The 2012 European School of High-Energy Physics, Anjou

Other physics - BSM

Part I

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CERN-Th
Motivations for BSM physics

细调问题

- 与Higgs相关的层次问题 [R. Rattazzi]
- 强CP问题 [D. Kazakov]
- 质量“为什么是这样”问题
- 为什么有3代

观测事实未解释

- 黑洞问题
- 物质-反物质不对称性问题

轻子质量层次
- 超对称解决方案 [G. Isidori]
- 多余维解决方案
- 4D强烈相互作用解决方案

- GUTs
- 质子稳定性
- 电荷量化
- 超对称

- 细调问题
Outline of these lectures

Part I

- Brief overview of BSM theoretical landscape
- Implications of (null) LHC searches for BSM physics
- TeV strong dynamics, the Higgs as a Pseudo Nambu Goldstone boson
- LHC tests of composite higgs & composite top, search for top partners, four-top events
- Search for new physics in ttbar

Part II

- GUTs
- axions <- probably no much time for it

Part III

- Dark Matter: evidence, model building, physics of wimps
  (freese-out, direct detection, indirect (cosmic ray) detection, LHC signatures)
- The matter-antimatter asymmetry: evidence, models (GUT baryogenesis, leptogenesis, EW baryogenesis)
- Linking the two: asymmetric dark matter
So far, everything amazingly consistent with the Standard Model

\[ \int L \, dt = 0.035 - 1.04 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

- Theory
- Data 2010 (~35 pb$^{-1}$)
- Data 2011

\[ \sigma_{\text{total}} \] [pb]
Exploration of the TeV scale territory definitely underway

**ATLAS Exotics Searches** - 95% CL Lower Limits (Status: Moriond EW 2012)

- ATLAS Preliminary

\[ \int L dt = (0.03 - 5.0) \text{ fb}^{-1} \]

\[ \sum \mathcal{S} = 7 \text{ TeV} \]

\[ \Lambda \text{ (constructive int.)} \]

- Large ED (ADD) : monojet
- Large ED (ADD) : diphoton
- UED : \( \gamma \gamma + E_{T,\text{miss}} \)
- RS with \( k/M_{\text{Pl}} = 0.1 \) : diphoton, \( m_{\gamma\gamma} \)
- RS with \( k/M_{\text{Pl}} = 0.1 \) : dilepton, \( m_{\ell \ell} \)
- RS with \( k/M_{\text{Pl}} = 0.1 \) : ZZ resonance, \( m_{\ell \ell}/m_{\gamma\gamma} \)
- Quantum black hole (QBH) : \( m_{\text{dijet}} F(x) \)
- ADD BH \( (M_{TH}/M_D=3) \) : multijet, \( \sum p_T, N_{\text{jets}} \)
- ADD BH \( (M_{TH}/M_D=3) \) : SS diquarks, \( N_{\text{ch. part.}} \)
- ADD BH \( (M_{TH}/M_D=3) \) : lepton + jets, \( \sum p_T \)

- \( q\bar{q} \) contact interaction : \( F_X(m_{\text{dijet}}) \)
- \( q\bar{q}l \) : ee, \( \mu\mu \) combined, \( m_{\text{eeqq}} \)
- u\bar{t}t \) : SS dilepton + jets + \( E_{T,\text{miss}} \)
- SSM \( Z \) : \( m_{eeqq} \)
- SSM \( W \) : \( m_{\text{eeqq}} \)

- LQ pairs (\( \beta=1 \)) : kin. vars. in eejj, e\( \nu \)jj

- LQ pairs (\( \beta=1 \)) : kin. vars. in mu\( \mu \)jj, \( \nu\nu \)jj

- **4th** generation : \( Q_4 \rightarrow Q_{\ell \ell} W_{\ell \ell} \)
- **4th** generation : \( \bar{Q}_4 \rightarrow \bar{Q}_{\ell \ell} W_{\ell \ell} \)
- **4th** generation : \( \bar{Q}_4 \rightarrow \bar{Q}_{\ell \ell} W_{\ell \ell} \)

- Excited quarks : \( \gamma \)-jet resonance, \( m_{\text{jet}} \)
- Excited quarks : dijet resonance, \( m_{\text{dijet}} \)
- Excited electron : \( e^-\gamma \) resonance, \( m_{\text{e\gamma}} \)
- Excited muon : \( \mu^-\gamma \) resonance, \( m_{\text{\mu\gamma}} \)

- Techni-hadrons : dilepton, \( m_{eeqq} \)
- Techni-hadrons : WZ resonance \( (\nu\nu ll), m_{\ell \ell} \)

- Major. neutr. (LRSM, no mixing) : 2-lep + jets
- LRSM (LRSM, no mixing) : 2-lep + jets
- \( H_{L/S} \) (DY prod., BR(+\( \rightarrow \mu \rightarrow \mu \)) : SS diquarks, \( m_{eeqq} \)

- Axigluons : dijet resonance, \( m_{\text{dijet}} \)
- Vector-like quark : CC, \( m_{\nu_{\text{CC}}} \)
- Vector-like quark : NC, \( m_{\nu_{\text{NC}}} \)

\[ 10^{-1} \]

\[ 1 \]

\[ 10 \]

\[ 10^2 \]

**Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena shown*
# Searches for SUSY at CMS

## 1 fb⁻¹ summary

**CMS Preliminary**

Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass Limit (fb⁻¹)</th>
<th>Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0$</td>
<td>$\alpha_g$, 1.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T1: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0$</td>
<td>$E_T + jets$, 1.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T1: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0$</td>
<td>MT2, 1.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T2: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0$</td>
<td>$\alpha_g$, 1.1</td>
<td>squark</td>
</tr>
<tr>
<td>T2: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0$</td>
<td>$E_T + jets$, 1.1</td>
<td>squark</td>
</tr>
<tr>
<td>T1bbbb: $\tilde{g} \rightarrow b \tilde{b} \tilde{\chi}^0$</td>
<td>$E_T + b$, 1.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T1bbbb: $\tilde{g} \rightarrow b \tilde{b} \tilde{\chi}^0$</td>
<td>MT2, 1.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T1lnu: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0$</td>
<td>$l^± l^±$, 0.98</td>
<td>gluino</td>
</tr>
<tr>
<td>T1Lh: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}^0</td>
<td>\tilde{\chi}^0$</td>
<td>$l^± l^±$, 0.98</td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_2^0$</td>
<td>$Z + E_T$, 0.98</td>
<td>gluino</td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_2^0$</td>
<td>JZB, 2.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow q \tilde{q} \tilde{\chi}_2^0$</td>
<td>$E_T + jets$, 1.1</td>
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<td>$\alpha_g$, 1.1</td>
<td>gluino</td>
</tr>
<tr>
<td>T1tttt: $\tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_1^0$</td>
<td>$l^± l^±$, 1.1</td>
<td>gluino</td>
</tr>
</tbody>
</table>

For limits on $m(\tilde{g}), m(\tilde{Q}), m(\tilde{\chi})$ (and vice versa), $\sigma_{\text{prod}} = \sigma_{\text{NLO+QCD}}$, $m(\tilde{\chi}^±), m(\tilde{\chi}_1^0) = m(\tilde{g}) + m(\tilde{\chi})$. $m(\tilde{\chi}^0)$ is varied from 0 GeV/\(c^2\) (dark blue) to $m(\tilde{g}) - 200$ GeV/\(c^2\) (light blue).
not yet any sign of new physics, despite extensive effort

- Many extensions of the SM have been developed over the past decades:
  - Supersymmetry
  - Extra-Dimensions
  - Technicolor(s)
  - Little Higgs
  - No Higgs
  - GUT
  - Hidden Valley
  - Leptoquarks
  - Compositeness
  - 4^{th} generation ($t', b'$)
  - LRSM, heavy neutrino
  - etc...

(for illustration only)
The Standard Model of Particle Physics

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

**Forces**

\[ \mathcal{L} = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\psi} \gamma^\mu D_\mu \psi + h.c. + N_i M_{ij} N_j + \left| D_\mu \phi \right|^2 - V(\phi) \]

\( \text{SU}(3)_c \times \text{SU}(2)_L \times U(1)_Y \)

**Matter**

**Background**

- (spontaneous) electroweak symmetry breaking sector
- flavour sector
- neutrino mass sector (if Majorana)

The Higgs is the only remaining unobserved piece and a portal to new physics hidden sectors

**Electroweak unification**

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

**HERA**

- electromagnetic
- weak force
- neutral current
- charged current

**EW unification**

\( \gamma \)
The (adhoc) Higgs Mechanism (a model without dynamics)

EW symmetry breaking is described by the condensation of a scalar field

$$V(\phi)/v^4$$

The Higgs selects a vacuum state by developing a non-zero background value. When it does so, it gives mass to SM particles it couples to.

$$V(h) = \frac{1}{2} \mu^2 h^2 + \frac{1}{4} \lambda h^4$$

Why is $$\mu^2$$ negative?

the puzzle:
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.
Electroweak symmetry breaking: 2 main questions

What is unitarizing the $W_L W_L$ scattering amplitude?

$$A \sim \frac{s}{v^2} - \frac{s}{v^2} \frac{s}{s - m_h^2} s \to \infty \frac{m_h^2}{v^2}$$

need for a UV moderator

the Higgs or something else?

What is cancelling the divergent diagrams?

$$\Rightarrow \delta M_H^2 \propto \Lambda^2$$

$i.e.$ what is keeping the Higgs light?

$
\Lambda$, the maximum mass scale that the theory describes

strong sensitivity on UV unknown physics

need new degrees of freedom & new symmetries to cancel the divergences

supersymmetry, gauge-Higgs unification, Higgs as a pseudo-goldstone boson...

→ theoretical need for new physics at the TeV scale
The naturalness scale of the Standard Model

Why is the Higgs boson light?
its mass parameter receives radiative corrections

\[ \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \]
\[ \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2 \]
\[ \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \]

\[ \delta m_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2} \left( 2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2 \right) \sim -(0.23\ \Lambda)^2 \]

(assuming the same \( \Lambda \) for all terms)

\( \Lambda = 5 \text{ TeV} \rightarrow \)
cancellation between tree level and radiative contributions
required by already 2 orders of magnitude
As today, still two paradigms for electroweak symmetry breaking:

- Weakly coupled New Physics (NP) at the TeV scale \(\rightarrow\) susy (elementary Higgs)

- Strongly coupled NP at the TeV scale \(\rightarrow\) composite higgs
Supersymmetry can solve the “big” hierarchy and naturalness is preserved up to very high scales if superparticle masses are at the weak scale.

\[
\Delta(m_{h_0}^2) = h^0 - t - h^0 - \tilde{t} - h^0 - \tilde{t}
\]

\[
\delta m_H^2 \sim -\frac{3}{8\pi^2} \frac{h_t^2}{m_t^2} \log \frac{\Lambda^2}{m_t^2}
\]
The Higgs sector consists of two SU(2)$_L$ doublets

\[ V = (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (bH_u^0 H_d^0 + c.c) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2 \]

The minimization of the higgs potential leads to:

\[ \frac{M_Z^2}{2} = -\mu^2 + \frac{m^2_{H_d} - m^2_{H_u} \tan^2 \beta}{\tan^2 \beta - 1} \]

with \( \tan \beta \equiv \langle H_u^0 \rangle / \langle H_d^0 \rangle \)

Terms in r.h.s much larger than \( M_Z^2 \)

Non trivial cancellation among them needed unless masses of SUSY particles are low. However:

The LEP bound on the Higgs mass, \( m_h \geq 115 \text{ GeV} \) forces the stop mass to be large.
\[ \Delta(m^2_{h_0}) = h^0 - t - - + h^0 - \tilde{t} - - + h^0 - \tilde{t} - - \]

\[ m^2_h \approx M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \left[ \log \frac{m^2_{\tilde{t}}}{m^2_t} + \frac{A_t^2}{m^2_t} \left( 1 - \frac{A_t^2}{12m^2_t} \right) \right] \]

**LEP limit** \( m_h \geq 115 \text{ GeV} \Rightarrow m_{\tilde{t}} \geq 1 \text{ TeV} \)

whereas the loop correction to the Higgs soft breaking mass is:

\[ \Delta m^2_{H_u} = -\frac{3y_t^2}{4\pi^2} m^2_{\tilde{t}} \log \frac{\Lambda}{m_{\tilde{t}}} \]

\[ \frac{M_Z^2}{2} = -\mu^2 + \frac{m^2_{H_d} - m^2_{H_u} \tan^2 \beta}{\tan^2 \beta - 1} \]

\[ \Rightarrow \text{tuning} \equiv \left| \frac{\Delta m^2_{H_u}}{M_Z^2} \right| \approx \frac{3y_t^2}{4\pi^2 M_Z^2} m^2_{\tilde{t}} \log \frac{\Lambda}{m_{\tilde{t}}} \approx 50 \quad \text{for} \quad m_{\tilde{t}} = 900 \text{ GeV} \]

\[ \Lambda = 100 \text{ TeV} \]

to make \( h \) heavy enough, increasing fine-tuning and superpartners increasingly harder to see
The naturalness problem of the MSSM

The problem with the MSSM: we did not see the Higgs at LEP

\( m_h > 114 \text{ GeV} \)

status of msugra pre-LHC

[Giudice & Rattazzi, ‘06]
Mass of 125 GeV puts severe constraints on minimal SUSY models

![Graph showing the maximal value of the Higgs mass as a function of tan β for various SUSY models.](image)

[Arbey et al, '1112.3028]
Addressing the hierarchy problem

\[ \delta m_h^2 |_{1 \text{-loop}} \sim -\frac{y_t^2}{8\pi^2} \Lambda_{UV}^2 \]

with a new symmetry

\[
\Psi \rightarrow e^{i\theta \gamma_5} \Psi
\]

\( \Psi \) massless:
protected by chiral symmetry

\[
\Psi \xrightarrow{\text{SUSY}} H
\]

\[
A_\mu \rightarrow A_\mu + \partial \theta
\]

\( A_\mu \) massless:
protected by gauge invariance

In 5 dimensions: \( H = A_5 \)

\[
H \rightarrow H + \theta
\]

H massless:
protected by a global symmetry

\textbf{SUSY}

fermion

\[
\Psi \rightarrow e^{i\theta \gamma_5} \Psi
\]

\( \Psi \) massless:
protected by chiral symmetry

\[
\Psi \xrightarrow{\text{SUSY}} H
\]

\textbf{Extra dimensions}

vector

\[
A_\mu \rightarrow A_\mu + \partial \theta
\]

\( A_\mu \) massless:
protected by gauge invariance

In 5 dimensions: \( H = A_5 \)

\textbf{new global symmetry}

scalar

\[
H \rightarrow H + \theta
\]

H massless:
protected by a global symmetry
Second paradigm:
postulate a new strongly interacting sector, responsible for EW symmetry breaking.

if replica of QCD at the TeV scale, Higgs = \langle Q'Q' \rangle condensate

no light scalar playing the role of the higgs: Higgsless
main objection: conflict with electroweak precision tests

-> a solution: a composite light higgs arising as a pseudo-goldstone boson
The strongly coupled “Higgs”: Composite Higgs

The Higgs is a bound state of the fundamental constituents.

hierarchy pb can be solved completely (no need of fundamental scalar)

corrections to $m_H$ are screened by $\Lambda = 1/l_H$

[Georgi & Kaplan, ‘80s]

Higgs unsensitive to UV effects above the composite scale. Thus composite scale cannot be higher than a few TeV.

The strongly coupled “Higgs” is characterized by one scale $m_{\rho} \sim \text{TeV}$ and one coupling $g_{\rho} \lesssim 4\pi$.

higgs naturally light if it is a Goldstone

$m_h \ll m_{\rho}$

$v \ll f \sim m_{\rho}/g_{\rho}$
New strong sector endowed with a global symmetry $G$ spontaneously broken to $H$ delivers a set of Nambu Goldstone bosons.

**QCD:**

$SU(2)_L \times SU(2)_R$

$SU(3)_c \to SU(2)_V$

$6 - 3 = 3$ PNGB $\pi^\pm, \pi^0$

**Composite Higgs:**

$SO(6) \times U(1)_x$

$SU(N_c) \to SO(5) \times U(1)_Y$

$16 - 11 = 5$ PNGB $H, S$

**Associated LHC tests:**

SO(5)/SO(4) $\to$ SM Higgs

SO(6)/SO(5) $\to$ SM + Singlet

SO(6)/SO(4) $\to$ 2 Higgs Doublet Model
Quantum numbers of the Goldstones fixed by the symmetry breaking pattern in the strong sector: \( G \rightarrow H \)

\[
\Psi \\
W_\mu^a, B_\mu \\
\begin{array}{c}
\text{strong} \\
\text{sector}
\end{array}
\begin{array}{c}
\text{custodial} \; \text{SO}(4) = \text{SU}(2) \times \text{SU}(2)
\end{array}
\]

\[
\mathcal{L}_{int} = A_\mu J_\mu + \bar{\Psi} O + h.c.
\]

\[\rightarrow \text{Agashe, Contino, Pomarol’05}\]

<table>
<thead>
<tr>
<th>( G )</th>
<th>( H )</th>
<th>( N_G )</th>
<th>NGBs rep, ([H] = \text{rep,}[\text{SU}(2) \times \text{SU}(2)])</th>
<th>[\text{Agashe, Contino, Pomarol’05}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(5)</td>
<td>SO(4)</td>
<td>4</td>
<td>4 = (2, 2)</td>
<td></td>
</tr>
<tr>
<td>SO(6)</td>
<td>SO(5)</td>
<td>5</td>
<td>5 = (1, 1) + (2, 2)</td>
<td></td>
</tr>
<tr>
<td>SO(6)</td>
<td>SO(4) \times SO(2)</td>
<td>8</td>
<td>(4_+2 + 4_-2 = 2 \times (2, 2))</td>
<td></td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(6)</td>
<td>6</td>
<td>(6 = 2 \times (1, 1) + (2, 2))</td>
<td></td>
</tr>
<tr>
<td>SO(7)</td>
<td>G_2</td>
<td>7</td>
<td>(7 = (1, 3) + (2, 2))</td>
<td></td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(5) \times SO(2)</td>
<td>10</td>
<td>(10_0 = (3, 1) + (1, 3) + (2, 2))</td>
<td></td>
</tr>
<tr>
<td>SO(7)</td>
<td>[SO(3)]^3</td>
<td>12</td>
<td>(2, 2, 3) = 3 \times (2, 2)</td>
<td></td>
</tr>
<tr>
<td>Sp(6)</td>
<td>Sp(4) \times \text{SU}(2)</td>
<td>8</td>
<td>(4, 2) = 2 \times (2, 2), (2, 2) + 2 \times (2, 1)</td>
<td></td>
</tr>
<tr>
<td>SU(5)</td>
<td>SU(4) \times U(1)</td>
<td>8</td>
<td>(4_-5 + 4_+5 = 2 \times (2, 2))</td>
<td></td>
</tr>
<tr>
<td>SU(5)</td>
<td>SO(5)</td>
<td>14</td>
<td>(14 = (3, 3) + (2, 2) + (1, 1))</td>
<td></td>
</tr>
</tbody>
</table>

\[[\text{Mrazek et al, 1105.5403}]\]
The Higgs couplings are modified

\[ \mathcal{L}_{\text{WSB}} = \frac{v^2}{4} \text{Tr} \left[ D_\mu \Sigma^* D^\mu \Sigma \right] \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - y_f \bar{f} \Sigma f_R \left( 1 + c \frac{h}{v} \right) \]

Unknown parameters \( a, b, c \).

<table>
<thead>
<tr>
<th>Model</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MCHM4</td>
<td>( \sqrt{1-\xi} )</td>
<td>1-2( \xi )</td>
<td>( \sqrt{1-\xi} )</td>
</tr>
<tr>
<td>MCHM5</td>
<td>( \sqrt{1-\xi} )</td>
<td>1-2( \xi )</td>
<td>( \frac{1-2\xi}{\sqrt{1-\xi}} )</td>
</tr>
</tbody>
</table>

Changes in branching ratios

\[ \xi \equiv \frac{\lambda^2}{f^2} \]

\( \xi = 0 \rightarrow \text{SM} \)

\( \xi = 1 \rightarrow \text{Technicolor limit} \)

EW precision tests prefer small \( \xi \)

Espinosa et al., 1003.3251

\( m_h = 120 \text{ GeV} \)
Limits from Higgs searches on the composite Higgs for the two minimal composite higgs models

\[ \xi = (v/f)^2 \text{, measures the amount of compositeness of the Higgs boson} \]

\[ \rightarrow 0 \text{ in the SM elementary Higgs limit} \]
General structure -> Partial compositeness

**SM sector**

\[ L = \bar{q}_L \bar{\phi} q_L + \bar{t}_R \bar{\phi} t_R \]

**linear couplings**

(for more successful phenomenology)

\[ L_{int} = A_\mu J^\mu + \bar{\Psi} O + h.c. \]

**strong sector**

\[ G \rightarrow H \supset SO(4) \]

ex: \[ SO(5) \rightarrow SO(4) \]

\[ \phi^\pm, \phi^0, h \]

custodial \( SO(4) \equiv SU(2) \times SU(2) \)

to avoid large corrections to the \( T \) parameter

**L_{elementary}**

**L_{mix}**

**L_{composite}**

\[ \Delta_L \bar{q}_L (T, B) + \Delta_R \bar{t}_R \tilde{T} \]

\[ \text{Tr} \left\{ \bar{Q} (\bar{\phi} - M_{\phi}) \bar{Q} \right\} + \bar{\tilde{T}} (\bar{\phi} - M_{\phi}) \tilde{T} \]

\[ + Y \text{Tr} \left\{ \bar{\bar{Q}} \bar{H} \right\} \tilde{T} + h.c \]
Extra-Dimensional point of view: Warped Geometry

Space-time is a slice of AdS$_5$

An almost CFT that becomes strongly interacting at the TeV scale & spontaneously breaks the conformal invariance

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$

$\text{TeV} \sim e^{-\pi kr} M_{Planck}$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)
Dual description in terms of higher-dimensional theories

- **strong sector**
- **resonances of the strong sector (heavy top partners)**
- **warped extra dimension**
- **Kaluza-Klein excitations**

→ UV completion
→ flavor addressed
Randall–Sundrum construction

An elegant understandable solution to both the EW/Planck hierarchy and the fermion mass hierarchy

Exponential hierarchies in masses and interactions from wave function overlaps

works qualitatively but not completely natural
(little hierarchy pb, like for any other solution to the hierarchy pb)
Like in QCD, spectrum of resonances (Kaluza-Klein states)

- Graviton resonances
- Gauge resonances
- Top fermionic resonances

- $m_h$ = 246 GeV
- $m_\rho$ = few TeV
- $4\pi f$ = 10 TeV
- $g_\rho f$
General structure -> Partial compositeness

\[ \mathcal{L}_{\text{elementary}} = \overline{q}_L \, \phi \, q_L + \overline{t}_R \, \phi \, t_R + \Delta_L \overline{q}_L \, (T, B) + \Delta_R \overline{t}_R \tilde{T} + \text{Tr} \left\{ \mathcal{Q} \left( \phi - M_2 \right) \mathcal{Q} \right\} + \tilde{T} \left( \phi - M_2 \right) \tilde{T} + Y \ast \text{Tr} \{ \overline{Q} \, \mathcal{H} \} \tilde{T} + h.c \]
Light custodial partners of the top quark

\[ 5 = (2, 2) \oplus (1, 1) \quad 2 \text{SU}(2)_L \text{ doublets} + 1 \text{ singlet} \]

**Custodial invariance of the strong sector implies larger multiplets of SU(2)_L \times SU(2)_R \times U(1)_X**

- Heavy partners of \((t_L, b_L)\) will form a \((2,2)_{2/3}\) [under \(\text{SU}(2)_L \times \text{SU}(2)_R \times U(1)_X\)]

**Composite (EW symm. break.) sector:**

- \((Q, Q') = (2, 2)_{2/3}\)
  \[ Q = \begin{bmatrix} T \\ B \end{bmatrix} \]
  electric charge \(+5/3\)
  \[ Q' = \begin{bmatrix} T_{5/3} \\ T_{2/3} \end{bmatrix} \]

- \((1, 1)_{2/3} = \tilde{T}\)

- \(H = (2, 2)_0 = \begin{bmatrix} \phi^0 & \phi^+ \\ -\phi^- & \phi^0 \end{bmatrix} \)

**SM sector:**

\[ M_{Q'} = M_2 = M_Q \cos \varphi_{qL} \]

\[ M_{Q'} \to 0 \quad \text{for} \quad \sin \varphi_{qL} \to 1 \]

**Custodians become very light if SM top is largely composite**

\[ Y* \text{Tr}\{\bar{Q}H\} \tilde{T} + h.c \]
\[ Q = (2, 2)_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix}, \quad \tilde{T} = (1, 1)_{2/3}, \quad H = (2, 2)_0 = \begin{bmatrix} \phi^+_0 & \phi^- \\ -\phi^- & \phi^+_0 \end{bmatrix} \]

We start with the lagrangian:

\[ \mathcal{L} = \bar{q}_L \not\partial q_L + \bar{t}_R \not\partial t_R + \text{Tr} \left\{ \bar{Q} (\not\partial - M_Q) Q \right\} + \bar{T} (\not\partial - M_{\tilde{T}}) \tilde{T} + Y_* \text{Tr} \{ \bar{Q} H \} \tilde{T} + h.c \]

\[ + \Delta_L \bar{q}_L (T, B) + \Delta_R \bar{t}_R \tilde{T} + h.c. \]

Mass terms before EW symm. breaking:

\[ -\text{Tr} \{ \bar{Q} M_Q Q \} - \bar{T} M_{\tilde{T}} \tilde{T} = -M_Q \left[ \bar{T} T + \bar{B} B + T_{5/3} T_{5/3} + T_{2/3} T_{2/3} \right] - M_{\tilde{T}} \tilde{T} \tilde{T} \]

\[ \text{do not mix with elementary fermions so we omit them for the moment} \]

Yukawa lagrangian

\[ \mathcal{L}_{yuk} = Y_* \text{Tr} \{ \bar{Q} H \} \tilde{T} = Y_* \text{Tr} \left( \begin{bmatrix} \bar{T} & \bar{B} \\ T_{5/3} & T_{2/3} \end{bmatrix} \begin{bmatrix} \phi^*_0 & \phi^+ \\ -\phi^- & \phi^+_0 \end{bmatrix} \right) \tilde{T} \]

\[ = Y_* \left( \bar{T} \phi^*_0 - \bar{B} \phi^- + T_{5/3} \phi^+ + T_{2/3} \phi_0 \right) \tilde{T} \]
Mixing terms between the $Q_e=2/3$ states

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} T_R \bar{T}_R \end{pmatrix} \begin{bmatrix} -M_Q & Y*\phi_0 & \Delta_L \\ 0 & -M_\tilde{T} & 0 \\ 0 & \Delta_R & 0 \end{bmatrix} \begin{pmatrix} T_L \\ \bar{T}_L \\ t_L \end{pmatrix}$$

Diagonalization before EW symm. breaking

$$M^+M = \begin{bmatrix} -M_Q^2 & 0 & -\Delta_L M_Q \\ 0 & -\Delta_R^2 + M_\tilde{T}^2 & 0 \\ -\Delta_L M_Q & 0 & \Delta_L^2 \end{bmatrix}$$

$$MM^+ = \begin{bmatrix} \Delta_L^2 + M_Q^2 & 0 & 0 \\ 0 & M_\tilde{T}^2 & -\Delta_R M_\tilde{T} \\ 0 & -\Delta_R M_\tilde{T} & \Delta_R^2 \end{bmatrix}$$

Mass eigen states in terms of $\tan \varphi_L = \frac{\Delta_L}{M_Q}$, $\tan \varphi_R = \frac{\Delta_R}{M_\tilde{T}}$

- massless mode identified with SM top
- heavier top partners

$$M = 0$$

$$\hat{t}_L = \cos \varphi_L t_L + \sin \varphi_L T_L$$

$$\hat{t}_R = \cos \varphi_R t_R + \sin \varphi_R \tilde{T}_R$$

The SM top is an admixture of elementary and composite states

$$M_1^2 = \frac{\Delta_L^2 + M_Q^2}{M_Q \cos \varphi_L}$$

$$M_2^2 = \frac{\Delta_R^2 + M_\tilde{T}^2}{M_\tilde{T} \cos \varphi_R}$$

$$\hat{T}_L = -\sin \varphi_L t_L + \cos \varphi_L T_L$$

$$\hat{T}_R = T_R$$

$$\tilde{T}_L = \tilde{T}_L$$

$$\tilde{T}_R = -\sin \varphi_R t_R + \cos \varphi_R \tilde{T}_R$$
Elementary SM fermions mix with fermionic resonances of the strong sector

"Partial compositeness"

After diagonalizing through a composite/elementary rotation:

$$|SM\rangle = \cos \varphi |elem\rangle + \sin \varphi |comp\rangle$$

SM Yukawa given by the composite components:

$$y_t = Y_* \sin \varphi_{qL} \sin \varphi_{tR}$$

the larger the mixing, the larger the mass

Yukawa hierarchy comes from the hierarchy of compositeness

Third family most sensitive to strong dynamics

Essentially only the top talks to the new strong sector
Re-write the Yukawa lagrangian in this new basis:

\[ \mathcal{L}_{\text{yuk}} = Y_* \sin \varphi_L \sin \varphi_R \left( \bar{t}_L \phi_0^\dagger t_R - \bar{b}_L \phi^{-} t_R \right) + Y_* \cos \varphi_L \sin \varphi_R \left( \bar{T}_0^\dagger t_R - \bar{B} \phi^{-} t_R \right) + Y_* \sin \varphi_L \cos \varphi_R \left( \bar{t}_L \phi_0^\dagger \bar{T}_L - \bar{b}_L \phi^{-} \bar{T}_L \right) + Y_* \cos \varphi_L \cos \varphi_R \left( \bar{T}_L \phi_0^\dagger \bar{T}_L - \bar{B}_L \phi^{-} \bar{T}_L \right) + Y_* \cos \varphi_L \left( \bar{T}_5/3 \phi_0^+ t_R + \bar{T}_2/3 \phi_0 t_R \right) + Y_* \left( \bar{T}_5/3 \phi_0^+ \bar{T}_L + \bar{T}_2/3 \phi_0 \bar{T}_L \right) + \ldots \]

We can therefore deduce the couplings of the top partners

(when neglecting EW symmetry breaking effects)
These new fermions couple strongly to the 3rd generation SM quarks plus one $W_L$, $Z_L$ or $h$

\[
\tan \varphi_L = \frac{\Delta_L}{M_Q} \quad \text{and} \quad \tan \varphi_R = \frac{\Delta_R}{M_{\tilde{T}}}
\]

\[Y_* \text{Tr}\{\tilde{Q}\mathcal{H}\} \tilde{T} + h.c\]

after rotating to mass eigen state basis

FCNC : absent for a 4th generation!

\[Y_* \cos \varphi_L \sin \varphi_R\]

\[Y_* \sin \varphi_L \cos \varphi_R\]

\[Y_* \sin \varphi_R\]

\[Y_* \cos \varphi_L \sin \varphi_R\]

\[Y_* \sin \varphi_R\]

Single production and decays proceed via these couplings

Pair production proceeds via the usual QCD coupling
And we also have:

\[ \mathcal{L}_{\text{mass}} = \frac{-M_Q}{\cos \varphi_L} (\bar{T}T + \bar{B}B) - \frac{M_T}{\cos \varphi_R} \bar{T}T - M_Q T_{5/3} T_{5/3} - M_Q T_{2/3} T_{2/3} \]

\[ \rightarrow \text{B is heavier than } T_{5/3} \]

After EW symmetry breaking the charged 2/3 states mix in the \((T_{2/3}, \tilde{T}, T, t)_{L,R}\) basis

\[ r = Y_* \frac{v}{\sqrt{2}} \]

\[ M_{+2/3} = \begin{pmatrix}
M_{(2,2)} & c_R r & 0 & s_R r \\
r & \frac{M_{(1,1)}}{c_R} & r & 0 \\
0 & c_L c_R r & \frac{M_{(2,2)}}{c_L} & c_L s_R r \\
0 & s_L c_R r & 0 & s_L s_R r
\end{pmatrix} \]

When considering light top partners, one should not neglect EW symmetry breaking effect. The correct mass spectrum and couplings are derived after diagonalizing the above full 4*4 matrix.
Examples of mass spectra for different sets of parameters ($Y^*$, $\sin \varphi_L$, $\sin \varphi_R$)

$M$ in GeV

$T_{2/3}$  $T_{5/3}$  $B$

$M$ in GeV

$1.0$  $1.5$  $2.0$  $2.5$  $3.0$

$200$  $400$  $600$  $800$  $1000$  $1200$  $1400$  $1600$
Naturalness implies light top partners

Higgs potential radiatively generated by resonance loops

\[
m_h^2 \sim \frac{3\lambda_t^2}{4\pi^2} \int_0^{M_T^2} dp^2
\]

\[
m_H^2 \sim \frac{3y_t^2}{8\pi^2} m_T^2
\]

\[
M_T \sim 450 \text{ GeV} \times \frac{m_h}{125 \text{ GeV}} \times \frac{1}{\sqrt{\epsilon_{tune}}}
\]
Light Higgs wants light top partners

[Contino, Da Rold, Pomarol’06]

Recently, many more studies on the top partners
Light Higgs wants light top partners

\[ f = 500 \text{ GeV} \]

- large mixing
- lightest fermion: doublet

\[ f = 800 \text{ GeV} \]
- partners above experimental bound

[Dé Curtis, Redi, Tesi 1110.1613]
The Higgs mass scales linearly with the mass of the lightest partner

\[ m_H \in [115, 130] \]

The relevant partners are those which are most strongly mixed with the elementary \( t_L \) and \( t_R \), namely \( T \) and \( \tilde{T} \)
The minimal case. The points which pass the EWPT have with See section 5 for a more complete description of this model. In this case, the LFR is the singlet, phenomenology, but it is fair to say that a model with light axial resonances and negative mass the region in parameter space where the lighter axial resonances has sub-TeV masses. This is can see that after having solved the two Weinberg sum rules in terms of the two axial decay constants. We particular, the vector resonance is always light:

\[ N_{\rho} = 2, \, N_a = N_Q = N_S = 1 - \xi = 0.1 \]

\[ N_{\rho} = 1, \, N_a = 2, \, N_Q = N_S = 1 - \xi = 0.1 \]

[Marzocca, Serone, Shu 1205.0770 ]
Figure 1: Masses of the two lightest fermion resonances for $m_h = 125$ GeV (taking $\llcorner = 0$ and $m_t = 160$ GeV (the running top mass at $\llcorner = 1$ TeV)). In blue we plot the MCHM$_5$ result; the solid line corresponds to Eq. (25) calculated in the approximation $\varepsilon^2 \ll 1$, while the dashed line is the exact result (always $F^2 = 0$). In solid red we plot the result for the MCHM$_{10}$ ($\varepsilon^2 \ll 1$ and $F^2 = 0$) with $m_{Q_1} = m_{Q_6}$. The black solid line is for $r_L = 5$ and $r_R = 1$ (denoted MCHM$_{5+1}$), fixing for illustration $F_L^{Q_4} = \sqrt{2} F_R^{Q_4}$. 

At least one top partner with a mass below a TeV

[Ref. Pomarol and Riva, 1205.6434]
Upper bound for the mass of the lightest fermionic resonance

\[ m_h^2 \sim \frac{N_c}{2\pi^2} m_t^2 \frac{m^2}{v^2} m_Q^2 \]

\[ m_h^2 \gtrsim \frac{N_c m_t^2}{4\pi^2 f^2} m_Q^2 \]

\[ m_h^2 \sim n(1 + n) \frac{N_c m_t^2}{2\pi^2 f^2} \frac{v^2}{f^2} m_Q^2 \]

[Pomarol and Riva, 1205.6434]
Look for $\bar{B}B$ and $T_{5/3} \bar{T}_{5/3}$ in same-sign dilepton final states.

$t\bar{t}$ WW final state

For the $T_{5/3}$ case one can reconstruct the resonant ($tW$) invariant mass.

Single production also relevant.

Expected reach at 14 TeV: $M \sim 1.5$ TeV

for study at 7 TeV see [Dissertori, Furlan, Moortgat, Nef ‘09]
Present constraints:
\(~ 550-600 \text{ GeV on the mass of } b' \text{ and } t' ~\)

\[
B \bar{B} \rightarrow WtW\bar{t} \rightarrow l^\pm l^\pm b \ 3j \ E_T \rightarrow lll \ b \ 1j \ E_T \]
\(m_B > 495 \text{ GeV}\)

\text{update at } L=4.6 \text{ fb}^{-1} \quad m_{b'} \gtrsim 611 \text{ GeV}

\text{[CMS L=1.1 fb}^{-1}] \quad t'b \rightarrow bWb \ ; \ b't \rightarrow t_{bW}WbW \ ; \ t't' \rightarrow bWbW \ ; \ b'b' \rightarrow t_{bW}Wt_{bW} \ ;
\text{ } m_{t'}=m_{b'} > 490 \text{GeV}

\text{[CMS L=4.7 fb}^{-1}] \quad \text{at least 1 lepton and 4 jets: } \quad M_{t'} \gtrsim 560 \text{ GeV}

\text{[CMS L=4.7 fb}^{-1}] \quad \text{dilepton: } \quad M_{t'} \gtrsim 552 \text{ GeV}

\text{[CMS L=1.1 fb}^{-1}] \quad \text{T->tZ: 3 leptons} \quad M_T \gtrsim 475 \text{ GeV}

\text{[ATLAS L=1.1 fb}^{-1}] \quad \text{arXiv:1202.6540} \quad 1 \text{ lepton:} \quad M_{b'} \gtrsim 480 \text{ GeV}
\quad \text{arXiv:1202.5520} \quad \text{same-sign dilepton + 2 jets} \quad M_{b'} \gtrsim 450 \text{ GeV}
\quad \text{arXiv:1202.3389} \quad \text{dilepton + 2 jets} \quad M_{t'} \gtrsim 350 \text{ GeV}
\quad \text{arXiv:1202.3076} \quad 1 \text{ lepton:} \quad M_{t'} \gtrsim 404 \text{ GeV}
\quad \text{arXiv:1204.1265} \quad b' \rightarrow bZ \quad M_{b'} \gtrsim 400 \text{ GeV}
Note:
Presented limits assume 100% BR \( t' \rightarrow Wb \) and 100% BR \( b' \rightarrow W^+ \)

Presented limits on \( b' \) apply to vector-like doublets, where \( B \rightarrow tW \) @ 100%, but not to singlets, which also decay into \( bZ \) and \( bH \).

Presented limits on \( t' \) apply to charge \(-4/3\) quarks in a doublet, but not to \( T \) singlets which also decay into \( tZ \) and \( tH \).

Present limits on \( \tilde{T} \) still quite weak ~ 370 GeV.

Conclusions:
Searches for \( t' \), \( b' \): crucial to test composite higgs models, although experimental papers motivate these searches in terms of 4th generation searches... not for long...
Constraint on 4th generation from Higgs searches

CMS PAS HIG-12-008  \( m_{b'} = m_{t'} = m_{W'} = 600 \text{ GeV}, \)

\[ m_{t'} = m_{b'} + \left[ 1 + \frac{1}{5} \ln \left( \frac{M_H}{115 \text{ GeV}} \right) \right] 50 \text{ GeV} \]

Higgs boson mass, GeV

\[ \frac{\sigma_{SM4}(gg\to H)}{\sigma_{SM3}(gg\to H)} \]

\[ \text{BR(SM4)/BR(SM)} \]

\( \text{gg} \to H \) enhanced by factor 4 to 9

decays in gluons and bb largely enhanced
\( \to \) supression of \( H \to 2 \) photons and partially also \( H \to WW \) and ZZ

The SM4 Higgs boson is excluded in the mass range 120-600 GeV at 95% CL and in the range 125-600 GeV at 99% CL
Prospects for $T \rightarrow tH$ & $B \rightarrow bH$ with $H \rightarrow b\bar{b}$

\[ T \bar{T} \rightarrow H t W^- \bar{b} \rightarrow HW^+ b W^- \bar{b} \]
\[ T \bar{T} \rightarrow H t V \bar{t} \rightarrow HW^+ b V W^- \bar{b} \]
\[ B \bar{B} \rightarrow H b W^+ \bar{t} \rightarrow H b W^+ W^- \bar{b} \]

\[ h^\pm + 4b \text{ final state} \]

\[ T \bar{T} \rightarrow H t H \bar{t} \rightarrow HW^+ b HW^- \bar{b} \]

\[ h^\pm + 6b \text{ final state} \]

\[ H \rightarrow b\bar{b}, WW \rightarrow \ell\nu q\bar{q}', \quad H \rightarrow b\bar{b}, WW \rightarrow \ell\nu q\bar{q}', V \rightarrow q\bar{q}/\nu\bar{\nu} \]
Prospects for T→tH

[Azatov et al, 1204.0455]

\[ thbW/thtZ/thth, \; h \rightarrow \gamma\gamma \]
Single production may start to play an important role for $M>\sim 600$ GeV

- CMS limit on $B\to tW$
- $\lambda = \frac{M_X}{M_W} \frac{g}{\sqrt{2}} \sin \theta$
- $\sqrt{s}=7\text{TeV}$

[Image of Feynman diagram showing $q\to W^+_L/W^-_L$ and $\lambda\to t\to T_{5/3}/B$]
Prospects for B→bH

\[ pp \rightarrow (\tilde{B} \rightarrow (h \rightarrow bb)b)t + X \]

\[ pp \rightarrow l^\pm + n \text{jets} + \not{E}_T, \quad n \geq 4, \quad \text{At least 2 b-tag} \]
Associated production (via a heavy gluon)

\[ q\bar{q} \rightarrow G^* \rightarrow \tilde{T}\tilde{t} + \tilde{B}\tilde{b} \]

- same final state as \( t\bar{t} \)

Mass reach depends on:

- the ratio \( M_{G^*} / M_{\tilde{T}, B} \)
- on coupling between \( G^* \) and the light fermions,
- on the top degree of compositesness

\( \rightarrow \text{model-dependence} \)

\[ m_{tot} \equiv m(W_t b_t W_{\not{b}} b_{\not{b}}) \]

[Contino et al ]
\[ q\bar{q} \rightarrow G^* \rightarrow \tilde{T}\tilde{t} + \tilde{B}\bar{b} \]

- same final state as \( t\bar{t} \)

Mass reach depends on:
- the ratio \( M_{G^*}/M_{\tilde{T},B} \)
- on coupling between \( G^* \) and the light fermions,
- on the top degree of compositeness
  \( \rightarrow \) model-dependence

Much better reach
([1 - 1.4 TeV])
in comparison with the previous
single+pair production process

if \( \frac{M_{G^*}}{M_{\tilde{T},B}} \sim 1.5 \)
$M_{G^*}/m_{\tilde{T}} = 1.5$ and $Y_* = 3$

almost 3 TeV reach for top partner!
New composite Higgs production mechanism from the single production and decay of a heavy top partner

\[ pp \to G \to T\bar{t} + \bar{T}t \to Ht\bar{t} \to 4b + 2j + l + \not{E}_T. \]

\[ \begin{align*}
\sigma(pp \to G \to Ht\bar{t}) &\approx 0.001 \quad \text{for } 7 \text{ TeV} \\
&\approx 0.0213 \quad \text{for } 8 \text{ TeV} \\
&\approx 0.142 \quad \text{for } 14 \text{ TeV}
\end{align*} \]

[Carmona et al, 1205.2378]
Other signature: Gluonic resonance

\[ pp \rightarrow G^* \rightarrow t\bar{t} \]

decay mainly into tops which have sizable coupling to the strong sector

![Graph showing mass distribution](image)

Possible up to 4 TeV

\[ \frac{d\sigma}{dm_{t\bar{t}}} (pp \rightarrow t\bar{t} \rightarrow b\bar{b}l\nu jj) \]

\[ \int Ldt = 100 \text{ fb}^{-1} \]

Agashe et al
Summary

A (4D) alternative to SUSY for solving the UV sensitivity of the Higgs sector

SUSY solution

Higgs as PGB solution

The Higgs is the Goldstone Boson of a spontaneously broken global symmetry

Experimental signatures:
- Modified couplings in the Higgs sector
- Resonances in the strong sector
  - light higgs accompanied by light fermionic resonances
  - already non-trivial exclusion

may be subtle and may take a while to test

under testing
So far ATLAS and CMS papers related to searches for heavy $b', t'$ ... remained mainly motivated by fourth generation

However, the search for heavy top partners is strongly motivated by models of Higgs compositeness

The presence of light top partners constitutes the most visible manifestation of the composite Higgs scenario