Effective field theories in Physics

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Lectures @

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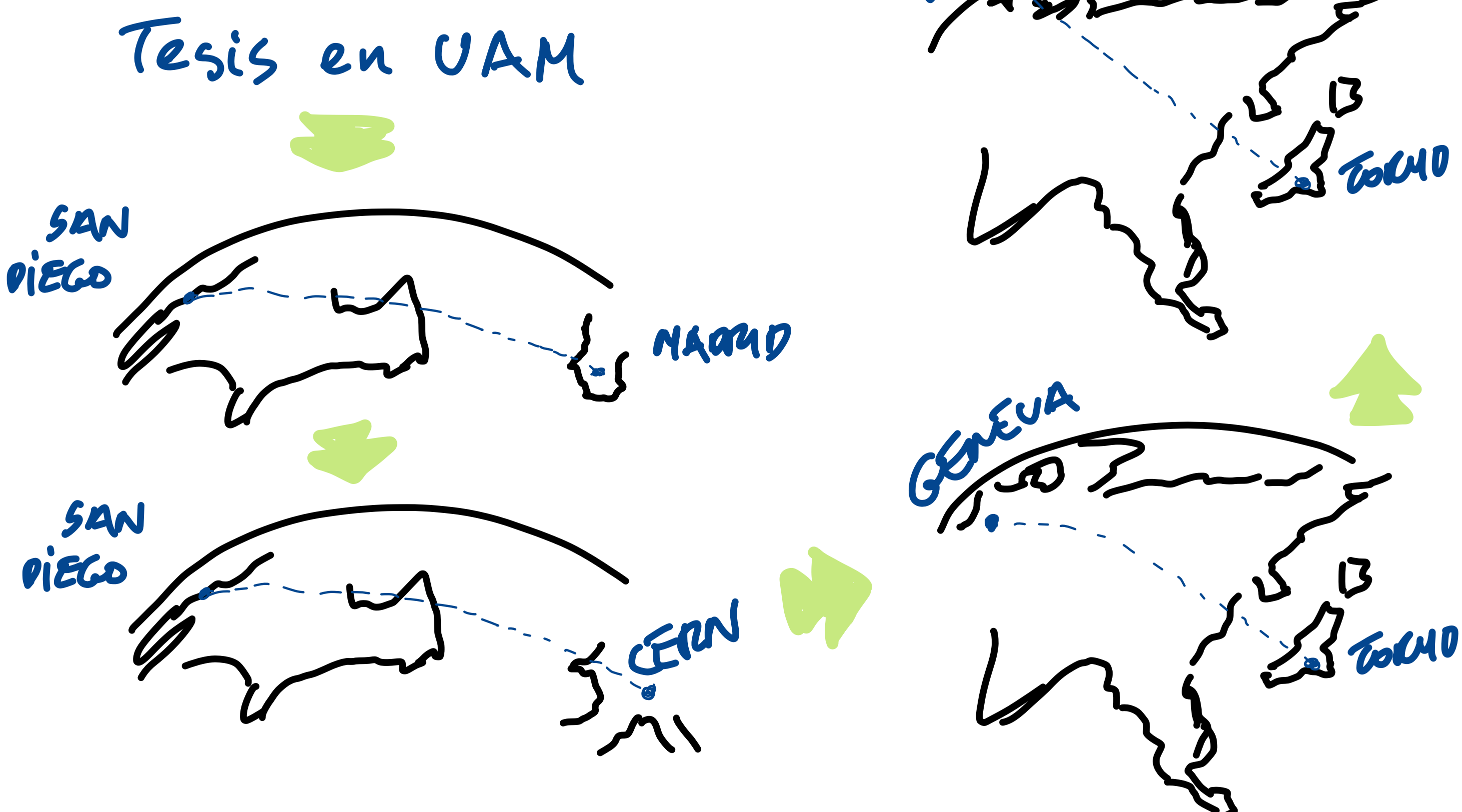
Outline

A) Describing Nature

B) Effective (Field) Theory
(a.k.a. Describing Nature with limitations)

C) EFT in Fundamental Physics

My trayectory : Partículas



Part A

Describing Nature

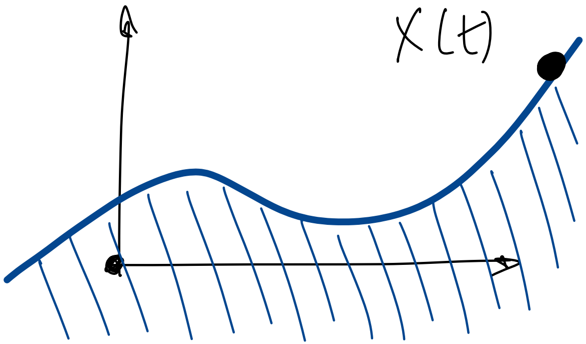
Describing Nature

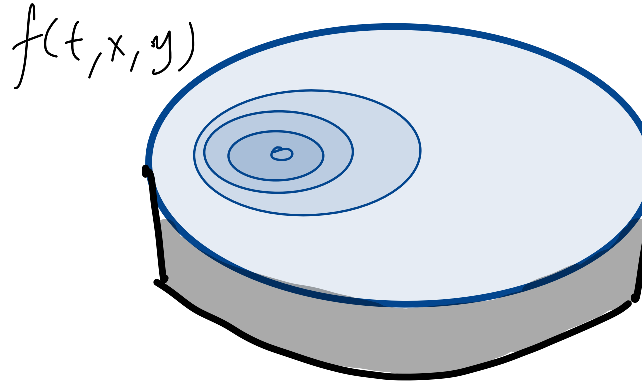
How do we describe Nature / Formulate our theories?

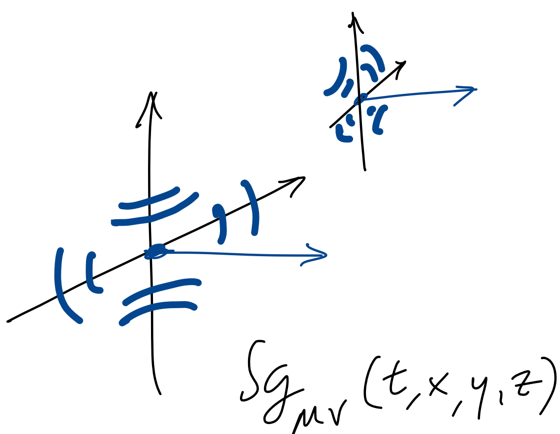
- Specify system to describe (e.g.: d.o.f.)
- Find the Symmetries in our system
- Identify small parameter to make theory predictions
- Encode Dynamics with the variational principle

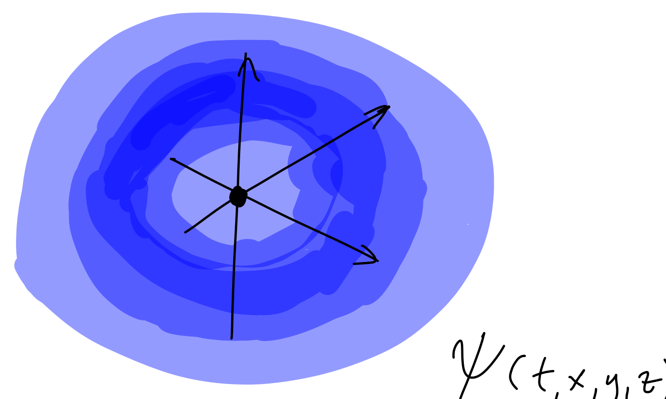
Describing Nature

System



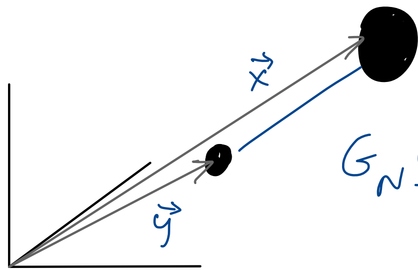






Describing Nature

Symmetry



$$G_N \frac{mM}{|x-y|}$$

$$x, y \to R \circ (x, y)$$

$SO(3)$

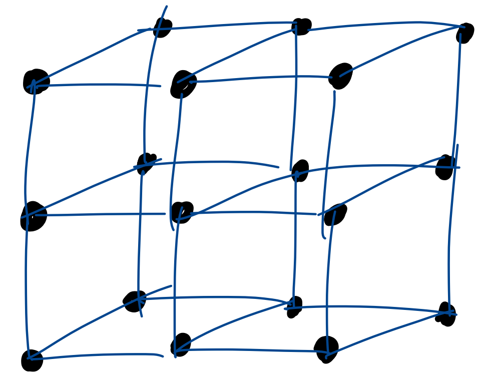
Continuous

$$R(\pi/2)\, \vec{x}_n$$

...

Z_3

Discrete



$$\Phi, \quad \vec{A},$$

$$\vec{E} = \frac{\partial}{\partial t}\vec{A} - \vec{\nabla}\Phi$$

$$\vec{B} = \vec{\nabla} \wedge \vec{A}$$

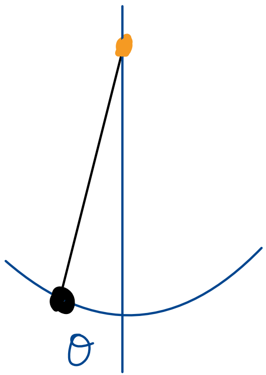
$U(1)$ local

$$\delta\Phi = \frac{\partial}{\partial t}\theta(t, \vec{x})$$

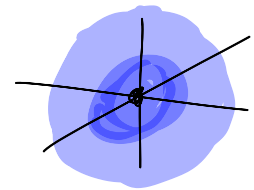
$$\delta\vec{A} = \vec{\nabla}\theta(t, \vec{x})$$

Describing Nature

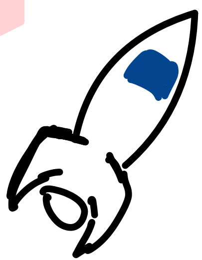
Expansion



$\theta \ll 1$



$$\frac{e^2}{4\pi\varepsilon_0\hbar c} \simeq \frac{1}{137} \ll 1$$



$v \ll c$

$$E_{kin} = \sqrt{p^2+m^2} = \frac{mc^2}{\sqrt{1-v^2/c^2}} \simeq mc^2 + \frac{p^2}{2m}$$

Describing Nature

Dynamics

The variational principle

Action = Integral of Lagrangian

$$S = \int d^{d-1}x \, dt \; \mathcal{L}(\text{degrees of freedom})$$

Dynamics $\quad \delta S = 0$

(e.g.

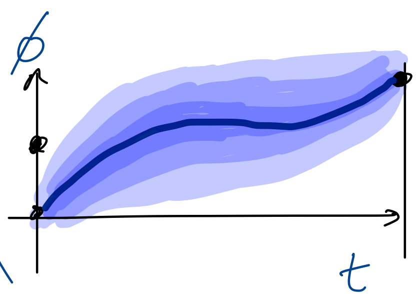
$d=1$, $\phi(t)$, $\displaystyle \int dt \, \delta\phi \left(-\frac{\partial}{\partial t} \frac{\partial \mathcal{L}}{\partial \dot{\phi}} + \frac{\partial \mathcal{L}}{\partial \phi} \right) = 0$)

Describing Nature (Q) Dynamics

The variational principle

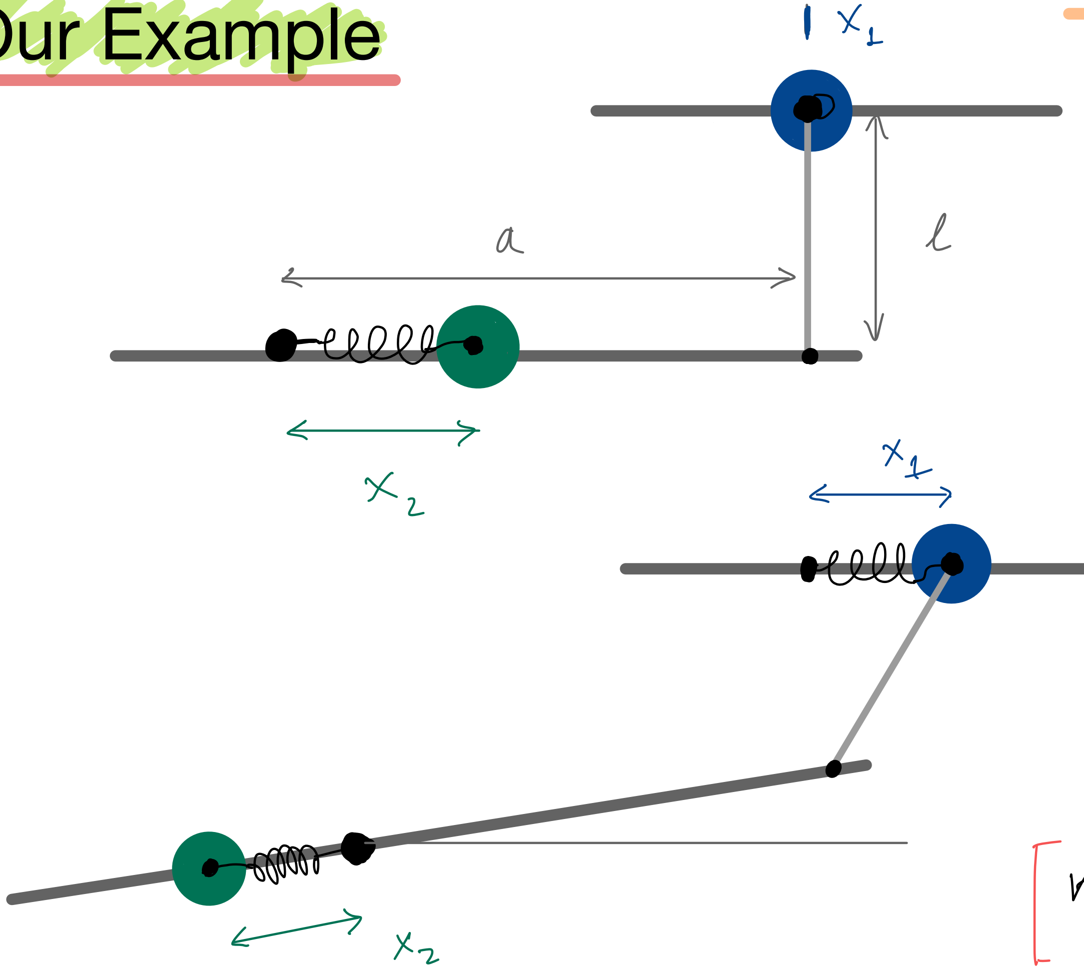
Quantum Systems $\hbar$ Planck's Constant

$$\text{Matrix element} = \int \mathcal{D}\,\text{d.o.f.}\; e^{iS/\hbar}$$



$$;\quad \langle \phi_1(t_1) | \phi_2(t_2) \rangle = N \int_{\phi_1}^{\phi_2} \mathcal{D}\phi(t)\, e^{iS[\phi]/\hbar}$$

Our Example



Lagrangian

$$\frac{1}{2} m_1 \left[\left(\frac{dx_1}{dt}\right)^2 - \omega^2 x_1^2 \right]$$

$$\frac{1}{2} m_2 \left[\left(\frac{dx_2}{dt}\right)^2 - \Omega^2 x_2^2 \right]$$

$$- k x_1^2 x_2$$

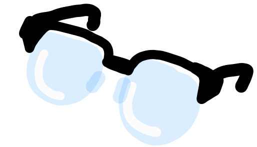
$$\left[k = \frac{g}{2a\ell},\ x_1 \ll \ell, a \right]$$

Part B

Effective (Field) Theory

Describing nature with limitations/unknowns

Effective (Field) Theories



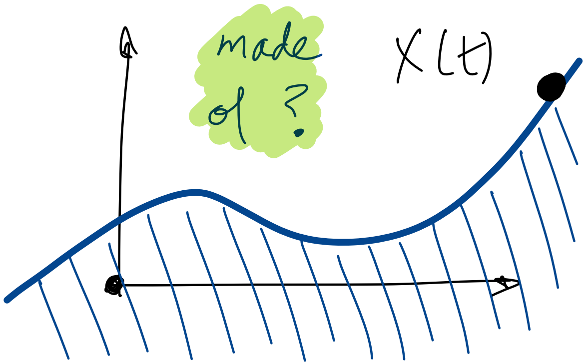
What if we don't see the whole
& the missing piece has small (perturbative) effects?

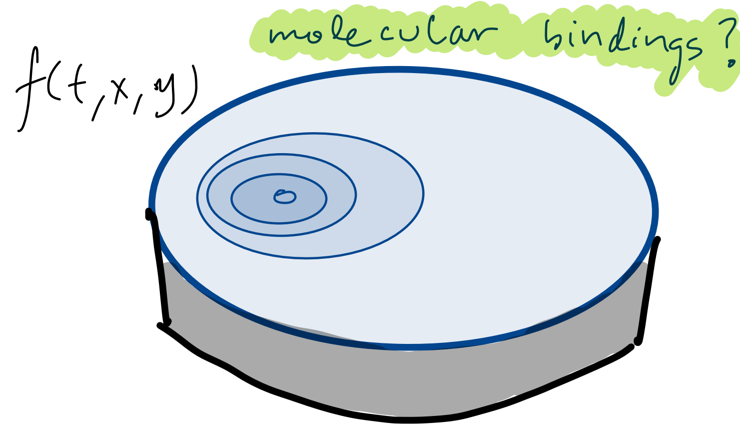
→ Apply the programe with the expansion
now on unseen (unknown) physics effects

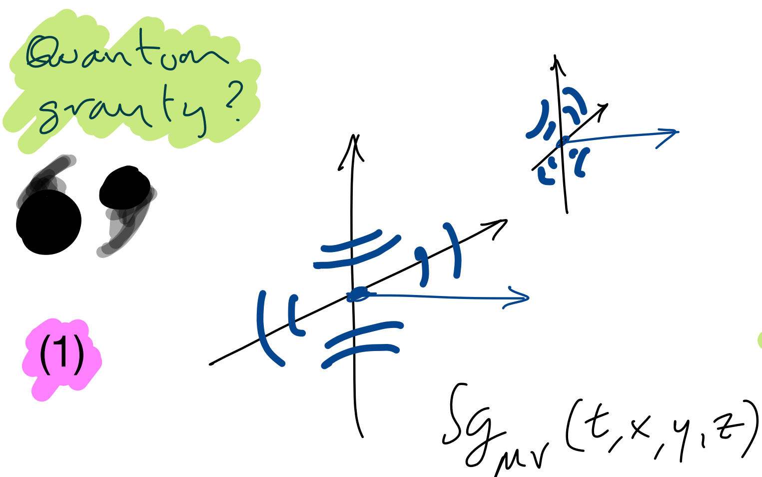
(Where for "whole"
we'll use abstraction:
Parts of our system
the underlying theory)

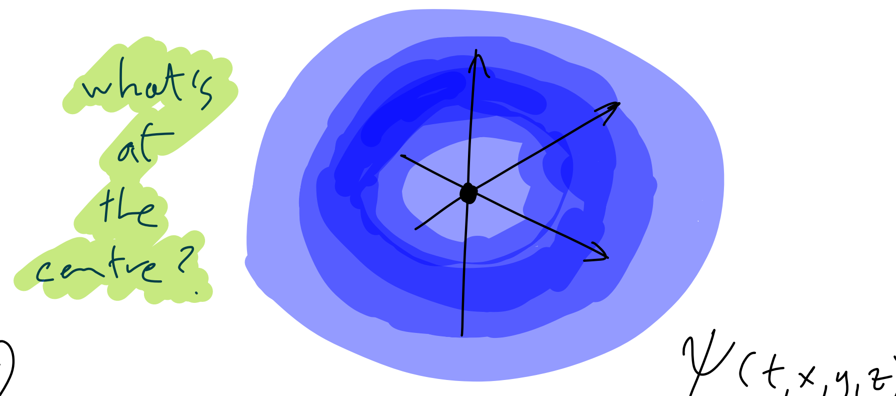
In fact, this situation is
very commonly the case

Effective (Field) Theories



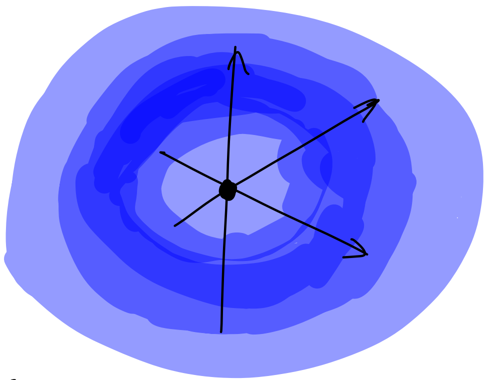






(1)

Effective (Field) Theories μ-atom

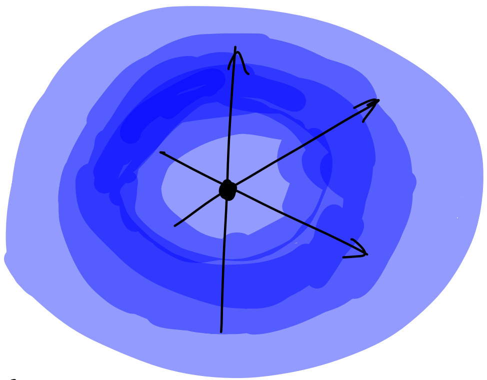


$\psi(t, x, y, z)$

Apply the programme here

- System electron $\vec{X}, \vec{P}, \vec{S}$
- Symmetries: Rotation, translations
- Expansion: $m_p \gg m_e$
- Dynamics: $\frac{P^2}{2m_e} - \underbrace{V(|\vec{X}|, \vec{S}, \vec{L})}_{?}$

Effective (Field) Theories   H-atom



$\psi(t,x,y,z)$

Apply the programme here

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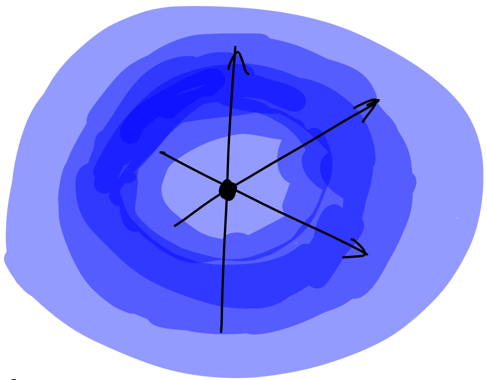
- Symmetries: Rotation, translations
- Expansion: $m_p \gg m_e$
- Dynamics: $\frac{P^2}{2m_e} - \underbrace{V(|\vec{X}|, \vec{S}, \vec{I})}_{?}$

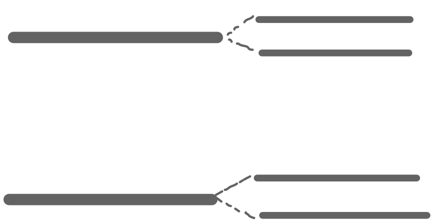
Electromagnetism: $V = -\frac{e^2 Z}{4\pi \varepsilon_0 |\vec{X}|} - \vec{\mu}\cdot\vec{B}$

Greatly symmplifies our theory

Effective (Field) Theories μ-atom



$\psi(t,x,y,z)$



Extra ingredient: electromagnetism

$$V = -\frac{e^2 Z}{4\pi\varepsilon_0|\vec{x}|} + \frac{e^2 Z}{4\pi\varepsilon_0|x|}\,\alpha^2\left(\frac{\vec{L}\cdot\vec{S}}{\hbar^2}\,\frac{a_0^2}{|x|^2}\right)$$

$$+\ \mathcal{O}\left(\frac{m_e}{m_p}\right)$$

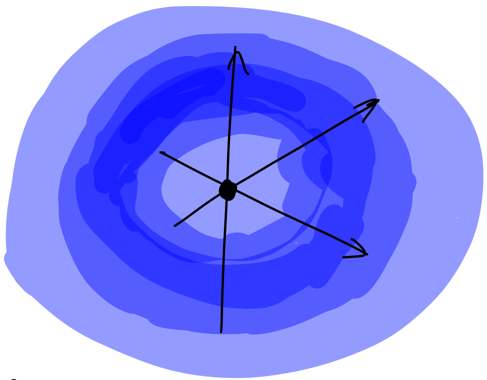
$$\left[\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c},\quad a_0 = (m_e c\,\alpha)^{-1}\right]$$

Precise predictions w/o knowing what sits at the centre

(massive, +e charge)

Effective (Field) Theories

H-atom

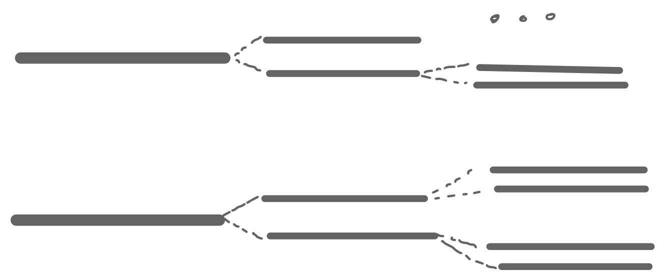


$\psi(t,x,y,z)$

Extra ingredient: electromagnetism

$$V = -\frac{e^2 Z}{4\pi\varepsilon_0|\vec{x}|} + \frac{e^2 Z}{4\pi\varepsilon_0|x|}\,\alpha^2\left(\frac{\vec{L}\cdot\vec{S}}{\hbar^2}\,\frac{a_0^2}{|x|^2}\right)$$

$$+\frac{e^2 Z}{4\pi\varepsilon_0|x|}\,\frac{m_e}{m_p}\,\frac{g_N}{2}\,\alpha^2\,\frac{\vec{S}\cdot\vec{I}}{\hbar^2}\,\frac{a_0^2}{|x|^2}$$



Hyperfine

$g_p \sim 5.$

Effective (Field) Theories

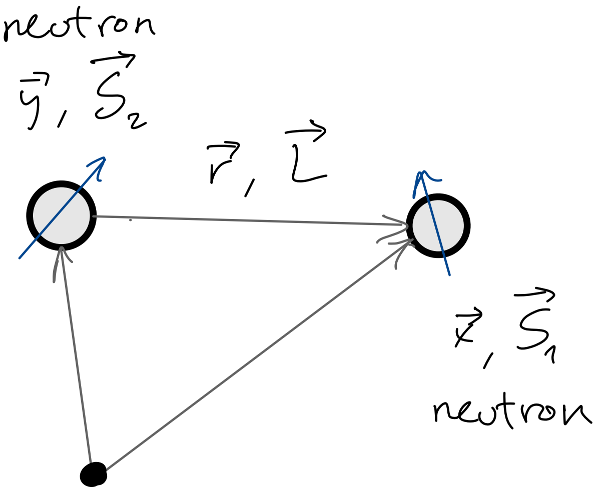
what we've learned

- Not knowing does not prevent predictivity

- Identifying & using expansion on "unknown" not only organizes predictions but teaches us about unknown

Effective (Field) Theories

Nuclear force

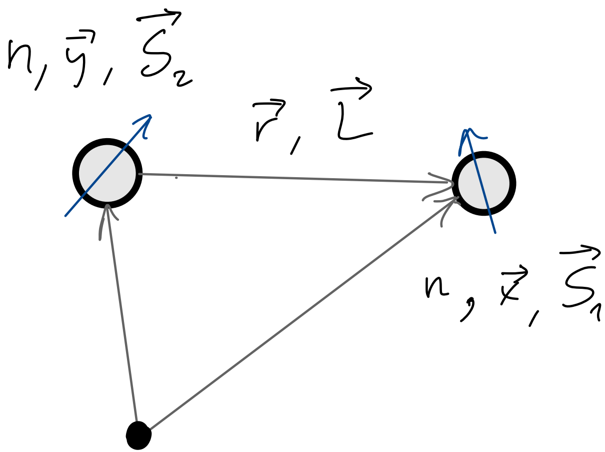


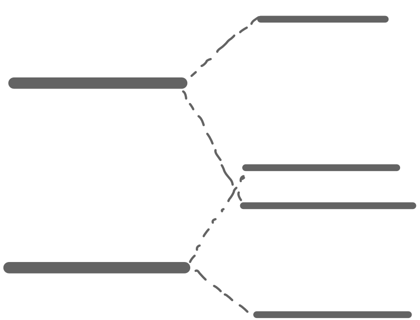
Hydrogen atom worked pretty well...

Try something similar

$$V = V_0(r) \quad ?$$

Effective (Field) Theories Nuclear force



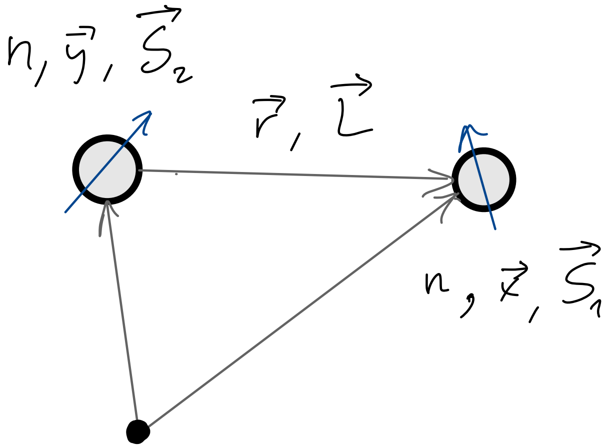


It fails miserably! Instead apply EFT

- System $\vec{x}, \vec{S}_1, \vec{y}, \vec{S}_2, \vec{L}$
- Symmetries Rotations, Translations
- Expansion: $r \ll r_p$, $p/m \ll 1$
- Dynamics

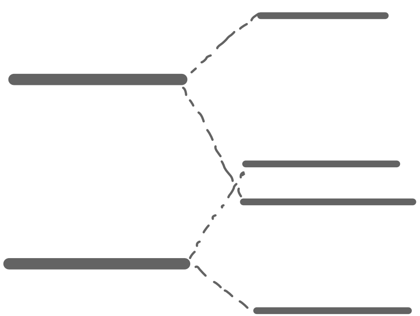
$$V = V_0(r) + V_{SS}(r)\, \vec{S}_1 \cdot \vec{S}_2$$
$$+ V_T(r)\left(3\,\frac{\vec{S}_1\cdot\vec{r}\;\vec{S}_2\cdot\vec{r}}{r^2} - \vec{S}_1\cdot\vec{S}_2\right)$$
$$+ V_{LS}(r)\,(\vec{S}_1 + \vec{S}_2)\cdot\vec{L} + \mathcal{O}(c^2)$$

Effective (Field) Theories — Nuclear force



Apply E(F)T programme

$$V = V_0(r) + V_{SS}(r)\, \vec{S}_1 \cdot \vec{S}_2 + V_T(r)\left(3\,\frac{\vec{S}_1\cdot\vec{r}\;\vec{S}_2\cdot\vec{r}}{r^2} - \vec{S}_1\cdot\vec{S}_2\right) + V_{LS}(r)\,(\vec{S}_1+\vec{S}_2)\cdot\vec{L} + \mathcal{O}(c^2)$$

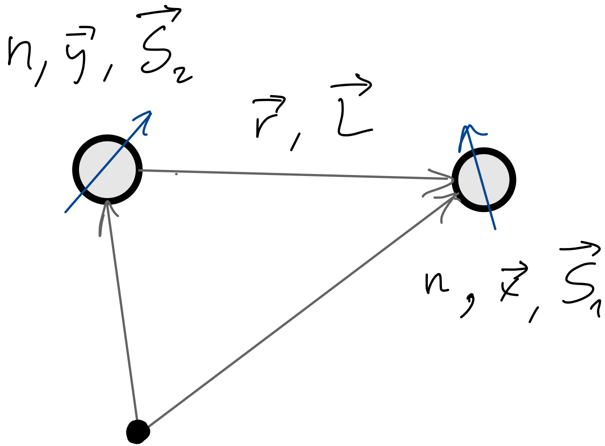


All terms present & relevant

- More complicated but more general

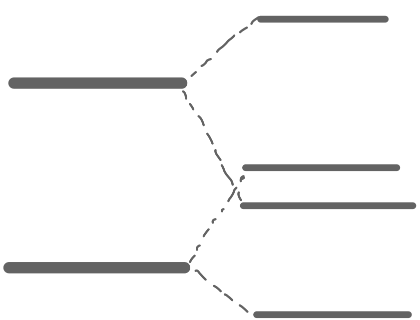
Effective (Field) Theories

Nuclear force



Apply E(F)T programme

$$V = V_0(r) + V_{SS}(r)\, \vec{S}_1 \cdot \vec{S}_2 + V_T(r)\left(3\,\frac{\vec{S}_1\cdot\vec{r}\,\vec{S}_2\cdot\vec{r}}{r^2} - \vec{S}_1\cdot\vec{S}_2\right) + V_{LS}(r)\,(\vec{S}_1 + \vec{S}_2)\cdot\vec{L} + \mathcal{O}(c^2)$$



All terms present & relevant

▶ Corrections $\mathcal{O}\left(\frac{r_p}{r} \sim \frac{q\, r_p}{\hbar}\right)$

tell us about neutron composition

Effective (Field) Theories

What we've learned

- Not knowing does not prevent predictivity
  (it's just computations are harder)

- Without crutch of E-M we write the most general action allowed by symmetries.

  Constructive & un-biased approach

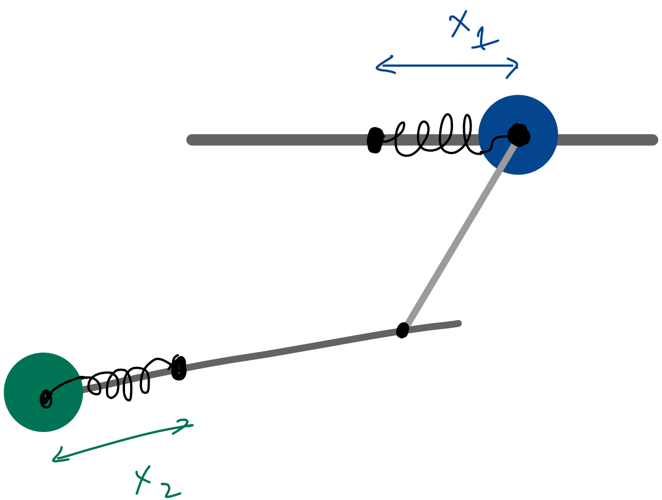
(2)

Effective (Field) Theories

Our example

$$[\omega_1 = \omega, \omega_2 = \Omega]$$

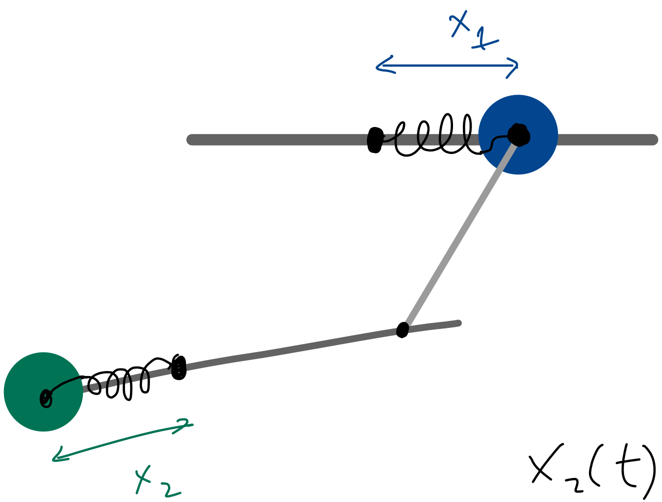
$$L = \sum_i \frac{1}{2} m_i \left(\left(\frac{dx_i}{dt} \right)^2 - \omega^2 x_i^2 \right) - \kappa x_1^2 x_2$$



Here we know everything, so we can un-know the ● ball & find an expansion

Effective (Field) Theories

$$L = \frac{1}{2} m_1 \left(\left(\frac{dx_1}{dt}\right)^2 - \omega^2 x_1^2 \right) + \frac{1}{2} m_2 \left(\left(\frac{dx_2}{dt}\right)^2 - \Omega^2 x_2^2 \right) - \kappa x_1^2 x_2$$



Compute the small effects of ● on ●

$$-\ddot{x}_2 - \Omega^2 x_2 = \frac{\kappa x_1^2}{m_2}$$

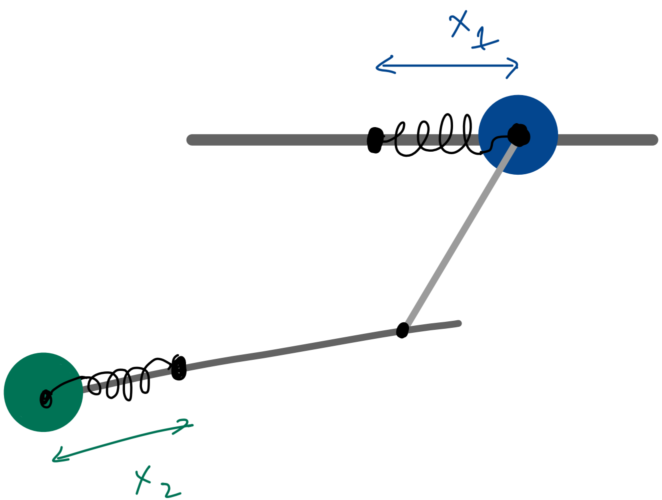
$$x_2(t) = \int \frac{d\nu}{2\pi} e^{i\nu t} \tilde{x}_2(\nu)$$

$$x_2(t) = \int \frac{d\nu\, dt'}{(2\pi)} \frac{e^{i\nu(t-t')}}{\nu^2 - \Omega^2} \frac{\kappa x_1^2(t)}{m_2}$$

Effective (Field) Theories

$$L = \sum_i \frac{1}{2} m_i \left(\left(\frac{dx_i}{dt}\right)^2 - \omega_i^2 x_i^2 \right) - \kappa x_1^2 x_2$$

$[\omega_1 = \omega, \omega_2 = \Omega]$



Compute the small effects of ● on ●

$$x_2(t) = \int \frac{d\nu\, dt'}{(2\pi)} \frac{e^{i\nu(t-t')}}{\nu^2 - \Omega^2} \frac{\kappa x_1^2(t')}{m_2}$$

This back into our L

$$\frac{1}{2} m_1 \left(\left(\frac{dx_1}{dt}\right)^2 - \omega^2 x_1^2 \right) - \frac{1}{2} \frac{\kappa^2}{m_2} \int \frac{d\nu\, dt'}{2\pi} x_1^2(t) \frac{e^{i\nu(t-t')}}{\nu^2 - \Omega^2} x_1^2(t')$$

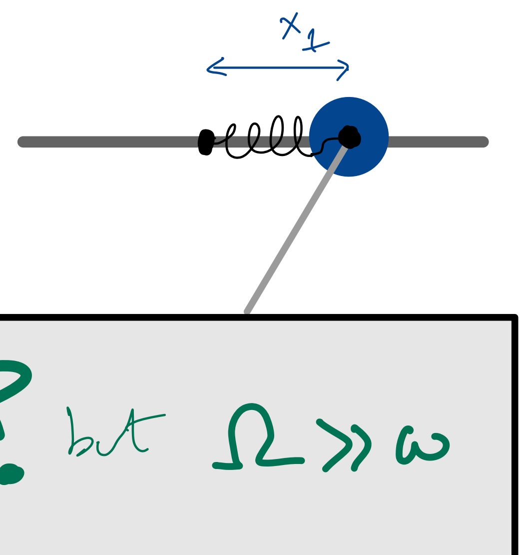
Effective (Field) Theories

$$\int \frac{dt'\, d\nu}{(2\pi)}\left(\frac{1}{\Omega^2} + \mathcal{O}\left(\frac{\nu^2}{\Omega^4}\right)\right) e^{i\nu(t-t')}\, x_1^2(t') \simeq \int dt'\, \delta(t-t')\, x_1^2(t')$$

(4)

Look at frequencies smaller than Ω

" at slow physics



$$L_{eff} = \frac{1}{2} m_1\left(\left(\frac{dx_1}{dt}\right)^2 - \omega^2 x_1^2\right) + \frac{1}{2}\frac{\kappa^2}{m_2 \Omega^2} x_1^4(t) + \dots$$

Part C

Effective Field Theory for Fundamental Physics

EFT use in Fundamental Physics

- Apply programme to particle physics
  - Sketch the peculiarities of particle physics theory
  - Symmetries take center-stage
  - Specify "system" to describe
  - EFT in particle physics
  - Advanced topics

EFT use in Fundamental Physics

Quantum Field Theory:

B Path (Field) Integral

d.o.f. $\phi(t,\vec{x})$, $A_\mu(t,\vec{x})$, $\mathcal{L} = \frac{L}{Vol}$

A Fields → Operators

$$\left[\phi, \frac{\delta \mathcal{L}}{\partial \dot\phi}\right] = 1$$

A)

$$\langle 0 | \phi(0) | p \rangle = 1$$

vacuum state

one particle state of momentum p

$$|p\rangle = a_p^\dagger |0\rangle$$

Creation/Annihilation Operators

$$[a_p^\dagger, a_{p'}] = 1_{pp'}$$

EFT use in Fundamental Physics

A) Canonical Quantization

$|p\rangle = a_p^{\dagger} |0\rangle$

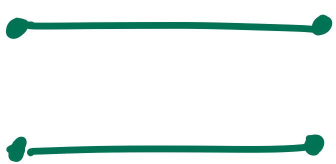
$[a_p^{\dagger}, a_{p'}] = 1_{pp'}$

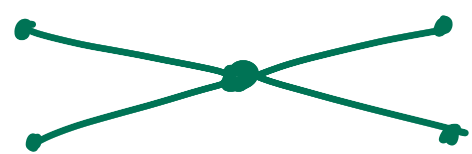
$$\text{Amplitude} = \langle \text{final} |\, e^{-iHT} \,| \text{initial} \rangle$$

say $\langle 0 | a_3 a_4 \, e^{-iHT} \, a_1^{\dagger} a_2^{\dagger} | 0 \rangle$ $\qquad [\, a|0\rangle = 0 \,]$

$$\langle 0 | a_3 a_4 a_1^{\dagger} a_2^{\dagger} | 0 \rangle + \langle 0 | a_3 a_4 (-i H_{int} T) a_1^{\dagger} a_2^{\dagger} | 0 \rangle + \ldots$$

say $H_{int} = \lambda \phi^4$



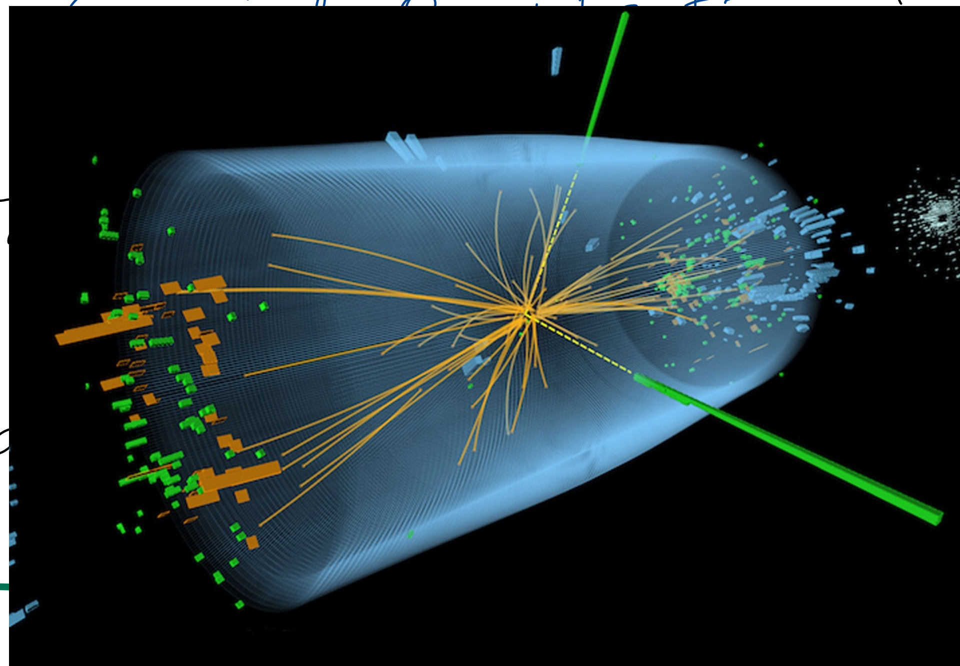


EFT use in Fundamental Physics

A)

$|p\rangle = a_p^\dagger |0\rangle$

$a_{p'}] = \delta_{pp'}$



A

$\rangle$

say

$a|0\rangle = 0$]

$\langle 0| a_3 a$

$a_2^\dagger |0\rangle + \ldots$

EFT use in Fundamental Physics

Lorentz symmetry tells us how space-time transforms under boosts

$$x_\mu \longrightarrow \Lambda_\mu^{\ \nu} x_\nu \qquad \eta_{\mu\nu} = \begin{pmatrix} 1 & & & \\ & -1 & & \\ & & -1 & \\ & & & -1 \end{pmatrix} \qquad \Lambda^T \cdot \eta \cdot \Lambda = \eta$$

Take momentum

$$p^\mu = \begin{pmatrix} E \\ \vec{p} \cdot c \end{pmatrix} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \begin{pmatrix} 1 & \frac{v}{c} \\ \frac{v}{c} & 1 \end{pmatrix} \begin{pmatrix} m c^2 \\ 0 \end{pmatrix} ;$$

$$E^2 = (mc^2)^2 + \vec{p}^{\,2} c^2 \qquad \eta_{\mu[\rho} \eta_{\nu\sigma]} \, \omega^{[\rho,\sigma]}$$

EFT use in Fundamental Physics

Lorentz symmetry tells us about spin:

Group theory: Representation R Transforms as $G \cdot R$

$$G^{i}{}_{j} = \delta^{i}{}_{j} + i (T^{\mu\nu})^{i}{}_{j}\, \omega_{\mu\nu} + \mathcal{O}(\omega^2)$$

$$[T, T] = i f \cdot T$$

First few representations

Trivial

No transform

Gamma Matrices

$$(T_{\mu\nu})^{i}{}_{j} = \frac{i}{2} [\gamma_\mu, \gamma_\nu]^{i}{}_{j}$$

$$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$$

Space-time like

$$(T_{\mu\nu})^{\rho}{}_{\sigma} = \frac{i}{4} \eta^{\rho}{}_{[\mu} \eta_{\nu]\sigma}$$

EFT use in Fundamental Physics

Lorentz group First few representations

Trivial

No transformation

Gamma Matrices

$$(T_{\mu\nu})^i{}_j = \frac{i}{2}[\gamma_\mu, \gamma_\nu]^i{}_j$$

$$\{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu}$$

Space-time like

$$(T_{\mu\nu})^\rho{}_\sigma = \frac{i}{4}\eta^\rho{}_{[\mu}\eta_{\nu]\sigma}$$

Angular momentum Op is Generator of rotations

$$(J_a)^i{}_j \sim \varepsilon_{abc}(T_{bc}) \qquad J^2 = j(j+1)$$

spin! 0 $\quad 1/2 \quad$ 1

EFT use in Fundamental Physics

Lorentz symmetry

spin: 0 $\qquad$ 1/2 $\qquad$ 1

Lagrangian density preserves & presents $E^2 - p^2 = m^2$
[set $c=1$] As opposed to Hamiltonian!

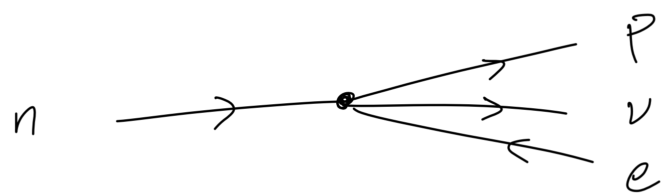
$$\frac{1}{2}\eta^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi \qquad \bar{\Psi}(i\gamma^\mu\partial_\mu - m)\Psi \qquad -\frac{1}{4}\left(\partial_\mu V_\nu - \partial_\nu V_\mu\right)^2$$

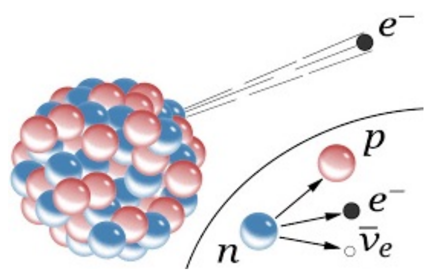
$$\left(\partial_\mu \equiv \frac{\partial}{\partial x^\mu}\right)$$

EFT use in Fundamental Physics

With this much we can look at an EFT:

$$\mathcal{L} = \mathcal{L}_{e.m} + \mathcal{L}_{strg} + G_F \, \bar{p} \, \gamma_\mu \, n_L \, \bar{e} \, \gamma^\mu \, \nu_L$$

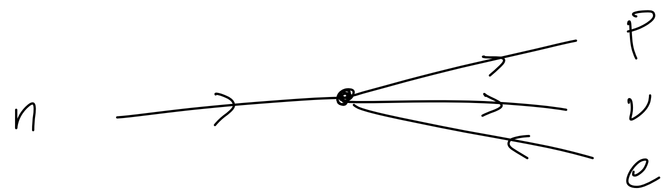




EFT use in Fundamental Physics

With this much we can look at an EFT:

$$\mathcal{L}_{eff} = \mathcal{L}_{e.m} + \mathcal{L}_{strg} + G_F\, \bar{p}\gamma_\mu n_L\, \bar{e}\gamma^\mu \nu_L$$



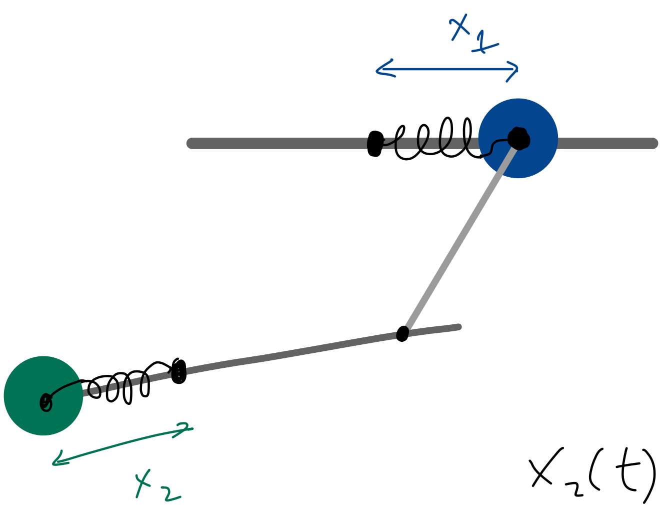
$$\mathcal{L} = \partial W^\dagger \partial W - M_W^2 W^\dagger W + \overbrace{g W(\bar{p}\gamma_\mu n + \bar{\nu}\gamma_\mu e)}^{gWJ} + \underbrace{g W^\dagger(\bar{e}\gamma\nu + \bar{n}\gamma p)}_{gW^+J^+}$$

- $W \longleftrightarrow X_2 \quad (m_1 \to \infty)$
  X_1^4 in correction $\to J^\dagger J$

Effective (Field) Theories

Our example

$$L = \frac{1}{2} m_1 \left(\left(\frac{dx_1}{dt}\right)^2 - \omega^2 x_1^2 \right) + \frac{1}{2} \left(\left(\frac{dx_2}{dt}\right)^2 - \Omega^2 x_2^2 \right) - \kappa x_1^2 x_2$$



Compute the small effects of ● on ●

$$-\ddot{x}_2 - \Omega^2 x_2 = \frac{\kappa x_1^2}{m_2}$$

$$x_2(t) = \int \frac{d\nu}{2\pi} e^{i\nu t} \tilde{x}_2(\nu)$$

$$x_2(t) = \int \frac{d\nu\, dt'}{(2\pi)} \frac{e^{i\nu(t-t')}}{\nu^2 - \Omega^2} \frac{\kappa x_1^2(t)}{m_2}$$

EFT use in Fundamental Physics

Gauge Principle

Local transformation $\quad \phi' = e^{i\alpha(x_\mu)}\,\phi \quad$ ✓

$$\partial_\mu \phi' = e^{i\alpha}\,\partial_\mu \phi + e^{i\alpha}\, i(\partial_\mu \alpha)\,\phi$$

Introduce $\quad A_\mu\,, \quad A'_\mu = A_\mu + \frac{i}{g}\,\partial_\mu \alpha$

EFT use in Fundamental Physics

Gauge Principle

Local transformation $\phi' = e^{i\alpha(x_\mu)}\phi$ ✓

$$\partial_\mu \phi' = e^{i\alpha}\partial_\mu \phi + e^{i\alpha} i(\partial_\mu \alpha)\phi$$

Introduce A_μ, $A'_\mu = A_\mu + \frac{i}{g}\partial_\mu \alpha$

$$\left(\begin{aligned} \delta \Phi &= \frac{\partial}{\partial t}\theta(t,\vec{x}) \\ \delta \vec{A} &= \vec{\nabla}\theta(t,\vec{x}) \end{aligned} \quad ! \right)$$

EFT use in Fundamental Physics

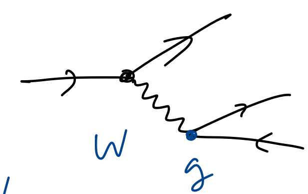
Gauge Principle

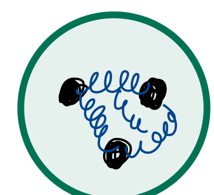
local transformation $\qquad \phi' = e^{i\alpha(x_\mu)}\phi$ ✓

$$D_\mu \phi \equiv \left(\frac{\partial}{\partial x^\mu} + i g A_\mu\right)\phi \qquad (D_\mu\phi)' = e^{i\alpha} D_\mu \phi$$ ✓

$U(1)_{em}$ $\qquad SU(2)_L$ $\qquad SU(3)_c$

$i\bar{\Psi}(\gamma^\mu \partial_\mu + ieA_\mu)\Psi$



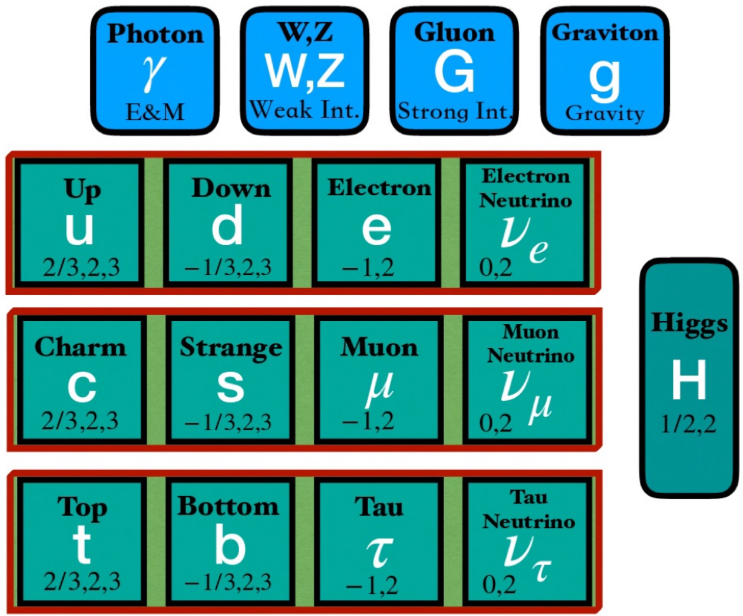


photon , Z , W

Gluons g_c

EFT use in Fundamental Physics

Gauge bosons



3 families

4 scalars

SU(2) doublets

EFT use in Fundamental Physics

Describe physics at any speed, classical or quantum

$E = mc^2$, $x = ct$, $E = \omega\hbar$

Measure velocity in units of c

Measure angular momentum in units of $\hbar$

$E = m$ $x = t$ $E = \omega$

$[E] = [t^{-1}] = [x^{-1}]$ use GeV

"Natural" units

EFT use in Fundamental Physics

Describe physics at any speed, classical or quantum

$$[E] = [t^{-1}] = [x^{-1}] = 1 \quad \text{use} \quad \text{GeV}$$

$$e^{iS} \qquad [S] = 0 \qquad S = \int d^4x\, \mathcal{L} \qquad [\mathcal{L}] = 4$$

$$[D_\mu] = [x^{-1}] = 1$$

$$[H] = \ ?$$

$$[D_\mu H^\dagger D^\mu H] = 4$$

EFT use in Fundamental Physics

Dimensional Analysis

$[E] = [t^{-1}] = [x^{-1}] = 1$ use GeV

e^{iS} $[S] = 0$ $S = \int d^4x\, \mathcal{L}$ $[\mathcal{L}] = 4$

Derivative

$[D_\mu] = 1$

Fermion

$[\psi] = 3/2$

Scalar

$[H] = 1$

Vector-Boson

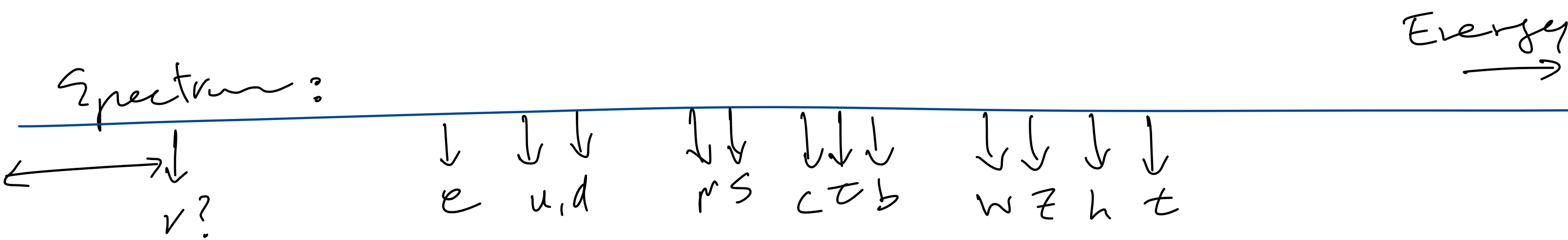
$[A_\mu] = 1$

EFT use in Fundamental Physics

Put it all together in Standard model

$$\mathcal{L}_{SM} = -\frac{1}{4}\sum_i F^i_{\mu\nu} F_i^{\mu\nu} + i \sum_A \bar{\Psi}_A D_\mu \gamma^\mu \Psi_A + D_\mu H^\dagger D^\mu H$$
$$- m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 - \bar{\Psi} H Y \Psi + h.c.$$

Spectrum:



EFT use in Fundamental Physics

$$\mathcal{L} = -\frac{1}{4}\sum_i F^i_{\mu\nu} F_i^{\mu\nu} + i\sum_A \bar{\Psi}_A D_\mu \gamma^\mu \Psi_A + D_\mu H^\dagger D^\mu H$$

$$- m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 - \bar{\Psi} H Y \Psi + h.c.$$

$$+ \sum_{i,d} c_{i,d}\, \mathcal{O}_{d,i}(\Psi, H, D_\mu, F_{\mu\nu})$$

$$[c_{i,d}] = 4-d \qquad \langle in\{p\}|\mathcal{O}^d|out\{p\}\rangle \sim (E)^d$$

$d > 4$ effects

$$c_d E^d \equiv c_d \left(\frac{E}{\Lambda}\right)^d$$

EFT use in Fundamental Physics

Back to our programme

- Decades of experimental search to specify our 'system'
- Symmetries give particle properties & Dynamics
- Standard Model is the most general first order in EFT

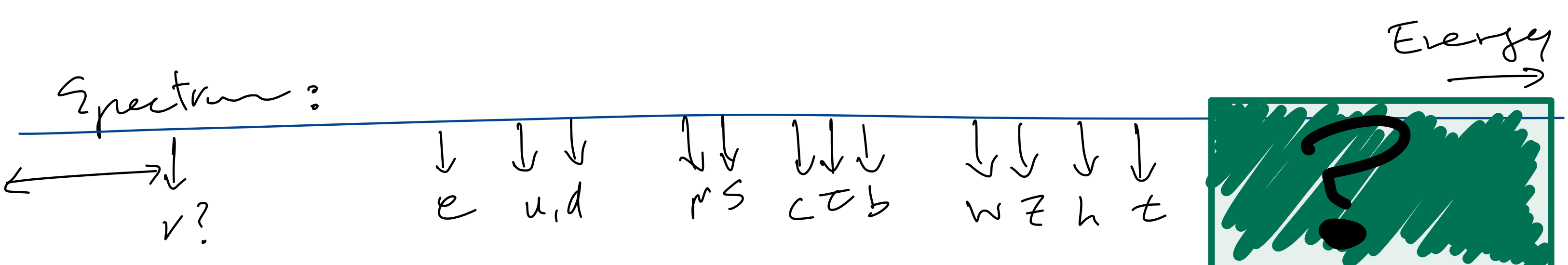
EFT use in Fundamental Physics

$$\mathcal{L} = -\frac{1}{4}\sum_i F^i_{\mu\nu} F_i^{\mu\nu} + i\sum_A \bar{\Psi}_A D_\mu \gamma^\mu \Psi_A + D_\mu H^\dagger D^\mu H$$

$$- m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 - \bar{\Psi} H Y \Psi + h.c.$$

$+$ $d > 4$ effects

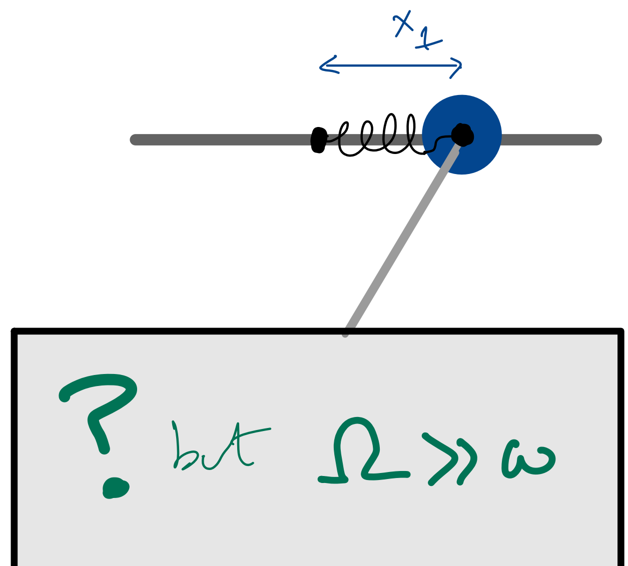
$$c_d E^d \equiv c_d \left(\frac{E}{\Lambda}\right)^d$$



Effective (Field) Theories

$$[\ x_1 = \theta \cdot \ell\ ]$$

$$L = \frac{1}{2} m_1^2 \ell^2 \left[\left(\frac{d\theta}{dt}\right)^2 - \omega^2 \theta^2 + \sum c_{i,p,k} \left(\frac{1}{\Omega}\frac{d}{dt}\right)^k \theta^p \right]$$

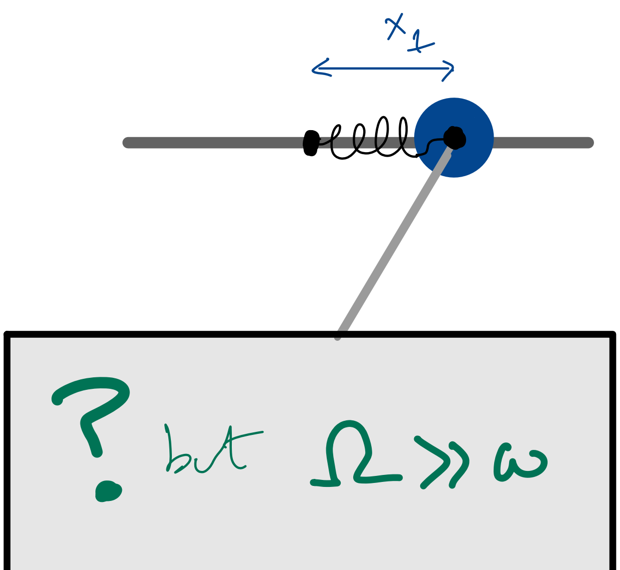


Effective (Field) Theories

$$[\, x_1 = \theta \cdot \ell \,]$$

$$\frac{d}{dt} \sim \omega \; ; \quad \frac{\omega}{\Omega} \sim \frac{1}{\Omega}\frac{d}{dt}$$

$$L = \frac{1}{2} m_1^2 \ell^2 \left[\left(\frac{d\theta}{dt}\right)^2 - \omega^2 \theta^2 + \theta^3 \right]$$



$$\theta^4$$

$$\theta^4 \frac{1}{\Omega} \frac{d}{dt}$$

$$\theta^4 \left(\frac{1}{\Omega} \frac{d}{dt}\right)^2$$

EFT use in Fundamental Physics

what lies beyond?

$+ \; d > 4$ effects $\qquad C_d E^d \equiv c_d \left(\frac{E}{\Lambda}\right)^d$

Experimental Evidence

Neutrino masses ($d=5$!)

Dark matter

Baryon Asymmetry of universe

Theory Hints

Hierarchy Problem

Flavour Puzzle

Strong CP problem

EFT use in Fundamental Physics

what lies beyond?

+ $d > 4$ effects e.g $\bar{\psi}\sigma_{\mu\nu}\psi H F^{\mu\nu}$

Baryon #, Lepton # violation?

$(u, d, \ldots, t) \to e^{iB/3}(u, d, \ldots, t)$

(5)

T-reversal (CP) violation?

neutron EDM

EFT use in Fundamental Physics

what lies beyond?

Whatever it is provided is

microscophic / High energy physics

EFT will describe it

FIN

$$-\ddot{x}_2 - \omega^2 x_2 = k x_1^2$$

$$x_2 = \int \frac{d\nu}{2\pi} e^{i\nu t} \tilde{x}_2(\nu)$$

$$\int \frac{d\nu}{(2\pi)} e^{i\nu t} \tilde{x}_2 (\nu^2 - \omega^2) = k x_1^2(t)$$

$$\int dt\, e^{-it\nu'} x_1^2(t) = \tilde{x}_2(\nu')(\nu'^2 - \omega^2)$$

$$x_2(t) = \int \frac{d\nu\, dt'}{(2\pi)} e^{i\nu(t-t')} \frac{x_1^2(t')}{\nu^2 - \omega^2}$$

Solution to (4)

$$+\frac{1}{2}m_2\left(\left(\frac{dx_2}{dt}\right)^2-\Omega^2 x_2^2\right)-\kappa\, x_1^2 x_2$$

$$-\ddot{x}_2-\Omega^2 x_2=\frac{\kappa\, x_1^2}{m_2}$$

$$x_2(t)=\int\frac{d\nu}{2\pi}\, e^{i\nu t}\,\tilde{x}_2(\nu)$$

$$x_2(t)=\int\frac{d\nu\, dt'}{(2\pi)}\,\frac{e^{i\nu(t-t')}}{\nu^2-\Omega^2}\,\frac{\kappa\, x_1^2(t)}{m_2}$$

$$-\frac{1}{2}x_2\left(\frac{d^2}{dt^2}+\Omega^2\right)x_2 \quad -\kappa x^2$$

$$-\frac{1}{2}x_2\int\frac{d\nu\, dt'}{(2\pi)}\, e^{i\nu(t-t')}\,(-1)\,\frac{\kappa\, x_1^2}{m_2}$$

$$-\frac{1}{2}x_2\,\kappa\, x_1^2$$

$$-\frac{1}{2}\frac{\kappa^2}{m_2}\int\frac{d\nu\, dt'}{2\pi}\, x_1^2(t)\,\frac{e^{i\nu(t-t')}}{\nu^2-\Omega^2}\, x_1^2(t')$$

$$-\frac{1}{2}\frac{\kappa^2}{m_2}\int\frac{d\nu\, dt'}{(2\pi)}\, x_1^2(t)\,\frac{e^{i\nu(t-t')}}{-\Omega^2}\left(\frac{1}{1-\frac{\nu^2}{\Omega^2}}\right)x_1^2(t')$$

$$\frac{1}{2}\frac{\kappa^2}{m_2}\frac{x_1}{\Omega^2}\left(1-\frac{1}{\Omega^2}\left(\frac{d}{dt}\right)^2\right)\int\frac{d\nu\, dt'}{(2\pi)}\, e^{i\nu(t-t')}\, x_1^2(t')$$

$$1 > \frac{300}{fb} \frac{1}{(4\pi)} (\hbar c)^2 \frac{100\,GeV^2}{(\Lambda_f)^4} \quad ; \quad (\Lambda_f)^4 > \frac{300}{4\pi} \frac{(0.2\,GeV\,fm)^2}{10^{-15}\,10^2\,fm^2} \frac{GeV^4\,100^2}{}$$

$$\frac{(\Lambda_f)^4}{GeV^4} > \frac{3 \times 4}{4 \cdot \pi} 10^{4-2+2-2+15}$$

4×4

$$10^{34}\,y < 4\pi\; 6.6\; 10^{-25}\,GeV\,s\; \frac{\Lambda_B^4}{1\,GeV^5} \quad ; \quad \frac{\Lambda_B^4}{GeV^4} > \frac{10^{34} \cdot \pi \cdot 10^7\,s}{4\pi\; 6.6\; 10^{-25}} = \frac{10^{66}}{4 \cdot 6}$$

16

Obtaining and processing feedback

The question I find asking myself repeatedly

Am I getting through?

Reflecting on my view 

I realize I initially taught how I'd have liked to be taught:

* emphasis on coherence
* Self-contained notes
* underline points I see as difficult

→ I am not the average student → Subjective

(In fact the kind "hard to keep from learning")

Obtaining and processing feedback

The question I find asking myself repeatedly

Am I getting through?

Student:  I extrapolate from me sitting at a seminar:

if too high-level / technichal or poorly organized (even if interesting!)

→ I tune out real quick

Peers:  In conversation with colleagues

Initially "Ask them" Then "Ask them better"

Obtaining and processing feedback

The question I find asking myself repeatedly

Am I getting through?

Student:  I extrapolate from me sitting at a seminar:

→ Pitch at adequate level but how do I know?

Peer:  → Ask them

Answer (I think) Obtaining representative timely feedback

Obtaining and processing feedback

- Pose questions in class to students

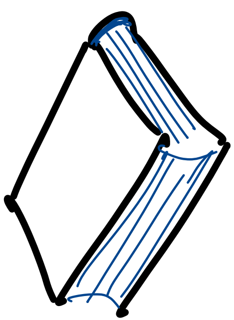
Low engagement → Use online forms instead of show of hands

from peer obs.

Sharpen & lay out plainly questions (time consuming!)

- Other means for feedback?

What if they learn after class?



Designing effective feedback...

Winstone Carless

Assessment for learning in HE

Sambell, McDowell, Montgomery