

EFT = Effective Field Theory

Why do quantum calculations work?

$$S_{dp} \rightarrow \sum_I \frac{\langle f | V | I \rangle \langle I | V | i \rangle}{E - E_I}$$

↑  
all  
intermediate states

on loops

/  
or Feynman

or FORTRAN

new particles not yet discovered ?

All of physics sensitive to high energies

## Uncertainty principle + locality

$$\Delta x \Delta p \approx \Delta E \Delta t$$

High  $E \Rightarrow \Delta x, \Delta t$  small  $\Rightarrow$  local

Looks like some term in  $L$

all local pieces

Come with parameters,  $e, m, \gamma$   
 $\underbrace{\gamma}_{\text{measure}}$

Unknown stuff  $\Rightarrow$  renorm constants

Example for  $\text{out} \xrightarrow{\text{very heavy particle}}$

$$\overline{\Sigma} + \overline{\zeta} = \frac{1}{q^2} \frac{\ell_0^2}{1 - \Pi(q^2)}$$

$\overline{\text{MS}} \text{ renormalization:}$

$$\ell_{\overline{\text{MS}}}^2 = \frac{\ell_0^2}{1 - \frac{\epsilon}{12\pi^2} \left[ \frac{1}{\varepsilon} - \gamma + \ln \frac{q^2}{\mu^2} \right]}$$

But  $\ln M_H^2$

$$\frac{1}{q^2} \frac{\ell_{\overline{\text{MS}}}^2}{1 + \frac{\epsilon}{12\pi^2} \ln M_H^2 / \varepsilon}$$

$\approx$  scattering depends on  $M_H^2$

$$\begin{aligned} \Pi(q) &= \frac{e_0^2}{12\pi^2} \left[ \frac{1}{\epsilon} + \ln(4\pi) - \gamma - 6 \int_0^1 dx x(1-x) \ln \left( \frac{m^2 - q^2 x(1-x)}{\mu^2} \right) + \mathcal{O}(\epsilon) \right] \\ &= \frac{e_0^2}{12\pi^2} \begin{cases} \frac{1}{\epsilon} + \ln(4\pi) - \gamma + \frac{5}{3} - \ln \frac{-q^2}{\mu^2} + \dots & (|q^2| \gg m^2), \\ \frac{1}{\epsilon} + \ln(4\pi) - \gamma - \ln \frac{m^2}{\mu^2} + \frac{q^2}{5m^2} + \dots & (m^2 \gg |q^2|). \end{cases} \quad (1.26) \end{aligned}$$

But when you measure  $\ln M_H^?$  disappears

$$\lim_{\vec{q} \rightarrow 0} g^2 \frac{1}{g^2} \frac{\ell_o^2}{1 - \pi(g^2)} \rightarrow \frac{1}{g^2} \underbrace{\frac{\ell_o^2}{1 - \pi(0)}}_{\ell_{ph}^2}$$

$$\frac{\ell_{ph}^2}{4\pi} = \frac{1}{1B}$$

$\leftarrow \ln M_H^?$   
disappears  
(in measured quantity)

Residual effect suppressed

$$\frac{1}{g^2} \frac{\ell_o^2}{1 - \pi(g^2)} = \frac{\ell_{ph}^2}{g^2} + \underbrace{\frac{g^2}{5m^2} \frac{\ell_o^2}{12\pi^2}}_{\frac{1}{m^2} \times g^2} \xrightarrow{F,T} \frac{1}{m^2} \Omega^2(r)$$

↑ Lamb shift

## Appelquist-Carrazzoni Theorem

Effect of a heavy mass particle appear either as

a renorm of coupling constant or

a power suppressed correction

1) EFT - "heavy particle"  $\rightarrow$  "high energy"

2) Caveat - Not true if limit violates symmetry

$(\begin{matrix} t \\ b \end{matrix})$ ,  $M_t \rightarrow \infty$ , in SM then  $M_t^2 \rightarrow$

but both  $M_t, M_b \rightarrow \infty$  (no large effect)