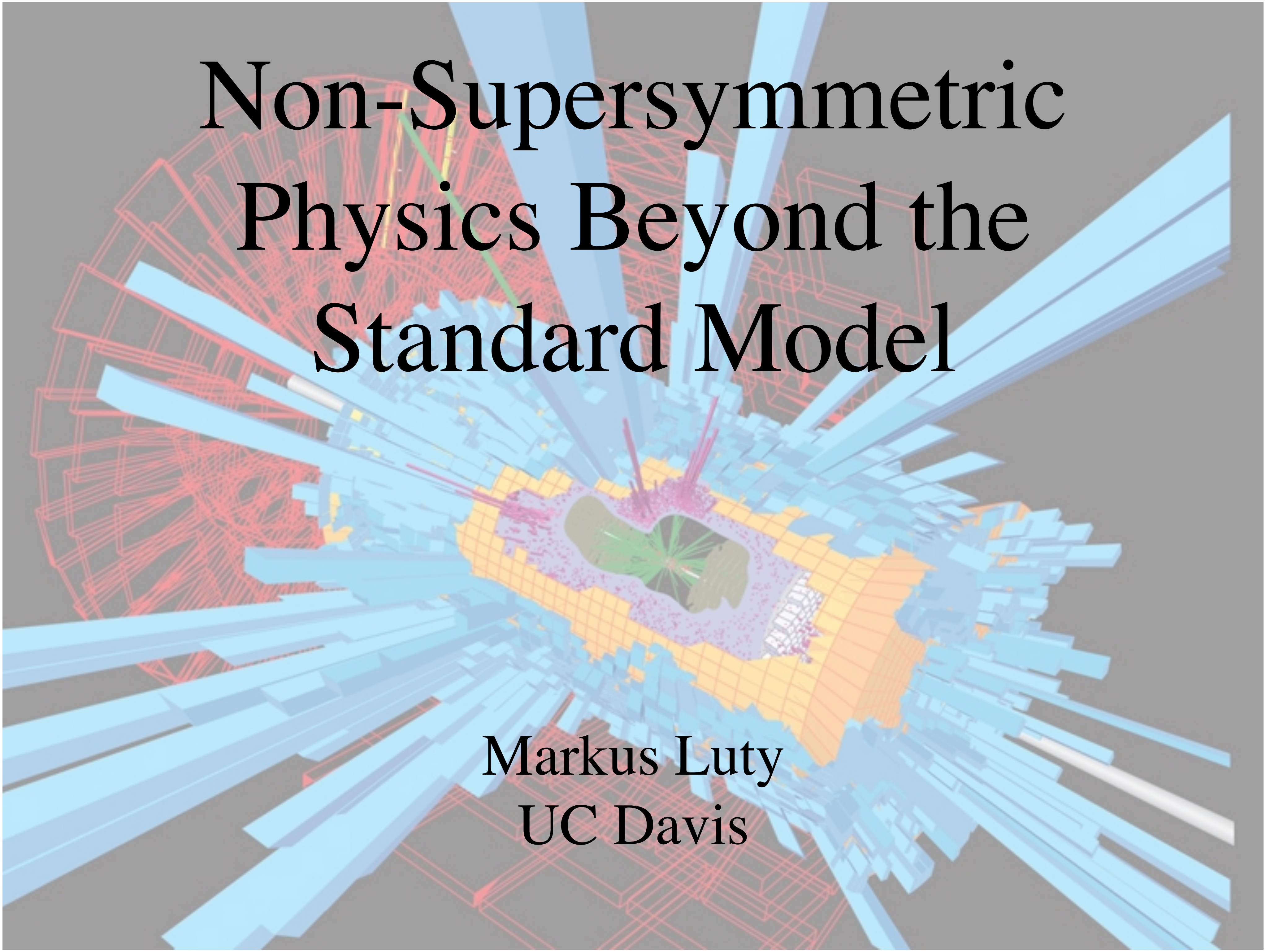

Non-Supersymmetric Physics Beyond the Standard Model

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Introduction

After 35 years of building models, electroweak symmetry breaking remains a mystery...

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vs.

Outline

- Standard model
- UV sensitivity
- Composite Higgs
    - Strong electroweak symmetry breaking
    - Pseudo-Nambu-Goldstone Higgs

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- Standard model
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Disclaimers

- No attempt at completeness
- Topics reflect personal interests

Standard Model

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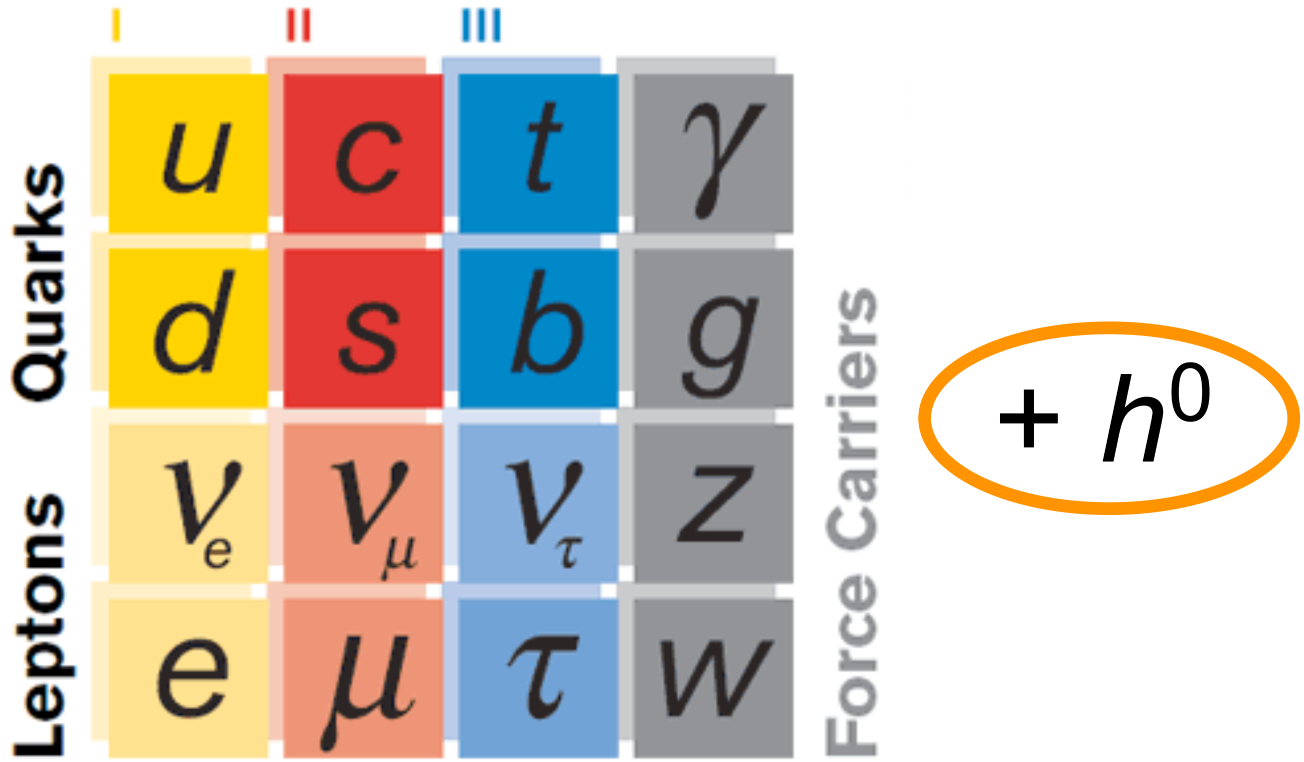

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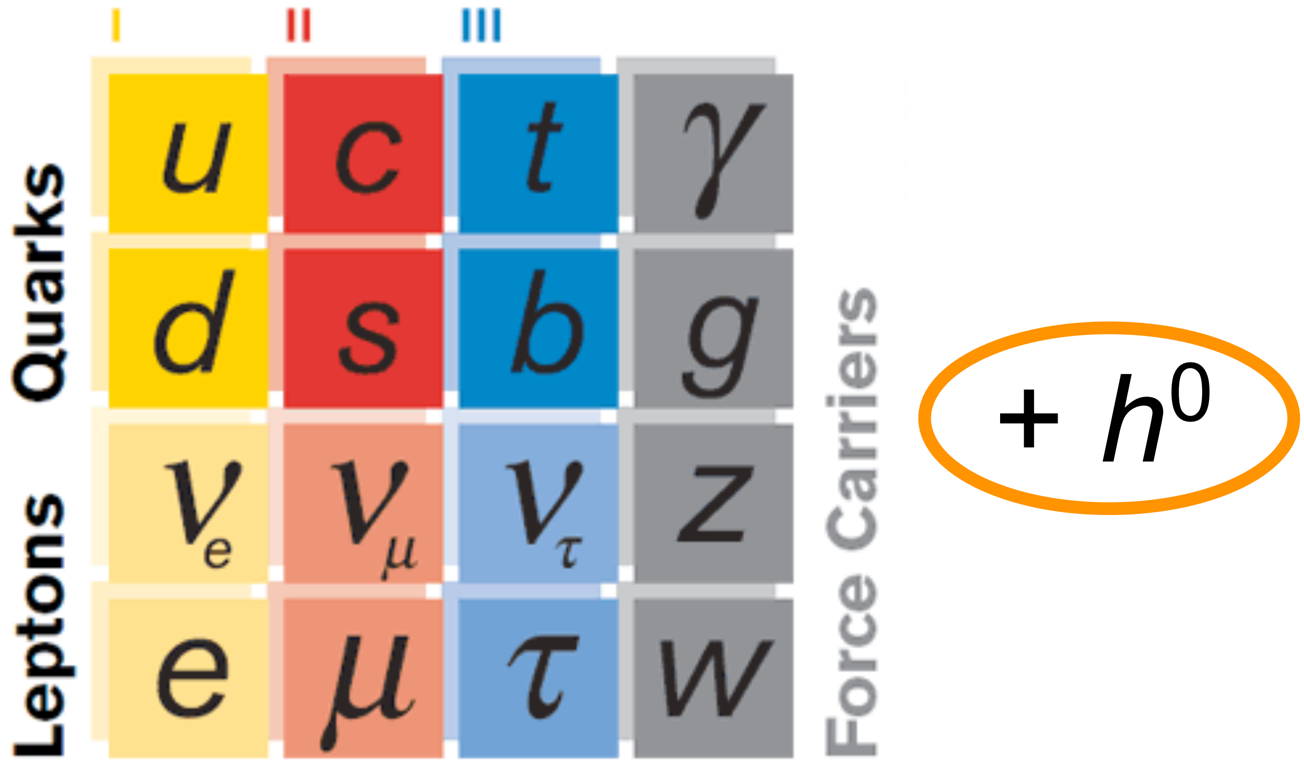


- Minimal model of electroweak symmetry breaking
- Agrees with all data
- Can’t be the whole story, even at LHC energies

Beyond the Standard Model

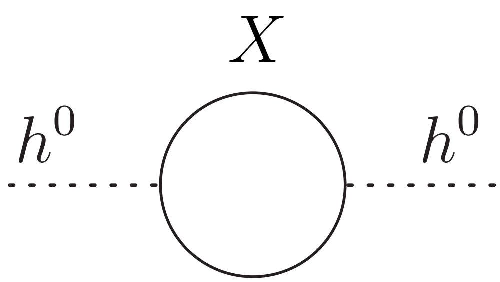
- Quantum gravity: $M_{\mathrm{Planck}} \sim 10^{19}$ GeV
- Grand unification: $M_{\mathrm{GUT}} \sim 10^{16}$ GeV
- Neutrino masses: $M_{\nu\,\mathrm{mass}} \sim 10^{14}$ GeV
- Baryogenesis
- Origin of masses and mixing angles
- Strong *CP*

$\Rightarrow$ Standard model is an effective low-energy theory

New physics may be beyond experimental reach, but...

UV Sensitivity

Electroweak symmetry breaking is sensitive to UV physics in standard model



$$\Rightarrow \Delta V \sim \frac{g^2_{h^0 \bar{X} X}}{16\pi^2} M_X^2 |H|^2 + \cdots$$

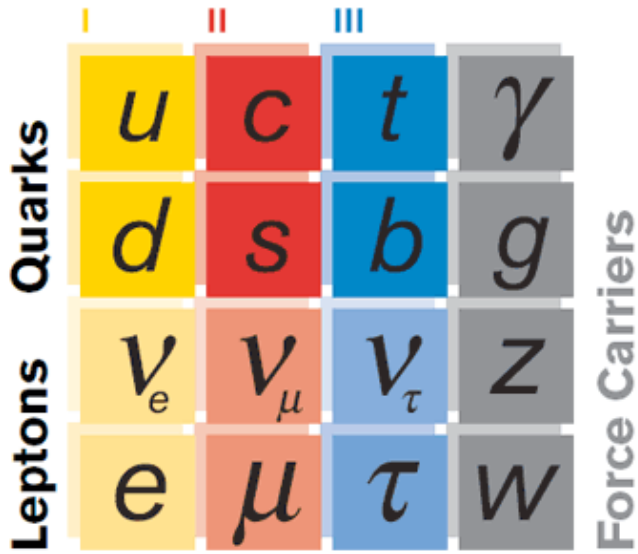
$$\Rightarrow v \sim M_X$$

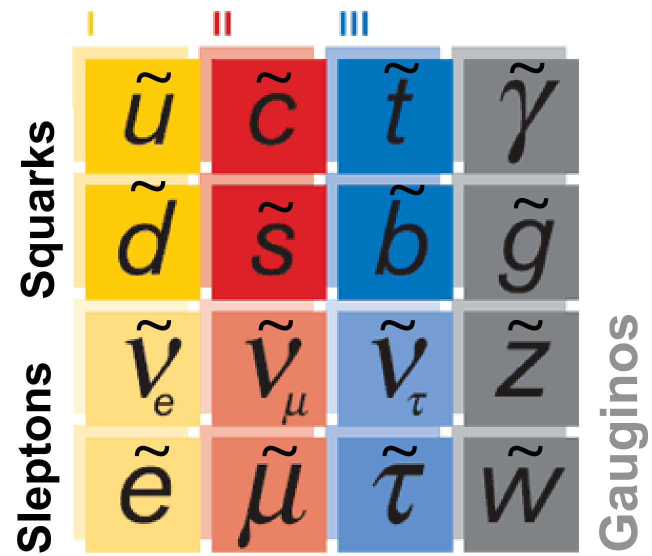
Note: problem *worse* for larger M_X!

All UV sensitivity in one parameter (coefficient of $|H|^2$ in effective potential)

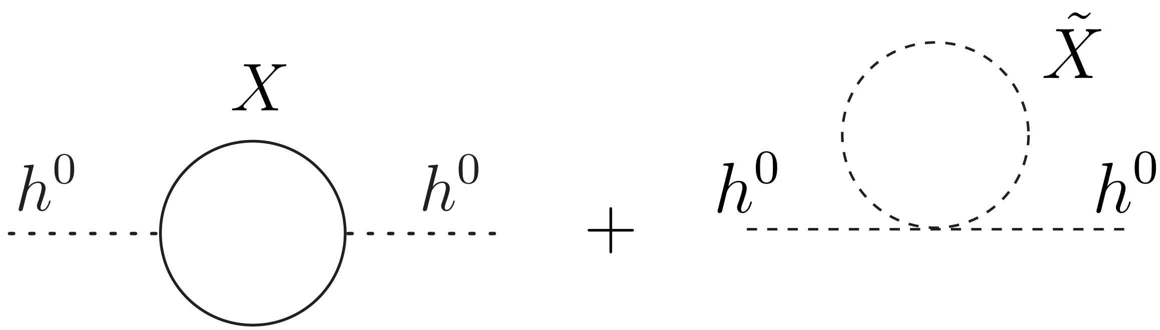
$\Rightarrow$ can "fine-tune" away problem

Supersymmetry





Superpartners cancel UV sensitivity:



$$\Rightarrow \Delta V \sim \frac{g^2_{h^0 \bar{X} X}}{16\pi^2} \left(M_X^2 - M_{\tilde{X}}^2 \right) |H|^2$$

Supersymmetric Fine Tuning

$$m_{h^0}^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3y_t^4}{4\pi^2} \ln \frac{m_{\tilde{t}}}{m_t}$$

$$m_{h^0} > 114 \text{ GeV} \quad \Rightarrow \; m_{\tilde{t}} \gtrsim \text{TeV}$$

$$\Delta V \sim \frac{3y_t^2}{8\pi^2}(m_{\tilde{t}}^2 - m_t^2)|H_u|^2$$

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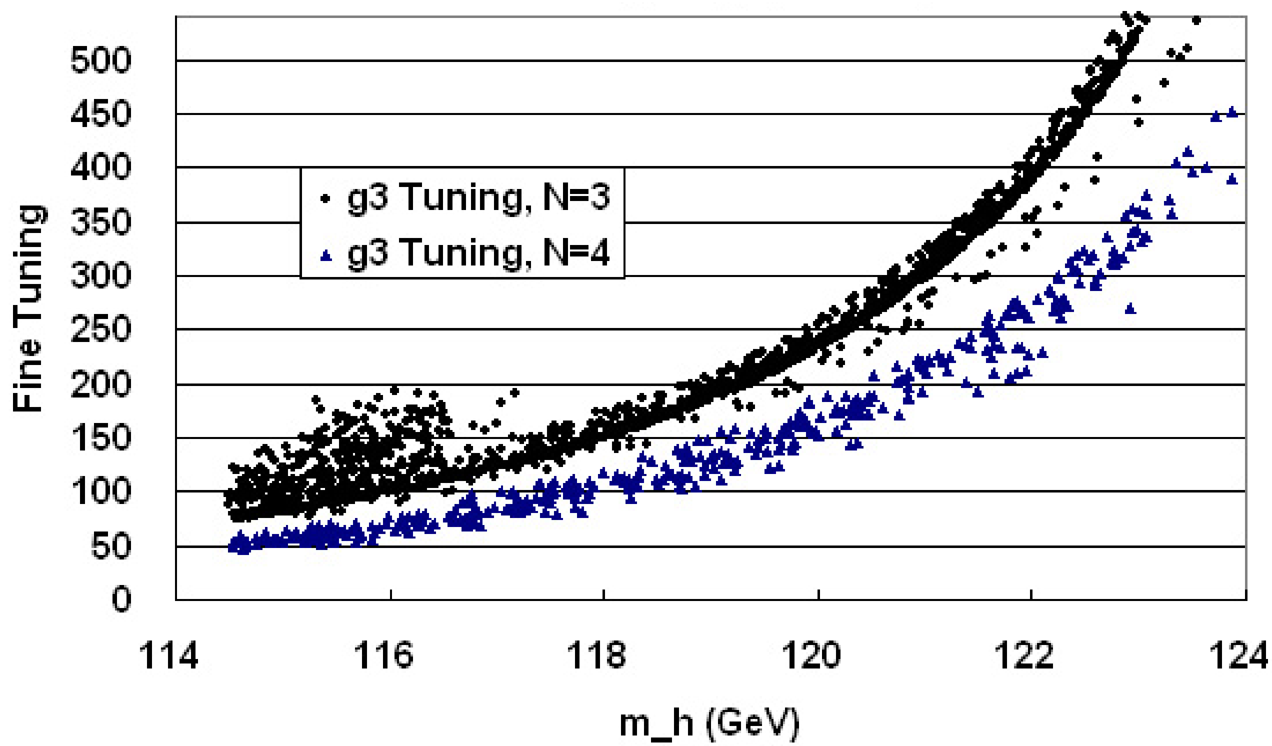
$\Rightarrow$ 1% tuning:

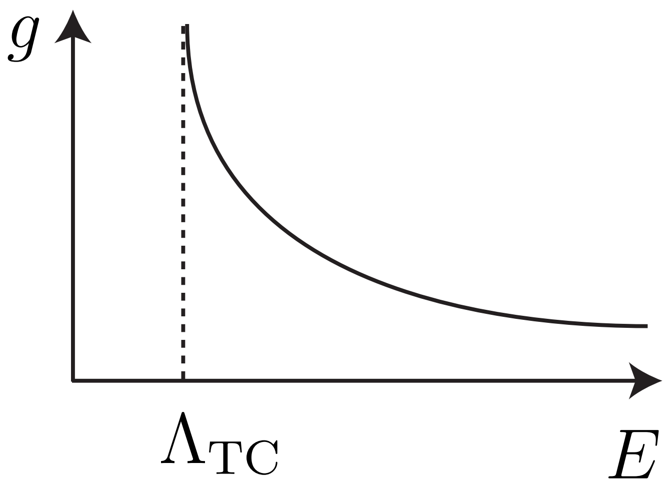


"Magnificent! And to think that someday they'll all be turned into supersymmetry phenomenology papers."

Strong Electroweak Symmetry Breaking

Technicolor:

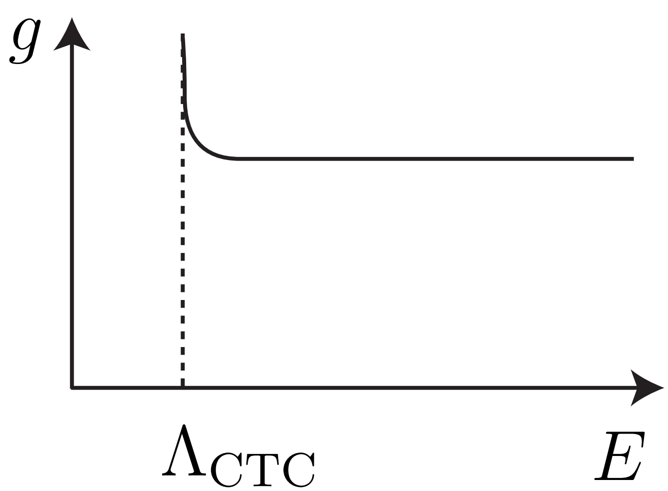
(Susskind, 1979; Weinberg 1979)



$$\Lambda_{\mathrm{TC}} \sim M_0 e^{-8\pi^2/g^2(M_0)}$$

Conformal Technicolor:

(Luty, Okui 2004; Luty 2008)

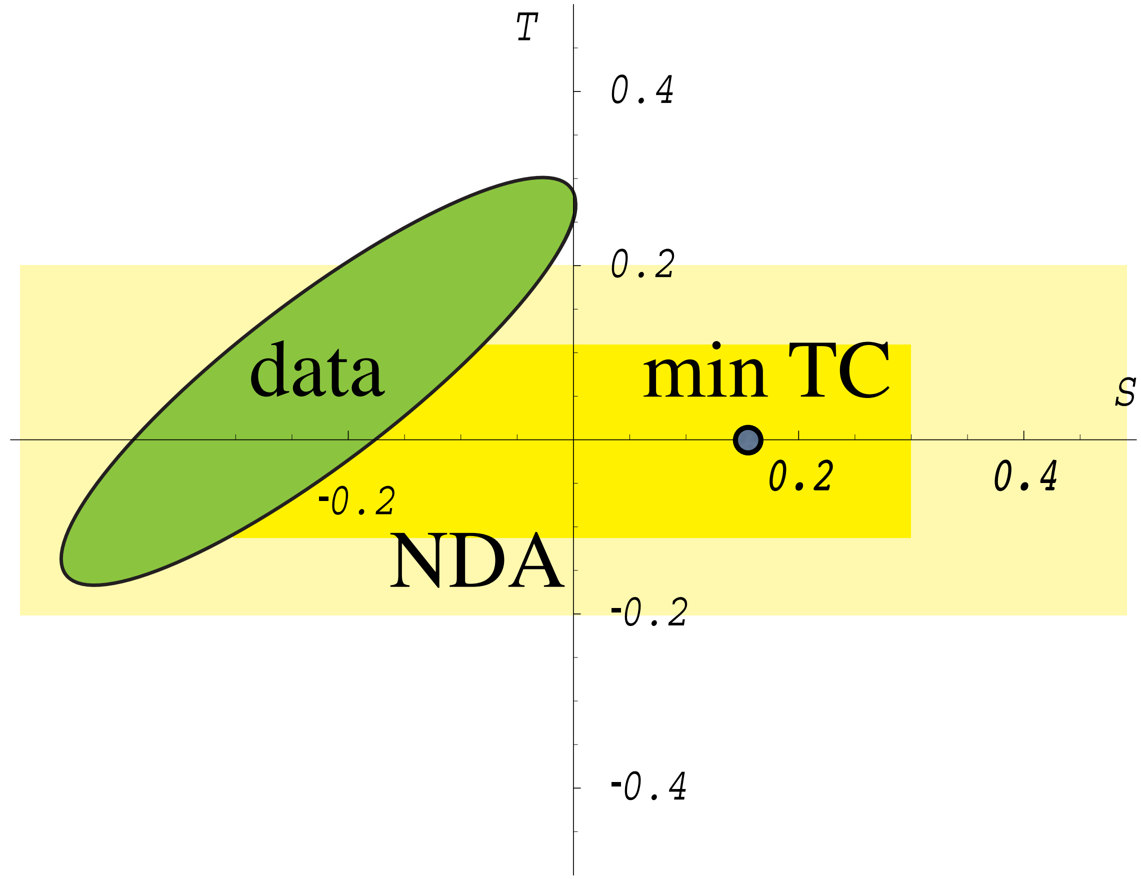


$$\Delta\mathcal{L} = m\,\bar{\psi}\psi$$

$$\Lambda_{\mathrm{CTC}} \sim M_0 \left(\frac{m(M_0)}{M_0}\right)^{1/(4-d)}$$

$$d = \dim(\bar{\psi}\psi)$$

Precision Electroweak Data



Good electroweak fit may be due to non-QCD dynamics and/or accidental cancelations

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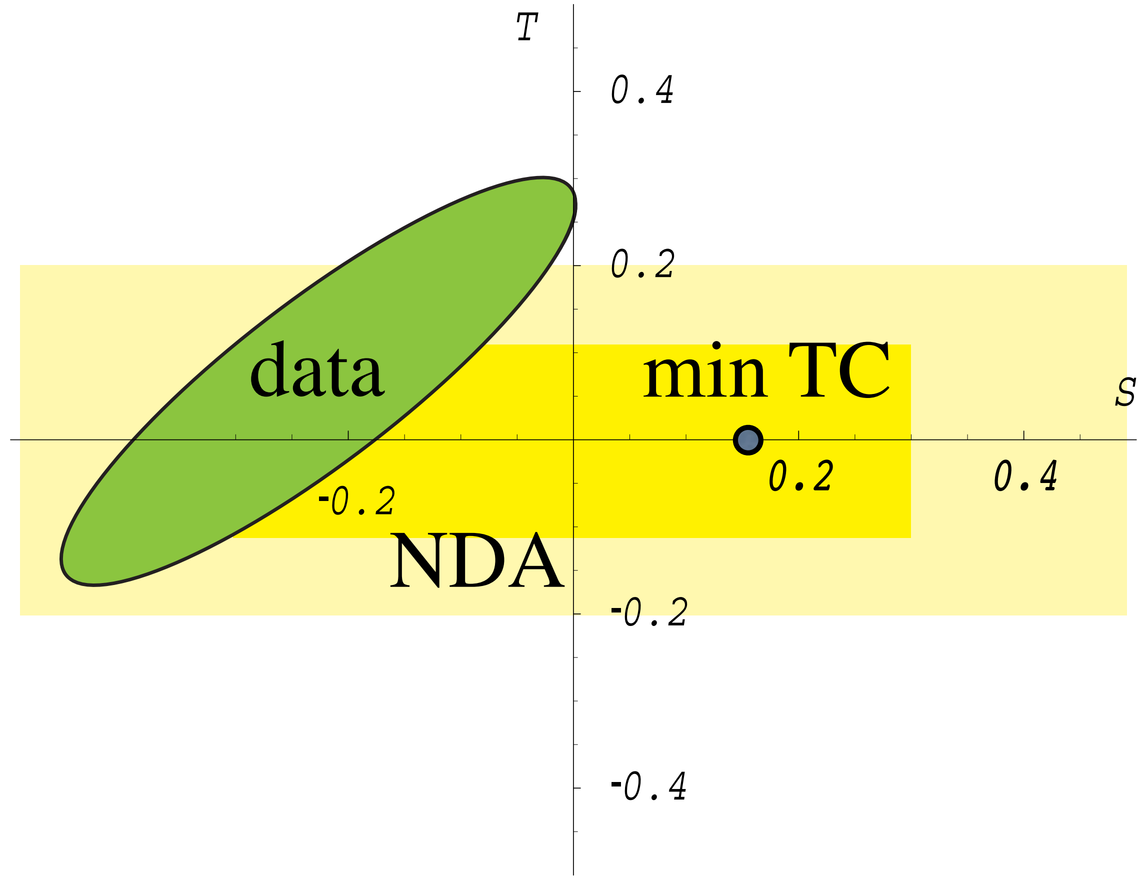


Good electroweak fit may be due to non-QCD dynamics and/or accidental cancelations

"Little hierarchy problem" $\rightarrow S < 0$ problem

Origin of Flavor

$$\Delta\mathcal{L} \sim \frac{1}{\Lambda_t^{d-1}}(\bar{Q}_{L3}t_R)(\bar{\psi}_L\psi_R) \qquad d = \dim(\bar{\psi}_L\psi_R)$$

$d > 1 \Rightarrow$ requires new physics at scale Λ_t

Technicolor: $d = 3 \;\Rightarrow \Lambda_t \sim 3\ \mathrm{TeV}$

Conformal technicolor: $d > 1$ (CFT unitarity bound)

$$\Rightarrow \Lambda_t \sim 10^{1/(d-1)}\ \mathrm{TeV}$$

("Walking" technicolor: Holdom 1981,...)

E.g. $d = 1.3 \Rightarrow \Lambda_t \sim 10^3\ \mathrm{TeV}$

Minimal Conformal Technicolor

$SU(N)_{\mathrm{CTC}} \times SU(2)_W \times U(1)_Y$

$$\left.\begin{aligned} \psi_L &\sim (N,2)_0, \\ \psi_{R1} &\sim (N,1)_{\frac{1}{2}}, \\ \psi_{R2} &\sim (N,1)_{-\frac{1}{2}}, \end{aligned}\right\} \text{ minimal technicolor}$$

$$\left.\begin{aligned} \chi_L &\sim (N,1)_0, \\ \chi_R &\sim (N,1)_0 \end{aligned}\right\} \times K$$

$$\Delta\mathcal{L} = m_\chi \, \bar{\chi}_L \chi_R$$

$m_\chi =$ soft breaking of conformal symmetry

Triggers $\langle \bar{\psi}_L \psi_R \rangle \neq 0 \Rightarrow$ electroweak breaking

Constraints on d

$H = \bar{\psi}_L \psi_R =$ Higgs operator $\qquad d = \dim(H)$

$\Delta\mathcal{L} \sim M_X^{4-\Delta} H^\dagger H \qquad \Delta = \dim(H^\dagger H)$

$\Delta < 4 \Rightarrow$ UV sensitivity $\Rightarrow$ fine tuning

- Large $N \Rightarrow \Delta = 2d + \mathcal{O}(1/N)$

  (explains “gap equation” result)

- $d \to 1 \Rightarrow \Delta \to 2$

  In fact, $d = 1 + \epsilon \Rightarrow \Delta = 1 + \mathcal{O}(\epsilon^{1/2})$

  (Rattazzi, Rychkov, Tonni, Vichi 2007)

  Rigorous bounds do not apply to singlet $H^\dagger H$

$\Rightarrow d \simeq 1.3, \;\; \Delta > 4$ compatible with all constraints

Lattice

Lattice can "easily" measure d: (Luty, 2008)

QCD in conformal window (e.g. $N_c = 3, N_f = 12$)

Hadron masses $\propto \Lambda \sim m^{1/(4-d)}$

$m =$ quark mass

$d = \dim(\bar{\psi}\psi)$

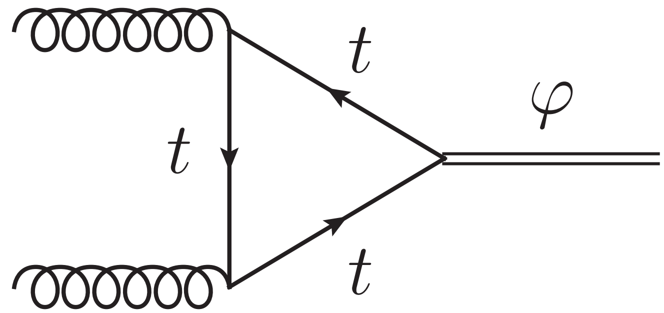
Measure scaling of hadron masses with m

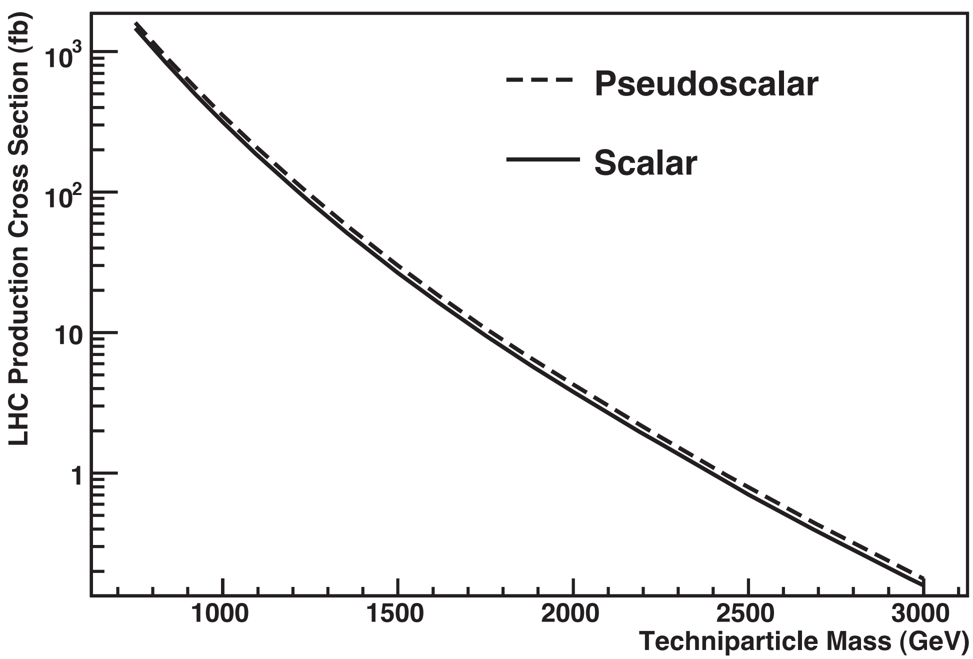
LHC Phenomenology

Strong $W_L W_L$ scattering requires 100 fb^{-1}...

Spin 0 resonances from top couplings (Evans, Luty 2009)

$$\Delta\mathcal{L} \sim \frac{1}{\Lambda_t^{d-1}}(\bar{Q}_L t_R)(\bar{\psi}_L \psi_R) \Rightarrow$$





(Note: 14 TeV!)

Spin 0 Resonances

$\varphi \to W_L W_L$ may be forbidden by strong symmetries

(e.g. isospin, P, C,...) $\Rightarrow$ narrow resonances!

(Resonances in $W_L W_L$ scattering have strong 2-body decays $\Rightarrow$ broad)

$$\frac{\Gamma(\varphi \to \bar{t}t)}{m_\varphi} \sim 10\% \qquad \Rightarrow \bar{t}t \text{ resonances}$$

QCD extrapolation: $$\frac{\Gamma(\varphi \to W_L W_L W_L)}{m_\varphi} \sim 1\%$$

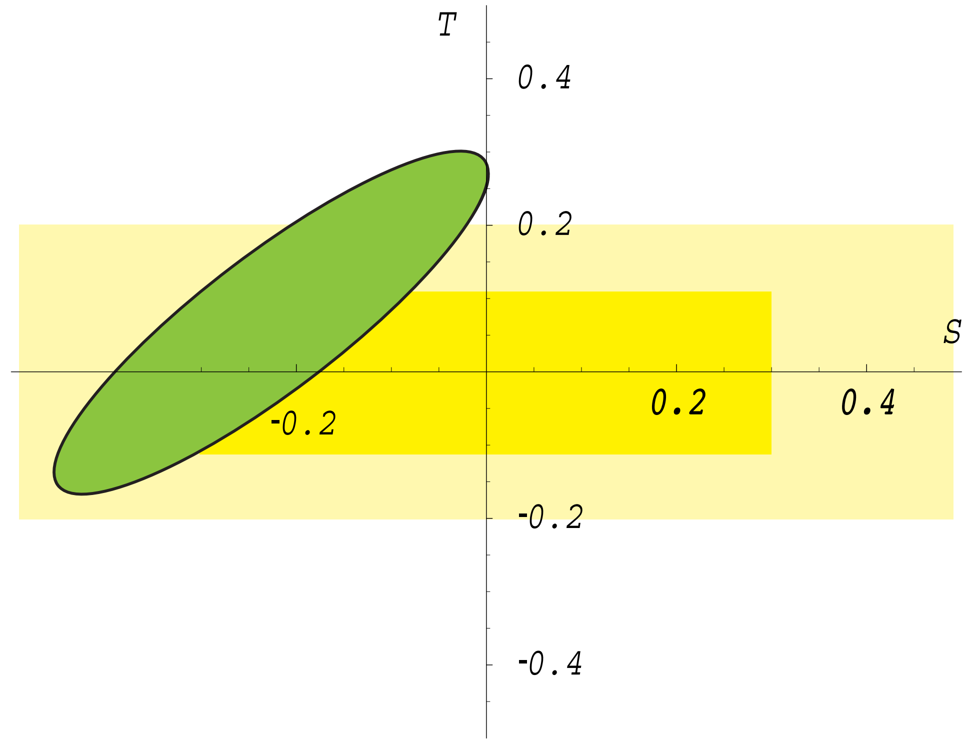
$\Rightarrow$ large cross section for resonant multi-W production

May be "smoking gun" of strong dynamics

Precision Electroweak Again

Experience with QCD and 5D “holographic” models suggests $S > 0$

(Agashe, Csaki, Grojean, Reece 2007)



Motivates models in which S is an adjustable parameter...

Pseudo Nambu-Goldstone Higgs

Toy model: $\Phi \sim 3$ of $SU(3)_{\text{glob}}$ symmetry

$\langle\Phi\rangle^\dagger\langle\Phi\rangle = f^2 \Rightarrow SU(3)_{\text{glob}} \to SU(2)_{\text{glob}}$

Weakly gauge $SU(2)_W \subset SU(3)_{\text{glob}} : T_a = \begin{pmatrix} \sigma_a & 0 \\ 0 & 0 \end{pmatrix}$

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ f\sin\theta \\ f\cos\theta \end{pmatrix} = \quad \text{general VEV}$$

$v = f\sin\theta =$ scale of $SU(2)_W$ breaking

$\theta \ll 1 \Rightarrow$ separation of scales

$\Rightarrow SU(2)_W$ broken by pseudo Nambu-Goldstone "Higgs"

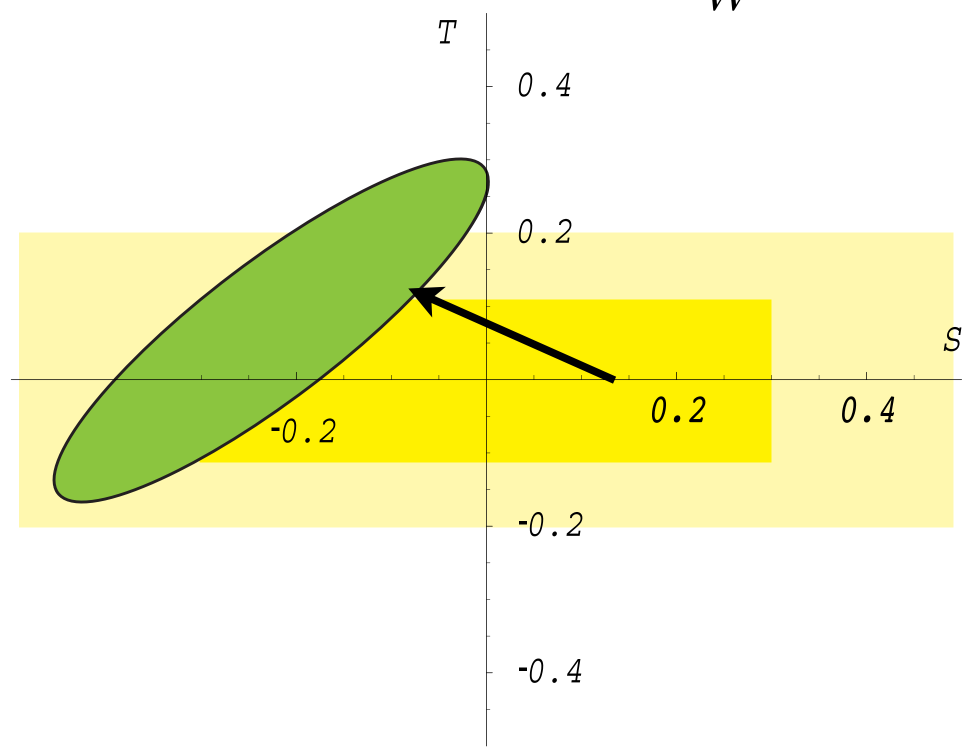
Pseudo Nambu-Goldstone Higgs

$\theta \ll 1$ requires tuning $\sim \sin^2\theta \sim \dfrac{v^2}{f^2}$

But: a little tuning goes a long way

$$S = S_0 \sin^2\theta + \frac{1}{12\pi}\ln m_h^2 \qquad T = T_0 \sin^2\theta - \frac{3}{16\pi c_W^2}\ln m_h^2$$

Recover electroweak fit with $\sim 10\%$ tuning



Models

Most literature based on 5D "holographic" models
(Contino, Nomura, Pomarol 2004, Agashe, Contino, Pomarol 2004,...)

$$\Leftrightarrow 1/N \text{ expansion} \quad N \sim \frac{\Lambda}{m_{\text{KK}}}$$

$$S_0 \sim +N \Rightarrow \text{ tune away expansion parameter}$$

Or: composite Higgs from small N strong dynamics
(Galloway, Evans, Luty, Tacchi, in preparation)

$$\Lambda_{\text{TC}} \sim \frac{\text{TeV}}{\sin\theta} \Rightarrow \text{ strong dynamics signals still possible}$$

Little Higgs?

- Aim to explain away 10% tuning required to get good electroweak fit

- Requires clever model building ("collective symmetry breaking")

- Good precision electroweak fit requires residual tuning or model-building ("*T* parity")

Conclusions

• No perfect models

• Strong electroweak symmetry breaking may be a reasonable compromise between tuning and excessive model-building

• Testable at LHC

• Let the data-driven LHC era begin (please)!