New Approaches to Effective Field Theories

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Leinweber Center for Theoretical Physics (LCTP)
at
University of Michigan

CTP 50 year celebration

MIT

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Based on arXiv:1712.09937 and work to appear with graduate students

Marios Hadjiantonis, Callum R. T. Jones, and Shruti Paranjape

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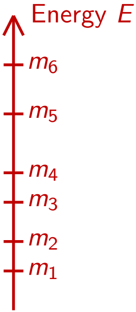
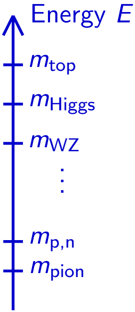
Energy scales

Particle spectrum in a theory



example: Standard Model



At high energy, can treat particles with $m \ll E$ as massless.

For $E \ll$ any $m_i \implies$ effective theory of only the massless particles.

The physical effect of the massive particles is encoded as effective interactions among the massless particles in the **low-energy effective field theory (EFT)**.

This talk

This talk is about Effective Field Theories of massless particles

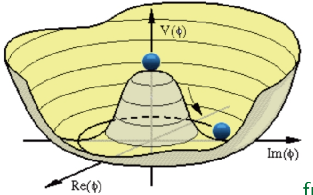
Specifically the types of Effective Field Theories (EFTs) that arises from spontaneous symmetry breaking.

Goals:

- Provide a *complete* classification of all such 4d EFTs, independent of their origin.
- Characterize relations among such EFTs.
- Utilize and develop new tools for such analyses.

Powerful feature:
characterization independent of unknown high-energy physics.

Spontaneous symmetry breaking



from arXiv:1201.6045

Spontaneous broken symmetry is a symmetry of the theory which is not a symmetry of the vacuum.
Higgs mechanism, superconductivity,. . .

Jeffrey Goldstone's Theorem. There is one massless particle (Goldstone particle) for every spont.broken internal symmetry.

3-flavor QCD.

High energy: u, d, and s quarks, and gluons.

Chiral flavor symmetry $SU(3) \times SU(3) \xrightarrow{\text{broken}} SU(3)$

Low energy: QCD confines $\Longrightarrow$ hadrons.

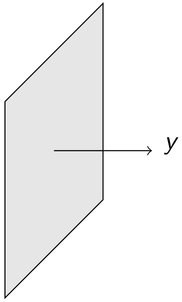
8 massless Goldstone bosons: octet of pions, kaons, η.

Internal symmetry spont. broken.

The Goldstone bosons described by a low-energy EFT:
"Non-Linear Sigma Model (NLSM)".

A second example

Can also have **spontaneously broken** **spacetime** **symmetries**



Breaks translation symmetry in transverse directions.
There is a massless Goldstone mode.
It describes fluctuations of the membrane in transverse directions.

Leading low-energy EFT is *Dirac-Born-Infeld (DBI)* model.

A third example

Spontaneously broken supersymmetry

gives fermionic Goldstone mode(s), called Goldstinos.

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Spontaneously broken supersymmetry

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These are examples of 3 quite different EFTs. Are there other ones?

Question:

How to characterize *all possible EFTs* that arise in the low-energy description of theories with spontaneous symmetry breaking?

Explicit construction approach:

The Lagrangians of the EFTs can be constructed for any given symmetry breaking pattern $G \to H$.

not useful for mapping out landscape of EFTs.

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Instead

focus on the physical observables: scattering amplitudes.

Idea

Traditionally: Lagrangian $\rightarrow$ Feynman rules $\rightarrow$ scattering amplitudes. The amplitudes inherit symmetry properties of the Lagrangian.

Instead: reverse the logic. Impose the symmetry constraints on the physical observables (the scattering amplitudes) and test consistency to examine if a theory can exist that produces those scattering processes.

Powerful approach.

Used previously (2010) in collaboration with MIT PhD Michael Kiermaier and faculty member Dan Freedman to examine UV properties of maximal supergravity in 4d.

From symmetry to amplitude

- *Unbroken symmetries* give Ward identities for amplitudes.
- *Spontaneously broken symmetries* give **soft theorems**:

$$A_n(p,\dots) \to \epsilon^\sigma \quad \text{when} \quad p^\mu \to \epsilon p^\mu \quad \text{and} \quad \epsilon \to 0$$

Shift symmetry $\phi \to \phi + c \quad \leftrightarrow \quad \sigma = 1$.
Shift symmetry $\phi \to \phi + c_\mu x^\mu \quad \leftrightarrow \quad \sigma = 2$.

Example: DBI action

$$S = -T \int d^4x \left(\sqrt{1 + (\partial\phi)^2} - 1 \right).$$

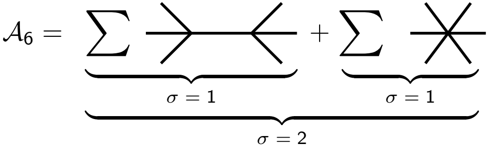
has obvious shift symmetry $\phi \to \phi + c$. Would expect $\sigma = 1$.
But has $\sigma = 2$. Why?

Illustrate in example

DBI action

$$S = -T \int d^4x \left(\sqrt{1 + (\partial\phi)^2} - 1 \right) .$$

- $\sigma = 2$ is facilitated by detailed cancellations between terms from pole diagrams and contact terms, e.g.



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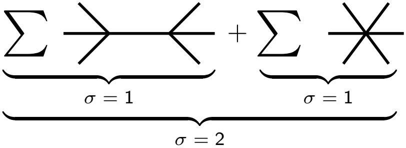
$\mathcal{A}_6 =$



- Lorentz boosts $J_{\mu 5} = x^\mu \partial_5 - x^5 \partial_\mu$ also spont. broken. Induces symmetry $\delta\phi = a_\mu(x^\mu + \phi\partial^\mu\phi)$. NOT obvious by simple inspection.

  $\delta\phi = a_\mu x^\mu + \ldots \implies \sigma = 2.$

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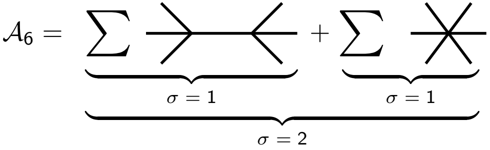

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  $\delta\phi = a_\mu x^\mu + \dots \implies \sigma = 2$.

- DBI is in fact the unique scalar theory based on a fundamental quartic interaction with a coupling g_4 of mass-dimension minus four, $[g_4] = -4$, that has $\sigma = 2$.

Algorithm:

Choose particle species, lowest-dim. couplings, and symmetries:

- Start with the most general ansatz for the lowest-point the amplitudes.
- Impose constraints of symmetry.
- Use recursive technique*) to generate higher-point amplitudes from lower-point input.
- Test if the results of recursion obey all mathematical and physical requirements.

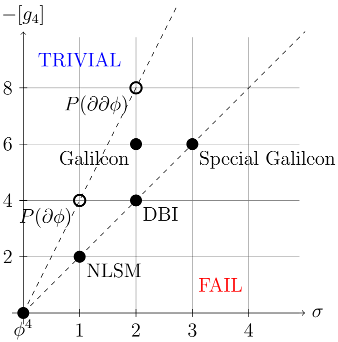
$\longrightarrow$ if **no**, then no such theory can exist.

$\longrightarrow$ if **yes**, evidence in favor of a theory with the given particle spectrum, couplings, and symmetries.

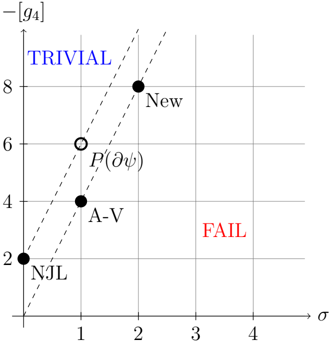
*) "subtracted soft recursion relations"
[Cheung, Kampf, Novotny, Shen, and Trnka 2014 & 2016]

Landscape of "special" EFTs with fundamental quartic vertices

Scalar theories



Fermion theories



$$A_n(p_1, \ldots, \epsilon p_i, \ldots) \to \epsilon^{\sigma_i} \quad \text{when} \quad \epsilon \to 0$$

[Cheung, Kampf, Novotny, Shen, and Trnka 2014 & 2016]

[HE, Hadjiantonis, Jones, Paranjape, to appear]

Summary of our results:

- Adapt subtracted recursion relations to any type of massless particle.
- Derived clean criterion for validity of subtracted recursion relations.
- Relation between soft behaviors of particles in a supermultiplet.
- Landscape of all possible fermion special EFTs.
- Study all possibilities of EFTs arising from *partially* broken supersymmetry.
- Accidental symmetries that arise in these EFTs.
- Analysis of supersymmetrizations of Galileon theories.

[HE, Hadjiantonis, Jones, Paranjape, arXiv:1712.09937 and to appear]

Reverse approach to field theory:
start with physical observables and deduce properties of underlying theories.

Thank you

Shruti Paranjape

Callum Jones

Marios Hadjiantonis

Happy Birthday, CTP!

Thank you for 3 formative postdoc years as a Pappalardo fellow and for many happy subsequent visits.