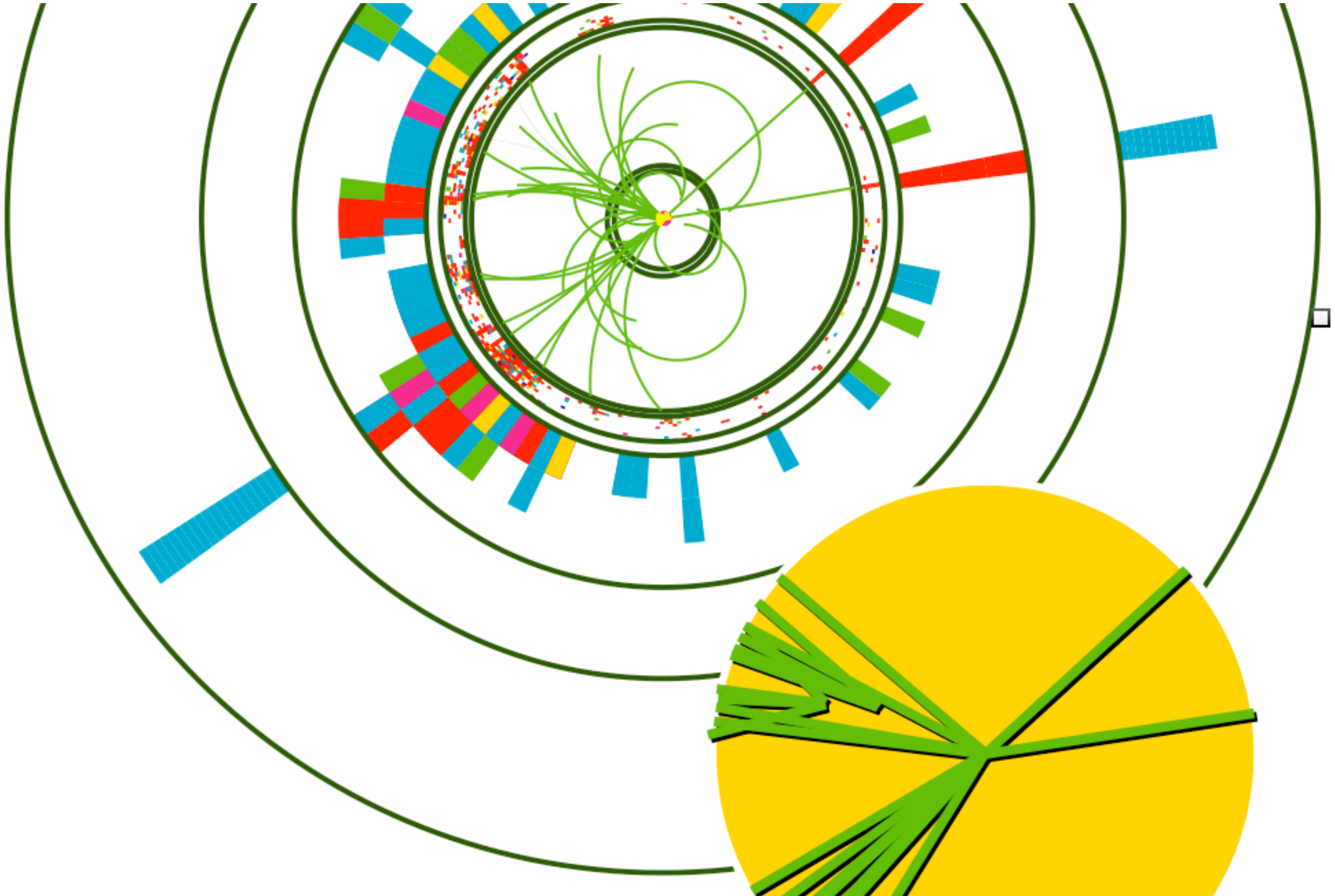
Secrets of the Higgs Boson

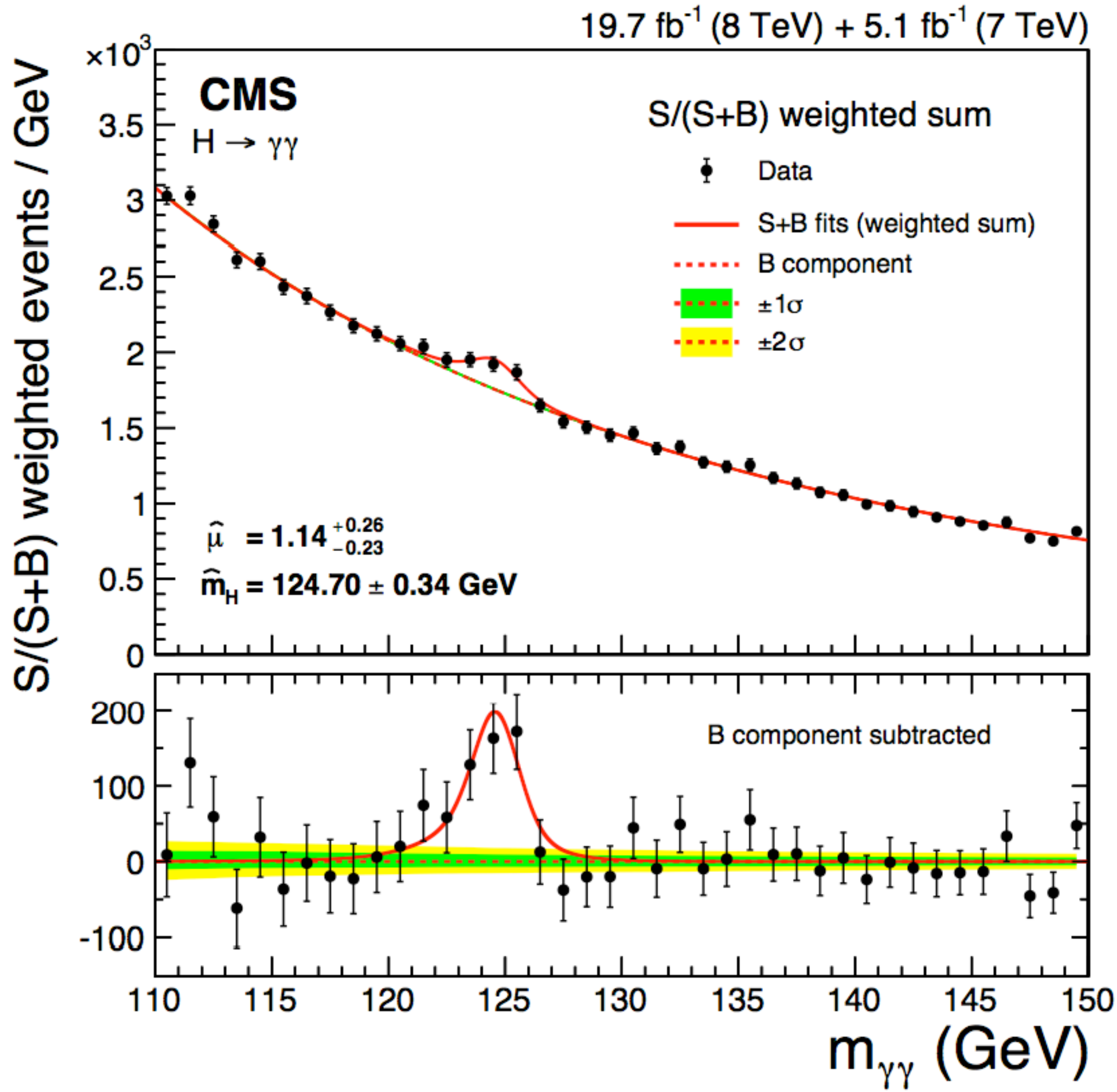


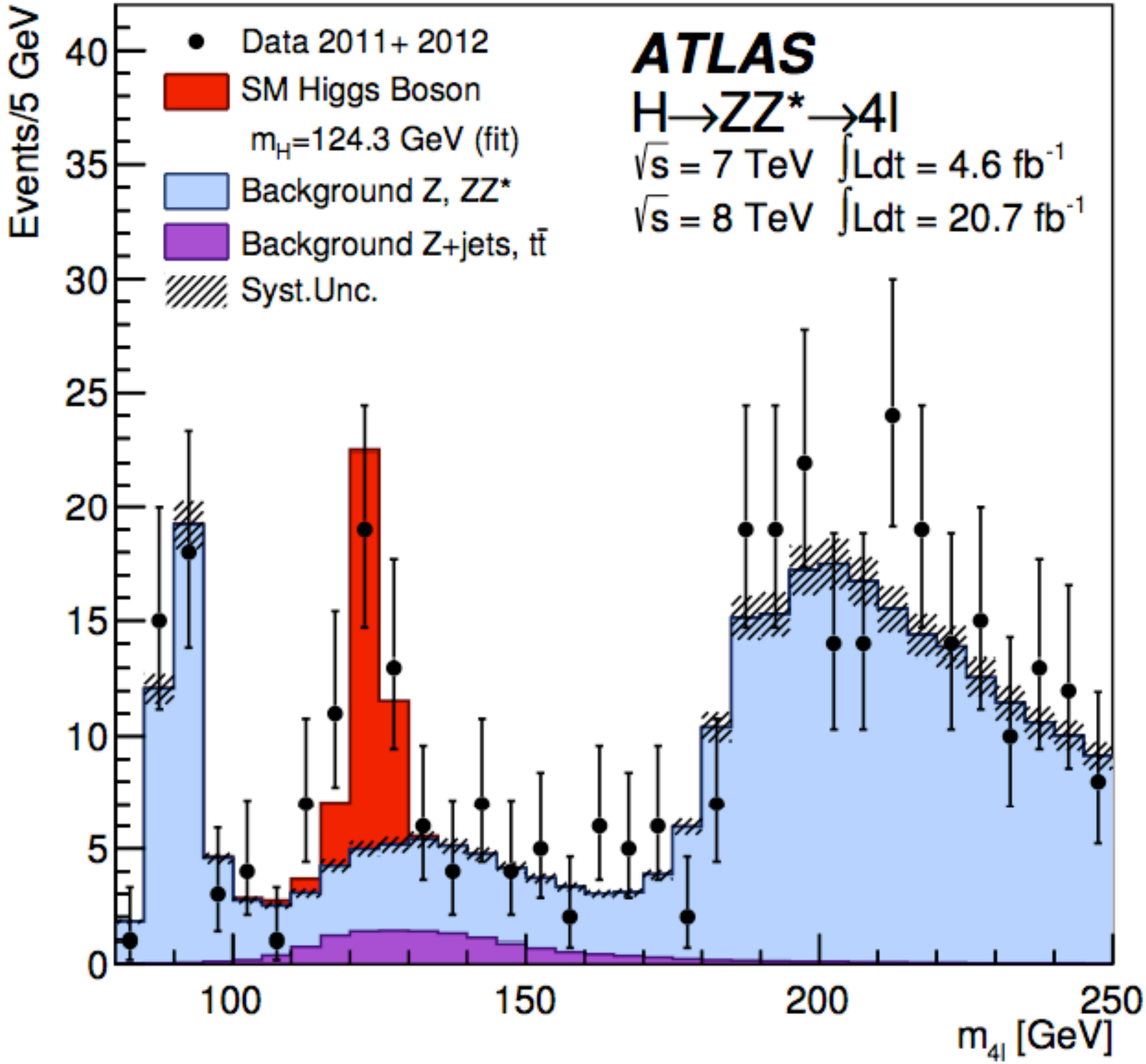
M. E. Peskin
January 2015

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.

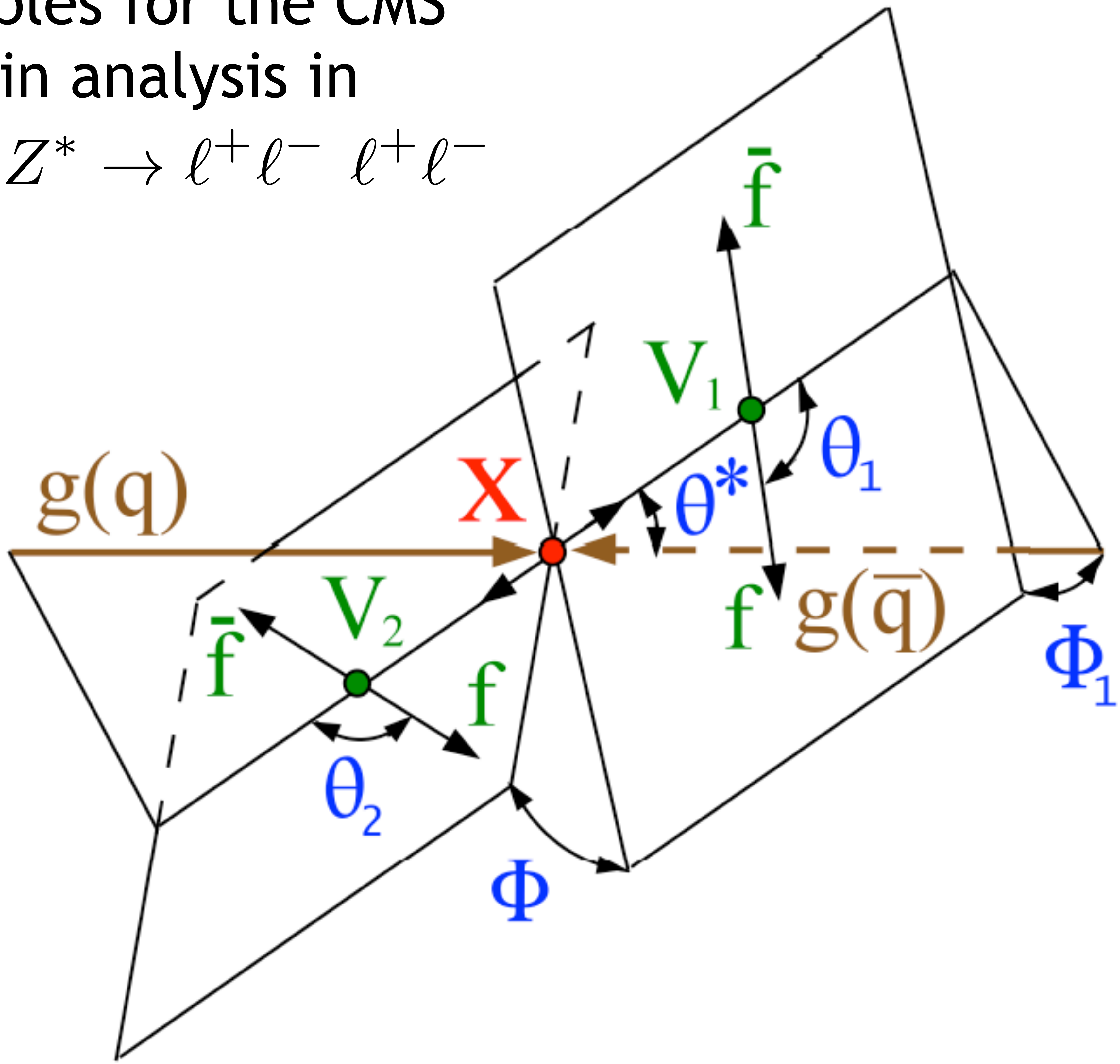

19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m̂H = 124.70 ± 0.34 GeV
S/(S+B) weighted events / GeV
×10³
B component subtracted
mγγ (GeV)

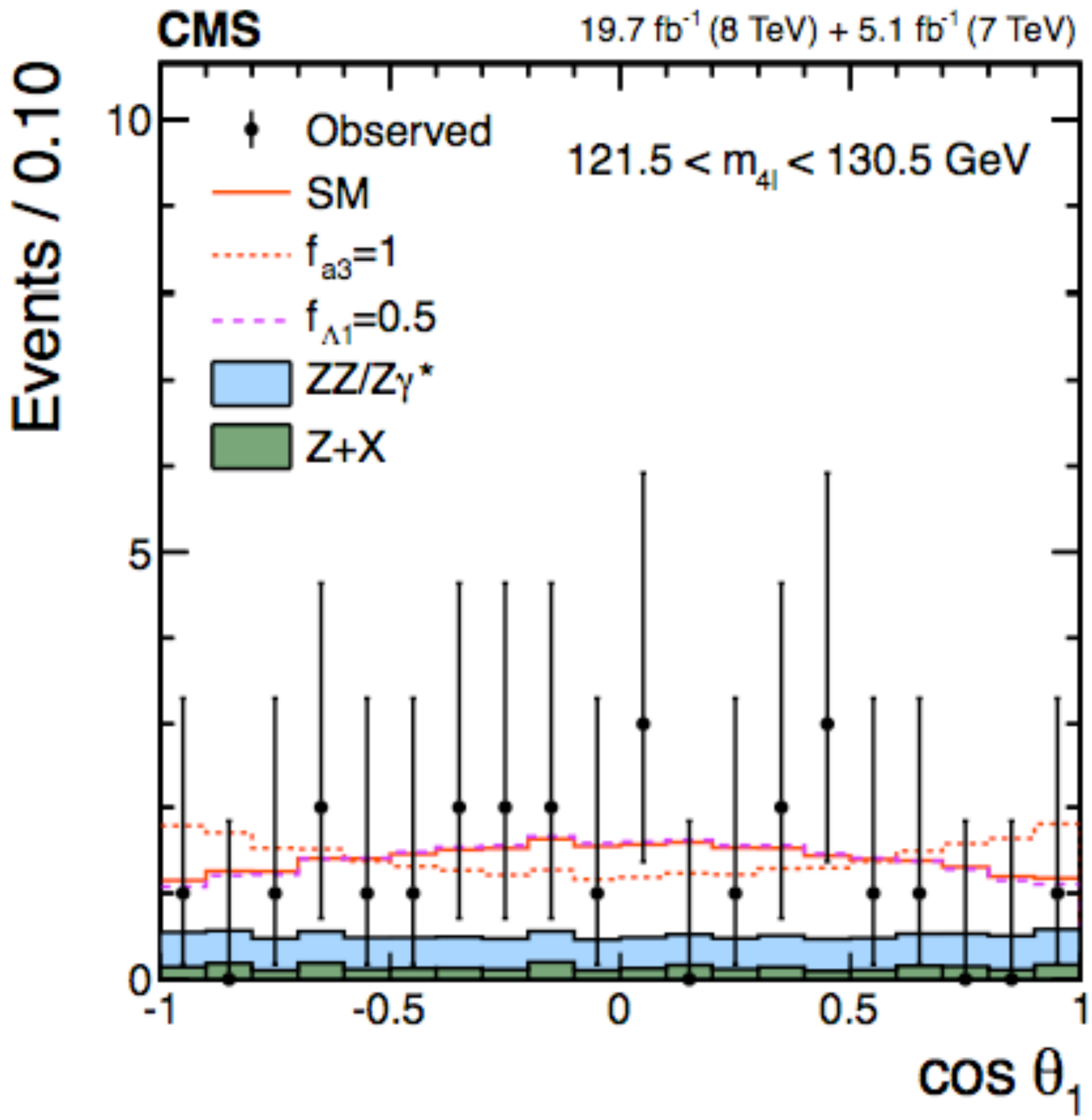


Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, tt̄
Syst.Unc.
ATLAS
H→ZZ*→4l
√s = 7 TeV ∫Ldt = 4.6 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
Events/5 GeV
m4l [GeV]
0
5
10
15
20
25
30
35
40
100
150
200
250

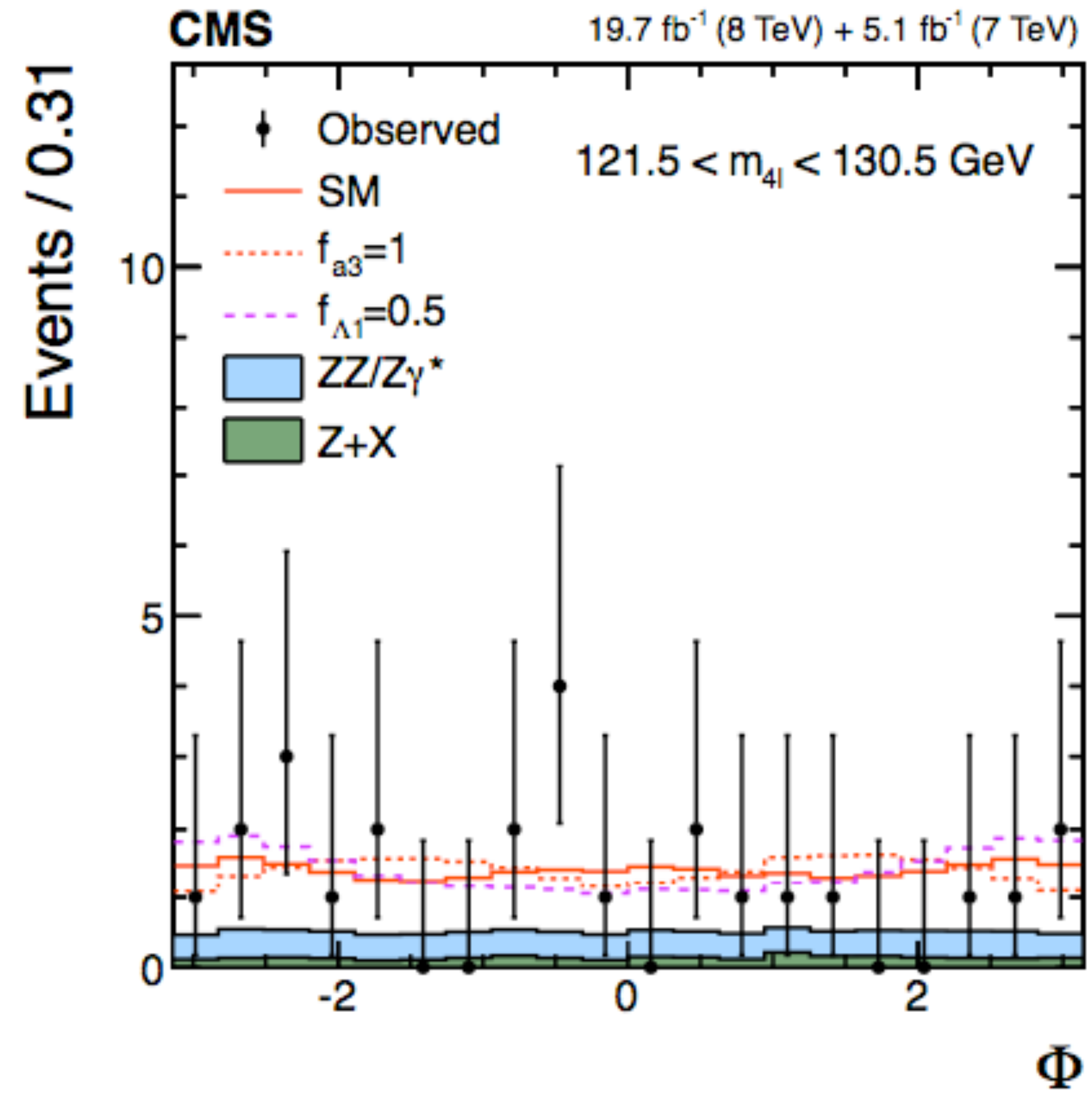
variables for the CMS spin analysis in

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

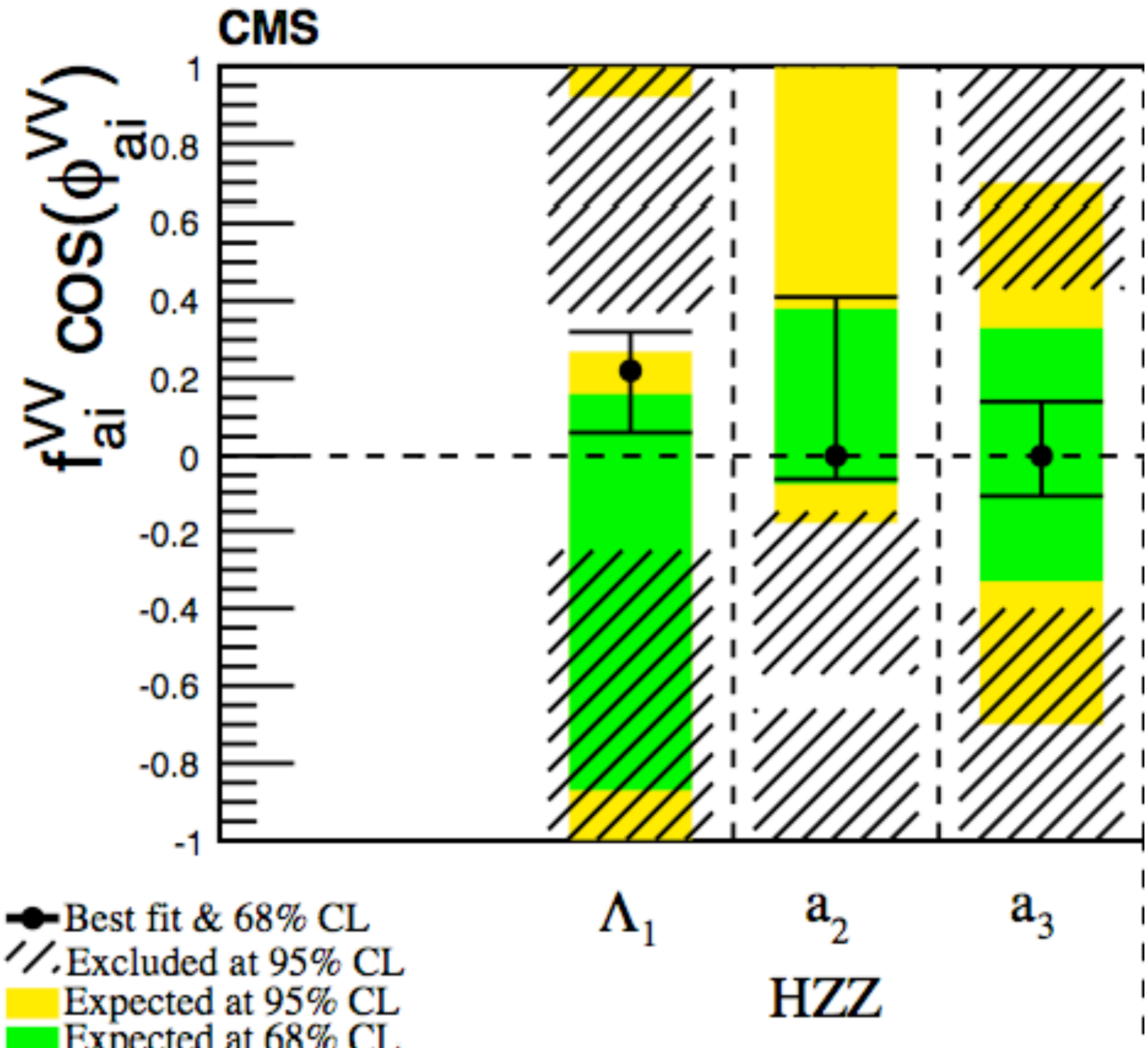




preference for Z to be longitudinally polarized



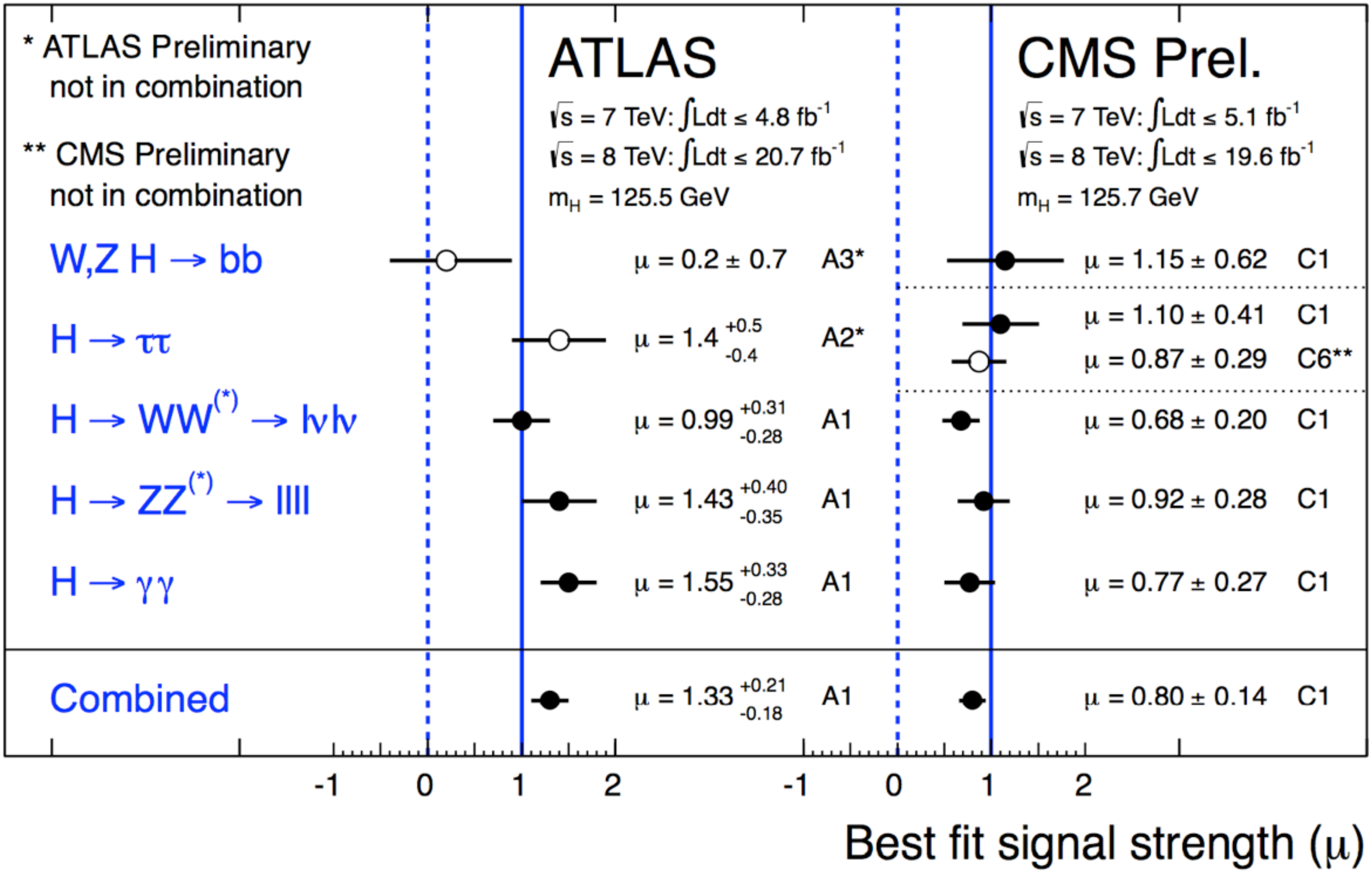
preference for Z decay planes to be parallel



CMS
$f_{ai}^{VV}\cos(\phi_{ai}^{VV})$
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Λ_1
a_2
a_3
HZZ
Best fit & 68% CL
Excluded at 95% CL
Expected at 95% CL
Expected at 68% CL

Many reactions involving the Higgs boson are now observed. The property that is measured is typically expressed as a "signal strength"

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



PDG summary 2014

These results present a picture that, taken at face value, implies that the new particle has exactly the properties expected for the Higgs boson of the Standard Model.

However, this presentation can hide a variety of secrets. In this talk, I will describe how these secrets can be hidden, why it is important to probe for them, and how we might accomplish this.

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

The Lagrangian is

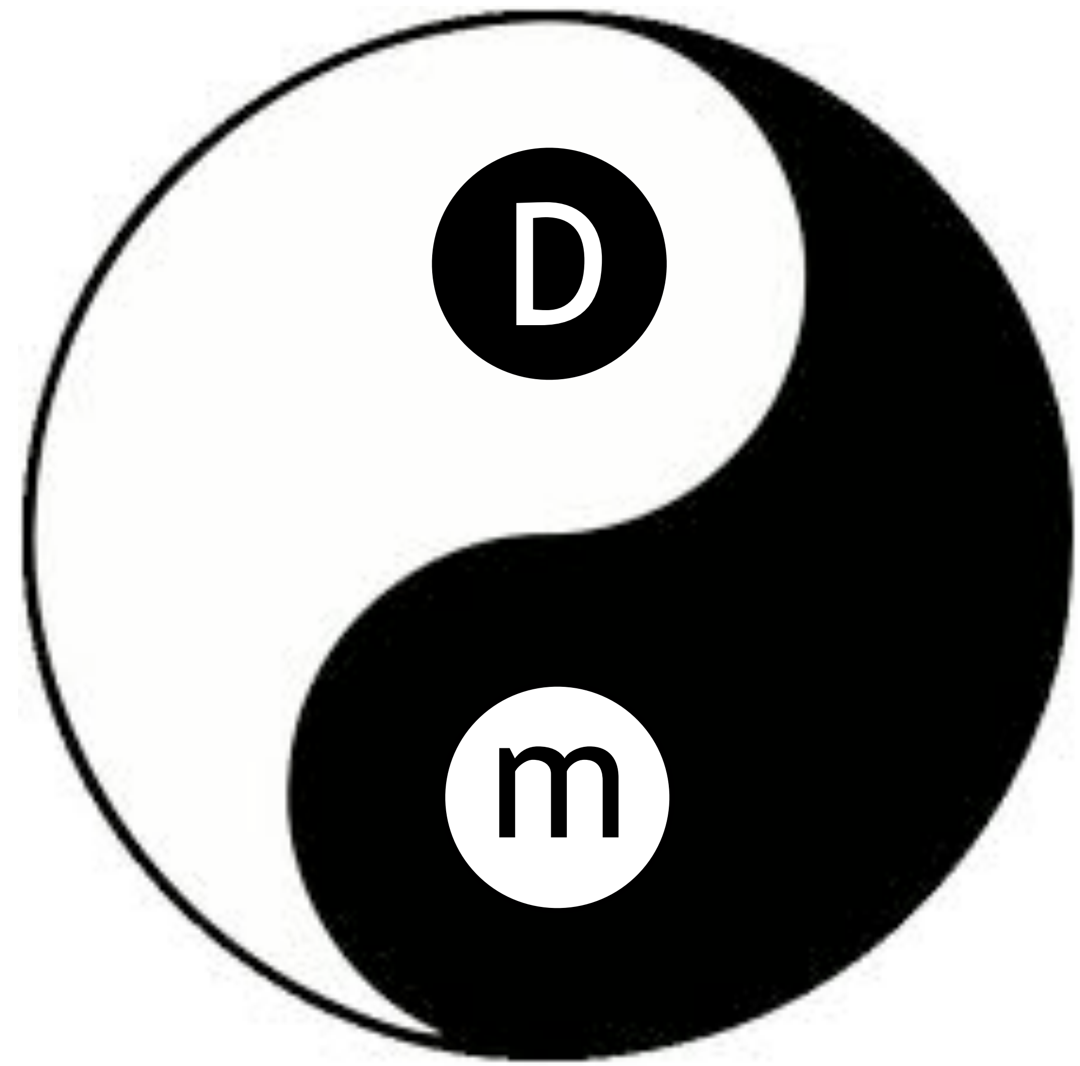
$$\mathcal{L} = -\frac{1}{4}\sum_a (F^a_{\mu\nu})^2 + \overline{f}(i\not{D})f$$
$$+|D_\mu\varphi|^2 - V(\varphi) - Y^{ij}\overline{f}_{iL}\cdot\varphi f_{jR} - h.c.$$

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:

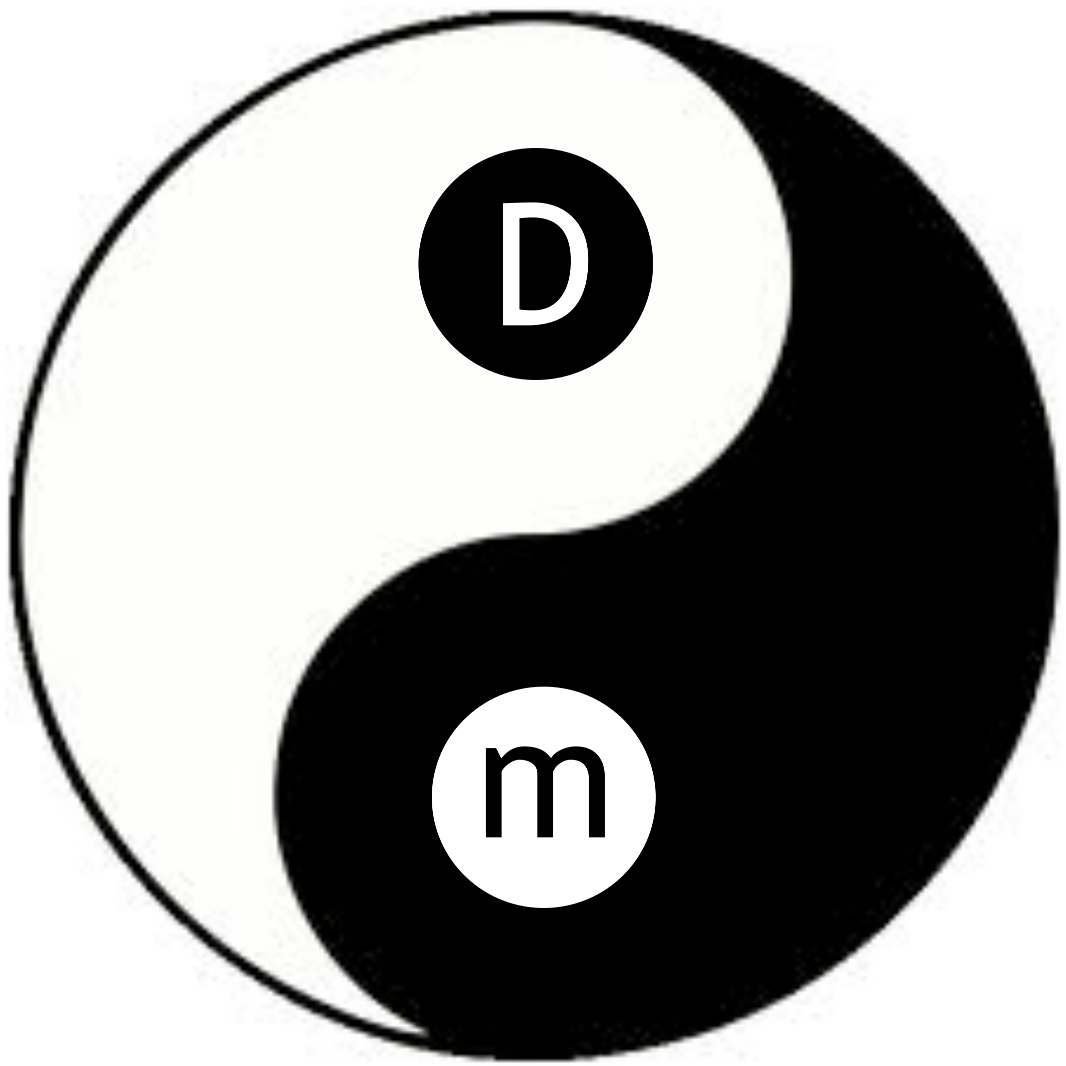
He emphasized that the search for and study of the Higgs boson was "problem #1" in particle physics.



I feel that this statement is still true today.

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

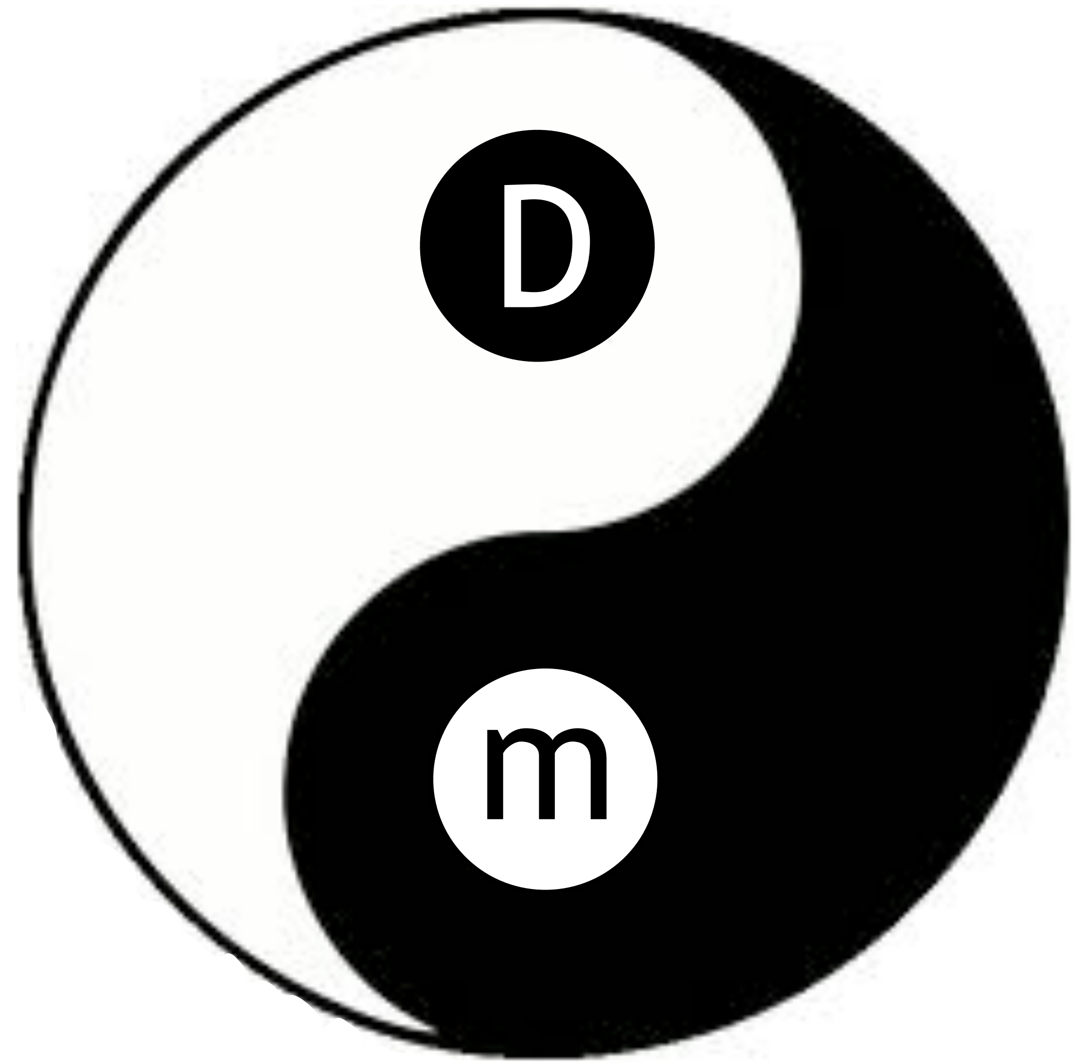
Dark matter ?

Standard Model is impotent

The mountain pass through which all explanations on the dark side must flow:

Why is electroweak symmetry broken ?

What is the mechanism ? What is the agent ?



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:

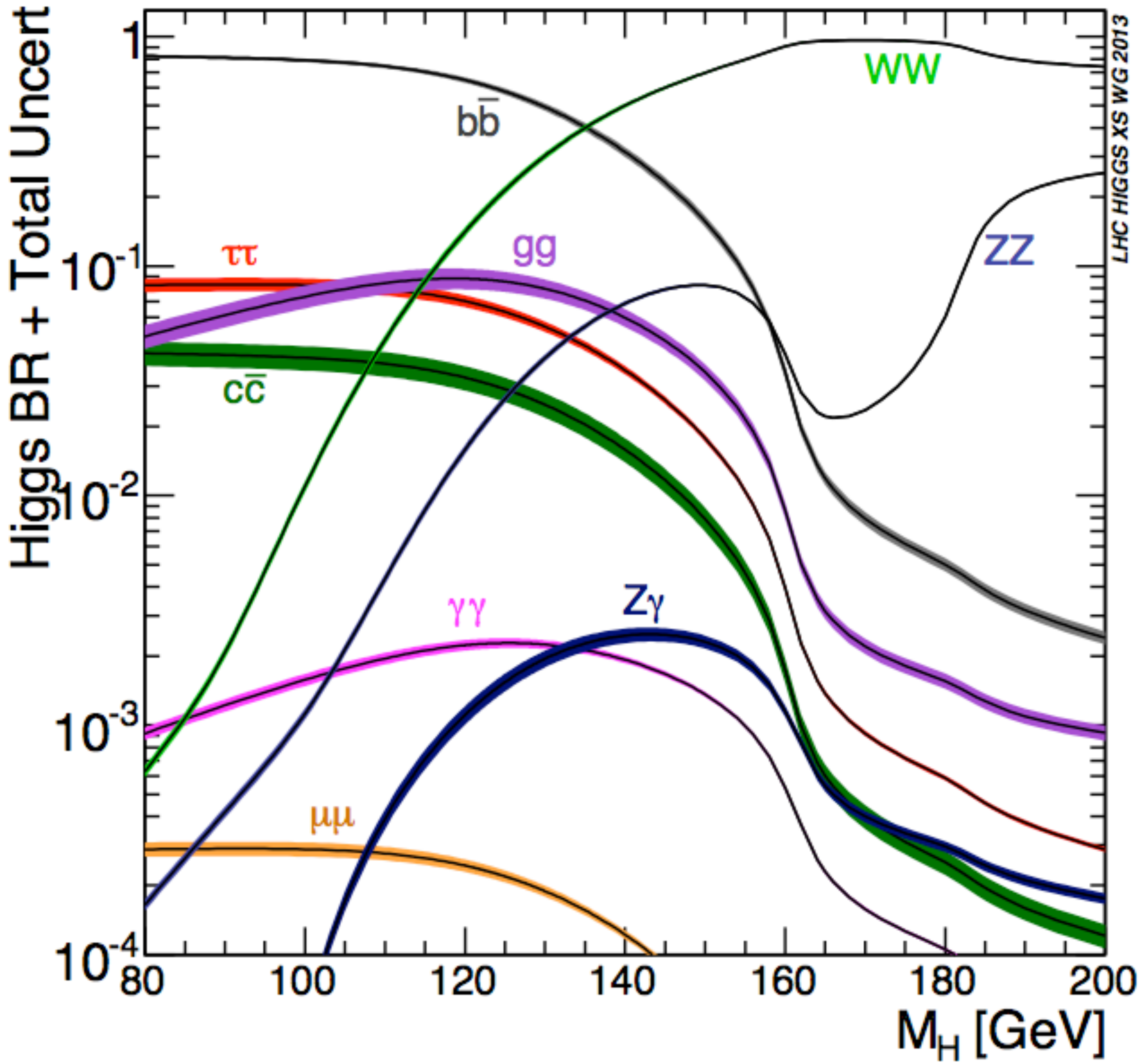
In most models of an extended Higgs sector or other new particles, the corrections to the Higgs couplings are at the few-% level. Precision measurement is needed to see these corrections.

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.

In the next part of the talk, I will go through the various Higgs boson couplings and discuss how they are influenced by new physics.

However, first, I should say more about the SM expectations and their tests at the LHC.



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

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

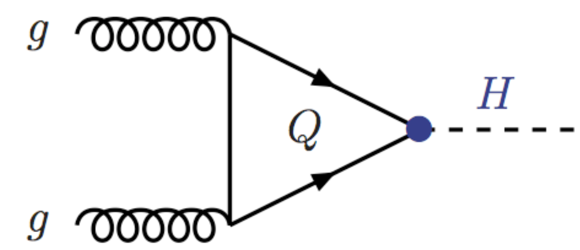
$b\bar{b}$	58%	$\tau^+\tau^-$	6.3%	$\gamma\gamma$	0.23%
WW^*	21%	$c\bar{c}$	2.9%	γZ	0.15%
gg	8.6%	ZZ^*	2.6%	$\mu^+\mu^-$	0.02%

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

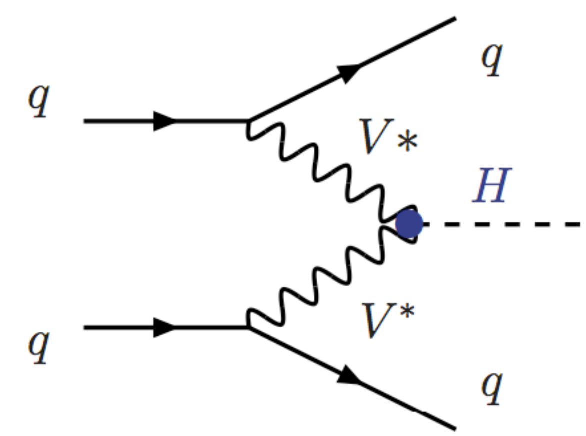
F. Gianotti: "Thank you, Nature."

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

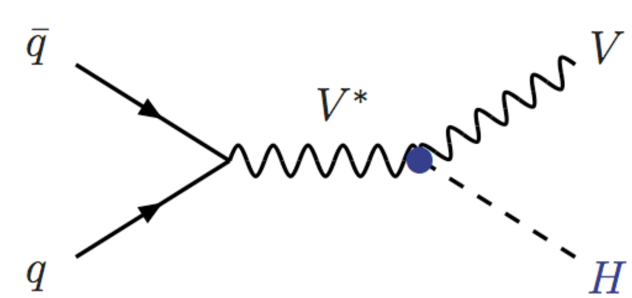
gluon-gluon fusion



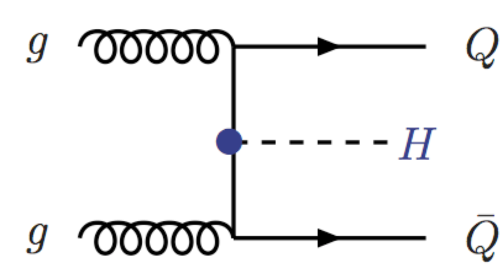
vector boson fusion

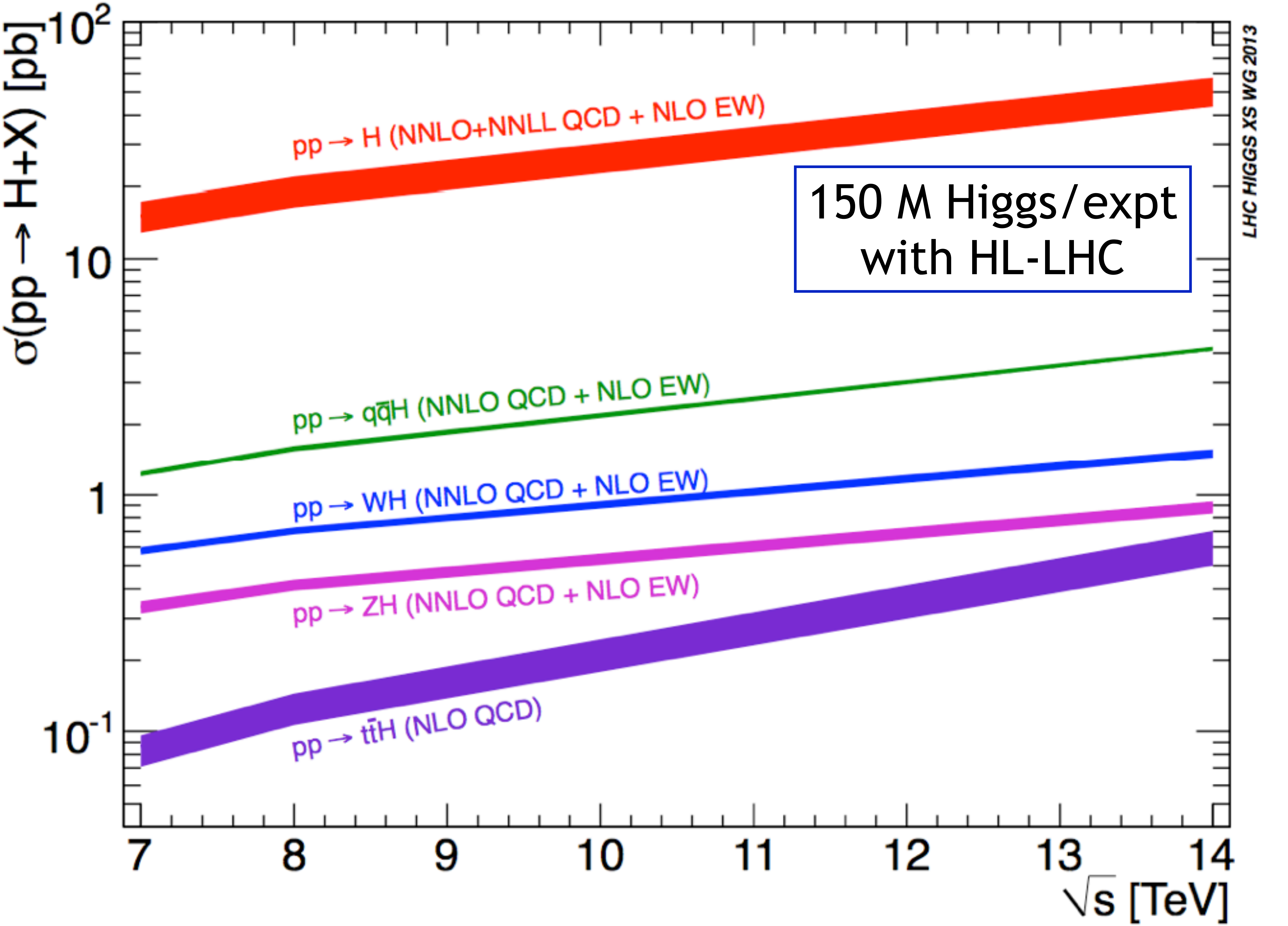


“Higgsstrahlung”
associated production
w. W, Z



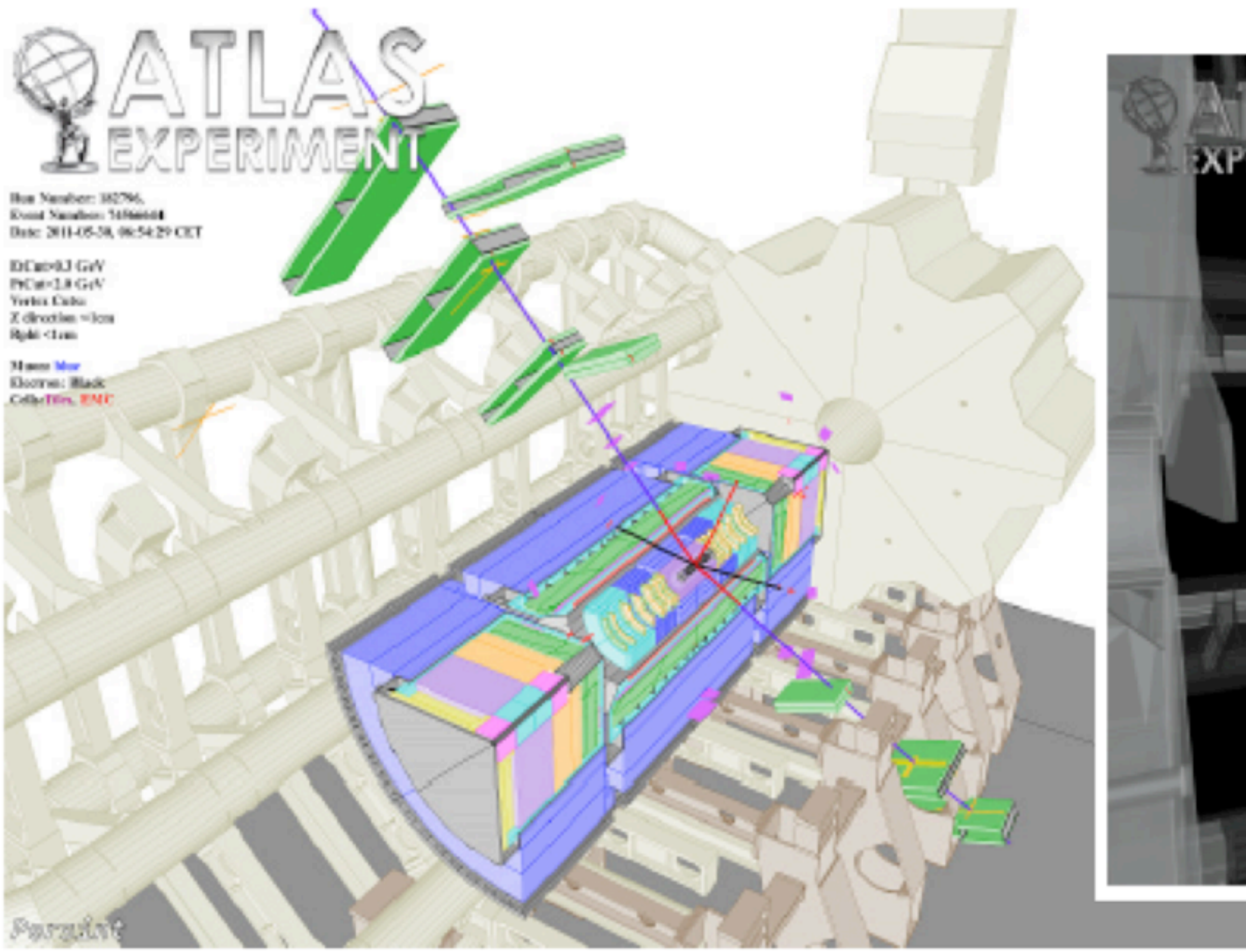
associated production
with top

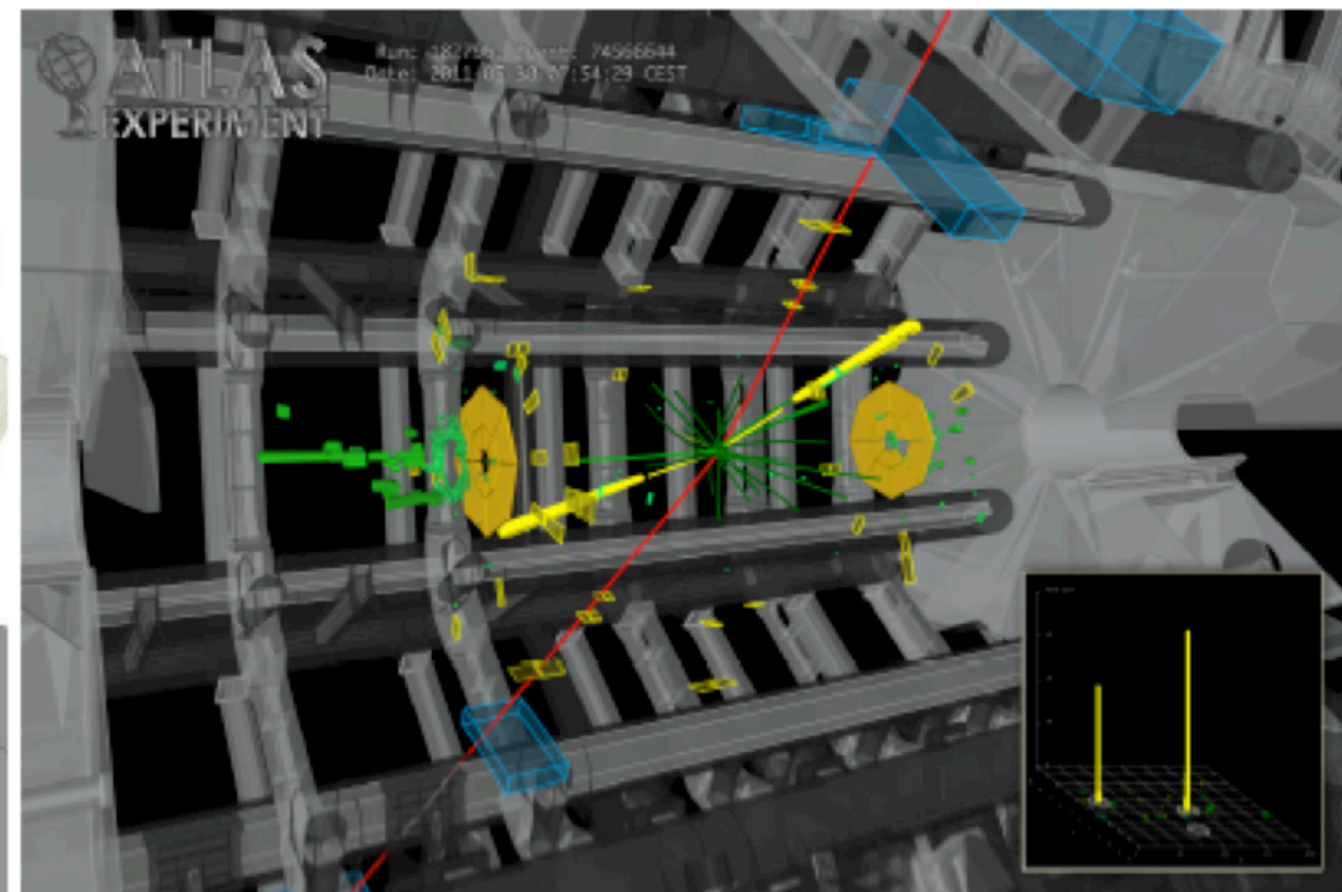


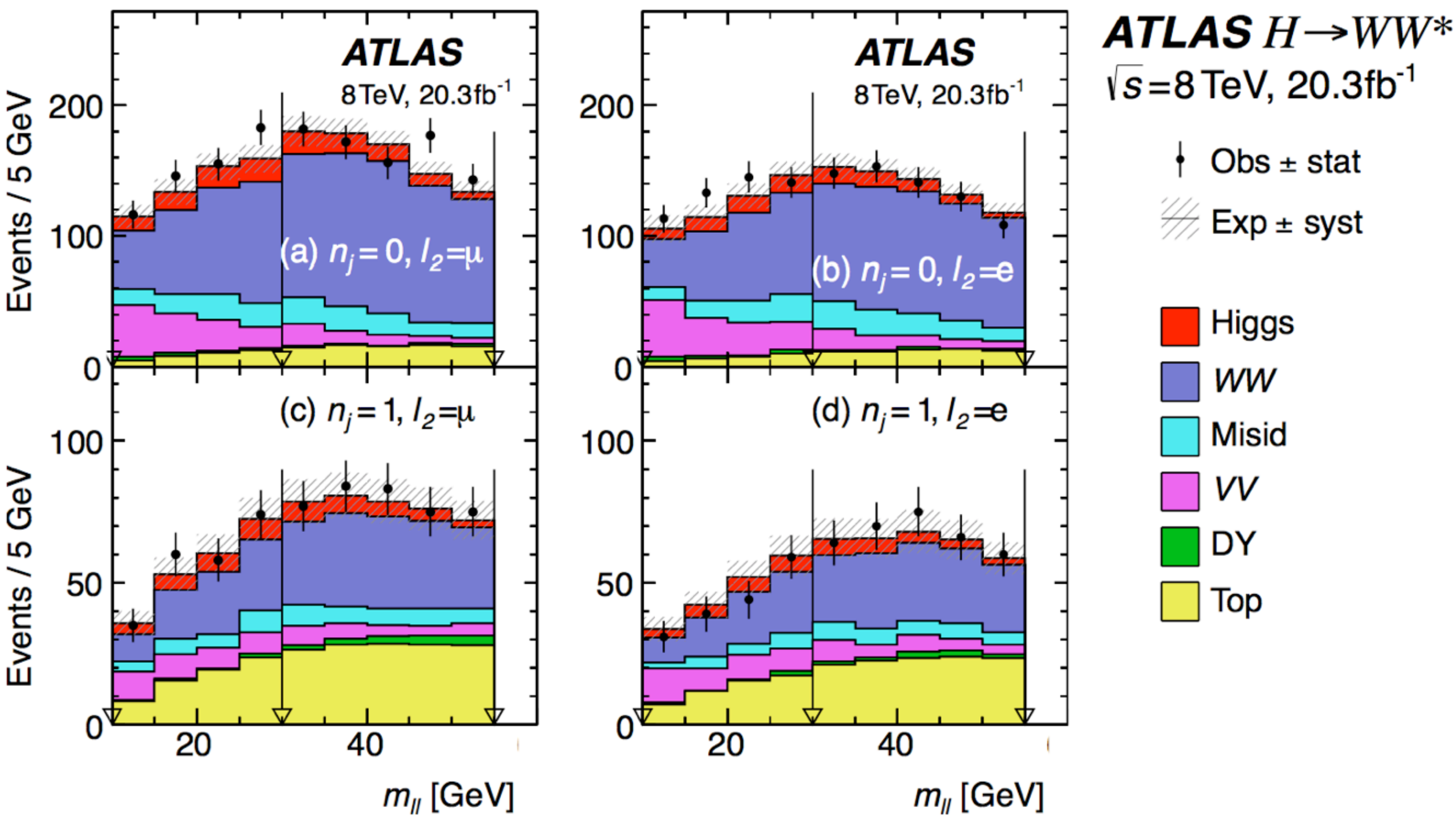


$\sigma(pp \to H+X)$ [pb]
10^2
10
1
10^{-1}
7
8
9
10
11
12
13
14
$\sqrt{s}$ [TeV]
pp → H (NNLO+NNLL QCD + NLO EW)
pp → q$\bar{q}$H (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → t$\bar{t}$H (NLO QCD)
150 M Higgs/expt
with HL-LHC
LHC HIGGS XS WG 2013

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



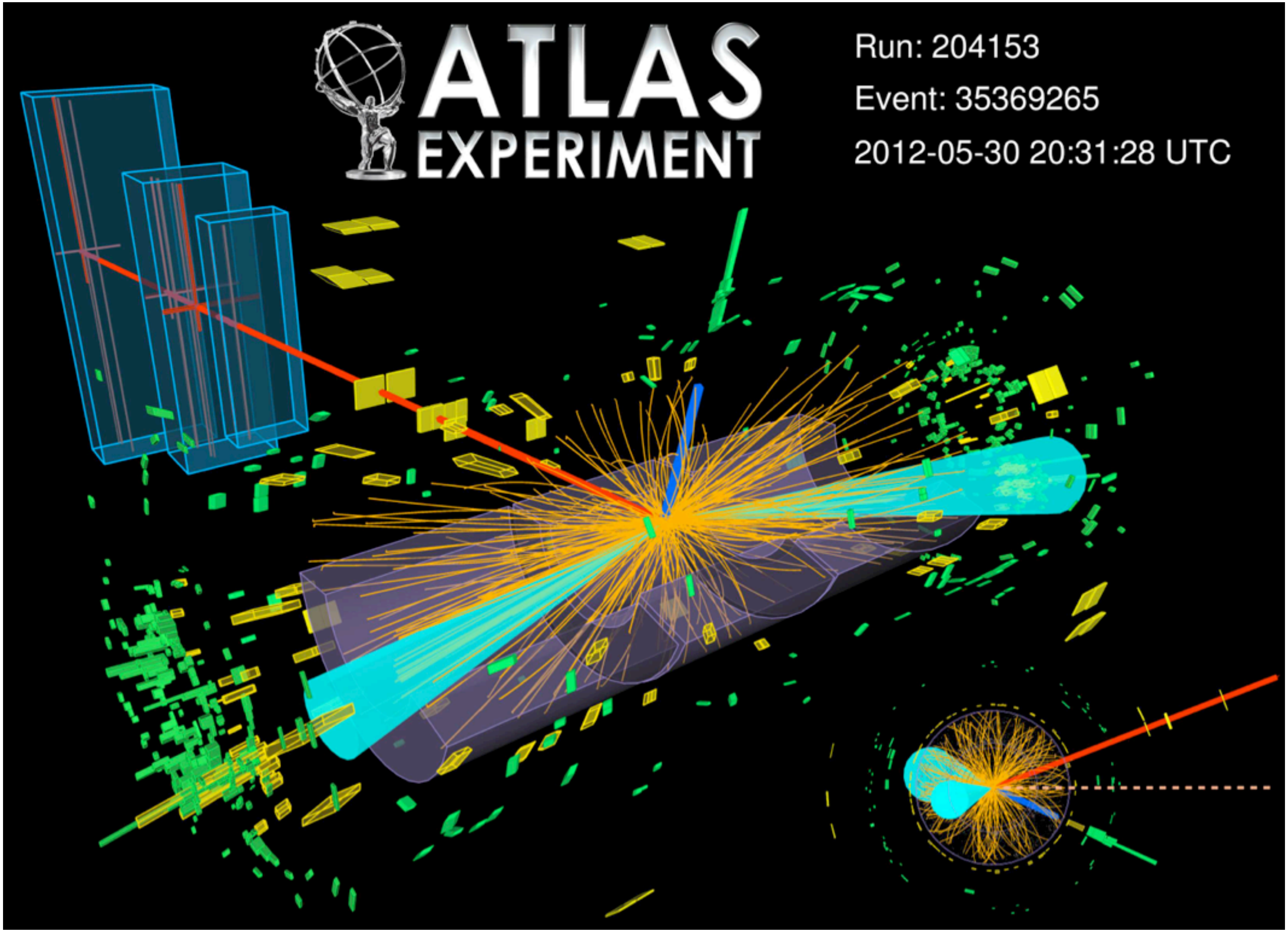


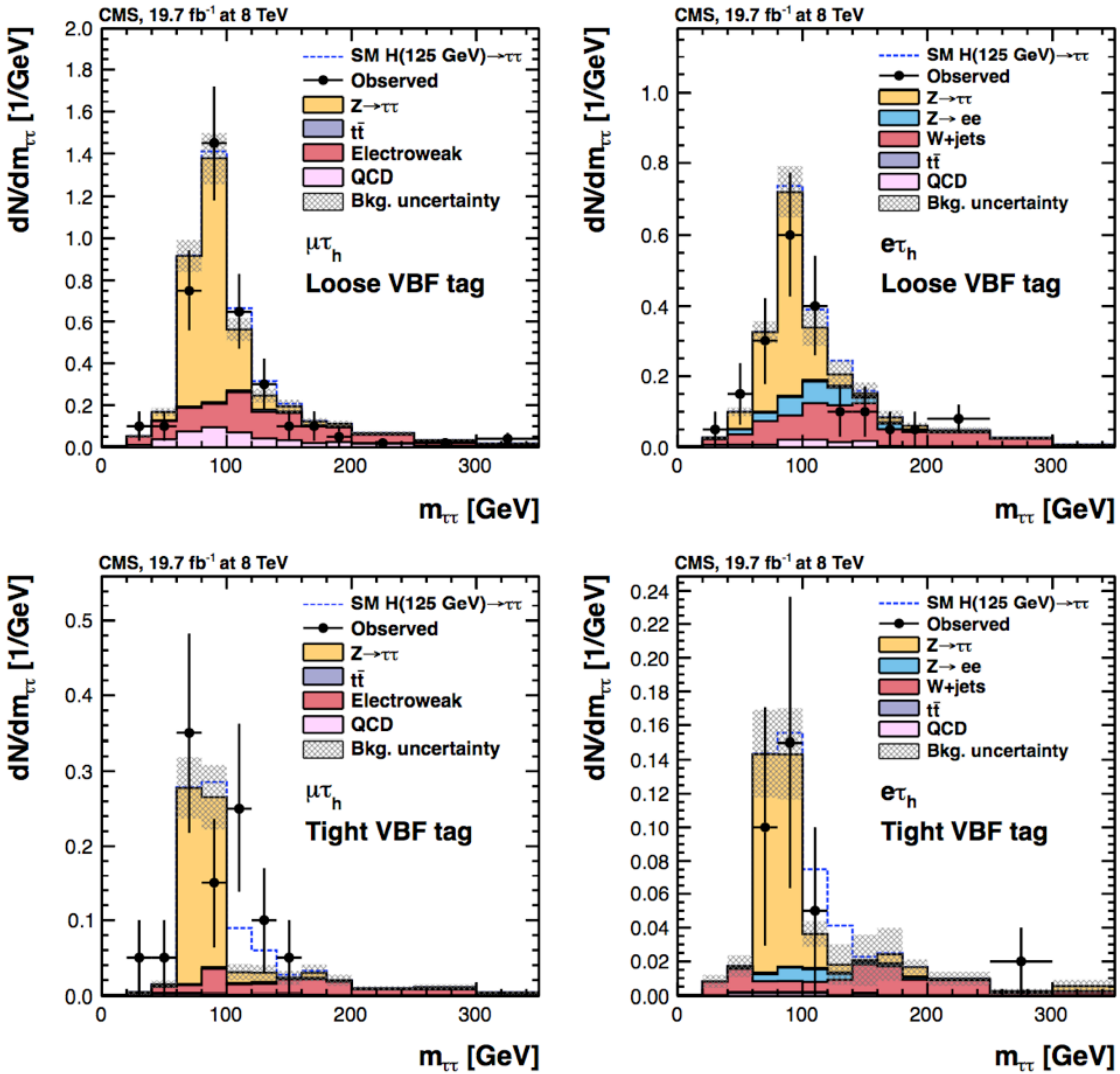

ATLAS
8 TeV, 20.3 fb-1
(a) nj = 0, l2=μ
ATLAS
8 TeV, 20.3 fb-1
(b) nj = 0, l2=e
(c) nj = 1, l2=μ
(d) nj = 1, l2=e
Events / 5 GeV
Events / 5 GeV
mll [GeV]
mll [GeV]
ATLAS H→WW*
√s=8 TeV, 20.3fb-1
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top

For $h \to \tau^+\tau^-$, the most promising production process is WW fusion, using the forward jets to tag the event as likely to contain Higgs production.

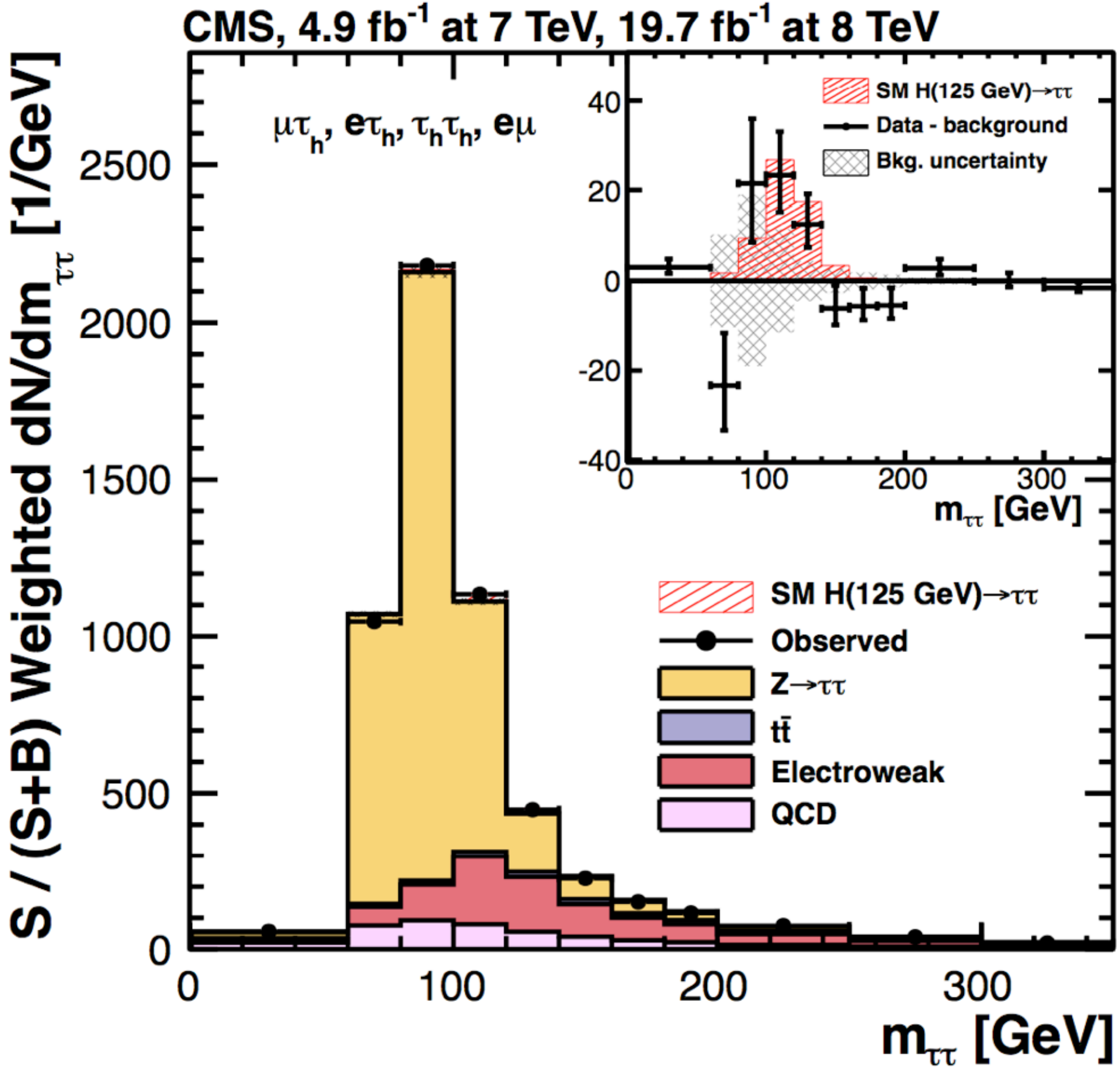
Eventually, WW fusion will become the most important production mode for almost all Higgs decays, since the theoretical error on the total cross section is much smaller.

It is still necessary to find the Higgs among other possible products of WW fusion (e.g. Z).


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

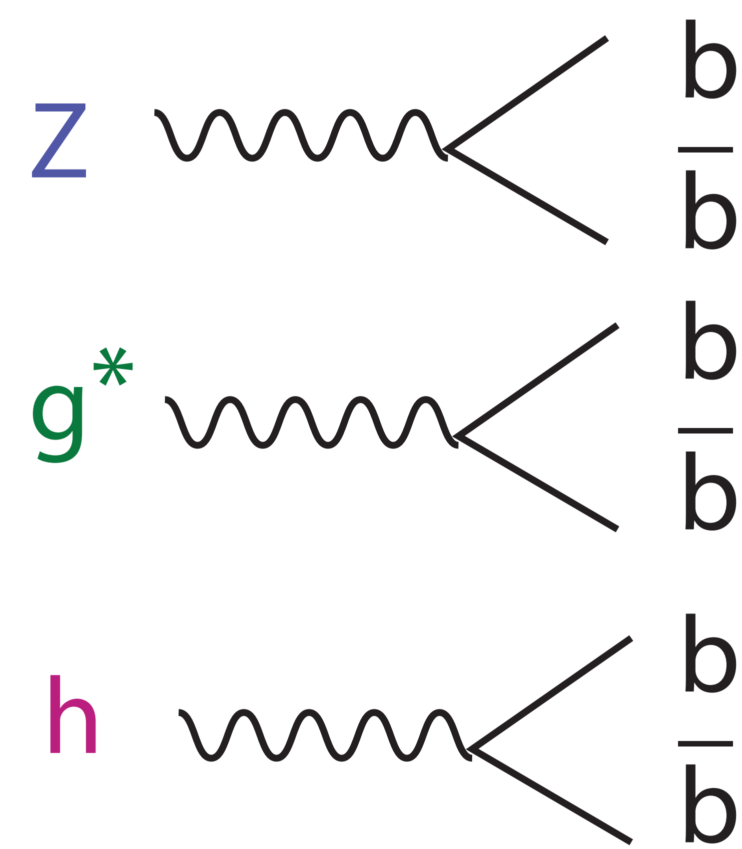


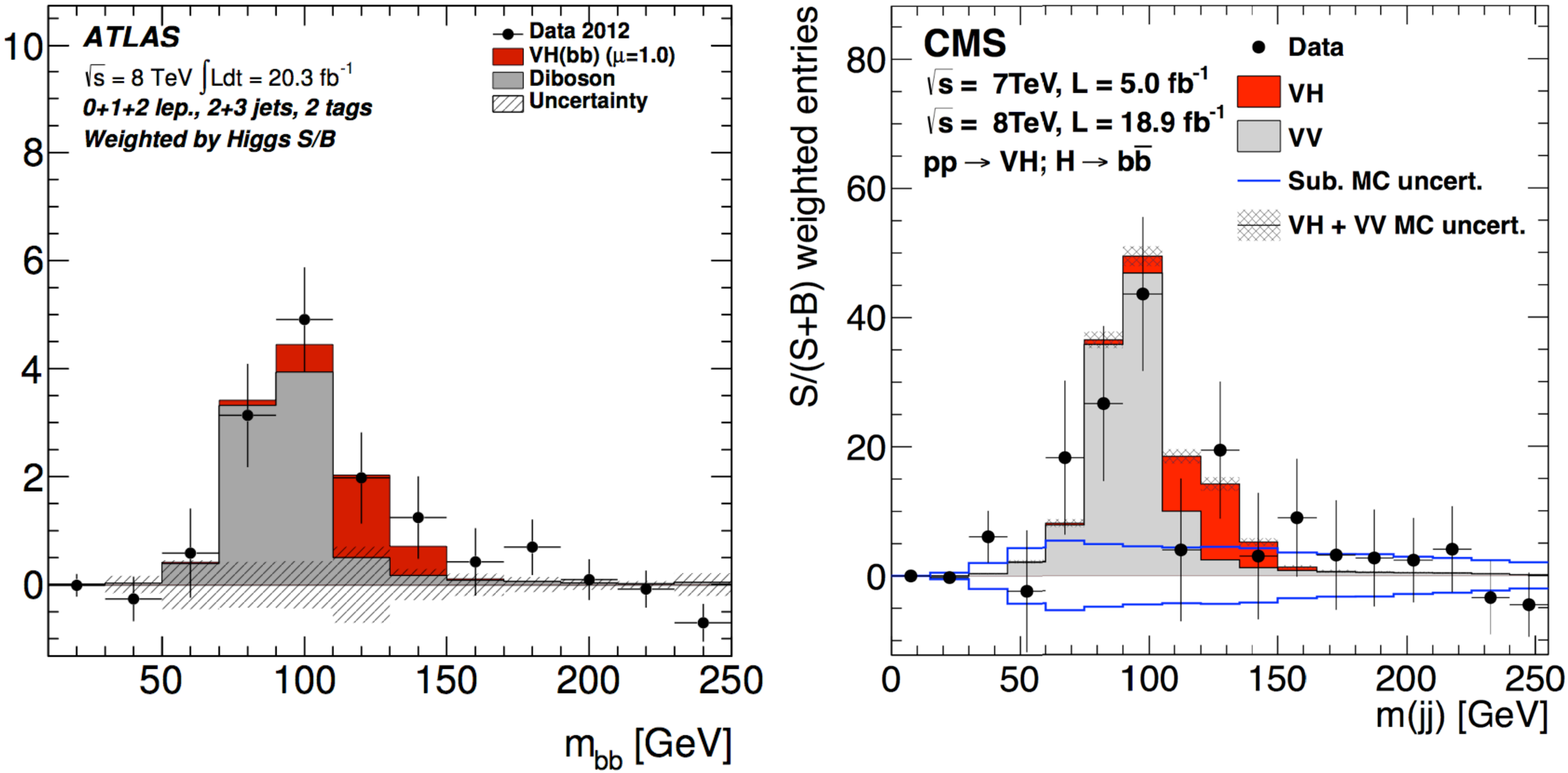
CMS, 4.9 fb^{-1} at 7 TeV, 19.7 fb^{-1} at 8 TeV
$\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$
S / (S+B) Weighted dN/dm$_{\tau\tau}$ [1/GeV]
$m_{\tau\tau}$ [GeV]
SM H(125 GeV)→ττ
Data - background
Bkg. uncertainty
SM H(125 GeV)→ττ
Observed
Z→ττ
$t\bar{t}$
Electroweak
QCD

For $h \to b\bar{b}$, the most promising mode in current studies is $pp \to W, Z + h$.

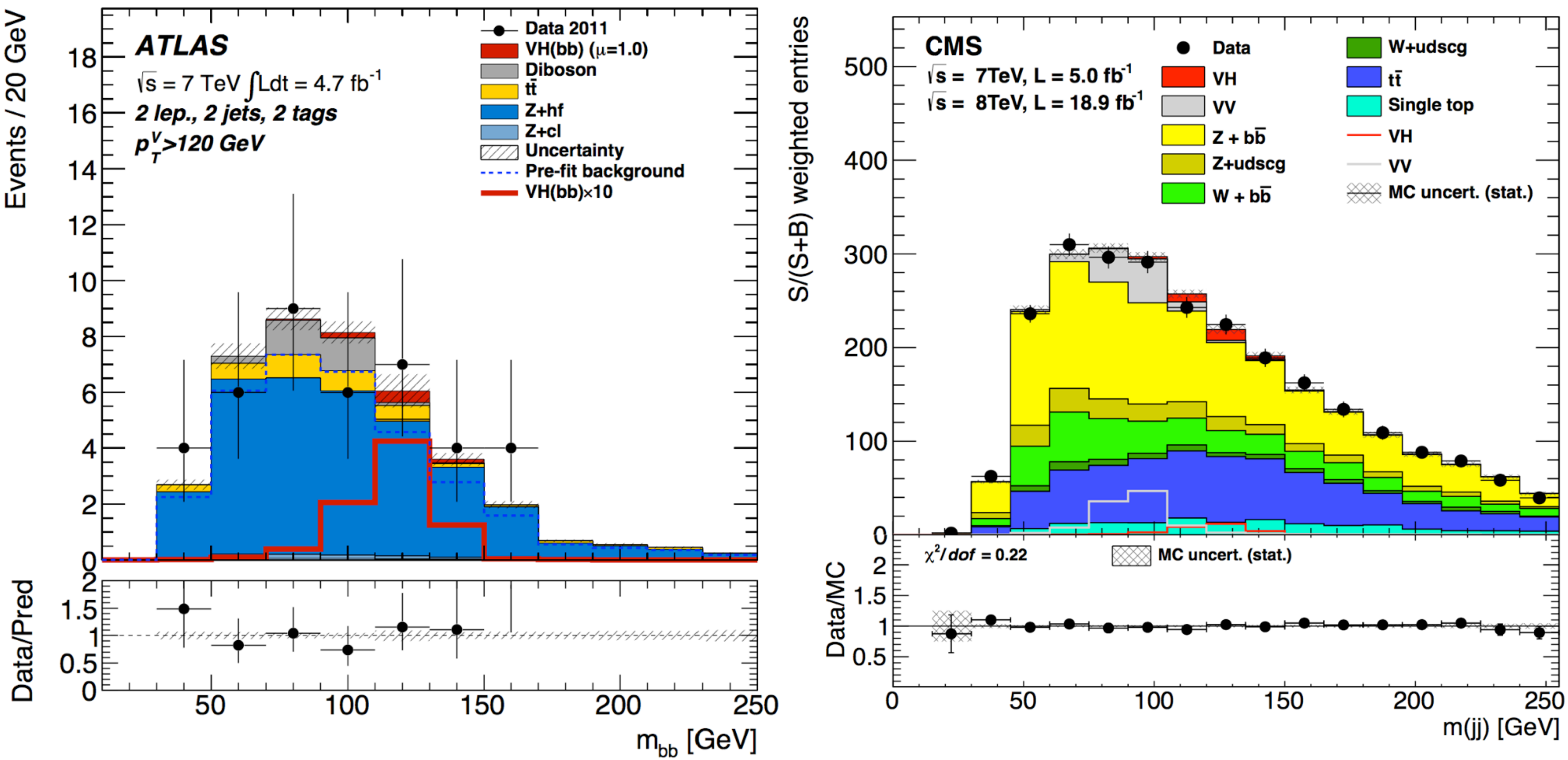
Butterworth, Davison, Rubin, and Salam introduced the idea of looking for a boosted Higgs boson decay by $h \to b\bar{b}$ as an exotic type of jet.

It is still a challenge, because there are three very similar states that can recoil against a W or Z . One must use jet substructure measurements and differences in the $m(b\bar{b})$ distribution to distinguish these possibilities.





ATLAS
$\sqrt{s}$ = 8 TeV $\int$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
$\sqrt{s}$ = 7TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8TeV, L = 18.9 fb^{-1}
pp $\rightarrow$ VH; H $\rightarrow$ b$\bar{b}$
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 comparision 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.

Now we turn to the influence of new physics on the Higgs boson couplings.

It is useful here to discuss the effects on individual Higgs partial widths

$$\Gamma(h \to A\overline{A}) \sim g^2(hA\overline{A})$$

Remember that

$$\mu(A,B) \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_h}$$

so eventually we must confront the problem of turning $\mu(A,B)$ meausurements into partial width measurements.

Begin with the Higgs coupling to fermions.

In the SM, simply

$$g(hf\overline{f}) = \sqrt{2}\frac{m_f}{v}$$

In models of the Higgs sector more general than the Standard Model, these couplings can be modified. The modifications might be either at the tree or loop level.

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

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

Then the coupling modifications are

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

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

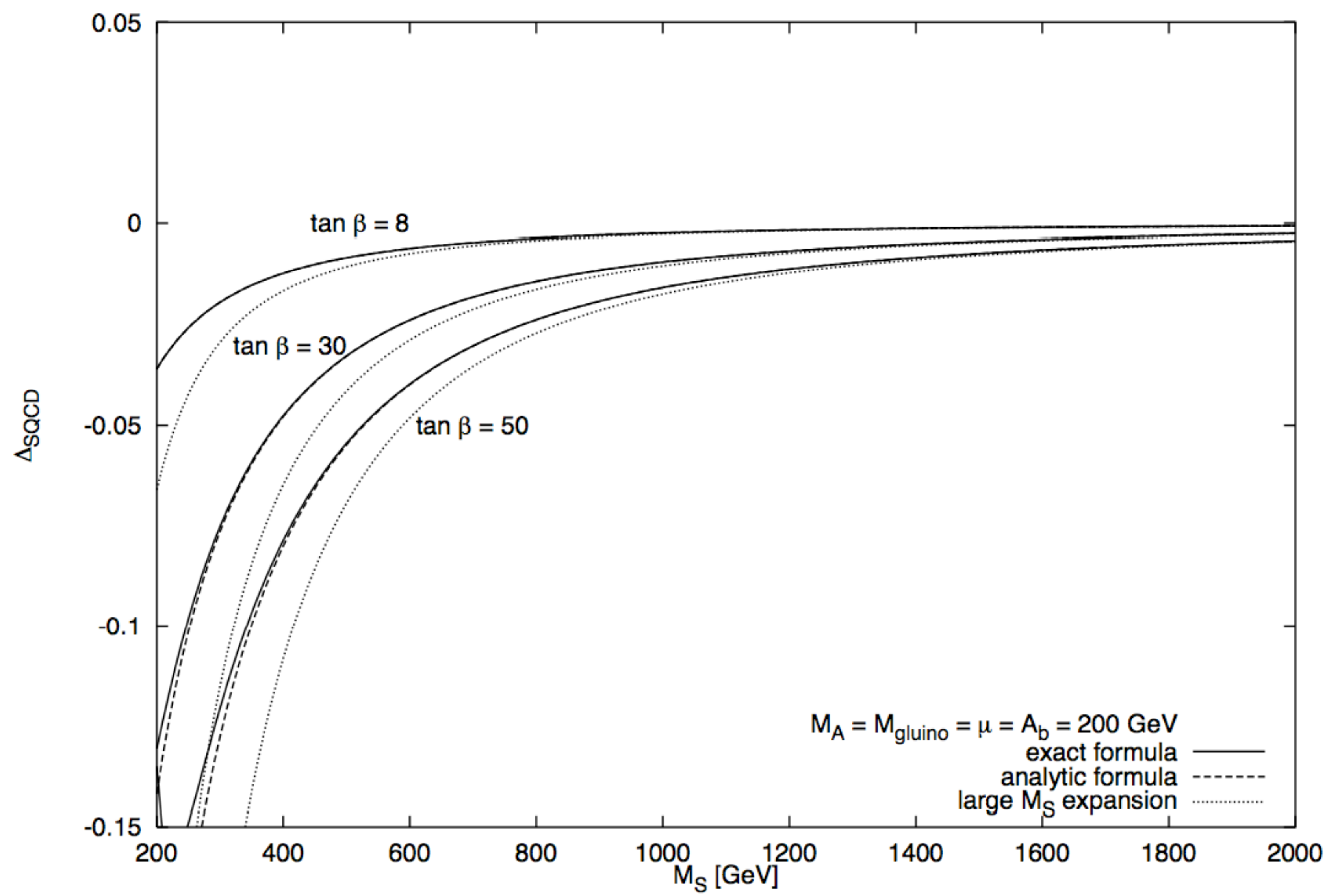
$$-\frac{\sin\alpha}{\cos\beta} = 1 + \mathcal{O}(\frac{m_Z^2}{m_A^2})$$

The predicted corrections decrease as the SUSY mass scale becomes larger, for example

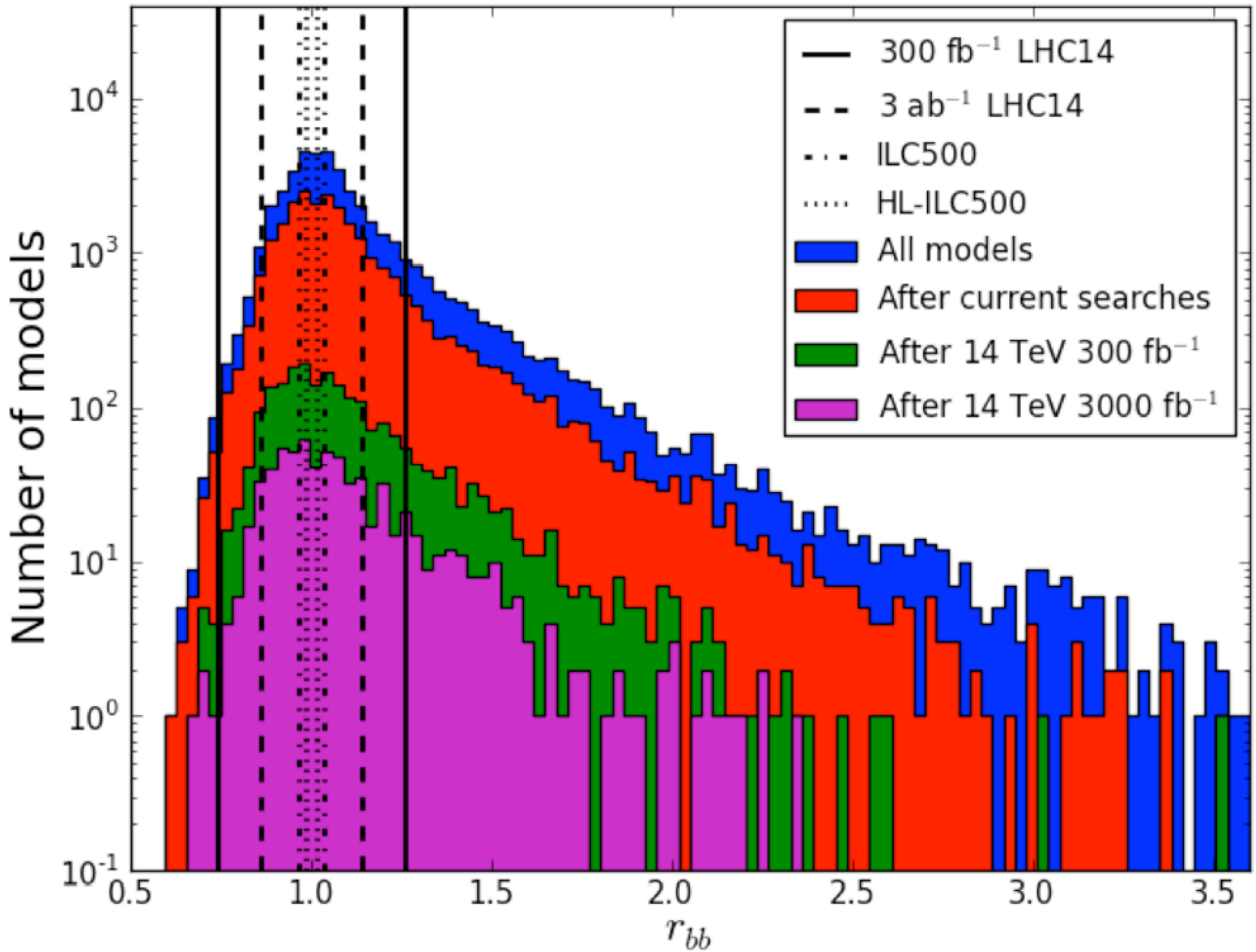
$$\frac{g_{hbb}}{g_{h_{\mathrm{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\mathrm{SM}}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

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

Haber, Herrero, Logan, Penaranda, Rigolin, Temes

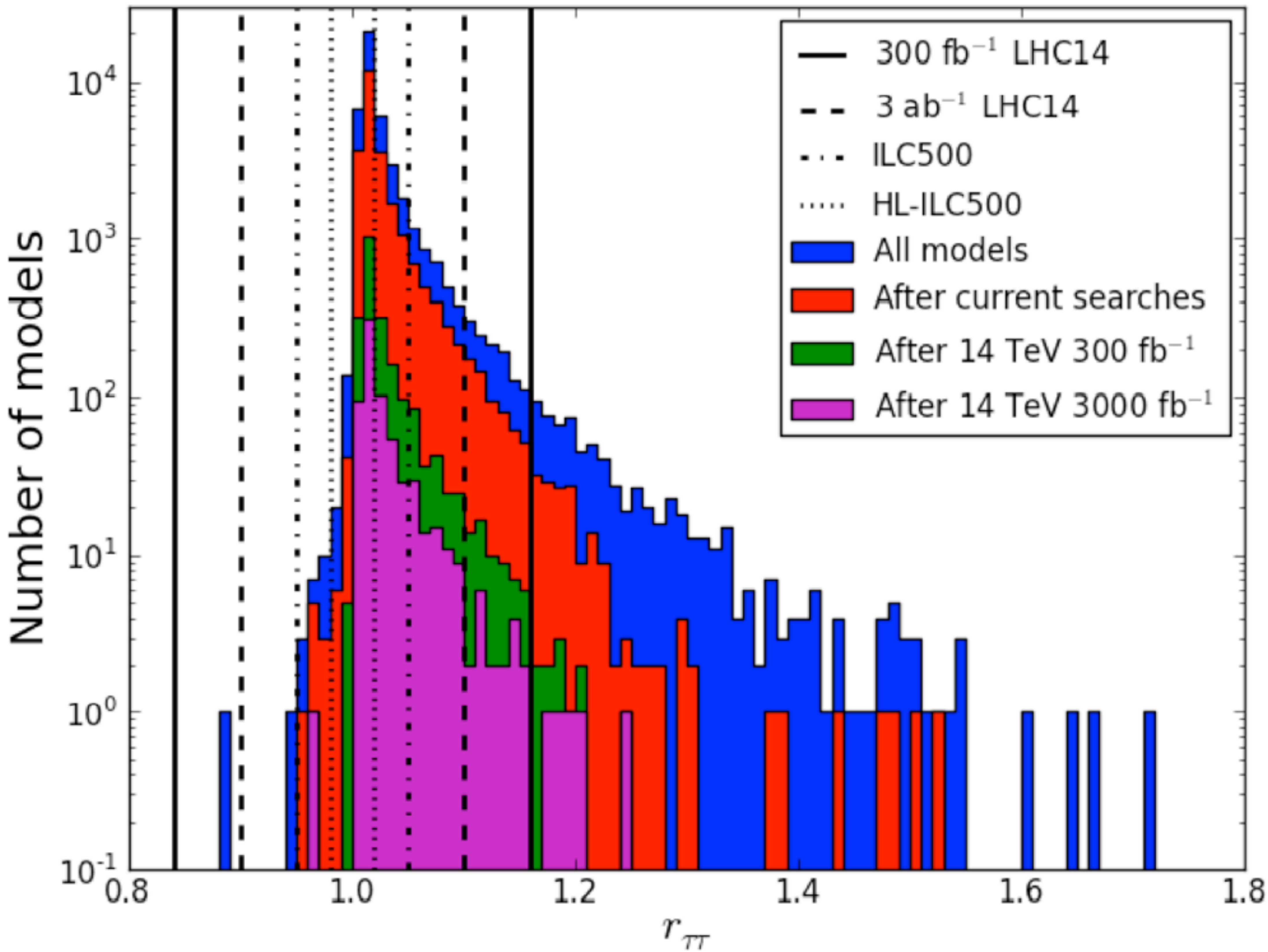


$\Gamma(h \to b\bar{b})$



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).

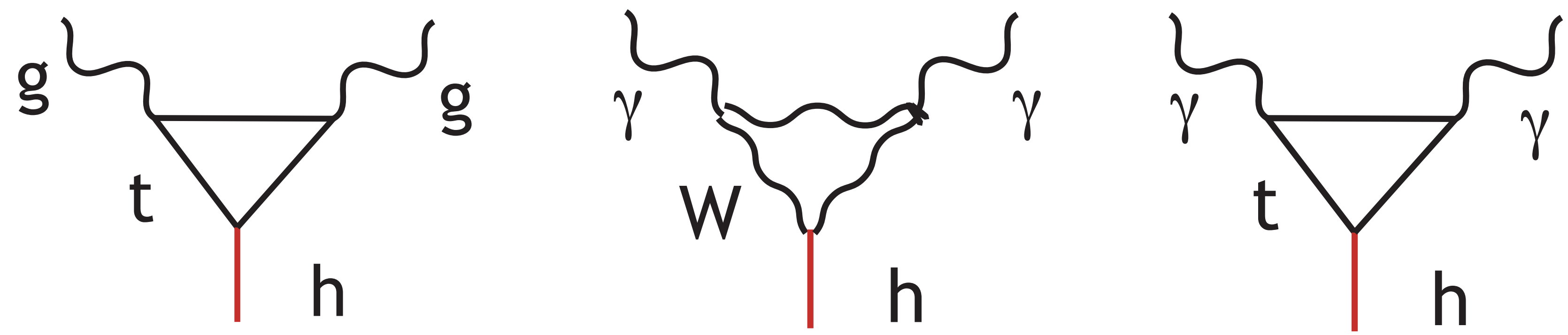
If the Higgs is a composite Goldstone boson, these couplings are corrected by (f ~ 1 TeV)

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

Finally, there are the decays

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

which 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

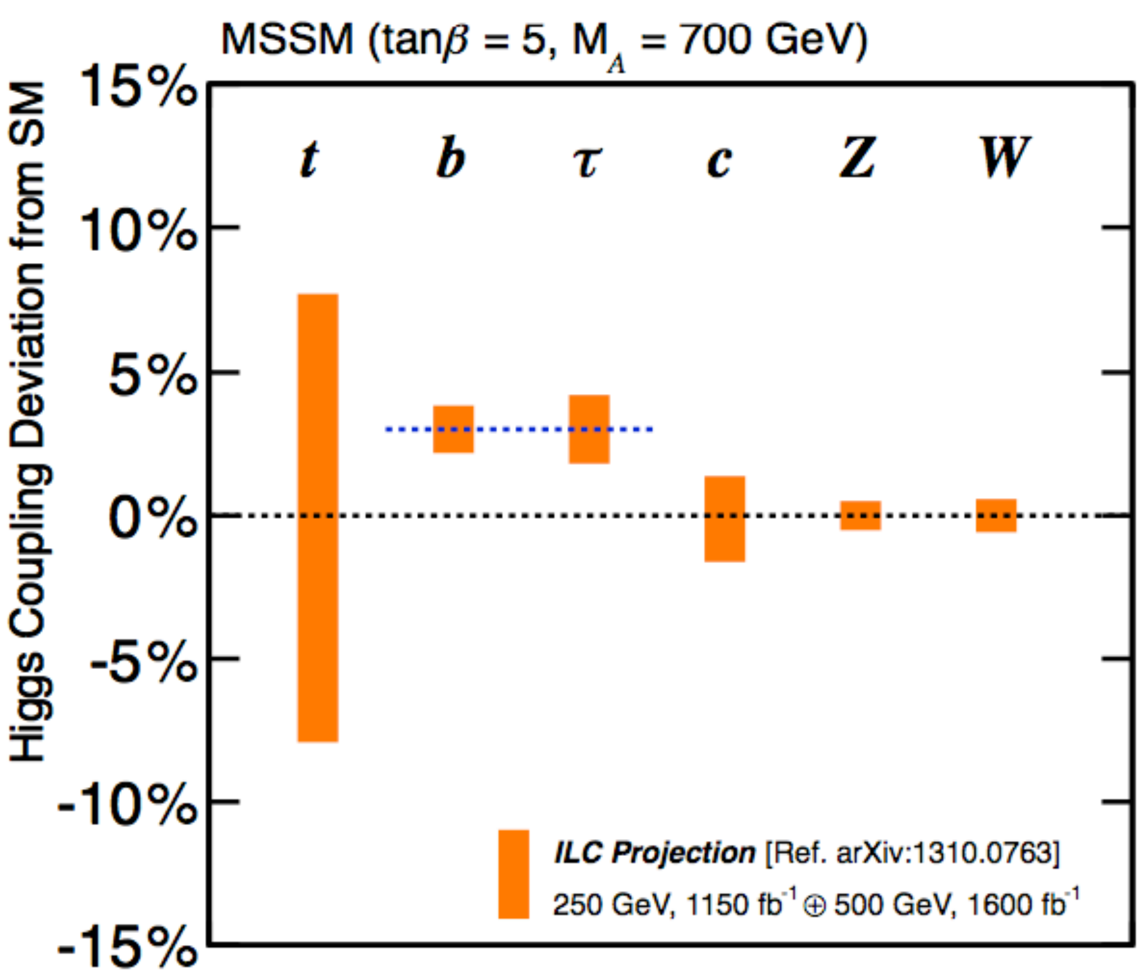
$$g(hgg)/SM = 1 - (5 - 9\%)$$

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

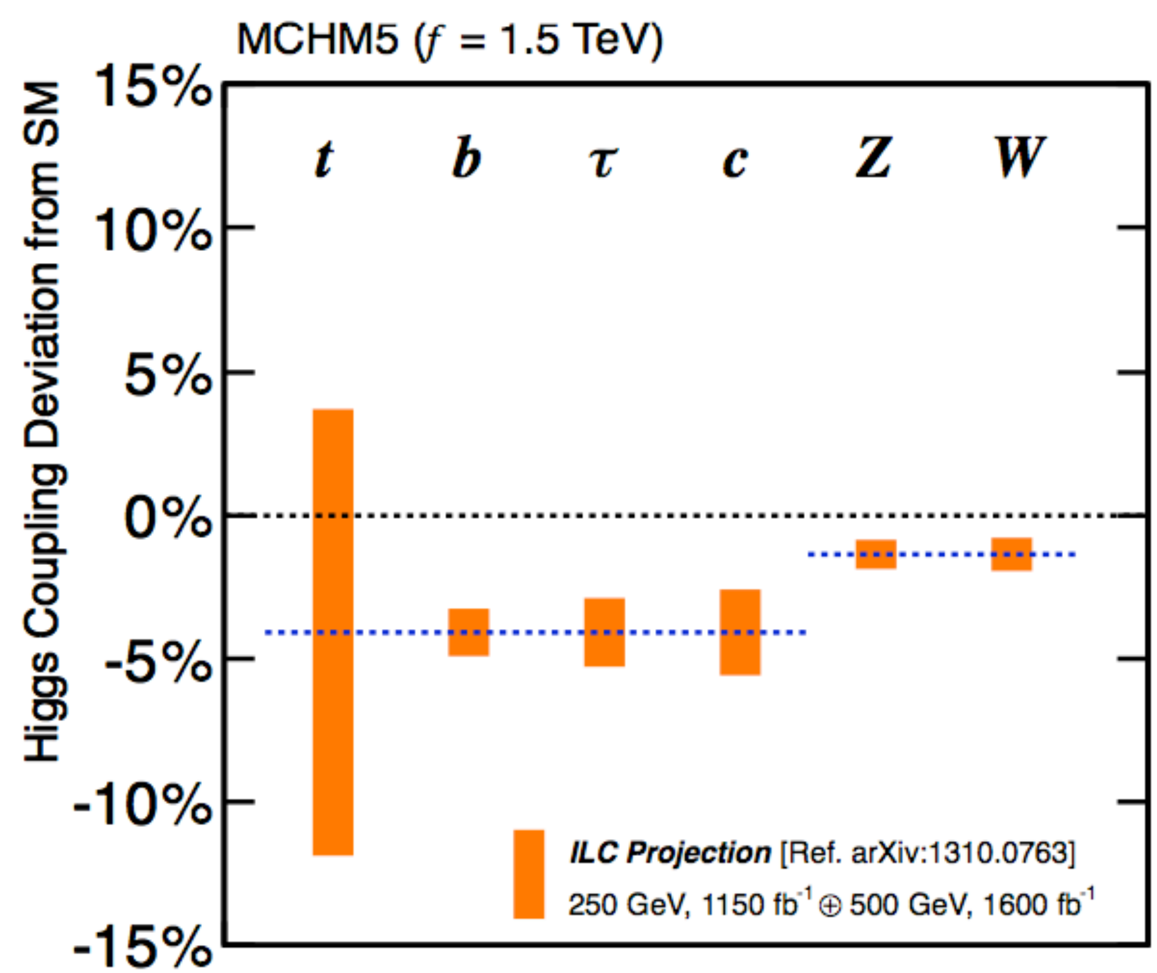
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs



Kanemura, Tsumura, Yagyu, Yokoya

At one time, it was thought that there were barriers to a precision theory of the SM Higgs couplings that would make it difficult to test these predictions. For example:

"... the SM uncertainty in computing B($h \rightarrow bb$) is presently 3.7% (sum of absolute values of all errors) and expected to not get better than 2.8%, with most of that coming from the uncertainty of the bottom Yukawa coupling determination ... Thus, without reducing this error, any new physics contribution to the bb branching fraction that is not at least a factor of two or three larger than 2% cannot be discerned."

- Almeida, Lee, Pokorski, and Wells (2013)

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 errors 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 $\mathcal{O}(\alpha\alpha_s)$

We will soon need a precision Higgs theoretical campaign similar to that done for precision electroweak.

For the dependence on input parameters, the situation is less clear. 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 $\Delta m_h = 30 \ \mathrm{MeV}$.

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

The program I have outlined here gives 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.

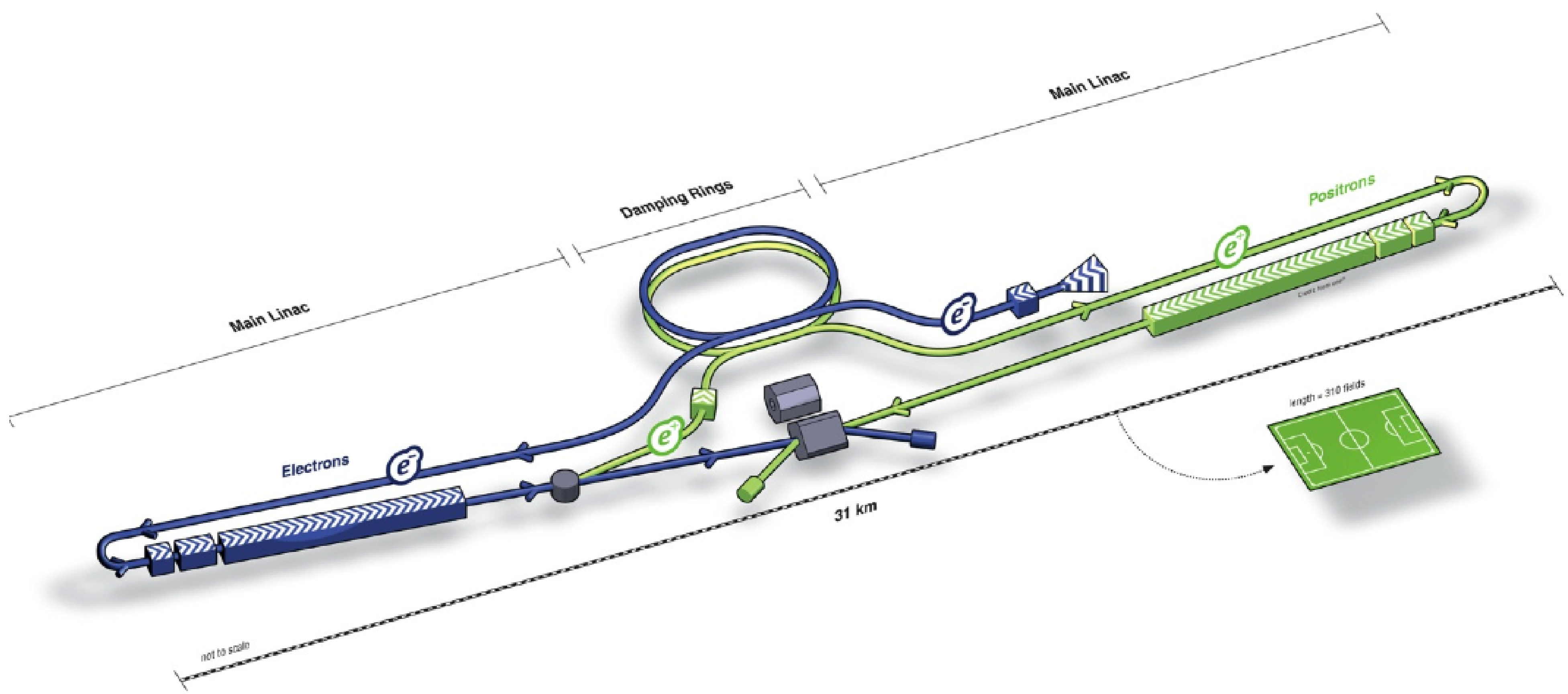
It would be best if the experiments were also highly sensitive to invisible and exotic Higgs decays, which might contribute to Γ_h and also signal new physics in their own right.

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.

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).

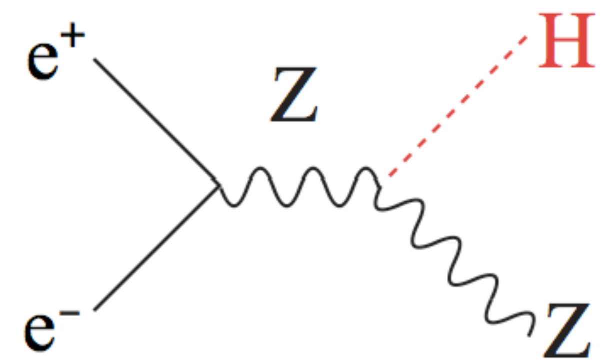


The ILC is now being considered seriously by the Japanese government for a construction start in the next few years and data in the late 2020's.

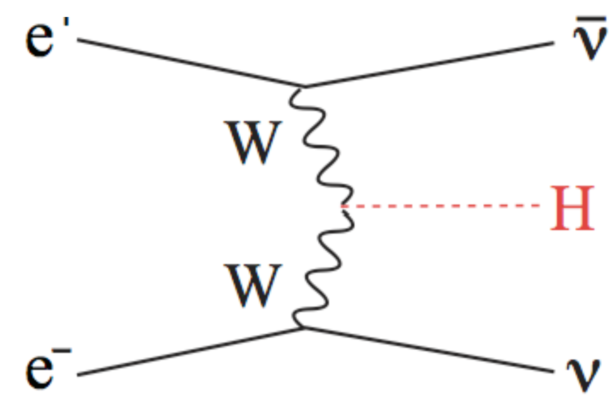
Here are a few snapshots from the physics expectations for the ILC.

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

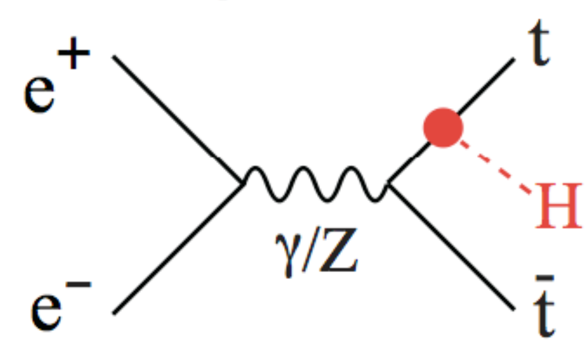
Higgsstrahlung



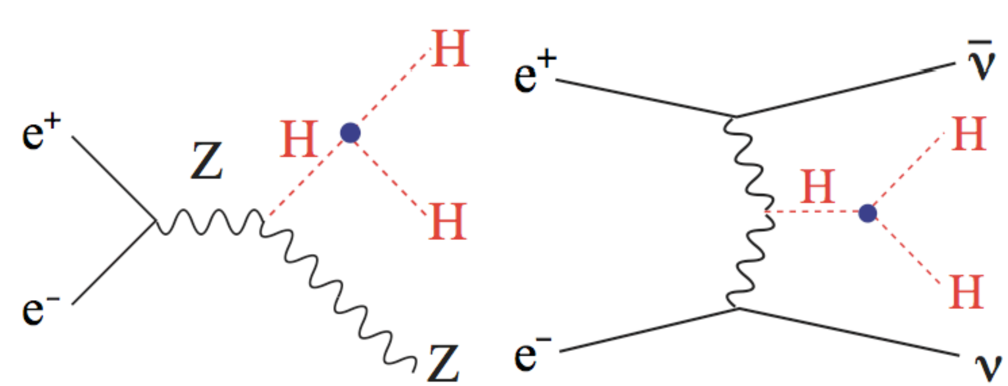
vector boson fusion

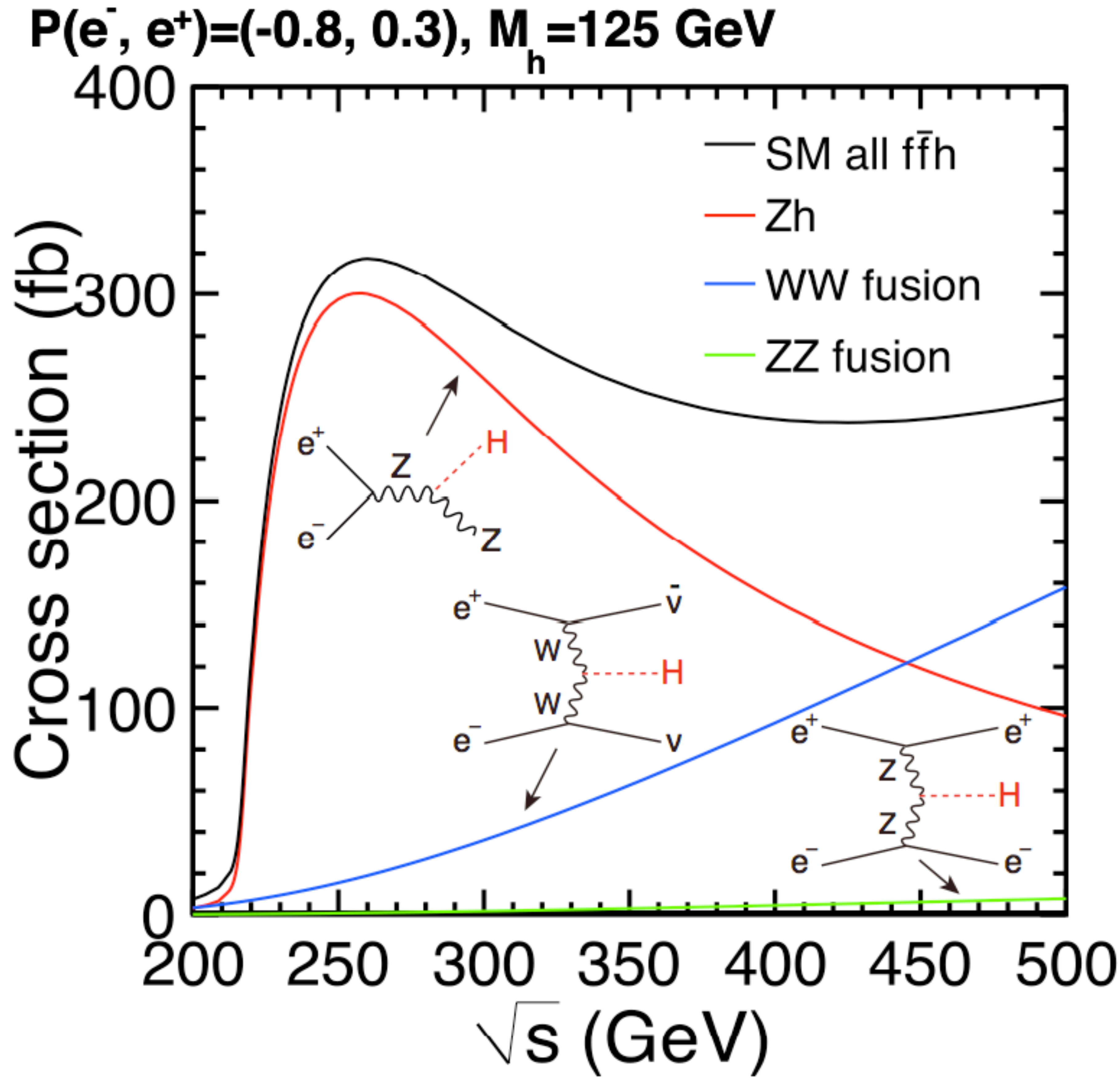


associated production with top



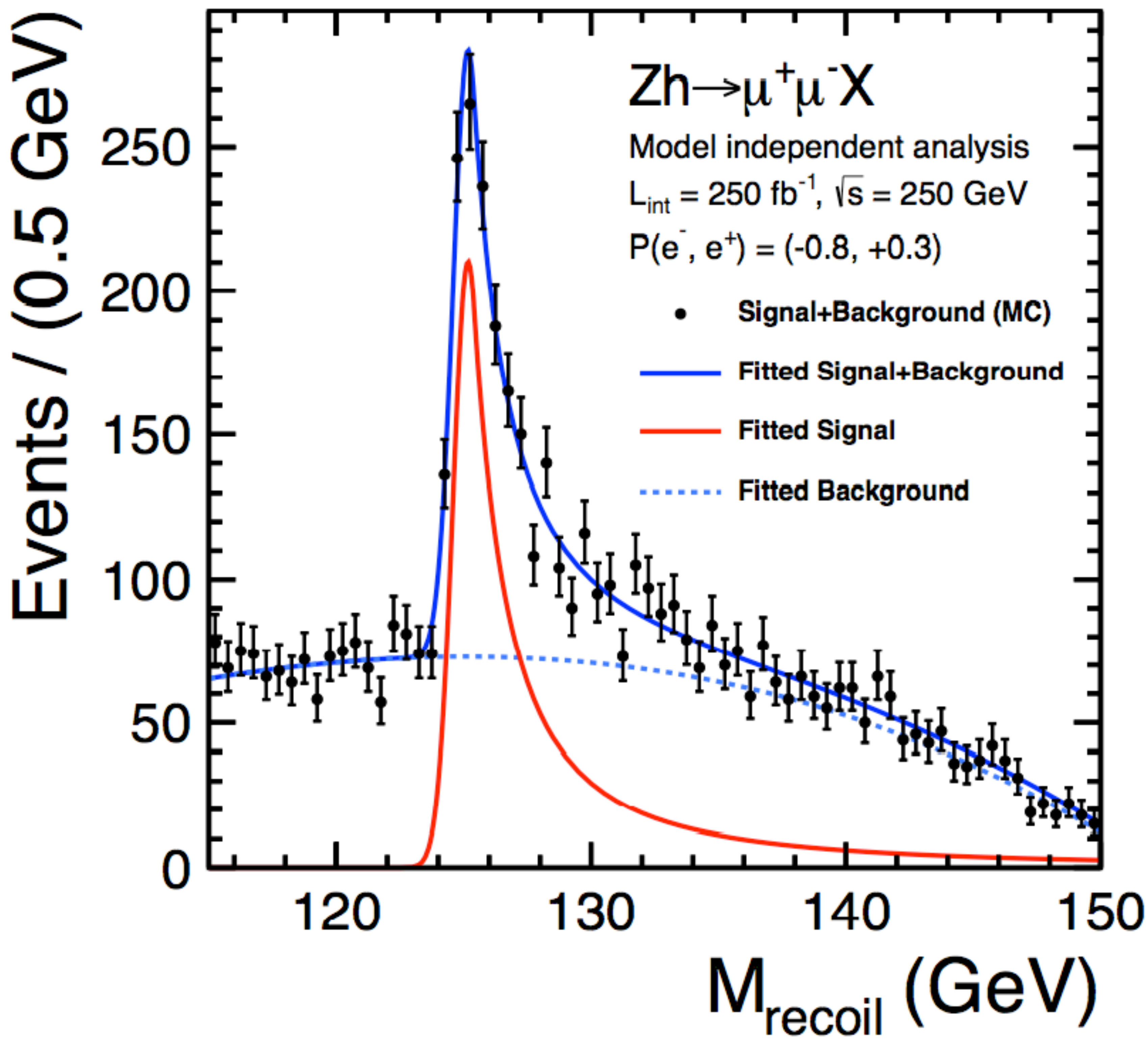
Higgs pair production





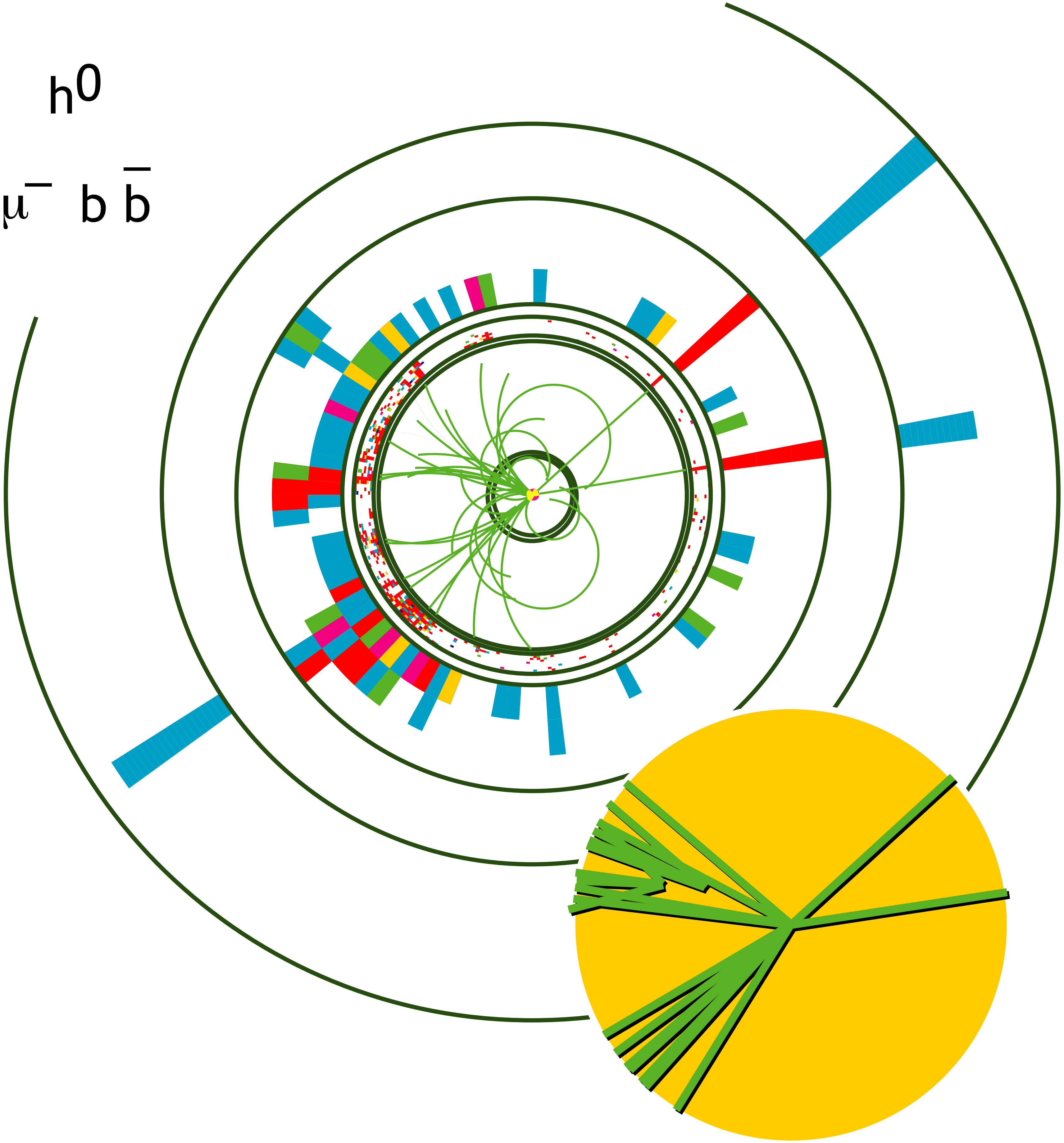
P(e-, e+)=(-0.8, 0.3), Mh=125 GeV
SM all ff̄h
Zh
WW fusion
ZZ fusion
Cross section (fb)
400
300
200
100
0
200
250
300
350
400
450
500
√s (GeV)
e+
e−
Z
H
Z
e+
ν̄
W
H
W
e−
ν
e+
e+
Z
H
Z
e−
e−

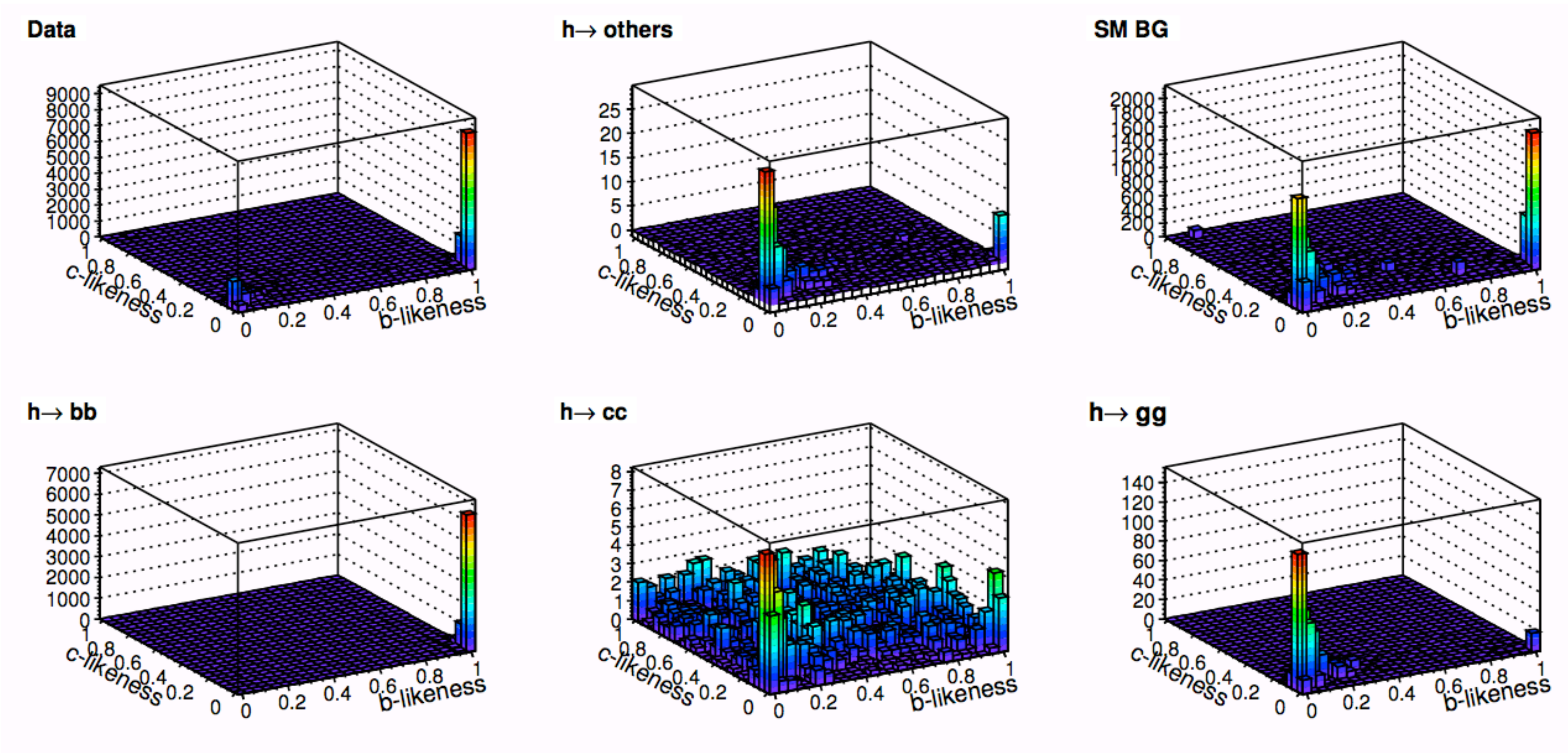
m_h to 30 MeV using a recoil technique

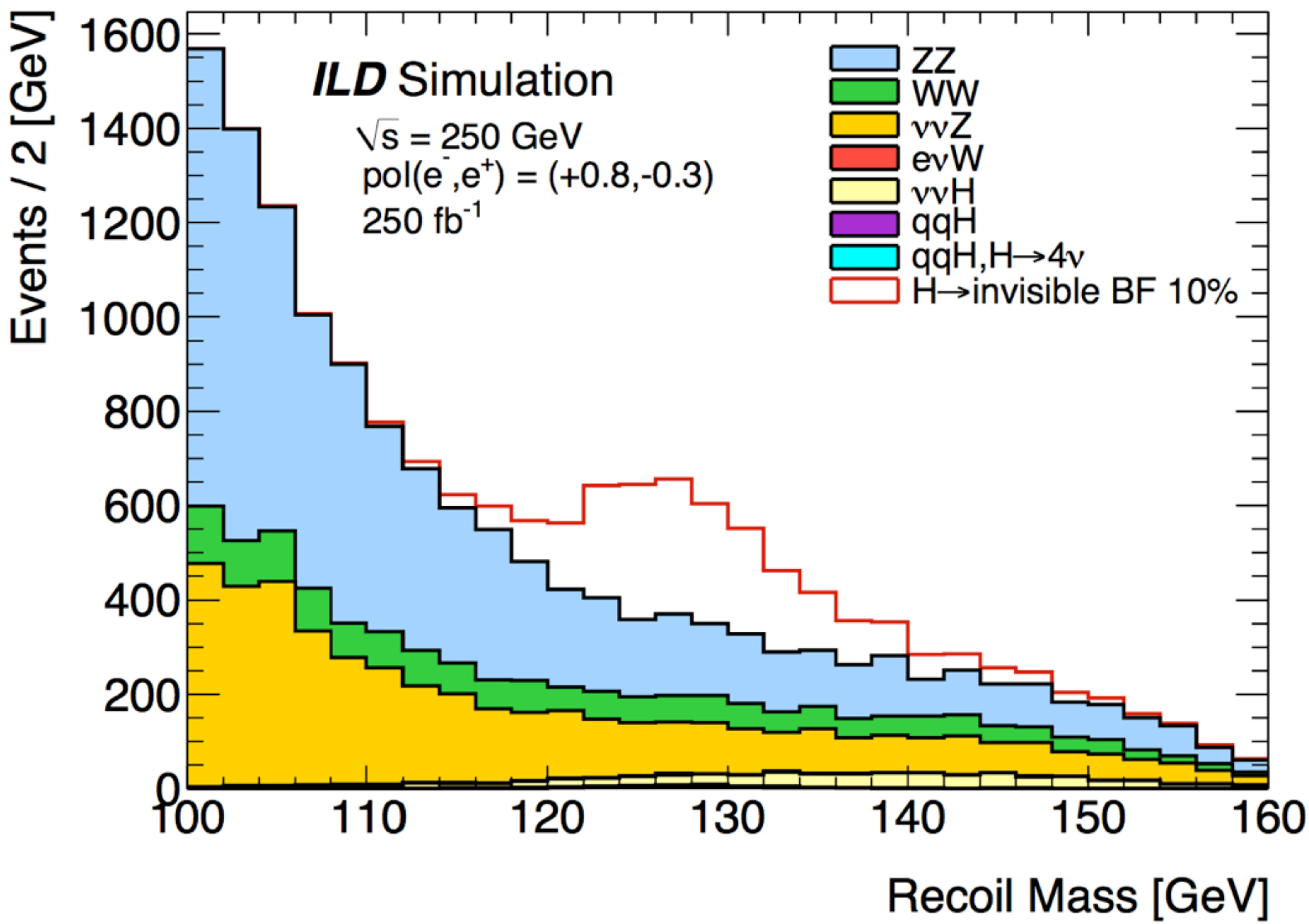


$e^+e^- \rightarrow Z^0 \quad h^0$

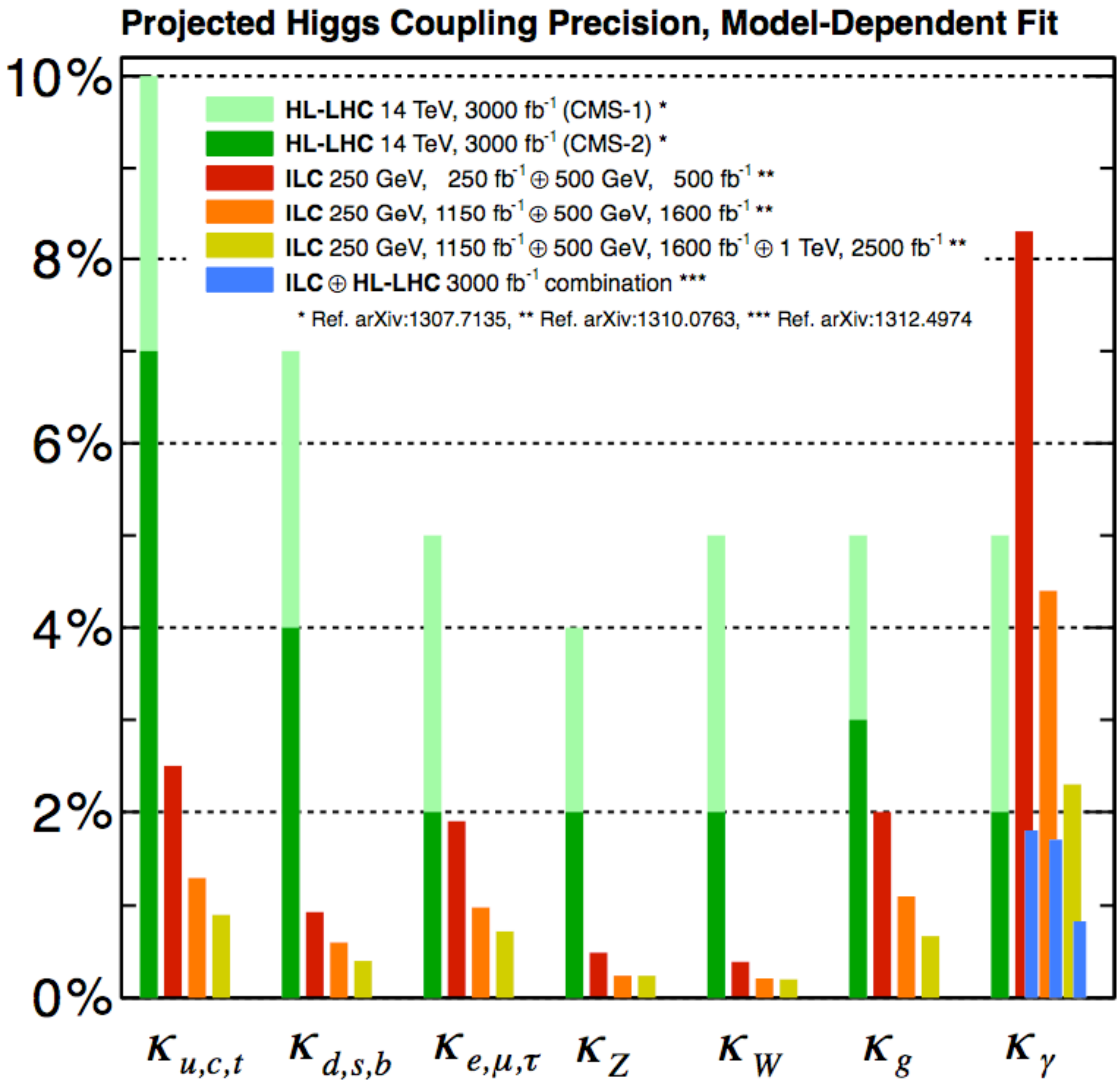
$\rightarrow \mu^+\mu^- \; b\,\bar{b}$



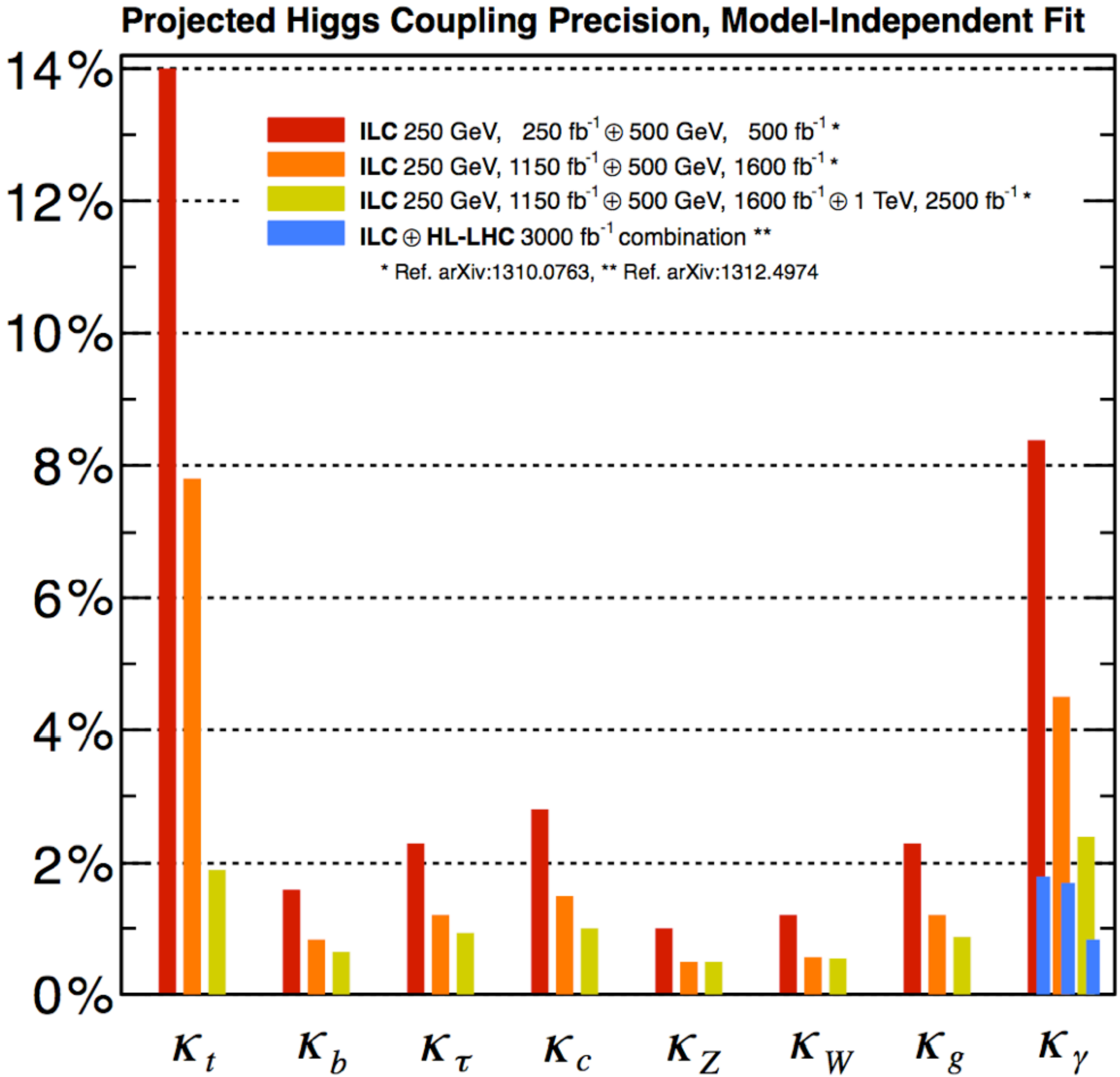

Data
h→ others
SM BG
h→ bb
h→ cc
h→ gg
c-likeness
b-likeness



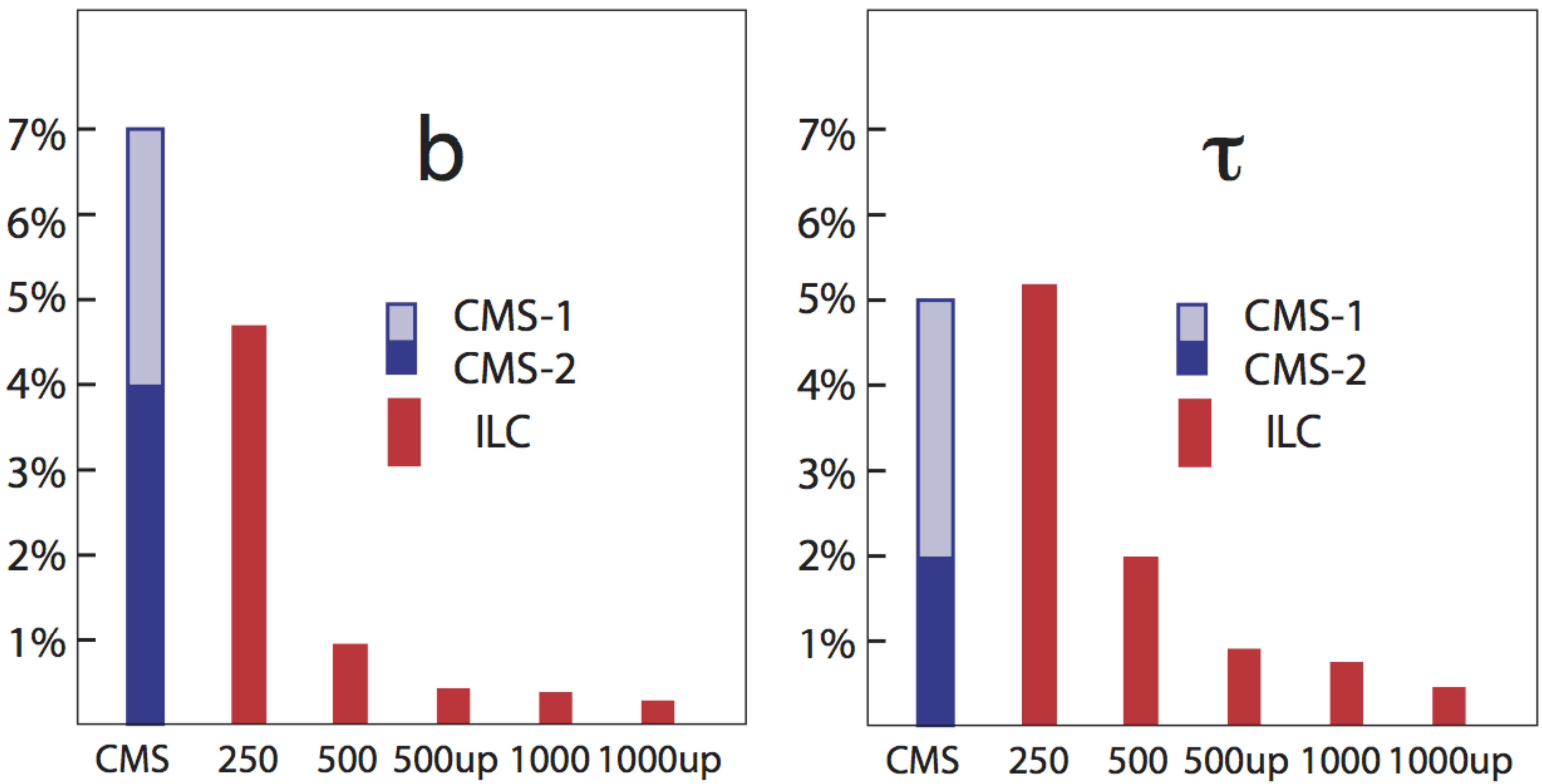
ILD Simulation
$\sqrt{s}$ = 250 GeV
pol(e$^-$,e$^+$) = (+0.8,-0.3)
250 fb^{-1}
ZZ
WW
ννZ
eνW
ννH
qqH
qqH,H→4ν
H→invisible BF 10%
Events / 2 [GeV]
Recoil Mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
100
110
120
130
140
150
160



Projected Higgs Coupling Precision, Model-Dependent Fit
10%
8%
6%
4%
2%
0%
HL-LHC 14 TeV, 3000 fb^{-1} (CMS-1) *
HL-LHC 14 TeV, 3000 fb^{-1} (CMS-2) *
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:1307.7135, ** Ref. arXiv:1310.0763, *** Ref. arXiv:1312.4974
$\kappa_{u,c,t}$
$\kappa_{d,s,b}$
$\kappa_{e,\mu,\tau}$
κ_Z
κ_W
κ_g
κ_γ

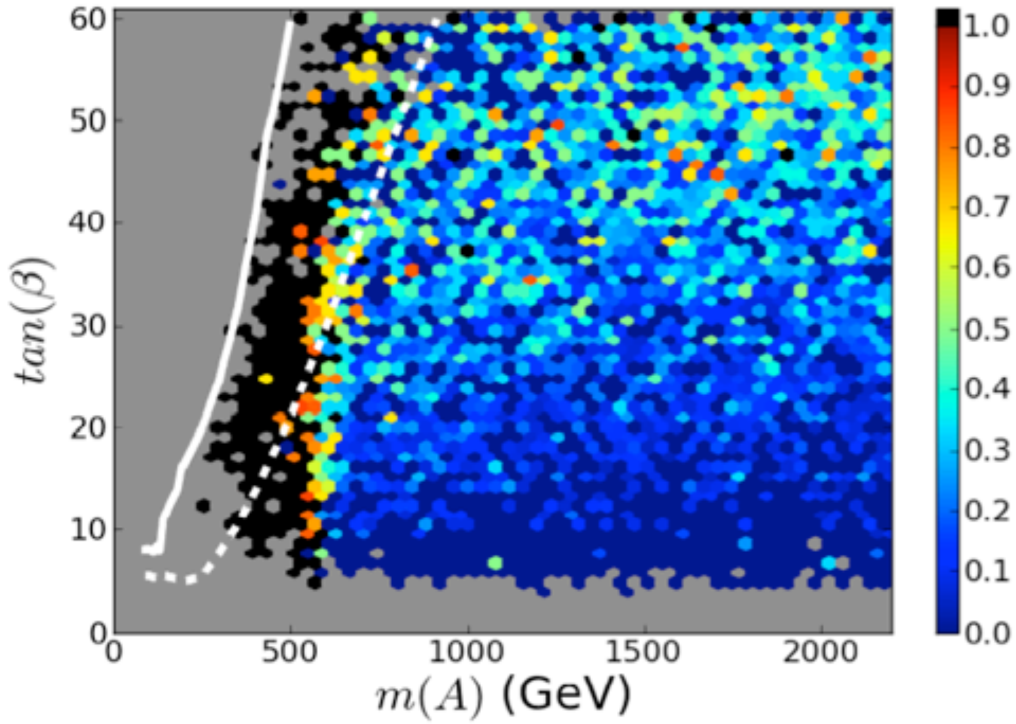

Projected Higgs Coupling Precision, Model-Independent Fit
14%
12%
10%
8%
6%
4%
2%
0%
ILC 250 GeV, 250 fb-1 ⊕ 500 GeV, 500 fb-1 *
ILC 250 GeV, 1150 fb-1 ⊕ 500 GeV, 1600 fb-1 *
ILC 250 GeV, 1150 fb-1 ⊕ 500 GeV, 1600 fb-1 ⊕ 1 TeV, 2500 fb-1 *
ILC ⊕ HL-LHC 3000 fb-1 combination **
* Ref. arXiv:1310.0763,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

The model-independent fit improves if we assume that invisible and exotic modes are measurable:

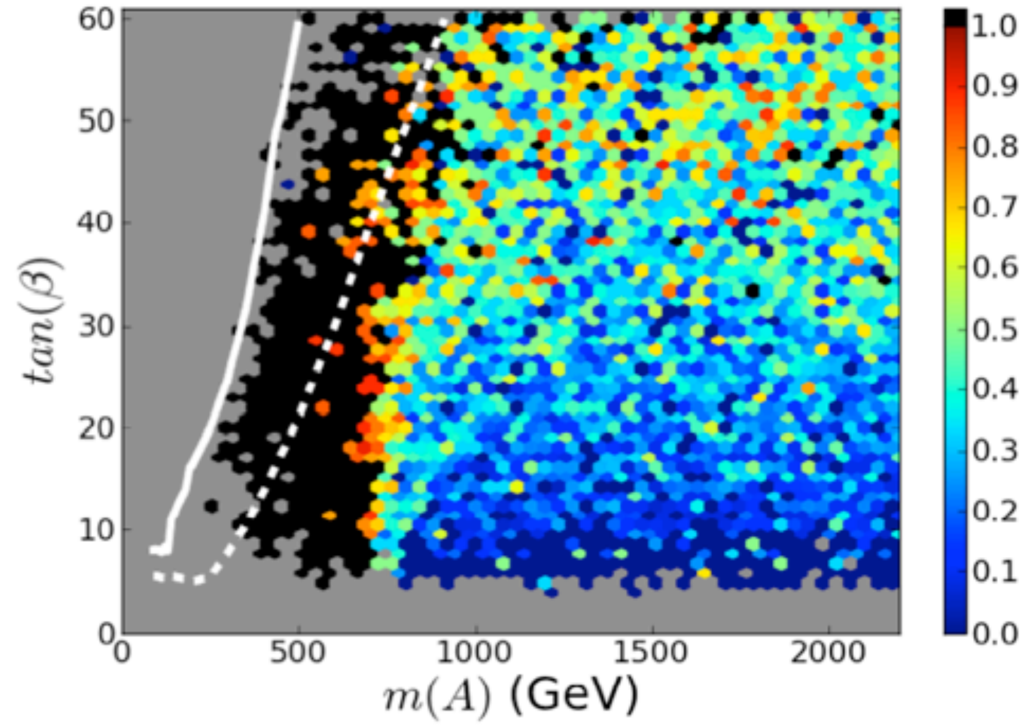


Sensitivity to the extended Higgs sector of SUSY

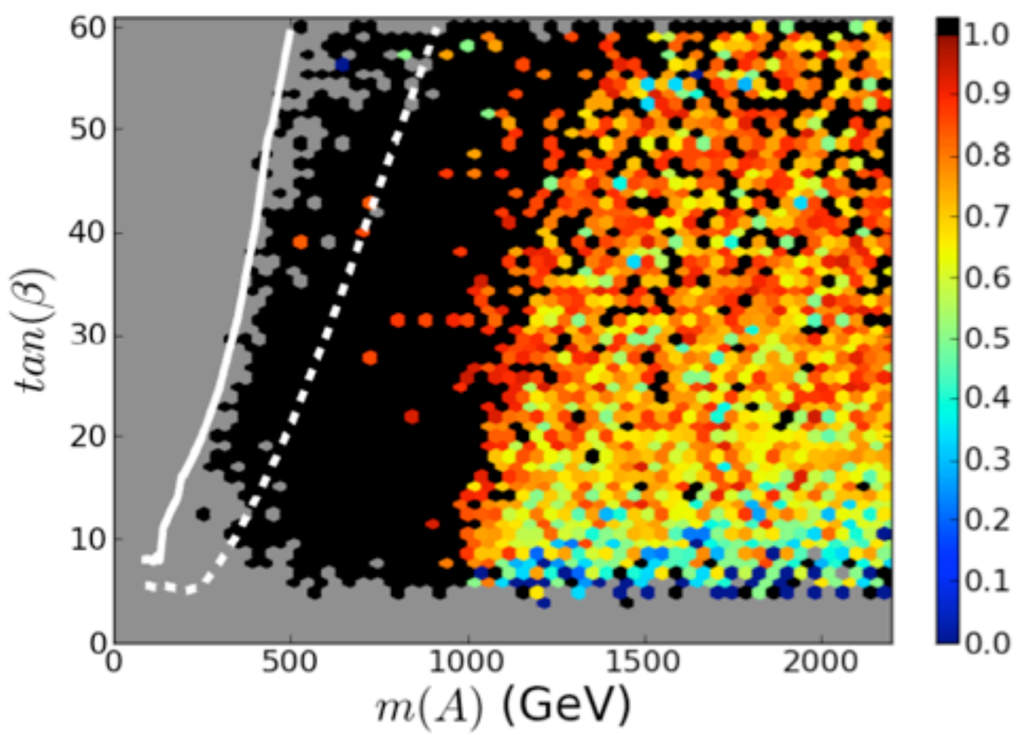
LHC 300/fb



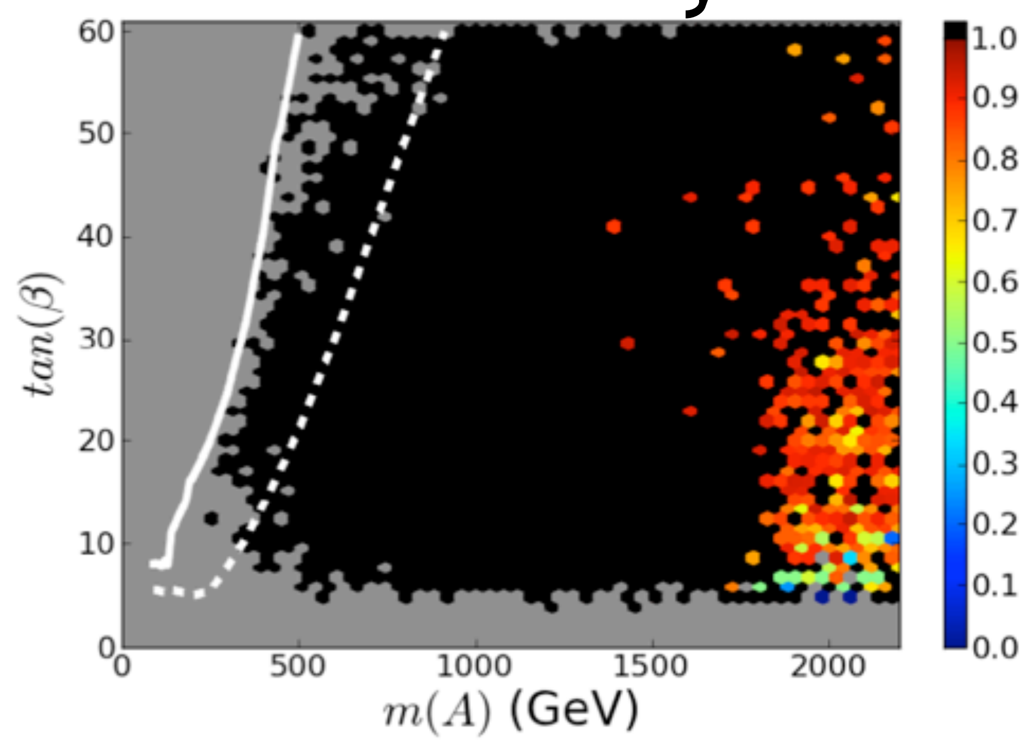
LHC 3000/fb



ILC TDR



ILC 20 yr



Cahill-Rowley, Hewett, Ismail, Rizzo

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.