ISSUES IN HIGGS PHYSICS LECTURE 2

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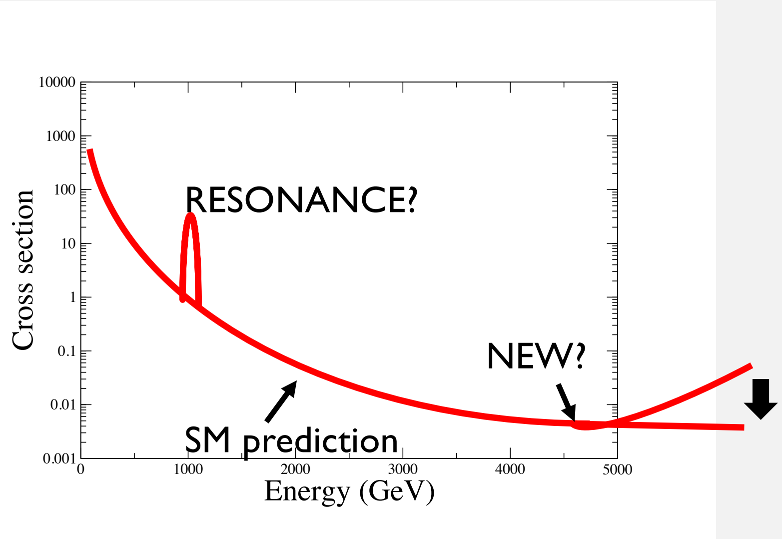
NO SIGN OF MORE HIGGS-LIKE PARTICLES

- No shortage of models predicting more Higgs particles
  - But no evidence yet….
- Look for new physics in tails of distributions
  - Requires precision calculations of SM predictions for comparison
  - This is much harder than looking for resonances



NEW PHYSICS IN HIGGS SECTOR

Use effective field theory

Can we determine source of new physics?

No resonance or light resonance

Current limits are being strengthened at LHC-13

Find resonance!

SCALES

- High scale, Λ: UV complete model with unknown heavy states
  - Integrate out heavy particles to get non-renormalizable effective Lagrangian
  - Renormalization group evolve to low scales

This is sad scenario where there is no intermediate scale physics

- Weak Scale, M_W: Standard Model + remnants of high scale model
  - Described by effective field theory

MOTIVATIONS FOR MORE HIGGS

- Why should the scalar sector be minimal?
  - 2HDM and singlet model don't mess up precision measurements
- Extended Higgs sectors can have dark matter candidate
- Extended Higgs sectors can explain baryogenesis with new sources of CP violation in Higgs sector
- Many BSM models require more Higgs (most famous example is MSSM)

OBVIOUS RESTRICTIONS ON EXTENDED HIGGS MODELS

- ρ parameter (and more generally electroweak corrections) limit extended Higgs sectors

$$\rho = \frac{\Sigma_i \left[T_i(T_i+1) - \frac{1}{4}Y_i^2 \right] v_i^2}{\frac{1}{2}\Sigma_i Y_i^2 v_i^2} = \frac{M_W^2}{M_Z^2 c_W^2}$$

T_i is weak isospin

- T_i=1/2 for doublet; can have as many doublets as you want

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v+h+i\phi_z) \end{pmatrix}, \; T_3 = \begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}, \; Q = T_3 + Y$$

$$\rho = \frac{\Sigma_i \left[\frac{1}{2}\cdot\frac{3}{2} - \frac{1}{4} \right] v_i^2}{\frac{1}{2}\Sigma_i v_i^2} = 1$$

- Singlet doesn't contribute to M_W, M_Z so ρ=1 trivially

New scalars typically contribute to other precision EW observables

2HDM

- Model has 2 Higgs doublets with vevs, v_1 and v_2, tan $\beta=v_2/v_1$
  - 2HDM has 8 degrees of freedom: 3 become longitudinal degrees of freedom of $W^\pm$, Z
- 5 degrees of freedom left: h, H (neutral), A (pseudoscalar), $H^\pm$
- Diagonalize neutral Higgs mass matrix with angle α

$$\sin 2\alpha = -\sin 2\beta \left(\frac{M_H^2 + m_h^2}{M_H^2 - m_h^2} \right)$$

For 2HDM, h (H) is lighter (Heavier) neutral Higgs

GENERAL 2 HIGGS DOUBLET MODEL

- 6 free parameters, plus a phase

$$
\begin{aligned}
V(H_1, H_2) &= \lambda_1 (H_1^+ H_1 - v_1^2)^2 + \lambda_2 (H_2^+ H_2 - v_2^2)^2 \\
&+ \lambda_3 \left[(H_1^+ H_1 - v_1^2) + (H_2^+ H_2 - v_2^2)\right]^2 \\
&+ \lambda_4 \left[(H_1^+ H_1)(H_2^+ H_2) - (H_1^+ H_2)(H_2^+ H_1)\right] \\
&+ \lambda_5 \left[\mathrm{Re}(H_1^+ H_2) - v_1 v_2 \cos\xi\right]^2 \\
&+ \lambda_6 \left[\mathrm{Im}(H_1^+ H_2) - v_1 v_2 \sin\xi\right]^2
\end{aligned}
$$

$$\langle H_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix}$$

- W and Z masses just like in Standard Model $\quad M_W^2 = \dfrac{g^2 (v_1^2 + v_2^2)}{2}$
- ρ parameter: $\quad \rho = \dfrac{M_W}{M_Z \cos\theta_W} = 1$

ρ=1 for any number of Higgs doublets or singlets

GAUGE BOSON COUPLINGS TO HIGGS IN 2HDM

- $g_{hVV}^2 + g_{HVV}^2 = g_{hVV}^2(SM)$
- Vector boson fusion and Vh production always suppressed

$$\frac{g_{hVV}}{g_{h,smVV}} = \sin(\beta - \alpha)$$
$$\frac{g_{HVV}}{g_{h,smVV}} = \cos(\beta - \alpha)$$

hVV couplings go to SM couplings when $\cos(\beta-\alpha) \to 0$

Alignment limit: couplings are SM like regardless of masses
Decoupling limit: couplings are SM like for heavy Higgs masses

HIGGS COUPLINGS IN 2HDM

- 2 Higgs doublet models with no FCNC
  - Parameters are α (mixing in neutral sector), λ_5, tan β, M_h, M_H, M_A, M_{H+}
  - 4 possibilities for Higgs coupling assignments

$$L = -g_{hii}\frac{m_i}{v}\overline{f}_i f_i h - g_{hVV}\frac{2M_V^2}{v}V_\mu V^\mu h$$

Need to forbid flavor changing neutral currents from Higgs exchange

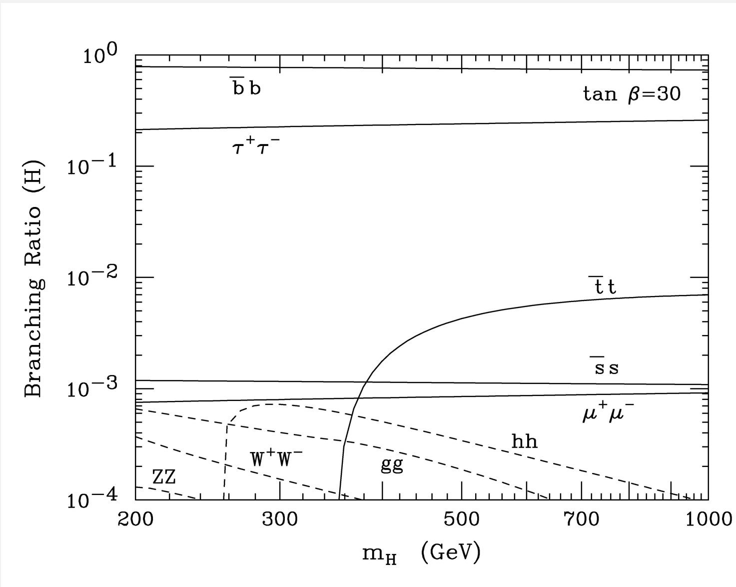
	I	II	Lepton Specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

Type II is MSSM – like 2 Higgs doublet model

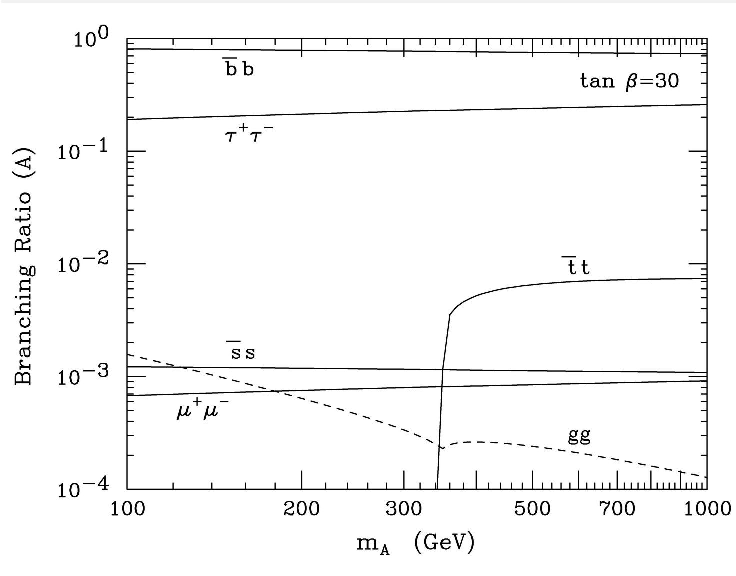
HIGGS DECAYS DEPEND ON TAN β

- At large tan β, rates to bb and $\tau^+\tau^-$ large and ~ constant in type-II 2HDM

Heavy H^0 BRs



A^0 BRs



HOW IS THE MSSM HIGGS SECTOR DIFFERENT FROM A 2HDM?

- MSSM and 2HDM both have 2 scalar SU(2) doublets
- 2HDM has 7 parameters in scalar potential: α, $\tan\beta$, M_H, M_h, M_A, $M_{H\pm}$, λ_5
- MSSM has 2 parameters in scalar sector: M_A, $\tan\beta$
- 2HDM Higgs masses are free parameters
- MSSM predicts (at tree level):

$$M_{H\pm}^2 = M_A^2 + M_W^2$$
$$m_h^2 + M_H^2 = M_A^2 + M_Z^2$$
$$m_h^2 M_H^2 = M_Z^2 M_Z^2 \cos^2(2\beta)$$

*large radiative corrections to MSSM mass relations

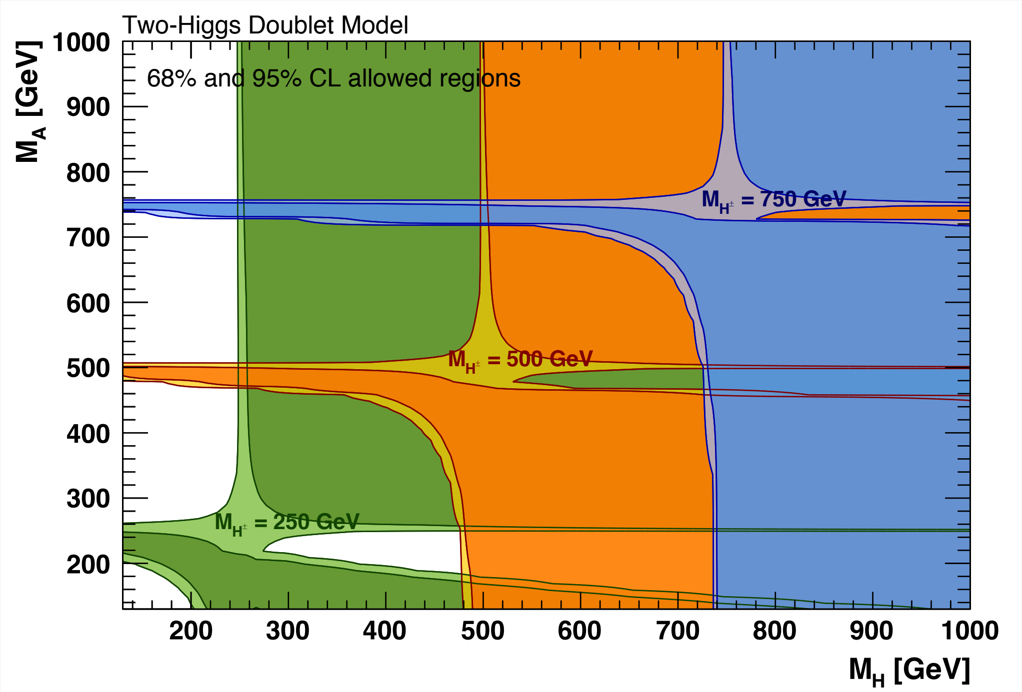
HOW IS THE MSSM HIGGS SECTOR DIFFERENT FROM A 2HDM?

- MSSM and 2HDM have same couplings of gauge bosons to scalars
- MSSM has same scalar- fermion couplings as Type-II 2HDM
- MSSM loops (Higgs decays to $\gamma\gamma$ and ZZ, along with gluon fusion production), depend on other particles of MSSM theory
- Cubic Higgs couplings different in 2HDM and MSSM
  - (this will show up in discussion of hh limits)

ONCE AGAIN LIMITS FROM PRECISION ELECTROWEAK

$$\rho \sim (m_i^2 - m_j^2)$$

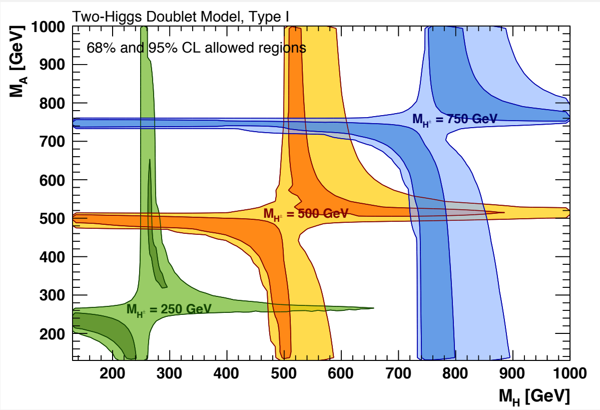
where m_i, m_j are the scalar masses

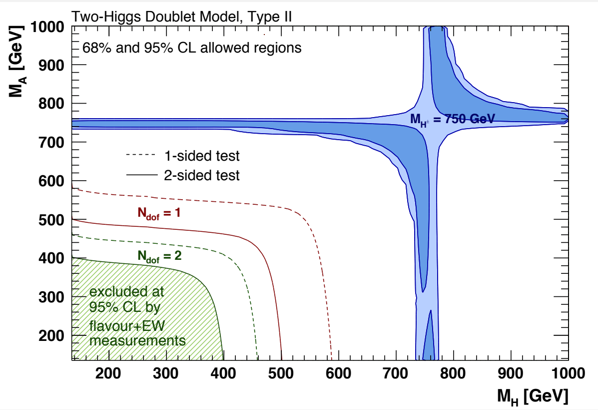


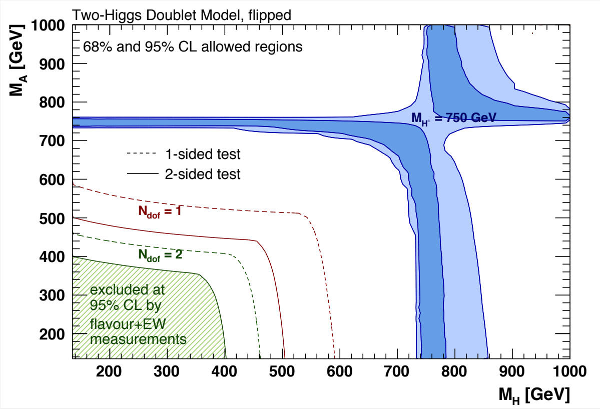
Haller, Hoecker, Kogler,Monig, Peiffer, Stelzer, 1803.01853

2HDM LIMITS

- Combine Higgs couplings, flavor, g-2, precision electroweak





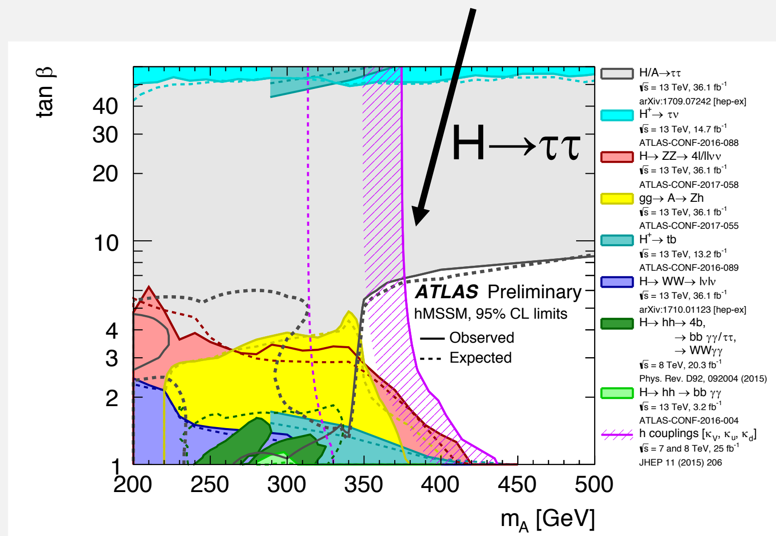


[Gfitter]

DIRECT SEARCH AND COUPLING MEASUREMENTS ARE TYPICALLY COMPLIMENTARY

- 2HDM: $h^0, H^0, A^0, H^\pm$
  - Scalar couplings of type-II 2HDM is identical to MSSM
- Higgs sector described in terms of $M_h, M_H, M_A, M_{H\pm}, \tan\beta$
- Plot assumes $M_H = M_A$

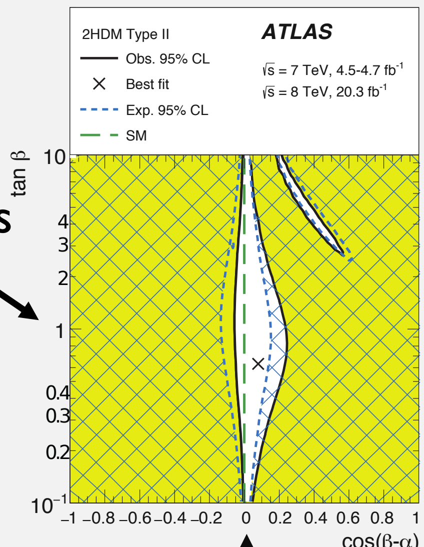
Higgs couplings



MSSM LIMITS

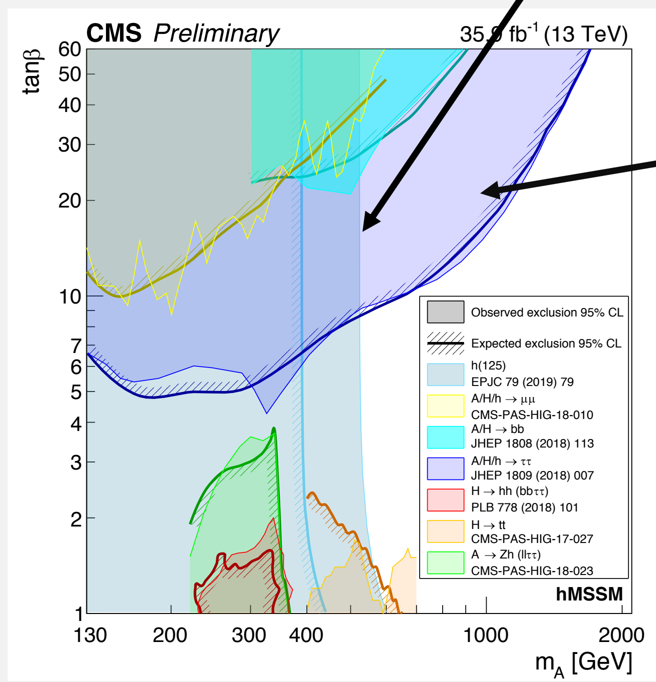
Large M_A, Higgs couplings approach SM couplings

Limits from couplings



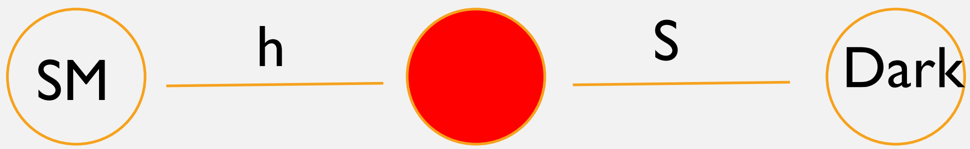
SM limit

Higgs couplings



H→ττ

SINGLET MODEL



PROS:

- Simple (one new scalar, gauge singlet, S)
- Singlet can be portal to hidden sector
- Can give first order EW phase transition for some parameter values
- Can generate enhancements of hh production

CONS:

- No prediction for mass/mixing parameters

SINGLET MODEL WITH Z_2

- Very predictive: (invariant under S→ -S)

$$V = -\mu^2 \phi^\dagger \phi - m^2 S^2 + \lambda (\phi^\dagger \phi)^2 + \frac{a_2}{2} (\phi^\dagger \phi) S^2 + \frac{b_4}{4} S^4$$

- Physical fields:

$$h = \cos\theta h_{SM} - \sin\theta S$$
$$H = \sin\theta h_{SM} + \cos\theta S$$

- Physical parameters:

$$M_h, M_H, v, tan\beta = \frac{v}{\langle S \rangle}, \theta$$

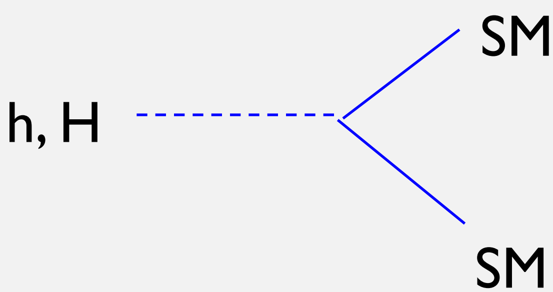
- Unitarity bound from hh→hh

$$\tan^2\beta < \frac{16\pi v^2}{3 M_H^2}$$

M_H is heavier Higgs
Model prefers small tan β

Z_2 SYMMETRIC SINGLET MODEL

- Very simple model:



Coupling to light Higgs ~ cos θ
Coupling to heavy Higgs ~ sin θ

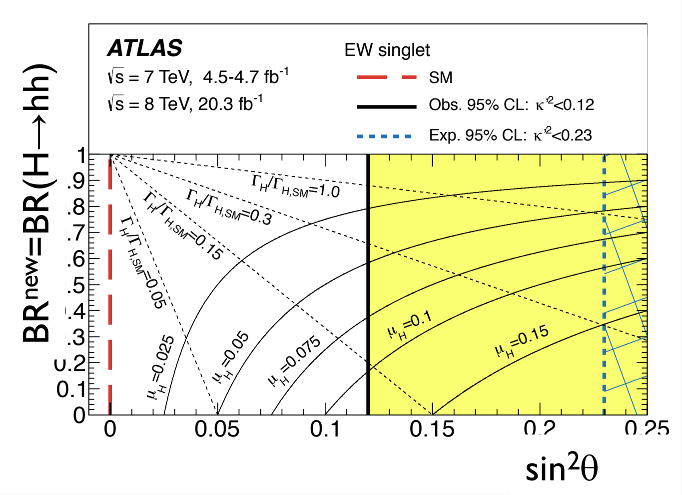
- If kinematically allowed, H → hh

$$\Gamma(h) = \cos^2\theta \Gamma_{SM}$$

$$\Gamma(H) = \sin^2\theta \Gamma_{SM} + \Gamma(H \to hh)$$

SINGLET MODEL

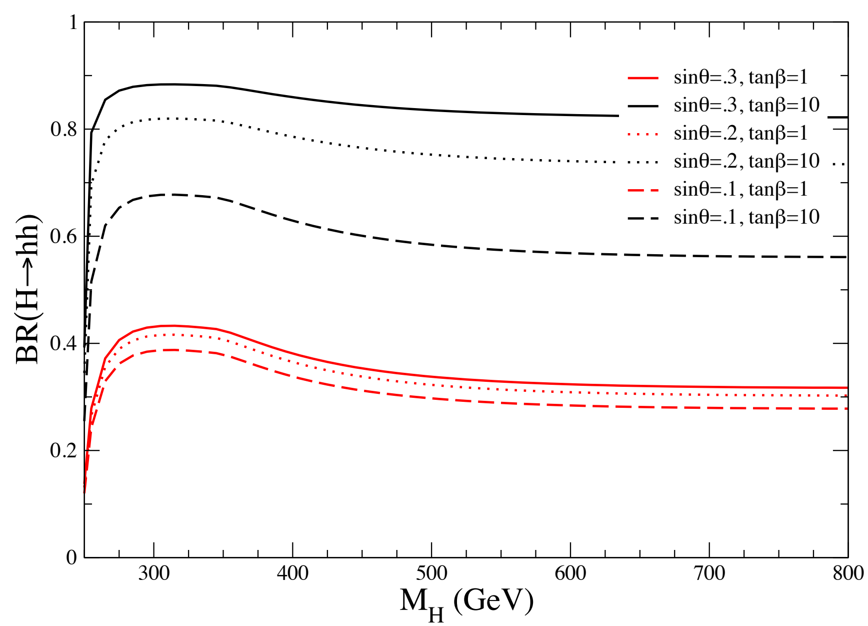
- Experimental limits on coupling suppression of SM-like Higgs to SM fermions ($\sin^2\theta < .12$)
- Information from recasting heavy Higgs searches can also be used
- BR(H→hh) can be up to ~ 30%



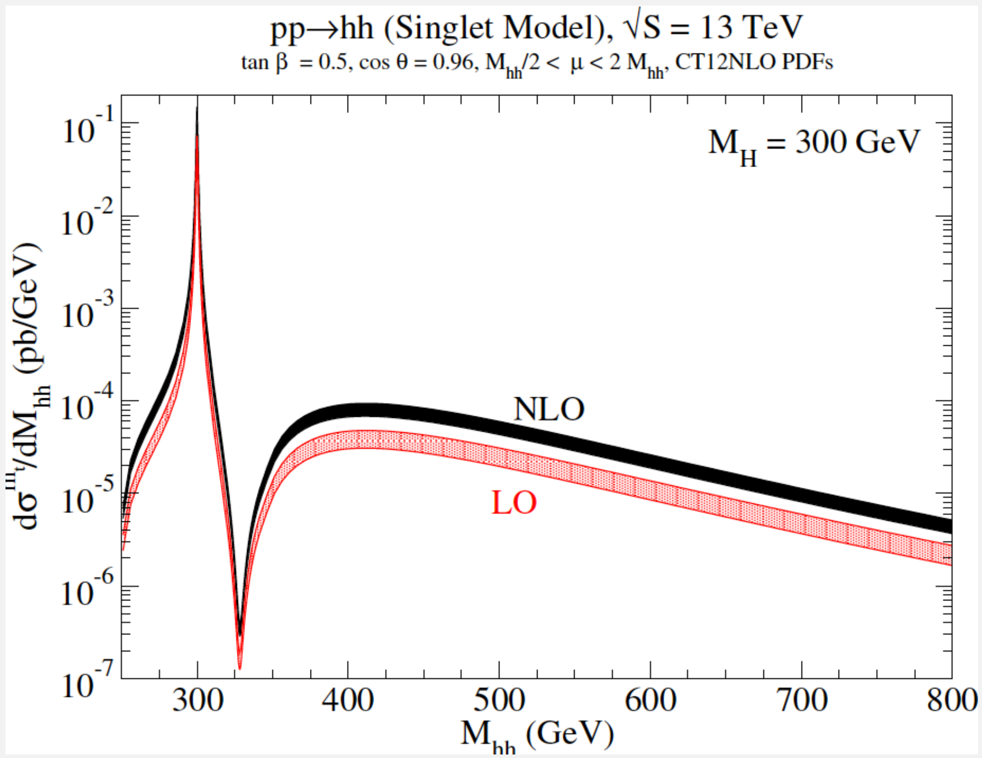
$$\sigma_h = \cos^2\theta\sigma_{SM}, \quad \Gamma_h = \cos^2\theta\Gamma_{SM}, \quad BR(h\rightarrow SM) = BR_{SM}, \quad \mu_h = \cos^2\theta$$

$$\sigma_H = \sin^2\theta\sigma_{SM}, \quad \Gamma_H = \sin^2\theta\Gamma_{SM} + \Gamma_H BR(H\rightarrow hh), \quad \mu_H = \sin^2\theta\left[1 - BR(H\rightarrow hh)\right]$$

BRANCHING RATIO $H \to hh$ CAN BE SIGNIFICANT



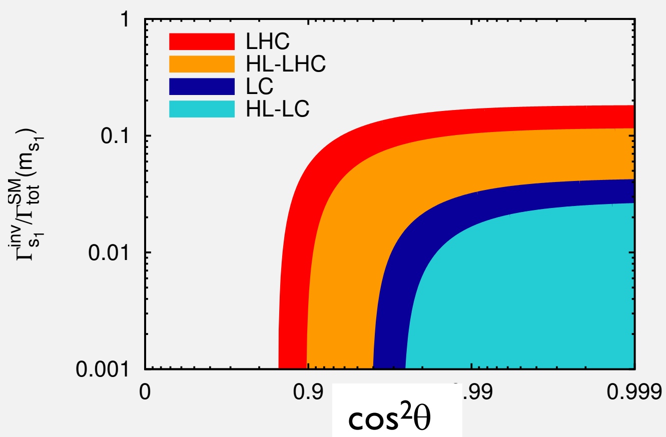
LARGE RESONANCE/INTERFERENCE EFFECTS IN hh PRODUCTION

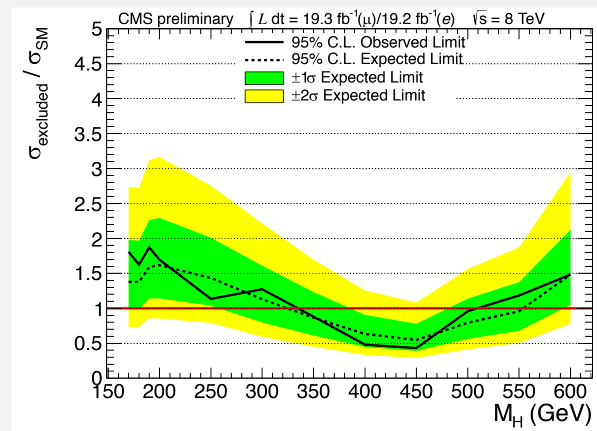


Dawson, Lewis, [1508.05397]

COMPLEMENTARITY OF APPROACHES

- Find heavier Higgs and measure deviations in couplings
- $\sin^2\theta < .12$ from h couplings
  - Need increased sensitivity in direct searches





$\sigma/\sigma_{SM} = \sin^2\theta$ with no BR (H→hh)

Englert et al, [1403.7191]

HIGGS SINGLET MODEL WITHOUT Z_2

$$V(\phi, S) = V_{SM}(\phi) + V_{\phi S}(\phi, S) + V_S(S)$$
$$V_{\phi S}(\phi, S) = \frac{a_1}{2}(\phi^\dagger \phi) S + \frac{a_2}{2}(\phi^\dagger \phi) S^2$$
$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

- Models without Z_2 symmetry motived by desire to explain electroweak baryogenesis
- (They typically prefer negative a_1, b_3 and lighter H)
- Can set tan β=0 in this case

More parameters, but still can be studied in terms of mass of H, coupling of h, H to SM fermions, coupling of Hhh

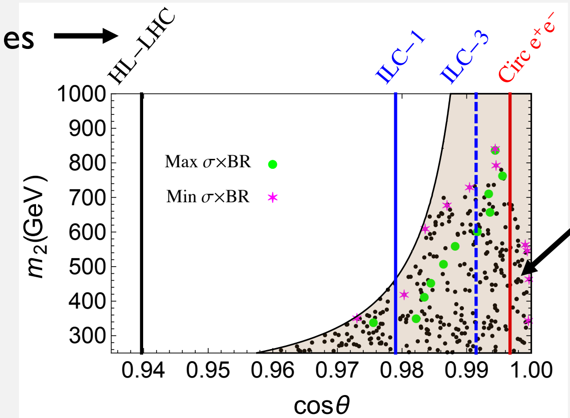
Profumo, Ramsey-Musolf, Wainwright, Winslow, 1407.5342;
Curtin, Meade, Yu, 1409.0005

HH CAN GIVE INFORMATION ON ELECTROWEAK PHASE TRANSITION

- Models with scalar singlets can allow first order electroweak phase transition

Limits from future machines →

Heavier scalar in singlet model



Suppression of SM Higgs couplings

- Motivation for high energy colliders
- Can probe region with EW phase transition in hh production

Kotwal, Ramsey-Musolf, No, Winslow, 1605.06123

EXTENDED HIGGS SECTORS

- 2 possibilities for Higgs triplets

$$X_t = \begin{pmatrix} \zeta^+ \\ \zeta^0 \\ \zeta^- \end{pmatrix} \qquad X_t' = \begin{pmatrix} \xi^{++} \\ \xi^+ \\ \xi^0 \end{pmatrix}$$

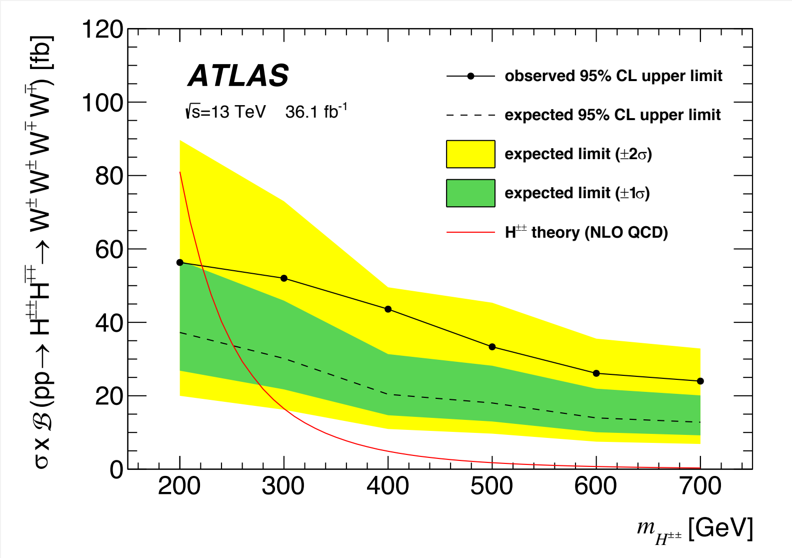
Doubly charged Higgs provides nice signature

- Extreme fine tuning required in general

$$\rho = 1 + \frac{4(v_\zeta^2 - v_\xi^2)}{v^2}$$

TRIPLET MODEL

- Unique signature, $H^{++} \to W^+W^+$



WHAT IF WE DON'T SEE A NEW PARTICLE?

- Most heavy Higgs limits will come with 300 fb^{-1} (limited by energy)
- Then we must search for new physics through precision measurements and searches for rare processes
- Will require precision theory calculations in both the SM and in EFTs
- Theory is already limiting factor in coupling extractions

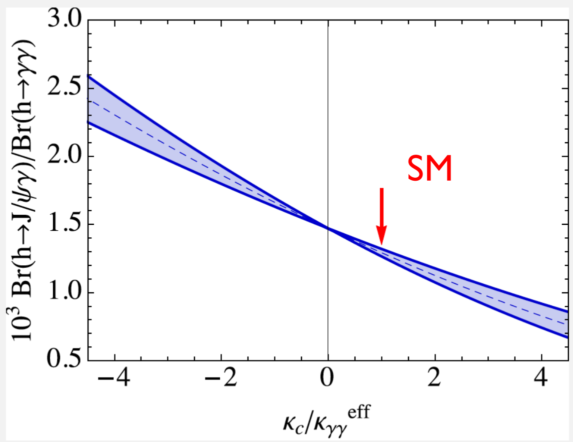
LOOK FOR RARE PROCESSES

- Does Higgs couple to 1st and 2nd generations? $\sigma_H \cdot BR(H \to \mu^+\mu^-) < 2.8[SM]$
- 3 ab^{-1} projection is 7σ for H $\to \mu\mu$ with $\delta\mu/\mu \sim \pm$ 20%

Small rates for H$\to\varphi\gamma$, $\psi\gamma$

3000 fb^{-1} ATLAS projects sensitivity to 15 x SM

LHCb ZH, H$\to$cc,
3000 fb^{-1} $\sigma/\sigma_{SM} < 2$



New ideas needed

Konig, Neubert, 1505.03870

LOOK FOR FLAVOR VIOLATION IN THE HIGGS SECTOR

- Higgs couples proportionally to mass

$$L = -Y_{ij}\overline{f}_i f_j H \qquad\qquad Y_{ij} = \frac{m_i}{v}\delta_{ij}$$

- Suppose there is new physics beyond the SM:

$$\delta L = -\frac{c_{ij}}{\Lambda^2}\overline{Q}^i_L \phi f^j_R(\phi^\dagger\phi) + hc \qquad Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}c_{ij}(...)$$

- Mass and Yukawas no longer proportional
- Can have flavor changing Higgs decays!
  - eg: $H \rightarrow \mu\tau$
- Easy to build models where this is the case

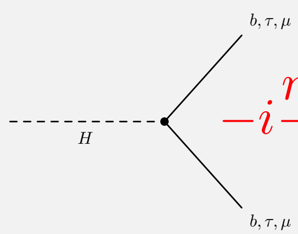
Smoking gun for new physics!

TESTING HIGGS COUPLINGS: RUN 1

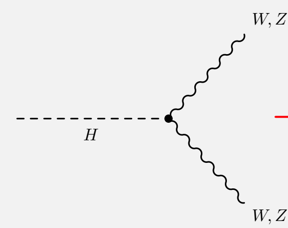
- Assume no new resonances/zero width approx/no new tensor structures

$$\sigma \cdot BR(ii \to h \to jj) = \frac{\sigma_{ii}\Gamma_{ij}}{\Gamma_h}$$

- Define scaling factors κ



$$-i\frac{m_f}{v}\kappa_f$$



$$-2i\frac{M_V^2}{v}g^{\mu\nu}\kappa_V$$

SM, gauge invariance requires κ=1

SMALL CORRECTIONS EXPECTED IN BSM

If new physics is at 1 TeV:

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

Limits are moving targets: as precision measurements and direct searches improve, allowed BSM parameter space shrinks

Patterns of deviations can pinpoint specific BSM physics

*limits go like $1/M^2$ and assume values of tan β

Snowmass Higgs report, 1310.8361

HOW TO GET THE MOST FROM HIGGS MEASUREMENTS

- Problems:
  - Gauge invariance requires $\kappa=1$
    - Higgs couplings not free parameters in SM
  - Not a consistent field theory $\rightarrow$ no higher order corrections
    - EW corrections don't factorize
  - No kinematic information
  - Higgs coupling measurements cannot be combined with other measurements

REQUIRES EFFECTIVE FIELD THEORY FRAMEWORK

- Assume SU(3) x SU(2) x U(1) gauge theory with no new light particles
- Assume Higgs particle is part of SU(2) doublet (defines SMEFT)
- SM is low energy limit of effective field theory with towers of higher dimension operators

$$L = L_{SM} + \Sigma \frac{c_i}{\Lambda^2} O_i^{d=6} + \Sigma \frac{d_i}{\Lambda^4} O_i^{d=8} + ...$$

BSM Effects SM Particles

- Renormalizable order by order in $1/\Lambda^2$

Dimension-5 operators contribute to lepton number violation

SM EFFECTIVE FIELD THEORY

- Many dimention -6 operators, so simplify by neglecting flavor …. Still 59 operators
  - Some operators strongly limited by low energy physics (eg STU, G_F…)
- Different parameterizations connected by equations of motion
  - Straightforward to go from one basis to another
  - Choice of basis reflects prejudice on high scale physics generating SMEFT
- Effects of derivatives in tails of distributions
- Radiative corrections can be systematically included in SMEFT

EXAMPLE OF CONSTRUCTING OPERATORS

- Take any SM interaction, say $L \sim -ig_s\bar{t}\gamma^\mu T^A t G^a_\mu$
- Tack on $\phi^\dagger\phi$

$$L \sim \left[-ig_s\bar{t}\gamma^\mu T^A t G^a_\mu\right] c_{tg}\left(\frac{\phi^\dagger\phi}{\Lambda^2}\right)$$

- Generate redefinition of SM terms plus Higgs couplings from

$$\phi^\dagger\phi = \frac{(h+v)^2}{2} \qquad L \sim \left[-ig_s\bar{t}\gamma^\mu T^A t G^a_\mu\right] c_{tg}\left(\frac{v^2+2vh+h^2}{2\Lambda^2}\right)$$

- First term redefines α_s

$$\alpha_s \rightarrow \alpha_s^{SM}\left(1+\frac{c_{tg}v^2}{\Lambda^2}\right)$$

Change SM interactions in gauge invariant manner

CONSTRUCT SMEFT FOR HIGGS

Change definitions on input parameters

g_s	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{\mu\nu,A}$	$gg \to h$
g	$(\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$	$h \to \gamma\gamma$
g'	$(\phi^\dagger\phi)W^a_{\mu\nu}W^{\mu\nu^a}$	$h \to Z\gamma$
M_W	$(\phi^\dagger\phi) \mid D_\mu\phi \mid^2$	$h \to VV^*$
M_H	$(\phi^\dagger\phi)^3$	λ_3
M_f	$(\phi^\dagger\phi)\overline{f}_L\phi f_R + hc$	$h\tau\tau, hb\bar{b}, ht\bar{t}$

Take SM operators and add

$$\phi^\dagger\phi = \frac{1}{2}(h+v)^2$$

OTHER OPERATORS MORE COMPLICATED

$$O_{3W} = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c\mu} \qquad O_{HD} = |\Phi^\dagger D_\mu \Phi|^2 \qquad O_{HWB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu}$$

$$O_{H\ell}^{(3)} = i\left(\Phi^\dagger \overleftrightarrow{D}_\mu \sigma^a \Phi\right) \bar{\ell}_L \gamma^\mu \sigma^a \ell_L \qquad O_{ll} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$$

These change 3 gauge boson couplings

$$O_{HQ,ij}^{(3)} = i\left(\Phi^\dagger \sigma^a D_\mu \Phi - (D_\mu \Phi)^\dagger \sigma^a \Phi\right) \bar{Q}_{Li} \gamma^\mu \sigma^a Q_{Lj}$$

$$O_{HQ,ij}^{(1)} = i\left(\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger \Phi\right) \bar{Q}_{Li} \gamma^\mu Q_{Lj}$$

$$O_{Hq,ij} = i\left(\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger \Phi\right) \bar{q}_{Ri} \gamma^\mu q_{Rj}$$

These change fermion/ gauge boson couplings

+ many, many more…..

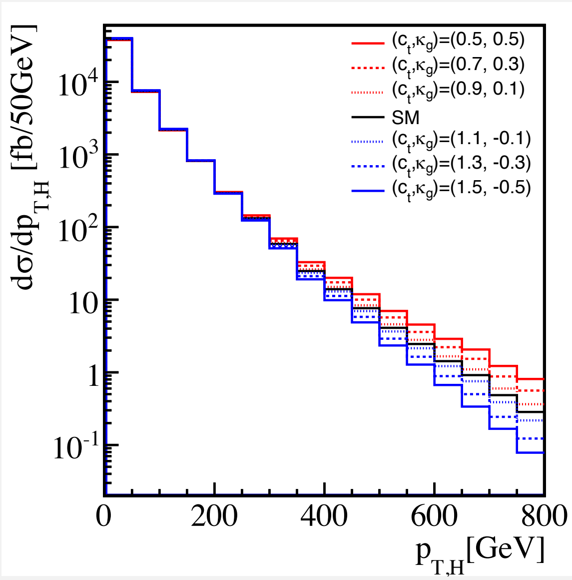
- The interesting operators are those with derivatives
- Derivative operators introduce new structures into interactions

MOMENTUM DEPENDENT OPERATORS CHANGE KINEMATIC DISTRIBUTIONS

- Look in tails of distributions
- Typically quite small effects:

$$\mathcal{O}\left(\frac{p_T^2}{\Lambda^2}\right)$$

- Couplings constrained to give correct rate for ggH



Higgs plus jet production at 14 TeV

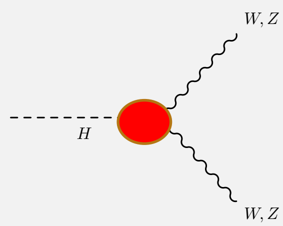
New physics in ggH and ttH couplings

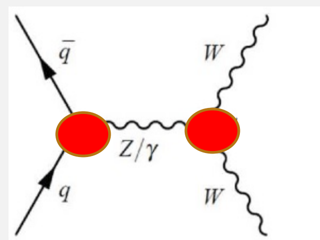
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, [1405.4295](https://arxiv.org/abs/1405.4295)

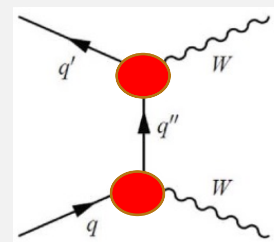
CAN'T JUST FIT HIGGS COUPLINGS

Operators that contribute to VVV vertices and Higgs-VV vertices

$$O_W = (D_\mu \phi)^\dagger W^{\mu\nu} (D_\nu \phi)$$
$$O_B = (D_\mu \phi)^\dagger B^{\mu\nu} (D_\nu \phi)$$
$$O_{WW} = Tr(W_{\mu\nu} W^{\nu\rho} W_\rho^\mu)$$







Anomalous qqW, qqZ vertices too!

- Changing ZWW, γWW vertices spoils high energy cancellations between contributions
- Effective field theory effects enhanced at high energy, high p_T
- Always looking at tails of distributions

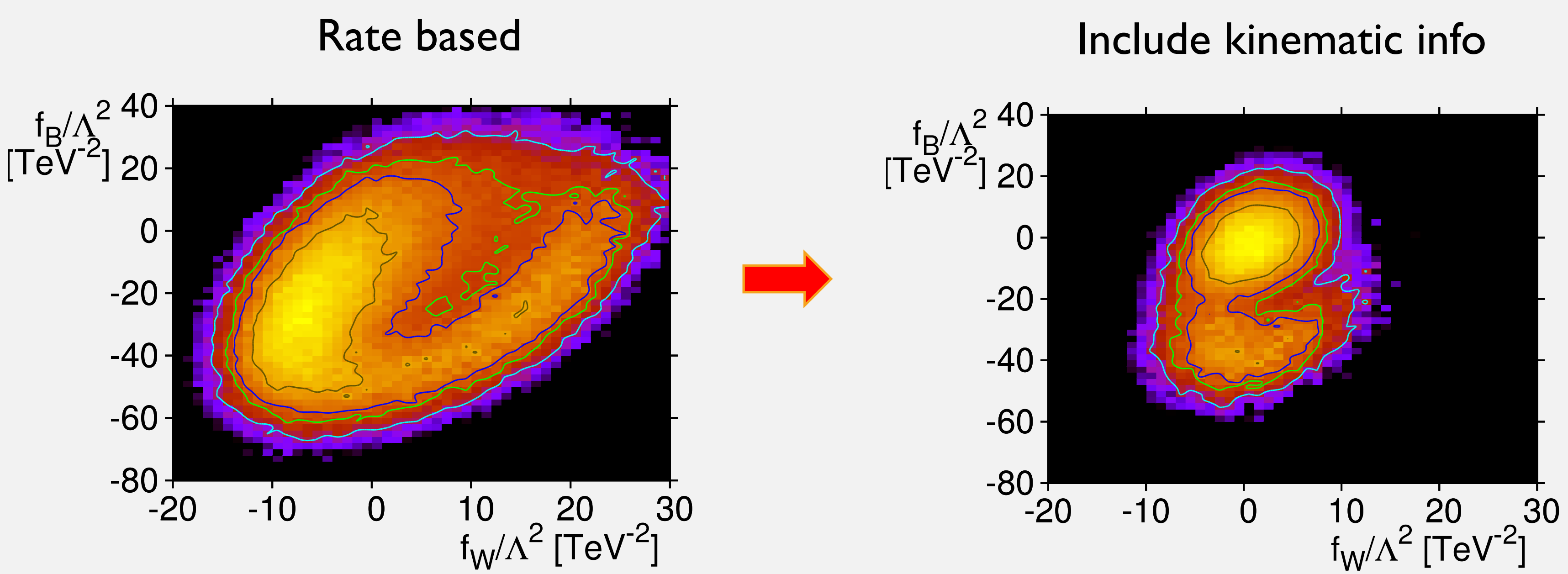
PRECISION BEYOND TOTAL RATES

- SMEFT extends SM Lagrangian assuming 1 Higgs doublet, SU(3) x SU(2) x U(1) symmetry, dimension 6 operators only, only SM particles
- Expansion in (Energy)$^2/\Lambda^2$

$$L \to L_{SM} + \Sigma_i \frac{C_{6i}}{\Lambda^2} O_{6i} + \Sigma_i \frac{C_{8i}}{\Lambda^4} O_{8i} + \ldots$$

  - Expect enhanced effects in tails of distributions
- Global fits include LEP precision data, VV production, Higgs production….
  - Effective field theory connects different processes with large correlations
  - Precision requires a complete set of operators, not just one at a time

IMPROVEMENT IN FITS WITH KINEMATIC INFORMATION



Corbett, Eboli, Goncalves, Gonzalex-Frail, Plehn, Rauch, [1505.05516](1505.05516)

WHEN IS EFT VALID?

$$L \to L_{SM} + \Sigma_i \frac{C_{6i}}{\Lambda^2} O_{6i} + \Sigma_i \frac{C_{8i}}{\Lambda^4} O_{8i} + \ldots$$

- SMEFT

$$A^2 \sim \mid A_{SM} + \frac{A_6}{\Lambda^2} + \ldots \mid^2 \sim A_{SM}^2 + \frac{A_{SM} A_6}{\Lambda^2} + \frac{A_6^2}{\Lambda^4} + \ldots.$$

- Problem is that $(A_6)^2$ terms are the same order as A_8 terms that we have dropped
- If I only keep A_6/Λ^2 terms and drop $(A_6/\Lambda^2)^2$, the cross section is not guaranteed to be finite
- Corrections are $O(s/\Lambda^2)$

COUNTING LORE

$$\sigma \sim g_{SM}^2 (A_{SM})^2 + g_{SM} g_{BSM} A_{SM} A_6 \frac{s}{\Lambda^2}$$
$$+ g_{BSM}^2 (A_6)^2 \frac{s^2}{\Lambda^4} + g_{SM} g_{BSM} A_{SM} A_8 \frac{s^2}{\Lambda^4}$$

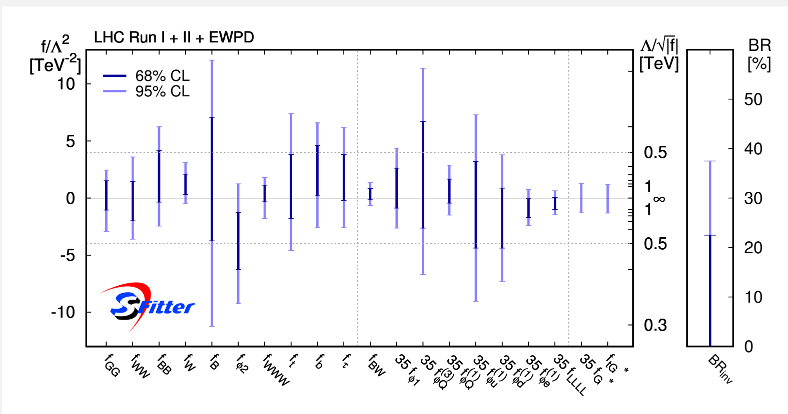
Same order of magnitude if $g_{SM} \sim g_{BSM}$

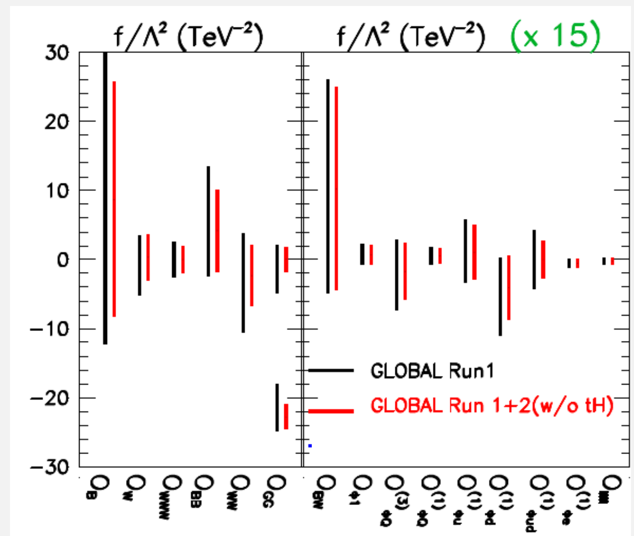
$(\text{Dim-6})^2$ could dominate if $g_{BSM} >> g_{SM}$

DIMENSION-6 EXPANSION WORKS FOR STRONGLY INTERACTING THEORY

GLOBAL FITS CONSTRAIN EFT OPERATORS

- Fits to Higgs data, gauge boson pair production, LEP observables

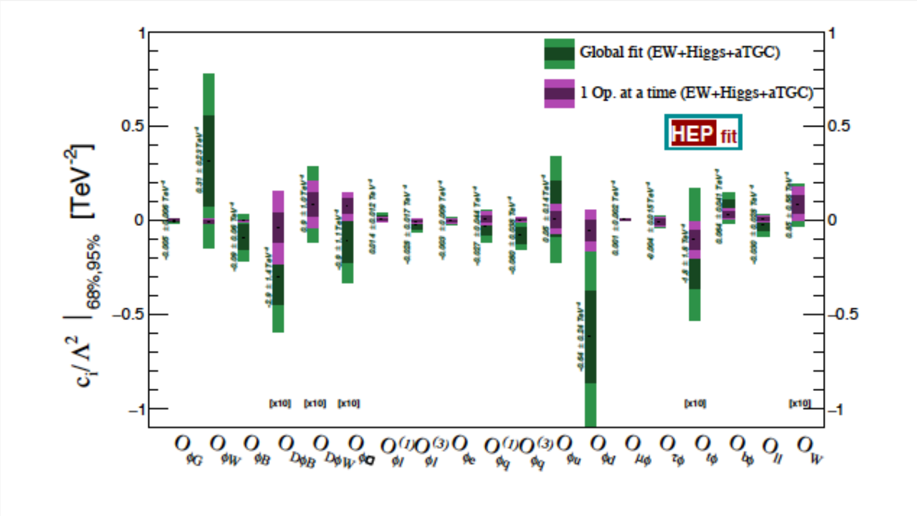




Biekotter, Corbett, Plehn, https://arxiv:1812.07587;
Almeida, Alves, Rosa-Agostinho, Eboli, Gonzalez-Garcia, arXiv:1812.01009

GLOBAL FITS CONSTRAIN EFT COEFFICIENTS

- Very different results when only a single operator is constrained

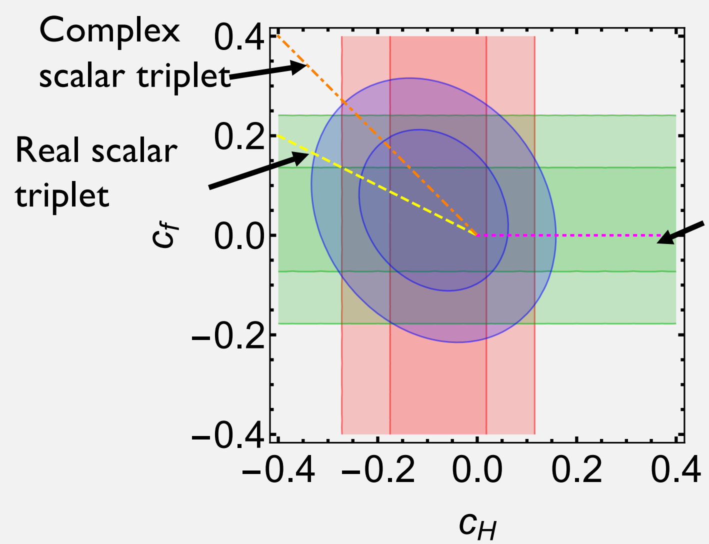


Reina, LHCP, 2019

WHAT DO WE LEARN BY FITTING HIGGS COUPLINGS?

- In any given high scale model, coefficients of EFT predicted in terms of small number of parameters
- Different coefficients are generated in different models
- By measuring the pattern of coefficients, information is gleaned about high scale physics

Fit to Higgs data

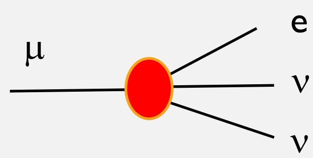


$$O_H = \frac{1}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$

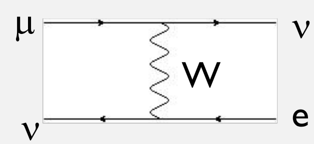
$$O_f = \frac{(\phi^\dagger\phi)}{v^2} c_f y_f (\overline{\psi}_L f_R \phi)$$

Dawson, Murphy, 1704.07851

WHAT NEXT?



- μ decay: Gives very precisely measured $G_F \sim 10^{-5}$ GeV^{-2}
  - 4 fermion interaction rate grows with energy ~ G_F^2 $(Energy)^2$
  - Theory only makes sense for Energy < 600 GeV
- Inverse μ decay: μ→ eνν
- W boson saves the day

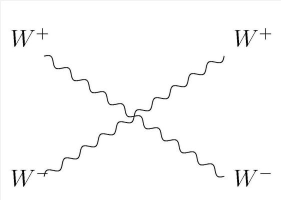


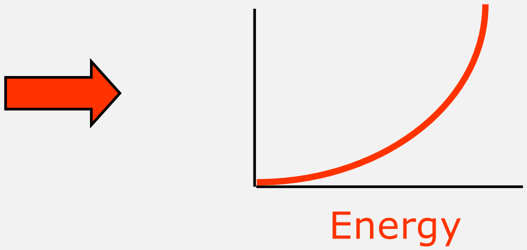
Rate ~ $G_F^2 M_W^2$

Something like the W had to exist

W BOSON RE-INTRODUCES THE SAME PROBLEM

- Scattering amplitudes of W's grow with energy





- WW scattering violates *unitarity* at energy of 3000 GeV = 3 TeV
- Higgs boson solves this as long as $M_H < 800$ GeV

Something like the Higgs boson had to exist

THE NEW PARADIGM

- Past: Guaranteed discoveries ensured by no-lose theorems
  - Beyond the Fermi theory (the W)
  - Beyond the bottom quark (the top)
  - Beyond the electroweak theory (the Higgs)

    - ➢ Scattering amplitudes grow with energy without W, top, Higgs….
    - ➢ Knew the scale of new physics

  - Future : No guarantees

CONCLUSIONS

- What I'd really like to know:
  - Are there more Higgs particles?
  - Is there a significant Higgs invisible width (clear signal for new physics)
  - Are the Higgs couplings within ~5% of the SM predictions (long and hard slog to get there; requires fits with gauge boson/top contributions)
    - Does the Higgs couple to 1st and 2nd generation fermions?
    - With no flavor changing Higgs couplings?
  - What is the Higgs self-coupling (ie, is it really the Higgs potential generating W/Z masses?) Motivation for higher energy machines