# New Era of Higgs Physics

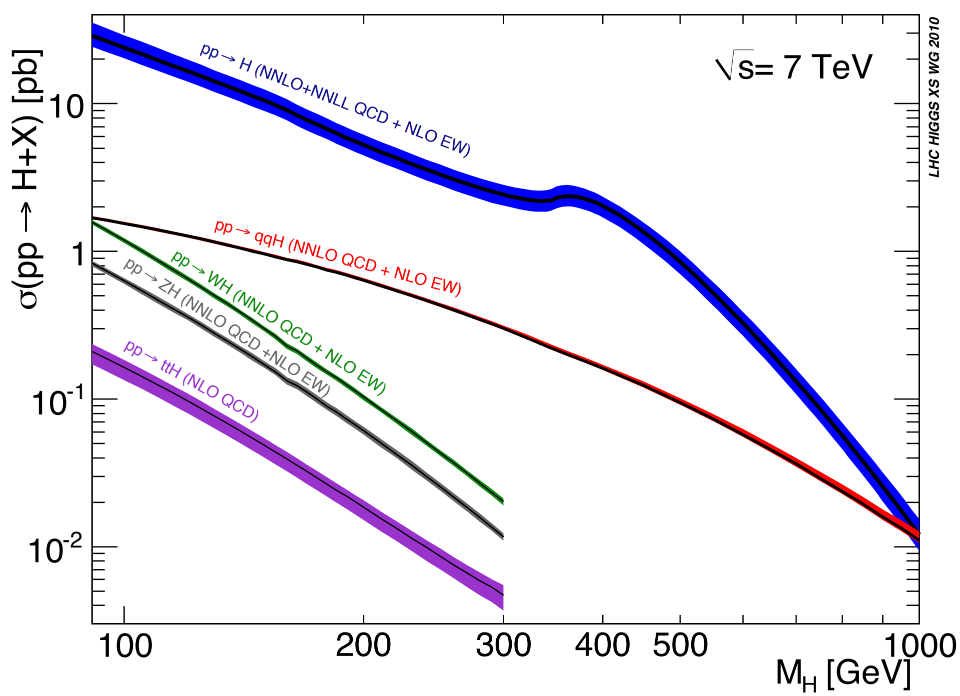
S. Dawson

Lecture 3, Fermilab 2012

- Vector Boson Fusion and Higgs-strahlung
- Characterize this Higgs-like object
  - What are its couplings? (remember in SM no freedom to adjust these)
  - What are the spin/parity properties?
  - Theoretical issues with the Higgs mechanism

The decade of precision Higgs physics

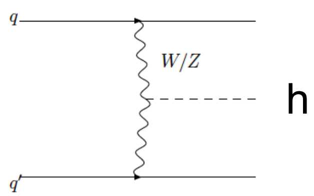
# Higgs at the LHC




$M_h$=125 GeV, σ (gg➔H) at 7 TeV: 15.3 pb
at 8 TeV: 19.5 pb
at 14 TeV: 49.9 pb

# Vector Boson Fusion

- Sensitive to VVh couplings
- Remember:
  - $g_{WWh}=gM_W=2M_W^2/v$, $g_{ZZh}=gM_Z/\cos\theta_W=2M_Z^2/v$
- Interaction vanishes if v=0 (not true for fermion Higgs Yukawa couplings!)




*Changing ratio of $g_{WWh}/g_{ZZh}$ implies isospin violation… must be small variation from SM*

# Vector Boson Fusion

- $W^+W^- \to X$ is a real process: $\sigma_{pp\to WW\to X}(s) = \int dz \left.\frac{dL}{dz}\right|_{pp/WW} \hat{\sigma}_{WW\to X}(zs)$

- Rate increases at large s: $\sigma \approx (1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

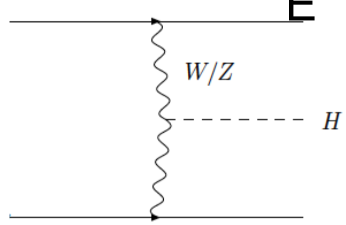
$$\int \frac{d\theta}{(k^2 - M_W{}^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos\theta) + M_W{}^2)^2}$$

**Peaks at small $\theta$**

- Outgoing jets are mostly forward and can be tagged

E

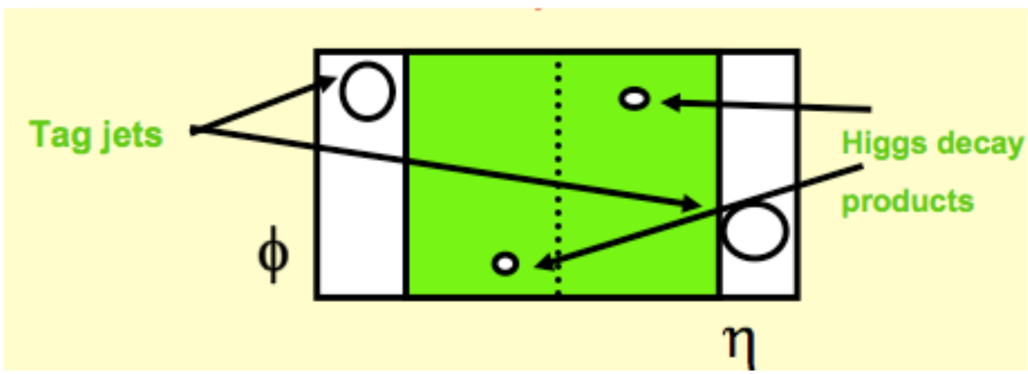
E'




k=W,Z momentum

# Vector Boson Fusion

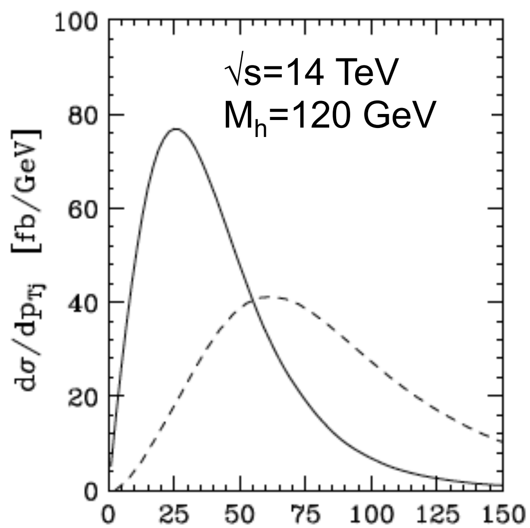
- Idea: Tag 2 high-mass jets with large rapidity gap in between
- No color flow between tagged jets – suppressed hadronic activity in central region



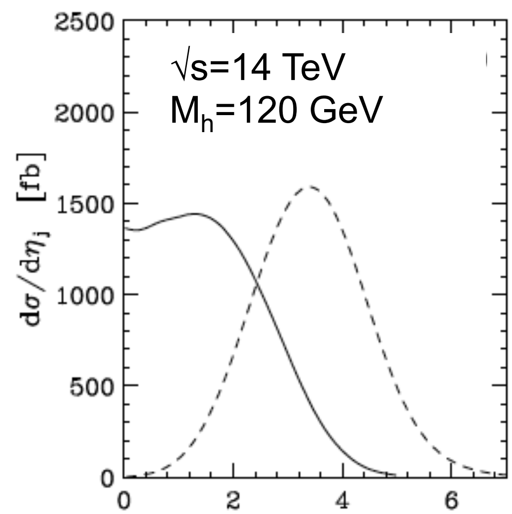
# Distinctive Distributions in VBF

- Higgs decay products are central
- Tagging jets are forward with large energy, small $p_T$ and produced at small angle

$$\eta = \frac{1}{2}\log\left(\frac{1+\cos\theta}{1-\cos\theta}\right)$$



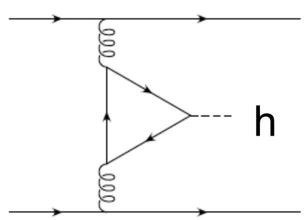

$p_T$ (tagging jets) [GeV]

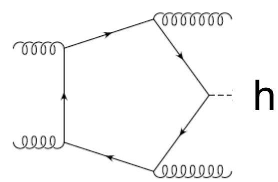



η of tagging jets

# Is VBF a different process from gluon fusion?

- Can we separate VBF from gluon fusion?
  - Would like to do this for coupling measurements



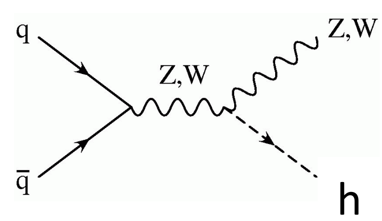




Both part of higher order contribution to Higgs plus 2 jet production

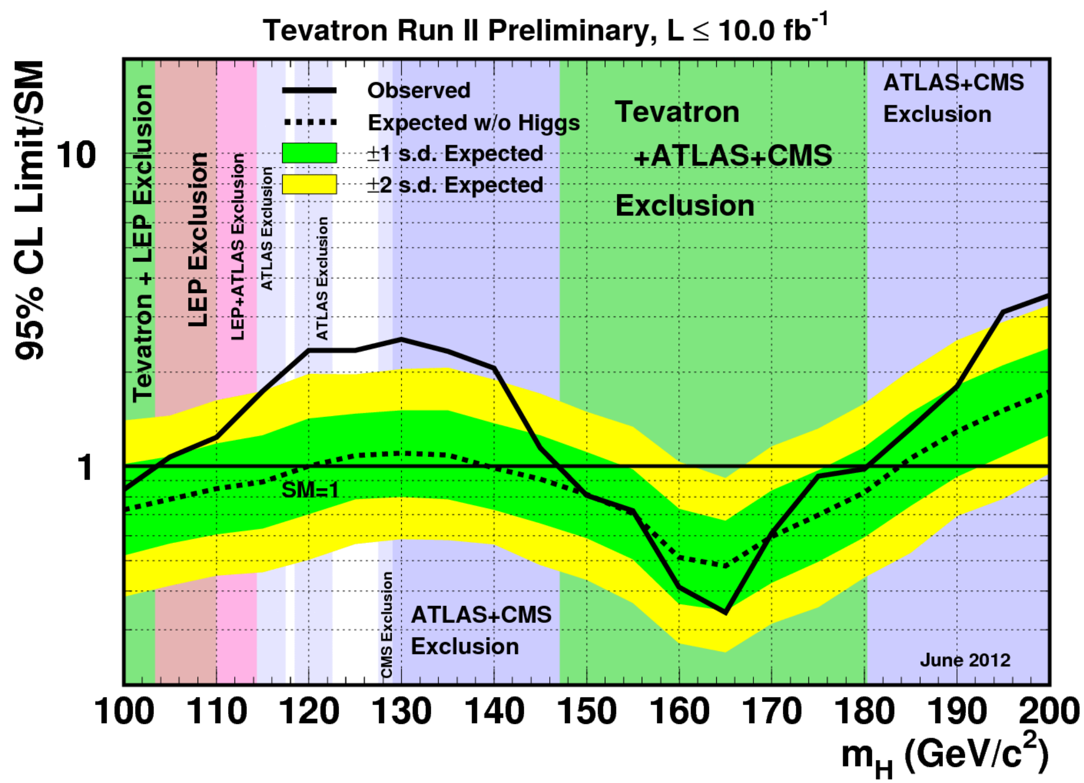
Cuts can effectively isolate VBF like diagrams from gluon fusion contributions

# W(Z)-strahlung

- W(Z)-strahlung ($q\bar{q} \rightarrow Wh, Zh$) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling
- Theoretically very clean channel
  - Important at the Tevatron
  - Can be used for high $p_T$ Higgs at the LHC



# CDF & D0 Searches



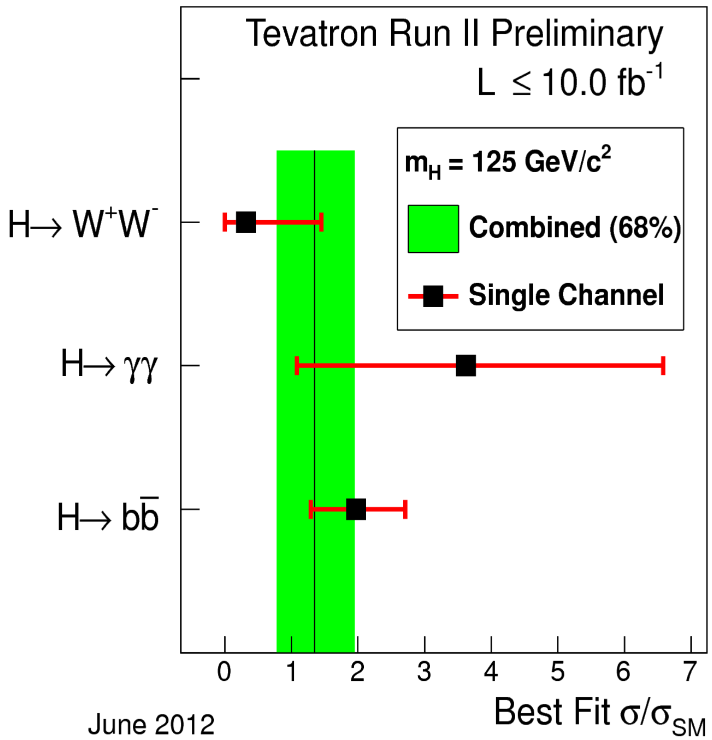

Excess at low Higgs mass in h → bb channel 3.3σ

# Tevatron Higgs Search

- Tevatron data are compatible with SM Higgs boson production in the mass range

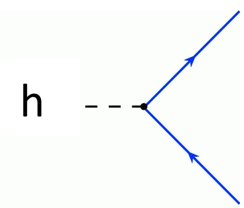
  120 GeV < $M_h$ < 135 GeV

  in all studied channels



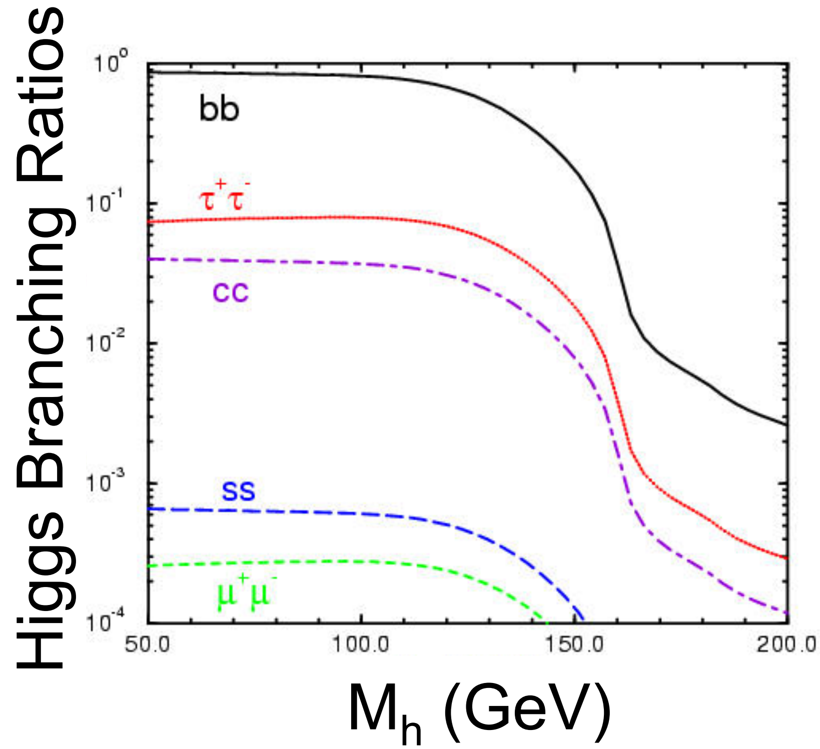
# Higgs Decays

- $h \rightarrow f\bar{f}$ proportional to $m_f^2$




$$\frac{BR(h \rightarrow b\bar{b})}{BR(h \rightarrow \tau^+\tau^-)} \approx N_c \left( \frac{m_b^{\ 2}}{m_\tau^{\ 2}} \right)$$

$$\Gamma_{ff} = N_c \frac{G_F}{4\sqrt{2}\pi} M_H m_f^2 \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

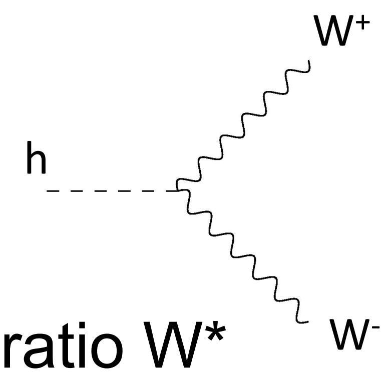



**For $M_h < 2M_W$, decays to $b\bar{b}$ most important**

# Higgs Decays to W/Z

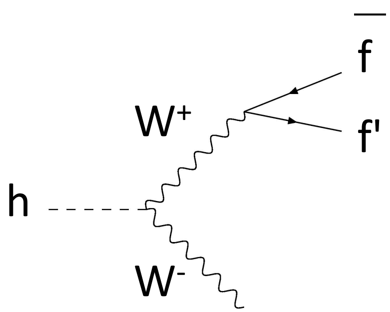
- Tree level decay

$$\Gamma(h \to W^+W^-) = \frac{\alpha}{16 s_W^2} \frac{M_h^3}{M_W^2} \sqrt{1 - x_W} \left(1 - x_W + \frac{3}{4} x_W^2\right) \qquad x_W = 4\frac{M_W^2}{M_h^2}$$




- Below threshold, h→WW* with branching ratio W* →ff' implied
- Final state has both transverse and longitudinal polarizations

Below threshold rates become quite small: BR(h➔ZZ➔ 4 leptons)=2 x $10^{-4}$



# Higgs decays to VV

- $\Gamma_{VV} \sim M_H^3$ comes from longitudinal gauge modes

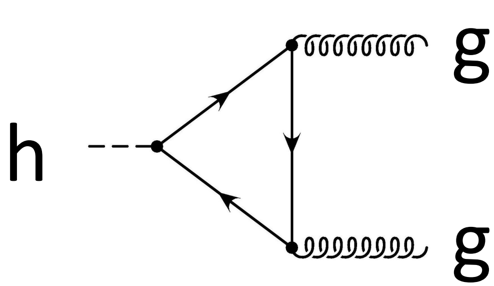
$$A(h \to W_L^+ W_L^-) = \frac{2M_W^2}{v} \epsilon_L^+ \cdot \epsilon_L^- \qquad \epsilon_L \sim \frac{p_W}{M_W}$$

$$A(h \to W_L^+ W_L^-) \sim -\frac{M_H^2}{v}$$

$$\boxed{\Gamma_{WW} \to \frac{G_F M_H^3}{8\pi\sqrt{2}}}$$

*Heavy Higgs is very broad*

# Higgs Decays to Gluons




- Top quark contribution most important
- Doesn't decouple for large $m_t$
- *Decoupling theorem doesn't apply to particles which couple to mass (ie Higgs!)*
- Decay sensitive to extra generations

$$\Gamma(h \to gg) \approx \frac{\alpha_s^2 \alpha}{72\pi^2 s_W^2} \frac{M_h^3}{M_W^2} + O\left(\frac{M_h^2}{M_t^2}\right)$$

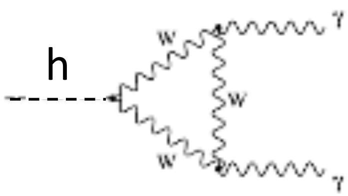
# Higgs Decays to Photons

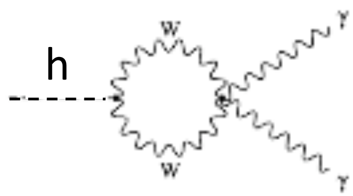
- Dominant contribution is W loops
- Contribution from top is small

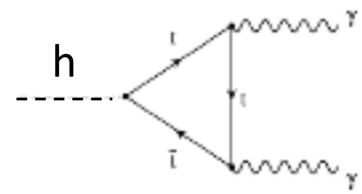
*Note opposite signs of t/W loops*

$$\Gamma(h \to \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_h^3}{M_W^2} \left| 7 - \frac{16}{9} + \ldots \right|^2$$

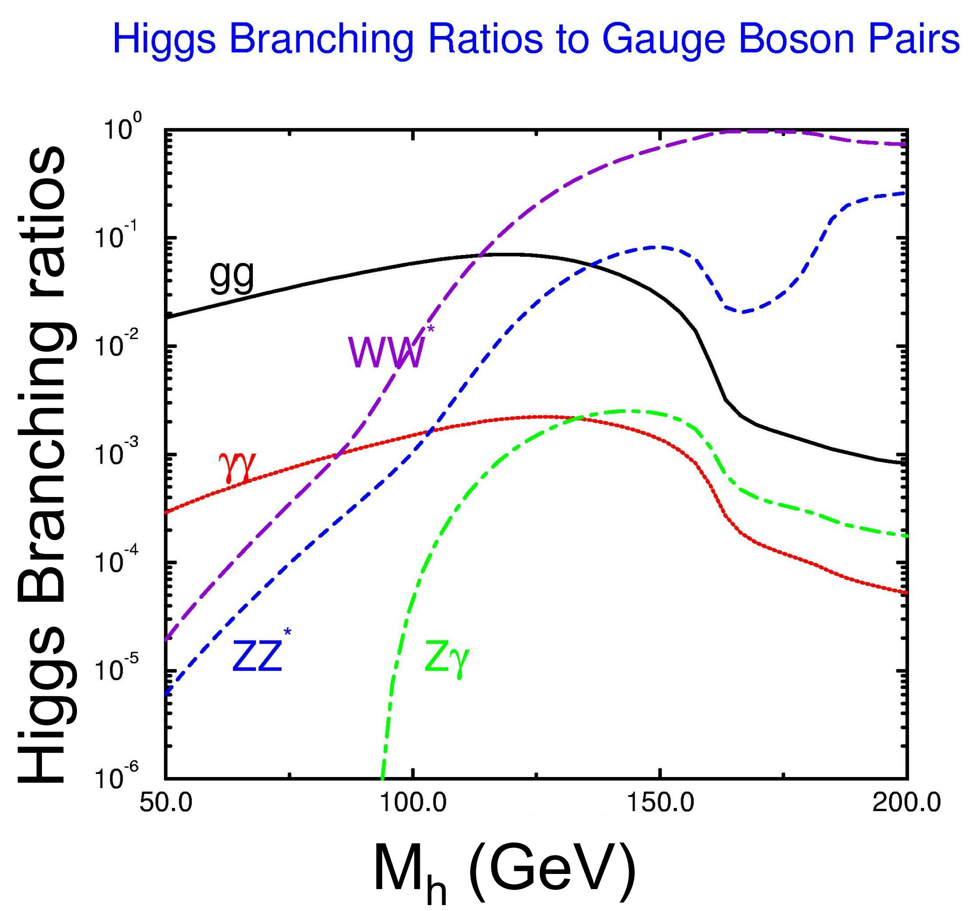
W top



# Higgs decays to gauge bosons

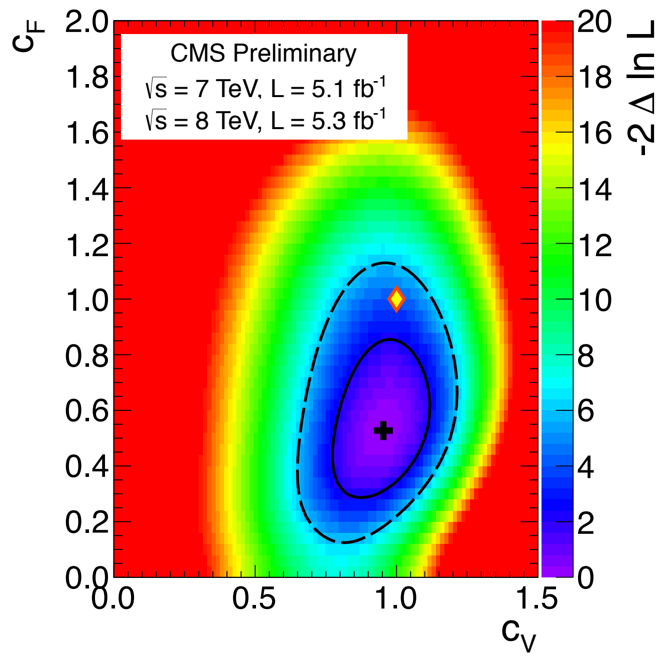


# Suppose we want to enhance $h \rightarrow \gamma\gamma$ ?

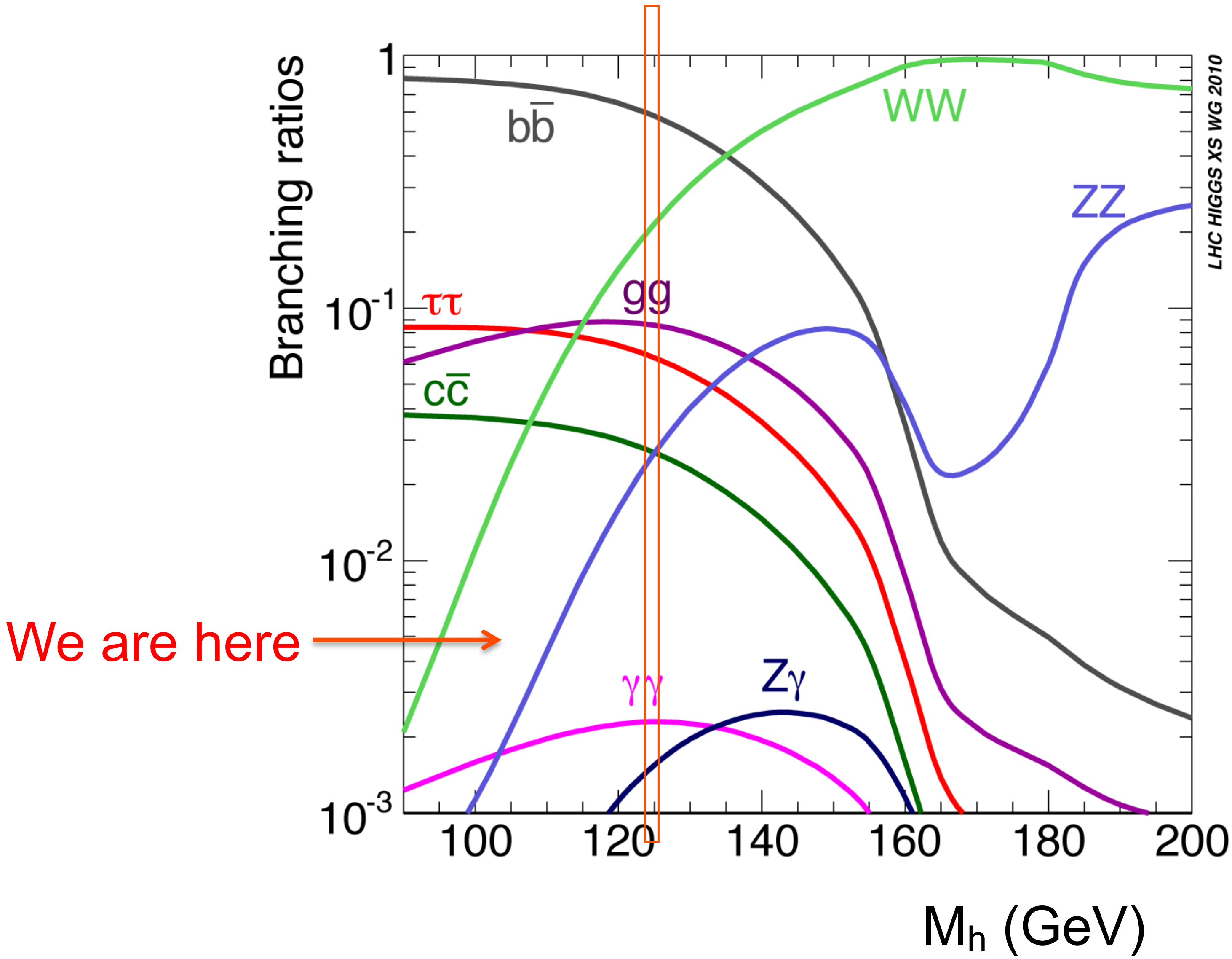
- Rescale top quark Yukawa: $c_F \frac{m_t}{v} \bar{t} t h$
- Rescale W Yukawa: $c_V g M_W W^{+\mu} W^{-}_{\nu} h$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \sim \left(1 - .2\frac{c_F}{c_V}\right)^2$$

- Or put something (without color) in loop to enhance rate…popular theorist's sport



# Higgs Branching Ratios

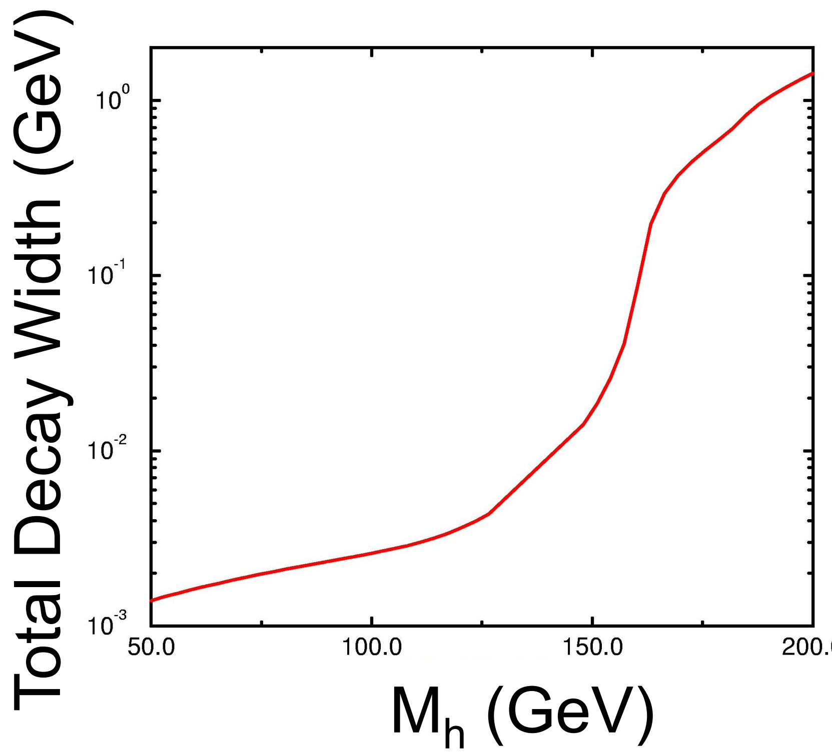


# Total Higgs Width

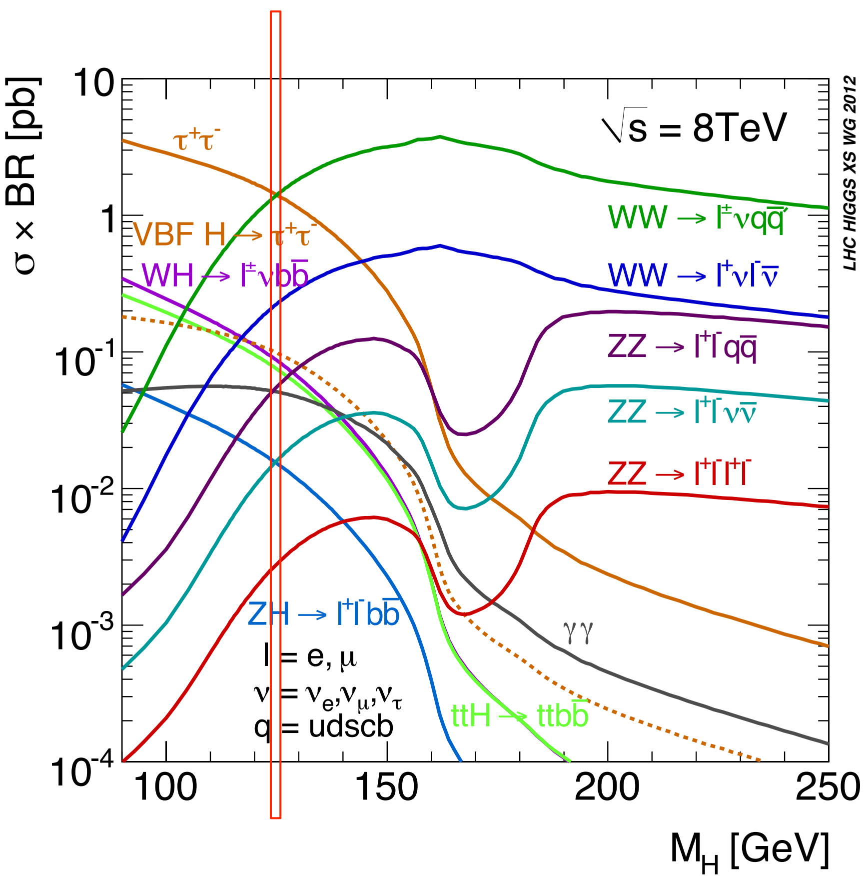
- Small $M_h$, Higgs is narrower than detector resolution
- As $M_h$ becomes large, width also increases
  - No clear resonance
  - For $M_h$ ~1.4 TeV, $\Gamma_{tot}$ ~$M_h$

$$\Gamma(h \rightarrow W^+W^-) \approx \frac{\alpha}{16\sin^2\theta_W}\frac{M_h{}^3}{M_W{}^2}$$

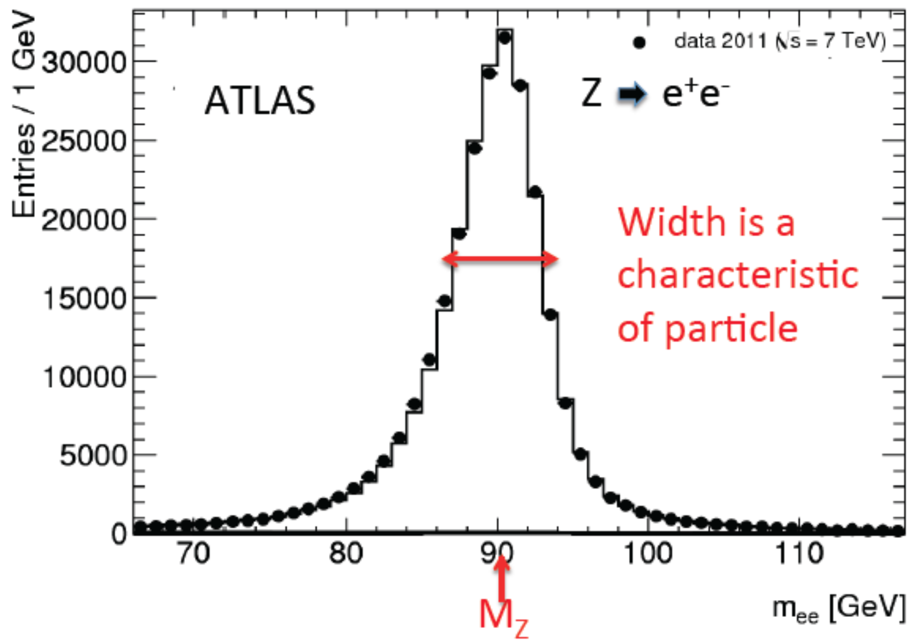
$$\approx 330 GeV\left(\frac{M_h}{1TeV}\right)^3$$



# Production + Decay



# Higgs Mass from Bump Hunting

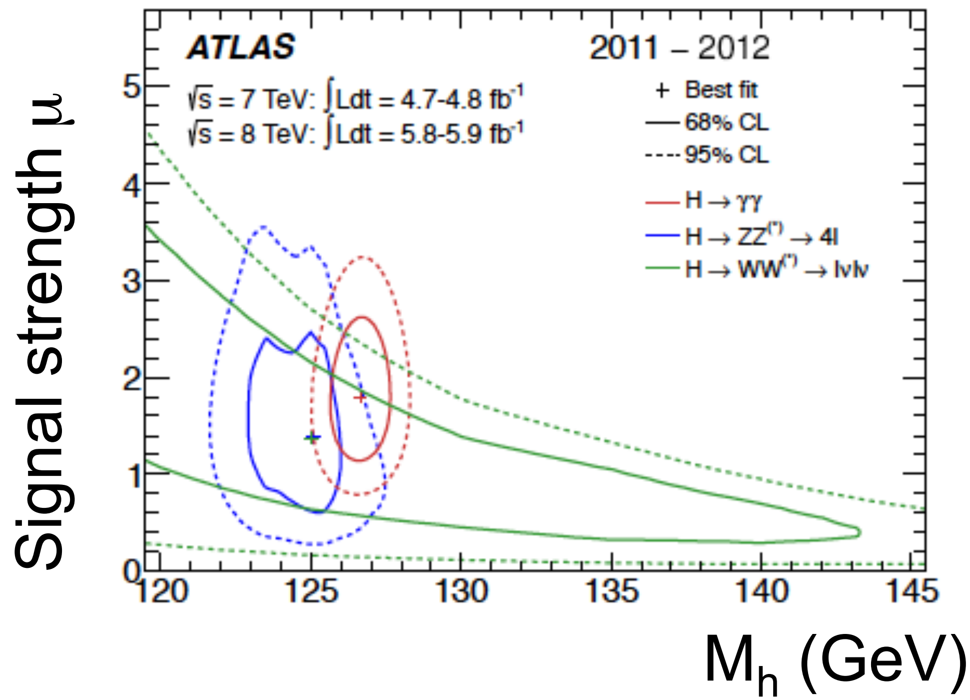



$$M^2 = (E_+ + E_-)^2 - (\vec{p}_+ + \vec{p}_-)^2$$

Use this technique for h $\rightarrow\gamma\gamma$ and h $\rightarrow$ZZ

$\Gamma_h \sim$ MeV

# Can't reconstruct mass in $h \rightarrow W^+W^-$




ATLAS

$h \rightarrow W^+W^- \rightarrow l\nu\ l\nu$

# Is it a *(the)* Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b^{\ 2}}{m_\tau^{\ 2}}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

- Measure self interactions

$$V = \frac{M_h^{\ 2}}{2}h^2 + \frac{M_h^{\ 2}}{2v}h^3 + \frac{M_h^{\ 2}}{8v^2}h^4$$

# Parameterize deviations from SM

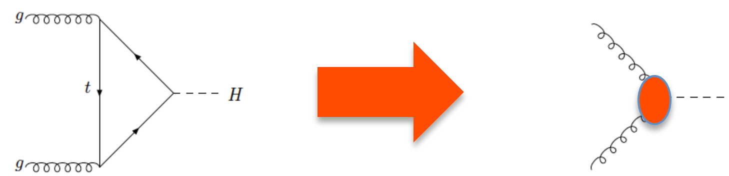
- Many possible parameterizations (only some terms shown here)

$$L \sim c_V \left( M_W^2 W_\mu^+ W^{-\mu} + \frac{M_Z^2}{2} Z_\mu Z^\mu \right) \frac{2h}{v} - c_t m_t \bar{t} t \frac{h}{v} - c_b m_b \bar{b} b \frac{h}{v}$$
$$+ \frac{g^2}{16\pi^2} \left( F_{\mu\nu} F^{\mu\nu} c_{\gamma\gamma} + G_{\mu\nu} G^{\mu\nu} c_{gg} \right) \frac{h}{v} + \ldots .$$

- In Standard Model, $c_V=c_t=c_b=1$, $c_{\gamma\gamma}=c_{gg}=0$
- No FCNC in Higgs sector parameterization
- No isospin violation in Higgs sector parameterization
- Assume no new light states

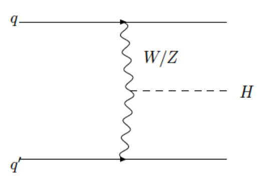
# Coupling Measurements

- Production:
  - Gluon Fusion




$$\sigma_{ggh} \sim c_t^2, c_b^2, c_{gg}$$

  - VBF



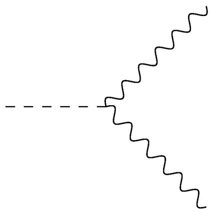

$$\sigma_{VBF} \sim c_V^2$$

# Decay

- h → γγ: $c_F$, $c_V$ , $c_{\gamma\gamma}$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}} \sim \left(1 - .2\frac{c_F}{c_V}\right)^2$$

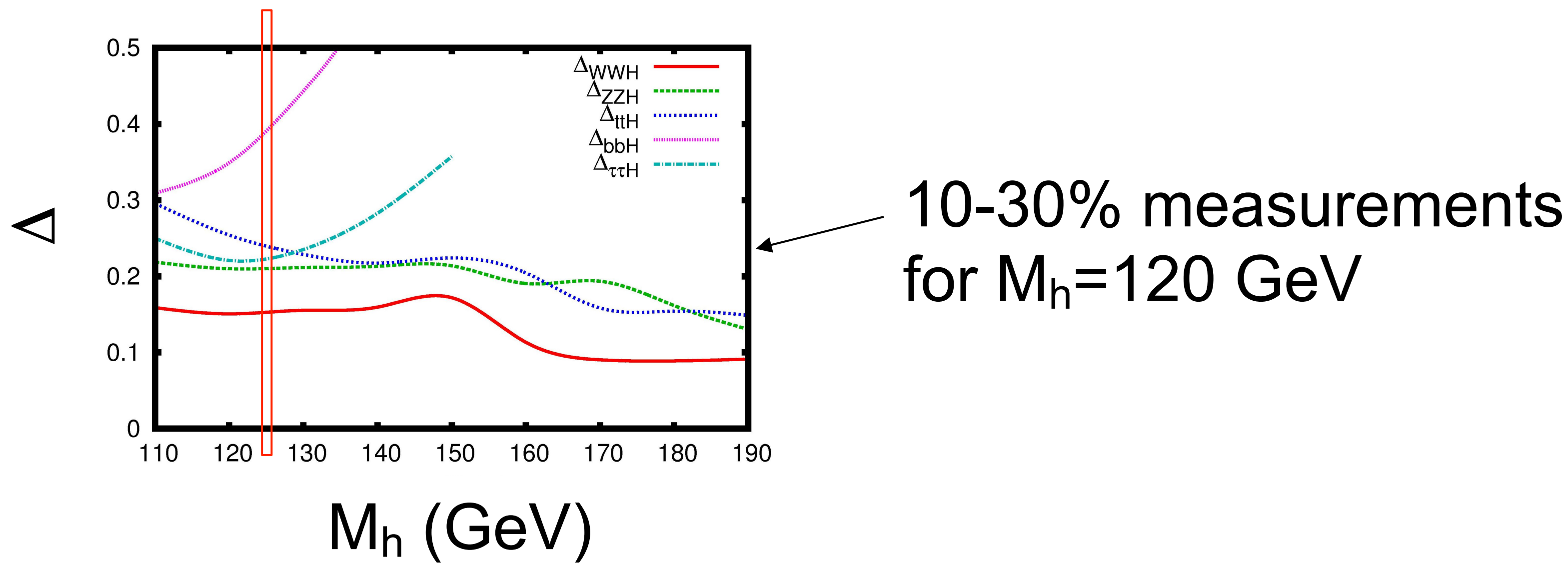
- h → WW, h → ZZ; $c_V$



- h → bb: $c_F$
- Could include decay to invisible particles
  - Desirable to explain dark matter
  - Severely restricted by current measurements

# Measuring Higgs Couplings

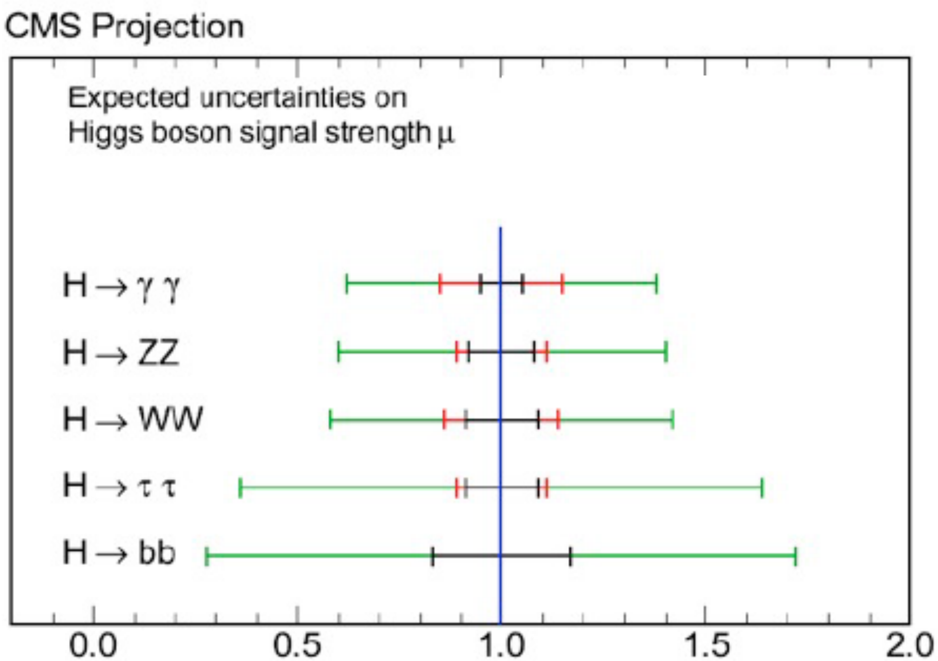
- SM coupling measurements with 30 $fb^{-1}$ at 14 TeV




- Parameterize couplings in terms of deviation from SM
  - $\Delta_F = c_F - 1$, $\Delta_V = c_V - 1$

Coupling measurements: Rauch, arXiv:1110.1196; Lafaye, Plehn, Rauch, Zerwas, arXiv: 0904.3806

# How well can we do with couplings?




— 10 $fb^{-1}$ at $\sqrt{s}$=7/8 TeV

— 300 $fb^{-1}$ at $\sqrt{s}$=14 TeV

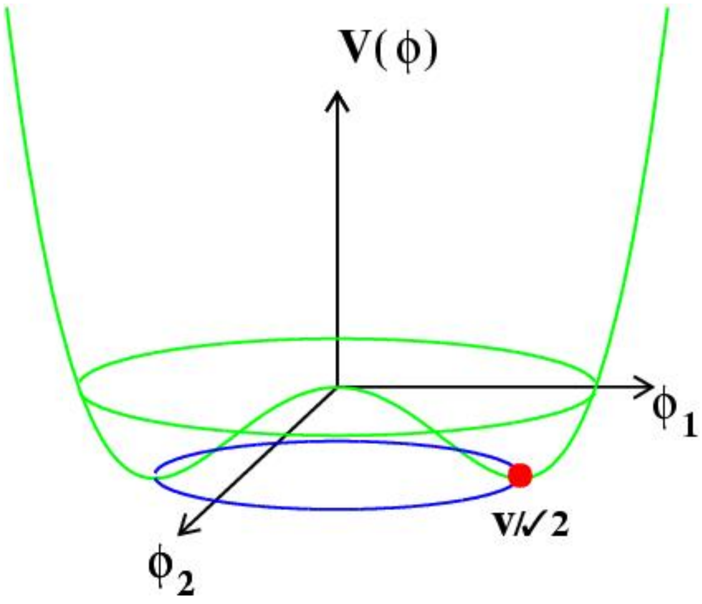
5-10% uncertainties on couplings with 300 $fb^{-1}$

Some channels ($c\bar{c}$, $\mu^+\mu^-$) extremely difficult at LHC mostly due to low rates

# Can we reconstruct the Higgs potential?

$$V = \frac{M_h{}^2}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

$$\boxed{SM : \lambda_3 = \lambda_4 = \frac{M_h{}^2}{2v^2}}$$

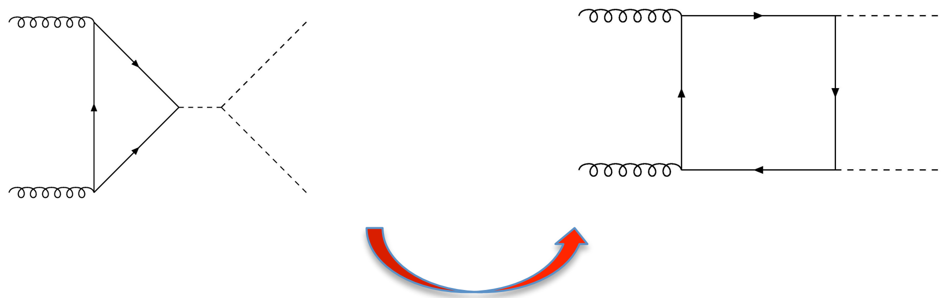



- Fundamental test of model!

- We have no idea how to measure $\lambda_4$

# Double Higgs Production

- Sensitive to hhh coupling, $\lambda_{hhh} = 3\ M_h^2/M_Z^2$

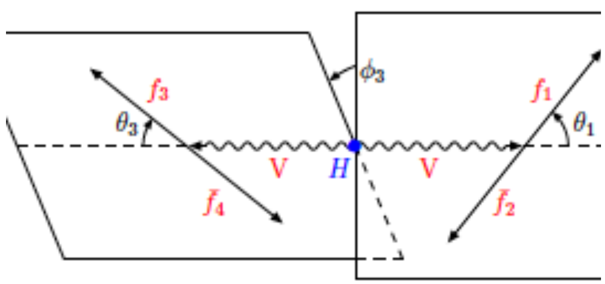


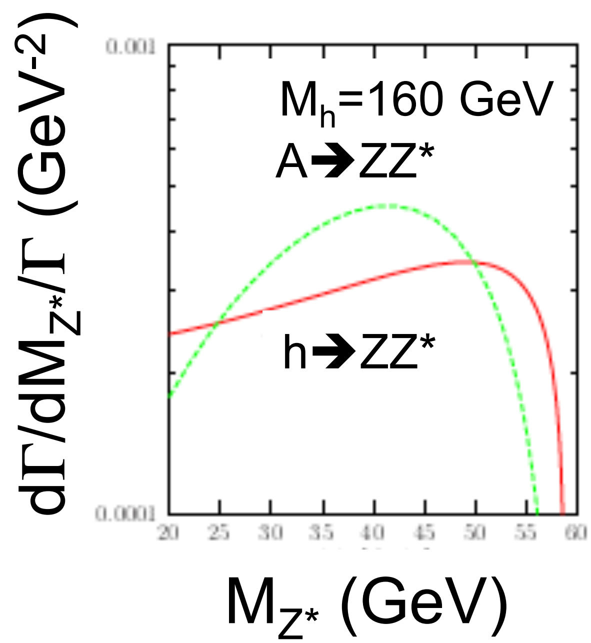
Contributions tend to cancel

$\sigma$~ 2 fb (then you need branching ratios to observable final states….)

# CP Properties

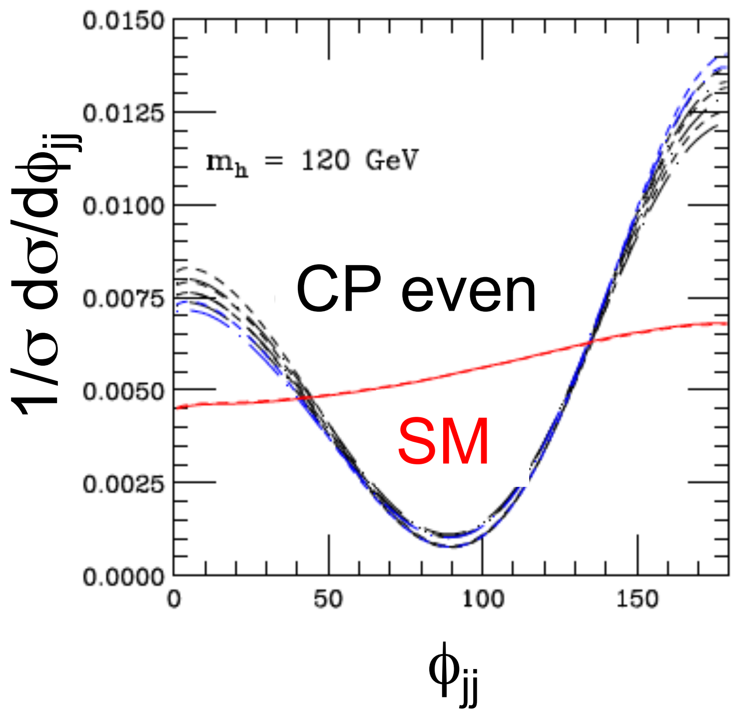
- Look at $h \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$
- Angular correlations depend on $J^{PC}$
- Compare predictions for $0^{++}$ with $0^{+-}$ boson
- Remember rate is small

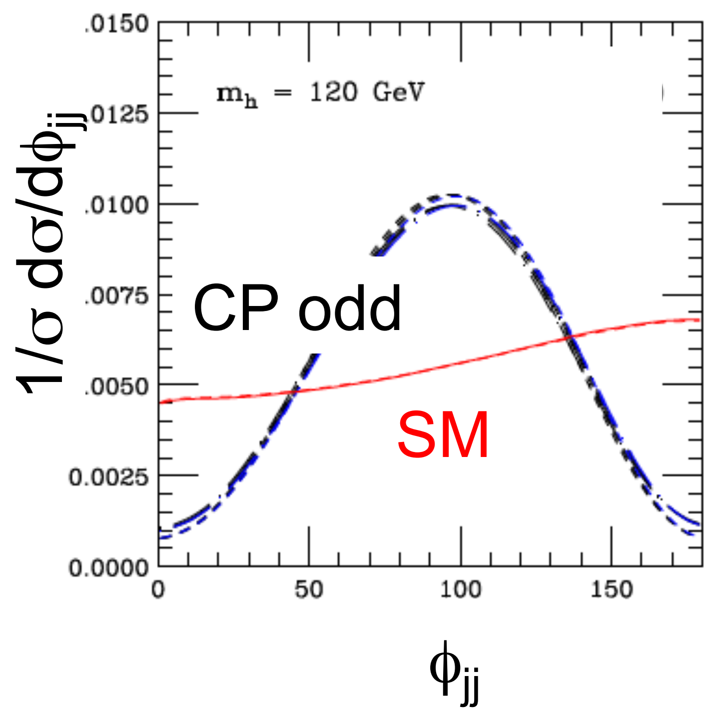


# CP Properties

- In vector boson fusion measure angle between tagging jets
- Sensitive to CP properties



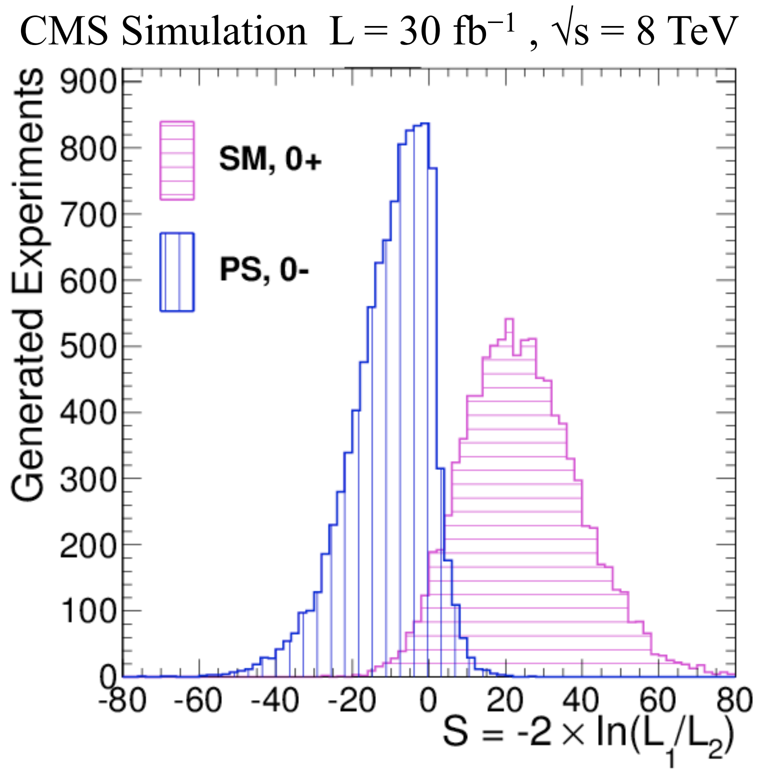




[Zeppenfeld]

# Scalar vs pseudoscalar: How well can we distinguish?

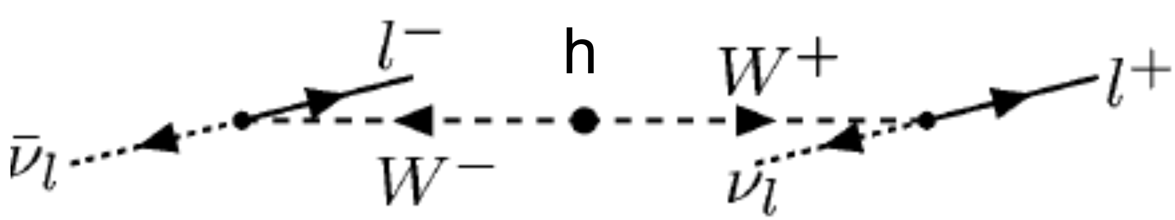
$h \to ZZ^* \to 4l$

SM predicts $0^{++}$ state



# Spin properties of Higgs-like Particle

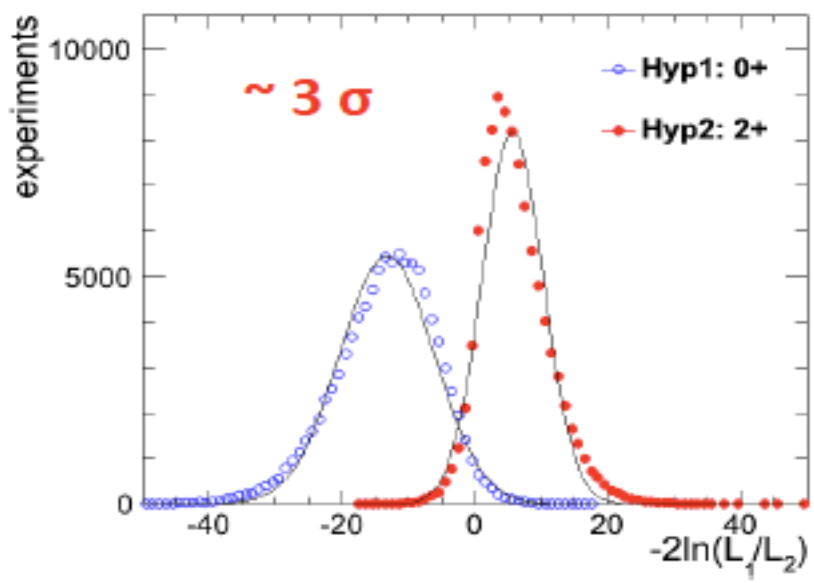
- h $\rightarrow \gamma\gamma$, so it can't be spin 1
- Could be spin 0 or spin 2
- Look at h$\rightarrow$ZZ$\rightarrow$ $l^+l^-l^+l^-$
- Angular correlations are different for spin 0 and spin 2
- VBF, h$\rightarrow W^+ W^- \rightarrow l\nu\ l\nu$
- Leptons from W decays tend to go in the same direction*




*Used in event selection

# Spin Measurements

- $h \rightarrow W^+W^- \rightarrow l\nu\ l\nu$
- Angular correlation of outgoing particles in $h \rightarrow ZZ \rightarrow 4l$




30 $fb^{-1}$

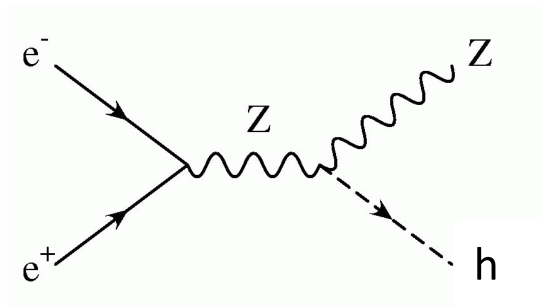
# Bottom Line

- With 30 $fb^{-1}$, should have a good handle on $J^{PC}$
- Coupling measurements at the 25% level in many channels

*So are we done?????*

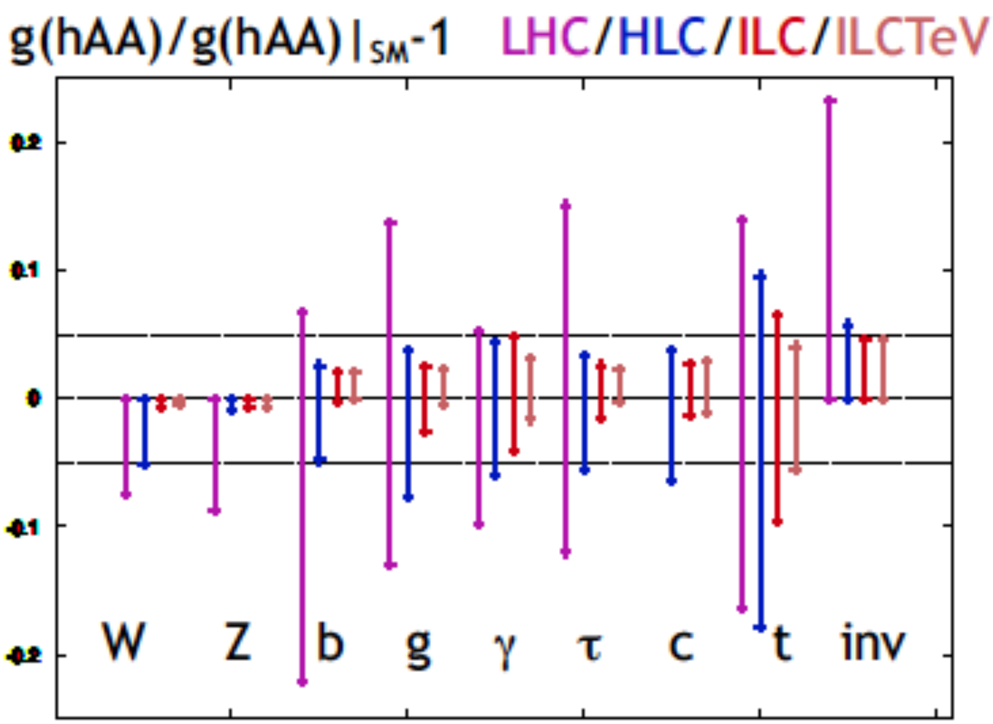
# Higgs Searches in e+e- Colliders

- LEP2 searched for $e^+e^-\rightarrow Zh$
- Rate turns on rapidly after threshold, peaks just above threshold, $\sigma \sim \beta^3/s$
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***
- Momentum conservation:
  - $(P_{e-}+P_{e+}-P_Z)^2=P_h^2=M_h^2$
  - $s-2\sqrt{s}\,E_Z+M_Z^2= M_h^2$




LEP2 limit, $M_h > 114.1$ GeV

# Coupling measurements at future colliders




LHC: 300 fb$^{-1}$ at 14 TeV
HLC: 250 fb$^{-1}$ at 250 GeV
ILC: 500 fb$^{-1}$ at 500 GeV
ILCTeV: 1 ab$^{-1}$ at 1 TeV

[Peskin, 1207.2516]

# What do we learn from the observation of a 125 GeV Higgs (like) boson?

Why we think there might be something else…..

Why particle physics isn't done….

# The Standard Model Works

- Any discussion of the Standard Model has to start with its success
- This is unlikely to be an accident!
- It's not perfect
  - Chimney plot: Consistency of the Standard Model
  - Higgs mass renormalization
  - Unitarity constraints

# Is the Standard Model Self-Consistent?

- $M_h$ is a free parameter in the Standard Model
- Can we derive limits on the basis of consistency?
- Consider a scalar potential:

$$V = \frac{M_h^2}{2} h^2 + \frac{\lambda}{4} h^4$$

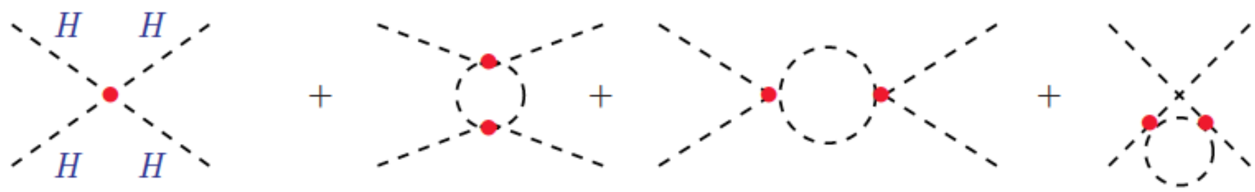
- This is potential at electroweak scale
- Parameters evolve with energy in a calculable way

Standard Model: $\lambda = M_h^2/(2v^2) = .13$ for $M_h = 125$ GeV

*Perturbative Regime*

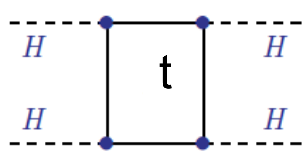
# Higgs Potential for Large h

- Self interactions of Higgs cause λ to grow at high energy




- Top interactions decrease λ at high energy

Trade-off



# High Energy Behavior of λ

- Renormalization group scaling

$$16\pi^2 \frac{d\lambda}{dt} = 12\lambda^2 + 12\lambda g_t^2 - 12 g_t^4 + (gauge)$$

$$t \equiv \log\left(\frac{Q^2}{\mu^2}\right) \qquad g_t = \frac{M_t}{v}$$

- *Large λ (Heavy Higgs):* self coupling causes λ to grow with scale
- *Small λ (Light Higgs):* coupling to top quark causes λ to become negative

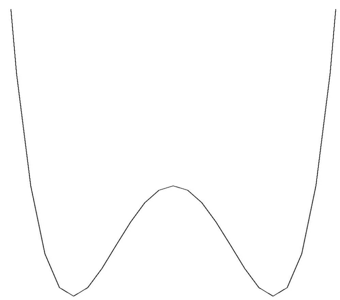
# Does Spontaneous Symmetry Breaking Happen?

- SM requires spontaneous symmetry breaking
- This requires

$$V(v) < V(0)$$

- For small λ

$$16\pi^2 \frac{d\lambda}{dt} \approx -12 g_t^4$$



- Solve

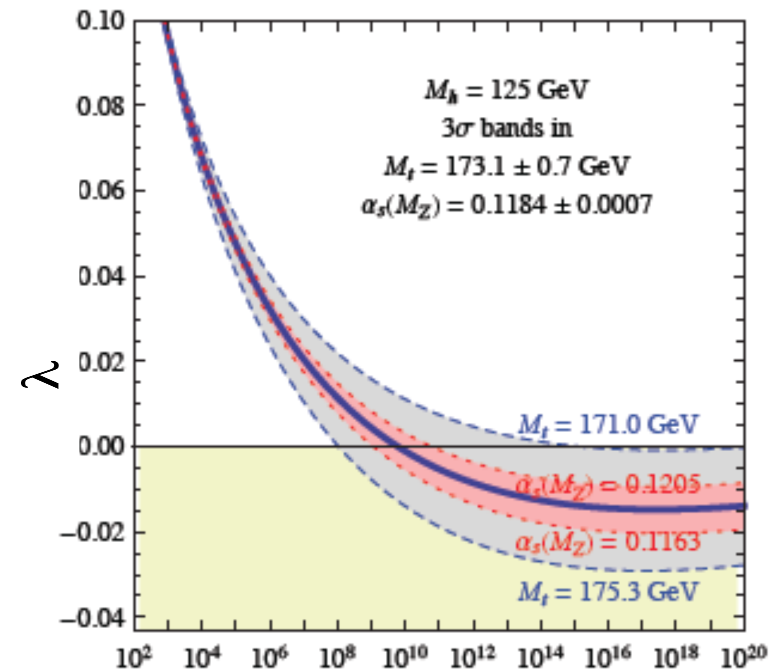
$$\lambda(\Lambda) \approx \lambda(v) - \frac{3g_t^4}{4\pi^2} \log\left(\frac{\Lambda^2}{v^2}\right)$$

# Does Spontaneous Symmetry Breaking Happen?

- $\lambda(\Lambda) > 0$ gives lower bound on $M_h$

$$M_h^2 > \frac{3v^2}{2\pi^2} g_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$$

- For any given $M_h$, there is an upper bound on $\Lambda$




$\Lambda$ [GeV]

This is very sensitive to $M_h$

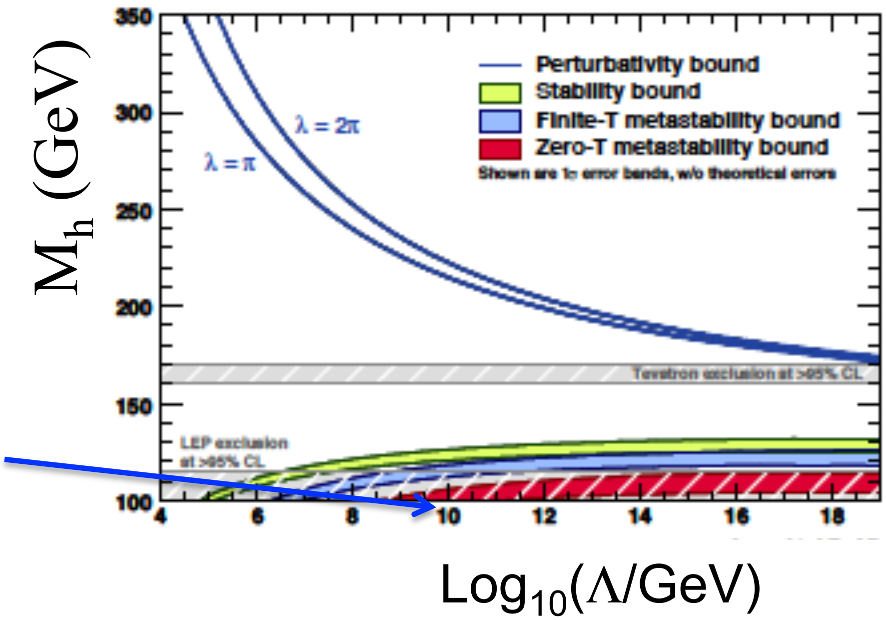
[DeGrassi et al, 1205.6497]

# Don't want λ to be infinite

- Point where $\lambda \to \infty$ called Landau pole
- Without $\lambda h^4$ interactions, theory is non-interacting
- Require quartic coupling be finite gives upper bound

$$\frac{1}{\lambda(\Lambda)} > 0$$

$$M_h^2 < \frac{32\pi^2 v^2}{9\log\left(\frac{\Lambda^2}{v^2}\right)}$$




Maybe vacuum can be unstable if lifetime is longer than lifetime of the universe

[Ellis,0906.0954]