Talking about Four Generations

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Outline

Chiral 4th Generation

Some questions [Sher; Holdom; Hou;... ;Kribs, TP, Spannowsky, Tait]

– simply phenomenological: why three generations? [review: Framton, Hung, Sher]

– anomaly cancellation?
light neutrinos and LEP?
Majorana neutrinos in neutrinoless double beta decay?
electroweak precision data?
flavor constraints?

⇒ none of the constraints convincing ['Why there should not be a fourth generation'; Feyerabend]

– strongly interacting theory?
electroweak baryogenesis?
dark matter?

⇒ at least as interesting as everything else

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The model [old story]

- complete additional generation $[Q_4, U_4, D_4, L_4, e_4, \nu_4]$
- masses from Yukawas
- representations as Standard Model: no FCNC
- charged currents: (4×4) fermion–mixing matrices [single-top (D0) $V_{bt} \gtrsim 0.68$]
- neutrino mass: $\mathcal{L} \sim y_4\ \tilde{H}\bar{L}_4\nu_{4R} + M\ \bar{\nu}^c_{4R}\nu_{4R}/2$

Electroweak precision data

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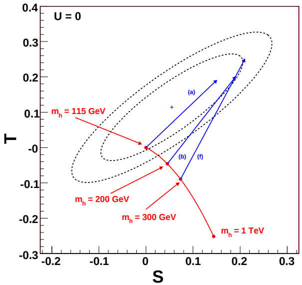
  Just as our 3rd generation??? [Holdom; Kribs, TP, Spannowsky, Tait]
- okay, got is, some people prefer a boring Z'
  but for the purpose of this talk let's be honest and open minded
- for our purpose: leading S and T [$\Delta U \sim 0$ as in SM]
- neutrino with Dirac mass [$\Delta S < 0$ for Majorana neutrinos: Kniehl, Kohrs]
- fermion doublet: $\Delta S = N_f/(6\pi)(1 - 2Y \log m_u^2/m_d^2)$ [$Y_\ell = -1/2$; $Y_q = 1/6$]
- old trick: compensate $\Delta S \sim \Delta T > 0$ [Hill]
  small m_H: $\Delta T \sim \Delta S \sim 0.2$
  large m_H: $\Delta T \sim \Delta S + 0.2 \sim 0.3$

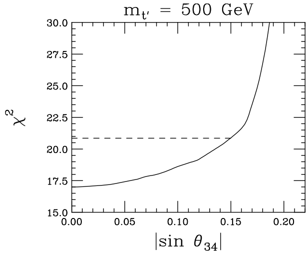
m_{u_4}	m_{d_4}	m_h	$\Delta S_{\rm tot}$	$\Delta T_{\rm tot}$
310	260	115	0.15	0.19
310	260	200	0.19	0.20
330	260	300	0.21	0.22
400	350	115	0.15	0.19
400	340	200	0.19	0.20
400	325	300	0.21	0.25

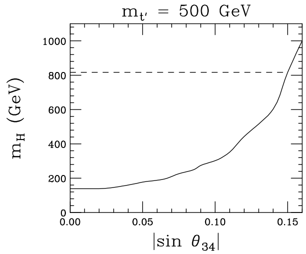


Flavor constraints

More precision data [Alex?]

– proper ew precision fit: $|\sin\theta_{34}| < 0.11$ for $m_H \lesssim 280$ GeV [Chanowitz]





– just had flavored coffee with Frau Prof Hiller
$B_s \to \ell^+\ell^-$ allowed in m_{u_4}-$\sin\theta_{34}$ plane for small θ_{34}

– all allowed region

$$m_{\ell_4}, m_{\nu_4} \gtrsim 100 \text{ GeV} \qquad m_{\ell_4} - m_{\nu_4} \simeq 30 - 60 \text{ GeV}$$

$$m_{u_4}, m_{d_4} \gtrsim 260 \text{ GeV} \qquad m_{u_4} - m_{d_4} \simeq \left(1 + \frac{1}{5}\ln\frac{m_H}{115\,\text{GeV}}\right) \times 50 \text{ GeV}$$

$$|V_{ud_4}|, |V_{cd_4}|, |V_{u_4 d}| \lesssim 0.04 \cdots$$

$$|U_{e4}|, |U_{\mu 4}| \lesssim 0.01 \cdots$$

– small but finite θ_{34} reasonable [CKMFitter? Heiko?]

Perturbativity

Perturbative validity [review: Sher]

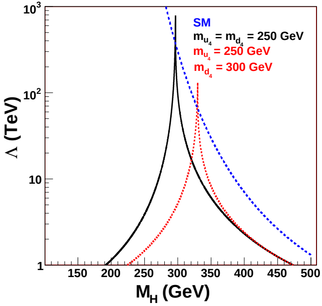
– Higgs mass and potential [dominant RGE effect in SM]:

$$m_H^2 = \lambda v^2 \qquad\qquad 16\pi^2 \frac{d\lambda}{d\log\mu} \sim 12\lambda^2 + 4\sum_f N_c^2 \left(\lambda y_f^2 - y_f^4\right) + \cdots$$

– stability bound ($m_H^{\rm min}$) vs Landau pole or triviality bound ($m_H^{\rm max}$)

– valid to scales comparable to Little Higgs

– different for 4MSSM [later]



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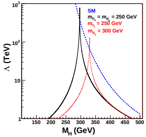


Turn this into virtue [Hill...; Holdom]

– coupling to weak Goldstone modes strong [$m_{q_4} \gtrsim$ 550 GeV and $\Lambda \gtrsim$ 1 TeV]

– condensates $\langle \bar{u}_4 u_4 \rangle = \langle \bar{d}_4 d_4 \rangle \neq 0$ [while $\langle \bar{t}t \rangle = \langle \bar{b}b \rangle = 0$]

– bottom-up: invoke series of $U(1)$ symmetries for

$$(\bar{q}_{4L} d_{4R}) \cdot (\bar{q}_{3L} t_R) \to (\bar{d}_{4L} d_{4R})(\bar{t}_L t_R) \to m_t (\bar{t}_L t_R)$$

$$(\bar{q}_{4L} u_{4R}) \cdot (\bar{q}_{3L} b_R) \to (\bar{u}_{4L} u_{4R})(\bar{b}_L b_R) \to m_b (\bar{b}_L b_R)$$

– improved compared to technicolored boson exchange:
no contribution to Zbb vertex a la $(\bar{T}_L T_R)(\bar{t}_R t_L) \sim (\bar{q}_L \gamma_\mu T_L)(\bar{T}_L \gamma^\mu b_L)$
similarly, no large u_4-d_4 mass splitting contributing to T

– computable as weakly interacting RS model [Burdman & De Rold]

⇒ simple theory without Higgs

Direct searches

Direct searches [Holdom,...]

– assume $m_{u_4} \gtrsim m_{d_4} + 50$ GeV [precision constraints]
– tree level via CKM: $d_4 \to tW$
pair production $d_4 \bar{d}_4 \to b\bar{b}WWWW$
– loop–induced $d_4 \to bZ$ [CDF $m_u \gtrsim 270$ GeV]
– tree level via CKM: $u_4 \to bW$ [CDF $m_u > 260$ GeV]
pair production $u_4 \bar{u}_4 \to b\bar{b}WW$
– small mixing: $u_4 \to d_4 W$
pair production $u_4 \bar{u}_4 \to b\bar{b}WWWWWW$
– single production better? [Fabio's talk]
the more Ws the better...
– bread–and–butter leptons plus missing energy

$\Rightarrow$ (Majorana) neutrinos more interesting?

Higgs physics

Dimension-5 Higgs couplings [e.g. SFitter-Higgs; got a hacked HDecay]

– loop effects of new particles [Arik, Arik, Cetin, Conca, Mailov, Sultansoy; Kribs, TP, Spannowsky, Tait]

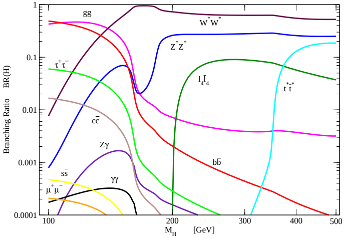
$$\Gamma_{H\to\gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2$$

$$\Gamma_{H\to gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2 \qquad \text{with} \quad \tau_i = \frac{m_H^2}{4 m_i^2}$$

$$A_f(\tau) = \frac{2}{\tau^2} \left[\tau + (\tau - 1) f(\tau) \right]$$

$$A_W(\tau) = -\frac{1}{\tau^2} \left[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau) \right] \qquad \text{with} \quad f(\tau \to 0) \to \tau$$

(1) increase $g_{ggH} \to 3 \times g_{ggH}$
decrease $g_{\gamma\gamma H} \to 1/3 \times g_{\gamma\gamma H}$
light–Higgs BRs suppressed by $H \to$ jets



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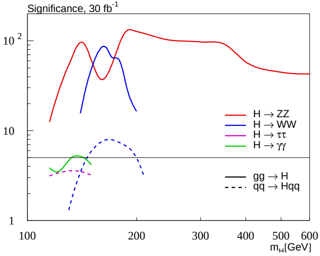
(2) factor 9 enhancement of $gg \to H$ [Tevatron!?]
$\sigma_{gg}\,\text{BR}_{\gamma\gamma} \to \sigma_{gg}\,\text{BR}_{\gamma\gamma}$
$\sigma_{gg}\,\text{BR}_{ZZ} \to (5\cdots8)\;\sigma_{gg}\,\text{BR}_{ZZ}$



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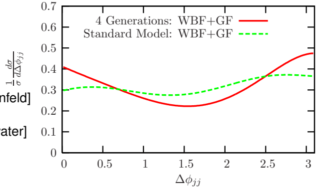
(3) misleading WBF correlations [TP, Rainwater, Zeppenfeld]

(4) Higgs pair production the winner [Baur, TP, Rainwater]

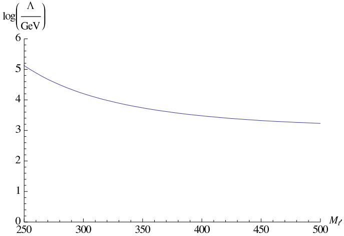
⇒ if nothing else — what a great straw man!



Supersymmetric fourth generation

Motivated by baryogenesis and little hierarchy [Fok, Kribs]

– cutoff dominantly from y_f Landau pole
preferable: $\tan\beta = 1$, $X_{b,t,d_4,u_4} \to 0$



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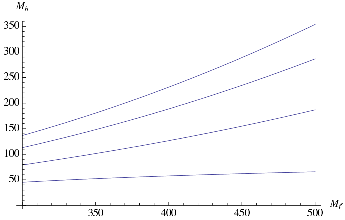
  $H \to WW$ discovery channel for 4MSSM
  light charged Higgs possible [m_A small] [Litsey & Sher]



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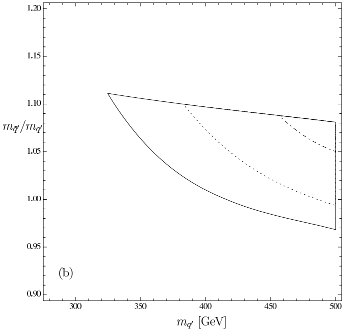
– electroweak baryogenesis [strongly first order]
net zero-temperature effects zero in SUSY limit
finite-temperature effects only helpful from bosons
finite-temperature W, Z too small for $m_H \lesssim m_W$ [Hebecker; Laine & Rummukainen]
sufficient from $\tilde{u}_4$ and $\tilde{d}_4$ [$2 \times 2 \times 3$ d.o.f]
mass range $1 \lesssim m_{\tilde{q}_4}/m_{q_4} \lesssim 1.1$ preferred

$\Rightarrow$ for once an actual motivation?



A fourth generation at the LHC

– it's fun
– it's not ruled out
– it has many interesting faces