Dear Colleagues,

Paolo Lodone is about to graduate from the Scuola Normale of Pisa. His expertise is Beyond the Standard Model phenomenology. He has worked on composite Higgs, low-energy supersymmetry, and TeV scale gravity. I know him quite well since I was an assistant professor at the Scuola Normale during his Master's thesis and the beginning of his PhD, and because we have a history of collaboration (see below). I think he is a very talented student, with strong technical skills. He is not afraid of hard problems which involve conceptual issues and which do not have ready-made solutions. Actually, I believe he prefers this kind of problems. I would classify him a “thinker”, i.e. someone who may not be incredibly fast at the onset of a project, but is eventually able to see farther, endure longer, and make nontrivial contribution rather than just follow advisor’s directions. He’s the strongest among several phenomenology students who are finishing in Pisa this year, including as well the students of the previous years going back perhaps as far as the stellar generation of Contino, Papucci etc.

Here’s how I got to know Paolo. For his first PhD project I proposed him the problem of QCD radiation in trans-Planckian scattering. As explained in a 2001 paper of Giudice, Rattazzi and Wells, small-angle trans-Planckian scattering is a complementary signal of TeV-scale gravity scenarios. It is not as widely acclaimed as the black hole production, but it has an advantage of being under theoretical control. However, QCD effects were never properly included in the calculation of the scattering amplitude. I knew about this problem from Riccardo Rattazzi, and I was also interested in it as a warmup for the more difficult problem of gravitational radiation. I had an idea how this could be approached so I suggested that Paolo look into this. Now, this was not the simplest thing to start your PhD with, but it proved an impressive test of Paolo’s abilities. (Paolo’s Master’s thesis - his first paper - was on the electroweak precision tests in the composite Higgs boson scenario. This was an interesting contribution to the subject and is recognized as such in the later literature. But he had no prior experience with Extra-dimensional theories.)

(see next page)
Plan

1. Basic tenets & Heresies

2. Comments on the models
   - susy
   - strong
   - composite
   - little
   - warped…
1. In Naturalness We Trust

Fundamental scalars are unnatural:

\[ \mathcal{L} = (\partial \phi)^2 + m^2 \phi^2 + \lambda \phi^4 \]

requires finetuning to be valid up to energies \( \Lambda \gg m \)

Experimentally verified!

Ferromagnets near Curie point \( T \sim T_c \) are described by this Lagrangian (in 3D) \(^{\text{Landau,Ginzburg}}\)

\[ \Lambda^{-1} \leftrightarrow a \quad - \text{atomic spacing} \]

\[ m^{-1} \leftrightarrow \xi \quad - \text{correlation length} \]

\[ \Lambda \gg m \quad \iff \quad \xi \gg a \quad - \text{critical point} \]
For generic $T$ ferromagnet is not a critical point:

$T \rightarrow T_c$ requires to finetune the temperature:
For generic $T$ ferromagnet is not a critical point:

$T \rightarrow T_c$ requires to finetune the temperature:

$T \approx T_c$
Exit strategies if naturalness fails

Minimality:

$\text{SM} + 3 \nu_R @ \text{keV-MeV}$

Shaposhnikov et al

- neutrino oscillations
- Dark Matter
- baryogenesis

$\text{SM} + 5\text{-plet } \Psi \text{ of } SU(2) @ 10 \text{ TeV}$

Cirelli, Fornengo, Strumia

- naturally stable Dark Matter

Environmental selection  ‘A new kind of science’

can make predictions assuming peaked distributions in the Landscape

$m_H = 115 \pm 6 \text{ GeV}$  Feldstein, Hall, Watari 2006

$m_H = 141 \pm 2 \text{ GeV}$  Hall, Nomura 2009

(obviously, different assumptions lead to different predictions)
2. Need for unitarization

Higgsless SM is incomplete, UV cutoff at $\Lambda \sim 4\pi v \sim 2-3 \text{ TeV}$

Just look at $W_L W_L$ scattering:
2. Need for unitarization

Higgsless SM is incomplete, UV cutoff at $\Lambda \sim 4\pi v \sim 2-3$ TeV

Just look at $W_L W_L$ scattering:

Expect this to be general:

scattering phase

resonance region
(Higgs, heavy vectors of TC, …)

new, better theory
Iconoclasm

Dvali, Giudice, Gomez, Kehagias “UV completion by Classicalization” 1010.1415

Claim:

Higgsless SM may be UV complete *by itself* in a novel sense. Processes at $E \gg \Lambda$ can be computed by solving classical field equations.

Weak points:

- What about the resonance region? (Most important for the LHC)
- Argument is rather handwaving. No concrete computation of, say, $WW$ scattering at 10 TeV is given
Plan

1. Basic tenets & Heresies

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Supersymmetry

Seen many new SUSY limits at this conference:

- Dilepton + $E_T^{miss}$
- Jets + $E_T^{miss}$

Taffard, Vivarelli talks

**Squark-gluino-neutralino model ($m_{UB} = 0$ GeV)**

**ATLAS Preliminary**

- 0 lepton 2011 combined
- CL$_S$ observed 95% C.L. limit
- CL$_S$ median expected limit
- exp. limit 68%, 90% CL
- 2010 data PCL 95% C.L. limit

L$^{inf}$ = 1.04 fb$^{-1}$, $\sqrt{s}$ = 7 TeV

$\sigma_{90\%} = 0.01$ pb

$\sigma_{68\%} = 0.1$ pb

$\sigma_{CL} = 1$ pb

$\sigma_{UB} = 10$ pb

**MSSM PhenoGrid2**

- Median expected limit (Comp. spectrum)
- Observed limit 95% CL (Light neutralino)
- Median expected limit (Light neutralino)
Impressive bounds on squarks and gluinos, into TeV range...

What do we learn? → Papucci talk

1. Plain vanilla SUSY models (like MSSM with flavor-universal soft masses) are being pushed into a corner

**but**

2. Several other, theoretically motivated, scenarios remain very poorly constrained by existing searches

| “Flavor-Split” spectra (heavy 1st-2nd gen squarks, gluino below 1-1.5 TeV, light 3rd gen) | “Squashed” spectra (everything below ~500GeV but splittings are small, O(10GeV)) | Low MET scenarios (not necessarily RPV) |
SUSY with flavor-split spectra

3rd generation "light" vs 1st-2nd generation "heavy"

Cohen et al ’96, Barbieri et al ’07-11 → Straub talk

\[ m_h \sim 200 \div 300 \text{ GeV} \]

\[ \tilde{f}_{1,2}, \tilde{f}_3 \]

\[ \tilde{m}_{1,2} \gtrsim 20 \text{ TeV} \]

\[ m_{\tilde{g}} \lesssim 1 \div 1.5 \text{ TeV} \]

\[ \tilde{m}_3 \lesssim 500 \div 700 \text{ GeV} \]

via `fat Higgs’ aka \( \lambda \)SUSY mechanism

\[ pp \rightarrow \tilde{g} \tilde{g} \rightarrow q_3 q_3 \bar{q}_3 \bar{q}_3 + \chi \chi \quad q_3 = t, b \]
SUSY with flavor-split spectra

3rd generation “light” vs 1st-2nd generation “heavy”

Cohen et al ’96, Barbieri et al ’07-11 \(\rightarrow\) Straub talk

\[ \begin{aligned}
  m_{\tilde{g}} &\gtrsim 1 \div 1.5 \text{ TeV} \\
  m_{\tilde{q}} &\gtrsim 1 \div 20 \text{ TeV} \\
  m_{\chi} &\sim 700 \text{ GeV}
\end{aligned} \]

\[ \begin{aligned}
  pp \rightarrow \tilde{g}\tilde{g} \rightarrow q_3q_3\bar{q}_3\bar{q}_3 + \chi\chi \\
  q_3 = t, b
\end{aligned} \]

as yet poorly constrained...
Strong EWSB  (Technicolor etc)

With 10% accident we may be in business...
It’s not going to be QCD-like  
flavor physics hints at that

Technicolor Higgs field is a composite operator
⇒ Yukawa couplings are not dimensionless:

\[
\frac{y}{\Lambda^{\text{dim}H-1}} H_{TC} (\bar{q}q)_{SM}
\]

If TC is QCD-like, then

\[ H_{TC} \sim \bar{\psi}\psi \quad \text{dim}H = 3 \gg 1 \]
⇒ strong FCNC

Way out: walking/conformal behavior above 1 TeV

1 < \text{dim}H < 3

Holdom  
Akiba and Yanagida  
Yamawaki, Bando, Matumoto  
Appelquist, Karabali, Wijewardhana
Much of the old literature focused on $\dim H \approx 2$

Most economic scenario; to give masses to all SM fermions (including top) without flavor problems requires

$$\dim H \lesssim 1.5$$

Rigorous inequalities about CFT dimensions allow this.

Luty and Okui ’04

Rattazzi, Tonni, Rychkov, Vichi
TC signals

1. **Heavy vectors** (techni-$\rho$), $M\sim 1$-$3$ TeV

NB rather narrow:
\[ \Gamma(\rho_{TC} \rightarrow WW) \sim 10\% \Gamma(H \rightarrow WW) \]

Decay into $WW, WZ$, produced in $WW$ fusion and Drell-Yan (need $\sim 100$ fb$^{-1}$)

2. **Heavy scalars**

a) Isospin singlets - wide, difficult to see (like $\sigma$ of QCD)
b) Isospin triplets (or neg. parity isosinglets) - narrow, decay into $WWW$ and $t\bar{t}$ produced in gluon fusion:

Evans, Luty
Strongish EWSB
(composite pseudo-NGB Higgs boson)

Postpone onset of truly strong interactions to \( \Lambda = (\text{few}) 4\pi v \)
(computable at LHC energies in terms of a few parameters)

One or more Higgs bosons emerge as low-energy remnants of this, unspecified, strong dynamics

Higgs is light because PNGB

Dynamics of Higgses is largely controlled by symmetry

Higgs potential is controlled by small symmetry breaking terms (like coupling to the rest of the SM)
We don’t know what the symmetry is (experiment will tell).

There is a discrete list of possibilities.

In order of increasing complexity:

<table>
<thead>
<tr>
<th>$G$</th>
<th>$H$</th>
<th>$N_G$</th>
<th>NGBs rep. [$H$] = rep. [$SU(2) \times SU(2)$]</th>
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<td>$G_2$</td>
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<td>SO(7)</td>
<td>SO(5) $\times$ SO(2)</td>
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**Minimal Composite Higgs Model**

Agashe, Contino, Pomarol

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Global group  
Unbroken group  
No. of PNGB’s  
Representation content
We don’t know what the symmetry is (experiment will tell).

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Next-to-Minimal Composite Higgs Model
Gripaios, Pomarol, Riva, Serra
We don’t know what the symmetry is (experiment will tell).

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Table 1: Cosets $G/H$ from simple Lie groups, with $H$ maximal subgroup of $G$. For each coset, its dimension $N_G$ and the NGBs representation under $H$ and $SO_4$ is reported. For $Sp(6)/SU_2 \times SU_4$, two embeddings are possible, we will be interested only in the first one, which leads to two Higgs 4-plets.

Global group

Unbroken group

No. of PNGB’s

Representation content
Generic predictions for Higgs physics

1. $M_H$ typically below 200 GeV, but can be as high as 300 GeV

2. $O(10-20\%)$ deviations in Higgs-boson couplings to all SM particles
   Giudice, Grojean, Pomarol, Rattazzi

3. Correlated! In minimal model controlled by just two coefficients

4. The sign of deviations can often be predicted (mostly suppression)
   Low, Rattazzi, Vichi

5. New Higgs decay channels in non-minimal models
   (with predicted BR). E.g. $H \rightarrow \eta\eta$ in SO(6)/SO(5)
   Gripaios, Pomarol, Riva, Serra

ILC would be required to fully explore this phenomenology if LHC sees hints of it
Connections with flavor physics → Weiler talk

Composite Higgs models typically use ‘partial compositeness’ mechanism for giving masses to SM fermions

Fermion mass and CKM hierarchies explained by hierarchies in mixing angles

This picture makes a lot of sense theoretically and allows a detailed and honest discussion of flavor effects involving all 3 generations (unlike in Little Higgs Models which usually do not go beyond top Yukawa)

Much of early literature was phrased in terms of (warped) extra dimensions. Red herring: this class of models is much more general.
(Some) Non-Higgs signals of Composite Higgs

New non-chiral quarks (top partners) with 500 GeV-1 TeV mass, perhaps exotic charge 5/3:

Contino, Servant
Mrazek, Wulzer

Anomalous $tttt$ production from top-right compositeness:

Lillie, Shu, Tait
Pomarol, Serra
Final remarks and conclusions

Many impressive new limits set at this conference

On what models???

Z'  CMSSM  split SUSY... (just a few examples)

Did we believe in these models?

Another casualty: Large Extra Dimensions (never a truly bona fide solution to the naturalness problem)

Truly motivated, not ad hoc models are very few:

SUSY / Strong EWSB / Composite Higgs
Kudoz to ATLAS for presenting the limits as a function of the width