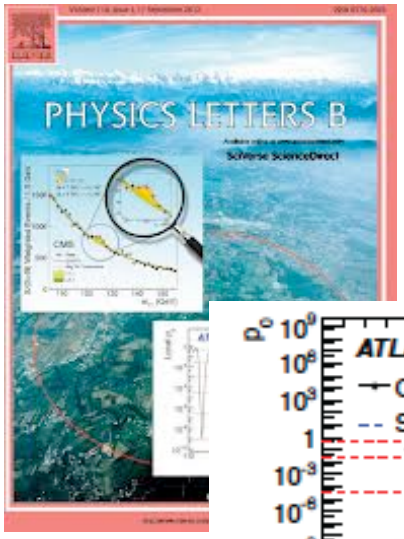
BSM Physics from Run 2

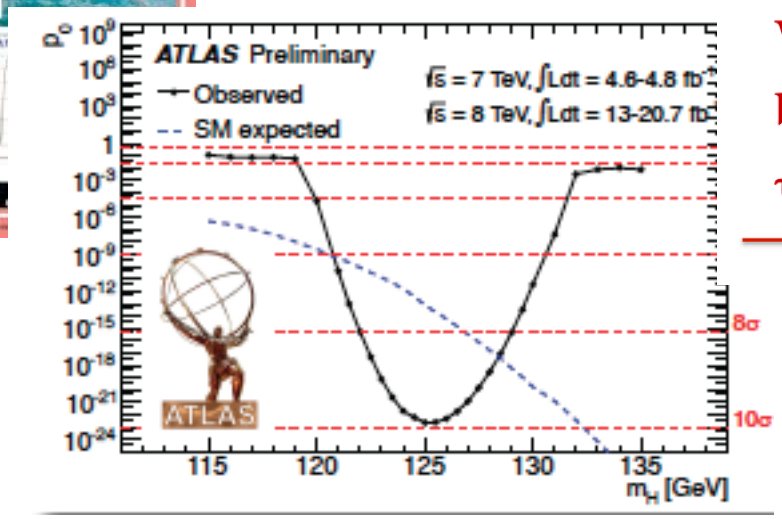
What can Higgs interactions tell us?

S. Dawson, BNL
Nov, 2014

We discovered a Higgs boson!

- The minimal Higgs model is very predictive
- Only free parameter is M_H





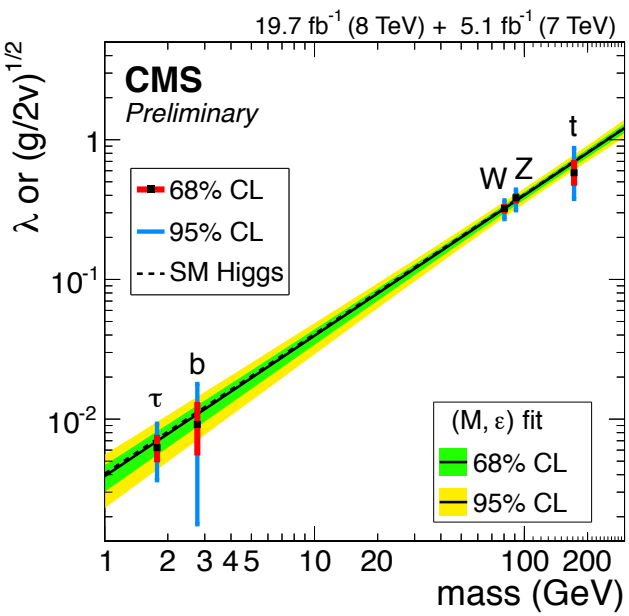
CMS

Decay	Expected	Observed
ZZ	7.1 σ	6.7 σ
γγ	3.9 σ	3.2 σ
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

Both ATLAS and CMS have close to 10σ significance

All Higgs Couplings predicted in SM

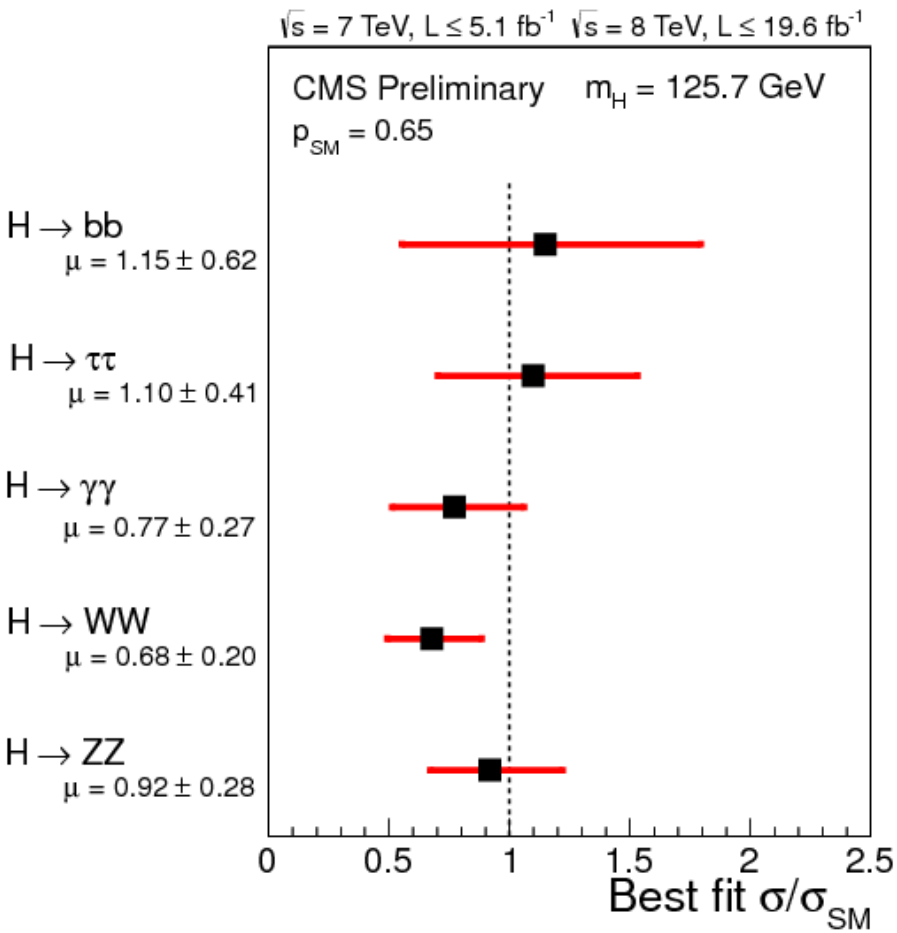
- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to (mass)^2
  - Higgs self-couplings proportional to M_H^2

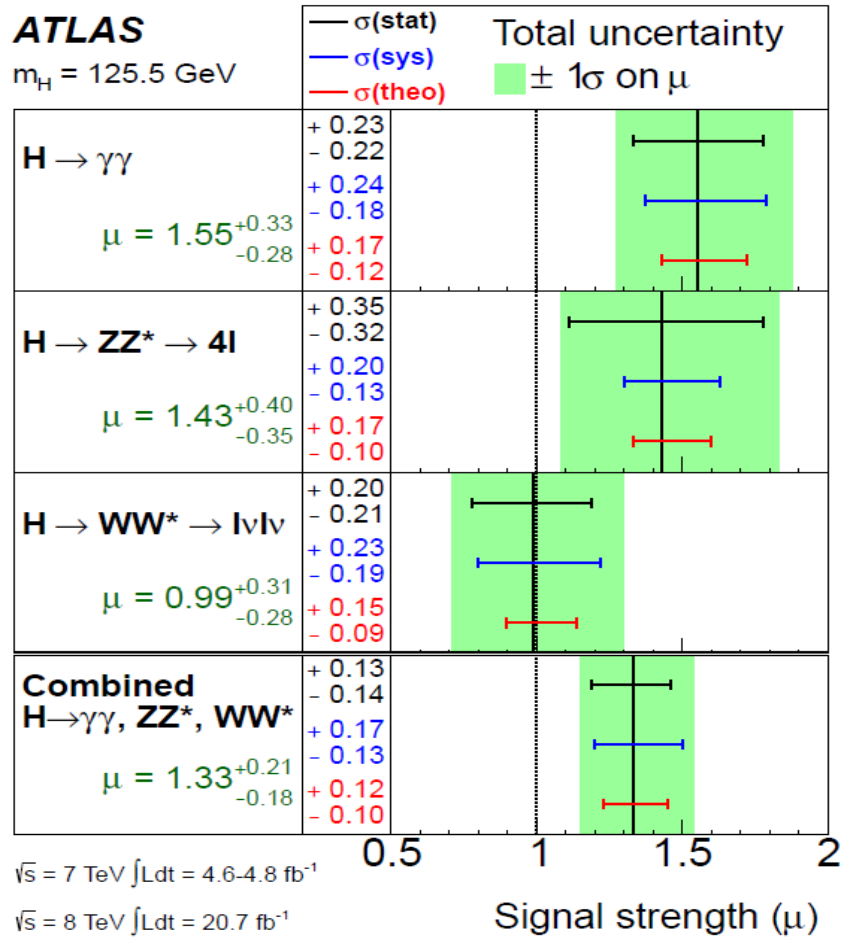


If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

*t coupling inferred from ggh top loop

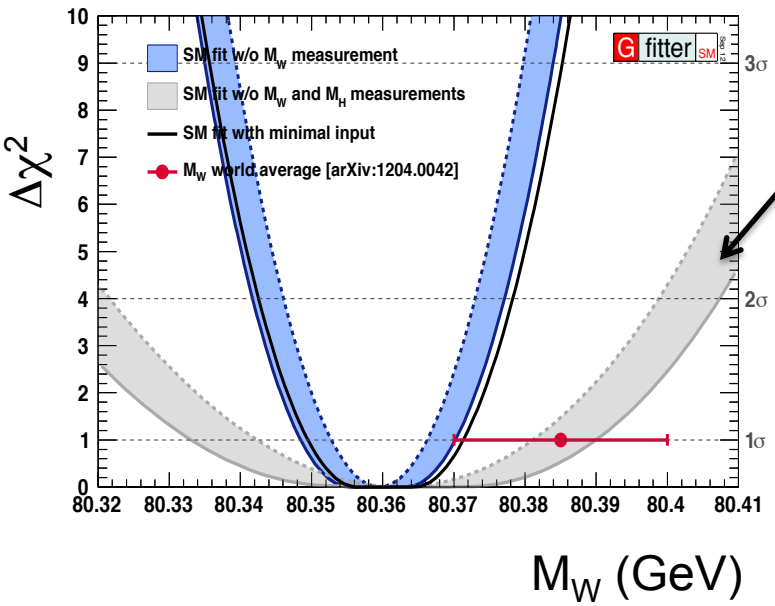
Consistent with SM Hypothesis



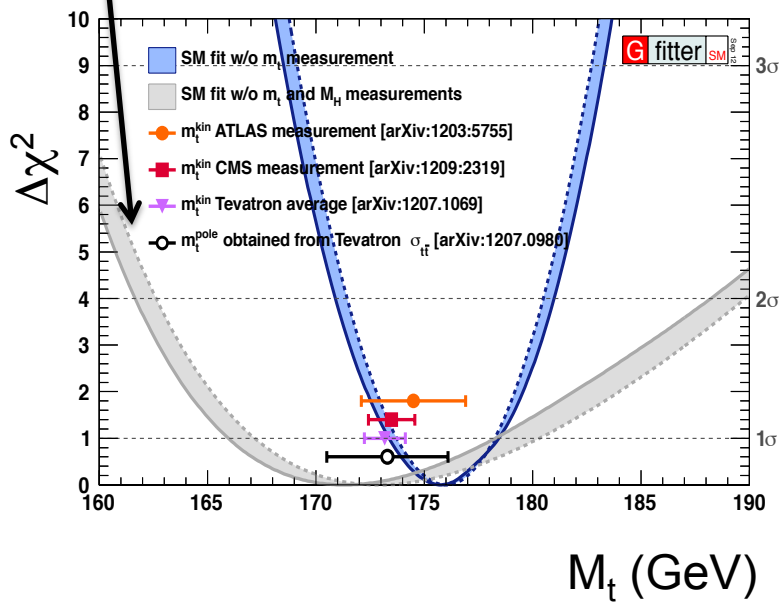


Note theory uncertainties

Precision Physics After Higgs Discovery



Fit without Higgs



The SM as an effective low energy theory is an extremely good approximation

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?
- …….

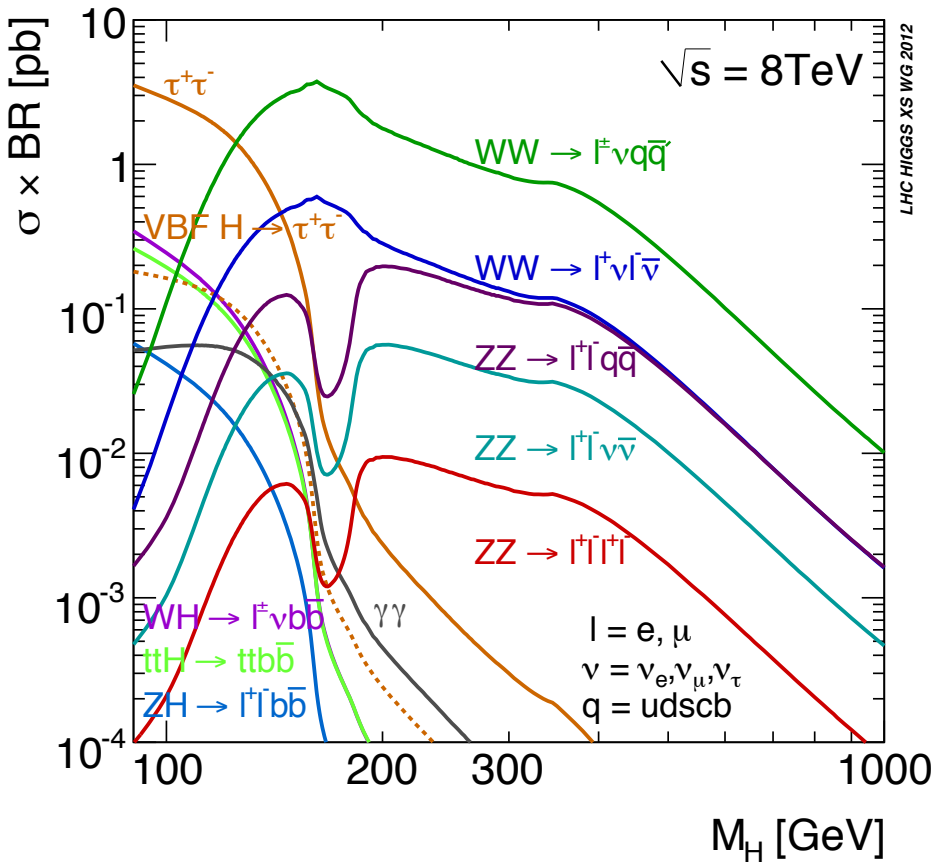
Higgs Production Increases at 13 TeV

	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

[Higgs Cross Section Working Group]

Look for Rarer Processes/Signatures



Wishlist #1

- Find more Higgs bosons
  - 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

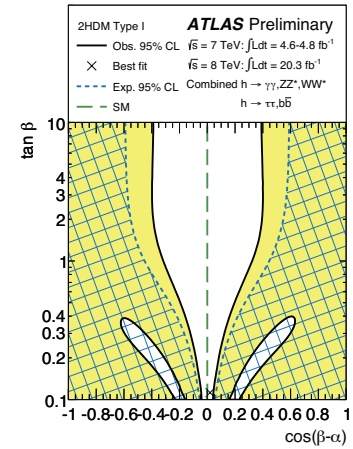
MORE HIGGS BOSONS, PLEASE

- 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

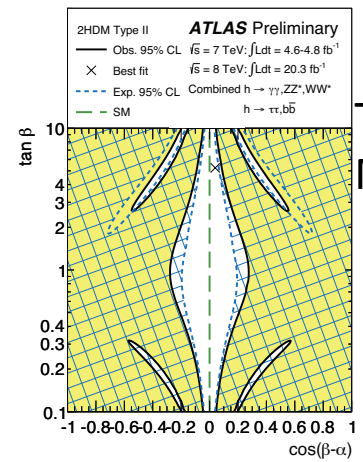
These models share the feature that there are a relatively small number of free parameters

Example: 2HDM

- 4 possibilities for H coupling assignments which conserve flavor
  - Decoupling: M_A, M_{H2}, M_{H+} ➔∞, couplings ➔SM
  - Alignment: A,H_2,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

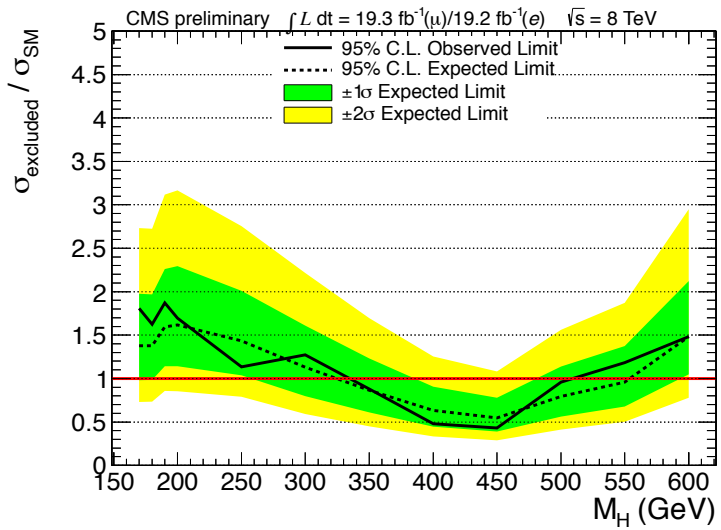


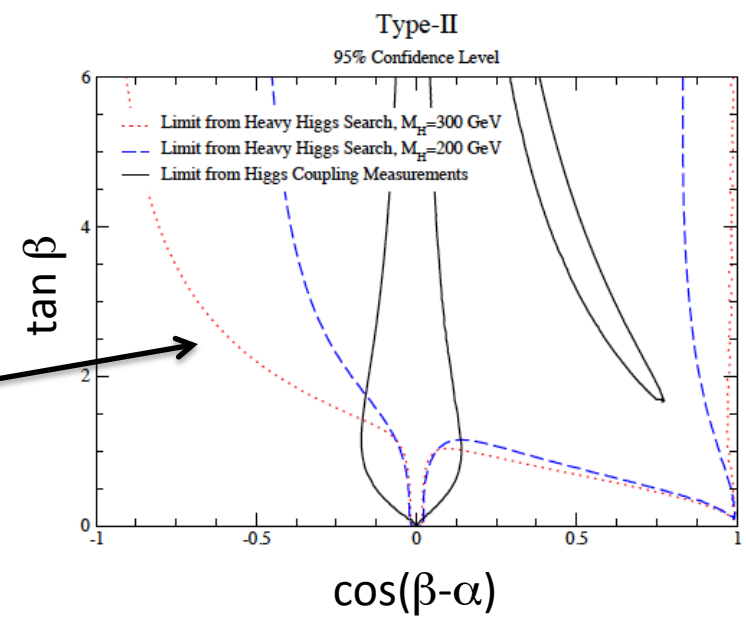
Type 2= MSSM

Limits from coupling measurements

2HDM, continued

- Search for 2nd neutral Higgs
  - Reuse SM searches in high mass region
  - Coupling limits and direct search limits complementary





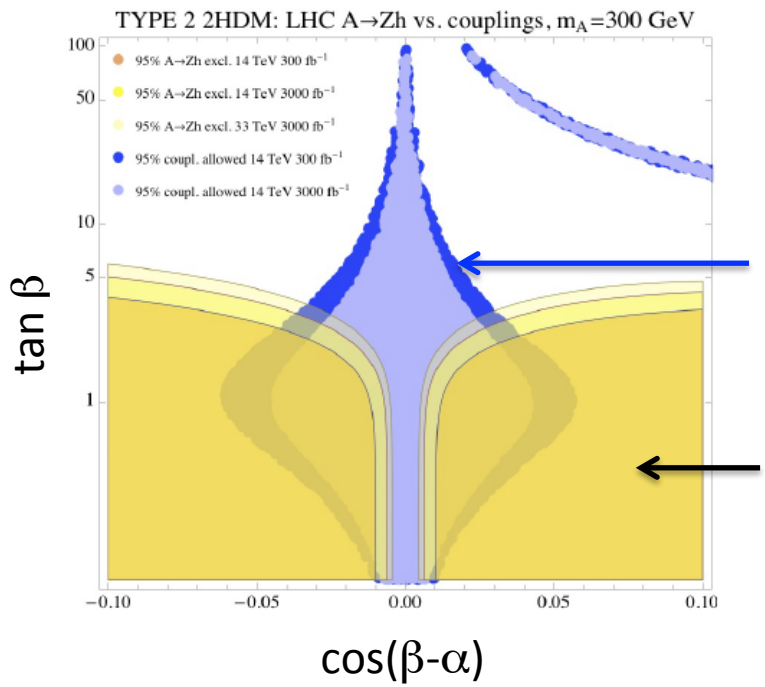
Pushing these limits lower is extremely useful

[Chen, Dawson, Sher, arXiv:1305.1624; Craig, Galloway, Thomas, arXIv:1305.2424]

New Higgs Bosons → New Signatures

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

14 TeV projections:



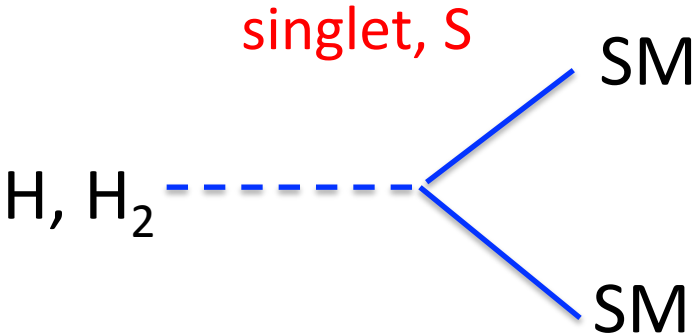
Limits from H coupling measurements

Limits from direct search

[Brownson, 1308.6334]

Is the Higgs a portal to the dark side?

- Models to explain dark matter, flavor often have more than 1 Higgs boson
  - Simple example: SM Higgs mixed with electroweak singlet, S



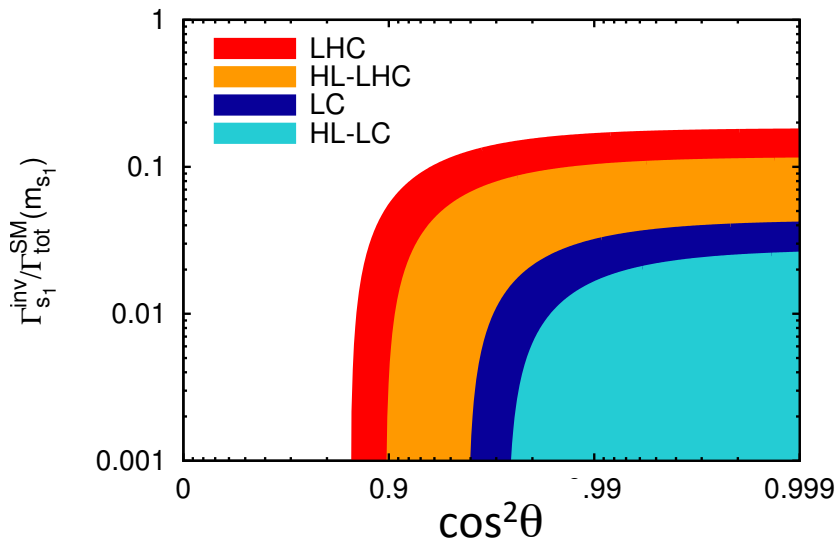
Coupling to light Higgs, H ~ cos θ
Coupling to heavy Higgs, H_2 ~ sin θ

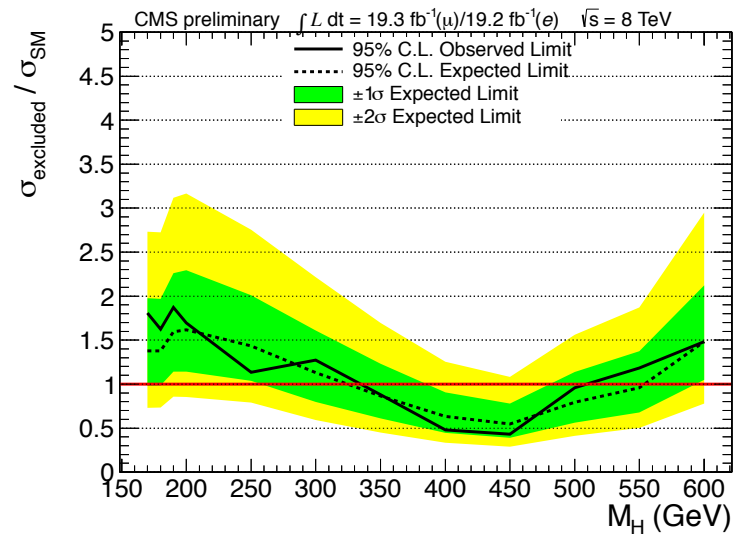
- More complicated models can generate electroweak phase transition

$$V \sim S\Phi^\dagger\Phi + S^2\Phi\Phi^\dagger + S^3 + S^4 + (\Phi\Phi^\dagger)^2$$

Complementarity of Approaches

- Find heavier Higgs and measure deviations in couplings
- $\sin^2\theta < .12$ (with no invisible BR) from H couplings
  - Need increased sensitivity in direct searches

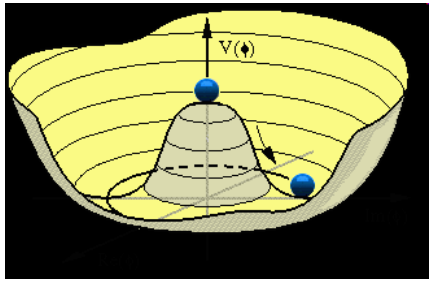




These simple studies are very important for limiting EWSB models

[Englert et al, arXiv:1403.7191]

Wishlist #2



- Di-Higgs Production
  - HHH and HHHH couplings prediction of theory

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

  - Couplings perturbative

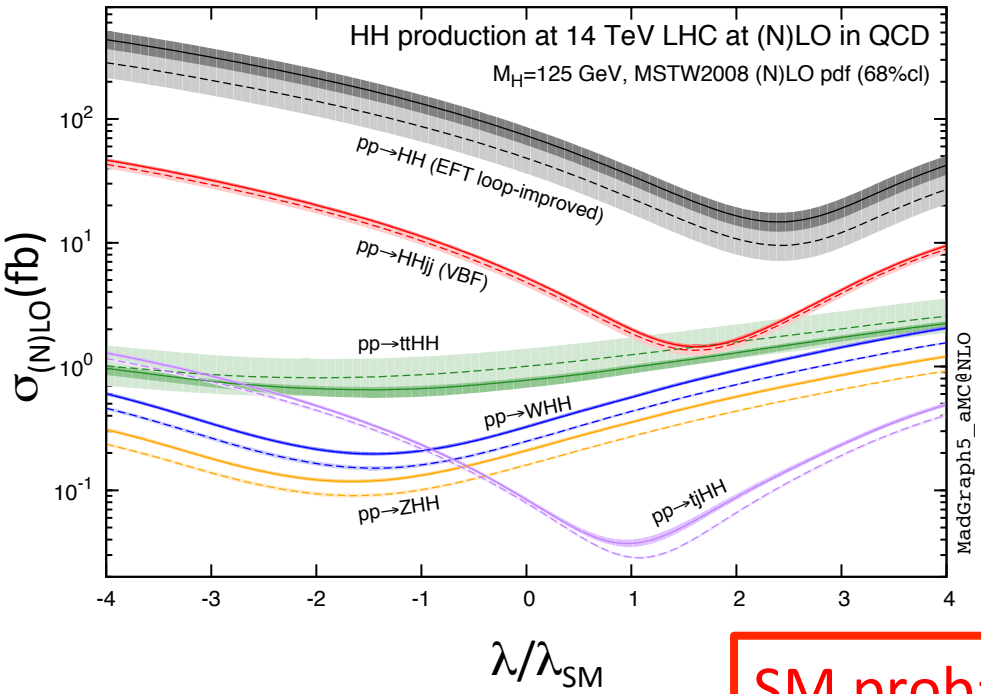
$$\lambda_3 = \frac{M_H^2}{2v} \sim .13v \qquad \lambda_4 = \frac{M_H^2}{8v^2} \sim .03$$

  - Calculations sensible

$$V = \Sigma_n \frac{c_n}{\Lambda^{2n}} \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^{2+n}$$

Corrections to relationship between λ_3 and λ_4 of $O(1/\Lambda^2)$

Small Rates for HH



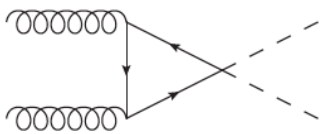
- gg rate increases by a factor of ~40 when going from 14 TeV to 100 TeV
- Gluon fusion is always the largest production channel

SM probably too small for Run 2

[Frederix et al, 1408.5147; Baglio et al, arXiv:1215.5581]

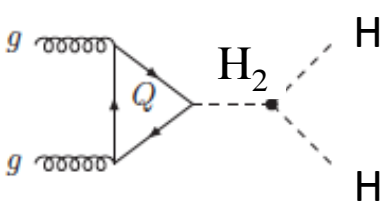
Look for enhanced HH

- Promising possibilities
  - Composite models with ttHH coupling



Hard to get enhancements of more than factors of ~2-3

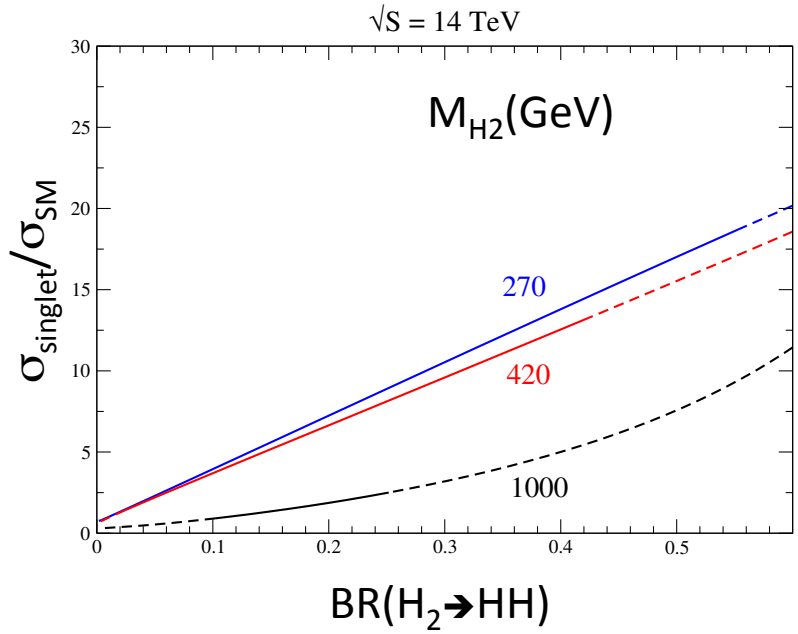
  - Models with resonances

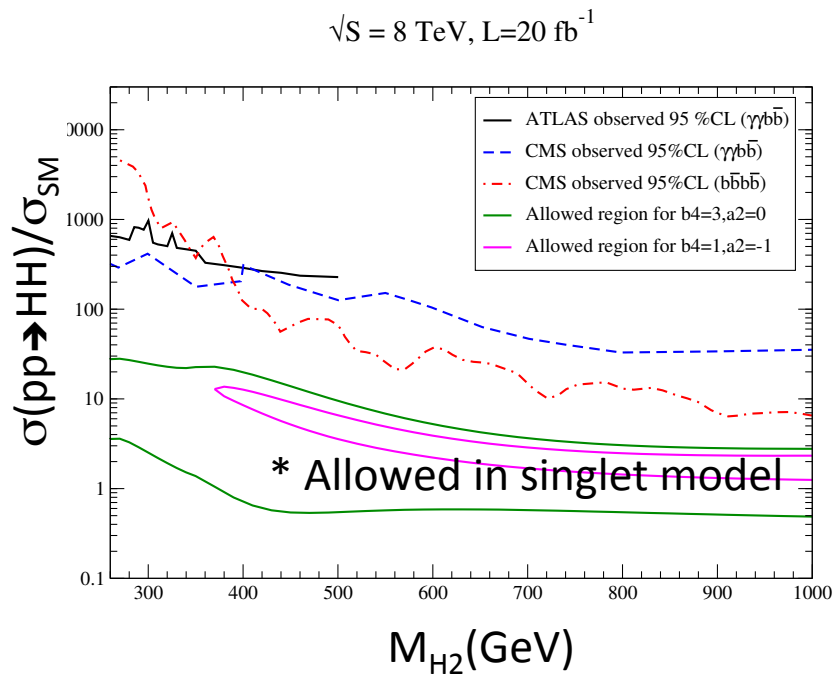


Can get enhancements of ~50 if H_2~$2M_H$

MSSM, NMSSM, 2HDM, Higgs portal models can all have enhanced resonant production

Enhanced HH in Singlet Model





- Enhancements of HH 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]

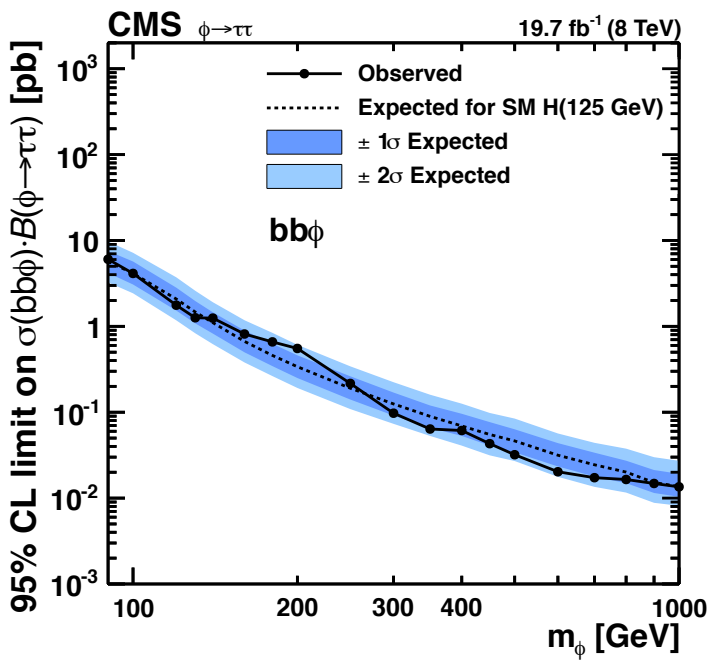
Wishlist #3

- Precision Higgs couplings
  - Model independent limits *(can apply to my brilliant new idea)* … or….
  - Model of the week *(cuts can be tuned for maximum sensitivity)* … or….
  - Effective Field Theory *(works if the new physics is heavy)*

Theorists would like all three

Model Independent if possible

- Let the theorists rescale
  - The favorite models/parameter space change



This type of information highly valued by theorists

Higgs Couplings: Is it the SM?

- SM Higgs couplings fixed—cannot be varied separately
  - Can test consistency of SM hypothesis
- Higgs cross section WG interim recommendation:
  - Rescale fundamental Higgs couplings: κ_W, κ_Z, κ_f and loop induced couplings, κ_γ, κ_g, $\kappa_{\gamma Z}$
  - Simple and easy to implement
  - Electroweak corrections not included exactly
  - No information from angular distributions
  - How to interpret deviations?
    - *Rescaling breaks gauge invariance, renormalizability*

Higgs Couplings Interesting

- Precision measurements of Higgs couplings rigorous tests of SM
  - NNLO QCD, NLO EW, resummation all needed!
  - Flavor structure of Higgs sector untested so far
- Models with TeV scale new physics give small corrections to κ parameters

- We would expect deviations from SM to be $O(v^2/TeV^2)$
- *Just starting to probe interesting region*

Small Corrections Expected

If new physics is at 1 TeV:

	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	~6%	~6%	~6%
2HDM	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

Patterns of deviations can pinpoint specific BSM physics

[Snowmass Higgs report, 1310.8361]

Effective Field Theory

- Operators obey symmetry of SM

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

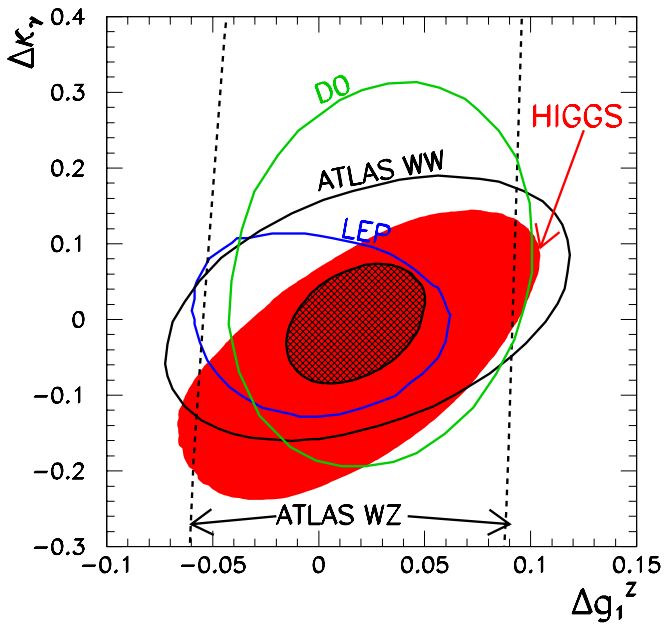
- New physics decouples at high scales
  - ***No new light particles***
  - n=6 operators expected to give dominant contribution
  - Λ is scale of new physics >> v
  - EFT valid at E << Λ
  - Consider all n-6 operators that can be constructed from SM fields
  - *No unique operator basis*

Interconnections

- 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]

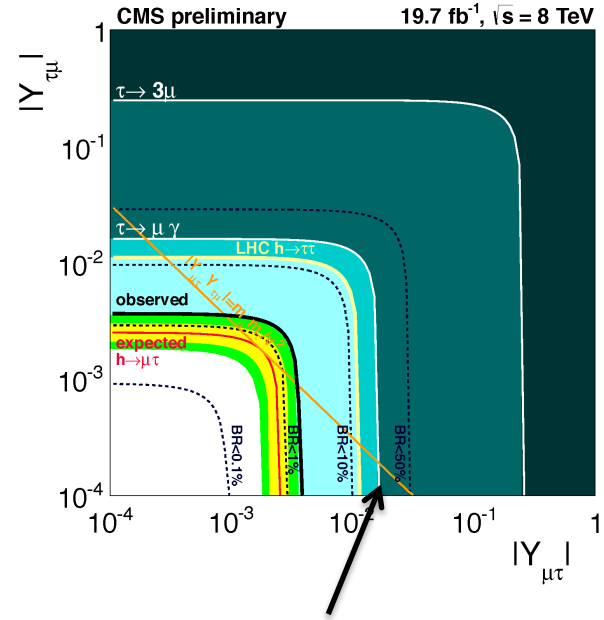
Effective Theory

- 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!

Wishlist #4

- Flavor/rare decays
  - $H \to \mu^+\mu^-$ probes 2nd generation couplings
- In SM, Yukawa interactions only source of fermion masses
  - No Flavor changing effects from Higgs couplings
- Not true if SM fermions mix with vector-like fermions *(ie not all mass from Higgs mechanism!)*
  - Look for $H \to \mu\tau$, $H \to e\,\tau$



Reinterpretation of ATLAS $H \to \tau\tau$ limit

[Harnik, Kopp, Zupan, arXiV: 1209.1397]

Wishlist #5: Distributions and BSM

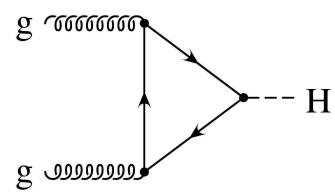
- We hope the LHC Run 2 finds some unexpected particles!
  - Heavy particles may have enhanced effects in tails of distributions
- Effective field theories are sensitive to heavy BSM
  - *EFT assumption: all kinematic quantities << scale of new physics, Λ*
  - New physics tends to show up in tails of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

This is physics motivation for boosted techniques

Effective Theory Example

- Very simple EFT:

$$L \sim L_{SM} + \frac{\alpha_s}{12\pi v} c_g G^{\mu\nu,A} G^A_{\mu\nu} H - \delta Y_t \frac{M_t}{v} \bar{t} t H$$



  – gg→H sensitive to $|c_g + \delta Y_t|^2$

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

Almost equal in SM

Can't distinguish *long distance* physics (δY_t) from *short distance* physics (new particles in loops, c_g nonzero)

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

New Physics from Higgs + jet

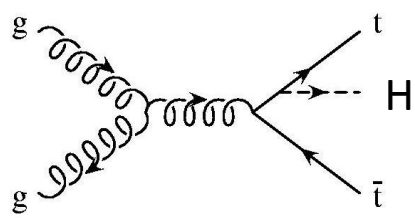
– EFTs and boosted signals

- $gg \to gH$ at high p_T separates c_g, δY_T

At 14 TeV: $\sigma_H \sim 50$ pb

σ_H+jet ~ 2 pb (with p_T(jet)>100 GeV)

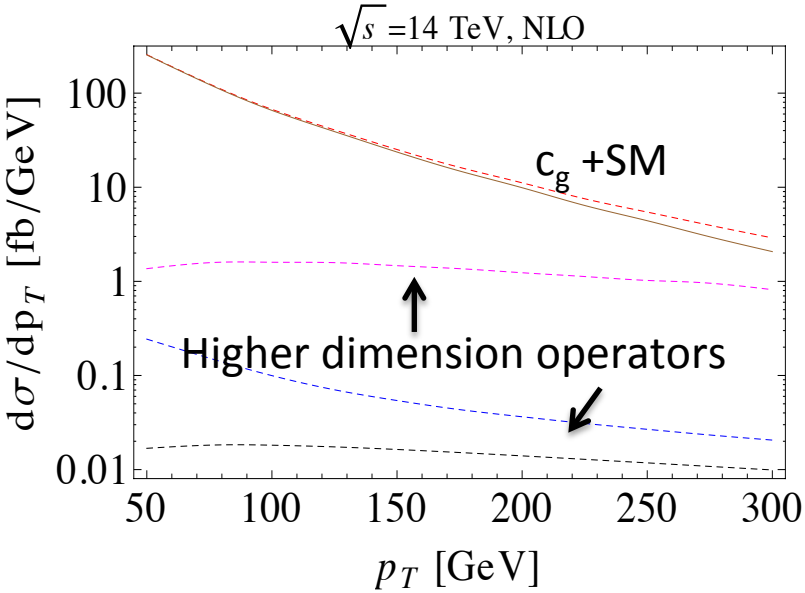
– Importance of $t\bar{t}H$ direct production!



Rate increases by factor of 4 going from 8 to 13 TeV

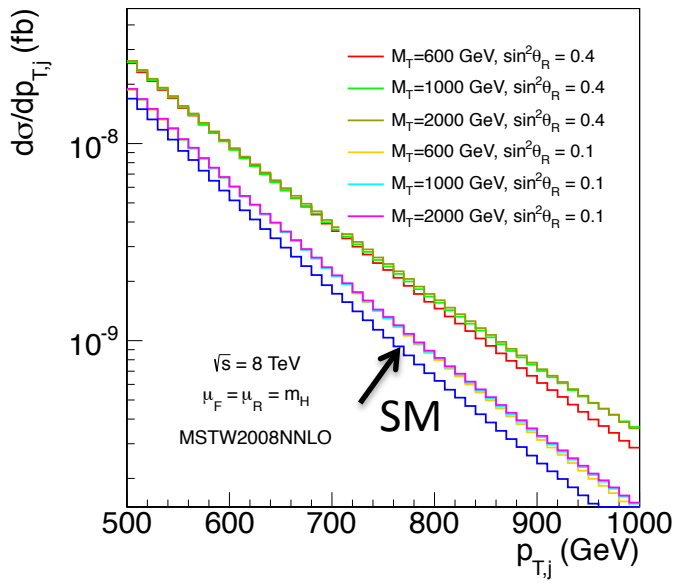
Higgs + Jet

EFT to dimension 7



EFT poorly defined at high p_T

Top partner model



Enhanced rate at high p_T from top partners: Note smallness of effect

[Dawson, Lewis, Zeng, arxXv:1409.6299; Harlander and Neumann, arXiv: 1308.2225; Banfi, Martin, Sanz, arXiv: 1308.4771]

Just the beginning

- Apologies….this talk is just a small sample of the Higgs physics that will be done in Run 2!
  - New Higgs searches
  - Limits on specific models
    - Higgs as a tool
  - SM Higgs properties
  - New channels, new searches
    - FC Higgs effects, rare decays
    - Boosted signatures

"Take a look at this everyone - it just could be the signature we've been looking for!"