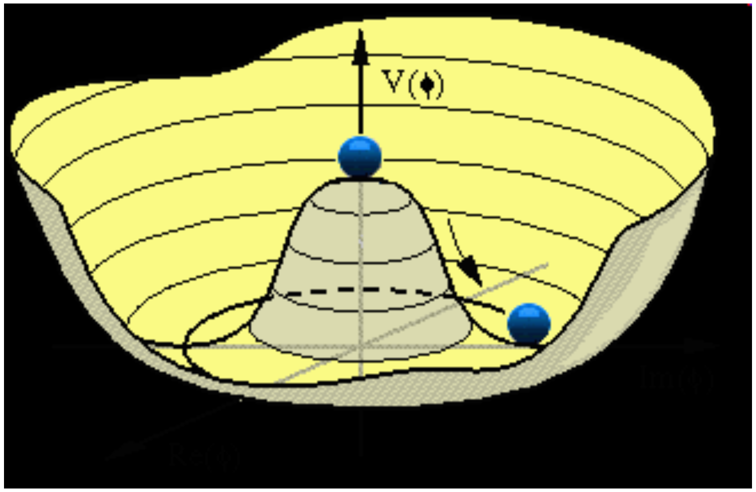
Exploring the Higgs Sector

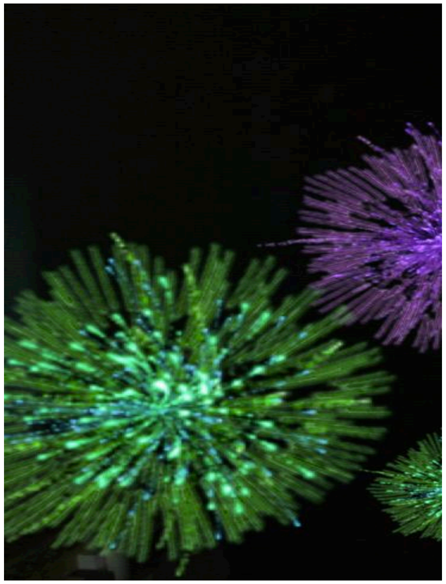
S. Dawson (BNL)

October 11,2012

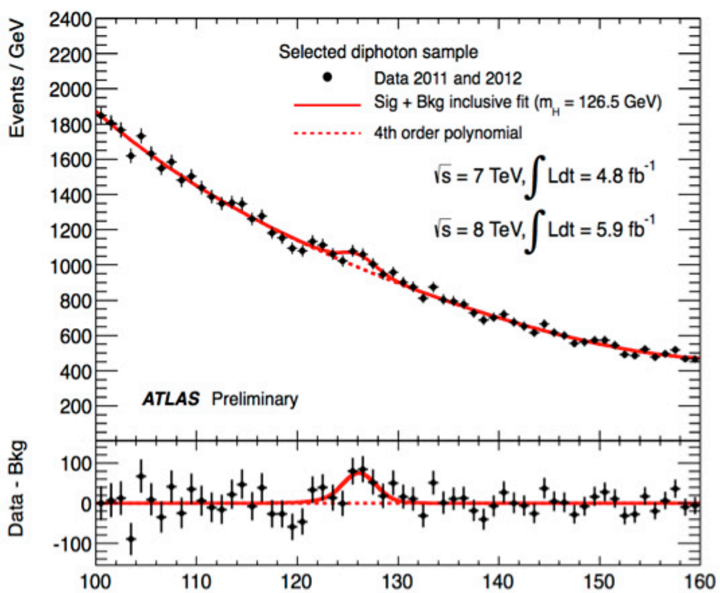
What do we know now?

What do we need to know
to verify the Standard Model
Higgs mechanism?

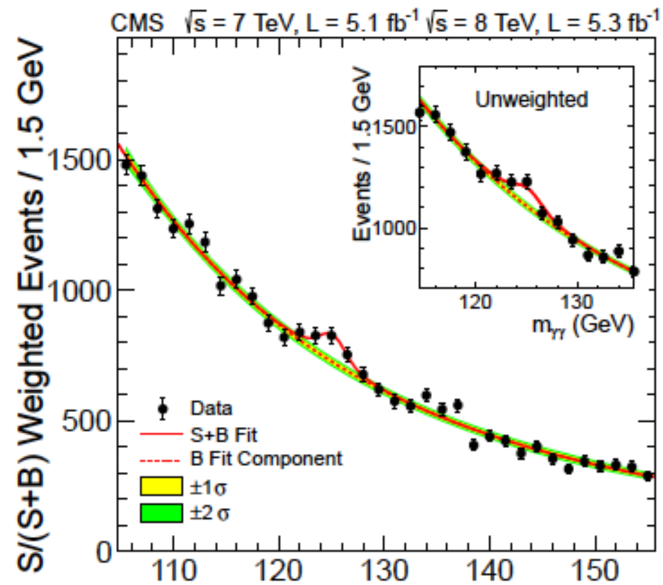




The 4th of July!



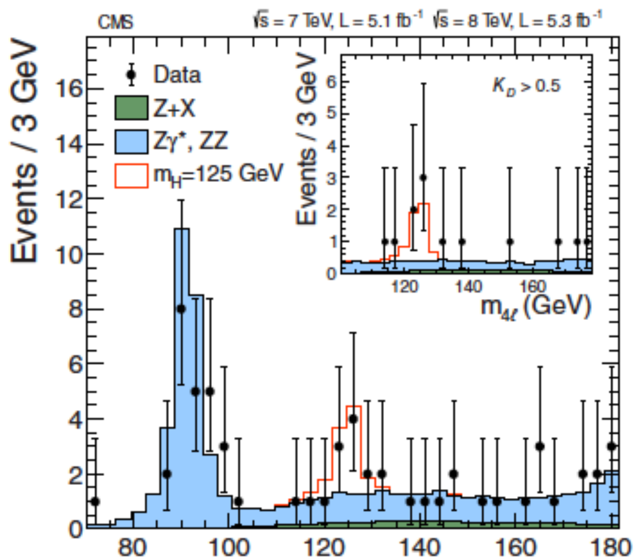
$M_{\gamma\gamma}$ (GeV)



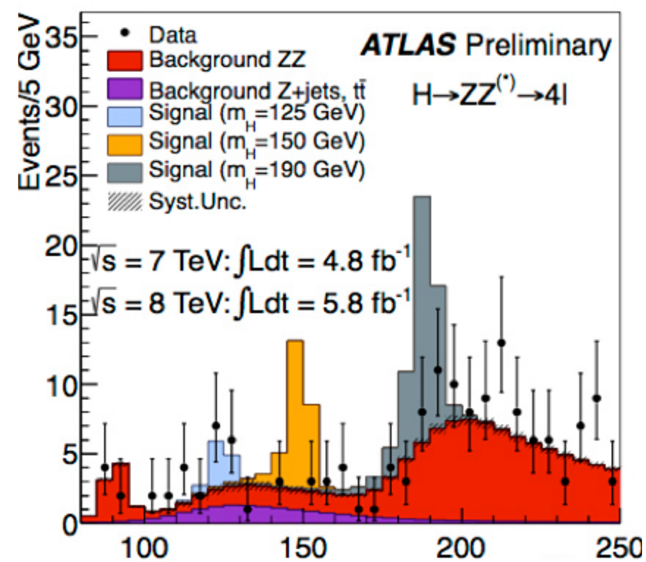
$M_{\gamma\gamma}$ (GeV)

$H \longrightarrow \gamma\gamma$

Multiple Channels in both CMS & ATLAS



M_{41} (GeV)

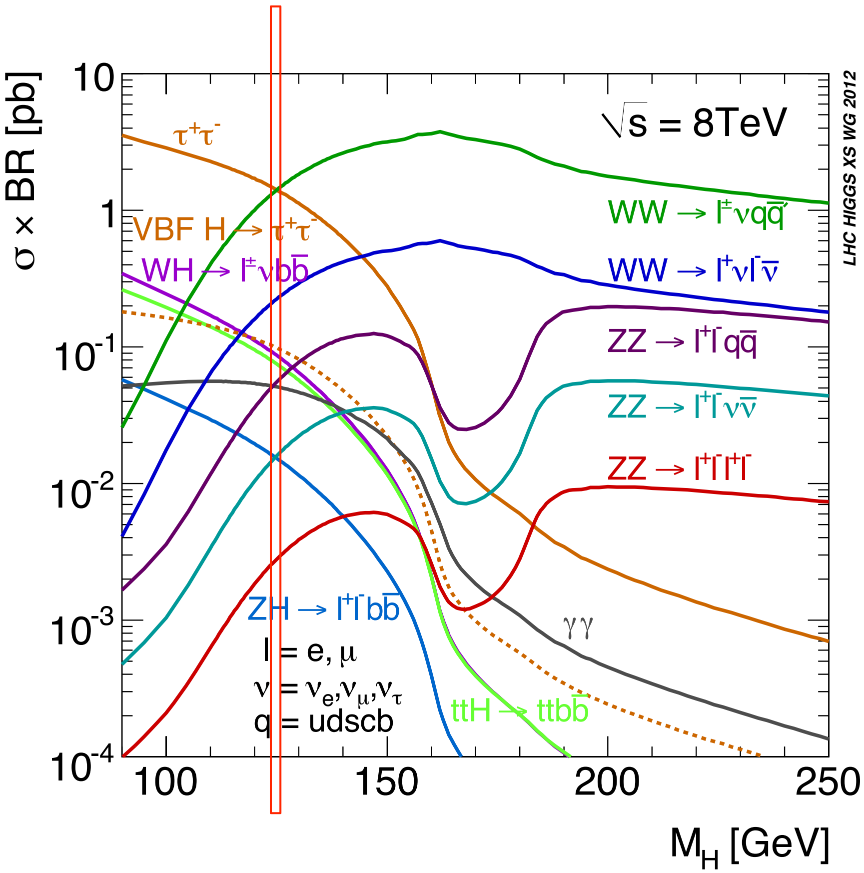


M_{41} (GeV)

$H \longrightarrow ZZ^* \longrightarrow 4$ leptons

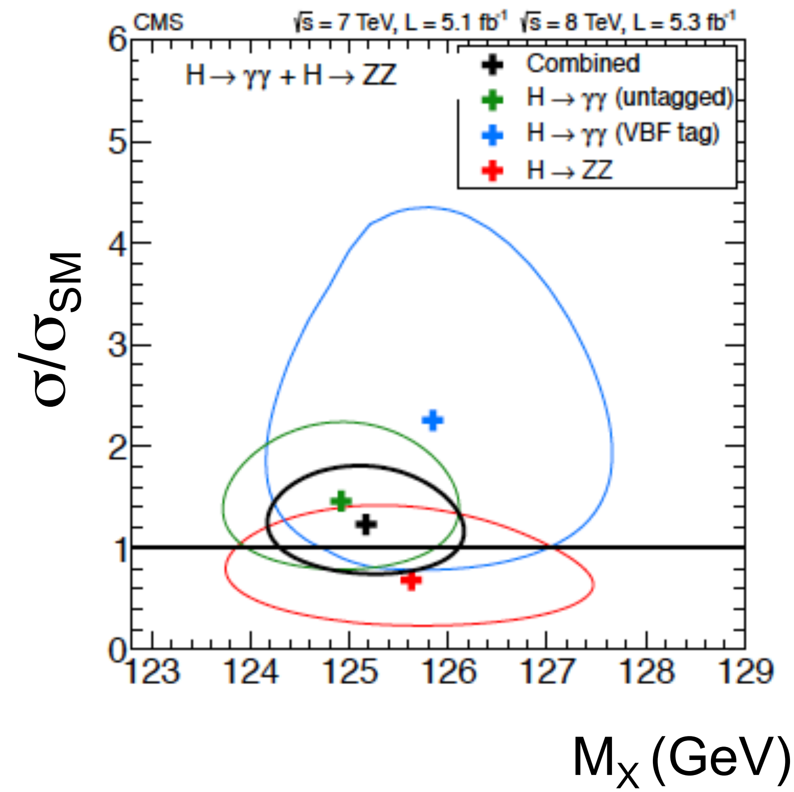
Small numbers of events

Production + Decay



Higgs Candidate looks SM-Like

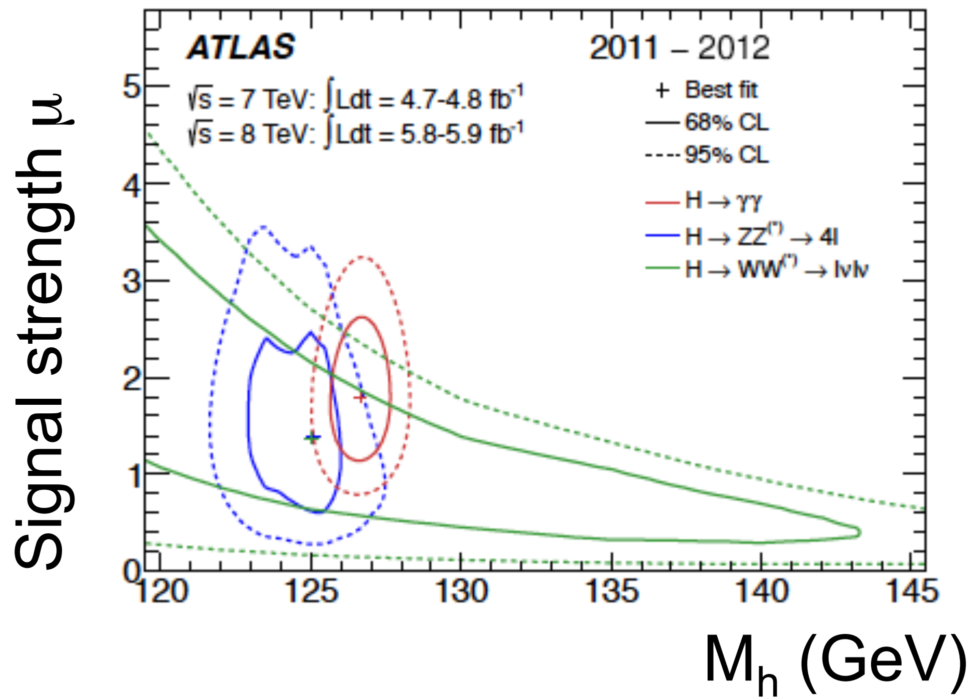
- Relative signal strengths constrained by SM expectations in this plot
- Theory assumptions!



CMS

M_h=125±.4(stat)±.5(syst) GeV

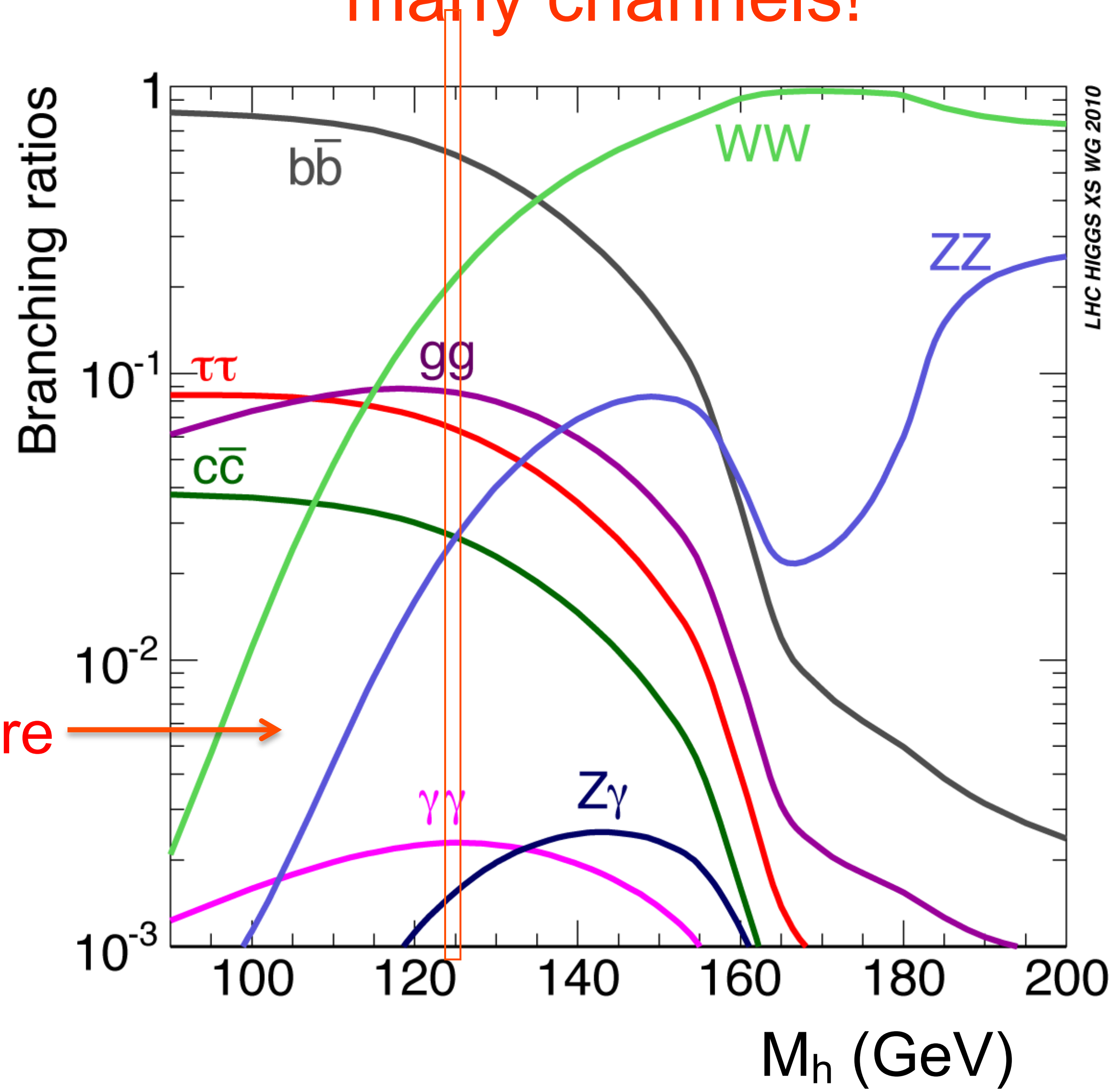
Higgs Candidate looks SM-Like



ATLAS

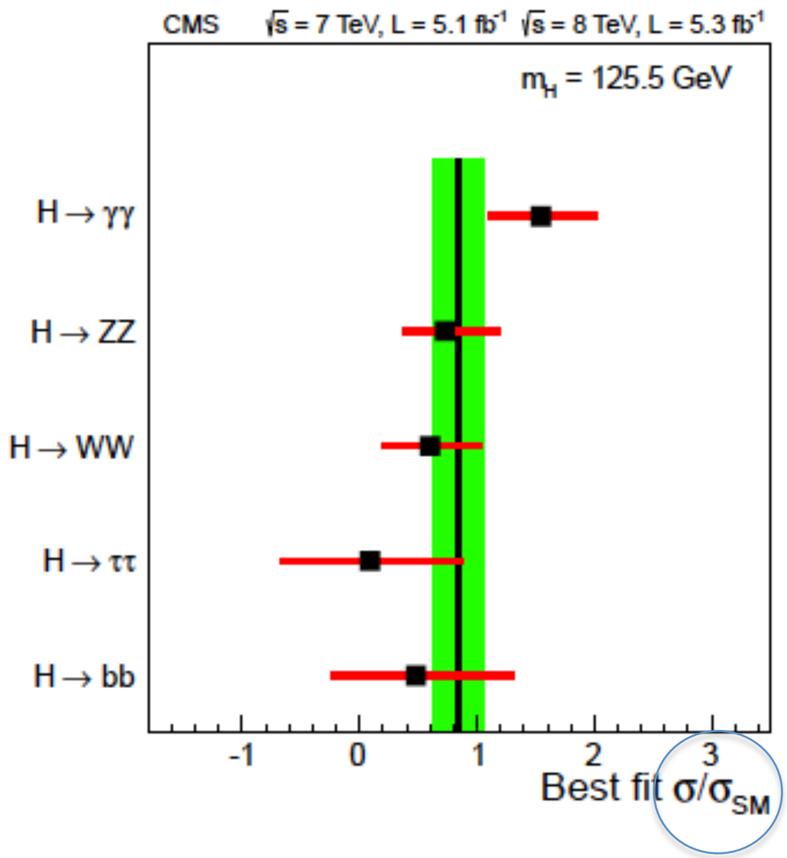
M_h=126 ± .4 (stat) ± .4 (syst) GeV

A 125 GeV Higgs can be observed in many channels!



We are here →

Higgs Candidate looks SM-like



CMS

red lines are 1σ errors (systematics and statistics combined)

[CMS,arXiv:1207.7235]

The World Has Changed

- Now that we have observed a Higgs-Like particle, the goal is:
  - Understand its properties and role in electroweak symmetry breaking
- The Higgs is our window into possible new high scale physics
  - We could be seeing some low energy remnant of more complicated theory

Minimal Higgs Theory is Predictive

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

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

Doesn't vanish for v=0

- Higgs couples to gauge boson masses

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

Vanishes for v=0

- Only free parameter is Higgs mass

Testable Theory

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

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

Observation in $\gamma\gamma$ channel requires J=0,2

- Measure self interactions

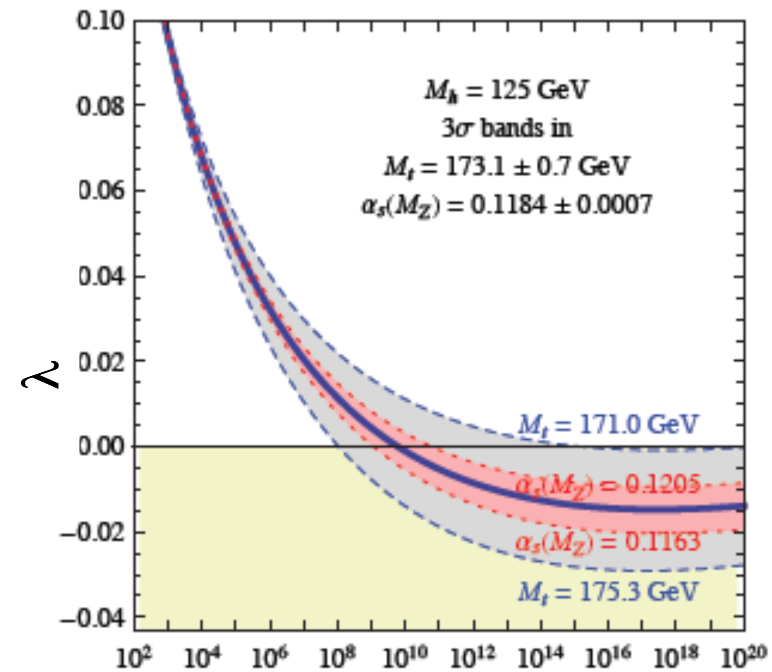
$$V = \frac{M_H^{\,2}}{2}H^2 + \frac{M_H^{\,2}}{2v}H^3 + \frac{M_H^{\,2}}{8v^2}H^4$$

We already know that M_H=125 GeV is perturbative!

$$M_H^2 = \lambda v^2 \to \lambda = 0.26$$

M_H=125 GeV Implies New Physics

- $\lambda(\Lambda) > 0$ gives scale of "New Physics"
  - Higgs potential must be positive
- For any given M_H, there is an upper bound on Λ
- Note sensitivity to M_t and α
- Plot has changed!



Λ [GeV]

This is very sensitive to M_t

[DeGrassi et al, 1205.6497]

Standard Model *Predicts* W Mass

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2(1-M_W^2/M_Z^2)}\frac{1}{(1-\Delta r)}$$

- SM predicts M_W
- Δr is a physical quantity which incorporates 1-loop corrections
- Contributions to Δr from top quark and Higgs loops

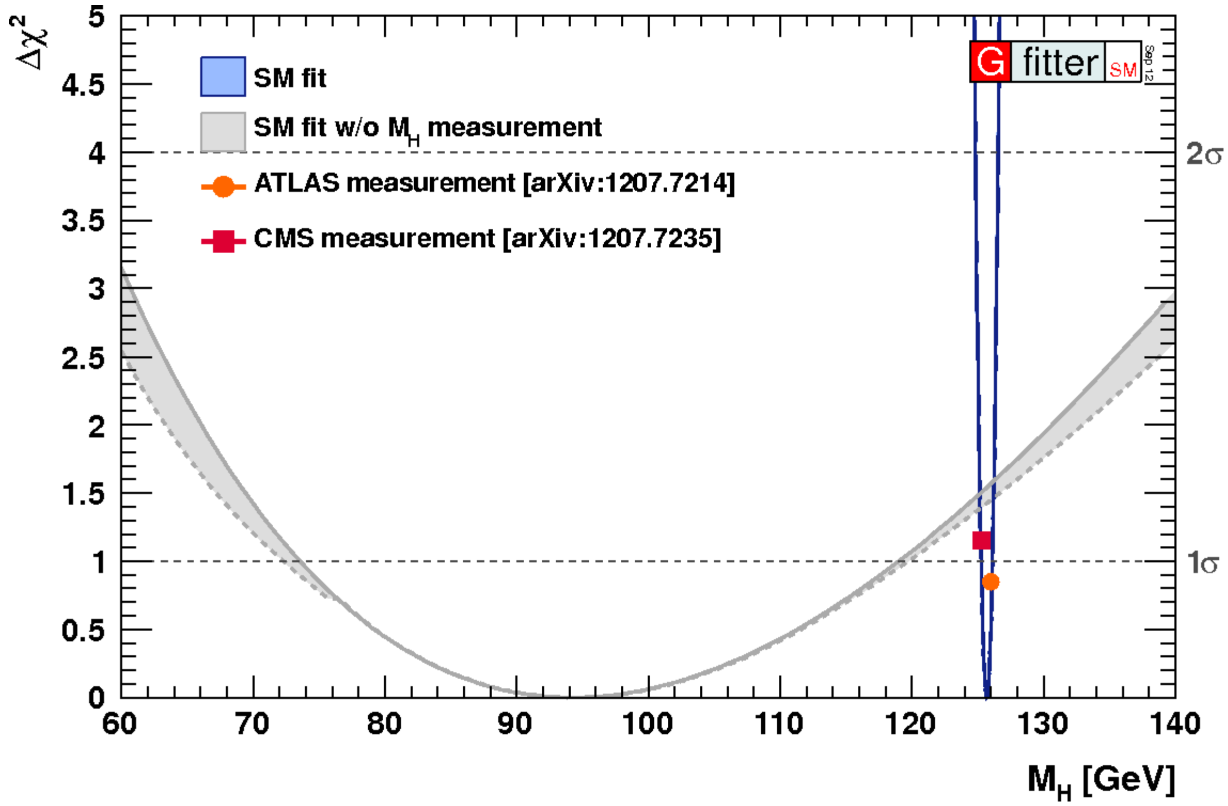
$$\Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)$$

$$\Delta r^h = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2}\right)$$

Extreme sensitivity of precision measurements to m_t

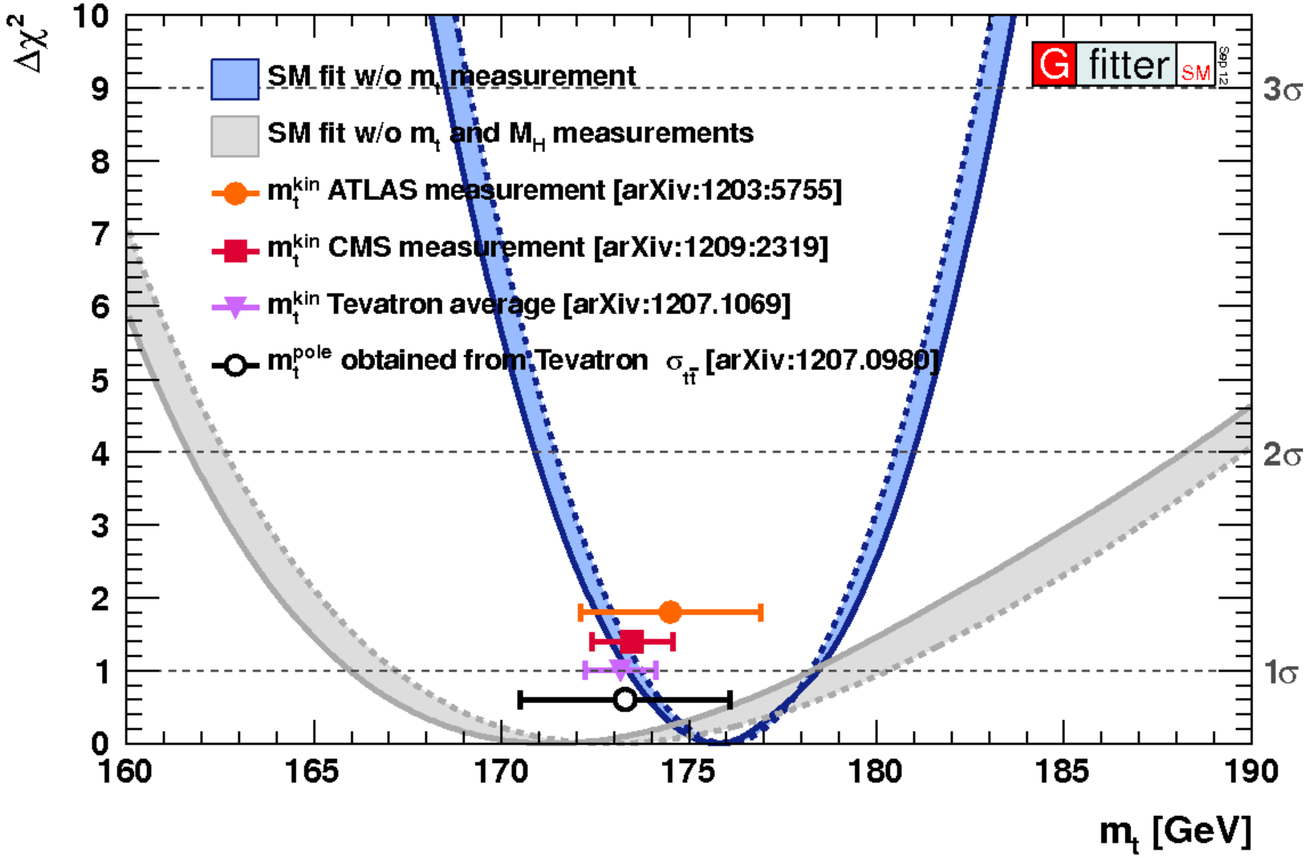
We’ve come a long ways!

M_H inferred from precision measurements



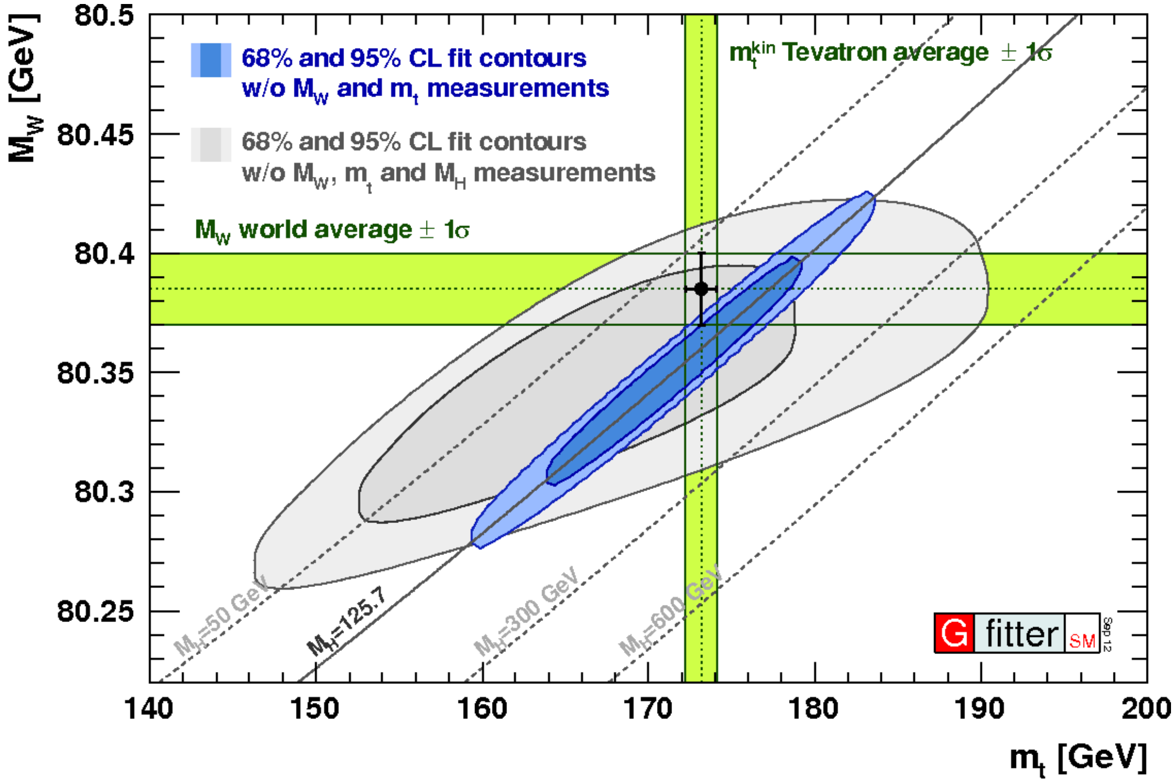
* GFITTER

Infer Top Mass



*Direct determinations of m_t excluded from fit

A consistent picture

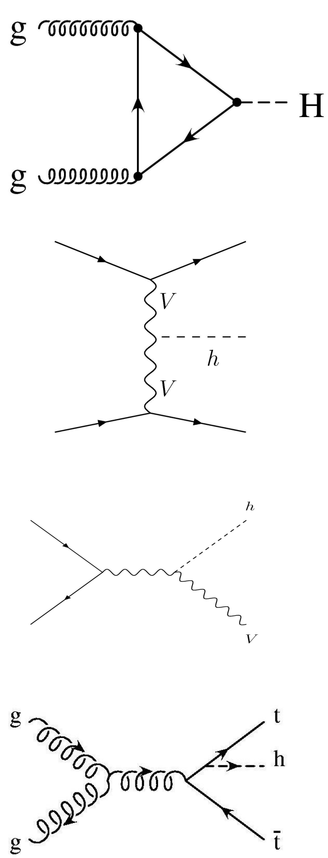


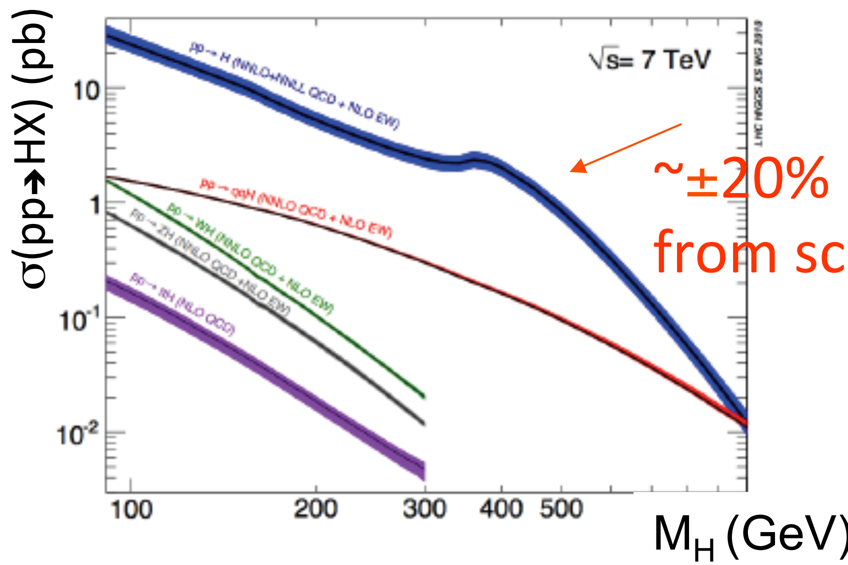
Important test of consistency of Standard Model

Higgs Theory

- Producing the Higgs
  - Tremendous advances in perturbative QCD
  - Signal vs background
- How do we know it's *the* Higgs?
  - Spin, couplings….
- What else could it be?
  - Huge number of possibilities

Higgs at the LHC



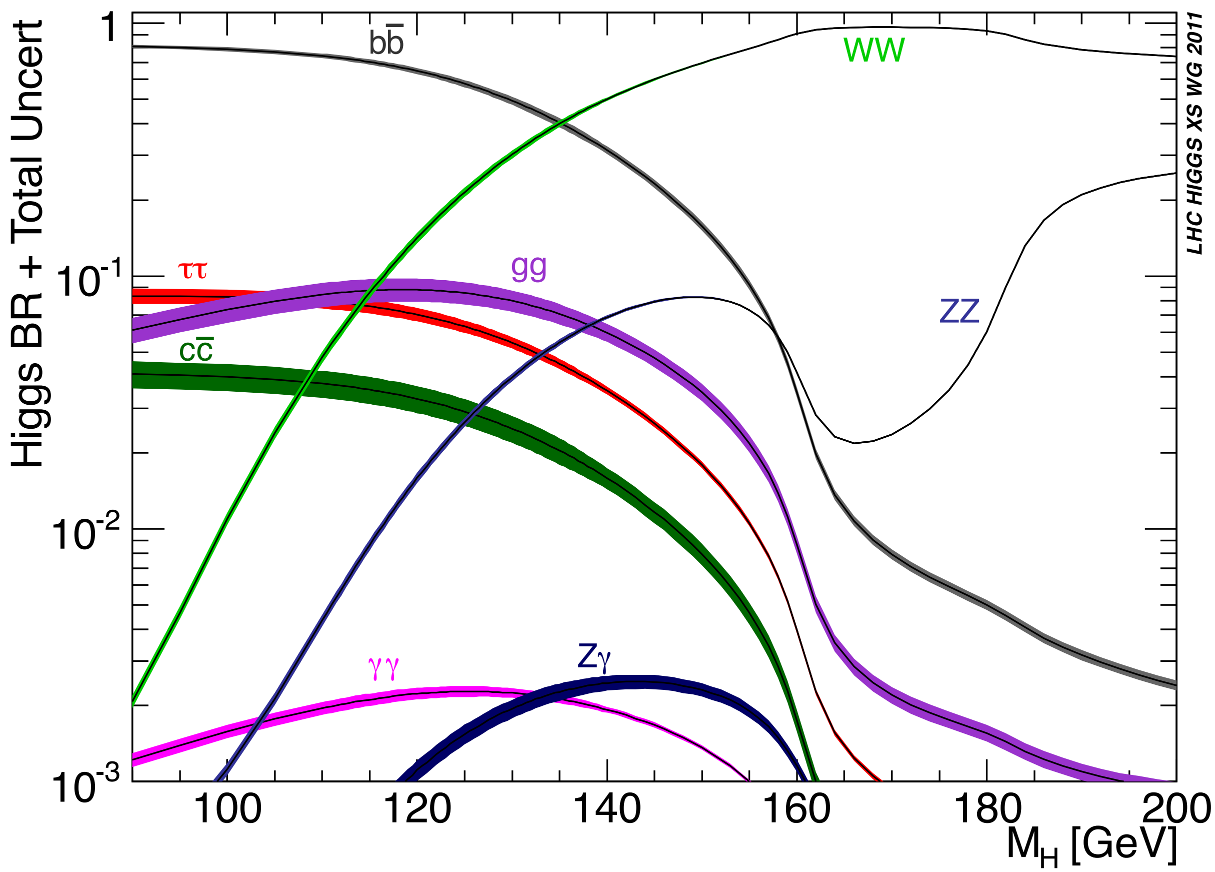


~±20% uncertainty from scale/PDFs

- Estimates of uncertainties
- Consistent calculation of rates

Theorists have nailed the total cross section

Small Uncertainties on Decays



Largest uncertainty is from b mass

$\delta\Gamma_{bb}$~3-4%

What Goes Into Predictions?

$$\sigma = \Sigma_{a,b} \int dx_a \int dx_b f_a(x_a, \mu_F) f_b(x_b, \mu_F) \hat{\sigma}_{ab}(x_a, x_b, \mu_R)$$

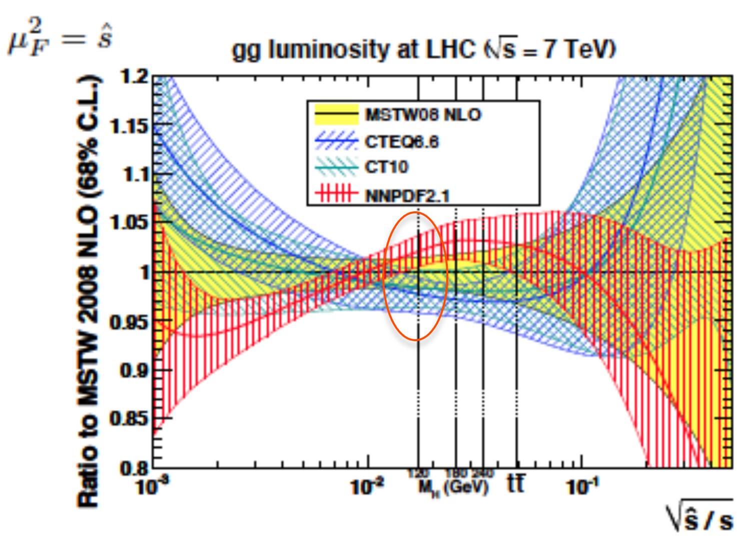
Non-perturbative:
Extracted from data
with theoretical input

Perturbative: Immense
theoretical effort

- All relevant SM cross sections known to at least NLO
- All relevant SM cross sections included in MCFM, POWHEG at NLO

PDFs and Higgs Predictions

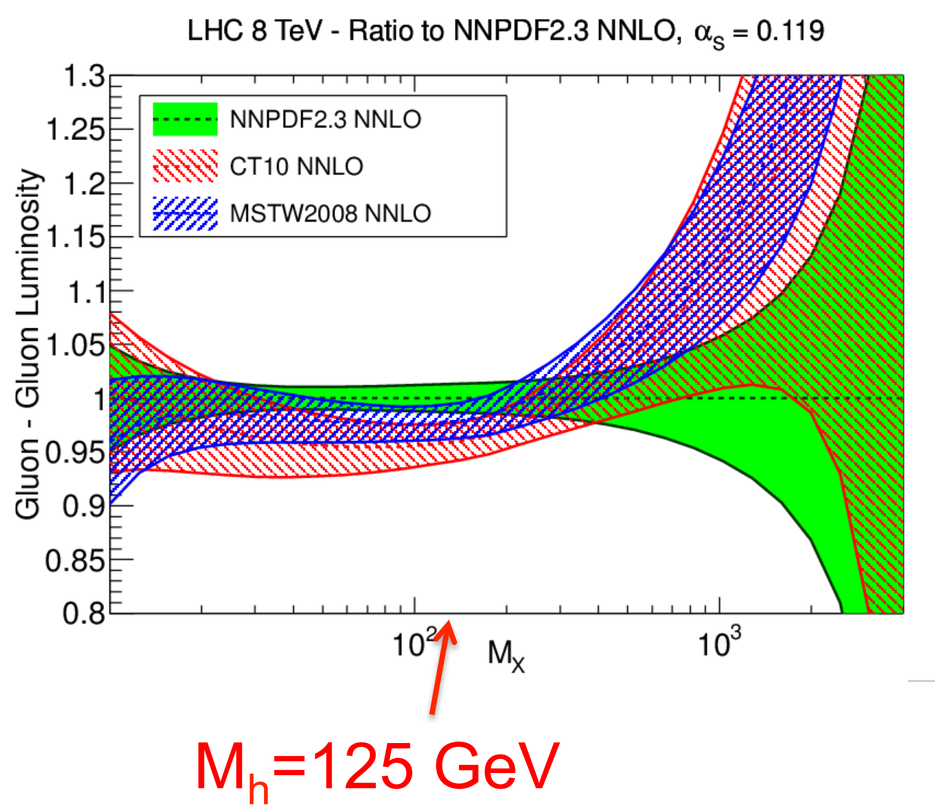
- MSTW, CT10, NNPDF are NNLO PDFs with global fit to data
  - Fits sensitive to Tevatron dijet data, but dijet calculation doesn't exist to NNLO
- Global fits in reasonable agreement but deviations sometimes as large as uncertainties



PDF4LHC: Take envelope of PDF 68% CL predictions

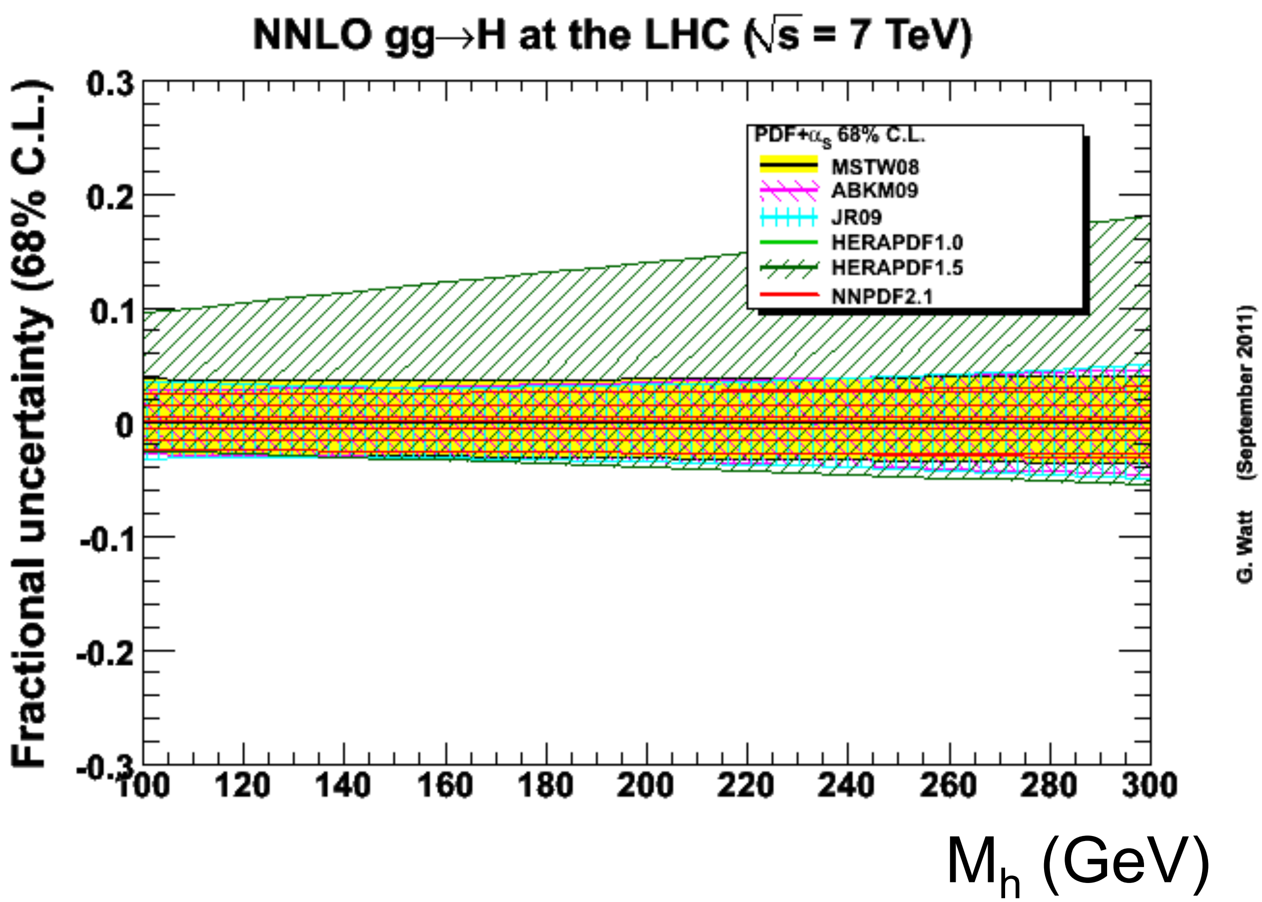
Dominant Higgs contribution is gg→h

- PDFs to NNLO
- NNPDFs, CT10, MSTW are global fits



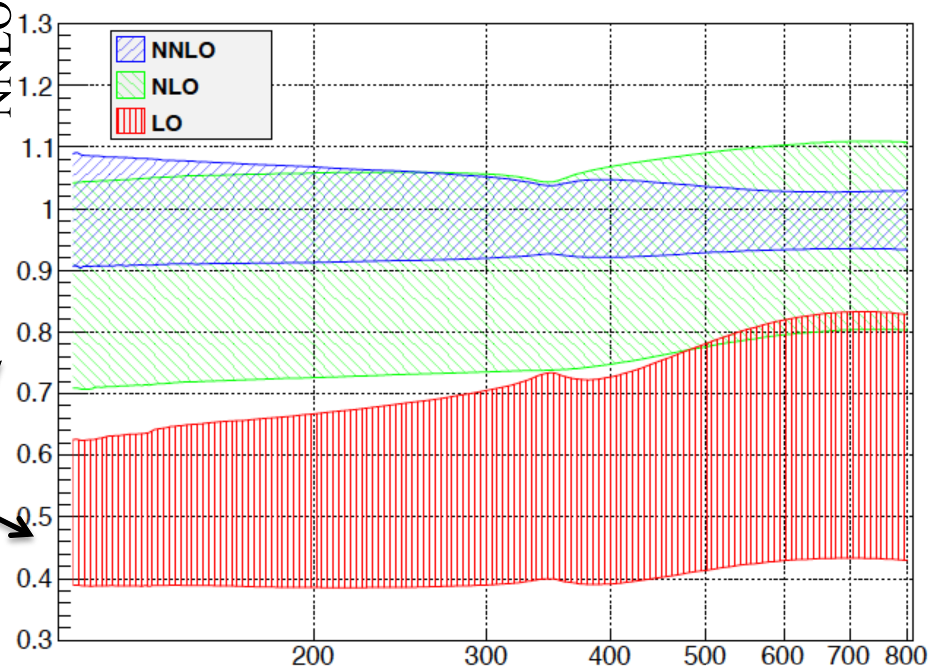
Differences between sets larger than PDF errors of a given set

PDF sets give (relatively) consistent NNLO predictions



Scale Dependence

- μ dependence would cancel in all orders result
- Scale variation can underestimate uncertainties



σ/σ_{NNLO}

M_H (GeV)

$\sqrt{s}$=8 TeV

$M_H/4<\mu<M_H$

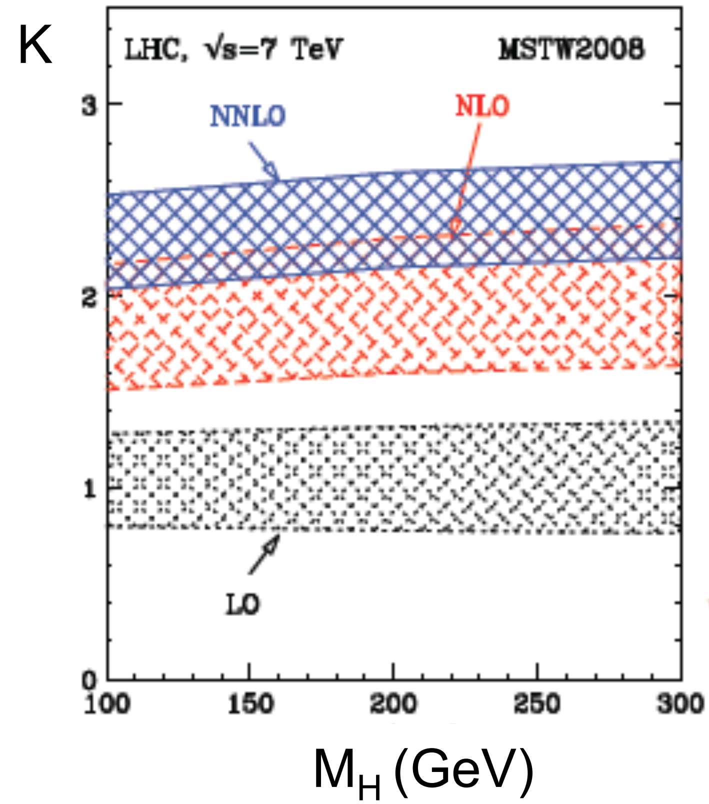
No overlap

[Anastasiou]

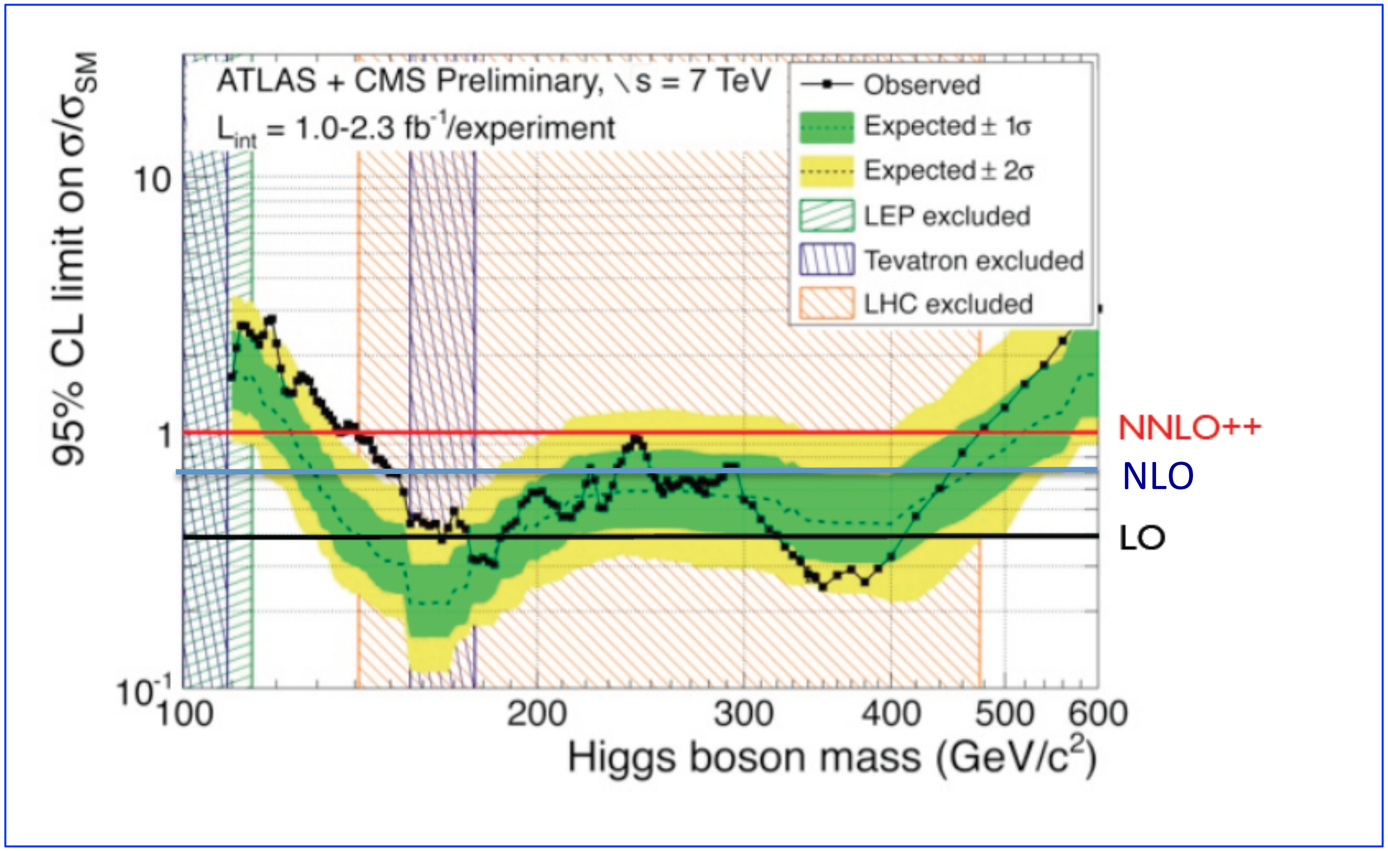
What Goes Into Predictions?

- Know pp→HX to NNLL
- Radiative corrections are large!
  - Also know EW corrections to 2-loops, mixed EW-QCD corrections
  - Publicly available exclusive NNLO and NNLL codes: FEHIP, HNNLO

$$pp \to HX$$



Discovery depends on radiative corrections



Bottom Line for Total Cross Section

At $\sqrt{s}$ = 7 TeV:

$$\sigma(M_H = 125\ GeV) = 15.31^{+11.7\%}_{-7.8\%}{}^{+7.8\%}_{-7.3\%}\ \text{pb}$$

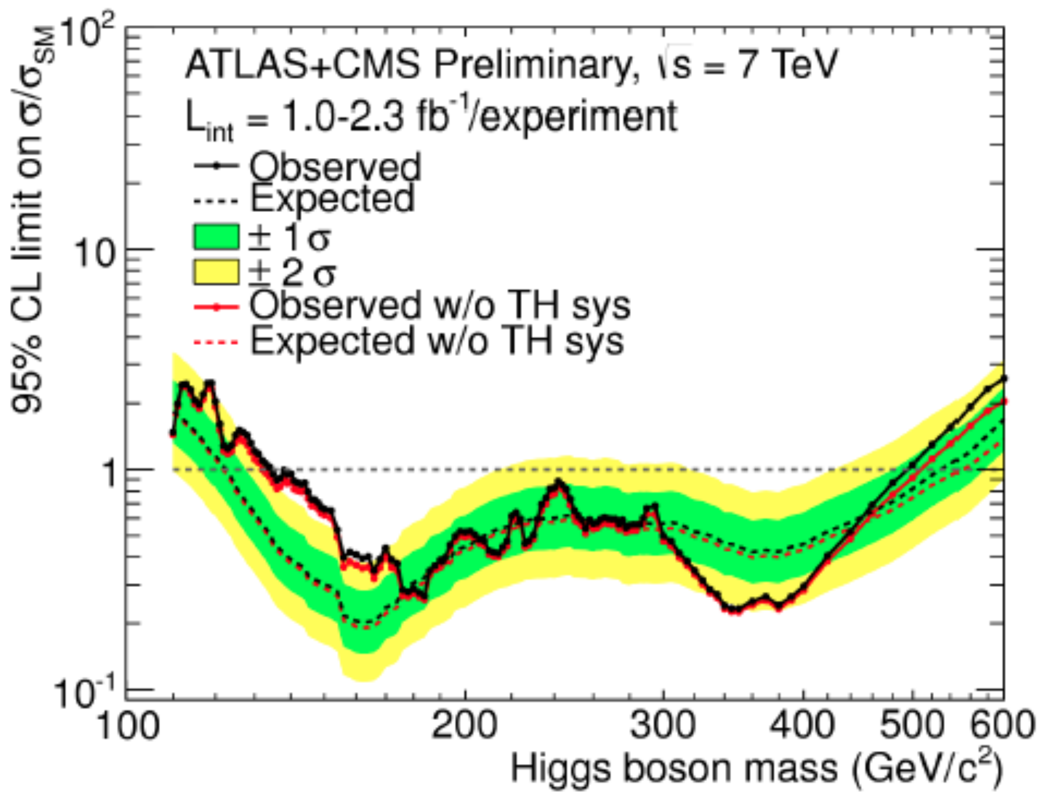
Scale   PDF + α_s

At $\sqrt{s}$ = 8 TeV:

$$\sigma = 19.52^{+7.2\%}_{-7.8\%}(scale)^{+7.5\%}_{-6.9\%}(PDF + \alpha_s)pb$$ deFlorian

$$\sigma = 20.69^{+8.4\%}_{-9.3\%}(scale)^{+7.8\%}_{-7.5\%}(PDF + \alpha_s)pb$$ Anastasiou

Are Theory Errors Relevant?



Exclusive Higgs Cross Sections

- Classify Higgs signal by number of jets
  - Require $p_T^{jet} < p_T^{cut}$
  - pp → H + 0 jets $\sigma_0 \pm \Delta_0$
  - pp → H + 1 jet $\sigma_1 \pm \Delta_1$
  - pp → H + 2 jets $\sigma_2 \pm \Delta_2$
- Backgrounds vary with number of jets
  - Optimize analysis for different jet bins
  - Example: H→WW +0 jets

p_T^{cut} introduces new uncertainties

Vetoing Jets

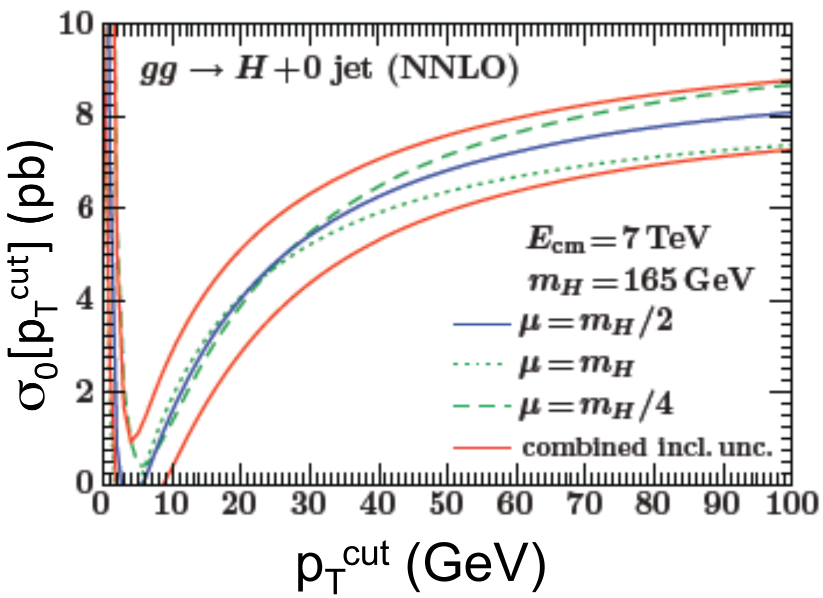
- Jet veto changes form of perturbation theory

$$\sigma(0\ Jet) = \sigma(p_T^{cut}) \sim \sigma_B \left(1 - (..)\alpha_s \ln^2 \frac{p_T^{cut}}{M_H} + \ldots\right)$$

- Logarithms can be large
- Varying scale in total cross sections underestimates scale uncertainties due to cancellations
- Better estimate: treat inclusive cross section errors as independent: $\Delta_{total},\ \Delta_{\geq 1}, \Delta_{\geq 2}$

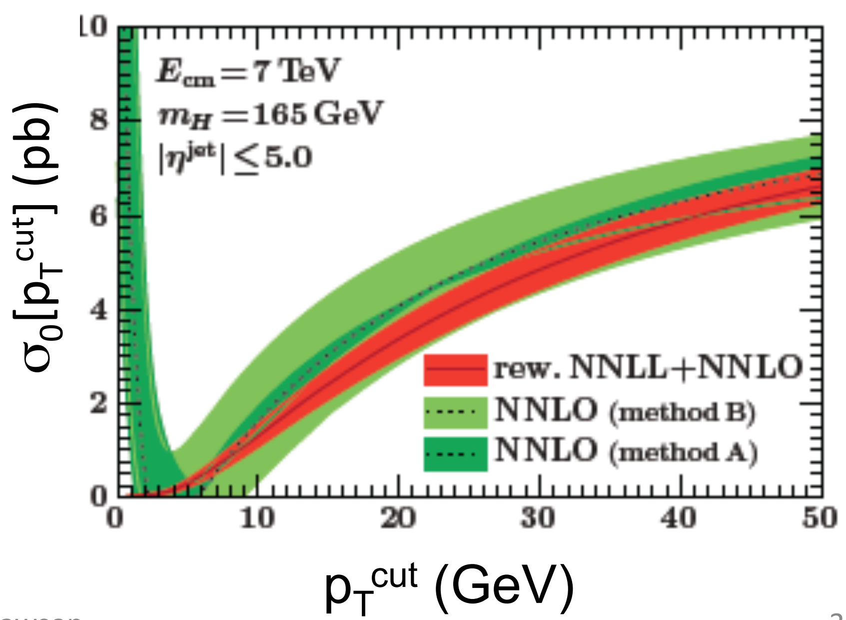
[Tackman, Stewart]

Fixed Order Predictions Have Large Uncertainties



FeHiP NNLO fixed order

NNLL resummation of $\text{Log}(p_T^{cut}/M_H)$



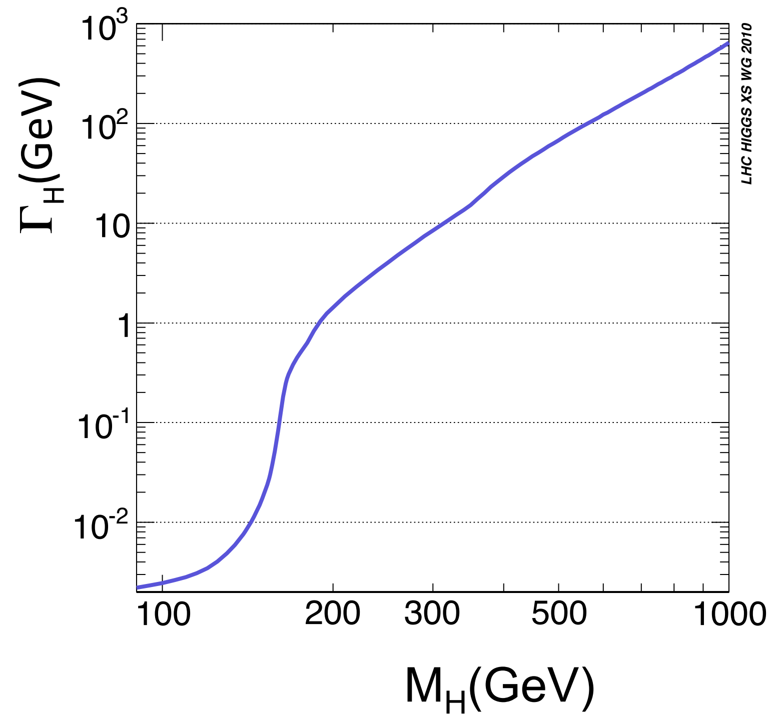
[Stewart, Tackman]

Separating Higgs from Background

- Light Higgs is narrow

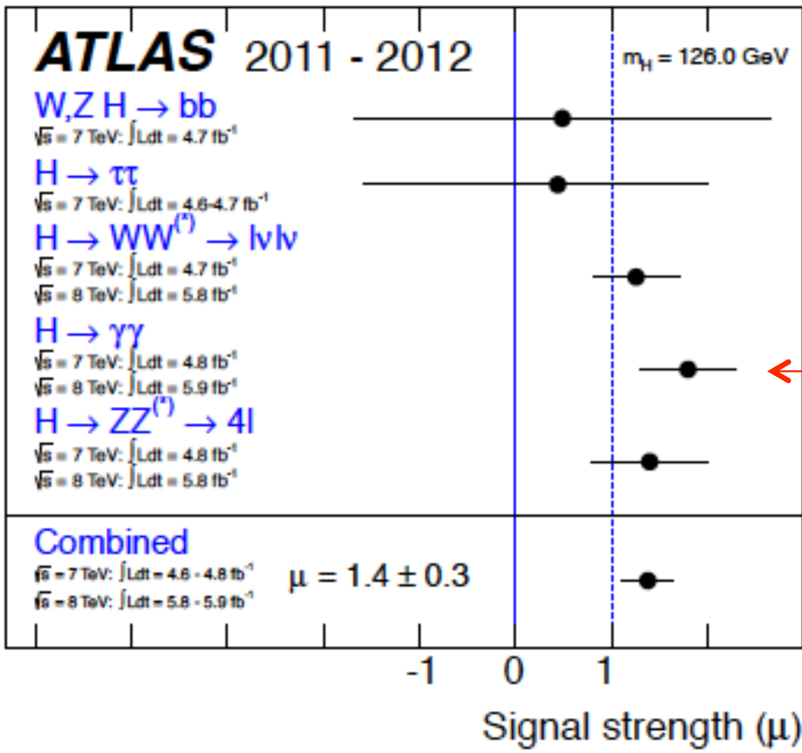
$$\sigma(pp \to H \to Z) = \sigma(pp \to H) \cdot BR(H \to X)$$

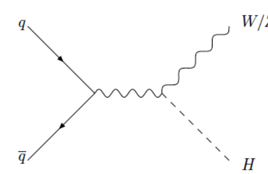
- Interference effects can be important for heavy Higgs, where Γ_H/M_H not small
- Interference effects small for light Higgs in ZZ and $\gamma\gamma$ channels due to excellent mass resolution

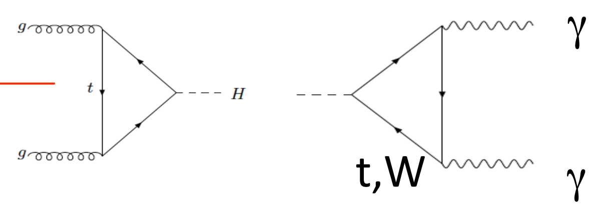


Higgs Candidate looks SM-like

- SM hypothesis μ=1





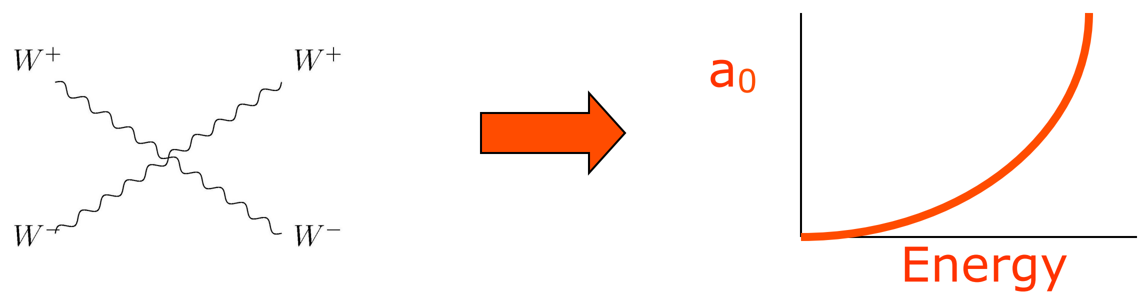


[ATLAS, arXiv:1207.7214]

Why are Coupling Measurements Important?

- Massive W and Z's have longitudinal polarizations
- Longitudinal interactions spoil nice properties of gauge theories:
  - Loops are not finite without Higgs

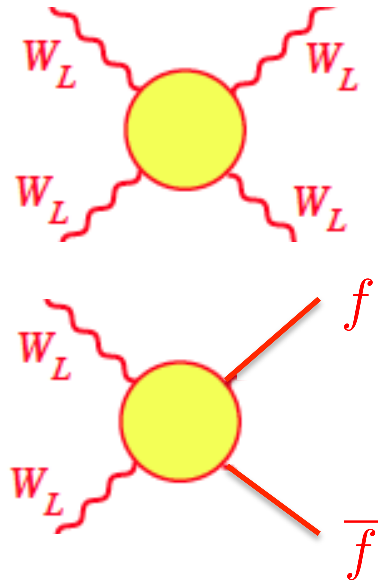
  - Scattering amplitudes grow with energy



Higgs Couplings are a Prediction

WW scattering violates unitarity unless:

$$hWW: \quad gM_W$$
$$hZZ: \quad \frac{gM_Z}{cos\theta_W}$$
$$hf\overline{f}: \quad \frac{gm_f}{2M_W}$$



Cross sections grow with energy unless Higgs couplings have EXACTLY these values!

Approaches to studying couplings

- Assume there are no new particles below the TeV scale and use effective Lagrangian approaches
  - Approach is sensitive to how many parameters you allow to vary from Standard Model values
- Build a model with new particles and see what the effects are
  - MSSM is the most popular example
- (This assumes only one Higgs and that it's not composite)

Parameterize deviations from SM

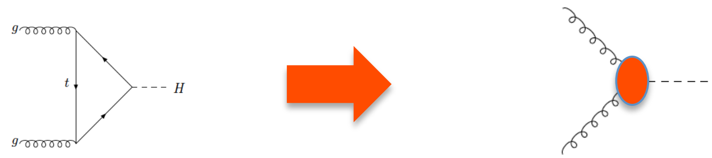
- Many possible parameterizations (only some terms shown here)

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

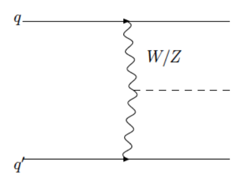
- In Standard Model, $c_V=c_t=c_b=1$, $c_{\gamma\gamma}=c_{gg}=0$
- No FCNC in Higgs sector parameterization
- No isospin violation in Higgs sector parameterization
- Assume no new light states

Start Simply:

- Production:
  - Gluon Fusion



  - Rescale quark Yukawas: $c_F \frac{m_t}{v} \bar{t} t h$
  - VBF
  - Rescale W Yukawa:



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

$$c_V g M_W W^{+\mu} W_\nu^- h$$

(Don't violate isospin)

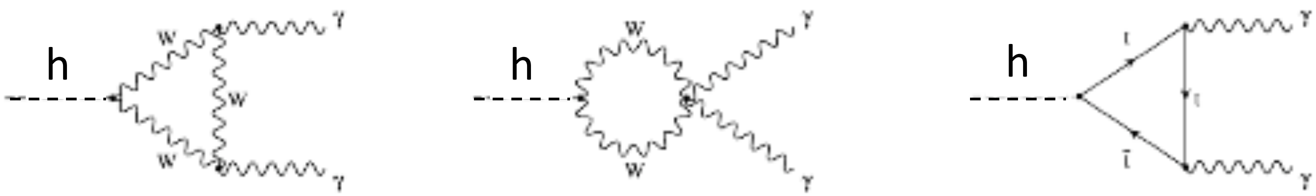
Higgs Decays to Photons

- 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



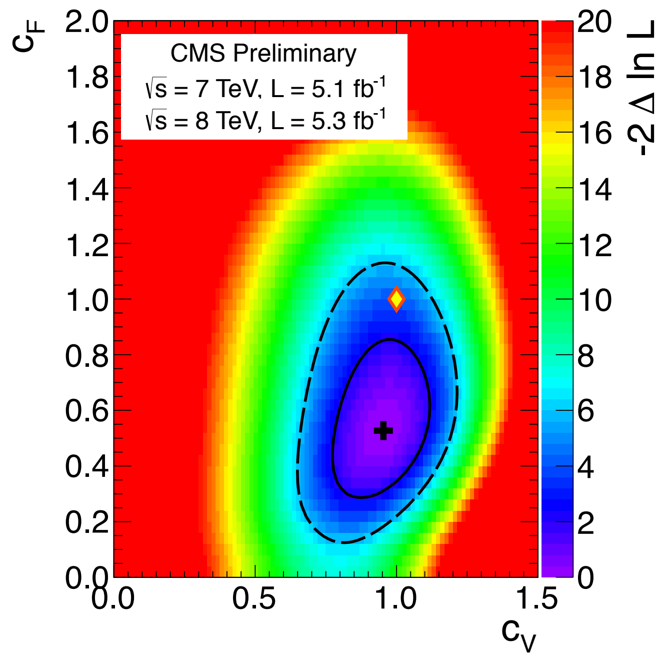
Suppose we want to enhance h $\rightarrow \gamma\gamma$?

- 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

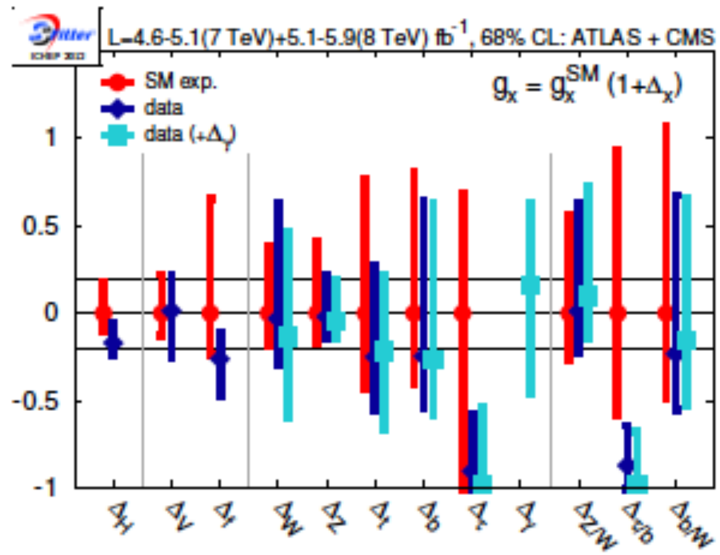


Fitting Higgs Couplings

- Assume SM with couplings rescaled*

$$g_{xxH} = (1+\Delta_x)g_{xxh}^{SM}$$

- Use current data to fit couplings
- Standard Model good fit to data
- Consistent secondary fit with large t & b Yukawa couplings

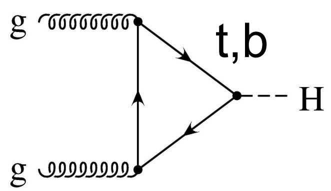


* This plot: no new particles, no new interactions

[Plehn,Rausch]

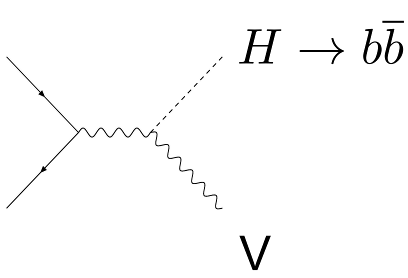
Higgs-Fermion Couplings

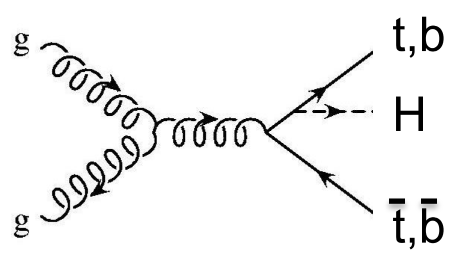
- Gluon fusion indirectly sensitive to t-b couplings



Negative interference between b-t loops for moderate b Yukawas

- Need to measure bbH, ttH couplings directly
- bbH enhanced in many BSM models

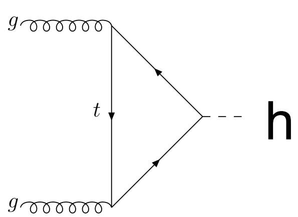


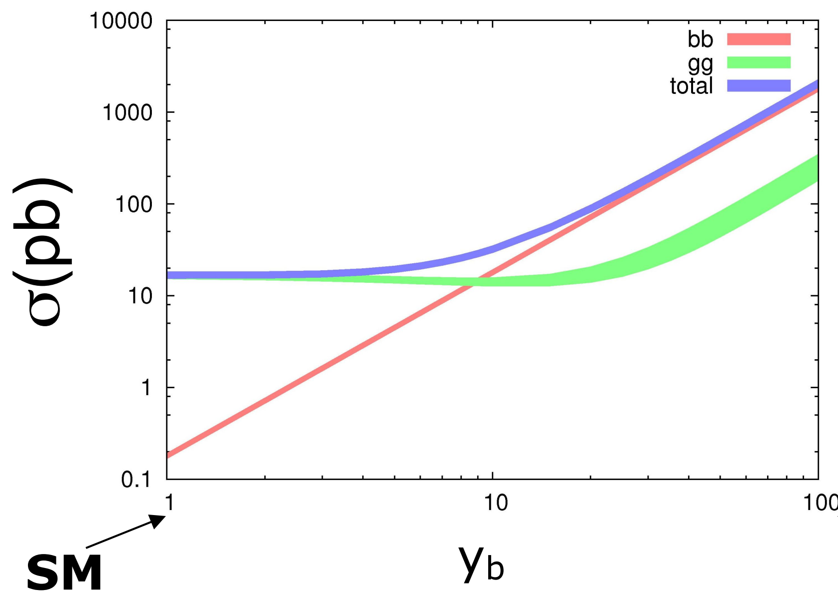


The Role of b-loops

Gluon fusion rate mostly depends on top yukawa

b loops are ~5% of SM gg→h





SM

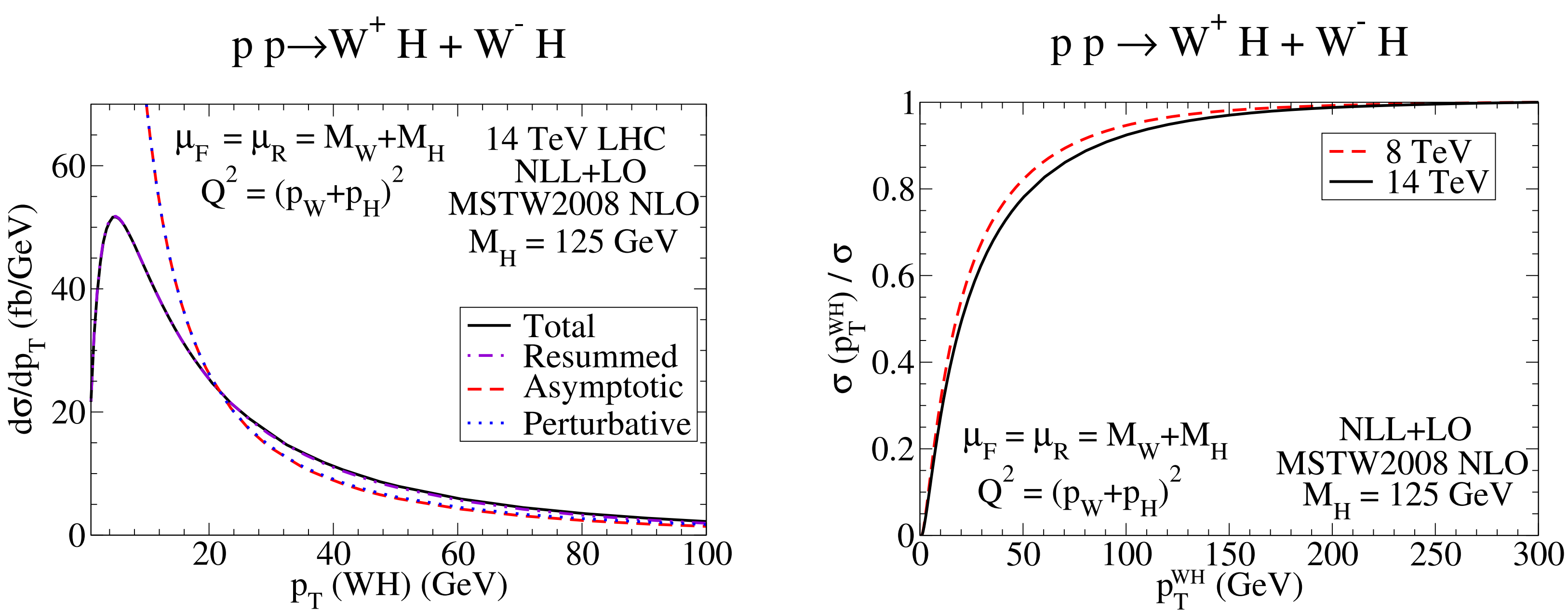
M_h=120 GeV
$\sqrt{s}$=7 TeV

gg “only” NLO

[Anastasiou, Buehler, Herzog, Lazopoulos]

Measure b-Higgs coupling

- WH production, followed by $H \to b\bar{b}$
  - Resum large logarithms
- Jet veto effects large



[Dawson, Lewis et al]

Can Higgs Couplings Tell us about EWSB?

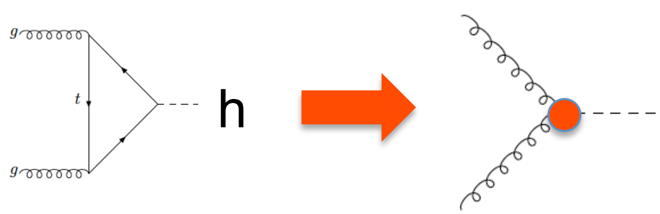
- Standard Model has chiral fermions
  - Left and right handed fermions transform differently, so Dirac mass term not allowed
  - Doesn't have to be this way in more complicated theories
- In heavy top quark mass limit, Higgs cross section is independent of fermion mass
  - Approximation extremely accurate (~2%)
  - This approximation used to calculate NNLO rate

Gluon Fusion

- Heavy fermions give mass independent contribution to gluon fusion……*no decoupling*
- This statement tests source of fermion mass from Yukawa

$$L_t = -\frac{m_t}{v}\bar{t}t\left(h + v\right)$$

- ggh described by effective Lagrangian (which can be used for higher order corrections)



$$L_{eff} = \frac{\alpha_s}{12\pi v} G^A_{\mu\nu} G^{A\mu\nu} h$$

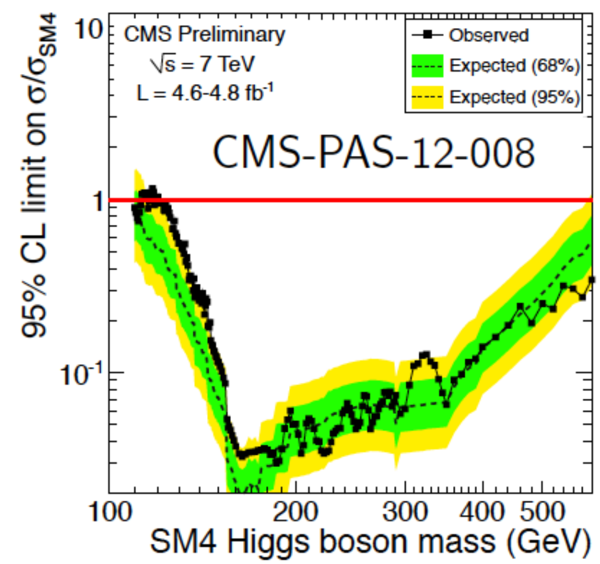
What if there were a SM 4th generation?

- Each fermion would contribute the same to gg→h: t, T, B (in heavy fermion limit)

$$\sigma \rightarrow \sigma_{SM}(1+1+1)^2 \rightarrow 9\sigma_{SM}$$

Important: Contribution from chiral fermions roughly independent of fermion mass

SM 4th generation is ruled out by Higgs observation!



Simple Example: New Charge 2/3 Quark

- Add SU(2) singlet, charge 2/3 quark, U
  - No charge -1/3 quark for now to avoid Z→bb constraints
- ***Motivated by top-color, top-seesaw models, little Higgs….***
- SM fields: $q_L=(u_L,b_L)$, u_R, b_R
- SM Lagrangian:

$$L_{SM} = -y_u \bar{q}_L \tilde{H} u_R - y_d \bar{q}_L H b_R + hc$$

- New contributions:

$$L_{NEW} = -y_u' \bar{q}_L \tilde{H} U_R - M \bar{U}_L U_R + hc$$

U is vector-like

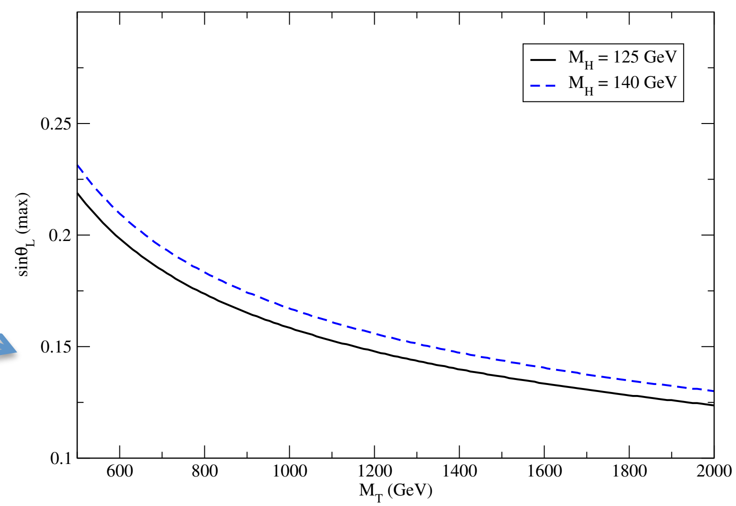
Dirac Mass

Vector-like Quarks in General

- Contributions to precision observables decouple
  - Significant contributions when new quark is allowed to mix with third generation

95 % CL Upper Limit from STU

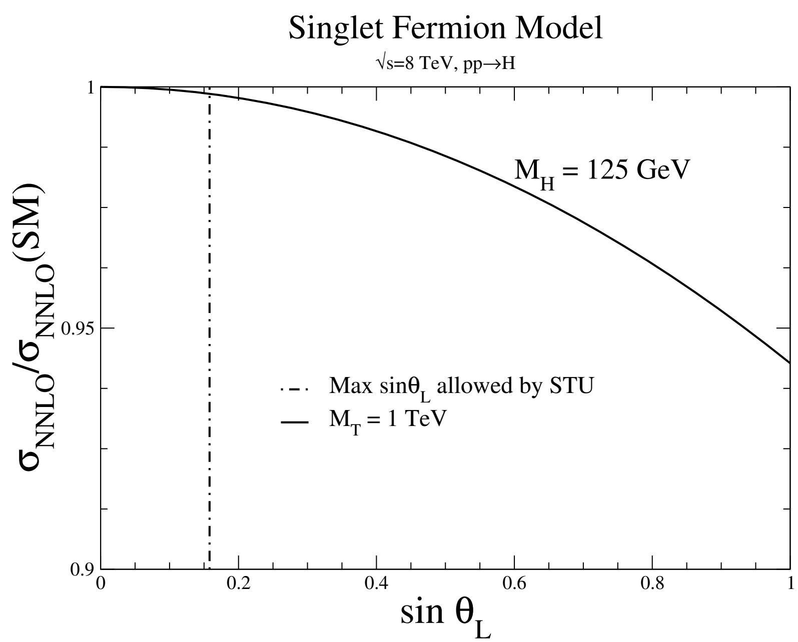
Mixing with SM top must be small



Decoupling

Top Partners, continued

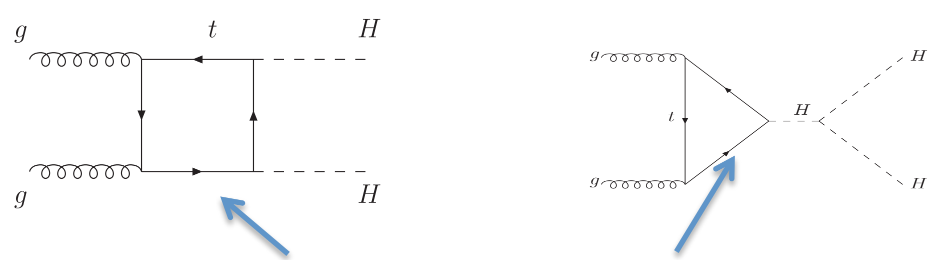
- New top partner mixes with Standard Model top
- Parameters restricted by EW precision measurements
- ***Higgs production looks just like Standard Model***
- General feature with vector fermions



[Dawson, Furlan]

More complicated Models

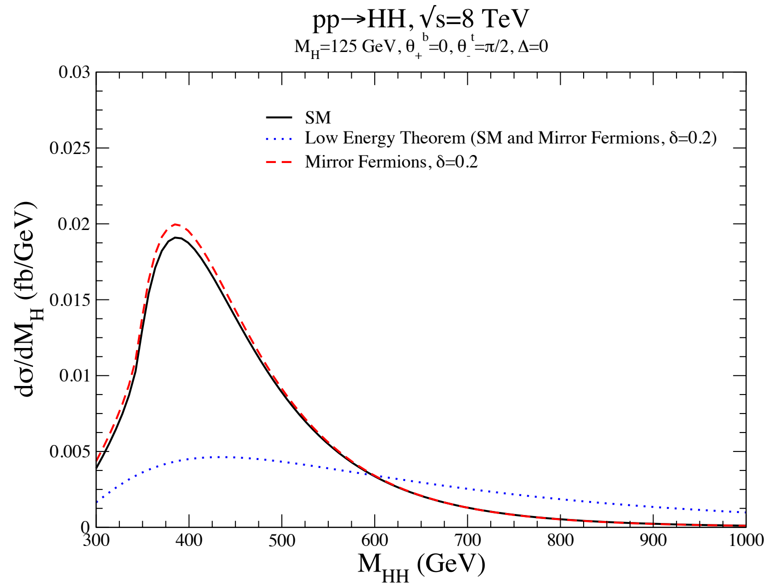
- Models with heavy fermions restricted by:
  - Precision electroweak measurements
  - Higgs production rate is approximately SM
- Could we have 2 Higgs production much different from SM rate?
  - In SM, σ_{HH} ~ 18 fb ➡ this is 300 fb^{-1} physics
  - Look for $HH \to b\bar{b}\gamma\gamma$



Influenced by new fermions

2 Higgs Production

- Simple models, get approximately SM rate
- Large 2 Higgs rate could be smoking gun for composite Higgs models (which have new contributions)



Require parameters to give SM single H production rate

[Dawson, Furlan, Lewis]

Conclusions

- Immense theoretical effort on cross sections
  - Still work to be done understanding effects of jet vetoes
- Measuring Higgs couplings is next frontier
- Many models look just like Standard Model as far as Higgs production goes
  - Question for ILC proponents: How well do we need to measure couplings?