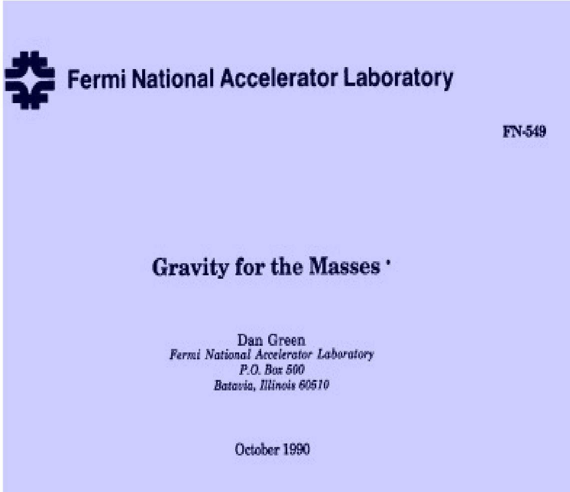
The Future Path Of Hadron Collider Physics

Dan Green

FNAL, CMS

Self - Introduction

- **ISR/D0/SSC/CMS**



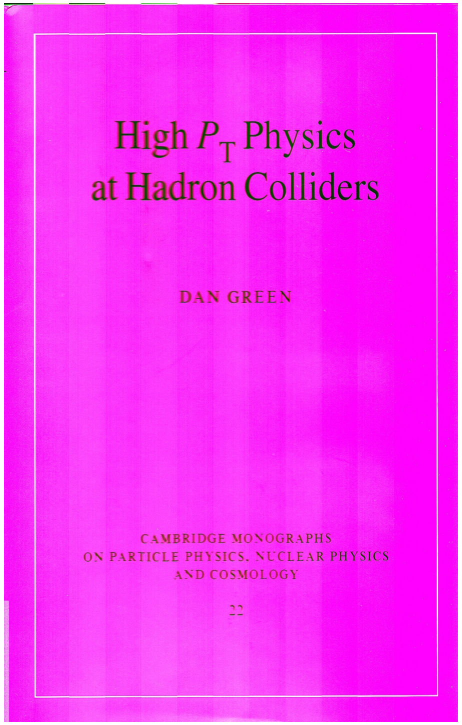
Fermi National Accelerator Laboratory

FN-549

Gravity for the Masses *

Dan Green
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

October 1990

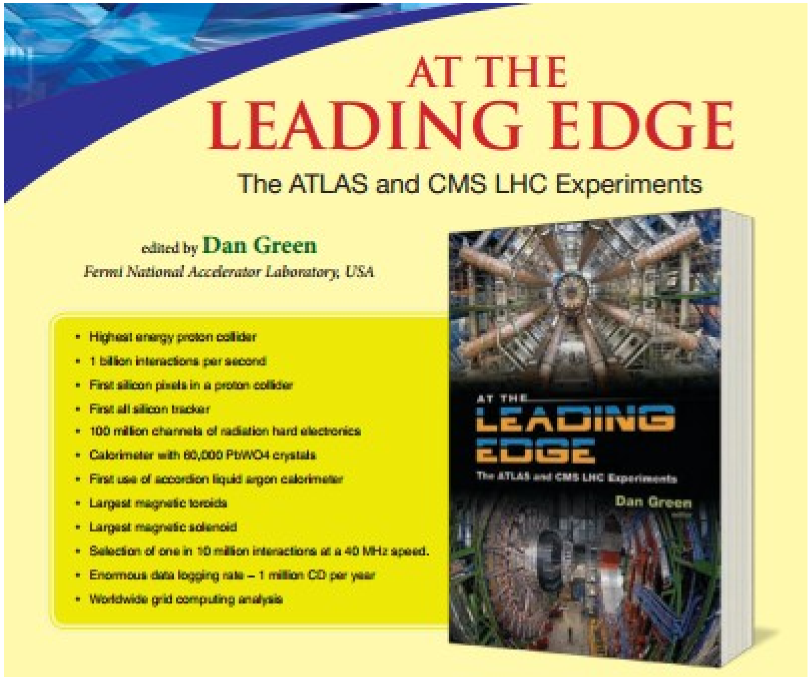


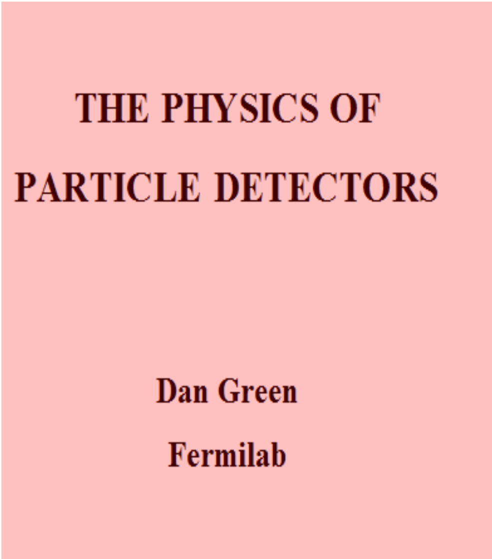
High P_T Physics
at Hadron Colliders

DAN GREEN

CAMBRIDGE MONOGRAPHS
ON PARTICLE PHYSICS, NUCLEAR PHYSICS
AND COSMOLOGY

22





THE PHYSICS OF
PARTICLE DETECTORS

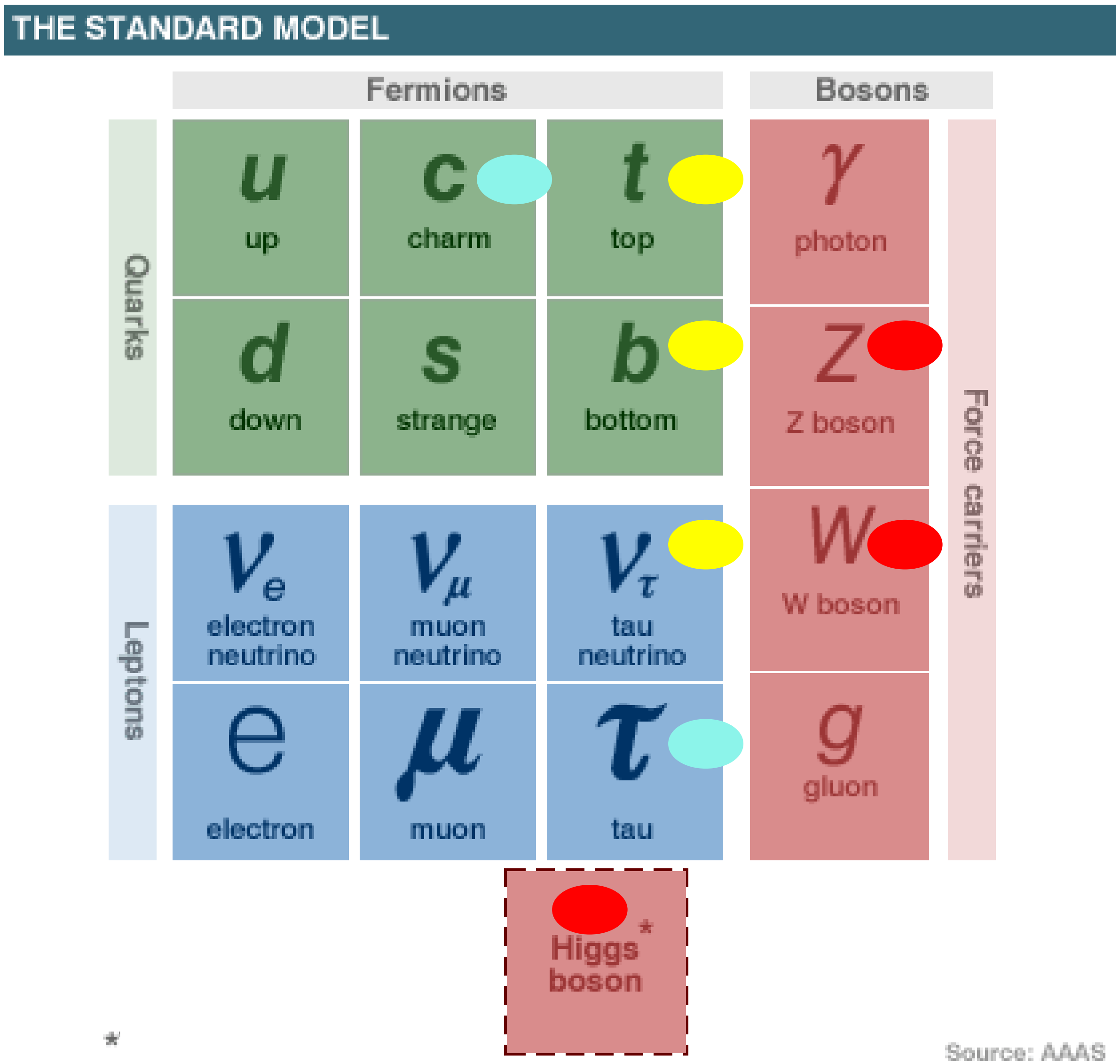
Dan Green

Fermilab

Outline

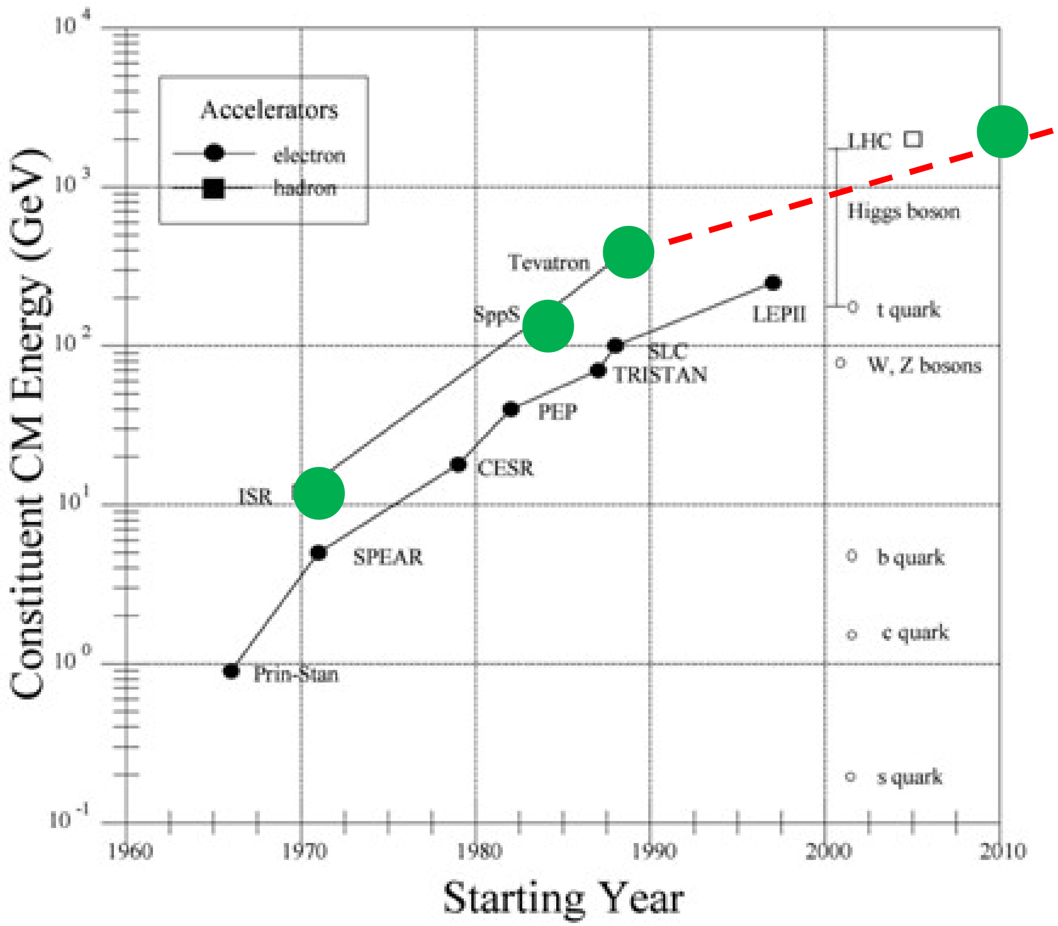
- The Higgs Discovery
- The "Higgs" particle ? SM or BSM ?
- What Next?
  - Near term
  - Long term

Periodic Table of HEP?



Like the periodic table, the SM provides a structure with missing "elements". In the last 40 years (1974, c quark) all the missing elements have been found. The third generation was found at SLAC – the c and the tau, completed by FNAL. CERN have found the W, Z and H.

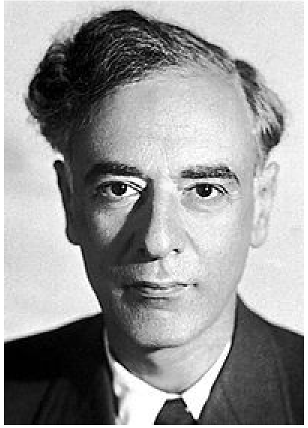
The Energy Frontier



Slide written in 1995

The advent of hadron colliders was in 1971 with the p-p ISR at CERN. The next step was the pbar-p collider at CERN (W and Z) and then a similar machine – the Tevatron at FNAL (t quark). The LHC is now operating at 4 times the Tevatron energy and 20 times the luminosity. These factors lead to a big increase in the chances of finding Physics Beyond the SM.

The "Higgs" Hunt - 1964



Lev Landau 1950, vacuum field in superconductors

R. Brout, F. Englert, G. Guralnik, C.R. Hagen, P. Higgs and T. Kibble

45 years ago. Experimenters did not have the tools to make the search. Need to rerig for the Higgs hunt.

SM H Basics

- **Lagrange Density**

$$\ell = \bar{\phi}(P^2 - M^2)\phi$$

$$S = \int \ell d^4x \;, [S] = 1, [\phi] = M$$

- **VEV and Cosmological Term**

$$V = \mu^2\phi^2 + \lambda\phi^4, \min$$

$$<\phi>^2 = -\mu^2 / 2\lambda$$

$$V(<\phi>) = -\lambda <\phi>^4$$

- **Higgs Boson**

$$\phi = <\phi> + \phi_H$$

$$V(\phi) = -\lambda <\phi>^4 + 4\lambda <\phi>^2 \phi_H^2 + 4\lambda <\phi> \phi_H^3 + \lambda\phi^4$$

$$M_H = 2\sqrt{\lambda} <\phi>$$

triplet, quartic coupling

EWSB - SM

- **Covariant Derivative**

  W Mass

$$\partial \to D = \partial - igV, V = W, Z, \gamma$$

$$D\bar{\phi}_H D\phi_H \sim (g_W^2/2)\bar{\varphi}_W \varphi_W (\langle \phi \rangle + \phi_H)(\langle \phi \rangle + \phi_H)$$

$$M_W = g_W \langle \phi \rangle / \sqrt{2}, M_Z = M_W / \cos\theta_W, M_\gamma = 0$$

- **H-W Interactions**

$$\ell_H = \alpha_W \langle \phi \rangle / 2[\phi_H \varphi_W \varphi_W] + \alpha_W / 2[\phi_H \phi_H \varphi_W \varphi_W]$$

- **Fermions**

$$\ell_f = g_f[\bar{\psi}\phi\psi], Dirac - \bar{\psi}(\not{\partial} - m)\psi$$

$$m_f = g_f \langle \phi \rangle$$

$$\ell_f = m_f \bar{\psi}\psi + g_f[\bar{\psi}\phi_H \psi]$$

$$g_f = g_W (m_f / M_W) / \sqrt{2}$$

Numerical Values

- **VEV**

$$G/\sqrt{2} = g_W^2 / 8M_W^2$$

$$M_W / g_W = <\phi> / \sqrt{2}$$

$$<\phi> = \sqrt{\sqrt{2}/4G}$$

$$<\phi> = 174\ GeV$$

Everything is now specified for the SM Higgs.

- **Masses, Couplings**

$$\sin\theta_W = 0.481$$

$$g_W = 0.63$$

$$\alpha_W = 1/31.6$$

$$M_W = 80\ GeV$$

$$M_Z = 91\ GeV$$

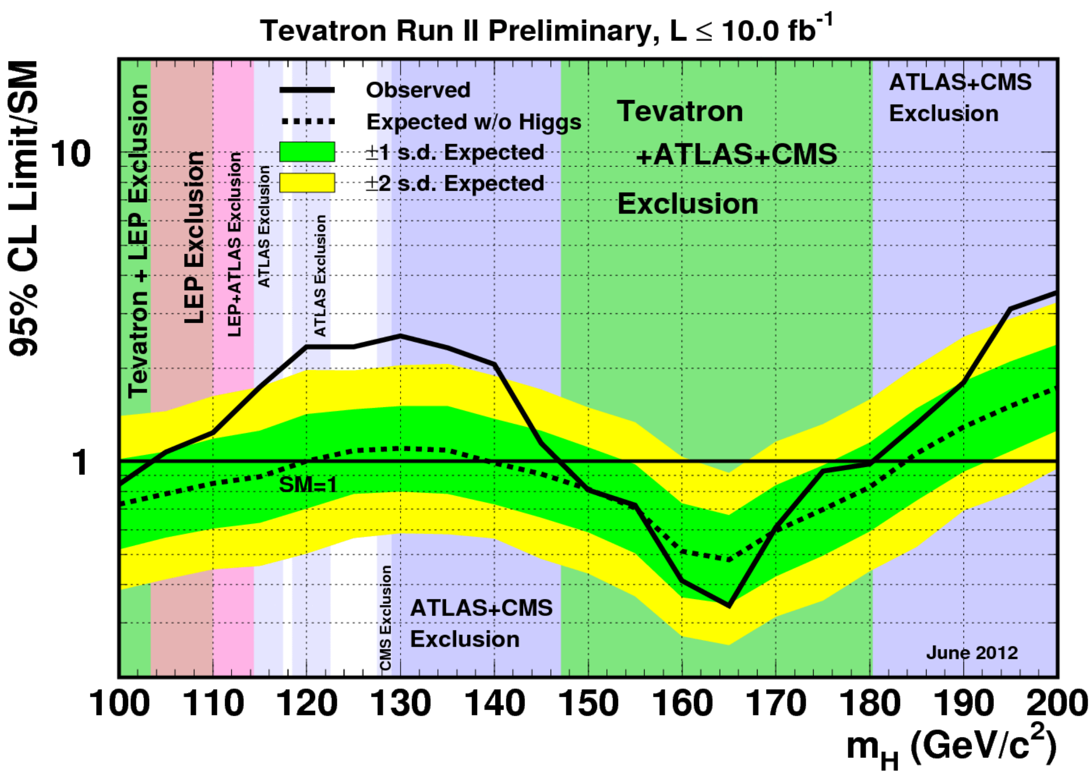
$$M_H = 126\ GeV \rightarrow \lambda = 0.60, \mu = 191\ GeV$$

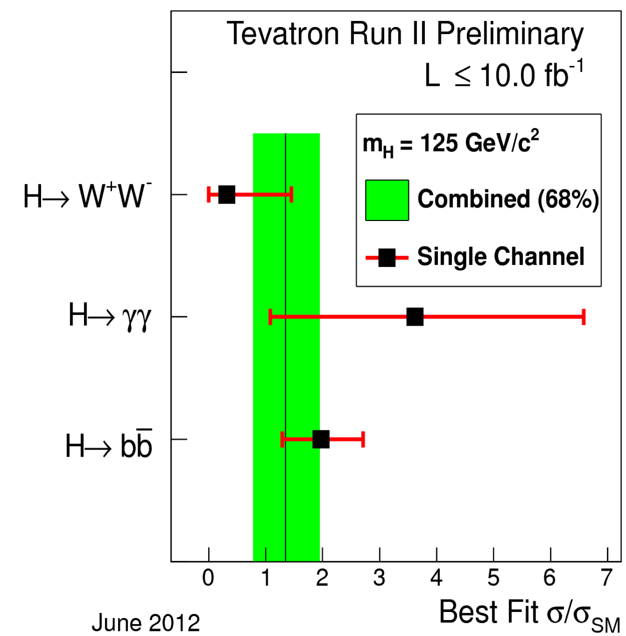
The Last 20 Years of H Hunting, 1988 - 2012

- SSC approved (25 years after H proposed) – 1988
- SSC canceled – 1993, where to build the tools? LHC ?
- US CMS formed, LOI – 1994
- Fermilab is host lab for US CMS - 1996
- US-CERN Agreement – 1997
- Upgraded CDF and D0 start Run II - 2001
- US CMS Detector Complete (CD4) – 2005
- First 7 TeV Beam – 2010
- Tevatron turns off, LHC delivers 5 /fb – 2011
- Tevatron final results, LHC delivers 5 /fb at 6x10^33 /cm^2*sec (~ 20 x Tevatron) – mid 2012
- ATLAS and CMS announce a new particle – July 4, 2012

Lesson – what a long, strange trip it's been. Need the energy, luminosity and much better detectors in order to confront the H search decisively.

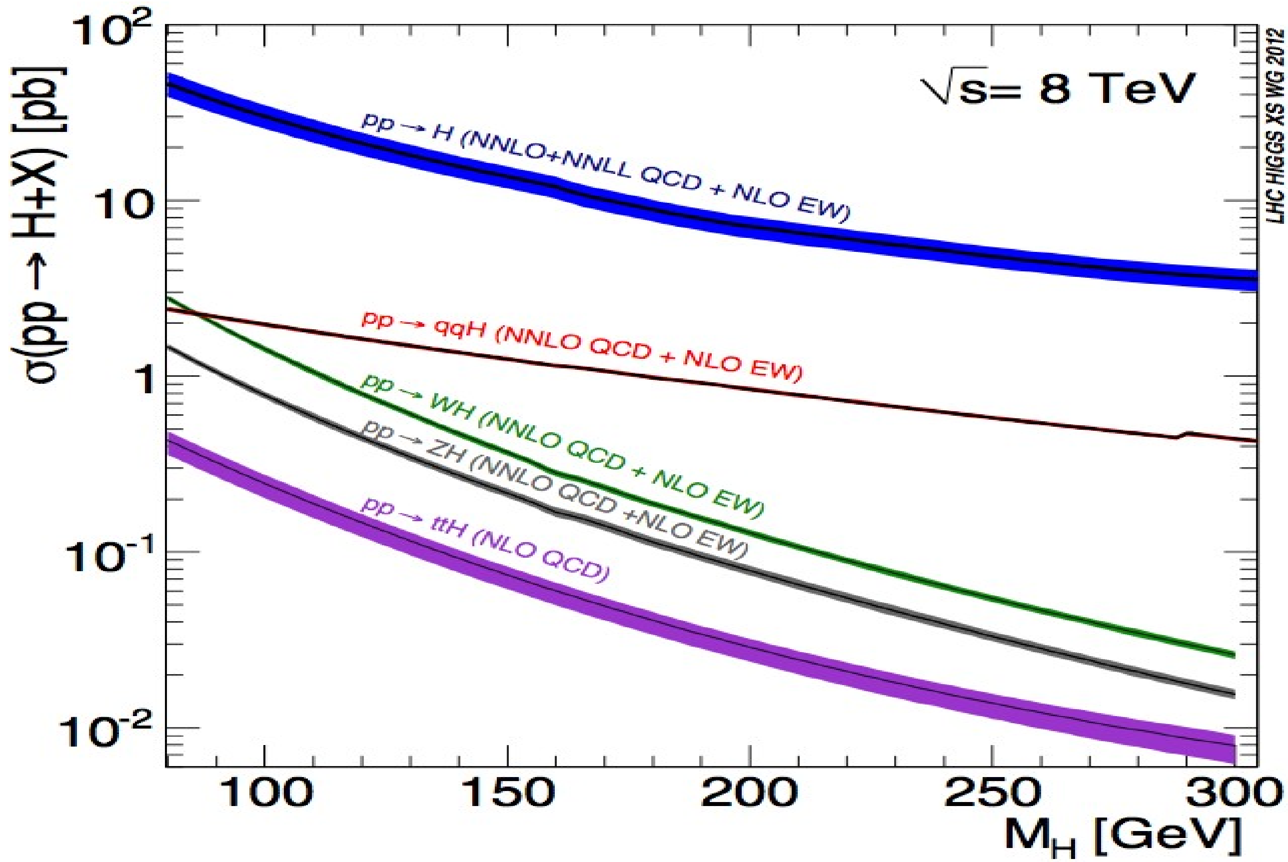
CDF and D0 Combination Limit

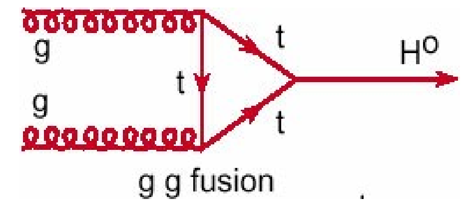


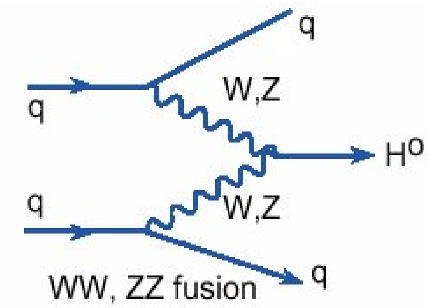


- **CDF and D0 were Upgraded in 2001 – Run II in order to make a plausible Higgs search.**
- **Precision W, t mass measurements are a lasting Tevatron legacy**
- **Kudos for CDF and D0 who have extracted the last full measure of the information available in the full data set.**

Higgs Boson Production







H is weakly produced. Design a p-p machine creating very high reaction rates (aka luminosity). Must be > 30x Tevatron, so detectors must be > 10x more complex. Radiation damage is now important.

H Decay Rates – V and f

$$\Gamma(\phi_H \to WW)/M_H = (\alpha_W/16)(M_H/M_W)^2\beta$$

$$\Gamma(\phi_H \to q\overline{q})/M_H = (3\alpha_W/8)(m_q/M_W)^2\beta^3$$

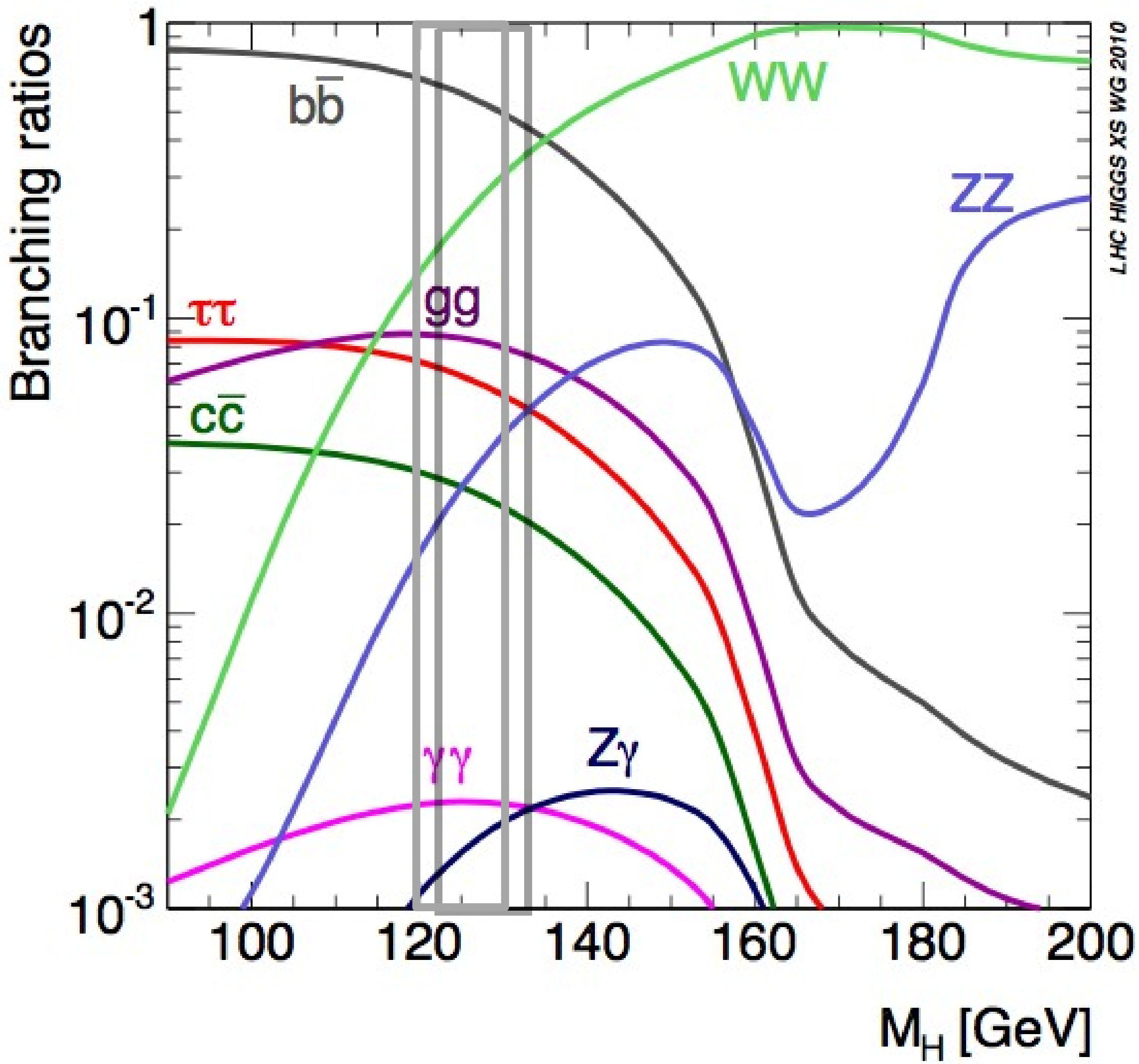
Photon and gluon pairs are connected to H by W or top pairs.

$$\Gamma(H \to gg) \sim \left[(\alpha_W/8)(M_H/M_W)^2\right]\left[(\alpha_s/\pi)^2|I_g|^2/9\right]M_H$$

$$\Gamma(H \to \gamma\gamma) \sim \left[(\alpha_W/9)(M_H/M_W)^2\right]\left[(\alpha/\pi)^2|I_\gamma|^2/9\right]M_H$$

The SM H has a fully specified production cross section and decay rates into fermions and vector bosons.

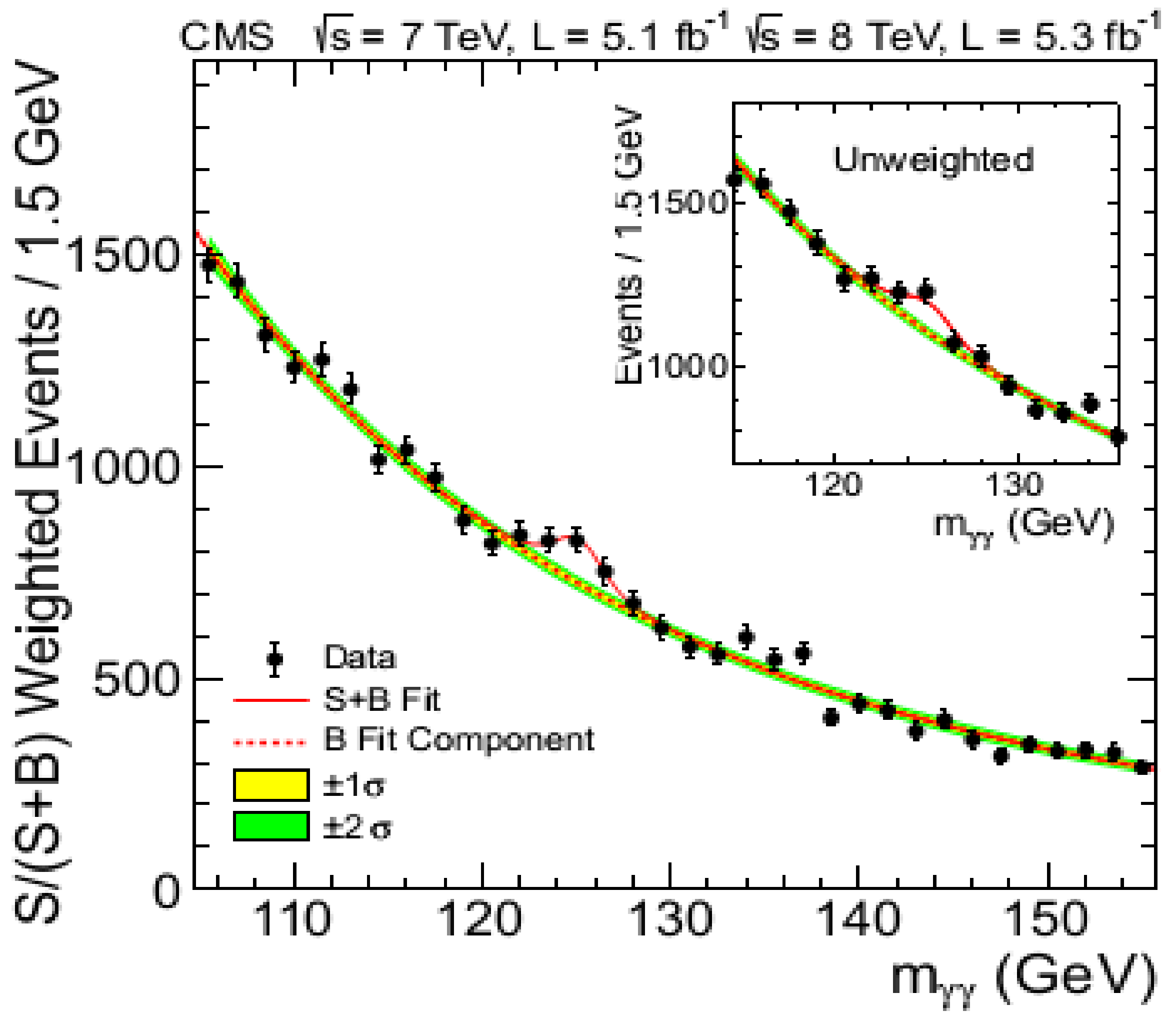
H Branching Ratios



Design a general purpose detector that can use the high luminosity. Mass is not predicted, so be prepared to look at W and Z pairs, but also b, g, c, tau, and photon pairs.

CMS is a ~ 10x increase in size and complexity – needed to address the H search up to 1 TeV mass.

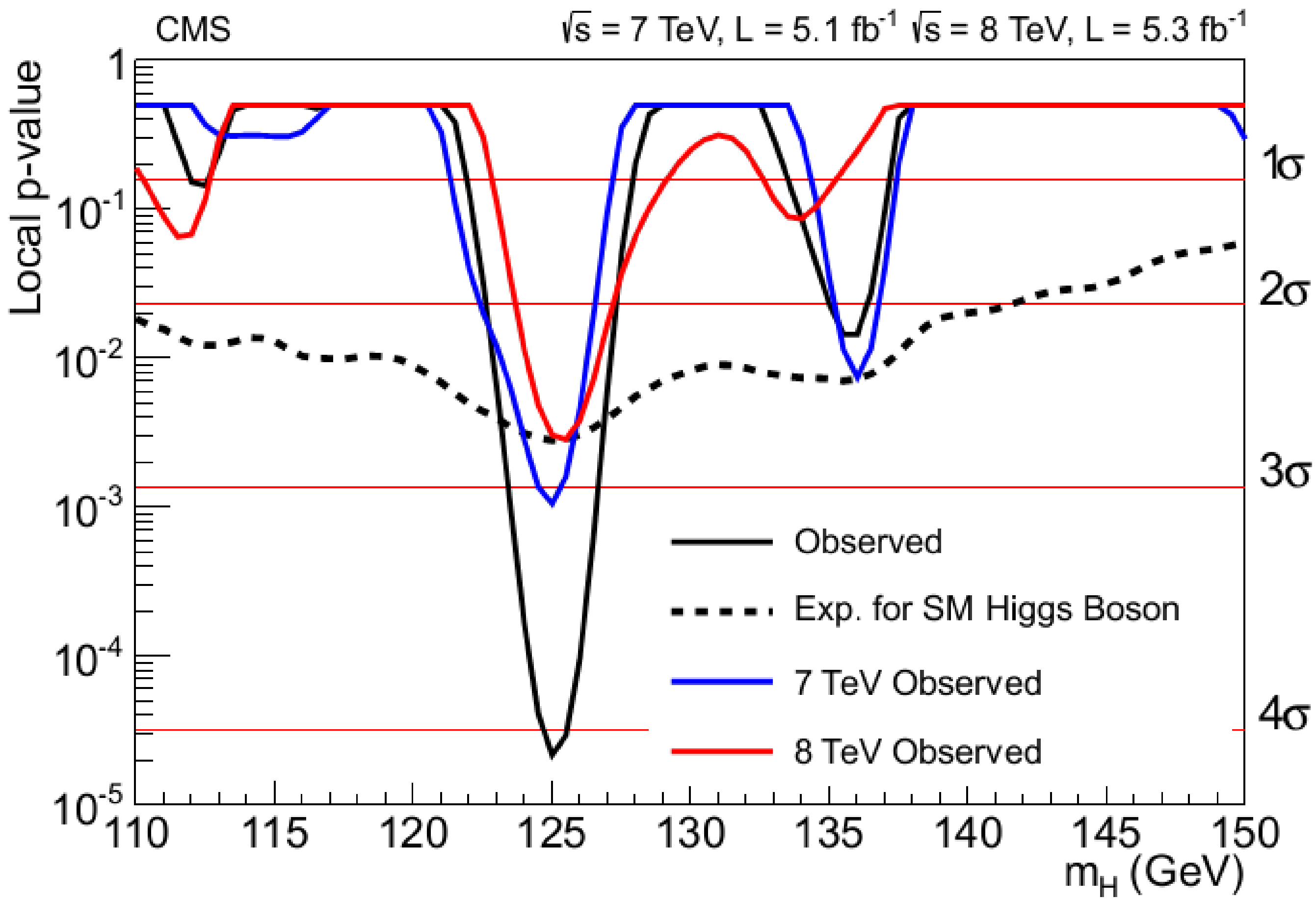
The 2 Photon Mass Spectrum



There is a narrow peak, consistent with the CMS mass resolution.

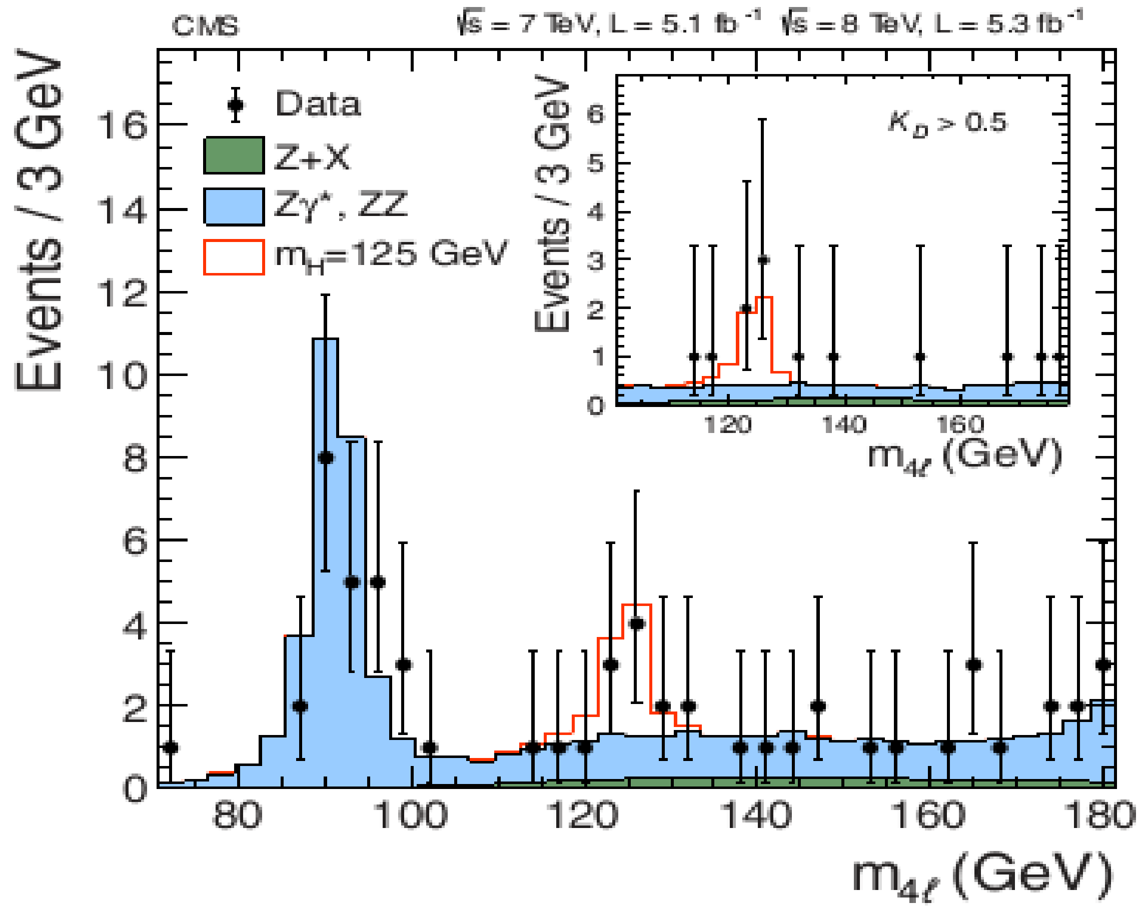
Lesson – mass resolution defines your discovery potential

The Probability of a H Signal



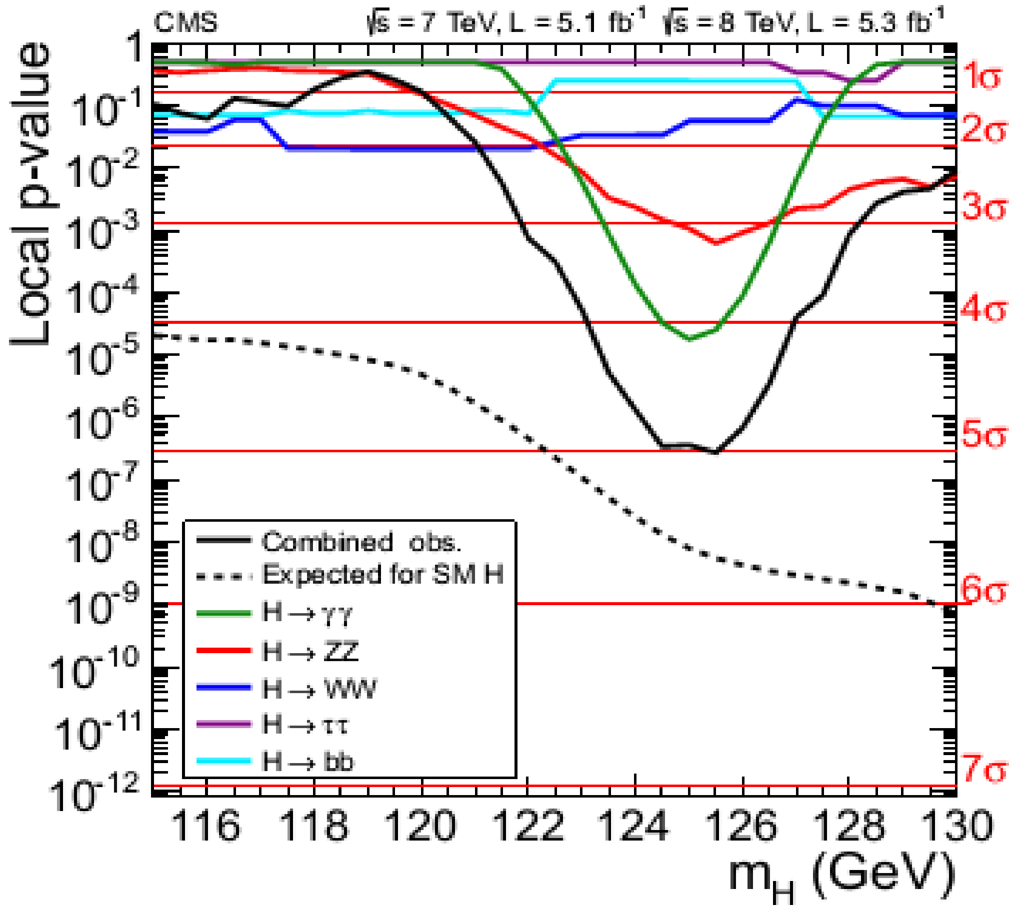
What is the probability that a SM H with variable cross section has been observed? The 7 and 8 TeV data are consistent which is a good check. The observed "signal" is larger than the SM H expected and has > 4 "sigma" significance.. The search "width is ~ 3 GeV FWHM

The Z + Z* Mass Spectrum



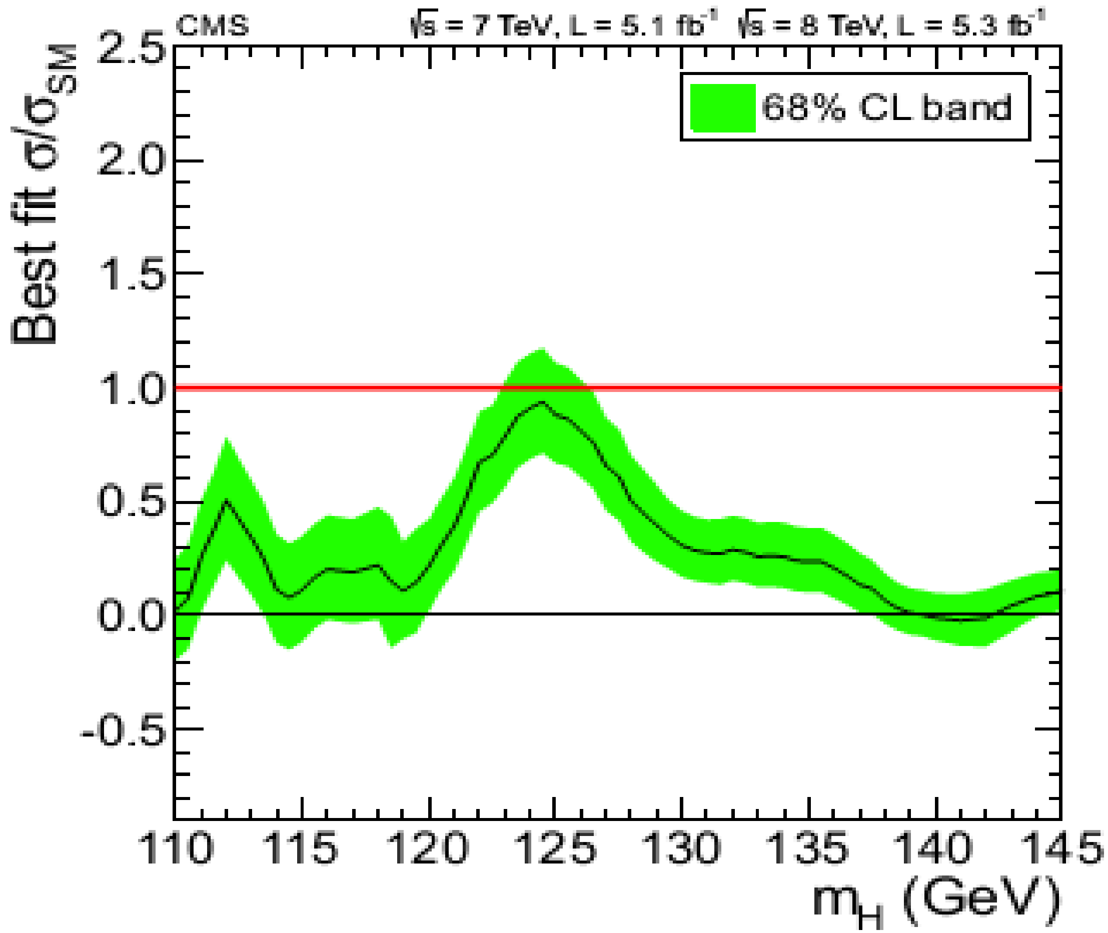
Before and after "MELA" cut on the sample. Z is a "standard candle"

Overall Probability



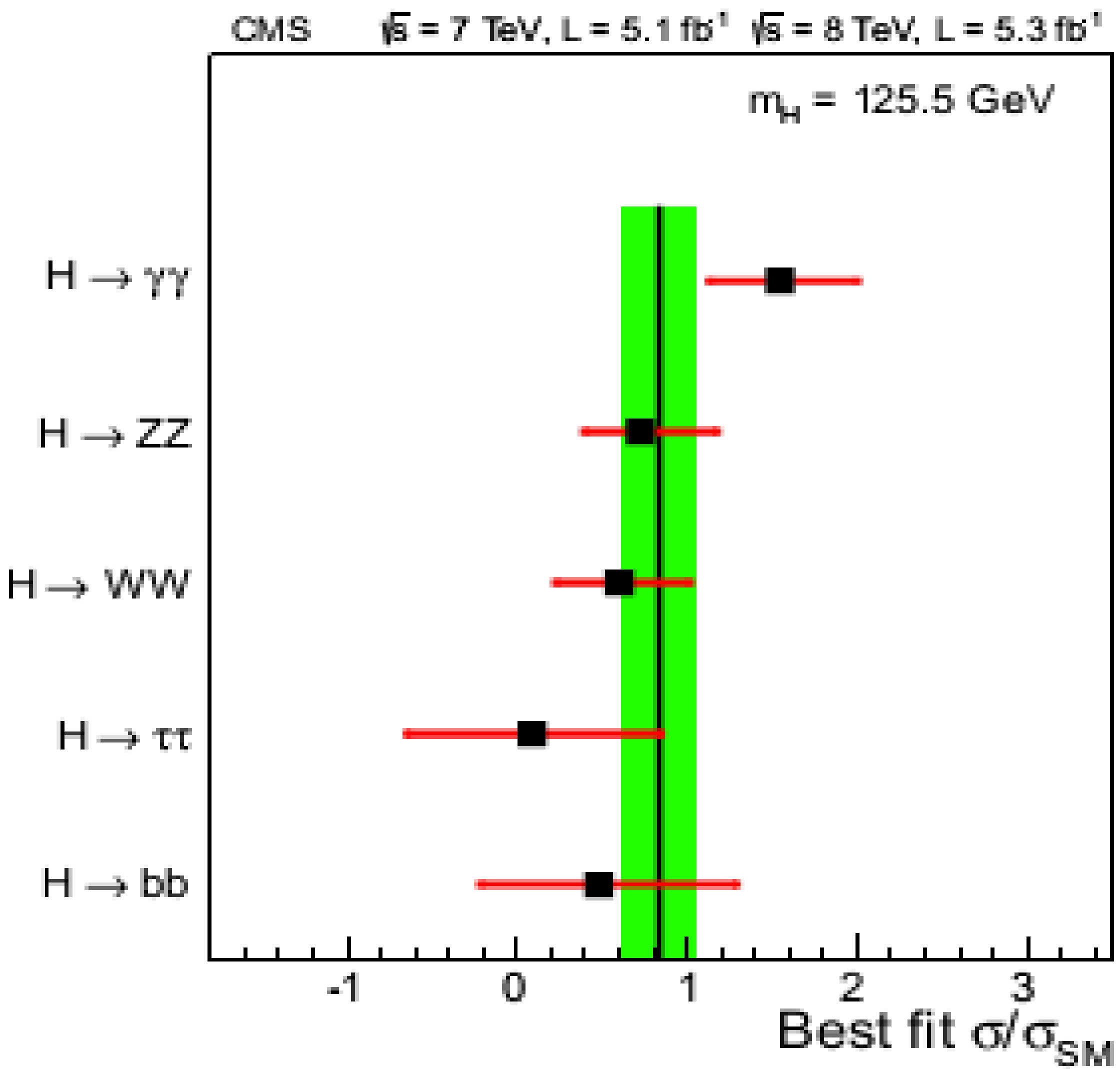
Because of the low result for b and tau pair final states, inclusion of all the expected SM H final states lowers the significance below that found for high resolution final states alone.

Production Cross Section



- **The resonance is produced with a cross section ~ SM H. That favors ~ SM coupling to t pairs in ggF loop.**

Decay Modes

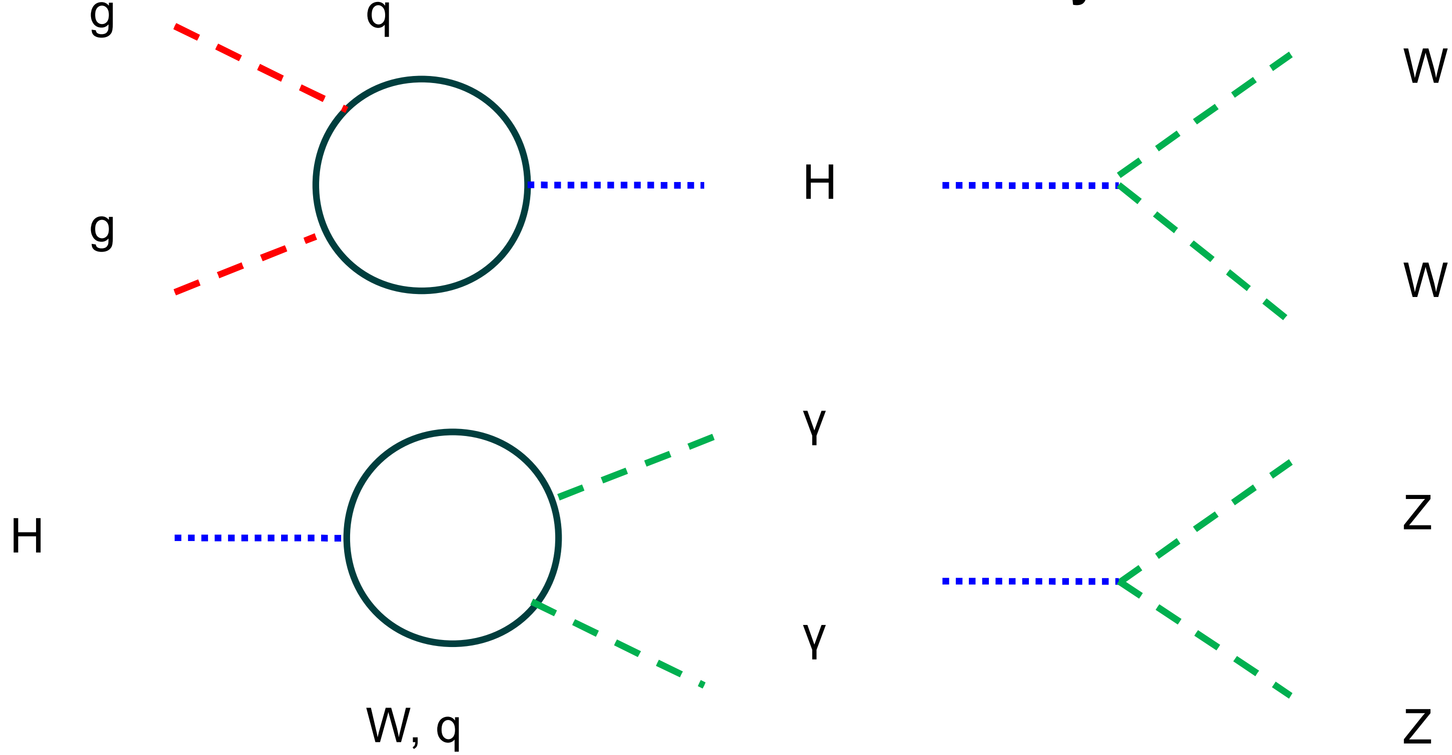


In CMS the fermions are low in coupling w.r.t. expectations, while the W and Z couplings are ~ correct and the photon coupling is a bit high. Clearly, more data are needed in order to sharpen those results.

Quantum Loops ?

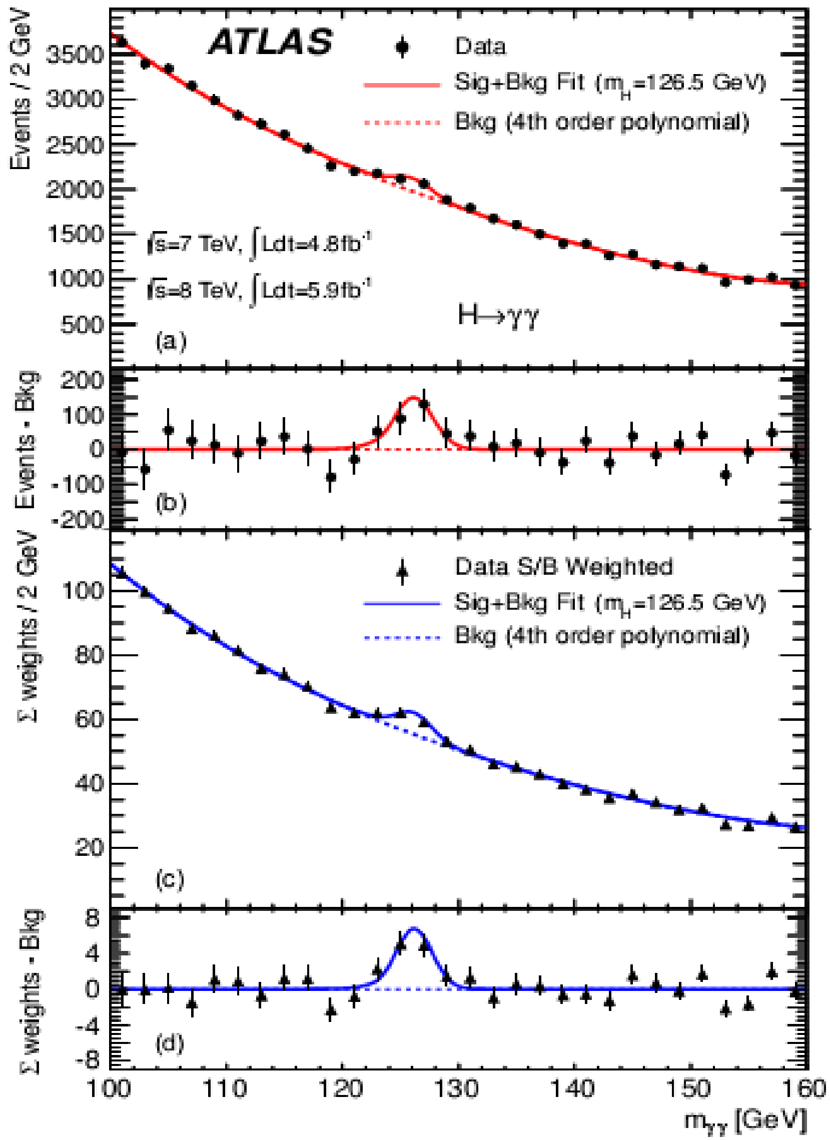
Basic VV decays

ggF – cross section needs top quarks in the loop



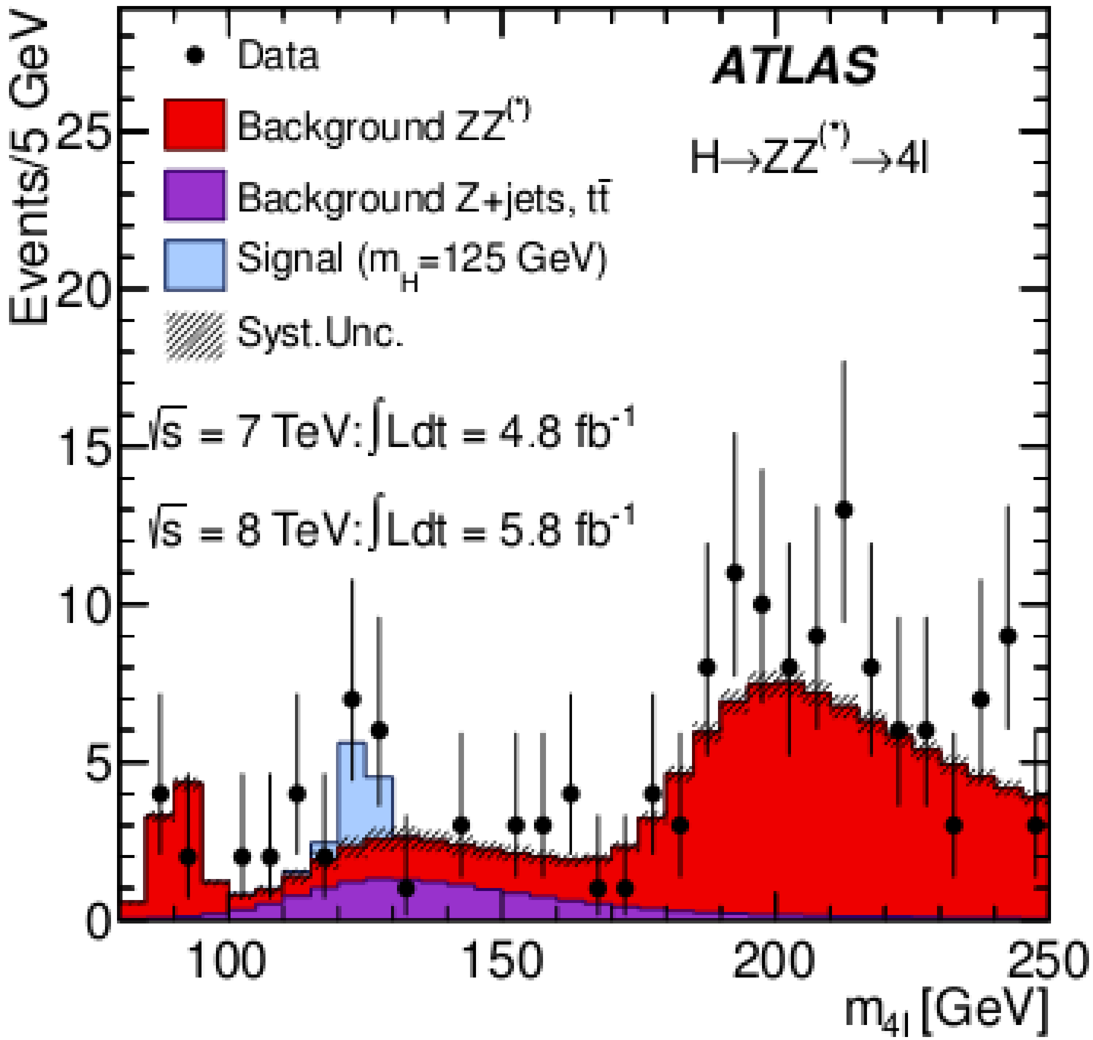
Photons are mass-less, so H decays to them only by means of a virtual loop of t and W ? Something else? Enhanced signal ? New Physics ?

ATLAS?



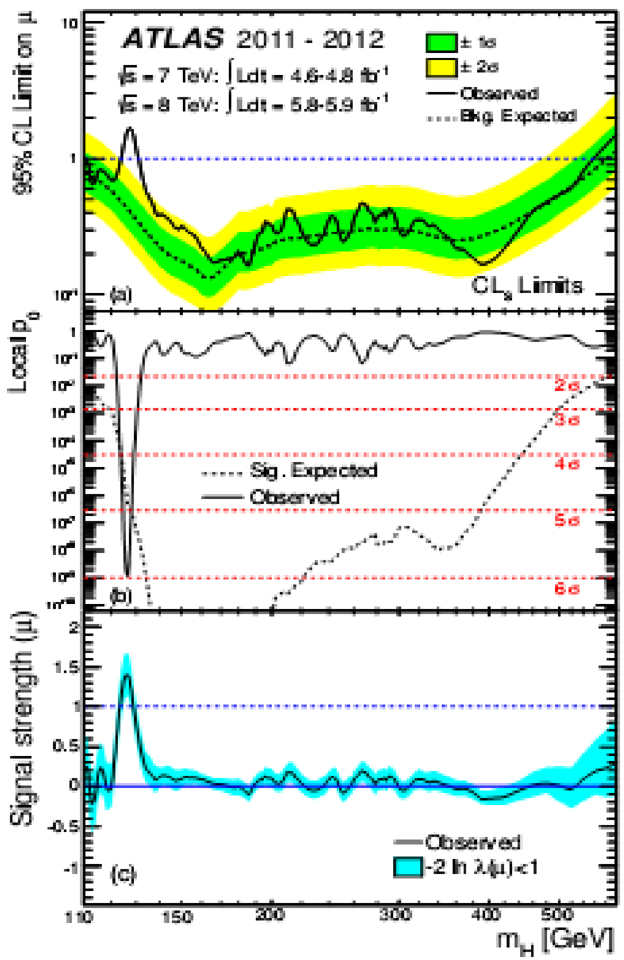
It is crucial to the credibility of the result that there is independent confirmation. That is not strictly necessary statistically, but experience has shown the need because of bias (blinding) and unknown systematic error. Because of that experience "5 sigma" is the gold standard while 3 sigma would be fine otherwise.

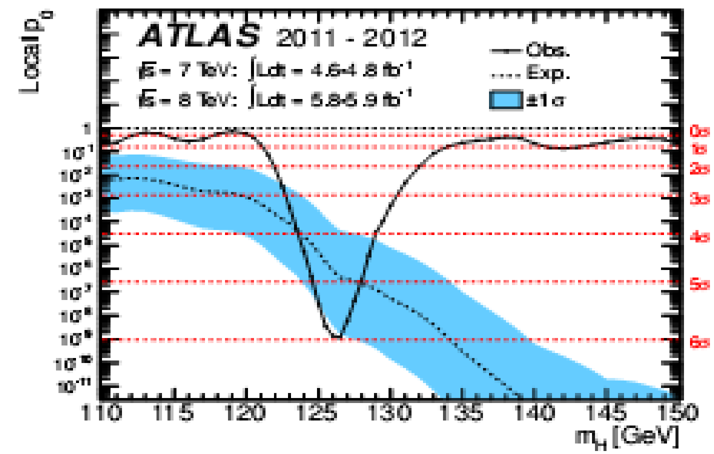
ATLAS – Z + Z*

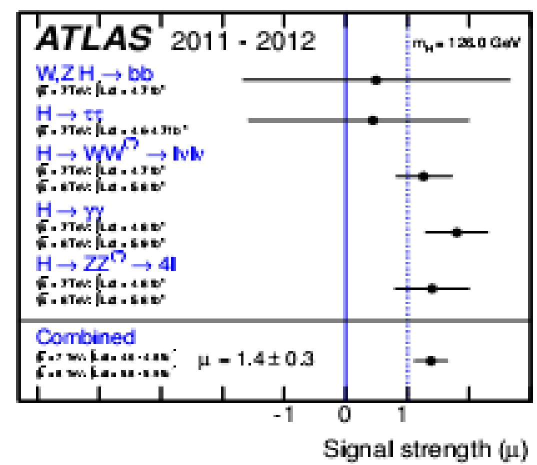


ATLAS have analyzed the 2 final states – photon pairs and Z pairs. They see consistent masses of the enhancement and consistent behavior for the 2011 and 2012 independent data sets.

ATLAS Combined



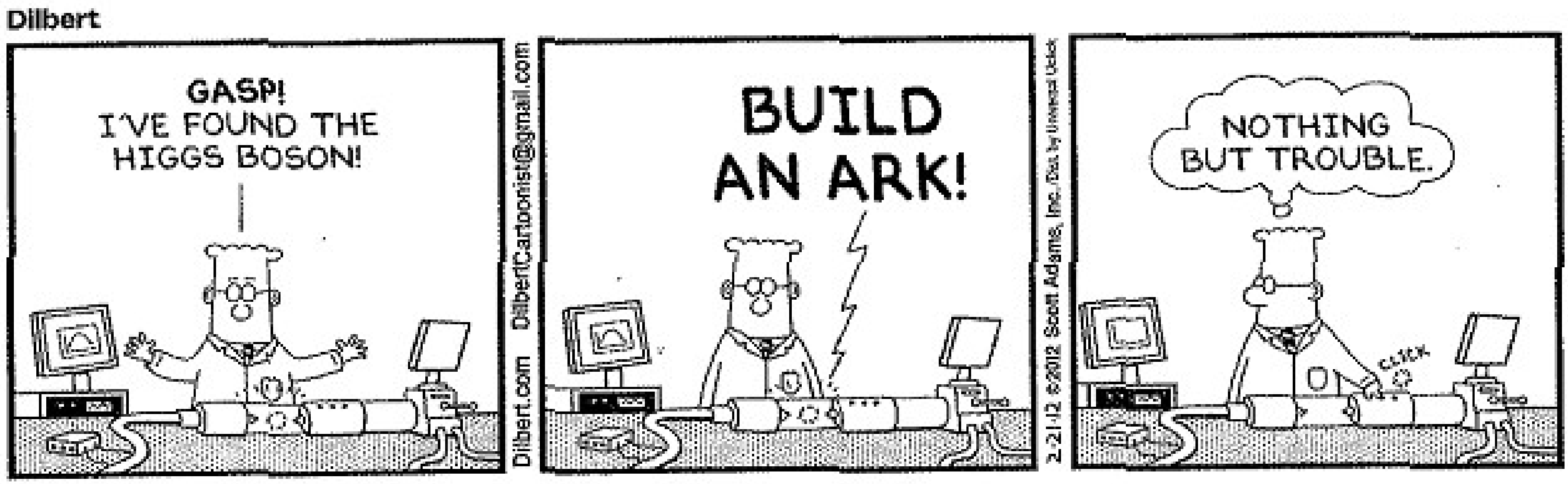




ATLAS see a larger cross section than a SM H , but that is not statistically significant. CMS sees a smaller ratio, also not significant.

What’s Next for 2012 and Beyond?

The 'god particle“

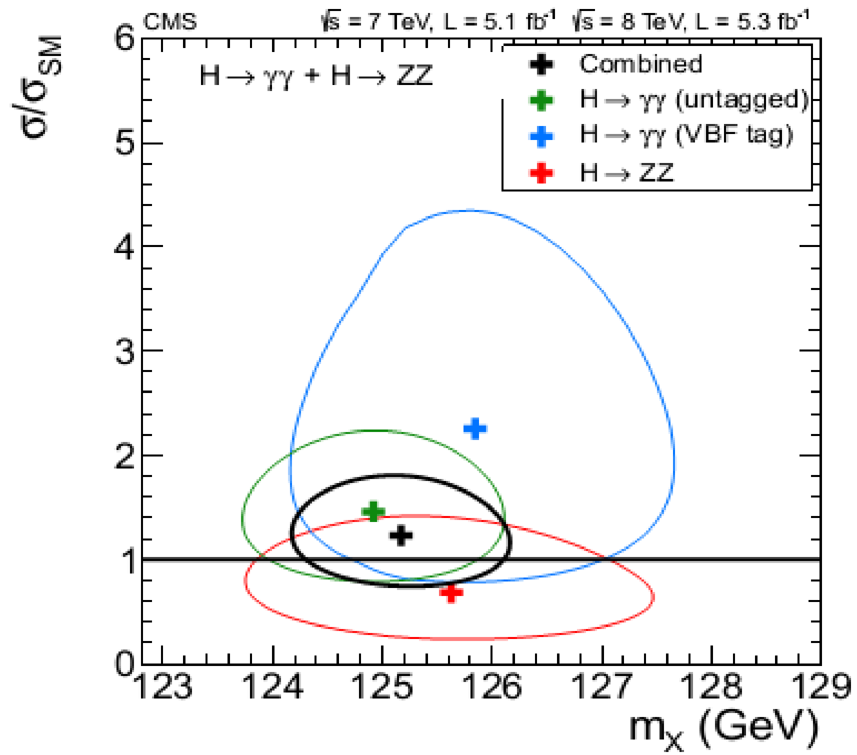


This is not just another particle. It is the glue that holds the SM together. There is a new field, uniform in space AND time – it is the new “vacuum” which is not empty (Landau). The vacuum can be excited (LHC – put energy into the vacuum) so it emits Higgs bosons like an excited EM field emits photons. Their properties are completely predicted in the SM once the mass is known and can be studied and verified – or not.

Near Future - “Run I”

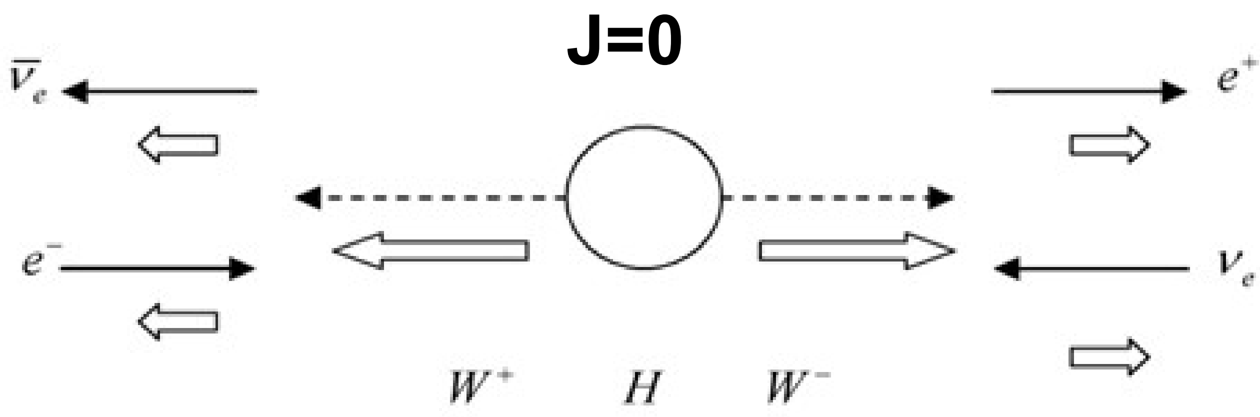
- LHC run of 2012 extended by 3 months ~ 30 /fb?
- Data set may be 3x improved – learn much more about properties of the new particle.
- Continue the search for the mechanism to keep the H mass low…
- Note that the SM H mass is not radiatively stable under quantum corrections. Something must keep the mass “low” – SUSY? Extra dimensions? (either cancel the loops or reduce the Planck mass). Another possibility is “composite” H – dynamics (BCS ? – technicolor ?).

Mass, Width, Spin



- The natural width is < CMS mass resolution of ~ 1 %. That would indicate weak decays of H, in fact weaker than W or Z gauge bosons.
- The spin cannot be 1 (Yang's theorem), so this particle is not like all the force carriers – which are vector particles with spin = 1 . The spin is, J = 0,2.
- It couples to vector bosons as a H must – unitarity in WW scattering.

H -> W+W, Scalar Boson

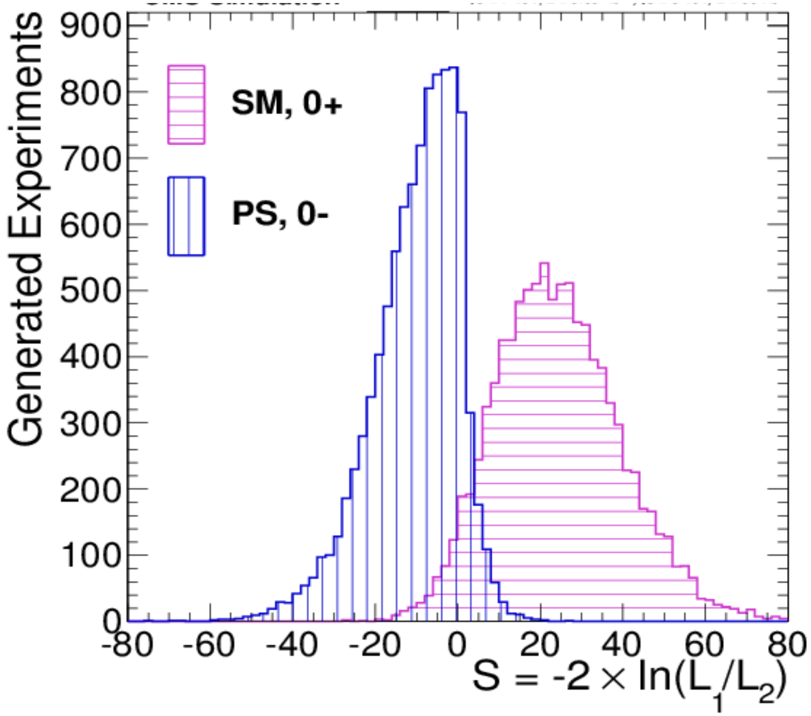


A scalar Higgs will decay into W pairs. The W spins must be oppositely directed. When the W decay into fermions, the (V-A) nature of the weak interactions make particles (electrons, neutrinos) left handed and anti-particles right handed. Spin conservation means the lepton pair moves in ~ the same direction, leading to a low value for the di-lepton mass.

J^{PC} Measurements – 30 /fb

$H \to ZZ \to 4l$

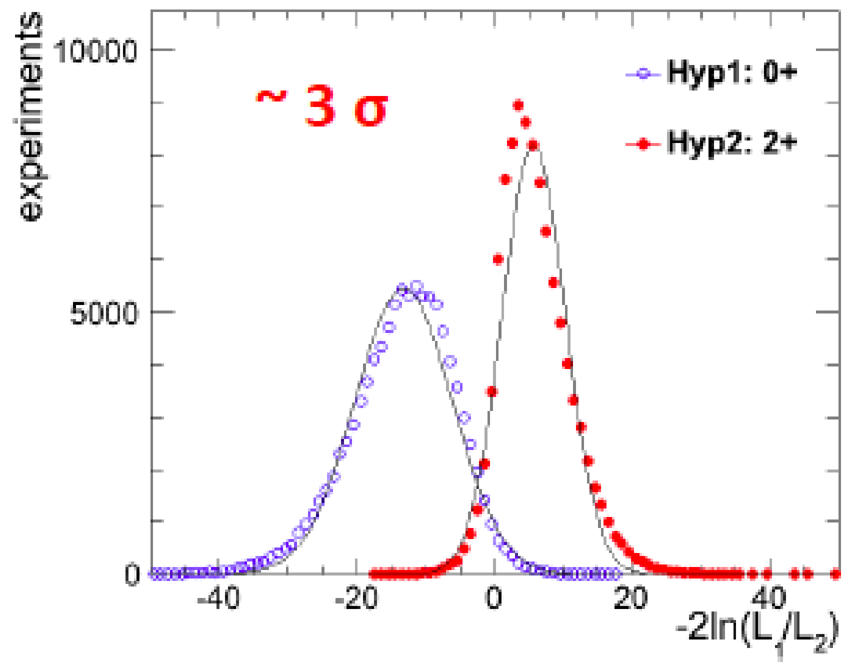
CMS Simulation $L = 30\ fb^{-1}$, $\sqrt{s} = 8$ TeV



Expect ~3σ separation between scalar and pseudo-scalar in 2012

$H \to WW \to 2l2\nu$

JHU Generator level $L = 10\ fb^{-1}$, $\sqrt{s} = 8$ TeV

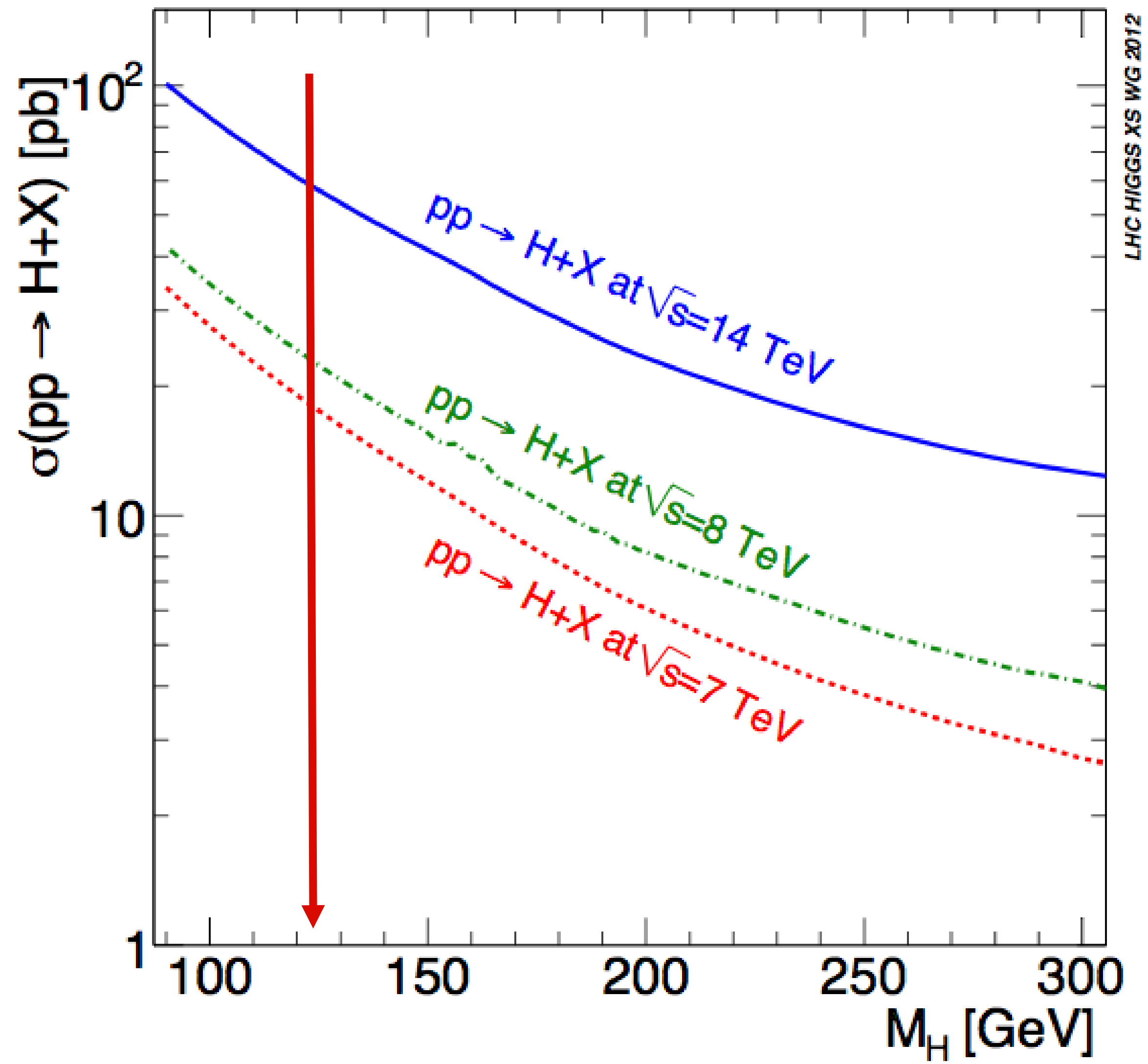


Expect ~3σ separation between spin 0, 2 with 10 fb^{-1} but assuming no systematics and WW as only background

http://indico.cern.ch/contributionDispl

LHC will Run @ 14 TeV in 2015 – Run II

The cross section For H(125) will then increase More than 2 fold. That is a L increase at fixed M......For high mass, Z' and SUSY searches there will be a ~ 2 fold increase in mass reach.



H Decays: Width, BR or Ratios

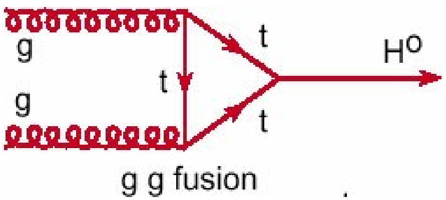
- The SM Higgs has a total width ~ 4 MeV
  - The mass resolution is ~ 1.3 GeV
  - Therefore, the H(125) total width is unknown
- The observed events are ~ the ggH partial width x the final state BR.
  - If the SM total width is assumed then the product of the ggH width x the final state width is measured
  - If, instead, ratios are taken then ony the ratios of final state partial widths are extracted.
- Thus, BSM final states increasing the H width are possible – "invisible H"

Coupling to Quarks?

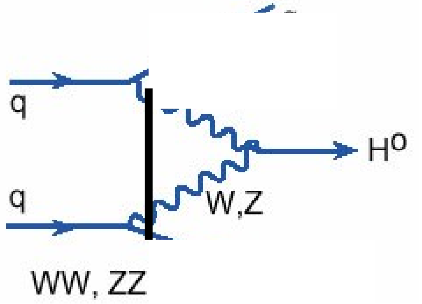
$$\hat{\sigma}(gg \rightarrow H) \sim \pi^2 \Gamma(H \rightarrow gg)/M^3 = [\alpha_W \alpha_s^2 |I|^2]/(72M_W^2)$$

$$\hat{\sigma}(q\bar{q} \rightarrow H) \sim \alpha_W^3 |I|^2]/(72M_W^2)$$

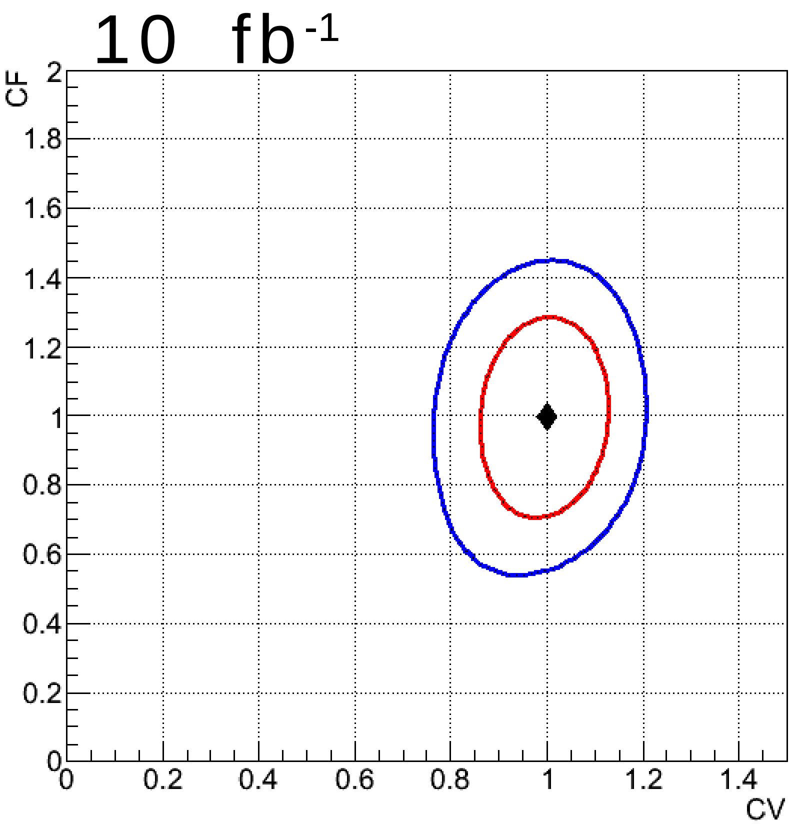
- The VBF process factors out V+V formation of the H, while the ggF process produces the H by the strong coupling of the H to top quarks. It is important, therefore, to compare production mechanisms to distinguish H coupling to V and f.

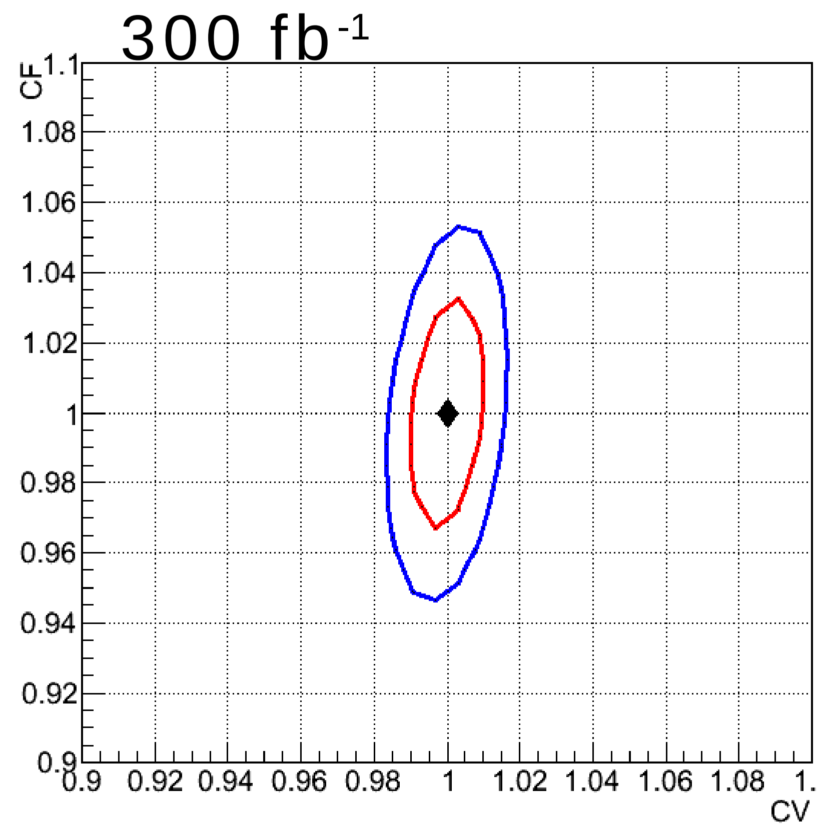


- Comparing g+g into a virtual top loop v.s. q + qbar with a virtual W loop for H production, the observed cross section is fully consistent with ggH production and not with DY-like production. Thus, the ~ SM coupling of the resonance to heavy top quarks is indicated.



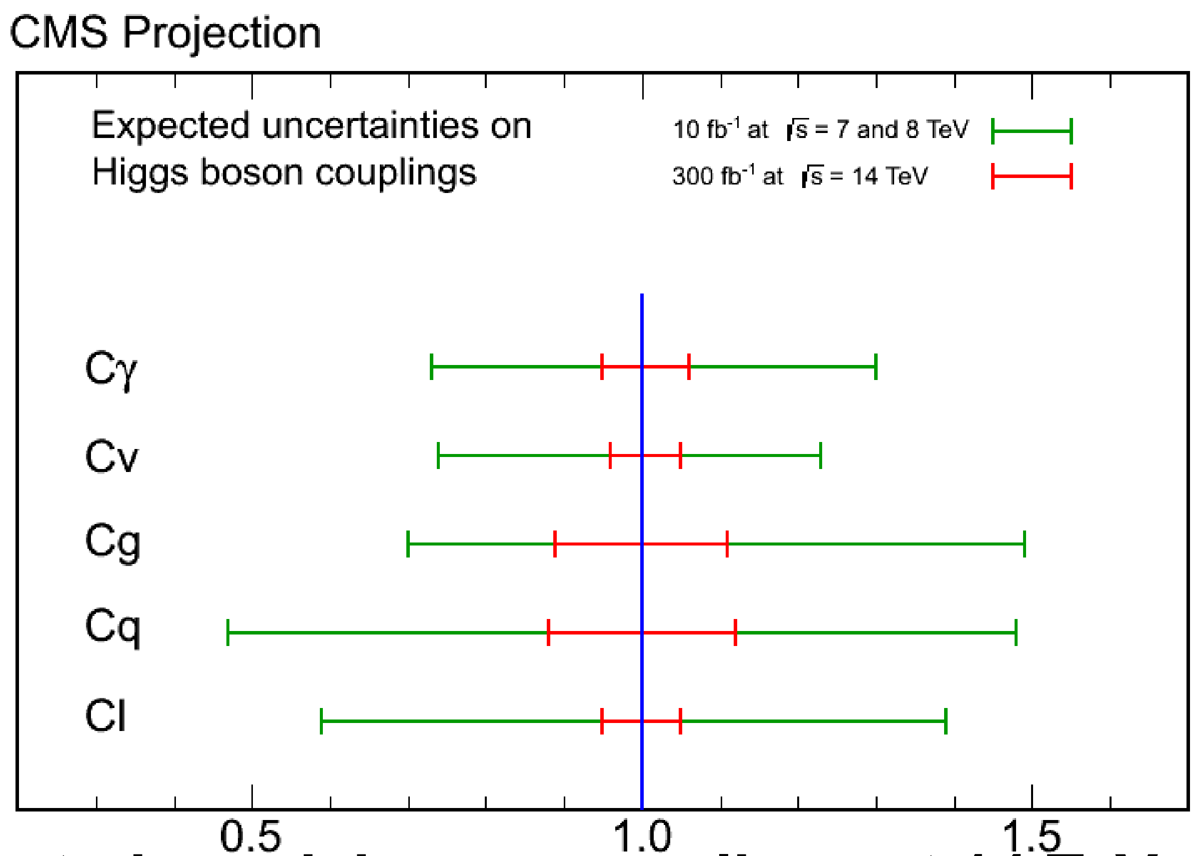
Higgs Couplings – 300 /fb





Running at 14 TeV for 300 /fb the LHC experiments can achieve a few % accuracy on the vector boson and the fermion couplings

Higgs Couplings



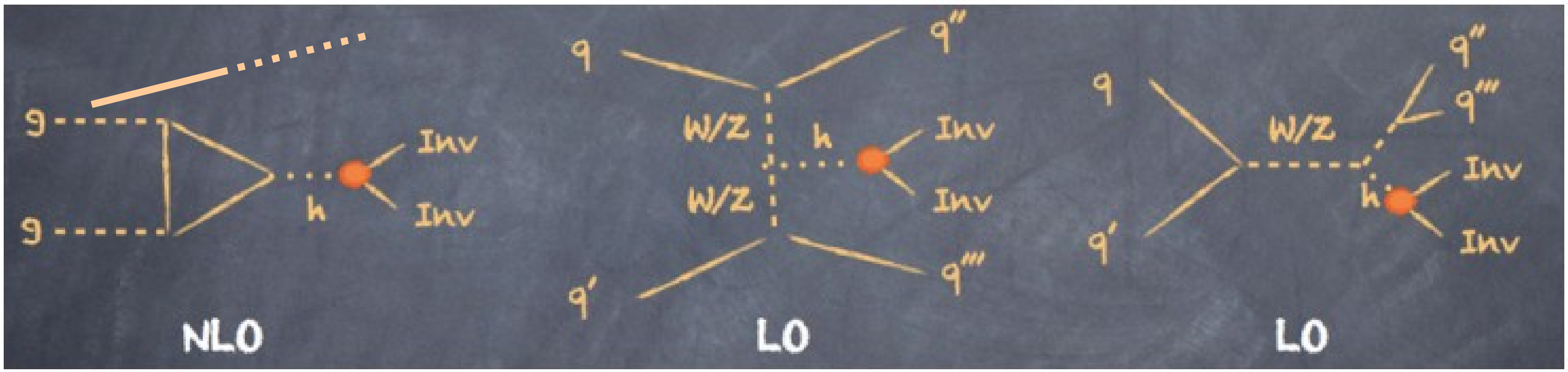
- **estimated precision on couplings at 14 TeV with 300 fb^{-1}**
- **based on 7+8 TeV CMS results get to ~ 10%**

Emily Says

- "The soul should always stand ajar, ready to welcome the ecstatic experience" - Emily Dickinson
- Be ready for BSM surprises... SUSY, DM-monojets, aTGC, WW scattering ....

Invisible Higgs ?

gluon-gluon fusion (ggF) | vector boson fusion (VBF) | Higgs-strahlung (VH)



$$R_{\mathrm{inv}} = \frac{\sigma(pp \to H) \times \mathrm{BR}(H \to \mathrm{inv.})}{\sigma(pp \to H)_{SM}} \lesssim 0.9 \ 95\%\mathrm{CL}$$

- **Use monojets (ISR), VBF, or associated production to search for H decays to BSM invisible states**
- **Limit is now not very constraining. Work on search strategies to get improvements.**

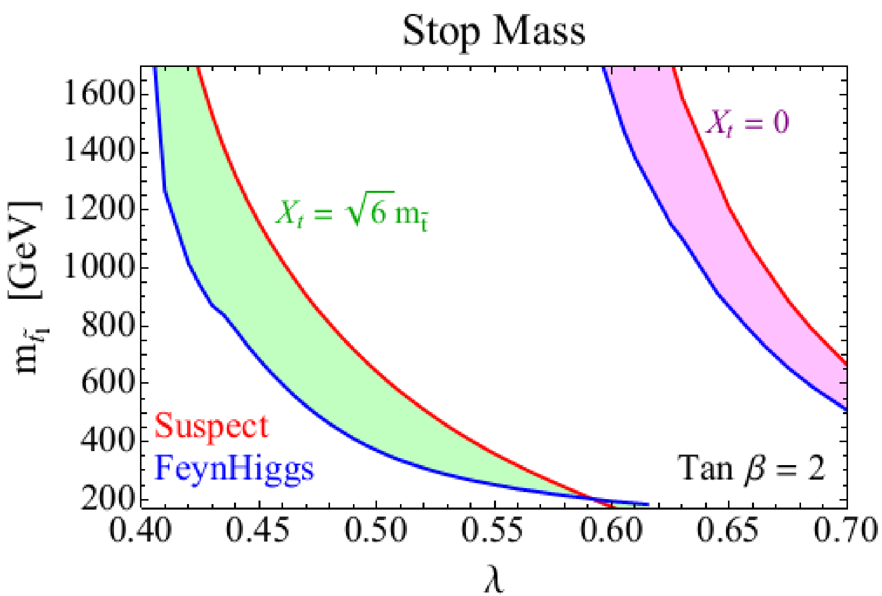
Radiative H(125) Stability

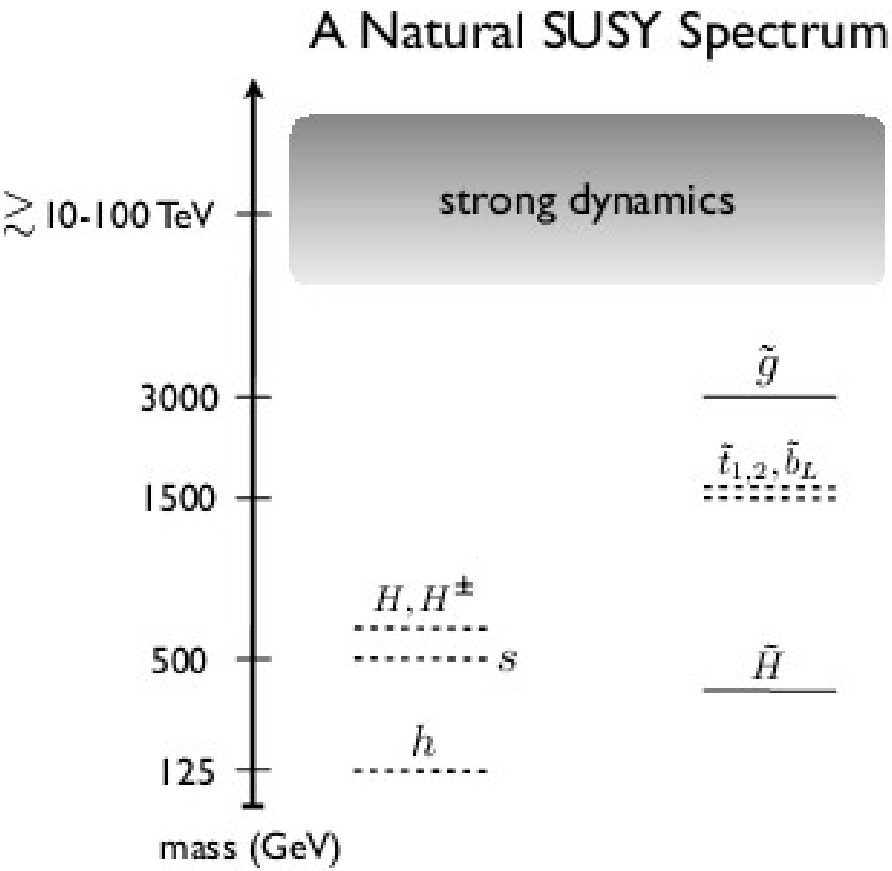
- **A fundamental scalar is prey to radiative loops driving the mass**
  - **Cancel the fermions with SUSY (amplitudes)**
  - **Reduce the mass GUT/Planck scale – extra dimensions**
  - **The H is a fermion pair composite (Cooper pairs)**

$$\delta M_H^2 = \alpha_W / 8\pi (\Lambda / M_W)^2 (6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2)$$

- **In SUSY the desire, the squark and gluino masses now excluded < 1 TeV , is to have small fine tuning.**

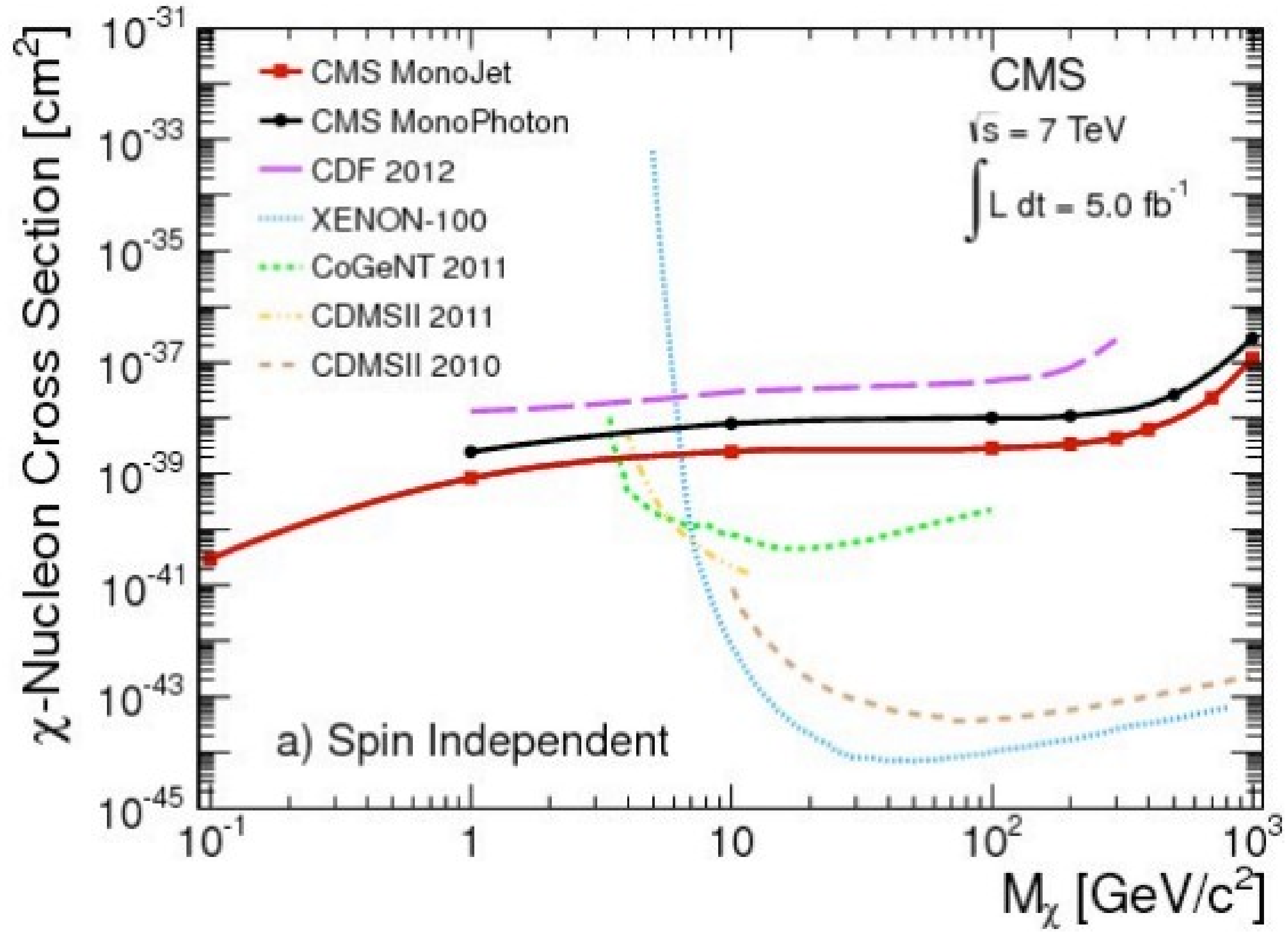
What Keeps the H Mass Low?





- In SUSY, the H mass is < the Z at LO. Loop corrections are needed. NMSSM - "Natural"

Dark Matter and Monojets



- **Dark Matter searched for in SUSY context with limits published, already > 1 TeV**
- **Also looked for in inclusive fashion with monojets**

Triple Gauge Coupling

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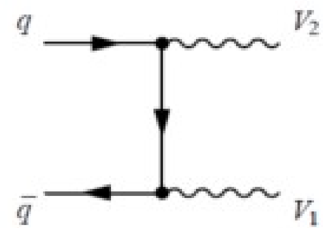
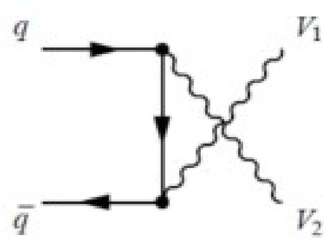
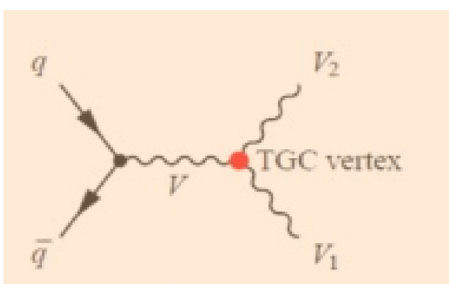
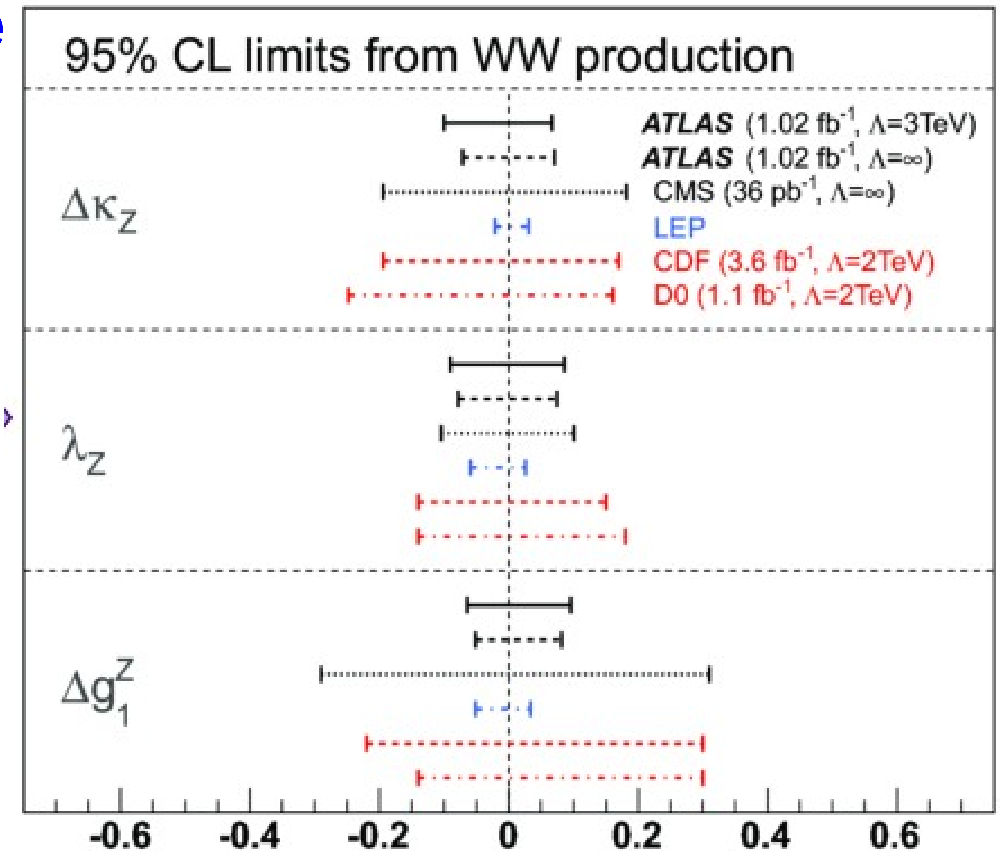
  Tes pling l .

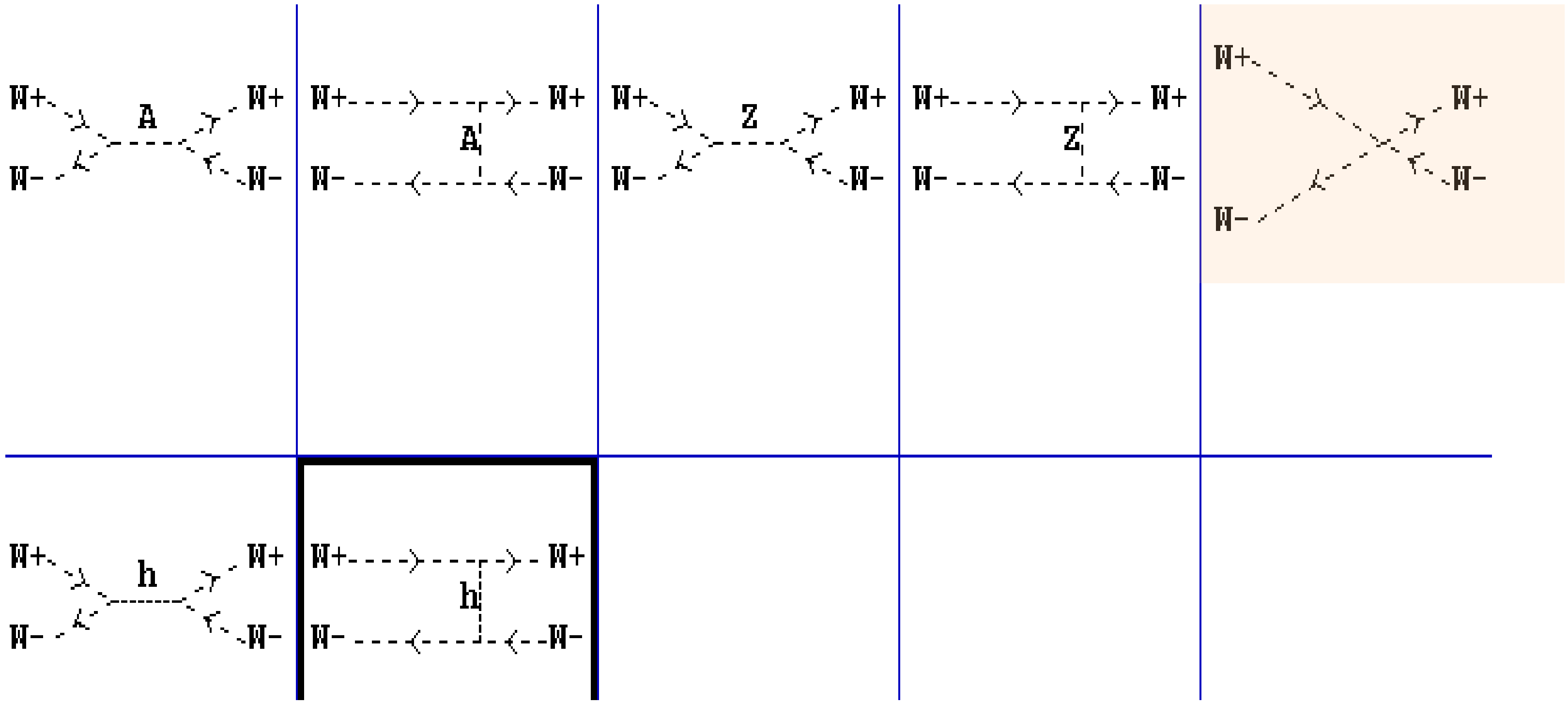








W+W Scattering



There are 7 Feynman diagrams. They are photon s and t channel exchanges, Z and Higgs = 6. the remaining is the quartic self-coupling characteristic of a non-Abelian theory. Cancellations are needed.

Partial Unitarization

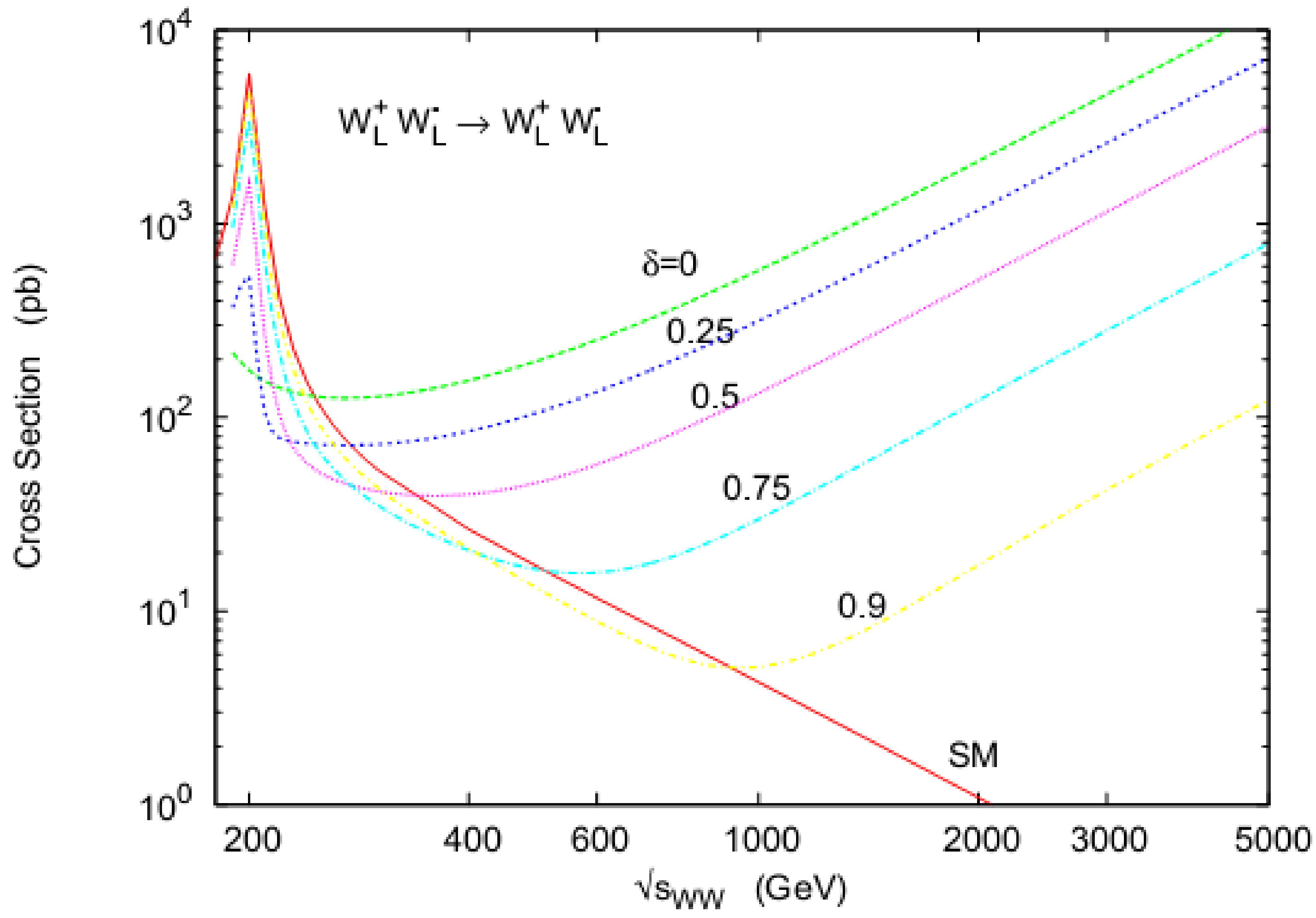
- Models where a H(125) does not unitarize
  - Two Higgs doublets – growth of WLWL with MWW
  - Strongly interacting light Higgs
  - Model assumes HWW coupling is a fraction of the SM value

$$\sqrt{\delta}$$

  - Then unitarization is not complete and a heavy H or other mechanism must intervene
- In this case the Feynman diagrams have s and t channel, W, H boson exchange partial cancellations.

Unitarized WW ?

- Map out the WLWL Mass spectrum at high mass



The Far Future?

> "It's tough to make predictions, especially about the future."
>
> *Yogi Berra*

High Mass Scales

- Exploring how the H stabilizes it's low mass
  - Seems to require looking at EW cross sections

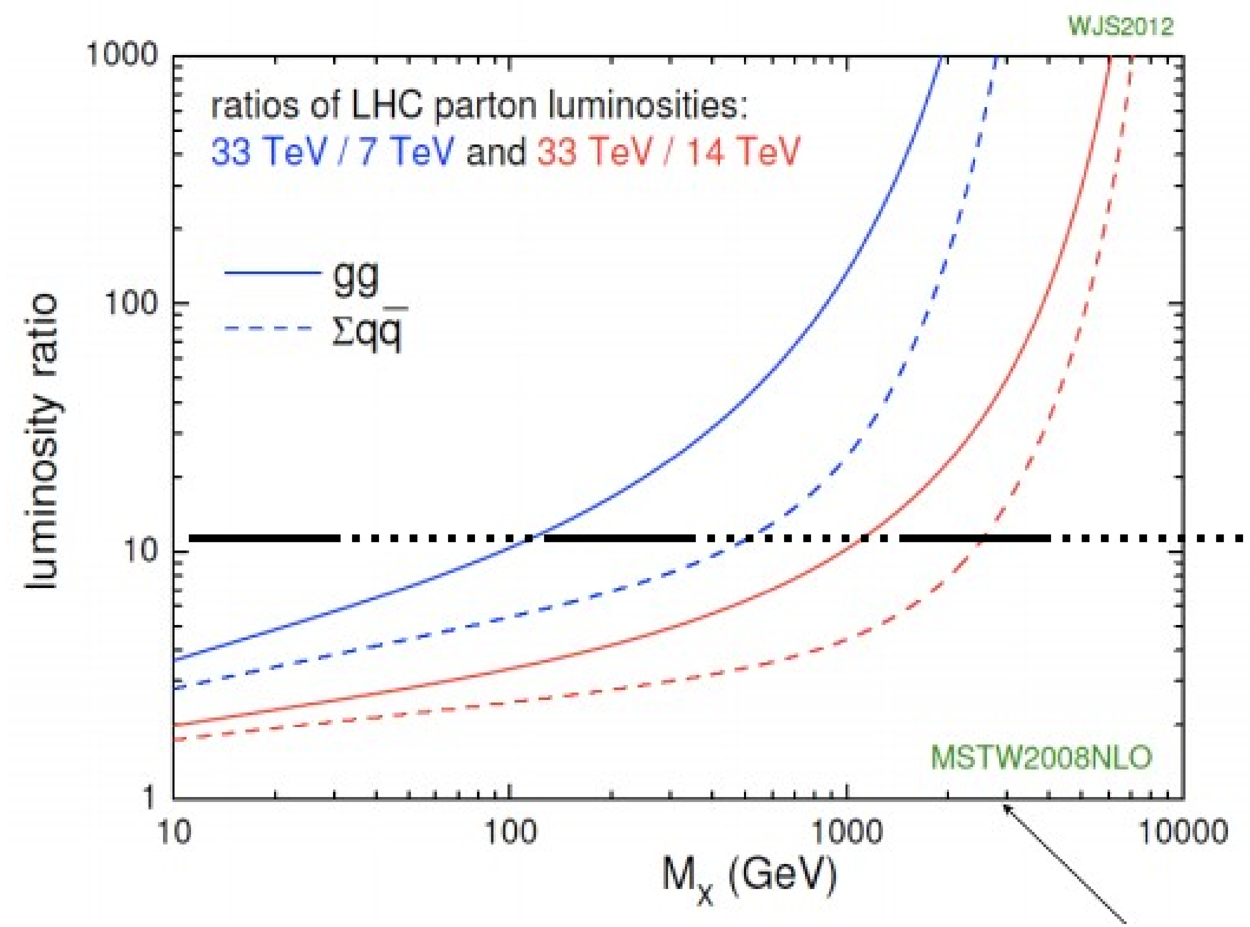
$$\hat{\sigma} \sim \alpha_W^2 / M^2$$

  - For 2 TeV the basic cross section is ~ 70 fb

$$gg \sim (1 - M/\sqrt{s})^{\alpha + \beta} \qquad \sigma \sim \hat{\sigma}\, gg$$

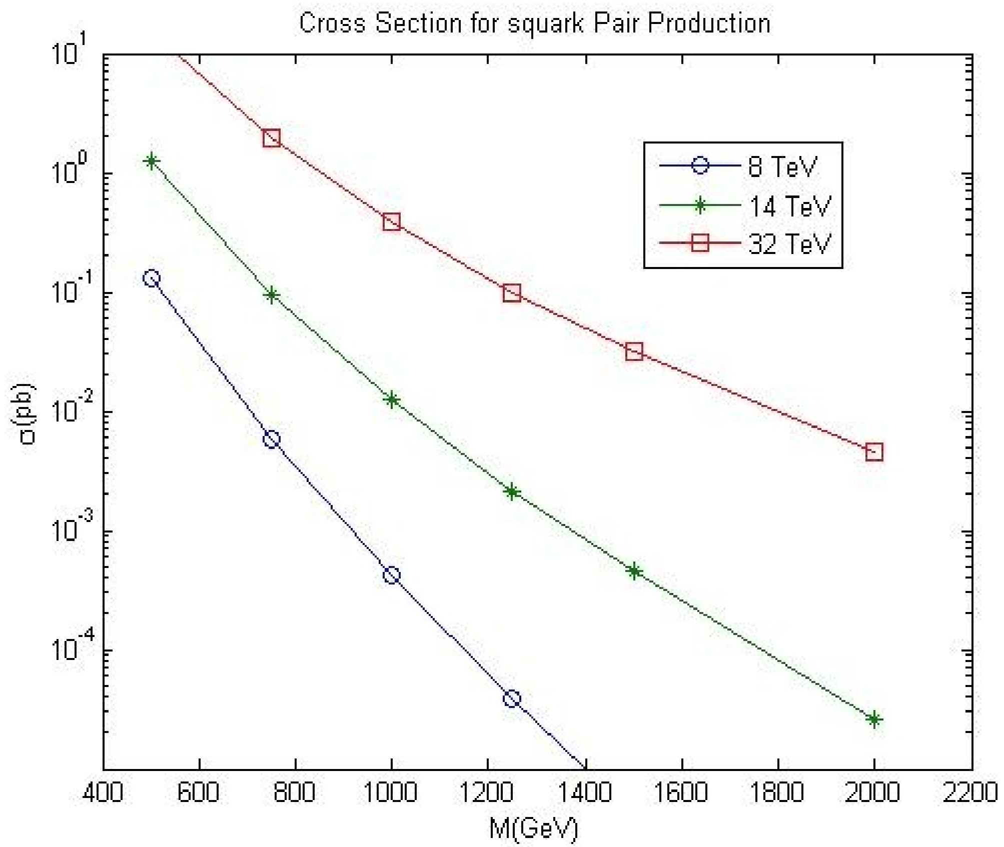
  - For "sea-sea" production, a la ggF, at 14 TeV the p-p cross section is ~ 10 fb.
- High L will be needed as well as high E.

Searches for BSM Physics



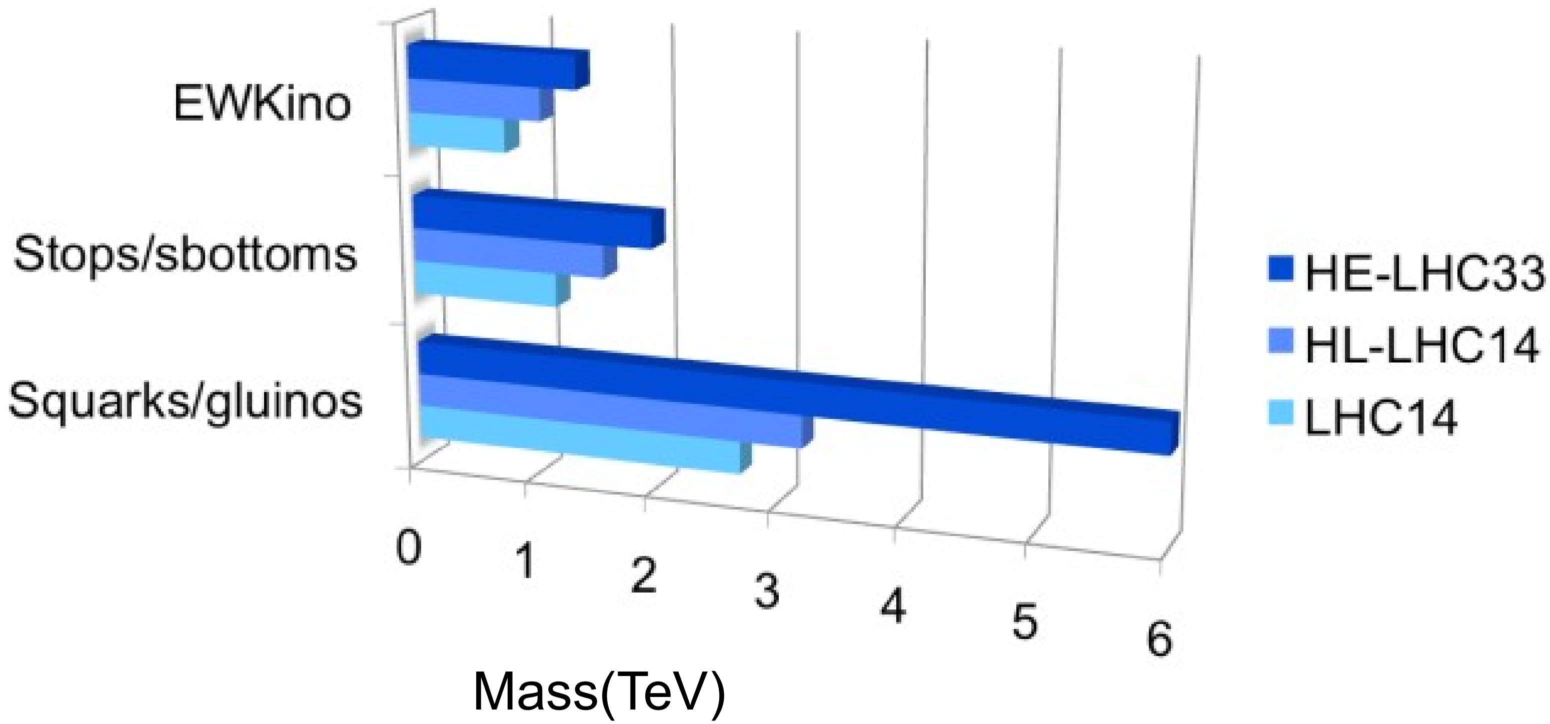
- **The PDF at high x will lead to dramatic increases in rates for high mass, M > 1 TeV, objects. Options are HE (33 TeV, 300 /fb) and HL(14 TeV 3000/fb)**

Squark Pairs – All g Sea



- **For g+g "sea" production, the 10x factor of L for HE/HL is at ~ 0.8 TeV which is already attained. At higher masses energy wins handily over luminosity**

The Far Future – L or E ?

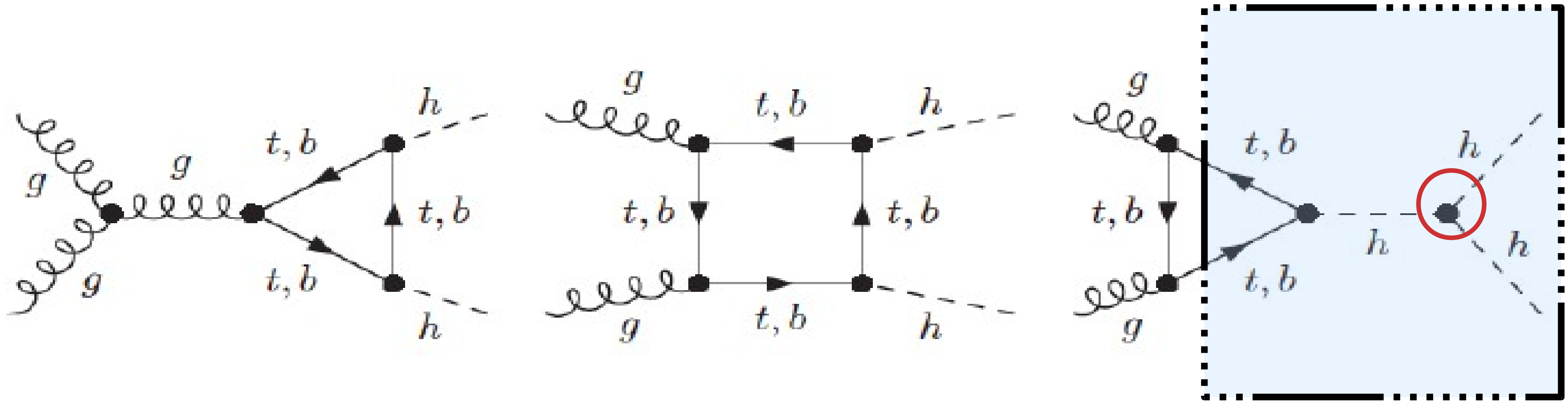


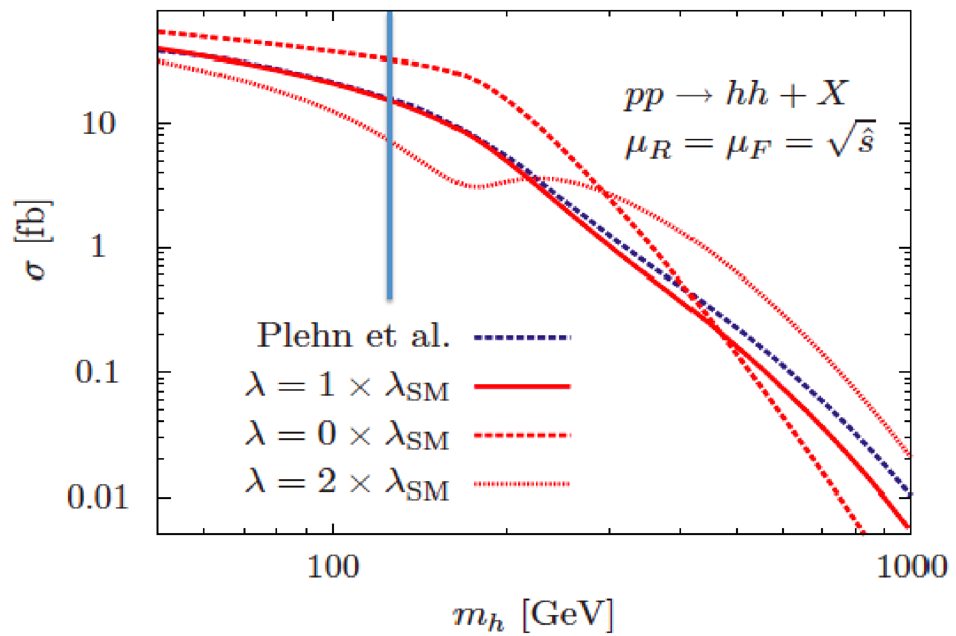
- Clearly, HE (if possible, 20 T dipoles, high T superconductor) is the winner with 2x mass reach.

H- Triplet and Quartic Couplings

- Triple and Quartic H coupling. Cross section for H(125) is~ 30 pb. For H+H it is about 30 fb (1000 x reduced), and some specific final states need to be used. For H+H+H detection seems out of reach.
  - The SM H has precisely defined triple and quartic couplings
  - It is likely to require another step in L and/or E to map out these couplings
  - It will take us a long time to know if we have a fully SM H.

Higgs Self Couplings





Since it took ~ 10/fb to observe H, perhaps 3000 /fb is appropriate for H+H observation

The Vacuum: L/G or BCS

- The dark energy is observed to be ~ 73% of the closure density of the Universe.
- But we have measured the W and Z mass, so we "know" that there is a vacuum Higgs field,

  - Landau-Ginzburg

$$M_W = g_W \langle \phi \rangle$$

- If so, there is a cosmological mass density ~

$$\Lambda \sim < \phi >^4$$

- This is ~ 10^52 larger than the observed dark energy density. The DE field is ~ 20 meV compared to 174 GeV!
- Is the Higgs field gravitationally inert? Try to study the Higgs boson excitation - mass and couplings (especially self couplings). Will we really find a SM Higgs "ether"? Do we understand the "vacuum"?

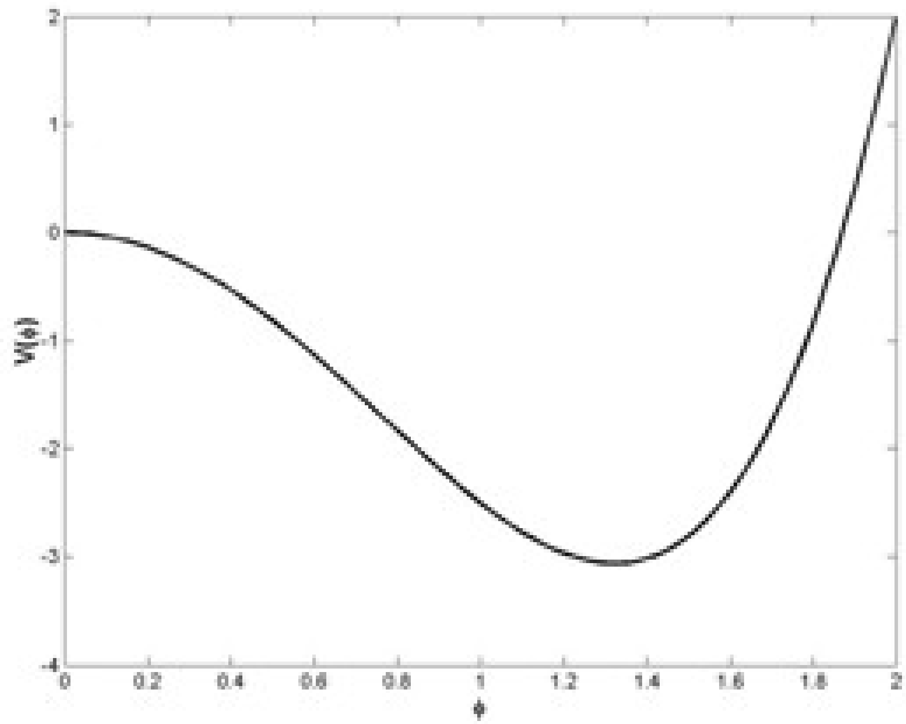
High Energy Collider Physics

"Nothing is too Wonderful to be true"

Michael Faraday

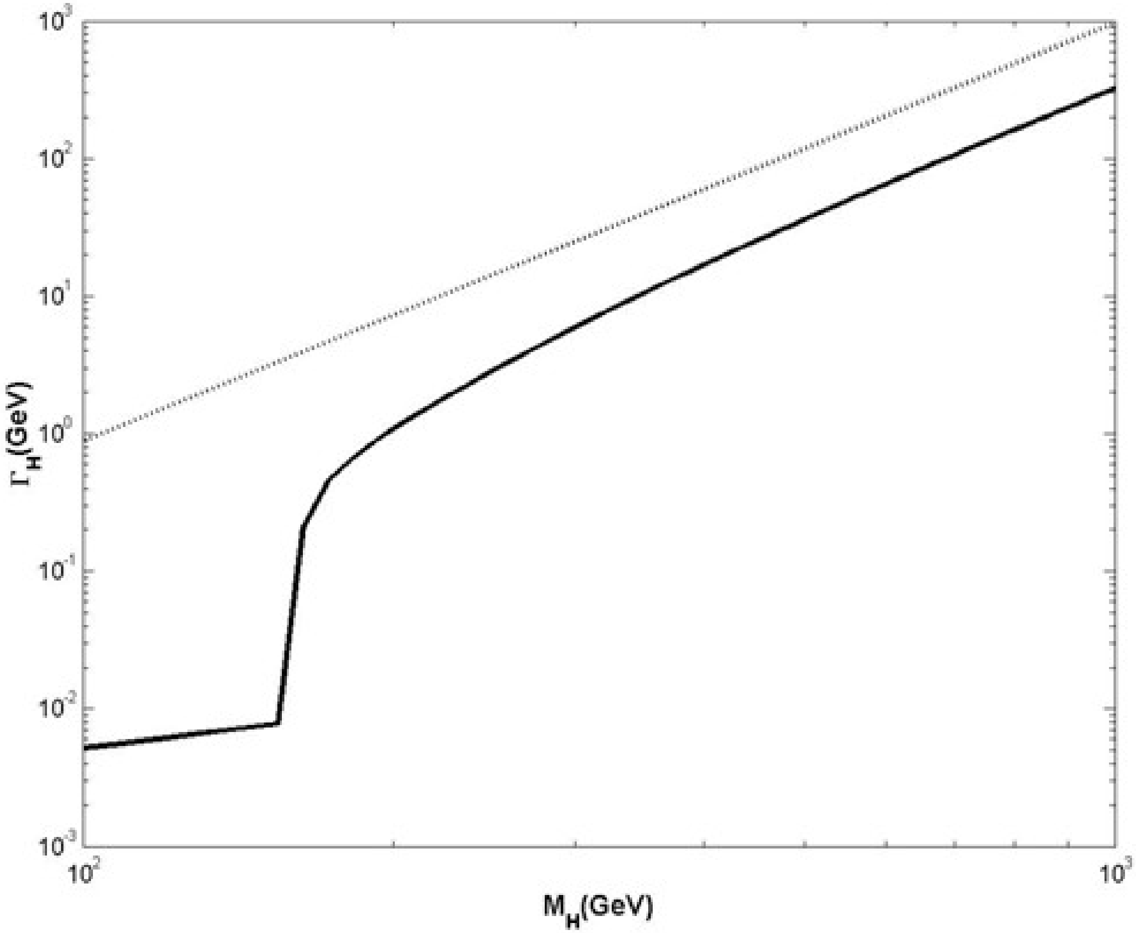
There is a 20 year program of great Physics to be done at the LHC

Higgs Potential



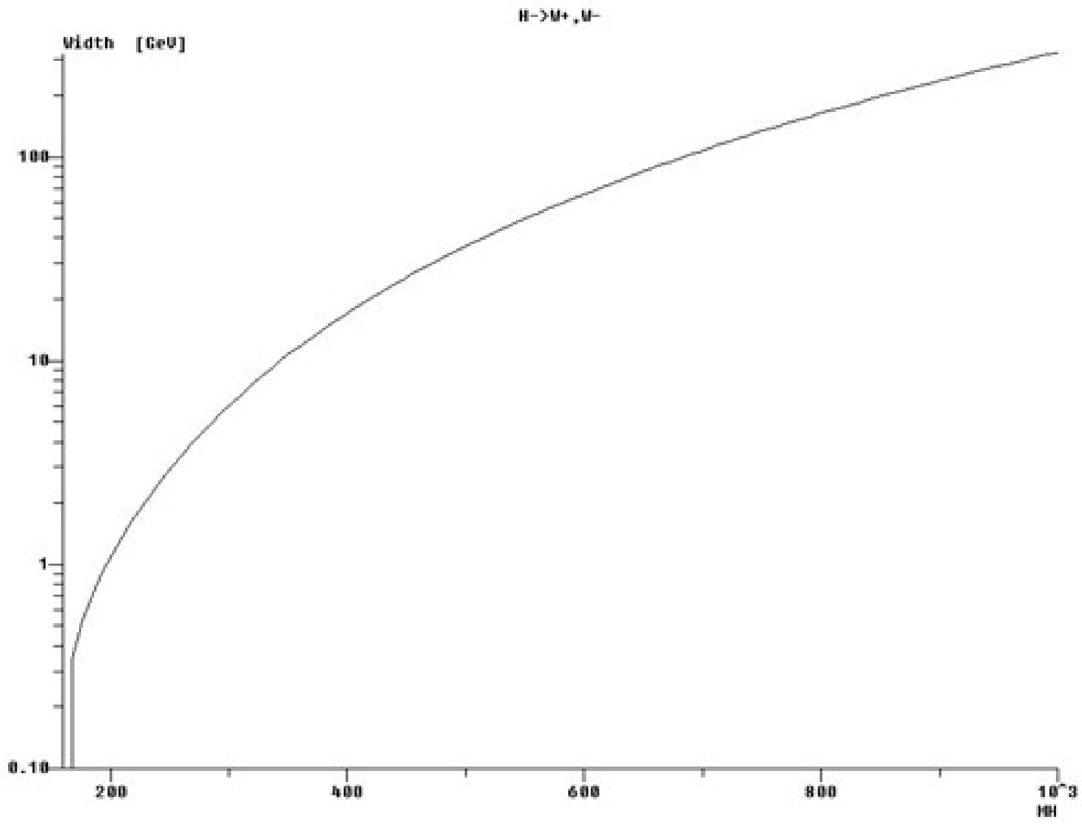
The Higgs potential has a minimum at a non-zero value of the vacuum field. There is a “vacuum expectation value” of the Higgs field.

Higgs Width

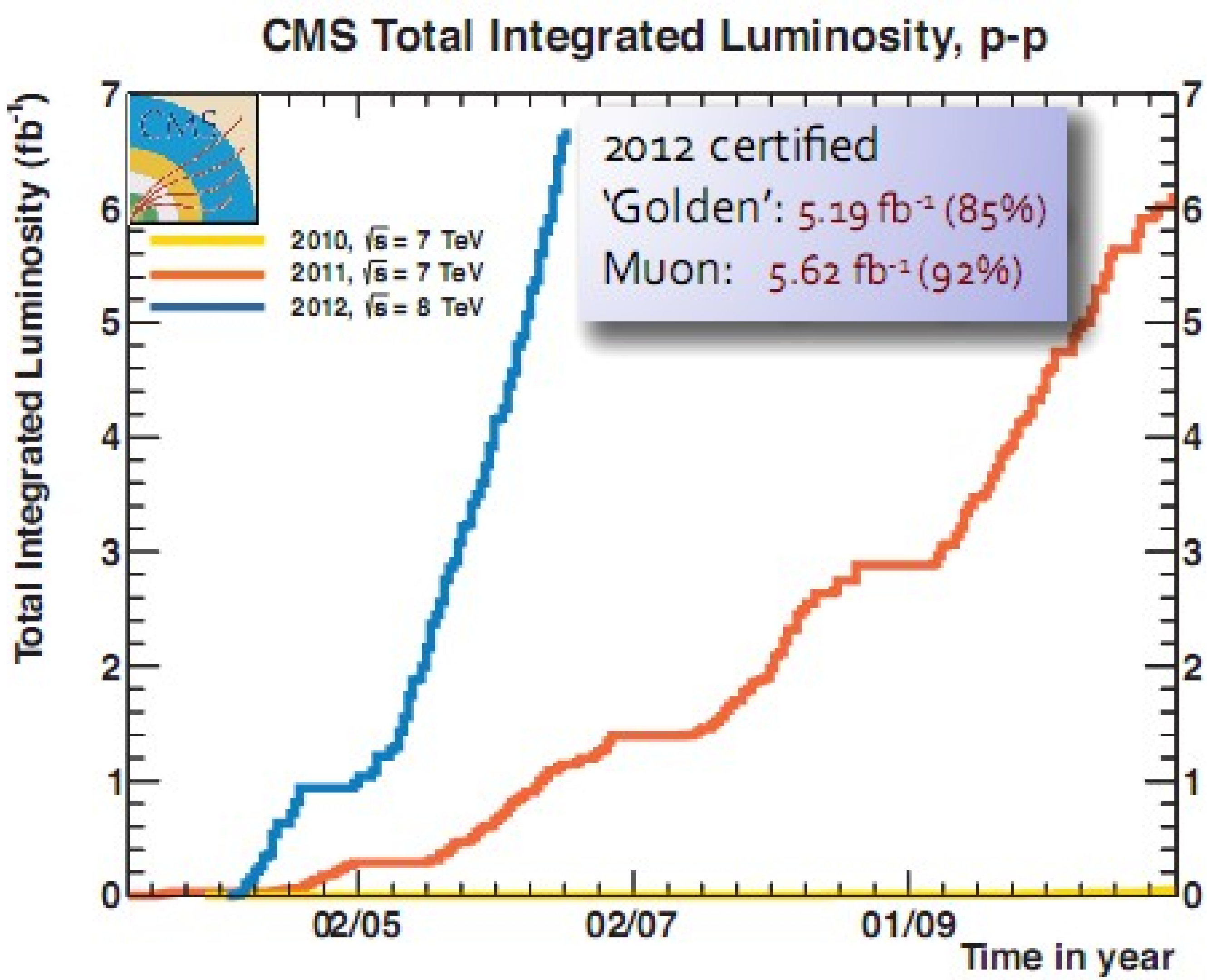


The SM H width is very narrow below the W , Z and t thresholds. Above then it goes as the cube of the H mass and the width exceeds the mass (resonance) at ~ 1 TeV.

H –W+W Partial Width

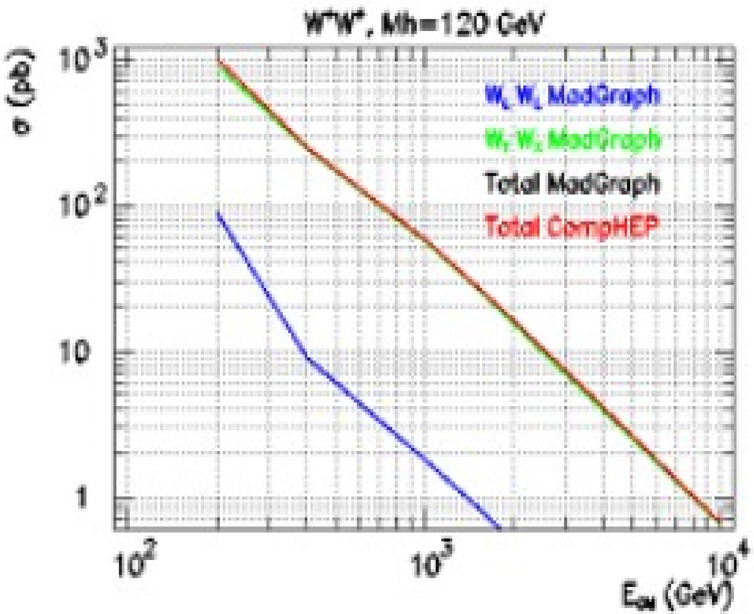


The LHC Accelerator

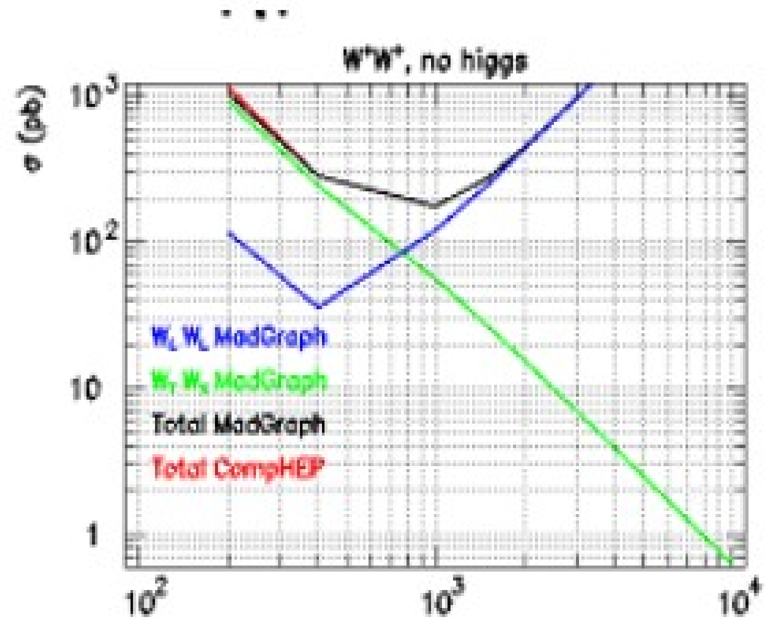


The LPC is a p-p machine because high luminosity is needed. In 2012 it is now running at > 6 x 10 ^ 33 / (cm^2*sec) with 50 nsec bunch spacing. The pileup is already beyond design specs. At 30x Tevatron L, with 8x the bx rate, the PU/bx is 4x.

W+W Scattering - Unitarized?



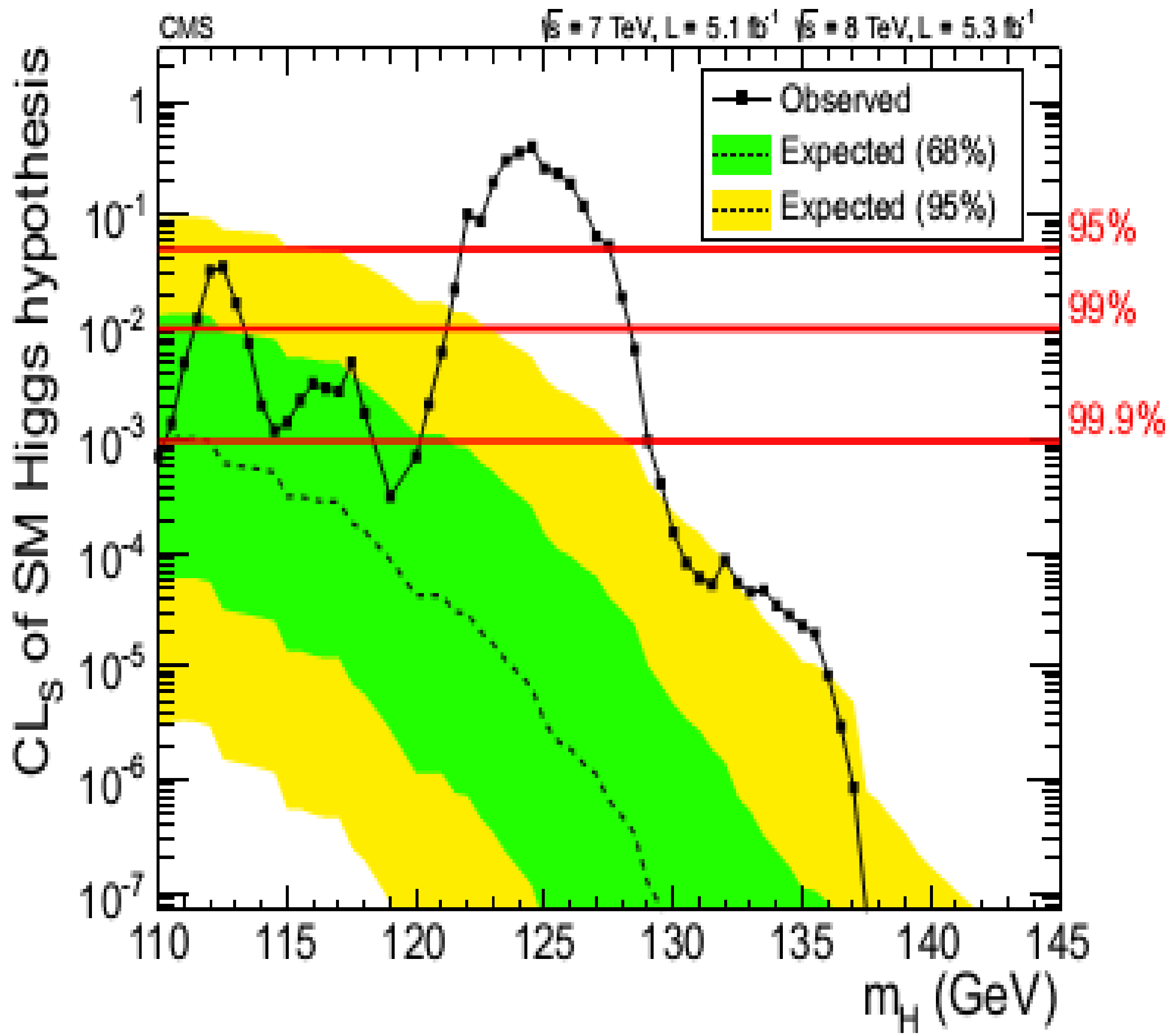
Light SM higgs case: WT by far dominates



No-higgs limit: WL rises with energy

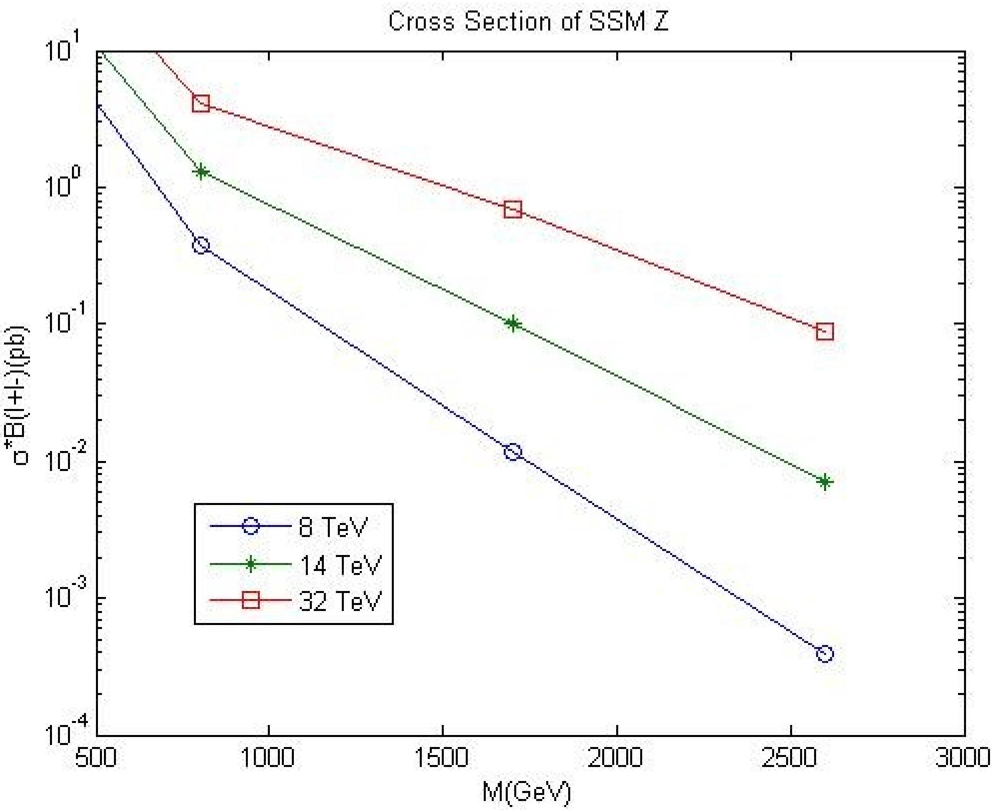
- **If the state at ~ 125 GeV is a SM H, then WLWL scattering is small**
- **Check by looking at W+W scattering at high WW masses.**

Overall Limits



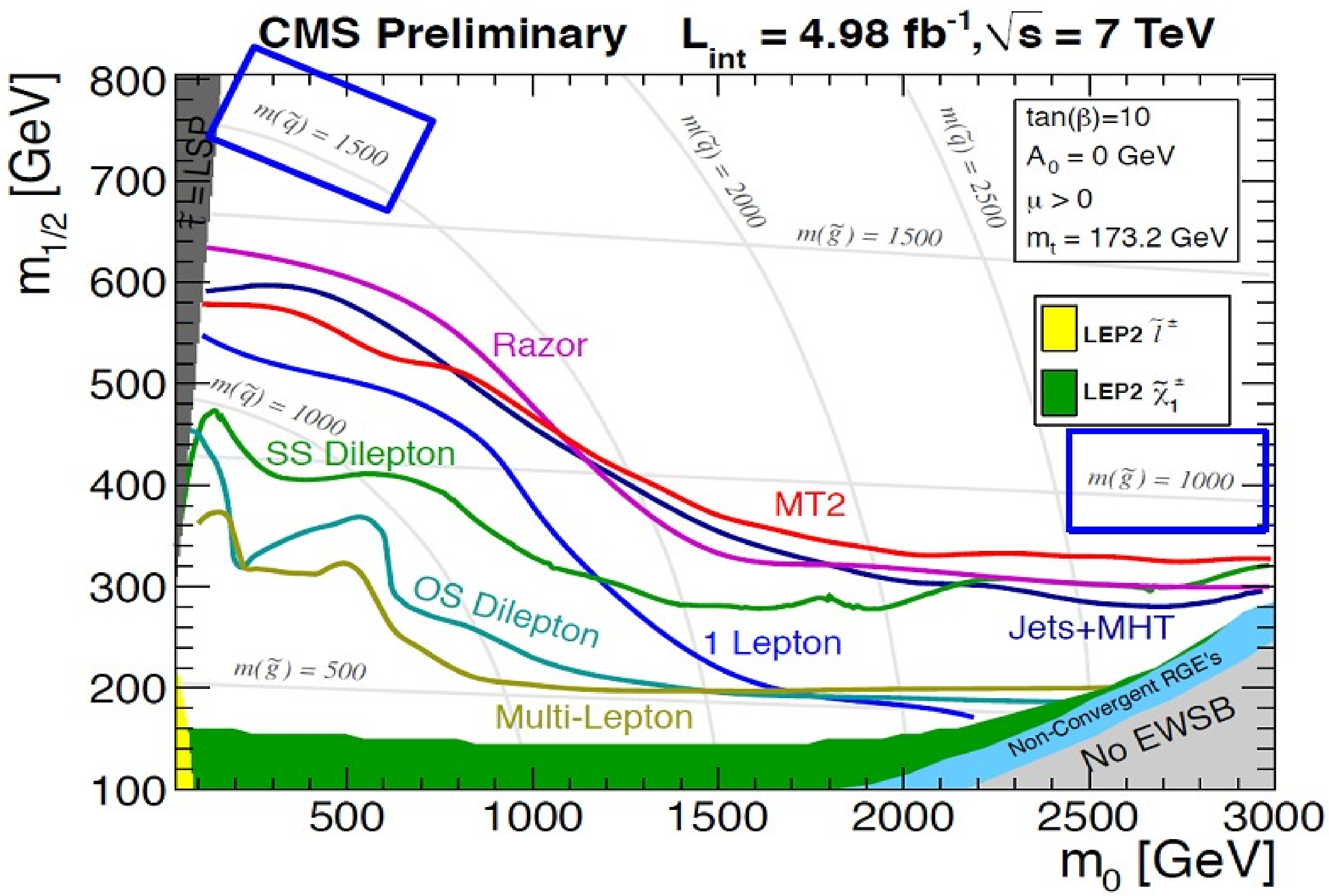
The full mass range < 0.6 TeV except ~ 0.125 TeV is excluded at 99% CL.

Sequential SM Z' – 1 Valence



- LHC experiments are already at 1 TeV limits
- HL or HE? At 2.5 TeV mass, HE is ~ 10x larger cross section -> 3000 /fb or 300 /fb?

At 8 TeV, SUSY is @ 1 TeV M



SUSY will jump in mass reach at 14 TeV.

How does the Higgs mass stabilize?

- **Cancel loops with SUSY**
- **Reduce GUT/Planck scale with ED**
- **Composite Higgs (Cooper pairs)**

Loops and 2 gluon/photon Decays

$$\Gamma(H \to gg) \sim \left[(\alpha_W/8)(M_H/M_W)^2\right]\left[(\alpha_s/\pi)^2 |I_g|^2/9\right] M_H$$

$$\Gamma(H \to \gamma\gamma) \sim \left[(\alpha_W/9)(M_H/M_W)^2\right]\left[(\alpha/\pi)^2 |I_\gamma|^2/9\right] M_H$$