# Fermion Condensate Model of Electroweak Interactions

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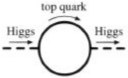
# Outline

1. Introduction, motivation
2. Fermion Condensate Model
   - Gap equations, masses, mixing
   - Phenomenology
3. Conclusion, Outlook

# BSM - Solutions to the Hierarchy Problem

Standard Model is incomplete
- theory problems & phenomenology indications

$$\delta M_H^2 \sim -\frac{3G_F}{2\sqrt{2}\pi^2} m_{top}^2 \Lambda^2 \sim -(0.2\Lambda)^2$$



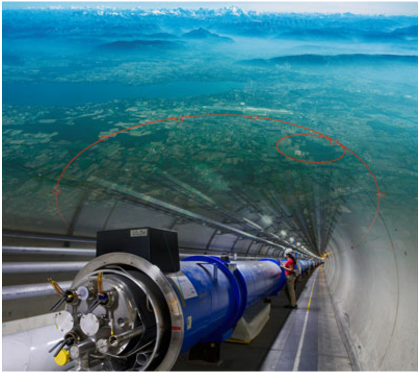

Solutions:

- Supersymmetry, perturbative cancellations
  Fermion-boson symmety (softly broken) $\Lambda \sim m_{\not{s}usy} \simeq m_{susy} - m$
- Dynamical symmetry breaking
  technicolor-like models, composite Higgs
- Extra dimensions
  Apparent Planck scale large, geometrical solution
- Little-Higgs
  Higgs: (Pseudo GB), B-B and F-F cancellation

# LHC - most important tasks

1. Reveal the mechanism of EWSB
   Find the Higgs, if it exists!
2. Search for new physics at the TeV scale
3. Dark matter candidates
4. Anything unexpected

LHC tunnel



The new physics is unknown, model dependent constraints

$\Longrightarrow$ Important to check alternative scenarios.

# Dynamical Symmetry Breaking w/ Vector-like Fermions

- Low energy non-renormalizable, effective model
  Without elementary scalar
- New fermions are non-chiral, differs from technicolor
- Dynamical condensate breaks EW symmetry.
  Mixing between doublet & singlet rep's is essential.
- Higgs: composite state.

G. C., E. Lendvai and G. Pócsik, EPJ C46 (2006)
G. C. ,E. Lendvai, J.Phys. G34 (2007), EPJ C58 (2008).
G. Cynolter and E. Lendvai, arXiv:1002.4490 [hep-ph]

# New fermions

SM elementary Higgs (sector) replaced by new vector-like fermions

$$\begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \rightarrow \left| \begin{array}{l} \Psi_S, \quad T = Y = 0 \text{ , singlet} \\ \Psi_D = \begin{pmatrix} \Psi_D^+ \\ \Psi_D^0 \end{pmatrix}, \quad T = \frac{1}{2}, \; Y = 1, \; SU_L(2) \text{ doublet} \end{array} \right.$$

Non-chiral representations $\Rightarrow$ anomaly free
Similar extra fermions investigated
MSSM neutralino sector,

- R. Barbieri, L.J. Hall, V.S. Rychkov: Improved naturalness..PRD74 (2006)
- P.J. Fox, L.J. Hall, M. Papucci,..., Dark matter... JHEP 0711
- M. Cirelli, A. Strumia,...Minimal dark matter, Nucl. Phys. B **753** (2006)
- Rakhi Mahbubani, Leonardo Senatore, Phys. Rev. **D73**: 043510 (2006).
- F. D'Eramo,: Dark Matter + Higgs phys., Phys.Rev.D76:083522 (2007).
- and many other ...

# Lagrangian (new terms)

$$
\begin{aligned}
L_\Psi = \;& i\overline{\Psi}_D D_\mu \gamma^\mu \Psi_D + i\overline{\Psi}_S \partial_\mu \gamma^\mu \Psi_S - m_{0D}\overline{\Psi}_D\Psi_D - m_{0S}\overline{\Psi}_S\Psi_S + \\
& + \lambda_1 \left(\overline{\Psi}_D\Psi_D\right)^2 + \lambda_2 \left(\overline{\Psi}_S\Psi_S\right)^2 + 2\lambda_3 \left(\overline{\Psi}_D\Psi_D\right)\left(\overline{\Psi}_S\Psi_S\right),
\end{aligned}
$$

$SU_L(2) \times U_Y(1)$ covariant derivative $D_\mu = \partial_\mu - i\frac{g}{2}\underline{\tau}\,\underline{A}_\mu - i\frac{g'}{2}B_\mu$,
$\underline{A}_\mu, B_\mu$ and $g$, $g'$ gauge fields and couplings

- Dimensionful couplings $\lambda_3 = \tilde{\lambda}_3/\Lambda^2$, $m_{0D}$, $m_{0S}$ allowed.
- Non-renormalizable effective theory with a $\Lambda$ (physical) cutoff.
- Further 4-fermion couplings are possible, argument unchanged.
- Do not mix w/ standard fermions,
  conserved new fermion-number (parity).

# Gap equations

Condensates formed, if $\lambda_i > \lambda_i^{crit}$:

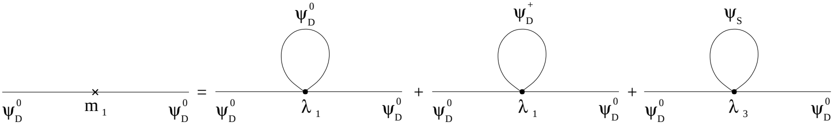
$$\left\langle \overline{\Psi}^0_{D\alpha} \Psi^0_{D\beta} \right\rangle_0 = a_1 \delta_{\alpha\beta}\,,$$

$$\left\langle \overline{\Psi}^+_{D\alpha} \Psi^+_{D\beta} \right\rangle_0 = a_+ \delta_{\alpha\beta}\,, \qquad \langle \overline{\Psi}_S \Psi_D \rangle_0 = \left\langle \begin{pmatrix} \overline{\Psi}_S \Psi_D^+ \\ \overline{\Psi}_S \Psi_D^0 \end{pmatrix} \right\rangle_0 = \begin{pmatrix} 0 \\ a_3 \end{pmatrix} \neq 0$$

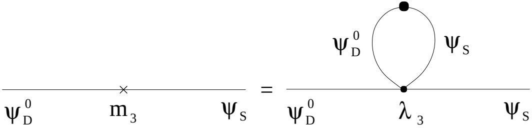
$$\langle \overline{\Psi}_{S\alpha} \Psi_{S\beta} \rangle_0 = a_2 \delta_{\alpha\beta}\,,$$

Self-consistent masses and mixing generated if $\lambda_i > \lambda_i^{crit}$.

„Diagonal" mass




Non-diagonal condensate triggers mixing and EWSB



# Gap equations II

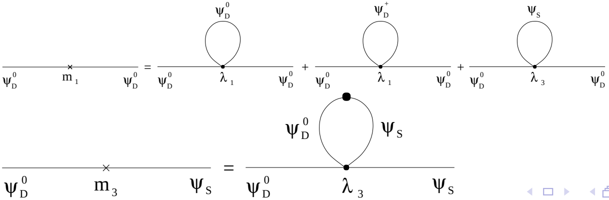
Condensates generate dynamical masses and mixing in L

$$L_\psi \to L_\Psi^{\rm lin} = -m_+ \overline{\Psi_D^+}\Psi_D^+ - m_1 \overline{\Psi_D^0}\Psi_D^0 - m_2 \overline{\Psi}_S \Psi_S - m_3 \left( \overline{\Psi^0}_D \Psi_S + \overline{\Psi}_S \Psi_D^0 \right)$$

$$\begin{aligned} m_+ &= m_{0D} - 6\lambda_1 a_+ - 8\left(\lambda_1 a_1 + \lambda_3 a_2\right) = m_1 + 2\lambda_1 \left(a_+ - a_1\right) && (1)\\ m_1 &= m_{0D} - 6\lambda_1 a_1 - 8\left(\lambda_1 a_+ + \lambda_3 a_2\right), && (2)\\ m_2 &= m_{0S} - 6\lambda_2 a_2 - 8\lambda_3 \left(a_1 + a_+\right), && (3)\\ m_3 &= 2\lambda_3 a_3 . && (4) \end{aligned}$$

$m_3 \neq 0$ neutral comp.of the doublet and singlet fermion mix.

$\Longrightarrow$ Electroweak symmetry breaking.



Diagonalized fields and (physical masses)

$$\begin{aligned} \Psi_1 &= \quad c\,\Psi_D^0 + s\,\Psi_S, & (M_1) \\ \Psi_2 &= -s\,\Psi_D^0 + c\,\Psi_S, & (M_2) \end{aligned}$$

$s = \sin\Phi$, $c = \cos\Phi$, mixing angle $\Phi$.

Condensates of physical fields

$$\frac{\delta_{\alpha\beta}}{4} I_i = \langle \overline{\Psi}_{i\alpha} \Psi_{i\beta} \rangle_0 = -\frac{\delta_{\alpha\beta}}{8\pi^2} M_i \left( \Lambda^2 - M_i^2 \ln\left(1 + \frac{\Lambda^2}{M_i^2}\right)\right) \quad \text{i=1,2,+.}$$

$$\begin{aligned} c \cdot s\,(M_1 - M_2) &= 2\lambda_3\, c \cdot s\,(I_1 - I_2), \\ c^2 M_1 + s^2 M_2 &= -\lambda_1 \left(6\left(c^2 I_1 + s^2 I_2\right) + 8 I_+\right) - 8\lambda_3 \left(s^2 I_1 + c^2 I_2\right), \\ s^2 M_1 + c^2 M_2 &= -6\lambda_2 \left(s^2 I_1 + c^2 I_2\right) - 8\lambda_3 \left(c^2 I_1 + s^2 I_2 + I_+\right), \\ M_+ &= -\lambda_1 \left(8\left(c^2 I_1 + s^2 I_2\right) + 6 I_+\right) - 8\lambda_3 \left(s^2 I_1 + c^2 I_2\right). \end{aligned}$$

Symm. breaking solution ($\sin 2\Phi \neq 0$), if $|\lambda_3| > \lambda_3^{crit} = \frac{\pi^2}{\Lambda^2}$.

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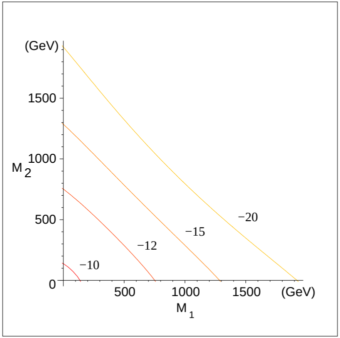
# Symmetry breaking solutions




$\lambda_3$ contours on $M_1$-$M_2$ plane $\lambda_3^{crit} = -\pi^2/\Lambda^2$

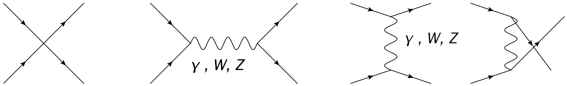
$\lambda_3 = \{-10, -12, -15, -20\} \cdot 1/\Lambda^2$, $\Lambda = 3$ TeV.

Mixing is essential $2c \cdot s = \sin 2\phi \neq 0$.

$$0 = (M_1 - M_2)\, c \cdot s \left( \frac{1}{\lambda_3} + \frac{\Lambda^2}{\pi^2} - \frac{M_1^3 \ln\left(1 + \frac{\Lambda^2}{M_1^2}\right) - M_2^3 \ln\left(1 + \frac{\Lambda^2}{M_2^2}\right)}{M_1 - M_2} \right)$$

# Perturbative unitarity

Consider $2 \to 2$ elastic scattering of $\Psi_{1,2}, \Psi^+$ new fermions and $|\Re a_0| \leq \frac{1}{2}$ for $J = 0$ partial wave

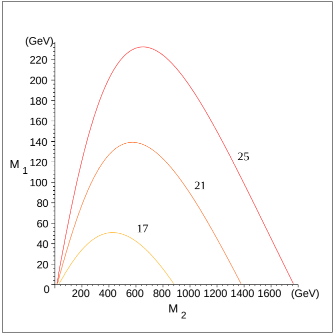



Dominant contribution from contact graph $\quad (+\ \gamma, W, Z$ exchange)

$$\lambda_i s \leq 8\pi, \qquad s \leq \Lambda^2$$

Most stringent for $\lambda_2$ coupling $\sim \lambda_2 \left(\bar{\Psi}_S \Psi_S\right)^2$.

# Unitarity + Gap equations




$\lambda_2$ contours on $M_1$-$M_2$ plane
$\lambda_2 \leq 8\pi/\Lambda^2$, $\Lambda = 3$ TeV, $m_{0D,0S} = 0$.

- 3 new fermions
  $\Psi_1, \Psi_2, \Psi_+$
  $M_1 \leq M_+ \leq M_2$
  par's $M_1, M_2, c^2$.


- favours small mixing ($c^2$)
- conserved global quantum number
- composite Higgs $\sim \overline{\Psi}_D \Psi_S$.

# Standard fermion masses

Higgs Yukawa interactions $\Rightarrow$ 4-fermion terms , $\Phi_{SM} \sim \overline{\Psi}_D \Psi_S$

$$L_f = g_f \left(\overline{\Psi}^f_L \Psi^f_R\right) \left(\overline{\Psi}_S \Psi_D\right) + g_f \left(\overline{\Psi}^f_R \Psi^f_L\right) \left(\overline{\Psi}_D \Psi_S\right),$$

dimensionful coupling constants $g_i = \tilde{g}_i / M^2$

The mixed condensate generates masses for the leptons and quarks.

The electron mass

$$m_e = -4 g_e a_3 = -4 \tilde{g}_e \frac{a_3}{M^2}.$$

Generates further $e^+ e^- \overline{\Psi}_S \Psi^0_D$ type interactions. ($g_e \sim m_e$)

Electron, $\nu_e$ doublet ($\sim$ down type quarks )

$$L^l = g_e \left(\overline{\nu} e_R \overline{\Psi}_S \Psi^+_D + \overline{e}_L e_R \overline{\Psi}_S \Psi^0_D + \overline{e}_R \nu \overline{\Psi}^+_D \Psi_S + e_L \overline{\Psi}^0_D \Psi_S\right).$$

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# Implications for Phenomenology

From $\Psi_D$ doublet covariant kinetic term **renormalizable** int's.

$$L^I = \overline{\Psi_D^+}\gamma^\mu\Psi_D^+\left(eA_\mu - e\cot 2\theta_W Z_\mu\right) + \frac{g}{2\cos\theta_W}\overline{\Psi_D^0}\gamma^\mu\Psi_D^0 Z_\mu + \\ + \frac{g}{\sqrt{2}}\left(\overline{\Psi_D^+}\gamma^\mu\Psi_D^0 W_\mu^+ + \overline{\Psi_D^0}\gamma^\mu\Psi_D^+ W_\mu^-\right).$$

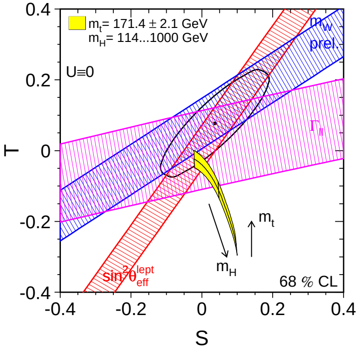
Mixing implies

$$L^I = \overline{\Psi_D^+}\gamma^\mu\Psi_D^+\left(eA_\mu - e\cot 2\theta_W Z_\mu\right) + \\ + \frac{e}{\sin 2\theta_W} Z_\mu\left(c^2\overline{\Psi}_1\gamma^\mu\Psi_1 + s^2\overline{\Psi}_2\gamma^\mu\Psi_2 - sc\left(\overline{\Psi}_1\gamma^\mu\Psi_2 + \overline{\Psi}_2\gamma^\mu\Psi_1\right)\right) + \\ + \left[\frac{g}{\sqrt{2}} W_\mu^+\left(c\overline{\Psi_D^+}\gamma^\mu\Psi_1 - s\overline{\Psi_D^+}\gamma^\mu\Psi_2\right) + h.c.\right].$$

$L_f^{\mathrm{mass}}$ "Yukawa" int's are weaker than in SM

$g_e \leq \sqrt{2h}\frac{m_e}{v} = \sqrt{2h}g_e^{SM}$ $h$ dimensionful! $\left(L_H = h\left(D_\mu\Phi\right)^\dagger\left(D^\mu\Phi\right),\right)$

Oblique corrections, '92 Peskin-Takeuchi, ...
only via $W^{\pm}$, $Z$ vacuum polarization if $M_{\text{New}\,Physics} \gg M_Z$




$$\frac{\alpha(M_Z)}{4 s_W^2 c_W^2} S = \Pi'_{W_3 B}(0),$$

$$M_W^2\, T = \Pi_{W_3 W_3}(0) - \Pi_{W^+ W^-}(0),$$

S$=-0.10 \pm 0.10$ (-0.08)
T$=-0.08 \pm 0.11$ (+0.09),

$$M_H^{ref} = 117(300)\ \text{GeV}$$

S and T vanish for no mixing $c^2 = 0$
(non-degenerate vector-like doublet + singlet).
Expect small corrections for the solution of the gap equations.

# S parameter in FCM

3 parameter, $M_1$, $M_2, c^2 = \cos^2\Phi.$, $T$, $S$ grows w/ $c^2$.

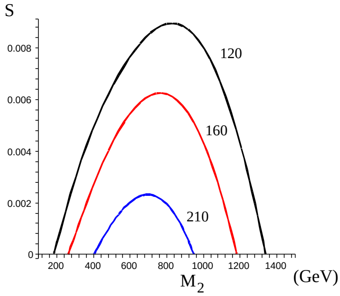



Figure: The max. value of the $S$ parameter vs. $M_2$ for $M_1 = 120, 160, 210$ GeV. The 95 % C.L. bounds [-0.296, 0.096] are outside the figure.

S parameter does not give constraints.

# T parameter in FCM

3 parameter, $M_1$, $M_2, c^2 = \cos^2\Phi$ , $(M_+ \sim c^2 M_1 + s^2 M_2)$.,
$T$, $S$ grow with $c^2$. $T > 0$ always

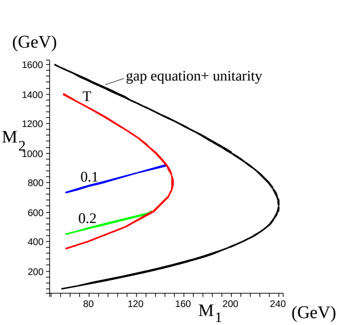
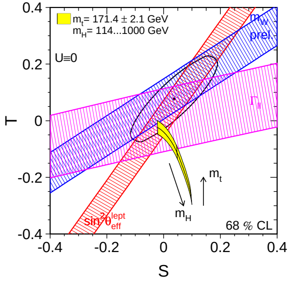



Figure: Constraints on $(M_1, M_2)$ plane. Red curve: $T$gives the max. value of $c^2$ (@ 95 % C.L.) . Below the 0.1 (blue) and 0.2 (green) line $c^2$ can exceed 0.1 and 0.2. Right panel - the maximum value of $T$ vs. $(M_1, M_2)$.

# Heavy Higgs bozon?

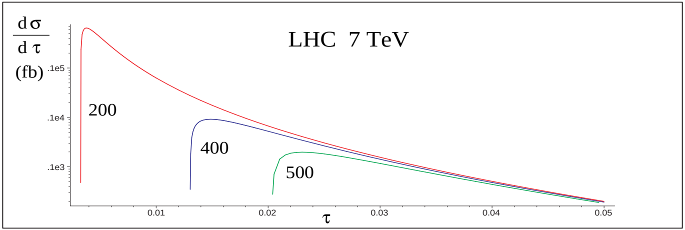
- Positive contrib'n to T -> YES
- E.g. $M_H = 300$ GeV, $\Delta T = -0.09$
- Compensated by $\Delta T_{NP} = +0.1$ (160,800) GeV and $c^2 = 0.115$ $M_+ \simeq 720$ GeV




Extension of the SM with vector type doublet fermions allows a heavy Higgs - "improved naturalness"

# Collider Constraints, LHC

- PDG: doublet $\Psi^+$ $M_+ > 100$ GeV
  neutral $M_{1,2} > 45$GeV w/o assumptions
- LHC example: Drell-Yan production
  $q\bar{q} \to \gamma^*, Z^* \to \Psi^+\Psi^-$, tree level ($\hat{s} = \tau s$), without cuts




Total cross section

| $M_+$(GeV) | 200 | 400 | 500 |
|---|---|---|---|
| $\sigma$ (fb) | 215 | 9.3 | 2.6 |

Small number of events with int. luminosity $10 - 100$ pb$^{-1}$.

# Summary, Outlook

- Dynamical SB Model is proposed with extra vector-like fermions (doublet + singlet)
- Mixed condensate,mixing between diff. rep's. $\Rightarrow$ EWSB
- Composite Higgs, Allows a Heavy Higgs boson naturally
- Unreachable at 7 TeV LHC with low luminosity
- At 14 TeV LHC dedicated analysis needed
- $\Psi_1$ is an ideal dark matter candidate

# Backups - Gauge boson masses

Effective doublet composite scalar (Y=1) gives masses

$$\Phi = \begin{pmatrix} \Phi^{+} \\ \Phi^{0} \end{pmatrix} = \overline{\Psi}_S \Psi_D,$$

$\Phi$ kinetic term is generated in the low energy effective description (like in top-condensate models).

$$L_H = h \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right) \quad \mathrm{dim(h)} = -4$$

$$h\,\Phi^{0\dagger}\Phi^0 \to h\left\langle \Phi^{0\dagger}\Phi^0 \right\rangle_0 = h\left(16 a_3^2 - 4 a_1 a_2\right) = \frac{v^2}{2},$$

get standard masses with, $v = \left(\sqrt{2} G_F\right)^{-1/2} = 254$ GeV

$$m_W = \frac{gv}{2}, \qquad m_Z = \frac{gv}{2\cos\theta_W}.$$

# LHC 14 TeV

- At 14 TeV LHC dedicated analysis
  - jetmass analysis (vector-like quarks)
    (Skiba and Tucker-Smith PR D75 2007 )
  - similar to chargino- neutralino production, when $\chi^0$is the LSP
  - like sign lepton final states, similar to $4^{\text{th}}$generation leptons
    (Özcan, Aguilar-Saavedra, Aguila, Tuominen et al. ...)
- New decay channel(s) ($H \to \bar{\Psi}_S \Psi^0_D$,...) for the Higgs boson is possible