After Discovery: Exploring Higgs Properties

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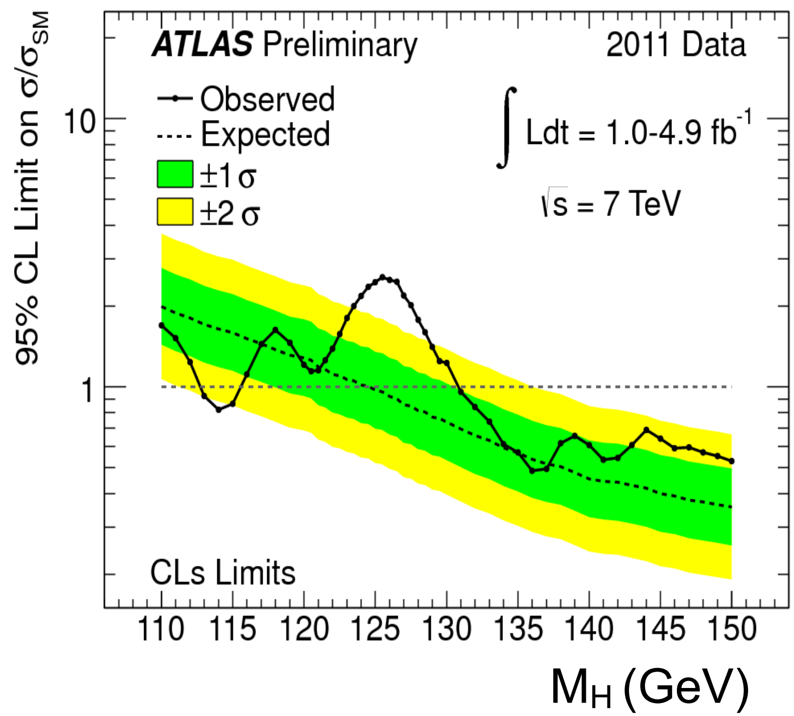
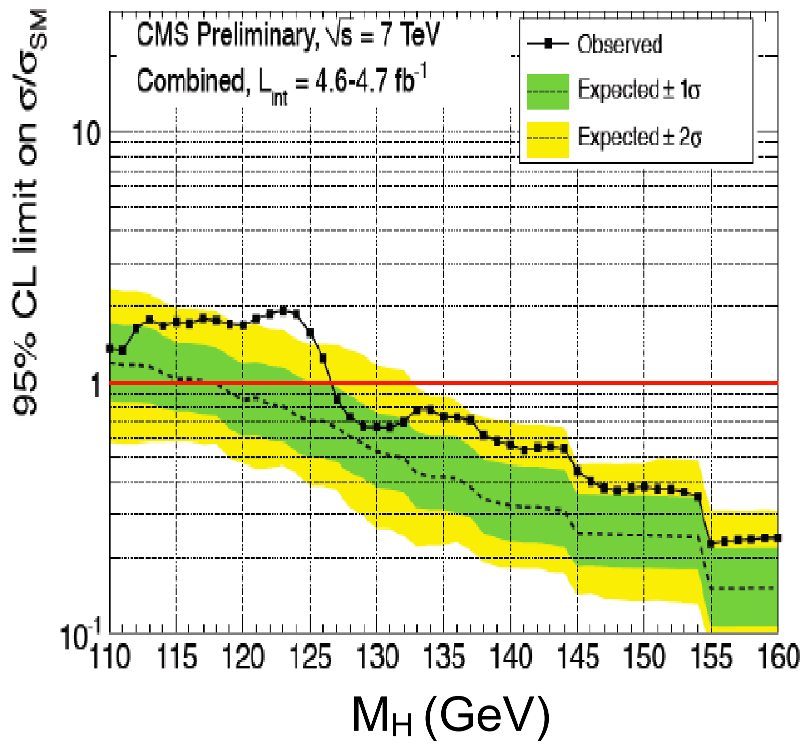
BNL

Jan 11, 2012

Suppose we find a “Higgs-like “ Object?





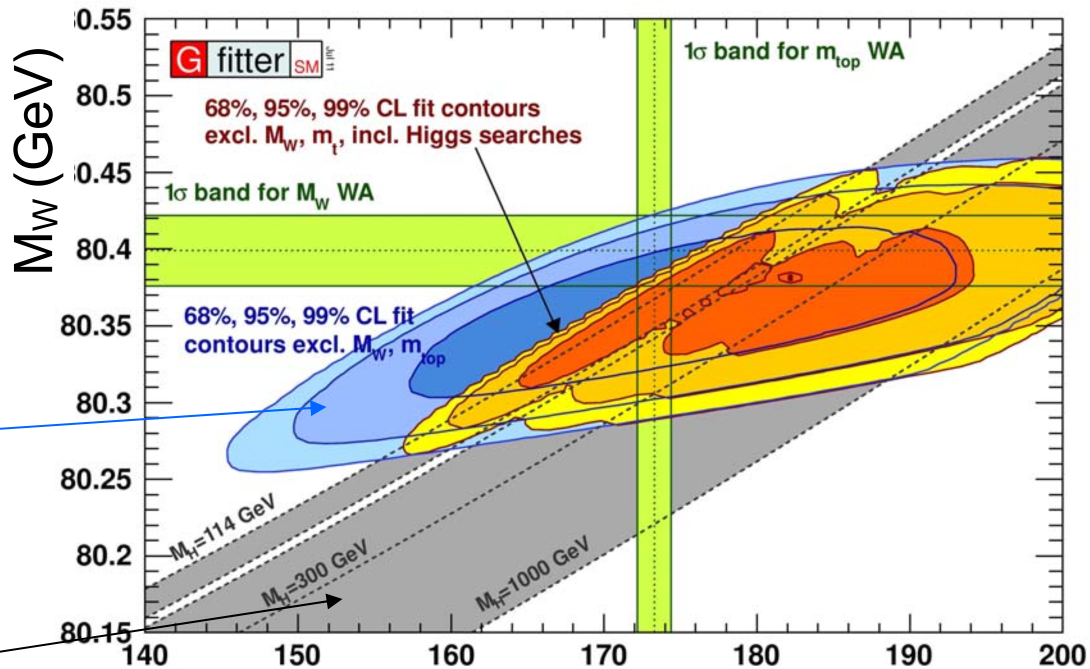
What comes next?

Our Prejudices say the Higgs is Light

Masses inferred from precision measurements and Higgs searches*

Masses inferred from precision measurements

SM Predictions



Higgs boson wants to be light

* Post-ICHEP 2011

Higgs Limits

- From Gfitter (2011)
  - If you don't include direct search limits for Higgs, 95% CL upper bound: $M_H < 169$ GeV
  - If you include LEP, Tevatron, LHC limits, 95% CL upper bound: $M_H < 143$ GeV
  - ***Test of consistency of Standard Model***

Not hard to fit bounds with new physics

http://gfitter.desy.de/

*Post-ICHEP2011

Minimal Higgs theory is predictive

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

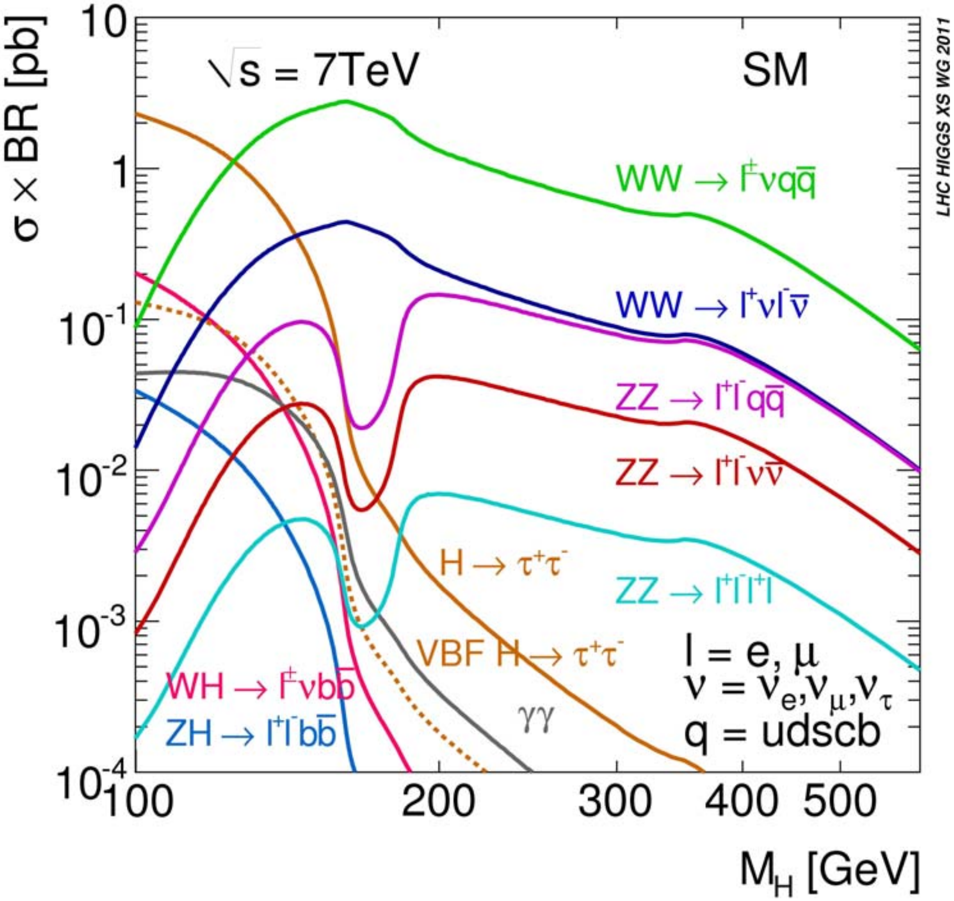
$$L = -\frac{m_f}{v} \bar{f} f H = -\frac{m_f}{v} \left(\bar{f}_L f_R + \bar{f}_R f_L \right) H$$

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses

$$L = g M_W W^{+\mu} W_\mu^{-} H + \frac{g M_Z}{\cos\theta_W} Z^\mu Z_\mu H + \ldots.$$

- Only free parameter is Higgs mass

Very Precise Predictions



- Precise predictions from LHC Higgs cross section working group
- Largest production channel, gg→H, can have contributions from unknown new physics in loop

LHC Higgs Xsections: arXiv:1112.1964

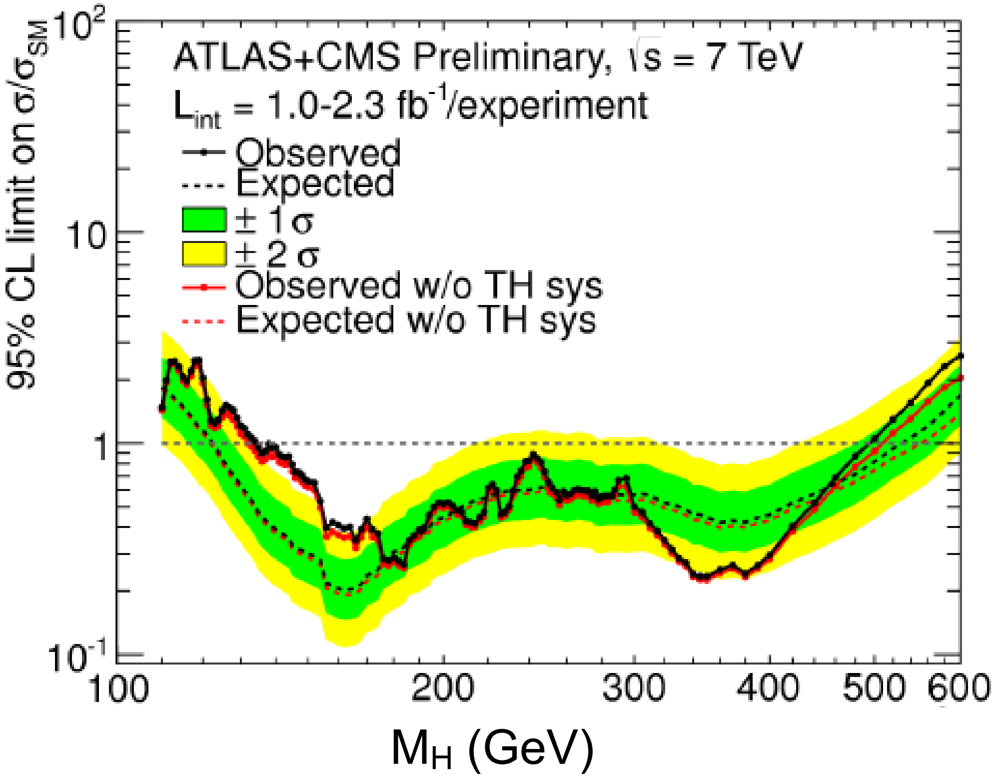
Where do uncertainties come from?

- Unknown higher order terms (TH)
- Scale dependence (TH)
- PDFs/α_s (TH + EXP)
- Other parameters: m_b, …. (TH+EXP)
- Effects of cuts (TH + EXP)
  - Do cuts script the result?
- BSM effects (TH) ← This is the biggest unknown

$$\sigma = \sum_{ij} f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}\left(\hat{s}, \alpha_k, M_n, cuts\ldots\right)$$

Do Theory Errors Matter?

- Useful to have limits for individual channels



Higgs Searches

- What do they mean?
- Do the limits tell us anything about physics at the TeV scale?
- We measure the event rate in each channel:

$$B\sigma(pp \to H \to X) = \sigma(pp \to H) BR(H \to X)$$

- Limits tell us that if M_H >135 GeV

$\sigma(pp \to H) < \sigma_{SM}(pp \to H)$ or

$BR(H \to X) < BR(H \to X)_{SM}$

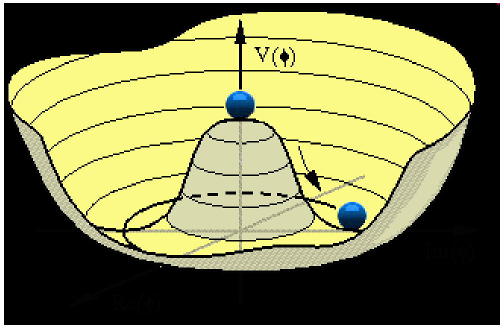
Is it ***the*** Higgs?

- 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

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



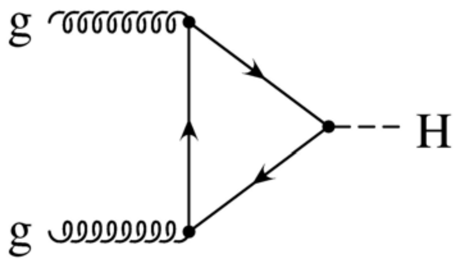
- Measure self interactions

$$V = \frac{M_H{}^2}{2}H^2 + \frac{M_H{}^2}{2v}H^3 + \frac{M_H{}^2}{8v^2}H^4$$

- Make sure there’s only one Higgs-like particle

Standard Model Higgs

- Gluon fusion rate is extremely sensitive to BSM physics



Largest contribution is top loop

b-loop contributes ~2-5%

Predictions at NNLO, NNNLL all assume SM

Explore BSM Contributions to $gg \rightarrow H$

- Many possibilities:
  - Supersymmetry (squarks in loop)
  - Color octets
  - New operators present in strongly interacting theory
  - New fermions
  - …

How far can Higgs production get from the SM prediction?

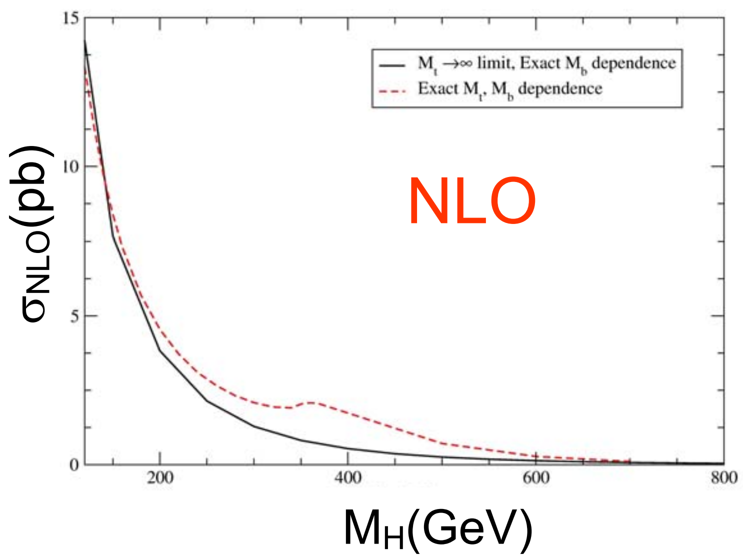
See talks by Rattazzi, Wulzer, Santiago, Harlander

Effective Theory Language for gg →H

$$L_{eff} = \frac{g_s^2}{16\pi^2}\left(\frac{1}{3}\right)\sum_F \log\left(\frac{H^+H}{v^2}\right) G_{\mu\nu}^A G^{A,\mu\nu}$$

True when only source of mass is EWSB and $M_t >> M_H$

gg→H, √s=7 TeV



Effective theory accurate except near $t\bar{t}$ threshold

L_{eff} verified at NNLO in SM: See Harlander talk

Example: Heavy Fermions

- If fermion gets mass from Spontaneous Symmetry Breaking, then $m_Q \sim v$
- If mass from Yukawa couplings, $M_{nm}=y_{nm}\, v$
- Generalize low energy theorem:

$$L_{eff} = \sum_F \frac{\alpha_s}{12\pi}\left(\frac{H}{v}\right)\sum_F \frac{\partial \log(M_F)}{\partial \log(v)} G^A_{\mu\nu} G^{A,\mu\nu}$$

Use Low Energy Theorem for BSM models and test gg→H rate

Falkowski, arXiv: 0711.0828; Low and Vichi, arXiv:1010.2753; Low, Rattazzi, and Vichi, arXiv:0907.5413

Chiral Fermions

- Suppose there are chiral fermions contributing to gg→H
- Fermions might be too heavy to observe directly
- Simplest example is 4th generation

$$\Psi_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix}, \quad U_R, \quad D_R$$

$$\Omega_L = \begin{pmatrix} N_L \\ E_L \end{pmatrix}, \quad N_R, \quad E_R$$

- Restricted by precision measurements

$$T = \left(\frac{1}{12\pi s_W^2 M_W^2}\right)\left[(M_U - M_D)^2 + (M_N - M_E)^2\right]$$

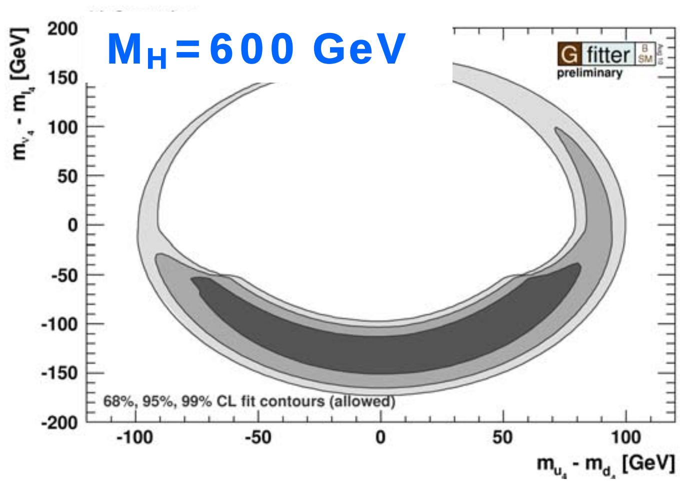
$$S = \frac{1}{6\pi}\left(2 - Y_\Omega \ln\left(\frac{M_N^2}{M_E^2}\right) - Y_\Psi \ln\left(\frac{M_U^2}{M_D^2}\right)\right)$$

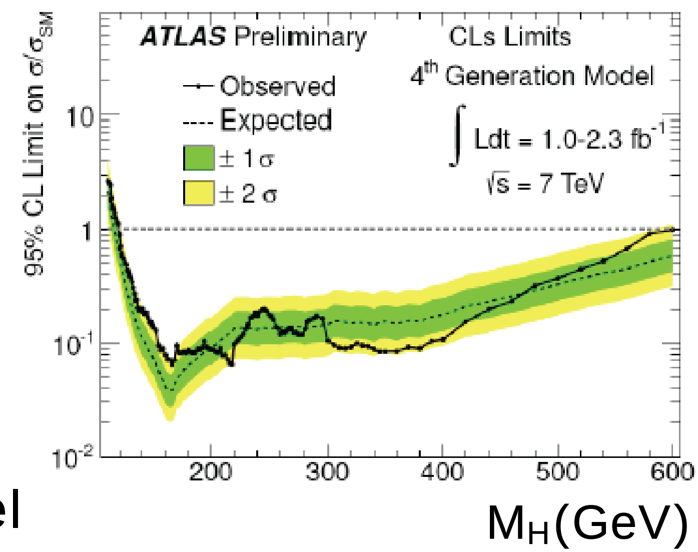
← Adjust masses

Kribs, Plehn, Spannowsky,Tait, arXiv:0706.3718

SM 4th Generation Allows Heavy Higgs

- SM 4th generation almost gone





$gg \rightarrow H$ enhanced by ~9 in 4G model

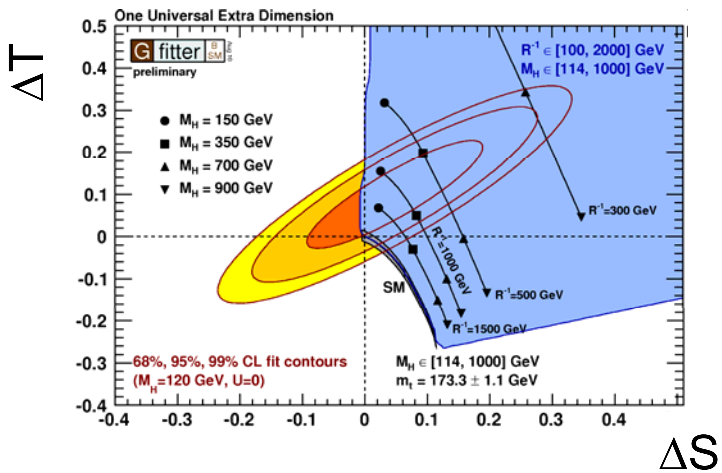
$H \rightarrow \gamma\gamma$ decay suppressed in 4G model

Rate known at NNLO: Anastasiou, Buehler, Furlan, Herzog, Lazopoulos, arXiv: 1103.3645; Anastasiou, Boughezal, Furlan, arXiv: 1003.4677

EW corrections to decay: Denner et al, arXiv:1111.6395

UED Models

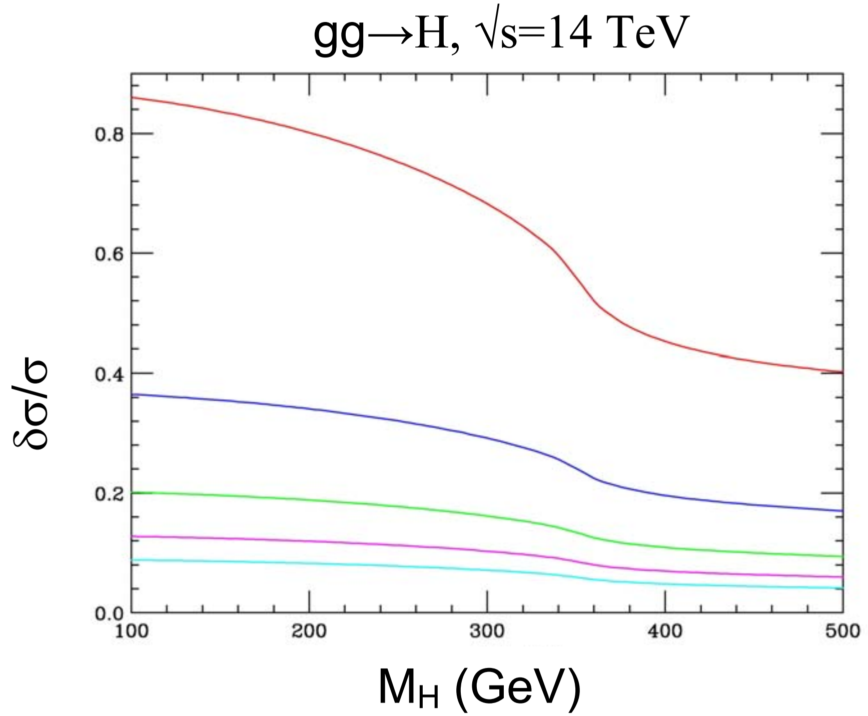
- Universal extra dimension models have new chiral fermions
  - Models have heavy copies of top quark, T_n
  - T_n doesn't get all of its mass from EWSB
  - Higgs couplings to $T_n \sim (M_t/v)(M_t/M_{Tn})$



$M_{Tn} \sim 1/R$

Higgs Production can't get too far from SM

- Allowed couplings restricted by STU



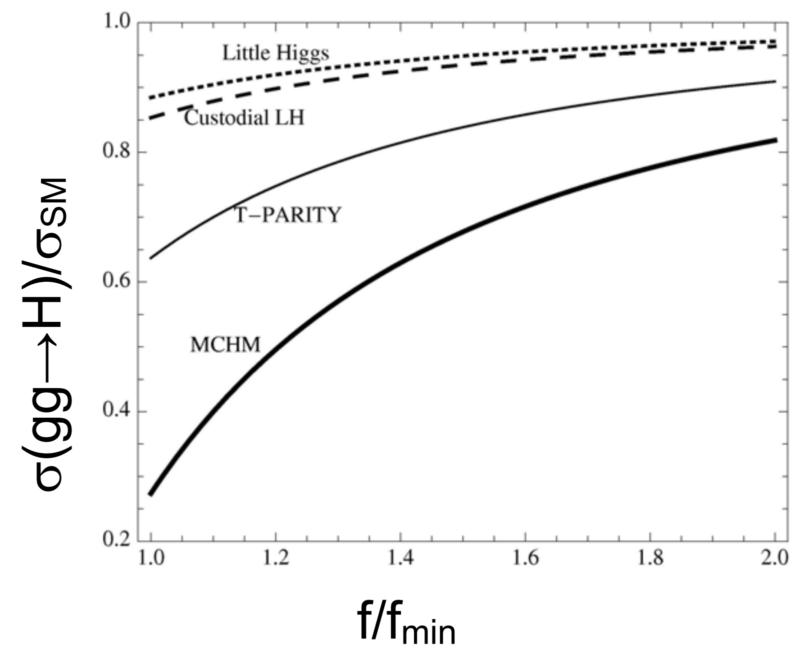
M_{Tn}=500,700,1000, 1250,1500 GeV

Models with new chiral fermions tend to have enhanced gluon fusion rate

Petriello, 0204067

Little Higgs Models

- Little Higgs like models
  - Higgs is Goldstone Boson of broken global symmetry
  - Top quark has a weak singlet partner which mixes with top
  - Higgs production can be significantly suppressed



Note decoupling for large f

f_{min} is minimum scale allowed by precision EW (500 -1200 GeV)

[Low & Vichi]

Top Seesaw, Little Higgs….

- These are all just special cases of models with with weak singlet vector like charge 2/3 quark, U_L, which mixes with SM-like third generation q_L~(u_L,d_L), u_R, d_R
- Generic mass matrix

$$L_M = -a\bar{q}_L\tilde{H}u_R - b\bar{q}_L\tilde{H}U_R - c\overline{U}_L u_R - d\overline{U}_L U_R + hc$$

- d is Dirac mass, typically >> other parameters
- Physical top is mixture of (u, U)

$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} c_L & -s_L \\ s_L & c_L \end{pmatrix} \begin{pmatrix} u_L \\ U_L \end{pmatrix}$$

SD, Furlan, in preparation

Interesting Effects

- Assume d >> a,b,c
  - $M_T \sim d$
  - $s_L \sim vb/M_T$

Same scaling observed in composite Higgs models

- Constraints from S/T/U

$$\alpha \Delta T \approx \frac{N_c}{16\pi^2} \frac{b^2 m_t^2}{M_T^2} \left(\log\left(\frac{M_T^2}{m_t^2} \right) - 1 \right)$$

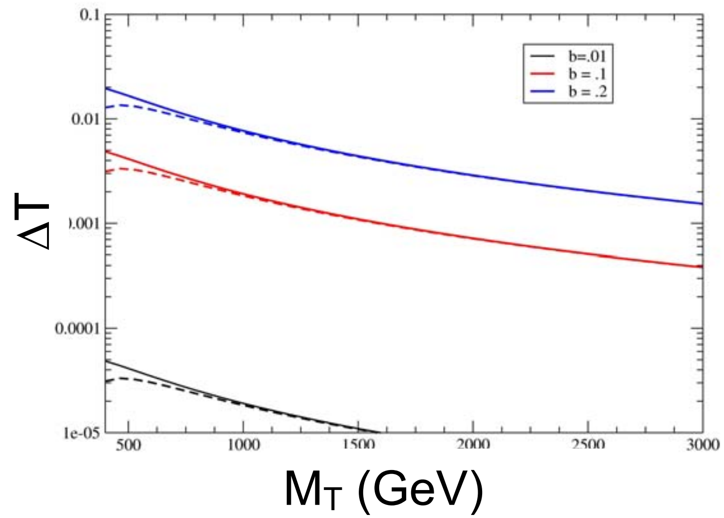
$$\alpha \Delta S \approx \frac{N_c}{18\pi^2} \frac{b^2 s_W^2 M_W^2}{M_T^2} \left(\log\left(\frac{M_T^2}{m_t^2} \right) - \frac{5}{2} \right)$$

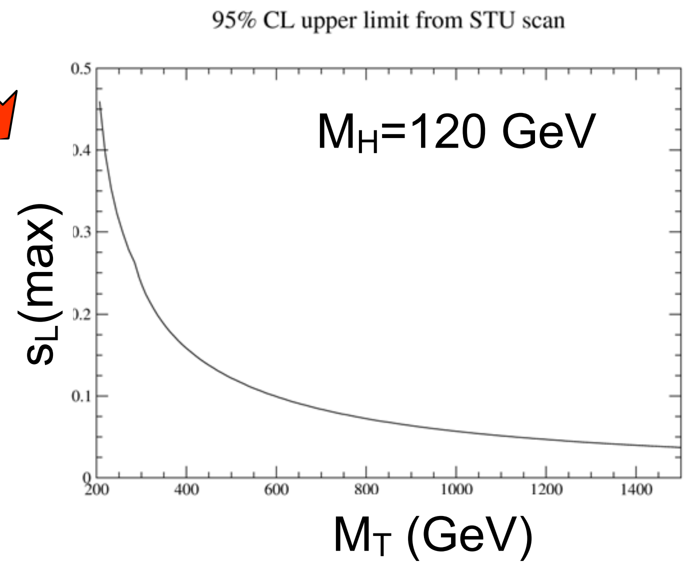
Decoupling for large M_T (General property of vector like fermions)

- Higgs production from gluon fusion: $\sigma_{gg} \approx \sigma_{SM} \left(1 - b^2 \frac{m_t^2}{M_T^2} \right)$

Limits from STU Global Scan

- Can't go too far from the SM (the moral of this story)





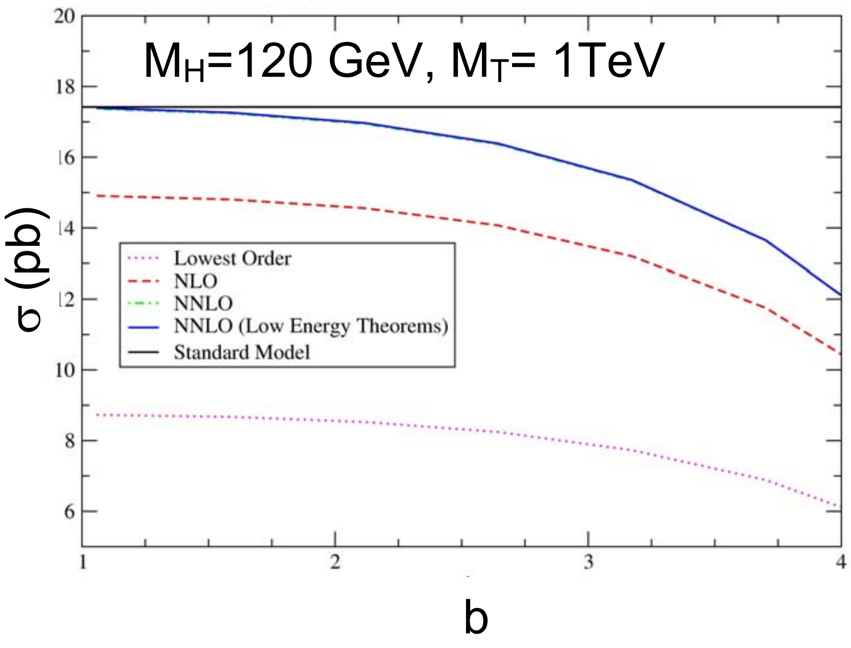
Maximum mixing
allowed by STU scan

For heavy Higgs: Bai, Fan, Hewett, arXiv:1112.1964

NNLO with Vector Fermions

- Compute gg→H for arbitrary fermions and Yukawa couplings: IHIXS
- Only a few diagrams which mix mass scales

gg→H, √s=7 TeV



- Rate suppressed from SM
- Low energy theorems very accurate

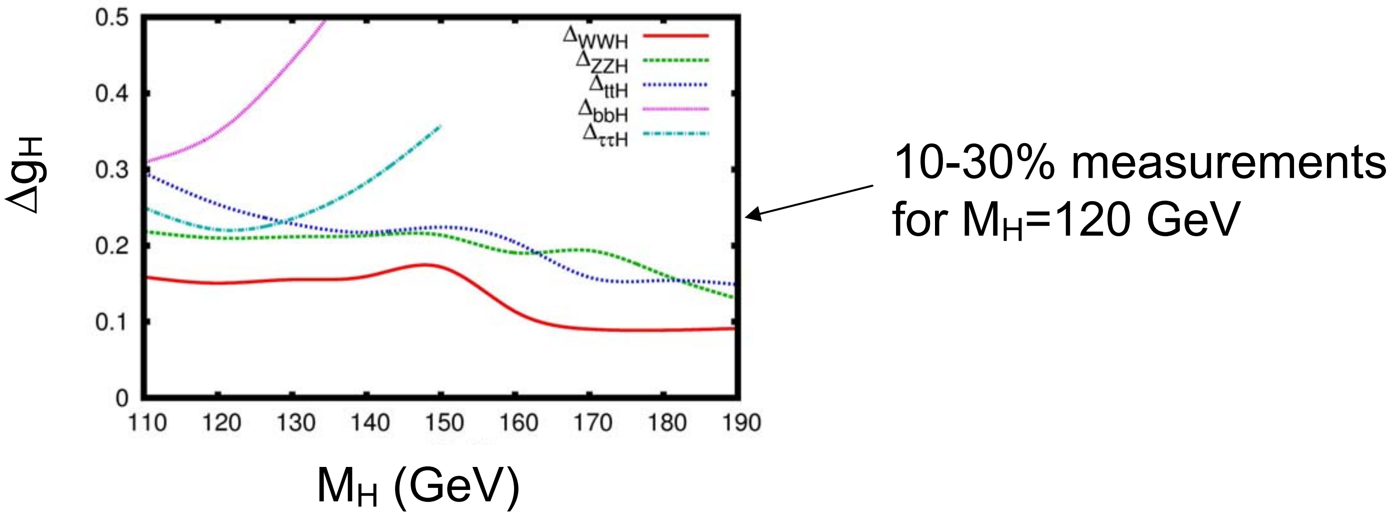
IHIXS: Furlan, arXiv: 1106.4024; Anastasiou, Buehler, Herzog, Lazopoulos, arXiv: 1107.0683

Framing the Question

- Experiments limit $\sigma B / (\sigma B)_{SM}$
  - How low do we need to go?
  - New physics limited by direct search and by STU
- Direct channels (VBF, VH, ttH) critical because they are not sensitive to BSM loops at leading order

Measuring Higgs Couplings

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



- Parameterize couplings in terms of deviation from SM
  - $g_H \sim g_{SM}(1+\Delta)$

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

Direct Measurements Crucial

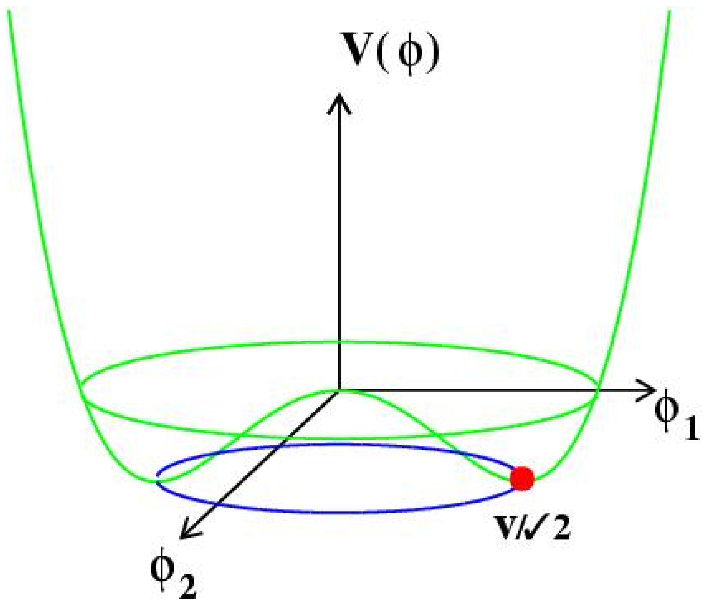
- VH, VBF, ttH measure couplings directly
  - WH known at NNLO, ttH & VBF at NLO
  - Reliable theory predictions
  - VH can give Hbb coupling, ttH gives Htt coupling
- Modern studies rely on high p_T region
  - Now have distributions at NLO
  - Theory uncertainties larger at tails of distributions
  - Direct processes implemented in POWHEG, mC@NLO (see Frixione talk)

Time to rethink ttH!

Can we reconstruct the Higgs potential?

$$V = \frac{M_H^{\,2}}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

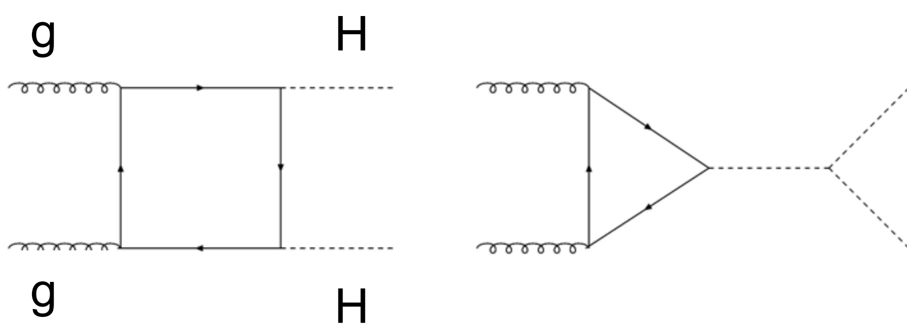
$$SM:\ \lambda_3 = \lambda_4 = \frac{M_H^{\,2}}{2v^2}$$



- Fundamental test of model!

Double Higgs Production from Gluons

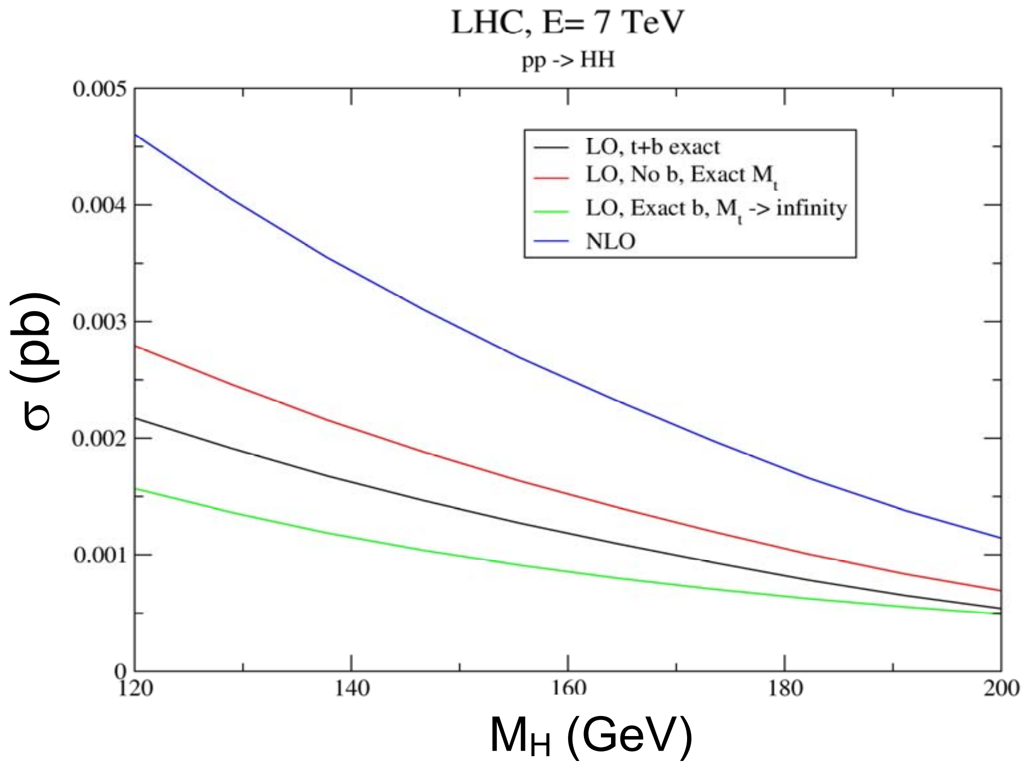
- Sensitive to heavy fermions (top quark)
- Contribution is dominantly triangle
- Destructive interference



$\sim\lambda_t^2$ $\sim\lambda_t\,\lambda_3$

SM: loops are mostly top, but sensitive to BSM physics

Small rate for HH production



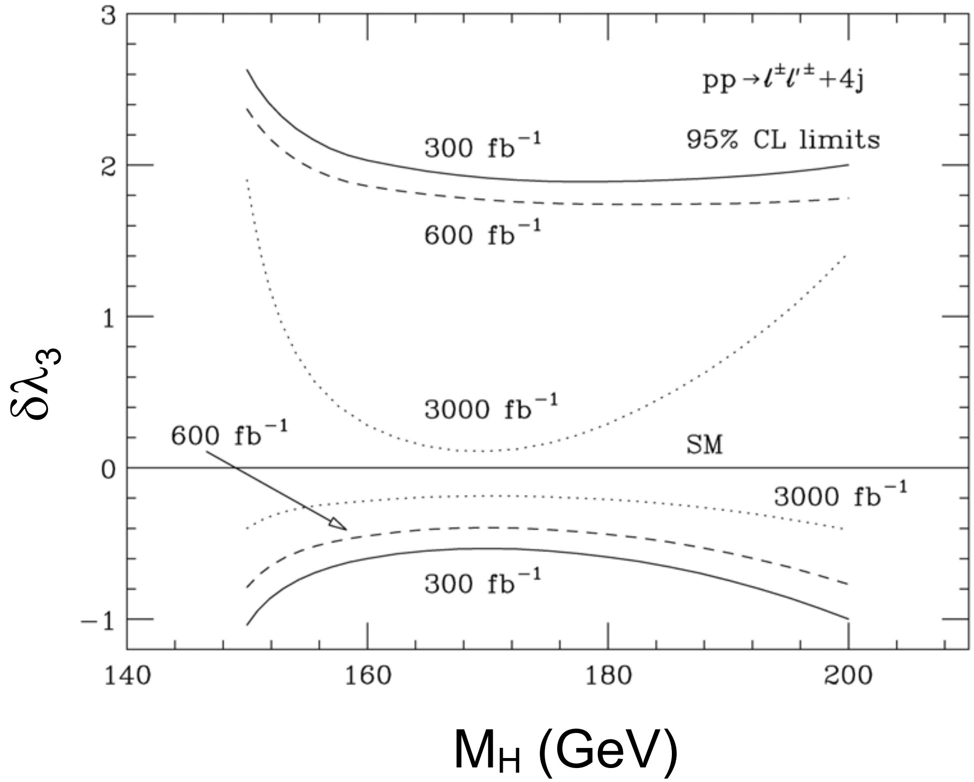
For M_H=160 GeV, 10 events in all channels with 3 fb^{-1}

HH Production can be enhanced in models with new physics

Small sensitivity to HHH coupling

- Can we do better?

pp → H H → $W^+W^-W^+W^-$ → 2 leptons + 4 jets



For lighter Higgs try $HH \rightarrow bb\gamma\gamma$

[Baur, Plehn, Rainwater 2002]

Measuring Higgs Self-Couplings

- Need this to nail down EWSB mechanism
  - Small rates for $gg \to HH$
- Very (!) hard at LHC
  - $150 < M_H < 200$ GeV, LHC (300 fb^{-1}) can exclude no self coupling hypothesis @95% C.L. (14 TeV)
  - $M_H < 140$ GeV, need 6000 fb^{-1} to measure

$$-.66 < \Delta\lambda_{HHH} < .82$$

Physics driver for next generation machine

[Baur, Plehn, Rainwater]

Single Higgs vs Double Higgs Production

- New physics can affect single and double Higgs production differently
- Heavy fermions which get mass from entirely from EWSB contribute to effective operator (low energy theorems):

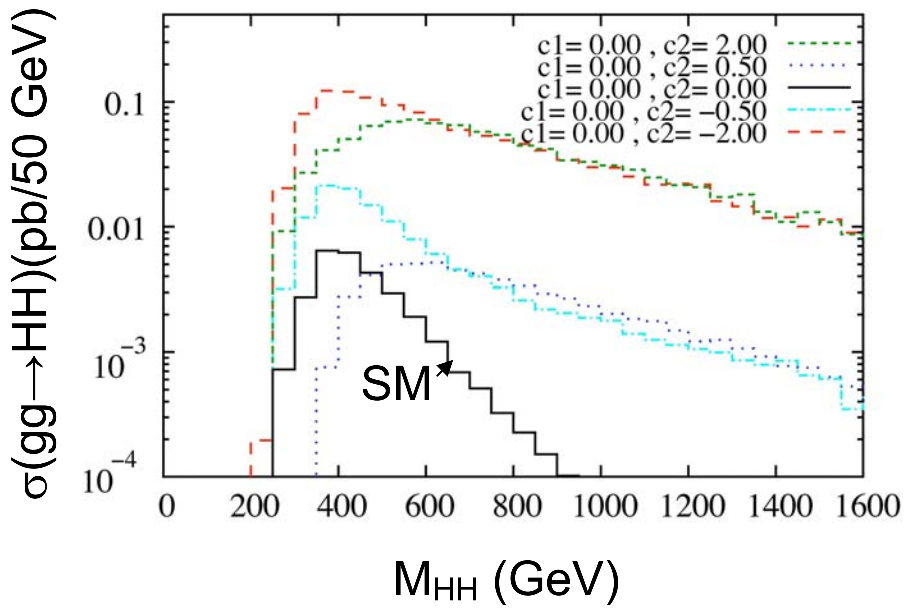
$$O_2 = \frac{\alpha_s}{8\pi} C_2 G_{\mu\nu} G^{\mu\nu} \log\left(\frac{HH^+}{v^2}\right) = \frac{\alpha_s}{4\pi} C_2 G_{\mu\nu} G^{\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2}\right)$$

- New physics can induce operator:

$$O_1 = \frac{\alpha_s}{4\pi} C_1 G_{\mu\nu} G^{\mu\nu} \frac{HH^+}{v^2} = \frac{\alpha_s}{4\pi} C_1 G_{\mu\nu} G^{\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2}\right)$$

New Physics changes 2-Higgs Production

- Easily get enhancements of 10-20 in 2-Higgs total rate
- Distributions very different with BSM physics



SM-like fermion:
$c_1=0, c_2=4/3$

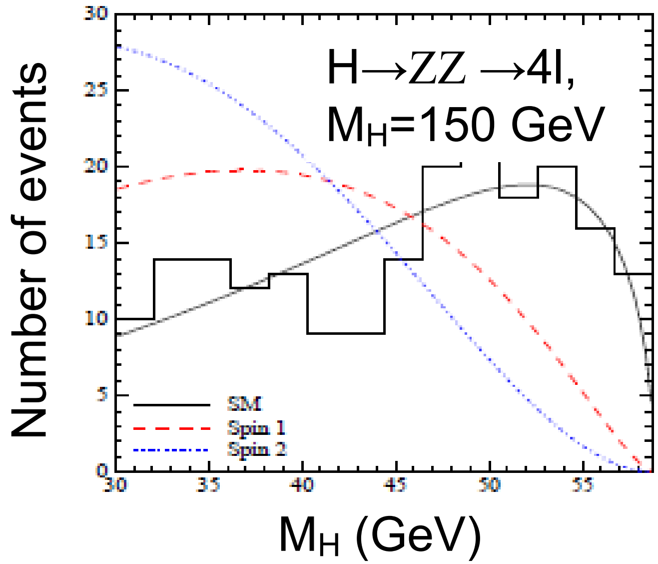
BSM physics large in tails of distributions

Effective theory: Pierce, Thaler, Wang, arXiv:0609049

Color Octets: Dobrescu, Kribs, Martin, arXiv:1101.2208

Higgs Spin

- If we see $H \rightarrow \gamma\gamma$ Higgs can't be spin 1
- Correlations in decay angles of $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ can determine Higgs spin (if there are enough events)
- Multivariate analysis, 10 fb^{-1} gives 3σ significance for M_H=200 GeV



100 fb^{-1} at $\sqrt{s}$=14 TeV

How to get to lower M_H? BR($H \rightarrow ZZ$) falls rapidly with decreasing M_H

Miller et al, hep-ph/0102023; Lykken et al, arXiv:1101.5300

Conclusions

- Once we find the Higgs boson, we're just beginning the exploration of EWSB
  – Need to measure couplings and spin
  – Need to check for more Higgs-like particles
- Higgs production is a window into BSM physics
  – Sensitive to whether fermion masses come from EWSB
  – Sensitive to new operator structures
  – Double Higgs production can potentially discriminate between models

Pheno 2012: May 7-9, LoopFest XI, May 10-12