Theory Summary Talk-- The Next Stretch of the Higgs Magnificent Mile

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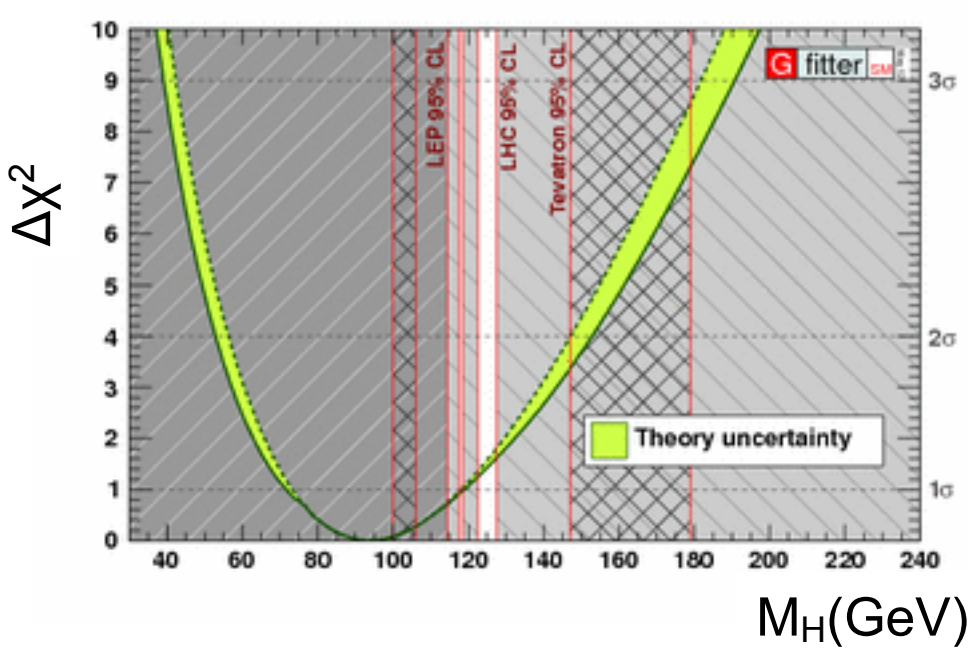
May 16, 2012

Higgs Theory

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

We Want to Believe!

M_H inferred from precision measurements



SM Higgs boson wants to be light

* GFITTER, May 2012

Minimal Higgs theory is predictive

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

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

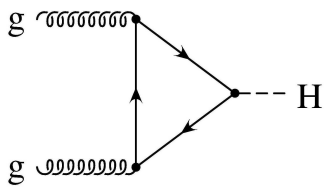
- Higgs couples to gauge boson masses

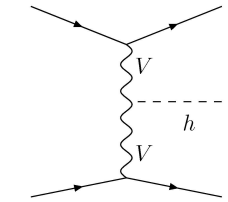
$$L = gM_W W^{+\mu} W_\mu^{-} H + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu H + ...$$

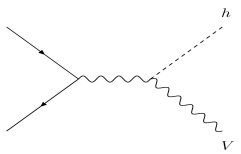
- Only free parameter is Higgs mass

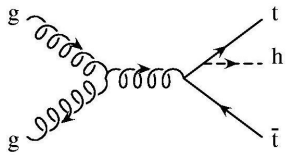
Testable Theory

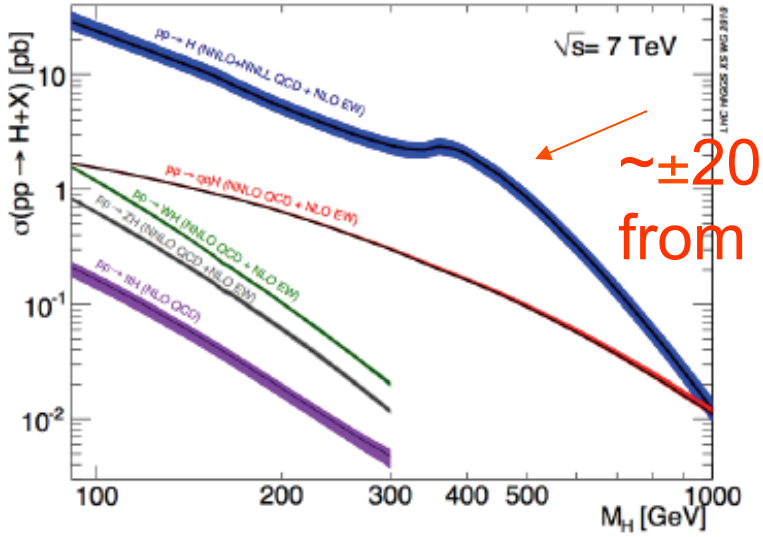
Higgs at the LHC











~±20% uncertainty from scale/PDFs

Estimates of uncertainties
Consistent calculation of rates

Largest uncertainties on gluon initiated processes

Theorists have nailed the total cross section

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

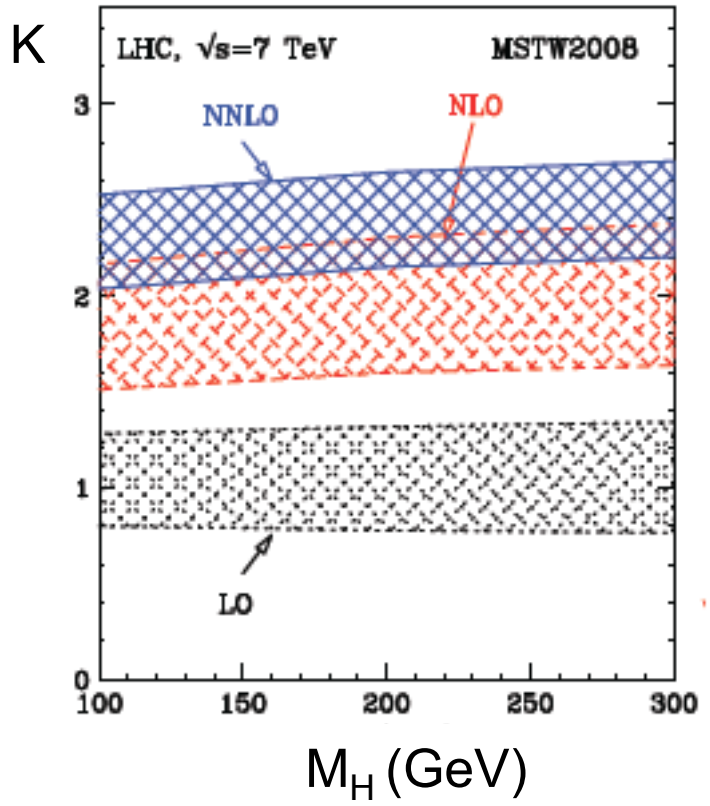
Perturbative: Immense theoretical effort

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

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

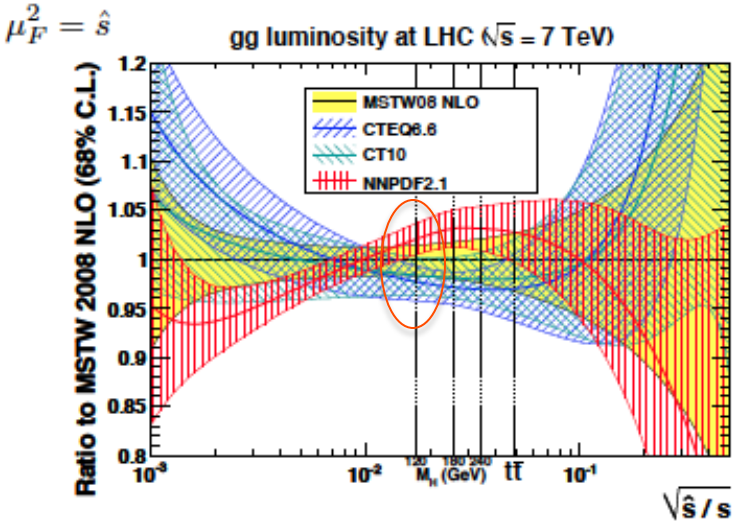
$$pp \to HX$$



[de Florian]

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

[de Florian]

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

How to include theoretical uncertainties?

* LHC Higgs cross section working group calculations extensively used by experimentalists

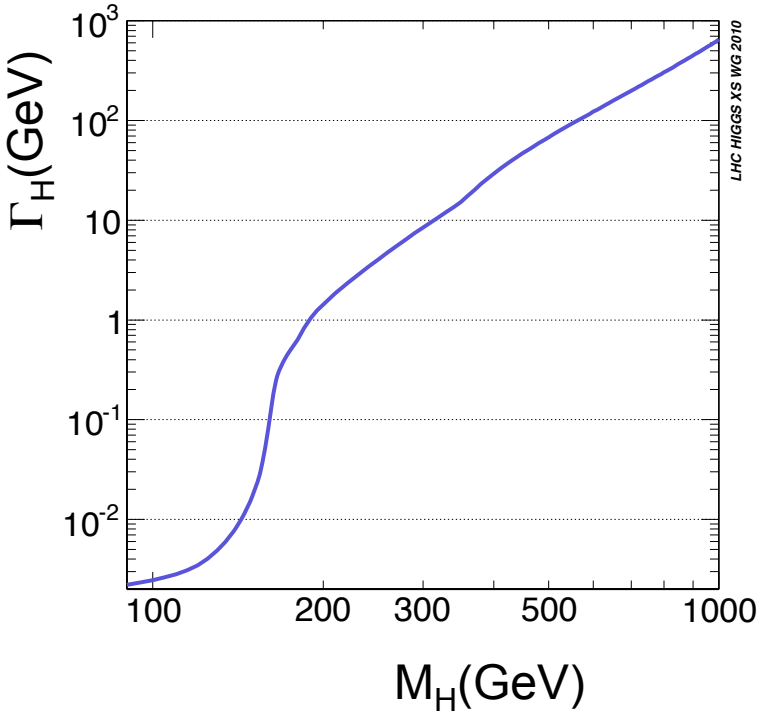
[de Florian]

Separating Higgs from Background

- Light Higgs is narrow

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

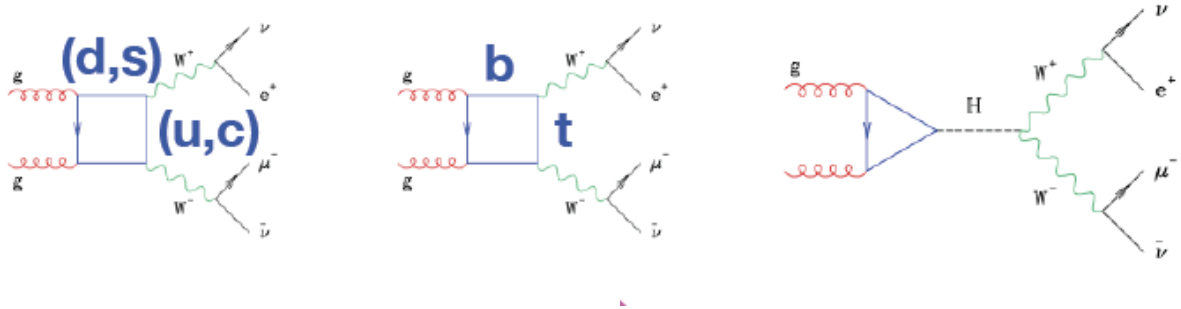
- Interference effects can be important for heavy Higgs, where Γ_H/M_H not small
- Interference effects small for light Higgs in ZZ and $\gamma\gamma$ channels due to excellent mass resolution

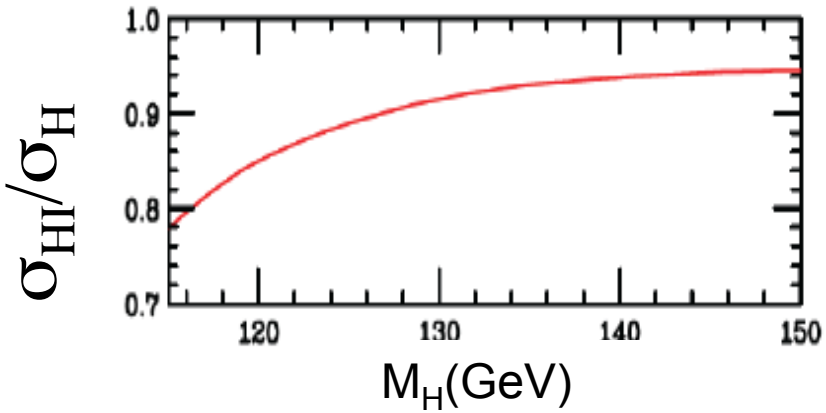


[Ellis]

H to WW Production

- Poor mass resolution in WW channel
- Signal and background interfere



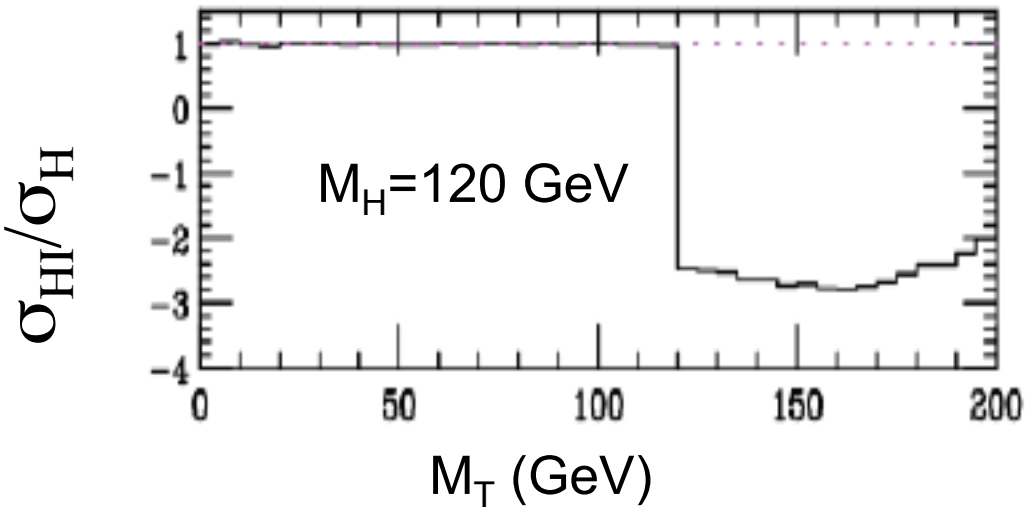


Interference effects around -10%

[Ellis]

Interference Effects in H→WW

- Interference effects can be reduced with M_T cuts
- Cut increases signal!



ATLAS cuts include .75 $M_H < M_T < M_H$

[Ellis]

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

[Stewart]

Vetoing Jets

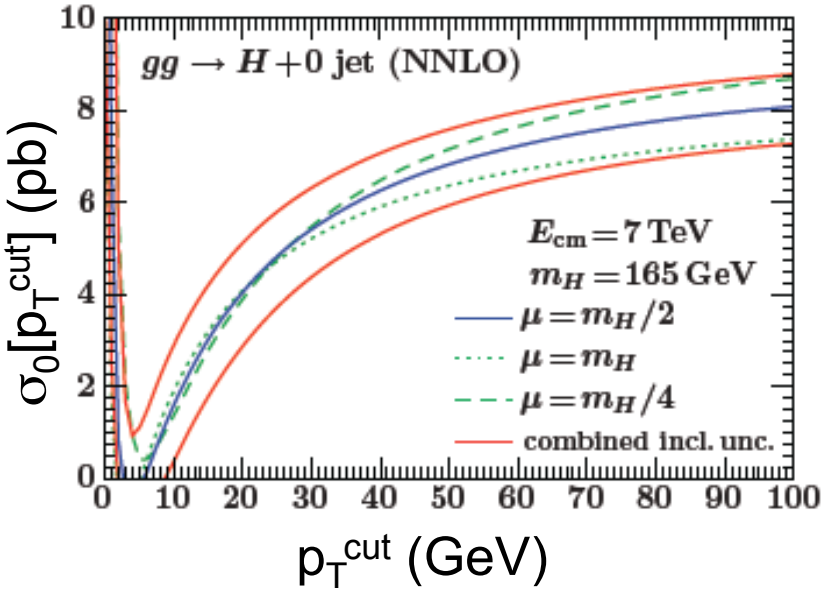
- Jet veto changes form of perturbation theory

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

- 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: $\Delta_{total},\ \Delta_{\geq 1}, \Delta_{\geq 2}$

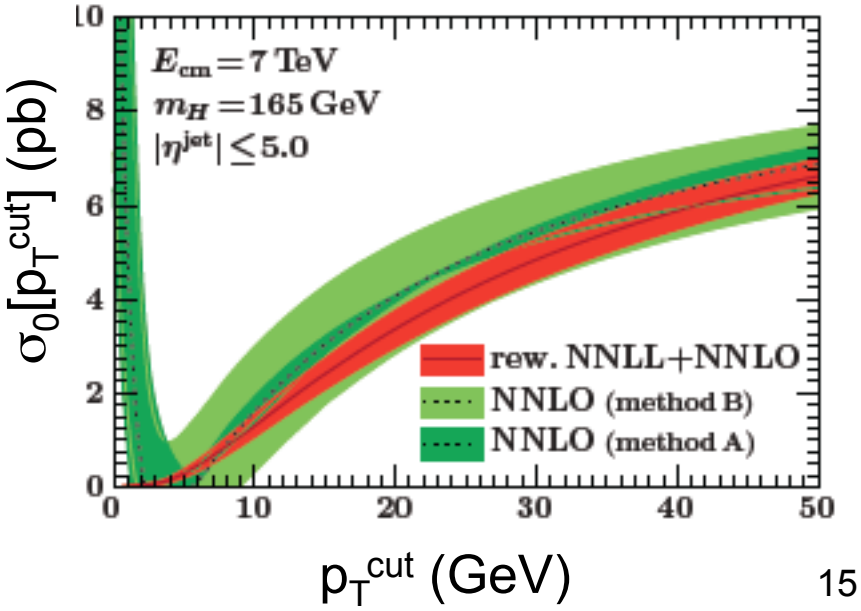
[Stewart]

Fixed Order Predictions Have Large Uncertainties



FeHiP NNLO fixed order

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

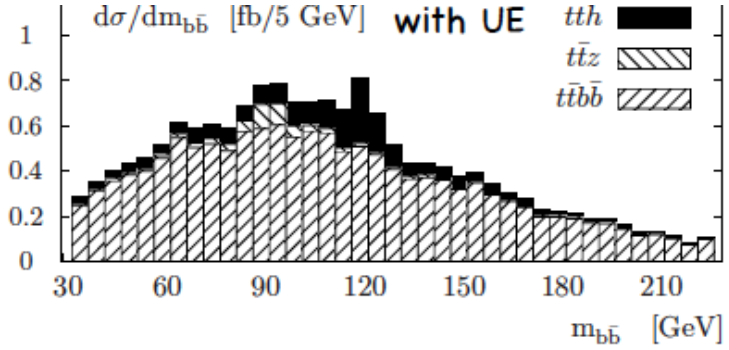


[Stewart]

New Techniques for Higgs Discovery

- Many techniques for studying jet substructure and boosted Higgs
- New physics typically manifests itself at large p_T
  - Classic example: VH, H➔bb
  - ttH
  - H➔aa➔gggg
  - SUSY cascades➔Higgs

5σ with 100 fb^{-1}



[Spannowsky]

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

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

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:

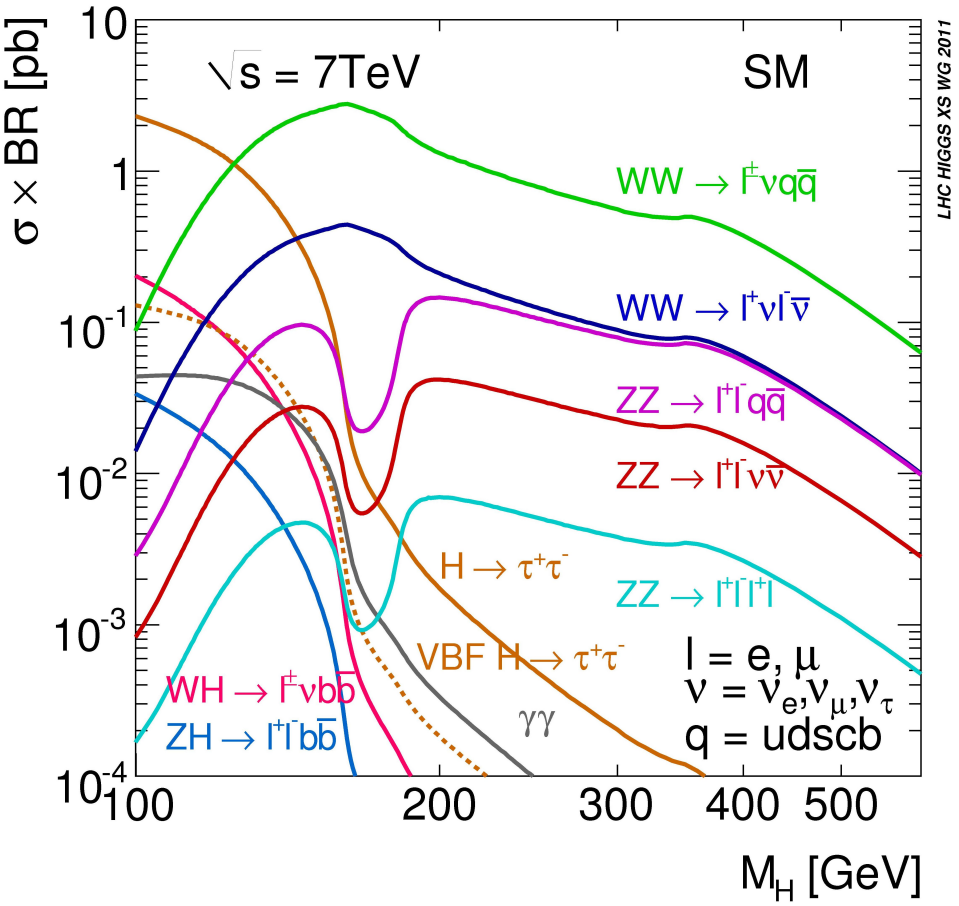
$$B\sigma(pp \to H \to X) = \sigma(pp \to H)BR(H \to X)$$

- Limits tell us that if M_H > 127 GeV:

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

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

We Measure $\sigma \cdot B$



- Largest production channel, gg→H, can have contributions from unknown new physics in loop
- Couplings could be different from SM

We don't really know much

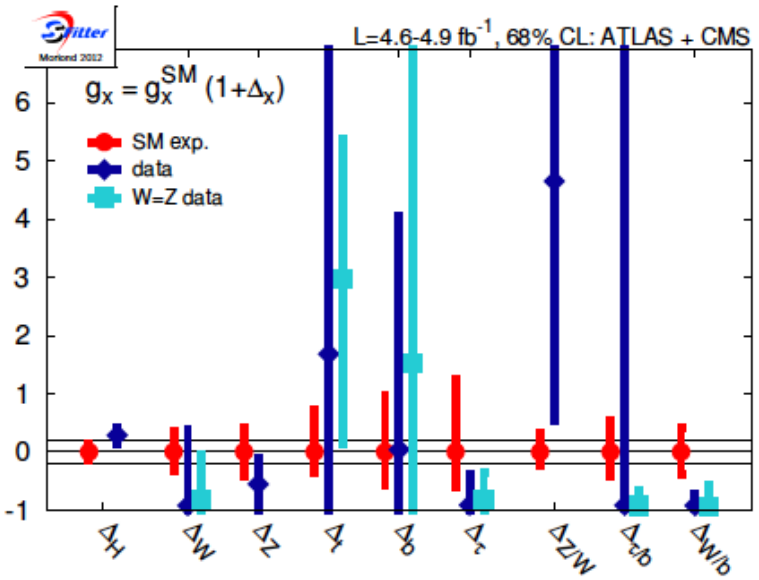
- Lots of possibilities for EWSB
- Could be rescaling of "SM-like" interactions
  - Fit data to effective Lagrangians [Rauch]
- Could be new interactions
  - Example: Composite Higgs [Grojean]
- Could be invisible or non-standard decays [Wang]
- Could be rich non-SM Higgs sector [Sher, Logan]
- Could be new particles in loops
- Is light Higgs consistent with SUSY? [Carena]

Fitting Higgs Couplings

- Assume SM with couplings rescaled

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

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



[Rausch]

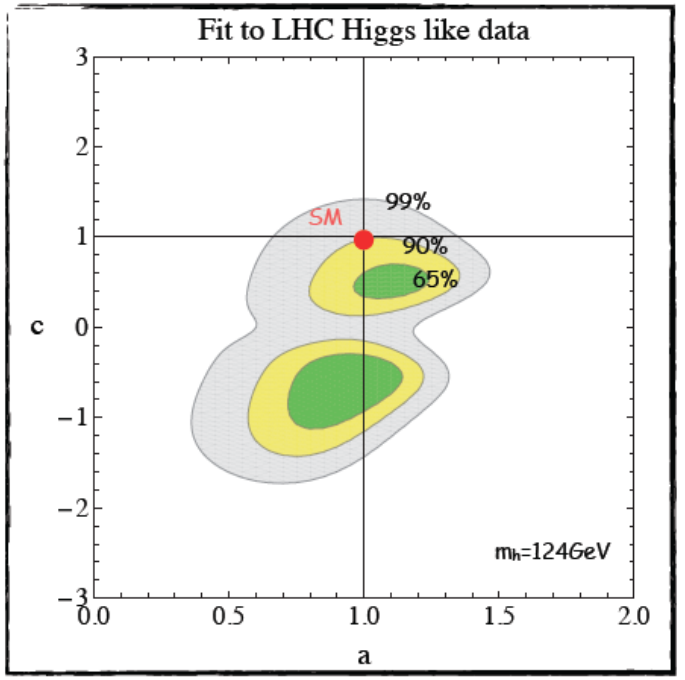
General Model of Symmetry Breaking

- Electroweak symmetry breaking gives 3 Goldstone Bosons (longitudinal components of W,Z)
- Couple scalar to Goldstone Bosons using effective Lagrangian
  - Symmetry breaking scenario defines theory
  - Scalar assumed to come from some strongly interacting sector
- Scalar sector described by 2 parameters: a, c
  - a describes scalar couplings to Goldstone Bosons
  - c describes scalar couplings to fermions
  - Electroweak fits constrain parameters to be close to Standard Model values

[Grojean]

General Model of Symmetry Breaking

- Rescale Higgs searches in terms of general model
- Solution with negative coupling to fermions to increase H➔γγ
- Many theoretical efforts to extract Higgs couplings from current data in various models

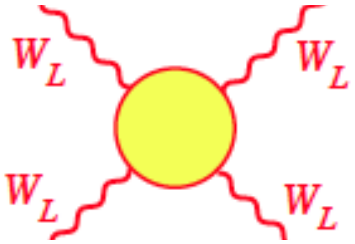


[Grojean]

General Interactions of Longitudinal W's

- Scattering amplitude sensitive to source of EWSB

$$\frac{\sigma(W_L^+W_L^- \to W_L^+W_L^-)}{\sigma(W_L^+W_L^- \to Z_LZ_L)} = \begin{cases} \sim 2 & \text{scalar } H \\ >> 1 & \text{vector } \rho \\ \sim \frac{2}{3} & \text{Higgsless} \end{cases}$$



- Measure W_LW_L scattering in VBF
  - Searching for TeV scale physics with small deviations from SM
  - Need highest possible energy
  - Perhaps boosted techniques can help

[Han]

MSSM is a Favorite Model

- MSSM predicts light Higgs boson
- To get M_H=125 GeV, need large mixing in stop sector
  - A_t > 1 TeV
  - No lower bound on stop mass
- Allowed parameter space gives slight suppression in gg→H→γγ rate
- To enhance di-photon rate add light staus with large mixing

Measurement of Higgs mass, rate and couplings will restrict MSSM parameters

[Carena]

Could be Multiple Higgs (without SUSY)

- Simple possibility is 2 Higgs doublet model: h, H, A
  - Cannot suppress both VVh and VVH couplings
  - 140 GeV < M_h, M_H < 500 GeV excluded by SM Higgs exclusion
- Stringent restrictions on possible Higgs couplings from LEP
  - If 125 GeV putative signal is lightest h of 2HDM, then definitive predictions for decays
- Could the putative signal be heavy H?
  - Requires h to have evaded discovery through H→hh

Testable

[Sher]

Dilaton versus SM Higgs?

- Properties of dilaton model defined by dilaton mass and scale parameter, f

- Predictions:

  Large enhancement of gluon fusion rate

  Dilaton wouldn't be seen in VBF

$$\frac{BR(dilaton \to \gamma\gamma)}{BR(dilaton \to ZZ)} \sim 2.4\ SM$$

Can be excluded with definitive VBF signal

[Logan]

Higgs can decay to non-SM Particles

- Many possibilities!
  - Higgs decays to dark matter
  - Higgs decays to light pseudoscalars
  - Higgs decays to aa → gggg
  - Higgs decays to "lepton jets"
  - …….
- Important to look for non-standard signatures
- Hard to exclude many of these possibilities

[Wang]

What's Next for Theorists?

- Lots of QCD
  - Need exclusive reactions to higher order
  - Need background processes to higher order
  - Need interfaces with shower Monte Carlos for all this
- How can we tell it's the Higgs and not the decoupling limit of some high energy theory? [Haber]
  - Spin, couplings, non-standard signatures and particles….

Conclusions

Thanks to the organizers!