

Beyond the Standard Model

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Outline

- ❑ The Standard Model is very successful, however ...
- ❑ ...several conceptual and phenomenological issues
 - Quantum Gravity
 - Naturalness/Hierarchy problem,
 - Dark Matter/Energy,
 - Strong-CP problem,
 - Matter/Antimatter asymmetry,
 -
- ❖ Very large literature, very diverse topics, often the "questions" are harder to understand than their "answers"

The role of the lattice.

A possible classification of BSM studies

- Top-down:
 - Pick a specific model to solve a specific issue.
 - Calculate phenomenologically relevant things.
- ❖ Bottom-up:
 - ❖ Study the properties of a class of models.
 - ❖ Get inspiration to address one of the above issues.
- ❖ Real life situations are often a superposition of the two approaches
- ❖ Examples:
 - ❖ Composite Higgs Models
 - ❖ Axions
 - ❖ Large-N
- The Lattice is the essential tool to explore **non-perturbative regime**

Composite Higgs Models

Template of course:

- Motivation: **naturalness problem, origin of EWSB.**
- Statement of the Composite Higgs solution:
 - Mimic **QCD**: New strongly-coupled sector at high energy scale.
 - At a suppressed scale, **spontaneous breaking of chiral symmetry.**
 - The Higgs is pNG boson, **radiatively generated potential.**
- ❖ Use of the Lattice:
 - ❖ Only with the lattice can we explore the non-perturbative regime.
 - ❖ Define the model in the UV **in isolation**, "simulate" it.
 - ❖ Compute masses and decay constants from correlation functions.
- Connect with continuum EFTs (**beware of chiral/continuum limit!**)

Composite Higgs Models

- Difficulty: **Intermediate**
- Resources:
 - *Tasi 2009 lectures: The Higgs as a Composite Nambu-Goldstone Boson – R. Contino*
 - *The Composite Nambu-Goldstone Higgs – G. Panico, A. Wulzer*
 - *Video Lectures @ICTP – A. Wulzer*
 - *Seminal papers by Kaplan, Weinberg, Georgi,...*
- Prerequisites
 - Renormalization group, EFTs
 - Simulation of gauge theories with different groups G (and N_c) (ex. $SU(N)$, $Sp(2N)$).
 - Fermions in multiple representations (and N_f).
 - Hadron spectrum calculations.
 - Scale Setting.
- Related:
 - Composite Dark Matter?
 - Location of Conformal Window?
 - Peskin-Takeuchi parameters?
 - Chiral lattice fermions?

Large-N

Template of course:

- ❖ Motivation: Gain a **better understanding of YM theories**, make predictions of phenomenological relevance
- ❖ Statement of Strategy:
 - ❖ Gauge theories **simplify** as N goes to ∞
 - ❖ Compute at large- N .
 - ❖ Obtain results for lower N in **powers of $1/N$** .
- Use of the Lattice:
 - Only with the lattice can we explore the non-perturbative regime.
 - Calculate at different values of **(largish)- N** .
 - Extrapolate to $N=\infty$ and **obtain the leading $1/N$ dependence**

Large-N

- Difficulty: **Easy/Intermediate**
- Resources:
 - *David Tong's notes on gauge theories*
 - *Coleman's "Aspects of symmetry"*
 - *Lectures on QFT by John Preskill*
- Prerequisites
 - Perturbative YM
 - Simulation of gauge theories with different groups G (and N_c) (ex. $SU(N)$, $Sp(2N)$).
 - Fermions in multiple representations (and N_f).
 - Hadron spectrum calculations.
 - Scale Setting.
- Related:
 - Witten-Veneziano?
 - BSM models?
 - Holography/Strings?
 - Universality in YM theories?

Axions

Template of course:

- ❖ Motivation: **Strong-CP problem**
- ❖ Statement of Peccei-Quinn Strategy:
 - ❖ Introduce a **new (broken) $U(1)$ symmetry**
 - ❖ Its pNG is the **Axion**
 - ❖ CP violations can then be strongly suppressed
- Use of the Lattice:
 - Theta-term is genuinely non-perturbative
 - Lattice can explore **complex** theta and finite T
 - Axion mass squared proportional to topological susceptibility.

Axions

- Difficulty: **Intermediate/Hard**
- Resources:
 - *Coleman's "Aspects of symmetry"*
 - "Theta dependence of SU(N) gauge theories in the presence of a topological term" – E. Vicari, H. Panagopoulos
 - *Schulman's "Techniques and applications of Path integration"*
 - *Lectures on QFT by John Preskill*
 - R. Peccei's - "The Strong CP Problem and Axions" - hep-ph/0607268
- Prerequisites
 - Renormalization, Anomalies
 - Simulation of SU(3) with fundamental fermions.
 - Calculation of Topological charge.
 - Scale Setting.
- Related:
 - Theta dependence in gauge theories?
 - Axion (relic) Dark Matter?
 - Witten-Veneziano?
 - Universality in YM theories?

Summary

- BSM is an umbrella term, covering a large literature.
- The Lattice allows to explore otherwise inaccessible regimes in specific models.
- Recovering phenomenologically relevant information is, in many cases, highly non-trivial.
- I have tried to propose templates for different topics, **let's discuss!**