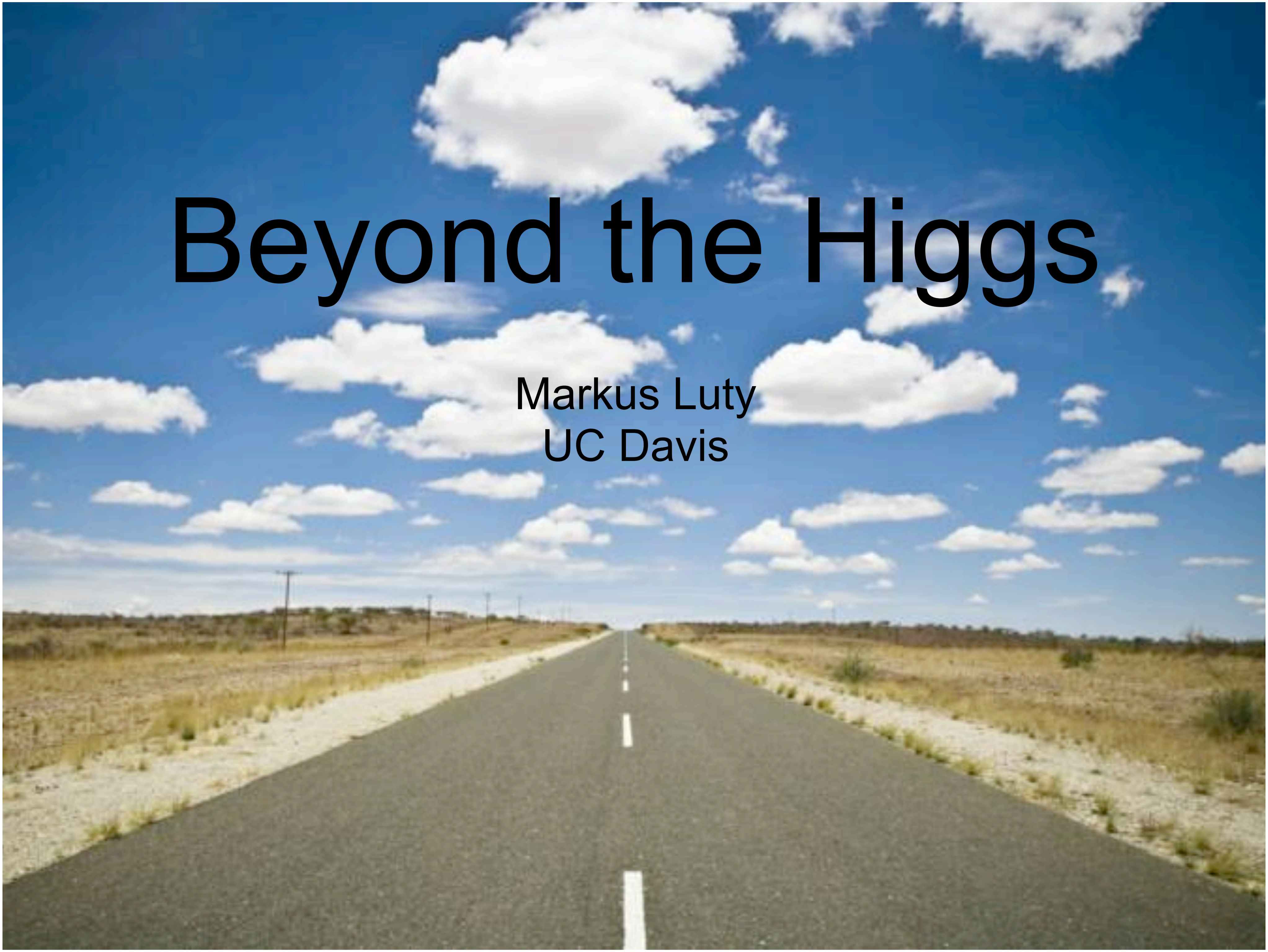
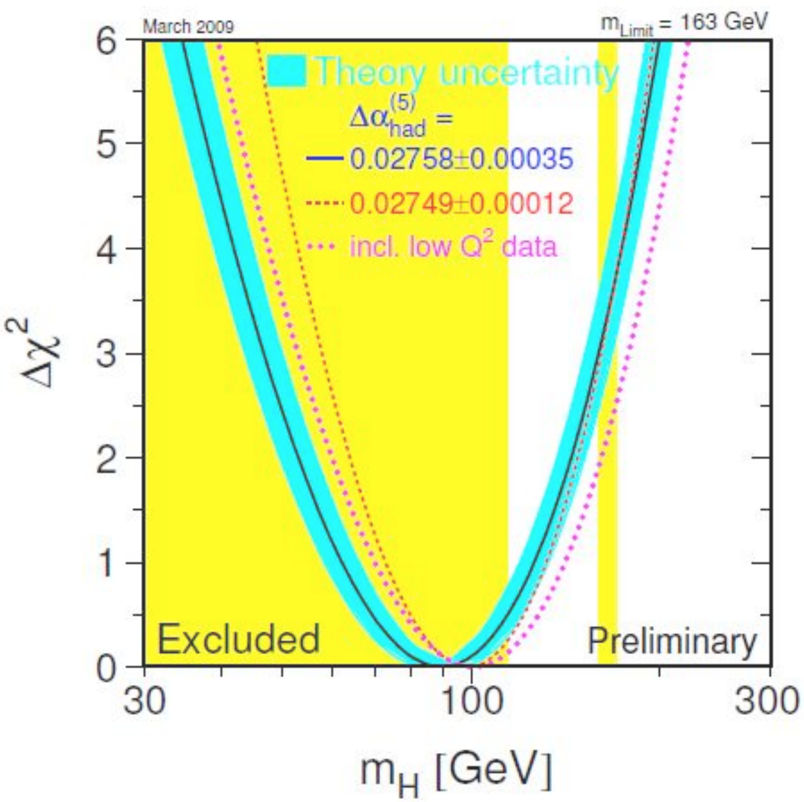


Beyond the Higgs

Markus Luty
UC Davis

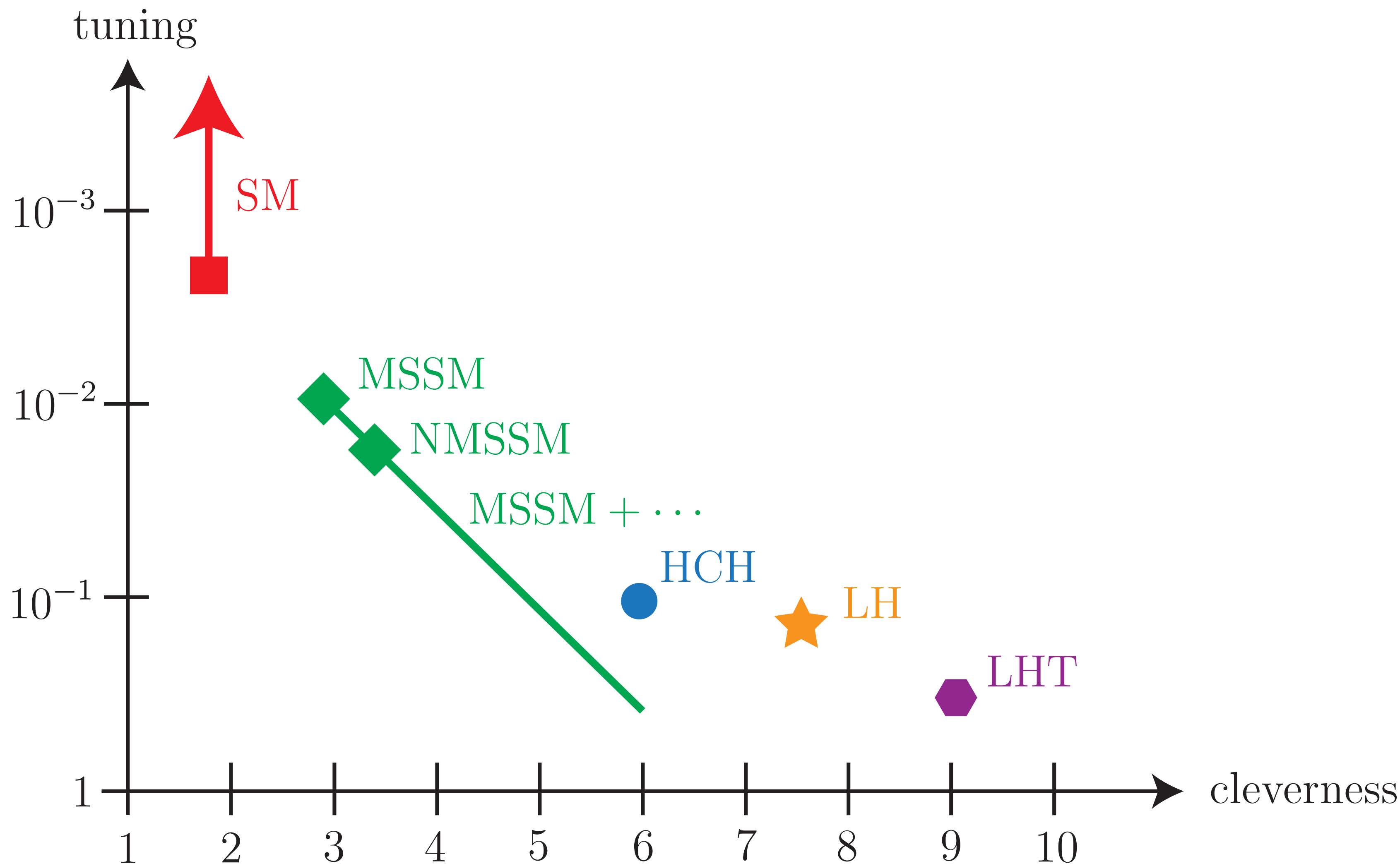
Introduction



Precision electroweak data $\Rightarrow$ elementary Higgs?

This talk: argue that strong electroweak dynamics at TeV scale is very plausible

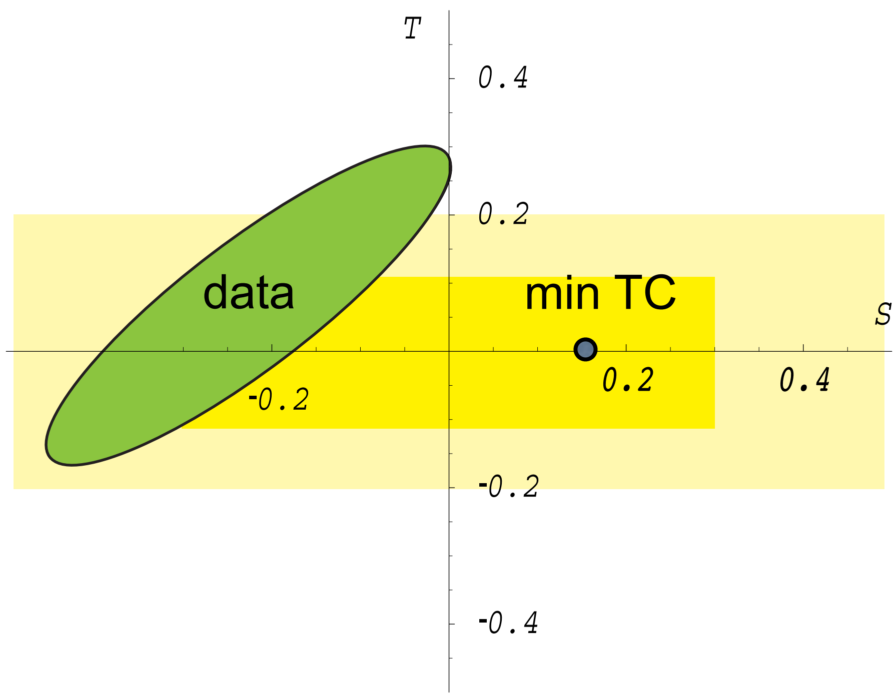
Tension in Model Building



Minimal Strong EW Breaking

Effective theory below TeV:

- No new states below TeV (no Higgs)
- Minimal flavor violation
- Custodial symmetry violated only by $Z,\ t$
- All allowed interactions strong at TeV ($\Rightarrow N \sim 1$)



"Little hierarchy problem" is "$S < 0$ problem"

$$\Delta\mathcal{L}_{\text{eff}} \sim S\, W_3^{\mu\nu} B_{\mu\nu}$$

Sign of S Parameter

Hints that $S > 0$:

- Data $\Rightarrow S > 0$ in QCD
- QCD theory:

  Large N_c + vector meson dominance + $m_\rho < m_a$

  $\Rightarrow S > 0$
- Holographic models $\Rightarrow S > 0$ when calculable

Nothing known about non-QCD-like theories with $N \sim 1$

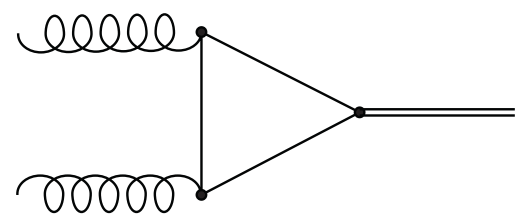
Must explore experimentally (LHC, lattice?)

Phenomenology

No complete theory, use general physical arguments to deduce signatures (c.f. exploration of GeV scale)

- Strong $W_L W_L$ scattering
- Narrow spin 0 resonances (Evans, Luty 2009)

$$\Delta\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda_t^{d-1}}(\psi\psi^c)(Qt^c) + \text{h.c.} \quad \Rightarrow$$



$\sigma(gg \to \varphi) \sim \text{pb}$ at LHC for $m_\varphi \sim \text{TeV}$

2-body strong decays forbidden by isospin, parity, etc.

$\Rightarrow$ can be narrow

$$\Gamma(\varphi \to \bar{t}t) \sim m_\varphi/10$$

$\Gamma(\varphi \to W_L W_L Z_L) \gtrsim m_\varphi/100$ plausible

Conformal Technicolor

(Luty, Okui 2004)

Biggest model-building challenge: top quark

$$\Delta\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda_t^{d-1}}(Qt^c)\mathcal{H} \qquad\qquad d = \dim(\mathcal{H})$$

E.g. $\mathcal{H} = \psi\psi^c$

$$\Lambda_t \sim \begin{cases} 3\ \text{TeV} & d = 3 \\ 10\ \text{TeV} & d = 2 \\ 10^3\ \text{TeV} & d = 1.3 \end{cases}$$

(c.f. “walking technicolor” 1980’s)

General conformal field theory: $d \geq 1$

Hierarchy problem: $\Delta = \dim(\mathcal{H}^\dagger\mathcal{H}) > 4$

$\Delta \neq 2d$ in strongly-coupled theories

Constraints on Dimensions

- Large N:

  $\Delta = 2d + \mathcal{O}(1/N)$ (includes "holographic" 5D theories)

- $d \to 1$ is weak-coupling limit:

  $\Delta \to 2 + \mathcal{O}((d-1)^{1/2})$

- Rigorous bounds:

  (Rattazzi, Rychkov, Tonni, Vichi 2008; Rychkov, Vichi 2009)

  So far only bound $\Delta_{\text{min}} = \min\{\dim(\mathcal{H}^\dagger\mathcal{H}),\ \dim(\mathcal{H}^\dagger\sigma_3\mathcal{H})\}$

- Lattice:

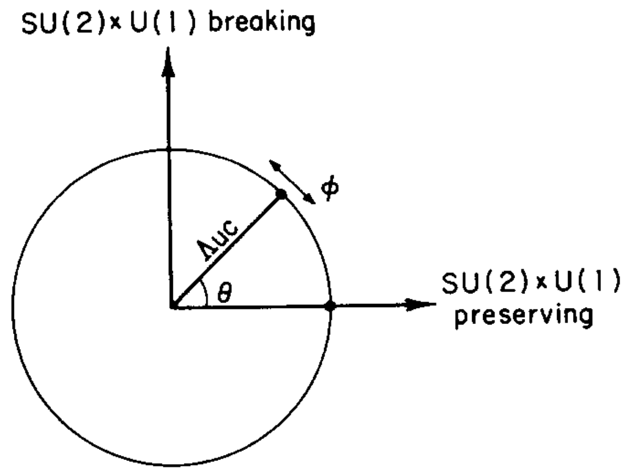
  Measure d by dependence on mass $m\psi\psi^c$ (Luty 2008)

  First measurement: $d \simeq 2.5$ in QCD with 2 sextet fermions (DeGrand 2009)

Composite Higgs

What if strong dynamics cannot give $S < 0$?

Higgs as composite pseudo Nambu-Goldstone boson



(Dugan, Georgi, Kaplan 1984)

$$\frac{v}{f} = \sin\theta \qquad \text{tuning} \sim \frac{v^2}{f^2} = \sin^2\theta$$

Top loop $\Rightarrow m_{h^0}^2 \sim \dfrac{N_c m_t^2}{N_{\rm UC}}$

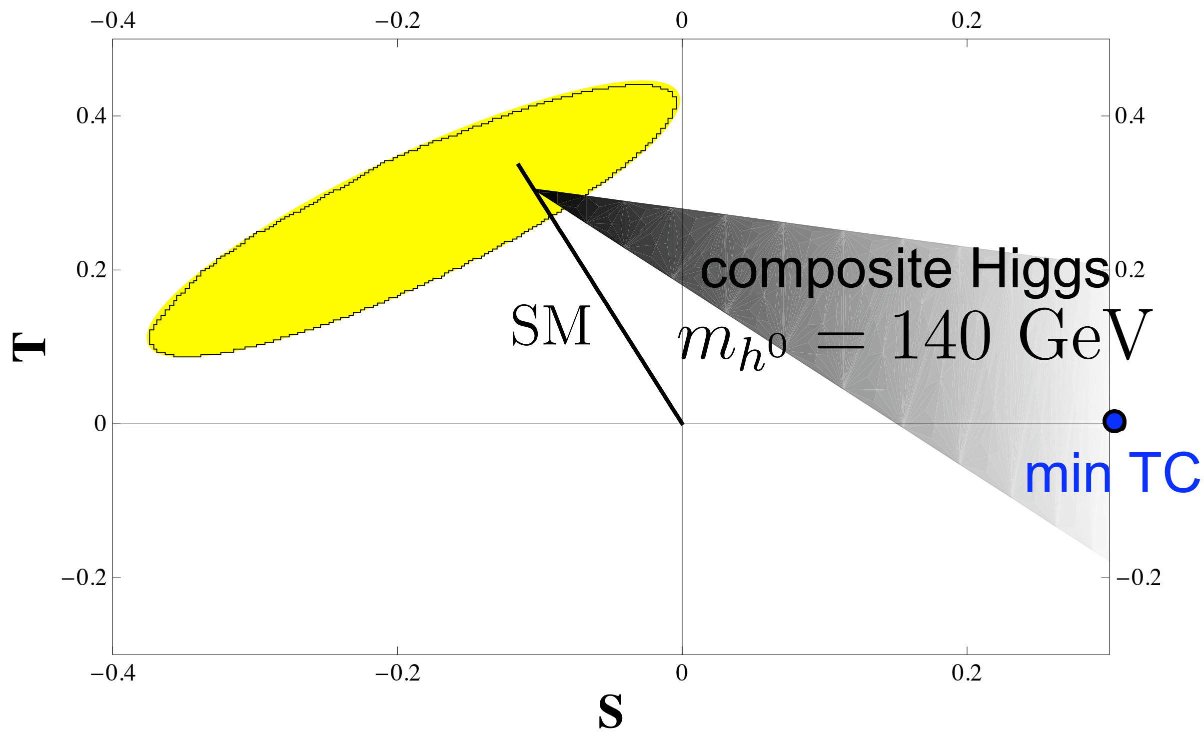
Precision Electroweak

$$S = \underbrace{S_{\rm UV}}_{>0} \sin^2\theta - \frac{1}{6\pi} \ln \frac{\rm TeV}{m_h^0} \cos^2\theta$$

$$T = T_{\rm UV} \sin^2\theta + \frac{3}{8\pi c_W^2} \ln \frac{\rm TeV}{m_h^0} \cos^2\theta$$

Good electroweak fit

for $\sin\theta \sim \frac{1}{4}$



General Phenomenology

- Higgs with non-standard couplings

  Suppressed standard model couplings (c.f. 2 Higgs model)

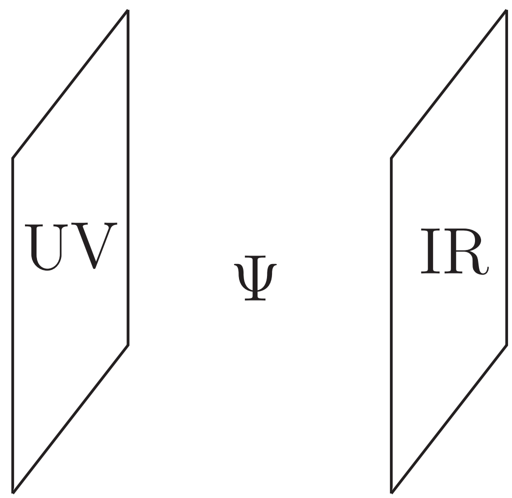
- New (strong?) physics at scale

  $$\Lambda \lesssim \frac{\mathrm{TeV}}{\sin\theta}$$

  Form of new physics depends on models...

Composite Top and Higgs

Composite fermions natural in “holographic” 5D models



$$\mathcal{L}_{4\,\mathrm{eff}} = \underbrace{\lambda_q q Q^c + \lambda_u u^c T}_{\text{Preserves EW}} + \underbrace{Q^c \mathcal{H} T}_{\substack{\langle H \rangle \sim \sin\theta \\ \text{breaks EW}}}$$

$q, u^c =$ elementary

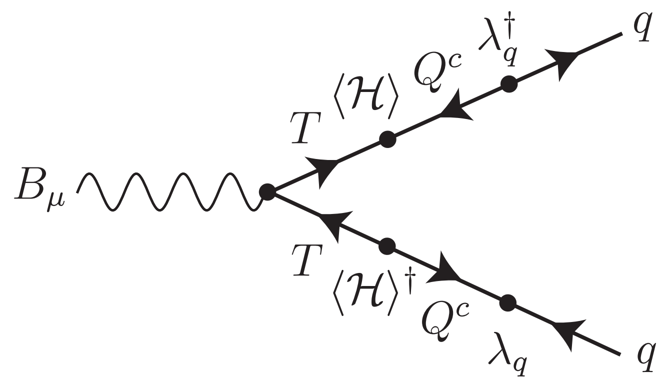
$Q^c, T, \mathcal{H} =$ composite

Note: not minimal flavor violation!

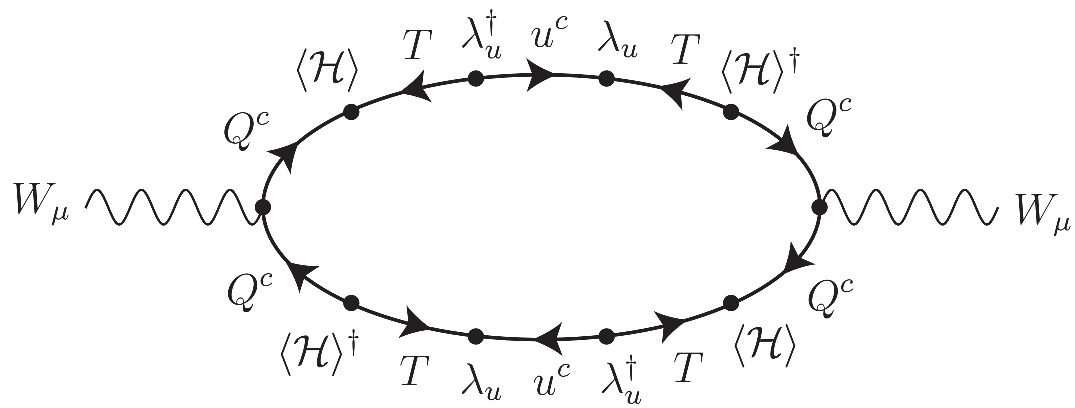
Precision Electroweak

(Agashe, Contino, Pomarol 2005)

$$\frac{\Delta g_{Z\bar{b}b}}{g_{Z\bar{b}b}} \sim \lambda_{q3}^2 \sin^2\theta$$



$$\alpha T \sim N_c \lambda_{u3}^4 \sin^2\theta$$



$$\alpha T \left(\frac{\Delta g_{Z\bar{b}b}}{g_{Z\bar{b}b}}\right)^2 \sim N_c \left(\frac{m_t}{\Lambda \sin\theta}\right)^4 \sin^6\theta$$

$m_t \sim \lambda_{q3}\lambda_{u3}\Lambda \sin\theta$

OK for $\sin\theta \sim \frac{1}{4}$

Elementary Top Quark

Minimal conformal technicolor is composite Higgs!

(Galloway, Evans, Luty, Tacchi, in preparation)

$$SU(2)_{\mathrm{CTC}} \times SU(2)_L \times SU(2)_R$$

$$\left.\begin{aligned} \psi &\sim (2,2,1), \\ \psi^c &\sim (2,1,2), \end{aligned}\right\} \text{ minimal technicolor}$$

$$\chi \sim (2,1,1) \times 8$$

$$\Psi = \begin{pmatrix} \psi \\ \psi^c \end{pmatrix} \qquad T_{\mathrm{EW}} = \begin{pmatrix} t_L & \\ & -t_R^T \end{pmatrix}$$

$$\Delta\mathcal{L} = \Psi^T m_\psi \Psi + \underbrace{\chi^T m_\chi \chi} \qquad m_\psi = \begin{pmatrix} m_L \epsilon & \\ & m_R \epsilon \end{pmatrix}$$

Breaks conformal invariance,
triggers chiral symmetry breaking

Vacuum Alignment

$$\langle \Psi^a \Psi^b \rangle = \Lambda^d \Phi^{ab}$$

$$\Phi^{ab} = -\Phi^{ba} \Rightarrow SU(4) \to Sp(4)$$

General vacuum up to EW gauge transformations:

$$\Phi = \begin{pmatrix} \cos\theta\,\epsilon & \sin\theta \\ -\sin\theta & -\cos\theta\,\epsilon \end{pmatrix} \qquad 0 \le \theta \le \pi$$

Physical PNGB's: h^0, a

Minimal conformal technicolor is composite Higgs!

(c.f. Katz, Nelson, Walker 2005)

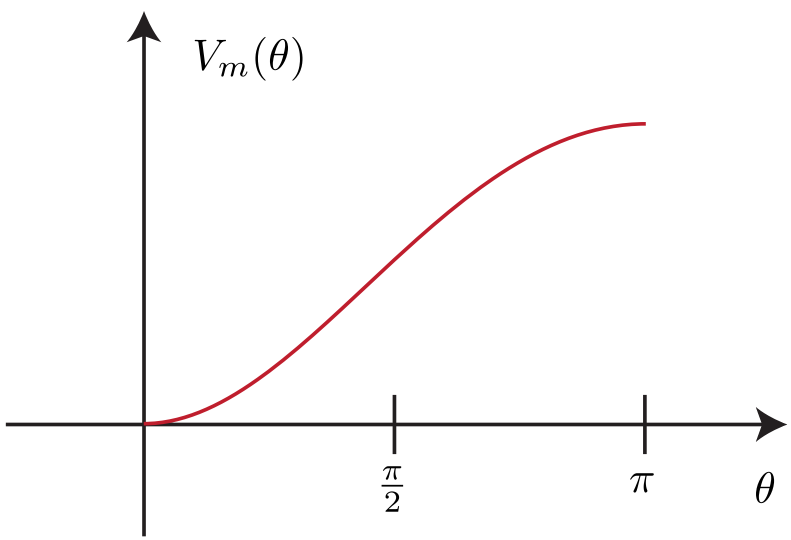
Technifermion Mass

$$\Delta\mathcal{L} = \underbrace{\Psi^T m_\psi \Psi}_{} + \chi^T m_\chi \chi$$

$m_\psi \sim m_\chi \Rightarrow$

m_ψ important at weak scale

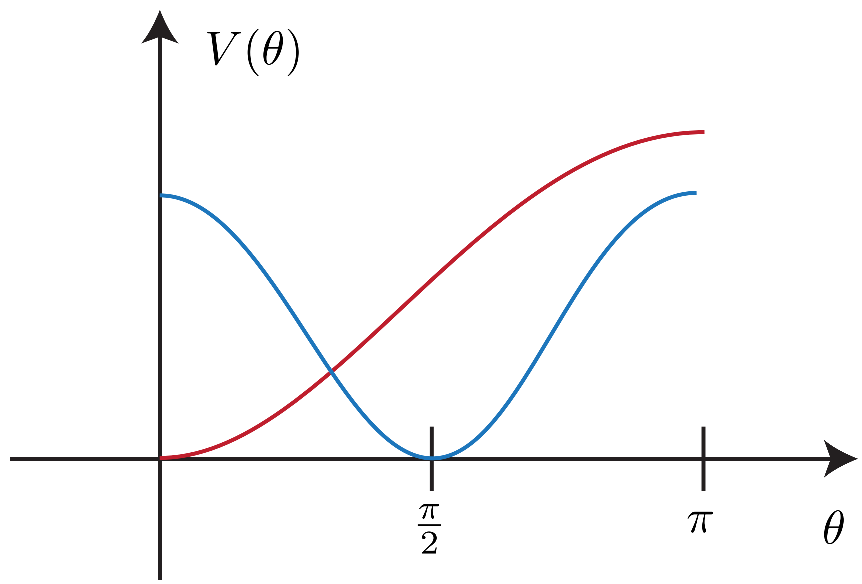
$$V_m(\theta) = a_m \frac{\Lambda^3}{16\pi^2} \mathrm{tr}(m_\psi \Phi) + \mathrm{h.c.}$$
$$\sim -\cos\theta$$



Breaks degeneracy between $\theta = 0$ and π

Vacuum Potential

$$V(\theta) = -\tfrac{1}{2} A_t \sin^2\theta - A_m \cos\theta \quad A_t, A_m > 0$$



$\Rightarrow 0 < \theta < \frac{\pi}{2}$

$$m_{h^0}^2 = \frac{\langle V''(\theta)\rangle}{f^2} = \frac{A_t \langle \sin^2\theta \rangle}{f^2} \qquad A_t \sim \frac{N_c m_t^2 \Lambda^2}{16\pi^2} \underbrace{\frac{1}{\langle \sin^2\theta\rangle}}_{m_t \text{ fixed}}$$

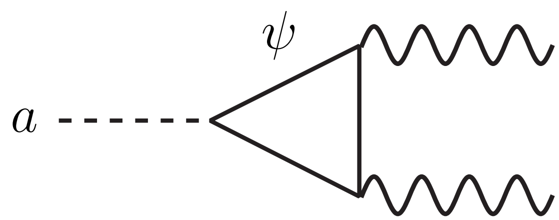
$$m_{h^0}^2 = c_t N_c m_t^2 \quad c_t \sim 1$$

Higgs mass completely determined by top loop

Pseudo Phenomenology

$$m_a^2 = \frac{m_h^2}{\sin^2\theta}$$

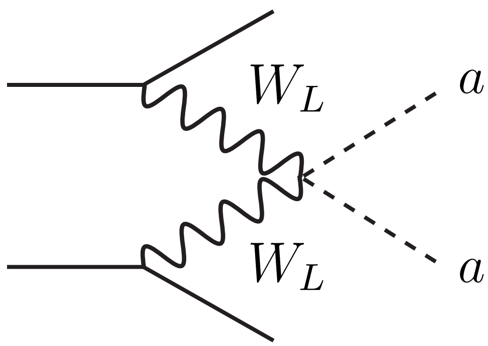
Decay:



$\Rightarrow a \rightarrow W^+W^-,\ ZZ,\ \gamma Z$

($\gamma\gamma,\ \bar{t}t$ suppressed)

Production:

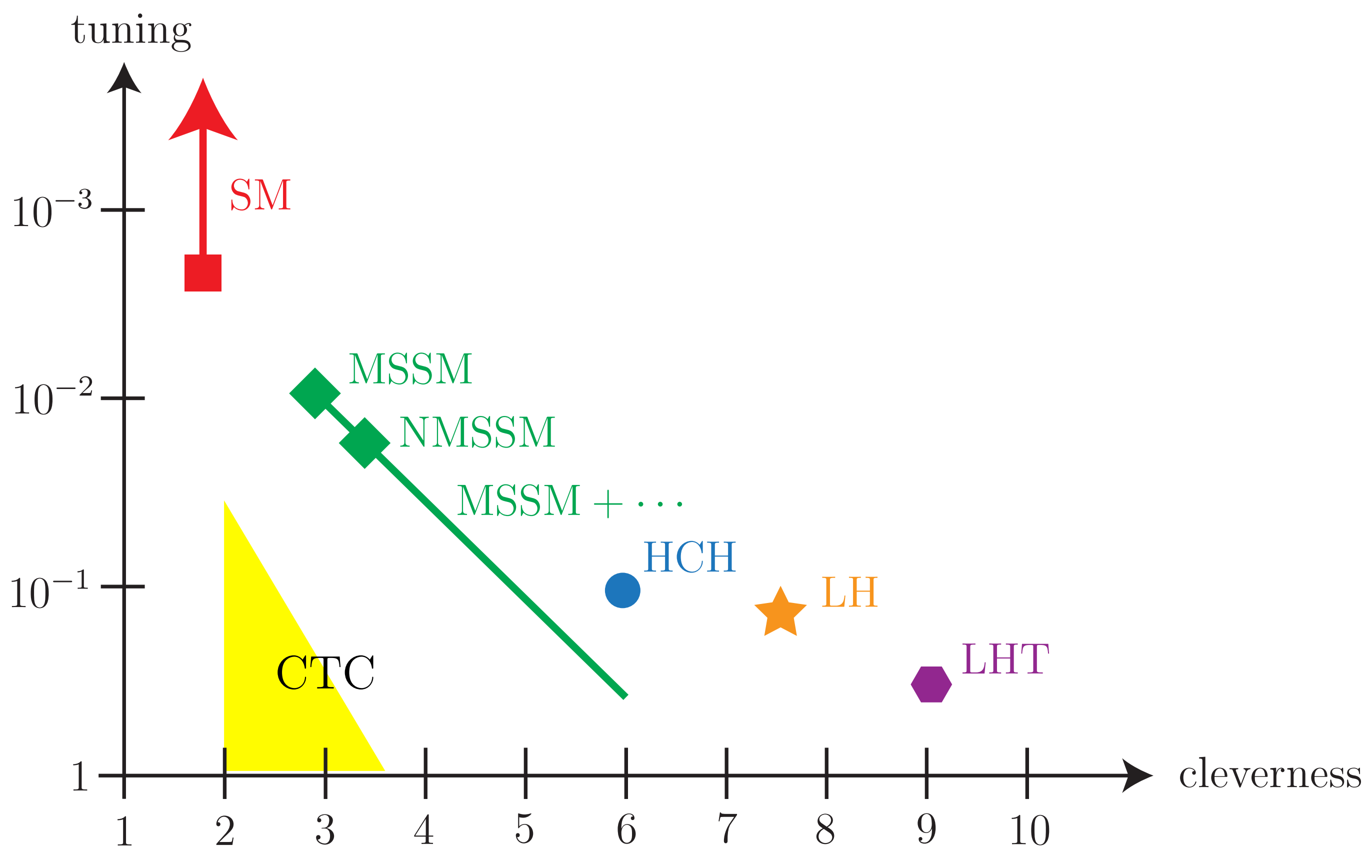


$\Rightarrow \sigma(pp \rightarrow aa) \sim 10$ attobarn

Decays of heavy resonances?

Conclusions

- Strong dynamics at a TeV is a real possibility



- LHC phenomenology much less studied, needs work

I WANT YOU

for the

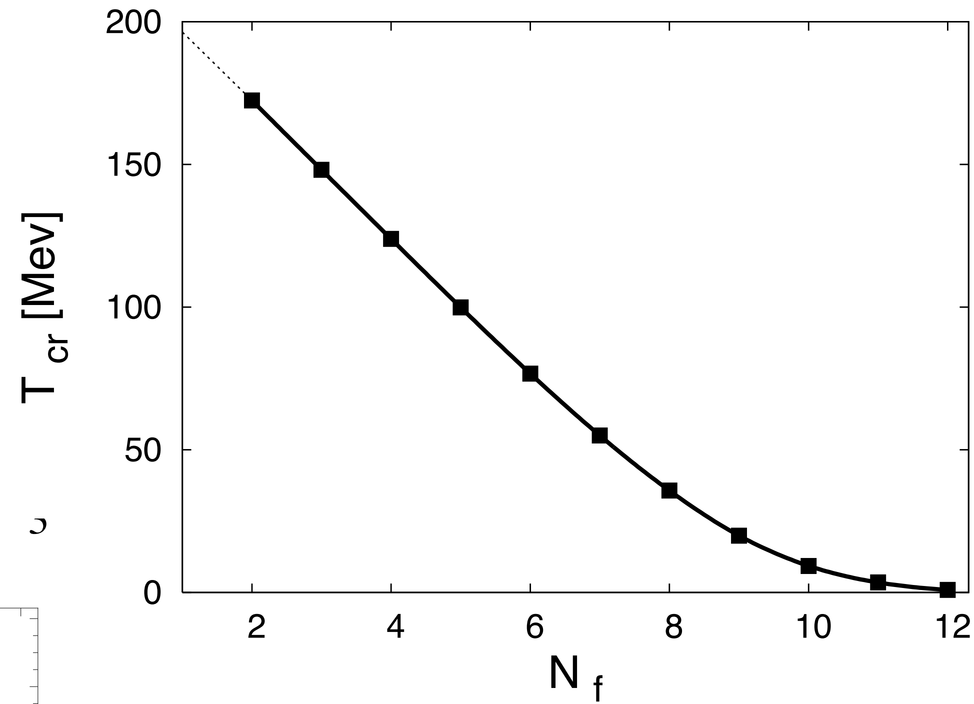
HIGH ENERGY FRONTIER

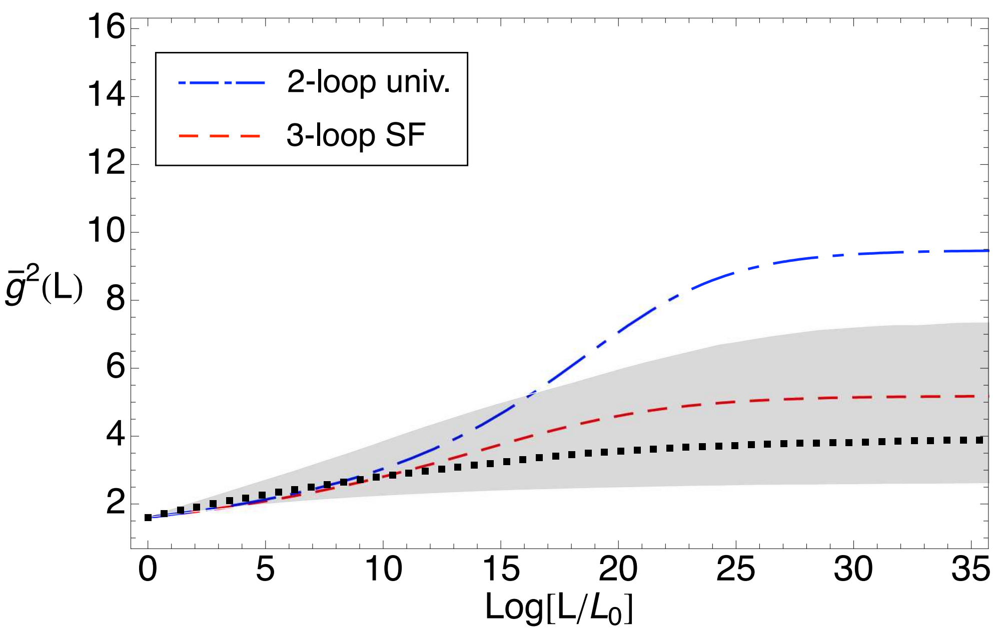
Backup Slides

QCD Conformal Window

Lattice studies $(N_c = 3)$

- Deconfinement transition
  (Braun, Gies 2007)

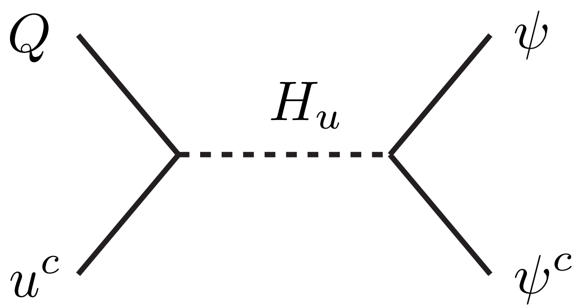




- Schrödinger functional
  (Appelquist, Fleming, Neil 2008)

Light Flavor?

Generate 4-fermion interactions with SUSY broken at $\gtrsim 10\ \mathrm{TeV}$ (Dine, Kagan, 1990)



$\Rightarrow$ minimal flavor violation

Also solves SUSY flavor problem!

But: theory must be conformal at SUSY breaking scale

Model-building in progress...

(with Galloway, Evans, Tacchi)