SM Higgs Studies and Couplings using 100 TeV Collider

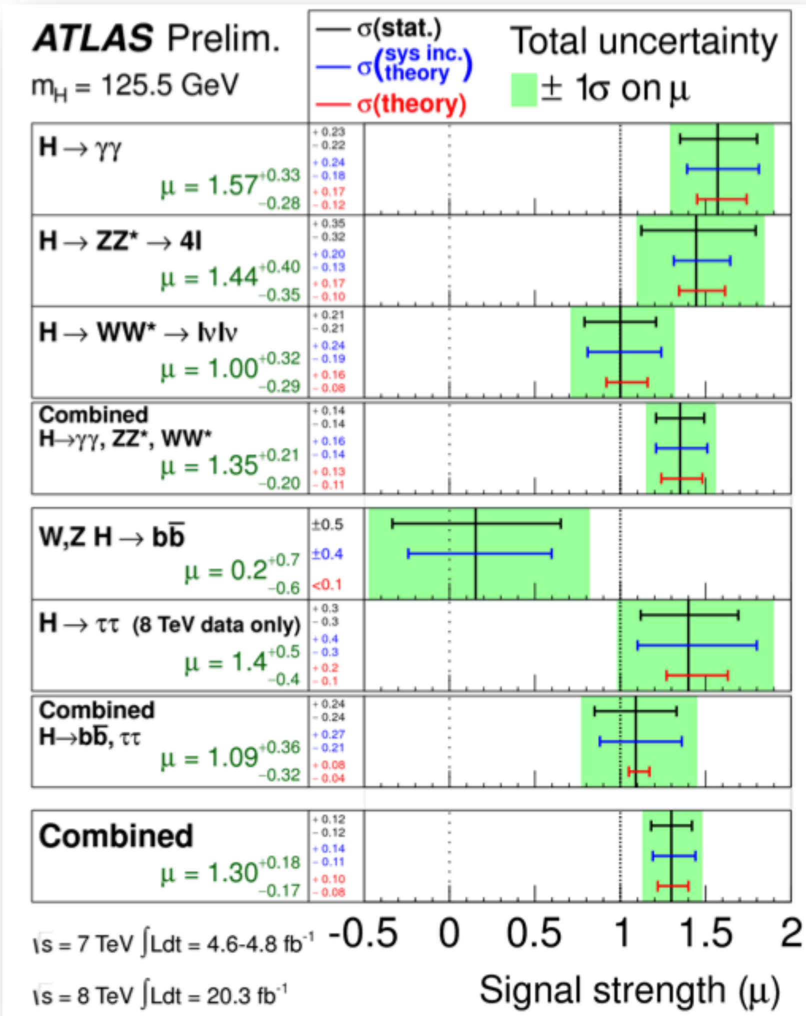
Ian Low
Argonne/Northwestern
Next Steps in Energy Frontiers @ FNAL

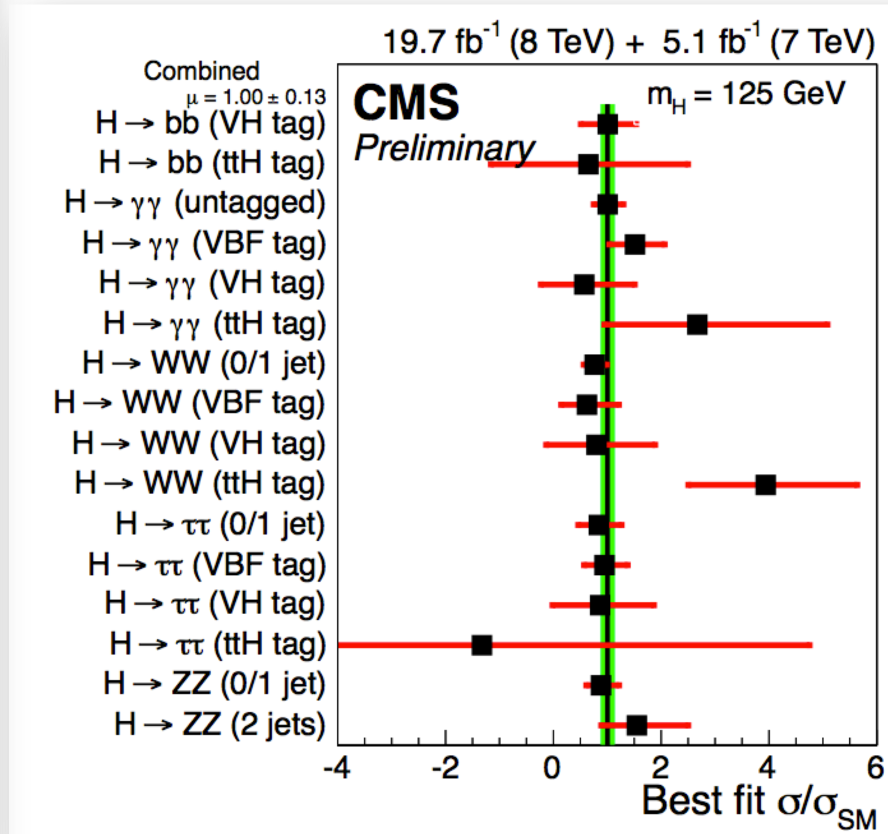
August 26, 2014

Argonne NATIONAL LABORATORY

NORTHWESTERN UNIVERSITY

We know a lot about the 125 GeV Higgs boson:





Everything we measured looks SM-like, within 20 – 30% uncertainty.

Let's call h(125) the SM Higgs, for now.

If we had a 100 TeV machine, what could we use it to study the 125 GeV Higgs?

The SM is incredibly predictive in the Higgs sector:

Couplings to massive gauge bosons → $\left(\frac{2m_W^2}{v}\, h\, W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v}\, h\, Z_\mu Z^\mu\right)$

Couplings to massless gauge bosons →

$$+c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w}\, h\, F_{\mu\nu} Z^{\mu\nu}$$

$$c_g^{(SM)}(125 \text{ GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125 \text{ GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125 \text{ GeV}) = 5.48\ .$$

Couplings to fermions → $\sum_f \frac{m_f}{v} h \bar{f} f$

Self-couplings → $\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$

Once the mass is known, every single coupling is then determined!!

So far we have only measured a subset of these couplings with uncertainties of 20 – 30 % or larger:

Couplings to massive gauge bosons → $\left(\frac{2m_W^2}{v}\, h\, W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v}\, h\, Z_\mu Z^\mu\right)$ ✔ ✔

Couplings to massless gauge bosons →

$$+c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} h\, F_{\mu\nu} Z^{\mu\nu}$$

✔ ✔ ?

$$c_g^{(SM)}(125\ \text{GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125\ \text{GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125\ \text{GeV}) = 5.48\ .$$

Couplings to fermions → $\sum_f \frac{m_f}{v} h \bar{f} f$? ✔ for *bb*, *tt*, and *ττ* only!

Self-couplings → $\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$ ✔ ? ?

To prepare for a 100 TeV collider, let's ask how new physics could show up in the property of the "125 GeV Higgs":

- The coupling strength could deviate from SM expectations.
  Most commonly considered.

- New coupling structure, beyond those existing in the SM, could arise.
  Getting more attention lately. Most interesting possibilities are CP- and Flavor-violating couplings.

- Higgs could couple to new degree-of-freedom.
  Higgs portal dark matter or other "soft" new physics.

- Higgs could have partners.
  New resonances in WW scattering.
  Additional scalars/fermions such as 2HDM, T-prime, etc.
  (see other talks at this workshop!)

Coupling Strength Deviations

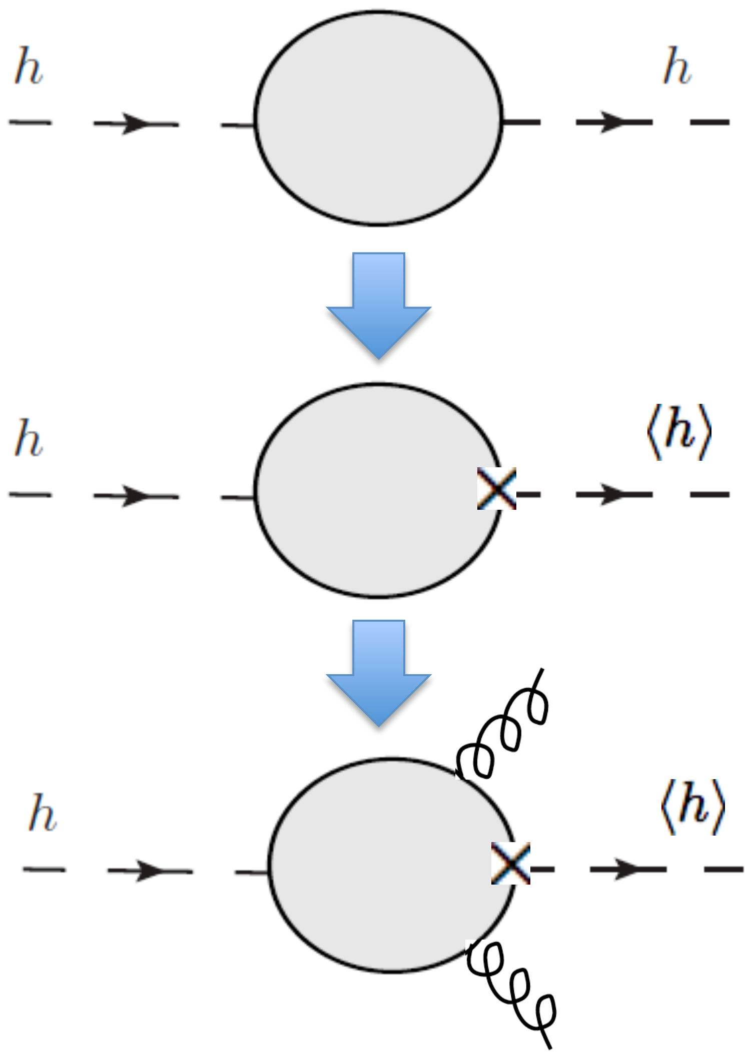
Deviations in SM couplings are *generically* dictated by the decoupling limit:

$$\mathcal{O}\left(\frac{v^2}{m_{\rm new}^2}\right) \approx 5\ \% \ \times \left(\frac{1\ \rm TeV}{m_{\rm new}}\right)^2$$

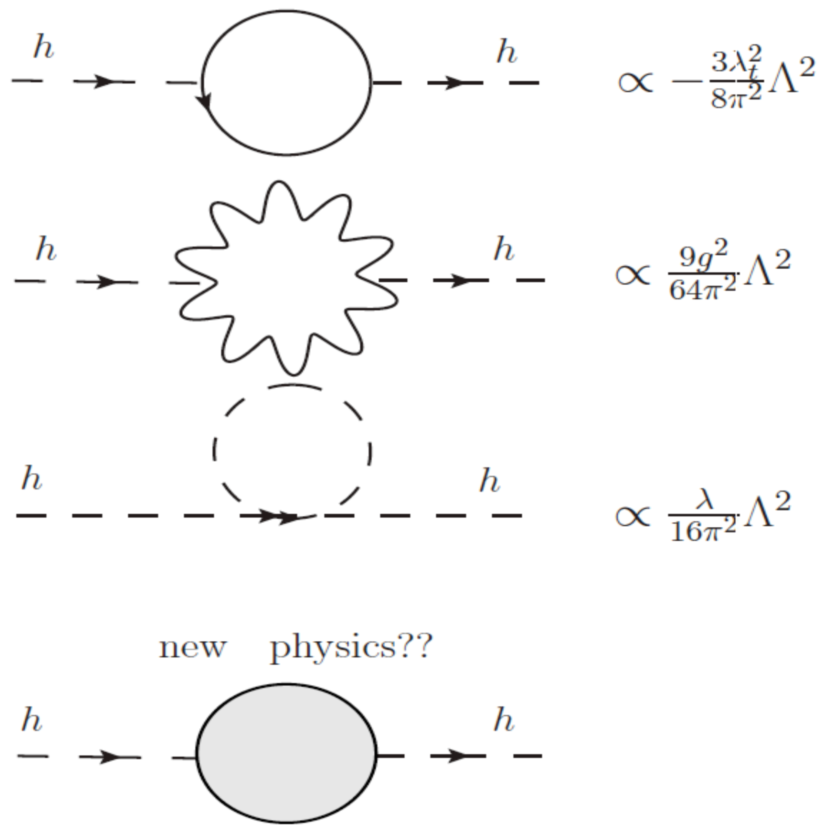
So present uncertainties of the order of 20 –30 % are simply too large to see these deviations.

(There are exceptions; see Carlos Wagner's talk on Wednesday on "Alignment without Decoupling.")

Among the couplings already existing in the SM, loop-induced couplings are particularly interesting because they are the new "oblique corrections:"



This argument is especially important given the naturalness expectation that "something" has to stabilize the Higgs mass:



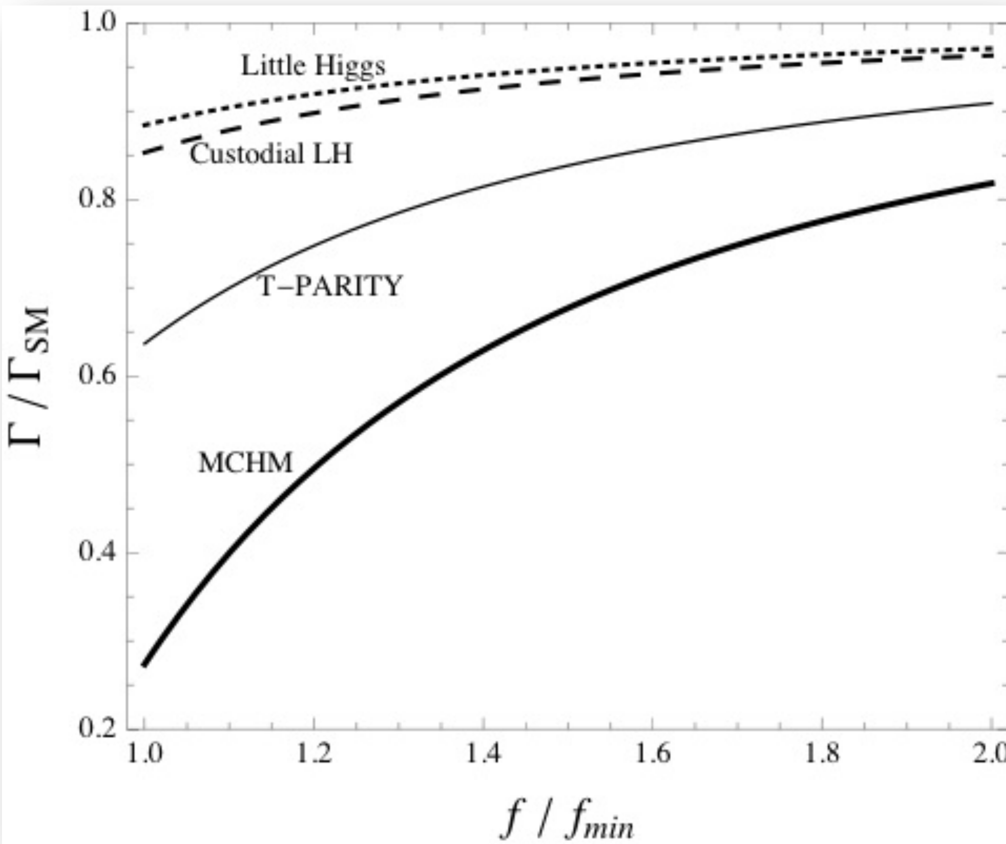
Unless that "something" resides in a hidden sector, SM loop-induced couplings must be modified.

- Loop-induced couplings are the new oblique observables.

- In “natural” EWSB these couplings are modified naturally.

- Any observed modification in loop-induced couplings is a smoking-gun signal for (un)naturalness.

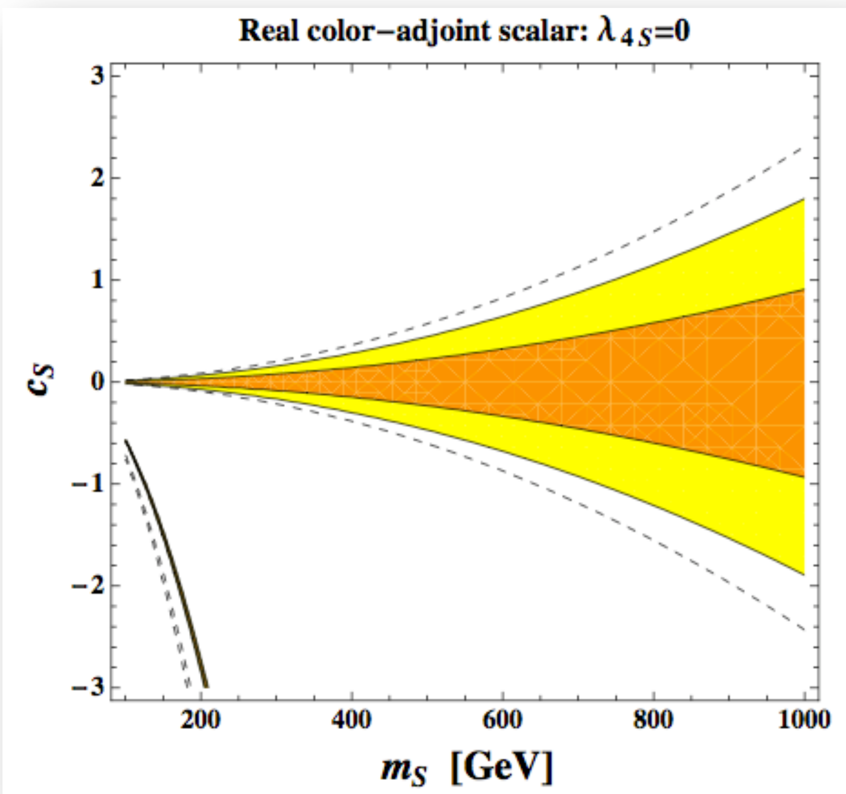
In Higgs-as-a-Pseudo-Goldstone-Boson models, ggh coupling is always reduced:



IL, Rattazzi, Vichi:0907.5413
IL and Vichi:1010.2753

However, as we go to better precision, higher-order corrections may become important especially for loop-induced couplings.

as a function of the new particle mass and its coupling to the Higgs. The orange and yellow region are for deviations within 5% and 10%, respectively. For comparison, we also show in dashed lines the contour of 10% deviation from only retaining the LO effect in new particles.

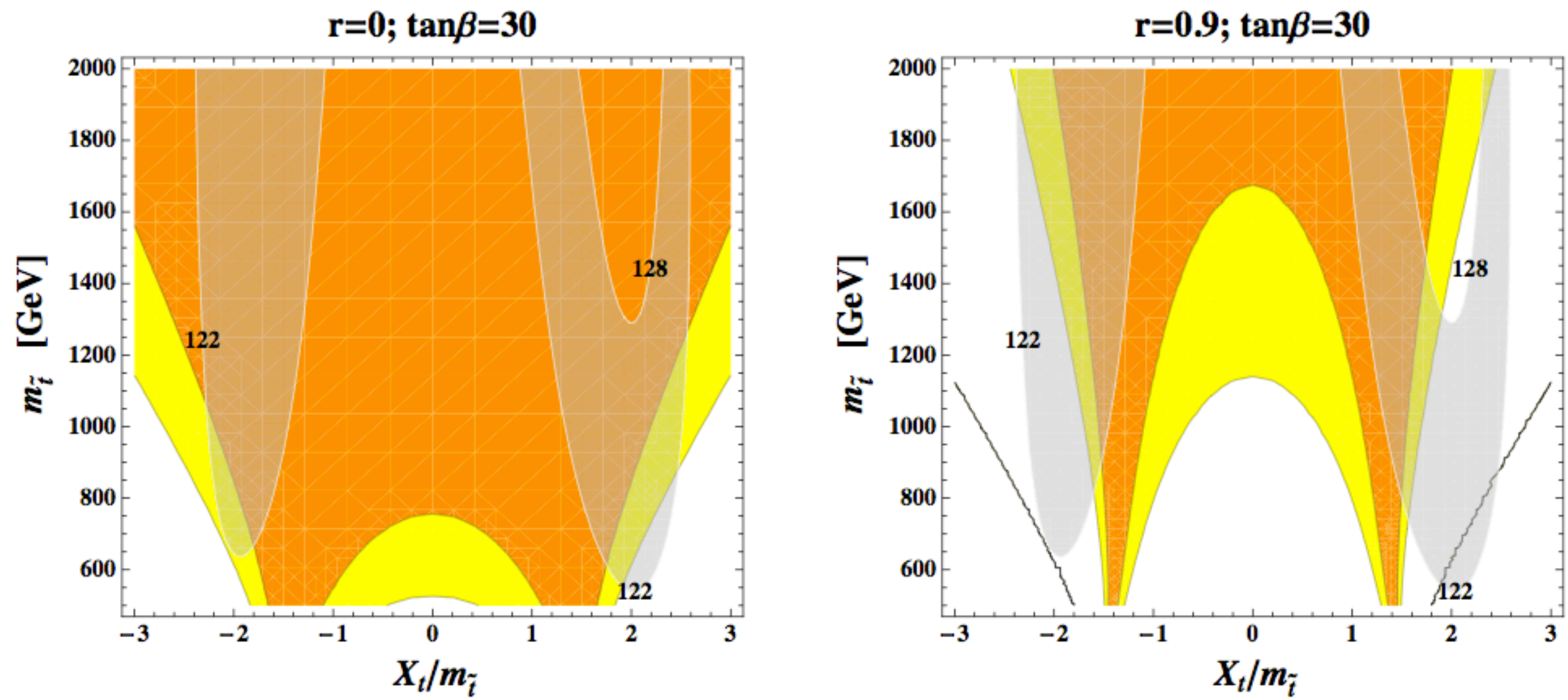


$$\mathcal{O}_S = c_S H^\dagger H S^\dagger S$$

Need a program for Next-to-leading order Naturalness at 100 TeV!

Gori and IL: 1307.0496

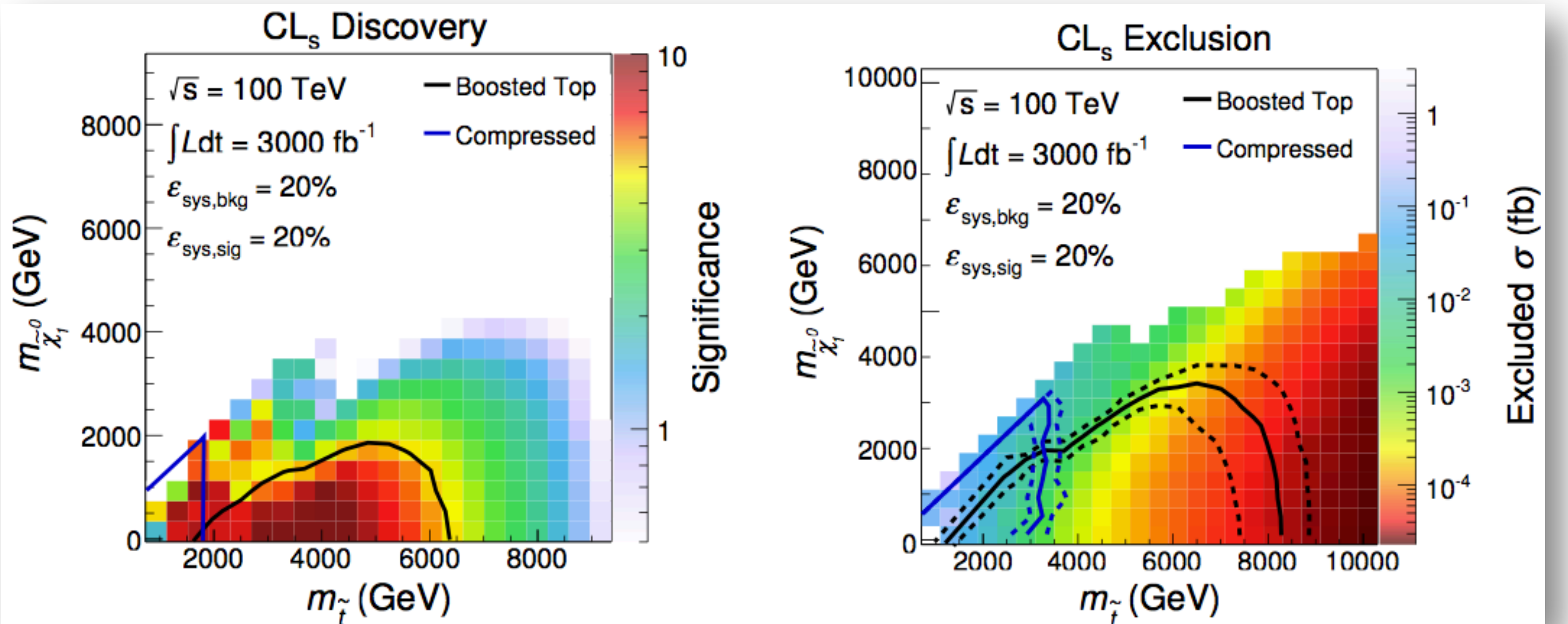
When there's more than one particle in the loop, things change drastically.
E.g., SUSY has two stops:



This is independent of MSSM and applies to SUSY in general!

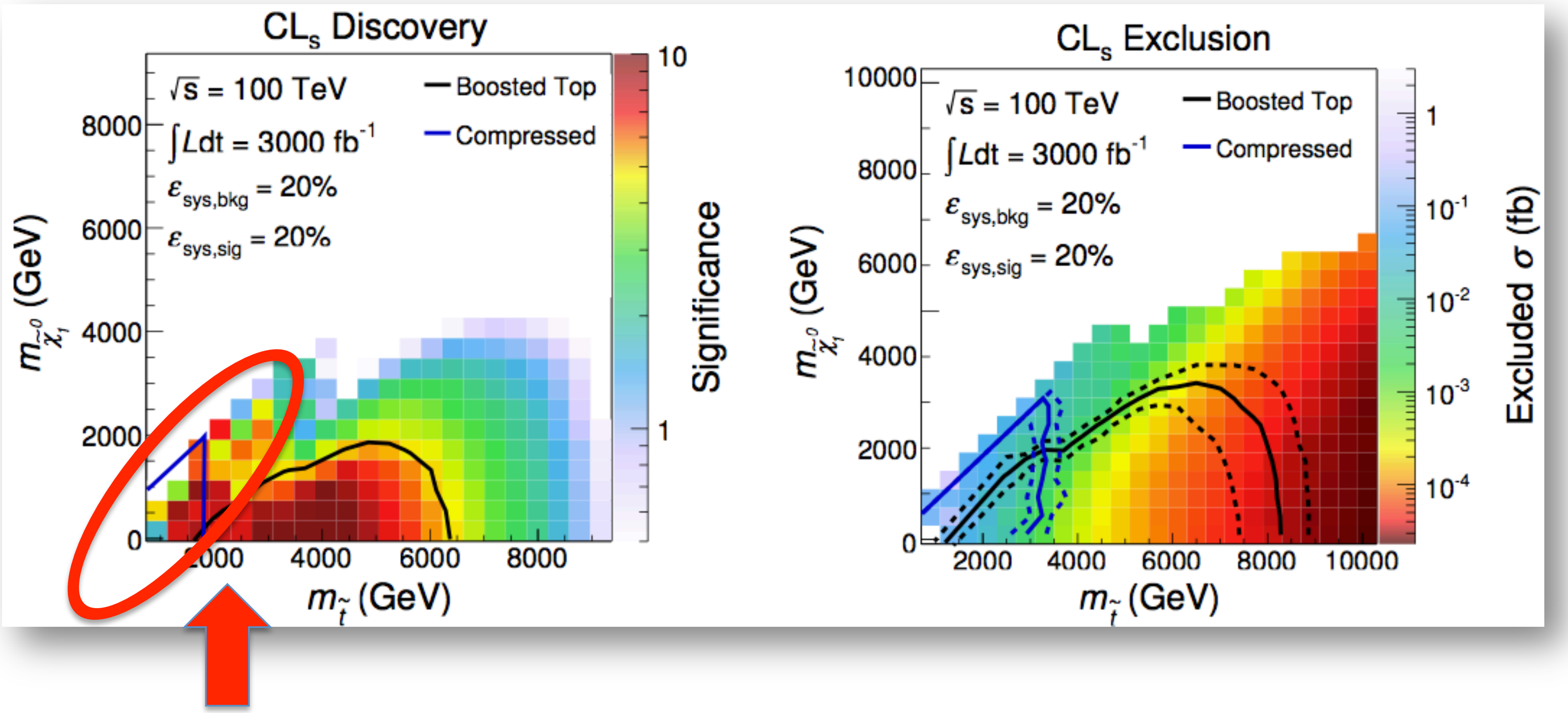
Gori and IL: 1307.0496

One is tempted to compare the bound from precision Higgs measurements with those from direct searches at a future machine:



Cohen et. al.: 1406.4512

However, it is important to recall that direct searches always depend on the decay final states and the rest of the spectrum:



Direct searches have less/no acceptances in this region due to kinematics, hence the degraded limits.

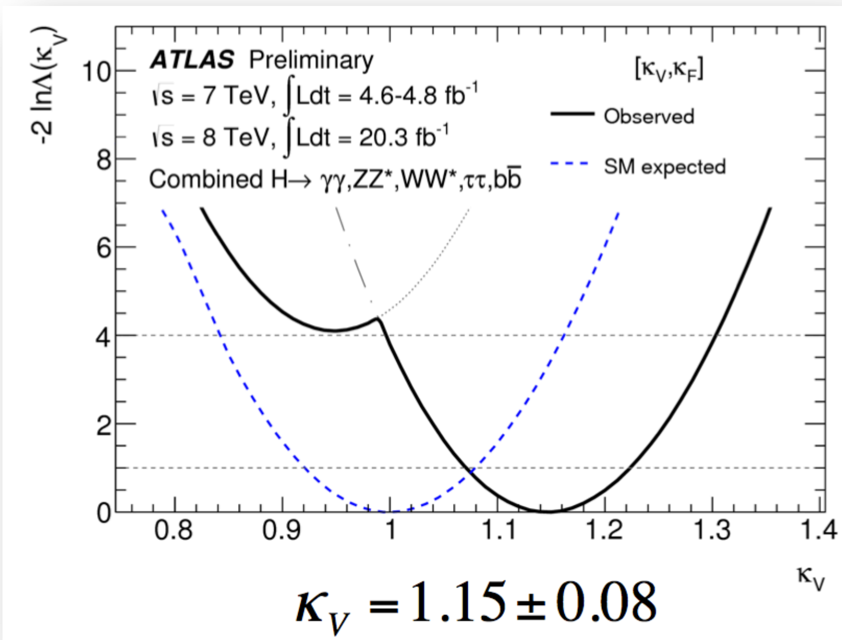
Cohen et. al.: 1406.4512

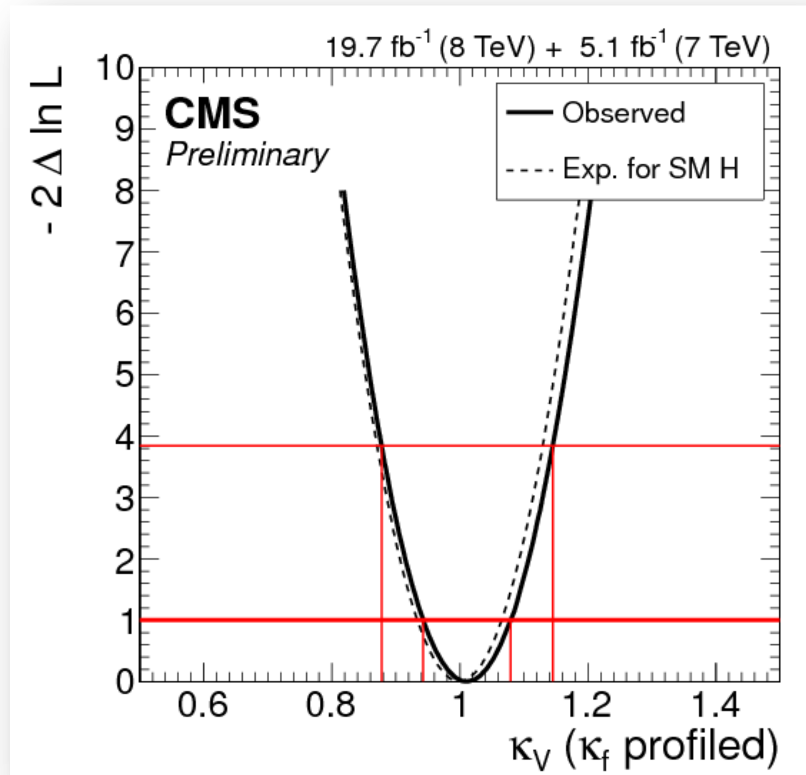
Constraints from precision Higgs measurements, on the other hand, involve a different set of assumptions from the direct searches.

So precision measurements and direct searches are very much complementary to each other!

Another complementarity --

Precision Higgs measurements and precision electroweak measurements:

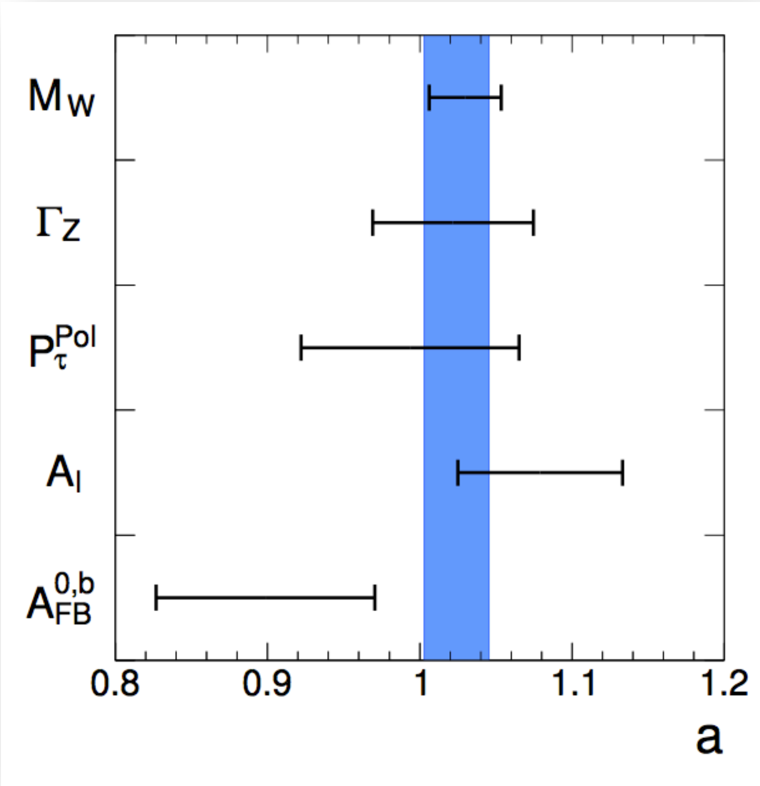


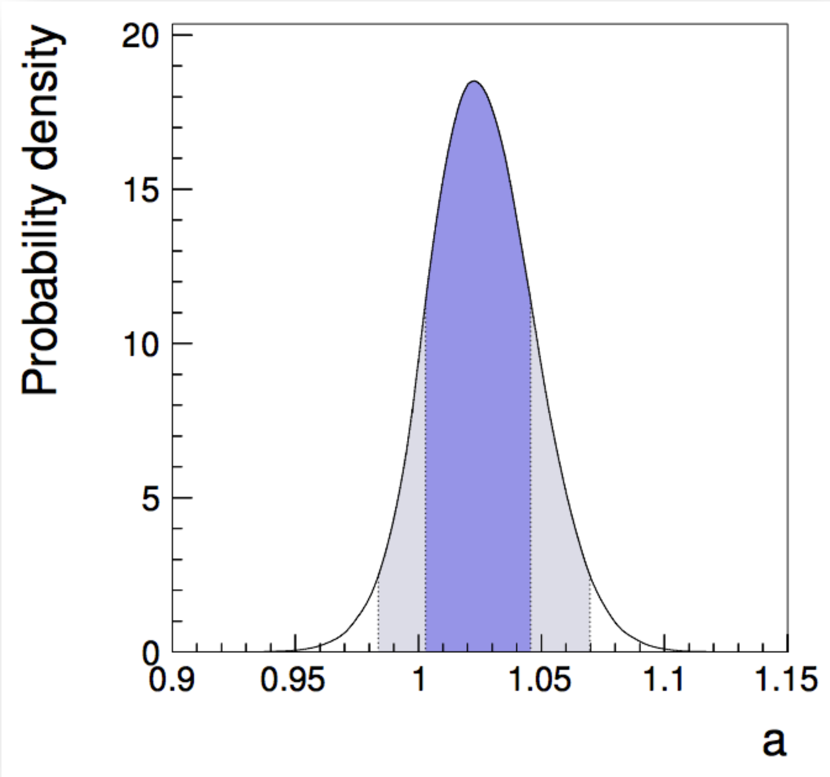


But now that the Higgs mass is known, precision electroweak measurements can be used to constrain Higgs couplings to W and Z:

Ciuchini et. al. : 1306.4644

$$a = \kappa_V$$



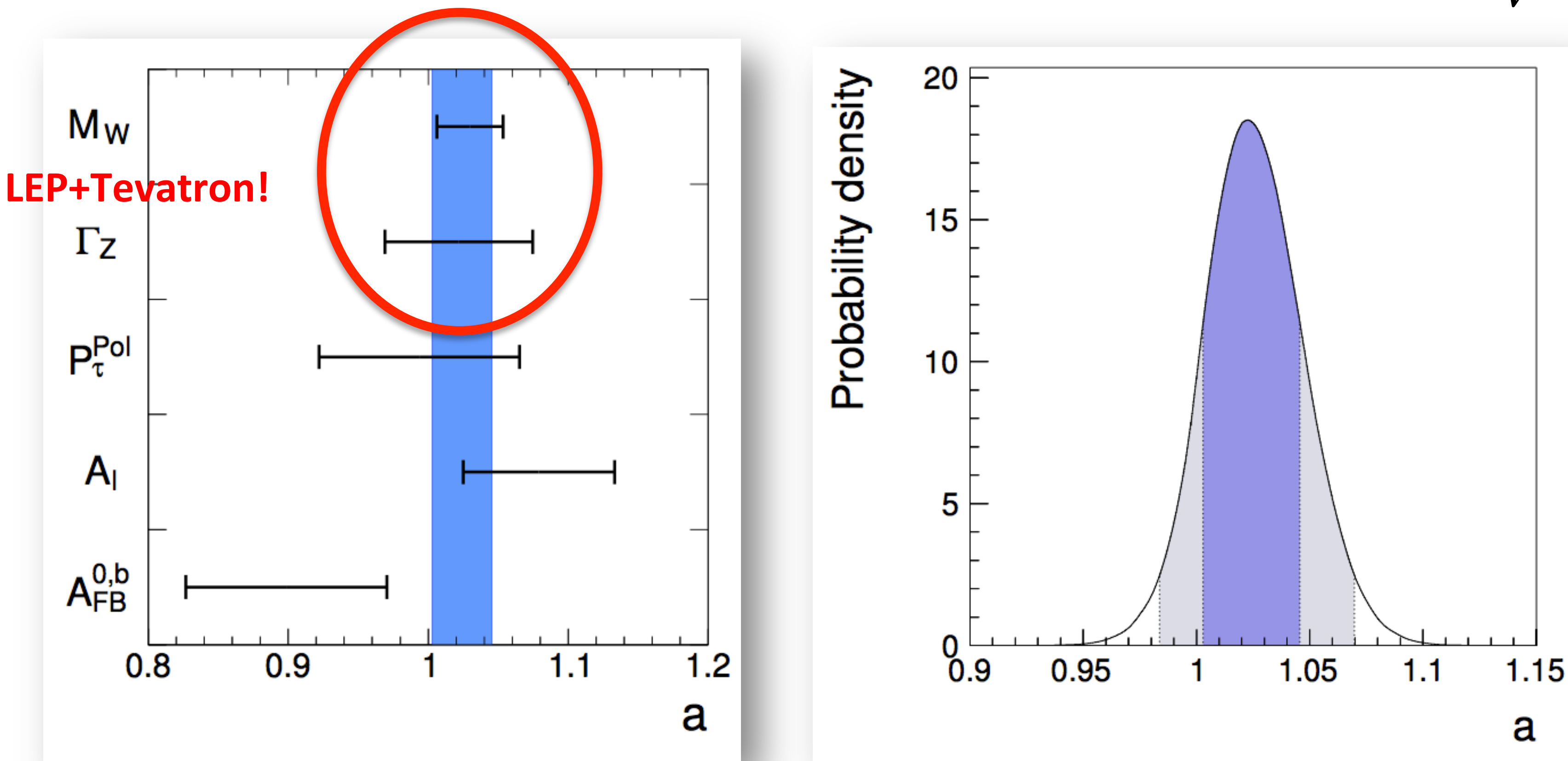


Opportunities in Higgs study using a Tera Z factory at 100 TeV!!

But now that the Higgs mass is known, precision electroweak measurements can be used to constrain Higgs couplings to W and Z:

Ciuchini et. al. : 1306.4644

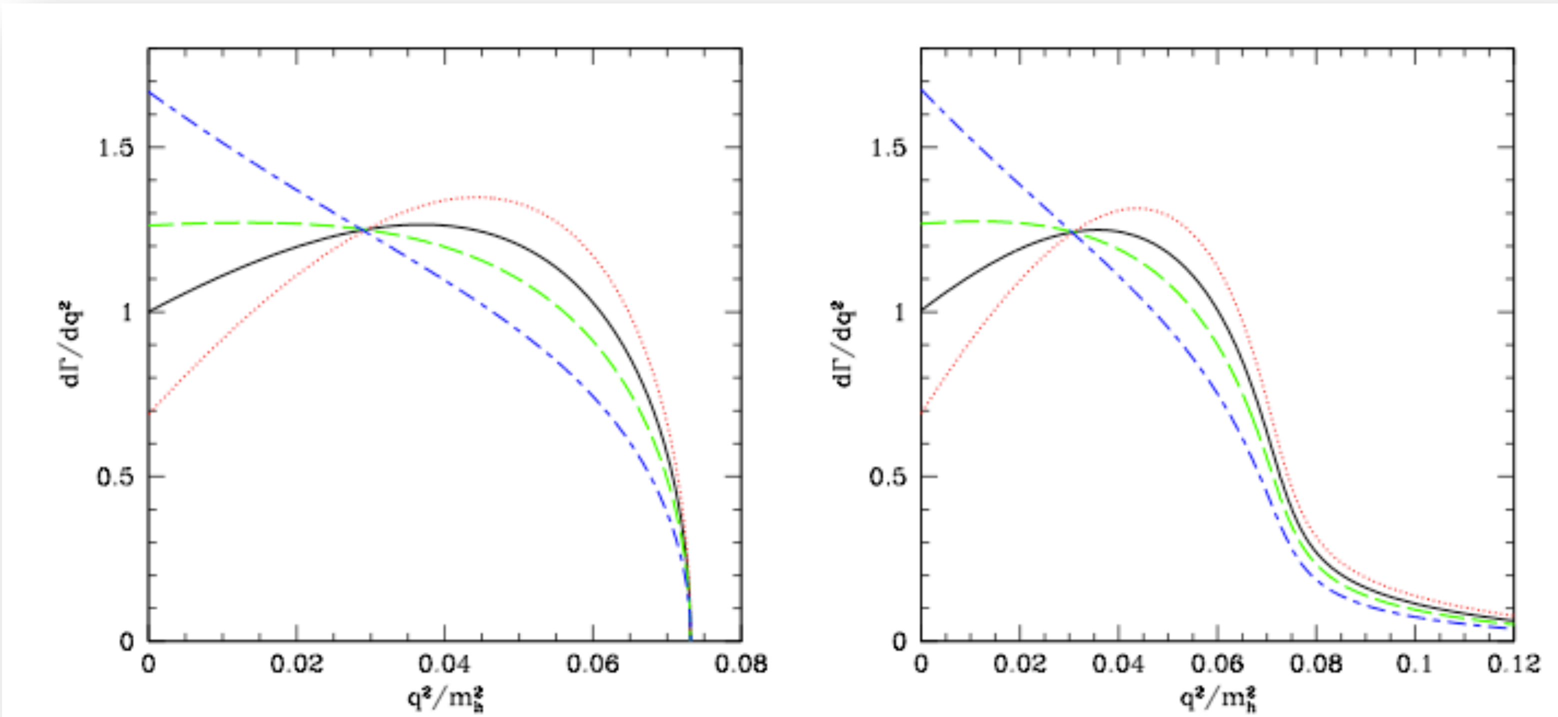
$$a = \kappa_V$$



Opportunities in Higgs study using a Tera Z factory at 100 TeV!!

Anomalous Coupling Structures

A case study on distributions in h-> V + $l^+ l^-$:



$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu \right.$$
$$\left. + f_3^V(q^2)(p \cdot q \; g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right] . \quad (2)$$

Isidori et. al.: 1305.0663

See also Grinstein, et. al.: 1305.6938

There is a forward-backward asymmetry in this channel that can be used to probe CP-violating Higgs-to-diphoton coupling:

Chen, Falkowski, IL and Vega-Morales: 1405.6723

$$\mathcal{L} \supset \frac{h}{4v}\left(2A_2^{Z\gamma}F^{\mu\nu}Z_{\mu\nu} + 2A_3^{Z\gamma}F^{\mu\nu}\widetilde{Z}_{\mu\nu} + A_2^{\gamma\gamma}F^{\mu\nu}F_{\mu\nu} + A_3^{\gamma\gamma}F^{\mu\nu}\widetilde{F}_{\mu\nu}\right)$$

$$A_{\rm FB}(M_1) = \frac{\left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_1 \frac{d\Gamma}{dM_1^2 d\cos\theta_1}}{\left(\int_0^1 + \int_{-1}^0\right) d\cos\theta_1 d\frac{d\Gamma}{dM_1^2 d\cos\theta_1}} = \frac{3}{8}\,\frac{d\Gamma_{\rm CPV}/dM_1^2}{d\Gamma_{\rm CPC}/dM_1^2}$$

A rough estimate at the LHC: $\frac{S}{\sqrt{B}} \sim \left(\frac{A_{\rm FB}}{0.1}\right)\sqrt{\frac{L}{3000\ {\rm fb}^{-1}}}$

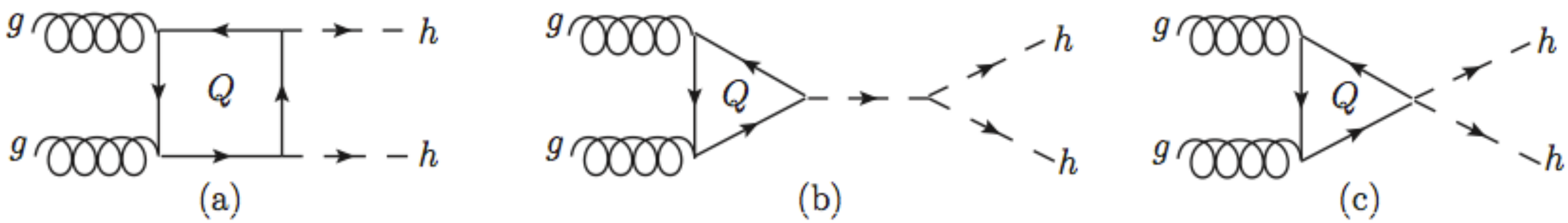
Obviously, can only do better at 100 TeV!

Anomalous couplings could show up everywhere!

- Self-coupling measurements offers the most direct way to test the paradigm of spontaneous symmetry breaking.

  In hadron colliders it can be accessed from double Higgs production:

SM **SM** **BSM**



$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \left(c_{tri} \frac{3m_h^2}{\hat{s} - m_h^2} + c_{nl} \right) F_\triangle + c_{box} F_\Box \right|^2 + |c_{box} G_\Box|^2 \right]$$

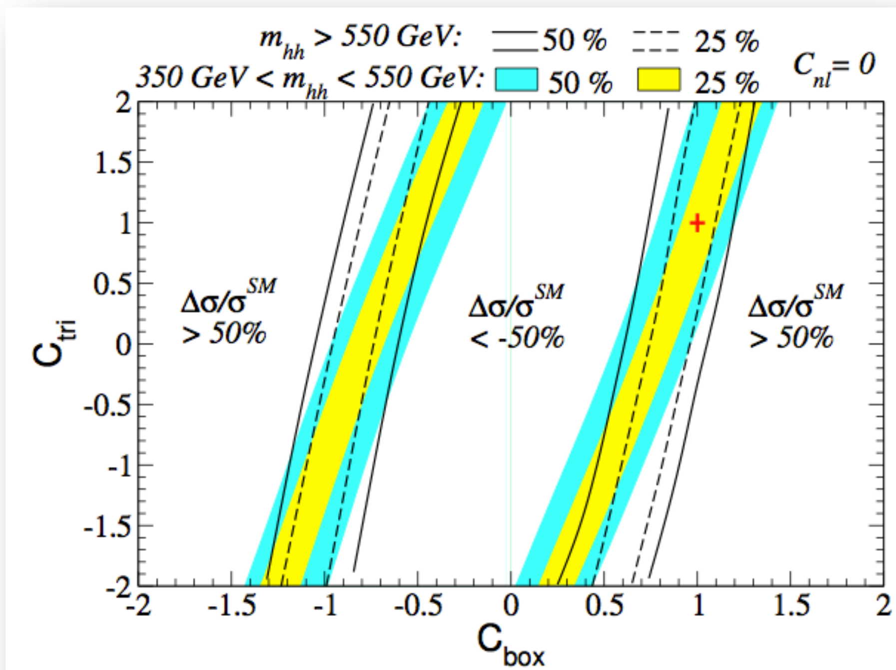
$$c_{box}^{(\mathrm{SM})} = 1 \, , \qquad c_{tri}^{(\mathrm{SM})} = 1 \, , \qquad c_{nl}^{(\mathrm{SM})} = 0$$

Higgs self-couplings

If one looks at the total rate only, there's going to be degeneracy in extracting the self-coupling:

$$\sigma(gg \to hh) = \sigma^{SM}(gg \to hh)[1.849\ c_{box}^2 + 0.201\ c_{tri}^2 + 2.684\ c_{nl}^2 - 1.050\ c_{box}c_{tri} - 3.974\ c_{box}c_{nl} + 1.215\ c_{tri}c_{nl}].$$

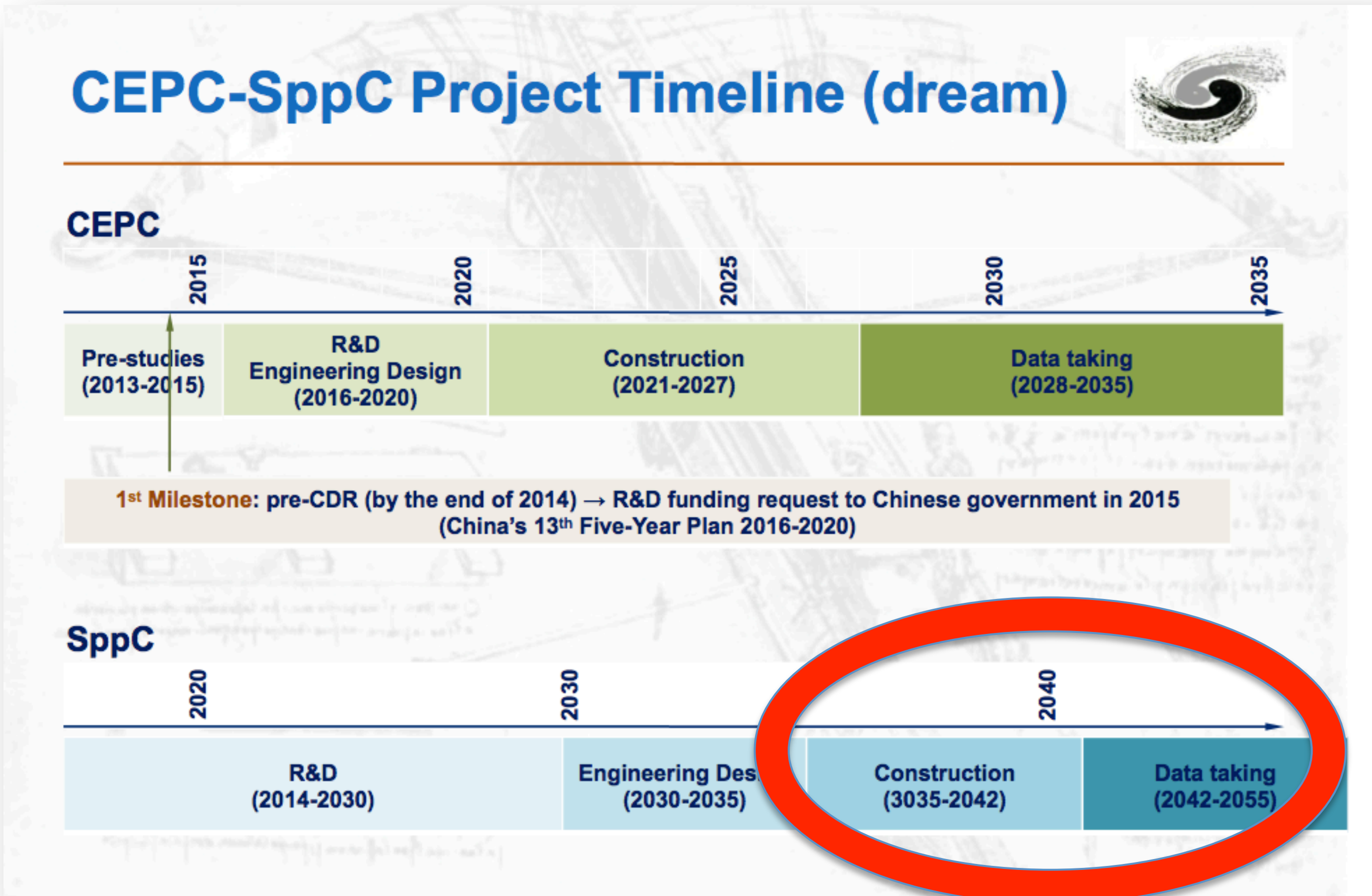
We need to look at distributions (again!)



C.-R. Chen and IL:1405.1040

By now it should be clear that "signal strength" is sooooo 20th century.

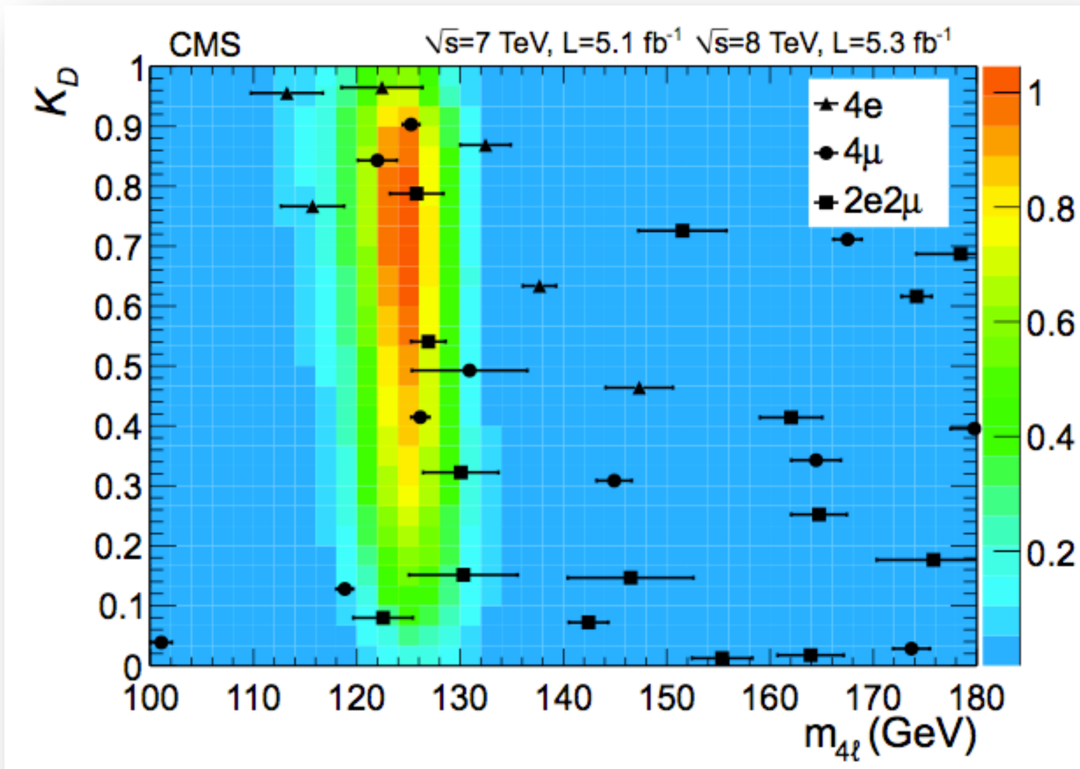
In 30 - 40 years we need to be extracting maximal information out of everything we measure….



Slide from Hongbo Zhu

To some extent we are already trying to get the most out of the LHC data.

One example is the “Matrix Element Method” as applied in the spin/CP of h(125):



But the framework adopted at the LHC is still very 20^{th} century because

We can only perform hypothesis testing.

For example, so far we are only testing a *pure* 0^+ scalar against a *pure* 0^- scalar in the case of h(125).

This is clearly inadequate.

It's time move away from "hypothesis testing" and start doing "parameter extraction" by assuming a general coupling structure.

Some young people are working very hard toward developing a 21^{st} century framework for Higgs studies in a hadron collider.

See for example Yi Chen, Roberto Vega-Morales + others in 1310.2893, 1401.2077, 1404.1336.

<u>Soft New Physics in Higgs Decays</u>

- Higgs portal dark matter gives rise to invisible decays, if $M_{DM} < M_h/2$.
  Again lots of work in the literature already.

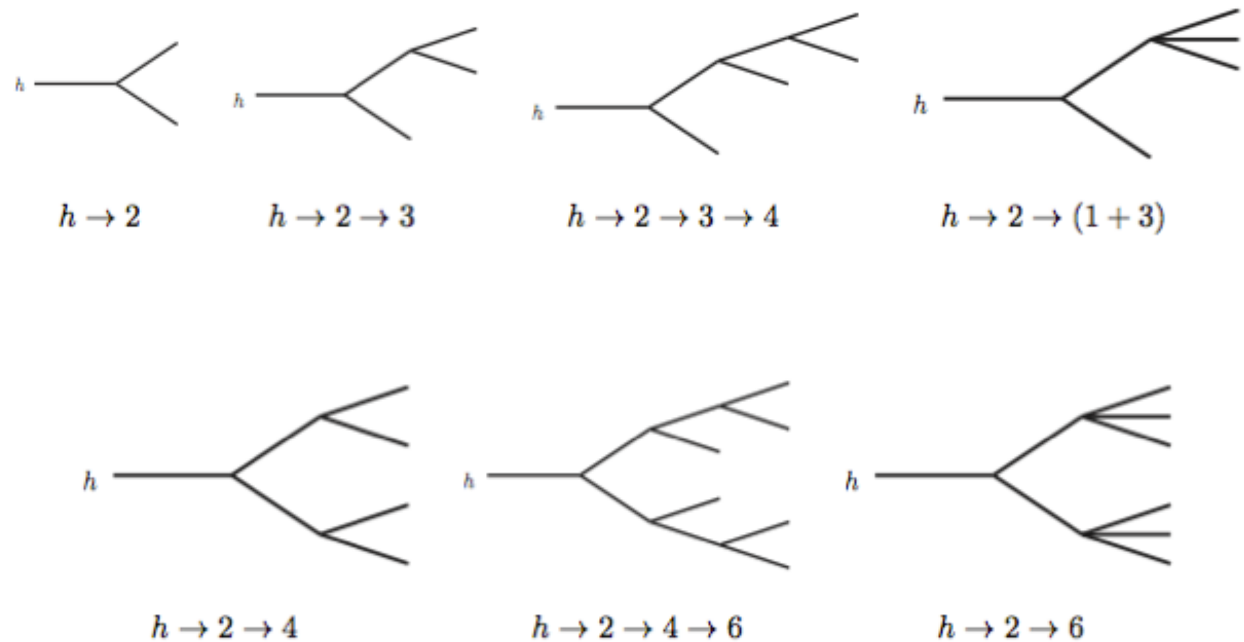
- But the soft new physics does not have to be DM, leading to exotic decays.

Exotic Decays of the 125 GeV Higgs Boson

David Curtin,[1] Rouven Essig,[1] Stefania Gori,[2,3,4] Prerit Jaiswal,[5]
Andrey Katz,[6] Tao Liu,[7] Zhen Liu,[8] David McKeen,[9,10] Jessie Shelton,[6]
Matthew Strassler,[6] Ze'ev Surujon,[1] Brock Tweedie,[8,11] and Yi-Ming Zhong[1,*]

arXiv:1312.4992

The study is very systematic:



The exotic Higgs decay topologies we consider. Intermediate lines represent an *on-shell*, *neutral* particle, which is either a Z-boson or a BSM particle.

Challenge: how do we dig out the "soft" signal?

This possibility of new physics highlights an important question for a 100 TeV collider:

Should we design a special detector for "soft stuff" at 100 TeV?

The field is wide open – for every study at the LHC, there's always a 100-TeV-version of the study to be completed.

The conclusion is yet to be written. So let me just leave you with the following table:

Comparison of Higgs cross-section at 14 and 100 TeV:

Process	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 100 TeV	
ggF [a]	50.35 pb	740.3 pb (14.7)	15-fold increase
VBF [b]	4.40 pb	82.0 pb (18.6)	20-fold increase
WH [c]	1.63 pb	15.90 pb (9.7)	10-fold increase
ZH [c]	0.904 pb	11.26 pb (12.5)	12-fold increase
ttH [d]	0.623 pb	37.9 pb (61)	60-fold increase
bbH [e]	0.581 pb	8.64 pb (15)	17-fold increase
$gg \rightarrow HH^{f}(\lambda=1)$	33.8 fb	1.42 pb (42)	50-fold increase

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy2012