e^-e^- Collisions and Generalized Higgs Boson Scenarios

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EXTENDED STANDARD MODEL

Even within SM context, should consider extended Higgs sector possibilities.

- Add triplets or higher reps. is a possibility.

  If neutral vev $\neq 0$, $\Rightarrow \rho$ is no longer computable (even if representations and vevs are chosen so that $\rho = 1$ at tree level); ρ becomes another input parameter to the theory; is this so bad?

  If neutral vev $= 0$, then no EWSB impact and $\rho = 1$ is natural.

  $T = 3, |Y| = 4$ representations $\Rightarrow \rho = 1+$finite loop correction for vev$\neq 0$

Coupling Unification Motivations for Multiple Exotic Representations

Recall 1-loop results (notation used is $N_{T,|Y|}$):

$$\alpha_s(m_Z) = \alpha_{QED}(m_Z)\frac{5(b_1-b_2)}{\sin^2\theta_W(5b_1+3b_2-8b_3)-3(b_2-b_3)}$$

$$M_U = \exp(2\pi t_U) \text{ with } t_U = \frac{3-8\sin^2\theta_W}{5(b_1-b_2)\alpha_{QED}(m_Z)}$$

$$b_1-b_2 \stackrel{SM}{=} \frac{1}{5}(N_{0,2}+4N_{0,4}) - \frac{1}{15}(N_{\frac{1}{2},1}+N_{1,2}) + \frac{11}{15}N_{\frac{1}{2},3} - \frac{2}{3}N_{1,0} + \ldots + \frac{616}{135}N_{3,4}$$

High-scale coupling unification (want small b_1-b_2):

Without SUSY

e.g. $N_{\frac{1}{2},1}=2, N_{1,0}=1 \Rightarrow \alpha_s(m_Z)=0.115$, $M_U=1.6\times10^{14}$ GeV.

e.g. $N_{\frac{1}{2},1}=1$, $N_{1,2}=2 \Rightarrow M_U\sim1.5\times10^{13}$ GeV.

e.g. $N_{\frac{1}{2},3}\neq0$ solutions $\Rightarrow M_U \lesssim 10^{13}$ GeV.

With SUSY,

The $N_{\frac{1}{2},1} = 2$ (only) solution with $M_U \gtrsim 2 \times 10^{16}$ GeV is far and away the solution with highest M_U.

The solution with next highest M_U is $N_{\frac{1}{2},3} = 4$, $N_{\frac{1}{2},1} = N_{1,2} = 2 \Rightarrow M_U \sim 5 \times 10^7$ GeV.

Low-scale (extra dimensions . . .) unification (want big $b_1 - b_2$)

Keeping all SM particles and Higgs on the brane:

e.g. SM case: $N_{\frac{1}{2},1} = N_{\frac{1}{2},3} = N_{1,2} = N_{1,0} = 4, N_{3,4} = 3 \Rightarrow \alpha_s(m_Z) = 0.112$, $M_U = 1000$ TeV, $\alpha_U = 0.04$.

e.g. SUSY case: $N_{\frac{1}{2},1} = N_{1,2} = N_{1,0} = 4, N_{3,4} = 4 \Rightarrow \alpha_s(m_Z) = 0.114$, $M_U = 4$ TeV, $\alpha_U = 0.07$.

Current Constraints

- Mass limits from LEP are model dependent, but certainly pair production pretty much excludes masses below 100 GeV.

- ρ at one-loop.

  In models with $\rho = 1$ at tree level and for which ρ is finitely calculable, parameters must still be chosen so that Higgs loop corrections to ρ are not too large. This is usually automatic in the SUSY models, but in general models, too large a mass separation between neutral and charged Higgs with W, Z couplings is problematical.

- $b \to s\gamma$.

  In non-SUSY models, the charged Higgs for a type-II doublet allows a graph which adds to the already excessive SM prediction, so $m_{H^\pm}$ must be large. Charged Higgs that do not couple to quarks (of which there are many in the models outlined earlier) are no problem.

  In SUSY models, a stop-chargino graph can cancel an excessive $H^\pm$ graph if $m_{\widetilde t}$ and $m_{\widetilde\chi_1^\pm}$ are small enough.

Couplings

This is a very complex topic and very model-dependent. I will simply outline some of the important issues and processes, focusing on triplets, for which I use the generic 2×2 notation: $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$.

Some reminders:

- There is never a $\gamma W^{\pm}\Delta^{\mp}$ vertex.

  There is generally a non-zero $ZW^{\pm}\Delta^{\mp}$ vertex if $v_\Delta = \langle\Delta^0\rangle \neq 0$ (for $|Y| \neq 0$ rep), even if ρ is tuned to $\simeq 1$.

- Charged and neutral (non-singlet) Higgs, triplet members or otherwise, have diagonal pair couplings to $\gamma \propto Q$ and $Z \propto A = T_3 - \sin^2\theta_W Q$.

- $W_L W_L$ couplings to Higgs bosons of triplet reps requires a neutral member of (L) triplet with non-zero v_Δ, which leads to need to fine-tune ρ.

- More generally, for Δ's in triplet representations, ΔVV couplings are proportional to the triplet vev (or zero if Δ is CP-odd in nature).

- Most $\Delta\Delta^{(\prime)}V$ couplings are non-zero even if the triplet vev is zero.

- Non-zero trilinear couplings of three Δ's require a triplet vev.

- $H\Delta\Delta$ couplings involving one doublet H and two triplet Δ's are non-zero if the doublet vev is non-zero, even if the triplet vev is zero.

- When quantum-number allowed, Δ-triplet couplings to $f^{(\prime)}\overline{f}$ require a non-zero triplet vev.

- There is a possibility of non-zero bi-lepton couplings of Higgs bosons. For example, for the standard SU(2)$_L$ case, with $Q = T_3 + \frac{Y}{2} = -2$, the allowed doubly-charged cases are:

$$\begin{array}{l} e^-_R e^-_R \to \Delta^{--}(T=0, T_3=0, Y=-4)\,, \\ e^-_L e^-_R \to \Delta^{--}(T=\frac{1}{2}, T_3=-\frac{1}{2}, Y=-3)\,, \\ e^-_L e^-_L \to \Delta^{--}(T=1, T_3=-1, Y=-2)\,. \end{array} \quad (1)$$

Note that the above cases do not include the $T=3, Y=-4$ representation that yields $\rho = 1$, nor the $T=1, Y=-4$ triplet with no neutral member, but do include the $T=1/2, Y=-3$ doublet representation with no neutral member, and the $T=1, Y=-2$ triplet representation. A $\nu_L \nu_L \to \Delta^0(T=1, T_3=+1, Y=-2)$ coupling also exists, but does not lead to neutrino mass if $v_\Delta = 0$ (as preferred for $\rho = 1$ to be natural).

In the case of a $|Y| = 2$ triplet representation the lepton-number-violating coupling to (left-handed) leptons is specified in the lepton-number violating Lagrangian form:

$$\boldsymbol{\mathcal{L}_Y = i h_{ij} \psi_i^T C \tau_2 \Delta \psi_j + \mathrm{h.c.}\,, \quad i,j = e, \mu, \tau\,.} \quad (2)$$

Limits on the h_{ij} by virtue of the $\Delta^{--} \rightarrow \ell^- \ell^-$ couplings: writing $|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2(\text{ GeV})$, strongest limits (no limits on $c_{\tau\tau}$) are:

- $c_{ee} < 10^{-5}$ (Bhabbha),
- $c_{\mu\mu} < 5 \times 10^{-7}$ ($(g-2)_\mu$ – predicted contribution has wrong sign) and
- $\sqrt{c_{ee} c_{\mu\mu}} < 10^{-7}$ (muonium-antimuonium).

If $\langle \Delta^0 \rangle = 0$ (for $\rho = 1$ = natural), $\Gamma^T_{\Delta^{--}}$ would be small. $\Rightarrow$ possibly very large s-channel $e^- e^-$ and $\mu^- \mu^-$ production rates.

Decays

- If the triplet vev is non-zero, then $\Delta \rightarrow VV$ (possibly virtual) decays and/or $\Delta \rightarrow f' \overline{f}$ decays are usually most significant.

- If the triplet vevs are zero, then many channels are eliminated; dominant modes are $\Delta \rightarrow \Delta' V$; since many of the Δ's of typical model are approximately degenerate, many of these modes will be virtual.

  $\Rightarrow$ dominance of bi-lepton modes is possible if bi-lepton couplings are non-zero.

For example, in the case of a $T=1, |Y|=2\ \Delta^{--}$, we have

$$\begin{aligned} \Gamma_{\Delta^{--}}^{\Delta^- W^-} &= \frac{g^2}{16\pi}\frac{m^3_{\Delta^{--}}\beta^3}{m_W^2} \sim (1.3\ \mathrm{GeV}) \left(\frac{m_{\Delta^{--}}}{100\ \mathrm{GeV}}\right)^3 \beta^3 \,, \\ \Gamma_{\Delta^{--}}^{\ell^-\ell^-} &= \frac{|h_{\ell\ell}^{\Delta^{--}}|^2}{8\pi} m_{\Delta^{--}} \sim (0.4\ \mathrm{GeV}) \left(\frac{c_{\ell\ell}}{10^{-5}}\right) \left(\frac{m_{\Delta^{--}}}{100\ \mathrm{GeV}}\right)^3 \,. \end{aligned} \quad (3)$$

where β is the usual phase space suppression factor.

- For example, if $m_{\Delta^{--}} = 360\ \mathrm{GeV}$, $m_{\Delta^-} = 250\ \mathrm{GeV}$ we find $\Gamma(\Delta^{--} \to \Delta^- W^-) \sim 2\ \mathrm{GeV}$ and $\Gamma(\Delta^{--} \to \ell^-\ell^-) = 19\ \mathrm{GeV}\left(\frac{c_{\ell\ell}}{10^{-5}}\right)$. If any $c_{\ell\ell}$ is near 10^{-5} then $\Gamma_{\Delta^{--}}^{\ell^-\ell^-} > \Gamma_{\Delta^{--}}^{\Delta^- W^-}$ is likely.
- Since there are currently no limits on $c_{\tau\tau}$, the $\tau^-\tau^-$ channel could easily have the largest partial width and be the dominant decay of the Δ^{--}.
- On the other hand, if all the $c_{\ell\ell}$ are very small then the $\Delta^- W^-$ mode is quite likely to be dominant if it is kinematically allowed.
- For zero triplet vevs, the Δ^0 (generally the lightest) will be stable unless it has bi-lepton couplings to $\nu_L\nu_L$.
  Such a Δ^0 would be a candidate for the dark matter.

Detection and Study:

- Discover Δ^{--} in $p\bar{p} \to \Delta^{--}\Delta^{++}$ with $\Delta^{--} \to \ell^-\ell^-, \Delta^{++} \to \ell^+\ell^+$ ($\ell = e, \mu, \tau$) at TeV33 or LHC (J.G., Loomis, Pitts: hep-ph/9610237). LHC reach up to $m_{\Delta^{--}} \sim 1\ \mathrm{TeV}$.

  $\Rightarrow$ TeV33 + LHC will tell us if such a Δ^{--} exists in the mass range accessible to NLC and FMC *and how it decays*.

  - If no W^-W^- decays are detected, it is very probable that $v_\Delta = 0$.
  - If it decays to $\ell^-\ell^-$ ($\ell = e, \mu, \tau$), then $\Rightarrow$ the $\ell^-\ell^-$ coupling clearly exists.
  - For any observed $\ell^-\ell^-$ mode, you know the $\Delta^{--} \to \ell^-\ell^-$ coupling is non-zero, but you do not know that the others are zero — only that they are relatively smaller.
  - Even if a Δ^-W^- mode is dominant, that still does not mean that the $c_{\ell\ell}$'s are zero, only that they are quite small.
    $\Rightarrow$ can we probe $c_{\ell\ell}$'s that are too small for $\ell^-\ell^-$ to appear in decays? Answer=yes.
  - If the Δ^-W^- mode is disallowed and the $c_{\ell\ell}$'s are all very small ($\lesssim 10^{-16}$), the Δ^{--} could be sufficiently long-lived to escape the detector.
    The hadron colliders would see the corresponding 'stable' particle highly ionizing tracks.

- $\Rightarrow$ **Look for (and study if found) in $e^-e^- \to \Delta^{--}$ s-channel collisions.**

This should be done no matter how the $\boldsymbol{\Delta^{--}}$ is seen to decay at the hadron colliders.

Event rates can be enormous (see JFG, hep-ph/9803222 and hep-ph/9510350): equivalently can probe to very small $c_{\ell\ell}$.

– Using the Gaussian approximation, the effective cross section for Δ^{--} production in the s-channel is obtained by convoluting the standard s-channel pole form with the Gaussian distribution in $\sqrt{s}$ of rms width $\sigma_{\sqrt{s}}$.
  A useful mnemonic for $\sigma_{\sqrt{s}}$ is

$$\sigma_{\sqrt{s}} \sim 0.2 \text{ GeV} \left(\frac{m_{\Delta^{--}}}{100 \text{ GeV}}\right) \left(\frac{R}{0.2\%}\right) , \tag{4}$$

  where R is the beam energy resolution in percent. The crucial issue is how $\sigma_{\sqrt{s}}$ compares to $\Gamma^T_{\Delta^{--}}$.
  The resulting cross section is denoted by $\overline{\sigma}_{\Delta^{--}}$. For $\Gamma^T_{\Delta^{--}} \gg \sigma_{\sqrt{s}}$, $\Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$,

$\overline{\sigma}_{\Delta^{--}}$ at $\sqrt{s} = m_{\Delta^{--}}$ is given by:

$$\overline{\sigma}_{\Delta^{--}} = \begin{cases} \frac{4\pi BR(\Delta^{--}\to e^- e^-)}{m^2_{\Delta^{--}}}, & \Gamma^T_{\Delta^{--}} \gg \sigma_{\sqrt{s}}; \\ \frac{\sqrt{\pi}}{2\sqrt{2}} \frac{4\pi \frac{\Gamma(\Delta^{--}\to e^- e^-)}{\sigma_{\sqrt{s}}}}{m^2_{\Delta^{--}}}, & \Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}} \ . \end{cases} \tag{5}$$

We compute rates as $L\overline{\sigma}_{\Delta^{--}}$ with $L = 50\mathrm{fb}^{-1}$ assumed under Gaussian peak (after accounting for losses in radiative tail).

Consider $\boldsymbol{\Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}}$.

This can occur if $\Delta^{--} \to \Delta^- W^-$ is either highly suppressed or forbidden, as is likely since the Δ's are typically rather degenerate, and all of the $c_{\ell\ell}$'s are relatively small, **the most likely case.**

Taking $L = 50\mathrm{fb}^{-1}$, and using Eq. (4) for $\sigma_{\sqrt{s}}$ and the earlier result for $\Gamma(\Delta^{--} \to e^- e^-)$, we find from Eq. (5) an event rate of

$$N(\Delta^{--}) \sim 3 \times 10^{10} \left(\frac{c_{ee}}{10^{-5}}\right) \left(\frac{0.2\%}{R}\right) . \tag{6}$$

An enormous event rate results if c_{ee} is within a few orders of magnitude of its upper bound.

– For 100 events, Eq. (6) $\Rightarrow$ we probe

$$c_{ee}|_{100 \text{ events}} \sim 3.3 \times 10^{-14} \left(\frac{R}{0.2\%}\right) \left(\frac{50\text{fb}^{-1}}{L}\right) , \quad \Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}} , \qquad (7)$$

independent of $m_{\Delta^{--}}$.
$\Rightarrow$ dramatic sensitivity — at least factor of $10^8 - 10^9$ improvement over current limits. **Observation $\Rightarrow$ actual measurement of c_{ee} at level relevant to neutrino mass generation by a right-handed partner Δ_R representation of the left-handed $\Delta_{(L)}$ representation (with $\langle\Delta^0_R\rangle \neq 0$).**

If $\Delta^{--} \to \mu^-\mu^-$ primarily, 10 events might $\to$ a viable signal.

If $\Delta^{--} \to e^-e^-$ or Δ^-W^-, 1000 events might be needed because of backgrounds. A better study is needed.

Other processes:

- $\Delta^{--}Z$ and $\Delta^{--}\gamma$ production in e^-e^- collisions.

This is essentially equivalent to using the bremsstrahlung tail in $\sqrt{s}$ at the e^-e^- collider to self-scan for the Δ^{--}. Depending on c_{ee}, it can allow discovery and mass measurement, which in turn allows centering in $\sqrt{s}$ for direct resonance production as above.

The total number of events is proportional to c_{ee} as in the $\Gamma^T_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$ limit of on-resonance production, but observable rates are only possible if c_{ee} is not too far below current bounds.

- $\Delta^- W^-$ production in e^-e^- collisions.

  This process relies on a $\Delta^- \to e^-\nu_e$ coupling, and would be an interesting way of both observing any Δ^- with such a coupling and a way of determining the magnitude of the coupling.

  Observable rates require substantial coupling.

CONCLUSIONS

- **Exotic Higgs representations, e.g. triplet as motivated by seesaw approach to neutrino masses, will lead to exotic collider signals of doubly charged Higgs pair production at hadron colliders.**

  The kinematic reach of such signals at the LHC will be up to $m_{\Delta^{--}} \sim 1~\mathrm{TeV}$, which means that for any lepton collider with $\sqrt{s} \lesssim 1~\mathrm{TeV}$, we will know ahead of time what e^-e^- $\sqrt{s}$ will be required for Δ^{--} production in the s-channel.

- **Even if the $\boldsymbol{\Delta^{--}}$ is not seen to decay to e^-e^-, it will be essentially mandatory to have e^-e^- collisions to produce the $\boldsymbol{\Delta^{--}}$ as a probe of the possibly quite small (but immensely important) coupling c_{ee}, since very! small values of c_{ee} can be probed.**