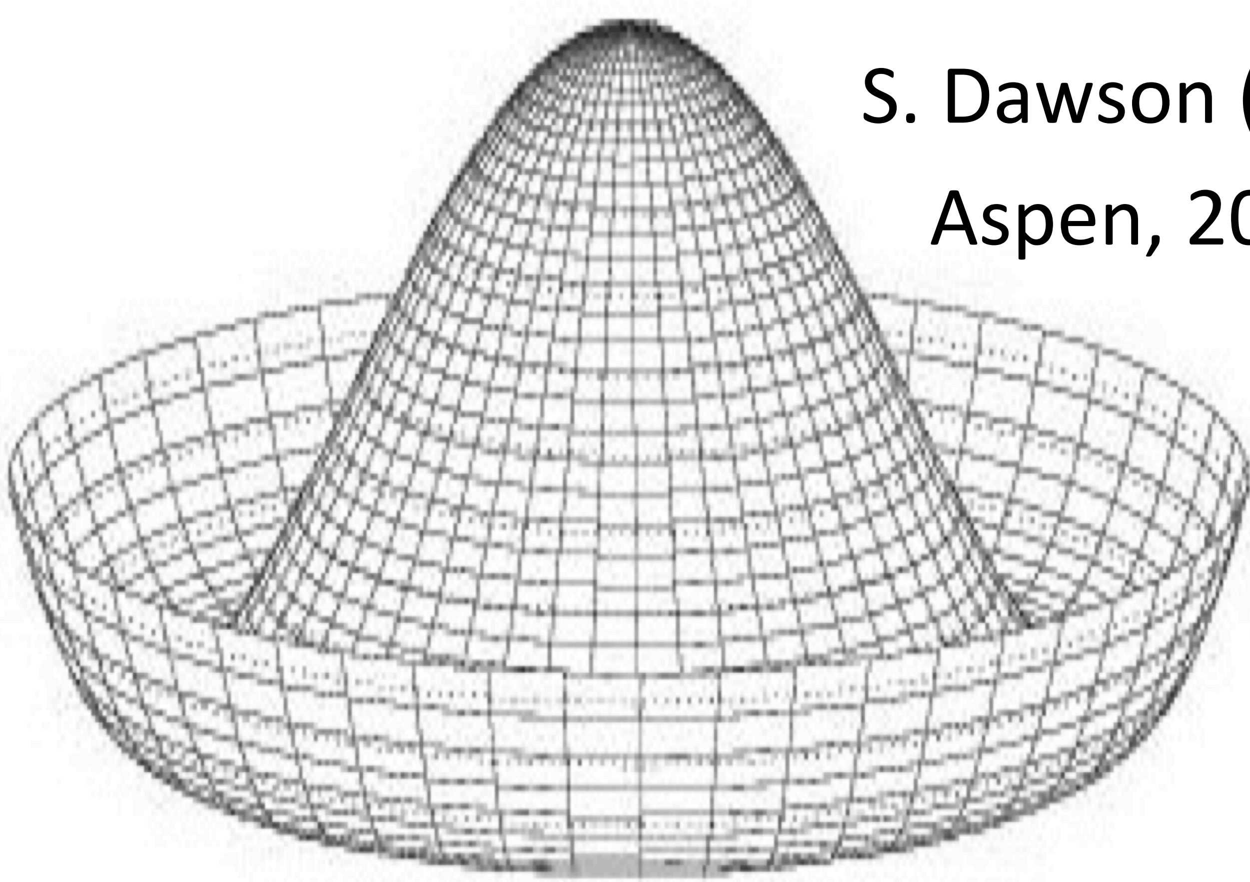
The Higgs Going Forward



S. Dawson (BNL)

Aspen, 2015

SM Very Predictive

- Very precise predictions
  - Couplings to fermions proportional to mass $\frac{m_f}{v} h \overline{f} f$
  - Couplings to massive gauge bosons proportional to (mass)^2

$$2m_W^2 \frac{h}{v} W_\mu^+ W^{-\mu} + m_Z^2 \frac{h}{v} Z_\mu Z^\mu$$

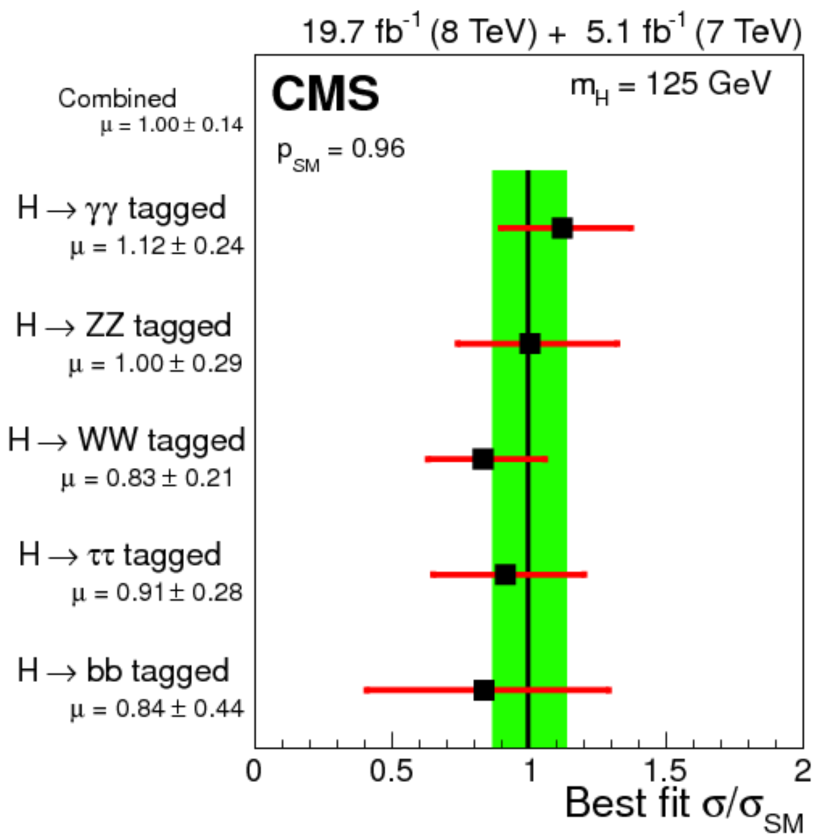
  - Couplings to massless gauge bosons at 1-loop

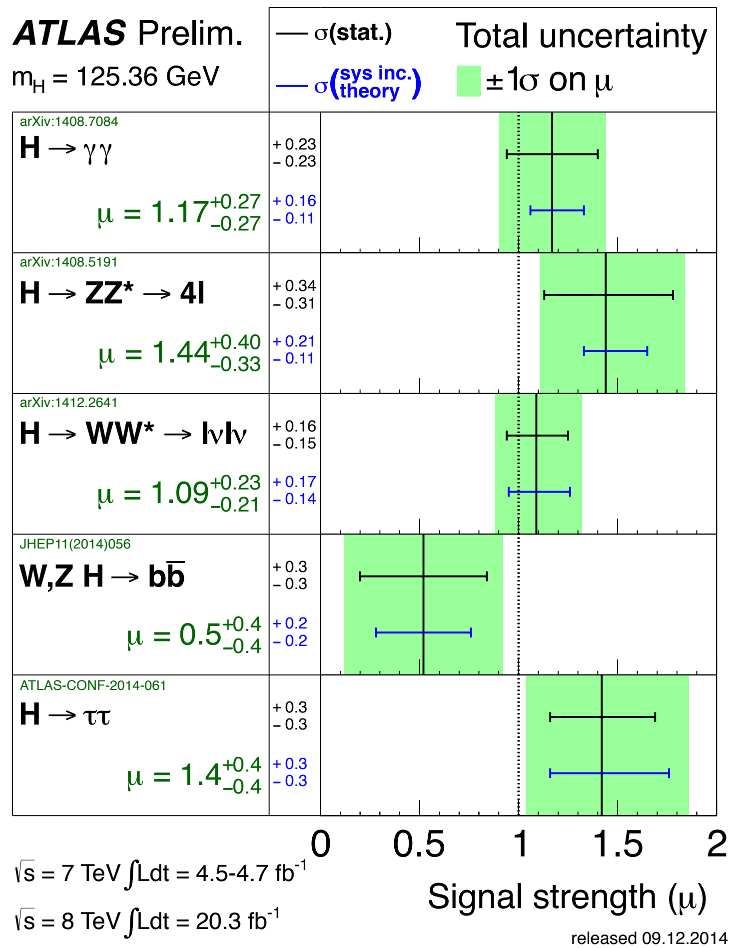
$$\kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu}^A G^{A,\mu\nu} + \kappa_\gamma \frac{\alpha}{8\pi} F_{\mu\nu} F^{\mu\nu} + \kappa_{Z\gamma} \frac{\alpha}{8\pi s_W} \frac{h}{v} F_{\mu\nu} Z^{\mu\nu}$$

  - Higgs self-couplings proportional to m_h^2

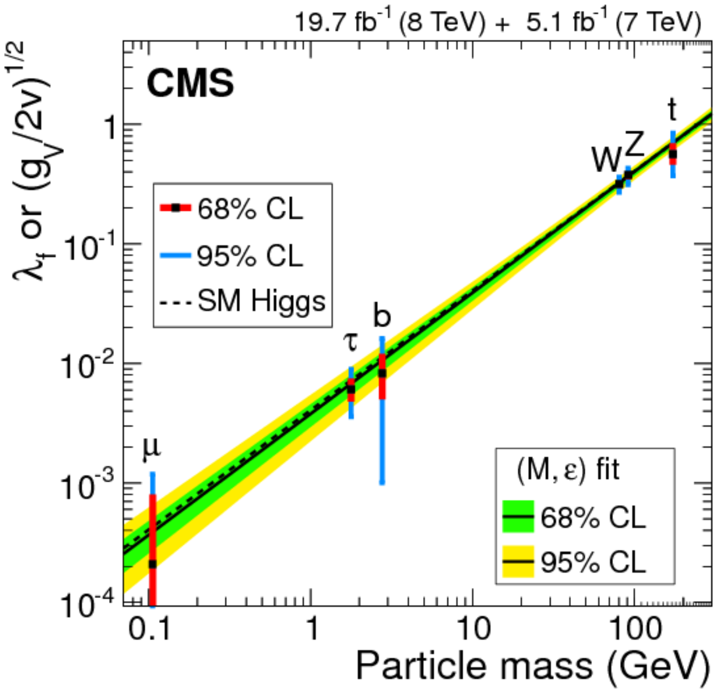
$$\frac{m_h^2}{2} h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$$

Consistent with SM Hypothesis

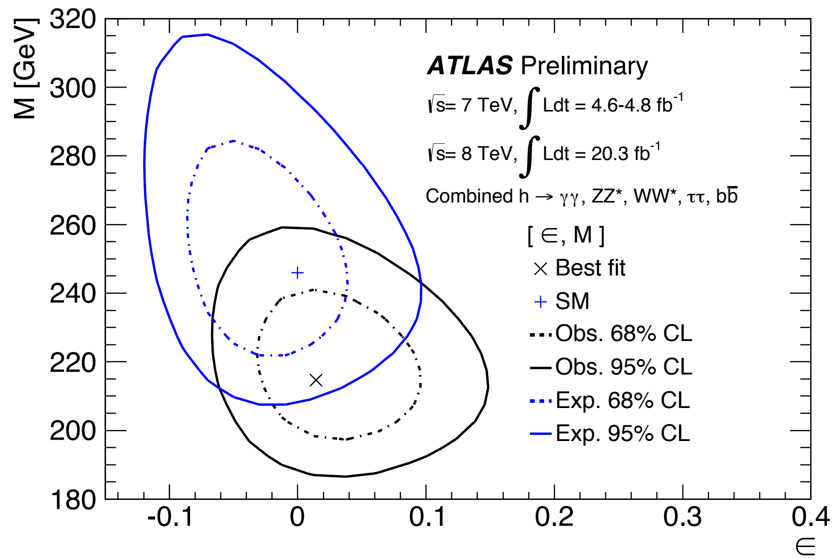




No Free Parameters in SM

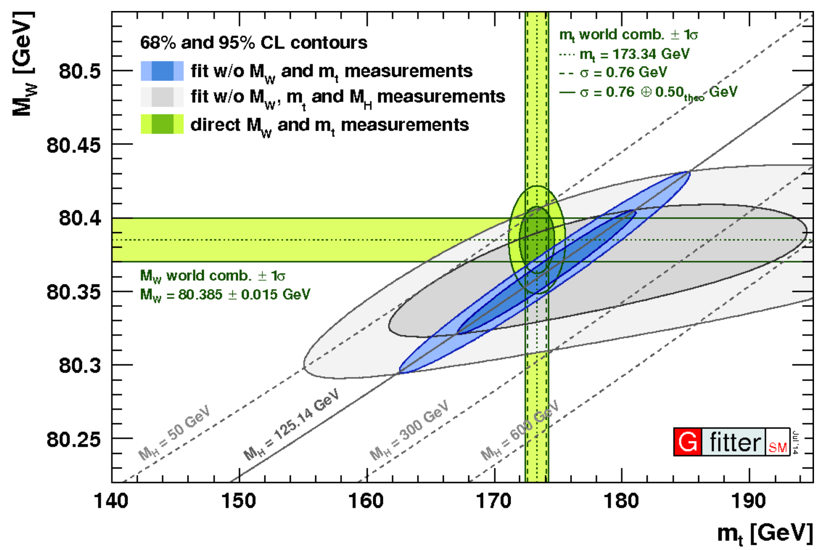


$$L \sim \left(\frac{m_f}{M}\right)^{1+\epsilon} h\bar{f}f + \left(\frac{M_V^{2+2\epsilon}}{M^{1+2\epsilon}}\right) hV_\mu V^\mu$$



Everything looks reasonably consistent with SM

The SM Works



Corollary: New Physics Effects highly restricted by data

At the 10-30% level:

- Fermion couplings to b, t, τ ✔
- Gauge boson couplings to W/Z/g/γ ✔
- Higgs h^2 coupling ✔
- No information on $hZ\gamma$, 2^{nd} generation fermions, h^3, h^4 couplings….
- Generically, Higgs coupling deviations in BSM:

$$\mathcal{O}\left(\frac{v^2}{M^2}\right) \sim 5\% \left(\frac{1\ TeV}{M}\right)^2$$

Much work to do!

The Story is Just Beginning

We are just starting the exploration of weak scale physics

- We know that deviations from SM predictions cannot be too large

- *But there is lots of room for discovery of new Higgs particles, measurements of Higgs signals in new channels, precision measurements of Higgs properties*

Big questions remain: Flavor, dark matter, hierarchy….

Open Higgs Questions

- Is it the SM Higgs?
  - Interactions?
  - Does the Higgs really give mass to all particles?
  - Spin/parity?
- Are there more Higgs-like particles?
  - Is it part of a SUSY spectrum?
  - Does it talk to dark matter?
- Is it elementary or composite?
- Are there new production/decay channels?
- …….

Higgs Production Increases at 13 TeV

	σ(pb) at 13 TeV	σ(pb) at 8 TeV
Gluon Fusion	43.9	19.27
Vector Boson Fusion	3.748	1.578
WH	1.38	.70
ZH	.87	.42
ttH	.51	.13
HH	.034	.008

Factors of 2-4 increases in rates

Note large increase in ttH rate!

[Higgs Cross Section Working Group]

Additional Higgs Searches

- Finding more Higgs bosons top priority
  - Many (well motivated) possibilities
    - Supersymmetry, NMSSM, 2Higgs doublet model, Higgs portal models, Little Higgs models, Composite models
  - Current limits are surprisingly weak
- This would be paradigm shifting
  - Clear evidence for BSM physics

Generic Signals Captured by Simple Models

- General 2 Higgs doublet models
  - The ever popular MSSM is a special case
  - 5 Higgs bosons: H, H_2, A, $H^{\pm}$
- Add a scalar singlet
  - Motivated by dark matter…
  - 2 neutral Higgs bosons

These models share the feature that there are a relatively small number of free parameters

By studying these models in detail, we can obtain many generic BSM signatures

Higgs Singlet Model

- Include scalar singlet S which could be portal to dark matter (or vestige of NMSSM)

$$V(H,S) = V_{SM}(H) + V_{HS}(H,S) + V_S(S)$$

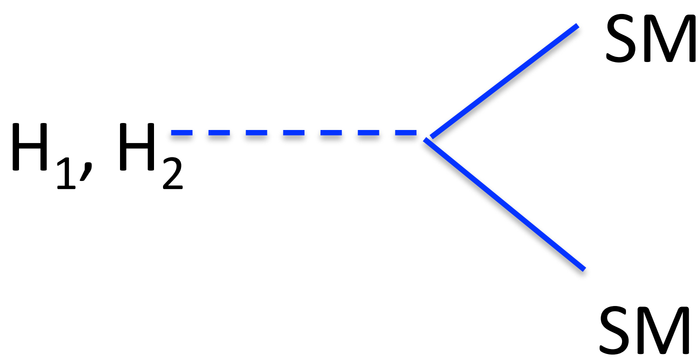
$$V_{HS}(H,S) = \frac{a_1}{2} H^\dagger H\, S + \frac{a_2}{2} H^\dagger H\, S^2$$

$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$

- Physical states are mixtures of h, S
- If S couples to dark matter, then mixing induces h coupling to dark matter (invisible decay)
- Models without Z_2 symmetry motived by desire to explain electroweak baryogenesis

Z_2 symmetric singlet model

- Very simple model: M_1=125 GeV, M_2, $\sin\theta$, v, <S>



Coupling to light Higgs, $H_1 \sim \cos\theta$
Coupling to heavy Higgs, $H_2 \sim \sin\theta$

- If kinematically allowed, $H_2 \rightarrow H_1 H_1$

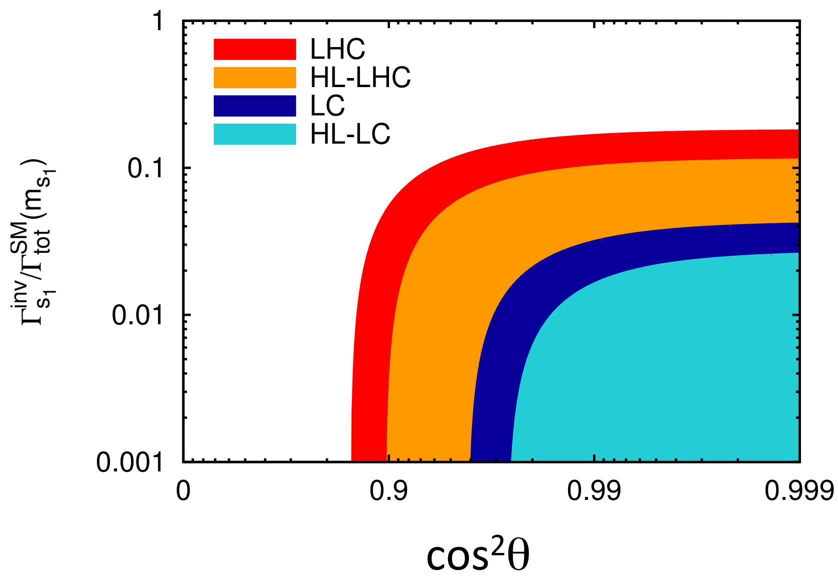
$$\Gamma(H_1) = \cos^2\theta \Gamma_{SM} + \Gamma(H_1 \rightarrow invisible)$$

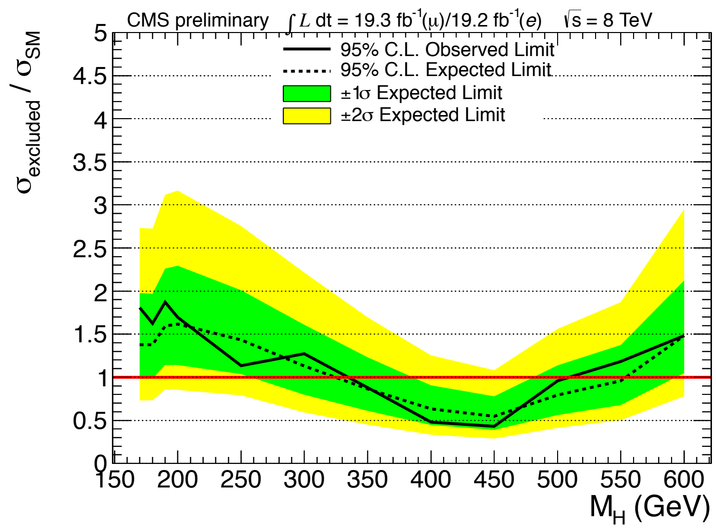
Might occur in Higgs portal models where invisible stuff is dark matter

$$\Gamma(H_2 \rightarrow H_1 H_1) \sim \sin^2\theta$$

Complementarity of Approaches

- Find heavier Higgs and measure couplings
  - Need inclusion of $H_2 \rightarrow H_1 H_1$ in direct searches
- $\sin^2\theta < .12$ (with no invisible BR) from H_1 couplings



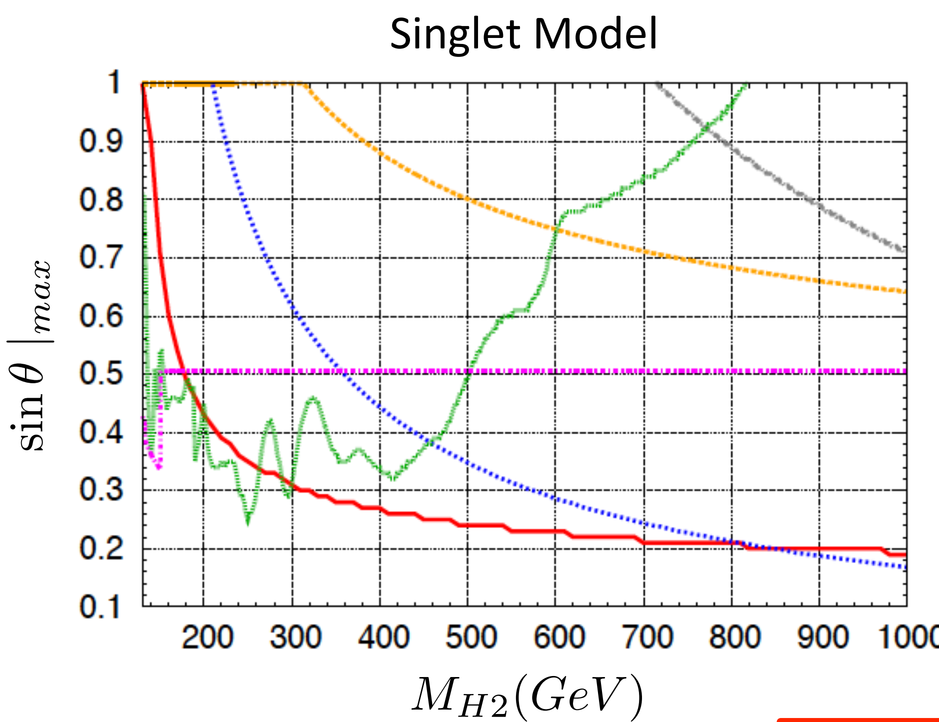


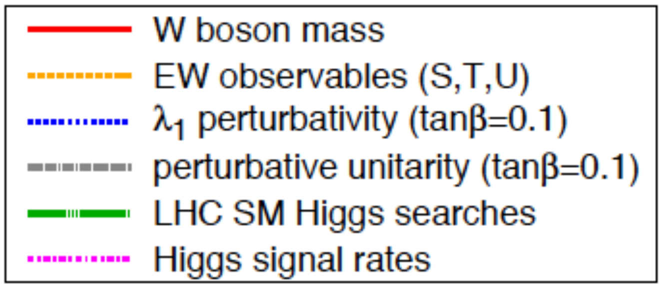
These simple studies are very important for limiting EWSB models

[Englert et al, arXiv:1403.7191]

Complementarity with Precision EW

- Best limit is from W mass for large M_{H2}





$$tan\beta = \frac{v}{\langle S \rangle}$$

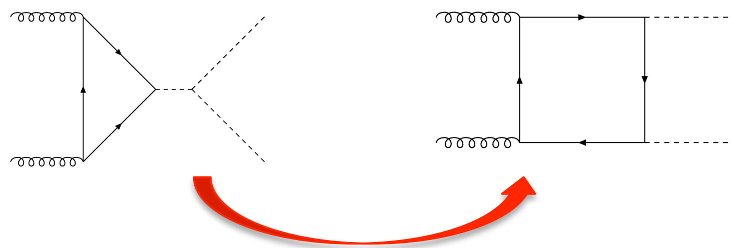
$$V_{SM} = -\mu^2 H H^\dagger + \lambda_1 (H^\dagger H)^2$$

[Robens and Stefaniak,arXiv:1501.02234]

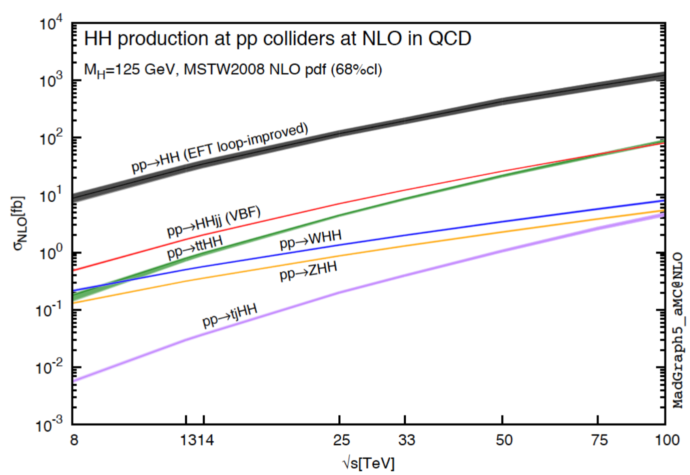
Higgs measurements are now precision observables

Double Higgs Production

- Sensitive to hhh coupling, $\lambda_3 = 3\ M_h^2/M_Z^2$
- Sensitive to new physics in loops



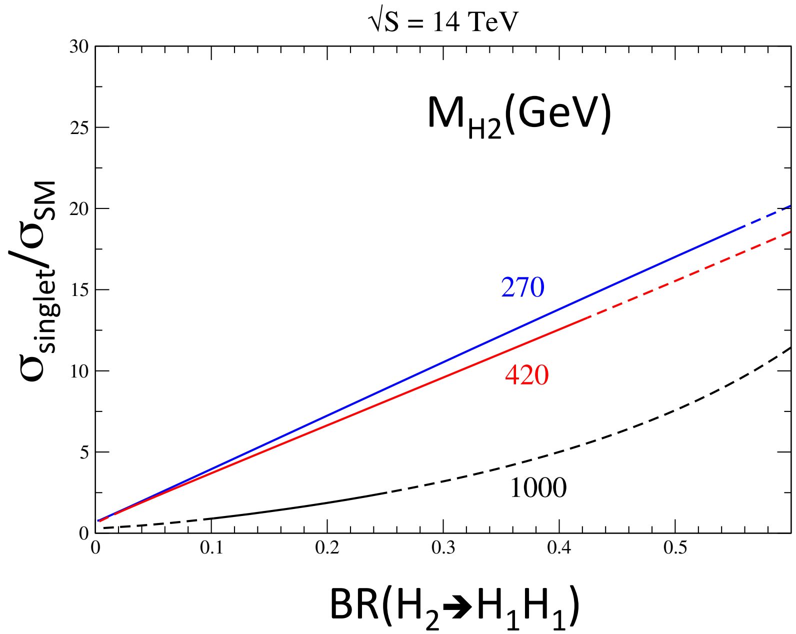
Destructive interference

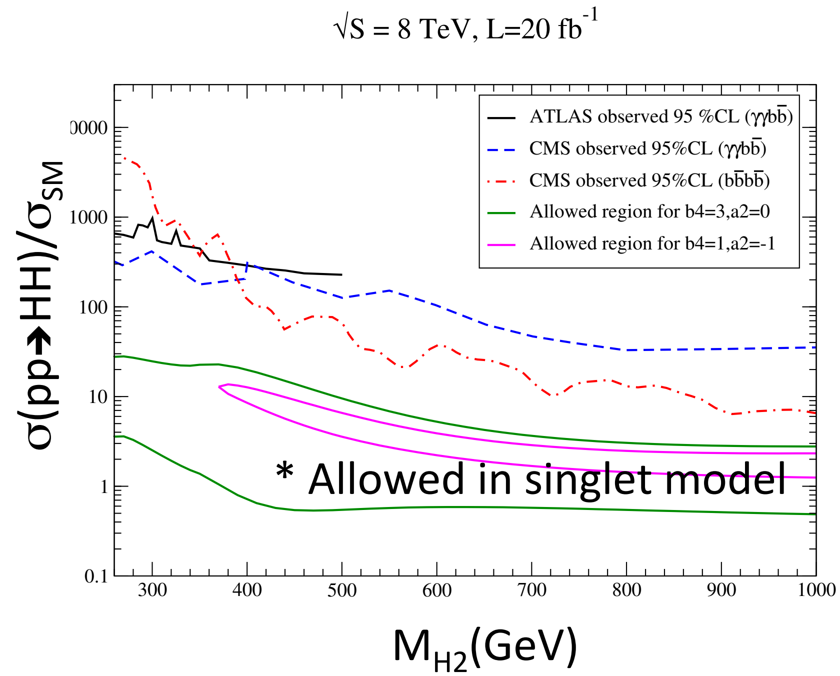


[Frederix et al, arXiv:1401.7440]

- Snowmass: 3 ab^{-1} will give~ 50% measurement of λ_3 at LHC
- Much on-going study…..
- hh production is strong motivation for higher energy

Enhanced hh in Singlet Model



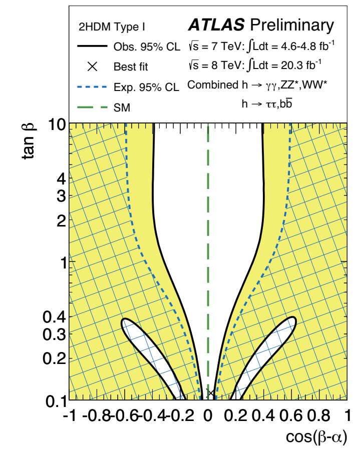


- Enhancements of H_1H_1 rate of factors 10-15 if M_{H2} < 400 GeV
- Easy to arrange in many models…. Major constraint is gg➔ h needs to have observed rate

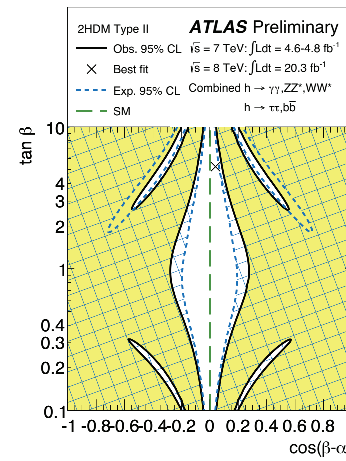
[Chen, Dawson, Lewis, arXiv:1410.5488]

Example: 2HDM

- 4 possibilities for Higgs coupling assignments which conserve flavor
  - Decoupling: M_A, M_{H2}, M_{H+} → ∞, couplings → SM
  - Alignment: ***A,H₂,H+ can be light,*** ***$\cos(\beta-\alpha)$ → 0***
  - Little sensitivity to tan β
- Interesting point—limits extracted by theorists very similar to ATLAS limits



Type 1



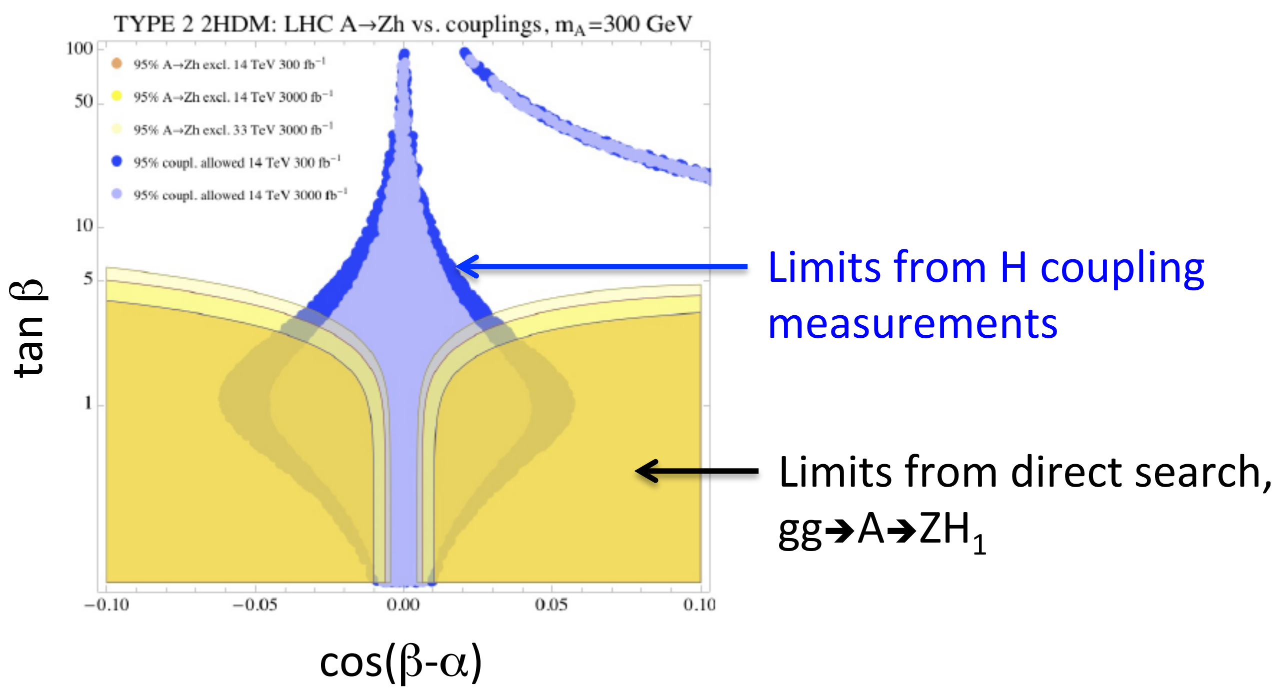
Type 2= MSSM

Limits from coupling measurements

New Higgs Bosons → New Signatures

- 2HDM example: gg→ A → ZH_1
  - Complementary limits from direct search/coupling measurements

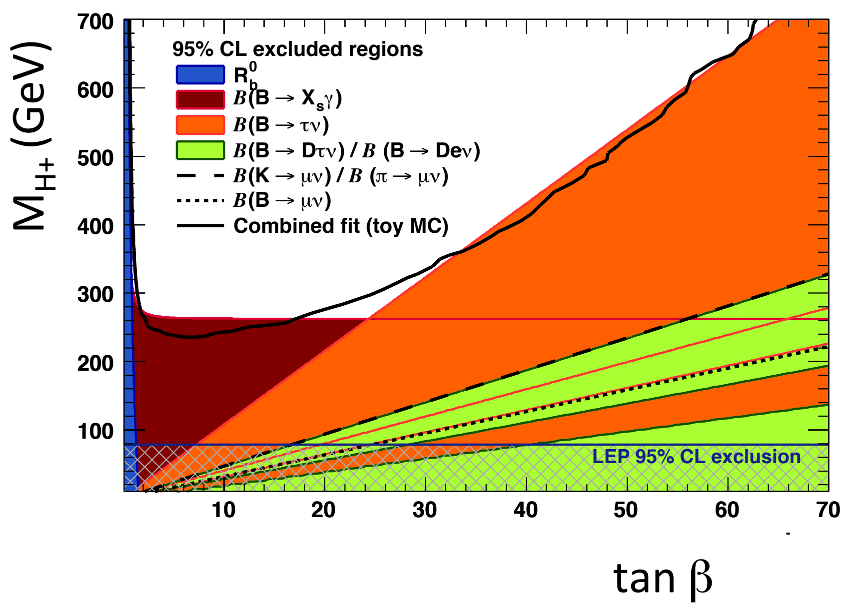
14 TeV projections:

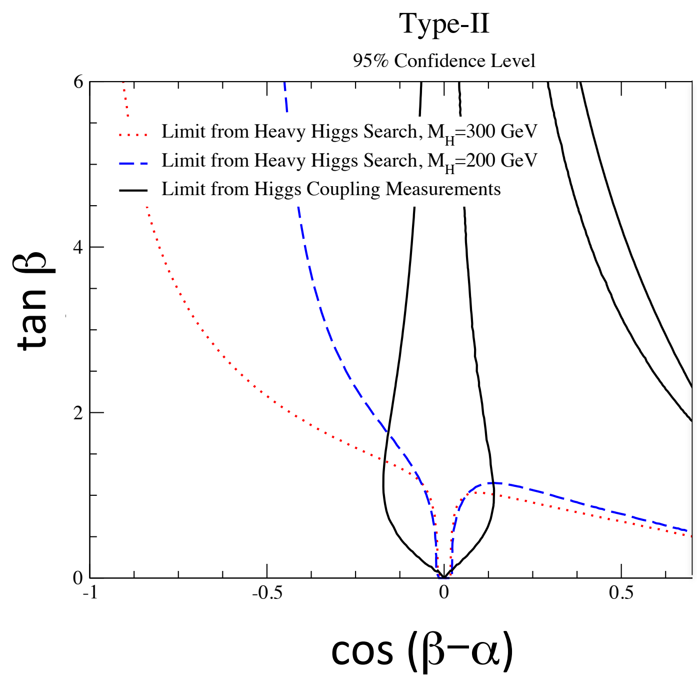


[Brownson, 1308.6334]

Again…. Complementarity

- Many limits on 2HDM besides Higgs parameters
- Precision EW, B physics…..





[Gfitter, arXIv0811.0009, Chen, Dawson, Sher, 1305.1624]

New Physics in Higgs Sector

Use effective field theory

Can we determine source of new physics?

No resonance or light resonance

Find resonance!

Current limits will be strengthened at LHC-13

Testing Higgs Couplings

- Assume 1 resonance/zero width approx/no new tensor structures
$$\sigma \cdot BR(ii \to h \to jj) = \frac{\sigma_{ii}\Gamma_{jj}}{\Gamma_h}$$
- Define scaling factors κ
$$\mu(gg \to h \to \tau^+\tau^-) = \frac{\sigma(gg \to h \to \tau^+\tau^-)}{\sigma(gg \to h \to \tau^+\tau^-)\mid_{SM}} = \frac{\kappa_g^2\kappa_\tau^2}{\kappa_h^2}$$
- This does not include information from kinematic distributions

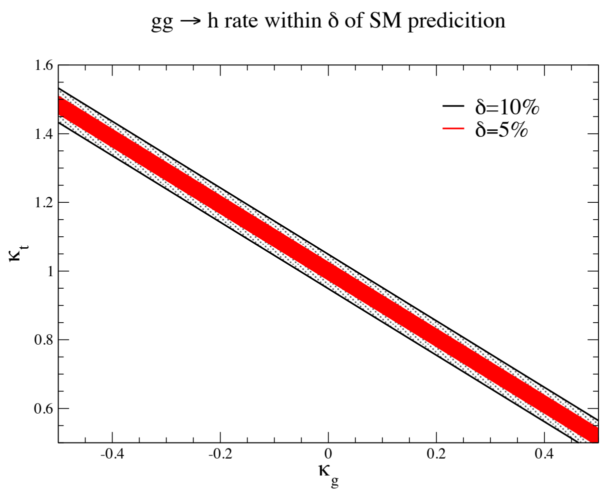
Can we do better?

Effective Theory Example

- Very simple EFT:

$$L \sim L_{SM} + \frac{\alpha_s}{12\pi v}\kappa_g G^{\mu\nu,A}G^A_{\mu\nu}H - (\kappa_t - 1)\frac{M_t}{v}\bar{t}tH$$

$$A(gg \to H) = A^{SM}\left(\frac{m_H^2}{M_t^2}\right)\left[1 + \delta\kappa_t\right] + A^{SM}(0)\kappa_g$$



Almost equal in SM

Can't distinguish *long distance* physics (δk_t) from *short distance* physics (new particles in loops, κ_g nonzero) in gluon fusion

[Azatov, Paul,1412.6038;Delauney, Grojean, Perez, 1309.090; Chen, Dawson, Lewis, 1406.3349]

Higgs Couplings & Effective Field Theory

- Operators obey symmetry of SM

$$L \sim L_{SM} + \Sigma_i \frac{C_i}{\Lambda^{n-4}} O_n$$

- New physics decouples at high scales
  - ***No new light particles***
  - n=6 operators expected to give dominant contribution
  - Λ is scale of new physics >> v
  - EFT valid at E << Λ
  - Consider all n=6 operators that can be constructed from SM fields
  - *No unique operator basis*

Effective Theory

- Many possible parameterizations:
  - HISZ (no fermions), Buchmuller/Wyler (59 operators before flavor), SILH,.....
  - Operators related by equations of motion
  - Need to simplify and make assumptions!
  - Reduce to 8 operators:
    - Assume CP conservation, minimal flavor violation
    - Neglect operators already constrained by precision EW
    - Only operators that affect Higgs physics at tree level

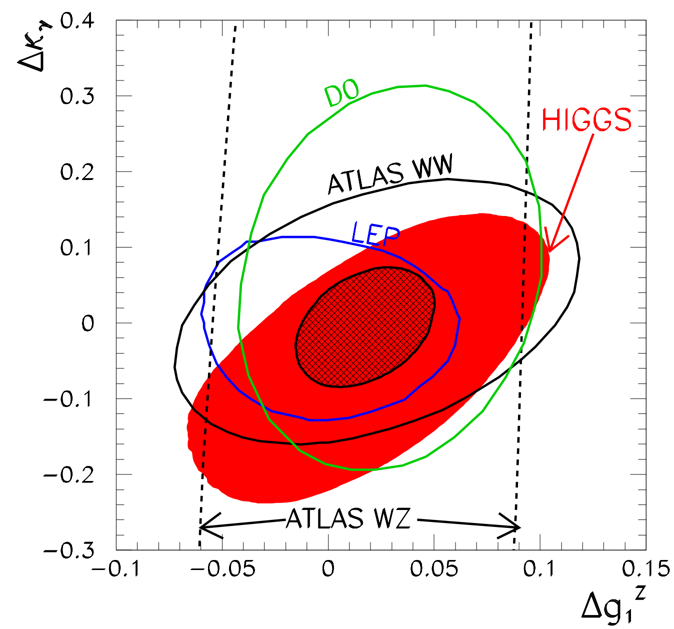
Higgs cross section working group will have recommendation soon

Complementarity

- Effective operators contribute to precision electroweak interactions
- Some operator coefficients known to be small from M_W, ρ…
- W^+W^- production probes complementary coupling space to Higgs coupling limits

$$\Delta\kappa_\gamma = \frac{M_W^2}{2\Lambda^2}(f_W + f_B)$$

$$\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} f_W$$

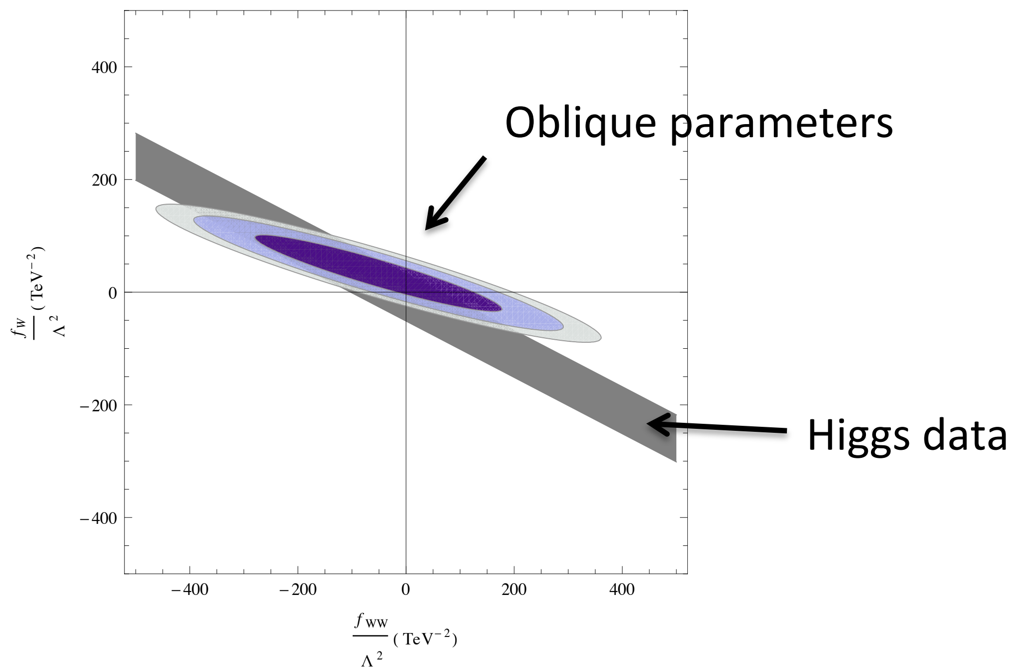


[Corbett et al, arXiv:1304.1151]

Limits highly correlated

Complementarity

$$\frac{\Gamma(H \to W^+W^-)}{\Gamma(H \to W^+W^-)_{SM}} \sim 1 + \left[.0086 f_{WW}(m_Z) + .017 f_W(m_Z)\right]\left(\frac{1\ TeV}{\Lambda}\right)^2$$



In principle, complementary data from oblique parameters and Higgs data

[Chen, Dawson, Zhang, arXiv:1311.3107]

Beyond total rates: Distributions and BSM

- We hope the LHC Run 2 finds some unexpected particles!
  - Heavy particles may have enhanced effects in tails of distributions
- Effective field theories are sensitive to heavy BSM
  - *EFT assumption: all kinematic quantities << scale of new physics, Λ*
  - New physics tends to show up in tails of distributions

This is physics motivation for boosted techniques

Cannot measure all relevant effective couplings with only total rates

Higgs plus Jet Production

- h+jet is sensitive to BSM physics
- At LO, gg➔gh, qg➔ gh, qq➔ gh from top/bottom loops
- Dimension-7 EFT for Higgs + jet strong couplings:

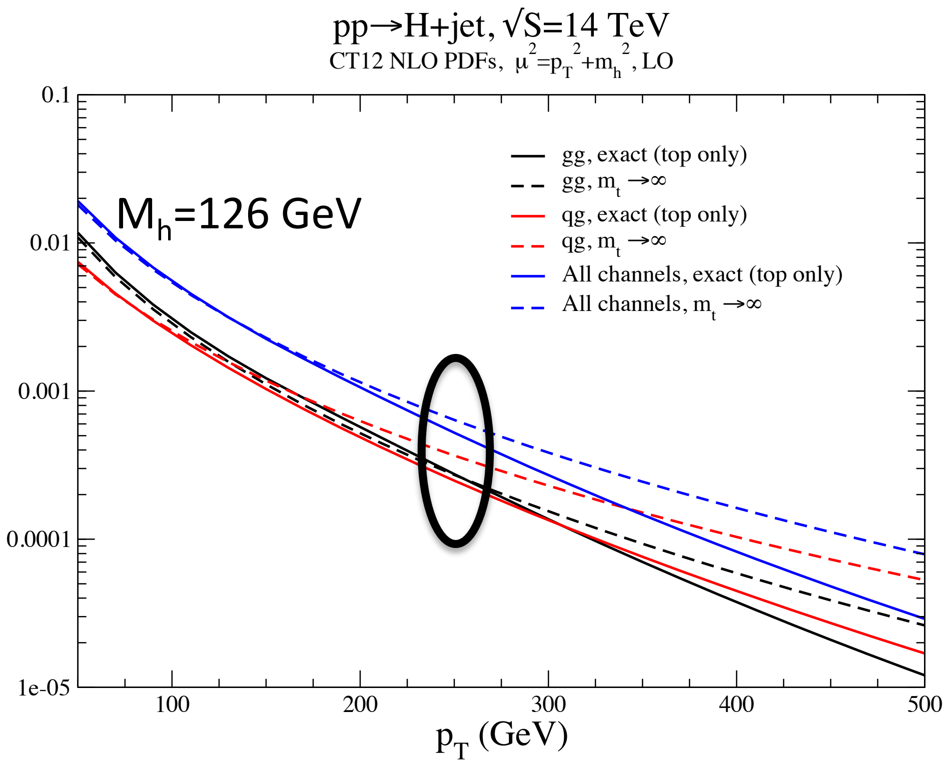
$$L_{BSM} = \frac{\alpha_s \kappa_g}{12\pi v} O_1 + \frac{1}{\Lambda^2}\left(C_3 O_3 + C_4 O_4 + C_5 O_5\right)$$

Calculate in EFT and in real theory… Compare

κ formalism cannot describe Higgs plus jet at high p_T

[Azatov, Paul, 1309.5273; Banfi, Martin, Sanz, 1308.4771; Dawson, Lewis, Zeng, 1409.6299, 1501.04103]

Higgs plus Jet Production



- Look for new physics at high p_T
- Just where EFT breaks down!
- qg important at high p_T
- EFT accurate for $p_T <$ 250 GeV

EFT in this plot includes only dimension-5 $G_{\mu\nu}G^{\mu\nu}h$ operator

EFT-pointlike coupling has different p_T shape than top quark loop

EFT for Higgs + Gluons

- Dimension-7 operators which contribute to Higgs + jet

$$O_2 = D_\sigma G^A_{\mu\nu} D^\sigma G^{A,\mu\nu} h$$
$$O_3 = f_{ABC} G^{A,\mu}_\nu G^{B,\nu}_\sigma G^{C,\sigma}_\mu h$$
$$O_4 = D^\sigma G^A_{\sigma\nu} D_\rho G^{A,\rho\nu} h \rightarrow_{eom} g_s^2 h \Sigma^{n_{lf}}_{i,j=1} (\overline{\psi}_i \gamma_\mu T^A \psi_i)(\overline{\psi}_j T^A \psi_j)$$
$$O_5 = G^A_{\sigma\nu} D^\nu D^\rho G^{A,\sigma}_\rho h \rightarrow_{eom} g_s h \Sigma^{n_{lf}}_{i=1} G^A_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^A \psi_i$$

- O_4 involves 4 light fermions
- O_2 eliminated by use of Jacobi identities

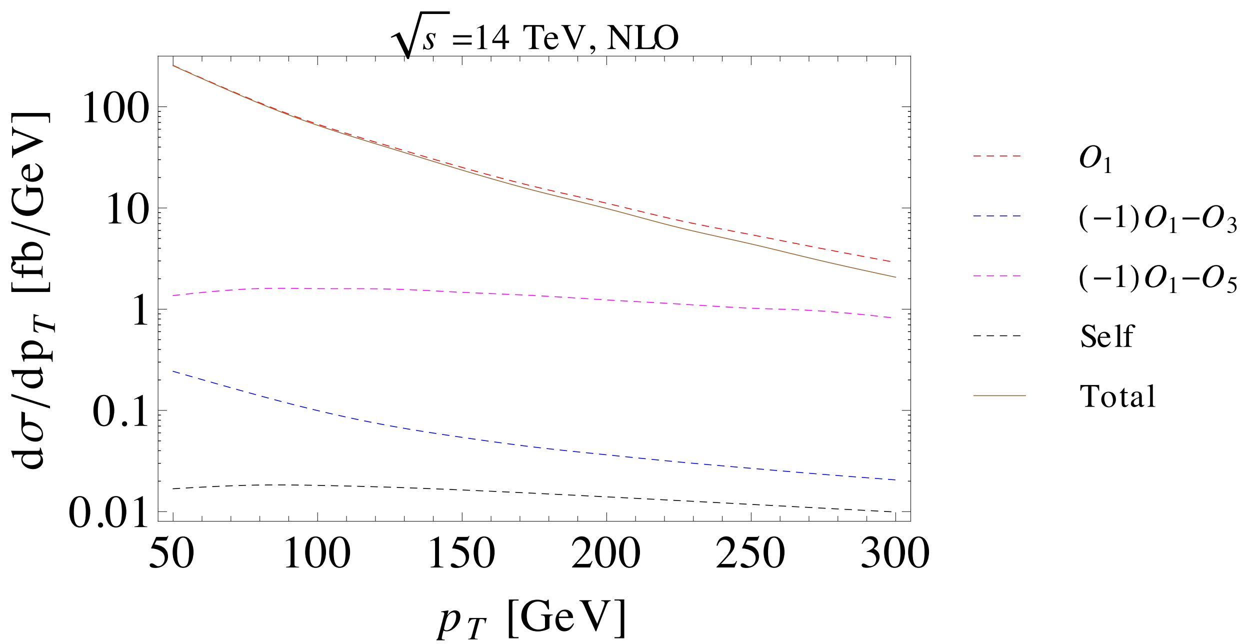
qg → qh $\quad A \sim (\ldots) \left[g_s \frac{C_1}{t} + g_s \frac{C_5}{\Lambda^2} \right]$

gg → gh $\quad A \sim [\ldots] g_s C_1 + [\ldots] g_s \frac{C_3}{\Lambda^2}$

Not a lot of free parameters

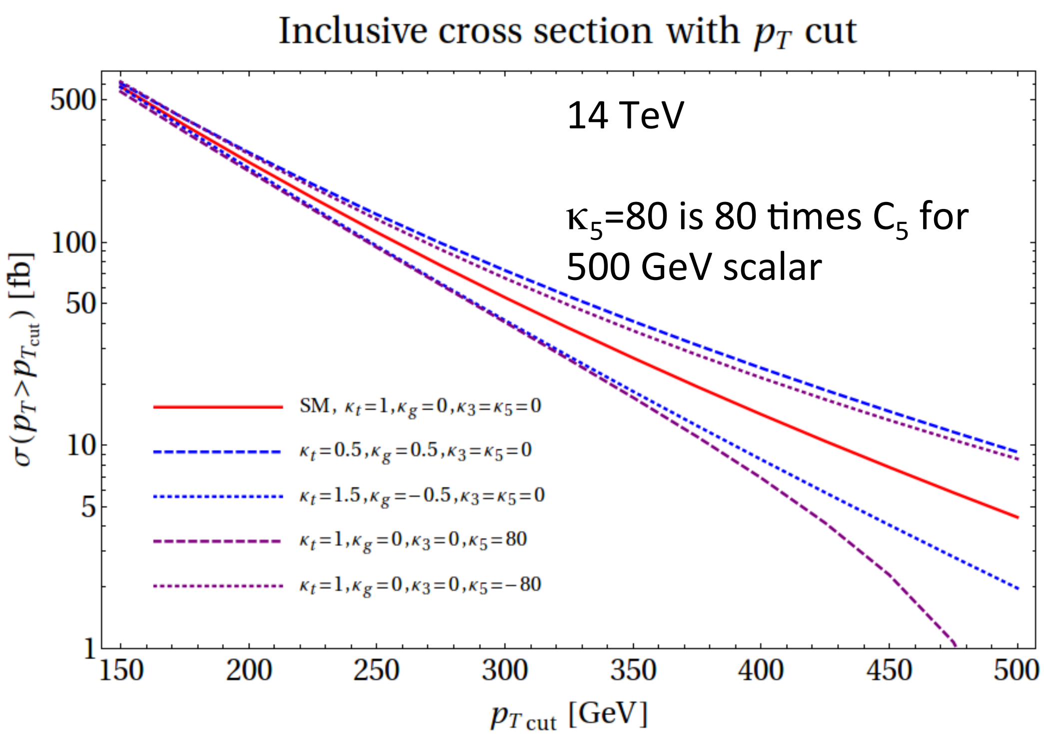
[Neill,0908.1573; Dawson, Lewis, Zeng,1409.6299; Harlander, Neumann, 1308.2225]

NLO Results



- Using only dimension-5 operator (O_1) is good approximation in region where EFT is valid
- Look for new physics (in dijets, top production) due to O_5 operator at high p_T

Need Higgs p_T Spectrum



Lesson 1: Spectrum well described by κ_t, κ_g (don't need higher dimension operators)

Lesson 2: Effects of EFT operators typically small!

Lesson 3: p_T spectrum distinguishes between κ_t and κ_g

$\sigma(p_T > p_{T\text{cut}})$ sensitive to new physics possibilities

[Arnesen, Rothstein, Zupan, 0809.1429; Dawson, Lewis, Zeng, 1501.04103]

Conclusions

- LHC-13 is just the beginning of exploration of EWSB
  - Many possibilities for new physics
- Precision measurements, direct searches for new Higgs bosons, and measurements of Higgs couplings give complementary information
  - Higgs is the new precision observable
  - Can not look at only one piece of the puzzle
- EFT needed to study new physics if no new light particles
  - Region of EFT consistency limits usefulness