ISSUES IN HIGGS PHYSICS
LECTURE 3

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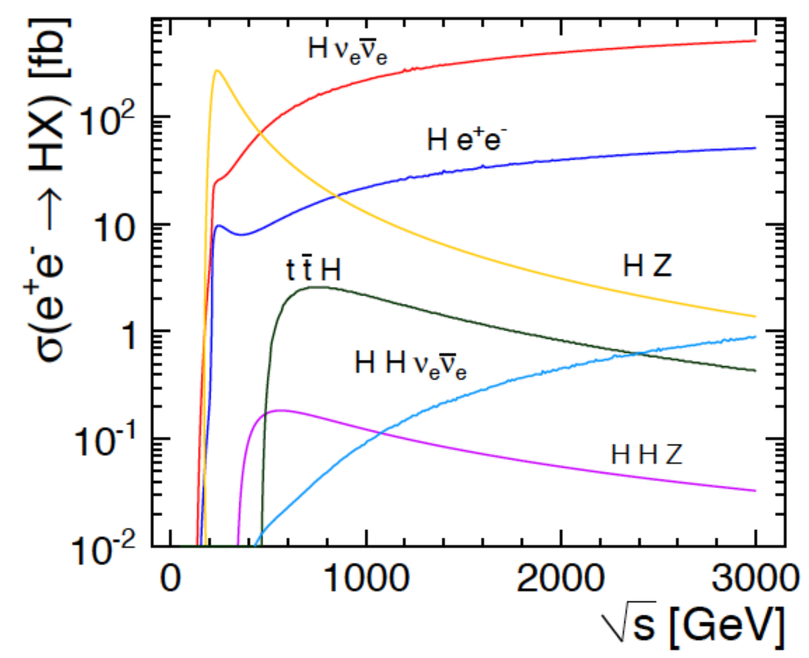
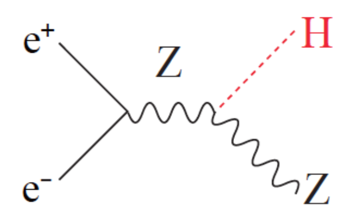
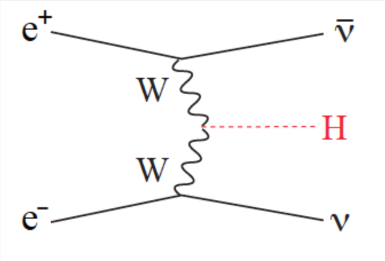
Please send questions or corrections to dawson@bnl.gov

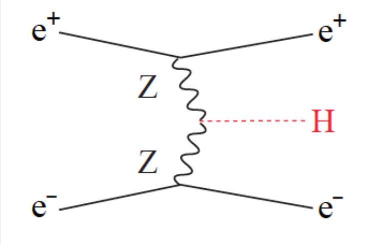
e^+e^- COLLIDERS





Note sharp threshold





HIGGS WIDTH AT e^+e^- COLLIDERS

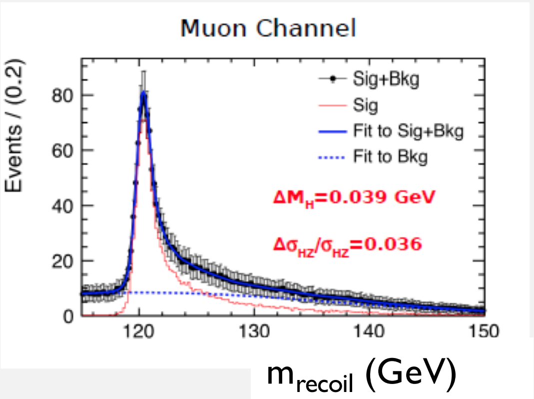
- Use recoil technique: $e^+e^- \rightarrow Zh$; tag $Z \rightarrow \mu^+\mu^-, e^+e^-$
  - Reconstruct recoil mass, $m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{l^+l^-})^2 - |\vec{p}_{ll}|^2$
  - Identify Higgs independent of decay
  - This gives: $\sigma(Zh) \sim (g_{hZZ})^2$
  - Classify the rest of the events to measure BR(h→ XX)

ILC250:

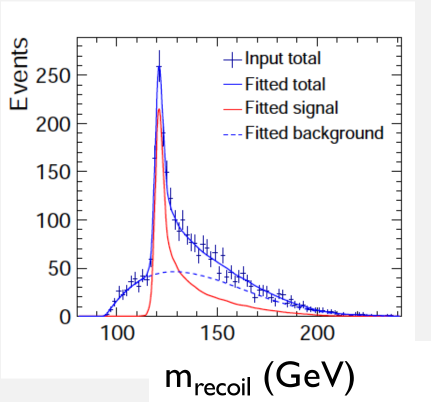
$$\frac{\Delta\sigma}{\sigma} = 2.5\%$$

$$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 1.3\%$$

$$\Delta\Gamma_h = 11\%$$



$e^+e^- \rightarrow Zh$, ILC at $\sqrt{s}$=250 GeV, 250 fb^{-1}



$e^+e^- \rightarrow Zh$, CLIC at $\sqrt{s}$=350 GeV, 500 fb^{-1}

CLIC350:

$$\frac{\Delta\sigma}{\sigma} = 4\%$$

$$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 2\%$$

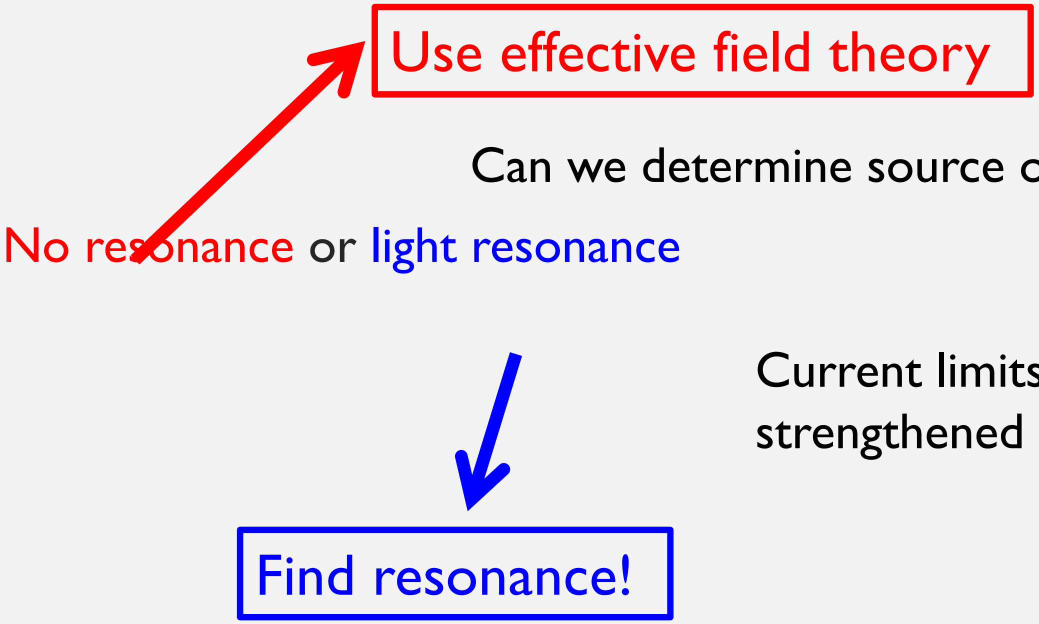
HIGGS WIDTH AT e^+e^- COLLIDERS

- Recoil technique gives independent measurements of total width and branching ratios
- Get total Higgs width: $\Gamma_h = \frac{\Gamma(h \to ZZ)}{BR(h \to ZZ)} \sim \frac{\sigma(Zh)}{BR(h \to ZZ)}$
- At higher energies can also use $e^+e^- \longrightarrow \nu\nu h$

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

Advantage: Coupling extractions don't need assumptions about total width

NEW PHYSICS IN HIGGS SECTOR



Use effective field theory

Can we determine source of new physics?

No resonance or light resonance

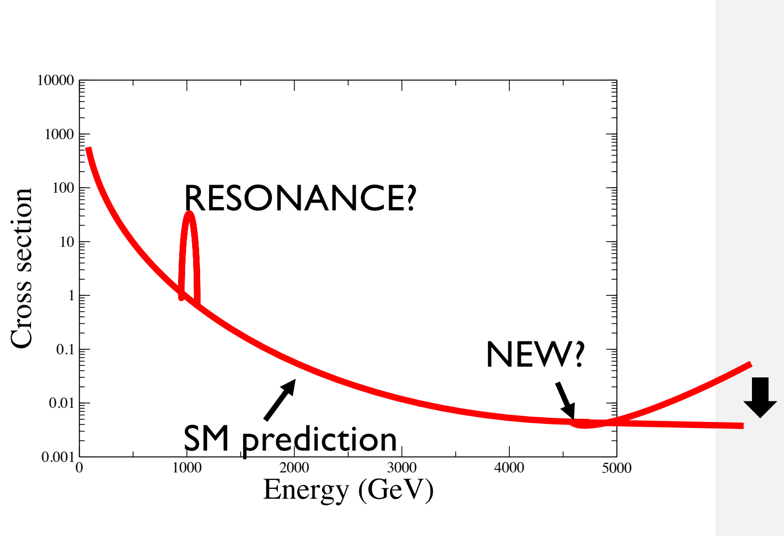
Current limits are being strengthened at LHC-13

Find resonance!

MORE HIGGS PARTICLES

NO SIGN OF MORE HIGGS-LIKE PARTICLES

- No shortage of models predicting more Higgs particles
  - Singlet model, 2HDM, Triplet model, MSSM, NMSSM…..
- Models typically do **not** predict masses of new Higgs particles ((N)MSSM is an exception)
- Models typically have a limit where all the new particles are heavy and all the Higgs couplings “look like” the SM



MOTIVATIONS FOR MORE HIGGS

- Why should the scalar sector be minimal?
- 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

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

EXTENDED HIGGS SECTORS

- 2 possibilities for Higgs triplets

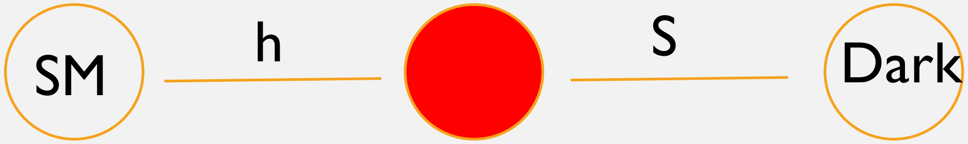
$$X_t = \begin{pmatrix} \zeta^+ \\ \zeta^0 \\ \zeta^- \end{pmatrix} \qquad X_t' = \begin{pmatrix} \xi^{++} \\ \xi^+ \\ \xi^0 \end{pmatrix}$$

Doubly charged Higgs provides nice signature

- Extreme fine tuning required in general

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

SINGLET MODEL



PROS:

- Simple
- 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:

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

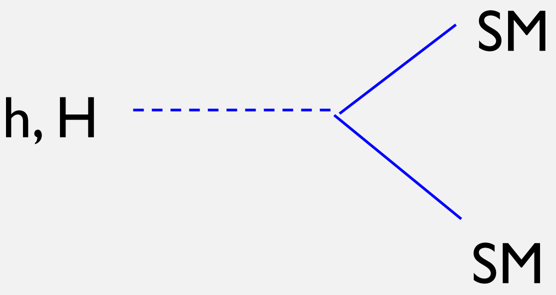
- Unitarity bound from hh→hh

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

M_H is heavier Higgs

Z_2 SYMMETRIC SINGLET MODEL

- Very simple model:



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

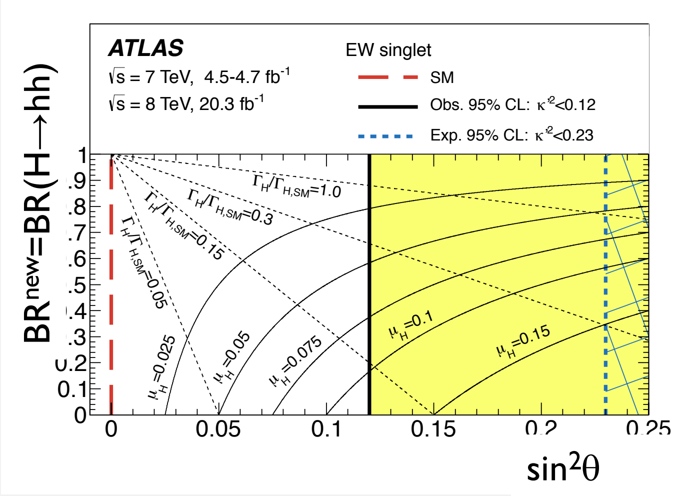
- If kinematically allowed, H → hh

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

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

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

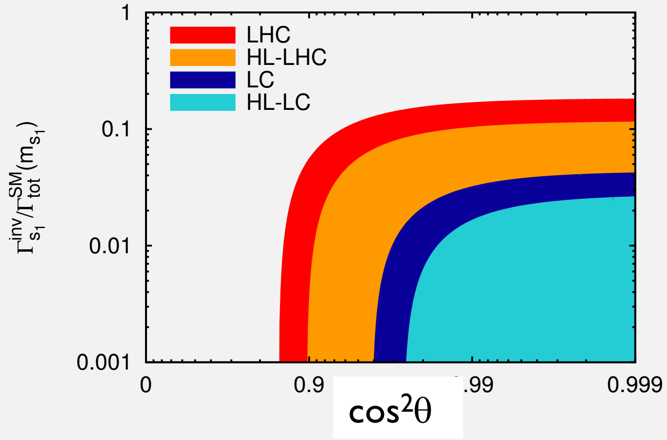


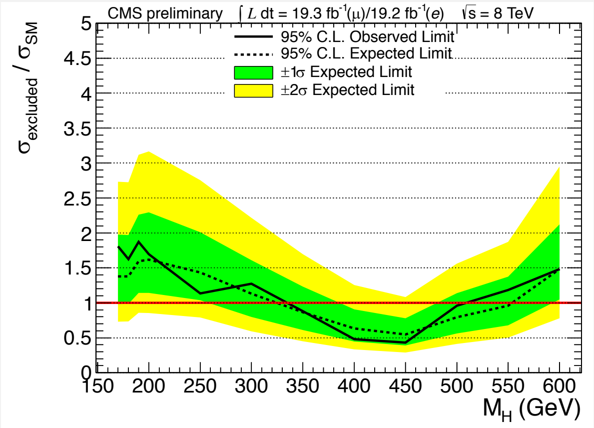
$$\sigma_h = \cos^2\theta\sigma_{SM}, \quad \Gamma_h = \cos^2\theta\Gamma_{SM}, \quad BR(h\to SM) = BR_{SM}, \quad \mu_h = \cos^2\theta$$

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

COMPLEMENTARITY OF APPROACHES

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



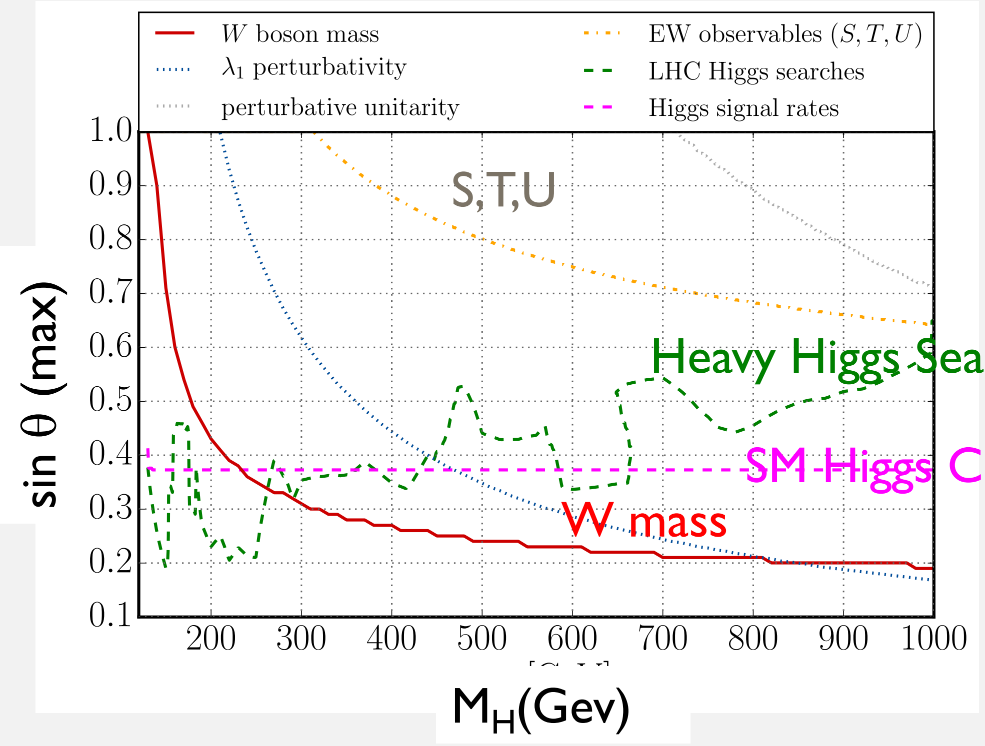


$\sigma/\sigma_{sm} = \sin^2\theta$ with no BR (H→hh)

Englert et al, arXiv:1403.7191

PREDICTIVE MODEL: NOT JUST HIGGS COUPLINGS

- $|\cos\theta| > .92$ from Higgs couplings, heavy Higgs searches, M_W



Strongest limit from W mass for heavy H

Ilnicka, Robens , Stefaniak, 1803.03594

DECOUPLING LIMIT OF SINGLET MODEL

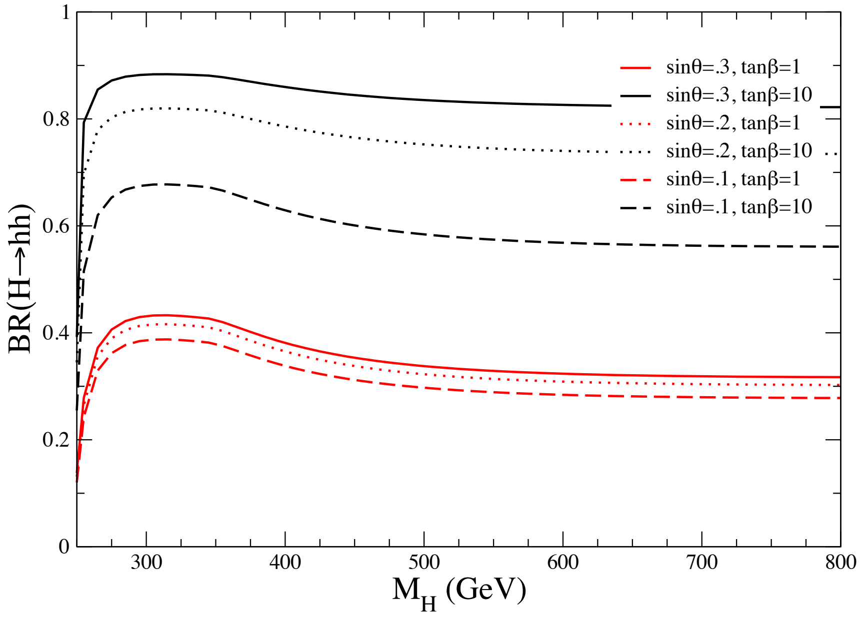
$$\langle\phi\rangle = \frac{v}{\sqrt{2}}, \quad \langle S\rangle = \frac{x}{\sqrt{2}}$$

- Decoupling:
  - $M_H >> m_h$

$$sin\ \theta \sim \frac{\mid a_2 \mid vx}{2(M_H^2 - m_h^2)} << 1$$

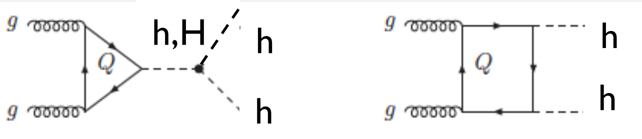
- Limit where model looks SM-like is typical of many extended Higgs sectors

BRANCHING RATIO $H \to hh$ CAN BE SIGNIFICANT

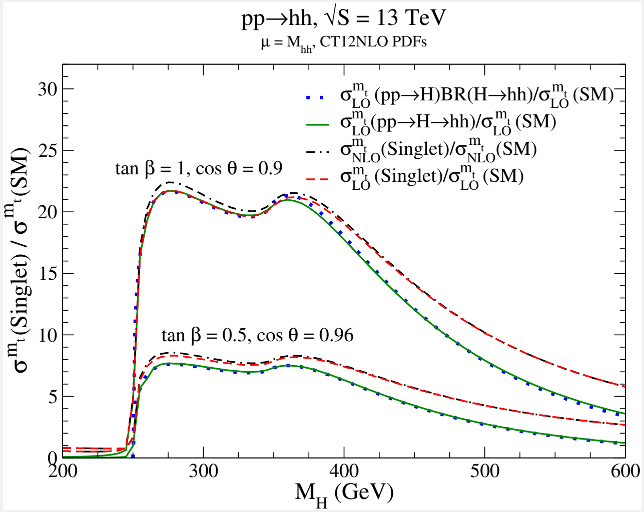


RESONANT PRODUCTION OF hh

- Large resonant effects when $M_H \sim 2M_h$
- NWA approximation accurate for M_H < 400 GeV



Can get factor of 20 enhancements in hh production

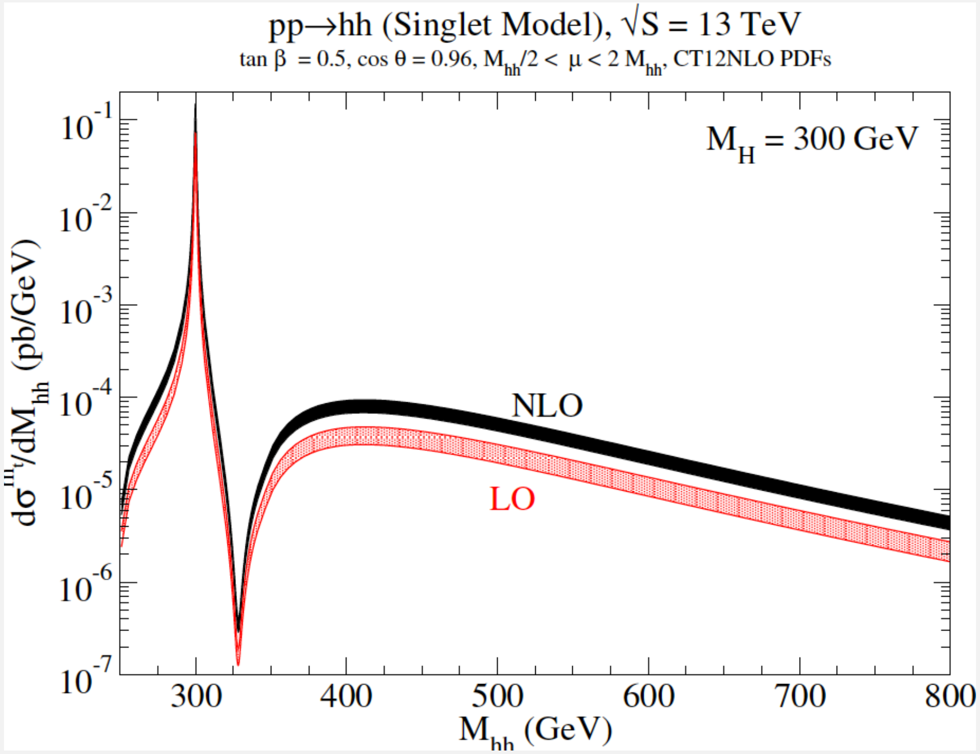


*Similar effects in MSSM, NMSSM models

Clear signal of new physics!

[Dawson, Lewis, arXiv:1508.05397]

LARGE RESONANCE/INTERFERENCE EFFECTS



[Dawson, Lewis, arXiv:1508.05397]

HIGGS SINGLET MODEL WITHOUT Z_2

$$V(\phi, S) = V_{SM}(\phi) + V_{\phi S}(\phi, S) + V_S(S)$$

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

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

- 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

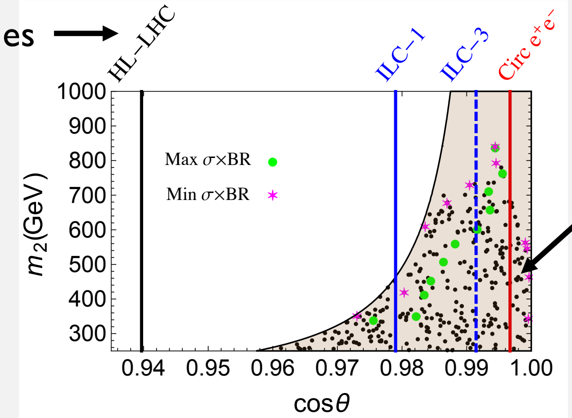
[Profumo, Ramsey-Musolf, Wainwright, Winslow, arXiv:1407.5342; Curtin, Meade, Yu, 1409.0005]

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

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

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

2HDM

PROS:

- No reason why SM should have only 1 Higgs doublet
- 2 Higgs doublets are just as good as 1
- Lots of new phenomenology (especially with charged H^+)
- FCNC from Higgs exchange easy to avoid in any model with doublets
- MSSM follows naturally from 2HDM

CONS:

- No predictions for masses/coupling constants

GENERAL 2 HIGGS DOUBLET MODEL

- 6 free parameters, plus a phase

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

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

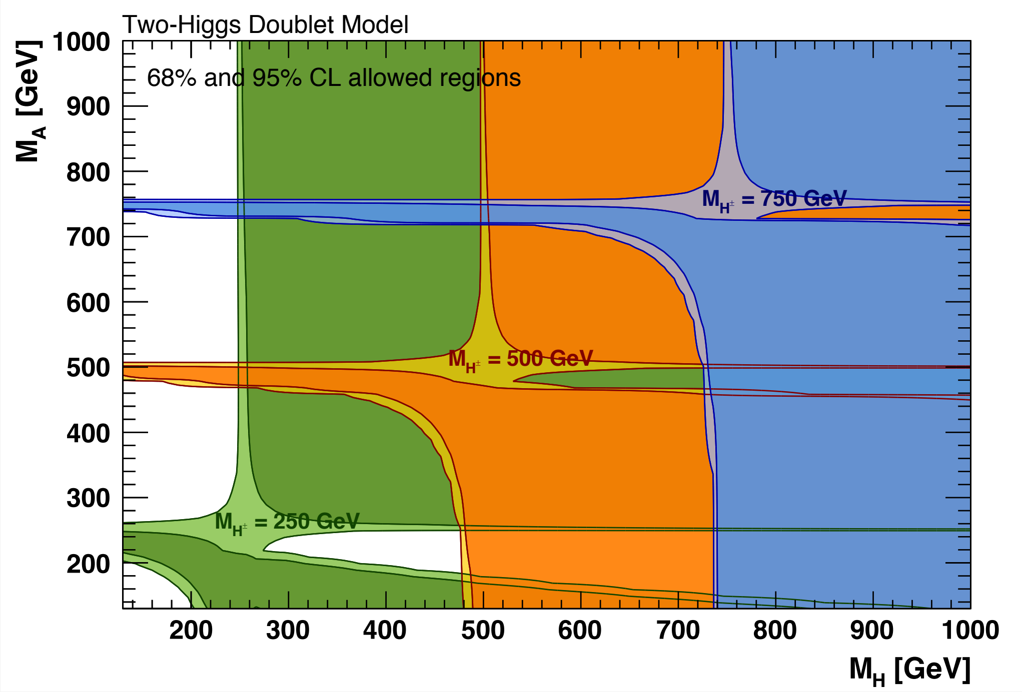
- W and Z masses just like in Standard Model $M_W^2 = \frac{g^2(v_1^2 + v_2^2)}{2}$
- ρ parameter: $\rho = \frac{M_W}{M_Z \cos\ \theta_W} = 1$

ρ=1 for any number of Higgs doublets or singlets

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

GAUGE BOSON COUPLINGS TO HIGGS IN 2HDM

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

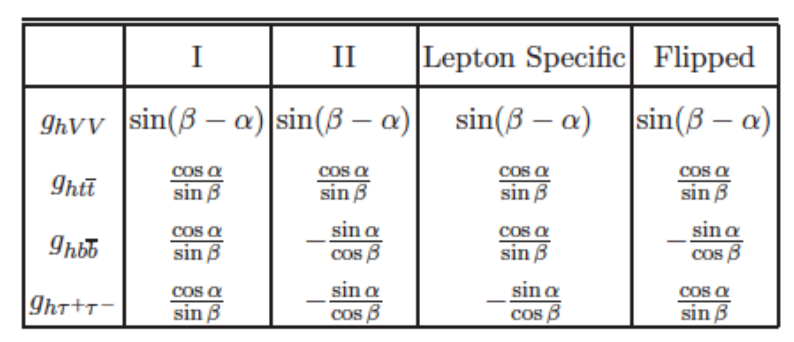
$$\boxed{\begin{aligned}\frac{g_{hVV}}{g_{h,smVV}}&=\sin(\beta-\alpha)\\ \frac{g_{HVV}}{g_{h,smVV}}&=\cos(\beta-\alpha)\end{aligned}}$$

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

HIGGS COUPLINGS IN 2HDM

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

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



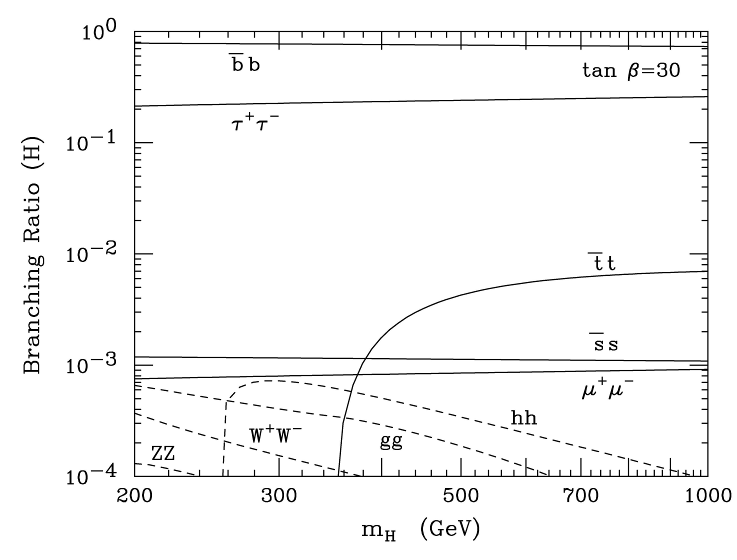
	I	II	Lepton Specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$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

Type II is MSSM – like 2 Higgs doublet model

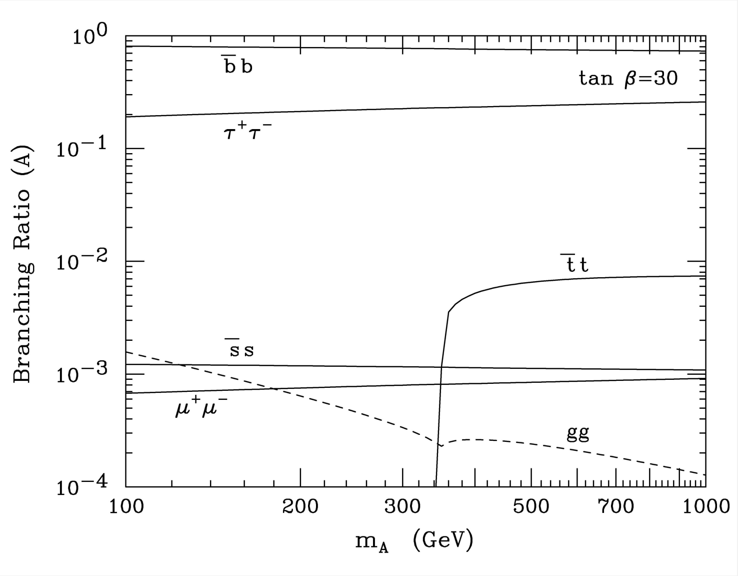
HIGGS DECAYS CHANGED AT LARGE TAN β

- At large tan β, rates to $b\bar{b}$ and $\tau^+\tau^-$ large

Heavy H^0 BRs



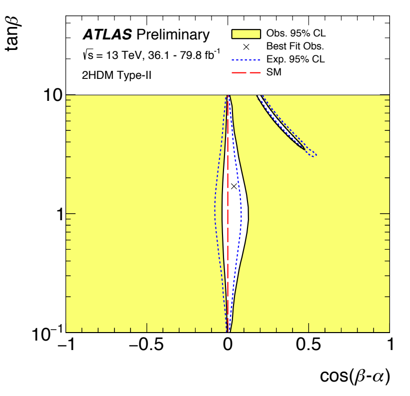
A^0 BRs

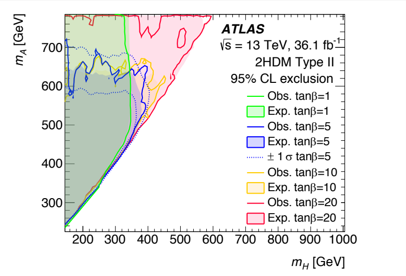


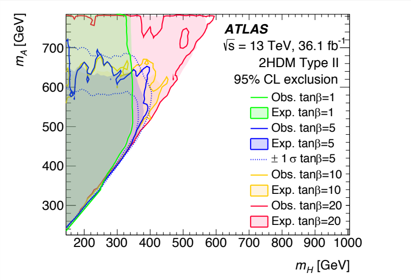
Rate to bb and $\tau^+\tau^-$ almost constant in type-II 2HDM for H,A

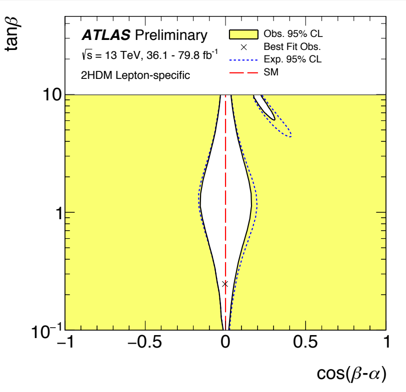
DECOUPLING LIMIT

- 2HDMs approach SM when cos(β–α) → 0
- Current limits allow non-SM like couplings
  - Higgs coupling measurements sensitive probes of theory even if new Higgs particles too heavy to be produced









$$pp \to A \to ZH, H \to b\bar{b}$$

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 β, M_H, M_h, M_A, $M_{H\pm}$, λ_5
- MSSM has 2 parameters in scalar sector: M_A, tan β
- 2HDM Higgs masses are free parameters
- MSSM predicts (at tree level):

$$M_{H\pm}^2 = M_A^2 + M_W^2$$

$$m_h^2 + M_H^2 = M_A^2 + M_Z^2$$

$$m_h^2 M_H^2 = M_Z^2 M_Z^2 \cos^2(2\beta)$$

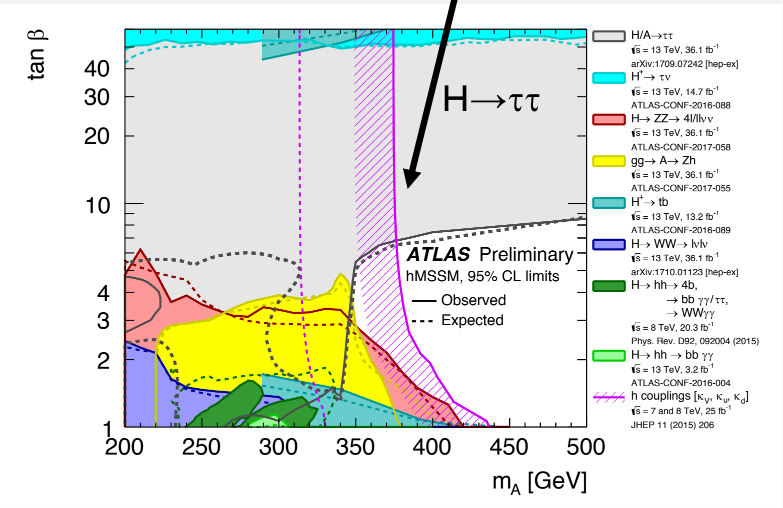
*large radiative corrections to MSSM mass relations

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
- Cubic Higgs couplings different in 2HDM and MSSM
    - (this will show up in hh limits)

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 β



Higgs couplings

H→ττ

ATLAS, 1610.07922

LOOKING FOR HEAVY HIGGS

- Mass reach grows slowly with luminosity, and faster with energy
- High luminosity LHC is all about coupling measurements

$pp \to tbH^{\pm} \to tb\tau\nu$

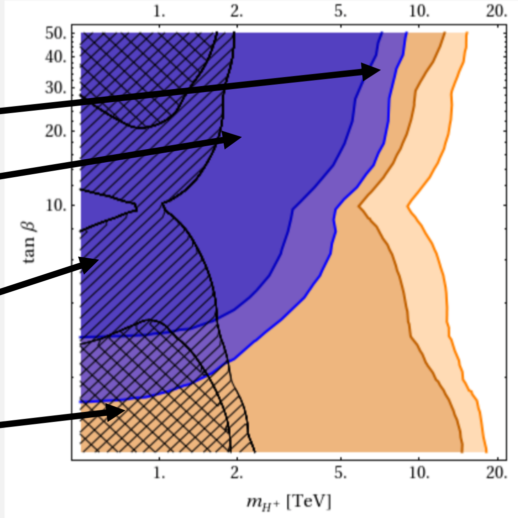
LHC exclusion with 300 fb^{-1}

100 Tev exclusion with 300 fb^{-1}

LHC exclusion with 3000 fb^{-1}

LHC exclusion with 300 fb^{-1}

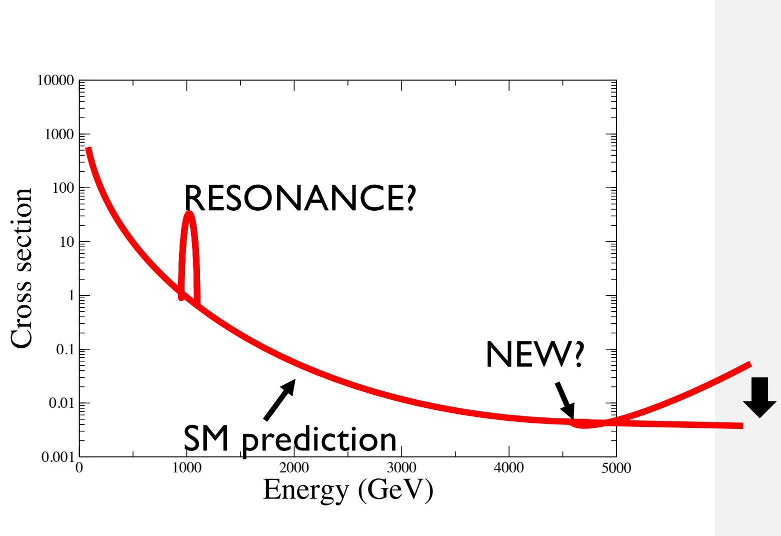
2HDM



PRECISION PROBES OF HIGGS COUPLINGS

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



MAJOR EWSB EXPLORATION OF LHC FUTURE RUNS WILL BE HIGGS COUPLINGS

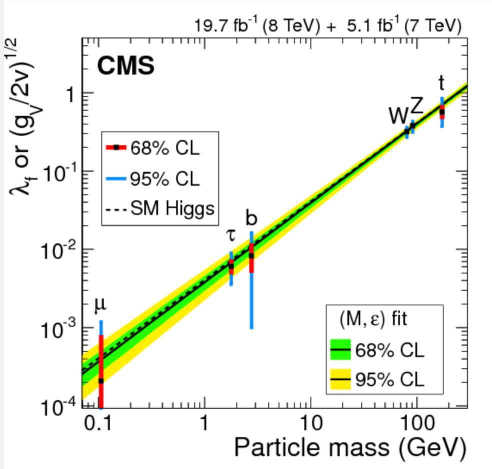
- Because most heavy Higgs limits will come with 300 fb^{-1}
- Will require precision theory calculations in both the SM and in EFTs
- Theory is already limiting factor in coupling extractions
- ATLAS/CMS 7-8 TeV data

$$\frac{\sigma}{\sigma_{SM}} \equiv \mu = 1.09 \pm 0.07(stat) \pm .04(syst)$$

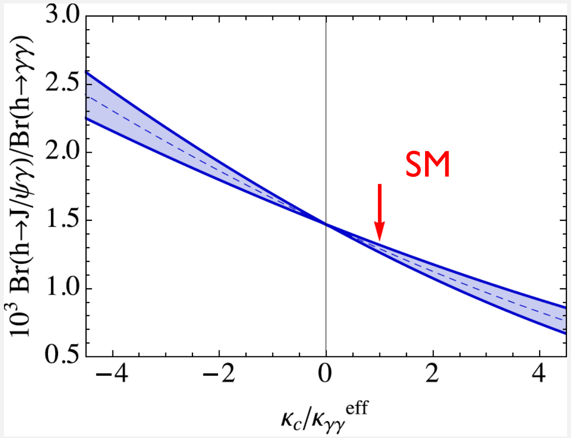
$$\pm .03(th\ bckd) \boxed{{}^{+.07}_{-.06}(th\ signal)}$$

ARE HIGGS COUPLINGS REALLY PROPORTIONAL TO MASS AND FLAVOR DIAGONAL?

- Does Higgs couple to 1st and 2nd generations?
- 3 ab^{-1} projection is 7σ for $h \rightarrow \mu\mu$ with $\delta\mu/\mu \sim \pm 20\%$



Small rates for $h \rightarrow \varphi\gamma$, $\psi\gamma$



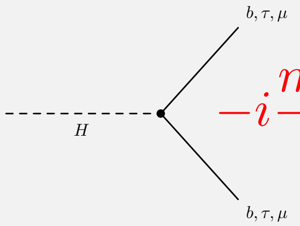
Konig, Neubert, 1505.03870

TESTING HIGGS COUPLINGS: RUN I

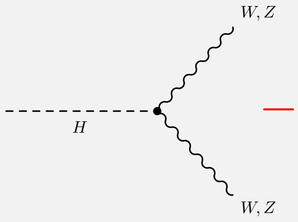
- Assume no new resonances/zero width approx/no new tensor structures

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

- Define scaling factors κ



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

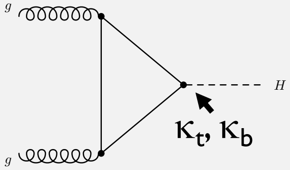


$$-2i\frac{M_V^2}{v}g^{\mu\nu}\kappa_V$$

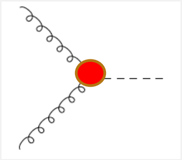
TESTING HIGGS COUPLINGS: RUN I

$$\mu(gg \to h \to X_iX_i) = \frac{\sigma(gg \to h \to X_iX_i)}{\sigma(gg \to h \to X_iX_i)\,|_{SM}} = \frac{\kappa_g^2\kappa_i^2}{\kappa_h^2}$$

- Approaches to loops: κ_γ, κ_g can be
  - Written as function of SM scaling factors: eg $\kappa_g=\kappa_g(\kappa_t,\kappa_b)$
  - Treated as free parameters to look for BSM contributions



or….



New interaction, with coupling κ_g

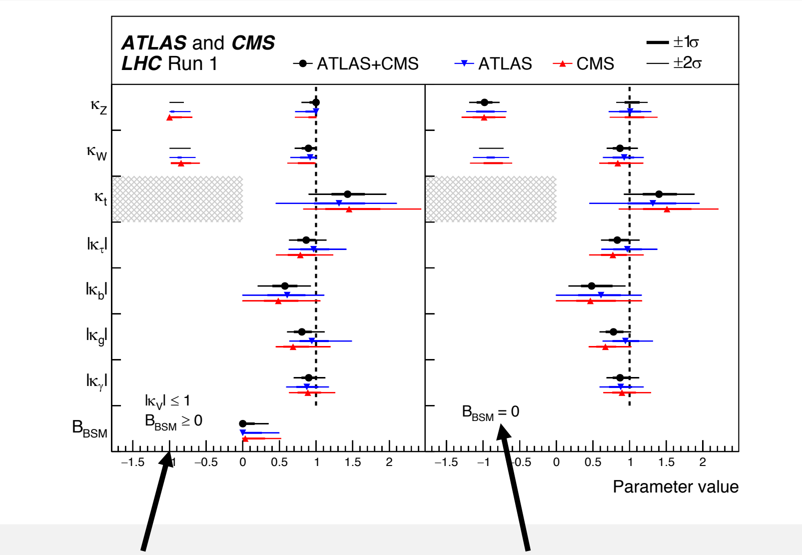
$$L = \frac{\alpha_s}{12\pi}\frac{h}{v}\kappa_g G^A_{\mu\nu}G^{\mu\nu,A}$$

WHAT DOES GLUON FUSION MEASURE?

$$L_{off} = L_{SM} - \frac{\alpha_s}{12\pi v}\delta\kappa_g G^A_{\mu\nu}G^{\mu\nu,A} - \delta\kappa_t \frac{m_t}{v}\bar{t}th$$

- New physics could be in ggh vertex or Yukawa couplings
- gg →h cannot distinguish $\delta\kappa_g$ from $\delta\kappa_t$ in the large m_t limit
- Not a clean measurement of tth coupling (and of course there could be new colored particles in the loop)
- Direct measurement of tth crucial

RUN I LIMITS



Invisible width allowed

No invisible width

Looks fairly SM like

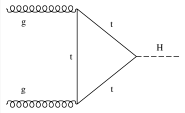
Run-2 h→ bb observation changes κ_b

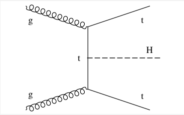
Run-2 tth observation changes κ_t

Need to improve fit technique to include kinematic effects and higher order theory

RUN-2 RESULTS

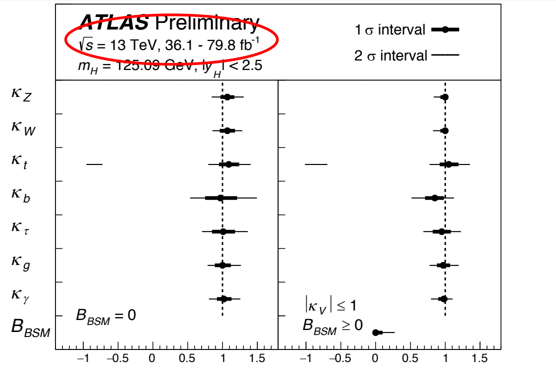
- ggh and gγγ loops can in principle distinguish sign of Yukawas

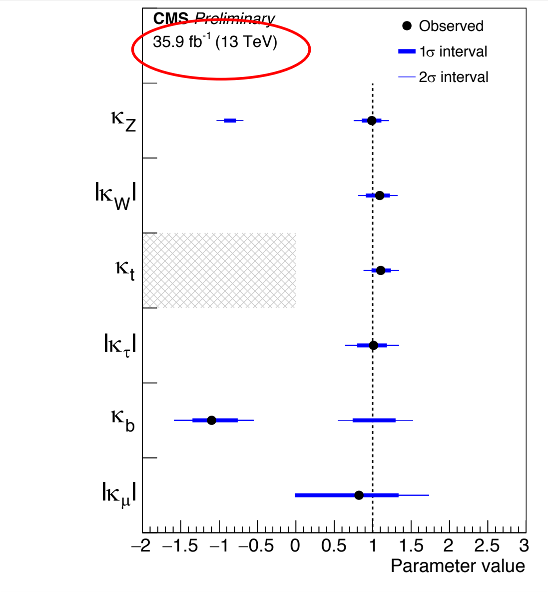




$$ggh: 1.04\kappa_t^2 + .002\kappa_b^2 - .038\kappa_t\kappa_b$$

$$h\gamma\gamma: 1.59\kappa_W^2 + .007\kappa_t^2 - .067\kappa_W\kappa_t$$





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%

Patterns of deviations can pinpoint specific BSM physics

* Numbers respect limits on BSM particles

[Snowmass Higgs report, 1310.8361]

κ RESCALING OF HIGGS COUPLINGS

- Problems:
  - Gauge invariance requires κ=1
    - Higgs couplings not free parameters in SM
  - Not a consistent field theory → 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

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

BSM Effects SM Particles

Dimension-5 operators contribute to lepton number violation

SMEFT

- Many operators, so simplify by neglecting flavor …. Still 59 operators
    - Some operators strongly limited by low energy physics (eg STU)
- 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

CONSTRUCT SMEFT FOR HIGGS

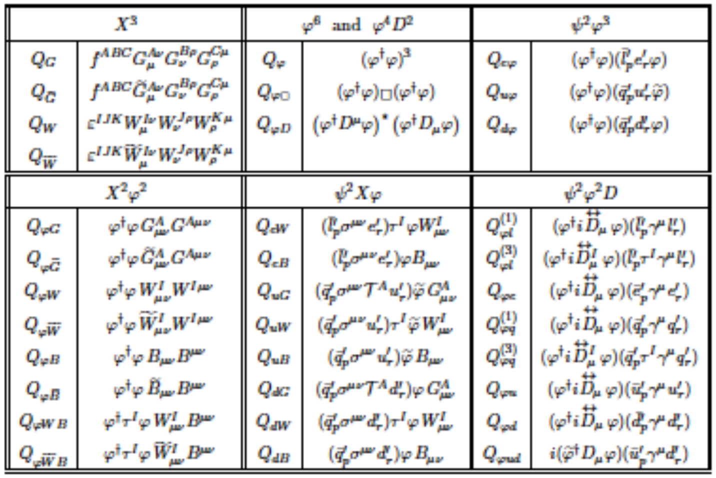
Limits from measurements

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	$(\phi^\dagger\phi)\overline{f}_L\phi f_R + hc$	$h\tau\tau, hb\bar{b}, ht\bar{t}$

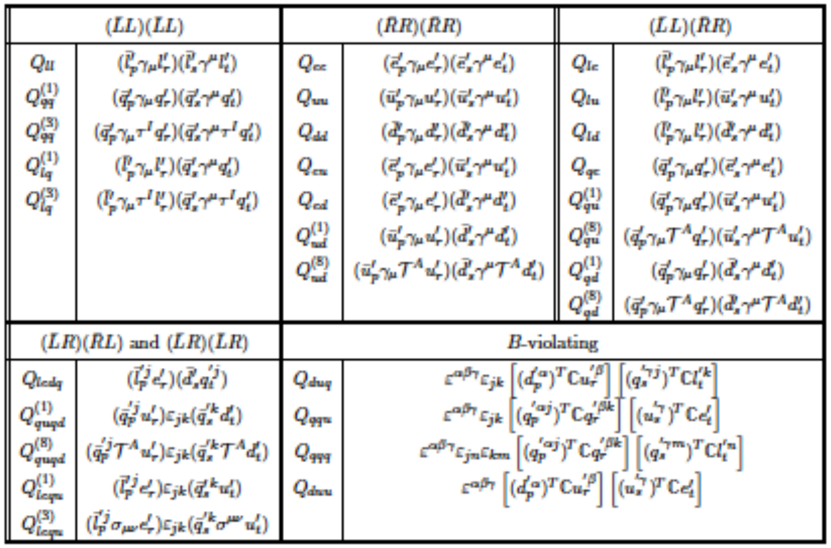
Take SM operators and add

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

OTHER OPERATORS MORE COMPLICATED



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l'_p e'_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q'_p u'_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q'_p d'_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l'_p \sigma^{\mu\nu} e'_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l'_p \gamma^\mu l'_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l'_p \sigma^{\mu\nu} e'_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l'_p \tau^I \gamma^\mu l'_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q'_p \sigma^{\mu\nu} T^A u'_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e'_p \gamma^\mu e'_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q'_p \sigma^{\mu\nu} u'_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q'_p \gamma^\mu q'_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q'_p \sigma^{\mu\nu} u'_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q'_p \tau^I \gamma^\mu q'_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q'_p \sigma^{\mu\nu} T^A d'_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u'_p \gamma^\mu u'_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q'_p \sigma^{\mu\nu} d'_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d'_p \gamma^\mu d'_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q'_p \sigma^{\mu\nu} d'_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u'_p \gamma^\mu d'_r)$



$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l'_p \gamma_\mu l'_r)(\bar l'_s \gamma^\mu l'_t)$	Q_{ee}	$(\bar e'_p \gamma_\mu e'_r)(\bar e'_s \gamma^\mu e'_t)$	Q_{le}	$(\bar l'_p \gamma_\mu l'_r)(\bar e'_s \gamma^\mu e'_t)$
$Q_{qq}^{(1)}$	$(\bar q'_p \gamma_\mu q'_r)(\bar q'_s \gamma^\mu q'_t)$	Q_{uu}	$(\bar u'_p \gamma_\mu u'_r)(\bar u'_s \gamma^\mu u'_t)$	Q_{lu}	$(\bar l'_p \gamma_\mu l'_r)(\bar u'_s \gamma^\mu u'_t)$
$Q_{qq}^{(3)}$	$(\bar q'_p \gamma_\mu \tau^I q'_r)(\bar q'_s \gamma^\mu \tau^I q'_t)$	Q_{dd}	$(\bar d'_p \gamma_\mu d'_r)(\bar d'_s \gamma^\mu d'_t)$	Q_{ld}	$(\bar l'_p \gamma_\mu l'_r)(\bar d'_s \gamma^\mu d'_t)$
$Q_{lq}^{(1)}$	$(\bar l'_p \gamma_\mu l'_r)(\bar q'_s \gamma^\mu q'_t)$	Q_{eu}	$(\bar e'_p \gamma_\mu e'_r)(\bar u'_s \gamma^\mu u'_t)$	Q_{qe}	$(\bar q'_p \gamma_\mu q'_r)(\bar e'_s \gamma^\mu e'_t)$
$Q_{lq}^{(3)}$	$(\bar l'_p \gamma_\mu \tau^I l'_r)(\bar q'_s \gamma^\mu \tau^I q'_t)$	Q_{ed}	$(\bar e'_p \gamma_\mu e'_r)(\bar d'_s \gamma^\mu d'_t)$	$Q_{qu}^{(1)}$	$(\bar q'_p \gamma_\mu q'_r)(\bar u'_s \gamma^\mu u'_t)$
		$Q_{ud}^{(1)}$	$(\bar u'_p \gamma_\mu u'_r)(\bar d'_s \gamma^\mu d'_t)$	$Q_{qu}^{(8)}$	$(\bar q'_p \gamma_\mu T^A q'_r)(\bar u'_s \gamma^\mu T^A u'_t)$
		$Q_{ud}^{(8)}$	$(\bar u'_p \gamma_\mu T^A u'_r)(\bar d'_s \gamma^\mu T^A d'_t)$	$Q_{qd}^{(1)}$	$(\bar q'_p \gamma_\mu q'_r)(\bar d'_s \gamma^\mu d'_t)$
				$Q_{qd}^{(8)}$	$(\bar q'_p \gamma_\mu T^A q'_r)(\bar d'_s \gamma^\mu T^A d'_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l'^j_p e'_r)(\bar d'_s q'^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d'^\alpha_p)^T C u'^\beta_r\right]\left[(q'^{\gamma j}_s)^T C l'^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q'^j_p u'_r)\varepsilon_{jk}(\bar q'^k_s d'_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(u'^\gamma_s)^T C e'_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q'^j_p T^A u'_r)\varepsilon_{jk}(\bar q'^k_s T^A d'_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q'^{\alpha j}_p)^T C q'^{\beta k}_r\right]\left[(q'^{\gamma m}_s)^T C l'^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l'^j_p e'_r)\varepsilon_{jk}(\bar q'^k_s u'_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d'^\alpha_p)^T C u'^\beta_r\right]\left[(u'^\gamma_s)^T C e'_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l'^j_p \sigma_{\mu\nu} e'_r)\varepsilon_{jk}(\bar q'^k_s \sigma^{\mu\nu} u'_t)$				

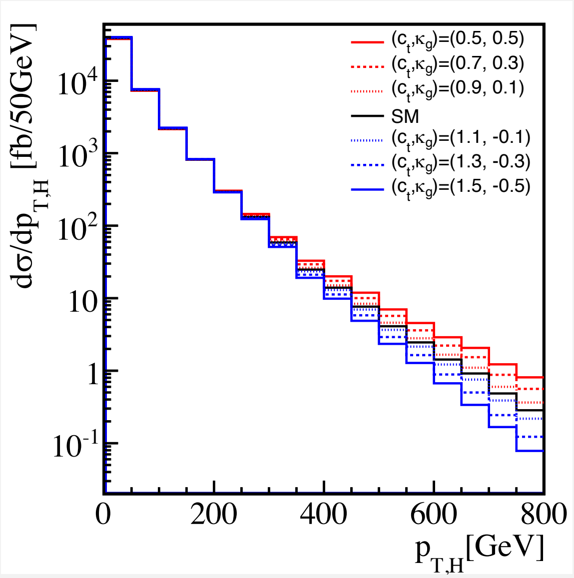
+…..

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 contrained to give correct rate for ggh



Higgs plus jet production at 14 TeV

New physics

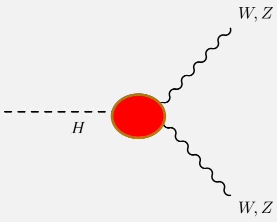
$c_t=k_t$

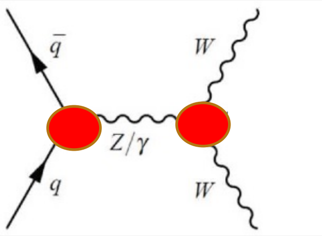
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant

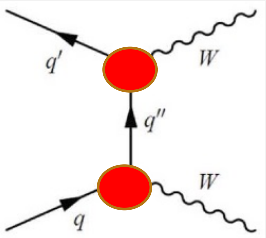
CAN'T JUST FIT HIGGS COUPLINGS

Operators that contribute to VVV vertices and Higgs-VV vertices

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





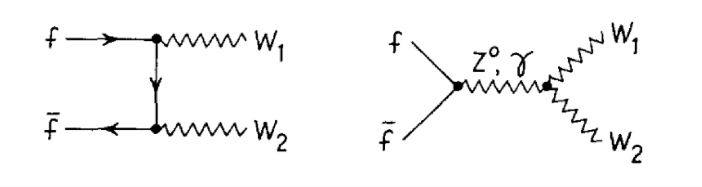


Anomalous qqZ vertices too!

- Changing ZWW, γWW vertices spoils high energy cancellations between contributions
- Effective field theory effects enhanced at high energy, high p_T

AN OLD STORY

- Understanding EFT expansion
- At high energy, $\varepsilon_{WL}{}^{\mu} \sim p^{\mu}/M_W$



$$| A_{\pm\mp LL} |^2 \sim \mathcal{O}(1)$$

$$| A_{\pm\mp L\pm} |^2 \sim \mathcal{O}(\frac{M_W^2}{s})$$

$$| A_{-+\pm\pm} |^2 \sim \mathcal{O}(\frac{M_W^4}{s^2})$$

γ, Z contributions combine so that no growth with energy in total cross section

Amplitudes for transverse W's in final state vanish in high energy limit

Duncan, Kane, and Repko NP B272 (1986) 517; Ahn, Peskin, Lynn, Selipsky, NPB309 (1988) 221

MORE OLD STORY

- Changing WWZ or WWγ coupling spoils unitarity conserving cancellation

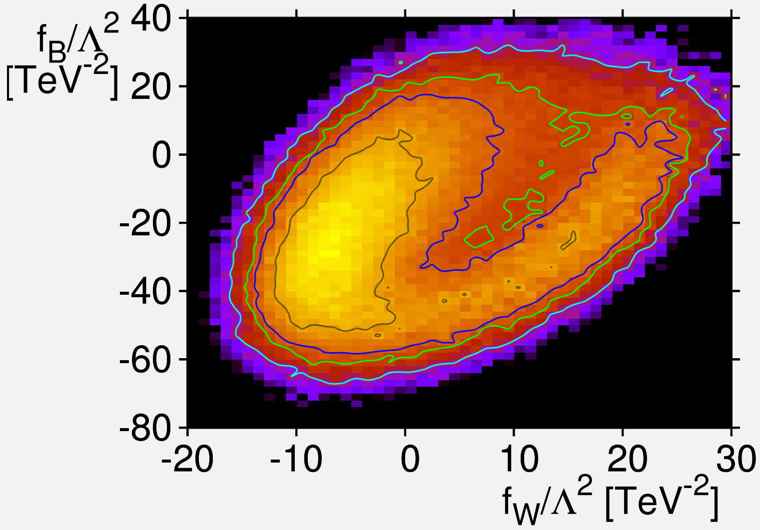
With non-SM VVV	SM
$A_{\pm\mp LL} \sim \mathcal{O}\left(\frac{s}{M_W^2}\right)$	$A_{\pm\mp LL} \sim \mathcal{O}\left(1\right)$
$A_{\pm\mp L\pm} \sim \mathcal{O}\left(\frac{\sqrt{s}}{M_W}\right)$	$A_{\pm\mp L\pm} \sim \mathcal{O}\left(\frac{M_W}{\sqrt{s}}\right)$
$A_{-+\pm\pm} \sim \mathcal{O}\left(\frac{s}{M_W^2}\right)$	$A_{-+\pm\pm} \sim \mathcal{O}\left(\frac{M_W^2}{s}\right)$

To dimension-6, we are sensitive to interference with SM

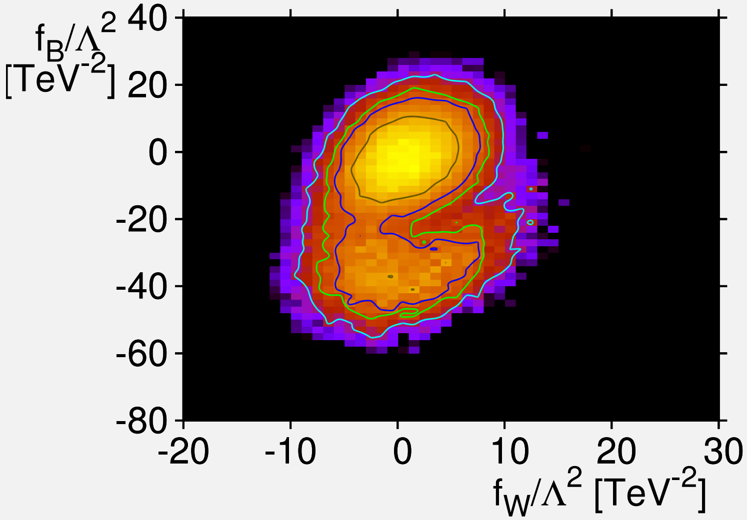
Dixon, Kunszt, Signer, PRD60 (1999) 114037; Hagiwara, Peccei, Zeppenfeld, NP282 (1987) 253

IMPROVEMENT IN FITS WITH KINEMATIC INFORMATION

Rate based



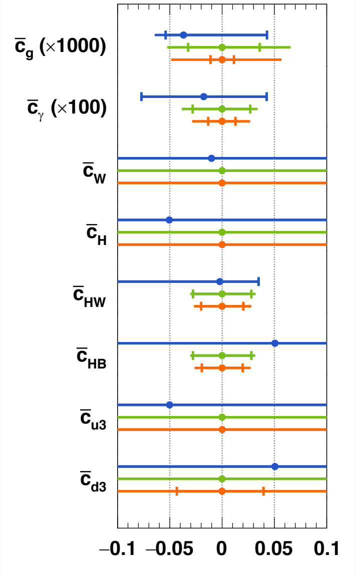
Include kinematic info



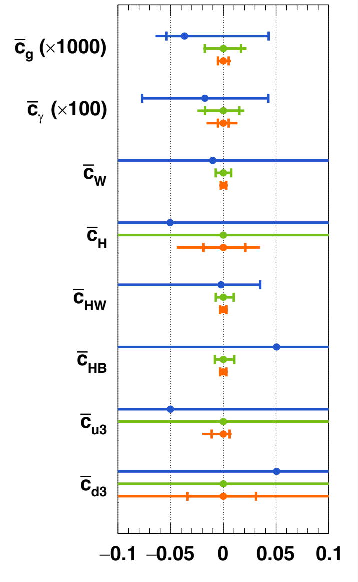
[Corbett, Eboli, Goncalves, Gonzalex-Frail, Plehn, Rauch]

FITS WITH KINEMATIC INFORMATION

Rates only



Kinematic info

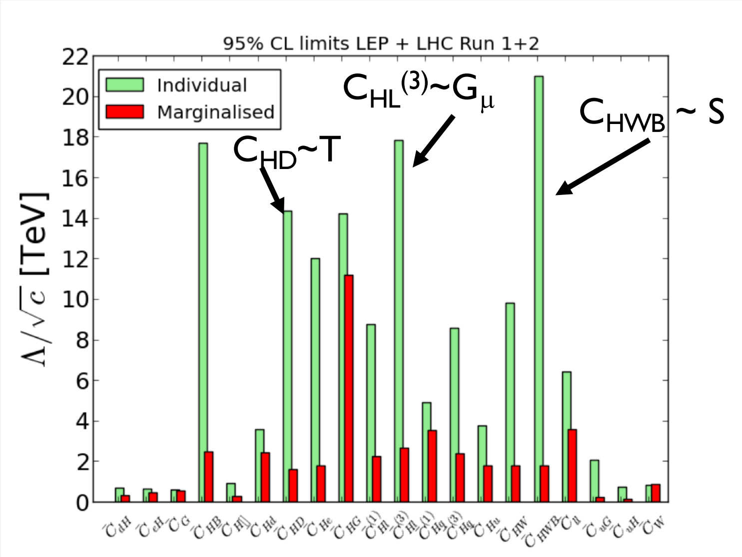


Blue: (Run-1 data)
Green: (300 fb^{-1})
Orange: (3000 fb^{-1})

Englert, Kogler, Spannowsky, 1511.05170

MORAL OF HIGGS COUPLING FITS

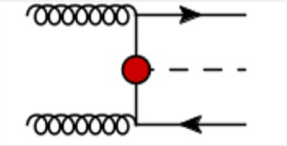
- You get much better fits if you fit only 1 coupling at a time (this is a bad idea since in any given UV complete model there will be multiple non-zero couplings)
- Fits are only sensitive to c/Λ^2



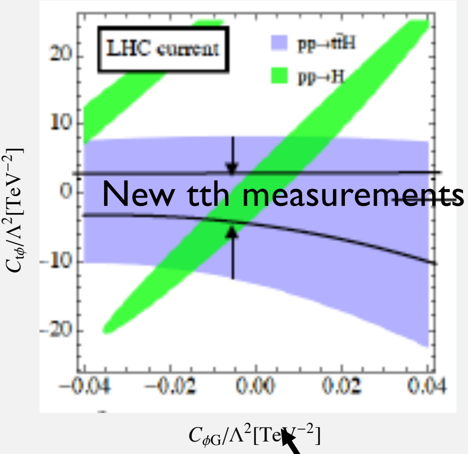
[Ellis, Murphy, Sanz, You,1803.03252]

HIGGS PHYSICS ISN'T ALONE

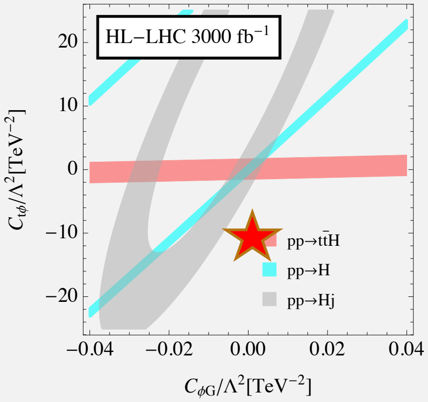
- Is the tth coupling the Standard Model coupling?
- Non-SM contributions change rate/distributions



Non-SM tth coupling



New tth measurements



- Observation of gluon fusion production of Higgs at expected rate doesn't mean Higgs has SM tth coupling
- Need tth production
- High luminosity will pin down coupling

Maltoni, Vryonidou, Zhang, 1607.05339

Non-SM ggh coupling

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

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

- To have small BSM effects ➔ $A_{SM} A_6 >> |A_6|^2$, $A_8 A_{SM}$
  - ie Interference must be largest contribution
  - This was the case at LEP
- Dimension-6 operators in HEFT form an expansion in s/Λ^2
- At some scale unitarity is violated

If I only keep C_6/Λ^2 terms and drop $(C_6/\Lambda^2)^2$, the cross section is not guaranteed to be finite

COUNTING LORE

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

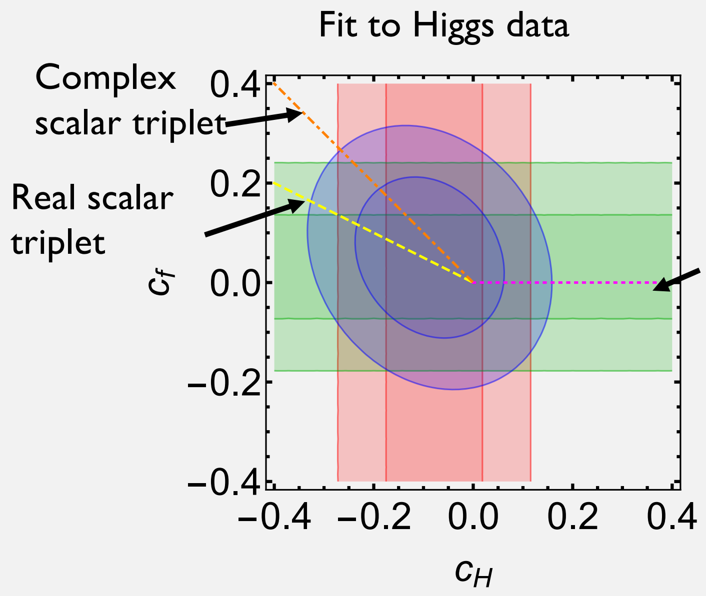
$$+ \underbrace{g_{BSM}^2 (A_6)^2 \frac{s^2}{\Lambda^4} + g_{SM} g_{BSM} A_{SM}} A_8 \frac{s^2}{\Lambda^4}$$

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

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

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



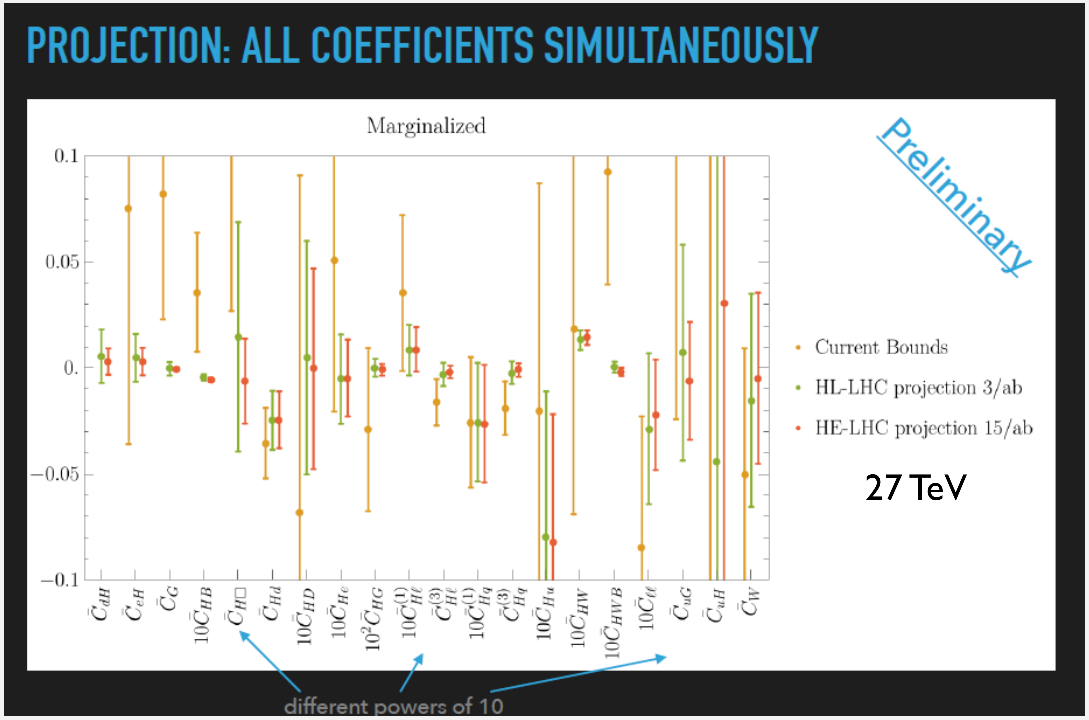
$$O_H = \frac{1}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$

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

Dawson, Murphy, 1704.07851

AT 27 TEV

Precision on
Higgs couplings
improved at
high energy



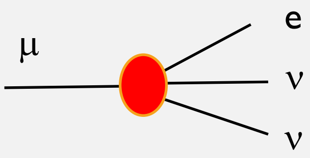
PROJECTION: ALL COEFFICIENTS SIMULTANEOUSLY

27 TeV

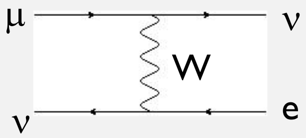
different powers of 10

C. Murphy

HISTORY AS A GUIDE



- μ decay: Gives very precisely measured $G_F \sim 10^{-5}$ GeV^{-2}
  - ➢ Rate grows with energy ~ G_F^2 (Energy)^2
  - ➢ Theory only makes sense for Energy < 600 GeV



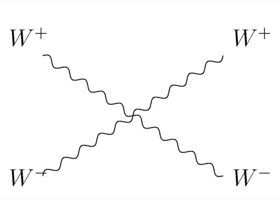
- Inverse μ decay: $\mu\nu \to e\nu$
- W boson saves the day

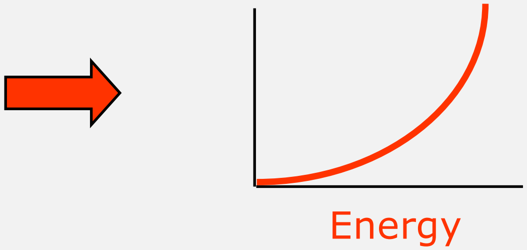
Rate ~ $G_F^2 M_W^2$

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 (should know soon)
  - 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