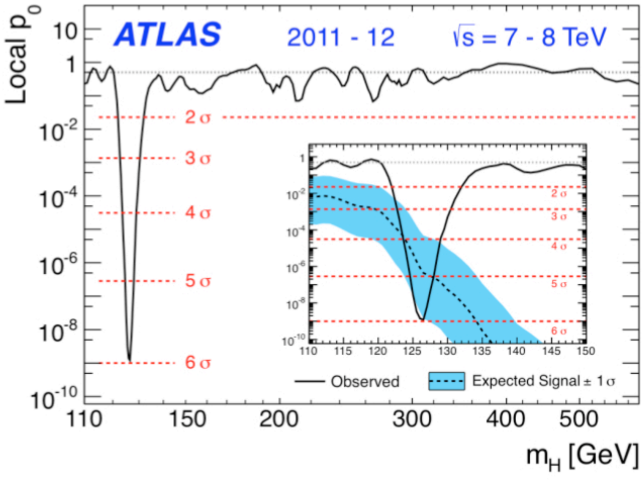
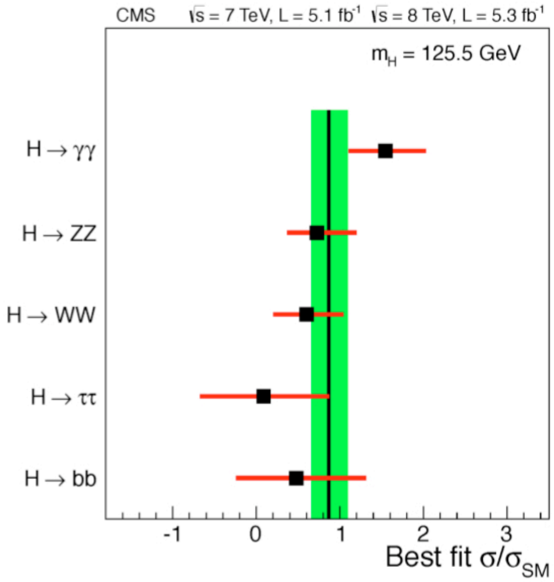
Higgs Identification

Ian Low

Argonne/ Northwestern/ KITP Santa Barbara

October 29, 2012 @ UC Davis

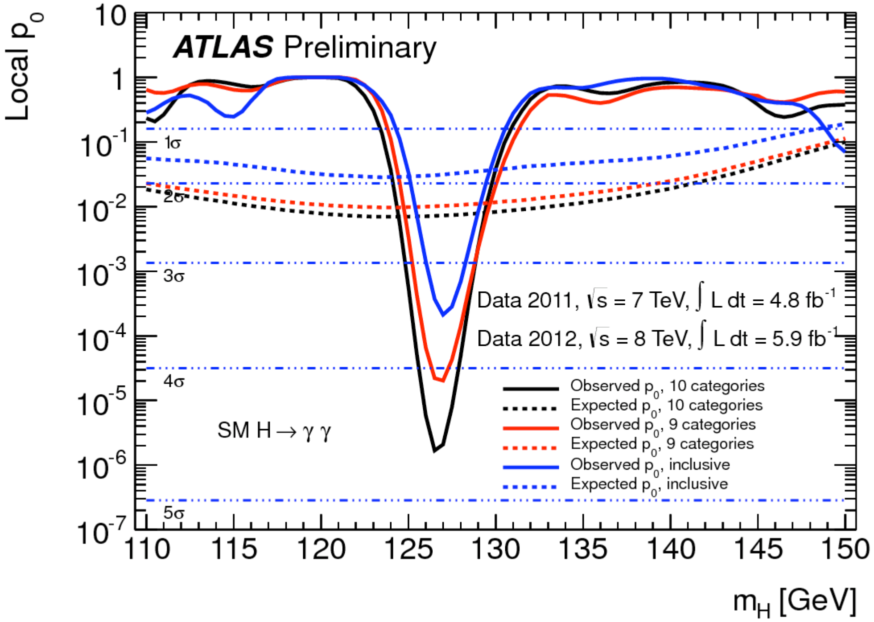


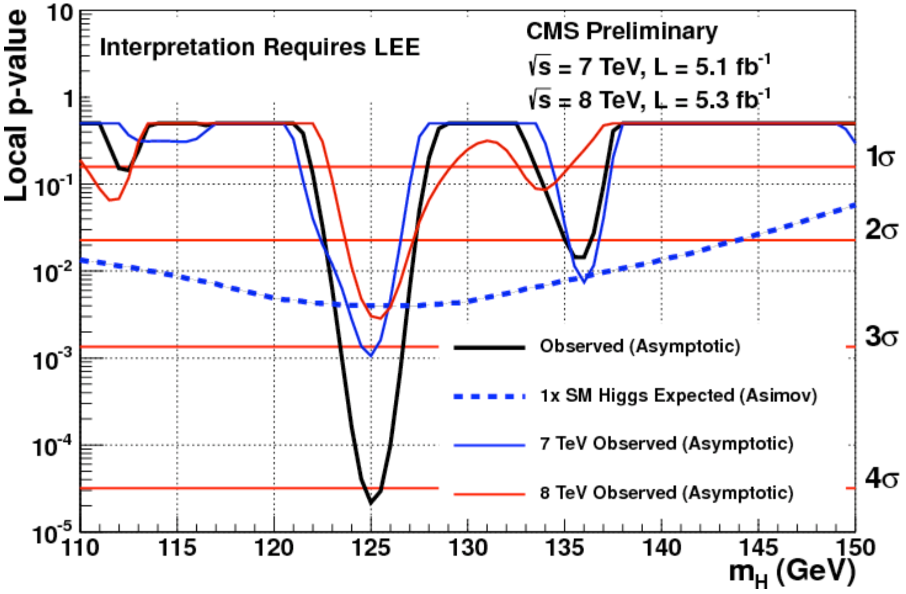


A Historic moment in science:

Scenes from the July 4, 2012 announcements --

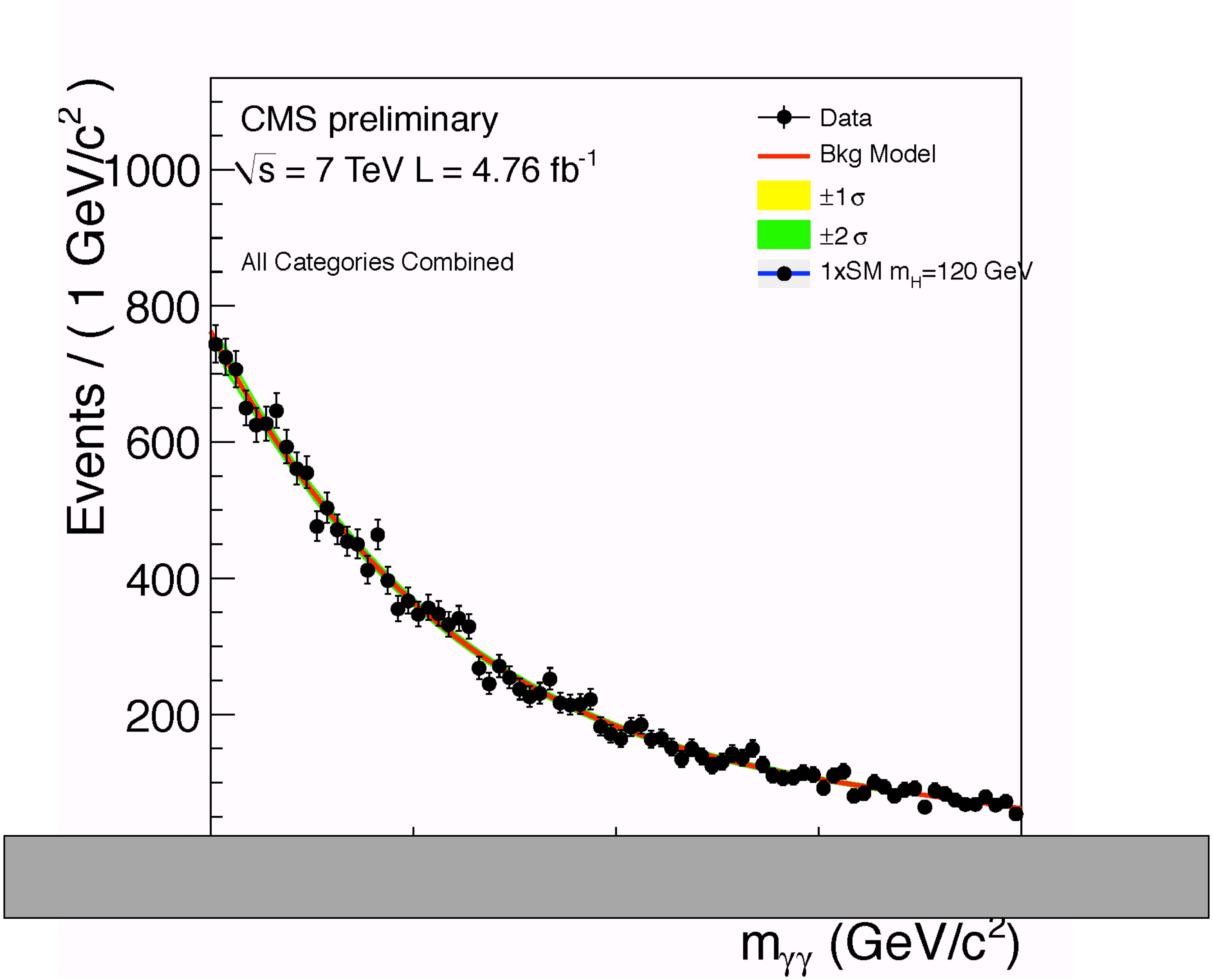
ATLAS and CMS both see a “new boson” decaying into two photons, with a mass at around 126 GeV:



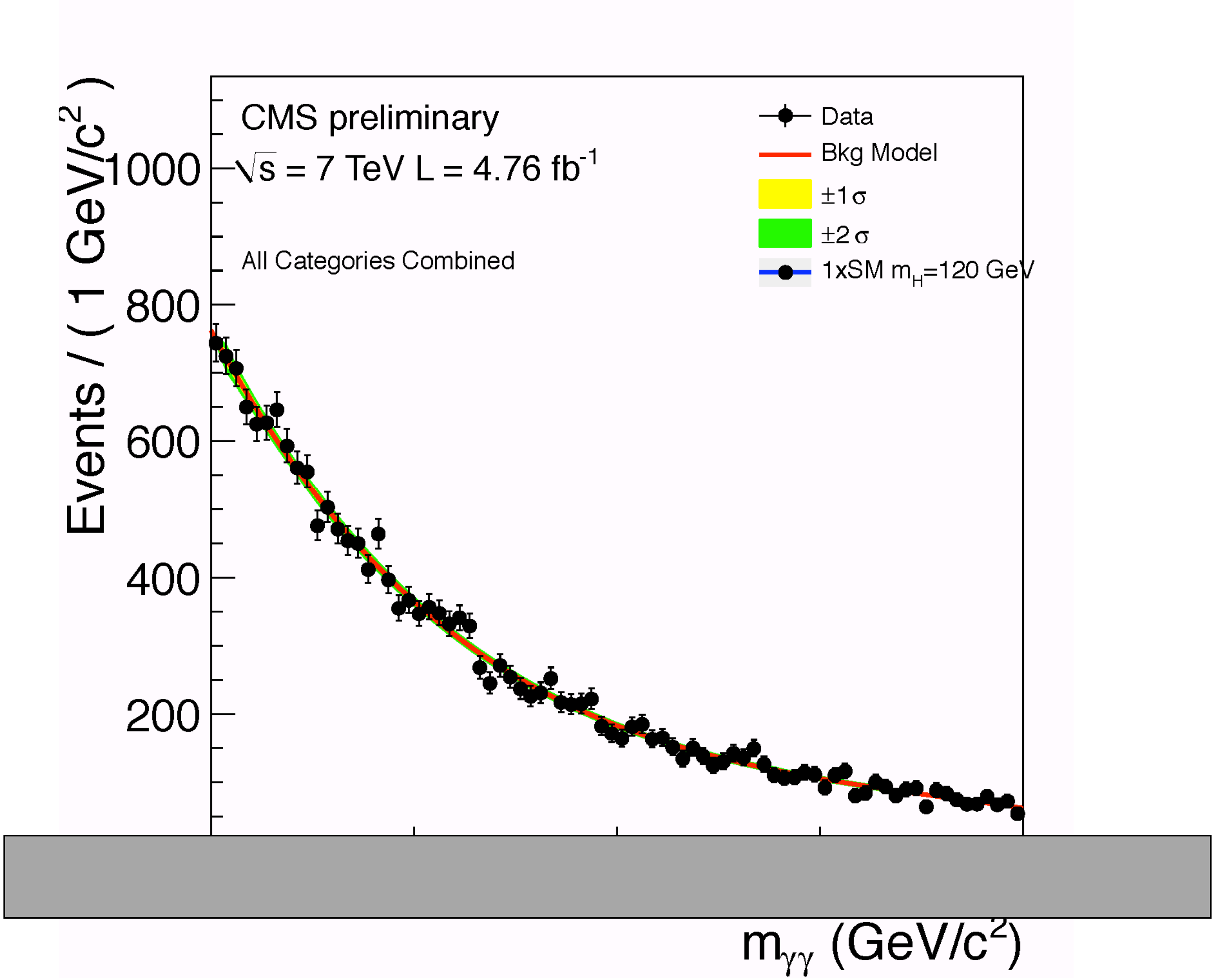


Local p-values are greater than 4sigma for both collaborations.

Before July 4 I used to give talks based on the following plot:



And I would ask the audience to look for a “bump” with their naked eyes:



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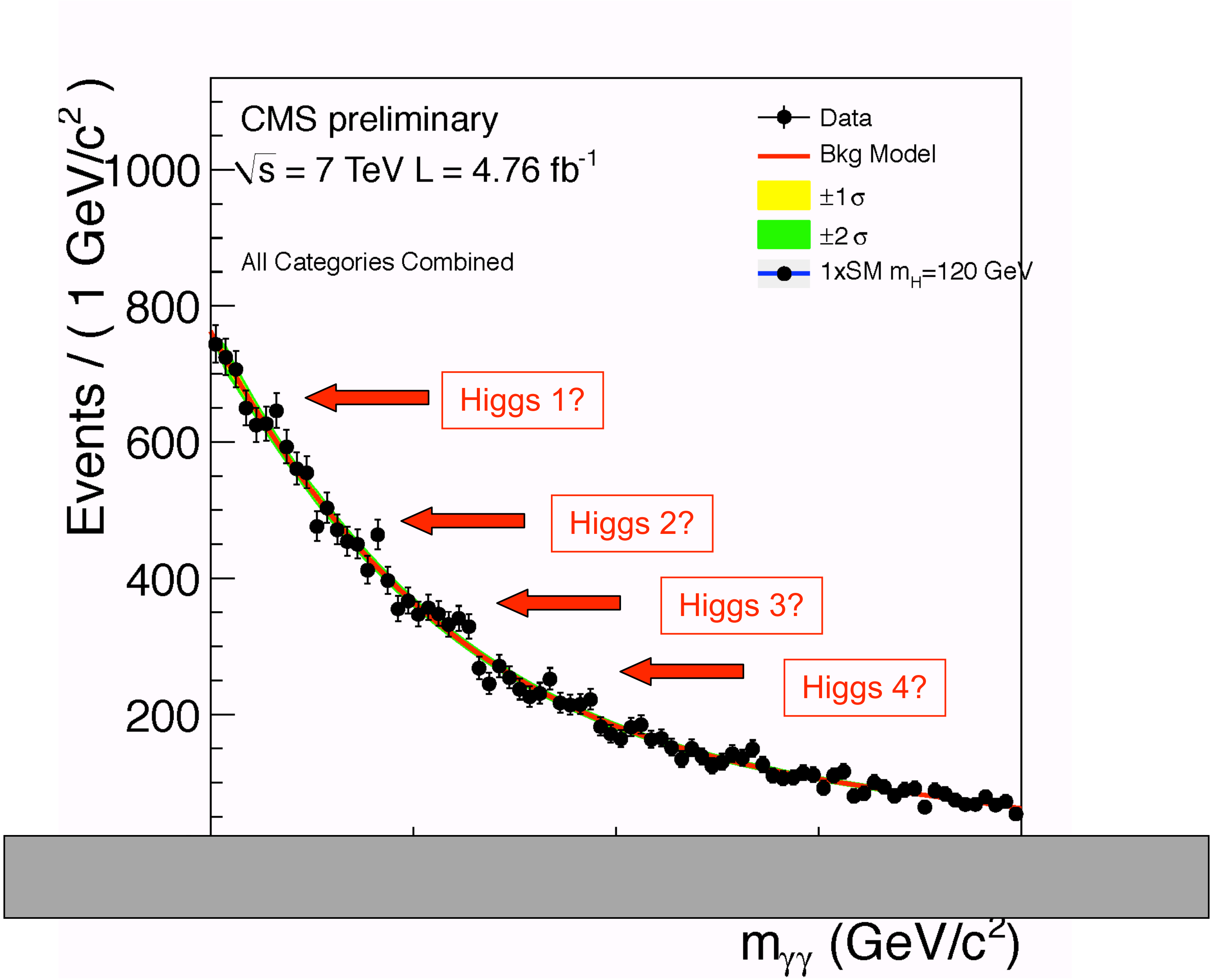

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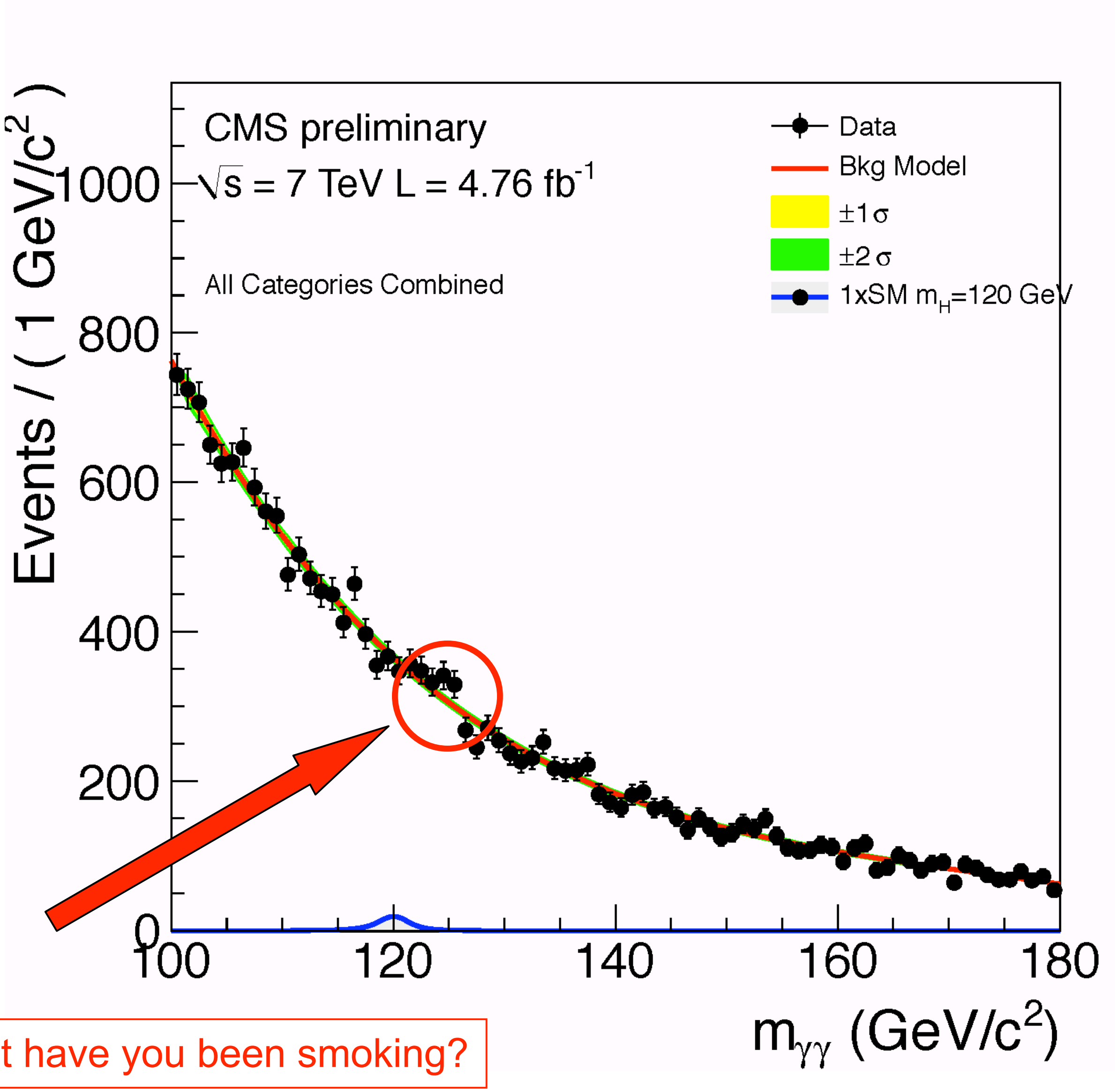
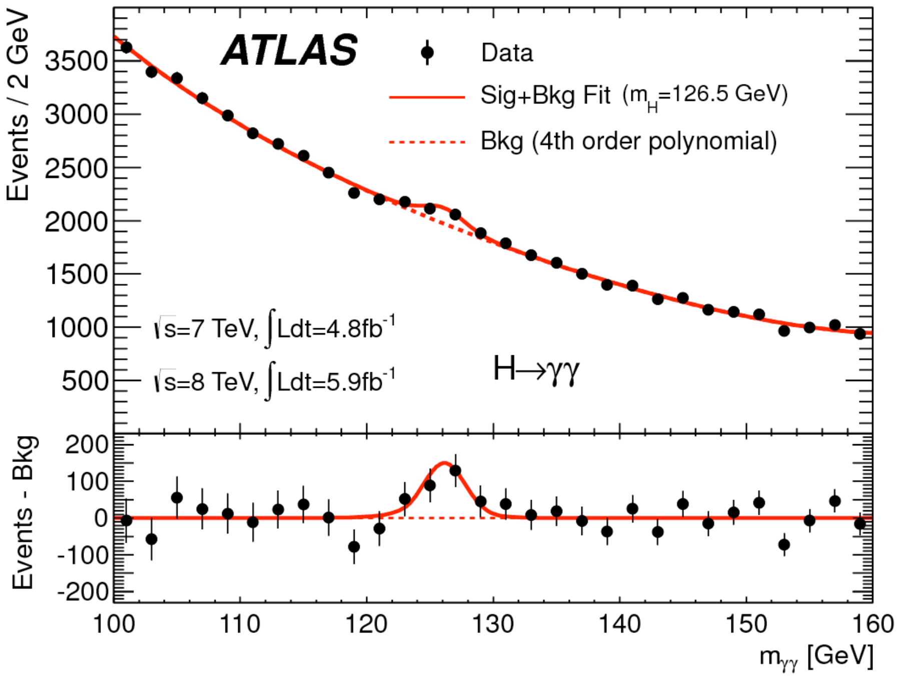
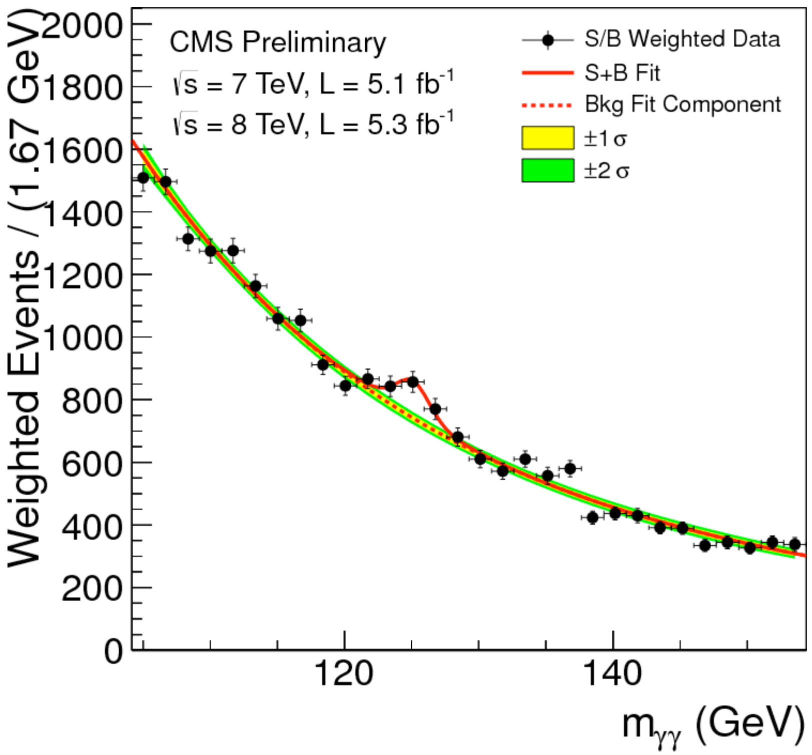


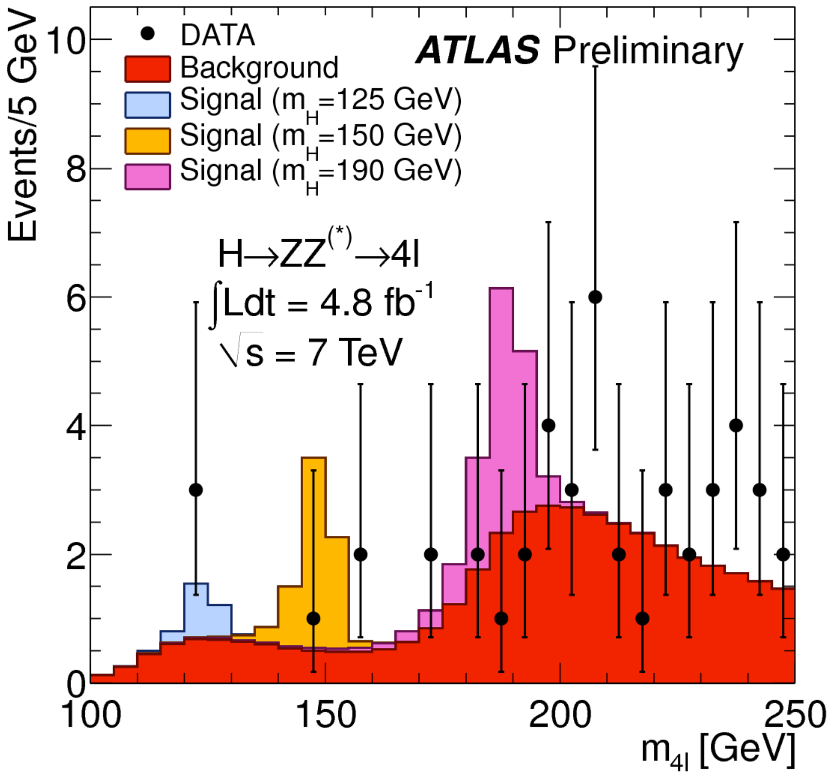
I get asked: what have you been smoking?

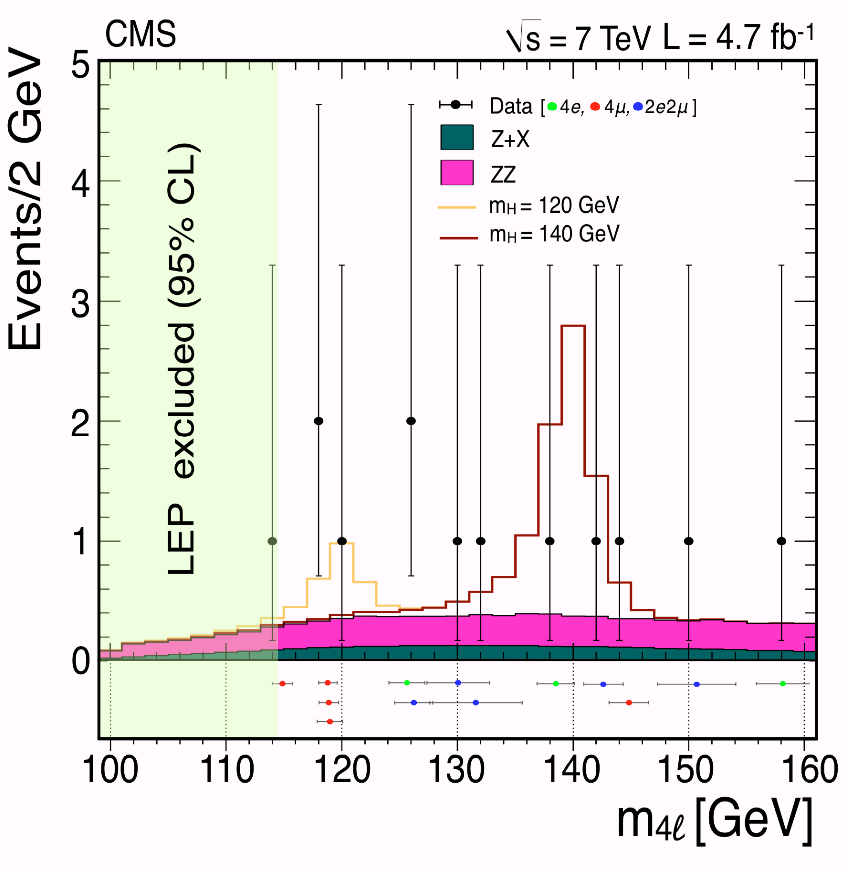
But with the new data, “Seeing is believing”!



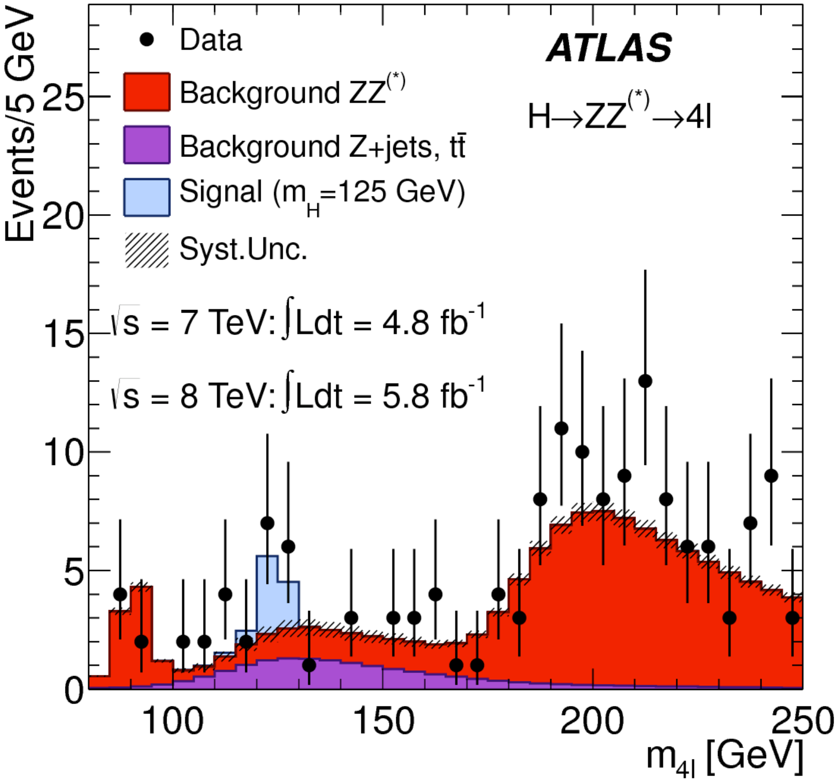


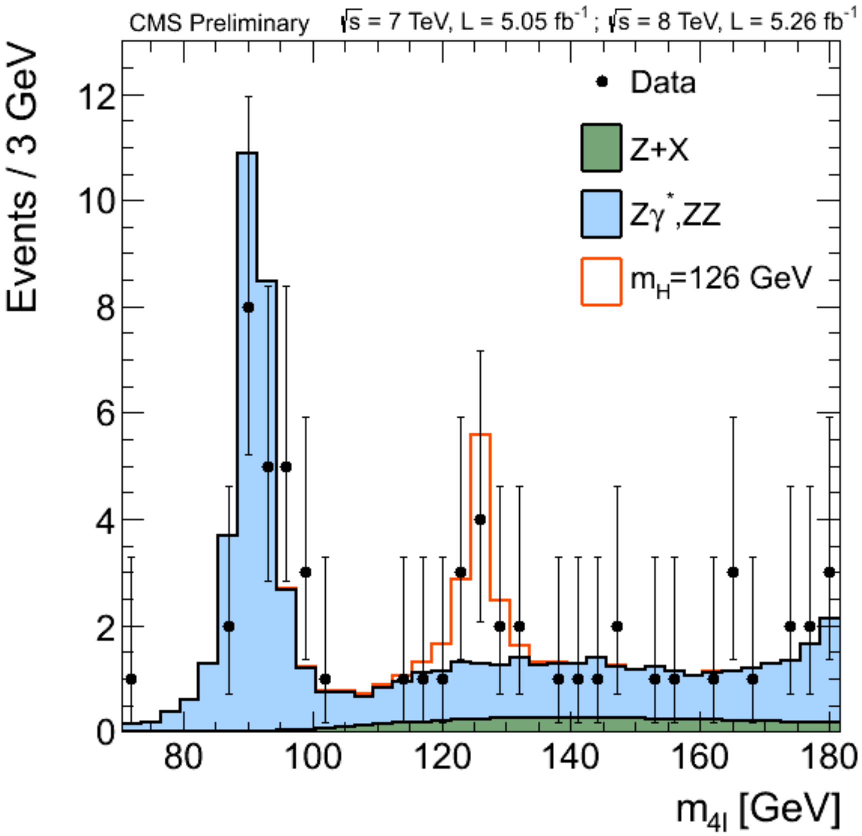
- It’s the same in the 4-lepton channel.
  Below are the pre-July 4 plots:



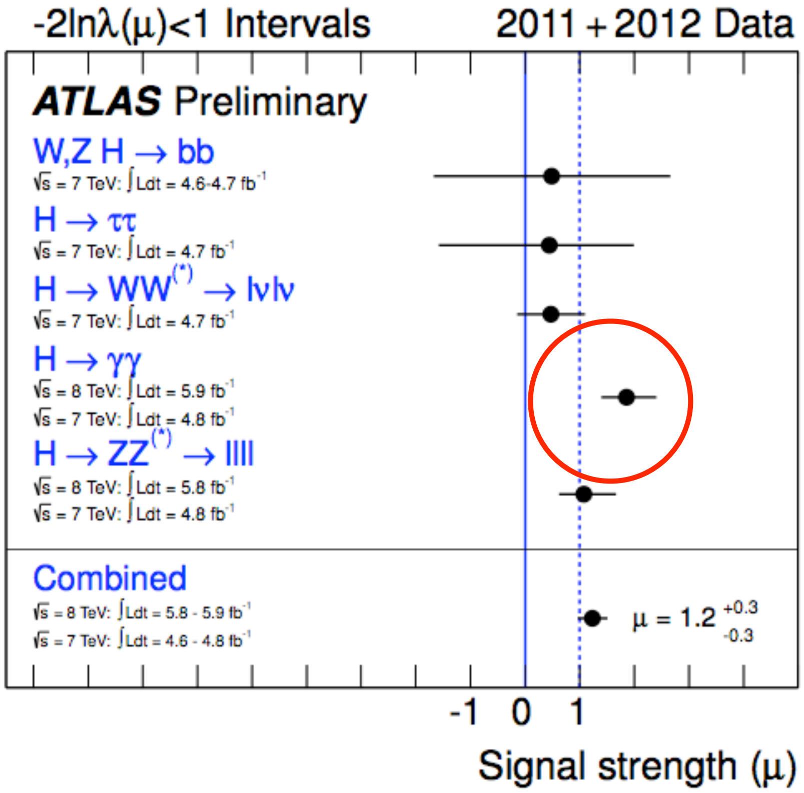


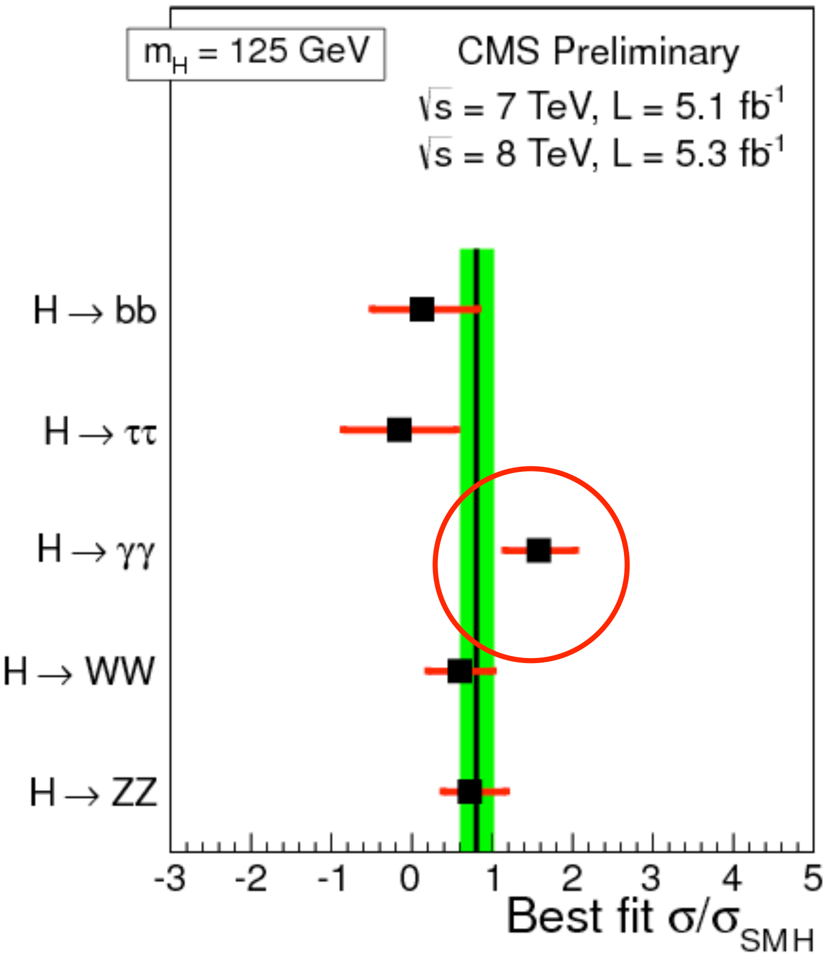
- It’s the same in the 4-lepton channel.
  Now the new plots:





A summary of current measurements in various channels:

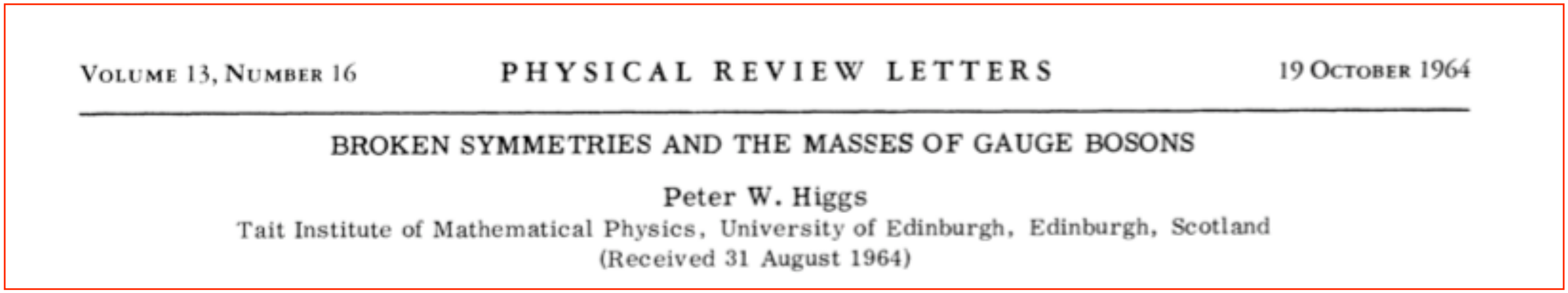




A “standard model” Higgs boson gives very good overall fits!

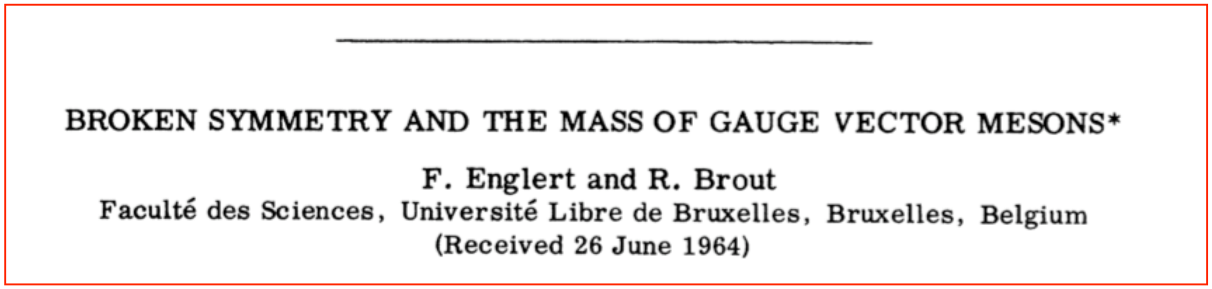
This is such a historic discovery that it is worth pausing for a moment to reflect what has happened….

In 1964 three PRL papers deposited the possibility of the Higgs boson:


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

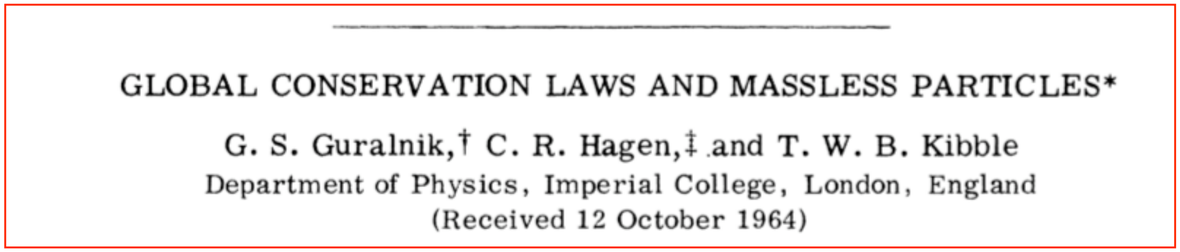
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

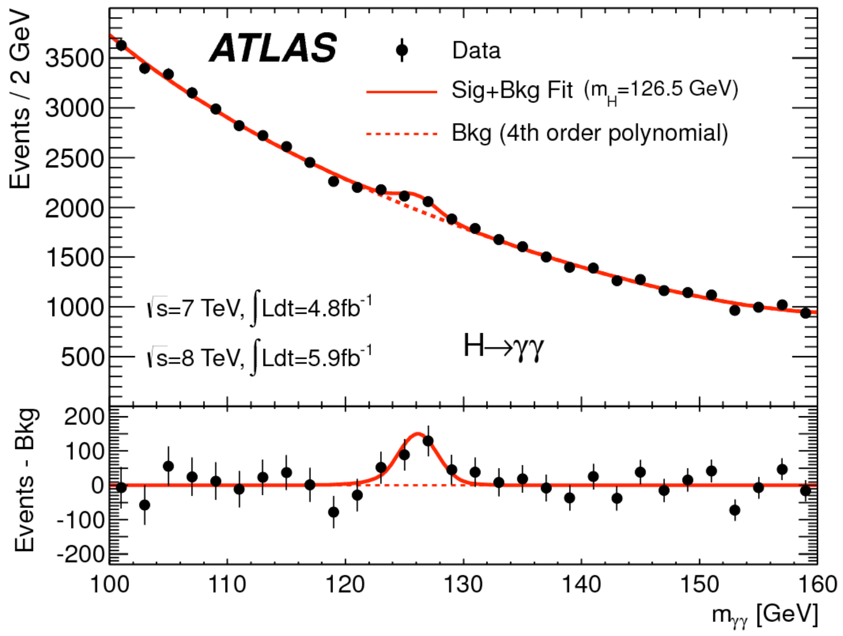
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

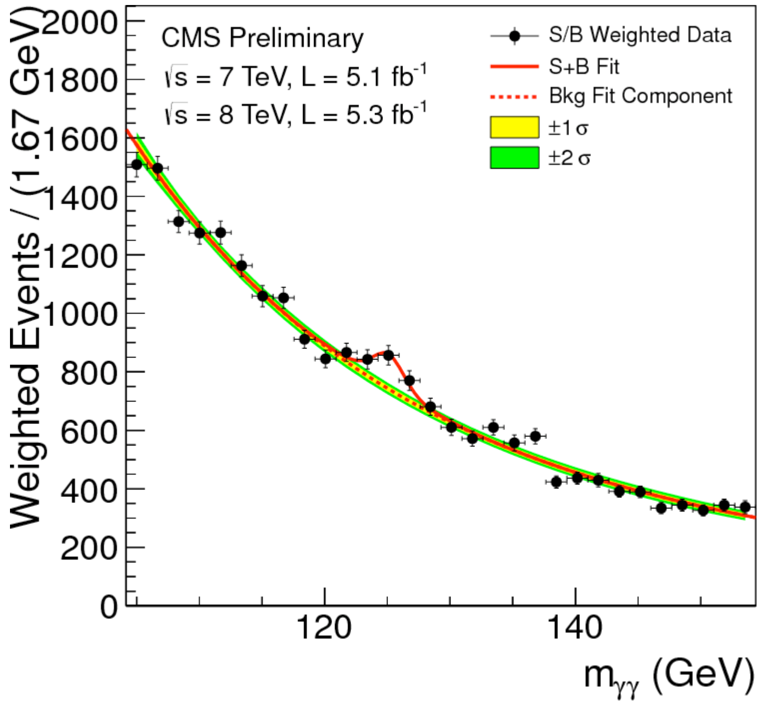


GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

To start from a pure Human thought process, and arrived 48 years later at





is an extraordinary achievement for both theoretical and experimental physics!

We should all be screaming out loud:

PHYSICS REALLY WORKS!!

But this is also a moment to be prudent….

Recall that CERN only announced the discovery of a *Higgs-like* boson.

“Extraordinary claims require extraordinary evidence.”

--Carl Sagan

We don’t want to be fooled into thinking it’s the long awaited Higgs boson when it is a Higgs imposter.

A Higgs boson is a particle that is

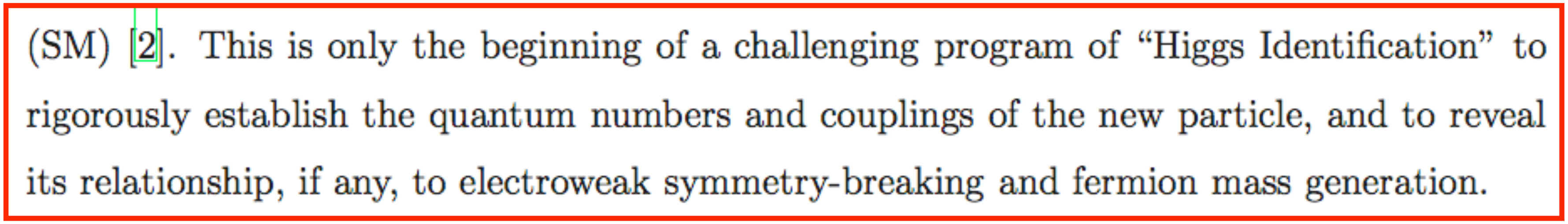
- Spin-0 (scalar)
- Charge and Parity (CP) even
- The neutral component of an electroweak doublet
- The origin of mass for W/Z bosons as well as the quarks and charged leptons

So far we have verified (with certainty) none of the above.

Even if we knew its quantum numbers, we still would like to know if it is a standard model Higgs boson or not…

The era of wild speculation is now over!

We have “real work” carved out for us:



(SM) [2]. This is only the beginning of a challenging program of “Higgs Identification” to rigorously establish the quantum numbers and couplings of the new particle, and to reveal its relationship, if any, to electroweak symmetry-breaking and fermion mass generation.

Low, Lykken, Shaughnessy: 1207.1093

So where do we go from here?

"Higgs Identification" --

Infrared Identity:

- Spin-0 (scalar)
- Charge and Parity (CP) even
- The neutral component of an electroweak doublet
- The origin of mass for W/Z bosons as well as the quarks and charged leptons

Ultraviolate Identity:

- Hints of more dynamic and symmetry princples? Supersymmetry? Compositeness?
- Does the naturalness principle work? Do we have to live with Anthropic principle and multiverse?
- Are there more new particles out there? Those enhancing the diphoton width? Those cancelling the Higgs quadratic divergences?

In order to confirm the identity of the new particle, it often easier establish what it is not.

We can already rule out some Higgs imposters given what we know today.

Some examples of Higgs imposter are

- An electroweak singlet scalar
- A dilaton/radion arising from a nearly conformal sector at high energy scale
- An electroweak triplet scalar

IL and Lykken, 1005.0872
IL, Lykken, and Shaughnessy,1105.4587
IL, Lykken, and Shaughnessy, 1207.1093

Let’s recall what we actually “measure”.

In each channel we measure one number --

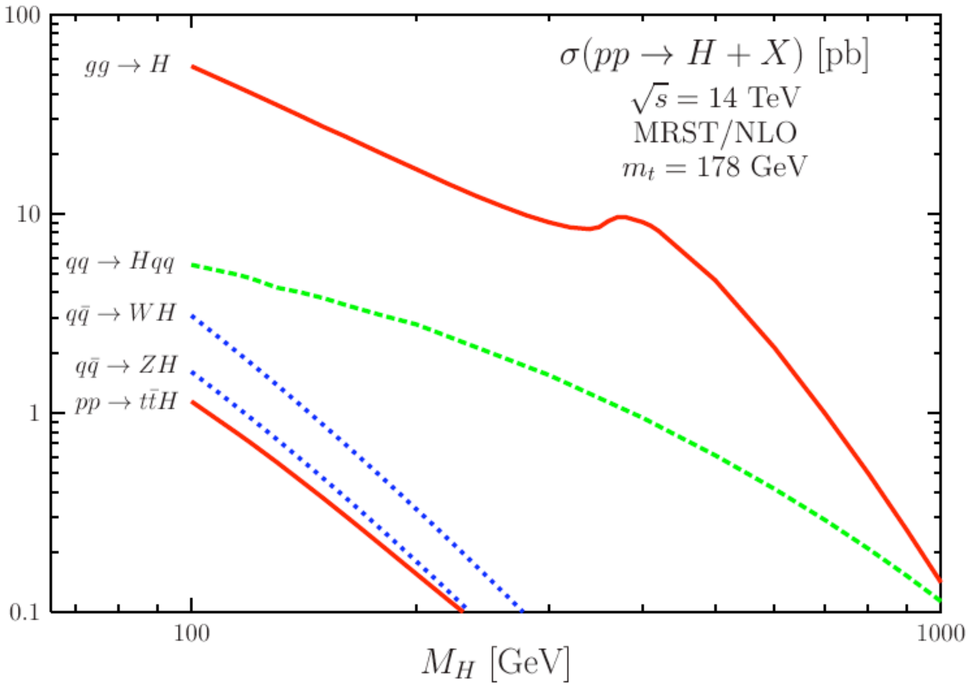
the event rate for a particular production mechanism X of the new boson Y, which subsequently decays into Y final states:

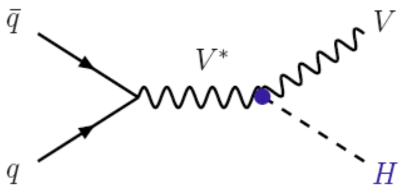
$$B\sigma_X(Y) \equiv \sigma(X \to S)\frac{\Gamma(S \to Y)}{\Gamma_{\text{tot}}}$$

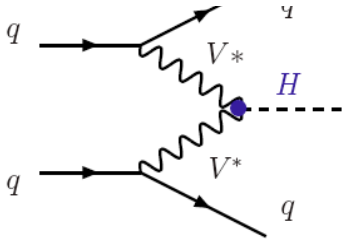
So any excesses in a given channel could be due to

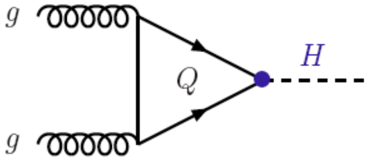
1. Increased production cross section
2. Reduced total width
3. Increased partial decay width

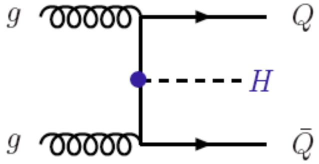
- The Higgs is produced at the LHC through four ways:









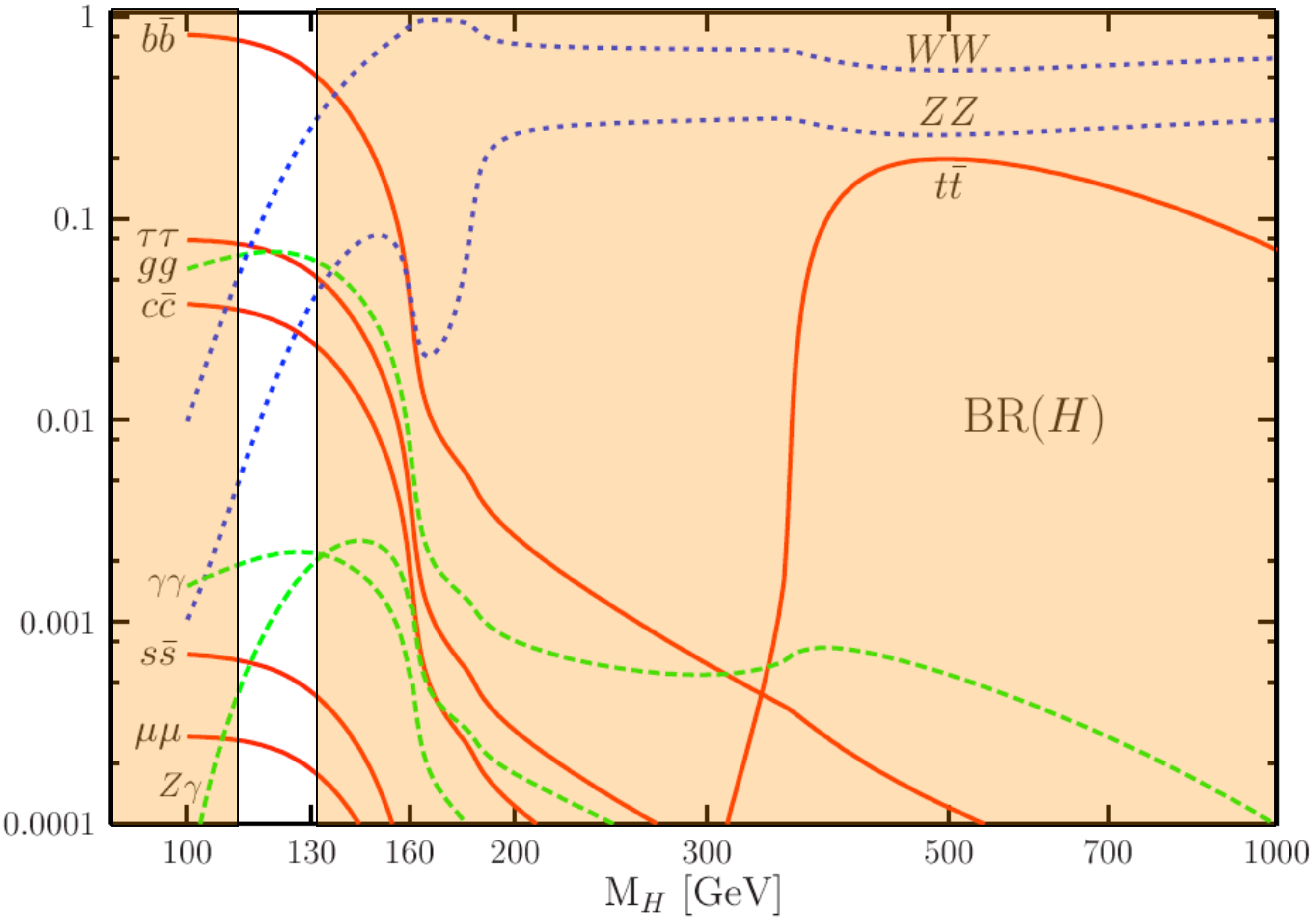


A. Djouadi:
hep-ph/0503172

- On the other hand, decay branching fractions depend on the Higgs mass:

A 125 GeV Higgs lives in a very interesting mass range!

LHC is most sensitive to WW, ZZ, and diphoton channels.



A. Djouadi: hep-ph/0503172

It turns out ratios of event rates are powerful model-independent discriminators of Higgs imposters.

- Same production but different decay channels:

$$\begin{aligned} D_{W/Z} &\equiv \frac{B\sigma_{gg}(WW)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \to WW)}{\Gamma(S \to ZZ)} \ , \\ D_{\gamma/Z} &\equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \to \gamma\gamma)}{\Gamma(S \to ZZ)} \ , \\ D_{Z\gamma/Z} &\equiv \frac{B\sigma_{gg}(Z\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to ZZ)} \ . \end{aligned}$$

- Different production but same decay channels:

$$P_{g/V} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{\rm VBF}(\gamma\gamma)} = \frac{\sigma(gg \to S)}{\sigma({\rm VBF} \to S)}$$

Ratios have the added advantage that common theoretical uncertainties (eg PDF) and systematic uncertainties should cancel.

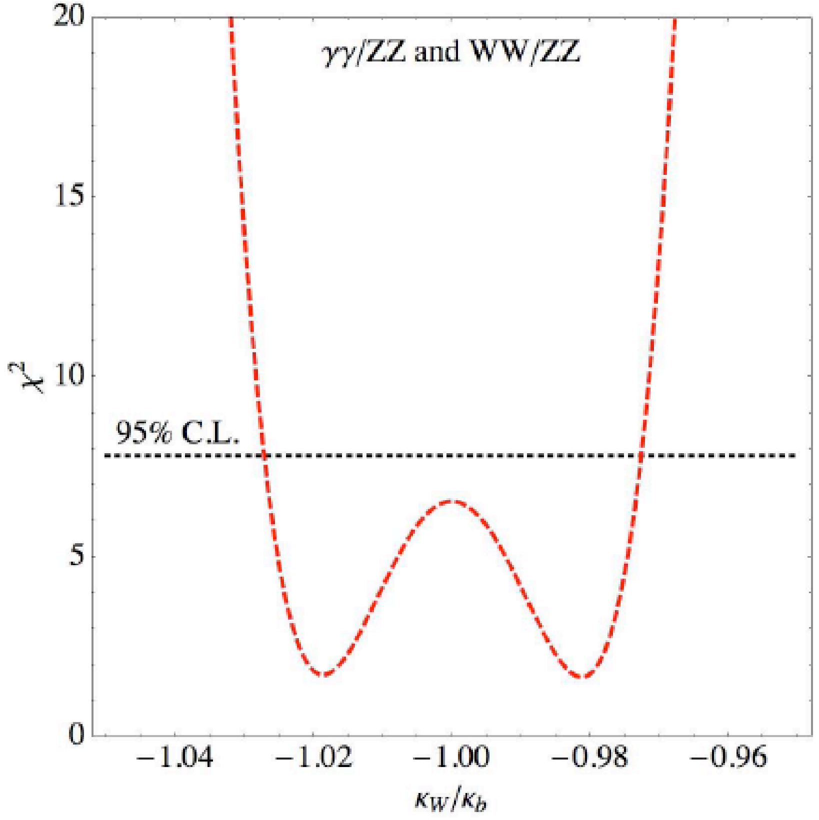
- Let’s not forget the the Higgs sector of the SM has never been verified.

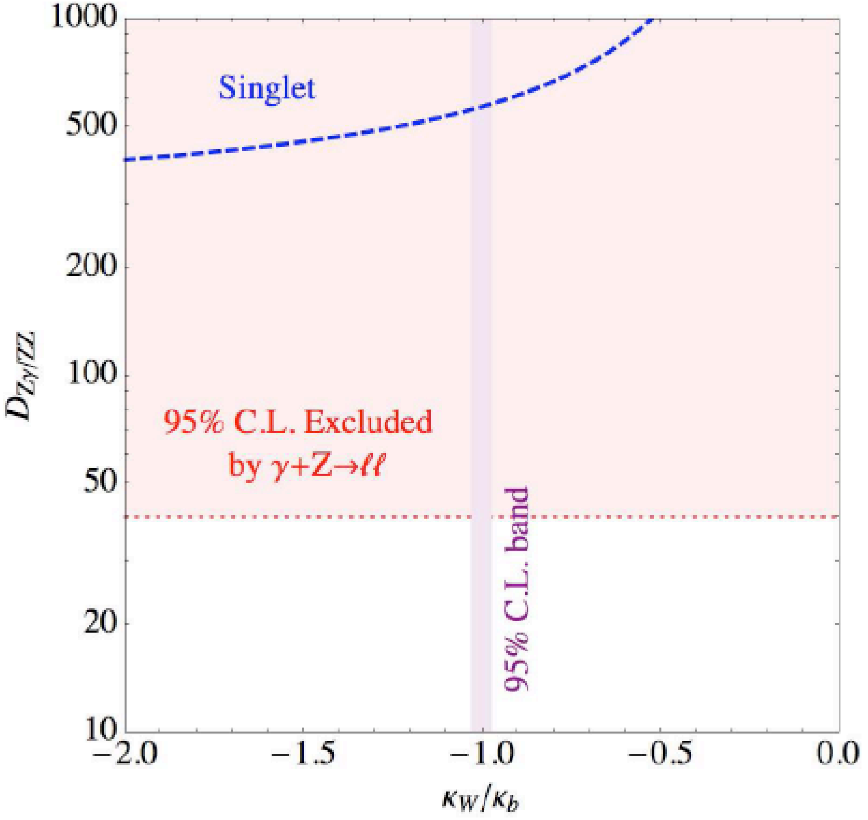
- An electroweak singlet scalar is ubiquitous in BSM theories, whose couplings to pairs of electroweak gauge bosons are controlled by only two parameters at leading order:

$$\kappa_W \frac{\alpha_{em}}{4\pi s_w^2} \frac{S}{4m_S} W^a_{\mu\nu} W^{a\,\mu\nu} + \kappa_B \frac{\alpha_{em}}{4\pi c_w^2} \frac{S}{4m_S} B_{\mu\nu} B^{\mu\nu}$$

Unlike a doublet scalar, the singlet couplings to VV are democratic, without any hierarchy!

Fitting the electroweak singlet imposter to WW/ZZ and diphoton/ZZ ratios, the predicted Z+Photon rate is so large that it is ruled out by “standard model” Z+Photon measurements!





The predicted Z+Photon/ZZ ratio would be 500, while it is <1 for a Higgs boson!

An electroweak doublet couplings to WW and ZZ are fixed by gauge symmetry:

$$g_{hWW/ZZ} = 2\frac{m^2_{W/Z}}{v} \;, \qquad \frac{g_{hWW}}{g_{hZZ}} = \frac{m^2_W}{m^2_Z} = c^2_w \left(1 + \mathcal{O}(\%)\right)$$

Constrained by precision electroweak measurements of $\Delta\rho \approx 1$!

As a result, a 125 GeV “SM” Higgs should have

$$\Gamma_{\rm SM}(h \to WW) \approx 8 \times \Gamma_{\rm SM}(h \to ZZ)$$

One could use other representations of $SU(2)_L$ while satisfying the electroweak constraint of $\Delta\rho \approx 1$.

There's only one other possibility in terms of the coupling to WW and ZZ,

$$\frac{g_{h_5^0 WW}}{g_{h_5^0 ZZ}} = -\frac{c_w^2}{2}$$

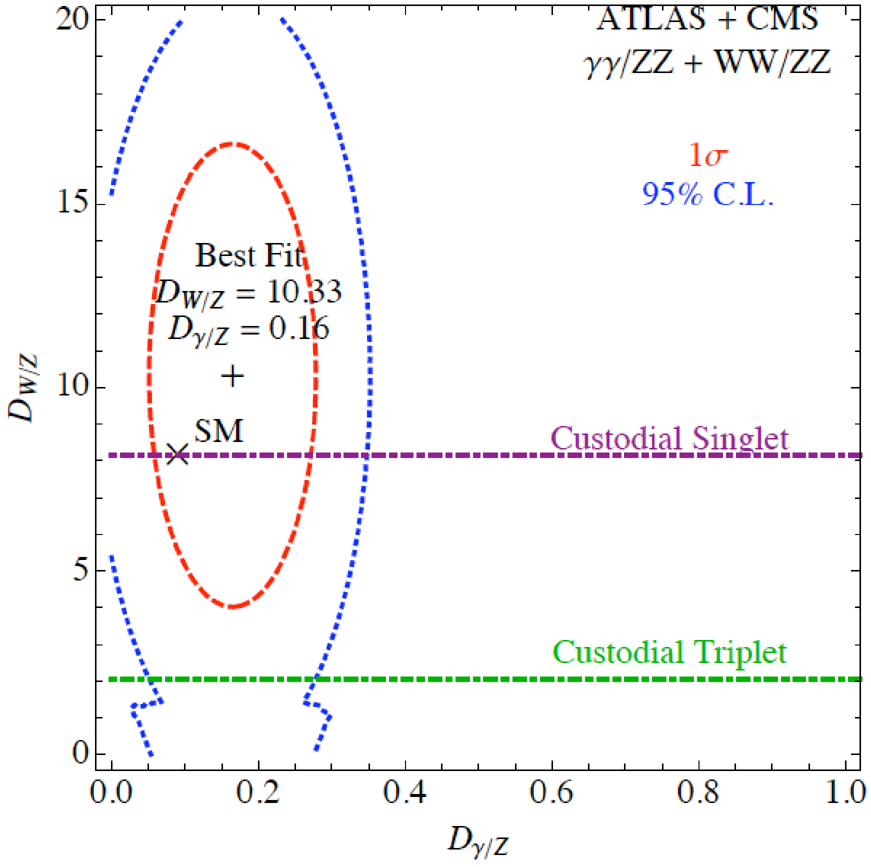
IL and Lykken:1005.0872

which implies a reduced WW coupling relative to ZZ coupling!

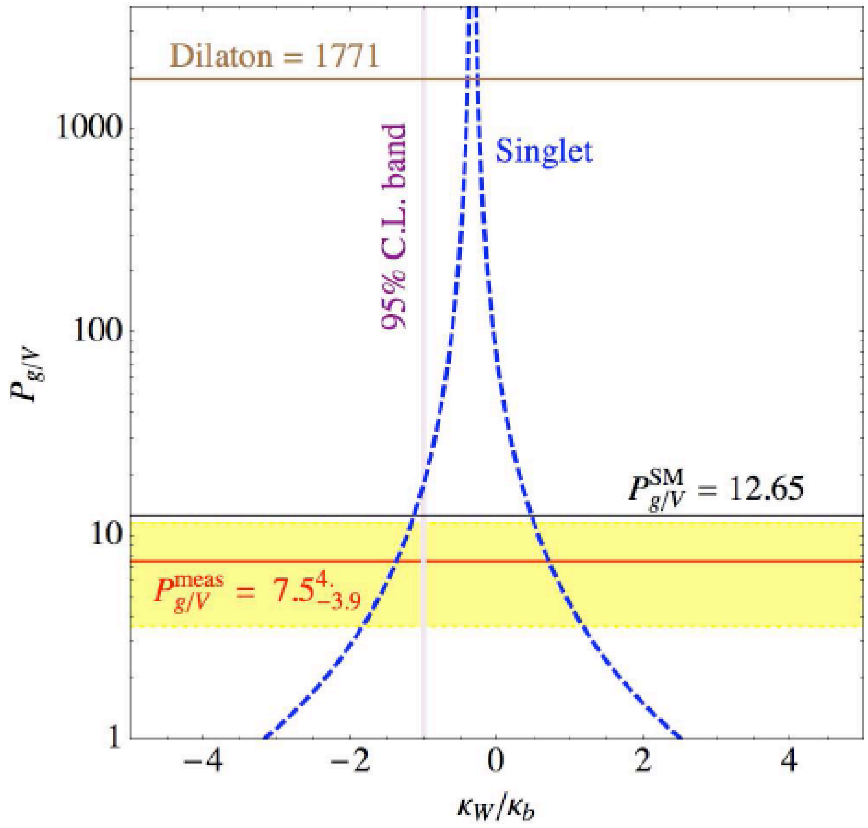
$$\Gamma(h_5^0 \to WW) \approx 2 \times \Gamma(h_5^0 \to ZZ)$$

See also Georgi and Machacek, NPB (1985)
Gunion, Vega, and Wudka, PRD (1990)

The 2D plot is very useful for discriminating between the Higgs and an electroweak triplet imposter:



The ggh over VBF ratio is a useful discriminator for the dilaton/radion imposter:



$$P^{(\mathrm{D})}_{g/V} = 140 \times P^{(\mathrm{SM})}_{g/V} \sim 1700$$

Basically as soon as one sees a non-zero VBF, the dilaton is dead.

But does anyone understand the ratio of gg->h+2j versus VV->h+2j in the VBF-tag bin??

I believe no theorists claim to have a solid understanding of that….

A caveat for the radion/dilaton exclusion is that one assumes both QCD and QED are part of the conformal sector.

In the language of Randall-Sundrum model, both QCD and QED live on the IR brane.

It is possible to cook up models where this is not the case. Then the exclusion limit is relaxed.

Chacko, Franceschini, Mishra: 1209.3259
Bellazzini, Csáki, Hubisz, Serra, Terning: 1209.3299

We have also attempted a theorists' naïve global fit, by using the following parameterization:

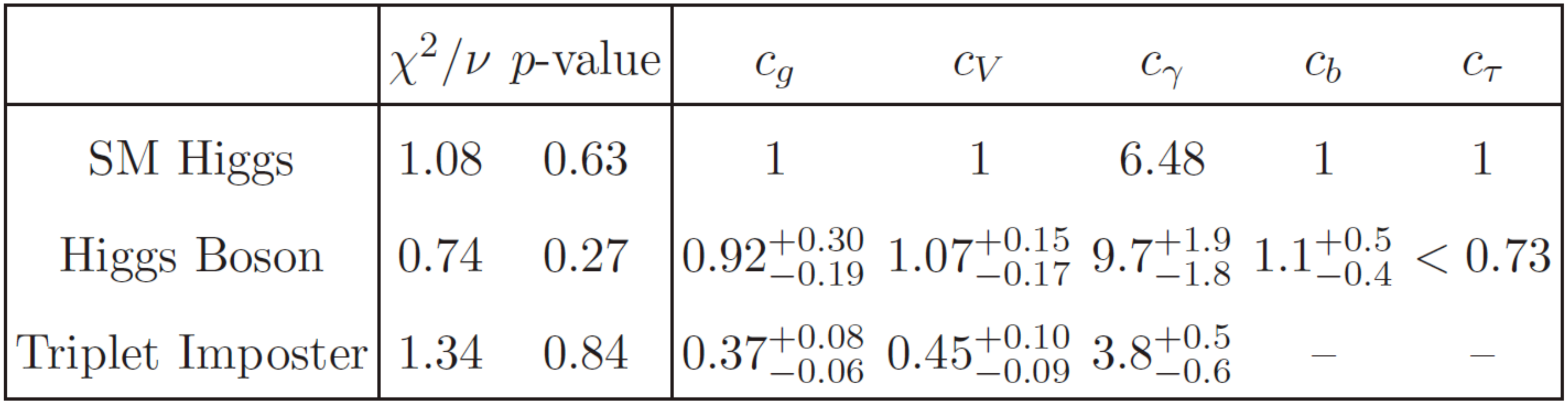
$$\mathcal{L}_{hV_1V_2} = c_V \left(\frac{2m_W^2}{v} h W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v} h Z_\mu Z^\mu \right) + c_g \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^a G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} h F_{\mu\nu} Z^{\mu\nu}$$

$$\mathcal{L}_{hff} = c_b \frac{m_b}{v} h \bar{b} b + c_\tau \frac{m_\tau}{v} h \bar{\tau} \tau$$

Such a global fit is model-dependent in that we have to make assumptions about the total width:

$$\Gamma_{\text{tot}}^h = \sum_{V_1V_2} \Gamma(h \to V_1V_2) + \sum_f \Gamma(h \to f\bar{f})$$

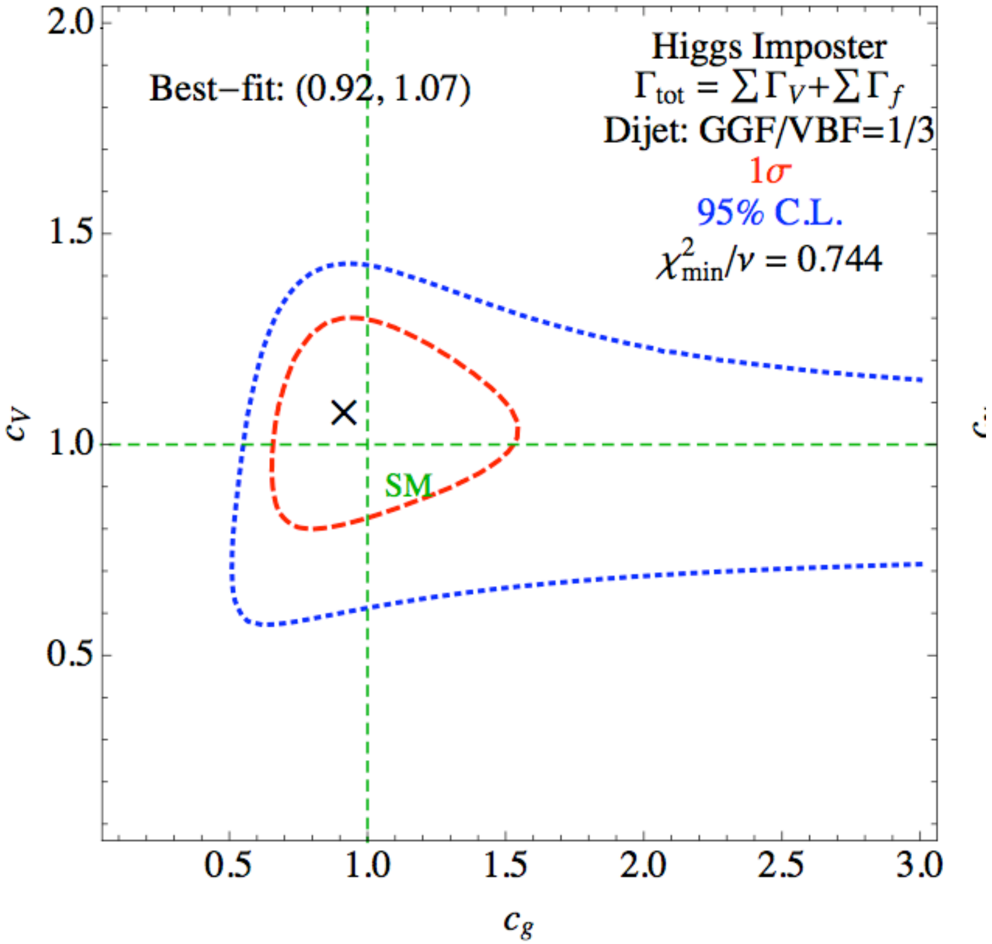
$$\Gamma_{\text{tot}}^{h_5} = \sum_{V_1V_2} \Gamma(h_5 \to V_1V_2)\ .$$



	χ^2/ν	p-value	c_g	c_V	c_γ	c_b	c_τ
SM Higgs	1.08	0.63	1	1	6.48	1	1
Higgs Boson	0.74	0.27	$0.92^{+0.30}_{-0.19}$	$1.07^{+0.15}_{-0.17}$	$9.7^{+1.9}_{-1.8}$	$1.1^{+0.5}_{-0.4}$	< 0.73
Triplet Imposter	1.34	0.84	$0.37^{+0.08}_{-0.06}$	$0.45^{+0.10}_{-0.09}$	$3.8^{+0.5}_{-0.6}$	–	–

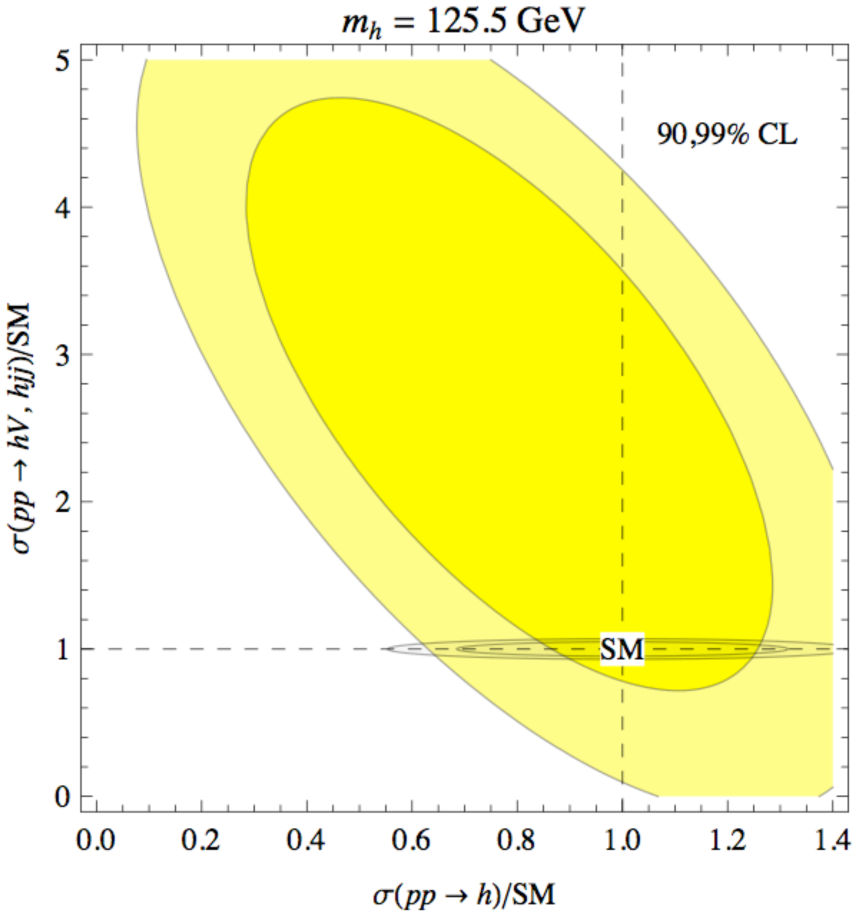
- Overall a Standard Model Higgs boson gives an excellent chi-square fit!
- a “generic” Higgs doublet gives a slightly better fit, due to the apparent enhancement in the diphoton channel.
- Electroweak triplet scalars are slightly disfavored because the excesses in the fermion final states.

A subject of controversy is the c_g v.s. c_V fit:



These two parameters determine the strength of Higgs production in ggh and VBF channels.

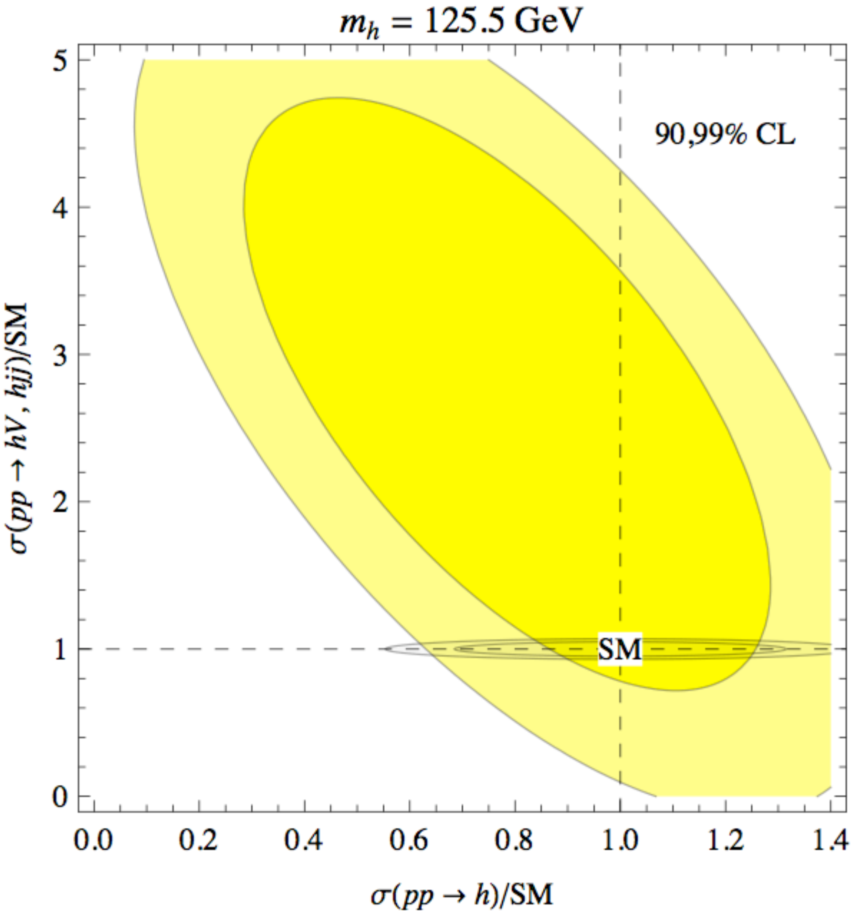
But if you look at the fit from 1207.1347 by Giardino, Kannike, Raidal, and Strumia, their fit allows VBF to go down to zero:



What they did is to perform a two-parameter fit by assuming all BR to be SM value.

In other words, if you assume the fluctuations in every channel come entirely from the production cross-sections, you reproduce their fit.

But this is not self-consistent theoretically, because the VBF signal strength is correlated with the Higgs widths in WW and ZZ channel!



That is, if you turn off VBF, you turn off WW and ZZ rates at the same time!

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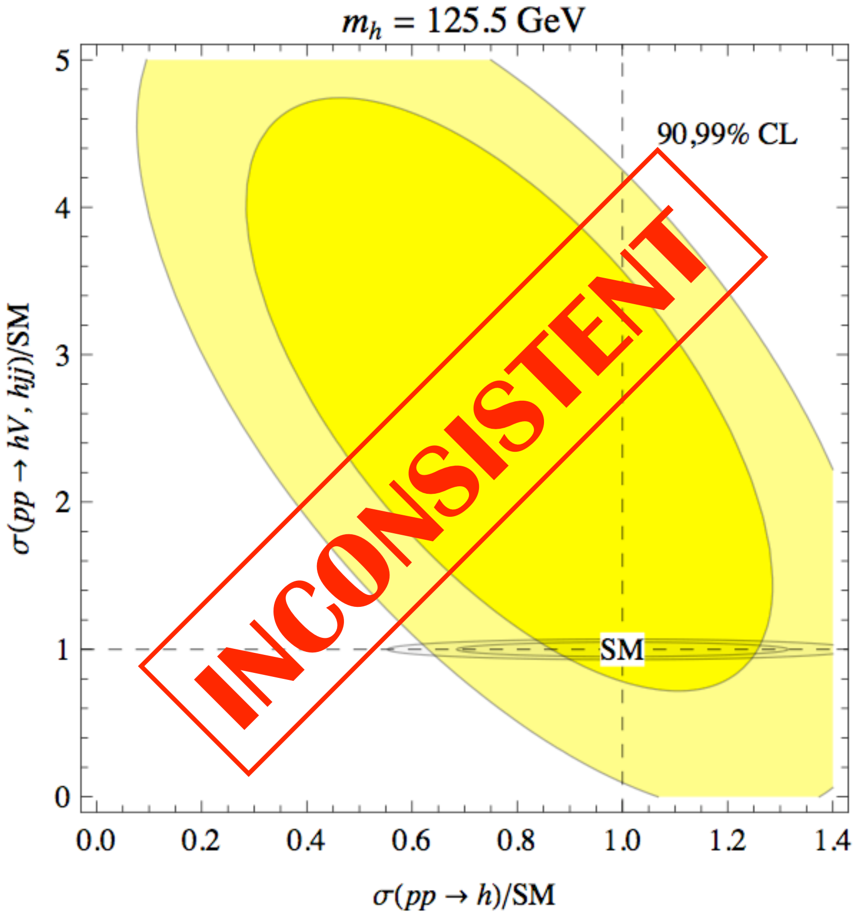


That is, if you turn off VBF, you turn off WW and ZZ rates at the same time!

Enhancements in the diphoton channel were present in last December in both the ATLAS and CMS data already.

Still there in the July 4, 2012 announcements.

Our global fits suggest the enhancement comes entirely from the partial decay width.

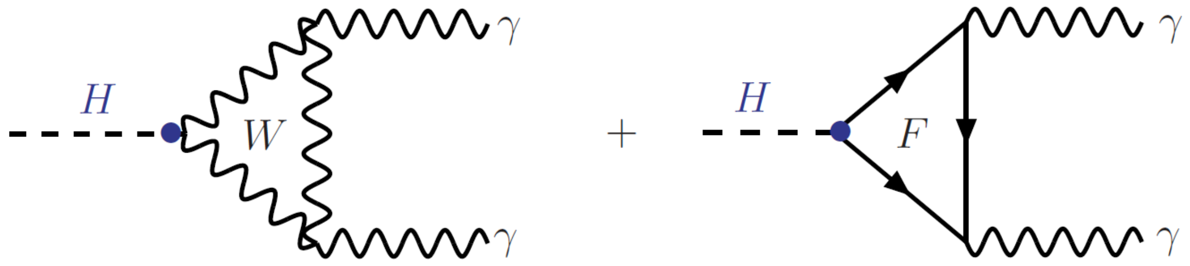
What are the implications of an enhanced Higgs to diphoton decay width??

Carena, IL, and Wagner, 1206.1082

Disclaimer: I am assuming only one Higgs at 125 GeV.

(See Gunion, Jiang, Kraml: 1207.1545 for two degenerate Higgses.)

In the standard model Higgs to diphoton width is loop-induced:



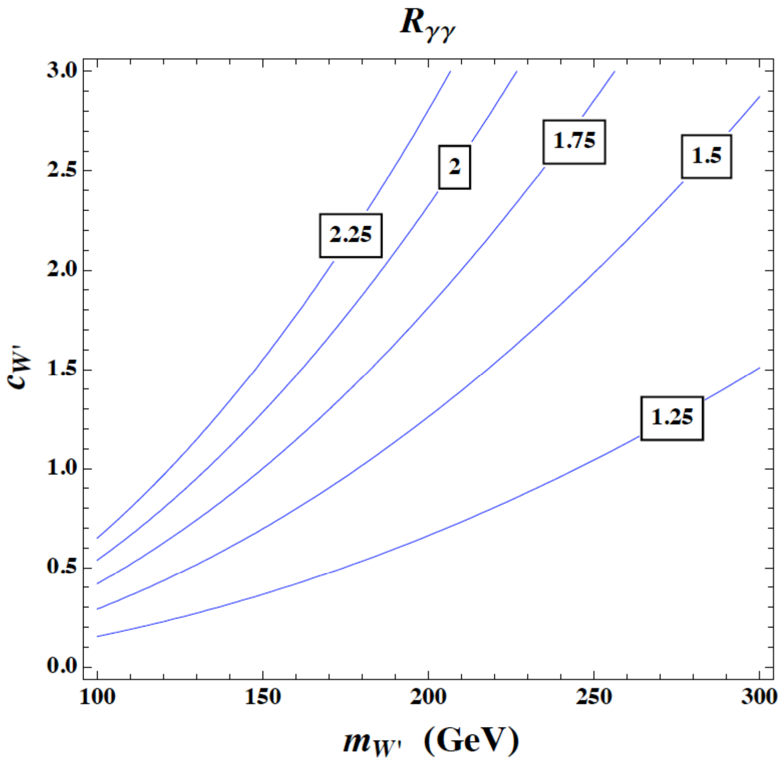
Moreover, SM W-loop is the dominant contribution and has the opposite to the SM top loop.

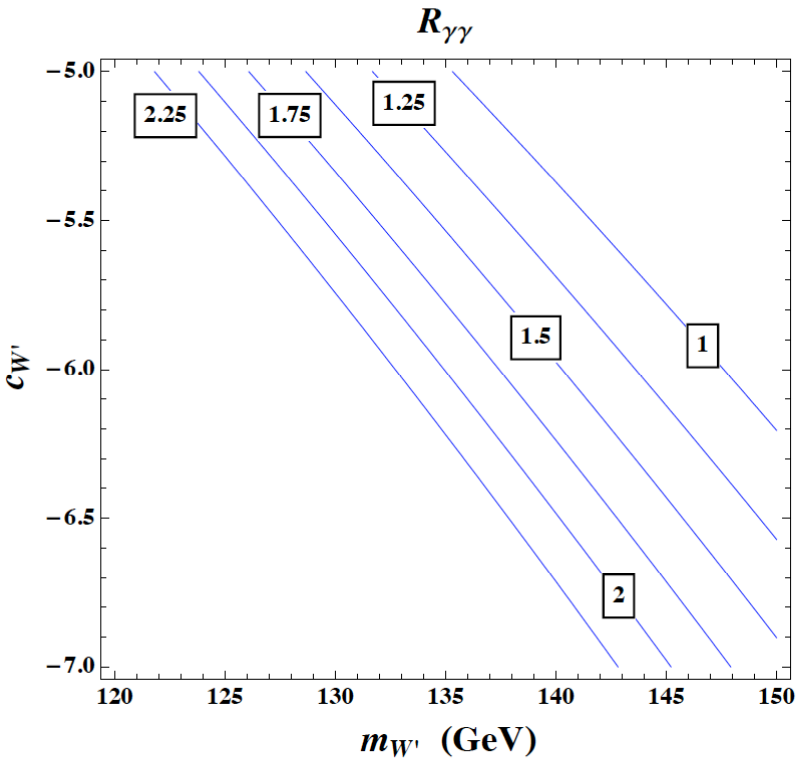
To modify the Higgs to diphoton width, one could add new charged particles with a significant coupling to the Higgs.

- A new W-prime boson:

$$m_{W'}(v)^2 = m_{W0}^2 + c_{W'}\, m_W^2$$

$$\mathcal{O}_{W'} = \frac{1}{2} c_{W'} g^2 H^\dagger H\, W'^{+}_{\mu} W'^{-\,\mu}$$





Hasn’t such a light W-prime been ruled out by current searches??

Not if the W-prime has a new parity such that it only couples to SM matter pair-wise.

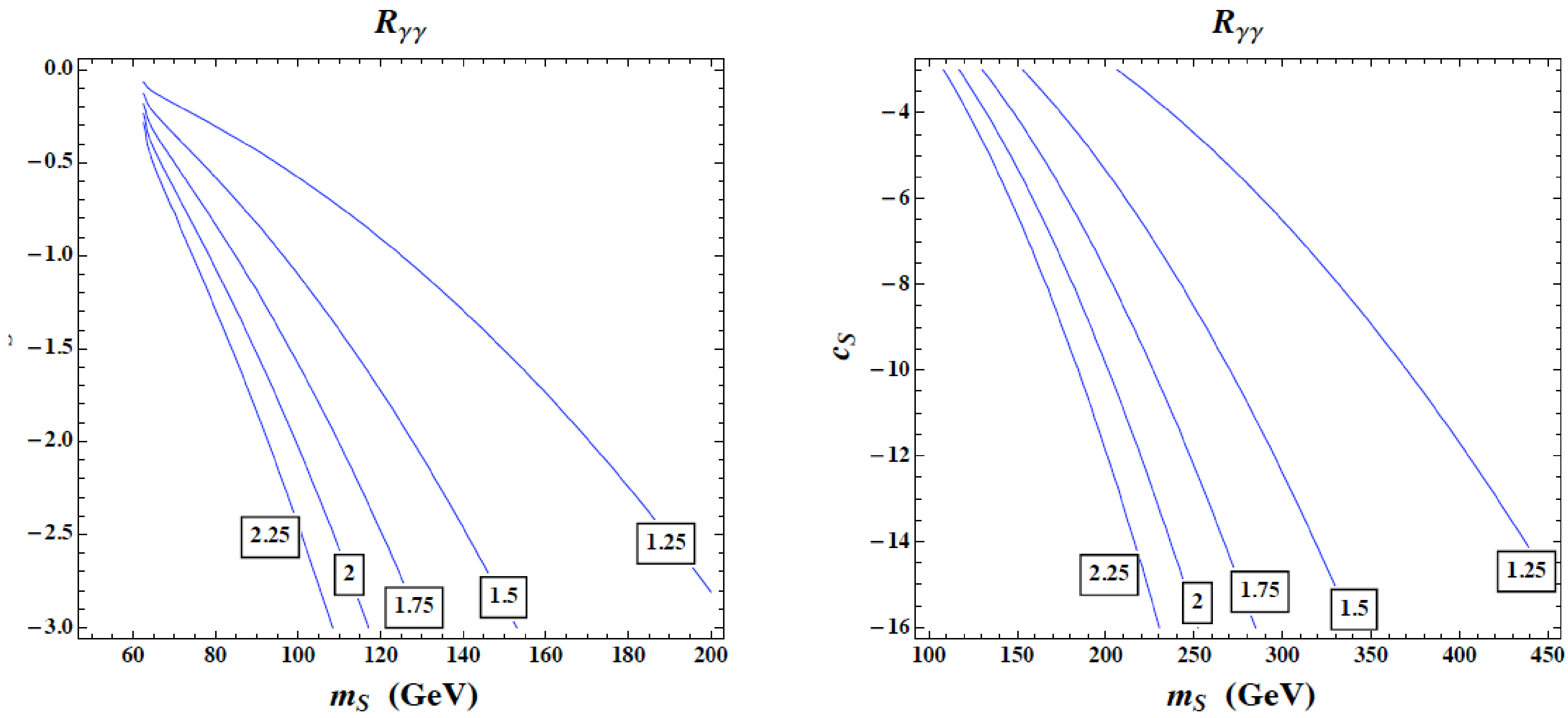
So if the W-prime is always pair-produced, and decays to dijet plus MET, there is no bound from the LHC!

(Four-jet plus MET has been searched in the context of gluino searches, but here we have electroweak production strength…)

(ATLAS has searched for doubly produced resonances decaying into four jets, but they didn’t tag on the MET…)

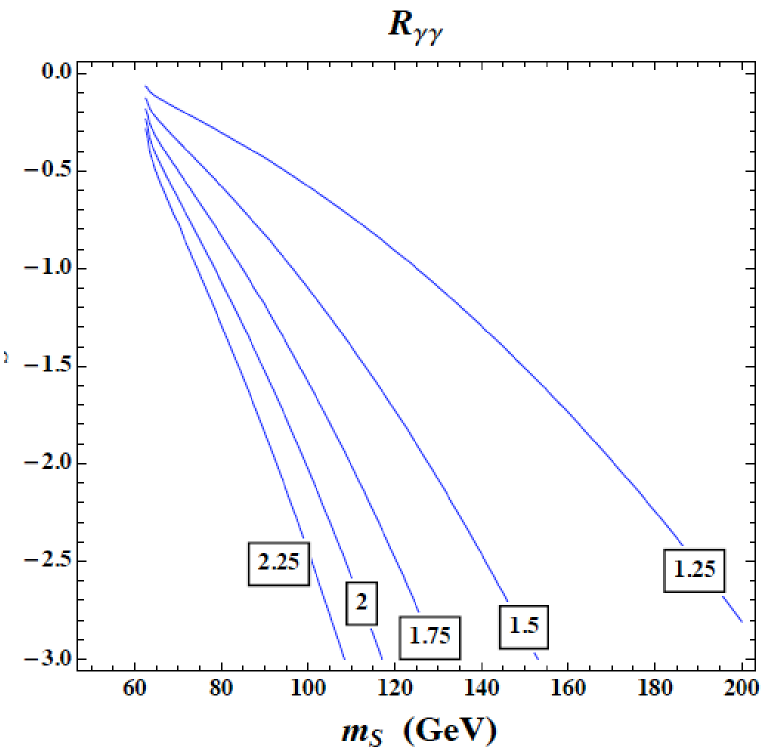
- We can also use a new charge scalar:

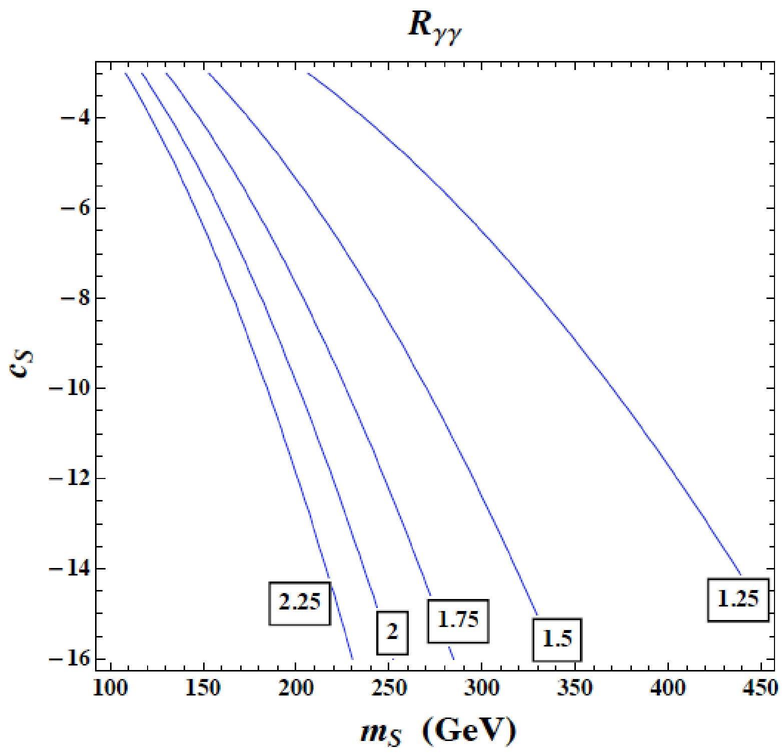
$$m_S^2 = m_{S0}^2 + \frac{1}{2} c_S \, v^2 \qquad\qquad \mathcal{O}_S = c_S H^\dagger H \, |S|^2$$



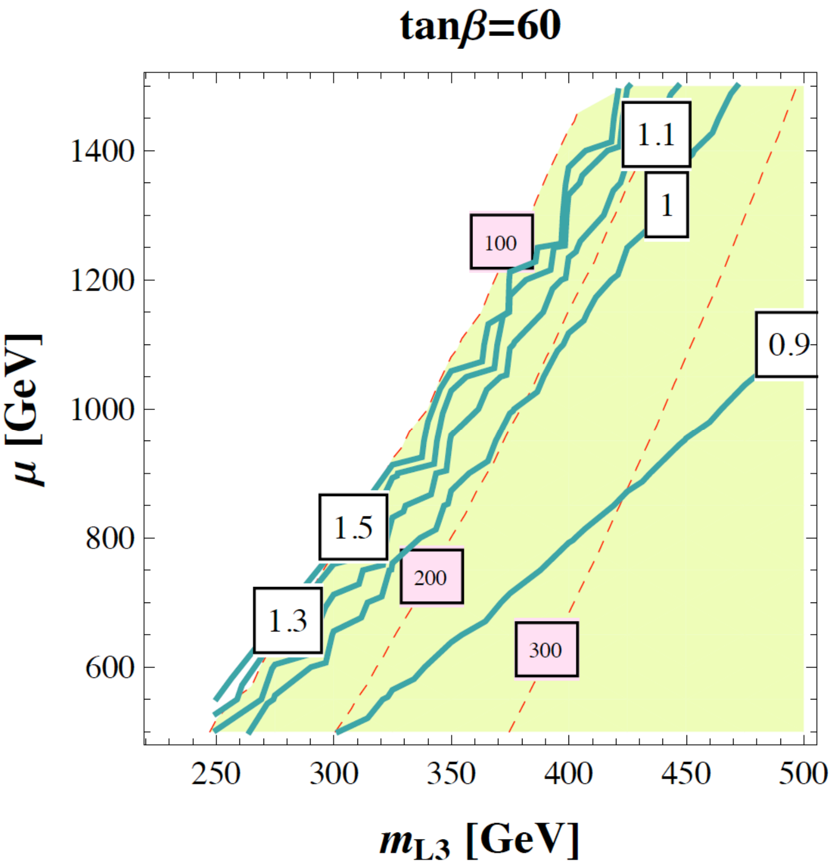
- Again a light mass or a large coupling is required.

- LEP has a search limit on stable charged scalar at around 100 GeV.





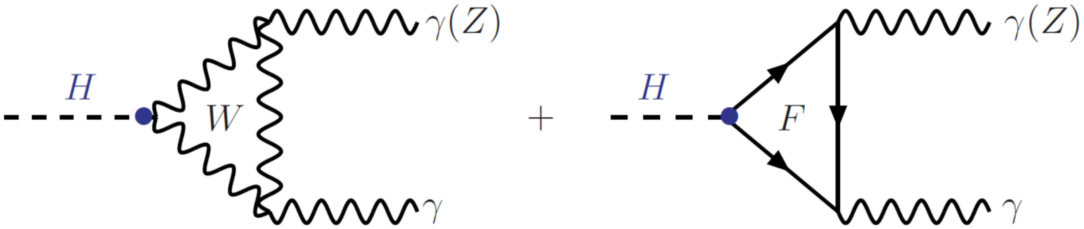
In MSSM the enhanced diphoton width could arise in light staus with large mass mxing, with stau1 mass close to the LEP limit of 100 GeV.



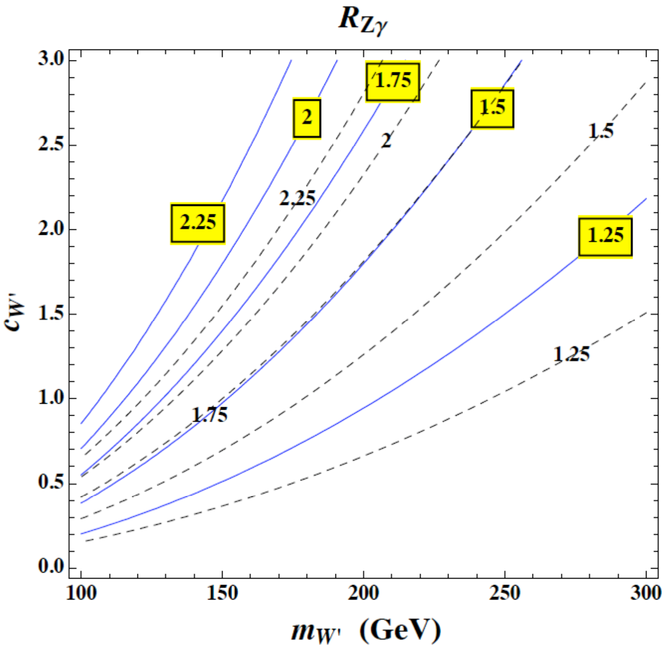
Carena, Gori, Shah, Wagner:1112.3336

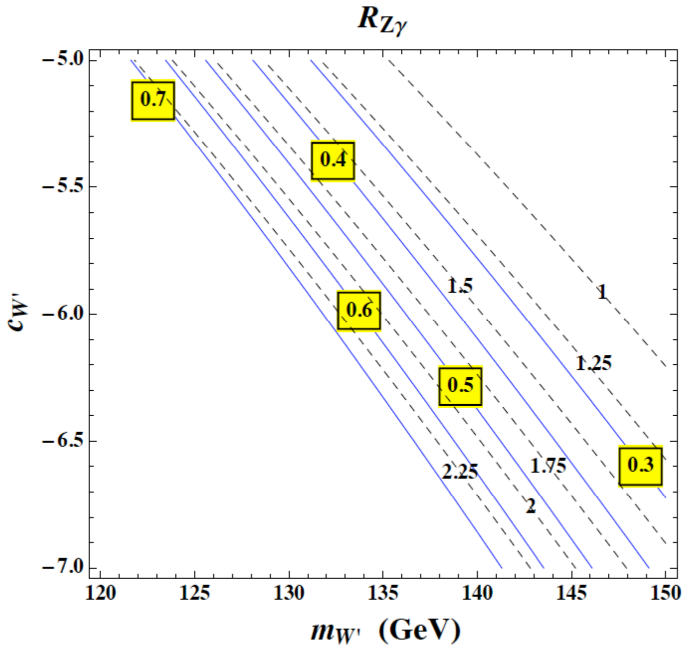
So how do we go about testing these scenarios that enhance the diphoton width?

Interestingly there're correlations between the h -> $\gamma\,\gamma$ partial width and h-> Z γ partial width:



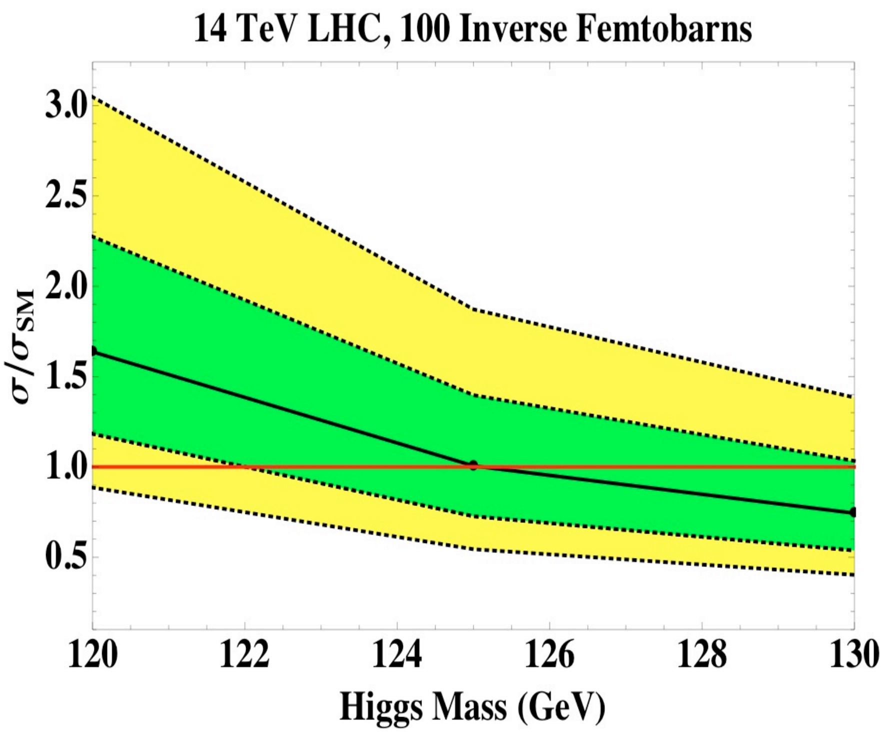
W-prime model again:

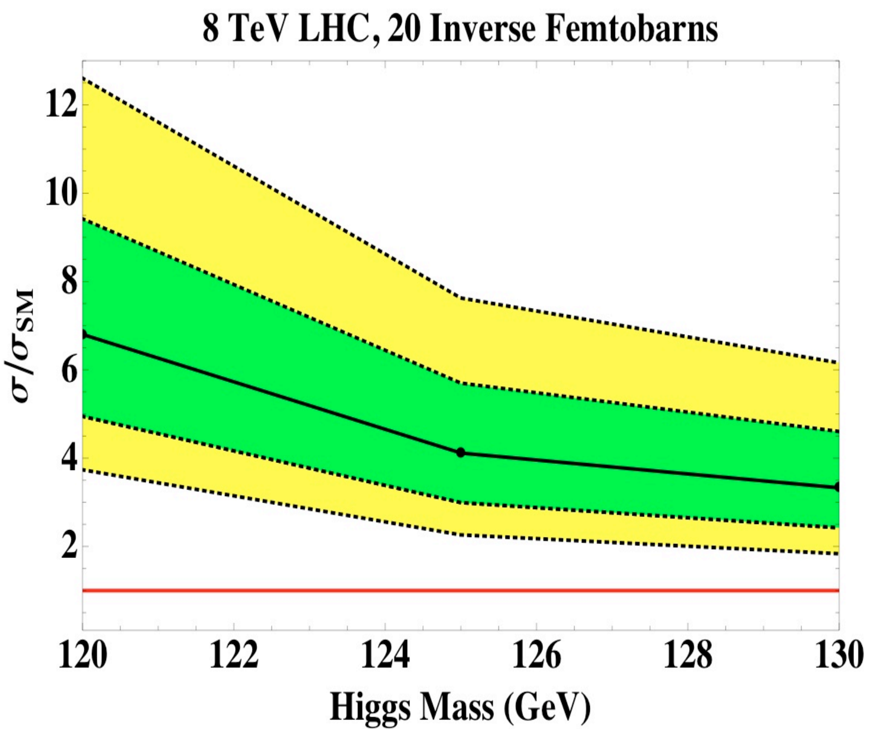




We see the Z + photon channel is very useful!!

- Higgs decays to Z + photon have been overlooked by both experimental collaborations, until recently….





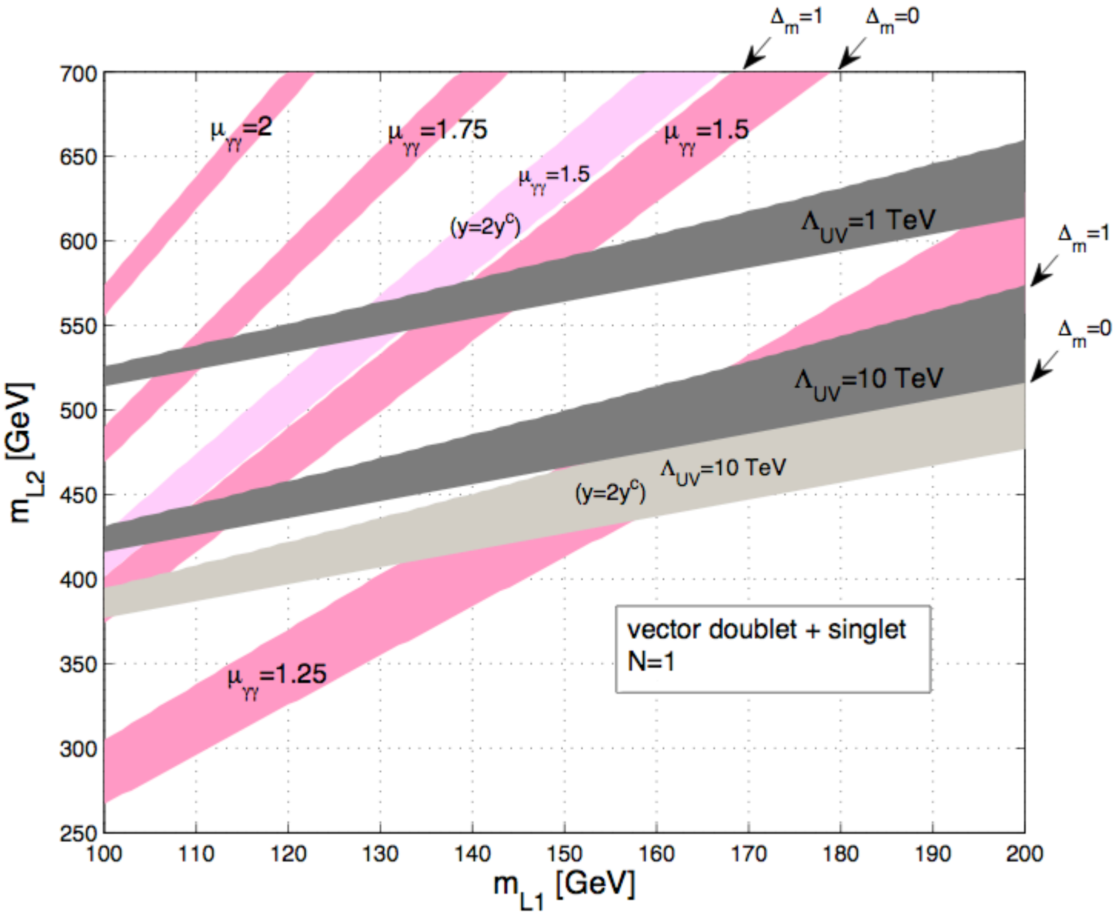
Gainer, Keung, Low, and Schwaller: 1112.1405v2

We also need to look for new particles, in particular those with significant couplings to the Higgs boson.

In fact, new particles with significant couplings to the Higgs have many theoretical and experimental consequences.

For example, the new particles could affect the vacuum stability of the Higgs.

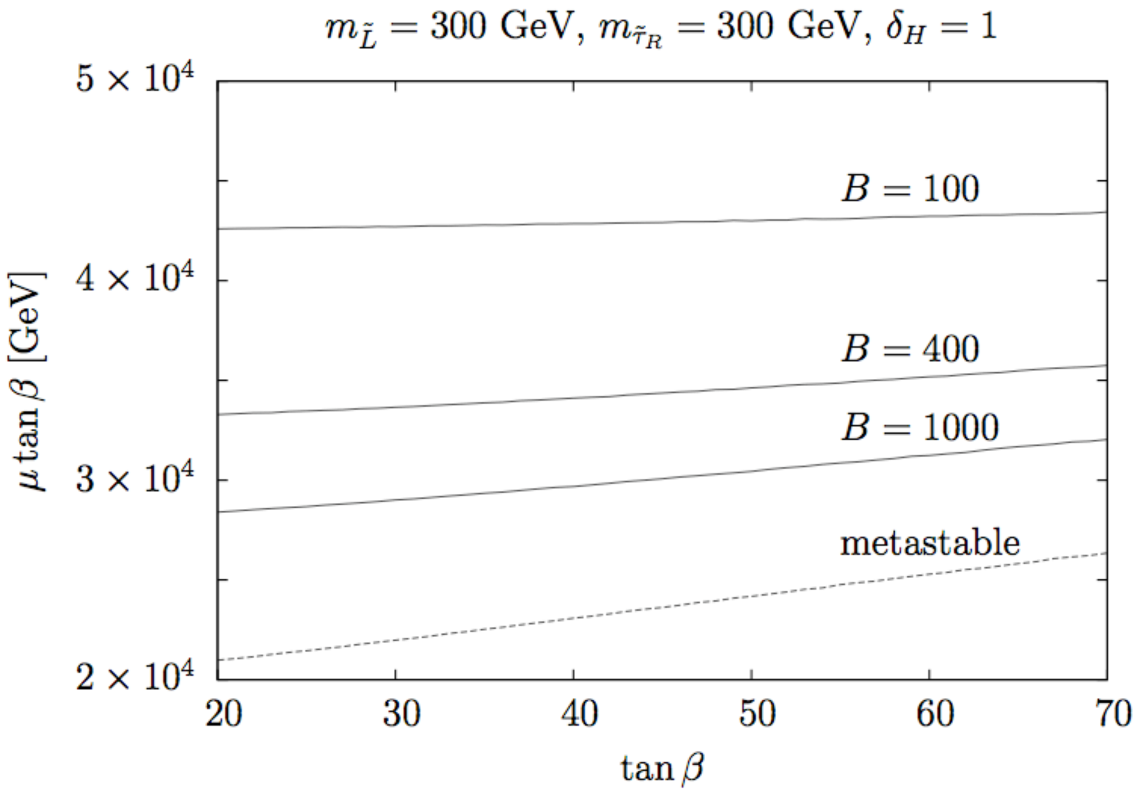
If the new particles enhancing the diphoton width are fermions, they drive the Higgs quartic coupling negative!



Arkani-Hamed, Blum, D'Aganolo, Fan: 1207.4482

See also Joglekar, Schwaller, Wanger:1207.4235

For scalars, there could be new charge-breaking minimum.
In the context of MSSM, vacuum meta-stability in the light stau scenario has been studied by Hisano and Sugiyama (1011.0260):



Notice the tan beta dependence here!

They summarized the meta-stability bound by neglecting the tan beta dependence:

$$\mu \tan\beta < 76.9\sqrt{m_{\tilde{L}} m_{\tilde{\tau}_R}} + 38.7(m_{\tilde{L}} + m_{\tilde{\tau}_R}) - 1.04 \times 10^4 \text{ GeV}$$

Applying this “bound,” it was found that the diphoton enhancement could only be at O(20%) in MSSM. (Kitahara:1208.4792)

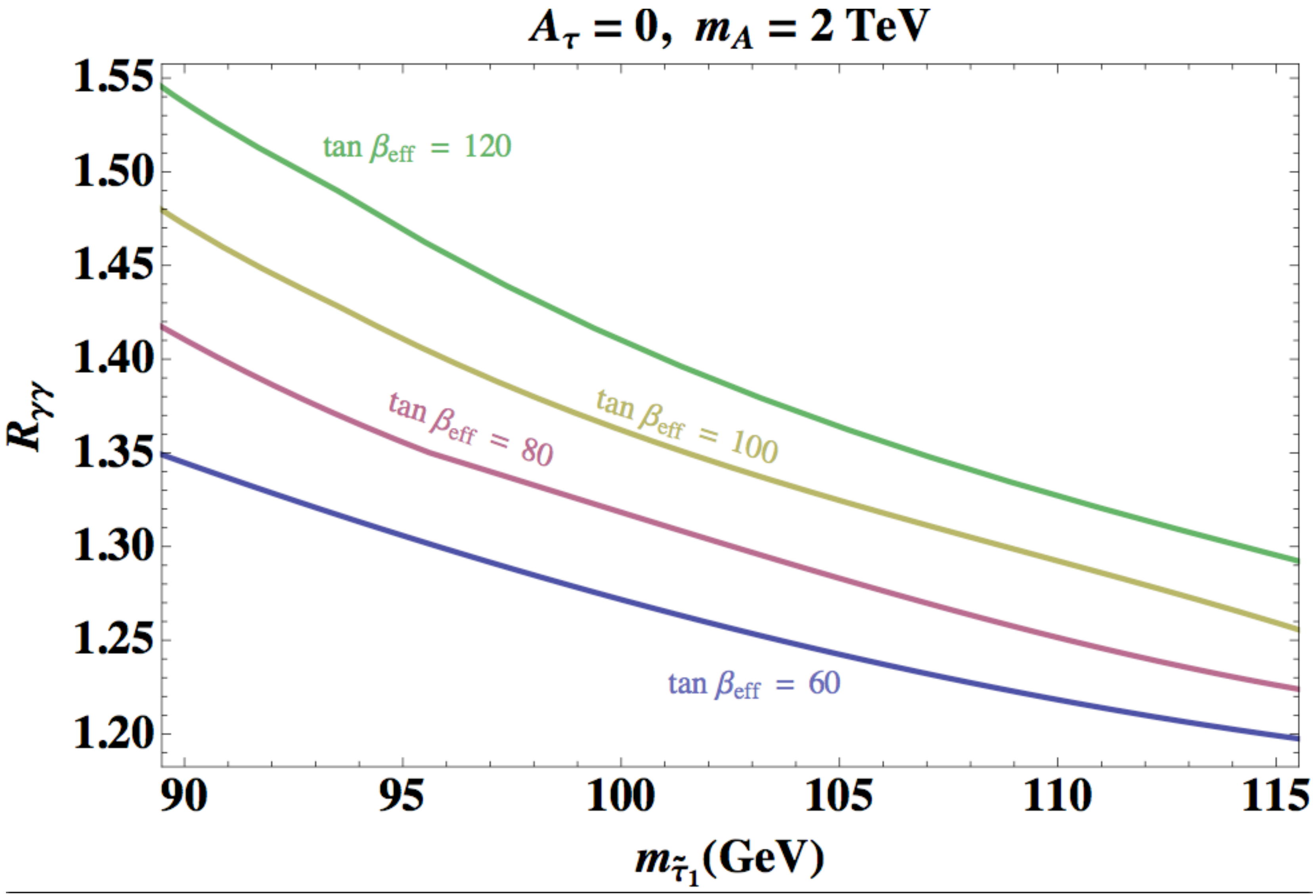
There are two assumptions in that study:

- Tree-level relation between tau-Yukawa and tau-mass.
- tan beta dependence is neglected in meta-stability bound.

If we use a one-loop corrected tau Yukawa,

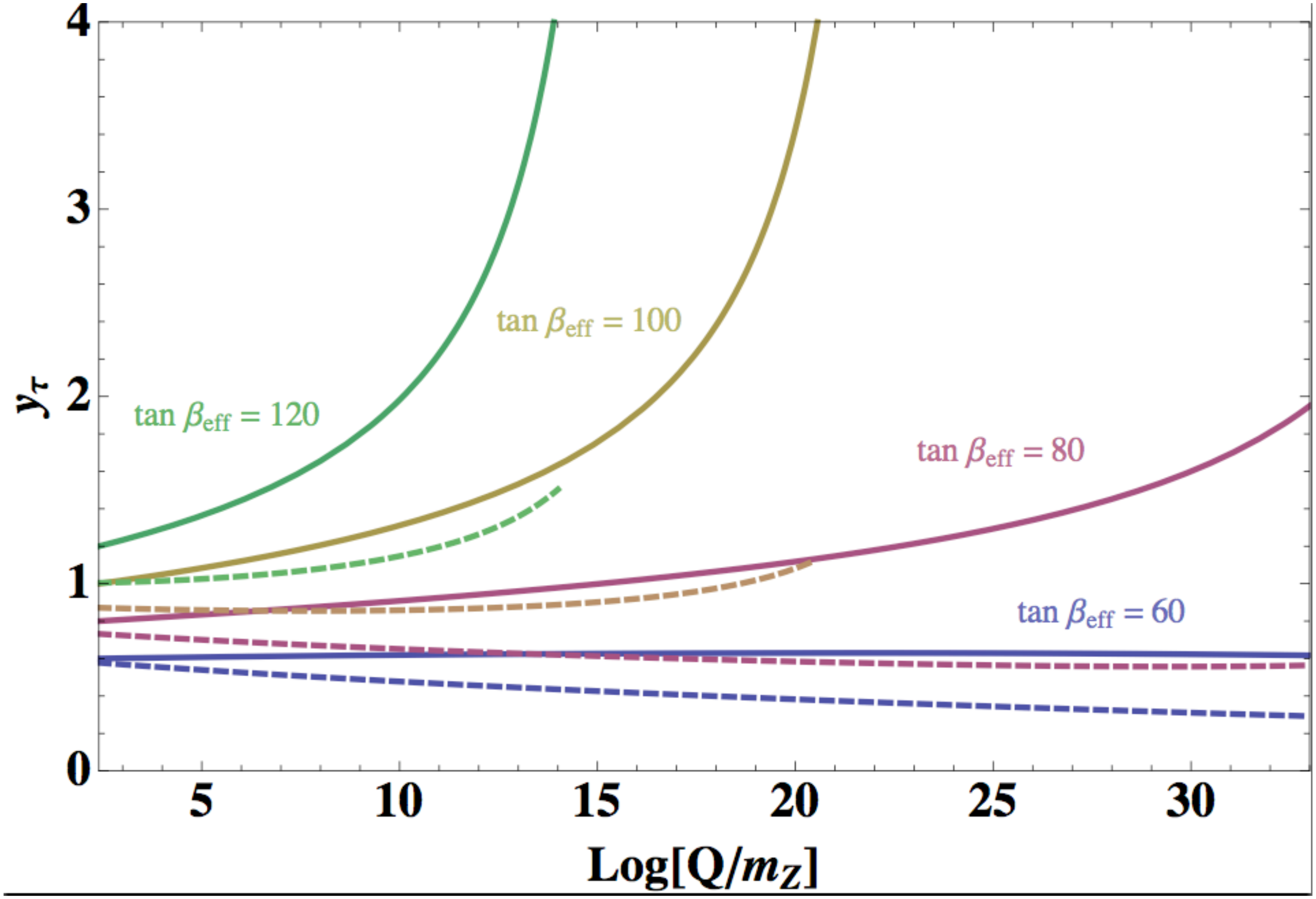
$$y_\tau \approx \sqrt{2}\,\frac{m_\tau}{v\cos\beta(1+\Delta_\tau)} \sim \frac{\tan\beta}{100(1+\Delta_\tau)}$$

and restore the tan beta dependence in the meta-stability bound,
then O(50%) enhancement is still possible in MSSM.



Carena, Gori, IL, Shah, Wagner: to appear

One doesn’t hit the Landau pole below GUT scale for tanbeta =80.



Carena, Gori, IL, Shah, Wagner: to appear

If the diphoton enhancement persists, the top priority should be on looking for light charged particles at the LHC and the Higgs factory!

People have considered direct production of these light charged particles.(Carena, Gori, Shah, Wagner, Wang: 1205.5842; Arkani-hamed, Blum, D'Agnolo, Fan:1207.4482)

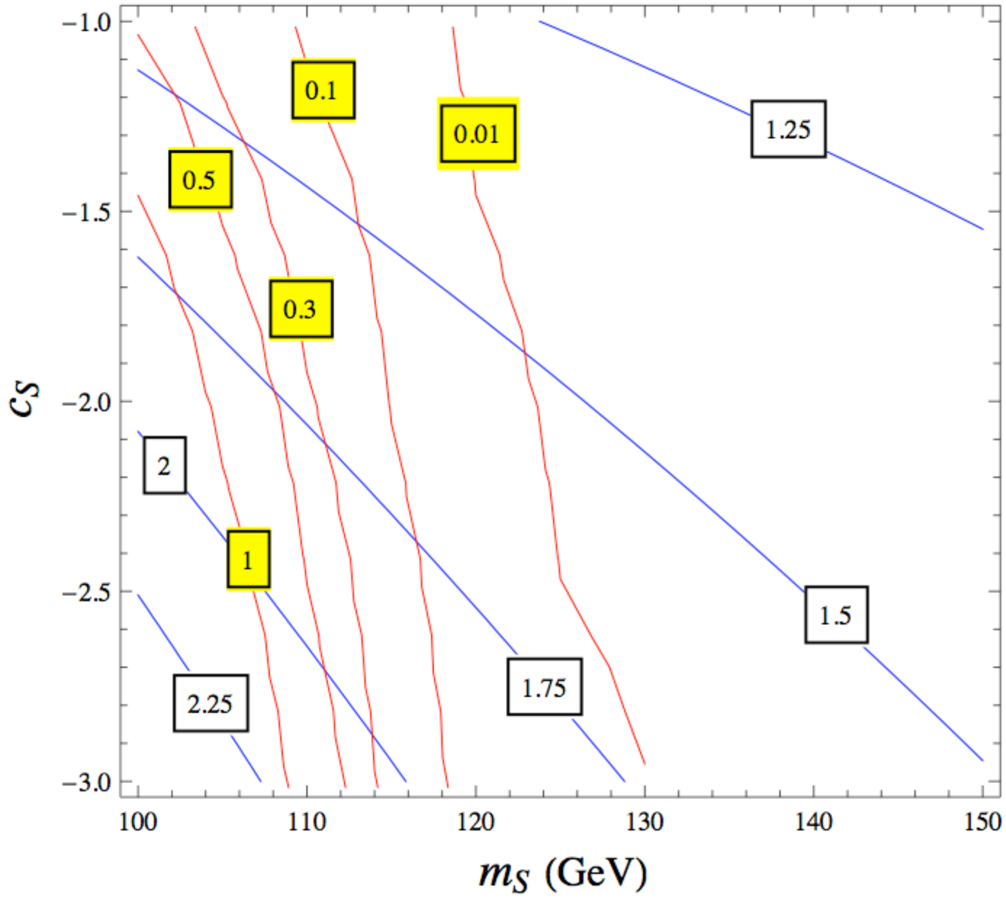
But these direct production modes do not tell us about their couplings to the Higgs.

We need something else…..

Since these new charged particles are light, and have significant couplings to the Higgs, they could show up in the Higgs decays!

For example, in the light stau scenario in MSSM, one could have

$$h \to \tilde{\tau}\tilde{\tau}^* \to \tau^+\tau^- + \mathrm{MET}$$



red lines : $\dfrac{\Gamma(h \to \tilde{\tau}\tilde{\tau}^*)}{\Gamma_{\mathrm{SM}}(h \to \tau\tau)}$

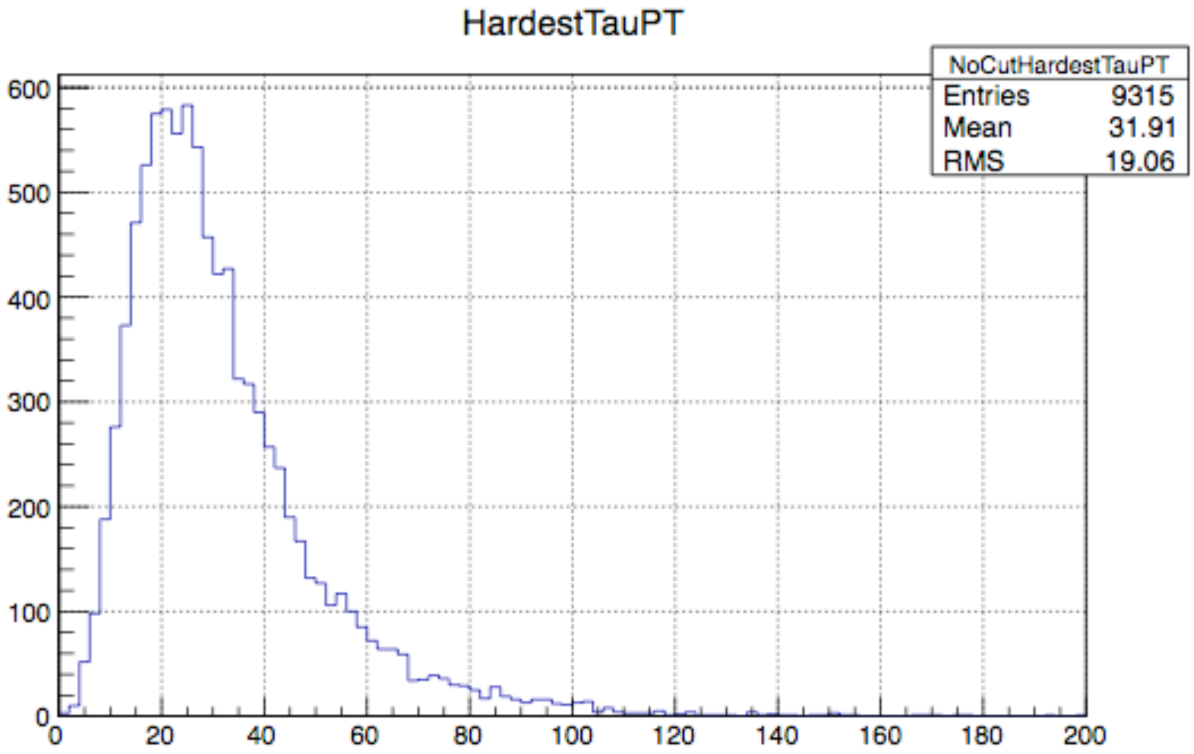
blue lines : $\dfrac{\Gamma(h \to \gamma\gamma)}{\Gamma_{\mathrm{SM}}(h \to \gamma\gamma)}$

assuming $\Gamma(\tilde{\tau}) = 0.25\ \mathrm{GeV}$

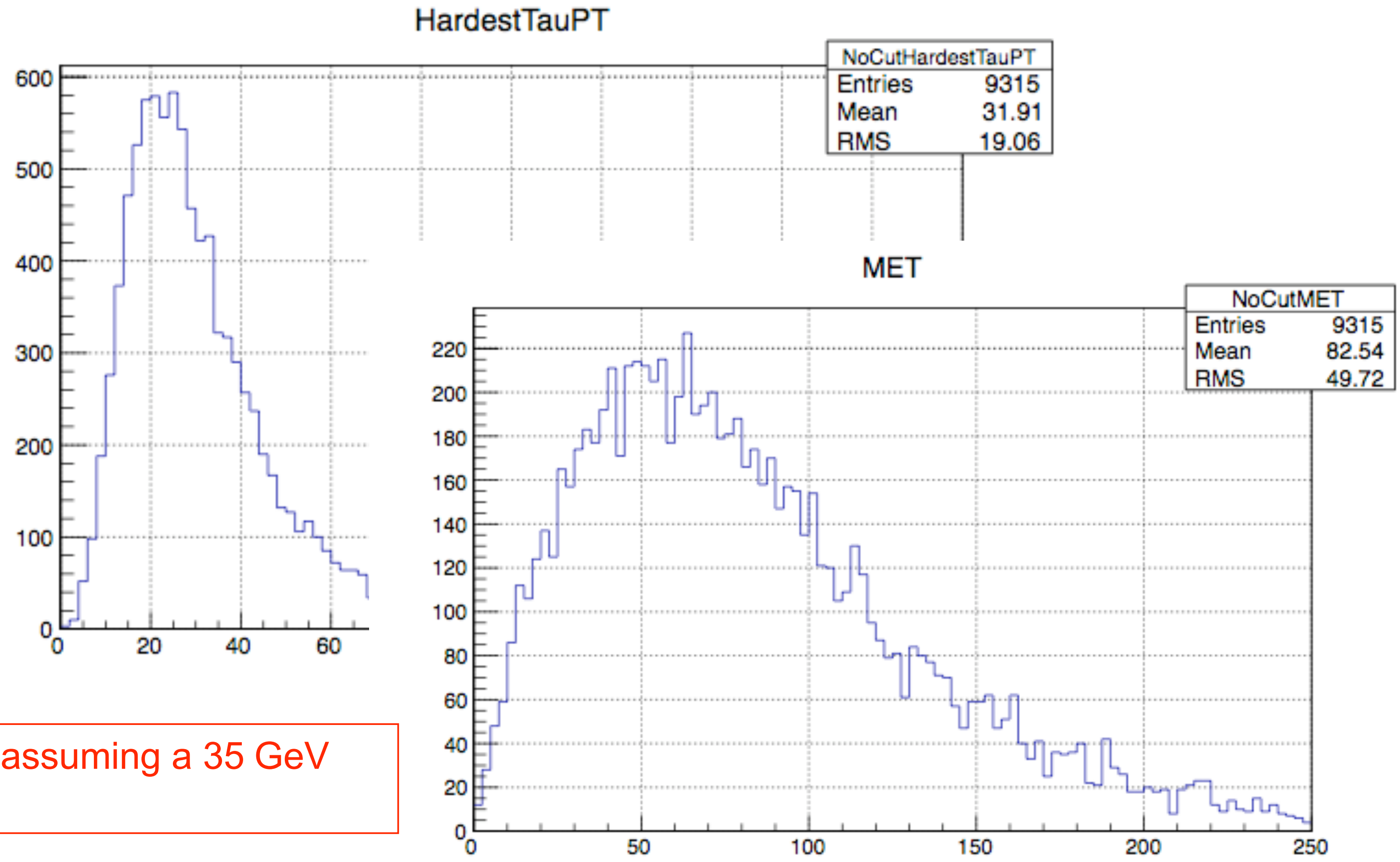
$\mathrm{BR}_{\mathrm{SM}}(h \to \tau\tau) = 0.64\%$

Giddings, Liu, IL, Mintun: work in progress

- We can trigger on the hard lepton and MET:

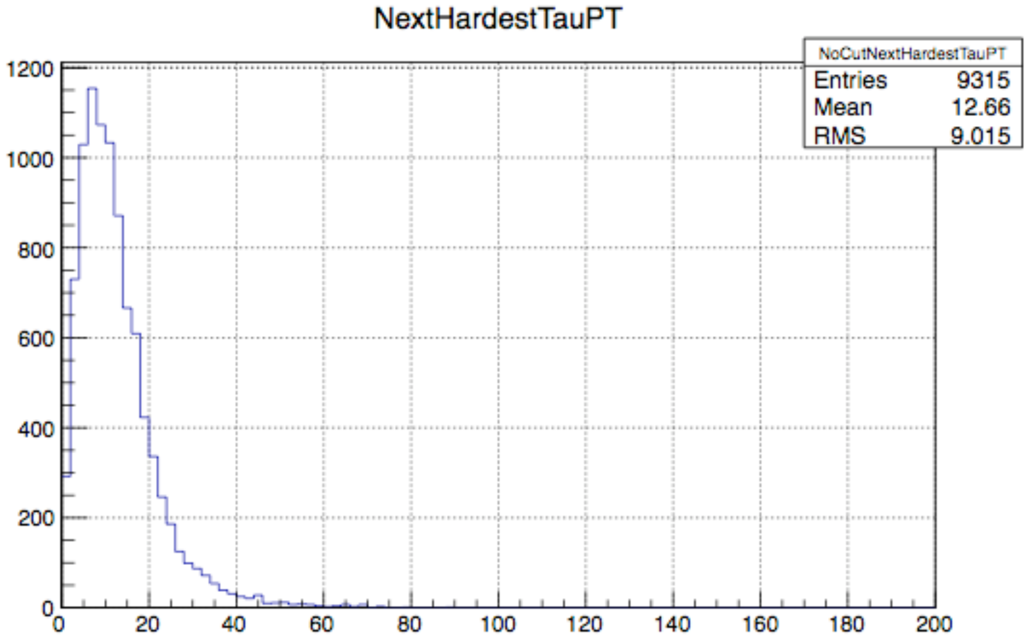


- We can trigger on the hard lepton and MET:

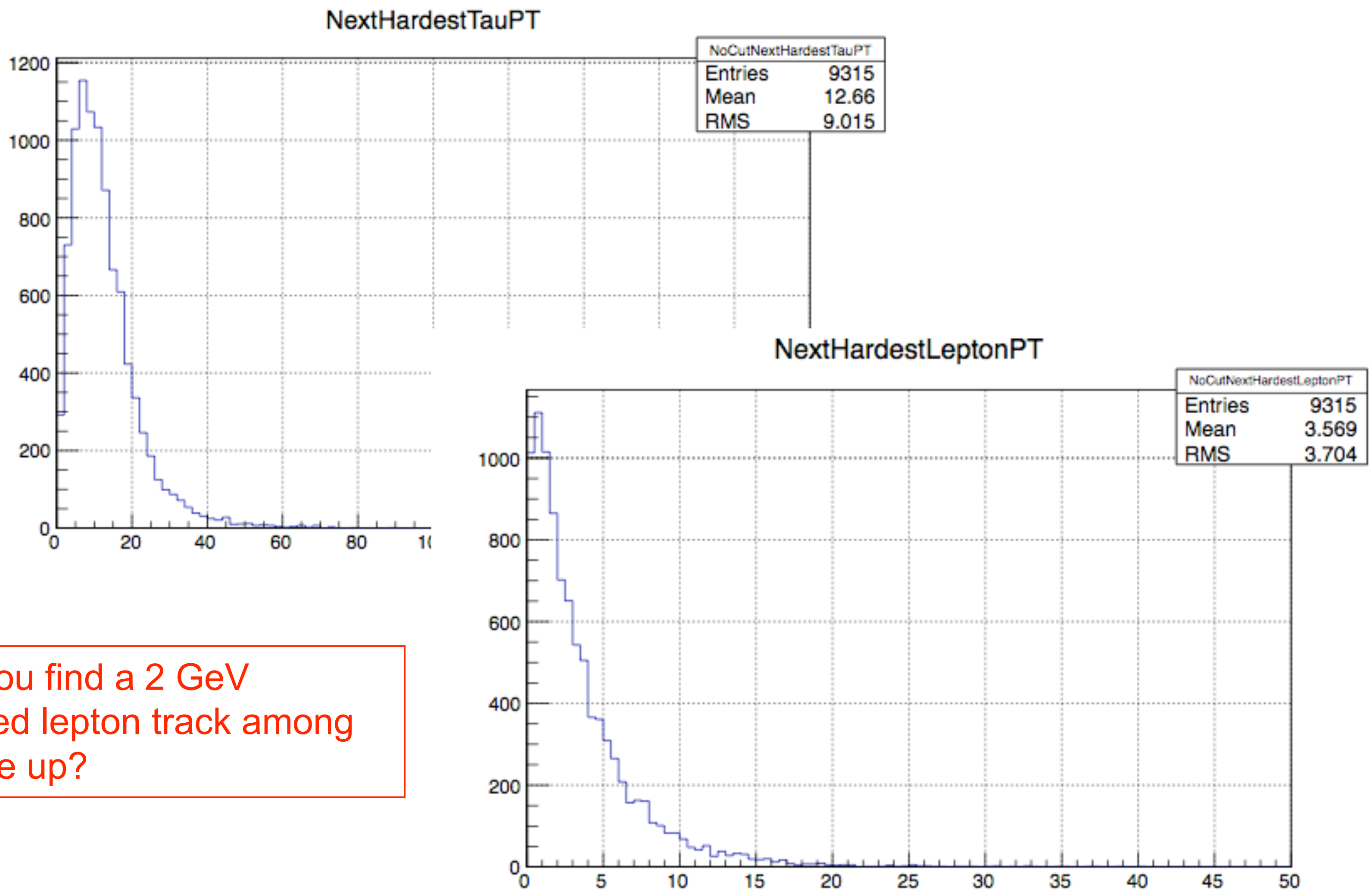


This is assuming a 35 GeV LSP.

- The only problem is the tau is too soft!



- The only problem is the tau is too soft!



Can you find a 2 GeV charged lepton track among the pile up?

However, this would be a great possibility for the Higgs factory to look for!

We really do not want the Higgs factory to only be a “precision machine.”

We want it to be a “discovery machine” as well!!

“Higgs Identification” --

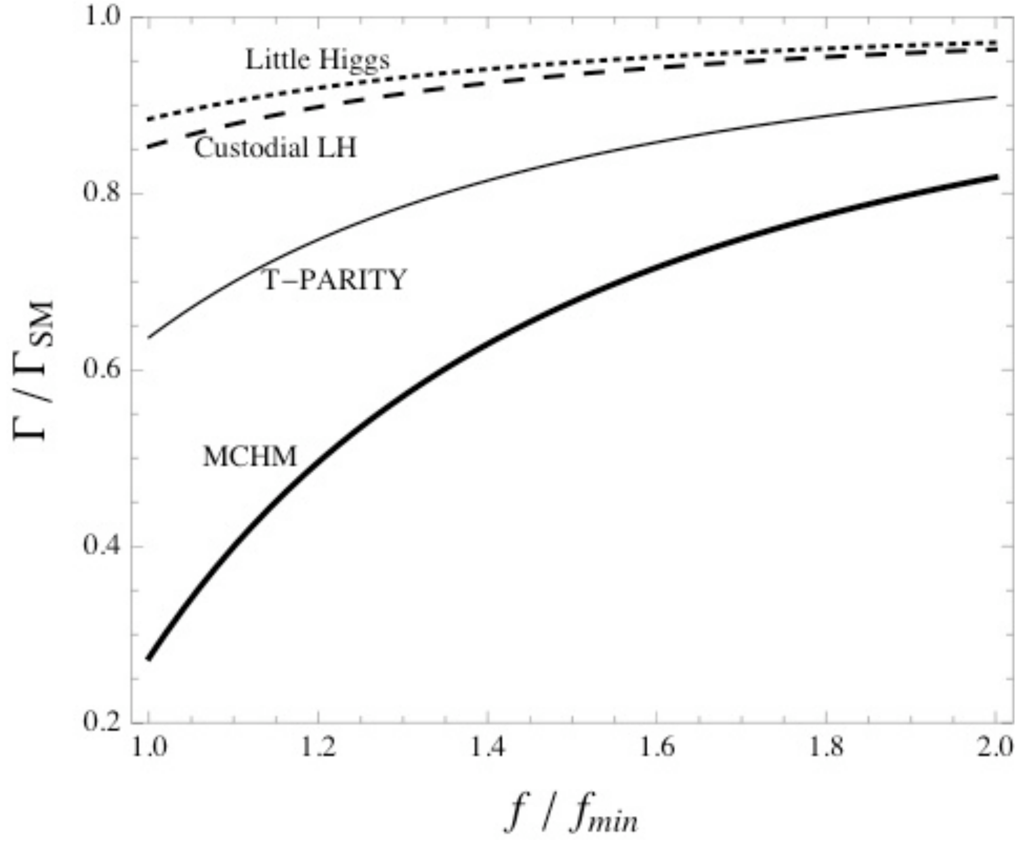
Infrared Identity:

- Spin-0 (scalar)
- Charge and Parity (CP) even
- The neutral component of an electroweak doublet
- The origin of mass for W/Z bosons as well as the quarks and charged leptons

Ultraviolate Identity:

- Hints of more dynamic and symmetry princples? Supersymmetry? Compositeness?
- Does the naturalness principle work? Do we have to live with Anthropic principle and multiverse?
- Are there more new particles out there? Those enhancing the diphoton width? Those cancelling the Higgs quadratic divergences?

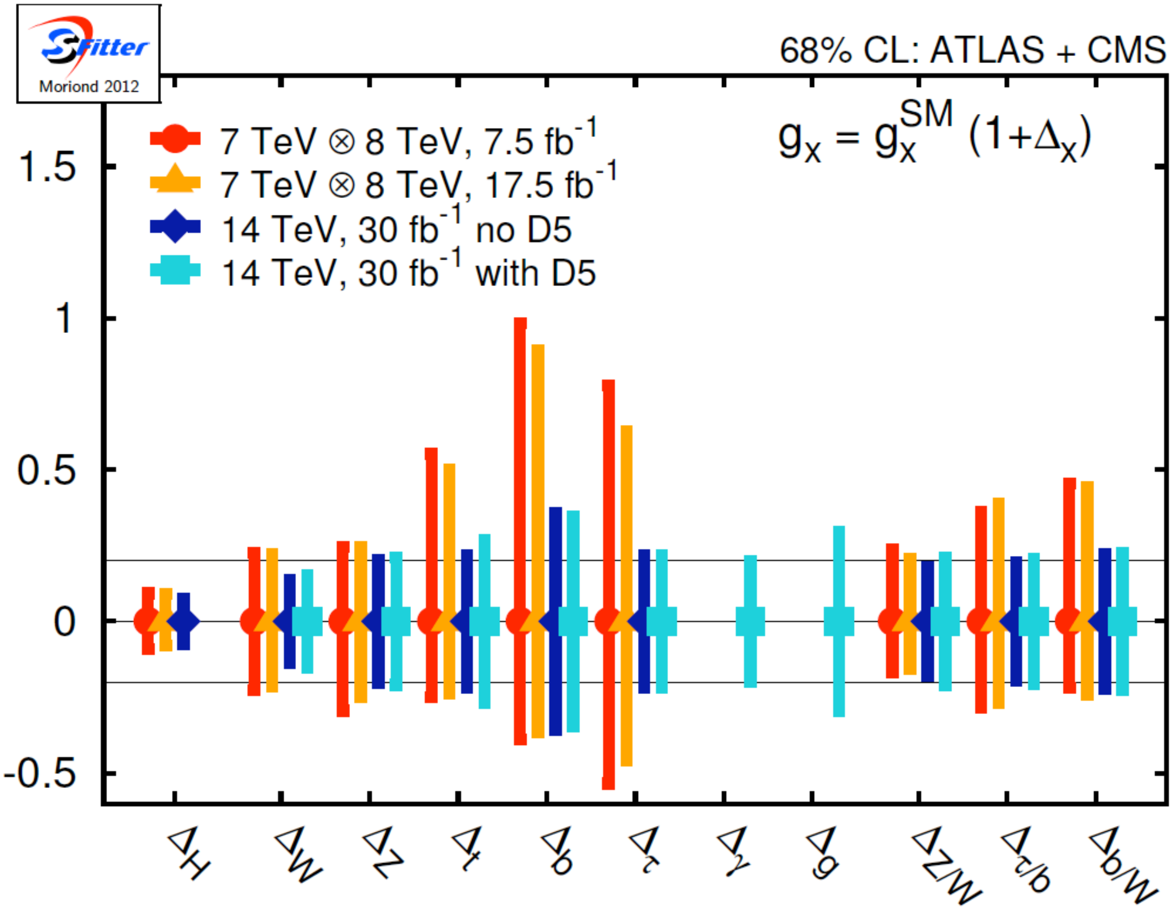
For the UV Identity, one particularly useful quantity is the Higgs coupling to two gluons:



In composite Higgs models this coupling is (almost) always suppressed!

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

Last but not least: a Higgs factory for precision measurements of Higgs properties!



SFitter, March 2012

A hadron machine is messy: Higgs coupling measurements can be done only with large uncertainties in O(20-50 %)….

A moment of truth:

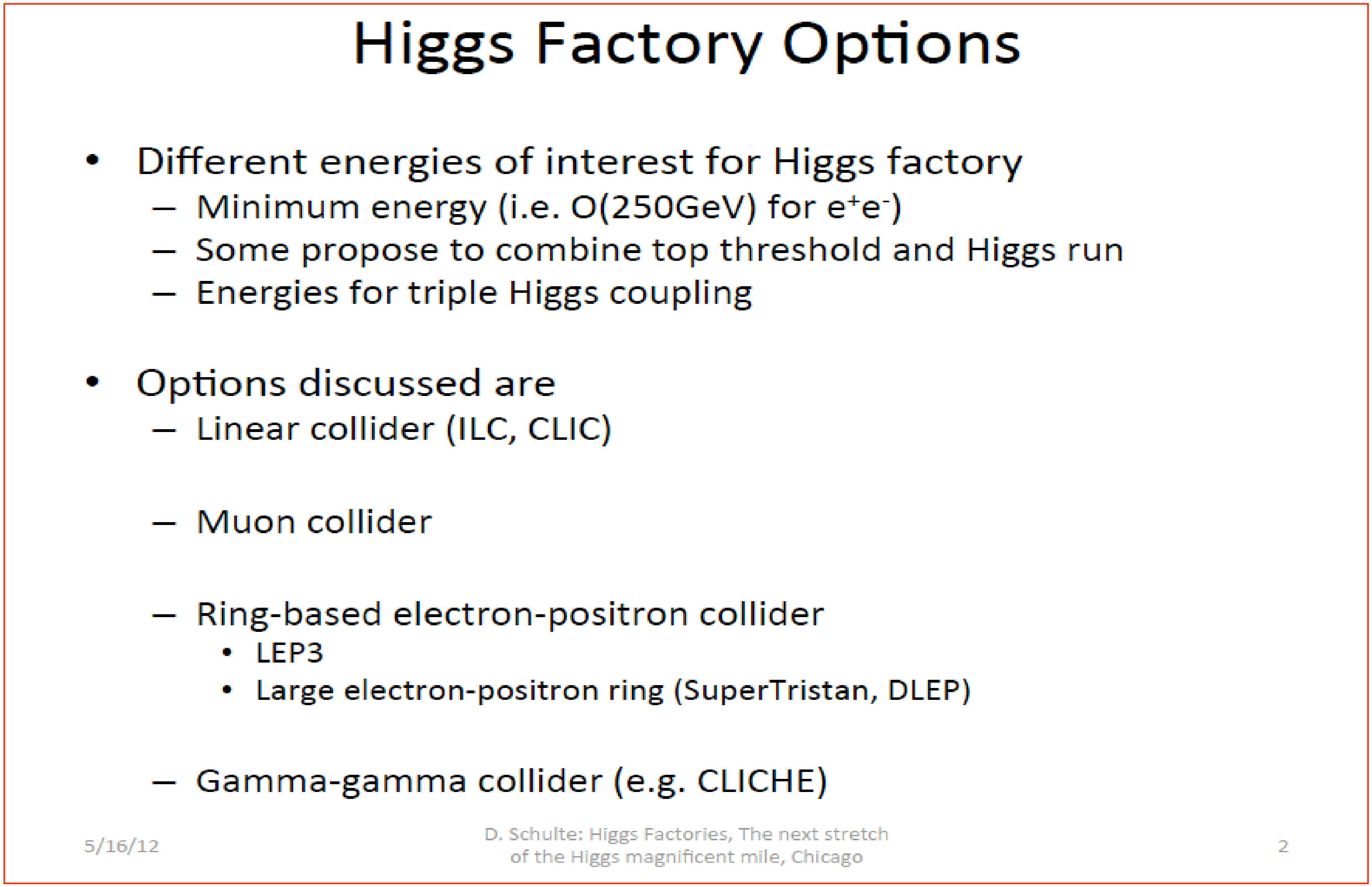
"The LHC can never claim the discovery a SM Higgs boson; at best the LHC can claim *the discovery of a SM-like Higgs boson*."

--- Quote from Howie Haber

In contrast, it is possible to rule out a SM Higgs boson at the LHC.

Precision measurements require intensity.

Is a Higgs factory one of the most compelling physics scenarios for intensity frontier?



Higgs Factory Options

- Different energies of interest for Higgs factory
  - Minimum energy (i.e. O(250GeV) for e^+e^-)
  - Some propose to combine top threshold and Higgs run
  - Energies for triple Higgs coupling
- Options discussed are
  - Linear collider (ILC, CLIC)
  - Muon collider
  - Ring-based electron-positron collider
    - LEP3
    - Large electron-positron ring (SuperTristan, DLEP)
  - Gamma-gamma collider (e.g. CLICHE)

5/16/12

D. Schulte: Higgs Factories, The next stretch
of the Higgs magnificent mile, Chicago

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