Beyond SM physics
(Introductory talk)

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Rencontres de Moriond - QCD & High Energy Interactions
La Thuile - March 28th 2017
Building on strong basis

W, Z
QCD
QCD:
soft, hard, PDFs, heavy ions

@ LHC:
precision perturbative calculations, non-perturbative, lattice, EFTs

EW tests

Higgs
(heavy) flavour, top
CKM, CP

Tests of the Standard Model and Beyond
BSM motivations @ LHC

- The detailed study of the Higgs sector can tell us a lot on BSM
- Some measurements show a tension with the SM (e.g. flavour)
- Naive tuning suggests particles @ TeV scale (but loopholes ...)
- Dark matter particles (simple add-on or something more?)
- Flavour puzzles in the quark and lepton sectors
- EFT approach vs models
- Important focus on details/hypotheses & combination of results
Natural or not? Scalar mass operator (dim 2 in 4D) is relevant

\[ m^2 = m_0^2 \left( 1 + a(\lambda, g) \log \frac{\Lambda^2}{m_0^2} \right) + b(\lambda, g) \Lambda^2 \]

- natural if \( b(\lambda, g) = 0 \) by a symmetry (ex. unbroken SUSY)
- can be natural if \( \Lambda \) is a physical cut-off (ex. compositeness)
- quasi-natural if \( b(\lambda, g) = 0 \) in pert. theory (ex. little-Higgs)
- tuned: any special value (ex. SM)

Another option: no \( d < 4 \) scalar operators (marginality)

ex. Technicolor (but you do not have the accidental symmetries of the SM: B, L, Flavour)
Naive tuning: max variation of observables w.r.t. input parameters

\[ \Delta m_h^2 = -\frac{y_t^2}{16\pi^2} \left( 2 \Lambda^2 + 6 m_t^2 \log \left( \frac{\Lambda}{m_t} \right) \right) \]

a) Renormalizable theory example (m.s.y.):

\[ \frac{\Lambda_3}{16\pi^2} \left( \Lambda^2 - 2 m_s^2 \log \left( \frac{\Lambda}{m_s} \right) + \ldots \right) \]

b) Effective model example (with a fermion, as in composite higgs):

A cut-off, but here physical meaning
Top and BSM

SM perspective: \( m_t \sim v_{\text{SM}} \sim m_Z \) "natural"
why the other quarks are so light?

Composite models: \( \times \rightarrow \frac{1}{\Lambda^2} \bar{Q}_L Q_R \langle QQ \rangle \)

\[ \sim \frac{\Lambda_{\text{HC}}}{\Lambda^2} \bar{Q}_L Q_R \quad \text{with} \quad \Lambda_{\text{HC}} \ll \Lambda, \text{why top is heavy?} \]

Partially composite top: \( y_L t_L O_L + y_R t_R O_R \)

formally bilinears but \( \frac{1}{\Lambda^2} t Q Q \mathcal{O} \rightarrow y_{L/R} \sim \left( \frac{\Lambda_{\text{HC}}}{\Lambda} \right)^{2-g} \)

if \( g \sim 2 \quad y_{L/R} \sim 1 \) even if \( \Lambda_{\text{HC}} \ll \Lambda \)
BSM and top phenomenology

- Single top: $Wtb$ coupling, $W' \rightarrow tb$, $b^* \rightarrow tW$, $T' \rightarrow tZ$
- New states decaying into top (VLQs, coloured scalars...)
- Top effective couplings (t-gauge couplings, t-higgs coupling)
- Monotop
- Multi top final states
BSM in flavour observables \[\rightarrow\] M. Neubert talk yesterday

LHC direct searches \sim\text{ few TeV range}

Flavour observables can partially explore a much higher range

Lepton flavour violations:

\( b \rightarrow s \mu \mu \, (\sim 4-5 \sigma) : Z', LQ, VLQ/scalars \)
\( R(D), R(D^*) \, (\sim 4 \sigma) : W', LQ \)

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FCNC in kaons: \( \epsilon'/\epsilon \, (\sim 2,85) \) improvement made possible by Lattice QCD and NNLO QCD calculations
Higgs and BSM  → see later today Marcella Carlena talk

- EFT can test effects in BSM which can be "integrated out"
- Larger scalar sectors are investigated in detail (not only EFT)
- The window for lighter Higgses is not closed!

From hep-ph/1607.08653

Type I - VBF/VH
Red points allowed
80 < m_h < 110 GeV
New constraints on $m_{H^\pm}$ in 2HDM

Belle data further increase the limits:

![Figure 4: 95% C.L. lower bounds on $M_{H^\pm}$ as functions of $\tan\beta$.](image)

Figure 4: 95% C.L. lower bounds on $M_{H^\pm}$ as functions of $\tan\beta$.

From hep-ph/1702.04571
Higgs and flavour

SM: \( y_{ij} \overline{\psi}_{Li} \ h \ \psi_{Rj} = \frac{y_{ij}}{\sqrt{2}} \overline{\psi}_{Li} \ \psi_{Rj} + \frac{y_{ij}}{\sqrt{2}} \ h \ \overline{\psi}_{Li} \ \psi_{Rj} \)

both terms diagonalized together \( \Rightarrow \) no FC currents

BSM can spoil that (ex. VLQ mixing or non-SM Yukawas)

\( y_{ij} \left(1 + c_{ij} \frac{\lambda h^2}{f_c^2}\right) \overline{\psi}_{Li} \ h \ \psi_{Rj} = \frac{y_{ij}}{\sqrt{2}} \left(1 + c_{ij} \frac{\lambda^2}{2 f_c^2}\right) \overline{\psi}_{Li} \ \psi_{Rj} + \frac{y_{ij}}{\sqrt{2}} \left(1 + 3 c_{ij} \frac{\lambda^2}{2 f_c^2}\right) \ h \ \overline{\psi}_{Li} \ \psi_{Rj} \quad \text{(Buras et al 2011)} \)

\( \Rightarrow \) check Flavour Violating couplings as \( h Z p, h t c \ldots \)
Elementary or Composite Higgs?

Probe the form factor:

\[ F(p) \]

- elementary
- composite

LHC reach

So not that easy, small deviations unless some new resonances are light (~TeV)

EFTs can handle both cases (e.g., linearized vs. non-linear Lagrangians)

Particle content, global & local symmetries are input assumptions
Composite: inspired by QCD & chiral Lagrangians

$m_\pi < m_e, m_\nu$ light as PGBs no naturalness pb

$h$ as a PGB (Gorzi, Kaplan, --)

the spectrum also include other
spin 0, spin 1, spin 1/2 composite states.

\[ G \rightarrow H \]

\[ SU(2) \times U(1) \rightarrow U(1)_{em} \]

\[ \begin{array}{c}
\text{a few TeV} \\
\text{125 GeV}
\end{array} \]

\[ \begin{array}{c}
\rightarrow e, \tau, \ldots \\
h
\end{array} \]
Which symmetries?

<table>
<thead>
<tr>
<th>$G$</th>
<th>$H$</th>
<th>$C$</th>
<th>$N_G$</th>
<th>$R_H = R_{SU(2) \times SU(2)} (R_{SU(2) \times U(1)})$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(5)</td>
<td>SO(4)</td>
<td>✓</td>
<td>4</td>
<td>$4 = (2, 2)$</td>
<td>11</td>
</tr>
<tr>
<td>SU(3) × U(1)</td>
<td>SU(2) × U(1)</td>
<td></td>
<td>5</td>
<td>$2_{±1/2} + 1_0$</td>
<td>10, 35</td>
</tr>
<tr>
<td>SU(4)</td>
<td>Sp(4)</td>
<td>✓</td>
<td>5</td>
<td>$5 = (1, 1) + (2, 2)$</td>
<td>29, 47, 64</td>
</tr>
<tr>
<td>SU(4)</td>
<td>[SU(2)]² × U(1)</td>
<td>✓*</td>
<td>8</td>
<td>$(2, 2)_{±2} = 2 \cdot (2, 2)$</td>
<td>65</td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(6)</td>
<td>✓</td>
<td>6</td>
<td>$6 = 2 \cdot (1, 1) + (2, 2)$</td>
<td>-</td>
</tr>
<tr>
<td>SO(7)</td>
<td>G₂</td>
<td>✓*</td>
<td>7</td>
<td>$7 = (1, 3) + (2, 2)$</td>
<td>66</td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(5) × U(1)</td>
<td>✓*</td>
<td>10</td>
<td>$10_0 = (3, 1) + (1, 3) + (2, 2)$</td>
<td>-</td>
</tr>
<tr>
<td>SO(7)</td>
<td>[SU(2)]³</td>
<td>✓*</td>
<td>12</td>
<td>$(2, 2, 3) = 3 \cdot (2, 2)$</td>
<td>-</td>
</tr>
<tr>
<td>Sp(6)</td>
<td>Sp(4) × SU(2)</td>
<td>✓</td>
<td>8</td>
<td>$(4, 2) = 2 \cdot (2, 2)$</td>
<td>65</td>
</tr>
<tr>
<td>SU(5)</td>
<td>SU(4) × U(1)</td>
<td>✓*</td>
<td>8</td>
<td>$4_{-5} + 4_{+5} = 2 \cdot (2, 2)$</td>
<td>67</td>
</tr>
<tr>
<td>SU(5)</td>
<td>SO(5)</td>
<td>✓*</td>
<td>14</td>
<td>$14 = (3, 3) + (2, 2) + (1, 1)$</td>
<td>9, 47, 49</td>
</tr>
<tr>
<td>SO(8)</td>
<td>SO(7)</td>
<td>✓</td>
<td>7</td>
<td>$7 = 3 \cdot (1, 1) + (2, 2)$</td>
<td>-</td>
</tr>
<tr>
<td>SO(9)</td>
<td>SO(8)</td>
<td>✓</td>
<td>8</td>
<td>$8 = 2 \cdot (2, 2)$</td>
<td>67</td>
</tr>
<tr>
<td>SO(9)</td>
<td>SO(5) × SO(4)</td>
<td>✓*</td>
<td>20</td>
<td>$(5, 4) = (2, 2) + (1 + 3, 1 + 3)$</td>
<td>34</td>
</tr>
<tr>
<td>[SU(3)]²</td>
<td>SU(3)</td>
<td></td>
<td>8</td>
<td>$8 = 1_0 + 2_{±1/2} + 3_0$</td>
<td>8</td>
</tr>
<tr>
<td>[SO(5)]²</td>
<td>SO(5)</td>
<td>✓*</td>
<td>10</td>
<td>$10 = (1, 3) + (3, 1) + (2, 2)$</td>
<td>32</td>
</tr>
<tr>
<td>SU(4) × U(1)</td>
<td>SU(3) × U(1)</td>
<td></td>
<td>7</td>
<td>$3_{-1/3} + 3_{+1/3} + 1_0 = 3 \cdot 1_0 + 2_{±1/2}$</td>
<td>35, 41</td>
</tr>
<tr>
<td>SU(6)</td>
<td>Sp(6)</td>
<td>✓*</td>
<td>14</td>
<td>$14 = 2 \cdot (2, 2) + (1, 3) + 3 \cdot (1, 1)$</td>
<td>30, 47</td>
</tr>
<tr>
<td>[SO(6)]²</td>
<td>SO(6)</td>
<td>✓*</td>
<td>15</td>
<td>$15 = (1, 1) + 2 \cdot (2, 2) + (3, 1) + (1, 3)$</td>
<td>36</td>
</tr>
</tbody>
</table>

**Table 1:** Symmetry breaking patterns $G \rightarrow H$ for Lie groups. The third column denotes whether the breaking pattern incorporates custodial symmetry. The fourth column gives the dimension $N_G$ of the coset, while the fifth contains the representations of the GB’s under $H$ and SO(4) $\cong SU(2)_L \times SU(2)_R$ (or simply $SU(2)_L \times U(1)_Y$ if there is no custodial symmetry). In case of more than two SU(2)’s in $H$ and several different possible decompositions we quote the one with largest number of bi-doublets.

Bellazzini et al 1401.2457
What underlying dynamics?

Consider a group $G$ with $N$ fermions in rep $R$

a) if $R$ real or pseudo-real,

$$\langle \psi_i^* \psi_i \rangle \begin{cases} \text{symmetric} & SU(N) \rightarrow SO(N) \\ \text{anti-sym} & SU(N) \rightarrow Sp(N) \end{cases}$$

b) if $R$ complex

$$\langle \bar{\psi}^i \psi_i \rangle \rightarrow SU(N) \times SU(N) \rightarrow SU(N)$$
Minimal models

- $SO(5) \rightarrow SO(4)$: custodial, minimal higgs content but no underlying fermionic theory
- $SU(4) \rightarrow Sp(4)$: custodial, minimal fermionic theory:
  \[ \langle 4^i 4^j \rangle = 6_{SU(4)} \rightarrow 5_{Sp(4)} + 1_{Sp(4)} \]

5 PCBs:
- $5_{Sp(4)} \rightarrow (2, 2) + (1, 1)$ of $SU(2) \times SU(2)
  \uparrow$ higgs doublet $\downarrow$ singlet $\eta$

1 massive:
- $1_{Sp(4)} \rightarrow (1, 1)$ singlet $\phi$
Vacuum structure

In $SU(4) \rightarrow Sp(4)$ breaking

$\langle 44 \rangle = \Sigma_{ch} = \begin{pmatrix} i \delta_2 & 0 \\ 0 & i \delta_2 \end{pmatrix} \rightarrow$ EW unbroken

$\langle 44 \rangle = \Sigma_{tc} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \rightarrow$ EW broken

generic vacuum alignment by an angle $\theta$: $\langle 44 \rangle = \cos \theta \Sigma_{ch} + \sin \theta \Sigma_{tc}$
$SU(4) \to Sp(4)$

Breaking pattern and spectrum from lattice:

- Vectors: $m_a \sim 16 \text{ TeV}$
- $m_e \sim 12 \text{ TeV}$

- Scalar: $m_\eta \sim 600 \text{ GeV}$

- Higgs: $m_h = 125 \text{ GeV}$ (not a prediction)

with $\sin \Theta = 0,2$
Vector-like fermions

- Top partners are an important in CH. They can also be obtained in dynamical realizations \((1311, 6562)\)

<table>
<thead>
<tr>
<th>spin</th>
<th>SU(4)×SU(6)</th>
<th>Sp(4)×SO(6)</th>
<th>names</th>
</tr>
</thead>
<tbody>
<tr>
<td>(QQ)</td>
<td>(6, 1)</td>
<td>(1, 1)</td>
<td>(\sigma)</td>
</tr>
<tr>
<td>(\chi \chi)</td>
<td>(1, 21)</td>
<td>(1, 1)</td>
<td>(\sigma_c)</td>
</tr>
<tr>
<td>(\chi QQ)</td>
<td>(6, 6)</td>
<td>(1, 6)</td>
<td>(\psi_1^{1})</td>
</tr>
<tr>
<td>(\chi QQ)</td>
<td>(6, 6)</td>
<td>(1, 6)</td>
<td>(\psi_2^{1})</td>
</tr>
<tr>
<td>(Q \bar{\chi} Q)</td>
<td>(1, (\bar{6}))</td>
<td>(1, 6)</td>
<td>(\psi_3)</td>
</tr>
<tr>
<td>(Q \bar{\chi} Q)</td>
<td>(15, (\bar{6}))</td>
<td>(5, 6)</td>
<td>(\psi_4^{5})</td>
</tr>
<tr>
<td>(Q \bar{\sigma} \mu Q)</td>
<td>(15, 1)</td>
<td>(5, 1)</td>
<td>(a)</td>
</tr>
<tr>
<td>(\bar{\chi} \bar{\sigma} \mu \chi)</td>
<td>(1, 35)</td>
<td>(1, 20)</td>
<td>(a_c)</td>
</tr>
</tbody>
</table>

\(\{\text{scalars}\}\)

\(\{\text{VLQs}\}\)

\(\{\text{vectors}\}\)
**Phenomenology**

Asking for a fundamental CH we get more than expected

- Coloured scalars: $2O_{SO(6)} = 8_0 + 6_{4/3} + 6_{-4/3}$
- Extra singlets
- VLQs, including bi-doublets used in CH eff. Lagrangians
- Vector and Axial-vector resonances

\[ \text{see} 1507.02283 \]
Mixing 1 VLQ doublet

\[ M_u = \begin{pmatrix} \tilde{m}_u & \tilde{m}_c & \tilde{m}_t \\ x_1 & x_2 & x_3 \end{pmatrix} = V_L \cdot \begin{pmatrix} m_u & m_c & m_t \\ & & M \end{pmatrix} \cdot V_R^\dagger \]

\[ V_L \implies M_u \cdot M_u^\dagger = \begin{pmatrix} \tilde{m}_u^2 & x_1^* \tilde{m}_u^2 \\ \tilde{m}_c^2 & x_2^* \tilde{m}_c^2 \\ \tilde{m}_t^2 & x_3^* \tilde{m}_t^2 \end{pmatrix} \begin{pmatrix} x_1^* \tilde{m}_u & x_1^* \tilde{m}_c & x_1^* \tilde{m}_t \\ x_2^* \tilde{m}_u & x_2^* \tilde{m}_c & x_2^* \tilde{m}_t \\ x_3^* \tilde{m}_u & x_3^* \tilde{m}_c & x_3^* \tilde{m}_t \end{pmatrix} \begin{pmatrix} x_1 \tilde{m}_u & x_2 \tilde{m}_c & x_3 \tilde{m}_t \\ x_1^2 + |x_2|^2 + x_3^2 + M^2 \end{pmatrix} \]

\[ m_q \propto \tilde{m}_q \]

mixing is suppressed by quark masses

\[ V_R \implies M_u^\dagger \cdot M_u = \begin{pmatrix} \tilde{m}_u^2 + |x_1|^2 & x_1^* x_2 & x_1^* x_3 & x_1^* M \\ x_2^* x_1 & \tilde{m}_c^2 + |x_2|^2 & x_2^* x_3 & x_2^* M \\ x_3^* x_1 & x_3^* x_2 & \tilde{m}_t^2 + x_3^2 & x_3^* M \\ x_1 M & x_2 M & x_3 M & M^2 \end{pmatrix} \]

mixing in the right sector present also for \( \tilde{m}_q \rightarrow 0 \)

flavour constraints for \( q_R \) are relevant
Mixing VLQs & SM in general

\[ \mathcal{L}_{\text{mass}} = \overline{q}_L \begin{pmatrix} \mu_1 & 0 & 0 & 0 & \ldots & 0 \\ 0 & \mu_2 & 0 & 0 & \ldots & 0 \\ 0 & 0 & \mu_3 & 0 & \ldots & 0 \\ y_{4,1} & y_{4,2} & y_{4,3} & M_4 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ y_{n_d+3,1} & y_{n_d+3,2} & y_{n_d+3,3} & 0 & 0 & M_{n_d+3} \\ 0 & 0 & 0 & 0 & \ldots & 0 \end{pmatrix} \begin{pmatrix} x_{1,n_d+4} & \ldots & x_{1,N} \\ x_{2,n_d+4} & \ldots & x_{2,N} \\ x_{3,n_d+4} & \ldots & x_{3,N} \\ \omega_{\alpha\beta} \\ \omega'_{\alpha\beta} \end{pmatrix} \cdot q_R + h.c. \]

\[ M_n = \begin{pmatrix} M_{n+4} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & M_N \end{pmatrix} \]

semi-integer isospin multiplets

integer isospin multiplets

ArXiv:1305.4172 M.Buchkremer et al.
VLQ phenomenology

• Not only top-partners (full multiplets)
• Mixing not only with 3rd generation (even a small coupling to light quarks can be important for production)
• Interplay of multiplets in evading bounds, or allowing some states to have an exclusive decay mode
• Flavour changing couplings
• Interplay with the Higgs boson (e.g. hh final states)
Conclusions

- BSM searches & model build on detailed knowledge of the SM
- EFT approach and detailed models are complementary
- Top and Higgs physics bring essential information
- Flavour extends the reach of direct searches and anomalies in flavour hint to new phenomena