BSM PHYSICS AT THE LHC LECTURE 2

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Trisep, June, 2021

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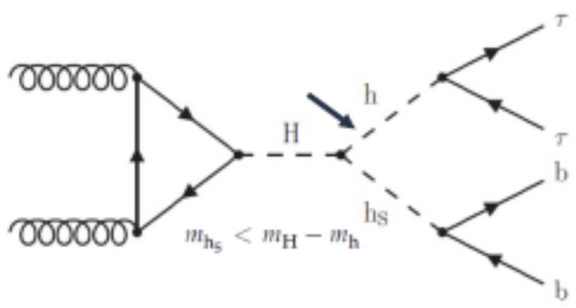
Slides posted at: Lecture_2.pdf

NEW SIGNALS IN hh PRODUCTION



- Can produce 2 different Higgs (generic in extended Higgs Models)
- BSM models with extra Higgs can have interesting di-Higgs signals

TODAY

- 2HDM
- MSSM
- Vector-like top quark
- Precision measurements and EFTs

It's a lot, so the bottom line: there are a lot of possibilities and we have to look not just at the LHC, but in low energy measurements, B physics, and other measurements

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
- Try to explain flavor anomalies in B sector

CONS:

- No predictions for masses/coupling constants

GENERAL 2 HIGGS DOUBLET MODEL

- 6 free parameters, plus a phase

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

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

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

ρ=1 for any number of Higgs doublets or singlets

GAUGE BOSON COUPLINGS TO HIGGS IN 2HDM

- Neutral Higgs: h and H
- Couplings to gauge bosons fixed by gauge symmetry
- $(g_{hVV})^2+(g_{HVV})^2=(g_{hVV})^2(SM)$
- Vector boson fusion and Vh production always suppressed in 2HDM

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

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

HIGGS COUPLINGS IN 2HDM

- 2 Higgs doublet models with no tree level 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

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

	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

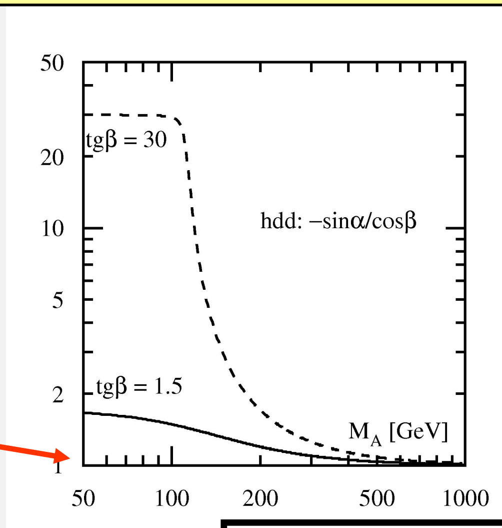
HIGGS COUPLINGS IN TYPE II

Lightest Neutral Higgs, h

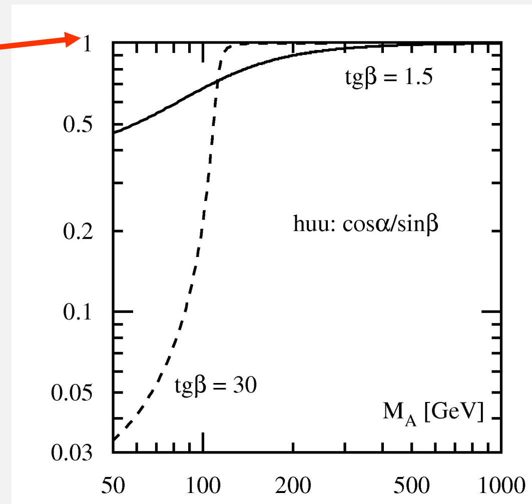
Couplings to d, s, b enhanced at large tan β for moderate M_A

Couplings to u, c, t suppressed at large tan β for moderate M_A

SM



SM



Decoupling limit: For $M_A \to \infty$, h couplings go to SM couplings

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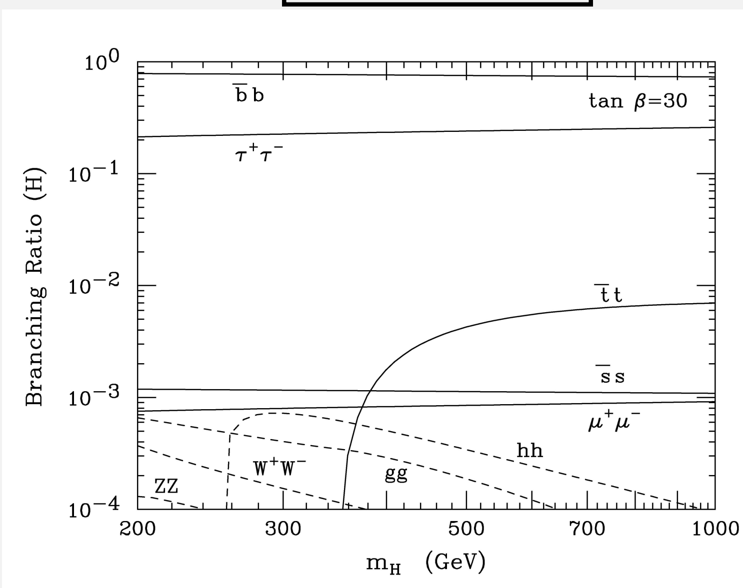
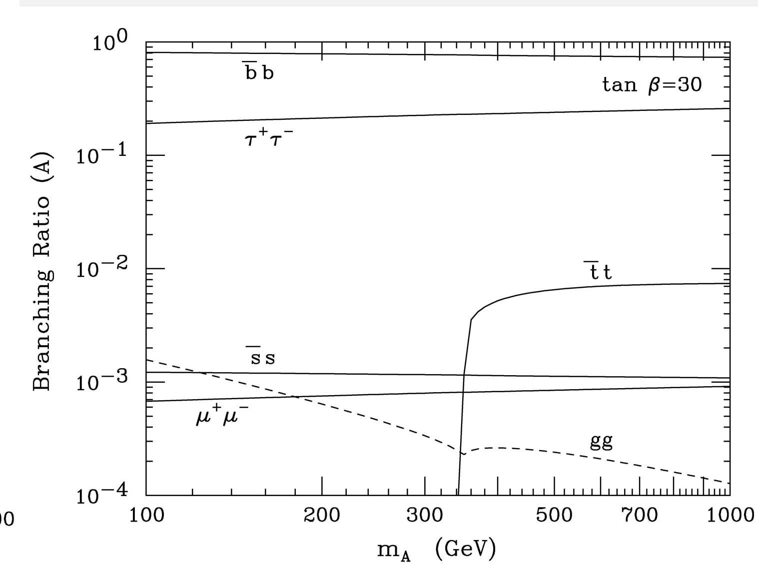
HIGGS DECAYS CHANGED AT LARGE TAN β

- At large tan β, rates to $b\bar{b}$ and $\tau^+\tau^-$ large in type-II 2HDM

Heavy H^0 BRs



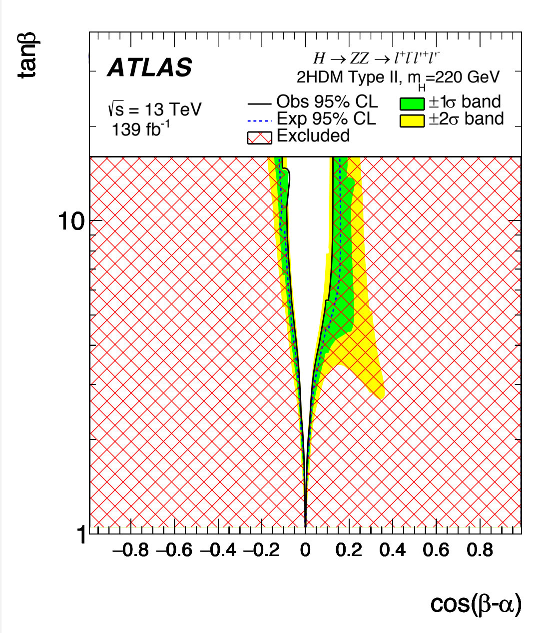
A^0 BRs

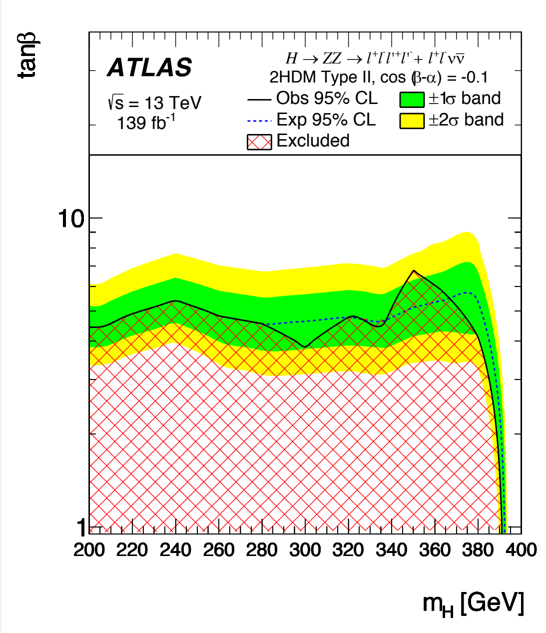


Rate to bb and $\tau^+\tau^-$ almost constant in type-II 2HDM for H, A

COMPLEMENTARITY OF DIRECT SEARCH/HIGGS COUPLINGS

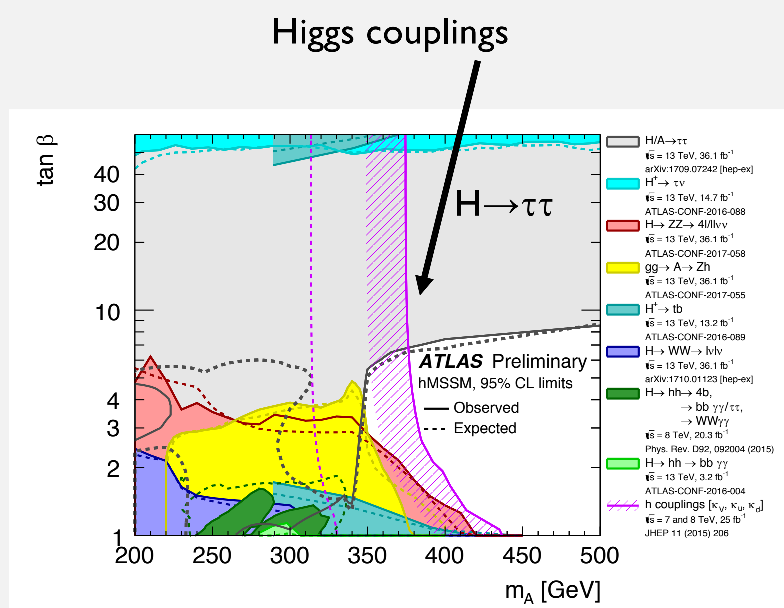
- $\cos(\beta-\alpha)=0$ is SM limit
- Larger tan β has larger couplings to b's which are relatively poorly constrained
- Limits allow for new relatively low scale physics





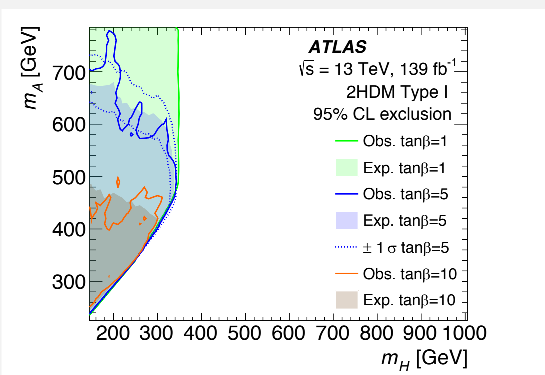
DIRECT SEARCH AND COUPLING MEASUREMENTS ARE TYPICALLY COMPLIMENTARY

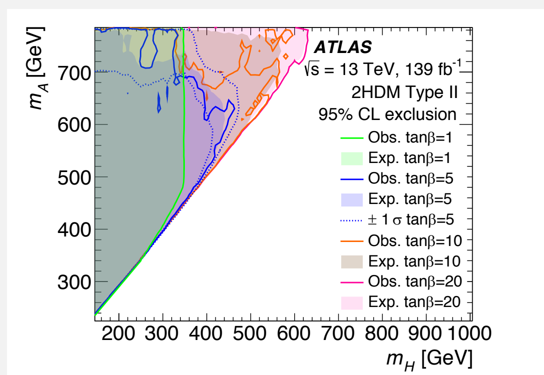
- 2HDM: h^0, H^0, A^0, $H^\pm$
  - Scalar couplings of type-II 2HDM is identical to MSSM
- Higgs sector described in terms of M_h, M_H, M_A, $M_{H\pm}$, tan β

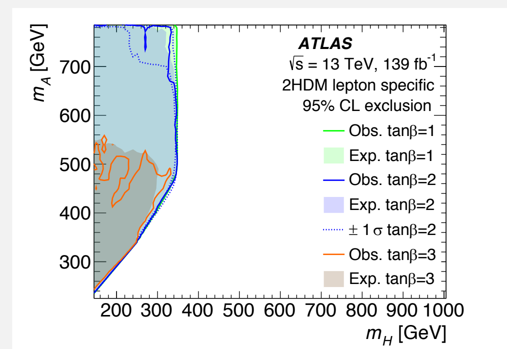


DECOUPLING LIMIT

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







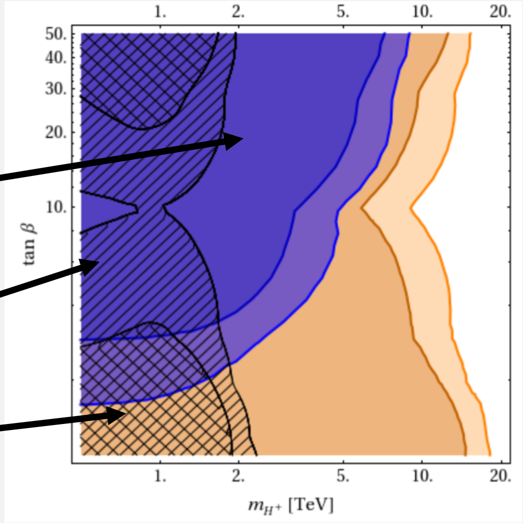
*Different types of fermion couplings

LOOKING FOR HEAVY HIGGS

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

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

2HDM



100 TeV exclusion with 300 fb^{-1}

LHC exclusion with 3000 fb^{-1}

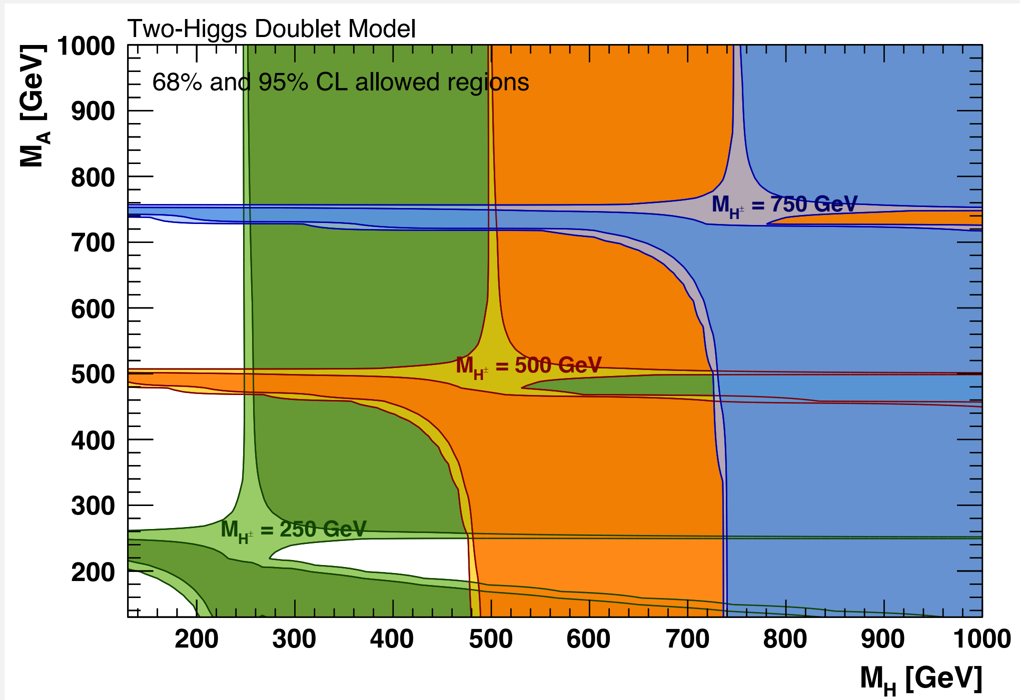
LHC exclusion with 300 fb^{-1}

ONCE AGAIN LIMITS FROM PRECISION ELECTROWEAK

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

where m_i, m_j are the scalar masses

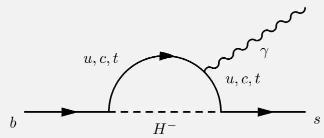
M_H, M_A, M_{H+} want to be of similar size barring cancellations

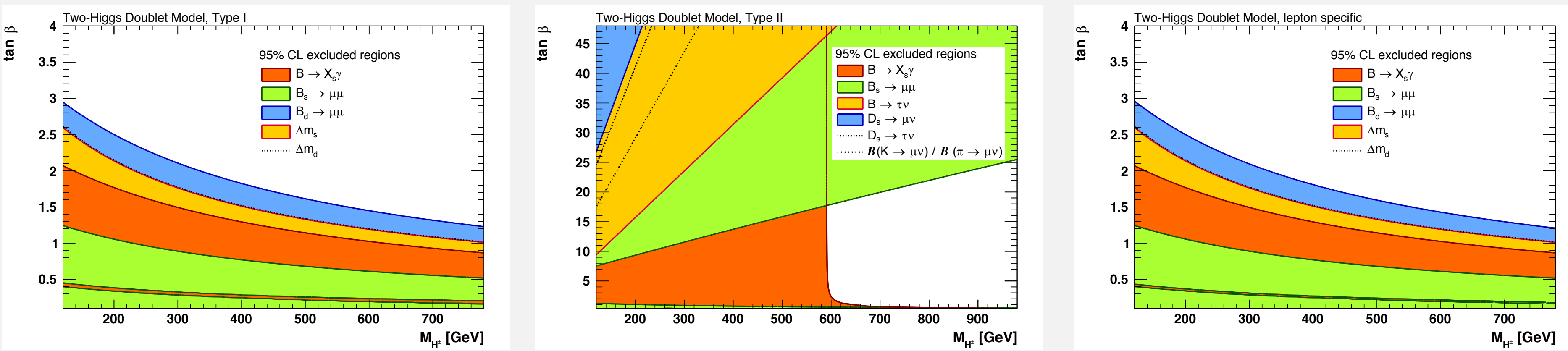


Haller, Hoecker, Kogler,Monig, Peiffer, Stelzer, 1803.01853

IMPORTANT LIMITS FROM FLAVOR PHYSICS

- B→sγ, B→μμ, B→τν….





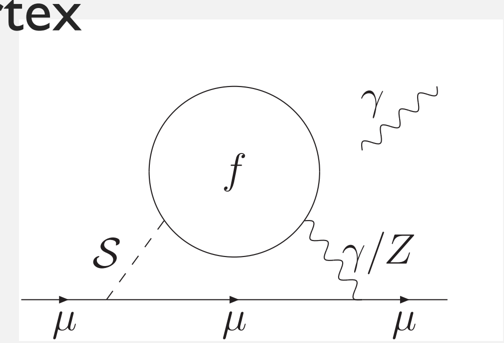
Limits on 2HDM from flavor physics

Gfitter, 1803.01853

2HDMS AND g-2

- Lepton-specific: quark couplings suppressed, lepton couplings enhanced by tan β
- Other 2HDM fermion assignments can't explain new g-2 and be consistent with Higgs and other flavor data
- Barr-Zee diagram: effective γγH vertex

Consider τ in loop: diagram enhanced by $\tan^2\beta$ in lepton specific 2HDM



2HDMS

- Look for heavy H, A H^+
- Look for new signatures
- Measure Higgs couplings
- Check B physics, g-2 limits

Need all the pieces to get a consistent picture

SUPERSYMMETRIC MODELS AS ALTERNATIVE TO STANDARD MODEL

Many New Particles:

- Spin ½ quarks $\Rightarrow$ spin 0 squarks
- Spin ½ leptons $\Rightarrow$ spin 0 sleptons
- Spin 1 gauge bosons $\Rightarrow$ spin ½ gauginos
- Spin 0 Higgs $\Rightarrow$ spin ½ Higgsino

Unbroken supersymmetry $\Rightarrow$ degenerate masses of partners

SUSY must be a broken symmetry

MSSM….OUR FAVORITE MODEL

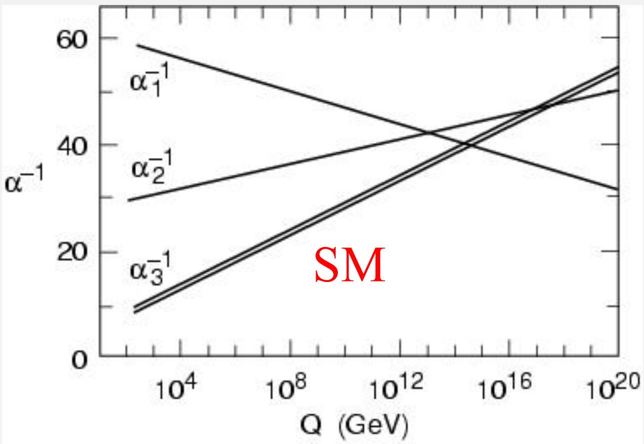
- Quadratic sensitivity to high scale physics cancelled automatically if SUSY particles at TeV scale
- Cancellation result of ***supersymmetry***, so happens at every order

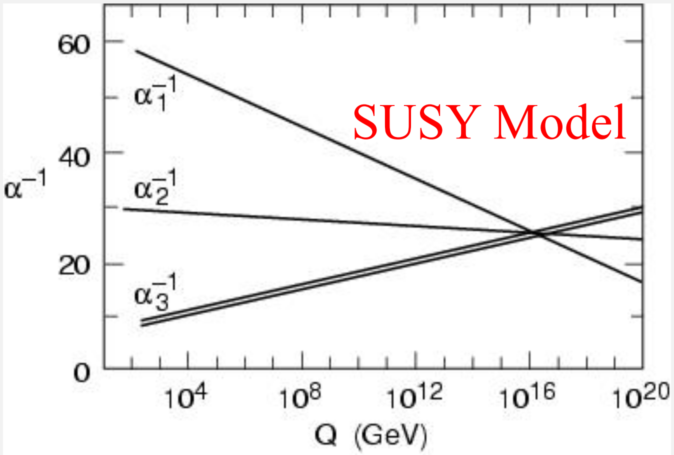
$$\delta m_h^2 \sim M_t^2 - m_{stop}^2$$

- Stop mass should be TeV scale

FURTHER MOTIVATION: SUSY MODELS UNIFY

- Coupling constants change with energy
- Assume new particles at TeV scale





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

MSSM CONSISTENT WITH 125 GEV HIGGS

- Higgs mass predicted
- Tree level

$$\delta m_h^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 - \sqrt{(M_A^2 - M_Z^2)^2 + 4M_A^2 M_Z^2 \sin^2(2\beta)}\right]$$

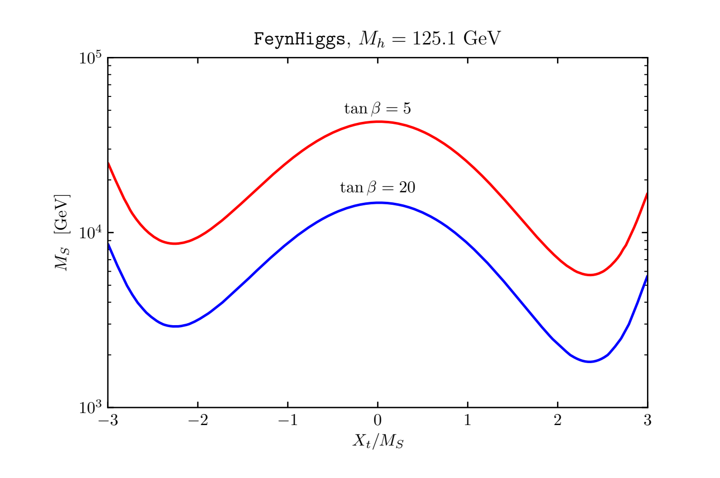
$$\rightarrow M_Z^2 \cos^2(2\beta)$$

- 1-loop with stops

$$\delta m_h^2 \sim \frac{3M_t^4}{4\pi^2 v^2}\left[\log\left(\frac{m_S^2}{M_t^2}\right) + \frac{X_t^2}{m_S^2} - \frac{X_t^4}{12 m_S^4}\right]$$

- Huge theory effort

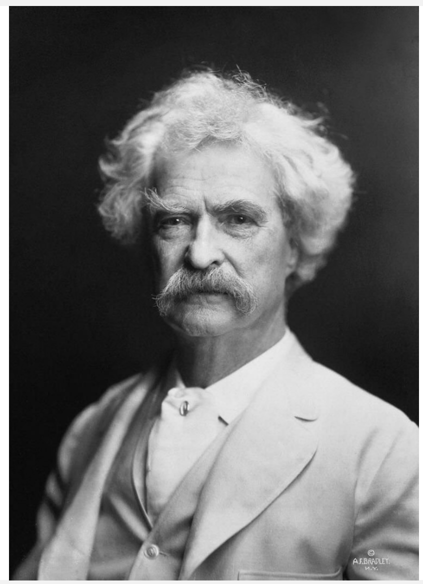
MSSM Higgs mass, 2012.15629



Motivation for heavy squarks

BUT ISN'T THE MSSM AT 1 TEV RULED OUT?

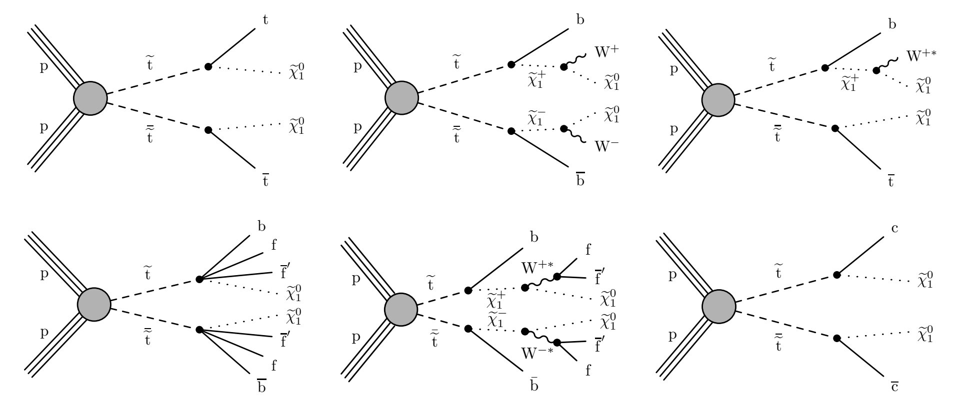
- Many assumptions in MSSM limits



The reports of my death have been greatly exaggerated. Mark Twain

EXAMPLE: LIMITS ON STOPS

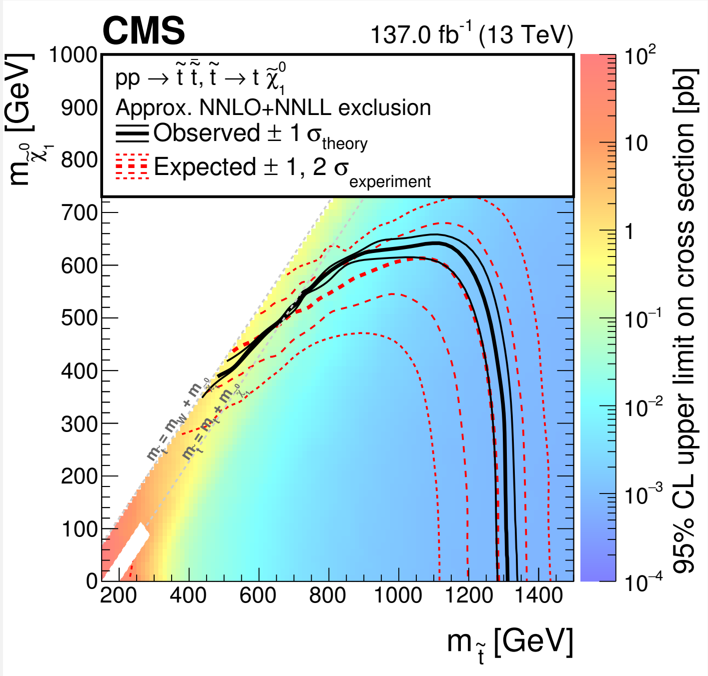
Production cross section fixed by QCD



Decays are model dependent

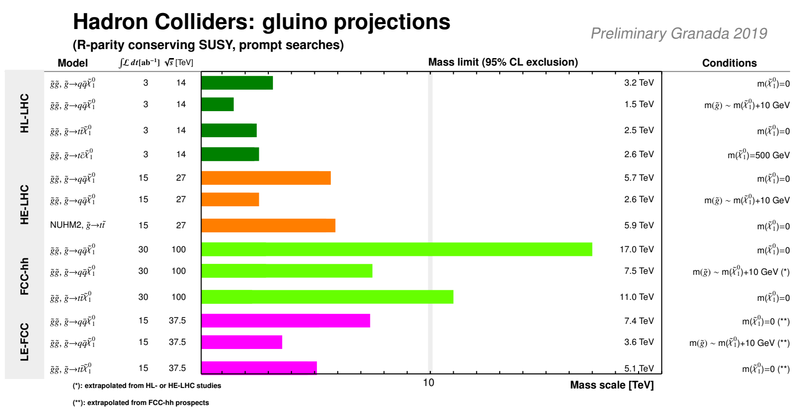
Interest in compressed spectrum: small mass difference between stop and neutralino

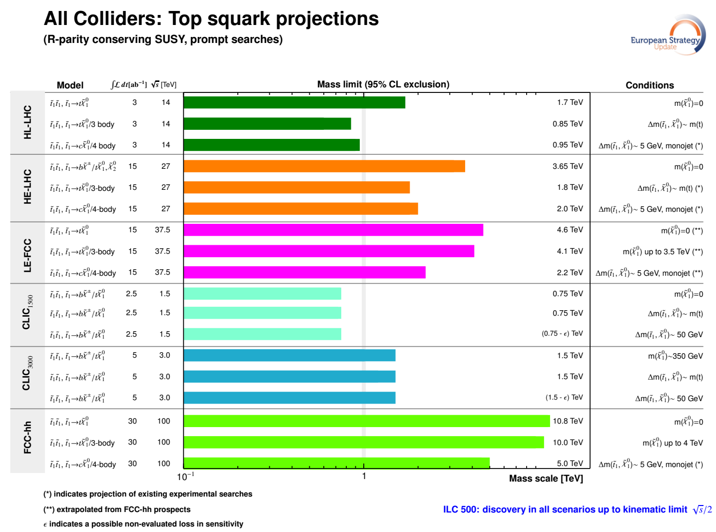
STOP LIMITS



CMS
137.0 fb^{-1} (13 TeV)
pp → $\tilde{t}\bar{\tilde{t}}$, $\tilde{t} \to t\,\tilde{\chi}_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1, 2 $\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]

MSSM PROJECTIONS

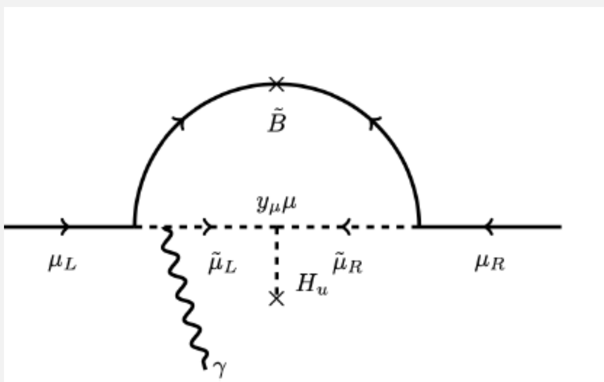


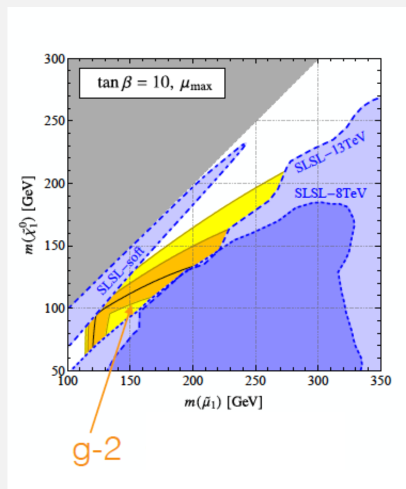


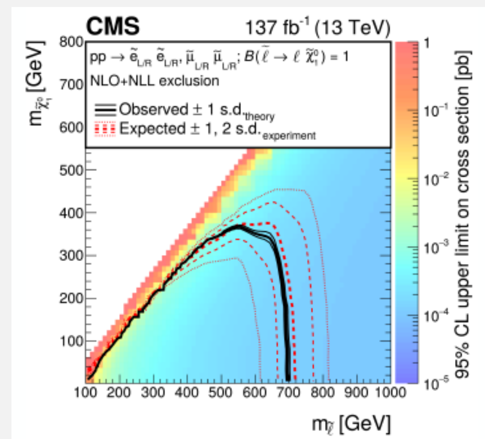
Energy wins

WHAT ABOUT EW SUSY?

- g-2 needs scales around 150 GeV with tan β enhancement
- Still room for light weak SUSY particles with compressed spectra







2104.03217

MODELS

- Lots of room at the LHC for singlet, 2HDM, MSSM models
  - Mass limits on new particles often surprisingly low
- New signatures:
  - Enhanced hh production
  - Compressed spectrum
- Connections to flavor physics
- Complementarity of precision couplings and direct searches

No particular reason to favor any specific model

NEW PHYSICS IN THE TOP SECTOR

WHY NEW PHYSICS IN THE TOP SECTOR????

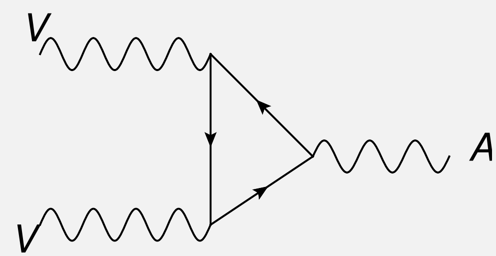
- The top is heavy, $M_t >> m_b$ *WHY?*
- The top quark plays a special role in precision measurements
- The t-b mass splitting contributes to the ρ parameter and M_w proportionally to M_t^2
- Top quark coupling to longitudinal gauge bosons is enhanced by M_t/v

SM 4TH GENERATION NOT ALLOWED

- Gluon fusion to Higgs rate prohibits SM 4th generation
- Add vector-like quarks (VLQs)
  - Left- and right-handed VLQs have identical gauge quantum numbers
- Simplest possibility:
  - Fermion with charge 2/3, $\mathcal{T}_L^2$, $\mathcal{T}_R^2$
  - $\mathcal{T}_L^2$, $\mathcal{T}_R^2$ have identical $SU(3) \times SU(2)_L \times U(1)$ couplings (vector-like)
- Mixes with SM fermions: $\psi_L=(\mathcal{T}_L^1, \mathcal{B}_L^1)$, $\mathcal{T}_R^1$, $\mathcal{B}_R^1$
- Motivated by Little Higgs and composite Higgs models which have VLQs

ANOMALIES

$$L \sim g_A \overline{\psi} T^A \gamma_\mu \gamma_5 \psi A^{A,\mu} + g_V \overline{\psi} T^A \gamma_\mu \psi A^{A,\mu}$$



- Physical theories must be anomaly free
- Anomaly results from divergence at high energy from

$$T^{ABC} \sim Tr\left[\eta_i T^A \{T^B, T^C\}\right] \int \frac{d^n k}{k^3}$$

η=∓ for Left/Right handed fermion

- SM contribution vanishes when summing over all particles in each generation

$$T_{SM} \sim \Sigma_i Tr\left[\eta_i Y_i \{T_i^B, T_i^C\}\right] \to 0$$

- *Vector-like particles anomaly cancellation happens automatically for each fermion*

TOP PARTNERS CAN HAVE DIRAC MASSES

- Most general mass terms:

$$-\mathcal{L}_{M,SM} = \lambda_2 \overline{\psi}^1_L \tilde{H} \mathcal{T}^1_R + h.c.$$

$$-\mathcal{L}_{M,1} = \lambda_3 \overline{\psi}^1_L \tilde{H} \mathcal{T}^2_R + \lambda_4 \overline{\mathcal{T}}^2_L \mathcal{T}^1_R + \lambda_5 \overline{\mathcal{T}}^2_L \mathcal{T}^2_R + h.c.$$

- Physical top's are combinations of $\mathcal{T}^1, \mathcal{T}^2$

$$\chi_L = \begin{pmatrix} t_L \\ T_L \end{pmatrix} \equiv U_L \begin{pmatrix} \mathcal{T}^1_L \\ \mathcal{T}^2_L \end{pmatrix} \qquad \chi_R = \begin{pmatrix} t_R \\ T_R \end{pmatrix} \equiv U_R \begin{pmatrix} \mathcal{T}^1_R \\ \mathcal{T}^2_R \end{pmatrix} \qquad U_{L,R} = \begin{pmatrix} \cos\theta_L & \sin\theta_L \\ -\sin\theta_L & \cos\theta_L \end{pmatrix}$$

  - λ_4 can be rotated away by field redefinitions
  - 4 physical parameters, m_b, M_t, M_T, θ_L $\qquad \sin\theta_R \sim \sin\theta_L \dfrac{M_t}{M_T}$
- Higgs, neutral current, charged current couplings changed

DECOUPLING OF HEAVY TOP PARTNERS

- Remember SM top doesn't decouple

$$M^t = \begin{pmatrix} \frac{\lambda_2 v}{\sqrt{2}} & \frac{\lambda_3 v}{\sqrt{2}} \\ \lambda_4 & \lambda_5 \end{pmatrix}$$

λ_2 is SM-like Yukawa, λ_5 is Dirac mass term, $\lambda_4 \rightarrow 0$

- Small mixing:

$$\lambda_2 \sim \frac{\sqrt{2} m_t}{v}\left[1 + \frac{s_L^2}{2}\left(\frac{M_T^2}{m_t^2} - 1\right)\right]$$

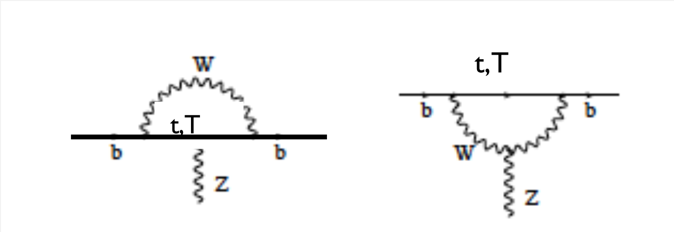
$$\lambda_5 \sim M_T\left[1 - \frac{s_L^2}{2}\left(\frac{M_T^2 - m_t^2}{M_T^2}\right)\right]$$

- Decoupling of T requires: $s_L \sim \frac{v}{M_T}$

COUPLINGS TO W/Z/H MODIFIED

- t-T mixing modifies Z→b$\bar{b}$ at one loop

$$L_W \sim \frac{g}{\sqrt{2}} W_\mu^+ \left\{ c_L \bar{t}_L \gamma^\mu b_L + s_L \overline{T}_L \gamma^\mu b_L \right\}$$



$$\delta g_L^b \sim \delta g_L^{b,SM} \left\{ 1 + s_L^2 \left[-(1+c_L^2) + s_L^2 \frac{M_T^2}{M_t^2} + 2c_L^2 \frac{M_T^2}{M_T^2 - m_t^2} \log\left(\frac{M_T^2}{m_t^2}\right) \right] \right\}$$

- *Vector-like top partners only decouple when $s_L \sim v/M_T$*
- *Evidence for T VLQs may come from b physics*

LIMITS FROM LEP

- Top partner (& top) couplings to Z change $Z \rightarrow b\bar{b}$

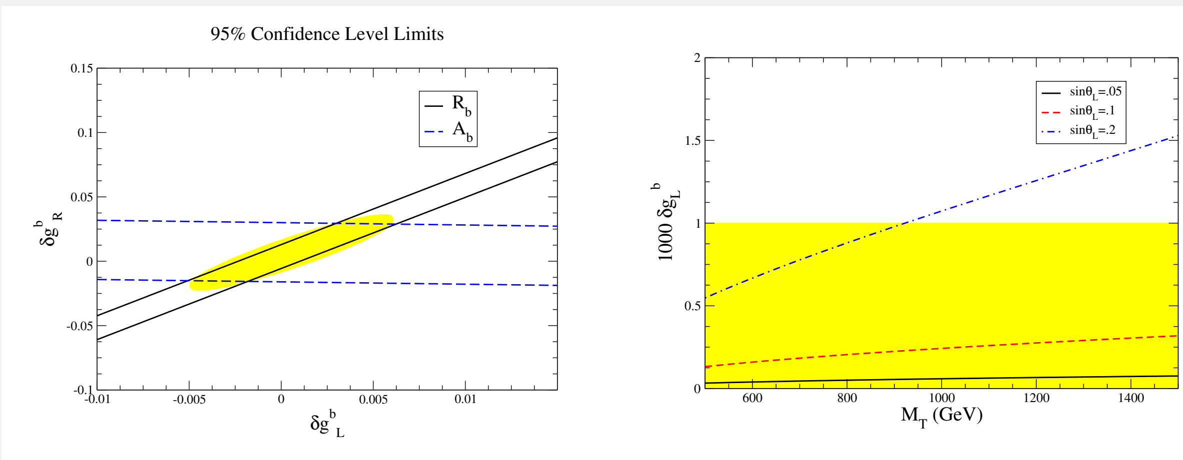
$$R_b \sim R_b^{SM}\left\{1 - 3.6\delta g_L^b + .65\delta g_R^b\right\}$$

$$A_b \sim A_b^{SM}\left\{1 - .32\delta g_L^b - 1.7\delta g_R^b\right\}$$

$$R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Sigma\Gamma(Z \rightarrow q\bar{q})}$$

$$A_b = \frac{\Gamma(Z \rightarrow b_L\bar{b}_L) - \Gamma(Z \rightarrow b_R\bar{b}_R)}{\Gamma(Z \rightarrow b\bar{b})}$$

- Top partner increases $\delta g_L{}^b$ and reduces R_b

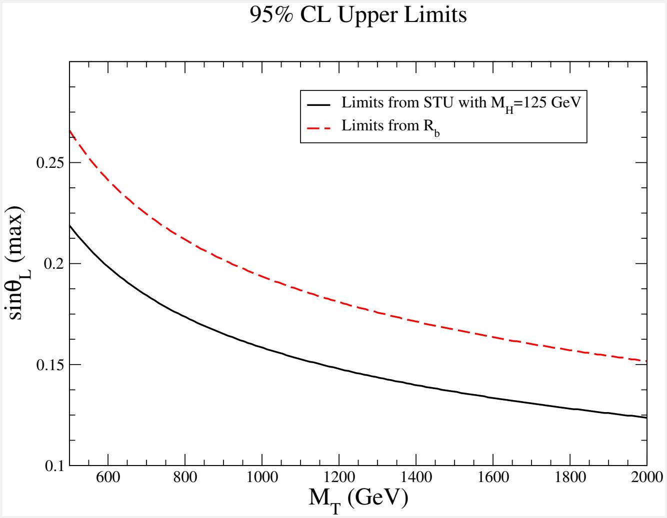


Limit on allowed mixing angle

TOP PARTNER MIXING LIMITED BY PRECISION EW

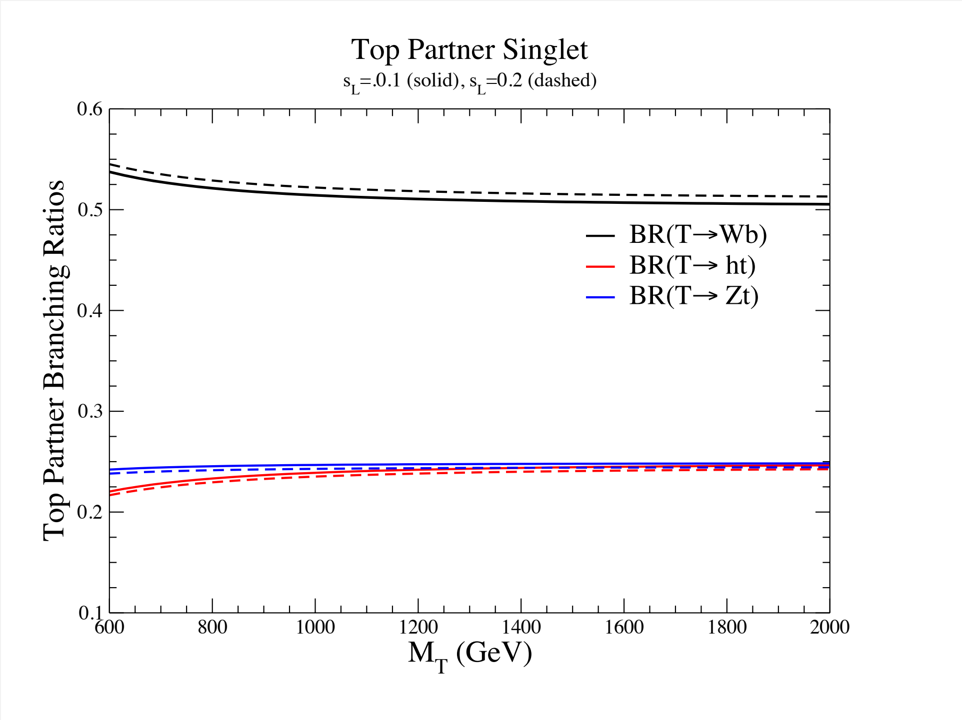
$$\Delta T \sim T_{SM} s_L^2 \left[-(1+c_L^2) + s_L^2 \frac{M_T^2}{m_t^2} + 2c_L^2 \log\left(\frac{M_T^2}{m_t^2}\right) \right]$$

$$\Delta S \sim -\frac{s_L^2}{6\pi} \left[5c_L^2 + (1-3c_L^2) \log\left(\frac{M_T^2}{m_t^2}\right) \right]$$



Strong limits from precision measurements complement direct searches

T MOSTLY DECAYS TO Wb



Look for all possible decays

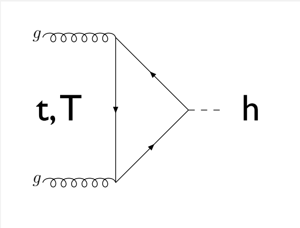
Unitarity bound:

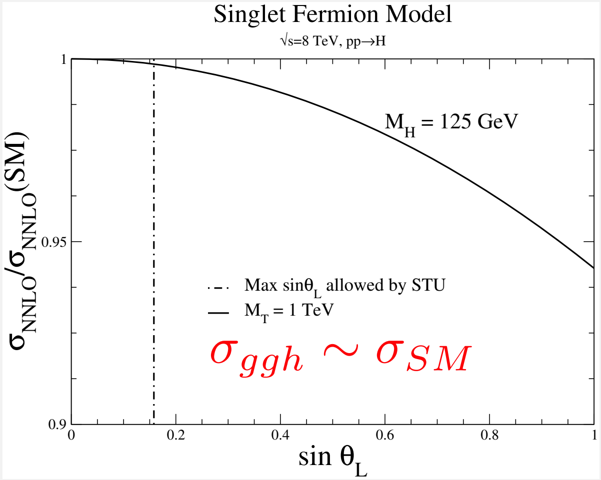
$$M_T < \frac{550\ GeV}{s_L^2}$$

TOP PARTNERS AND GLUON FUSION

- SM top + Top partner:

$$L_h \sim \frac{M_t}{v} c_L^2 \bar{t} t h + \frac{M_T}{v} s_L^2 \overline{T} T h$$



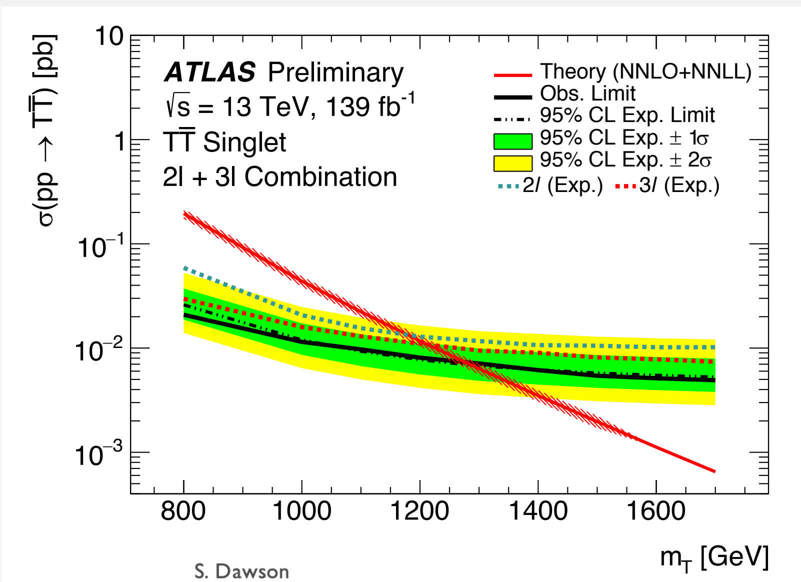


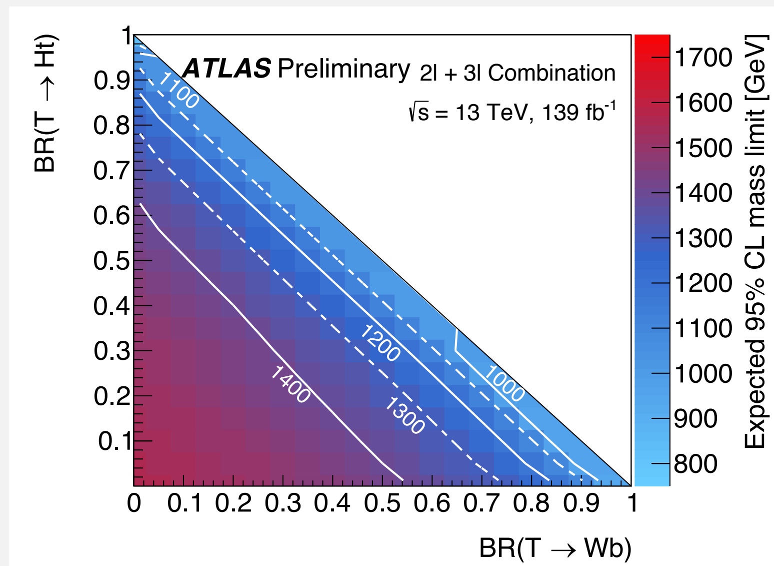
$\sigma_{ggh} \sim \sigma_{SM}$

➡ Very different from adding a chiral 4^{th} generation

TOP PARTNER LIMITS

- $gg \to T\overline{T}$ cross section model independent
- LHC limits look for all possible decays: T→bW, T→tH, T→tZ

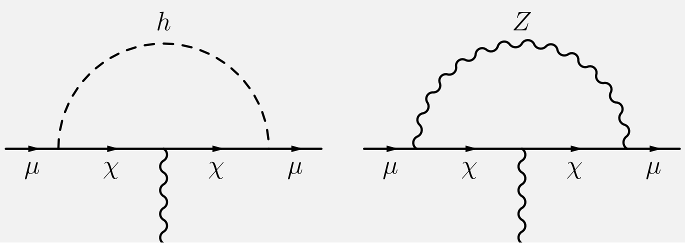




VECTOR LIKE LEPTONS

- Can play exactly the same game for leptons
- Add vector-like SU(2) doublet and/or singlet $L = (N, E), \ \tilde{E}$
- Physical charged leptons (μ and χ) are mixtures of gauge eigenstates (just like in Top VLQ)
- LHC limits from Drell Yan searches for $\chi^+\chi^-$ are relatively weak (~600 GeV)
- $h\mu\mu$ coupling changed from SM by diagonalizing mass matrix (charged singlet case)

MORE CONNECTIONS



Heavy vector-like leptons contribute to μ mass and to g-2 and the contributions are correlated

Motivation for looking for heavy charged and neutral leptons

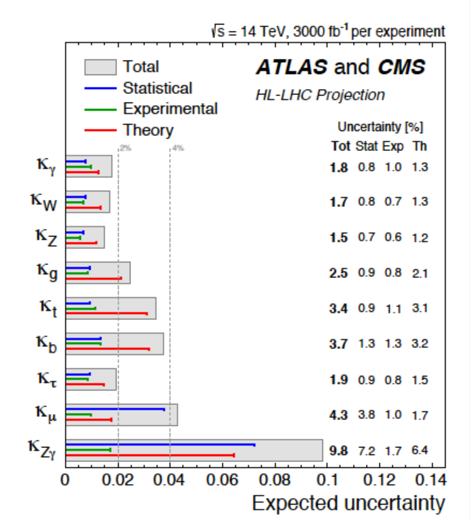
WHAT IF THERE ARE NO NEW PARTICLES DISCOVERED?

BSM PHYSICS FROM PRECISION MEASUREMENTS

- Higgs precision program
- Generically, if new physics is at scale Λ, deviations in Higgs couplings are

$$\delta\kappa \sim \frac{v^2}{\Lambda^2} \sim 5\% \left(\frac{1\ TeV}{\Lambda}\right)^2$$

- Need SM theory at few % level for this program to be feasible



SMALL CORRECTIONS EXPECTED IN MANY BSM MODELS

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: As direct search limits improve, target precision gets smaller

[Snowmass Higgs report, 1310.8361]

PROBLEM WITH PRECISION PROGRAM

- SM Higgs/fermion/gauge couplings are fixed in SM
- You are not allowed to vary them arbitrarily
  - Gauge invariance fixes couplings
- Need to construct a consistent field theory as benchmark comparison to SM

SMEFT: SM EFFECTIVE FIELD THEORY

- Assumptions: New physics decouples Λ >> v, E
- At the weak scale: SM SU(3) x SU(2) x U(1) symmetry and SM particles only
- New physics described by

$$L_{SMEFT} = L_{SM} + \frac{L_5}{\Lambda} + \frac{L_6}{\Lambda^2} + \frac{L_7}{\Lambda^3} + \frac{L_8}{\Lambda^4}$$

$$L_n = \Sigma_i C_i^n O_i^n$$

- New physics contributions contained in coefficients C
- Operators form a complete basis (not unique)
- L_5 and L_7 are lepton number violating

- Assume no new light fields
- Assume Higgs is in an SU(2) doublet

ADVANTAGES OF SMEFT APPROACH

- Quantum field theory where calculations done order by order in $1/\Lambda$
  - Compute cross sections without knowing high scale (UV) physics
- Systematically improvable
- At this level, SMEFT calculations are model independent
- Measurements interpreted in terms of SMEFT coefficients
- Can compare very different classes of measurements

Sounds good, but how does this work in practice?

And even more important, how model independent is this?

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

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

- 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 $O(s/\Lambda^2)$ or $O(v^2/\Lambda^2)$

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 $g_{BSM} >> g_{SM}$

GETTING STARTED

- Start with Warsaw basis and ignore flavor (A VERY BIG ASSUMPTION)
  - Operators in different bases related by equations of motion
- Baby steps first: Consider interference of SM and dimension-6 operators
  - ie, new physics contributions are linear in Wilson coefficients
  - So we need (energy of process) << Λ
  - (No problem for fits to LEP electroweak precision data)

WARSAW BASIS

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}	$(\bar q'_p \sigma^{\mu\nu} \mathcal{T}^A u'_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e'_p \gamma^\mu e'_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	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}	$(\bar q'_p \sigma^{\mu\nu} \mathcal{T}^A d'_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u'_p \gamma^\mu u'_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q'_p \sigma^{\mu\nu} d'_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d'_p \gamma^\mu d'_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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}	$(\bar e'_p \gamma_\mu e'_r)(\bar d'_s \gamma^\mu d'_t)$	$Q_{qu}^{(1)}$	$(\bar q'_p \gamma_\mu q'_r)(\bar u'_s \gamma^\mu u'_t)$
		$Q_{ud}^{(1)}$	$(\bar u'_p \gamma_\mu u'_r)(\bar d'_s \gamma^\mu d'_t)$	$Q_{qu}^{(8)}$	$(\bar q'_p \gamma_\mu \mathcal{T}^A q'_r)(\bar u'_s \gamma^\mu \mathcal{T}^A u'_t)$
		$Q_{ud}^{(8)}$	$(\bar u'_p \gamma_\mu \mathcal{T}^A u'_r)(\bar d'_s \gamma^\mu \mathcal{T}^A d'_t)$	$Q_{qd}^{(1)}$	$(\bar q'_p \gamma_\mu q'_r)(\bar d'_s \gamma^\mu d'_t)$
				$Q_{qd}^{(8)}$	$(\bar q'_p \gamma_\mu \mathcal{T}^A q'_r)(\bar d'_s \gamma^\mu \mathcal{T}^A d'_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l'^j_p e'_r)(\bar d'_s q'^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d'^\alpha_p)^T \mathbb{C} u'^\beta_r\right]\left[(q'^{\gamma j}_s)^T \mathbb{C} l'^k_t\right]$
$Q_{quqd}^{(1)}$	$(\bar q'^j_p u'_r)\varepsilon_{jk}(\bar q'^k_s d'_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q'^{\alpha j}_p)^T \mathbb{C} q'^{\beta k}_r\right]\left[(u'^\gamma_s)^T \mathbb{C} e'_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q'^j_p \mathcal{T}^A u'_r)\varepsilon_{jk}(\bar q'^k_s \mathcal{T}^A d'_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q'^{\alpha j}_p)^T \mathbb{C} q'^{\beta k}_r\right]\left[(q'^{\gamma m}_s)^T \mathbb{C} l'^n_t\right]$
$Q_{lequ}^{(1)}$	$(\bar l'^j_p e'_r)\varepsilon_{jk}(\bar q'^k_s u'_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d'^\alpha_p)^T \mathbb{C} u'^\beta_r\right]\left[(u'^\gamma_s)^T \mathbb{C} e'_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l'^j_p \sigma_{\mu\nu} e'_r)\varepsilon_{jk}(\bar q'^k_s \sigma^{\mu\nu} u'_t)$		

- The interesting operators are those with derivatives
- Derivative operators introduce new structures into interactions
- 2499 operators with flavor
- Many operators are *not just a rescaling of SM operators* 1 1

SMEFT EXAMPLE: HIGGS PRODUCTION FROM GLUONS

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

- 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)
- In SMEFT language:

$$O_G = (\phi^\dagger\phi)G^A_{\mu\nu}G^{A,\mu\nu}$$

$$O_{tH} = (\phi^\dagger\phi)\overline{\psi}_L\tilde{H}t_R$$

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

- (This example really just looks like rescaling vertices, but note contribution to hh)

$$\kappa = 1 + \delta\kappa$$

GLUON FUSION IN THE κ FRAMEWORKS

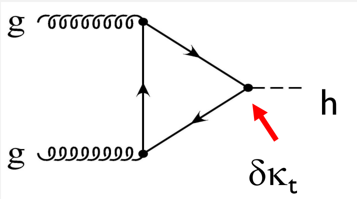
t

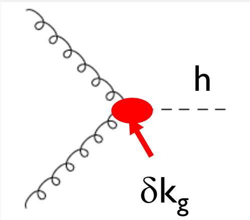
gg→h sensitive to $|\delta\kappa_g - \delta\kappa_t|^2$

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

Almost equal in SM

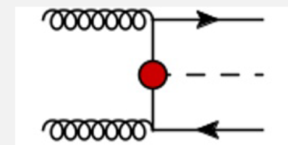
Can't distinguish *long distance* physics ($\delta\kappa_t$) from *short distance* physics (new particles in loops, $\delta\kappa_g$ nonzero)



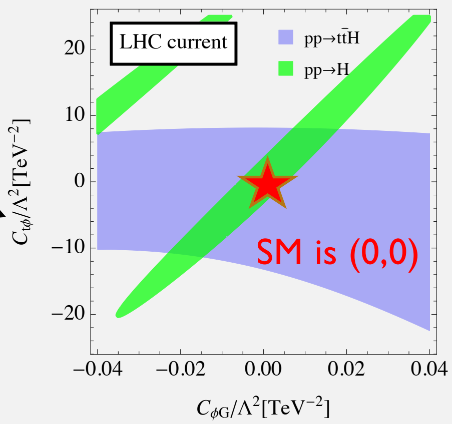


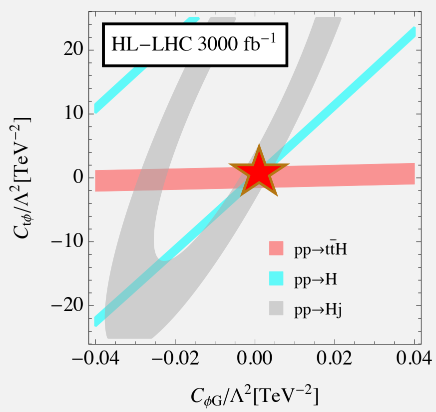
NEW PHYSICS IN THE TOP-HIGGS SECTOR

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



Non-SM tth coupling





Non-SM ggh coupling

- 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

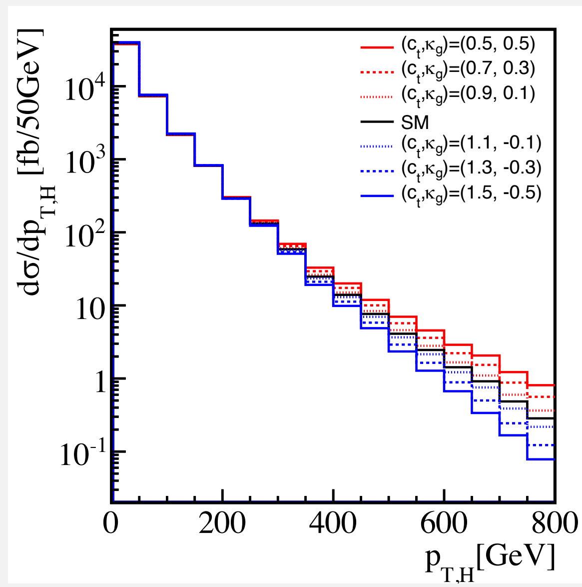
Maltoni, Vryonidou, Zhang, 1607.05339

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

$c_t=k_t$

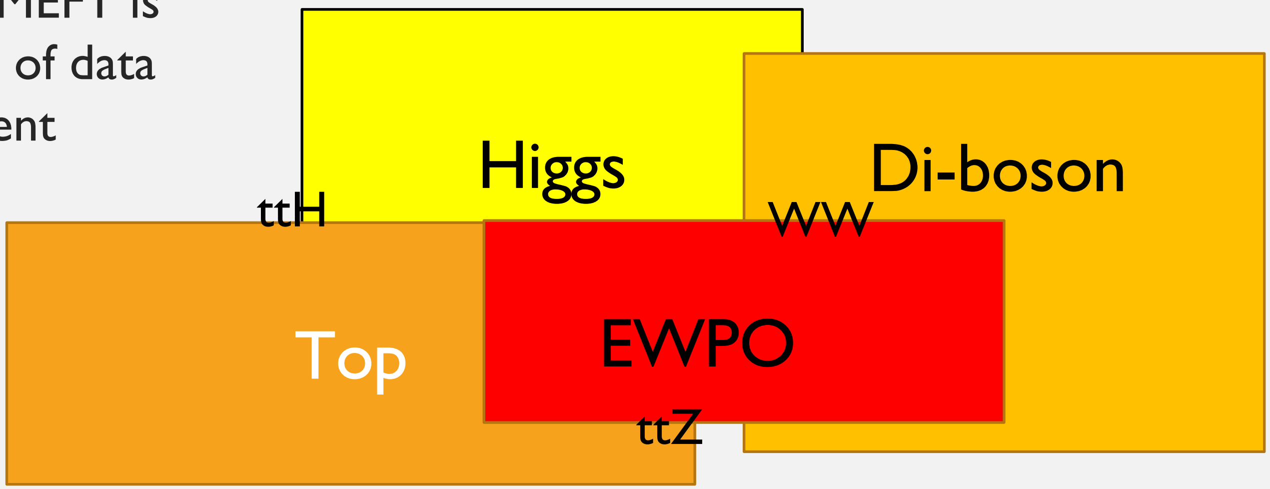
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant

POWER OF SMEFT

- Gauge invariant operators contribute to Z-pole observables, Higgs physics, diboson production, top quark physics, B physics
- Limits from different processes can be combined
- Hope is that pattern of new coefficients will point to underlying UV physics

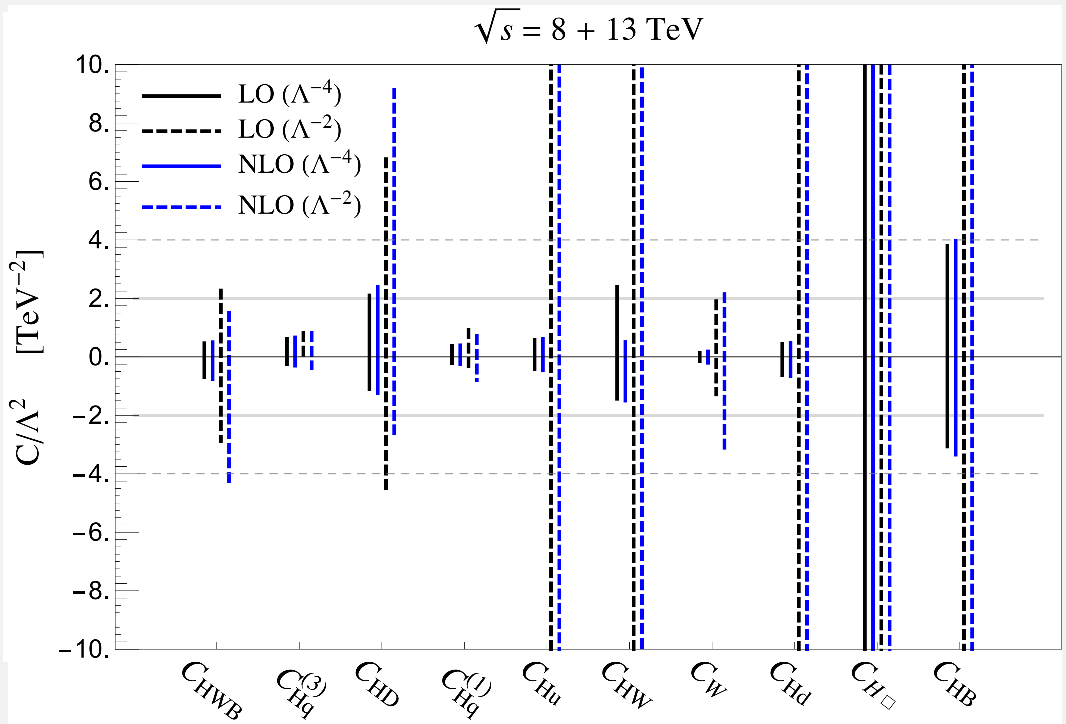
COMPLICATED

- Power of SMEFT is connection of data from different processes



ASSUMPTIONS CREEP IN

- Single parameter fit to WW/WZ/Wh/Zh data
- Include QCD and $1/\Lambda^4$ terms
- Fit assumes SM efficiencies in each bin (not necessarily true)
- Fit ignores flavor

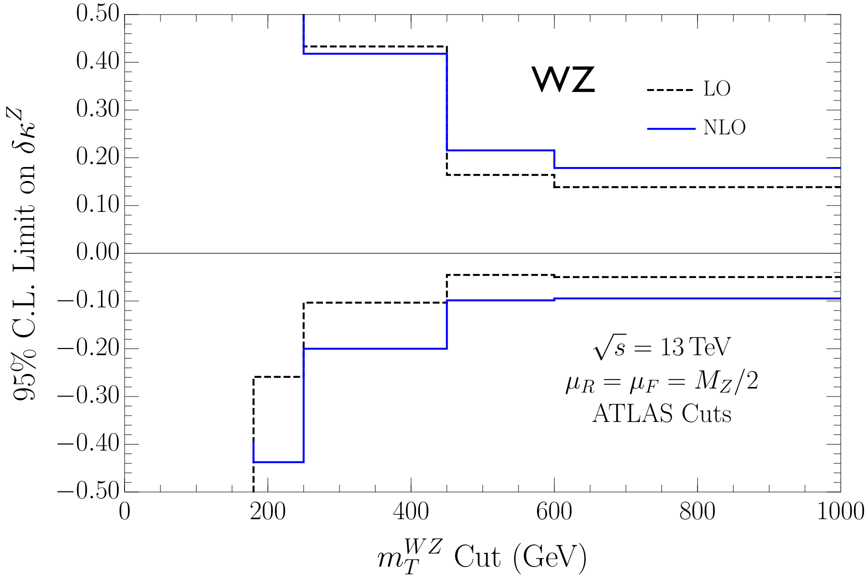


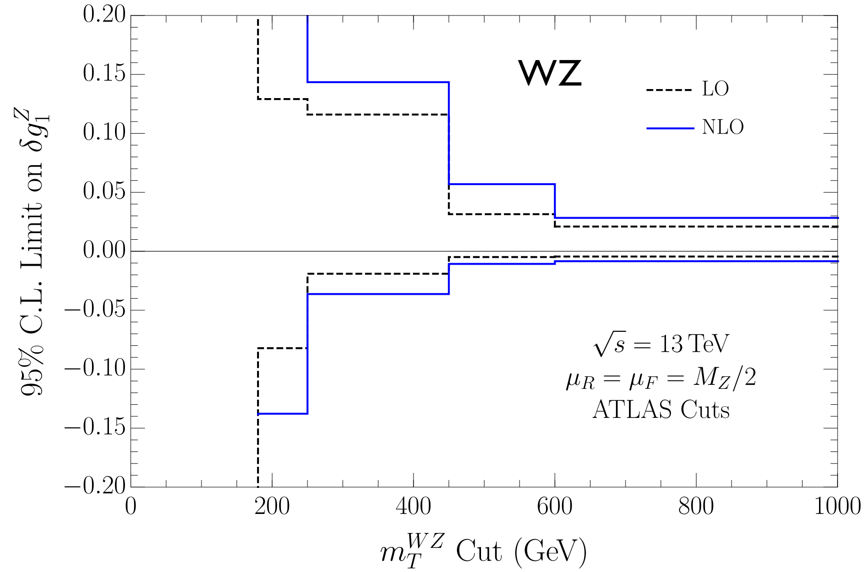
2003.07862

IS IT ALL THE LAST BIN?

- Fit results depend on cut on maximum energy

Plots successively remove high m_T bins





SITUATION IS EVEN MURKIER WITH NLO EW

All SMEFT effects here

- Example $M_W = M_W^{SM} + \delta M_W$
- Dependence on many coefficients at NLO (QCD + EW)
- Always use "best" SM prediction for fits

$$\delta M_W^{LO} = \frac{v^2}{\Lambda^2}\left\{ -30C_{\phi l}^{(3)} + 15C_{ll} - 28C_{\phi D} - 57C_{\phi WB} \right\}$$

$$\delta M_W^{NLO} = \frac{v^2}{\Lambda^2}\left\{ -36C_{\phi l}^{(3)} + 17C_{ll} - 30C_{\phi D} - 64C_{\phi WB} \right.$$
$$- 0.1C_{\phi d} - 0.1C_{\phi e} - 0.2C_{\phi l}^{(1)} - 2C_{\phi q}^{(1)} + C_{\phi q}^{(3)} + 3C_{\phi u} + 0.4C_{lq}^{(3)}$$
$$\left. - 0.03C_{\phi B} - 0.03C_{\phi \Box} - 0.04C_{\phi W} - 0.9C_{uB} - 0.2C_{uW} - 0.2C_W \right\}$$

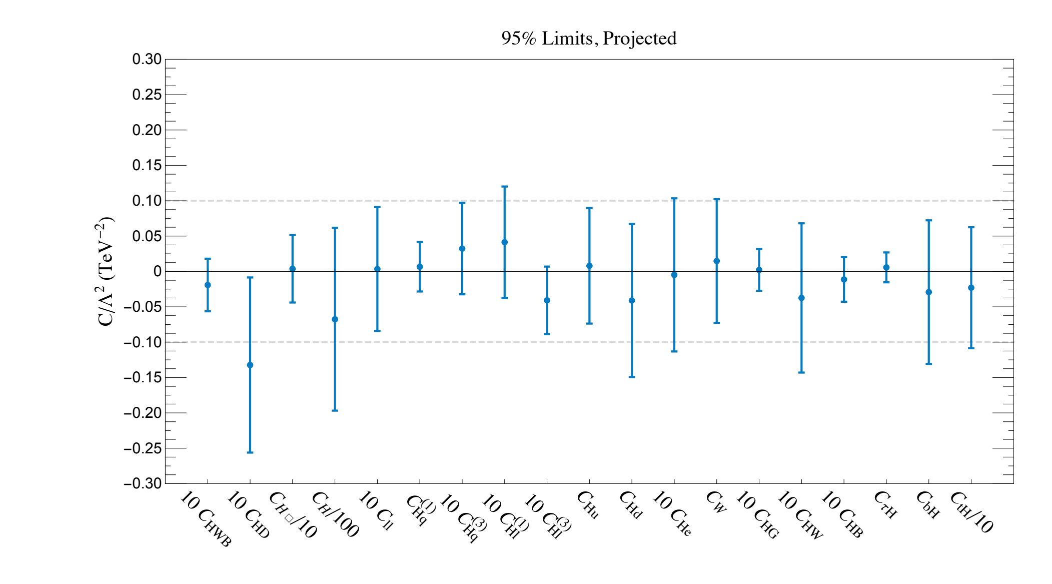
Dawson, Giardino; ArXiv:1909.02000

α, G_μ, M_Z scheme

MANY SOPHISTICATED GLOBAL FITS

- Include Higgs data, WW, WZ production with kinematic distributions
- Include precision observables from LEP/SLD
- Compare with "best SM theory"
- Calculate to NLO QCD SMEFT
- Some fits include flavor observables
- Some fits include top observables

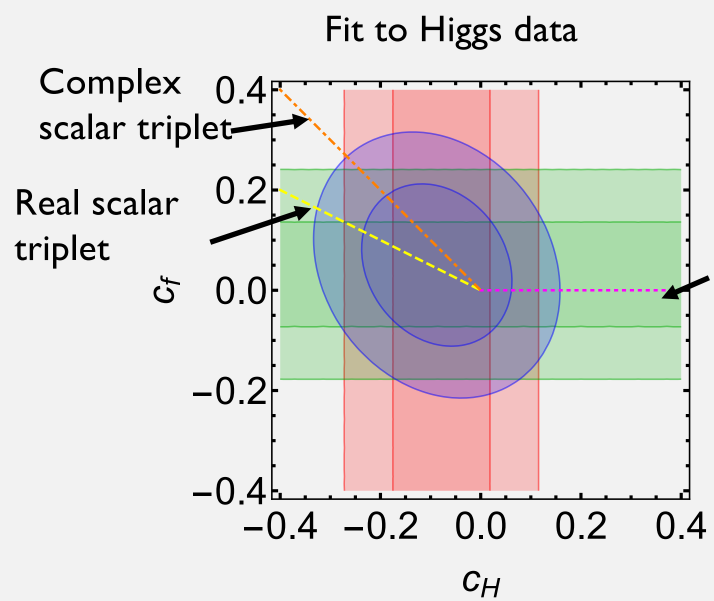
GLOBAL FIT



S. Dawson

WHAT DO WE LEARN BY FITTING SMEFT 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



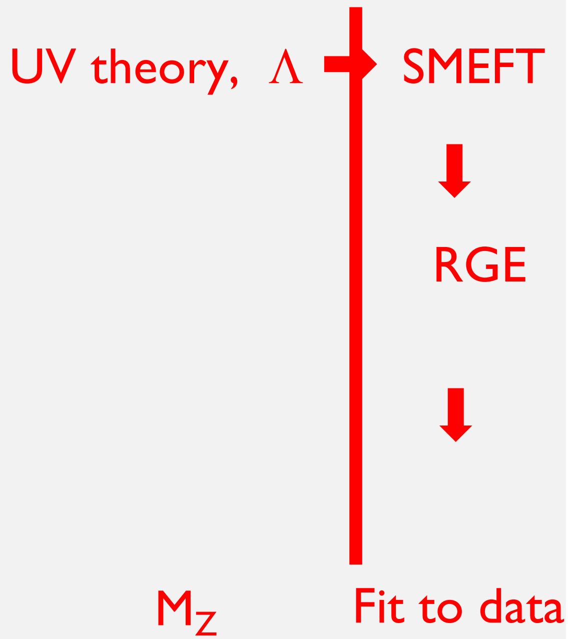
$$O_H = \frac{1}{2v^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$

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

Dawson, Murphy, 1704.07851

COMPUTING SMEFT COEFFICIENTS

- Start with Lagrangian in full theory (including heavy states)
- Use equations of motion to integrate out heavy particles
- Match to dimension-6 EFT at high scale
- RGE evolve operators to weak scale
- Fit to data



EXAMPLE: SINGLET MODEL

- High scale is M_H, mass of heavy scalar
- Integrating out H generates 2 operators:

$$O_H = (\phi^\dagger \phi)^3$$
$$O_{H\Box} = (\phi^\dagger \phi)\Box(\phi^\dagger \phi)$$

- Coefficients are predictions from matching model to SMEFT:

$$\frac{v^2}{\Lambda^2} C_{H\Box} = -\frac{1}{2}\tan^2\theta$$
$$C_H = C_{H\Box}\left(\tan\theta \frac{b_3}{3v} - a_2\right)$$

C_H=0 in Z_2 symmetric model

$$L \sim \frac{a_2}{2}(\phi^\dagger\phi)S^2 + \frac{b_3}{6}S^3$$

SINGLET EXAMPLE, CONTINUED

- So we have coefficients at high scale Λ
- Data is at M_Z

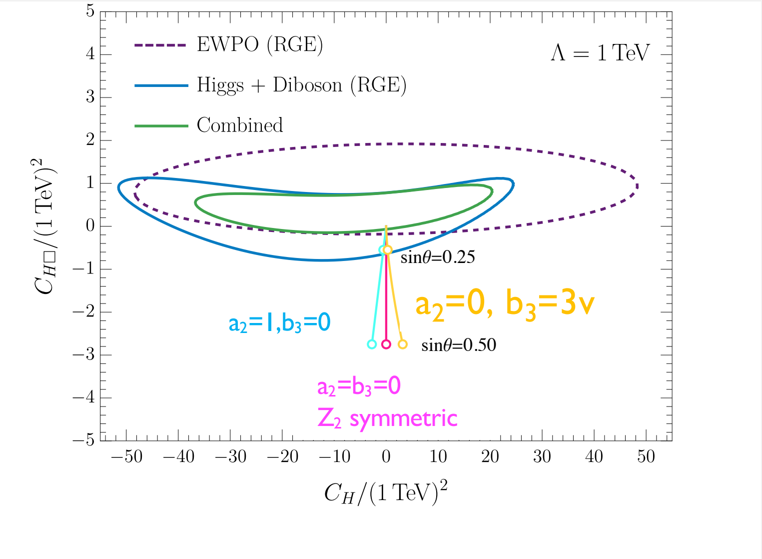
$$C_i(M_Z) = C_i(\Lambda) - \frac{\gamma_{ij} C_j}{16\pi^2} \log\left(\frac{\Lambda}{M_Z}\right)$$

- Operators mixing under RGE: **generate C_{HD}~ΔT**

$$\gamma_{C_{HD},C_{H\Box}} \sim \frac{20}{3} g_1^2$$

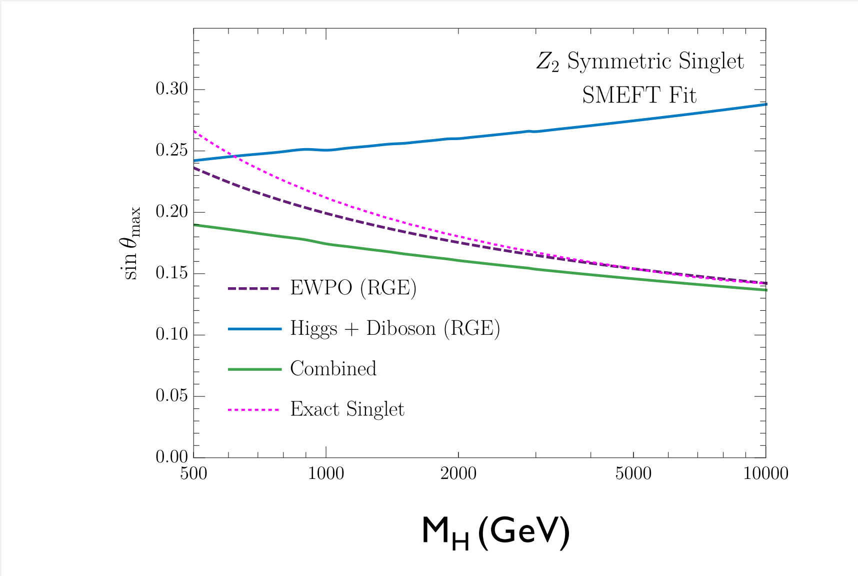
SINGLET MODEL ↔ SMEFT

- C_H limits from loop contributions involving hhh coupling: very weak
- Only points on yellow, magenta, cyan lines correspond to points in singlet model
- Hope is that precision measurements would pick out model point



SINGLET MODEL ↔ SMEFT

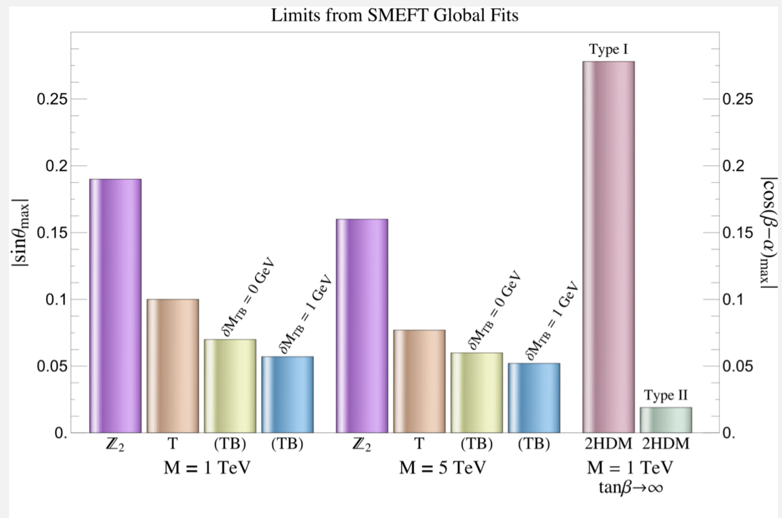
- SMEFT limits accurately reproduce complete singlet model results
- Limits dominated by EWPO contributions through RGE generated C_{HD} contribution



Dawson, Homiller, Lane, 2007.01296

PATTERNS OF COEFFICIENTS

	$\text{Singlet}_{\not{\mathbb{Z}}_2}$	$\text{Singlet}_{\mathbb{Z}_2}$	2HDM	T VLQ	(TB) VLQ	s
$\frac{v^2 C_H}{\Lambda^2}$	$\frac{\tan^2\theta}{2}(\tan\theta \frac{m}{3v} - \kappa)$		$\frac{\cos^2(\beta-\alpha) M^2}{v^2}$			
$\frac{v^2 C_{H\Box}}{\Lambda^2}$	$-\frac{\tan^2\theta}{2}$	$-\frac{\tan^2\theta}{2}$				
$\frac{v^2 C_{bH}}{\Lambda^2}$			$-Y_b \eta_b \frac{\cos(\beta-\alpha)}{\tan\beta}$		$Y_b (s_R^b)^2$	
$\frac{v^2 C_{tH}}{\Lambda^2}$			$- Y_t \eta_t \frac{\cos(\beta-\alpha)}{\tan\beta}$	$Y_t (s_L^t)^2$	$Y_t (s_R^t)^2$	
$\frac{v^2 C_{\tau H}}{\Lambda^2}$			$-Y_\tau \eta_\tau \frac{\cos(\beta-\alpha)}{\tan\beta}$			
$\frac{v^2 (C_{Hq}^{(1)})_{33}}{\Lambda^2}$				$\frac{(s_L^t)^2}{2}$		
$\frac{v^2 (C_{Hq}^{(3)})_{33}}{\Lambda^2}$				$-\frac{(s_L^t)^2}{2}$		
$\frac{v^2 C_{Hb}}{\Lambda^2}$					$(s_R^b)^2$	
$\frac{v^2 C_{Ht}}{\Lambda^2}$					$-(s_R^t)^2$	
$\frac{v^2 C_{Htb}}{\Lambda^2}$					$2 s_R^t s_R^b$	
$\frac{v^2 C_{HG}}{\Lambda^2}$				$-\frac{\alpha_s (s_L^t)^2}{8\pi}(.02)$	$\frac{\alpha_s (s_R^b)^2}{8\pi}(.65)$	$-\frac{\alpha_s \kappa v^2}{96\pi m_s^2}$



* These are particularly simple models

SMEFT HARD WAY TO FIND NEW PHYSICS

- Lots of work (theory and experiment) to find BSM physics from SMEFT fits
- Need to make sure theory is accurate enough to allow for drawing conclusions
- Need to include data from many sources
- Need to study how well we can discriminate between models

This program is in its infancy at the LHC

THE END

- Much motivation to search for new BSM physics
  - Unanswered questions
  - We don't know where new physics might be
- I have only presented a very small slice of this huge subject
- Almost all BSM physics has implications for LHC new particle searches, precision measurements, and flavor physics