Beyond the Standard Model: Charting Fundamental Interactions via Lattice Simulations

Claudio Pica

LATTICE 2016

CP³ Origins
Cosmology & Particle Physics
• Thanks to the LOC for the invitation to review how “Lattice Field Theory is impacting the quest for new physics”

• Thanks to all who sent details on their work
• Apologies to all I will not be able to address

- SUSY  Talks on Tue by: Kanata, Giedt, Schaich, August, Joseph, Giudice
- extradimensions  Talk on Thu by Alberti
- new mechanism for mass generation  Talk on Thu by Garofalo
- non-perturbative Higgs physics  Talks on Thu by Maas, Toerek
- Gauge/gravity duality  Talk on Mon by Bennett
- Asymptotic Safety  Talk on Mon by Buyukbese, Bond
The Standard Model

<table>
<thead>
<tr>
<th>1st generation</th>
<th>2nd generation</th>
<th>3rd generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>everyday matter</td>
<td>exotic matter</td>
<td>force particles</td>
</tr>
<tr>
<td>2.4M u</td>
<td>1.27G c</td>
<td>171.2G t</td>
</tr>
<tr>
<td>4.8M d</td>
<td>104M s</td>
<td>4.2G b</td>
</tr>
<tr>
<td>0.511M e</td>
<td>1.057M μ</td>
<td>1.777G τ</td>
</tr>
<tr>
<td>ν_e</td>
<td>ν_μ</td>
<td>ν_τ</td>
</tr>
<tr>
<td>W^+</td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gauge Fields</th>
<th>Fermions</th>
<th>Scalar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Claudio Pica

CP^3 Origins

Cosmology & Particle Physics
The SM Higgs?

- Spin 0?
- Is it a scalar (or pseudoscalar)?
- Coupling to other SM particles proportional to their mass?
  - origin of mass
- Quantum effects consistent with SM Higgs?
- It is Elementary or Composite?

ATLAS and CMS are providing precise measurements of the properties of the Higgs and strong constraints on Beyond SM physics
### ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2016

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\mathbf{f}[E_{T}^{miss}]$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSM</td>
<td>0-3 c, μ/1-2 τ</td>
<td>2-10 jets/3 b</td>
<td>Yes</td>
<td>20.3</td>
<td>1.03 TeV</td>
<td>1.85 TeV</td>
</tr>
<tr>
<td>GMSB (NLSP)</td>
<td>1-2 r + 1 f</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>3.2</td>
<td>1.03 TeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
</tr>
<tr>
<td>GGM</td>
<td>1 c, μ</td>
<td>0-6 jets</td>
<td>Yes</td>
<td>3.2</td>
<td>1.51 TeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0 mono-jet</td>
<td>Yes</td>
<td>20.3</td>
<td>865 GeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
</tbody>
</table>

### 3rd gen. quarks and med. inclusive searches

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\mathbf{f}[E_{T}^{miss}]$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{1}/b_{2}, b_{1}/b_{2}$ &amp; etc.</td>
<td>0 b</td>
<td>Yes</td>
<td>3.3</td>
<td>1.78 TeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
<tr>
<td>$b_{1}/b_{2}, b_{1}/b_{2}$ &amp; etc.</td>
<td>0 c</td>
<td>Yes</td>
<td>2.3</td>
<td>1.37 TeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
</tbody>
</table>

### EW direct

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\mathbf{f}[E_{T}^{miss}]$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{1}/b_{2}, b_{1}/b_{2}$</td>
<td>0 b</td>
<td>Yes</td>
<td>3.2</td>
<td>325-540 GeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
<tr>
<td>$b_{1}/b_{2}, b_{1}/b_{2}$</td>
<td>0 c</td>
<td>Yes</td>
<td>3.2</td>
<td>840 GeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
</tbody>
</table>

### Long-lived particles

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\mathbf{f}[E_{T}^{miss}]$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>1 jet</td>
<td>Yes</td>
<td>20.3</td>
<td>90-135 GeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
<tr>
<td>Stable, stopped</td>
<td>1-5 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>140-475 GeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
</tbody>
</table>

### RPV

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\mathbf{f}[E_{T}^{miss}]$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFV</td>
<td>0-2 c</td>
<td>Yes</td>
<td>20.3</td>
<td>510 GeV</td>
<td>$m(\tilde{g})=m(\tilde{t})$</td>
<td></td>
</tr>
</tbody>
</table>

* Only a selection of the available mass limits on new states or phenomena is shown.

The Standard Model Works
## ATLAS Exotics Searches* - 95% CL Exclusion

**Status:** March 2016

### ATLAS Preliminary

\[ \int L \, dt = (3.2 \cdot 20.3) \, fb^{-1} \]

\[ \sqrt{s} = 8, \, 13 \, \text{TeV} \]

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}} )</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD GQ + g/(q)</td>
<td>(\ell\ell)</td>
<td>(\geq 1)</td>
<td>Yes</td>
<td>3.2</td>
<td>6.58 TeV</td>
</tr>
<tr>
<td>ADD non-resonant (\ell\ell)</td>
<td>(e, \mu)</td>
<td>(\ell\ell)</td>
<td></td>
<td>3.2</td>
<td>4.7 TeV</td>
</tr>
<tr>
<td>ADD OBH (\ell\ell)</td>
<td>1</td>
<td>1</td>
<td>Yes</td>
<td>20.3</td>
<td>5.2 TeV</td>
</tr>
<tr>
<td>ADD OBH</td>
<td>(\ell\ell)</td>
<td>(\geq 2)</td>
<td>Yes</td>
<td>20.3</td>
<td>8.3 TeV</td>
</tr>
<tr>
<td>ADD BH high (S_{\text{PR}})</td>
<td>(\ell\ell)</td>
<td>(\geq 1)</td>
<td>Yes</td>
<td>3.2</td>
<td>8.2 TeV</td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>2</td>
<td>3</td>
<td>Yes</td>
<td>3.2</td>
<td>9.55 TeV</td>
</tr>
<tr>
<td>RS1 GQ, (\ell\ell)</td>
<td>2y</td>
<td>(\gamma)</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>Bulk RS GQ + WW \rightarrow WW</td>
<td>1</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Bulk RS GQ + WW \rightarrow WW</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>Bulk RS GQ + tt</td>
<td>1</td>
<td>4b</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Bulk RS GQ + tt</td>
<td>1</td>
<td>1</td>
<td>4b, 1j/2</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>2UED/RPP</td>
<td>1</td>
<td>1</td>
<td>2b, 4j</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>SSM Z' (\ell\ell)</td>
<td>2</td>
<td>2</td>
<td>Yes</td>
<td>3.2</td>
<td>2.02 TeV</td>
</tr>
<tr>
<td>SSM Z' (\tau\tau)</td>
<td>2</td>
<td>2</td>
<td>Yes</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Leptophobic Z' (\ell\ell)</td>
<td>2</td>
<td>2</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>SSM W' (\tau\tau)</td>
<td>2</td>
<td>2</td>
<td>Yes</td>
<td>3.2</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>HVT W' (\ell\ell)</td>
<td>0</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
<td>4.07 TeV</td>
</tr>
<tr>
<td>HVT W' (\tau\tau)</td>
<td>0</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>HVT W' (\ell W)</td>
<td>1</td>
<td>1</td>
<td>1 + 2</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>HVT W' (\ell\ell B)</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>HVT ZZ' (\ell\ell B)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>LRSM WW' (\ell\ell B)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>LRSM WW' (\ell\ell B)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>Yes</td>
<td>3.2</td>
</tr>
</tbody>
</table>

### Extra dimensions

<table>
<thead>
<tr>
<th>Model</th>
<th>(\ell\ell)</th>
<th>Jets</th>
<th>(E_{\text{miss}})</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl qqqq</td>
<td>(\ell\ell)</td>
<td>(\leq 2)</td>
<td>Yes</td>
<td>3.6</td>
<td>17.5 TeV</td>
</tr>
<tr>
<td>Cl qq'(\ell\ell)</td>
<td>(\ell\ell)</td>
<td>(\leq 2)</td>
<td>Yes</td>
<td>3.2</td>
<td>23.1 TeV</td>
</tr>
<tr>
<td>Cl wut</td>
<td>(\ell\ell)</td>
<td>(\leq 2)</td>
<td>Yes</td>
<td>3.2</td>
<td>43.0 TeV</td>
</tr>
<tr>
<td>Axial-vector mediator (Dirac DM)</td>
<td>0</td>
<td>1, 2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>Axial-vector mediator (Dirac DM)</td>
<td>0</td>
<td>1, 2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>ZZ' (\ell\ell) EFT (Dirac DM)</td>
<td>0</td>
<td>1, 2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
</tr>
<tr>
<td>Scalar LO 1(\ell\ell) gen</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td>550 GeV</td>
</tr>
<tr>
<td>Scalar LO 2(\ell\ell) gen</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td>640 GeV</td>
</tr>
<tr>
<td>Scalar LO 3(\ell\ell) gen</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>LO QCD</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td>1.05 TeV</td>
</tr>
<tr>
<td>LO QCD</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td>640 GeV</td>
</tr>
</tbody>
</table>

### Heavy quarks

<table>
<thead>
<tr>
<th>Model</th>
<th>(\ell\ell)</th>
<th>Jets</th>
<th>(E_{\text{miss}})</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLO TT (\ell\ell) (\rightarrow H + X)</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>685 GeV</td>
</tr>
<tr>
<td>VLO YY (\ell\ell) (\rightarrow W + X)</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>775 GeV</td>
</tr>
<tr>
<td>VLO TH (\ell\ell) (\rightarrow H+b) (+ X)</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>735 GeV</td>
</tr>
<tr>
<td>VLO BB (\ell\ell) (\rightarrow B + X)</td>
<td>2 (+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>735 GeV</td>
<td>1505.04306</td>
</tr>
<tr>
<td>VLO QQ (\ell\ell) (\rightarrow W + W)</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>685 GeV</td>
</tr>
<tr>
<td>VLO QQ (\ell\ell) (\rightarrow W + W)</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>685 GeV</td>
</tr>
<tr>
<td>VLO T (\ell\ell) (\rightarrow W + t) (+ X)</td>
<td>2</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>840 GeV</td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Excited fermions</td>
<td>1</td>
<td>(+ \ell\ell)</td>
<td>Yes</td>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

† Small-radius (large-radius) jets are denoted by the letter j (J).
The Standard Model Works

- Minimal Walking Technicolor search at LHC

The Standard Model Works

\[ m_H = 125.09 \pm 0.24 \text{ GeV} \]

Phys. Rev. Lett. 114, 191803

arXiv:1606.02266
Flaws of the SM

**Theoretical**
- Effective description / not UV complete
- EW scale stability / naturality
- Flavour problem / undetermined fermion masses & mixing angles
- EW vacuum meta-stability...

**Unexplained phenomena**
- Neutrino masses and their origin/nature
- Dark matter / dark energy
- Matter-antimatter asymmetry
- gravity...

Plenary Talk Nicholson

Plenary Talk Rinaldi
Experimental tensions

- $g-2$
- proton radius puzzle
- some few sigma deviations in heavy flavour / lepton systems
- some “bumps”…
Tantalising hints of new physics?

• heavy vectors?

\[ \begin{align*}
\text{Significance (stat)} &= 8 \text{ TeV, 20.3 fb}^{-1} \\
\text{Significance (stat + syst)} &
\end{align*} \]

\[ \begin{align*}
\text{Data} &
\end{align*} \]

\[ \begin{align*}
\text{Background model} &
\end{align*} \]

\[ \begin{align*}
\text{ATLAS} &
\end{align*} \]

\[ \begin{align*}
\text{WW Selection} &
\end{align*} \]

\[ \begin{align*}
\text{ATLAS} &
\end{align*} \]

\[ \begin{align*}
\text{WW+ZZ+WZ Selection} &
\end{align*} \]

\[ \begin{align*}
\text{Events / 100 GeV} &
\end{align*} \]

\[ \begin{align*}
\text{Significance} &
\end{align*} \]

arXiv:1506.00962
Tantalising hints of new physics?

- new scalars?

 Few sigmas excesses come and go…
 stay tuned for updates soon

arXiv:1606.03833
• Most models for BSM traditionally based on weakly-coupled/calculable extensions. Experimental bounds are now constraining many models to tight corners of parameter space.

• Strongly coupled model requiring non-perturbative dynamics are becoming more popular. In particular for the Lattice: Walking Technicolor and pNGB Composite Higgs.

• Phenomenology needs non-perturbative input for strongly coupled models: quantum symmetries, spectrum, low energy constants, …

Lattice can provide input for BSM physics/searches!

Claudio Pica
Anatomy of Composite Higgs

\[ \mathcal{L}_{SM-\text{Higgs}} \]

\[ G_{SM} = SU(3) \times SU(2) \times U(1) \]
Anatomy of Composite Higgs

$\mathcal{L}_{\text{SM-Higgs}} + \mathcal{L}_{\text{SD}}$

$\mathcal{L}_{\text{SD}} = -\frac{1}{4} F_{\mu\nu}^2 + i \bar{\psi} D\psi$

Gauge group: $G_{TC} = SU(N), SP(N), SO(N), \ldots$

Nf fermions $\psi$

- "Higgs Impostor": Scalar composite state
- W/Z mass generation
- new resonance spectrum (dark matter?)
- …
Anatomy of Composite Higgs

$$\mathcal{L}_{\text{SM-Higgs}} + \mathcal{L}_{SD} + \mathcal{L}_{\text{int}}$$

$$\mathcal{L}_{\text{int}}$$ contains:

- (effective) interactions to generate SM fermion masses, such as:
  $$\frac{1}{\Lambda_{\text{UV}}^2} \overline{q}q O_B, \quad \frac{1}{\Lambda_{\text{UV}}^2} q O_F$$
  among SM fermions $$q$$ and operators $$O$$ from SD

- other possible dim=6 or higher operators:
  $$\frac{1}{\Lambda_{\text{UV}}^2} \overline{q}q\overline{q}q$$
  \(\Rightarrow\) FCNC
Anatomy of Composite Higgs

\[ \mathcal{L}_{UV} \]

\[ \mathcal{L}_{SM-Higgs} + \mathcal{L}_{SD} + \mathcal{L}_{int} \]

\[ \mathcal{L}_{SM} + \text{new physics} \]

UV
\[ \sim 10^{3-4} \text{ TeV} \]

IR
\[ 1 \text{ TeV} \]

5\~10 \text{ TeV}
Anatomy of Composite Higgs

$+ \mathcal{L}_{SD}$

On the Lattice we only study the SD in isolation

Realistic phenomenology requires taking into account back-reactions from SM and other interactions.

1. Identify quantities which only depend on the new SD
2. Compute (small?) corrections from other sectors

Ruling in or out a realistic model always requires to consider the full setting!
If EWSB is due to a new of strongly-interacting sector with fermions, one would expect, in general, composite scalar particles.

To not be excluded by experiments, this scalar states should mimic a SM-like Higgs boson: correct mass and couplings.

This could happen if the composite scalar is a light pseudo-Goldstone boson of some broken symmetry:

1. Scale invariance symmetry (dilaton) - Walking Technicolor
2. Flavour symmetry (pNGB) - pNGB Higgs
I. Walking Technicolor

### Technicolor

TCfermion condensate breaks EW
Higgs is the lightest scalar excitation of the condensate

<table>
<thead>
<tr>
<th>Plus</th>
<th>Minus</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Natural</td>
<td>• Fermion masses vs FCNC</td>
</tr>
<tr>
<td>• UV complete theories available to explore</td>
<td>• Electroweak precision data</td>
</tr>
<tr>
<td></td>
<td>• Light Higgs</td>
</tr>
<tr>
<td></td>
<td>• Higgs couplings</td>
</tr>
</tbody>
</table>
• Extended TC interactions are needed.

\[ \mathcal{L}_{\text{int}}, \text{below } \Lambda_{ETC}: \]

\[ \alpha_{ab} \frac{\bar{Q} T^a Q \bar{\psi} T^b \psi}{\Lambda_{ETC}^2} + \beta_{ab} \frac{\bar{Q} T^a Q \bar{Q} T^b Q}{\Lambda_{ETC}^2} + \gamma_{ab} \frac{\bar{\psi} T^a \psi \bar{\psi} T^b \psi}{\Lambda_{ETC}^2} \]
### SM Fermion Masses

\[ \alpha_{ab} \frac{\bar{Q} T^a Q \bar{\psi} T^b \psi}{\Lambda_{ETC}^2} + \beta_{ab} \frac{\bar{Q} T^a Q \bar{Q} T^b Q}{\Lambda_{ETC}^2} + \gamma_{ab} \frac{\bar{\psi} T^a \psi \bar{\psi} T^b \psi}{\Lambda_{ETC}^2} \]

<table>
<thead>
<tr>
<th>Bound (GeV(^{-2}))</th>
<th>(\Lambda_{ETC} (10^3 \text{ TeV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-9.6 &lt; \Re(C_1^K) \times 10^{13} &lt; 9.6)</td>
<td>1.0</td>
</tr>
<tr>
<td>(</td>
<td>C_B^1</td>
</tr>
<tr>
<td>(</td>
<td>C_{Bd}^1</td>
</tr>
<tr>
<td>(</td>
<td>C_{Bs}^1</td>
</tr>
<tr>
<td>(-4.4 &lt; \Im(C_1^K) \times 10^{15} &lt; 2.8)</td>
<td>10</td>
</tr>
</tbody>
</table>

\[ C_{K}^1 (\bar{s}_L \gamma^\mu d_L) (\bar{s}_L \gamma^\mu d_L) \]
\[ C_{D}^1 (\bar{c}_L \gamma^\mu u_L) (\bar{c}_L \gamma^\mu u_L) \]
\[ C_{Bd}^1 (\bar{b}_L \gamma^\mu d_L) (\bar{b}_L \gamma^\mu d_L) \]
\[ C_{Bs}^1 (\bar{b}_L \gamma^\mu s_L) (\bar{b}_L \gamma^\mu s_L) \]

Limits from UTFit coll.  
See [1005.5727], [1104.1255]
SM Fermion Masses

\[ \alpha_{ab} \frac{\bar{Q} T^a Q \psi T^b \psi}{\Lambda_{ETC}^2} + \beta_{ab} \frac{\bar{Q} T^a Q \bar{Q} T^b Q}{\Lambda_{ETC}^2} + \gamma_{ab} \frac{\bar{\psi} T^a \psi \bar{\psi} T^b \psi}{\Lambda_{ETC}^2} \]

**SM fermion mass**

\[ m \sim \frac{\langle \bar{Q} Q \rangle_{ETC}}{\Lambda_{ETC}^2} \]

\[ \langle \bar{Q} Q \rangle_{ETC} = \langle \bar{Q} Q \rangle_{TC} \exp \left[ \int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \gamma(\alpha(\mu)) \right] \]

\[ \langle \bar{Q} Q \rangle_{TC} \approx \Lambda_{TC}^3 \]

In QCD-like dynamics:

\[ \alpha(\mu) \sim \frac{1}{\ln \mu} \quad \gamma \propto \alpha \quad \Rightarrow \quad \langle \bar{Q} Q \rangle_{ETC} \approx \langle \bar{Q} Q \rangle_{TC} \left( \ln \frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^k \]

\[ \Rightarrow \quad m \sim \Lambda_{TC} \left( \frac{\Lambda_{TC}}{\Lambda_{ETC}} \right)^2 \sim 1 \text{ MeV} \]

**Need enhancement mechanism**
Walking Technicolor

Running QCD-Like

IR fixed point IR conformal

Walking Deformed/“Near” IR conformal

Claudio Pica
SM Fermion Masses - Walking

\[
\alpha_{ab} \frac{\bar{Q} T^a Q \bar{\psi} T^b \psi}{\Lambda_{ETC}^2} + \beta_{ab} \frac{\bar{Q} T^a Q \bar{Q} T^b Q}{\Lambda_{ETC}^2} + \gamma_{ab} \frac{\bar{\psi} T^a \psi \bar{Q} T^b \psi}{\Lambda_{ETC}^2}
\]

\[m \sim \frac{\langle QQ \rangle_{ETC}}{\Lambda_{ETC}^2}\]
\[
\langle QQ \rangle_{ETC} = \langle QQ \rangle_{TC} \exp \left[ \int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \gamma(\alpha(\mu)) \right]
\]

\[\langle QQ \rangle_{TC} \approx \Lambda_{TC}^3\]

Extreme Walking:
\[\alpha(\mu) \approx \alpha^* \quad \gamma \approx \gamma^* \quad \Rightarrow \quad \langle QQ \rangle_{ETC} \approx \langle QQ \rangle_{TC} \left( \frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma^*}\]

\[\Rightarrow \quad m \sim \Lambda_{TC} \left( \frac{\Lambda_{TC}}{\Lambda_{ETC}} \right)^{2-\gamma^*} \sim 1 \text{ GeV}\]

Need large \(\gamma^* \sim 1\)

Claudio Pica
4-Fermion interactions

\[ \alpha_{ab} \frac{\bar{Q} T^a Q \bar{\psi} T^b \psi}{\Lambda^2_{ETC}} + \beta_{ab} \frac{\bar{Q} T^a Q \bar{Q} T^b Q}{\Lambda^2_{ETC}} + \gamma_{ab} \frac{\bar{\psi} T^a \psi \bar{\psi} T^b \psi}{\Lambda^2_{ETC}} \]

4-F

Modify SD:

- Generate mass for TCPions
- If TC conformal:
  - change anomalous dimensions?
  - drive away from IR fixed point / generate Walking

Talk Rantaharju Thu
see also: Talk Schmidt Wed

S-parameter

\[ S_{\text{naive}} = N_D \frac{D_R}{6\pi} \]

Models with small number \(N_D\) of gauged fermions favored

Some indications of reduced S-parameter near the conformal window
S-parameter

LSD collaboration,
Phys.Rev. D90 (2014) no.11, 114502

Difficult chiral extrapolation when approaching the CW
More investigations of this mechanism needed
SM radiative corrections shift the TC Higgs mass

R. Foadi, M. Frandsen, F. Sannino, Phys.Rev. D 87, 095001

\[(M_{TC}^H)^2 \approx M_H^2 + 12 \kappa^2 r_t^2 m_t^2\]

Narrow due to kinematics, similar to \(f_0(980)\) in QCD
Near the conformal window, as conformal invariance of the theory is approximatively restored, one can speculate the existence of an associated pNGB, the dilaton.  

Consider the theory:  

\[ \mathcal{L} = \sum_i g_i(\mu) \mathcal{O}_i(x), \text{ with } [\mathcal{O}_i] = d_i \]

Introduce a "conformal compensator": \( \chi(x) \rightarrow e^\lambda \chi(e^\lambda x) \) (under scale transf.)

The Lagrangian is scale invariant if we replace: \( g_i(\mu) \rightarrow g_i(\mu \frac{\chi}{f}) \left( \frac{\chi}{f} \right)^{4-d_i} \)

where \( f = \langle \chi \rangle \) is the scale of conformal symmetry breaking.

Introducing \( \bar{\chi}(x) = \chi(x) - f \) and expanding around \( f = \langle \chi \rangle \), we have:

\[ \mathcal{L}_\chi = \frac{1}{2} \partial_\mu \bar{\chi} \partial^\mu \bar{\chi} + \frac{\bar{\chi}}{f} T_\mu^\mu + \cdots \]

See e.g. Goldberger, Grinstein, Skiba [0708.1463]
Replacing the SM Higgs with the dilaton in the same way:

\[ \mathcal{L}_{\chi,SM} = \left( \frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2} \right) \left[ m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right] + \frac{\bar{\chi}}{f} \sum_\psi m_\psi \bar{\psi} \psi \]

(at tree level) which is identical in form to the couplings of the SM Higgs.

Couplings to gluons and the photon are induced in the same way as for the SM Higgs and are also similar if \( f \sim v \) (EW vev).

For Walking TC \( f \sim v \) is expected since the same TCquark condensate breaks EW and conformal invariance.

\[ \Rightarrow \] Similar couplings to the SM Higgs, difficult to distinguish at the experiments!  Bellazzini et al. [1209.3299]

See e.g. Goldberger, Grinstein, Skiba [0708.1463]
2. pNGB Higgs

## Composite pNGB Higgs

Higgs is a pseudo Goldstone boson
EW symmetry broken via radiative corrections

<table>
<thead>
<tr>
<th><strong>Plus</strong></th>
<th><strong>Minus</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Higgs is light</td>
<td>• Higgs mass</td>
</tr>
<tr>
<td>• Gauge boson couplings</td>
<td>• EW vacuum alignment</td>
</tr>
<tr>
<td></td>
<td>• Fermion masses</td>
</tr>
</tbody>
</table>
Consider a SD with global symmetry breaking pattern

\[ G_F \to H_F \supseteq SU(2)_L \times SU(2)_R \times U(1)_X \]

which preserves custodial symmetry. To give the correct hypercharge to all SM fields we need a NGB with

\[ \text{Higgs} = (2, 2)_0 \in G_F / H_F \]

For EW breaking the minimal cosets are:

<table>
<thead>
<tr>
<th>Representation</th>
<th>SU(4) × SU(4)'/SU(4)D</th>
<th>SU(4)/Sp(4)</th>
<th>SU(5)/SO(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 ( \psi_\alpha, \tilde{\psi}_\alpha ) Complex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 ( \psi_\alpha ) Pseudoreal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 ( \psi_\alpha ) Real</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- SU(3) Nf=4 Fund Dirac
- SU(2) Nf=2 Fund Dirac
- SU(4) Nf=2.5 2-A Dirac
Loop corrections of EW gauge bosons will generate a potential for the Higgs but will not break EW symmetry (Higgs remains massless).

However in any realistic model, couplings to SM fermions will be present

\[ \frac{1}{\Lambda^2_{UV}} \bar{q} q O_B \]
\[ \frac{1}{\Lambda^2_{UV}} q O_F \]

ETC like Linear coupling

in particular top quark corrections will offset the minimum and generically tend to align the vacuum in the EW symmetry breaking (TC) direction.
Another generic feature of pNGB Higgs models is that couplings to the EW gauge bosons and SM fermions mimic those of the SM Higgs for small $\theta$

\[
\frac{g_{WW h_1}}{g_{WW h}} = 1 + C\theta + \mathcal{O}(\theta^2)
\]
\[
\frac{g_{tth_1}}{g_{tth}} = 1 + D\theta + \mathcal{O}(\theta^2)
\]
Fermion masses are generated via linear couplings

\[
\frac{1}{\Lambda_{UV}^2} q O_F \rightarrow m_q \sim v \left( \frac{\Lambda}{\Lambda_{UV}} \right)^{2(\text{dim}[O_F] - 5/2)}
\]

If \( \text{dim}[O_F] \leq 2.5 \) then large SM fermion masses can be generated.

E.g. if \( O_F \) is a baryon, then we should have \( \gamma_B \geq 2 \) (unitarity bound 3)

Other possibilities exist: e.g. if the new strong sector feature elementary TCcoloured scalars then \( O_F \) can be a composite \( \Psi S \) which have engineering dimension 5/2, so that no anomalous dimension is needed.

Realistic models which can generate all SM masses exist.

See Sannino, Strumia, Tesi, Vigiani [1607.01659]

See also Pica, Sannino [1604.02572]
Partial Compositeness Models

- SU(3) with Nf>6 Fund Dirac fermions [Vecchi 1506.00623]
- For SD models with only fermions and 2 representations [Ferretti 1604.06467]

<table>
<thead>
<tr>
<th>$G_{HC}$</th>
<th>$\psi$</th>
<th>$\chi$</th>
<th>$G/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(7, 9)</td>
<td>5 $\times$ F</td>
<td>6 $\times$ Spin</td>
<td>$SU(5)$ $SU(6)$ $SU(6)$ $SO(5)$ $SO(6)$ $U(1)$</td>
</tr>
<tr>
<td>SO(7, 9)</td>
<td>5 $\times$ Spin</td>
<td>6 $\times$ F</td>
<td>$SU(5)$ $SU(6)$ $SU(6)$ $SO(5)$ $SO(6)$ $U(1)$</td>
</tr>
<tr>
<td>Sp(4)</td>
<td>5 $\times$ A$_2$</td>
<td>6 $\times$ F</td>
<td>$SU(5)$ $SU(6)$ $SU(6)$ $SO(5)$ $Sp(6)$ $U(1)$</td>
</tr>
<tr>
<td>SU(4)</td>
<td>5 $\times$ A$_2$</td>
<td>3 $\times$ (F, F)</td>
<td>$SU(5)$ $SU(3) \times SU(3)'$ $SO(5)$ $SU(3)D$ $U(1)$</td>
</tr>
<tr>
<td>SO(10)</td>
<td>5 $\times$ F</td>
<td>3 $\times$ (Spin, Spin)</td>
<td>$SU(5)$ $SU(3) \times SU(3)'$ $SO(5)$ $SU(3)D$ $U(1)$</td>
</tr>
<tr>
<td>Sp(4)</td>
<td>4 $\times$ F</td>
<td>6 $\times$ A$_2$</td>
<td>$SU(4)$ $SU(6)$ $SU(6)$ $Sp(4)$ $SO(6)$ $U(1)$</td>
</tr>
<tr>
<td>SO(11)</td>
<td>4 $\times$ Spin</td>
<td>6 $\times$ F</td>
<td>$SU(4)$ $SU(6)$ $SU(6)$ $Sp(4)$ $SO(6)$ $U(1)$</td>
</tr>
<tr>
<td>SO(10)</td>
<td>4 $\times$ (Spin, Spin)</td>
<td>6 $\times$ F</td>
<td>$SU(4)$ $SU(4)'$ $SU(4)D$ $SU(6)$ $SO(6)$ $U(1)$</td>
</tr>
<tr>
<td>SU(4)</td>
<td>4 $\times$ (F, F)</td>
<td>6 $\times$ A$_2$</td>
<td>$SU(4)$ $SU(4)'$ $SU(3) \times SU(3)'$ $SU(3)D$ $SU(3)D$ $U(1)$</td>
</tr>
<tr>
<td>SU(5, 6)</td>
<td>4 $\times$ (F, F)</td>
<td>3 $\times$ (A$_2$, A$_2$)</td>
<td>$SU(4)$ $SU(4)'$ $SU(3) \times SU(3)'$ $SU(3)D$ $SU(3)D$ $U(1)$</td>
</tr>
</tbody>
</table>

See also talk by Del Debbio [Thu]
Impact of Lattice

- Location of the boundary of the Conformal Window

- Can we exhibit an IR conformal model with $\gamma^* \sim 1$?
  - or one with large anomalous dimensions for baryons $\sim 2$?

- Find SD models with light scalars / “Higgs impostors”
  - how the spectrum of SD changes when approaching the CW?
  - is the light scalar a dilaton?

- Couplings of the composite Higgs

- Spectrum, S-parameter, other LEC of viable models
SU(N) phase diagram @ Lattice 2016
In the first two cases, the hypercolor group is fixed and we scan over the two irreps:

\[ SU(4) \] case:
- \( = 1404.7137 \)
- \( = \text{"swapped"} \)

\[ Sp(4) \] case:
- \( = 1311.6562 \)
- \( = \text{"swapped"} \)

For an estimate of the conformal window, see also:
Conformal Window / Large $\gamma^*$
new results at Lattice 2016
• Long history of previous studies
  (see review talks at past Lattice conferences)
• New high precision study of GF coupling with controlled systematics
• Use of significantly larger volumes respect to previous state-of-the-art.

\[ g^2 (\text{tuned}) = 6.3925 \pm 0.0019 \]
\[ \chi^2/\text{dof} = 0.35 \quad Q = 0.85 \]

\[ g^2 (\text{tuned}) = 6.1846 \pm 0.0021 \]
\[ \chi^2/\text{dof} = 1.07 \quad Q = 0.37 \]

\[ g^2 (\text{tuned}) = 5.9793 \pm 0.0021 \]
\[ \chi^2/\text{dof} = 0.27 \quad Q = 0.85 \]

\( s=2 \) stepped lattice sizes: \( L/a = 32, 36, 40, 48, 56 \)
Long history of previous studies (see review talks at past Lattice conferences)

New high precision study of GF coupling with controlled systematics

Use of significantly larger volumes respect to previous state-of-the-art.

\[
\frac{g^2(sL) - g^2(L)}{\log(s^2)} = c_0 + c_1 \cdot \frac{a^2}{L^2}
\]

\[c_0 = 0.112 \pm 0.013\]
\[c_1 = -26.8 \pm 4.3\]
\[\chi^2/dof = 0.81 \quad Q = 0.44\]

\[
\frac{g^2(sL) - g^2(L)}{\log(s^2)} = c_0 + c_1 \cdot \frac{a^2}{L^2}
\]
\[c_0 = 0.113 \pm 0.015\]
\[c_1 = -38.1 \pm 5.9\]
\[\chi^2/dof = 0.19 \quad Q = 0.83\]

\[
\frac{g^2(sL) - g^2(L)}{\log(s^2)} = c_0 + c_1 \cdot \frac{a^2}{L^2}
\]
\[c_0 = 0.113 \pm 0.014\]
\[c_1 = -46.4 \pm 5.5\]
\[\chi^2/dof = 0.82 \quad Q = 0.44\]
**SU(3) N_f=12**

- Long history of previous studies (see review talks at past Lattice conferences)
- New high precision study of GF coupling with controlled systematics
- Use of significantly larger volumes respect to previous state-of-the-art.
- Exclude fixed-point around 1-$\sigma$ of previous best estimate of location
- Fixed point at higher $g^2$ ??

**Use of Large Volumes is mandatory close to IR point!**
• Updates [arXiv:1603.08854] with larger 32 volume  \textbf{Talk by Chiu [Tue]}
• Finite volume GF coupling with Optimal Domain-Wall fermion action

\[ \beta = \frac{6}{g^2} \]

\begin{align*}
1 / g^2(L,a) & \\
\beta & = 15.0 \\
& = 12.0 \\
& = 10.0 \\
& = 9.00 \\
& = 8.00 \\
& = 7.50 \\
& = 7.00 \\
& = 6.80 \\
& = 6.70 \\
& = 6.60 \\
& = 6.50 \\
& = 6.45 \\
\end{align*}
SU(3) \( N_f = 10 \)

- Updates [arXiv:1603.08854] with larger 32 volume  
  Talk by Chiu [Tue]
- Finite volume GF coupling with Optimal Domain-Wall fermion action
• Updates [arXiv:1603.08854] with larger 32 volume

• Finite volume GF coupling with Optimal Domain-Wall fermion action

• Largest volume still running

• Estimate of systematic error of continuum extrapolation needed

• Anomalous dimensions $\gamma^*$?
SU(2) Fund $N_f=6$

- measure of GF coupling with SF bc
- Similar method to previous $N_f=8$ determination

- extrapolation near FP still affected by systematics: larger volumes required?
- small $\gamma^*$?

<table>
<thead>
<tr>
<th>$N_f$</th>
<th>$\beta$</th>
<th>$\gamma_M$</th>
<th>$\gamma_{SD}$</th>
<th>$\gamma_{SF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.5</td>
<td>0.382(12)</td>
<td>0.280(2)</td>
<td>0.142(27)</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.314(7)</td>
<td>0.231(2)</td>
<td>0.414(63)</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.248(3)</td>
<td>$\sim 0.16$</td>
<td>0.157(21)</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
<td>0.293(30)</td>
<td>$\sim 0.13$</td>
<td>0.072(24)</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.238(31)</td>
<td>0.111(1)</td>
<td>0.109(14)</td>
</tr>
</tbody>
</table>

Talk by Leino [Thu]
Posters by Tähtinen, Soursa [Tue]
SU(2) Adj N_f=2, 3/2

- Spectrum (including scalar) and γ*
  - new results for N_f=2, 3/2
  - 2 lattice spacings

Talk by Bergner [Mon]
SU(2) Adj $N_f=2$, 3/2

- Spectrum (including scalar)

$\beta=1.5$ $N_F=2$

$\beta=1.7$

Significant $\beta$ dependence, Finite size effects at small quark mass.

Claudio Pica
SU(2) Adj \(N_f=2, 3/2\)

- First results for \(N_f=3/2\)

\(N_F=3/2\)

![Graph](image-url)
### SU(2) Adj $N_f=2, 3/2, 1, 1/2$

#### Talk by Bergner [Mon]

<table>
<thead>
<tr>
<th>Theory</th>
<th>Scalar Particle</th>
<th>$\gamma_*$ Small $\beta$</th>
<th>$\gamma_*$ Larger $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_f = 1/2$ SYM</td>
<td>part of multiplet</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$N_f = 1$ adj QCD</td>
<td>light</td>
<td>0.92(1)</td>
<td>0.75(4)*</td>
</tr>
<tr>
<td>$N_f = 3/2$ adj QCD</td>
<td>light</td>
<td>0.40(5)*</td>
<td>0.32(5)*</td>
</tr>
<tr>
<td>$N_f = 2$ adj QCD</td>
<td>light</td>
<td>0.376(3)</td>
<td>0.274(10)</td>
</tr>
</tbody>
</table>

(*) preliminary

- Significant $\beta$ dependence, needs to be clarified
  - corrections to scaling? larger volumes?

- **Very large volumes required** as demonstrated in [arXiv:1512.08242] for $N_f=2$

- Large $\gamma_*$ for $N_f=1$? Inside the CW?
  - See also [1412.5994]
Models Light $\sigma$ Scalars
new results at Lattice 2016
SU(3) Fund $N_f=4l+8h$

- Mass deformation induces "Walking"

Talks by Hasenfratz, Rebbi [Mon]

![Graph showing $g^2(\mu; m_h)$ for different $m_h$ values and $N_f = 4$. The graph indicates a "shoulder" effect as $m \to 0$.](image-url)

- $m_\ell = 0$
SU(3) Fund $N_f=4l+8h$

See also [1512.02576]

Talks by Hasenfratz, Rebbi [Mon]

Claudio Pica

- Light scalar as $m_h$ is decreased.
  - How light is it? Requires controlled extrapolation…
- Other ratios appear only mildly dependent on $m_h$, i.e. "QCD-like"
**SU(3) Fund N_f=4l+8h**

- Hyperscaling in spectrum expected close to an IR fixed point:

\[ M_{H_1} / F_\pi = \tilde{\Phi}_H (m_\ell / m_h) (1 + c_0 m_\omega^0) \]

**Talks by Hasenfratz, Rebbi [Mon]**

---

**light-light hadrons**

<table>
<thead>
<tr>
<th>( M_{H_1} / F_\pi )</th>
<th>( a \times m_\ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.050</td>
</tr>
<tr>
<td>10</td>
<td>0.060</td>
</tr>
<tr>
<td>8</td>
<td>0.080</td>
</tr>
<tr>
<td>6</td>
<td>0.100</td>
</tr>
</tbody>
</table>

**heavy-heavy**

<table>
<thead>
<tr>
<th>( M_{H} / F_\pi )</th>
<th>( m_\ell / m_h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0.2</td>
</tr>
<tr>
<td>24</td>
<td>0.4</td>
</tr>
<tr>
<td>16</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

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Claudio
SU(3) Sextet $N_f=2$

Talks by Kuti, Wong for LHC [Mon,Tue]

- New: Preliminary $\eta'$ from topological charge density with WF smearing
- Relatively heavy $\eta' \sim 3\text{TeV}$ (assuming $F_{ps}=246\text{GeV}$)

$$
\begin{align*}
\langle q(x)q(y) \rangle &= A K_r(M_\eta r)/r \\
A &= 6.6(2) \times 10^{-9}, M_\eta = 0.419(2), \chi^2/dof = 0.3 \\
\text{for } t_f = 5.0 \\
\end{align*}
$$
SU(3) Sextet $N_f=2$

Talks by Kuti, Wong for LHC [Mon,Tue]

- Nearly conformal model with light $\sigma$
- Spectrum not compatible with mass-deformed hyper scaling
- Problem of chiral extrapolation in presence of a light $\sigma$
• Sextet model with non-improved Wilson fermions
• Study of the phase diagram, spectrum, $w_0/t_0$ scale setting
• Preliminary analysis shows no clear signs of ChSB, but conformal hypothesis does not fit well data
SU(3) Fund $N_f=8, 4$

- Updated spectrum for $N_f=8$, see LatKMI [1403.5000]
- New results for $N_f=4$
- New: $\eta'$ mass from topological charge density with WF smearing
• Preliminary results show heavy $\eta'$ as approaching the CW.
  ‣ is there a reason for this enhancement? [Matsuzaki, Yamawaki JHEP2015]
• Light $\sigma$ for $N_f=8$, compatible with pion mass in the explored mass range

**SU(3) Fund $N_f=8, 4$**

**Talk by Aoki for LatKMI [Tue]**

![Graphs showing $N_f=2+1$, $N_f=4$, and $N_f=8$](image)
SU(3) Fund $N_f=8$

Talks by Fleming, Gasbarro for LSD [Tue]

- Updated spectrum for $N_f=8$, see LSD [1601.04027]
- Use of new action respect to previous USBSM studies allows use of coarser lattices
SU(3) Fund $N_f=8$

- $M_V/F_{PS} \approx 8$ like in QCD
- Use vector meson dominance and KSRF relation
  \[ \Gamma_\rho \approx g_{\rho\pi\pi}^2 M_\rho / 48\pi \approx M_\rho^3 / 96\pi F_\pi^2 \]
  to estimate $\Gamma_\rho/M_\rho \approx 20\%$
- Too broad to explain LHC excess?
- What about the scalar?

Talks by Fleming, Gasbarro for LSD [Tue]
• Good agreement with LatKMI
• Scalar as light as pions

• If dilaton-like, $\sigma$ is expected to become much lighter than $\rho$
• Not clear how to extrapolate: different extrapolations give wildly different results

Need good effective description of pi-$\sigma$ system

Claudio Pica
Effective action for pi-\(\sigma\) dilaton

- Near CW assume \(\partial_\mu S_\mu = T_{\mu\mu} \sim (n_f - n_f^*)^\eta\) at the ChSB scale
- Systematic expansion in: \(m, p^2, 1/N, n_f-n_f^*\)
- LO Lagrangian (\(\tau\) dilaton):

\[
\mathcal{L} = \mathcal{L}_\pi + \mathcal{L}_\tau + \mathcal{L}_m + \mathcal{L}_d
\]

\[
\mathcal{L}_\pi = \left(\frac{f_\pi^2}{4}\right) e^{2\tau} \text{tr} (\partial_\mu \Sigma^\dagger \partial_\mu \Sigma)
\]

\[
\mathcal{L}_\tau = \left(\frac{f_\tau^2}{2}\right) e^{2\tau} (\partial_\mu \tau)^2
\]

\[
\mathcal{L}_m = -(mf_\pi^2 B_\pi/2) e^{y\tau} \text{tr} \left(\Sigma + \Sigma^\dagger\right)
\]

\[
\mathcal{L}_d = [\tilde{c}_{00} + (n_f - n_f^*)(\tilde{c}_{01} + \tilde{c}_{11}\tau)] f_\tau^2 B_\tau e^{4\tau}
\]
Effective action for pi-\(\sigma\) dilaton

Talks by Shamir, Golterman [Mon]

- Results (more in Shamir, Golterman talks):
  
  \[
m^2_{\pi} = 2\hat{B}_\pi m e^{(y-2)v(m)}
  \]
  
  \[
m^2_{\tau} = 4\tilde{c}_{11}(n_f - n_f^\ast)\hat{B}_\tau e^{2v(m)}(1 + (4 - y)v(m))
  \]
  
  \[
\langle \overline{\psi}\psi \rangle = -\frac{B_\pi}{f_\pi} \exp \left[\gamma_m^* \left(\frac{1}{4} + \frac{\tilde{c}_{00}}{\tilde{c}_{11}(n_f - n_f^\ast)}\right)\right]
\]
  
  \[
-(\beta(g^2)/g^2)\langle F^2 \rangle = \hat{f}_\tau^2 m^2_{\tau}
\]

- Use EFT to “test” diatonic nature of light scalar from Lattice data
  - close enough to CW?
  - need higher order corrections?
  - correct assumptions for EFT?
pNGB Higgs
new results at Lattice 2016
SU(2) Fund $N_f=2$

- Simple realistic model for pNGB Higgs
  - First full determination of spectrum including $\sigma$ and $\eta'$
    - 4 lattice spacings
    - Scale setting via $w_0$
    - Non-perturbative renormalization in RI-MOM scheme
    - Both chiral and continuum extrapolation (better control of systematics needed to reduce errors)

Based on [1602.06559], [1607.06654]

Talks by Drach, Janowski [Mon,Thu]

Cacciapaglia, Sannino, JHEP04(2014)111
Arbey et al. [1502.04718]
SU(2) Fund $N_f=2$

- new scalar spectrum

 Talks by Drach, Janowski [Mon,Thu]
• Spectrum of heavy resonances >15 TeV (depends on EW vacuum alignment angle)

• Better control of extrapolations needed

• Predicts pNGB Higgs with no extra resonances to be seen at LHC, barring extra pNGB in the spectrum
• First investigation of model with 2 irreps, same as Ferretti’s [1404.7137]
• Partially quenched (sextet) exploration of “chimera” baryons
  ‣ can be light → good for phenomenology
  ‣ anomalous dimensions?

\[ \text{SU}(4) \ N_f = 2F + 2 \text{ Sextet} \]

Talk by Jay [Thu]

\[ \text{Full baryon spectrum, } \beta = 10.2, \ \kappa_5 = 0.1265 \]

\[ (J(J+1) \text{ Rotor}) \]

\[ \text{Constant vs } \kappa_5 \]

\[ Qqqq \]

\[ [J(J+1) \text{ Rotor}] \]
• Radiative contribution to pNGB Higgs potential from EW gauge bosons

\[ V_{EW}(h) = (3g^2 + g'^2)C_{LR} \left( \frac{h}{f} \right)^2 + O(h^4) \]

\[ C_{LR} = \int_0^\infty d q^2 q^2 \Pi_{LR}(q^2) \]

\[ (q^2 \delta_{\mu\nu} - q_\mu q_\nu) \Pi_{LR}(q^2) = - \int d^4 x e^{i q x} \langle J^L_\mu(x) J^R_\nu(0) \rangle \]

• Currents calculated with overlap fermions on 2 sea actions

• Alternative method via “Minimal Hadron Approximation” consistent

![Graph showing the relationship between \( C_{LR}/f^2 \) and \( m_v \) for two ensembles.](image)
Conclusions

• Much activity and progress both on model exploration and tools

• Lattice simulations yield first principle results for the SD dynamics which can provide crucial input for model building

• BAD:
  ‣ Despite many efforts, still controversy on the location of the Conformal Window. Need better methods?
  ‣ IR conformal models with large $\gamma^*$: where are they?
  ‣ Difficult to control systematics for “walking” models
Conclusions

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**GOOD:**

- Phenomenologically interesting models are being investigated:
  1) strongly coupled models with light scalars;
  2) pNGB Higgs models
- New tools for BSM models are being developed
- (Preliminary) Results for the resonance spectrum of many models (Nc, Nf, irrep) are available
  Already useful for model builders?
Conclusions

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Thank you!
Conformal Window

- Gauge Group: SU, SO, SP, Exceptional
- Matter Representation(s)
- # of Flavors per Representation

QCD-like  IR conformal  No AF

$N_f$

$\alpha$ $\Lambda_{IR}$ $\Lambda_{ETC}$ $\Lambda$ $\Lambda_{IR}$ $\Lambda_{ETC}$ $\Lambda$ $\Lambda$ $\Lambda$

Energy

Claudio Pica
Other methods to estimate the lower boundary available: Schwinger–Dyson eq, counting of thermal d.o.f., not all in agreement ➔ **NEED non-perturbative Lattice determination**
Other Gauge Groups

SO(N)

Sannino 09
Pica & Sannino 10

SO(2n+1)

Mojaza, Pica, Rytov
Sannino 12

SO(2n+2)

Ladder
Four Loops $\gamma^* = 1$
All Orders $\gamma^* = 1$

Mojaza, Pica, Rytov
Sannino 12

Exceptional
Multiple Representations

In the first two cases, the hypercolor group is fixed and we scan over the two irreps:

SU(4) case:
- $\rho = 1404.7137$
- $\xi = \text{"swapped"}$

Sp(4) case:
- $\rho = 1311.6562$
- $\xi = \text{"swapped"}$

For an estimate of the conformal window, see also: Ryttov, Sannino, Int.J.Mod.Phys. A25 (2010) 4603-4621 [0906.0307]
Are light scalar states a generic feature of mass deformed (weakly coupled?) IR models?