Higgs ID

Ian Low @

Chicago 2012 LHC Worskhop

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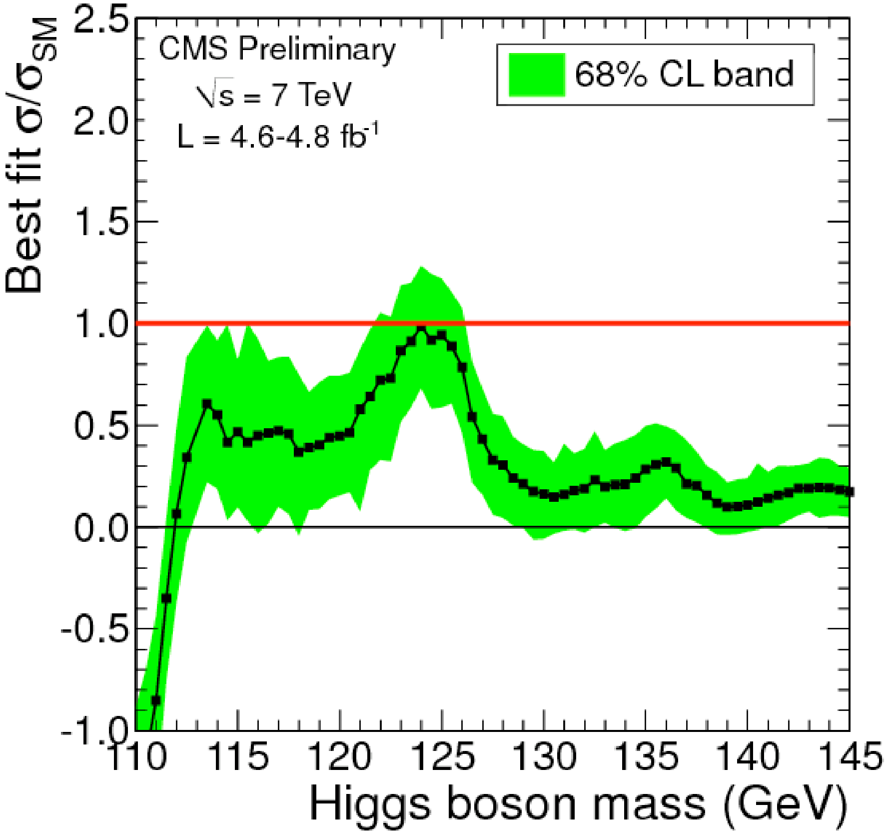
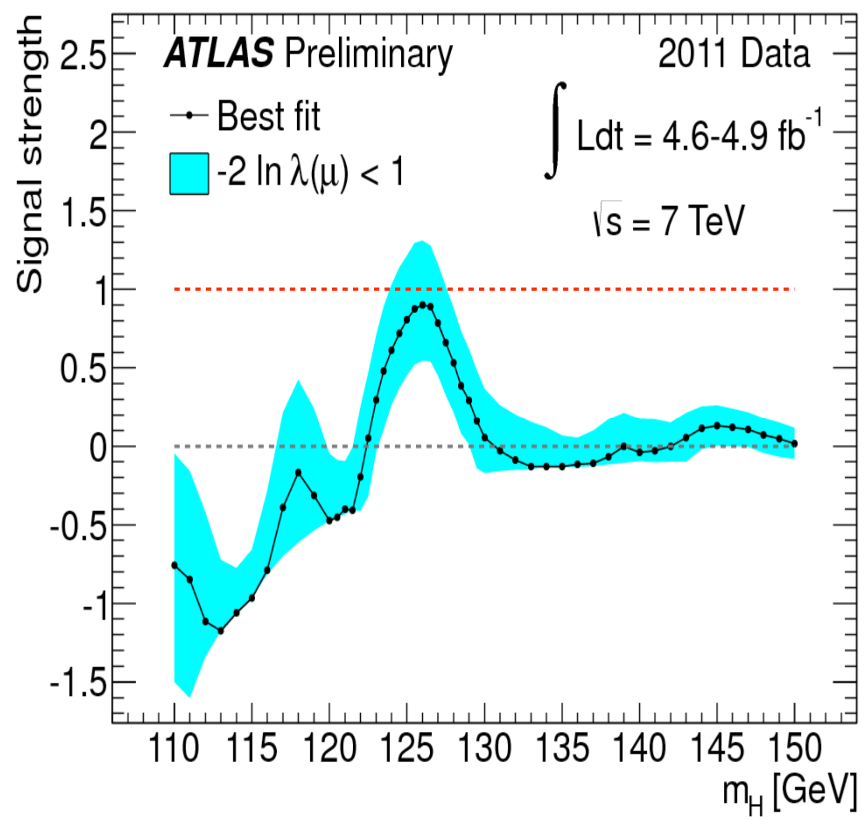
Argonne NATIONAL LABORATORY

NORTHWESTERN UNIVERSITY

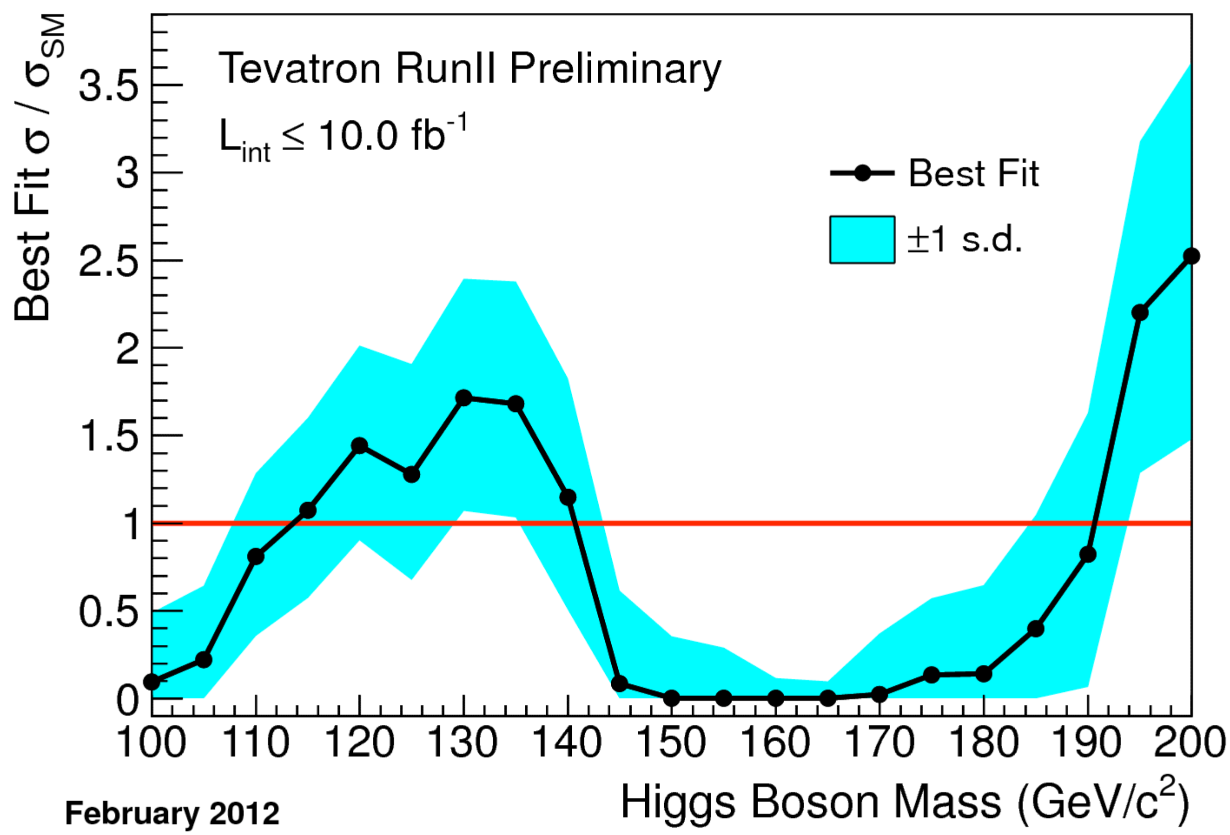
Where is the Higgs boson?

- Both ATLAS and CMS claimed excesses at around 125 GeV!

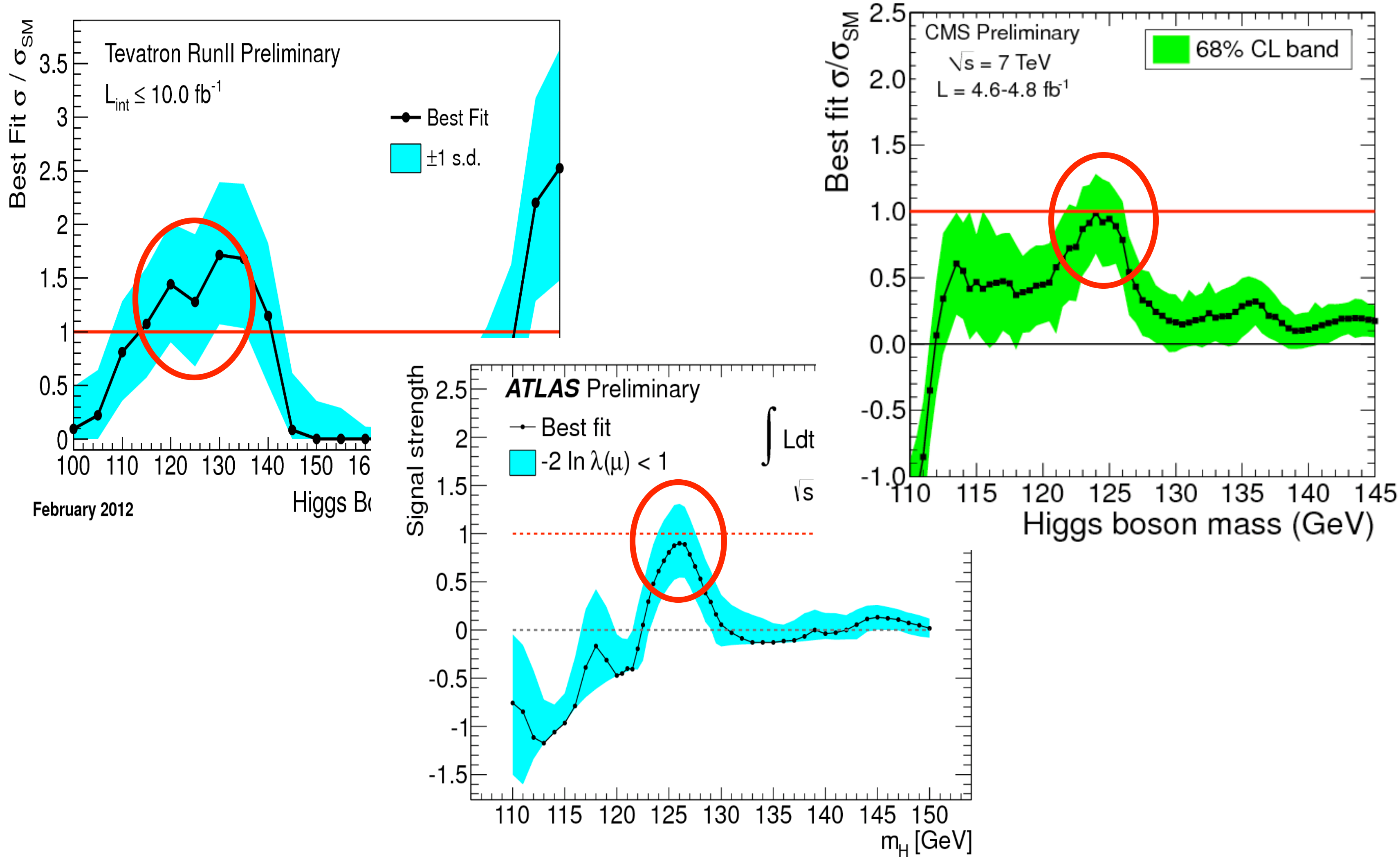




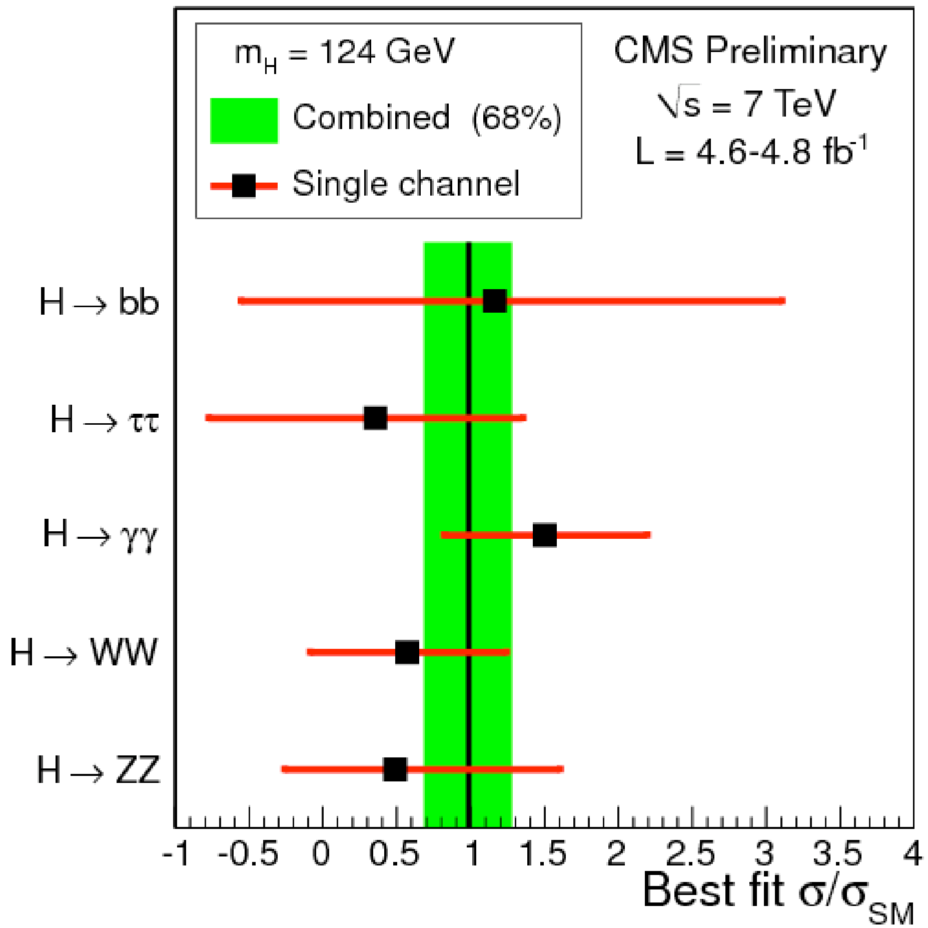
- Tevatron also has excesses in the same region:



- When looking at combined fits, a standard model Higgs is within one sigma range at around 125 GeV:



- Individual channels paint a somewhat different picture (in the eyes of the beholder):



All within one sigma range for CMS!

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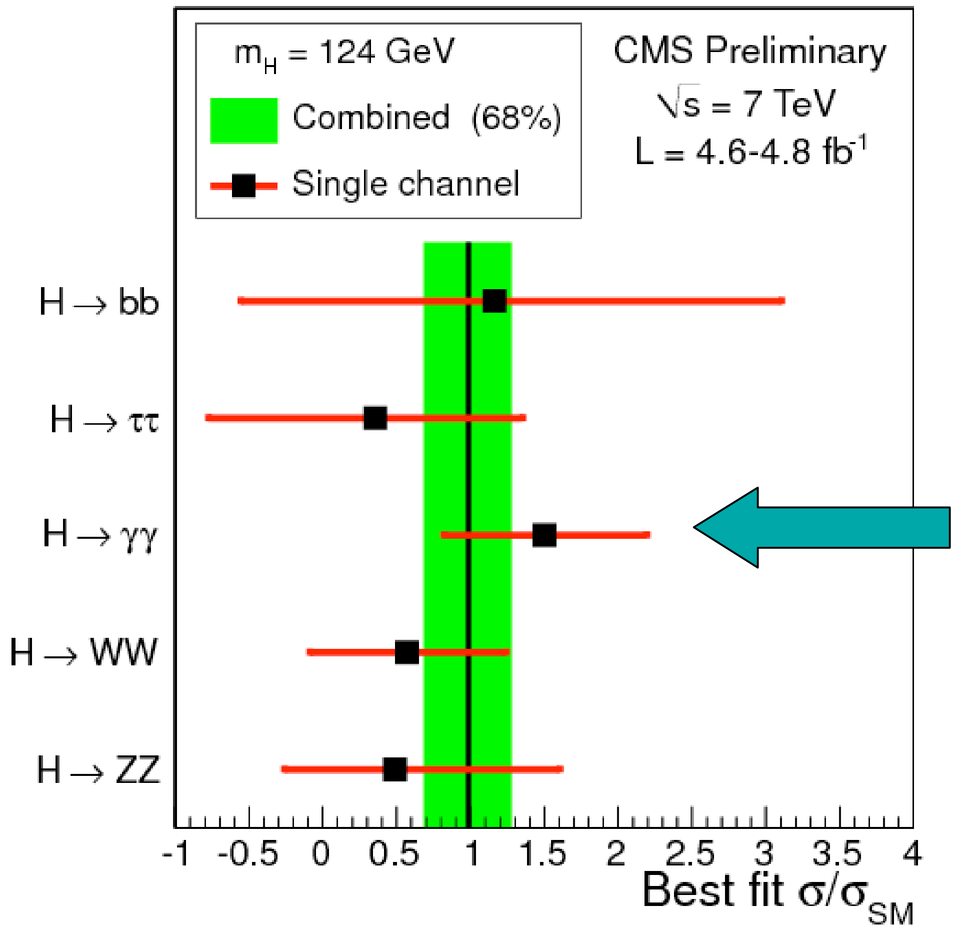

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Slight enhancement in diphoton mode! Not so interesting by itself.

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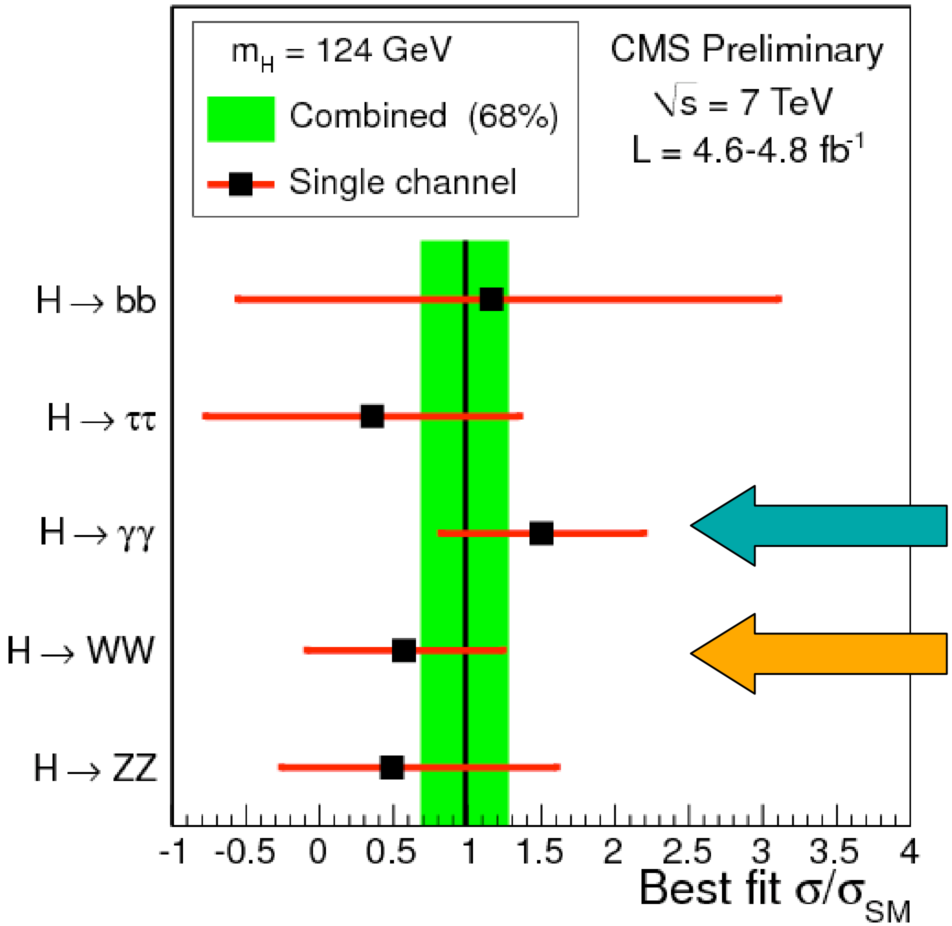
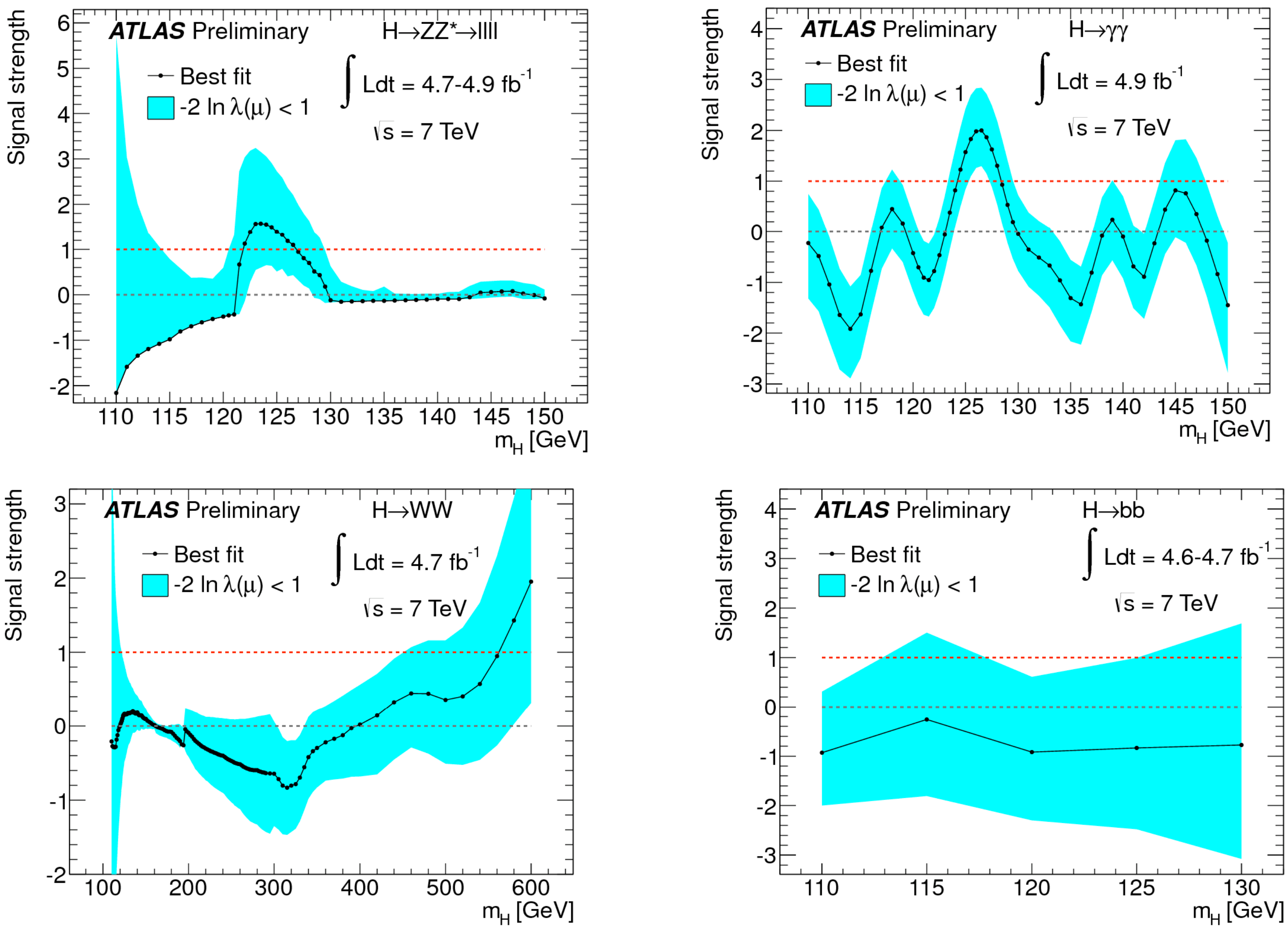


All within one sigma range for CMS!

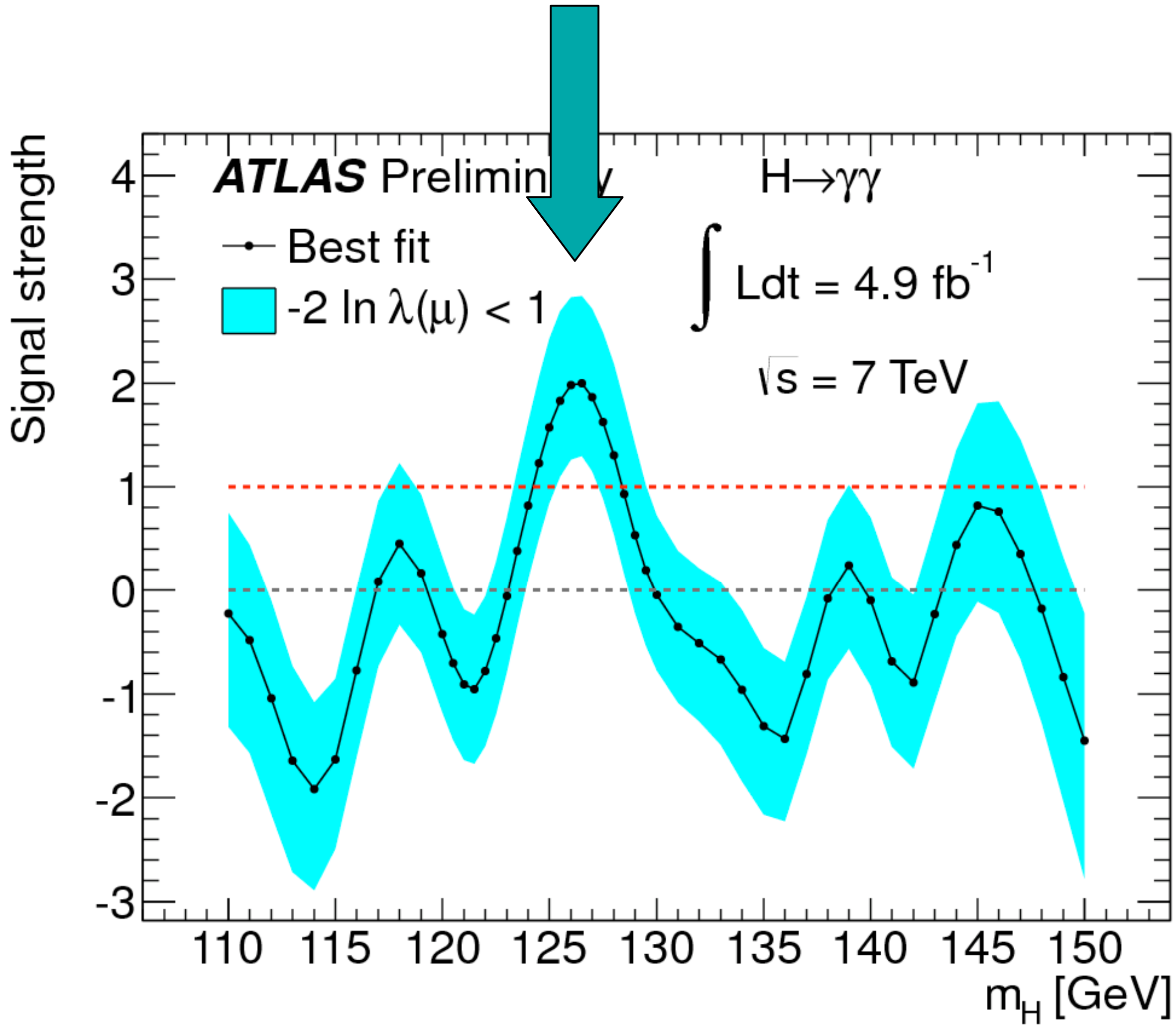
Slight enhancement in diphoton mode! Not so interesting by itself.

Slight reduction in WW mode. Again not so interesting by itself.

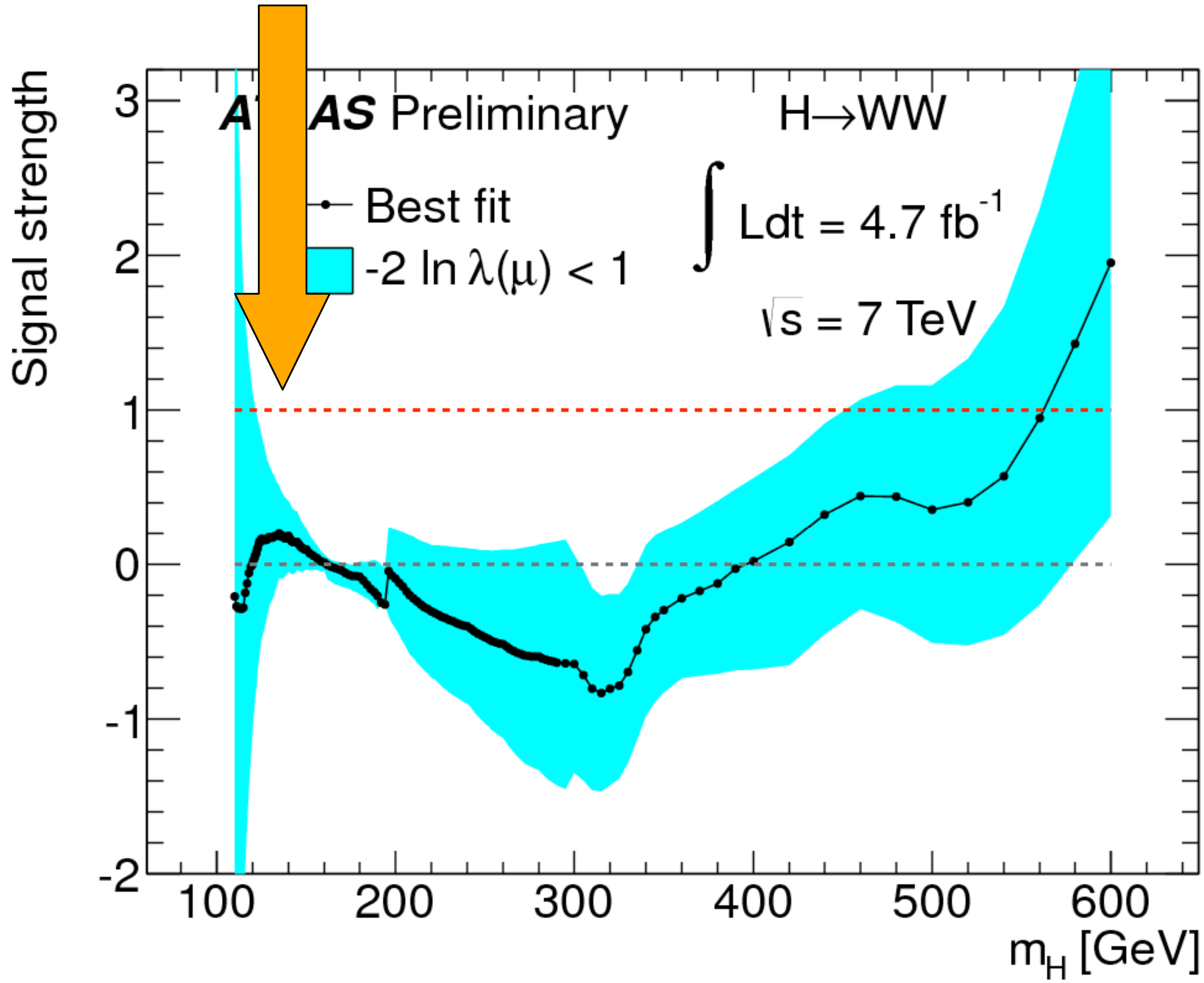
ATLAS has a slightly different story (or Higgs?)



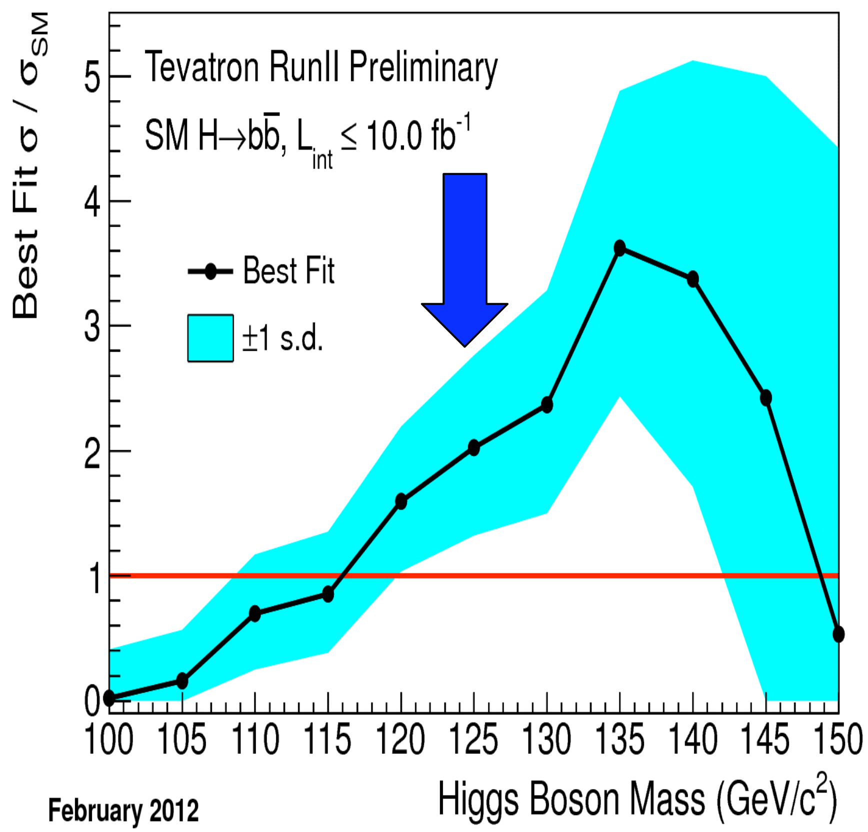
Diphoton excess is one sigma away from SM.
If combined with CMS, should we take it seriously??

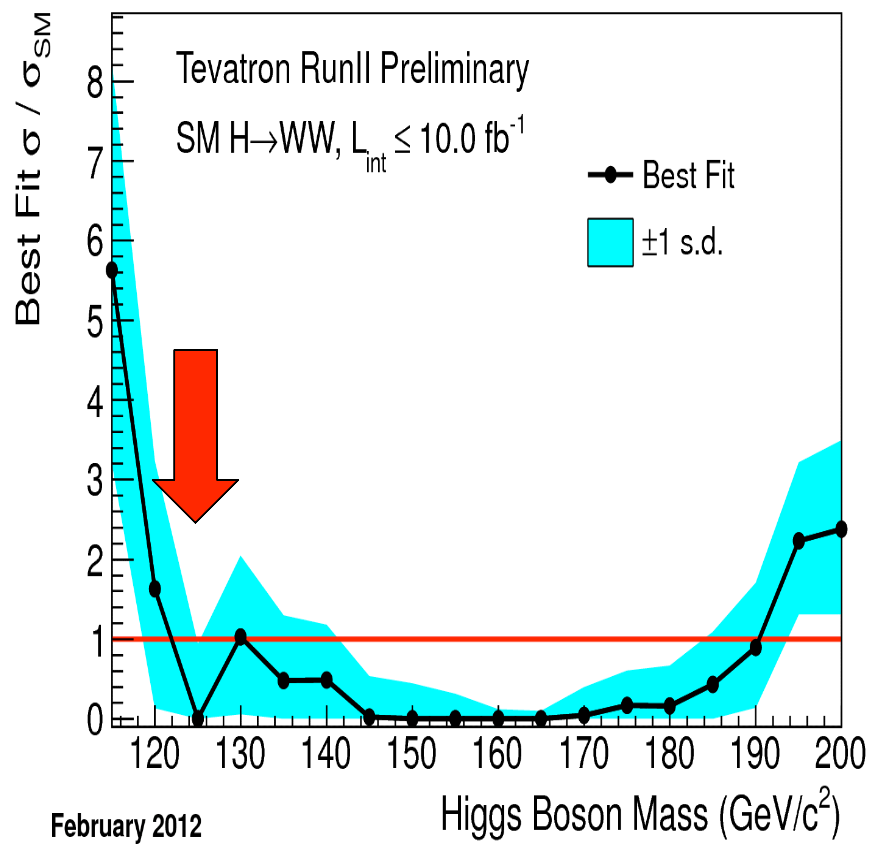


Significant deficit in the WW channel.
In fact, the reduction in CMS is more severe than shown in public…..



- Tevatron excess is driven by bbar channel, which sees enhancement in the 120-130 GeV region.
- But also a deficit in WW channel!





- A lot of people (mostly theorists!) are excited about the excess. Some say “it smells right!”

  (What does a Higgs smell like anyway?)

- Certainly we need more data!

- But we should start piecing together the puzzle now, one way or the other.

Time to start a program of Higgs ID!

- IR identity:
  spin, CP, electroweak quantum numbers.

- UV identity:
  is it supersymmetric?
  is it composite?
  is it extra-dimensional?
  something we never thought of so far??

What are being measured?

- Mass of the Higgs
  (relatively) easy to measure with precision.

- Event rates in bbar, gg, WW, ZZ, and diphoton channels.
  (much) harder to measure with precision.

The annoying thing about the mass:

We can’t predict it!

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There are two free parameters in the Higgs potential:

$$V(H) = \frac{\lambda}{4}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \qquad \langle H \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

The Higgs mass is controlled by the quartic coupling:

$$m_h^2 = \lambda v^2 \ , \qquad v \approx 246 \quad \mathrm{GeV}$$

So knowing the mass gives an estimate on the quartic coupling:

$$m_h \approx 125 \quad \text{GeV} \qquad \Rightarrow \qquad \lambda \approx 0.26$$

In any given theory, the quartic coupling has two generic sources:

$$\lambda = \lambda^{(\text{tree})} + \lambda^{(1-\text{loop})}$$

If the tree-level quartic is already O(1), then
we don't learn much about the theory.
(It's just a free parameter!)

But if the tree-level quartic is small, a large one-loop quartic is needed to get to 125 GeV!

- A new particle with a significant coupling to the Higgs should exist in order to give a large one-loop contribution.

  To achieve this one typically need

$$m_{\rm new} \quad \geq \quad \mathcal{O}(\rm TeV)$$

- But at the same time the new particle introduces additional fine-tuning in the Higgs mass, typically at O(%) or worse!

Not many theories have a small tree-level quartic. The most famous example is

The MSSM: $\lambda_{\mathrm{mssm}}^{(\mathrm{tree})} \leq 0.14$

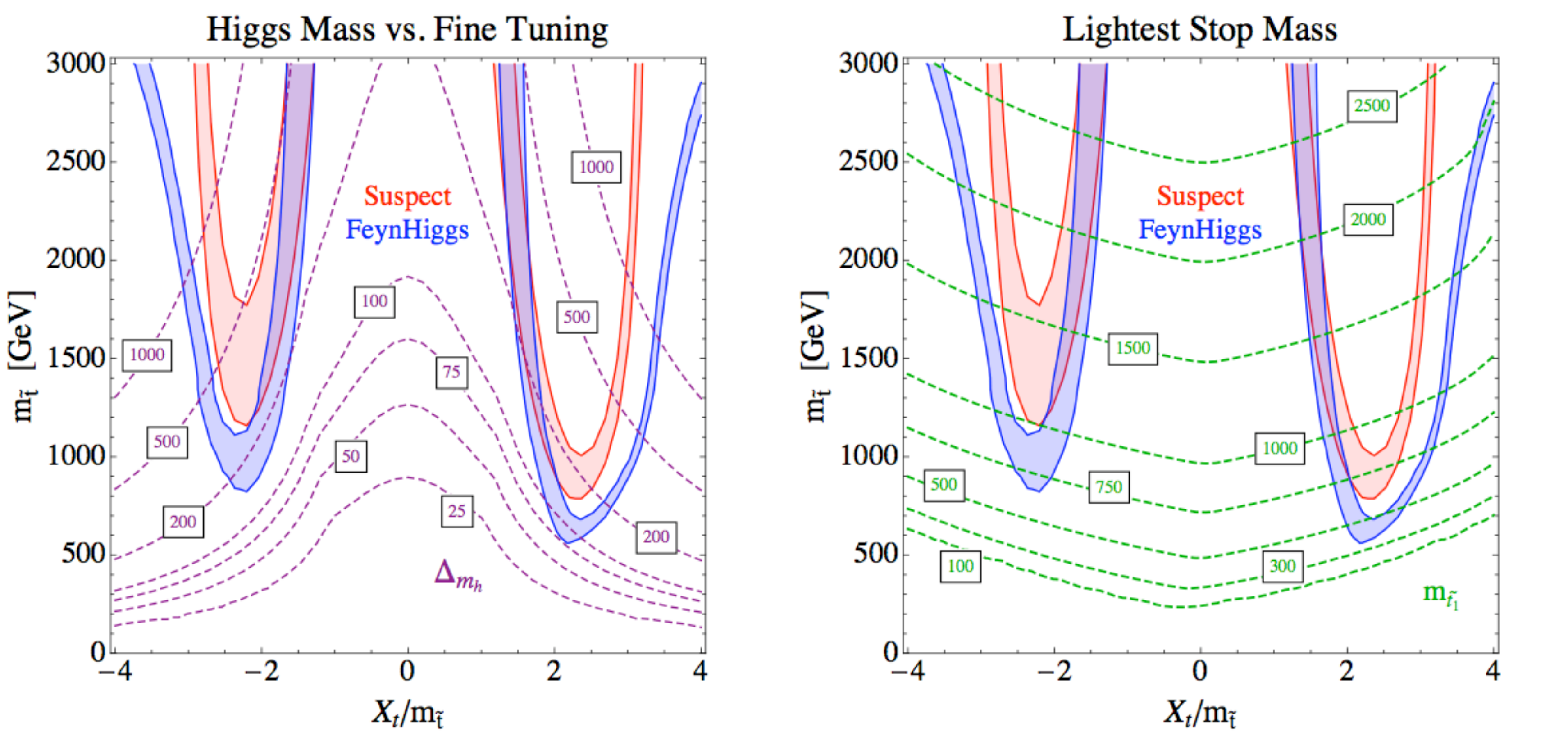
(The less famous example is the Georgi-Kaplan composite Higgs.)

- A 125 GeV Higgs is bad news for the naturalness of this class of theories.
- A 125 GeV Higgs also points to a very specific region of parameter space.

In MSSM if we consider a Higgs mass around 125 GeV,

- Top squarks are heavier than O(1 TeV).
- MSSM fine-tuned at less than one percent level.

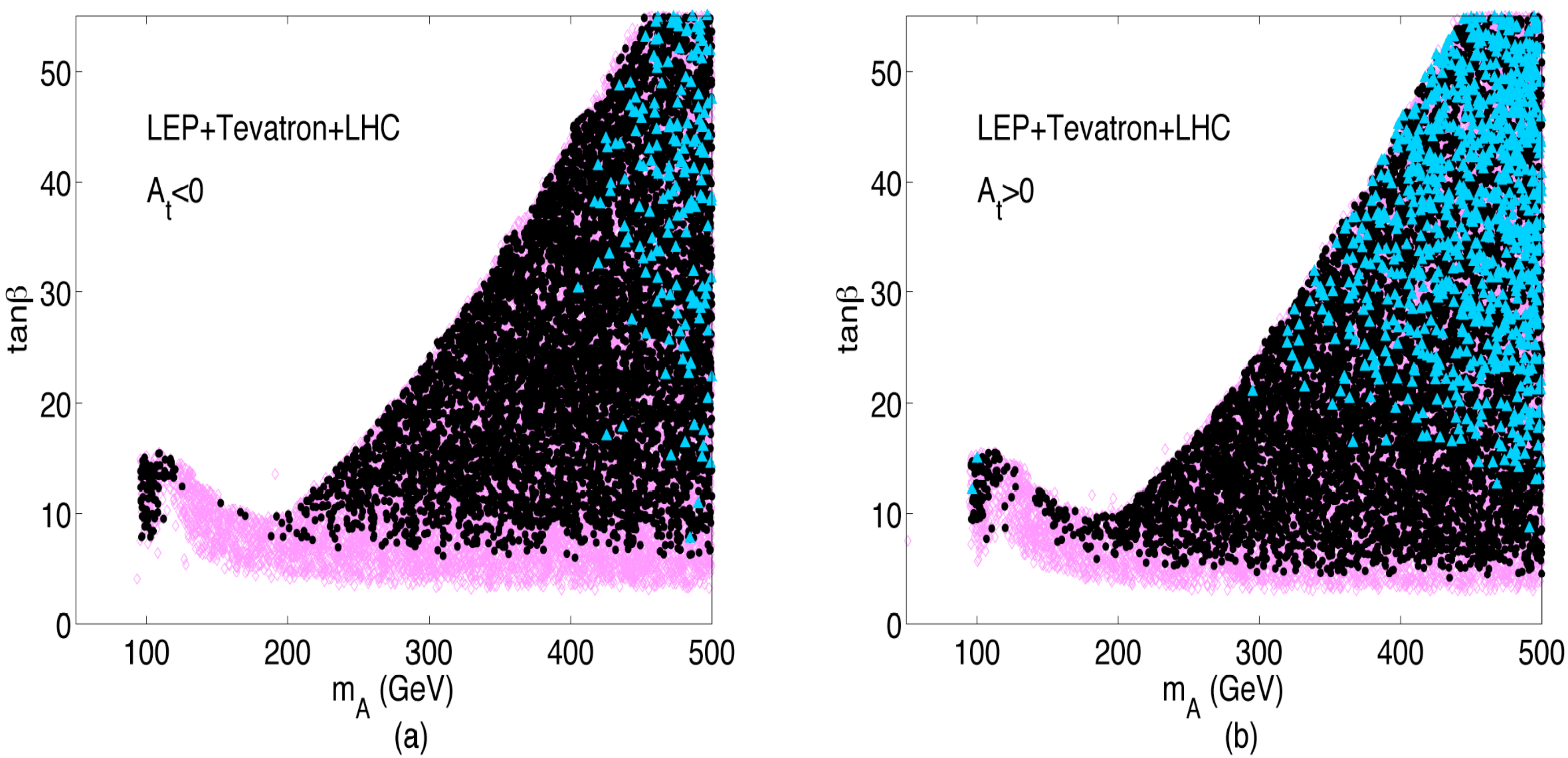
Color bands are for 124-126 GeV mass:



Hall, Spinner, Ruderman: 1112.2703

- Special corners in m_A - $\tan\beta$ plane:

Black dots are for 123-127 GeV mass:



Christensen, Han, Su: 1203.3207

However, once we go outside of MSSM, very little information is carried by the Higgs mass measurements.

Most theories do have a sizeable tree-level quartic coupling.

(Again, Higgs mass is a free parameter and cannot be predicted!)

The good thing about the event rate:

We can predict it!

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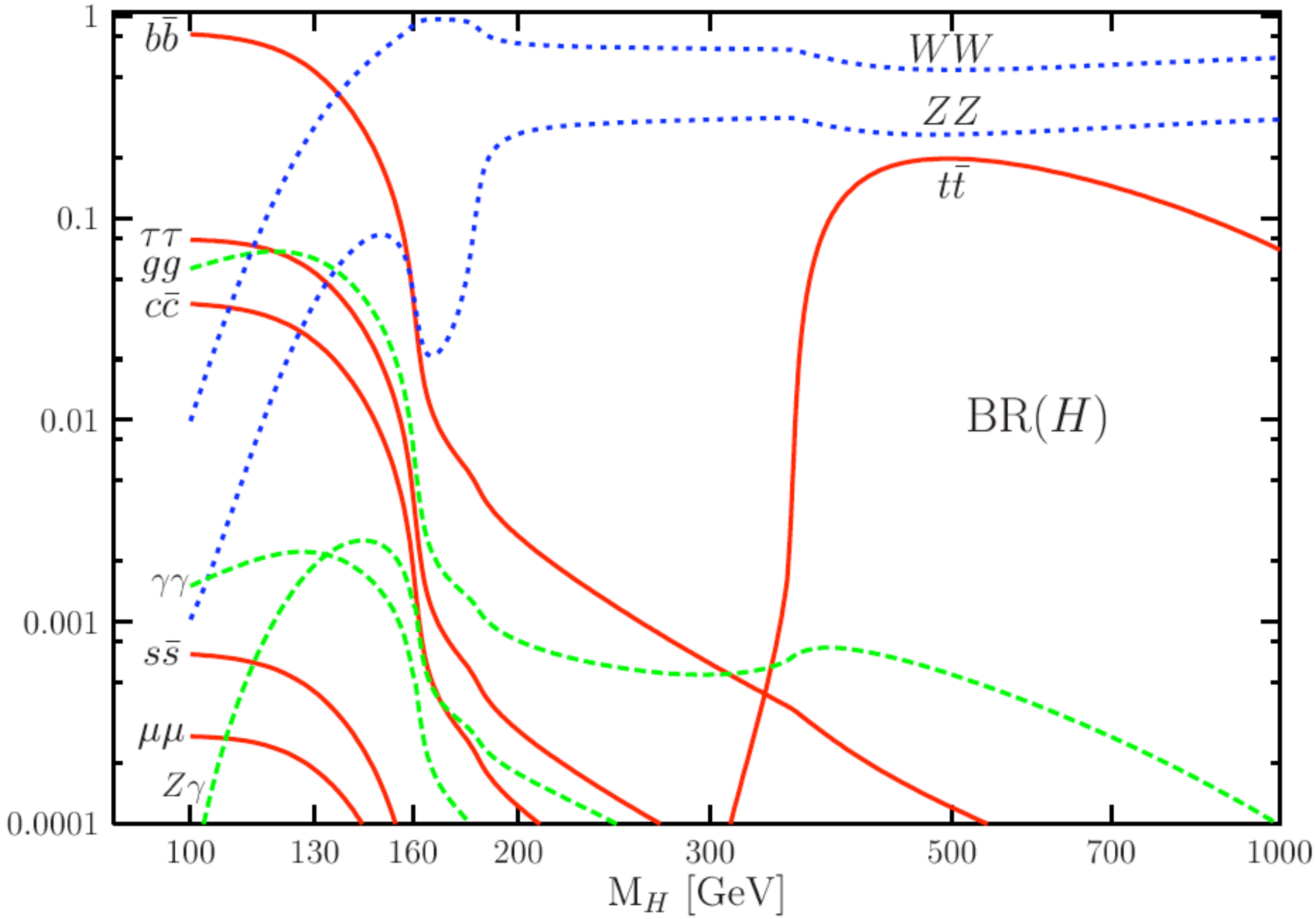

A. Djouadi, hep-ph/0503172

- The event rate is:

$$B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h) \times br(h \to X_{\rm SM})$$

$$br(h \to X_{\rm SM}) = \frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$$

- Two *universal* strength modifiers:
  *) the production cross-section
  *) the total width

  An upper limit on production rate is a lower limit on total width!
  (IL, Schwaller, Shaughnessy, Wagner:1110.4405)

- One *individual* strength modifier:
  *) the partial width

Taking current measurements at face value, we don't see a universally modified signal strength.

→ The deviations should come from the individual partial widths!

A simple (minded) scenario:

$$\Gamma(h \to \gamma\gamma) \;>\; \Gamma^{(\mathrm{SM})}(h \to \gamma\gamma)$$

and/or

$$\Gamma(h \to WW) \;<\; \Gamma^{(\mathrm{SM})}(h \to WW)$$

First consider the enhanced diphoton width.

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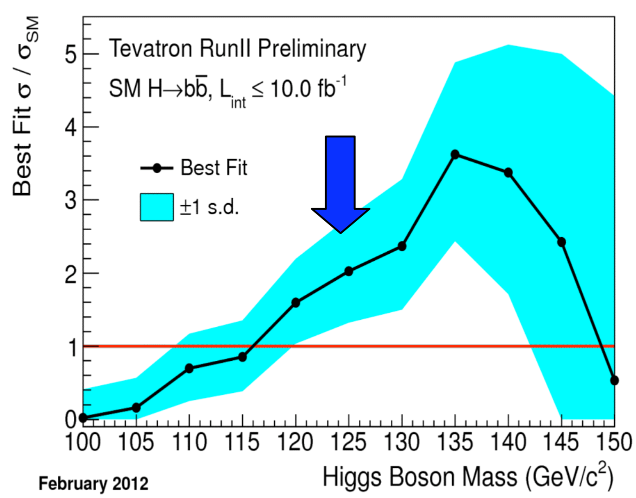
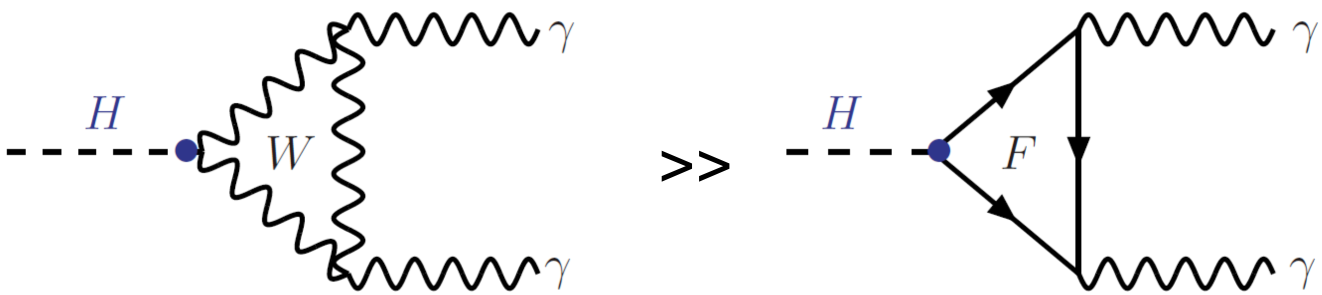
The problem is every other channel will be enhanced universally, which we are not seeing!

Moreover, Tevatron excess is not supporting this claim!



In the SM the diphoton decay is loop-induced:

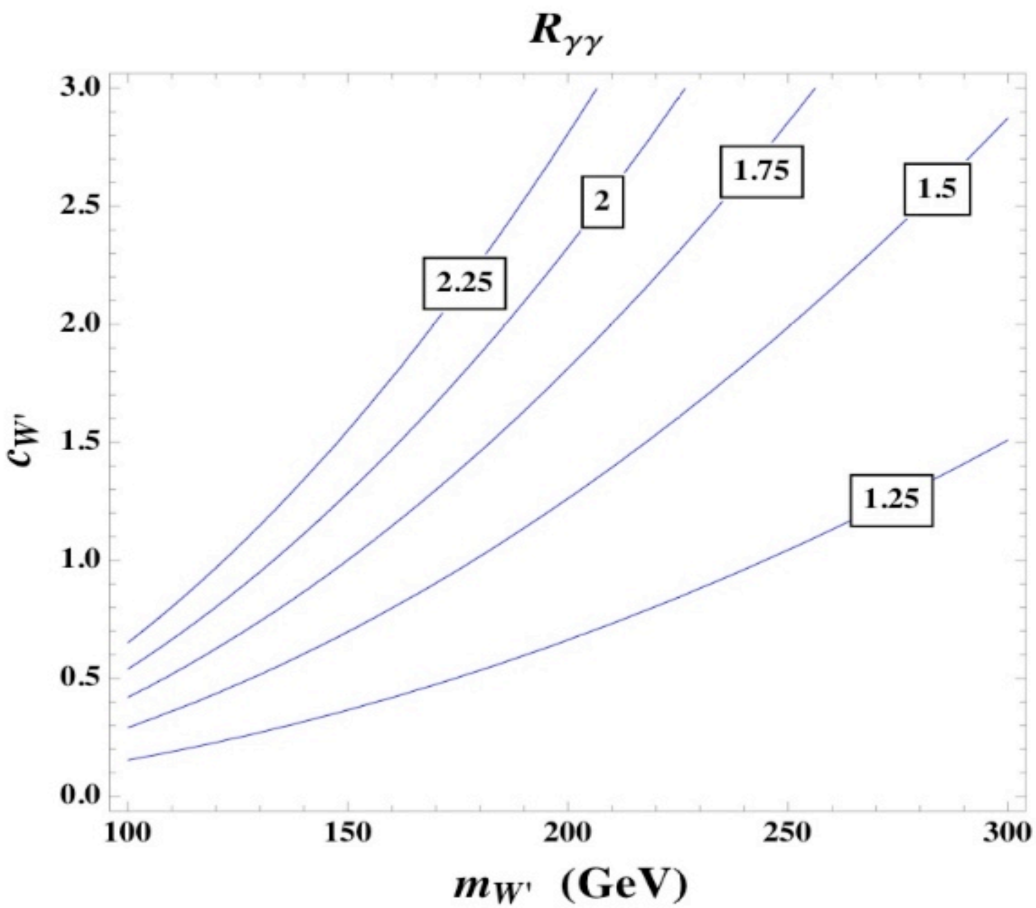


One can add new colorless particles in the loop:

- a new W-prime boson
- a new charged scalar
- a new charged fermion

- Effects of new particles, generically, go like

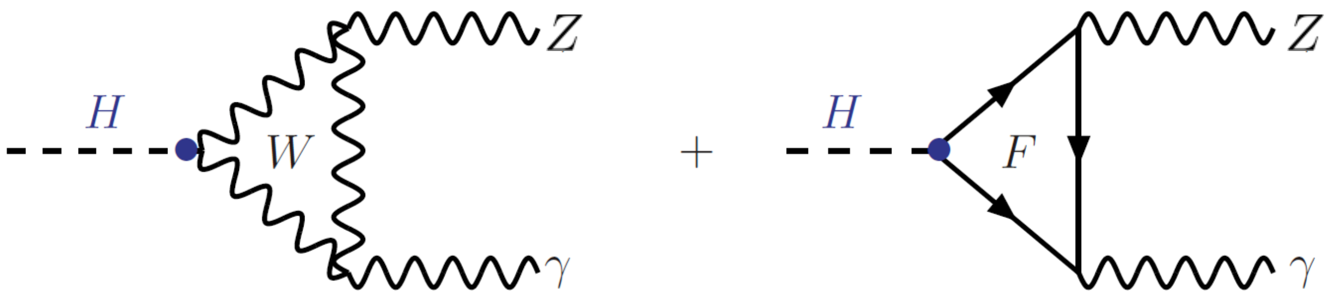
$$\mathcal{O}\left(\frac{v^2}{m_{\rm new}^2}\right) \sim 1 \quad \Rightarrow \quad m_{\rm new} \sim \mathcal{O}(200 \ \ \mathrm{GeV})$$



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

Carena, IL, Wagner: to appear

- Interestingly, a modified diphoton width is accompanied by a modified Z+photon width!



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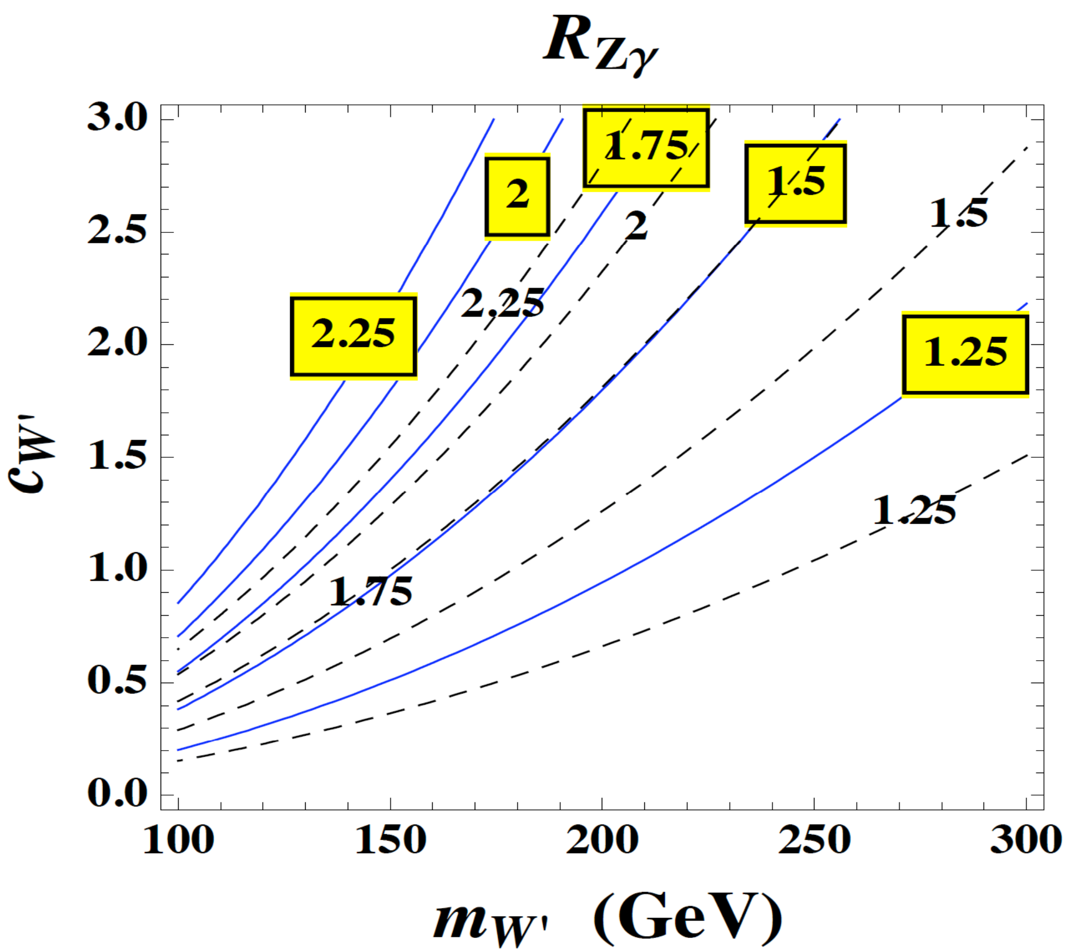
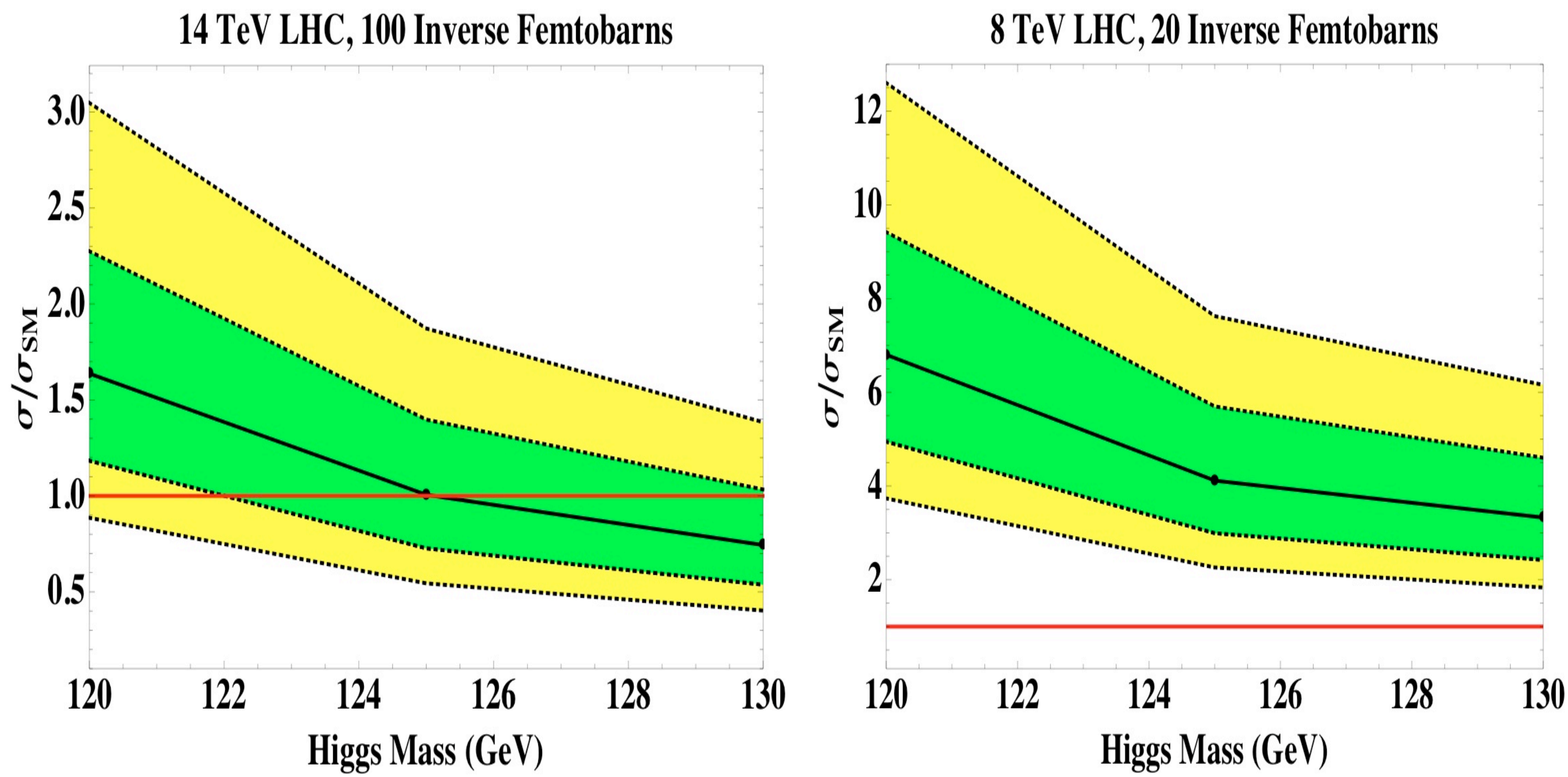


Different new physics gives different correlations!

Carena, IL, Wagner: to appear

- Z+photon seems to have been overlooked in Higgs searches (at least until very recently!)

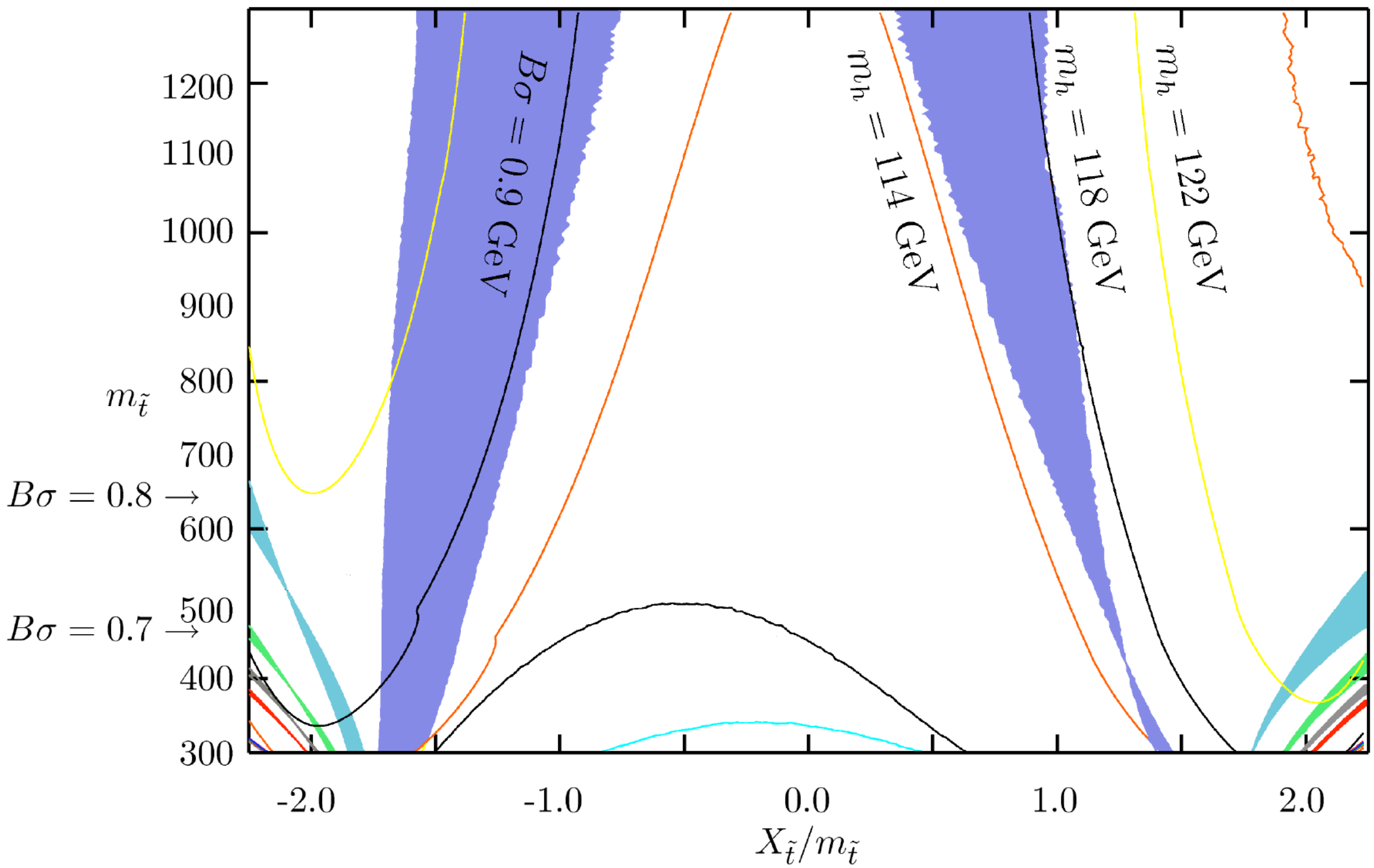


Gainer, Keung, IL, Schwaller:1112.1405v2

One should <u>always</u> combine the rate information with the mass information!

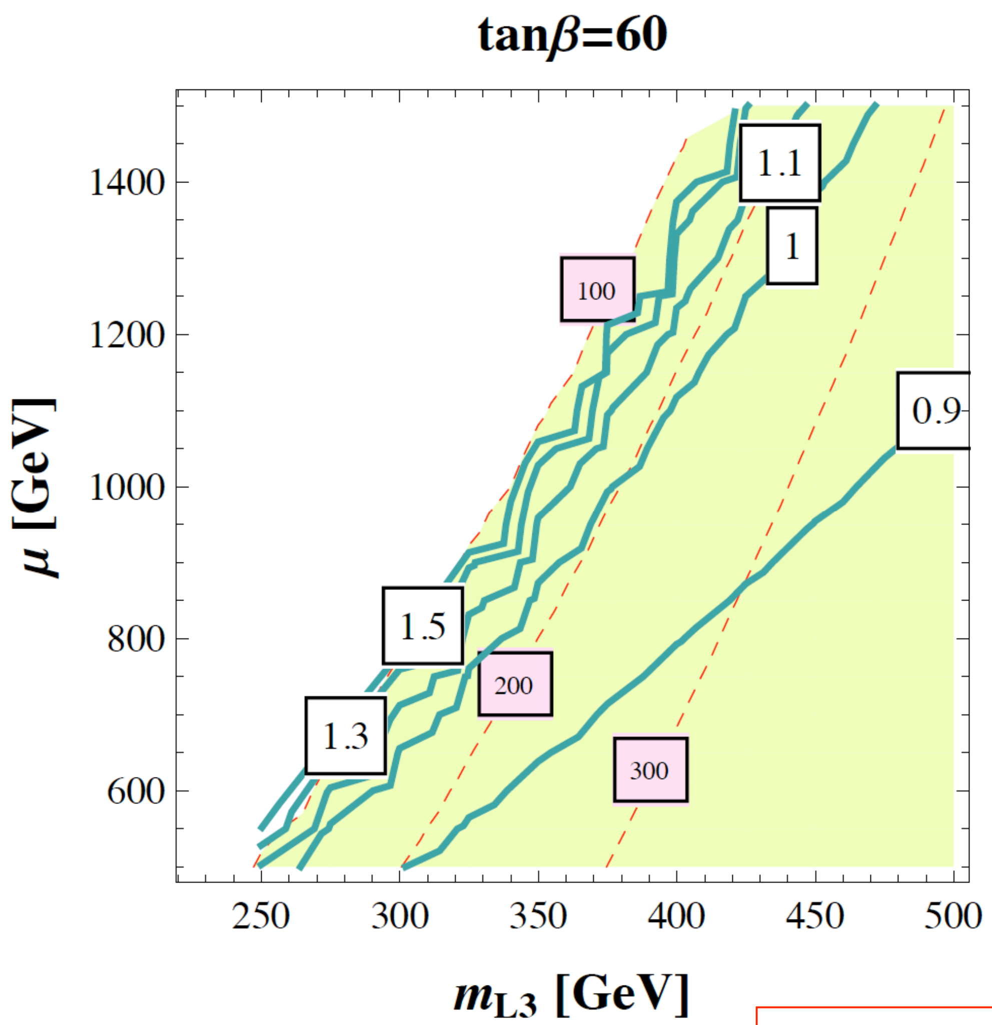
Especially in MSSM, a 125 GeV Higgs is non-generic and already points to special corners of parameter space!

- It turns out it's even less generic to get an enhanced diphoton signal!



IL and Shalgar: 0901.0266

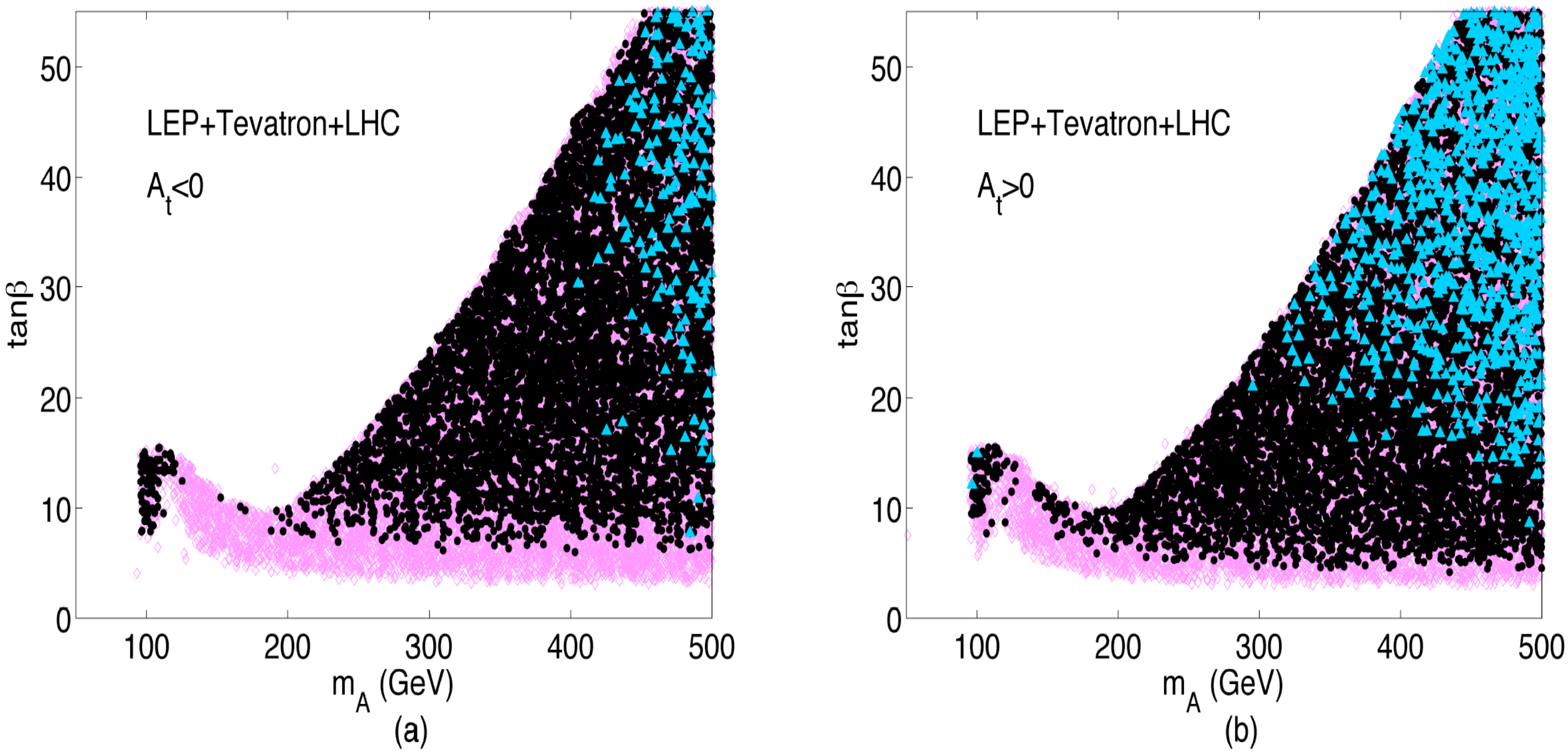
- The only way to get an enhanced diphoton width in MSSM is to have very light staus, close to the LEP limit of 100 GeV.



Carena, Gori, Shah, Wagner:1112.3336

- Including the rate information, even more special corners in m_A -tanβ plane:

Light blue triangles are from requiring $B\sigma(pp \to h \to \gamma\gamma)_{\mathrm{MSSM}} > 80\% \times B\sigma_{\mathrm{SM}}$



Christensen, Han, Su: 1203.3207

Next consider a reduced WW width.

In the SM Higgs couplings to WW and ZZ are fixed by gauge symmetry:

$$g_{hWW/ZZ} = 2\frac{m_{W/Z}^2}{v} \,, \quad \frac{g_{hWW}}{g_{hZZ}} = \frac{m_W^2}{m_Z^2} = c_w^2\,(1+\mathcal{O}(\%))$$

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

As a result, a 125 GeV "SM" Higgs should have

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

These statements are derived assuming the Higgs is a doublet under $SU(2)_L$.

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,

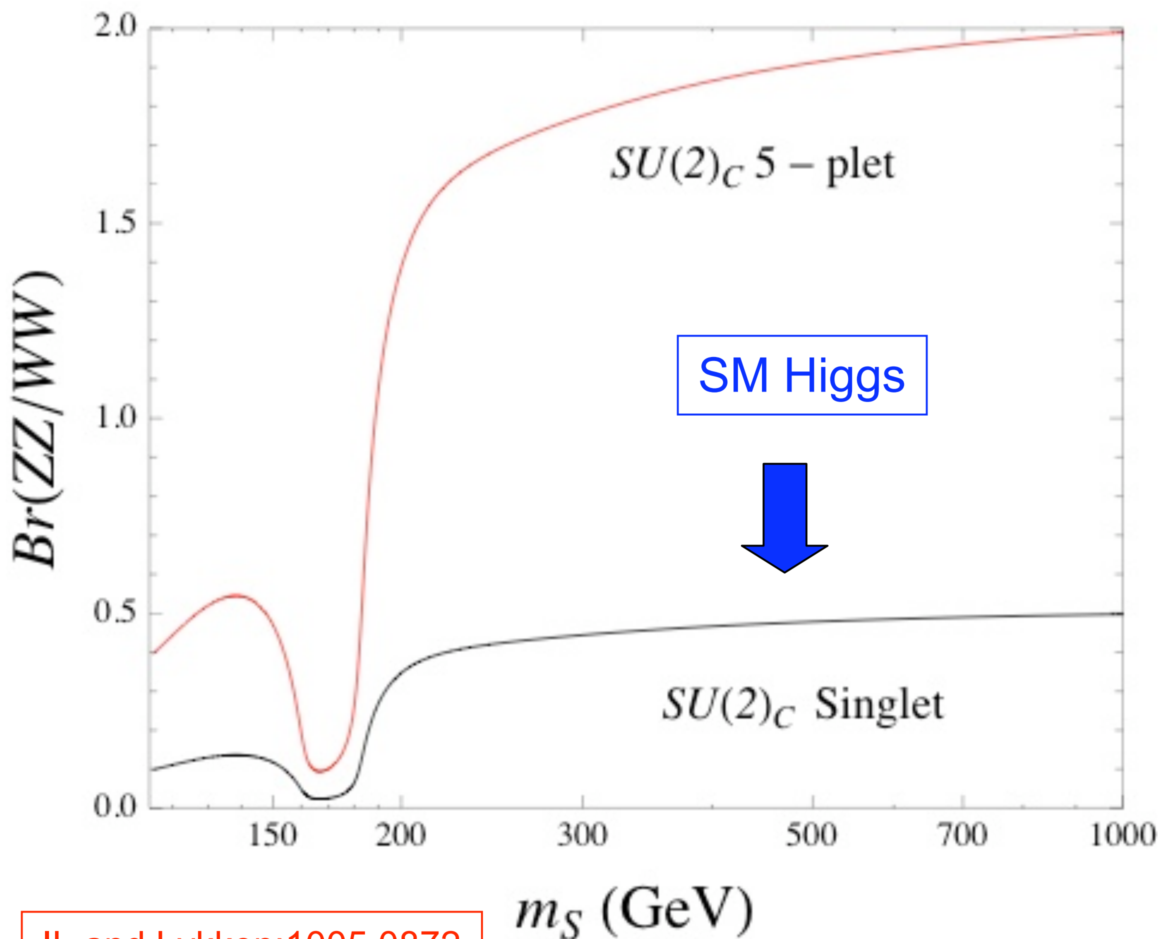
$$\frac{g_{h_5^0 WW}}{g_{h_5^0 ZZ}} = -\frac{c_w^2}{2}$$

which implies a reduced WW coupling relative to ZZ coupling!

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

IL and Lykken:1005.0872

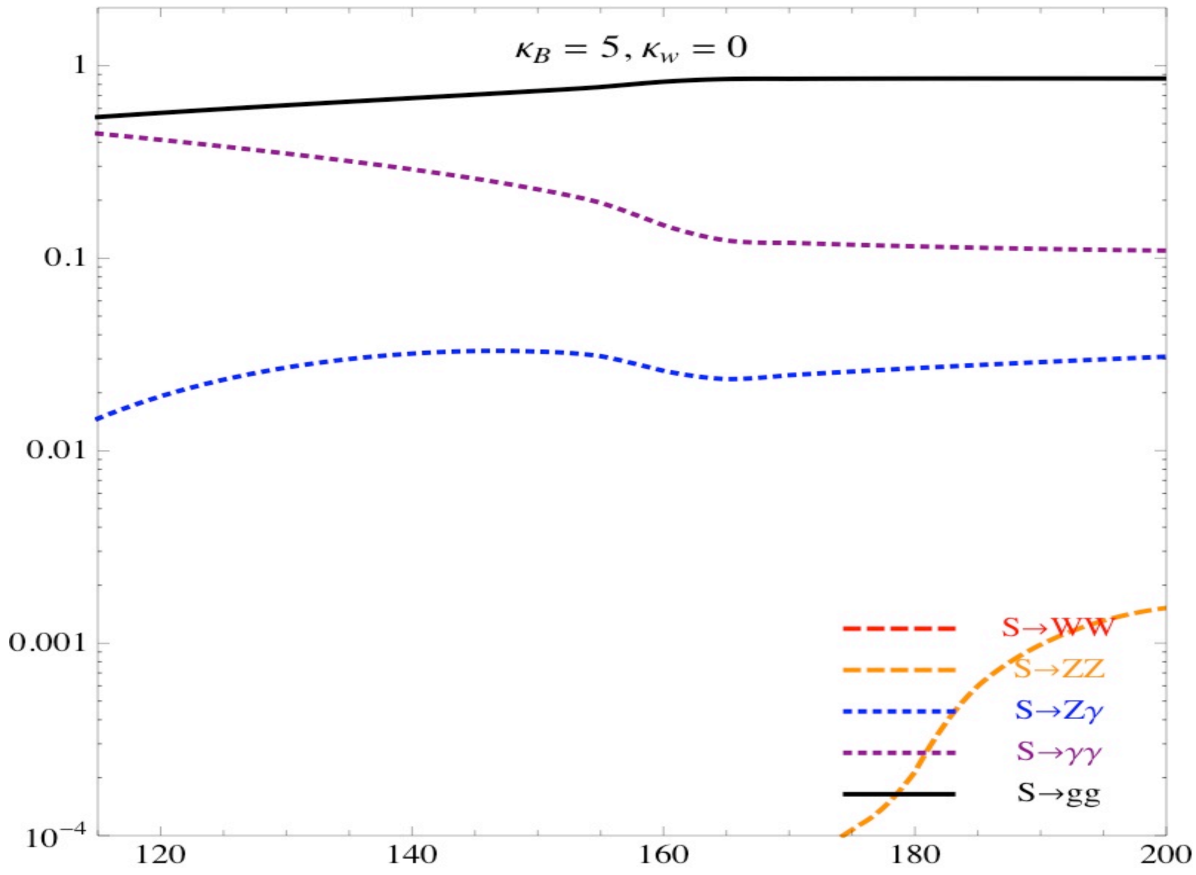
- So when normalizing to the ZZ width, WW width is reduced from the SM expectation by a factor of 4!



IL and Lykken:1005.0872

One concrete model is the Georgi-Machacek model, where there are electroweak triplet scalars

- If there is an electroweak singlet scalar, the WW channel could even disappear all together:



IL, Lykken, Shaughnessy:1105.4587

Where do we go from here?

- More bang for the buck out of Higgs searches.

  → measure those angular correlations!

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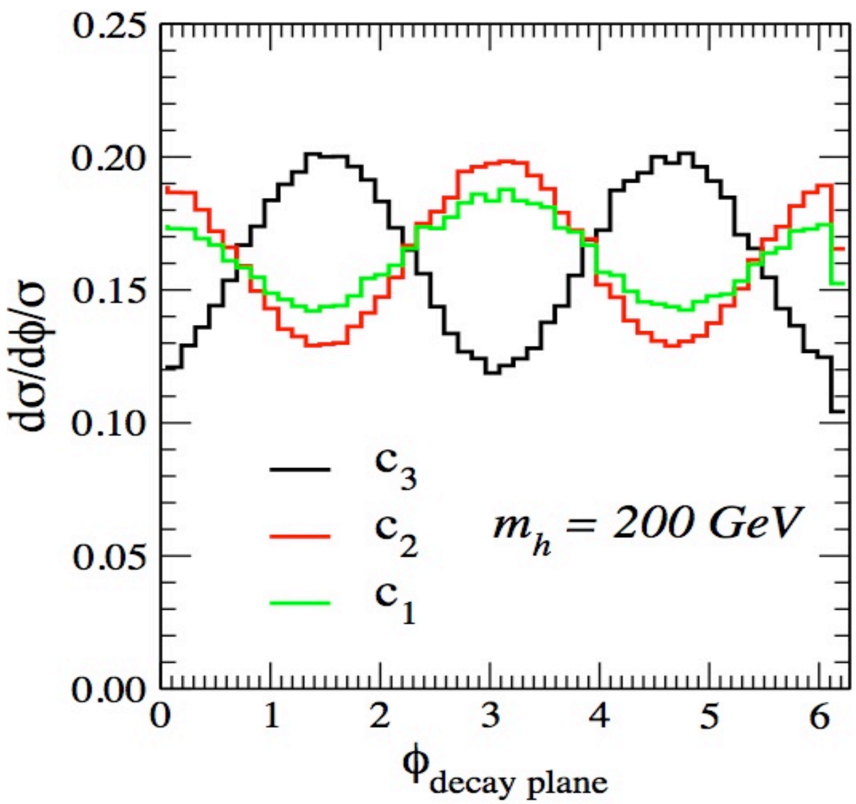
  angular correlations in the 4l channel allow for determination of spin and CP property of the resonance:



$$\frac{1}{2} m_S \, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2} \frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4} \frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

Cao, Jackson, Keung, IL, Shu:0911.3398
See also
Gao et al: 1001.3396
De Rujula et al:1001.5300

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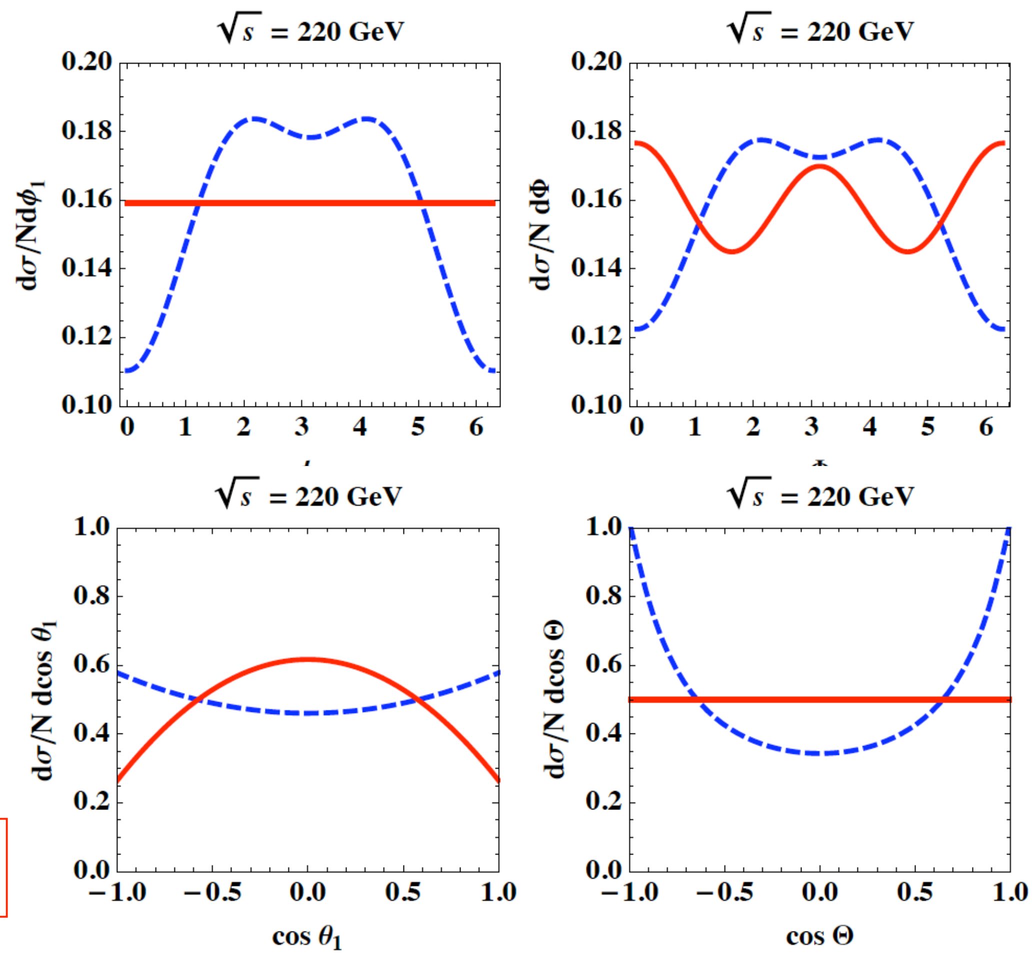
- More bang for the buck out of Higgs searches.

  angular correlations also allows for better separation of background and signal:



Gainer, IL, Kumar, Vega-Morales:1108.2274

Where do we go from here?

- We need to measure all five decay channels into pairs of vector bosons.

→ WW, ZZ, $\gamma\gamma$, gg (production), and don't forget about Zγ!

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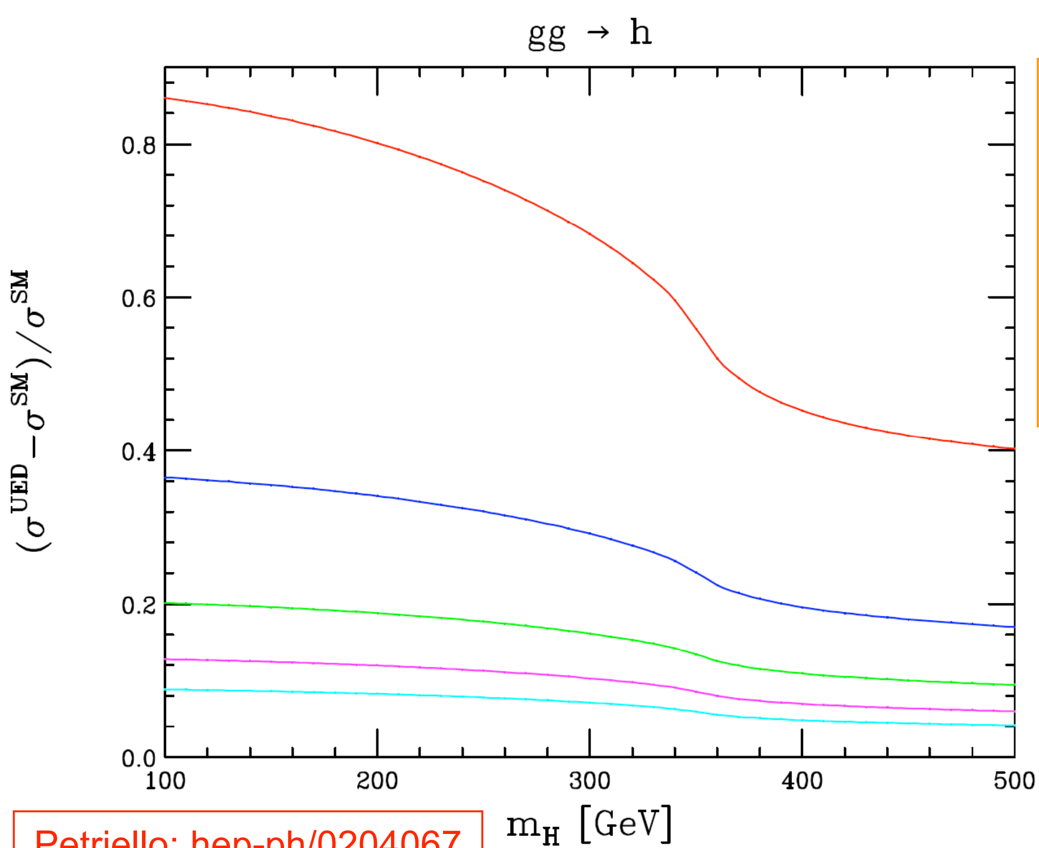
- We need to measure all <u>five</u> decay channels into pairs of vector bosons.

Couplings to two gluons are especially useful in discerning models:



In models where the Higgs mass is fine-tuned, the production rate is *enhanced*!

Example: minimal universal extra-dimensional model.

Petriello: hep-ph/0204067

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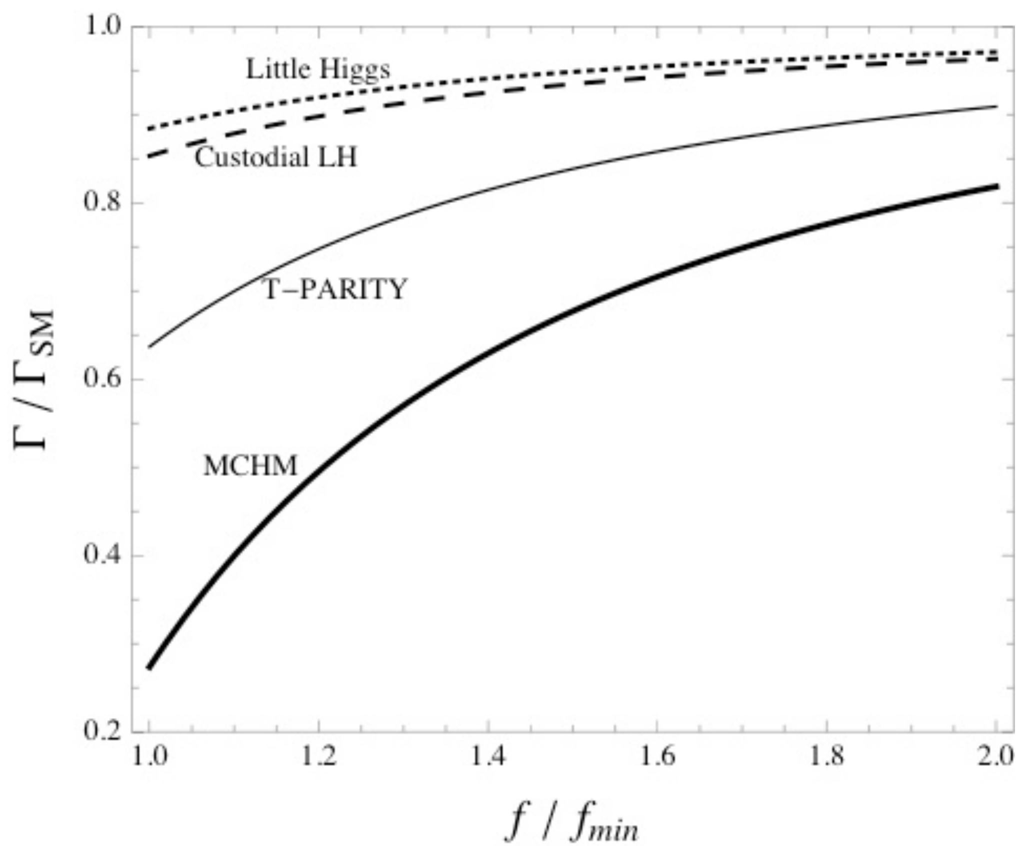


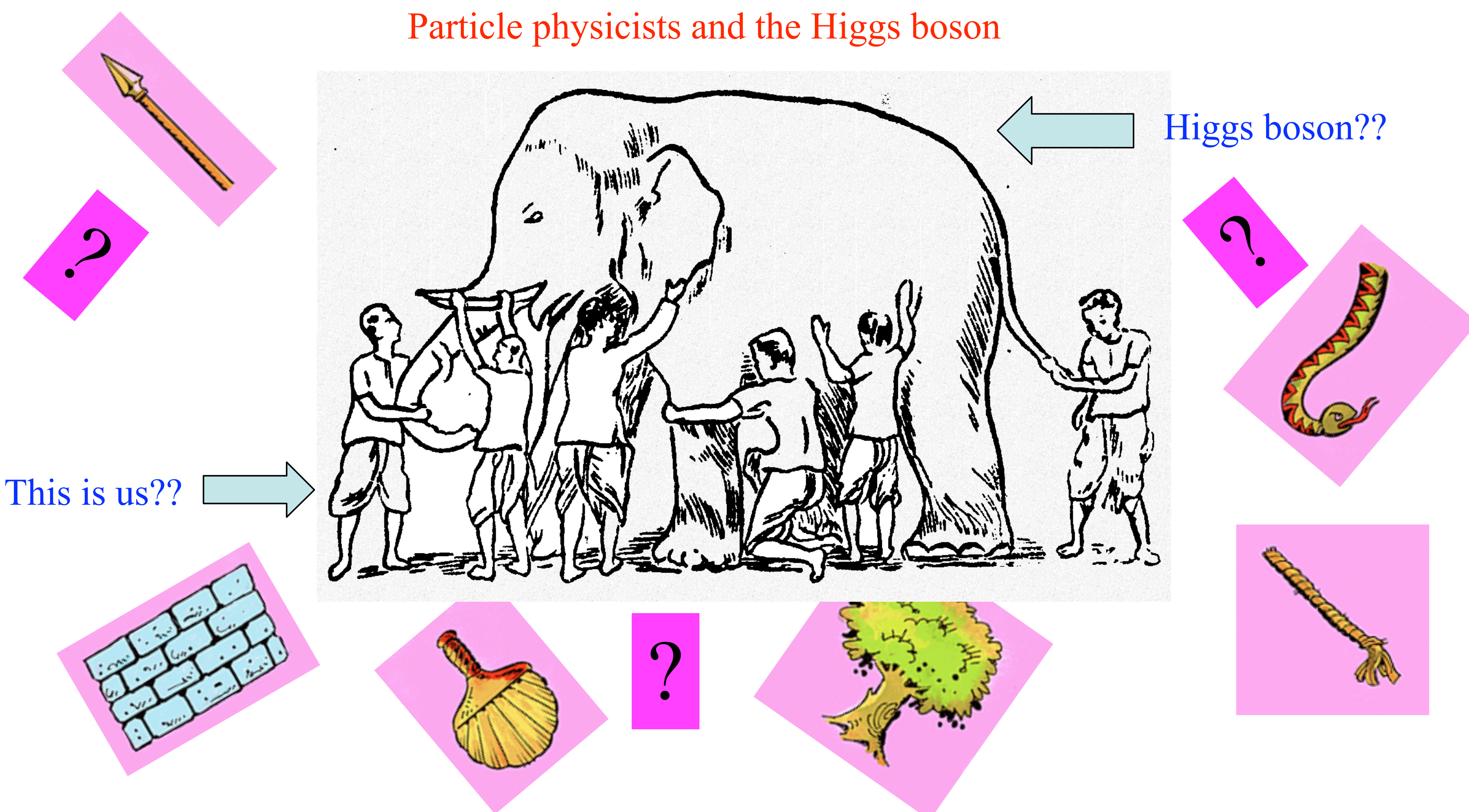
In models where the Higgs mass is natural, the production rate is *reduced*!

Example: composite Higgs models.

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

Via AdS/CFT, the same holds for warped extra-dimension!

A final remark:
Whatever you choose to believe in, always keep an open mind on other possibilities!



Let’s not discover an elephant like this: