

Theoretical Implications of Experimental Results

Matt Strassler

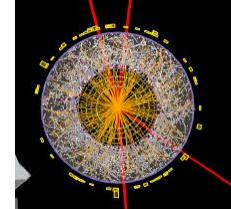
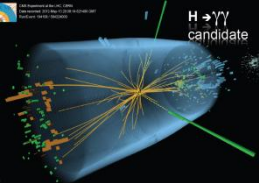
Higgs Hunting, Orsay, July 2012

Theoretical Implications of Experimental Results:

If Only I Knew

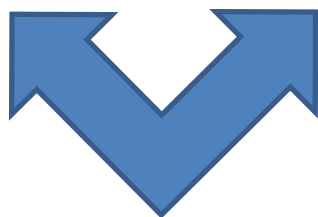
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Higgs Hunting, Orsay, July 2012



SM Not
Immediately
Excluded

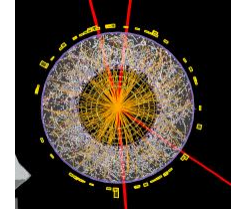
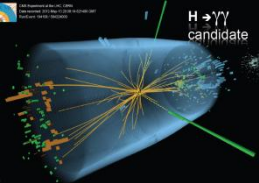
SM Immediately
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H-like Particle Observed

No H-Like Particle
Observed





SM Not
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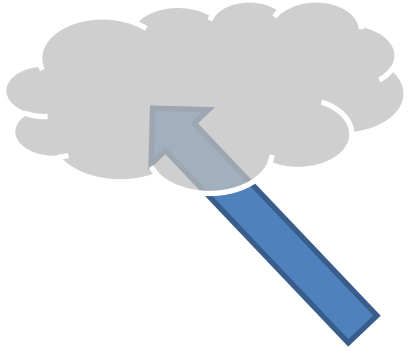
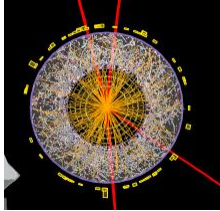
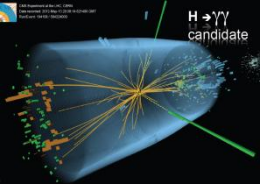
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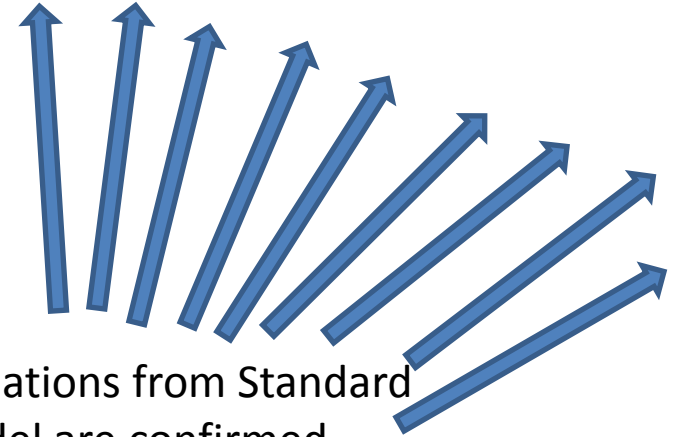
H-like Particle Observed

No H-Like Particle
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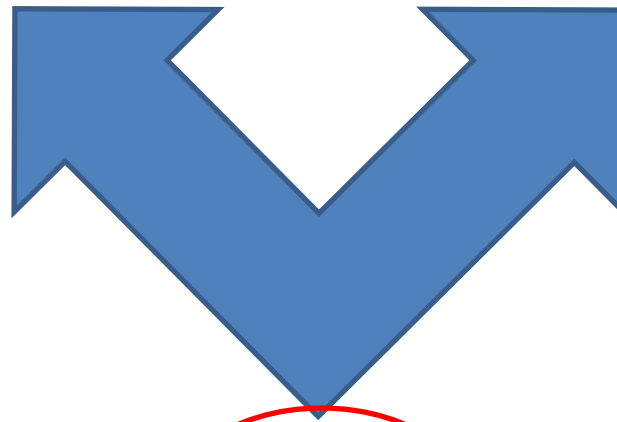




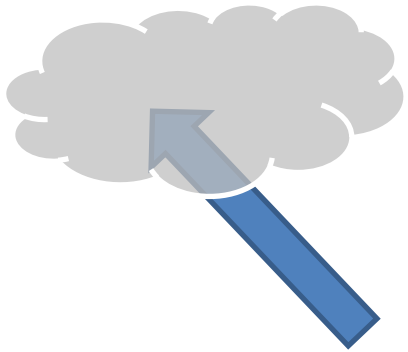
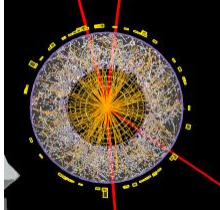
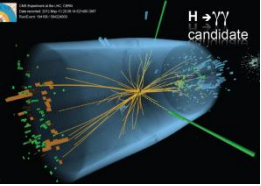
Standard Model successfully describes all LHC and pre-LHC particle physics data to within available precision



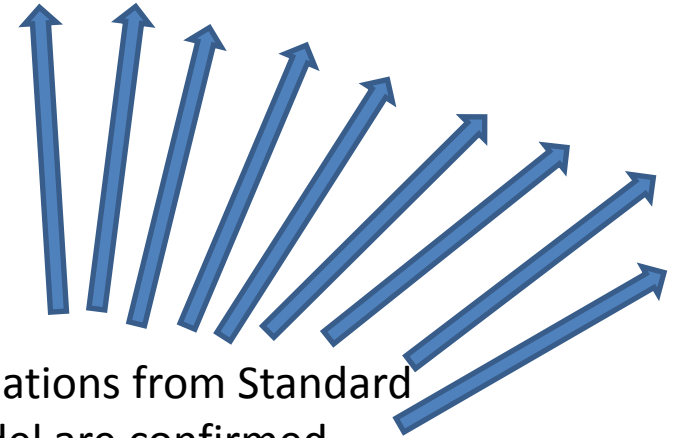
Deviations from Standard Model are confirmed



SM Not Immediately Excluded



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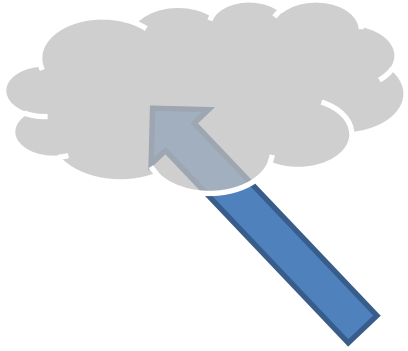
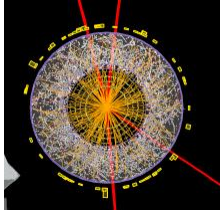
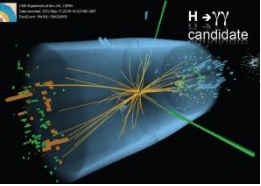


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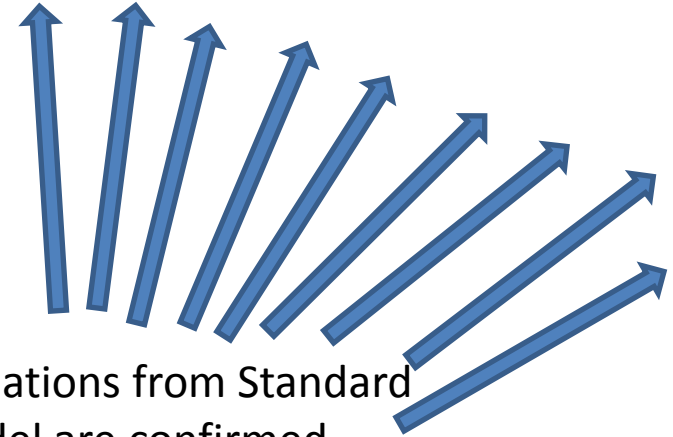


SM Not Immediately Excluded

The theoretical implications depend crucially on what these deviations are



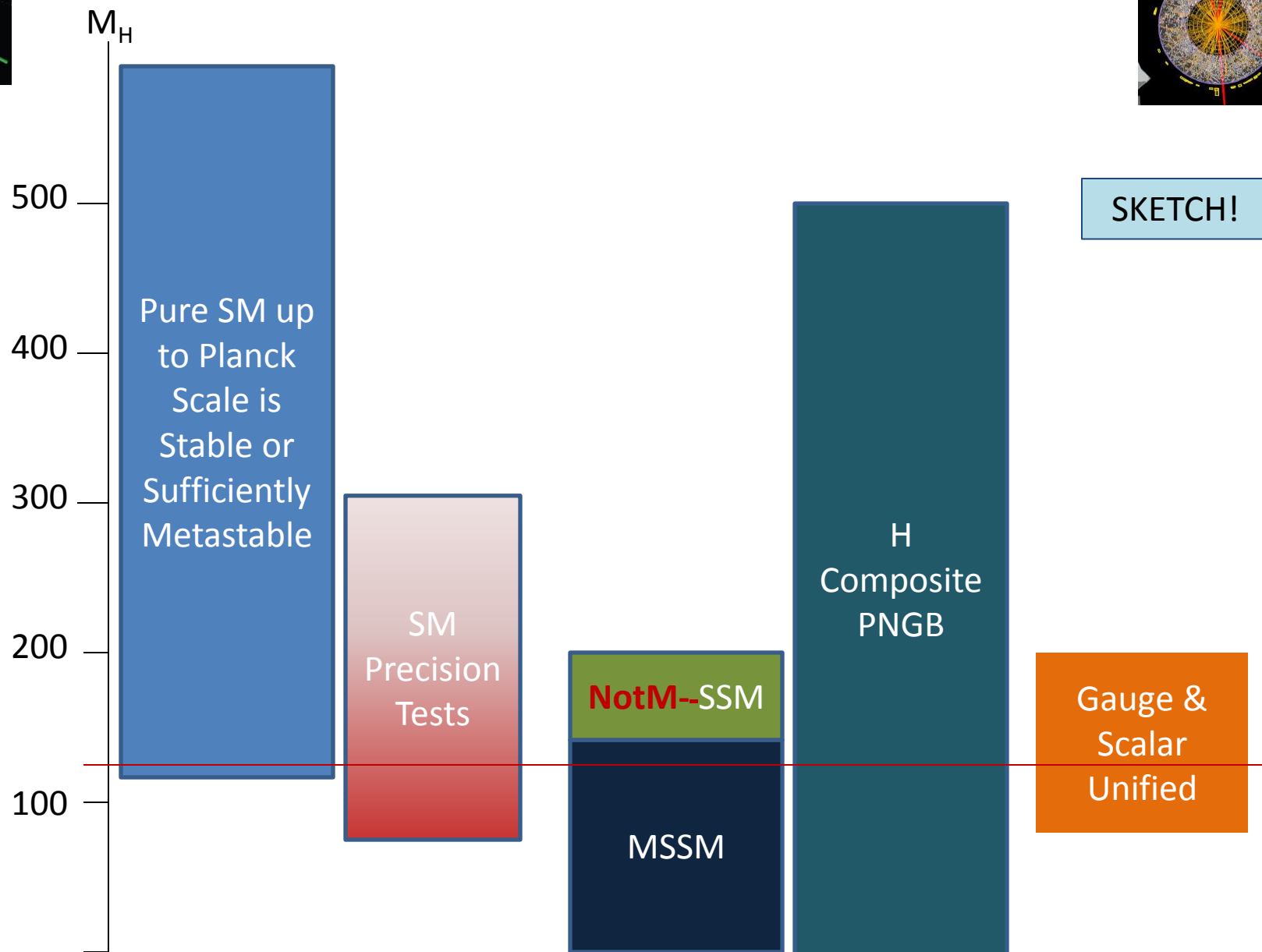
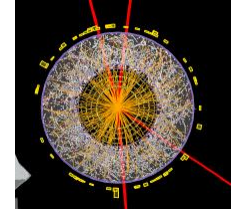
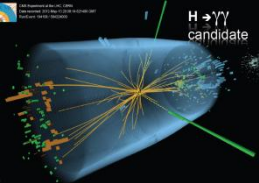
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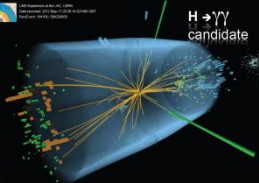


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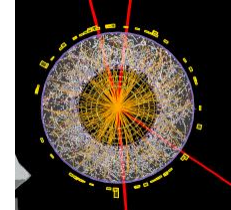
The theoretical implications are so deep and unclear as to be difficult to formulate

SM Not Immediately Excluded

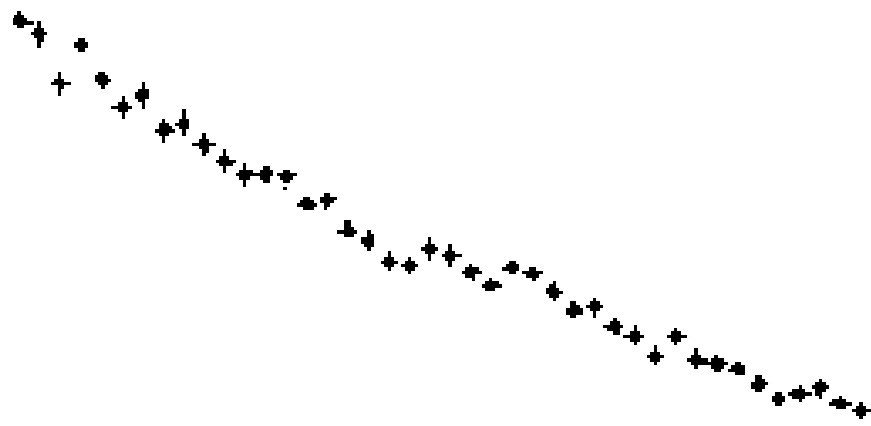
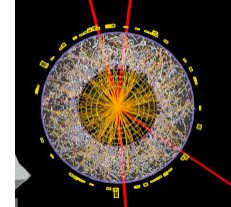
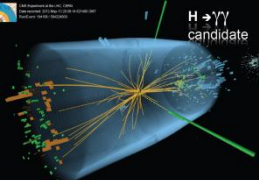


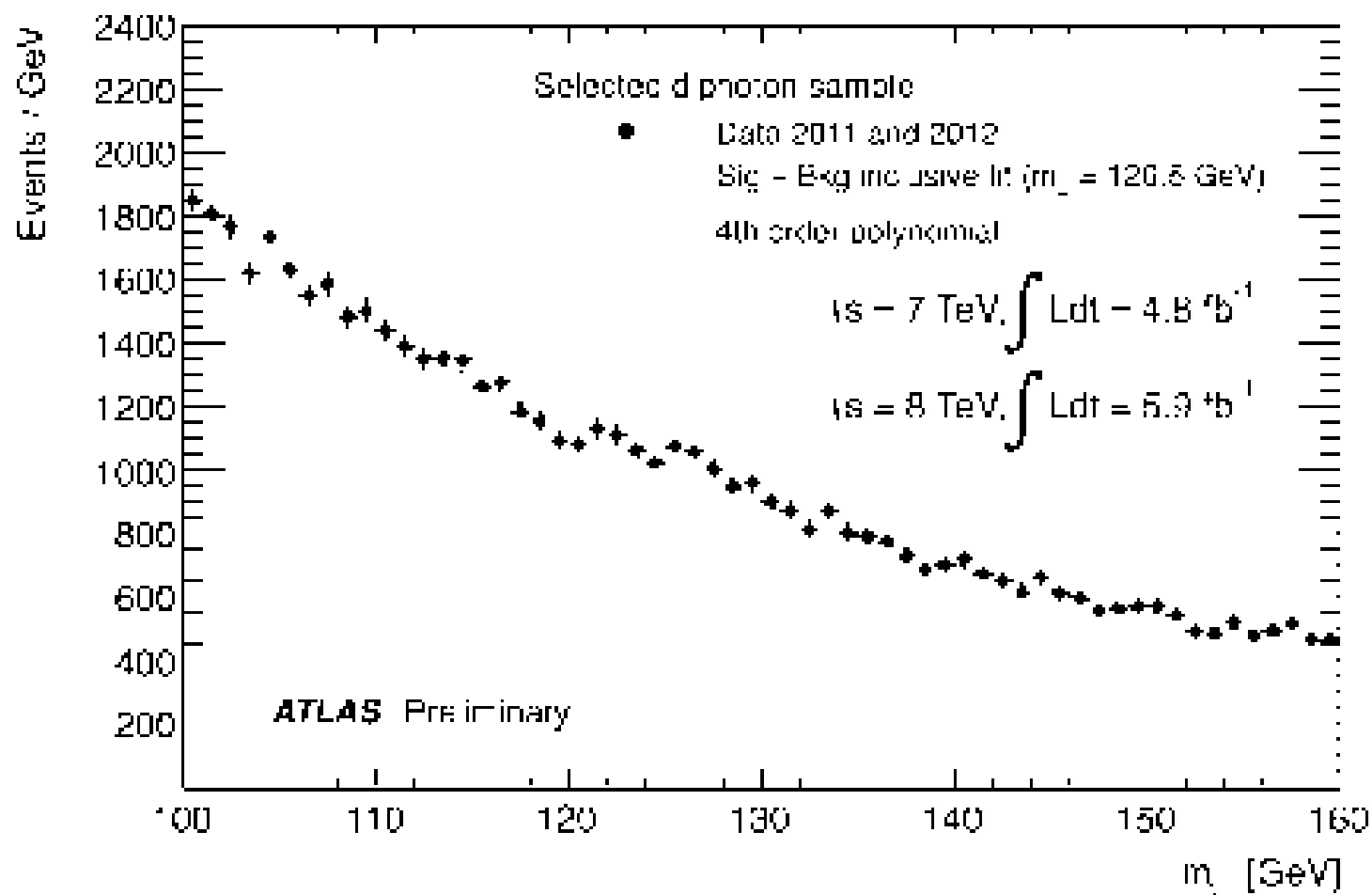
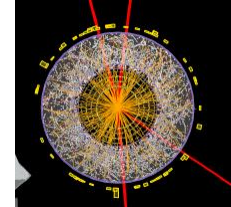
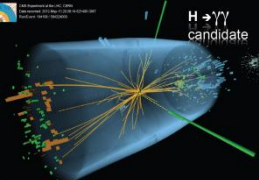


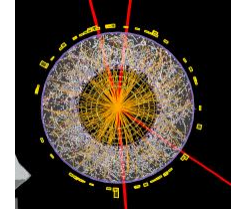
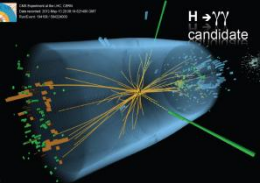
Thanks

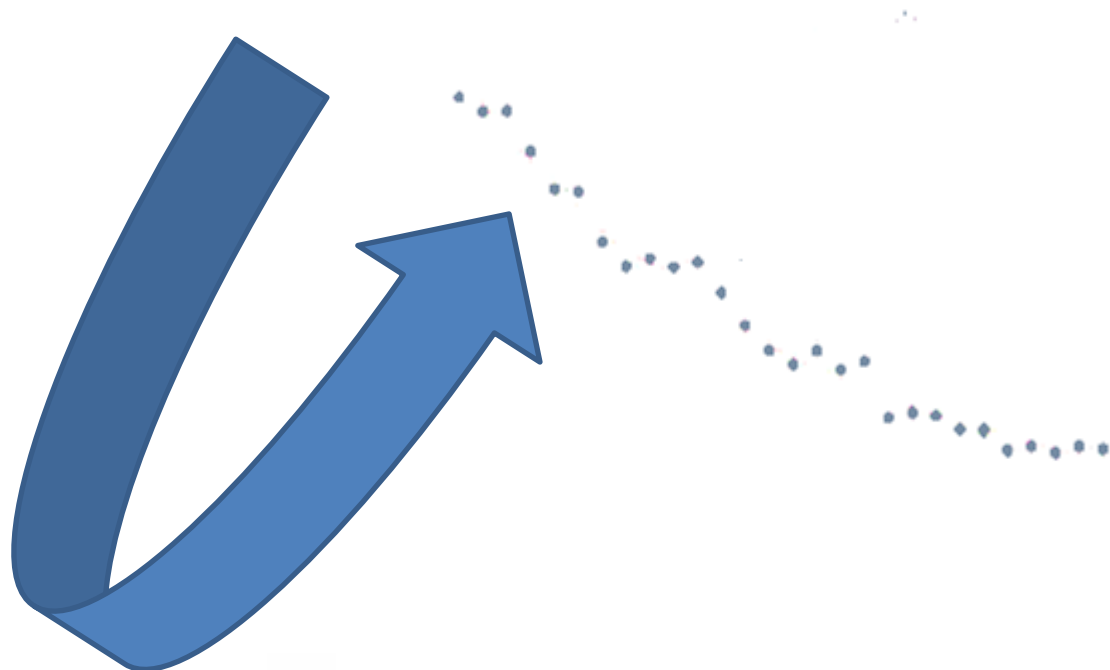
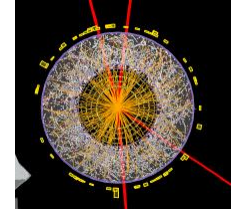
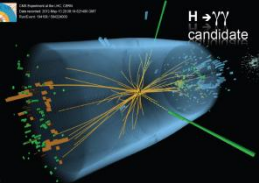


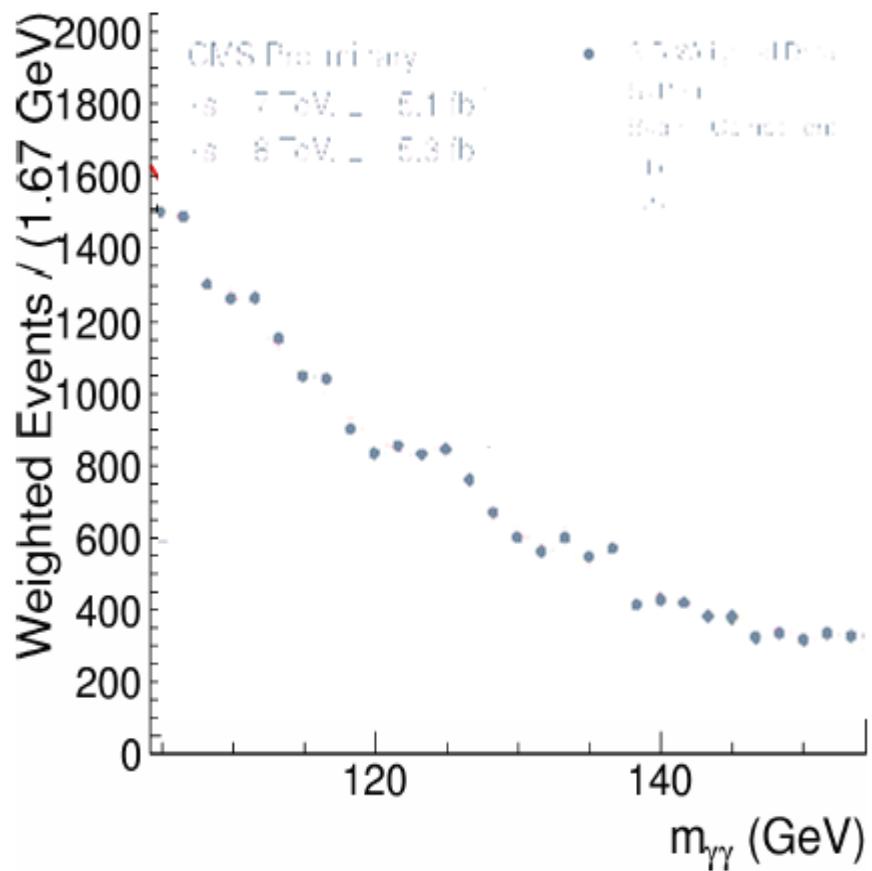
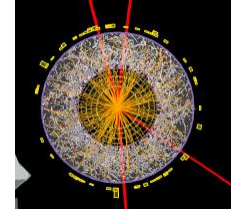
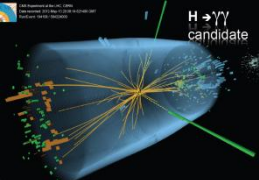
- Still learning a lot
 - Useful conversations over past two weeks with many people including
 - M. Carena, B. Gripaios, C. Grojean, G. Guidice, M. Neubert, M. Peskin, A. Strumia
 - Too many ATLAS and CMS experts to list

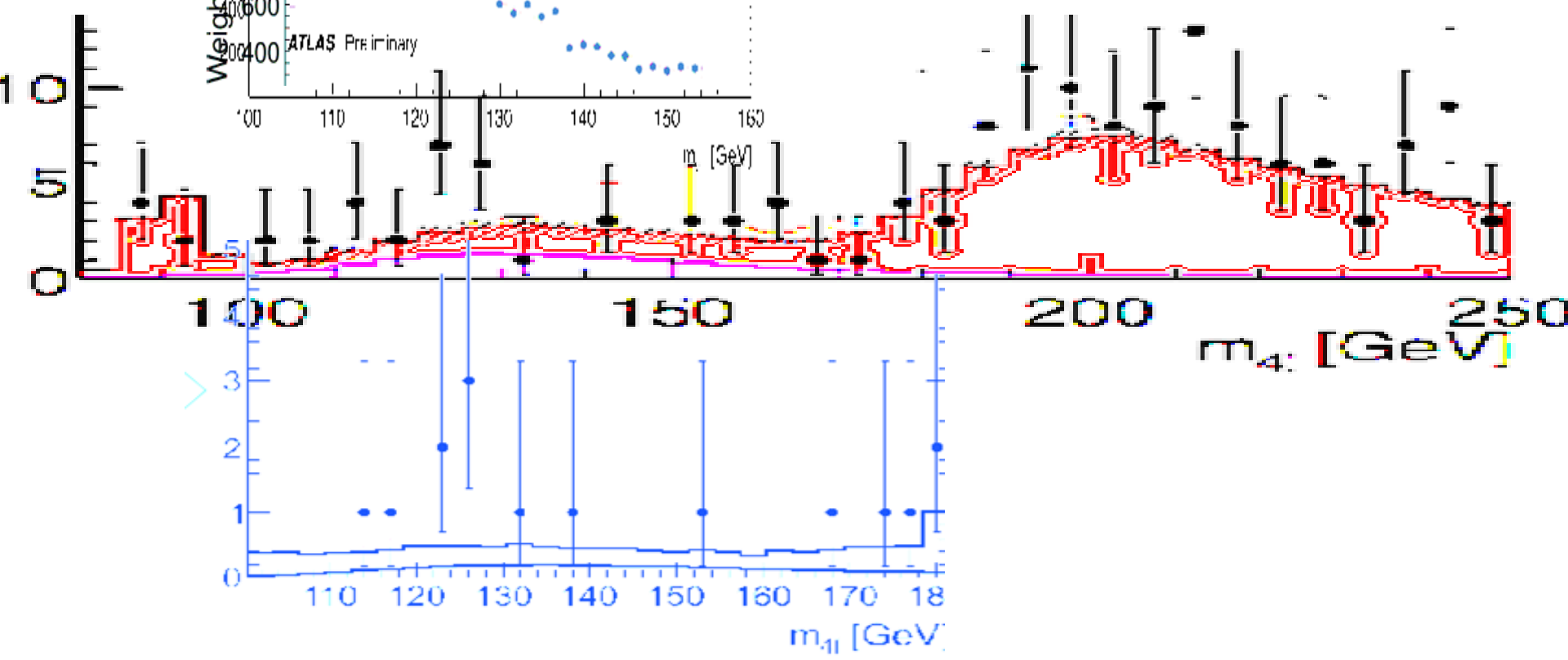
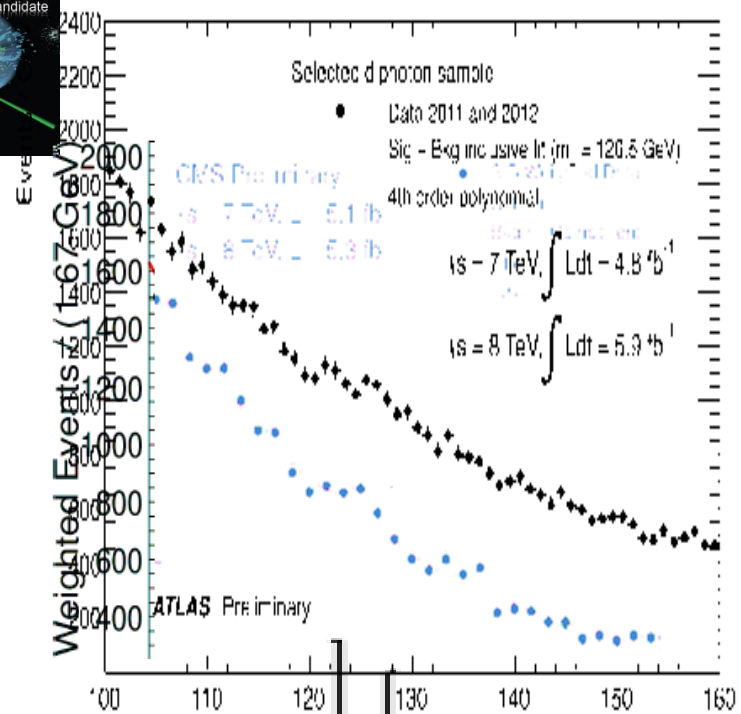
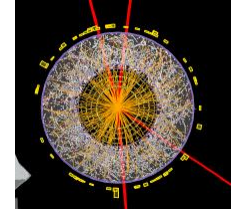
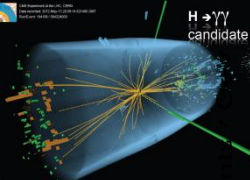


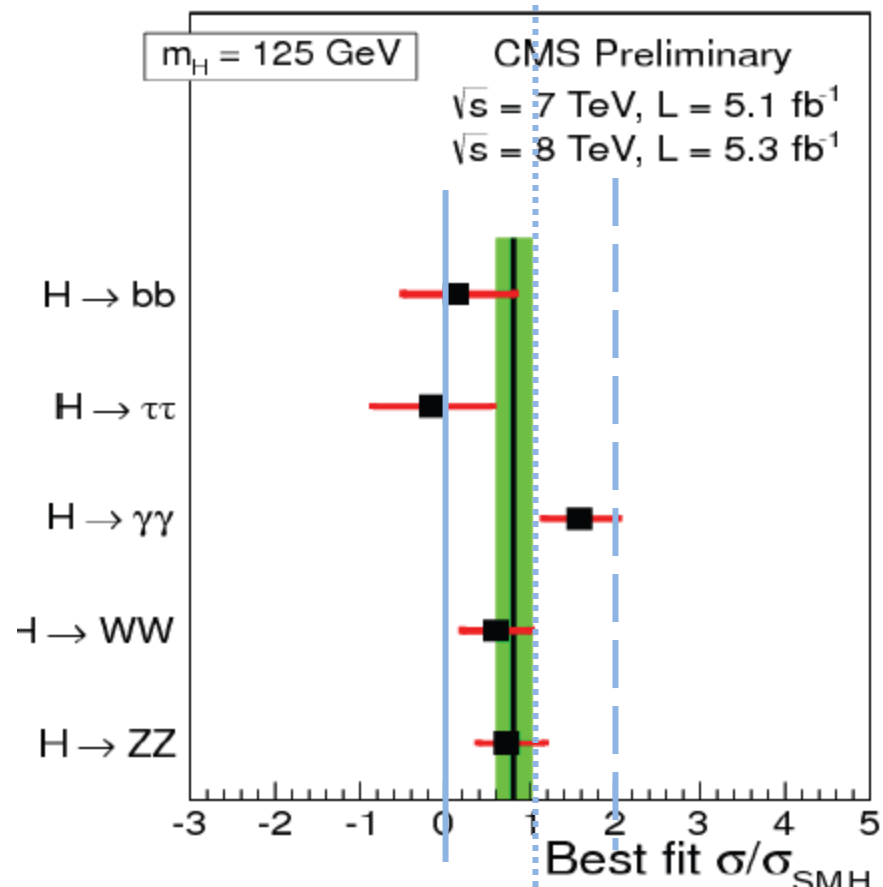
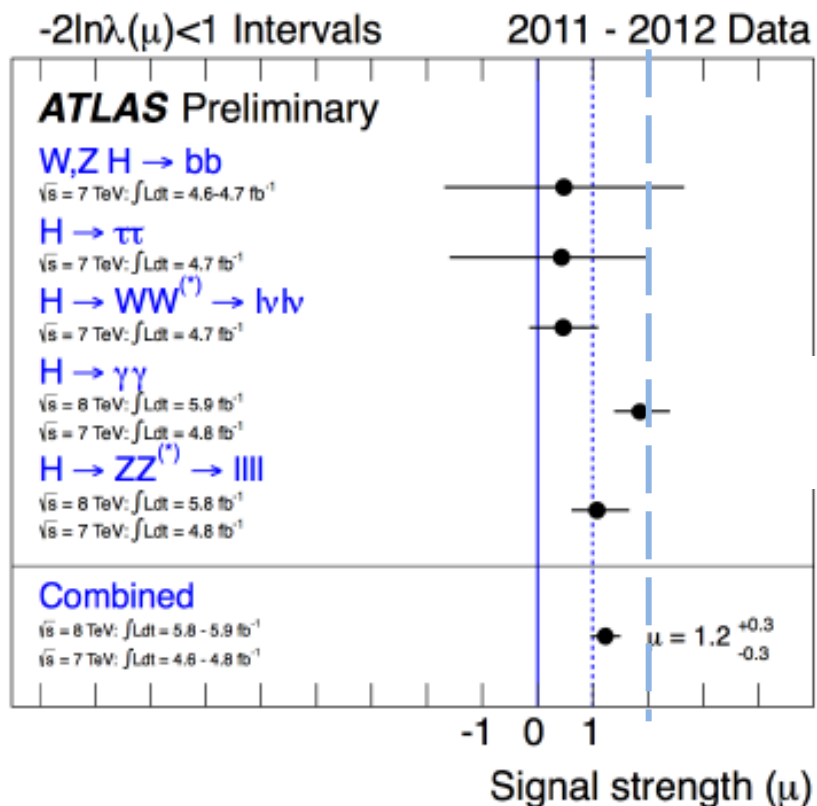
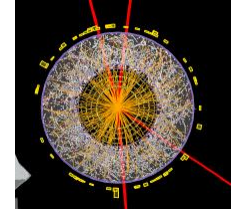
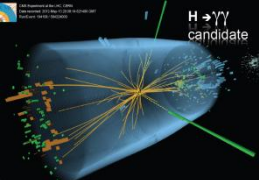


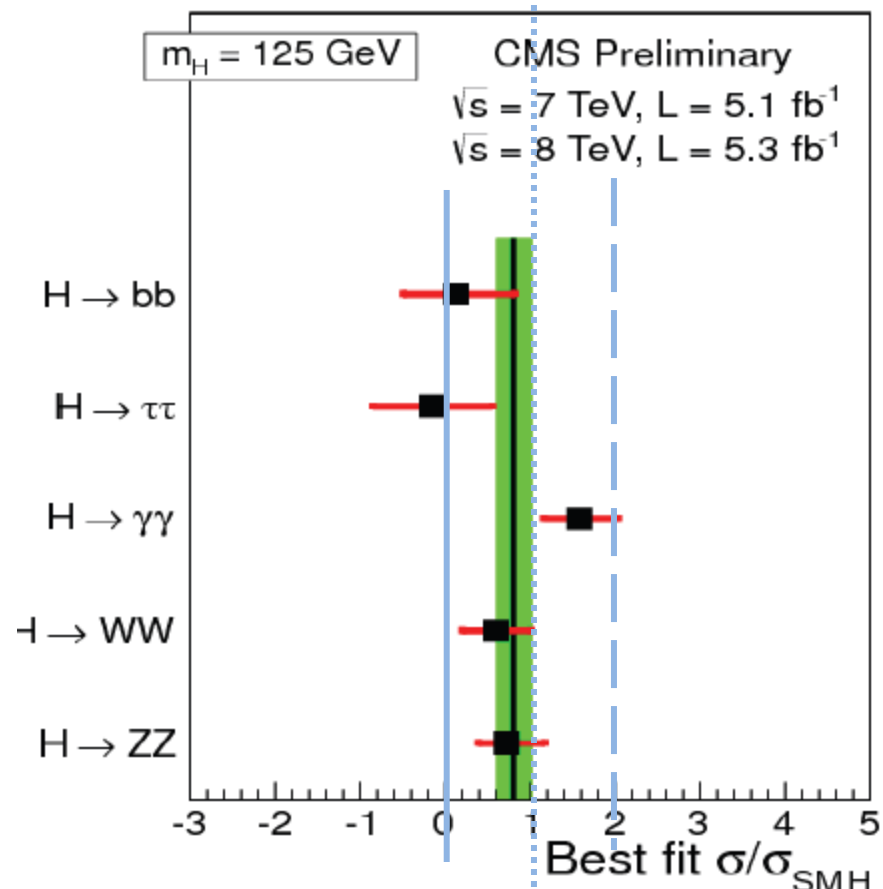
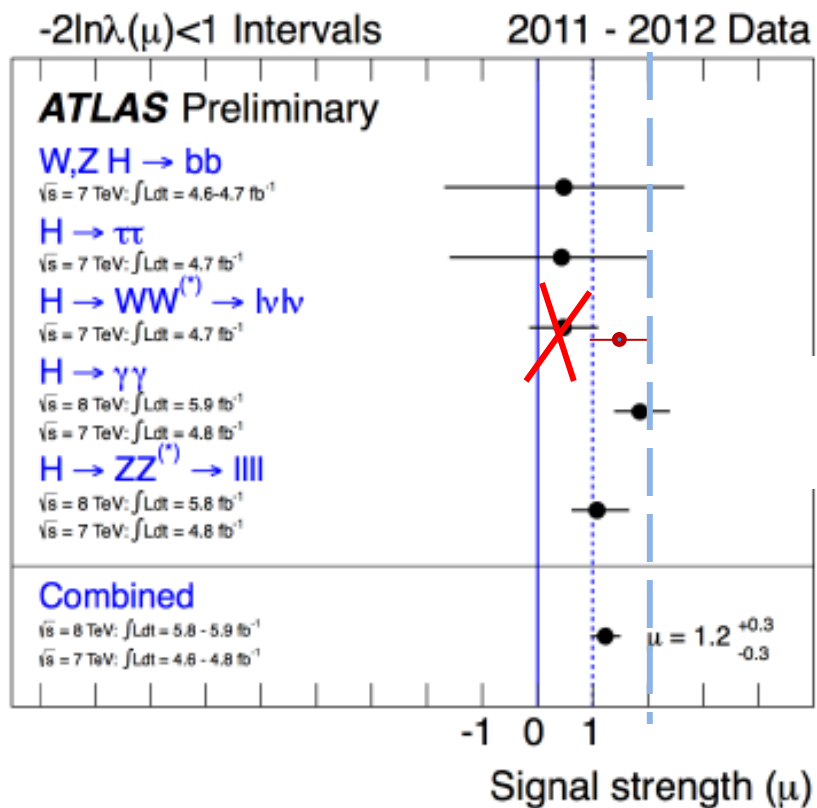
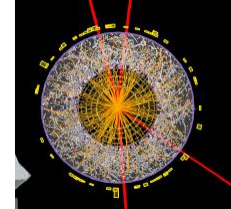
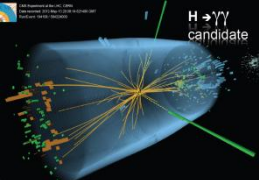


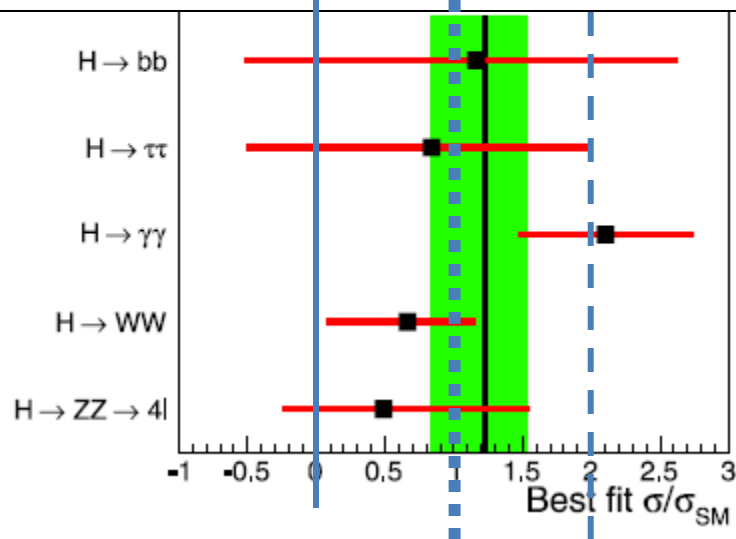
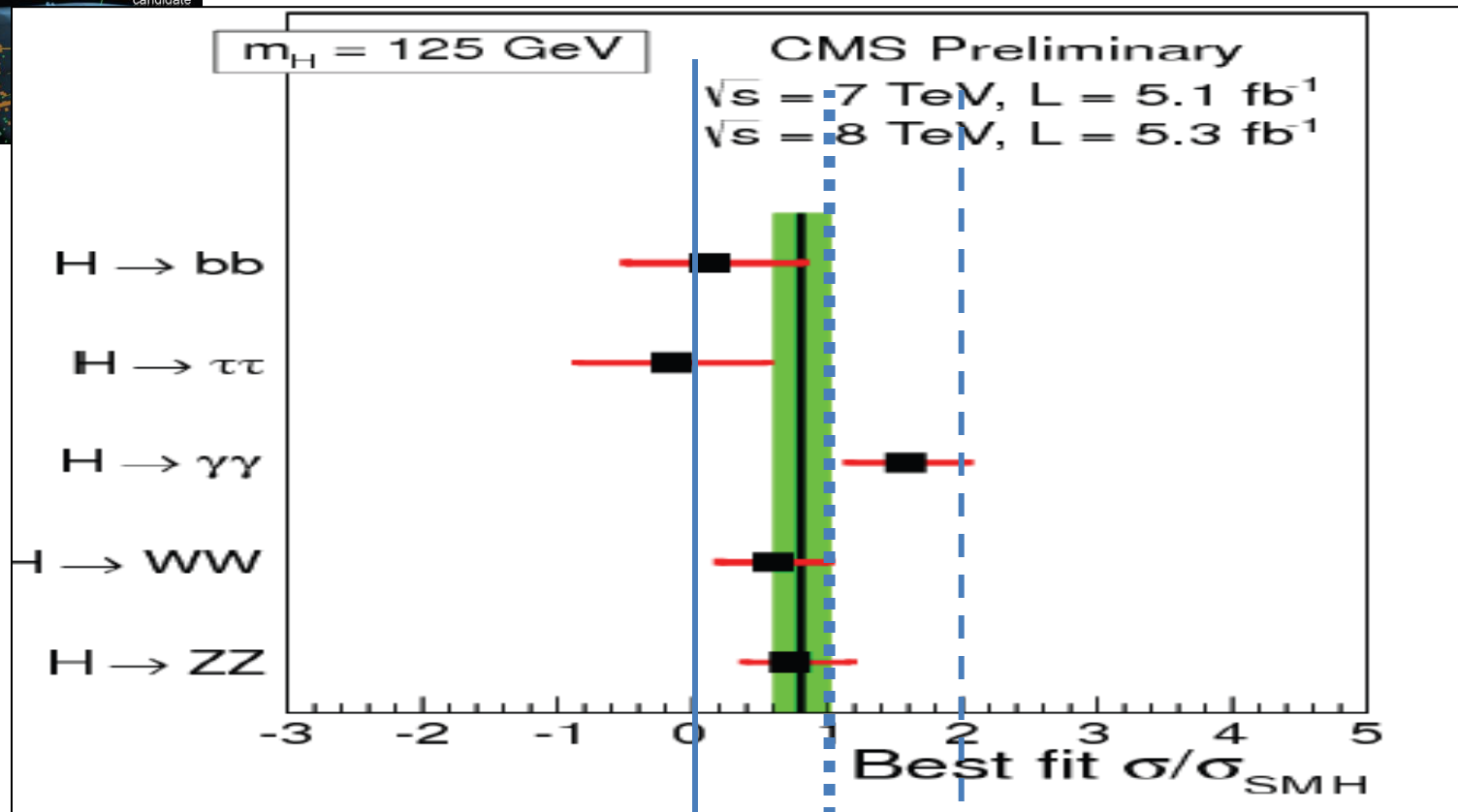
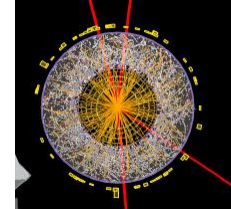


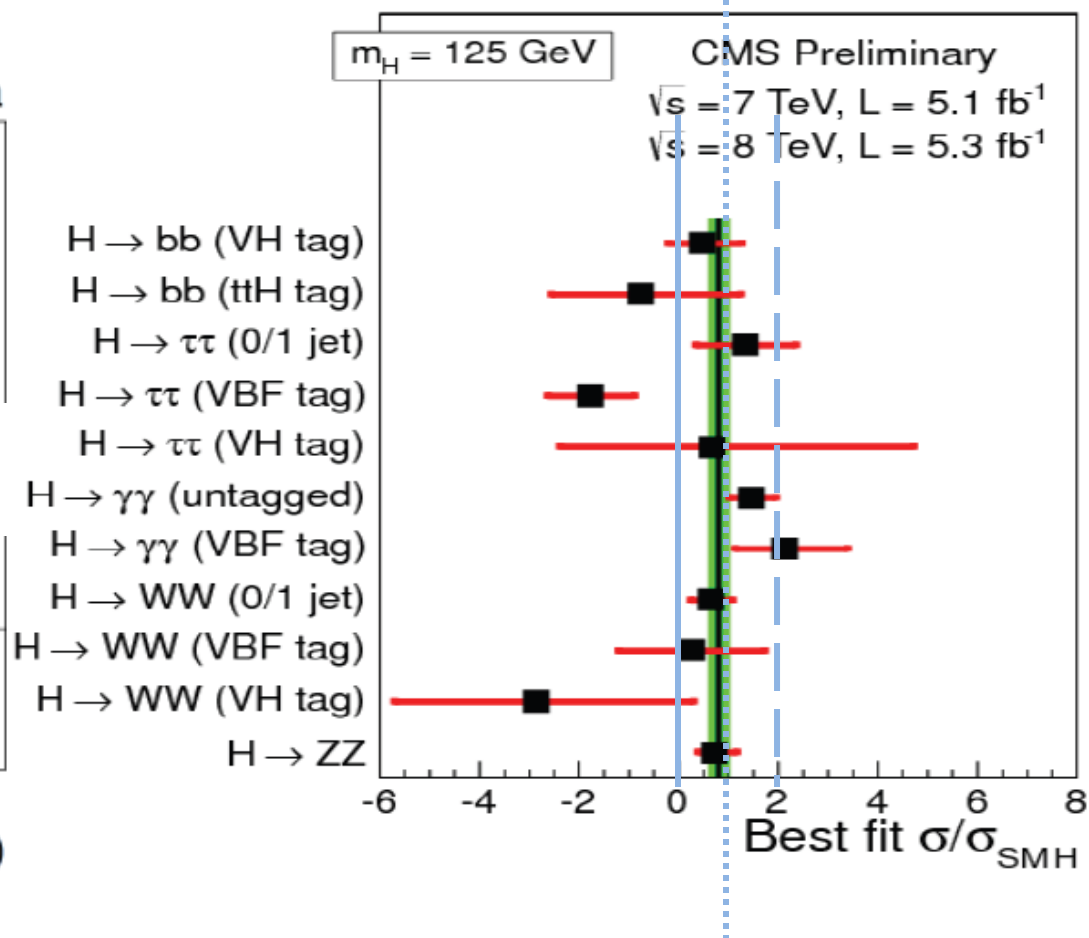
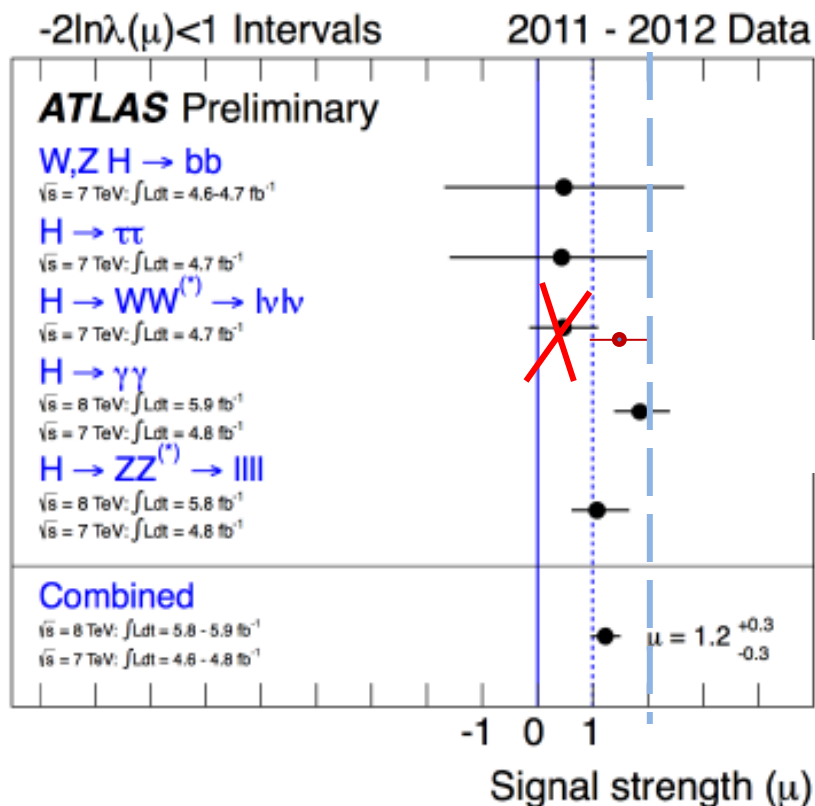
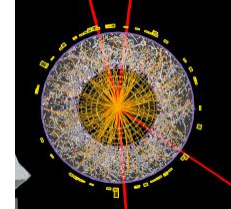
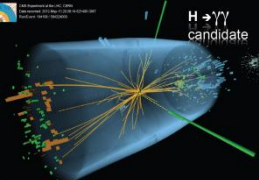


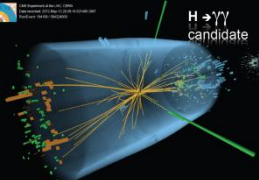




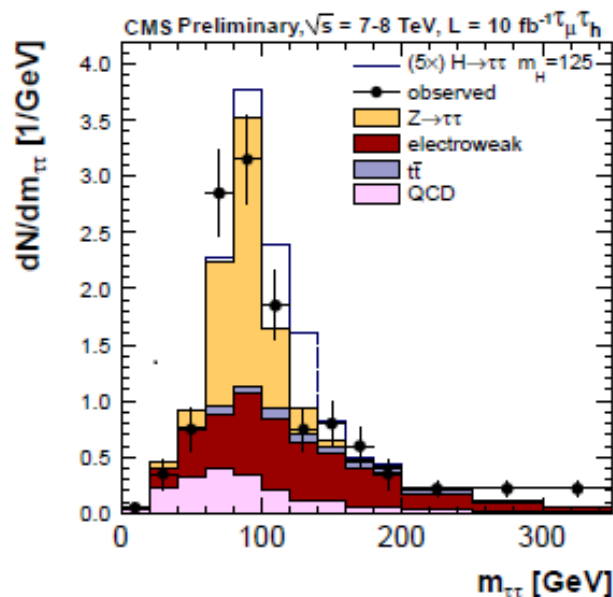
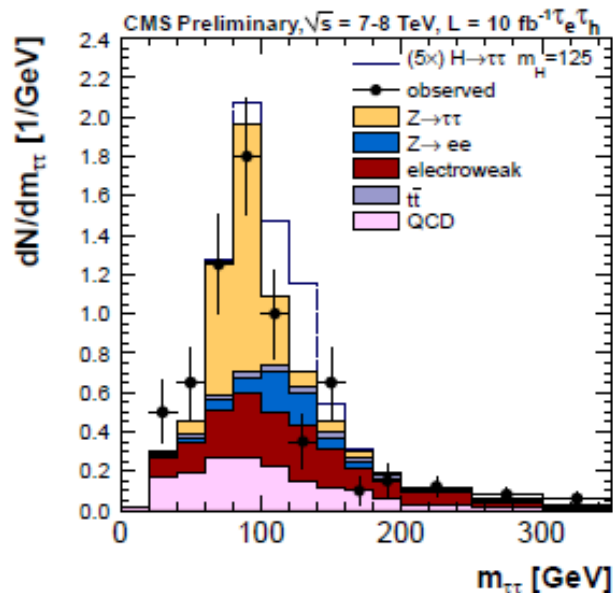
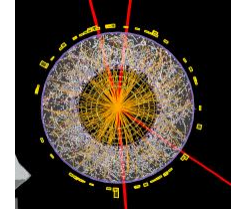




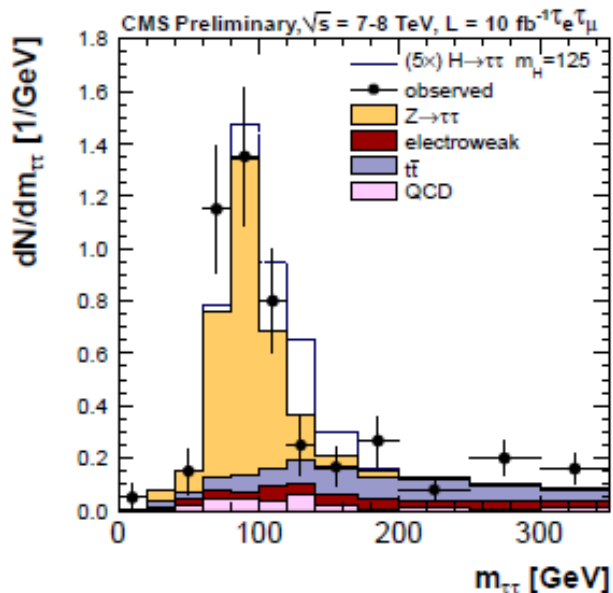




Deficit in Taus? Maybe

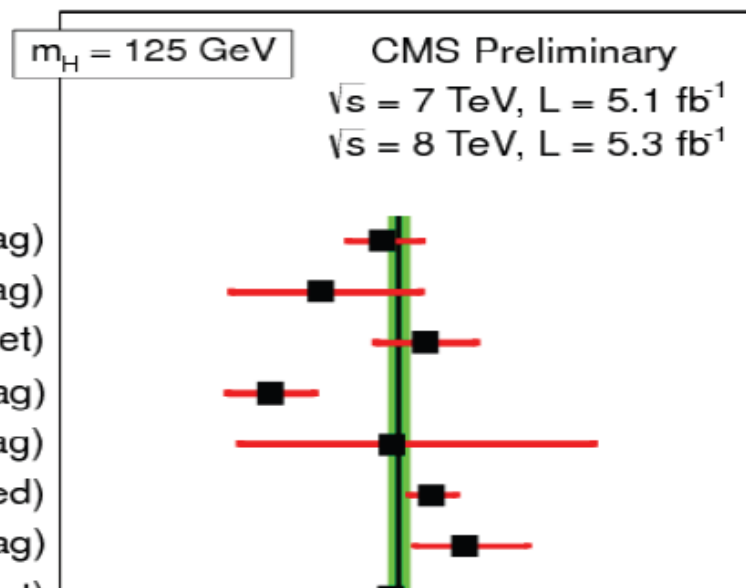


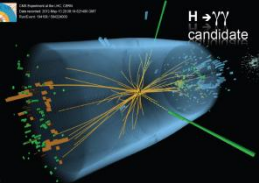
White = HSM **x 5**
Orange = $Z \rightarrow \text{taus}$



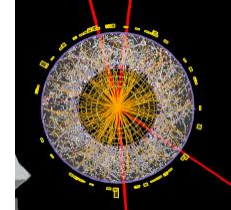
$m_H = 125$ GeV

$H \rightarrow bb$ (VH tag)
 $H \rightarrow bb$ (ttH tag)
 $H \rightarrow \tau\tau$ (0/1 jet)
 $H \rightarrow \tau\tau$ (VBF tag)
 $H \rightarrow \tau\tau$ (VH tag)
 $H \rightarrow \gamma\gamma$ (untagged)
 $H \rightarrow \gamma\gamma$ (VBF tag)



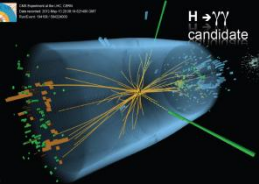


Robust Statements?

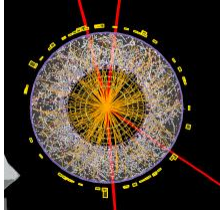


- Robust results cannot be obtained from statistically/systematically questionable trends
 - Good fit to SM and bad fit to SM+H, or vice versa, versus bad fit to both
 - Some results easily affected by presence/absence of one extra event
 - Discovery biases, other effects, that aren't symmetric up and down
 - Arbitrary choices in statistical methods
- Maybe spend some time trying to understand what is 99% excluded, even conservatively, not merely what is 1 or 2 sigma favored?

Robust exclusions of models may be more useful in the long run than chasing after excesses that are statistically and/or systematically suspect.



What Is This Object?

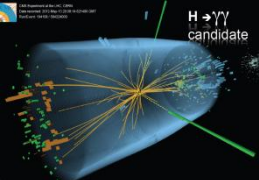


- **Possible but Implausible**

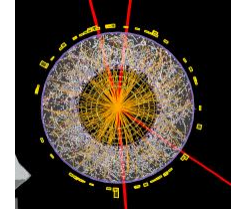
- Spin 2
- Pure CP odd Spin 0
- CP even spin 0
 - Pure dilaton or radion
 - Pure singlet
 - Particle with couplings sign-flipped relative to H_{SM}

- **Possible and Plausible**

- Standard Model itself
- H mixed with the above CP even or odd scalars
- Theories with decoupling limit (H couplings approach SM)
 - Two-H Doublet, SUSY, Composite H
- Theories with small mixing of H with SM-singlet sector (“hidden”)
 - NMSSM, hidden valleys (cf. inelastic dark matter models, etc.)



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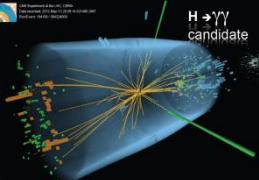
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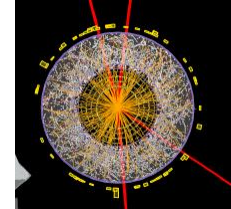
I'm glad someone
thought of that!

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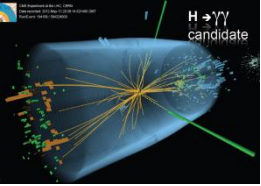
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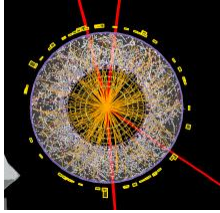
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I wish I'd thought of that!!

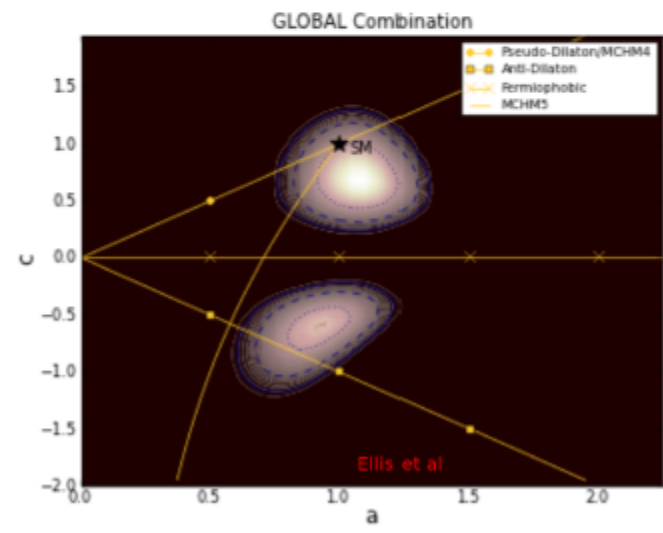
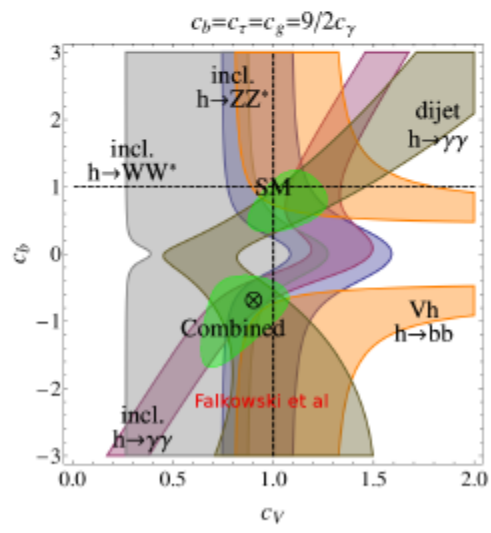
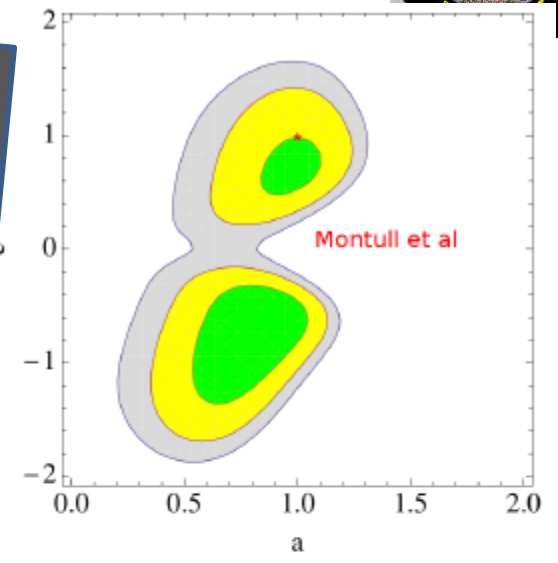
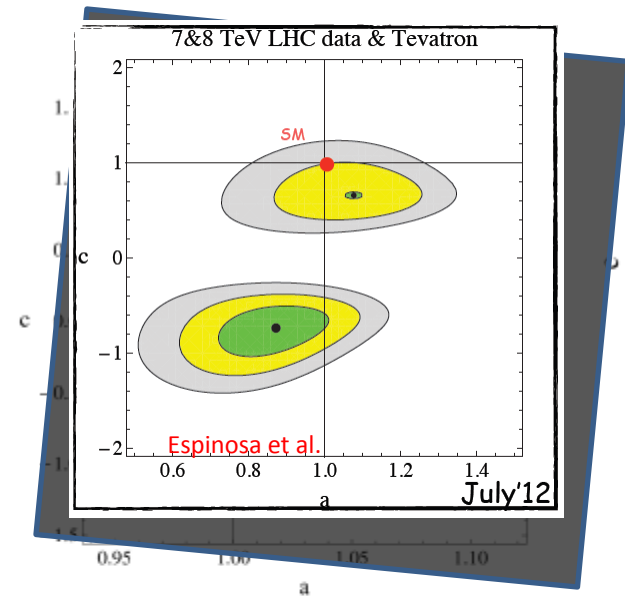
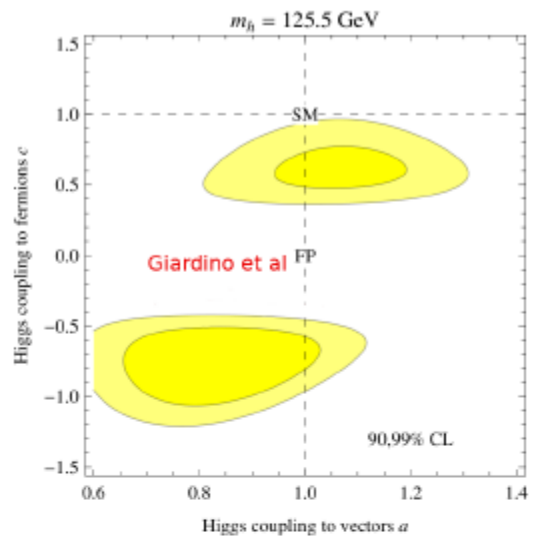
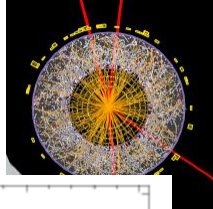
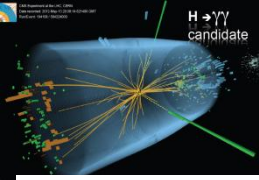
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Notation

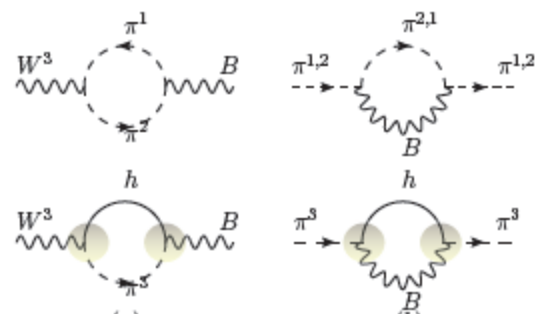


- H couplings
 - $g_W, g_Z ; g_b, g_\tau ; g_t$
 - g_g, g_γ
 - Functions of the others, unless new particles or UV interactions
 - $c_V = a =$ overall rescaling factor for g_W, g_Z
 - $c_F = c =$ overall rescaling factor for g_b, g_τ, g_t
 - Indirectly impact gluon, photon coupling through W, t, even b



EW constraints

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables



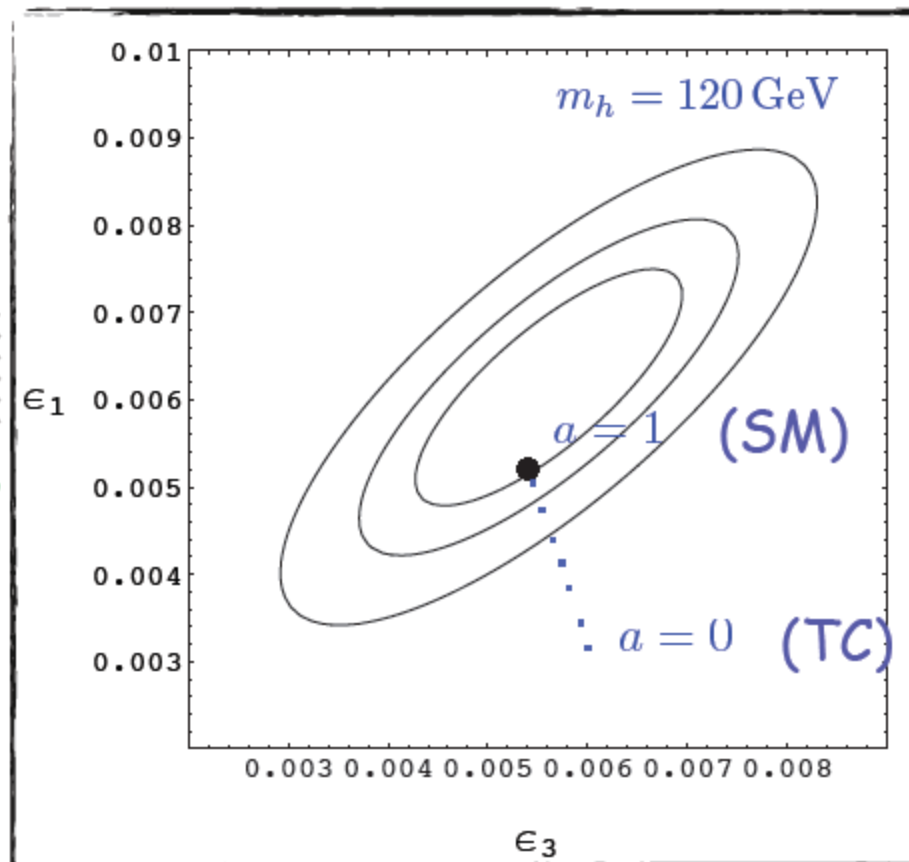
$$\epsilon_{1,3} = c_{1,3} \log(m_Z^2/\mu^2) - c_{1,3} a^2 \log(m_h^2/\mu^2) - c_{1,3} (1 - a^2) \log(m_\rho^2/\mu^2) + \text{finite terms}$$

$$c_1 = + \frac{3}{16\pi^2} \frac{\alpha(m_Z)}{\cos^2 \theta_W}$$

$$c_3 = - \frac{1}{12\pi} \frac{\alpha(m_Z)}{4 \sin^2 \theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3} (1 - a^2) \log(m_\rho^2/m_h^2)$$

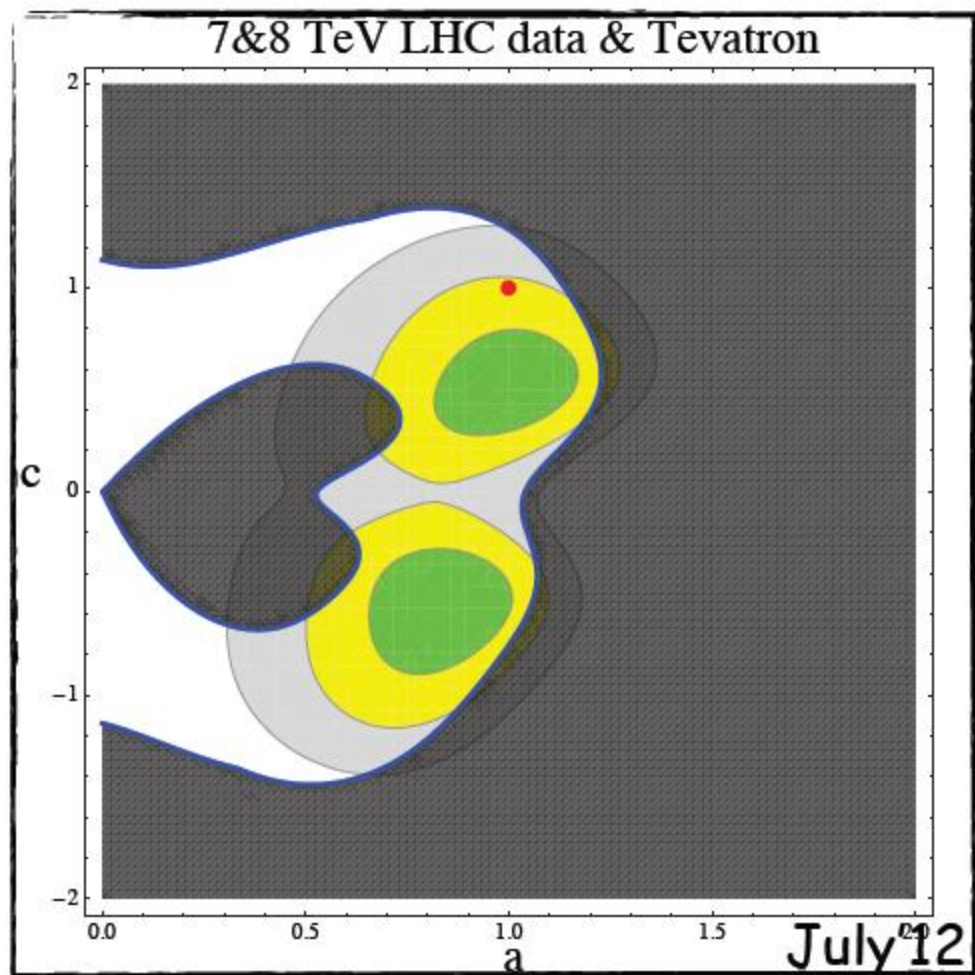
Barbieri, Bellazzini, Rychkov, Varagnolo '07

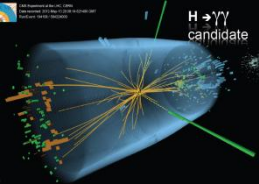


Excluding some (a,c) points

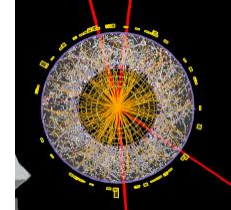
Espinosa, Grojean, Muhlleitner, Trott '12

determine the 95% CL allowed values of the signal strength





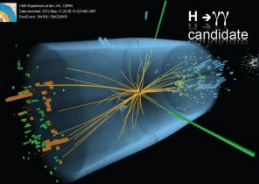
Possible but Implausible



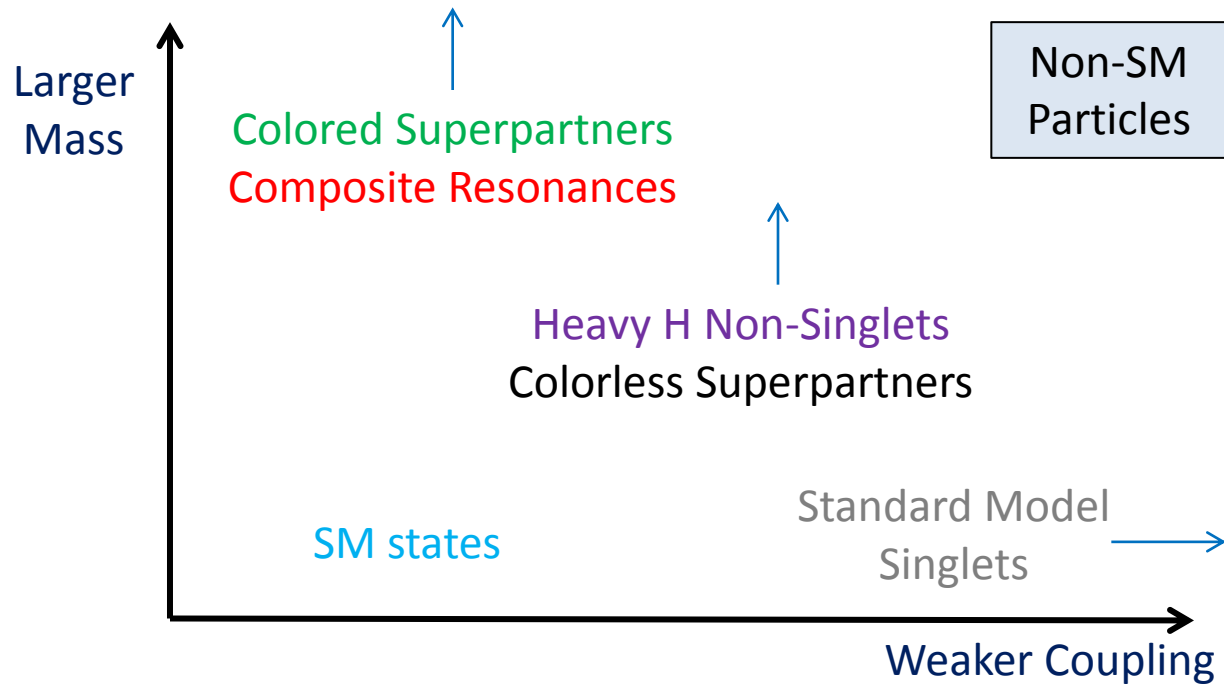
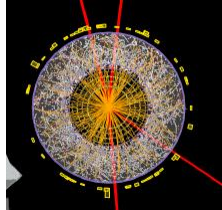
- Of course we **do** have to check! (had to check top didn't have charge 4/3...)
- Implausibility of spin 2, CP odd, pure dilaton, etc.?
 - Theory of longitudinal gauge bosons = gauged nonlinear sigma model
 - Theory with H_{SM} = gauged linear sigma model → SM predictions
 - All couplings predicted – rigid structure
 - *Multiple H 's: participate in the structure, with a sum rule*
 - Any other particle S with no EWSB vev has no link to this rigid structure
 - g_γ not related properly to g_Z (requires $g_W/g_Z = m_W/m_Z$)
 - g_γ not related properly to g_g (through loops, $g_W/g_t = m_W/m_t$)

Why should either $\gamma\gamma$ or ZZ rate come out within a factor of 2 of the SM?

Why do precision tests of SM come out so well?

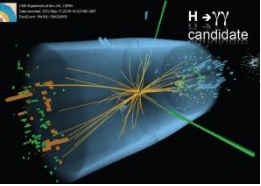


Decoupling

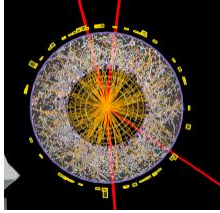


The existence of a decoupling limit in a given theory suggests that in the absence of easily observed light particles **one may find a nearly-SM H particle**

- What do we learn about nearly-SM H particles from the data?



Start From H_{SM}



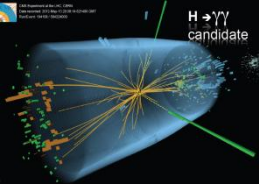
Let's start from H_{SM} and ask what we can change in reasonable situations

- Single H: g_W, g_Z fixed (nearly) through EWSB so effects only on flavor (g_t, g_b, g_τ);
 - Can alter g_g but VBF, VH production rates are **known**
 - $g_g \propto g_t$ fixed relative to total H width from measured ZZ rate
 - Upper bound on VBF $\rightarrow \tau\tau \rightarrow$ Linear bound on g_τ^2 vs. g_b^2

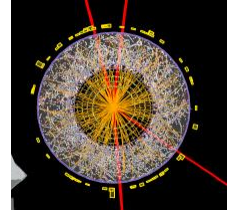
$$\text{Br}(H \rightarrow \tau\tau) = \Gamma(H \rightarrow \tau\tau) / \Gamma(H) \quad \text{with } N_{ZZ} \text{ fixed} \rightarrow \text{linear equation for } g_\tau^2 \text{ vs. } g_b^2$$

- Observation of VBF $\rightarrow \tau\tau$ would put a lower bound on $g_\tau / \max(g_b, g_W)$

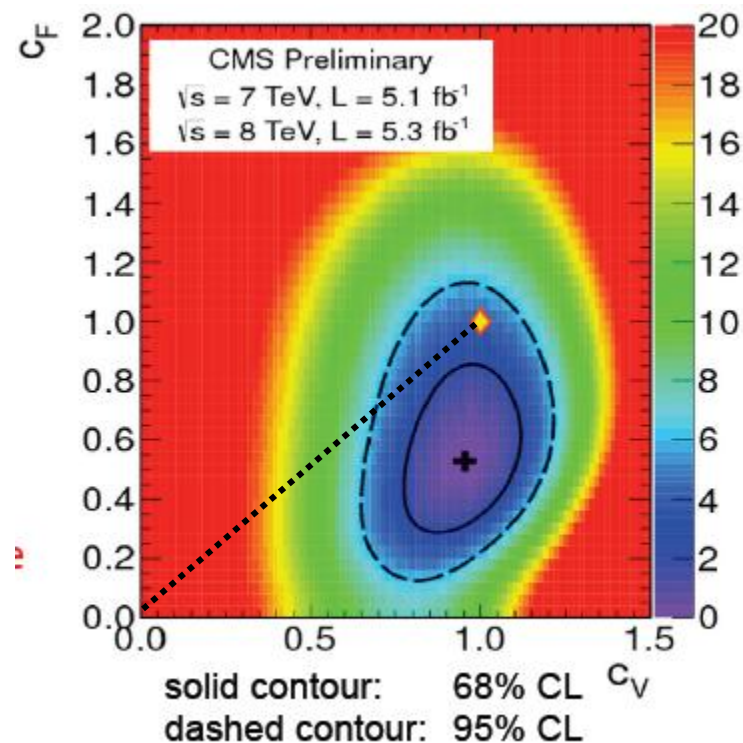
$$\text{Br}(H \rightarrow \tau\tau) = \Gamma(H \rightarrow \tau\tau) / \Gamma(H) < \Gamma(H \rightarrow \tau\tau) / \max[\Gamma(H \rightarrow bb), \Gamma(H \rightarrow WW)]$$

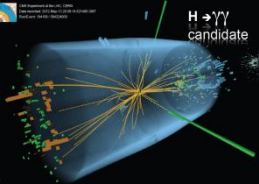


Start From H_{SM}

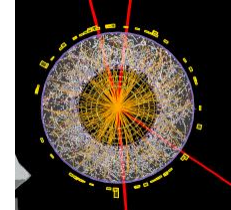


- Multiple Scalars: reduce g_W , g_Z keeping ratio [cannot increase it -- sum rule!]
- Overall large mixing disfavored
 - This would reduce all couplings
 - 50% mixing [reduction of couplings by $1/\sqrt{2}$] almost excluded

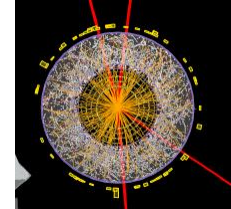
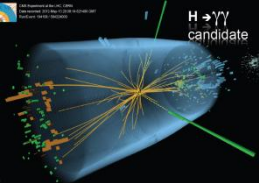




Start From H_{SM}



- Multiple Scalars: reduce g_W , g_Z keeping ratio [cannot increase it -- sum rule!]
- Overall large mixing disfavored
 - This would reduce all couplings
 - 50% mixing [reduction of couplings by $1/\sqrt{2}$] almost excluded
- Only possible if g_g increased e.g. through additional colored particles
 - Must do this while avoid changing g_γ/g_Z
 - VBF, VH for the 125 GeV H reduced
 - Tevatron result apparently excludes
 - Caution: other H's may affect tau, b, WW* channels
 - Ruled out if observe VBF or VH with 125 GeV $H \rightarrow \gamma\gamma$



SM Not
Immediately
Excluded

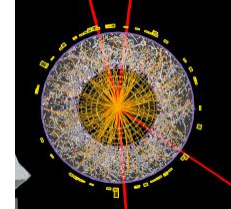
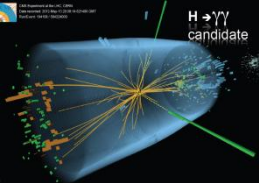
SM Immediately
Excluded



H-like Particle Observed

No H-Like Particle
Observed





SM Not
Immediately
Excluded

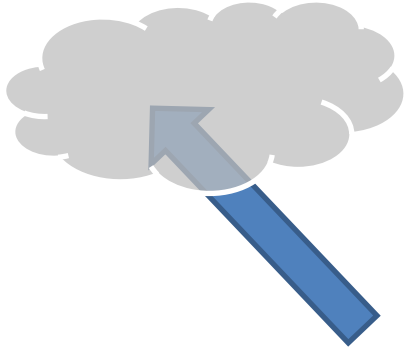
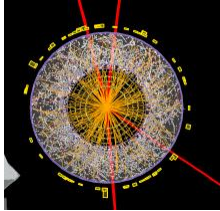
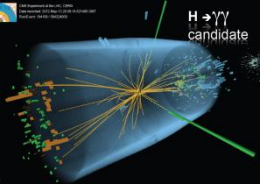
SM Immediately
Excluded

DEAD OR LUCKY:
Models With No Decoupling Limit
Models Far From Decoupling Limit

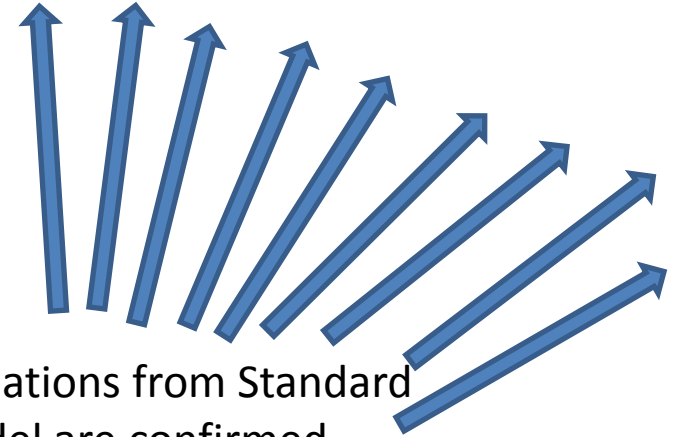
H-like Particle Observed

No H-Like Particle
Observed

Basically DEAD:
Simplest Higgs-Free Models
Technicolor
“Higgsless”



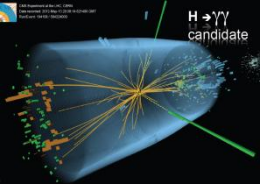
Standard Model successfully describes all LHC and pre-LHC particle physics data to within available precision



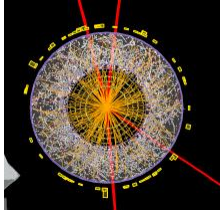
Deviations from Standard Model are confirmed



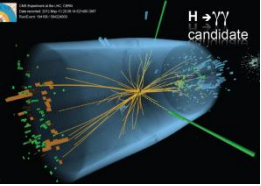
SM Not Immediately Excluded



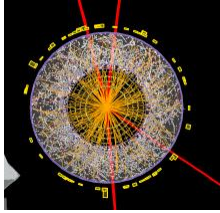
What's still allowed?



- Deviations (of moderate or small size) in any classic H_{SM} processes
- Other Higgs particles, heavy and/or rare and/or exotically decaying
 - Charged
 - Neutral
 - If partially-H , then observe in all SM modes w/ weak coupling
 - If not, then no VBF/VH; no decays to WW,ZZ
 - Exotic decays may dominate
- Unusual production modes [*observe in standard decay modes*]
 - $t \rightarrow c H$
 - $t H$
 - $t' \rightarrow t H$
 - $Z' \rightarrow Z H$, γH (?) ; $W' \rightarrow W H$
 - LSP/LKP/LTP $\rightarrow H$ + invisible



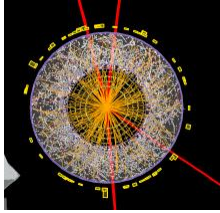
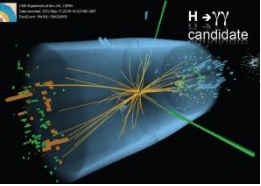
Exotic H Decays



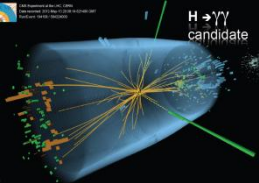
Unusual decay modes *[observe in standard production modes]*

- Also **may need** these searches to find 2nd H state with $m > OR < 125 \text{ GeV}$
- H : neutral scalar with no powerful conservation laws
- H : very sensitive to small couplings to as-yet unknown particles
 - All of its SM decays have suppressed widths
- New lightweight ultra-weakly-coupled neutral particles **unconstrained**
 - Why? Will explain if there are questions
 - Many theories of dark matter, non-minimal H physics
 - e.g. “lepton-jets”

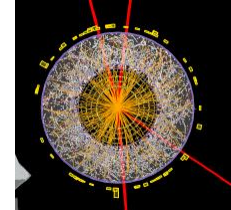
Very long list of H final states do actually appear in these theories



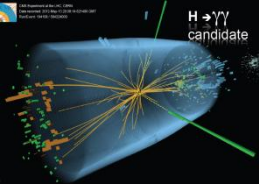
Aside On Exotic Decays



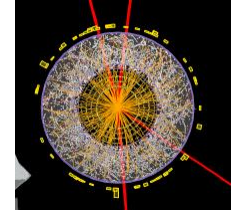
The Hidden Valley FAQ



- *How can there be particles below $M_H/2$ not yet excluded by LEP/Tevatron?*
 - If they are ultra-weakly coupled to the SM, then can't easily produce them
- *But then if so weakly coupled then like neutrinos – undetectable! Right?*
 - **NO!!!** Do the math:



Example: Z-Like Particle



SKETCH!

Lifetime

10^{-9} s

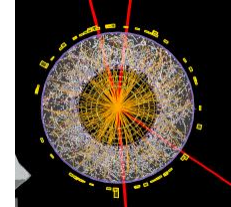
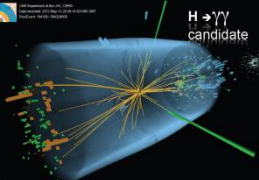
10^{-12} s

10^{-24} s

Decreasing Coupling

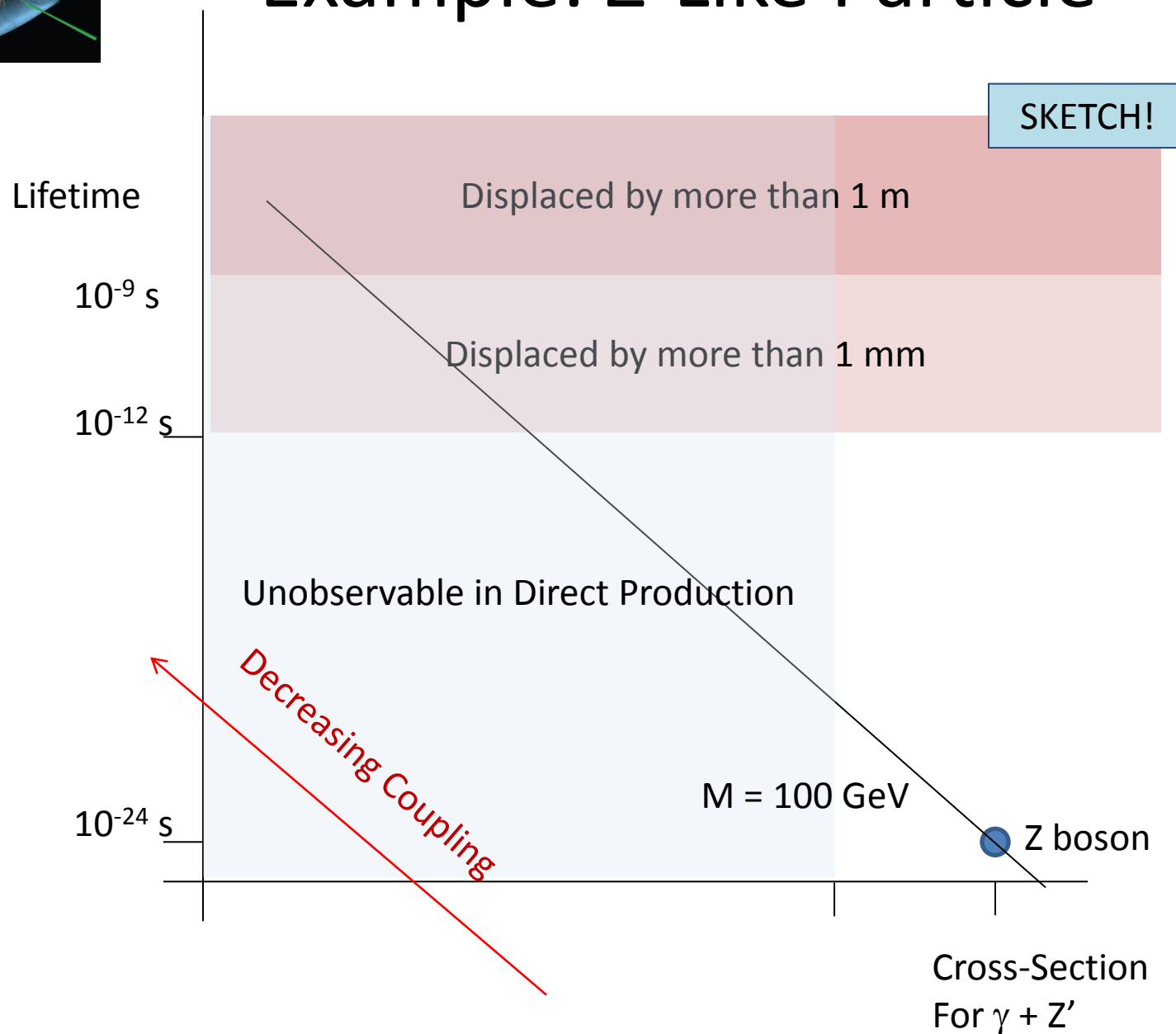
● Z boson

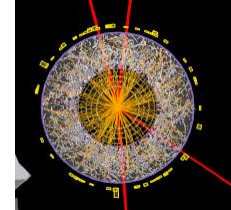
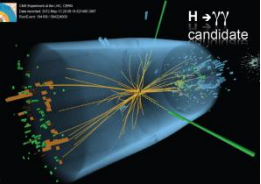
Cross-Section
For $\gamma + Z'$



Example: Z-Like Particle

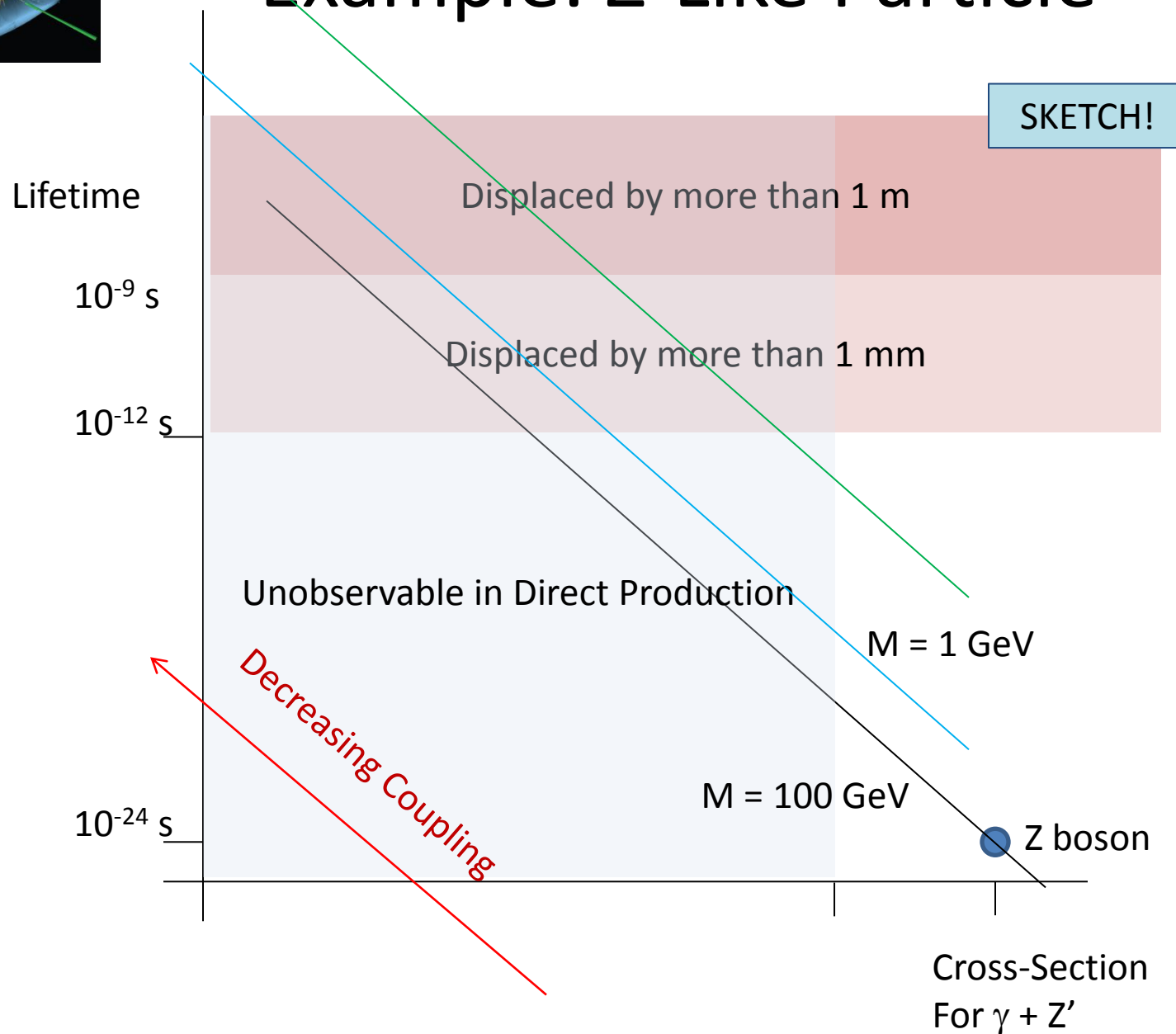
SKETCH!

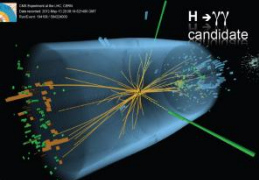




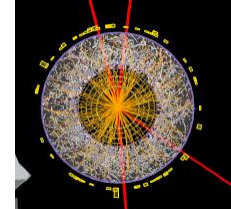
Example: Z-Like Particle

SKETCH!





H as Portal to a Hidden Valley



What does this have to do with the H?

- As a scalar, H can couple easily to Standard Model singlets ($H^2 S^2$)
- Can then couple to hidden sector particles

Schabinger & Wells 05
Strassler & Zurek 06
Patt & Wilczek 06

- This can give **invisible** decays
- This can give many types of **visible** decays!

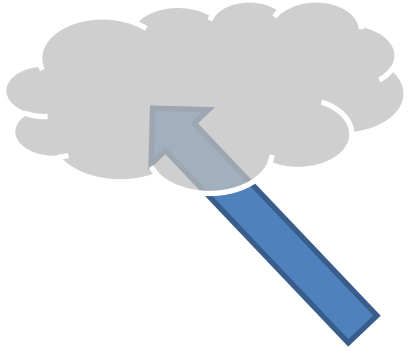
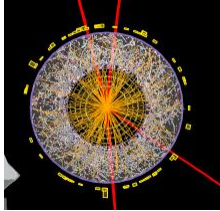
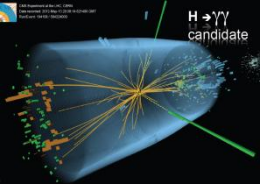
Prehistory back to 83
Dermisek & Gunion 04, 05, 06
Chang, Fox & Weiner 05
Strassler & Zurek 06
Kaplan, Carpenter, Rhee 06

...

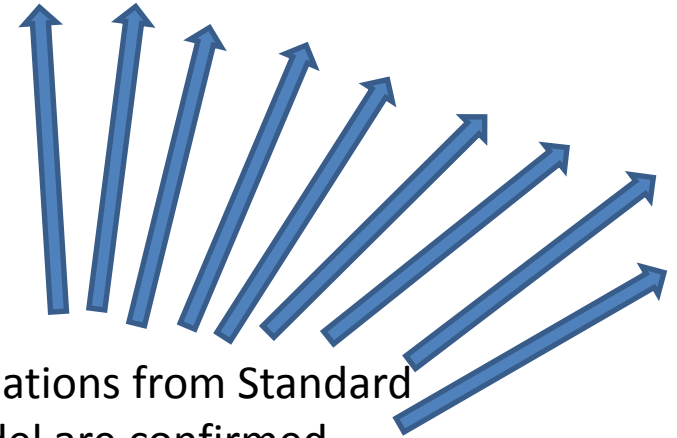
- Hidden Valley Scenario:

- If new light hidden particles in 'hidden valley' or 'dark sector'...
- ...then wide range of possible many-body final states for the Higgs **Strassler & Zurek 06**

- In some models of this type, this will be the **ONLY** new physics at the LHC !
 - SM will work for EVERYTHING else, to available precision.
 - Need systematic exotic decay search program (*remember 10^6 H this year*).



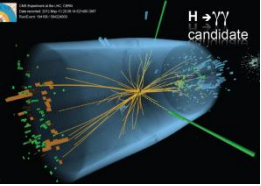
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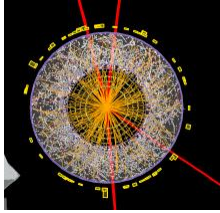
Deviations from Standard Model are confirmed



SM Not Immediately Excluded



Should We Just Accept the SM?



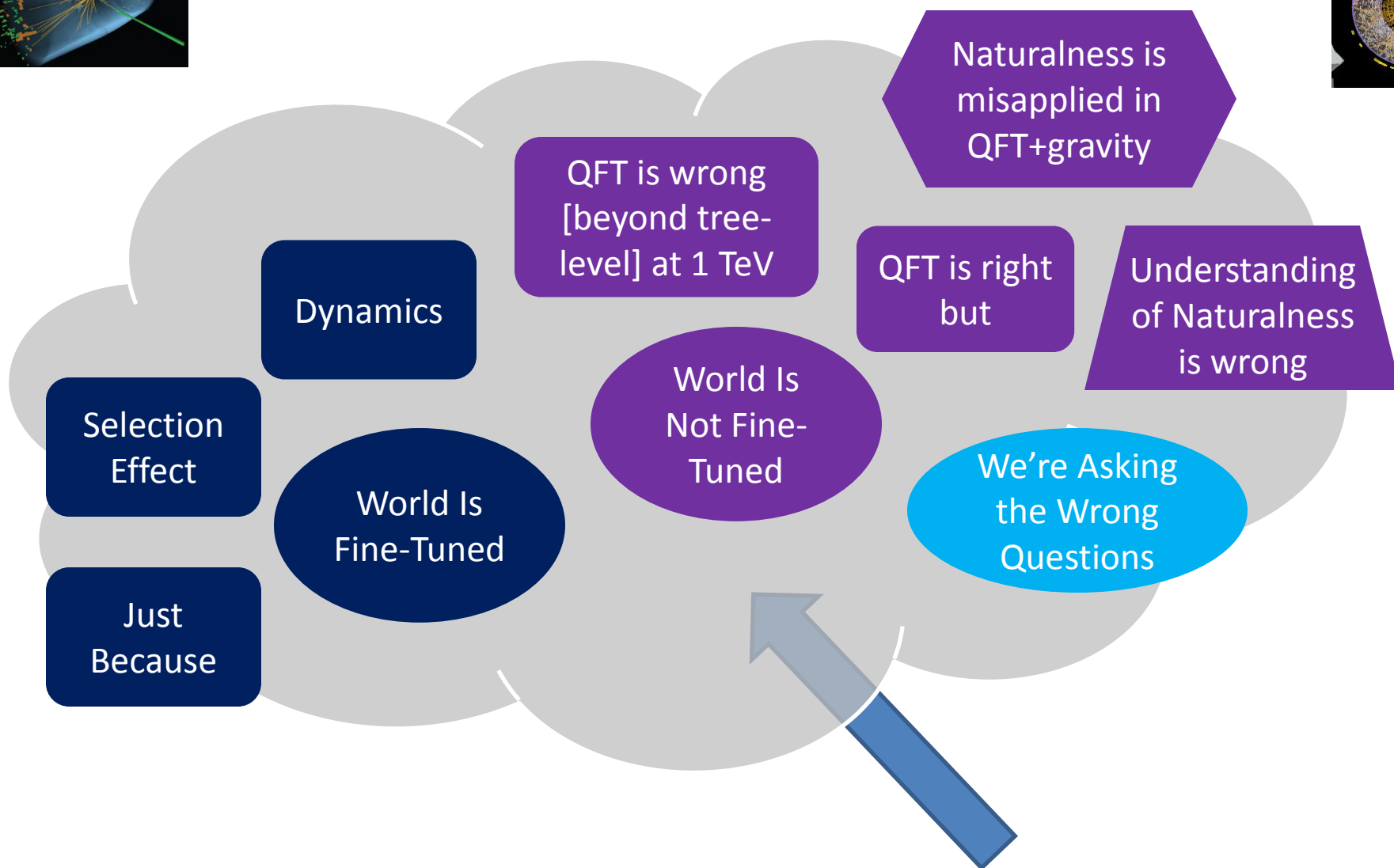
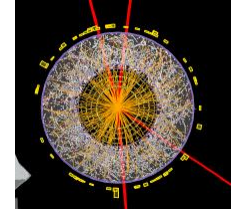
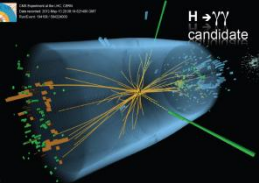
H has appeared, with couplings close to SM; nothing else yet...

Accept the Standard Model as the description of nature at TeV scale?

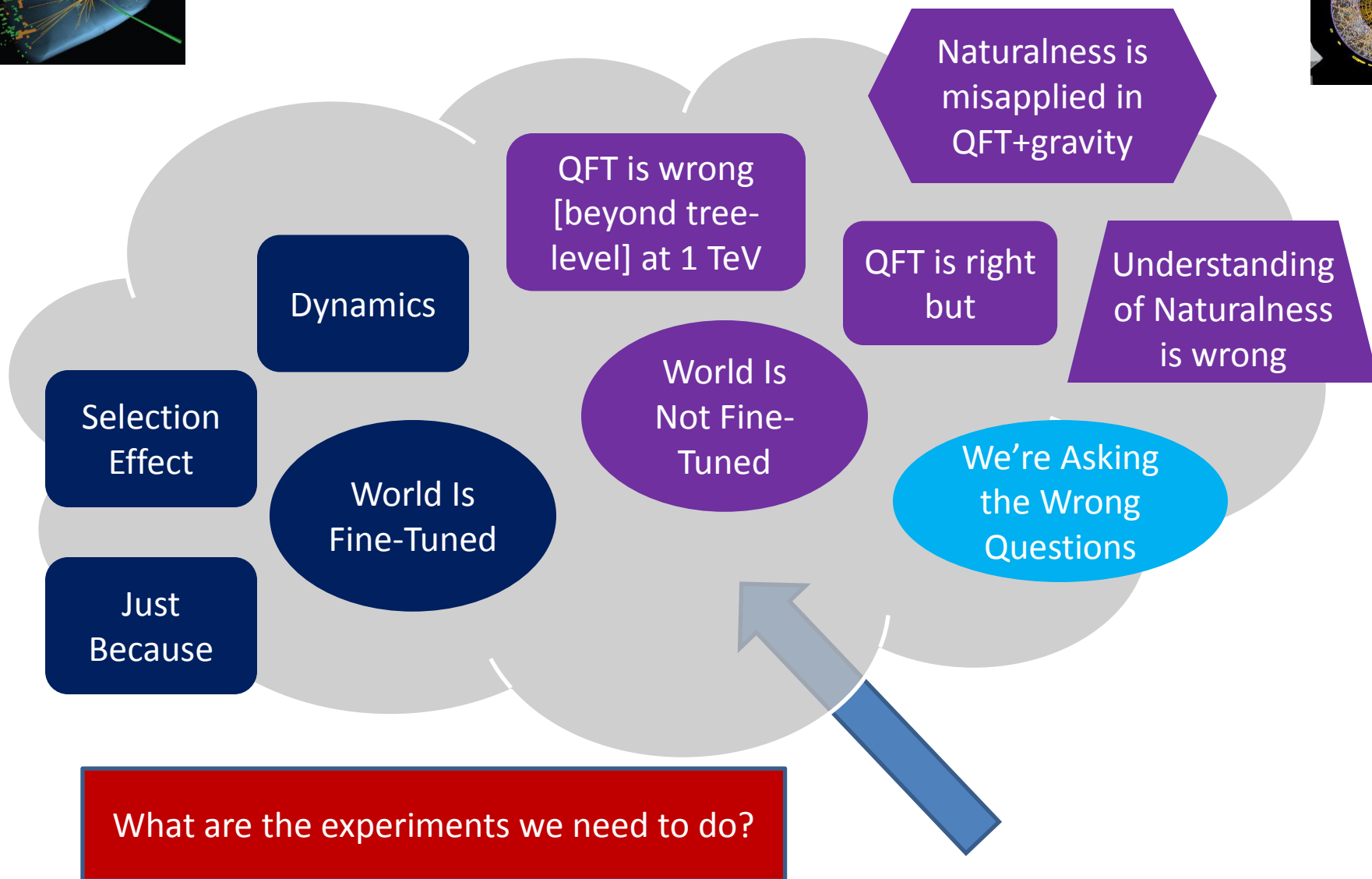
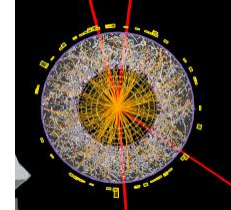
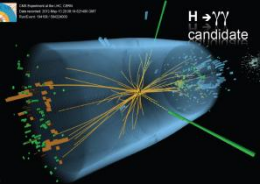
- Not so fast...
 - Decoupling limits
 - Many theories of new physics can closely resemble SM
 - Incomplete searches in relatively small data sets
 - Many theories of new physics can escape ATLAS/CMS searches so far

But clearly SM is in even better shape after H discovery

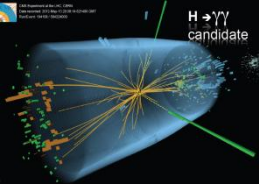
- Precision tests worked
- Basic predictions for H are working so far
- Searches for new physics increasingly require **high precision SM predictions**



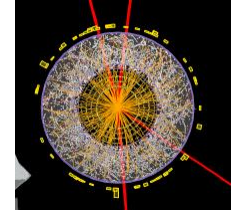
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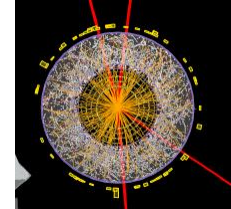
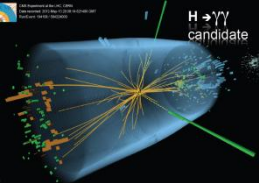
Nightmare or Not?

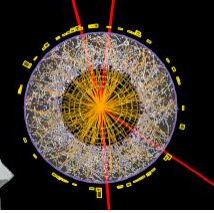
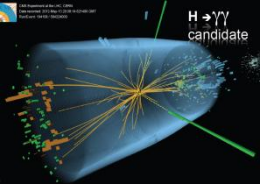


- From our current point of view this is sometimes called “nightmare” scenario
 - Political challenges
 - No new clues for solving flavor problems & most other puzzles of SM

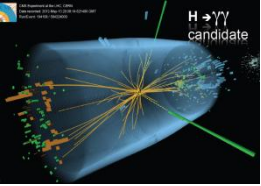
But observation of scalar with mass unprotected by symmetry or nearby dynamics is

- Not seen before in particle physics
 - Not seen (without tuning) in condensed matter physics
 - Not expected (without tuning) in quantum field theory
- *If this perhaps spurs us to*
drop a set of wrong ideas [think: aether]
and open our minds to new possibilities [think: Lorentz contractions of matter]
and perhaps revolutionary ideas [think: contractions of space itself]
this scenario could be quite different from a nightmare...

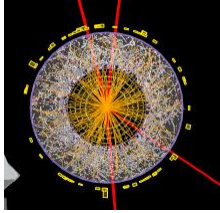




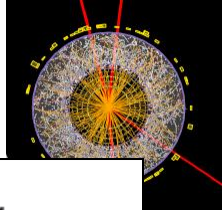
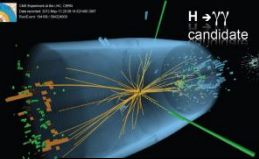
Additional Comments



Possible but Implausible

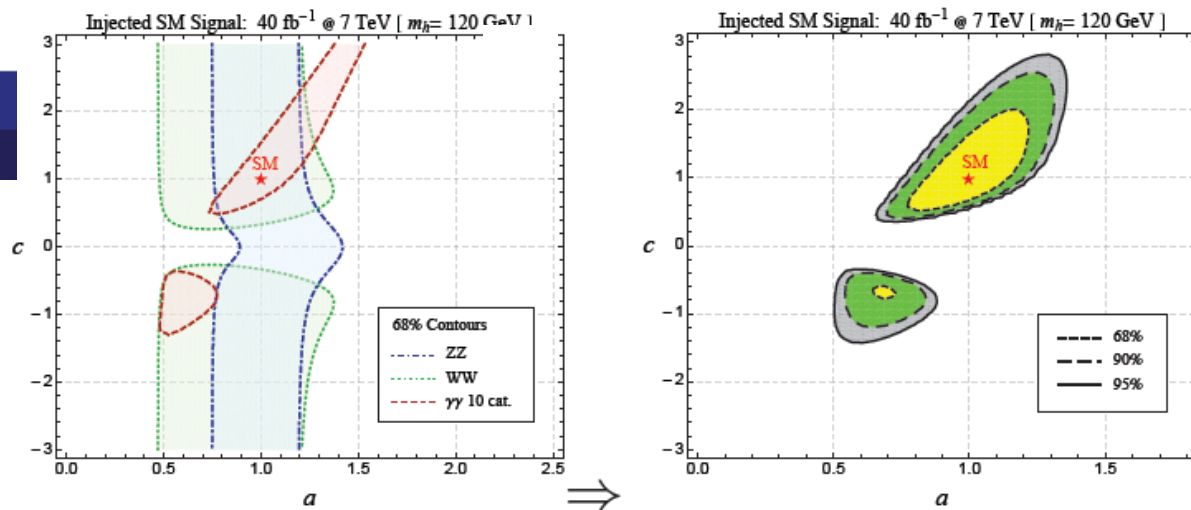


- Dilaton
 - Requires coupling suppression of $v/f = 1/4$ on all except gluon ($f=1$ TeV)
 - But precision electroweak requires c_W near SM value unless yet more stuff
 - And if there's more stuff, can't do the fit anyway
- Flipped signs on all couplings are allowed
 - i.e. $H \rightarrow v + h$ replaced by $v + h - 2h$
- Ambiguity inevitably leads to near-degeneracies with SM predictions for rates
 - Flipping a gauge coupling or Yukawa coupling requires a higher dimension operator with multiple higgses and an unsuppressed coupling
 - Flipping a loop coupling possible by adding enough particles into the loop
 - Affects precision tests
 - Affects production with interference



- Can we rule out one solution by measuring precisely a ? For example by adding WW or ZZ channels ?

Aleksandr Azatov



- unfortunately even 40 fb^{-1} are not enough to rule out negative c solution at 68% level.