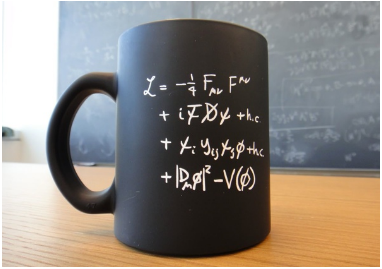
The Unreasonable Effectiveness of Quantum Field Theory

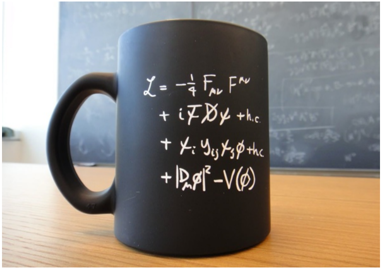
M. Beneke (TU München)

On the occasion of the Julius Wess Award to Prof. Mark Wise
KIT, November 05, 2021


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

量子场论

Standard Model and the Principles of Quantum Field Theory

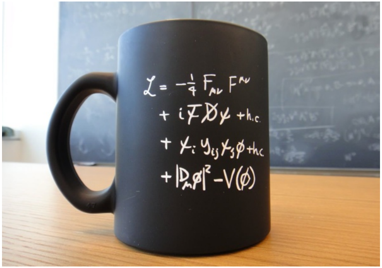


- Relativity
- Quantum
- Action

Data: Fields ψ_i and symmetries

$\hookrightarrow \quad \mathcal{L}(\psi_i; g_k)$

Effective Quantum Field Theory

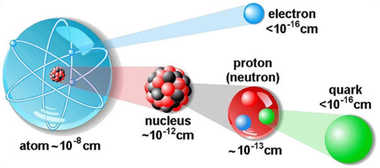


- More than a framework to describe fundamental laws of Nature
- Local fields and interactions must be thought of as approximations
- Descriptions of Nature at a given scale

$$\hookrightarrow \quad \mathcal{L}(\psi_i; g_k; \mu)$$

Expansion in a series of local terms valid for $\mu < \Lambda$.

Effective Quantum Field Theory



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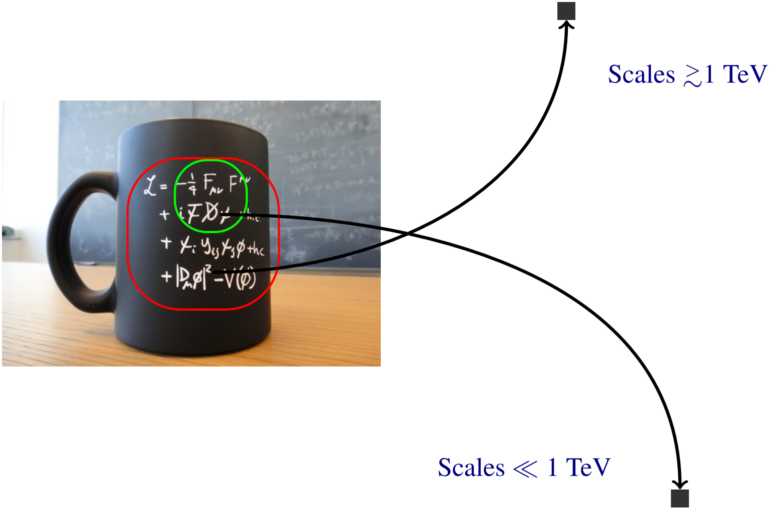
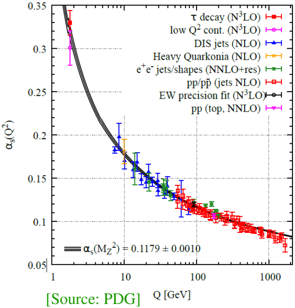
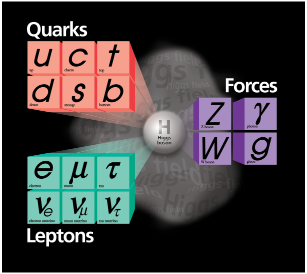


The strong interaction, quantum chromodynamics

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} + \sum_{\psi=q,Q} \bar\psi i \not{D}\psi - \sum_{q=u,d,s} m_q \bar q q - \sum_{Q=c,b,t} m_Q \bar Q Q$$

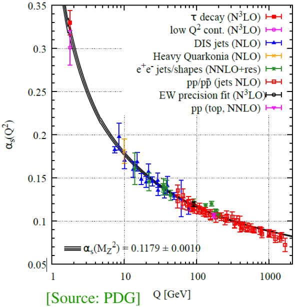


[Source: PDG]



The strong interaction, quantum chromodynamics

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} + \sum_{q=u,d,s} (\bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R) - \sum_{q=u,d,s} m_q (\bar{q}_L q_R + \bar{q}_R q_L)$$



[Source: PDG]

$$\langle \bar{q}_L q_R \rangle \neq 0$$

Strong dynamics breaks chiral SU(3)$\times$ SU(3) symmetry spontaneously. Goldstone bosons π^a.

The strong interaction, quantum chromodynamics

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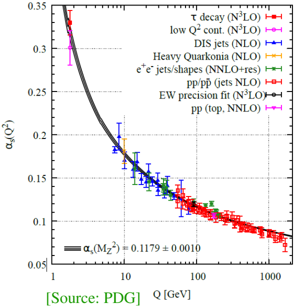

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$\langle \bar q_L q_R\rangle \neq 0$

Strong dynamics breaks chiral SU(3)× SU(3) symmetry spontaneously. Goldstone bosons π^a.

For $\mu \lesssim 0.5\,$GeV:

$$\mathcal{L}^{\rm eff}_{\rm QCD} = \frac{f_\pi^2}{4}\,{\rm tr}\left(\partial^\mu\Sigma^\dagger\partial_\mu\Sigma\right) + \sum_i \frac{L_i}{\Lambda^2}\,{\rm tr}\left(\partial^2\Sigma^\dagger\partial^2\Sigma\right) + \ldots \qquad \left(\Sigma = e^{2i\pi/f_\pi}\right)$$

[Weinberg 1979; Gasser, Leutwyler 1984]

Chiral Effective Field Theory

	χEFT
UV	strongly coupled non-perturbative matching
IR	weakly coupled symmetry breaking

$$\mathcal{L}_{\mathrm{QCD}}[A, q]$$

$$\downarrow$$

$$\mathcal{L}_{\chi\mathrm{EFT}}[\pi]$$

Heavy Quarks & Heavy Quark Symmetry

Charm quark discovered in 1974, bottom quark in 1977, B-mesons 1983.

$$\mathcal{L}_{\text{QCD}}^{\text{heavyQ}} = \sum_{q=c,b} (\bar{Q} i \not{D} Q - m_Q \bar{Q} Q)$$

$m_Q \gg \Lambda$. What happens for $m_Q \to \infty$?

[Isgur, Wise 1989; Shifman, Voloshin, late 80s]

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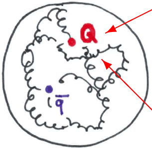
$Q = b$ or c



$\Longrightarrow$ SU(2) flavour symmetry

Soft gluons don't probe the mass of a heavy object

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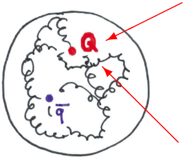
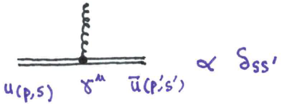
Spin ↑ or ↓



$\Longrightarrow$ SU(2) spin symmetry

Soft gluons don't flip
the spin of a heavy object



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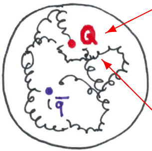

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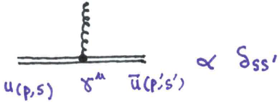
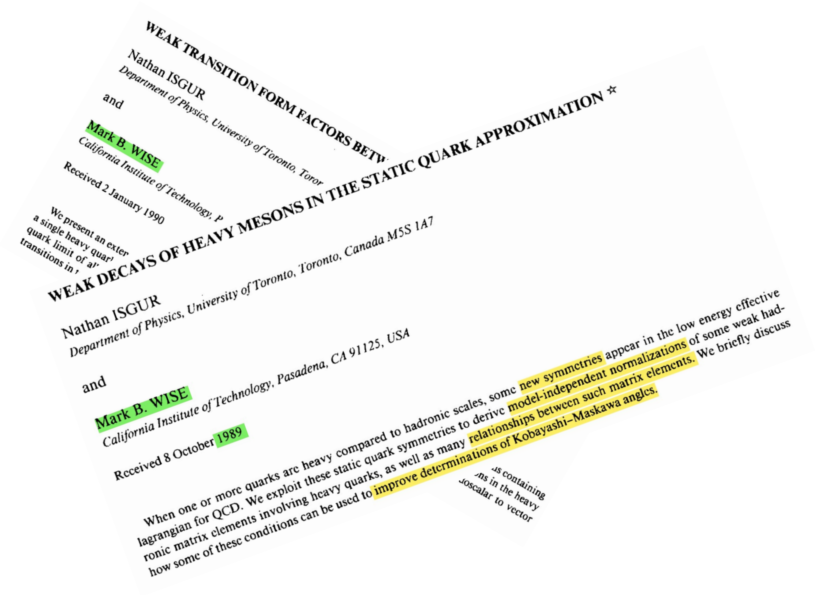


$\hookrightarrow$ Emergent spin-flavour symmetry at low energies $E \ll m_Q$ that relates different strongly coupled systems

The Birth of Heavy Quark Symmetry



WEAK TRANSITION FORM FACTORS BETW…

Nathan ISGUR
Department of Physics, University of Toronto, Toror…

and

Mark B. WISE
California Institute of Technology, P…

Received 2 January 1990

We present an exter… a single heavy quar… quark limit of al… transitions in …

…is containing …ns in the heavy …oscalar to vector

WEAK DECAYS OF HEAVY MESONS IN THE STATIC QUARK APPROXIMATION ☆

Nathan ISGUR
Department of Physics, University of Toronto, Toronto, Canada M5S 1A7

and

Mark B. WISE
California Institute of Technology, Pasadena, CA 91125, USA

Received 8 October 1989

When one or more quarks are heavy compared to hadronic scales, some new symmetries appear in the low energy effective lagrangian for QCD. We exploit these static quark symmetries to derive model-independent normalizations of some weak hadronic matrix elements involving heavy quarks, as well as many relationships between such matrix elements. We briefly discuss how some of these conditions can be used to improve determinations of Kobayashi–Maskawa angles.

Heavy Quark Effective Field Theory

$$\mathcal{L}_{\rm QCD}^{\rm heavyQ} = \sum_{q=c,b} (\bar{Q} i \not{D} Q - m_Q \bar{Q} Q)$$

remove

$$Q(x) = e^{-im_Q v\cdot x}\,(h_v + H_v)$$

$$\not{v} h_v = h_v \qquad (v = \text{ velocity of quark})$$

Eliminate part of the field and short-distance fluctuations

$$\mathcal{L}_{\rm HQET} = \sum_i \bar{h}_v\, iv\cdot D\, h_v + \mathcal{O}(1/m_Q)$$

[Eichten, Hill; Georgi 1990]

Chiral EFT vs. HQET

	χEFT	HQET
UV	strongly coupled non-perturbative matching	weakly coupled perturbative matching
IR	weakly coupled symmetry breaking	strongly coupled emergent symmetry

Chiral EFT vs. HQET

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UV	strongly coupled non-perturbative matching	weakly coupled perturbative matching
IR	weakly coupled symmetry breaking	strongly coupled emergent symmetry

- Effective QFT as a tool to construct a systematic expansion in Λ/m_Q of a known theory + ...
- ... new non-perturbative symmetry relations

- Do not eliminate the field completely, only certain fluctuations.

  Effective QFT as a tool to construct a systematic expansion in a certain kinematic limit.

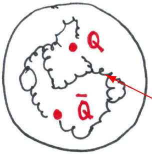
$$h_v \quad \leftarrow \quad \text{kinematic label } v$$

- Use UV renormalization and renormalization group methods to solve an infrared problem of the original theory efficiently.

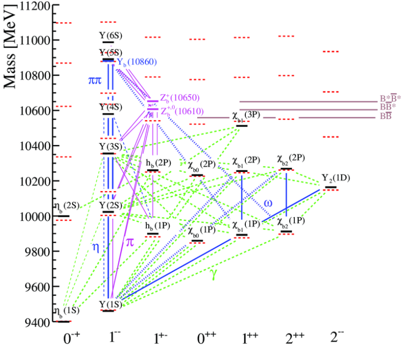
  ↪ anomalous dimensions depend on kinematic variables, e.g. $v \cdot v'$, because IR logs do

Non-relativistic effective field theory

Caswell, Lepage (1986)



$Q = b$ or c
or e^-, μ^-



[Source: Olsen et al, 1708.04012]

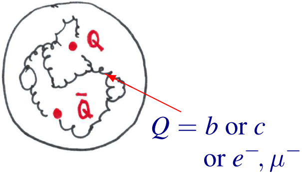
$$m_Q, \Lambda \quad \longrightarrow \quad m_Q, m_Q v, m_Q v^2$$

Quantum fluctuations at different scales — potential, soft, ultrasoft — cause distinct physical effects

Non-relativistic effective field theory

Pineda, Soto; Labelle; Luke, Manohar; Grinstein, Rothstein; Beneke, Smirnov; Luke, Savage; Brambilla et al., 1996-1999

New idea: QCD field matched to <u>several</u> fields representing different quantum fluctuations



$$\mathcal{L}_{\text{QCD}} \qquad \mu \sim m$$

$$\downarrow$$

$$\mathcal{L}_{\text{NRQCD}}\,[Q(s,p),\; g(s,p,us)] \qquad \mu \sim mv$$

$$\downarrow$$

$$\mathcal{L}_{\text{PNRQCD}}\,[Q(p),\; g(us)] \qquad \mu \sim mv^2$$

Rigorous definition of “potentials”, nonrelativistic quantum mechanics from QFT
More precise calculations of quantum corrections in QCD and QED bound state problems through dimensional regularization

Nucleon-Nucleon EFT

Quarks	$\rightarrow$	Nucleons
Gluons	$\rightarrow$	Pions

Nucleon–nucleon scattering from effective field theory

David B. Kaplan[a,1], Martin J. Savage[b,2], Mark B. Wise[c,3]

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[b] *Department of Physics 1560, University of Washington, Seattle, WA 98195-1560, USA*

[c] *California Institute of Technology, Pasadena, CA 91125, USA*

Received 13 May 1996;

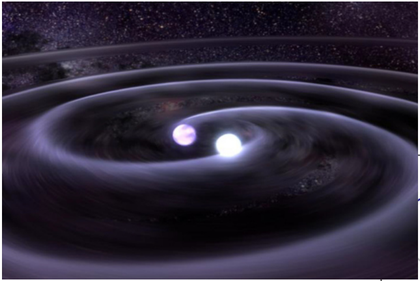
Abstract

We perform a non-perturbative calculation of the $^1S_0$ NN scattering amplitude, using an effective field theory (EFT) expansion. The expansion we advocate is a modification of what has been used previously; it is not a chiral expansion in powers of m_π. We use dimensional regularization throughout, and the $\overline{\mathrm{MS}}$ renormalization scheme; our final result depends only on physical observables. We show that the EFT expansion of the quantity $|\boldsymbol{p}|\cot\delta(\boldsymbol{p})$ converges at momenta much greater than the scale Λ that characterizes the derivative expansion of the EFT Lagrangian. Our conclusions are optimistic about the applicability of an EFT approach to the quantitative study of nuclear matter.

Subtle problem of large scattering length in dimensional regularization

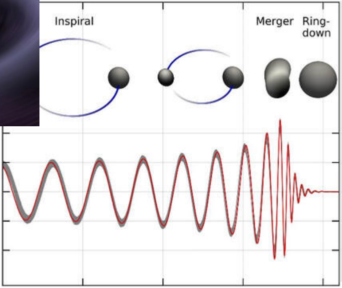
Gravitational Wave Emission from Inspiral of Compact Binaries

Goldberger, Rothstein (2004)



Quarks → Neutron stars, black holes
Gluons → Gravitons

Non-relativistic classical point particles emitting gravitational radiation



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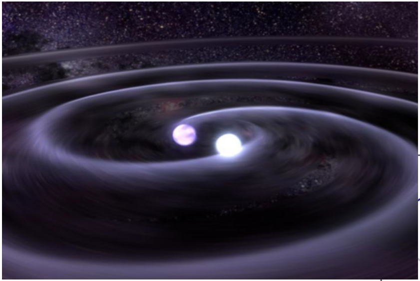

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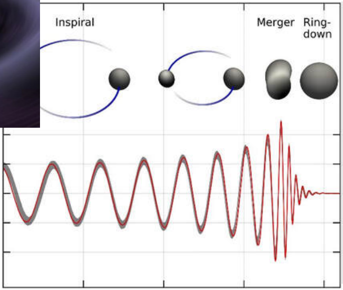

Quantum EFT and amplitude methods to solve classical physics problems

Soft-collinear effective theory - multi-scale problems in high-energy scattering

Bauer, Fleming, Pirjol, Stewart (2000); Beneke, Chapovsky, Diehl, Feldmann; Bauer, Fleming, Pirjol, Rothstein, Stewart (2002)

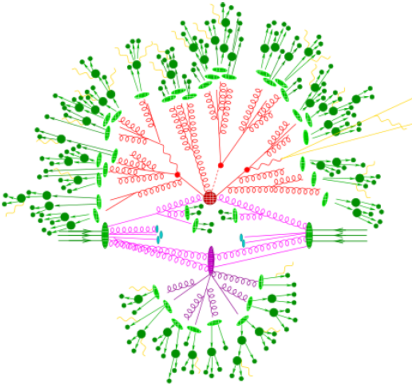

Figure credit: Frank Krauss

Interactions of massless quanta cause soft and collinear divergences.

$\hookrightarrow$ factorize

Remnant effects cause large quantum corrections to multi-scale processes

Soft-collinear effective theory - multi-scale problems in high-energy scattering

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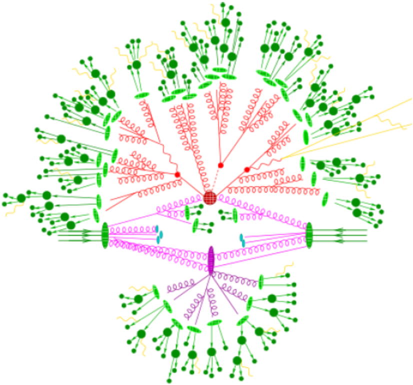


Figure credit: Frank Krauss

Interactions of massless quanta cause soft and collinear divergences.

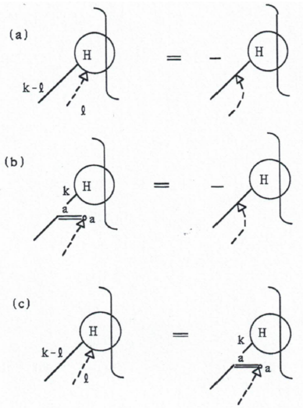
$\hookrightarrow$ factorize

Remnant effects cause large quantum corrections to multi-scale processes

SCET is the EFT that reproduces the dynamics in the soft and collinear kinematic regions.

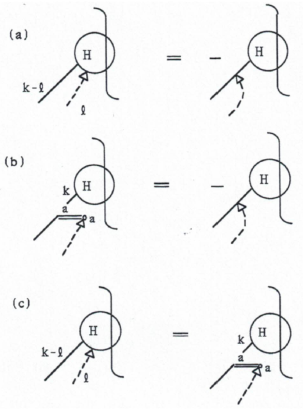
$$m_Q \longrightarrow E = n_+ p$$

Soft and collinear decoupling and factorization



Collins, Soper, Sterman, in: Perturbative QCD

Soft and collinear decoupling and factorization



Collins, Soper, Sterman, in: Perturbative QCD

Separate fields for collinear and soft modes

$$\mathrm{QCD}[A,\psi] \quad \longrightarrow \quad \mathrm{SCET}[A_c, A_s, \xi_c, q_s]$$

- Gauge invariant collinear fields

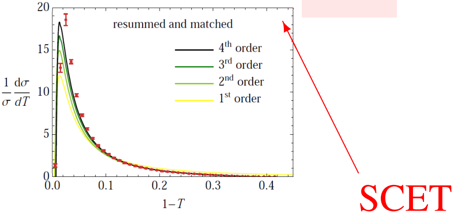
$$\chi \equiv W_c^\dagger \xi, \qquad \mathcal{A}^\mu_{c\perp} \equiv W_c^\dagger [iD^\mu_{c\perp} W_c]$$

- Soft-decoupling transformation [Bauer, Pirjol, Stewart, 2001]

$$\hat{\xi} = Y[A_s]\xi, \qquad \hat{A}^\mu_c = Y[A_s] A^\mu_c Y^\dagger [A_s]$$

Feynman diagrams $\rightarrow$ EFT operators

NNNLL resummation (2008–)



[Becher, Schwartz (2008)]

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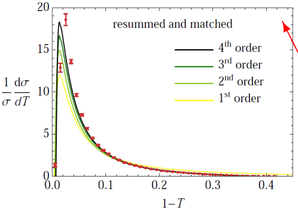

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TMD factorization and rapidity divergences (2012–)

SCET

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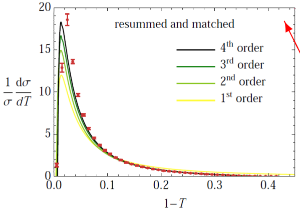

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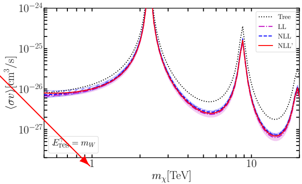
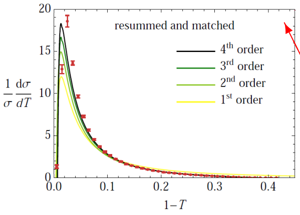
[1903.08702]



Electroweak interaction (2008–)
and dark matter annihilation (2014–)

NNNLL resummation (2008–)



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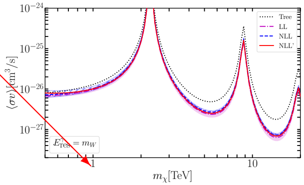
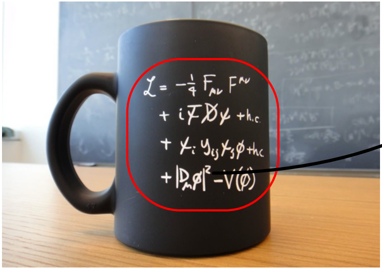


Next-to-leading power resummation (2004, 2017–)

Electroweak interaction (2008–)
and dark matter annihilation (2014–)

The Unfinished Story of the Standard Model



Scales $\gtrsim 1$ TeV

$$\lim_{\Lambda \to \infty} \text{SMEFT}$$

Standard Model Effective Field Theory (SMEFT)

Buchmüller, Wyler (1985)

- Most general EFT with SM data – fields + SU(3)⊗ SU(2)⊗U(1) gauge symmetry

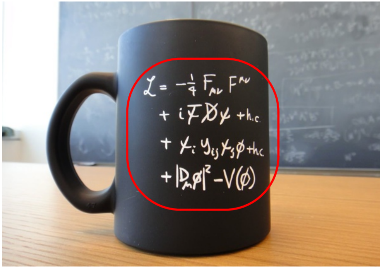
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{f_{ij}}{\Lambda_{\rm LNV}}\,(\bar{L}_i\tilde{\phi})(\tilde{\phi}L_j) + \frac{1}{\Lambda^2}\sum_{i=1}^{59}\mathcal{O}_i + \ldots$$

Neutrino masses
Scale of lepton number violation, $\Lambda_{\rm LNV} < M_{\rm Planck}$

Indirect effects of new particles

- SM of the post-Higgs discovery era

Can the EFT Paradigm ever fail?



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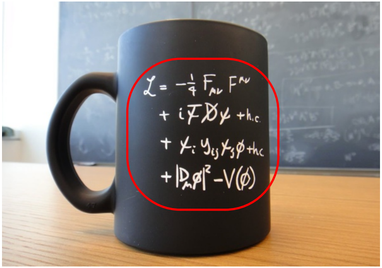

Two missing pieces on the cup

Gravitational force

$$\mathcal{L}_{\rm EH} = \frac{M_{\rm pl}^2}{2} \sqrt{g}\,(R - 2\Lambda) + \ldots$$

Dark matter

$$\mathcal{L}_{\rm DM} = \sqrt{g} f(\chi_{\rm DM}, \psi_{\rm SM}) = ???$$

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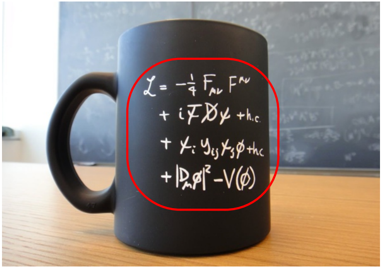

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New light particles can still exist, if their coupling to the SM is very weak.
There could be hidden sector worlds constrained only by cosmology.