Dynamical Electroweak Symmetry Breaking

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University of Virginia

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Hot News!

Fresh from The News of the World: The Higgs boson has been discovered at the LHC!

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Just kidding:))

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- Speculation: SM4 merges into a theory with no mass scales $\rightarrow$ Conformally invariant theory above the condensation scale.

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- If $\Lambda \sim M_P \Rightarrow$ precise cancellation between boson and fermion masses $\Rightarrow$ Extreme fine tuning such that $m_H \ll M_P$. Higher order corrections will destroy this $\Rightarrow$ Back to the same problem.

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- However, no elementary scalar field has been found $\Rightarrow$ SUSY has to be broken, not only broken but broken spontaneously so as to preserve the stability of the result at higher orders.
- It is not yet clear what mechanism is responsible for the spontaneous breakdown of SUSY: gravity-mediated, gauge-mediated,...? One thing that most workers in that field agree on is that the spontaneous breakdown of SUSY is in a Hidden Sector which is then mediated to the supersymmetric SM.

The hierarchy problem

ARE THERE SIMPLER ALTERNATIVES? In particular, we are interested in scenarios in which the electroweak breaking scale of O(TeV) is DYNAMICAL $\rightarrow$ Natural physical cutoff scale.

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- Chiral symmetry breaking in Quantum Chromodynamics (QCD) as an example.

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- The Lagrangian has a global chiral symmetry: $SU(2)_L \times SU(2)_R$ with $q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$ and $q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$ transforming as doublets under $SU(2)_L$ and $SU(2)_R$ respectively.

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- The running coupling g_3 grows strong at low energy and become large at roughly $E \sim 300\ MeV \Rightarrow$ chiral symmetry breaking and quark confinement.

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- Notice that the composite scalars have exactly the same EW quantum numbers as the SM Higgs: $\phi = \begin{pmatrix} \pi^+ \\ \sigma + i\,\pi_3 \end{pmatrix}$.

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- Problems with Electroweak Precision Parameters!

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- S, T and U enter electroweak measurables as $M_Z^2 = M_{Z0}^2 \frac{1-\hat{\alpha}(M_Z)T}{1-G_F M_{Z0}^2 S/2\sqrt{2}\pi}$, etc...

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- More problems to come when one looks at how fermions get masses.
- In the SM, fermions get masses by coupling to the Higgs (see Ling-Fong Li's lecture). In TC models, The Higgs is a composite of Technifermions. Question: For standard fermions (t, b, c, s, u, d,...) to get masses in TC, they should somehow couple to TC fermions.

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- So what are the problems with this?

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- What to do next is a Big Question for the ETC community!

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- Enhance $\langle \bar{T} T \rangle_{ETC}$. How? Making $\gamma_m(\mu)$ large. How? By bringing $\alpha_{TC}(\mu)$ close to a critical coupling α_C such that $\gamma_m(\mu) = 1 - \sqrt{1 - \frac{\alpha_{TC}(\mu)}{\alpha_C}} \rightarrow \gamma_m(\Lambda_{TC}) \approx 1 \rightarrow \beta(\alpha_{TC}(\mu)) \approx 0$ for $\mu > \Lambda_{TC}$.

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- It is however quite complicated to find a model which can do all these things! In particular the aforementioned phenomena occur in a nonperturbative regime.

Extended Technicolor

Is there a simpler alternative to Extended Technicolor?

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Is there a simpler alternative to Extended Technicolor? The Standard Model with 4 generations.

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where m_H is the Higgs mass and $\alpha_Y = \frac{m_1 m_2}{4\pi v^2}$ with $v = 246$ GeV, with m_1, m_2 being masses of the 2 fermions. Reduced mass: $M = m_1 m_2/(m_1 + m_2)$.

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- Rayleigh-Ritz variational method with the trial wave function $u(y,r) = 2y^{\frac{3}{2}}\ e^{-yr}$. y: variational parameter.

Bound States of heavy 4th Generation

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- Numerical integration of the Schrödinger equation gives

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- Relativistic corrections to the Yukawa potential by Ishiwata and Wise came to similar conclusions that, for $m_{q'} > 350\ GeV$, the Higgs Yukawa coupling plays a crucial role in the formation of bound states. The bound state is loose when the 4th generation quark mass is comparable to the Higgs mass and the binding energy increases as the Higgs mass becomes smaller than the 4th generation mass.

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- The information about Dynamical Chiral Symmetry Breaking encoded in $\Sigma(p)$ and f_π .

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- Explicitly, take e.g. the 4th generation quarks (t', b') and assuming $g_{t'} = g_{b'} = g_{4Q} \rightarrow$

$$g_f \bar{\psi}_L \phi \psi_R + H.c. = g_{4Q}\{\bar{q}_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} b^{'}_R + \bar{q}_L \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix} t^{'}_R + H.c.\}$$

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- Schwinger-Dyson equation for the fermion self-energy $\Sigma(p)$ in the ladder approximation for such a Higgs-Yukawa sector. (See Fukuda and Kugo; Leung, Love and Bardeen;..)

4th generation condensates: Dynamical Electroweak Symmetry Breaking

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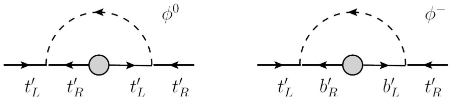

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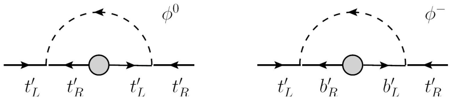

- $\Sigma(p) = \frac{+2g_{4Q}^2}{(2\pi)^4} \int d^4q \frac{1}{(p-q)^2} \frac{\Sigma(q)}{q^2+\Sigma^2(q)}$

4th generation condensates: Dynamical Electroweak Symmetry Breaking

- Integral equation converted into differential equation:

$$u^{''} + 4u^{'} + 3u + (\frac{\alpha_{4Q}}{\alpha_4^c})\frac{u}{1+u^2} = 0$$

where $\Sigma(p) = e^t u(t + t_0)$, $t_0 = \ln(\Sigma(0))$, $t = \ln(p)$, $\alpha_{4Q} = \frac{g_{4Q}^2}{4\pi}$, and $\alpha_4^c = \frac{\pi}{2} \approx 1.57$ is the critical coupling.

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- Above differential equation + Boundary conditions $\equiv$ Integral equation

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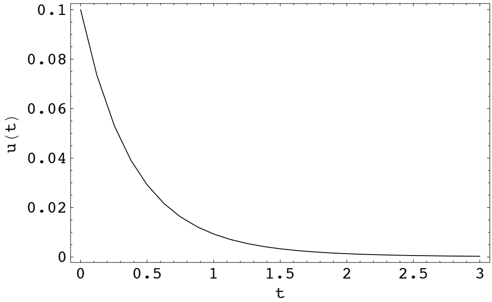
- $\alpha_{4Q} < \alpha_4^c$: No solution. Does not satisfy the boundary conditions.



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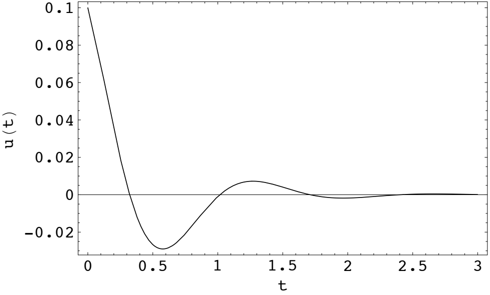
- $\alpha_{4Q} > \alpha_4^c$: Non trivial solution satisfying the boundary conditions



4th generation condensates: Dynamical Electroweak Symmetry Breaking

- Asymptotic solution:

$$\Sigma_{4Q}(p) \sim p^{-1} \sin[\sqrt{\frac{\alpha_{4Q}}{\alpha_4^c} - 1}(\ln p + \delta)], \quad \text{for } \alpha_{4Q} > \alpha_4^c$$

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- For the strong Yukawa coupling solution to satisfy the boundary condition, we must have $\Sigma(0)_{4Q} = \Lambda e^{1 - n\pi/\sqrt{\frac{\alpha_{4Q}}{\alpha_4^c} - 1} + \delta}$; Vacuum solution with $n = 1$.

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- $\delta = \ln(\frac{\Lambda}{\Sigma_{4Q}(0)}) + \frac{\pi}{\sqrt{\frac{\alpha}{\alpha_4^c} - 1}} - 1$

4th generation condensates: Dynamical Electroweak Symmetry Breaking

- Condensates with electroweak quantum numbers:

$$\langle \bar{t'}_L t'_R \rangle = \langle \bar{b'}_L b'_R \rangle = -\frac{3}{4\pi^4} \int d^4q \frac{\Sigma_{4Q}(q)}{q^2 + \Sigma_{4Q}^2(q)}$$

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4th generation condensates: Dynamical Electroweak Symmetry Breaking

- Condensates with electroweak quantum numbers:

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- The condensates break the electroweak symmetry: Requirement $\propto O(-\Lambda_{EW}^3)$

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- Possible solution to the hierarchy problem!

4th generation condensates: Dynamical Electroweak Symmetry Breaking

- At the electroweak scale, the fundamental scalar also obtains an induced negative mass squared $\frac{1}{2}\{\frac{2g_{4Q}^2}{\Sigma_{4Q}(0)}\langle\bar{t'}_L t'_R\rangle + \frac{2g_{4L}^2}{\Sigma_{4L}(0)}\langle\bar{L}_L L_R\rangle\}|\phi^0|^2$ $\Rightarrow$ It also develops a VEV.

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- Three Higgs doublets: Two composites and one fundamental. The Goldstone bosons eaten up by W and Z are three combinations of these scalars. Rich spectrum of scalars!

4th generation condensates: Dynamical Electroweak Symmetry Breaking

So from the SD equation, we know that $\alpha_{4Q} > \frac{\pi}{2} \sim 1.57$ for condensates to form. But at what energy scale?

Heavy 4th generation: Condensate energy scale

- Run the 2-loop RG equations:

$$16\pi^2 \frac{dY}{dt} = \beta_Y$$

from Λ_{EW} on, with $Y = \lambda, g_t^2, g_q^2, g_l^2$(quartic, top, 4th quark, 4th lepton couplings).

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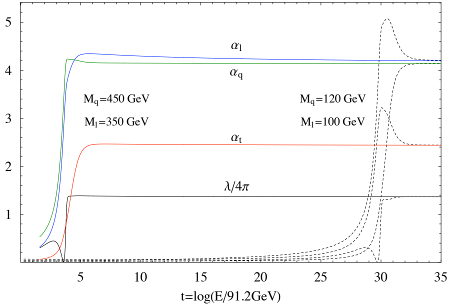
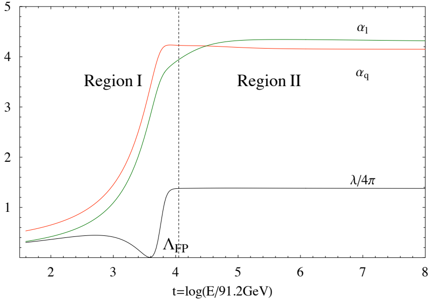
- Start with initial values of the couplings at Λ_{EW} translated into the naive masses by $m_f = g_f v/\sqrt{2}$ ($v = 246\ GeV$).

Heavy 4th generation: Condensate energy scale



Quasi-fixed point at $O(TeV)$ for heavy 4th generation. The (ruled out) light case is shown for comparison.

Heavy 4th generation: Condensate energy scale



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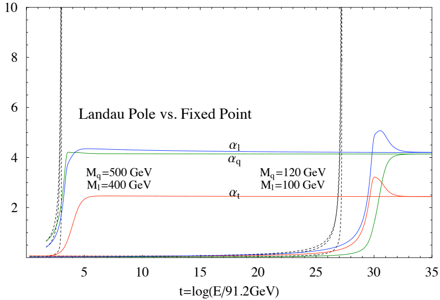
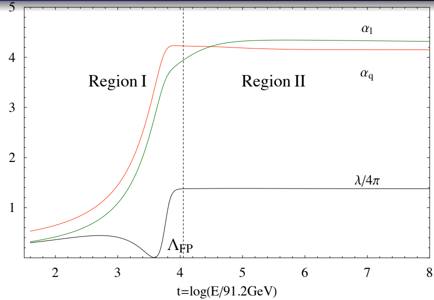


The Landau pole (at one loop) is shown for comparison. Λ_{FP} or a scale close to it could play the role of a physical cut off scale.

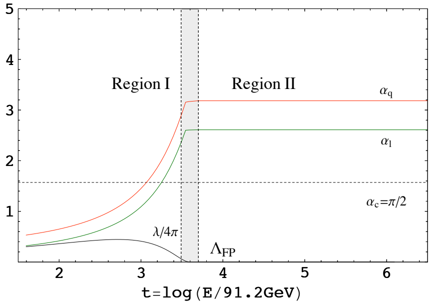
Heavy 4th generation: Condensate energy scale



Possibilities: Region II is characterized by a scale invariant theory both at the classical and quantum levels. Near the boundary between Regions I and II, a fermion-antifermion bound state can get formed by the exchange of a massless scalar $\Rightarrow$ Dynamical electroweak symmetry breaking at O(TeV)! (P. Q. Hung and Chi Xiong, arXiv:1012.4479 [hep-ph], NPB)

4th generation condensates: Dynamical Electroweak Symmetry Breaking

- A possible scenario:



4th generation condensates: Dynamical Electroweak Symmetry Breaking

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Experimental constraints on the 4th generation

- EW precision data: The 4th generation is not ruled out at 6σ by the S-parameter as claimed by PDG which applies only to degenerate doublets, e.g. $\Delta S = \frac{2}{3\pi} - \frac{1}{3\pi}(\ln \frac{m_{t'}}{m_{b'}} - \ln \frac{m_N}{m_E})$. Adjusting the mass splitting in both S and T $\Rightarrow$ OK with EW precision data $\Rightarrow$ can accommodate a heavier Higgs. (Gfitter)

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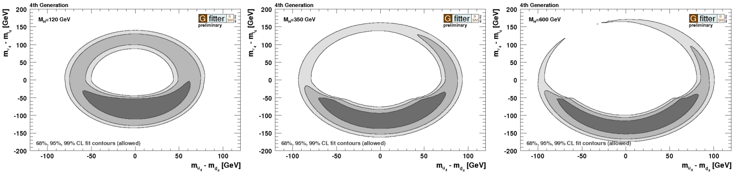

Experimental constraints on the 4th generation

- Lower bounds on 4th quark masses (CDF): $m_{b'} > 385\ GeV$ from $b' \rightarrow Wt$ and $m_{t'} > 335\ GeV$ from $t' \rightarrow Wq$. Caution: A certain number of assumptions have been used e.g. 100% branching ratio,...

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- Advantage: Conformality at $\Lambda_{FP} \sim O(TeV)$ is as competitive as SUSY. Much fewer parameters.

Conclusions

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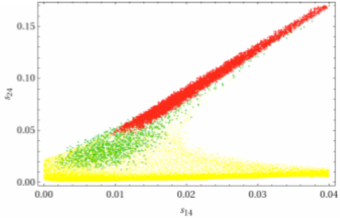
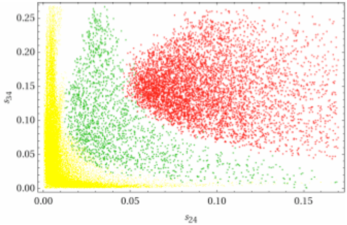
- SM4 may merge into a conformally invariant theory at the TeV scale.

Back-up slides: Phenomenology of the 4th generation

Mixings:





Back-up slides: Experimental constraints on the 4th generation

- Bounds on mixings between the 4th generation and the other three: Directly measured matrix elements and ϵ_K, Δm_u, Δm_s, with $m_{t'} > 300\ GeV$ (Lacker)

$$:\left|V^{4\times4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.038 & {<0.123 \atop >0.021} & >0.78 & <0.63 \\ <0.074 & <0.20 & <0.63 & >0.78 \end{pmatrix}$$

Limits @ ~2σ

Phenomenology of the 4th generation

- Flavour violations in K, B_d and B_s systems coming from SM4 can be spectacular (Buras and collaborators). $\Delta F = 2$ transitions as well as rare K and B decays can constrain the new mixing angles: θ_{14}, θ_{24}, θ_{34} and the new phases: δ_{14} and δ_{24}.

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- Buras et al also investigated the effects of SM4 on mixing and CP violation in the Charm system: Large effects in K , D and B_s systems possible, disfavoured in B_d system. $S_{\psi\,\phi}(B_s) > 0.2$ plus measured $\frac{\epsilon'}{\epsilon}$: Significant reduction of SM4 effects in the D system.

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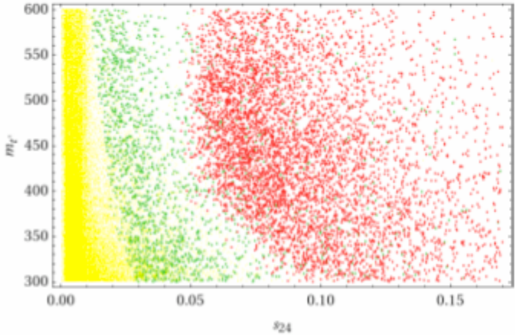
- Soni et al also studied rare K and B decays: Current data favor $m_{t'} \sim 400 - 600\ GeV$, $|V^*_{t'b} V_{t's}| \sim (0.05 - 1.4) \times 10^{-2}$, large CP-odd associated phase.

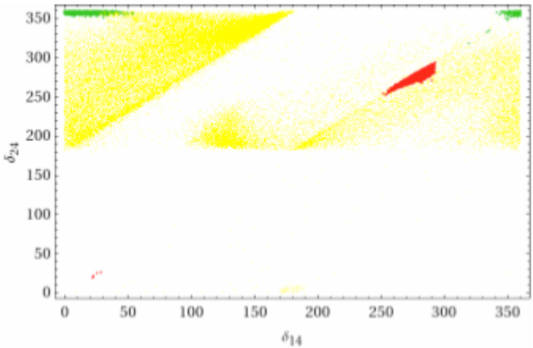
Back-up slides: Phenomenology of the 4th generation

t' mass:

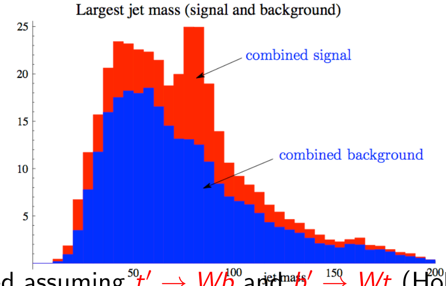


Back-up slides: Phenomenology of the 4th generation

Phases:



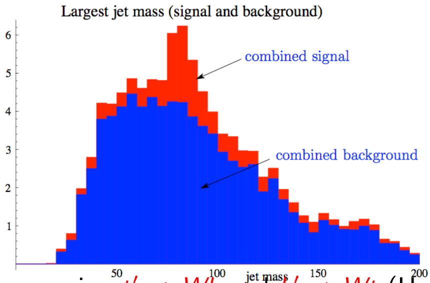
Back-up slides: Phenomenology of the 4th generation



$\bar{t}' t'$, $\bar{b}' b'$ combined assuming $t' \to Wb$ and $b' \to Wt$ (Holdom)

Back-up slides: Phenomenology of the 4th generation

- $\sqrt{s}$ = 7 TeV and 1 fb^{-1}
- $m_{q'} = 600$ GeV



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Back-up slides: Phenomenology of the 4th generation

- $\sqrt{s} = 10$ TeV and 1 fb^{-1}
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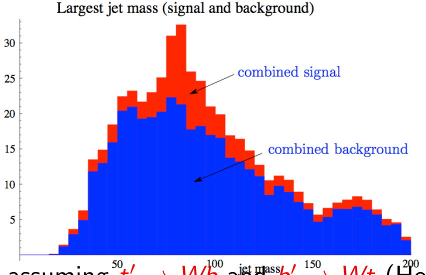

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- LHC studies of Higgs compositeness by Soni and Bar-shalom