Higgs Hunting: Theoretical Conclusions

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Higgs Hunting
July 2012

Two weeks after the July 4
Higgs Festival,

I feel

- awestruck
- impatient
- poised

Awestruck !

We have been waiting a long time for the discovery of the Higgs boson:

1967 - Weinberg and Salam

1976 - Ellis, Gaillard, Nanopoulos "Phenomenological Profile"

1976 - Bjorken hZZ coupling as a means of discovery

1981 - Okun at Lepton-Photon 1981 "Problem number 1"

1982 - Snowmass 1982

1984 - "ECFA-CERN Worksop on a Large Hadron Collider ..."

1987 - Gunion, Kane, Wudka $h\gamma\gamma$ as a means of discovery

1993 - cancellation of the SSC

2000 - LEP to 209 GeV

It is not only the time scale.

Those of us who scribble equations are humbled by the effort it takes to find out if those equations conform to reality.

This is measured in some ways that are apparent:

27 km tunnel

world’s largest cryogenic system

5-story high detectors

3,000 - member scientific collaborations

Higgs is the world's hardest data problem:

the Higgs boson appears in fewer than 1 in 10^{12} pp collisions

ATLAS and CMS push out 1,000 Tb / sec

their permanent databases are 10s of Pb

these databases are shared and analyzed globally

July 1962 - the Telstar satellite ; now the frontier is us !

The discovery also relies on the intense commitment of scientists and laboratories to the LHC over more than 25 years.

Denegri told us a part of this story. Let's also remember

young scientists in 1985: Fabiola Gianotti, Jim Virdee, ...

and many others, including our LAL hosts

Louis Fayard, Daniel Fournier, ...

the amazing institutional continuity and persistence of CERN (across 6 DGs), the CERN Council, and the taxpayers of Europe.

Do not forget the contributors to QCD theory over many decades

Harlander

Oleari, Bagnaschi, Zaro

These are among the most difficult calculations ever done.

They require creativity, not just persistence.

NLO: Spira, Djouadi, Graudenz, Zerwas '91, '93
Dawson '91
~80%

NNLO: RH, Kilgore '02
Anastasiou, Melnikov '02
Ravindran, Smith, v. Neerven '03
~30%

Resummation:
Catani, de Florian, Grazzini, Nason '02
Ahrens, Becher, Neubert, Zhang '08
~10%

Electroweak:
Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
Djouadi, Gambino '94
~5%

Mixed EW/QCD:
Anastasiou, Boughezal, Petriello '09

Fully differential NNLO:
Anastasiou, Melnikov, Petriello '04
Catani, Grazzini '07

After July 4, we find ourselves in a new era of particle physics.

Many questions that we had before have become irrelevant.

Other questions need to be restated in the new framework.

Some questions that previously were merely bothersome have now become central.

Impatient !

Is it the Higgs boson ?

Both ATLAS and CMS report strong signals for decays both to WW and to ZZ. The ATLAS report is new at this workshop (Arnaez).

A scalar field with a vacuum expectation value can couple to WW and ZZ in order 1:

$$
\begin{aligned}
|D_\mu \varphi|^2 \quad &\to \quad \frac{g^2}{4}(v + h(x))^2 W^+ W^- \\
&\to \quad m_W^2 W^+ W^- + \frac{2m_W^2}{v} h\, W^+ W^- + \cdots
\end{aligned}
$$

A field without a vacuum expectation value can couple to WW and ZZ through dimension-5 operators. In a weak-coupling theory, these operators come from loops.

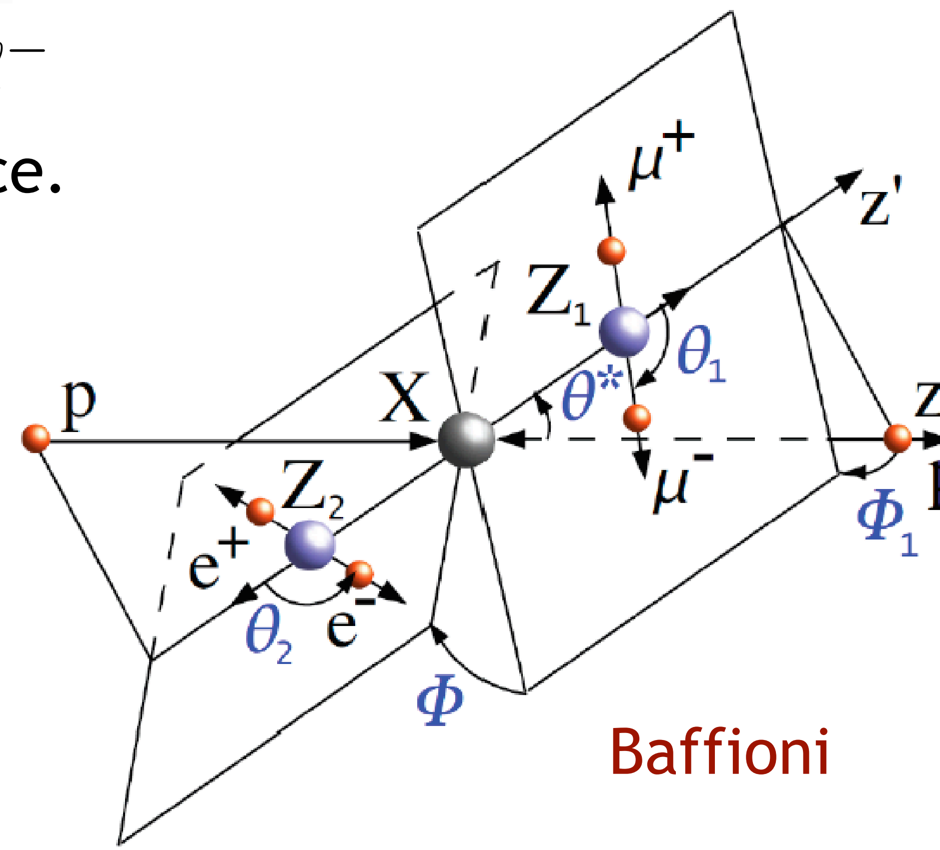
$$
A \frac{\alpha}{4\pi} \frac{1}{M} h\, F_{\mu\nu} F^{\mu\nu} + B \frac{\alpha}{4\pi} \frac{1}{M} h\, \epsilon_{\mu\nu\lambda\sigma} F^{\mu\nu} F^{\lambda\sigma}
$$

So, the fact that we see WW and ZZ at nearly Standard Model strength is prima facie evidence that the particle is a CP even spin 0 state from a field with a vacuum expectation value that breaks SU(2)xU(1).

The quantum numbers can be verified by angular analysis of

$$pp \to ZZ \to \ell^+\ell^-\ell^+\ell^-$$

This already enters the CMS evidence.



Baffioni

The hWW vertex gives dominantly longitudinal W polarization

The A and B vertices give transverse polarization.

CMS: MELA already favors the scalar hypothesis at about 1 sigma.
3 sigma separation between scalar and pseudoscalar hypostheses is possible with 30 fb-1.

From here on, I will call the new particle at 125 GeV "the Higgs boson" without further apology.

We still must find out whether this particle has the properties predicted in the Standard Model.

In the Standard Model, the Higgs boson is the unique source of mass for all quarks, leptons, and gauge bosons.   Is it really so ?

At 125 GeV, the Higgs boson is exceptionally hard to find.

However, once found, it offers us a large number of decay channels for study.

Gianotti: "Thank you, Nature."

$m_H \sim 126$ GeV

$\Gamma_H = 4.2$ MeV

$\lambda = (m_H/v)^2/2 = 0.131$

$H \to WW^*$ 23%*

$H \to ZZ^*$ 2.9%*

$H \to bb$ 56%*

$H \to cc$ 2.8%

$H \to \tau\tau$ 6.2%*

$H \to \mu\mu$ 0.21‰

$H \to gg$ 8.5%*

$H \to \gamma\gamma$ 2.3‰*

$H \to \gamma Z$ 1.6 ‰*

new set of reference SM parameters

many couplings accessible at LHC (*)!

5

Mele

Our understanding of this boson will advance in stages.

I expect 3 stages:

1. Are the major decay modes present ?

2. Standard-Model-like Higgs boson, or not ?

3. Are there small deviations from the Standard Model ?

Stage 1: Are the major decay modes present ?

Already at this meeting, many of the key qualitative properties of the Higgs boson are falling into place:

$\gamma\gamma$ decay mode ✓

ZZ decay mode ✓

WW decay mode ✓

bb decay mode Tevatron only (Buzatu) ;
hopeful report from CMS (Bortignon)

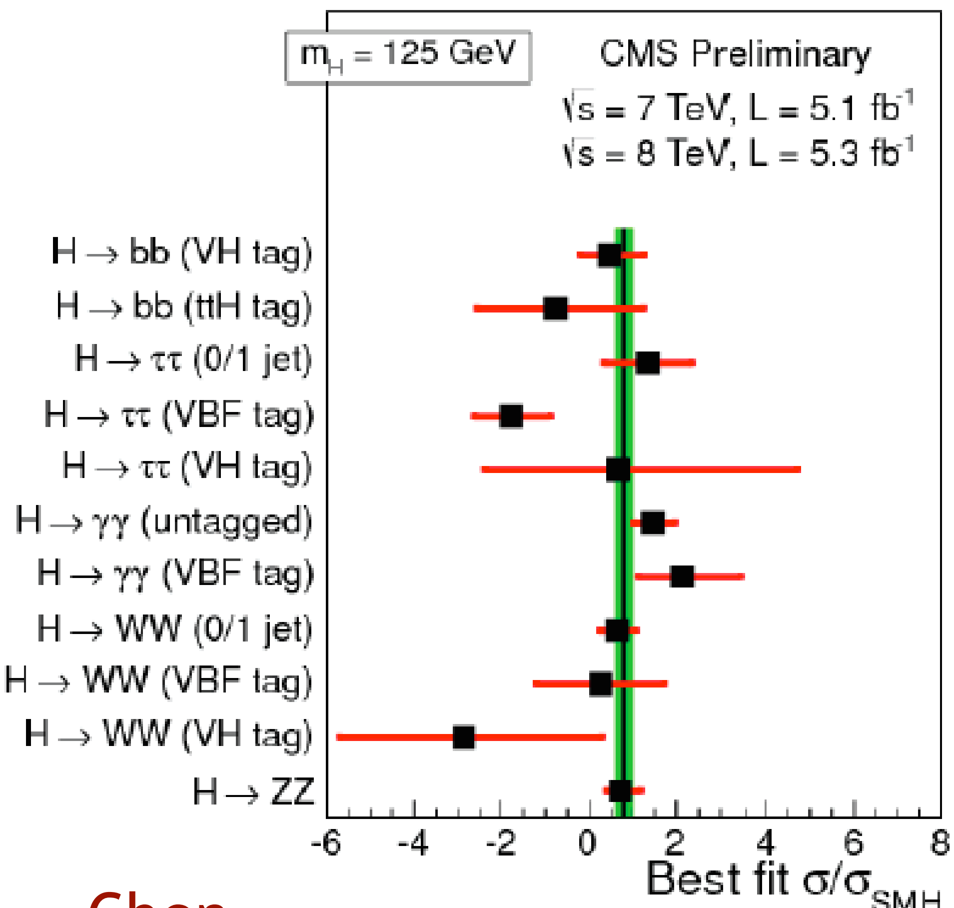
$\tau\tau$ decay mode ? deficit at CMS (De Gruttola)

spin-parity	preliminary evidence from CMS (Baffioni)
gg production mode	✓
VBF production mode	marginal
Higgsstrahlung mode	Tevatron only (Buzatu)

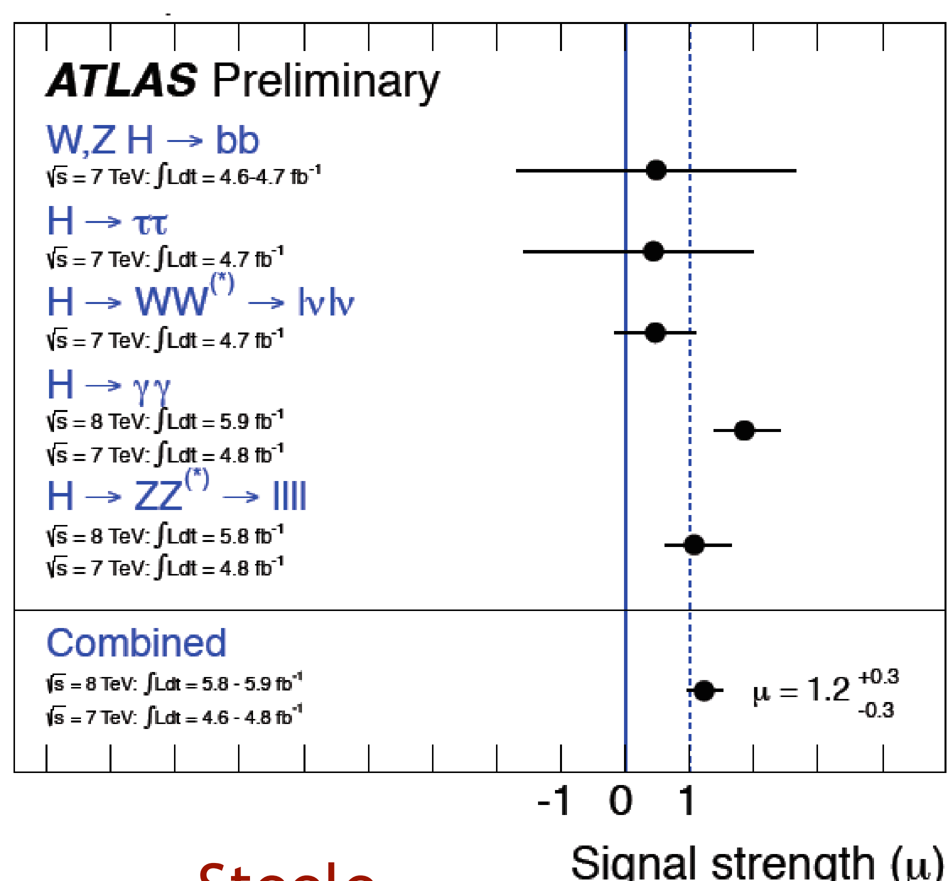
All of these issues could be settled with the full 2012 LHC data set.

Stage 2: Standard-Model-like Higgs boson, or not ?

There is much interest now in parsing the deviations from the Standard Model predictions for rates, expressed as signal strengths μ relative to the Standard Model.

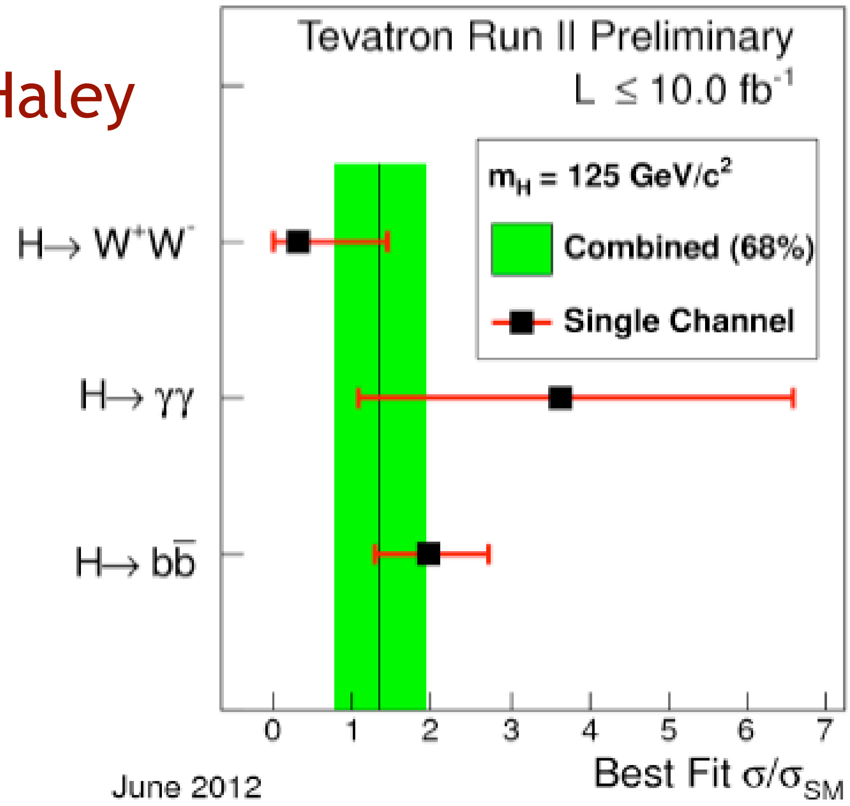


Chen



Steele

Haley


Tevatron Run II Preliminary
L ≤ 10.0 fb^{-1}
m_H = 125 GeV/c^2
Combined (68%)
Single Channel
$H \to W^+W^-$
$H \to \gamma\gamma$
$H \to b\bar{b}$
0
1
2
3
4
5
6
7
Best Fit σ/σ_{SM}
June 2012

This is very much fun for theorists.

There are many interesting model-building solutions that give order-1 modifications of the Higgs boson couplings. These involve:

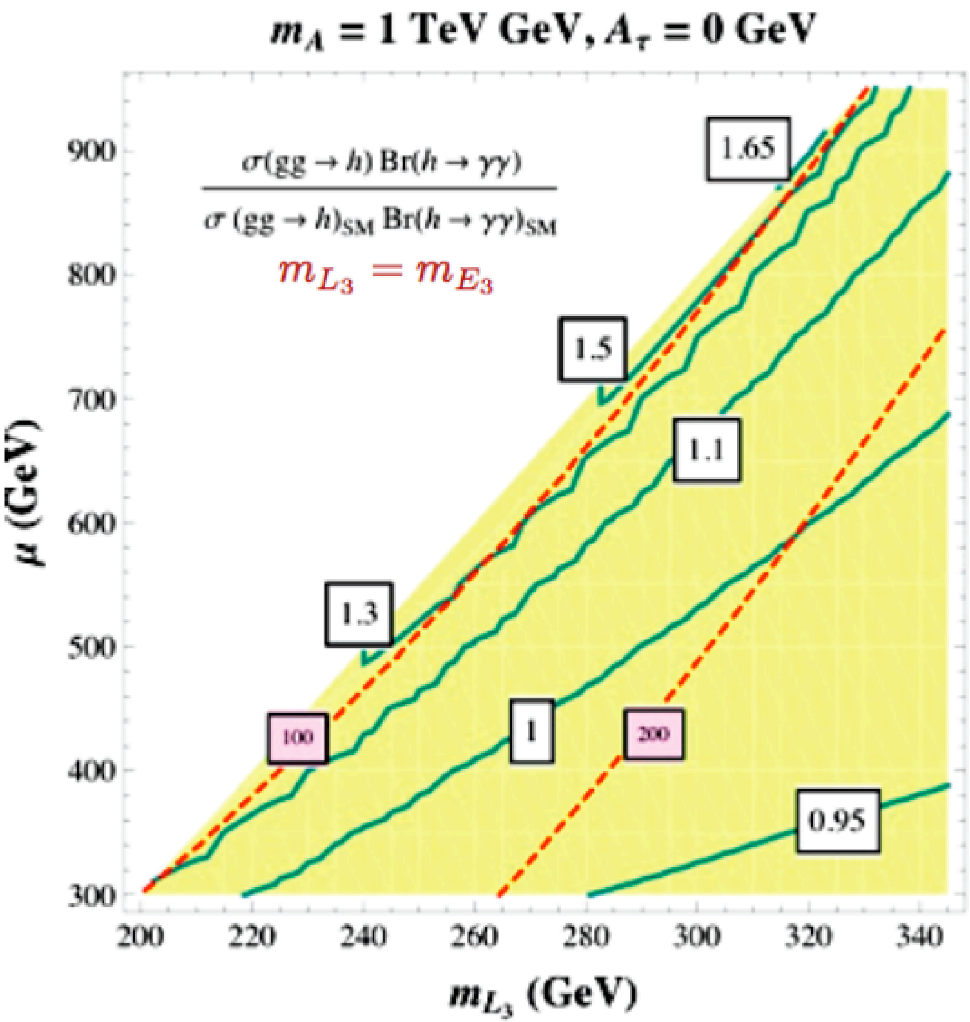
an extended Higgs boson sector
with extra Higgs bosons below 200 GeV

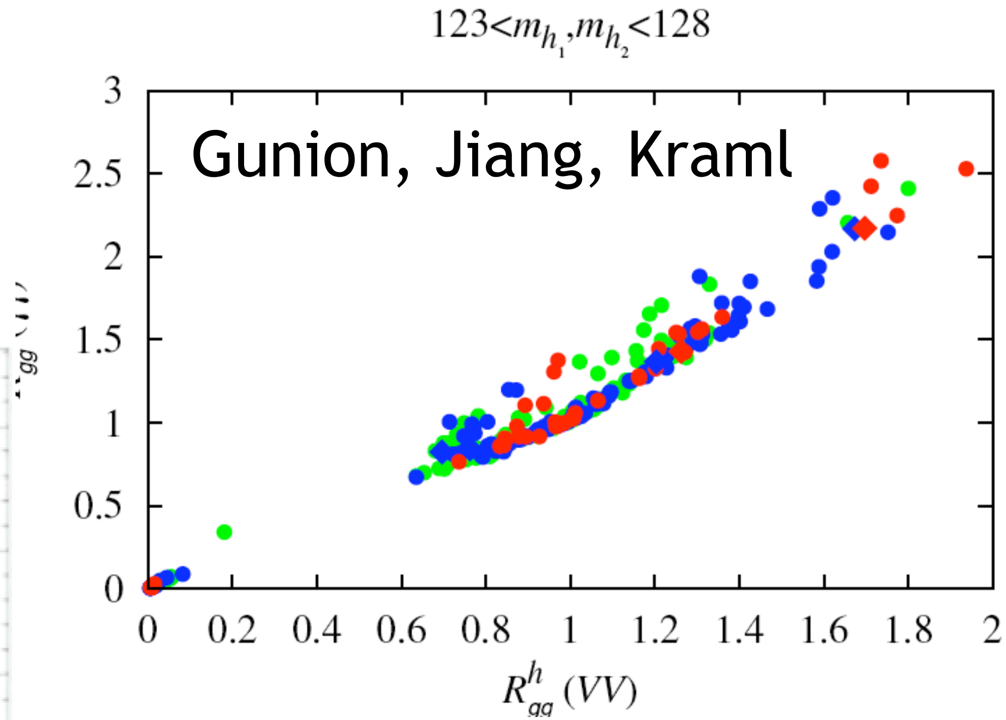
new color-singlet particles with masses below 200 GeV

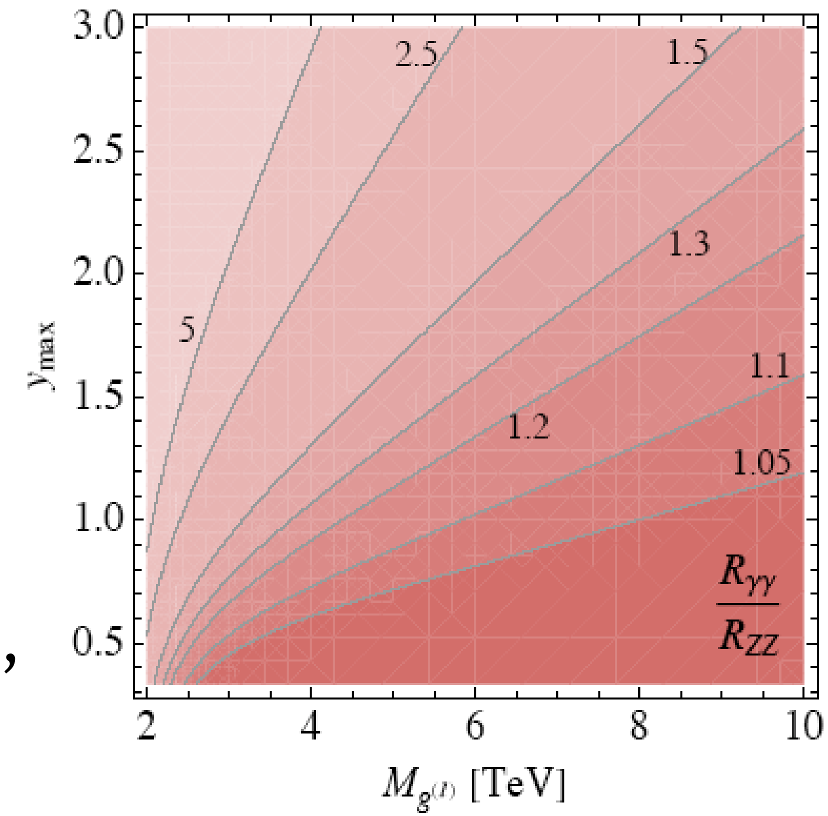
new colored particles (e.g. stop) that are stealthy at LHC

composite Higgs with compositeness scale below 1 TeV

Carena, Gori, Shah, Wagner







Carena

Goertz, Haisch, Neubert

Fits to the current measurements tend to be 2-parameter fits under specific model hypotheses. Several of these fits were discussed by Espinosa.

More general fits are not yet constrained by the data. That is where we are now.   The 2-d fits help us make sense of the current results.

But, we have to be cautious in our interpretations.

Remember that

$$\mu(A\overline{A} \to h \to B\overline{B}) = \frac{\Gamma(A)\Gamma(B)}{\Gamma_T} \ / \ (SM)$$

So, for example, for an excess of

$$\mu(gg \to h \to \gamma\gamma)$$

the explanation could be

an enhancement of $\Gamma(\gamma)$
an enhancement of $\Gamma(g)$
a suppression of $\Gamma(b)$ or $\Gamma(W)$

or any combination of these.

Without accurate determinations of bb signals or VBF cross sections, global fits that attempt to address this question are unstable.

I doubt that this problem will be resolved in 2012.

However, there are good prospects for its resolution later in the decade, when we have data from the LHC at 14 TeV and 10's of fb-1.

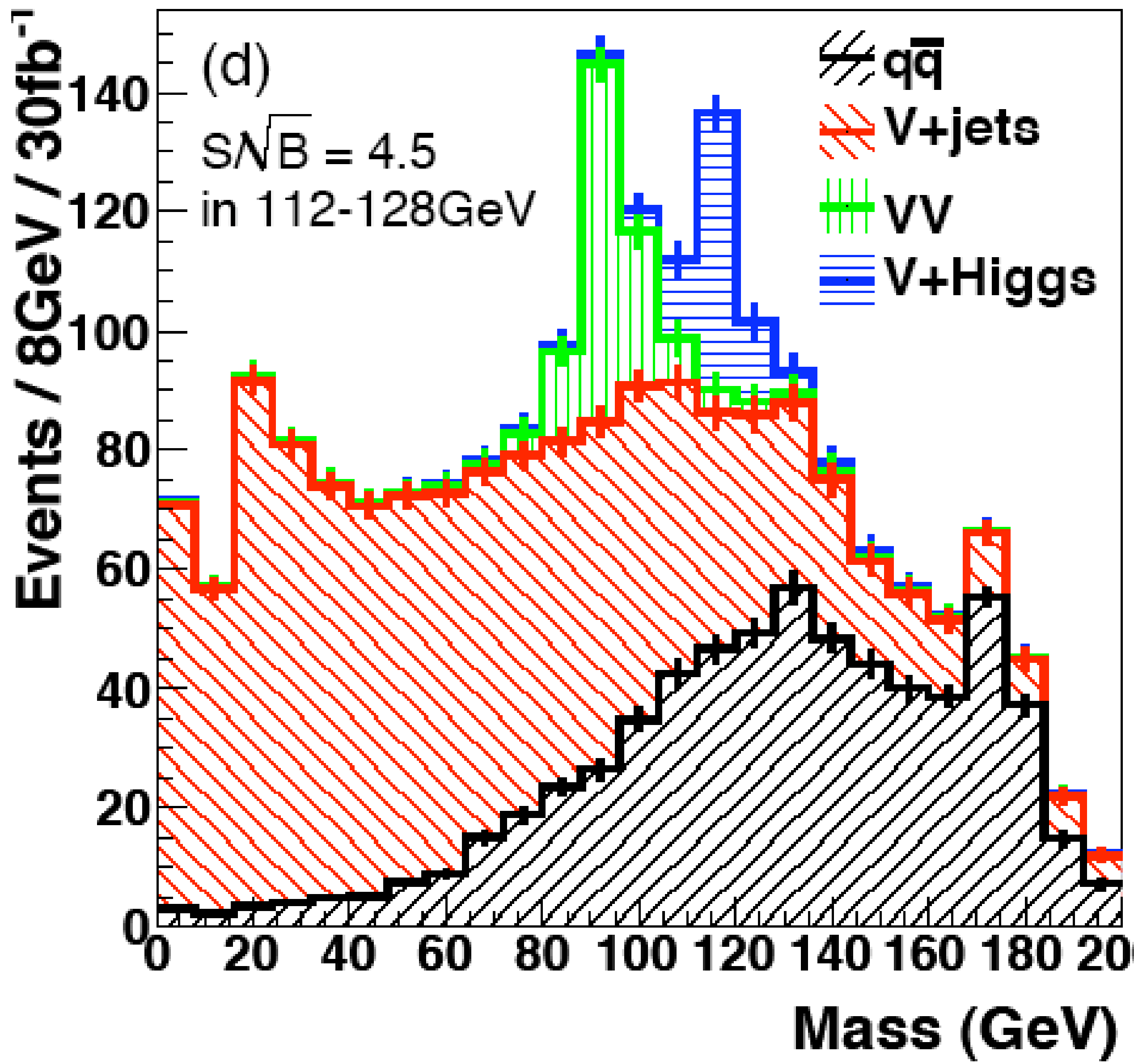
A crucial new element will be the measurement of Higgs decays to b using "boosted" techniques. (Salam)

A very troublesome background to $pp \to Vh \to b\bar{b}$ is

$$pp \to Vg \to b\bar{b}$$

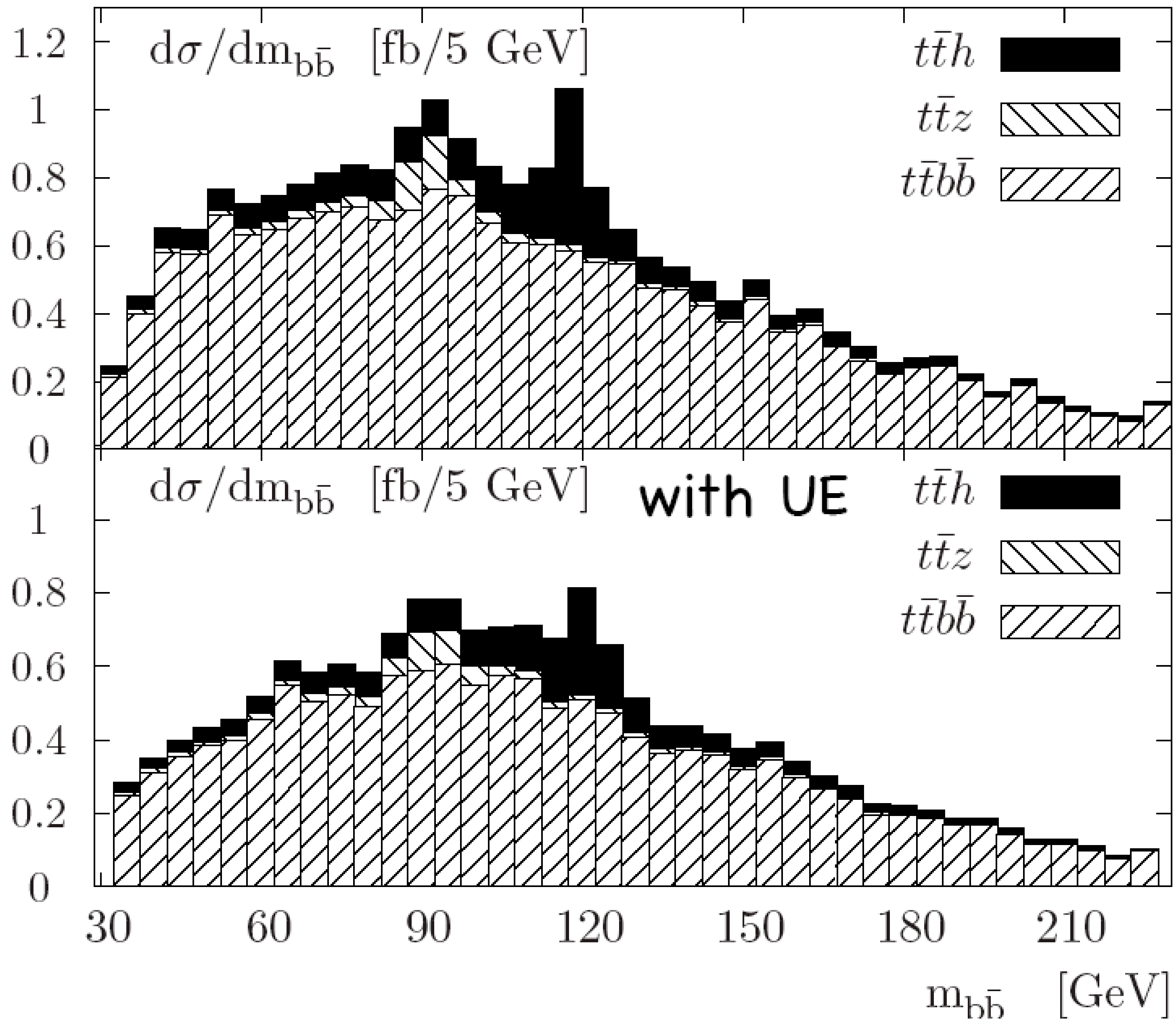
To eliminate this, deconstruct the $b\bar{b}$ jet(s), measure the color charge, remove if it is color octet!

$pp \rightarrow (W, Z) + h$



Butterworth, Davison, Rubin, Salam

$pp \to t\bar{t} + h(\to b\bar{b})$



Plehn, Spannowsky, Takeuchi

Recently, I tried to estimate how well LHC could do with 300 fb-1 of data, applying a model-independent (9 parameter) fit.

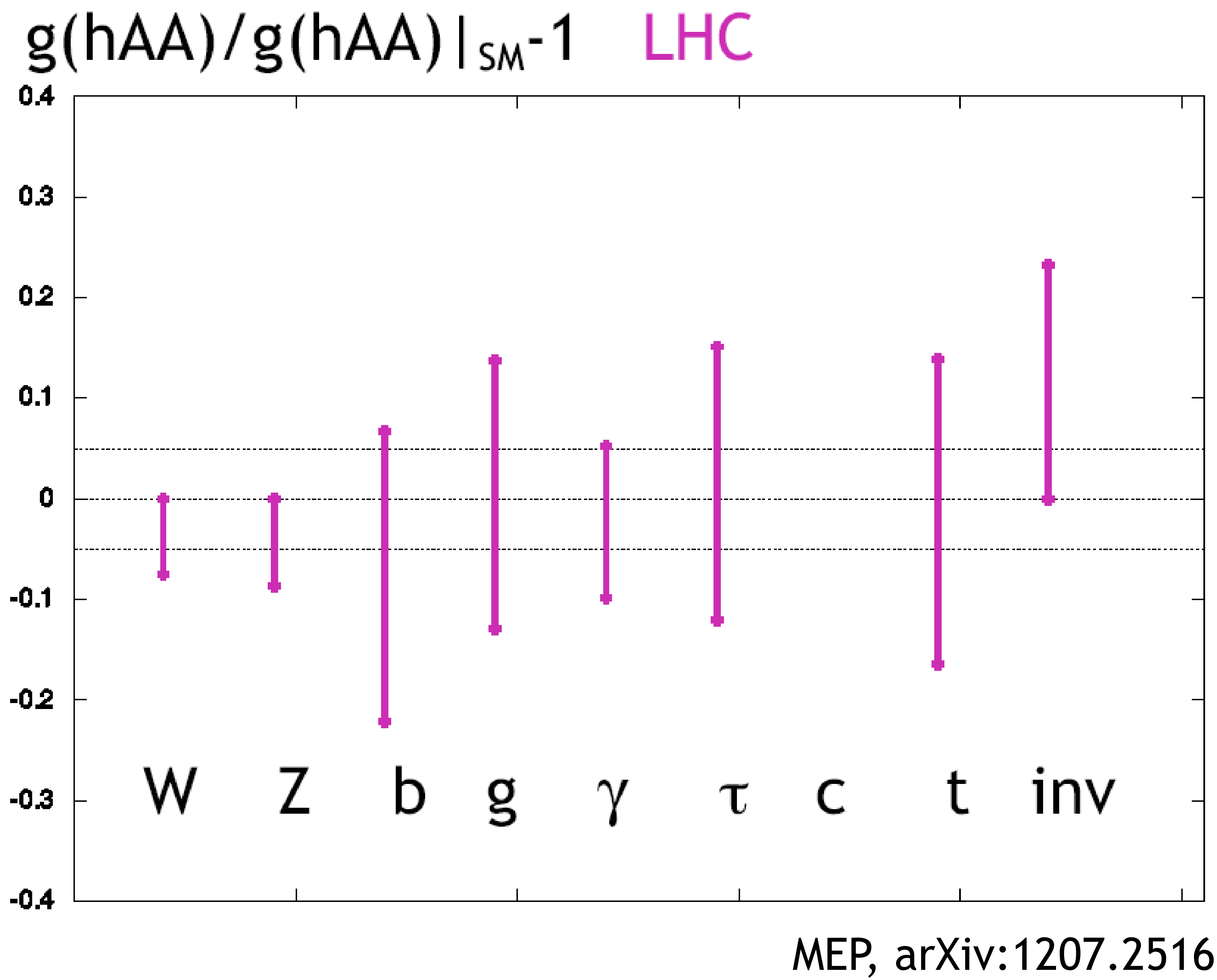
The only important theoretical assumption is

$$\Gamma(W) \leq \Gamma(W)|_{SM} \quad \Gamma(Z) \leq \Gamma(Z)|_{SM}$$

Violation of this assumption requires models with φ^{++} (Gunion, Haber, and Wudka)

The loop couplings to g and γ are treated independently of the t and W couplings. Loops can be affected by unknown particles as well as by t and W.

Similar work by Klute et al. was shown yesterday in Mele's talk. We come to similar conclusions. My fit is more naive, but more transparent. For its complete details, see arXiv:1207.2516.



g(hAA)/g(hAA)|SM-1
LHC
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
W
Z
b
g
γ
τ
c
t
inv
MEP, arXiv:1207.2516

But, this is not good enough !

Stage 3: Are there small deviations from the Standard Model ?

Why should we care about this ? In fact, it is crucial.

1. The Higgs might turn out to look Standard Model like. But, the Standard Model Higgs makes no sense. In this model, the complete explanation for spontaneous symmetry breaking is

$$\mu^2|_{\mathrm{TeV}} < 0$$

As physicists, we should be ashamed of ourselves to be satisfied with this.

2. In dynamical models of electroweak symmetry breaking (supersymmetry, Little Higgs, Randall-Sundrum, ...), there is a light Higgs boson. If all other particles are heavy (TeV mass), we are in the Decoupling Limit described by Haber. The properties of the Higgs are those of the Standard Model Higgs up to corrections of order $(m_h^2, m_t^2)/M^2$.

Examples: (see also Gupta, Rzehak, Wells (2012))

SUSY:

$$\begin{aligned} g(\tau\tau)/SM &= 1 + 10\% \left(\frac{400\ \mathrm{GeV}}{m_A}\right)^2 \\ g(b\bar{b})/SM &= g(\tau\tau)/SM + (1-4)\% \end{aligned}$$

Composite Higgs:

$$g(f\bar{f})/SM = 1 + (3-9)\% \left(\frac{1\ \mathrm{TeV}}{f}\right)$$

Littlest Higgs:

$$\begin{aligned} g(gg)/SM &= 1 + (5-9)\% \\ g(\gamma\gamma)/SM &= 1 + (5-6)\% \end{aligned}$$

In general, corrections to the Decoupling Limit can tweak any individual Higgs coupling independently of the others.

After July 4,

the issue of the precise values of the Higgs couplings has vaulted to the top of the list of problems in high energy physics.

The level of precision that is needed is very high.

Can we get there ?

Poised

There is much interest now in the possibilities for precision Higgs coupling measurements at the HL-LHC.

We should go for it.

The goal is tremendously challenging.

It is not obvious that there is any advantage for Higgs couplings in going from 300 fb-1 to 3000 fb-1.

ATLAS and CMS are studying ambitious detector modifications for the 10^35 luminosity era to attack these measurements.

Theorists will also need a round of improvement of their tools.

It is unlikely that this will be understood better in time for the European Strategy Study. A new simulation framework is needed. It will take close to 1 year -- and the end of the current LHC data taking -- to allow the preparations for this study.

Higgs physics, and this question in particular, will be a major topic in the HEP community study in the US, "Snowmass 2013".

The Energy Frontier part of this study is being organized by Chip Brock and me.

Snowmass 2013 will take place July 29 - August 10 , not in Colorado but instead at a U S university campus.

For all details and updated information, see the Snowmass wiki:

http://www.snowmass2013.org/

High-energy physics is global. We welcome your participation.

Now I will take off my hat as an organizer of Snowmass and put on a different hat.

I will give you my personal opinion about the long-term future of Higgs physics and how we should respond to it.

We know now that the Higgs boson exists, at a mass that gives the possibility of a very rich experimental program.

We know that high-precision measurement of couplings, to few percent or even 1% accuracy, is needed to fully understand the Higgs boson.

We know that the WW and ZZ couplings are large enough that the Higgs boson can be studied with large samples in e+e- .

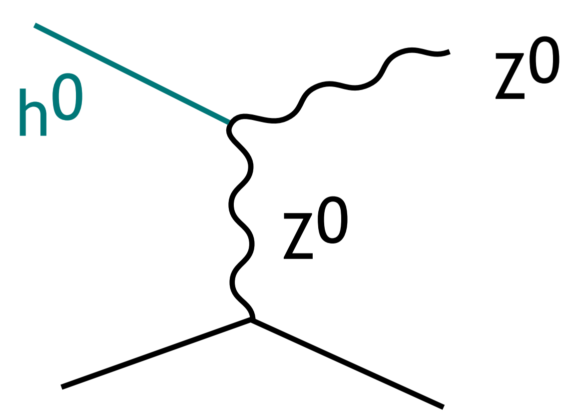
So, it is now compelling to propose a Higgs factory to study the Higgs boson in e+e- collisions.

An e+e- Higgs factory has strong advantages over the study of the Higgs boson in pp collisions:

Higgs boson production is 1%, not 10^{-10} of the total rate.
Higgs production events are characteristic with respect to SM backgrounds.

Decays of Higgs to quarks and to WW and ZZ in hadronic modes are manifest as mass peaks.

Higgs boson decays can be tagged, allowing direct measurement of branching ratios, even for invisible modes.



The environment of e+e- colliders allows improved detectors with unique capabilities.

high efficiency b/c/g   discrimination by vertex tagging

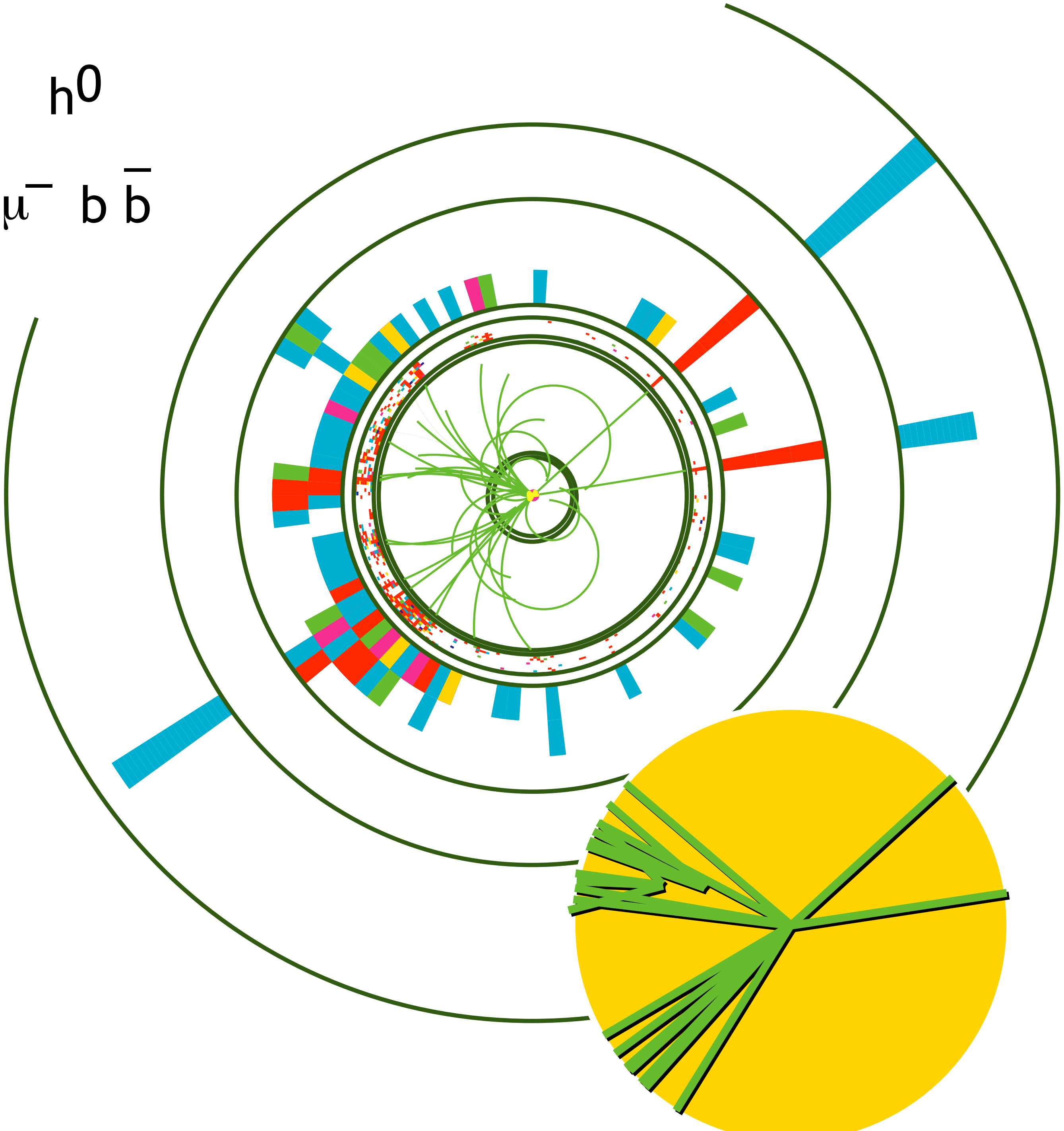
recognition and separation of W and Z in hadronic decays by calorimetry

full-event spin analysis constrained by knowledge of the center of mass system

For details, see the ILD and SiD LOIs.

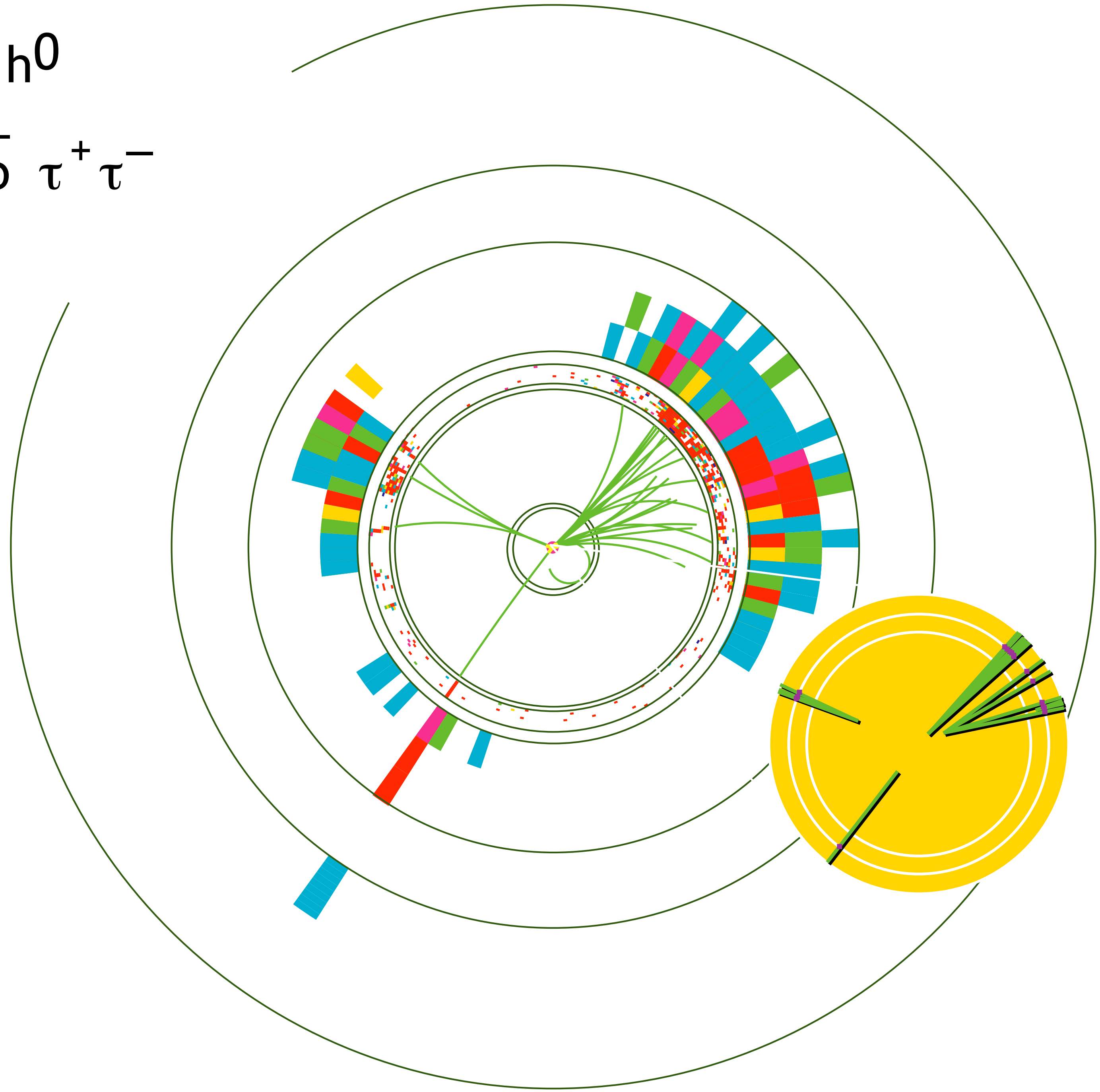
$e^+e^- \rightarrow Z^0 \quad h^0$

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



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

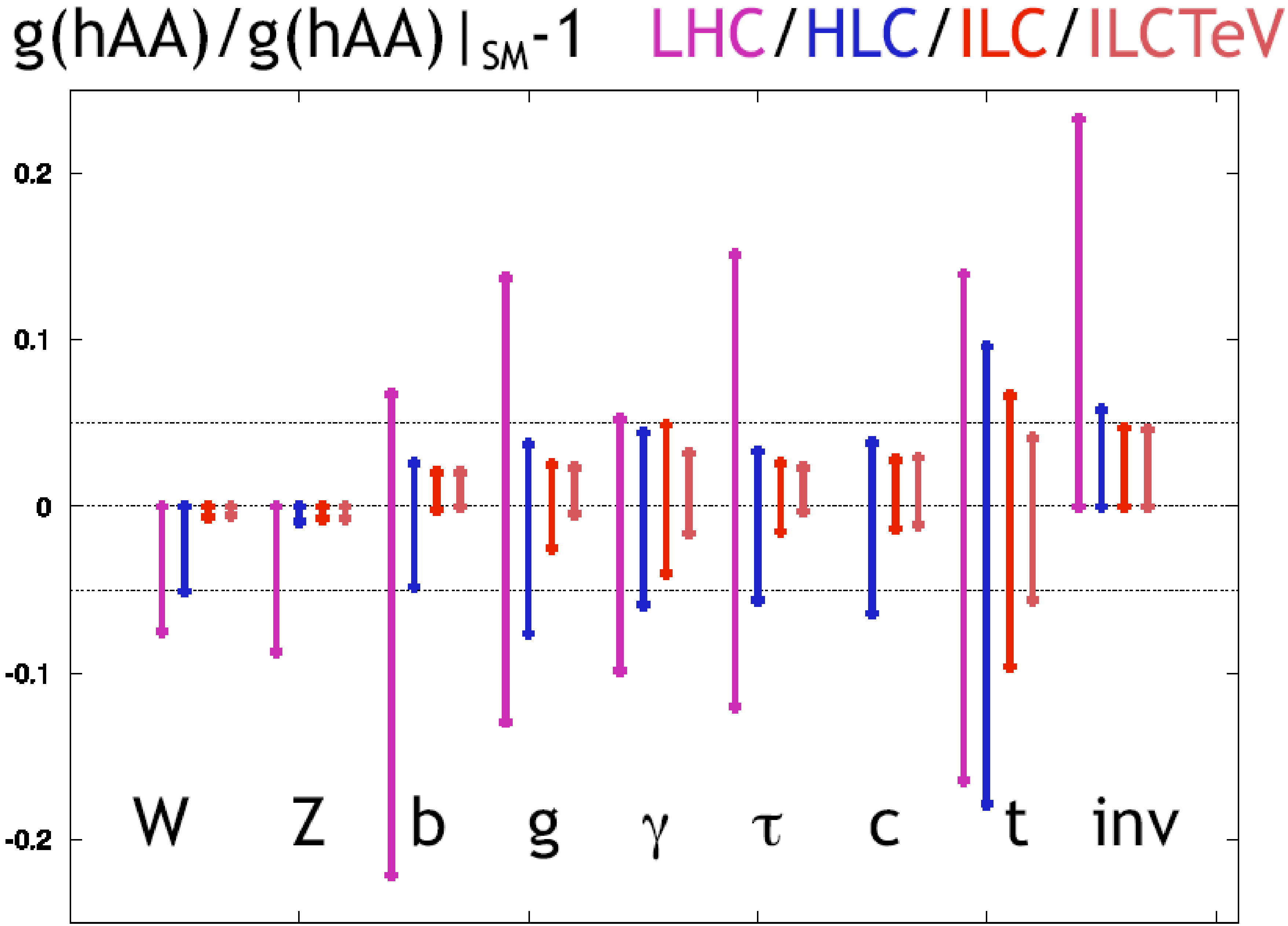
$\rightarrow b\,\bar{b}\ \tau^+\tau^-$



Among the technological solutions for building a Higgs factory, a compelling one is the International Linear Collider.

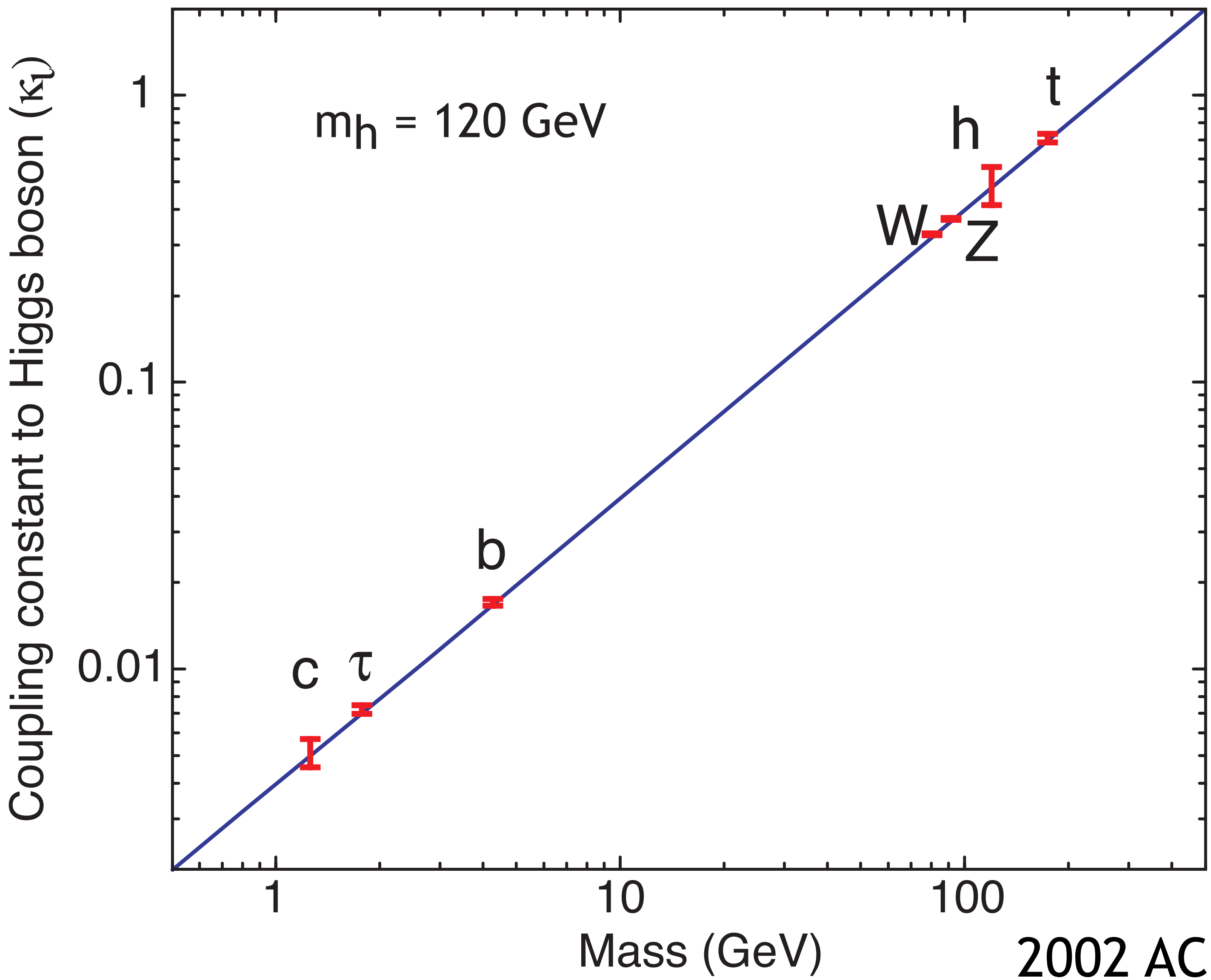
The ILC has been intensively engineered over the past decade. The TDR is being prepared for a deadline at the end of 2012.

The capabilities for Higgs measurements are impressive. Current estimates are supported by full-simulation studies with realistic inclusion of the machine environment.



MEP, arXiv:1207.2516

If the simple scalar Higgs model is correct, the Higgs couplings to each particle is proportional to its mass. We can test this hypothesis to high accuracy.



2002 ACFA LC study

Over the years, much scorn has been poured on the ILC because its design energy is "only" 500 GeV, extendable to 1 TeV.

In the new era, those arguments are completely turned around.

The ILC capabilities are a perfect match to the needs of a precision Higgs boson experimental program.

The ATLAS and CMS discovered no other new particles. Thus, there is no motivation for an e+e- experimental program above 600-700 GeV, and there may not be for a long time.

Rolf Heuer (Lepton-Photon 2011):

The case for the next machine must be based on discoveries made at the LHC.

Now we have made the discovery. It is time to begin the campaign for the next machine.

These arguments are recognized by members of the government in Japan. Europeans and American should recognize how wonderful it would be for high energy physics to have a frontier facility in Asia operating in the same period as the HL-LHC.

S. Yamashita at KILC12

The new era of high energy physics
-- the Higgs era -- has begun.

We are awestruck at the accomplishments of the LHC experiments, and we are impatient to learn more of the Higgs story.

But, also, we are ready for an exciting ride.