Beyond the Standard Model – (some) Theory Intro

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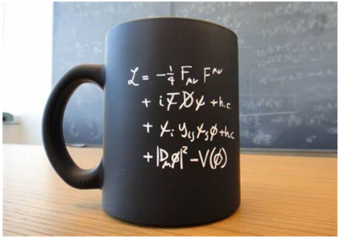

CPPS Center for Particle Physics Siegen

TP1 Theoretical Particle Physics

Ingredients of the SM Theory – and beyond?

Quantum field theory $\mathcal{L}[\phi_i(x), \partial_\mu \phi_i(x)]$	$\to$	quantum gravity ? string theory ?
Special relativity / Poincaré symmetry (3+1 flat space-time dimensions)	$\to$	(warped) extra dimensions ? SUSY ? low-energy imprints of gravity ? violation of Lorentz symmetry?
Gauge symmetries $SU(3)_C \times SU(2)_L \times U(1)_Y$	$\to$	GUTs ? leptoquarks ? heavier gauge bosons ?
3 generations of matter multiplets $Q_L, U_R, D_R, \ell_L, E_R$	$\to$	4th fermion generation ? right-handed neutrinos? DM candidates? exotic fermions ?
Spontaneous symmetry breaking from the VEV of a complex scalar Higgs doublet: $\phi = \left(H^+, H^0\right)\ , \quad \langle H^0 \rangle = v/\sqrt{2}$	$\to$	extended Higgs sector ? Little Higgs models ? dynamical symm. breaking (technicolor) ?
Yukawa couplings to the Higgs field $Y_U\,,\ Y_D\,,\ Y_E$ mass hierarchies, CKM mechanism	$\to$	new sources of flavour symm. breaking ? new sources of CP violation ? origin of neutrino masses ? charged-lepton flavour violation ?

Parameterizing the ”Beyond”

- ”Derive the SM” from a more fundamental underlying (renormalizable) theory ?
- Construct ”Simplified Models” that can address some of the above issues ?
- Consider the SM as a low-energy effective theory
  and include higher-dimensional operators (SM-EFT)

Confront with experimental data:

- Direct Searches for resonances and thresholds in decay spectra,
  due to production and decay of new particles at high energies
- Indirect Searches for deviations from SM predictions in low-energy observables
- measure decays that are forbidden in the SM (”Null Tests”)

More on SM-EFT

Generic rules of the EFT game:

- Identify/postulate the symmetries of the EFT Lagrangian, here:
  $SU(3) \times SU(2) \times U(1)$
- Identify/postulate the field/particle content, here:
  SM fermions, SM gauge bosons, SM Higgs doublet
- Organize the interaction terms as a power series, here:
  expansion in $v/\Lambda_{\rm NP} \ll 1$
  (SM = dim-4, "Weinberg operator" for Majorana neutrino masses at dim-5, many operators at dim-6)
- Assume generic values for dimensionless coefficients, here:
  2499 unknowns of $\mathcal{O}(1)$ at dim-6 ???
  (more than half of it related to flavour-specific couplings!)

Phenomenological Challenges

WHAT SHOULD BE THE TYPICAL SIZE OF THE NEW COUPLINGS IN SM-EFT

$$\mathcal{L}_{\rm SM-EFT} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm Weinberg}^{\rm dim-5} + \sum_{n=1}^{2499} \frac{c_n(\mu)}{\Lambda_{\rm NP}^2}\, \mathcal{O}_n^{\rm dim-6} + \ldots$$

- Allowing for anomalous couplings in the electroweak sector,
  how does this compare with electroweak precision measurements ?
  (imprints of the ”custodial symmetry” of the SM Higgs sector)
- Do neutrino masses stem from Weinberg operator?
  (violation of accidental lepton-number symmetry of the SM)
- Figure out hierarchies in flavour-specific couplings at dim-6?
  (relation to SM Yukawa matrices?)
- Couplings mix under renormalization
  (change of reference scale μ) !

Example for flavour-specific couplings

- four-fermion operators with two quark and two lepton fields in SMEFT: (→ LFU violation)

$$\frac{1}{\Lambda_{\rm NP}^2}\,[\mathcal{C}_{\ell q}]^{ij\alpha\beta}\,\left(\bar{Q}_i\gamma_\mu Q_j\right)\left(\bar{L}_\alpha\gamma^\mu L_\beta\right)$$

(for $i,j,\alpha,\beta = 1\ldots 3$ generations)

- flavour tensor $[\mathcal{C}_{\ell q}]^{ij\alpha\beta}$ introduces $3^4 = 81$ free parameters:

generic EFT:	all coefficients satisfy $\mathcal{C}_{\ell q}^{ij\alpha\beta} \sim \mathcal{O}(1)$ $\to$ flavour constraints require $\Lambda_{\rm NP}$ to be very high $\to$ or: 81 coefficients must be fine-tuned

MFV:	expansion: $\#1\left(\delta^{ij} + \#2\,(Y_U Y_U^\dagger)^{ij} + \#3\,(Y_D Y_D^\dagger)^{ij} + \ldots\right)\left(\delta^{\alpha\beta} + \ldots\right)$ $\to$ reduction to a few unknown numbers $\to$ inherits flavour hierarchies from SM $\to$ independent of flavour bases $\to$ self-consistent under renormalization $\to$ value of $\Lambda_{\rm NP}$ can be reasonably low

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	$\updownarrow$ alternatives ? $\updownarrow$
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Example: Simplified models with Leptoquarks

- four-fermion operators with two quark and two lepton fields in SMEFT: ($\to$ LFU violation)

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leptoquark exchange: $\mathcal{C}_{\ell q}^{ij\alpha\beta} \sim \#1\,(\Delta_{QL})^{i\beta}(\Delta^\dagger_{QL})^{\alpha j} + \ldots$

$\to$ reduction to $2\times 9 = 18$ parameters (leptoquark couplings)
$\to$ new leptoquark couplings also enter renormalization of SM Yukawa matrices
$\to$ requires self-consistency relations among Yukawas $Y_{U,D,E}$ and Δ_{QL}
$\to$ e.g. in the SM, we have $|Y_U^{ij}| \geq |(Y_D Y_D^\dagger Y_U)^{ij}|$
$\to$ now, also require $|Y_E^{\alpha\beta}| \geq |(\Delta^\dagger_{QL}\Delta_{QL}Y_E)^{\alpha\beta}|$

Self-consistency from Froggatt-Nielsen power-counting

- Easiest way to fulfill self-consistency relations via FN charges

$$
\begin{aligned}
(Y_U)^{ij} &\sim \lambda^{|b_Q^i - b_U^j|} \\
(Y_D)^{ij} &\sim \lambda^{|b_Q^i - b_D^j|} \\
(Y_E)^{\alpha\beta} &\sim \lambda^{|b_L^\alpha - b_E^\beta|} \\
(\Delta_{QL})^{i\alpha} &\sim \lambda^{|b_Q^i - b_L^\alpha|}
\end{aligned}
$$

  with generation-dependent FN charges b_X, and $\lambda \ll 1$
- Consistency relations automatically fulfilled due to triangle inequalities
- Different viable choices for FN charges to reproduce SM Yukawa hierarchies, where

$$
y_u \sim \lambda^{|b_Q^1 - b_U^1|} \quad \text{etc.} \qquad \theta_{ij}^{\text{CKM}} \sim \lambda^{|b_Q^i - b_Q^j|}
$$

(my personal) Lessons for Top-Bottom Connection

- Generic EFT is already spoiled by the SM Yukawas
- MFV is too special !
- Before adressing the SM-EFT flavour structure, we first have to understand the origin of the SM flavour hierarchies encoded in the Yukawa matrices !
- In the meantime, NP operators with bottom or top quarks have a priori independent coefficients, with no particular correlations between BSM effects in top or flavour observables !
- Keep in mind that any connection between BSM searches in the top or bottom sector is based on (more or less) ad-hoc model assumptions !

. . . but let's see how this works in practice . . .