Effective field theory approach to physics beyond standard model

廖益

华南师大量子物质研究院

合作者：马小东，王昊琳，梁锦汉

2023年BESIII新物理研讨会

Status of standard model in a few words

- No new particles found up to mass ~ 1 TeV $> \Lambda_{\mathrm{EW}} \approx 100\ \mathrm{GeV}$
  although some apparent tension exists between SM and expts.
  $\rightarrow$ SM phenomenologically very healthy
- Still, two practical issues remain to be addressed:
  $m_\nu < 1\ \mathrm{eV}$, believed to originate from phys well above Λ_{EW}
  If DM is of particle nature, SM cannot offer a candidate.
- There are more advanced theoretical challenges:
  flavor puzzle
  origin of electroweak symmetry breaking
  ……

Status of standard model in a few words

- Thus new phys is called for, which must involve particles of

  either mass $\gg \Lambda_{\mathrm{EW}}$

  $\longrightarrow$ not directly reachable at colliders

  or mass $\lesssim \Lambda_{\mathrm{EW}}$, interacting feebly with SM particles

  $\longrightarrow$ not yet detected in precision measurements

- Question:

  How to investigate new phys in such a circumstance?

Modern view of standard model

- All quantum field theories are effective field theories appropriate to a certain range of energy scales.
- SM is based on QFT.

  It should be considered the leading part of an EFT appropriate to

  $\mathrm{E} \leq \Lambda_{\mathrm{EW}}$.
- SM is successful because it parameterizes all possible interactions among known particles that are permitted by gauge symmetry.

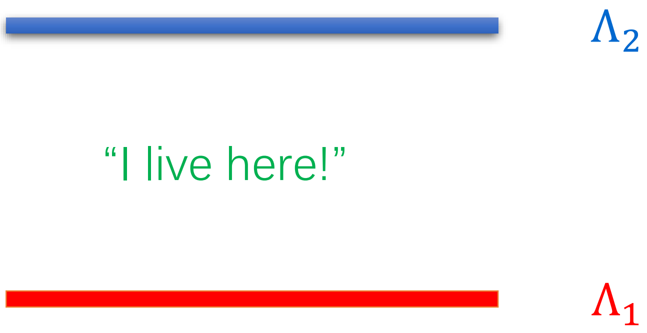
  It is self-contained in that it is "closed" under renormalization.

  — a very important property for

  self-consistency and predictability.

EFT： general discussion

- An EFT is an infinite tower of effective interactions organized by their relative importance.
- Given an accuracy expected for a measurement, only a finite number of effective interactions are important, which are also self-contained in a similar sense as in a renormalizable theory.
- An EFT defined in an energy range $\Lambda_1 < E < \Lambda_2$ is always a low-energy EFT relative to Λ_2.



EFT: general discussion

Three essential elements to specify an EFT:

- Dynamical degrees of freedom.

  — *what are prepared and produced?*

- Symmetries as a guiding principle for constructing interactions.

  — *most sacred are gauge symmetries and dynamically broken symmetries*

- A power counting rule telling what would be more important.

  — *low-energy EFT: importance decreases with increasing power of*

  p/Λ_2 *in amplitude* $\leftrightarrow$ ∂/Λ_2 *in Lagrangian*

➡

✓ to establish a basis of effective interactions/operators
at each order in low-energy expansion;

✓ to renormalize them to improve perturbation calc, i.e., RGE

EFT: general discussion

- Usually, the characteristic scale of a physical process lies well below the scale at which the mechanism for the process occurs.

  — *a sequence of EFTs is required to connect data with physical origin*

→ matching is required at the boundary of two neighboring EFTs to connect them

- Two types of matching:

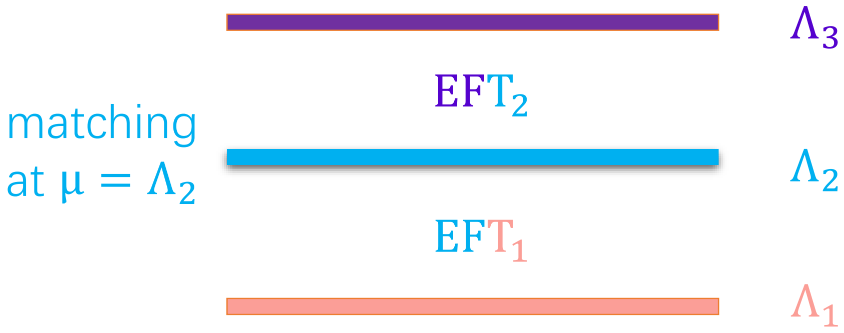
✓Strong dynamics involved

— completely new dynamical DoFs appear,

e.g., chiral symmetry breaking in QCD at Λ_χ

✓Perturbative interactions only

— from $\mu > \Lambda_2$ to $\mu < \Lambda_2$, integrate out heavy fields of mass $O(\Lambda_2)$.



Λ_3

EFT_2

matching at $\mu = \Lambda_2$

Λ_2

EFT_1

Λ_1

How EFT works: $K^- \to \pi^+ l^- l^-$

The process occurs at $\mu \sim 10^2$ MeV.

It violates lepton number

— its mechanism is new phys at $\mu \gg \Lambda_{\mathrm{EW}}$

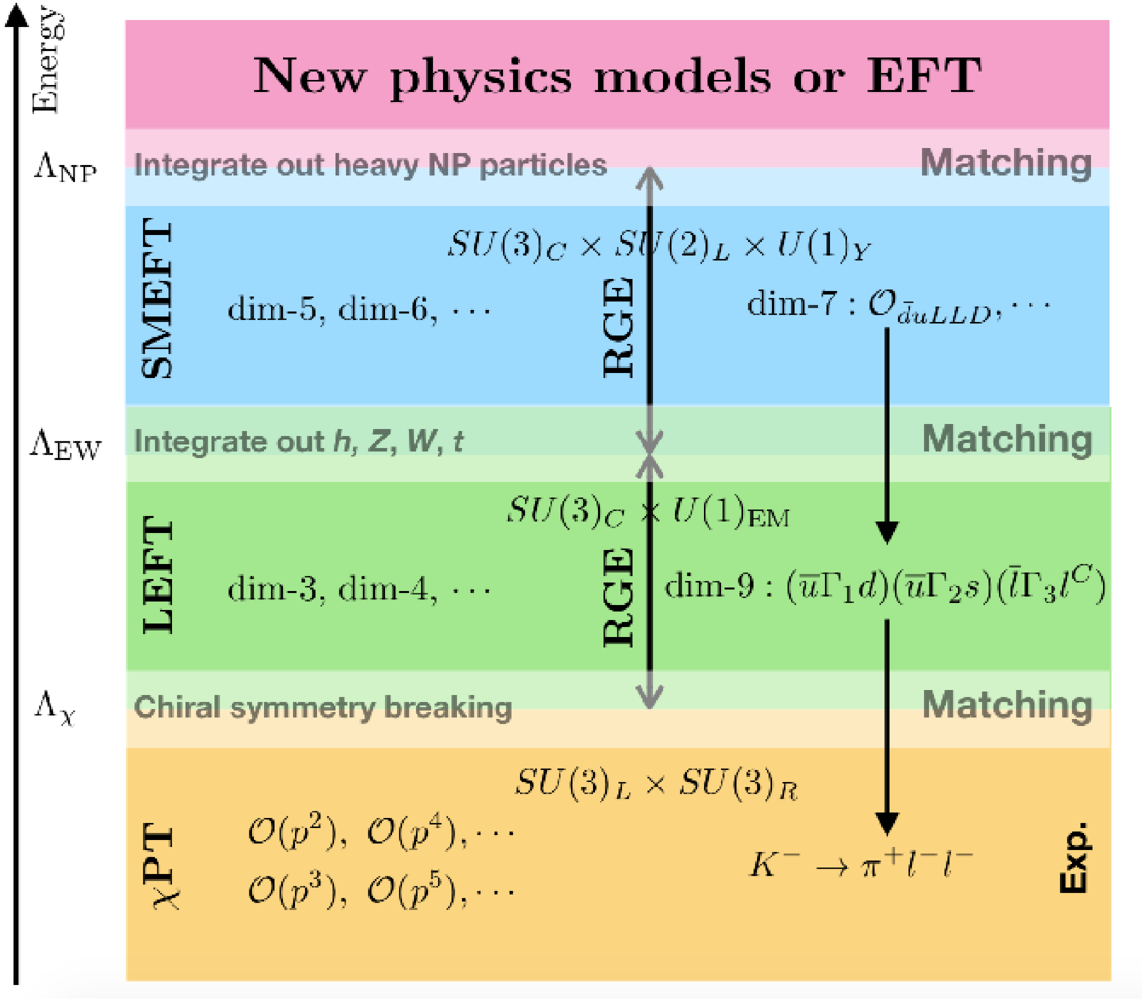
→ a sequence of EFTs required
to connect them

- A sequence of EFTs: SMEFT, LEFT, χPT

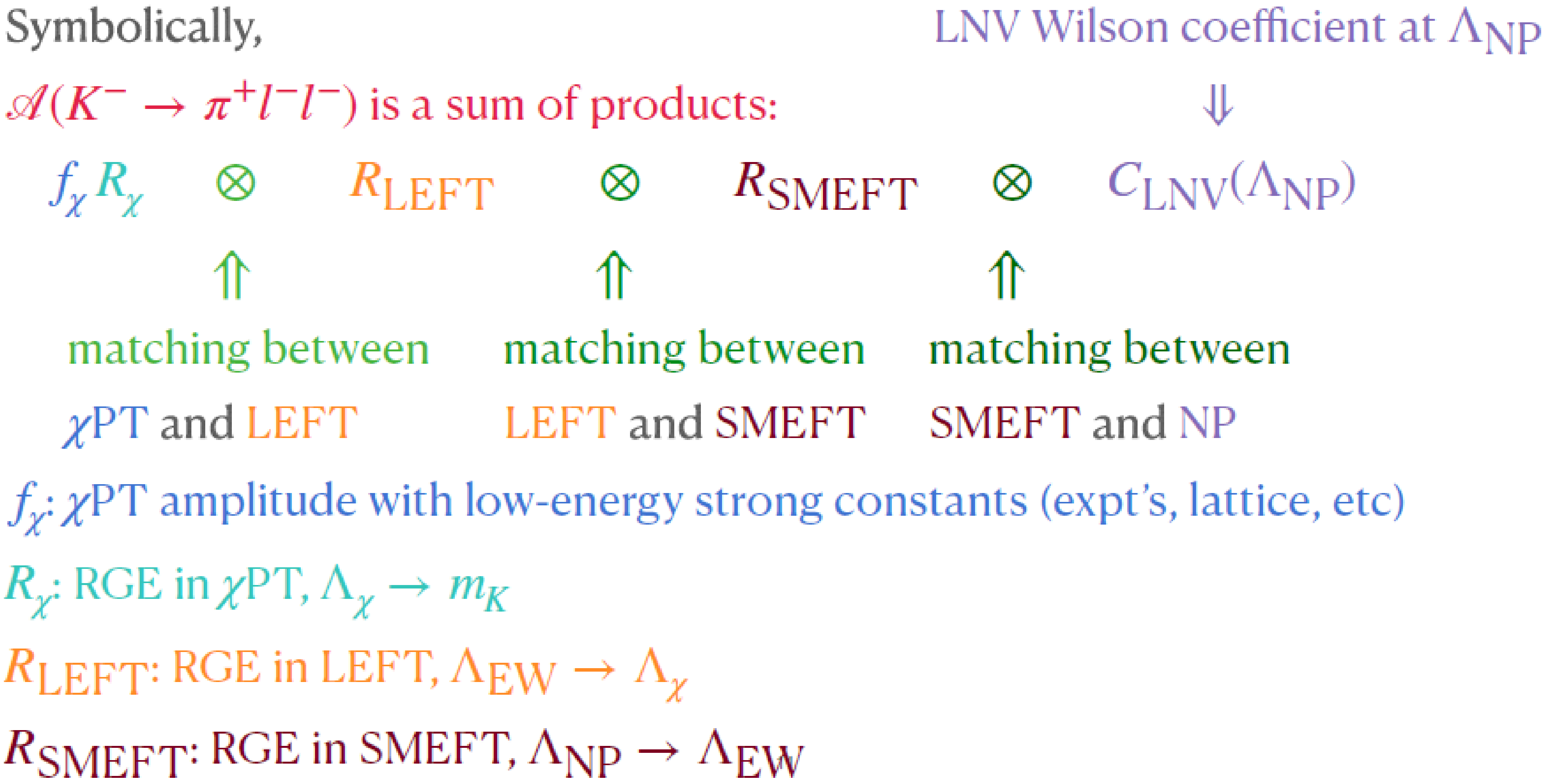
✓Bases of operators and RGE in each EFT;

✓Matching between SMEFT and LEFT,
and between LEFT and χPT.

- Matching between SMEFT and
your desired new phys model.



How EFT works: $K^- \to \pi^+ l^- l^-$



Symbolically,

LNV Wilson coefficient at Λ_{NP}

$\mathscr{A}(K^- \to \pi^+ l^- l^-)$ is a sum of products:

$\Downarrow$

$$f_\chi R_\chi \quad \otimes \quad R_{\text{LEFT}} \quad \otimes \quad R_{\text{SMEFT}} \quad \otimes \quad C_{\text{LNV}}(\Lambda_{\text{NP}})$$

$$\Uparrow \qquad\qquad \Uparrow \qquad\qquad \Uparrow$$

matching between χPT and LEFT

matching between LEFT and SMEFT

matching between SMEFT and NP

f_χ: χPT amplitude with low-energy strong constants (expt's, lattice, etc)

R_χ: RGE in χPT, $\Lambda_\chi \to m_K$

R_{LEFT}: RGE in LEFT, $\Lambda_{\text{EW}} \to \Lambda_\chi$

R_{SMEFT}: RGE in SMEFT, $\Lambda_{\text{NP}} \to \Lambda_{\text{EW}}$

I’ll focus on field theoretical aspects
and only indicate possible phenomenology.

Episode 1:
No new light particles

Below some $\Lambda_{\mathbf{NP}}$, we are coping exclusively with SM particles.

Interactions among SM particles are effective in the sense that they may originate from any high energy scale physics as well as the SM itself.

Guiding principles for these effective interactions:
Known, confirmed symmetries, like gauge sym and dynamical sym appropriate to the range of energy under consideration,
e.g., no assumption on lepton (L)/baryon (B) number conservation.
Power counting rule to keep/discard effective interactions.

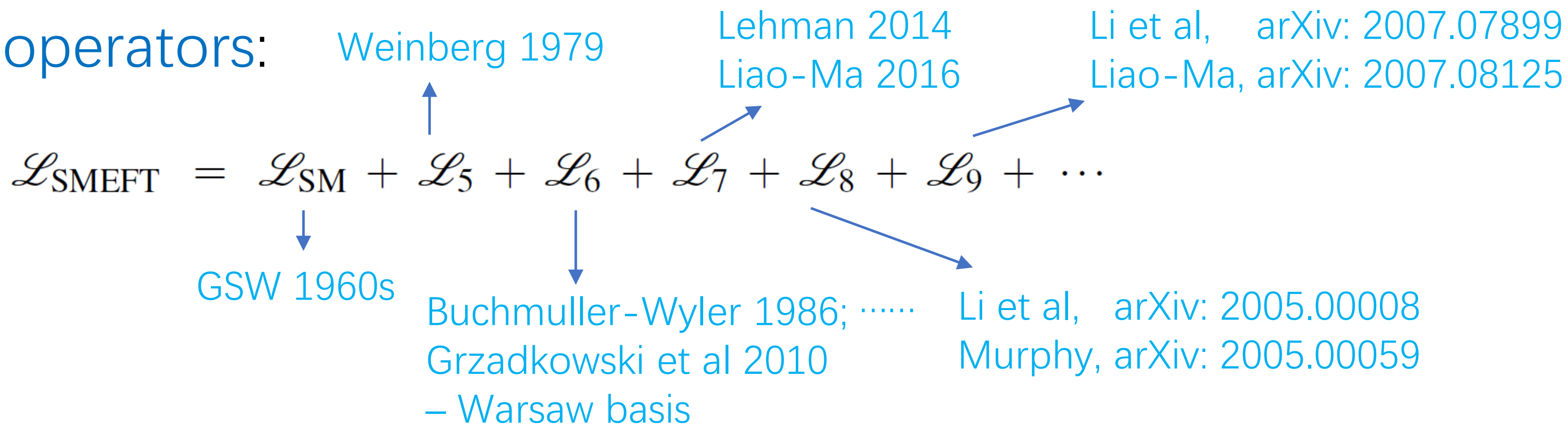
Precision measurements of processes allowed by SM or breaking conservation laws like L/B.

Standard model EFT (SMEFT)

Defined between Λ_{NP} and Λ_{EW}:

- Dynamical degrees of freedom (DoFs) restricted to SM fields;
- Symmetries – $SU(3)_C \times SU(2)_L \times U(1)_Y$, no L or B conservation requirement etc;
- Power counting – expansion in p/Λ_{NP}.

SMEFT is an infinite tower of effective interactions involving higher and higher dimensional operators:



Weinberg 1979

Lehman 2014
Liao-Ma 2016

Li et al, arXiv: 2007.07899
Liao-Ma, arXiv: 2007.08125

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \mathscr{L}_8 + \mathscr{L}_9 + \cdots$$

GSW 1960s

Buchmuller-Wyler 1986; ……
Grzadkowski et al 2010
– Warsaw basis

Li et al, arXiv: 2005.00008
Murphy, arXiv: 2005.00059

Latest: up to dim-12, Harlander et al, 2305.06832

Summary of physics interest in SMEFT

dim-5

Majorana m_ν, *standard mass mechanism* for $0\nu\beta\beta$ decay.

dim-6

rich phenomenology both at colliders and in low energy experiments

usual proton decay $p \to e^+\pi^0$ with $B - L$ conserved

dim-7

phenomenology limited to L- (and B-) violating phys —

unusual proton decay $p \to \nu\pi^+$ with $B + L$ conserved

various long- and short-range contri. to $0\nu\beta\beta$, $M_1^- \to M_2^+ l^- l^-$, $\tau^- \to l^+ M_1^- M_2^-$, etc

dim-8

mostly conserve L and B, others break $\Delta B = \Delta L = 1$

phenomenology partly explored, mainly with bosonic operators:

electroweak precision data, triple gauge couplings, diboson production

dim-9

various fate concerning $L,\ B$ conservation/violation

phenomenology partly done: $0\nu\beta\beta$ decay, $n - \bar{n}$ oscillation, rare nucleon decays

SMEFT: higher-dim operators less important?

- Generally yes, barring one caveat.
- L- or B-violating effects are much smaller than conserving effects

  → L or B violation should originate at a higher scale

  → Wilson coeffs. for operators of different L or B pattern cannot be compared in a model-independent manner.
- General results on L or B pattern in SMEFT:

Kobach, 2016

✓ $(\Delta B - \Delta L)/2$ and dimension d of an operator share the same odd or even nature.

✓ Imposing flavor symmetry postpones occurrence of L or B violation at a higher d:

L or B violation impossible for $d < 9$ except for $|\Delta L| = 2$;

Helset and Kobach, 2019

e.g., proton decay severely suppressed:

$d = 9$: 2 operators involve $3l3q$ but necessarily with c or t → tree level impossible

$d = 10$: 4-body decay with $\Delta B = -\frac{\Delta L}{3} = 1$; $d = 11$: 3-body decay with $\Delta B = \frac{\Delta L}{3} = 1$

Low-energy EFT（LEFT）

When $E < \Lambda_{\mathrm{EW}}$, electroweak SSB manifests itself.

Heavy particles $(h, W^{\pm}, Z^{0}, t)$ of mass $\sim\Lambda_{\mathrm{EW}}$ are integrated out → LEFT

Defined between Λ_{EW} and $\Lambda_{\chi} \sim 1\ \mathrm{GeV}$:

- Dynamical DoFs = SM fields other than above heavy ones;
- Symmetries – $SU(3)_C \times U(1)_Q$;
- Power counting – expansion in p/Λ_{EW}.

Actually well applied in the past, e.g., in b phys, although not studied systematically.

Jenkins et al, 2017

Murphy, 2020

$|\Delta L| = 2$ sector:
Liao et al, 2019

$$\mathscr{L}_{\mathrm{LEFT}} = \mathscr{L}_{\nu} + \mathscr{L}_{\mathrm{QED}} + \mathscr{L}_{\mathrm{QCD}} + \mathscr{L}_{5} + \mathscr{L}_{6} + \mathscr{L}_{7} + \mathscr{L}_{8} + \mathscr{L}_{9} + \cdots$$

Liao et al, 2020

Li et al, 2020

Attention: combined power counting in $1/\Lambda_{\mathrm{EW}}$ and $1/\Lambda_{\mathrm{NP}}$

Episode 2:
One new light particle

It could be stable DM if it is restricted to, e.g., pair interactions with SM particles, which respects a Z2 symmetry.

Or, it is not protected by a symmetry but could be long-lived by arranging an appropriate mass range or feeble interactions with SM particles.

Could be any spin:
scalar (axion or axion-like), fermion including sterile neutrino, vector including dark photon

Phenomenology depends strongly on its mass range.

Typical at BES: missing energy

Summary of the literature (incomplete)

- SMEFT with sterile neutrinos, now called νSMEFT, up to dim 7 Liao-Ma 1612.04527
- SMEFT with a real/complex scalar, or a Dirac/Majorana fermion, stabilized by some dark symmetry, up to dim 7 Brod et al 1710.10218

  Assuming lighter than Λ_{EW}, also matched to LEFT
- SMEFT with a DM particle of spin 0, 1/2, or 1, that belongs to a multiplet of SM and is stabilized by a Z2, up to dim 6 Criado et al 2104.14443
- SMEFT with an axion-like particle, Majoron, or dark photon, up to dim 8, assuming Nambu-Goldstone nature Song et al 2305.16770

  SMEFT with a singlet scalar, fermion, or vector, protected by a Z2, or related by shift symmetry to the above particles Song et al 2306.05999

- LEFT with a spin 3/2, Z2 protected DM particle interacting with SM fermions

  Yu et al 1112.6052, Ding-Liao 1201.0506

  SMEFT with a singlet, spin 3/2, Z2 protected DM particle interacting with SM fermions Ding et al 1302.4034

Brief discussion of two topics

- νSMEFT:SMEFT extended with sterile neutrinos of mass $\leq \Lambda_{\text{EW}}$

✓ Sterile neutrino N introduces new operators in effective Lagrangian:

dim ≤ 4: kinetic, Majorana mass, and Yukawa terms

dim $=$ 5: $\overline{N^C} N H^\dagger H$, $\overline{N^C} \sigma_{\alpha\beta} N B^{\alpha\beta}$

✓ Bases of dim-6, -7 operators completed in Liao-Ma 1612.04527

various cases of baryon and lepton number violation

✓ Extended further up to dim-9 operators in Li et al 2105.09329

✓ Rich phenomenology in low energy processes, typically as missing energy

vast literature on this topic.

- Spin-3/2 DM

✓ Comprehensive analysis seems not yet available.

✓ Pheno roughly explored.

Episode 3:
Two new light particles

General discussion

- Why more than one new light particles?

  No definite argument for or against it.

  It is natural to relate new particles to DM or origin of neutrino mass.

  Multi-component DM is a viable option to avoid various severe constraints.

  Or, there is a dark sector in parallel to the visible sector, and DM is the lightest dark particle.

- Preliminary study on effective interactions between dark and SM fields in the presence of a spin 0, 1/2, and 1 dark fields. Gonzalez Macisa-Wudka 1506.03825

  First systematic analysis up to dim 6 in both SMEFT and LEFT extended with dark fields each of spin 0, 1/2, or 1; matching between DSMEFT and DLEFT.

  Aebischer et al 2202.06968

Dark sector EFT Liang et al 2309.12166

Start from the next-to-the simplest.

Assume two dark fields of mass $\leq \Lambda_{\mathrm{EW}}$ for each spin:

spin 0: S, ϕ spin 1/2: χ, ψ spin 1: X, V

In the framework of LEFT extended with the above fields, consider effective interactions between a pair of *different* dark fields and SM fields:

$S\phi - \mathrm{SM}$, $\chi\psi - \mathrm{SM}$, $XV - \mathrm{SM}$;

$\phi\chi - \mathrm{SM}$, $\phi X - \mathrm{SM}$, $\chi X - \mathrm{SM}$.

These interactions respect a Z2 symmetry, which may be broken by single-dark-SM interactions.

Bases of complete and independent operators are established up to dim 7.

Dark sector EFT: neutron lifetime anomaly

- Anomaly: two types of measurements yield different answers

  bottle-type: $1/\Gamma_n^{\text{tot}} = (878.3 \pm 0.3)\ \text{sec}$

  beam-type: $1/\Gamma_n^{\beta} = (888 \pm 2)\ \text{sec}$

- Possible way-out: neutron dark decay escapes beam detection, i.e.,

$$\Gamma_n^{\text{dark}} = \Gamma_n^{\text{tot}} - \Gamma_n^{\beta} = (8.184 \pm 1.688)10^{-30}\ \text{GeV}$$

- Explanations in dark sector EFT:

  either $\phi\chi - \text{SM}$ or $\chi X - \text{SM}$ interactions induce the dark decay $n \to \phi\chi$ or χX

Typical at BES: invisible decay

Dark sector EFT: $n \to \phi\chi$

- Effective interactions from operator basis:

$$O^{VV} = \epsilon^{ijk}(\bar{\chi}\gamma_\mu u_i)(\overline{d_j^C}\gamma^\mu d_k)\ \phi, \qquad O^{AV} = \epsilon^{ijk}(\bar{\chi}\gamma_\mu\gamma_5 u_i)(\overline{d_j^C}\gamma^\mu d_k)\ \phi$$

$$O^{T1} = \epsilon^{ijk}(\bar{\chi}\sigma_{\mu\alpha} u_i)(\overline{d_j^C}\sigma^{\mu\alpha} d_k)\ \phi, \qquad O^{T2} = \epsilon^{ijk}(\bar{\chi}\sigma_{\mu\alpha}\gamma_5 u_i)(\overline{d_j^C}\sigma^{\mu\alpha} d_k)\ \phi$$

equivalent by Fierz identities to the set of operators:

$$O^{LR} = \epsilon^{ijk}(\bar{\chi}P_L d_i)(\overline{d_j^C}P_R u_k)\ \phi, \qquad O^{RL} = \epsilon^{ijk}(\bar{\chi}P_R d_i)(\overline{d_j^C}P_L u_k)\ \phi$$

$$O^{LL} = \epsilon^{ijk}(\bar{\chi}P_L d_i)(\overline{d_j^C}P_L u_k)\ \phi, \qquad O^{RR} = \epsilon^{ijk}(\bar{\chi}P_R d_i)(\overline{d_j^C}P_R u_k)\ \phi$$

relations between Wilson coefficients in two sets of operators:

$$C^{LR} = 4(C^{VV} + C^{AV}), \quad C^{RL} = 4(C^{VV} - C^{AV})$$

$$C^{LL} = 8(C^{T1} - C^{T2}), \quad C^{RR} = 8(C^{T1} + C^{T2})$$

- Nucleon matrix elements:

$O^{\Gamma\Gamma'} = \bar{\chi}N^{\Gamma\Gamma'}\phi$ with $\Gamma, \Gamma' = L, R$, $\quad N^{\Gamma\Gamma'} = \epsilon^{ijk}P_\Gamma d_i \overline{d_j^C}P_{\Gamma'}u_k$, $\quad \langle 0|N^{\Gamma\Gamma'}|n\rangle = \alpha_n^{\Gamma\Gamma'}P_\Gamma u_n$

parity conservation: $\alpha_n^{\mathrm{LR}} = -\alpha_n^{\mathrm{RL}},\ \alpha_n^{\mathrm{LL}} = -\alpha_n^{\mathrm{RR}}$

lattice QCD: $\alpha_n \equiv \alpha_n^{\mathrm{LR}} = -\alpha_n^{\mathrm{LL}} = -0.0144(3)(21)\ \mathrm{GeV}^3$ Aoki et al 1705.01338

Dark sector EFT: $n \to \phi\chi$

- Dark decay width:

$$\Gamma=\frac{\alpha_n^2\lambda^{\frac{1}{2}}(m_n^2,m_\chi^2,m_\phi^2)}{\pi m_n^3}\{\Lambda_a^{-6}[(m_n - m_\chi)^2-m_\phi^2]+\Lambda_b^{-6}[(m_n + m_\chi)^2-m_\phi^2]\}$$

$$\Lambda_a = |C^{VV} - 2C^{T1}|^{-1/3},\ \Lambda_b = |C^{AV} + 2C^{T2}|^{-1/3}$$

- Constraint from nuclear stability, best for beryllium:

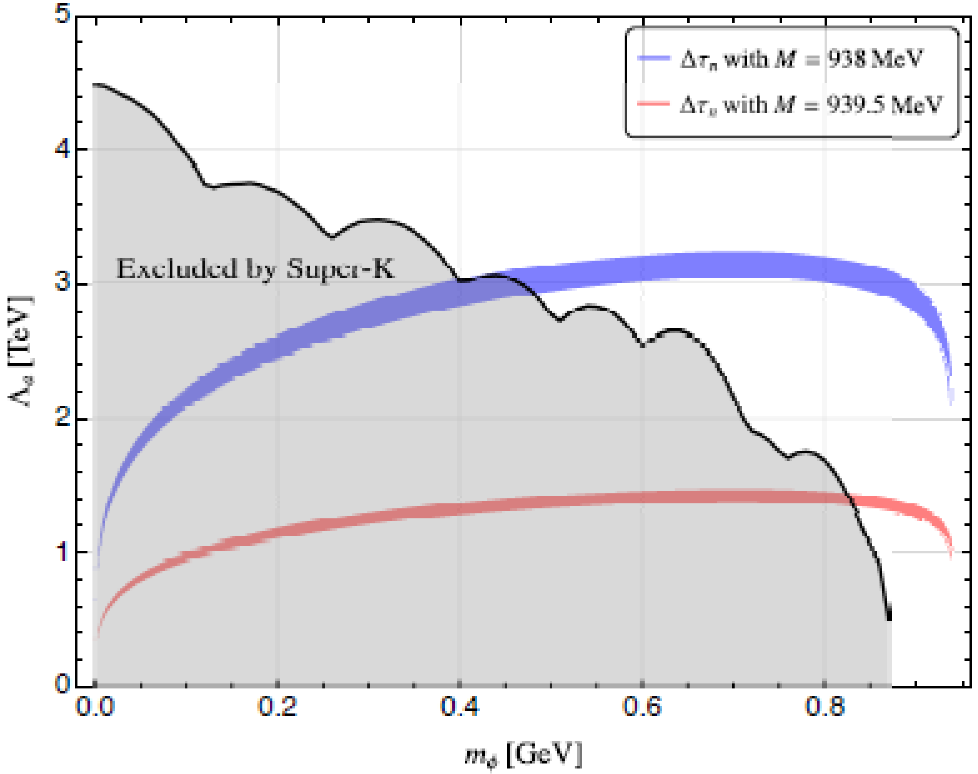
$$937.900\,\mathrm{MeV} < M \equiv m_\chi + m_\phi < 939.565\,\mathrm{MeV}$$ Fornal-Grinstein 1801.01124

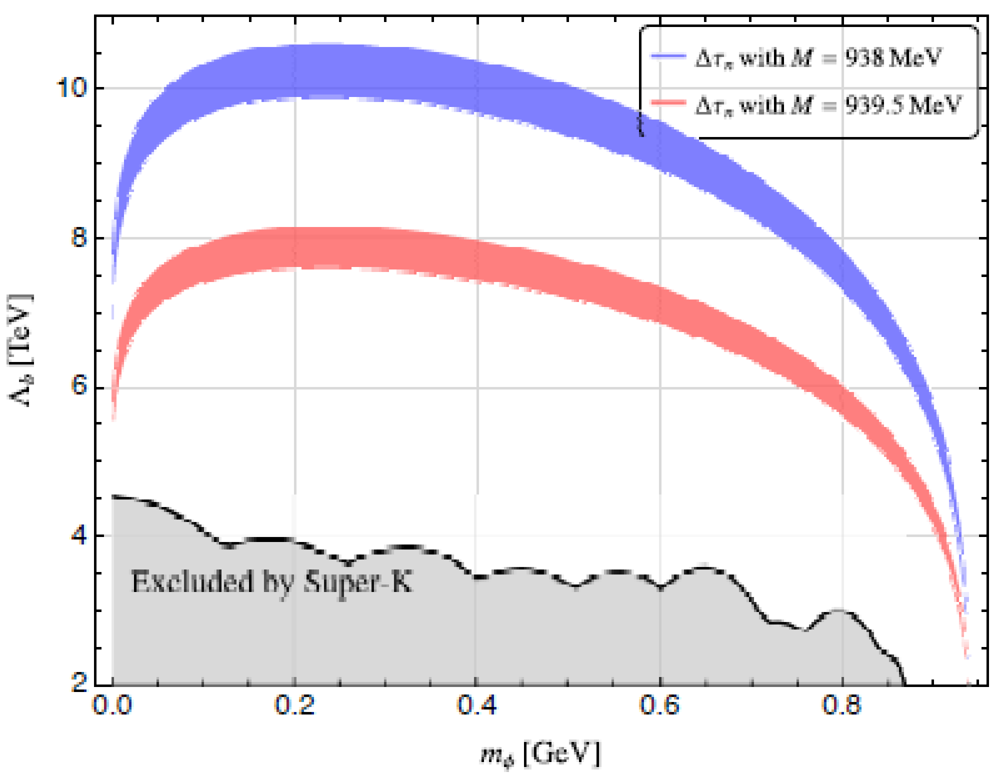
- With above constraint dark particles are stable.

  Assuming χ as DM, effective interactions are constrained by DM-n annihilation $\chi + n \to \phi + \pi^0$ at Super-K.

  Theoretical analysis detail skipped.

Dark sector EFT: $n \rightarrow \phi\chi$





Dark sector EFT: $n \to \chi X$

- Eight effective interactions can contribute. They contribute to the decay amplitude in two sets whose Wilson coefficients combine to

$$\begin{aligned} C^a_{\chi X} &\equiv \frac{1}{2}(C^{\mathrm{LRR}}_{\chi X} - C^{\mathrm{LLL}}_{\chi X} - C^{\mathrm{RLL}}_{\chi X} + C^{\mathrm{RRR}}_{\chi X}) = C^{\mathrm{PV}}_{\chi X} - 3C^{\mathrm{T2V}}_{\chi X} + 2C^{\mathrm{AT1}}_{\chi X} + 2C^{\mathrm{VT2}}_{\chi X}, \\ C^b_{\chi X} &\equiv \frac{1}{2}(C^{\mathrm{LRR}}_{\chi X} - C^{\mathrm{LLL}}_{\chi X} + C^{\mathrm{RLL}}_{\chi X} - C^{\mathrm{RRR}}_{\chi X}) = C^{\mathrm{SV}}_{\chi X} - 3C^{\mathrm{T1V}}_{\chi X} - 2C^{\mathrm{VT1}}_{\chi X} - 2C^{\mathrm{AT2}}_{\chi X}. \end{aligned}$$

- With same nucleon matrix elements, the decay width is,

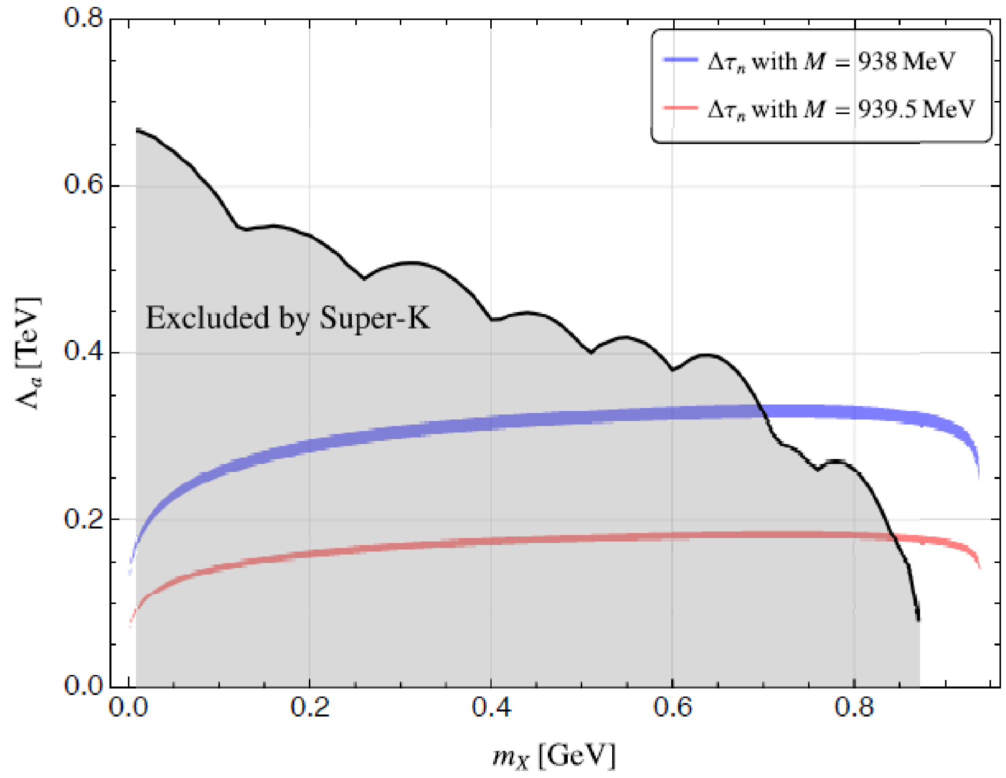
$$\Gamma_{n\to\chi X} = \frac{\alpha_n^2 \lambda^{\frac{1}{2}}(m_n^2, m_\chi^2, m_X^2)}{16\pi m_n^3}\left(\frac{F_a}{\Lambda_a^8} + \frac{F_b}{\Lambda_b^8}\right)$$

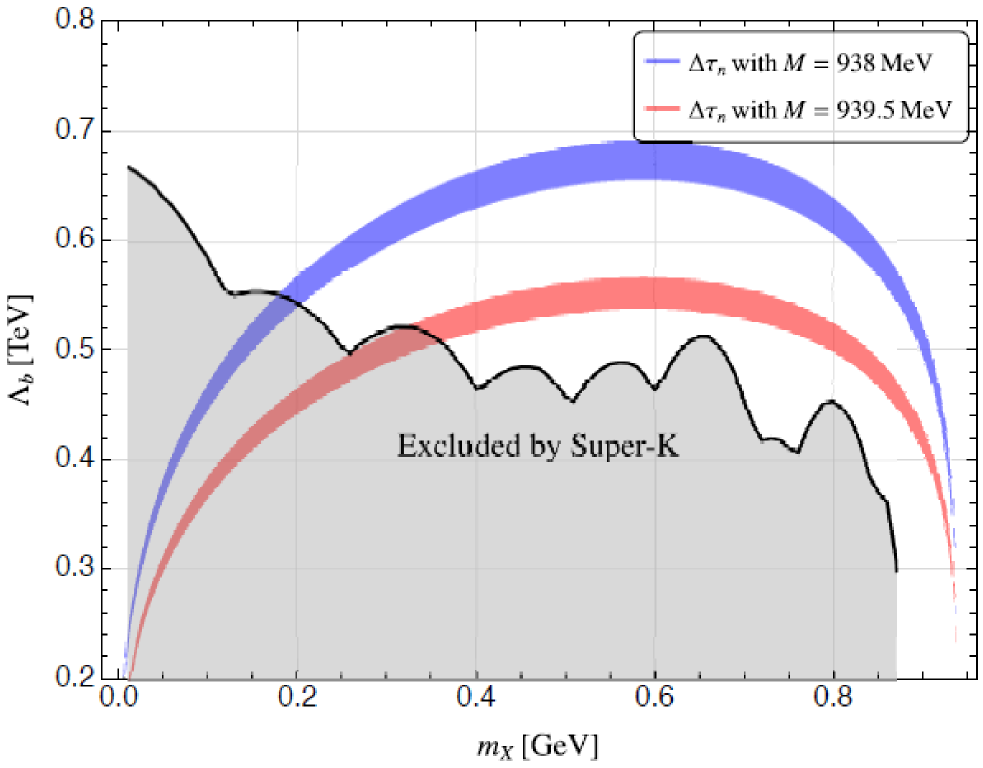
$$F_{a,b} = [(m_n \pm m_\chi)^2 + 2m_X^2][(m_n \mp m_\chi)^2 - m_X^2]$$

$$C^a_{\chi X} \equiv m_X/\Lambda_a^4 \text{ and } C^b_{\chi X} \equiv m_X/\Lambda_b^4$$

Similar analysis on DM-n annihilation as in $\phi\chi$ case.

Dark sector EFT: $n \to \chi X$





Summary

- EFT is a systematic framework to study low energy effects of physics beyond SM.

  It is universal to a large set of UV theories with minimal assumptions on the latter.

  Matching EFT with a specific UV theory yields correlated Wilson coefficients.
- Assuming no new light particles of mass $\leq \Lambda_{\mathbf{EW}}$, this is SMEFT with all EFTs descending from it.

  Theoretical framework is well established, with some matching and RGE to be done.
- Assuming existence of new light particles, one works with extended versions of the above EFTs. They are relatively less developed.
- With a series of EFTs from the scale where physics originates down to the scale where physical effects are measured, we can collect all experimental eggs in one basket with little risk.
- For physics at BES the main theoretical uncertainty is hadronic models which I try to avoid in ongoing study.