

Standardmodell (SM) kvarker Bygger opp

125,1 GeV/c<sup>2</sup>

	Three generations of matter (fermions)			Standardmodell (SM) kvarker	
	I	II	III	125,1 GeV/c <sup>2</sup>	
mass	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0	7 GeV/c <sup>2</sup>
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
name	u up	c charm	t top	γ photon	H Higgs boson (2012)
Quarks	d down	s strange	b bottom	g gluon	
	ν <sub>e</sub> electron neutrino	ν <sub>μ</sub> muon neutrino	ν <sub>τ</sub> tau neutrino	Z <sup>0</sup> Z boson	G graviton
	e electron	μ muon	τ tau	W <sup>±</sup> W boson	
Leptons				Gauge bosons	

materiepartikler spin = 1/2

leptoner

Bygger opp

protoner p (u u d)

neutroner n (d d u)

atomer p, n og e<sup>-</sup>

neutrinoer

n → p<sup>+</sup> e<sup>-</sup> ν<sub>e</sub>

kraftberende partikler spin = 1

x 2 anti-partikler med motsatt ladning  
(antall γ, g, Z<sup>0</sup>, W<sup>±</sup>, H) f.eks. positron e<sup>+</sup>, anti-utvask u<sup>-</sup>

Universets byggestener: p, n, e<sup>-</sup>, ν<sub>e</sub>, ν<sub>μ</sub>, ν<sub>τ</sub>, γ, π<sup>0</sup> (uū + dđ), π<sup>-</sup> (ud), π<sup>+</sup> (dū)

synlige 4%

Usynlige graver: mørk materie 20%, mørk energi 76%

## Herhill

F. eks.  $H \rightarrow \bar{b}\bar{b}$ .

Kan ikke beskrive herhill med vanlige Hamiltonoperatører.

V: tar utgangspunkt i SL for en partikkel i et potensial  $V$

$$\hat{H}_0 \bar{\Psi} = i\hbar \frac{\partial}{\partial t} \bar{\Psi}, \quad \hat{H}_0 = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V(x)$$

La nå  $\hat{H} = \hat{H}_0 - i\frac{\Gamma}{2}$  hvor  $\Gamma \in \mathbb{R}$  ( $\Gamma$  kalles vidde/broxde)

Ikke en Hermitisk operator.

V: finner de stasjonære tilstandene ved separasjon av variable

$$\bar{\Psi}(x, t) = \psi(x)\phi(t)$$

$$\text{Da er } \hat{H} \bar{\Psi} = i\hbar \frac{\partial}{\partial t} \bar{\Psi} \Rightarrow \hat{H}_0 \bar{\Psi} = \left(i\hbar \frac{\partial}{\partial t} + i\frac{\Gamma}{2}\right) \bar{\Psi}$$

$$\Rightarrow \phi(t) \hat{H}_0 \psi(x) = \psi(x) \left(i\hbar \frac{\partial}{\partial t} \phi(t) + i\frac{\Gamma}{2} \phi(t)\right) \quad \Big| \cdot \frac{1}{\phi(t)\psi(x)}$$

$$\Rightarrow \frac{1}{\psi(x)} \hat{H}_0 \psi(x) = \frac{1}{\phi(t)} \left(i\hbar \frac{\partial}{\partial t} \phi(t) + i\frac{\Gamma}{2} \phi(t)\right) = \underline{E_0}$$

$$\Rightarrow \hat{H}_0 \psi = E_0 \psi \quad \text{og} \quad i\hbar \frac{\partial}{\partial t} \phi + i\frac{\Gamma}{2} \phi = E_0 \phi$$

Vi kan skrive

$$\frac{d\phi(t)}{dt} = -\frac{i}{\hbar} (E_0 - i\frac{\Gamma}{2}) \phi(t)$$

$$\int \frac{dx}{x} = \ln x$$

$$\int \frac{d\phi(t)}{\phi(t)} = -\int \frac{i}{\hbar} (E_0 - i\frac{\Gamma}{2}) dt$$

$$\ln \phi(t) = -\frac{i}{\hbar} (E_0 - i\frac{\Gamma}{2}) t + C'$$

$$|e^{ix}|^2 = 1 \quad x \in \mathbb{R}$$

$$\phi(t) = \underline{e^{-\frac{i}{\hbar}(E_0 - i\frac{\Gamma}{2})t}} = \underline{e^{-\frac{i}{\hbar}E_0 t}} \underline{e^{-\frac{\Gamma}{2\hbar}t}}$$

Sannsynligheten for å finne partikkelen (i det hele tatt)

$$P(t) = \int_{-\infty}^{\infty} |\Psi(x,t)|^2 dx = \int_{-\infty}^{\infty} |\psi(x)|^2 |\phi(t)|^2 dx = \int_{-\infty}^{\infty} |\psi(x)|^2 e^{-\frac{\Gamma}{\hbar}t} dx = e^{-\frac{\Gamma}{\hbar}t} \underbrace{\int_{-\infty}^{\infty} |\psi(x)|^2 dx}_1 = e^{-\frac{\Gamma}{\hbar}t}$$

Vi har fått eksponentielt henfall med levetid

$$\tau = \frac{\hbar}{\Gamma}, \quad P(t) = e^{-\frac{t}{\tau}}$$

Hvorfor heter  $\Gamma$  vidde?

Vi fant  $\phi(t) = e^{-\frac{i}{\hbar}(E_0 - i\frac{\Gamma}{2})t}$ . Dette kan skrives som

$$\underline{\phi(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{i}{E - E_0 + i\frac{\Gamma}{2}} e^{-\frac{i}{\hbar}Et} dE}$$

Residuer (Fouriertrans.)

$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-ipx} g(p) dp$$

$$f(x) = e^{-\beta x} e^{i\lambda x}, \quad g(p) = \frac{i}{\lambda + p + i\beta}$$

$$x = t, \quad p = \frac{E}{\hbar}, \quad \beta = \frac{\Gamma}{2\hbar}, \quad \lambda = -\frac{E_0}{\hbar}$$

Tolkem  $\psi(E) = \sqrt{\frac{\Gamma}{2\pi}} \frac{1}{E - E_0 + i\frac{\Gamma}{2}}$  som en sannsynlighet for å finne partikkelen med energien  $E$ .

Der.  $|\psi(E)|^2$  er sannsynligheten.

$$\left( \begin{aligned} \phi(t) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \underbrace{\frac{i}{E - E_0 + i\frac{\Gamma}{2}}}_{\psi(E)} e^{-\frac{i}{\hbar}Et} dE \\ \phi(x) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \underline{\Psi(k, 0)} e^{-ikx} dk \end{aligned} \right)$$

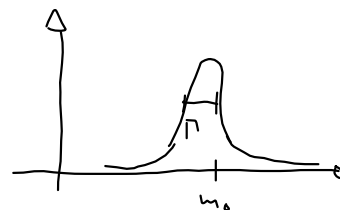
$$|\psi(E)|^2 = \frac{\Gamma}{2\pi} \frac{1}{(E - E_0)^2 + (\frac{\Gamma}{2})^2}$$

I tilfellet til partikkelen  $E = mc^2$  og da blir  $\left( \frac{dE}{dm} = c^2 \right)$

$$\underline{|\psi(m)|^2} = |\psi(E = mc^2)|^2 \left| \frac{dE}{dm} \right| = c^2 \frac{\Gamma}{2\pi} \frac{1}{(mc^2 - m_0c^2)^2 + (\frac{\Gamma}{2})^2}$$

$$= \frac{\Gamma}{2\pi c^2} \frac{1}{(m - m_0)^2 + (\frac{\Gamma}{2c^2})^2}$$

Breit-Wigner fordelingen  
(ikke-relativistiske)



$$E_0 = m_0 c^2$$

$$m_2 = 91,1876 \pm 0,0031 \text{ GeV}/c^2$$

$$\frac{\Gamma}{c^2} = 2,4192 \pm 0,0023 \text{ GeV}/c^2$$