

# **XII. PREDAVANJE**

## **SAŽETAK FEYNMANOVOG OPISA ELEKTRODINAMIKE**

- **QED U 2. REDU RAČUNA SMETNJE**
- **ELASTIČNO RASPRŠENJE  
ELEKTRONA NA MIONU**
- **KRIŽNI PROCES ANIHILACIJE U MIONE**

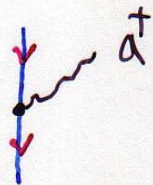
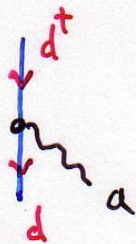
# Temelj QED

$$H_I(t) = - \int d^3x \mathcal{L}_{int}(\vec{x}, t) = \int d^3x j^\mu(\vec{x}, t) A_\mu(\vec{x}, t)$$

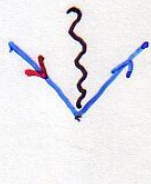
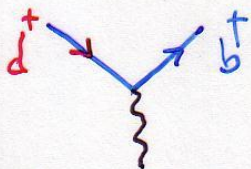
$$= -e \int d^3x : \bar{\Psi}(\vec{x}, t) \gamma^\mu \Psi(\vec{x}, t) : A_\mu(\vec{x}, t)$$

$$\sim : (b^\dagger + d) (b + d^\dagger) : (a + a^\dagger)$$

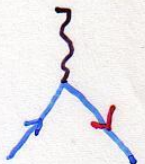
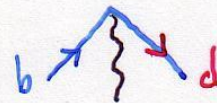
$$= -d^\dagger d (a + a^\dagger)$$



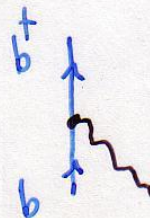
$$+ b^\dagger d^\dagger (a + a^\dagger)$$



$$+ d b (a + a^\dagger)$$



$$+ b^\dagger b (a + a^\dagger)$$



$$S = \lim_{\substack{t \rightarrow \infty \\ t_0 \rightarrow -\infty}} U_I(t, t_0) = T \exp\{-i \int dx^4 \mathcal{H}_I(x)\}$$

$$S_{fi} = \langle f | S | i \rangle = \delta_{fi} + i T_{fi}$$

$$|T_{fi}|^2 = \frac{[(2\pi)^4 \delta^4(p_f - p_i)]^2}{\prod_i (2E_i V) \prod_f (2E_f V)} |M_{fi}|^2$$

### Feynmanova pravila

#### I Ulažne crte $|i\rangle$

fermiona  $\xrightarrow{p,s} \bullet = u_a(p,s)$

anti-fermiona  $\xleftarrow{\bullet} = \bar{u}_b(p,s)$

fotona  $\xrightarrow{k,\lambda} \bullet = \epsilon^\mu(k,\lambda)$

#### II Vrhovi

#### III Propagatori

fermiona  $\bullet \xrightarrow{a} \bullet \xrightarrow{b} = \frac{i(\not{p} + m)_{ba}}{p^2 - m^2 + i\epsilon}$  ; fotona  $\xrightarrow{M} \bullet \xrightarrow{U} \bullet = \frac{-ig_{\mu\nu}}{k^2 + i\epsilon}$

#### Izlazne crte $|f\rangle$

$\bullet \xrightarrow{p,s} = \bar{u}_a(p,s)$

$\bullet \xleftarrow{} = u_b(p,s)$

$\xrightarrow{k,\lambda} \bullet = \epsilon^{\mu*}(k,\lambda)$

$= -ie(\gamma^\mu)_{ba}$

# QED-PROCESI U 2. REDU RAČUNA SMETNJE

## INVARIJANTNE AMPLITUDE

&

## FEYNMANOVA PRAVILA za postavljanje "i M"

# QED U 2. REDU RAČUNA SMETNJE

$$S^{(2)} = \frac{(-ie)^2}{2!} \iint d^4x d^4y T(\mathcal{L}_I(x) \mathcal{L}_I(y))$$

$$\propto T(:\bar{\Psi}(x) \gamma^\mu \Psi(x)::\bar{\Psi}(y) \gamma^\nu \Psi(y):) T(A_\mu(x) A_\nu(y))$$

**UZ WICKOV TEOREM ZA KRONOLOŠKE  
PRODUKTE:**

$$T(\phi_1 \phi_2 \dots \phi_N) = :\phi_1 \dots \phi_N: + \overbrace{:\phi_1 \phi_2 \dots \phi_N:} + \overbrace{:\phi_1 \dots \phi_N:} \\ + \overbrace{:\phi_1 \phi_2 \phi_3 \phi_4 \dots \phi_N:} + \dots$$

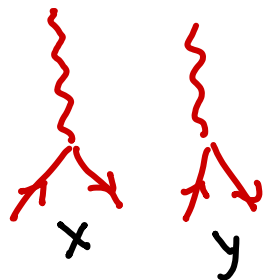
# 8 članova iz umnoška

$$T(A_\mu(x) A_\nu(y)) = :A_\mu(x) A_\nu(y): + \overbrace{A_\mu(x) A_\nu(y)}$$

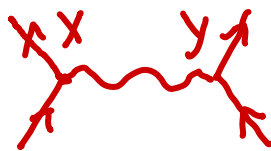
$$T(:\bar{\Psi}(x)\delta^\mu\Psi(x): :\bar{\Psi}(y)\delta^\nu\Psi(y):) = :\bar{\Psi}(x)\delta^\mu\Psi(x)\bar{\Psi}(y)\delta^\nu\Psi(y):$$

$$+ \overbrace{:\bar{\Psi}(x)\delta^\mu\Psi(x)\bar{\Psi}(y)\delta^\nu\Psi(y):} + :\bar{\Psi}(x)\delta^\mu\Psi(x)\bar{\Psi}(y)\delta^\nu\Psi(y): +$$

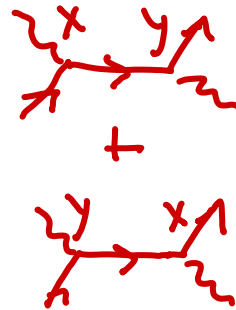
$$+ \overbrace{:\bar{\Psi}(x)\delta^\mu\Psi(x)\bar{\Psi}(y)\delta^\nu\Psi(y):}$$



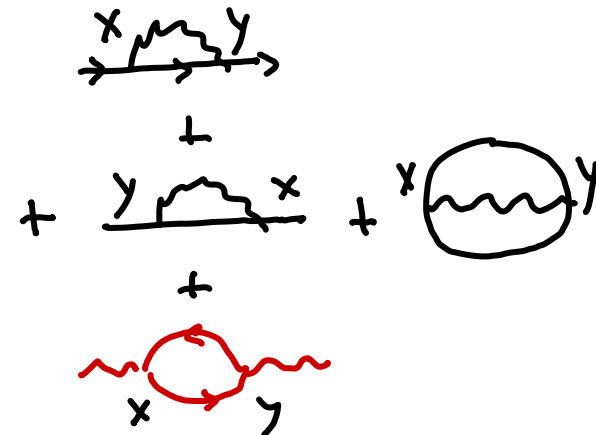
+



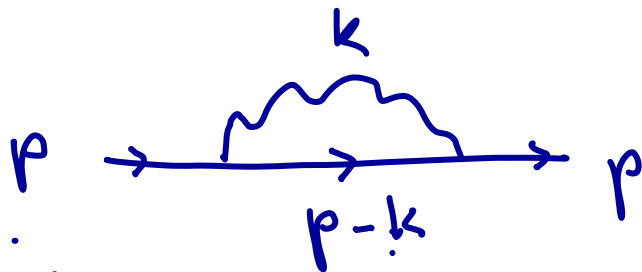
+



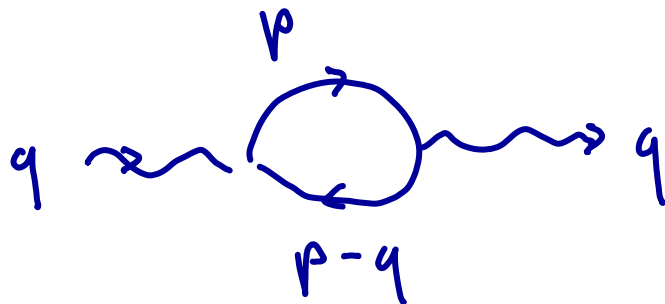
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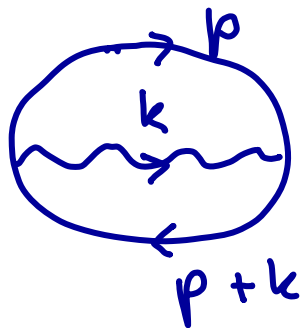
# KVANTNE PETLJE



vlastita energija



vakuumaska polarizacija



vakuumaska petlja

# S-matrični element, izborom $f, i$ -stanja, vodi na karakteristične elektromagnetske procese

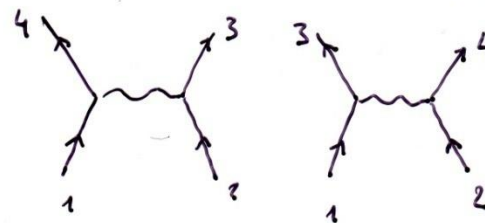
QED u 2. redu  
računa smetnje

FEČ § 3.3.2  
|  
str. 155

Møllerovo

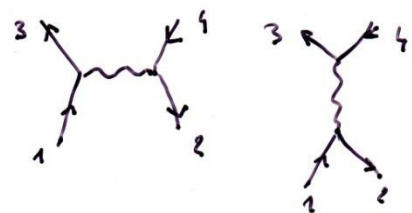
$$e^-(p_1, \nu_1) + e^-(p_2, \nu_2) \rightarrow e^-(p_3, \nu_3) + e^-(p_4, \nu_4)$$

$\uparrow$   
 $t$



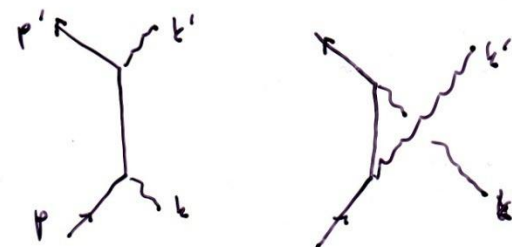
Bhabhino

$$e^-(p_1) + e^+(p_2) \rightarrow e^-(p_3) + e^+(p_4)$$



Komptovsko

$$\gamma(k) + e^-(p) \rightarrow \gamma(k') + e^-(p')$$

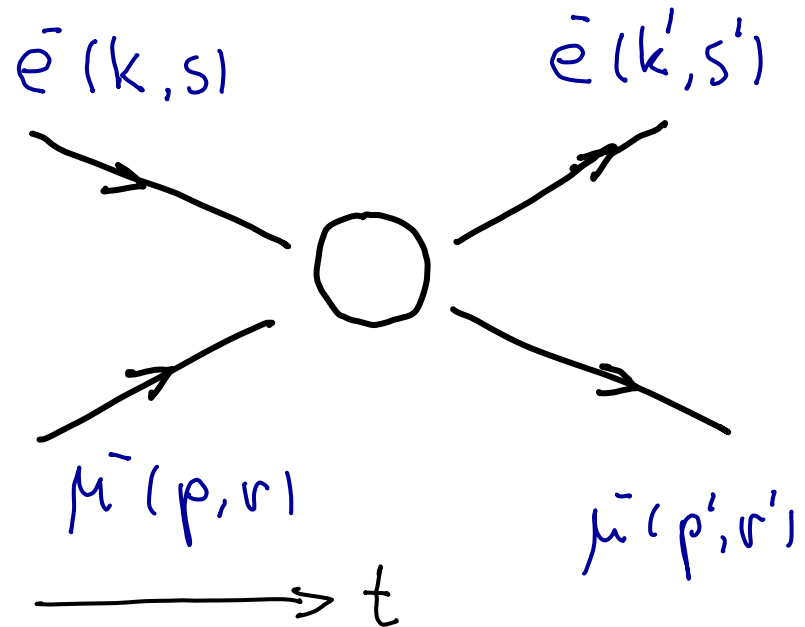


$\rightarrow$   
Anihilacija

$$e^+ + e^- \rightarrow \gamma + \gamma$$

# ELASTIČNO RASPRŠENJE ELEKTRONA NA MIONU

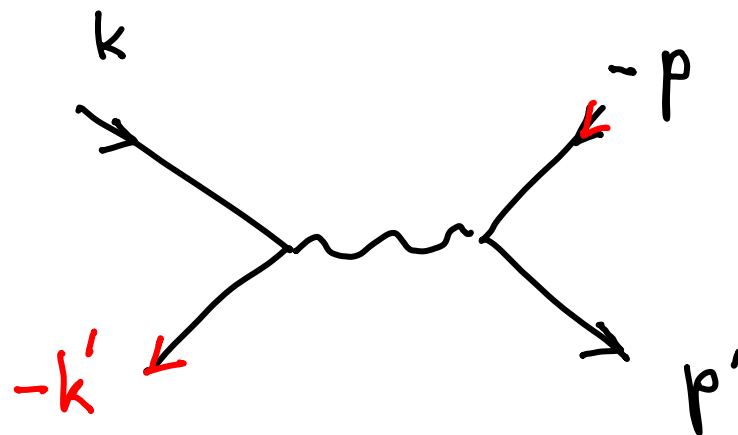
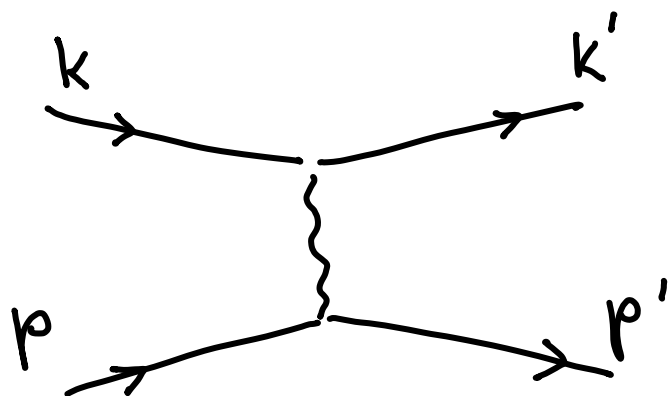
$$\mathcal{L}_I = -e \bar{\Psi}_{(e)} \not{A} \Psi_{(e)} - e \bar{\Psi}_{(\mu)} \not{A} \Psi_{(\mu)}$$



$$iM = \bar{u}(k',s') (-ie\gamma^\mu) u(k,s) \frac{-ig_{\mu\nu}}{q^2} \bar{u}(p',r') (-ie\gamma^\nu) u(p,r)$$



# PROCES i njemu KRIŽNI



$$M \sim [\bar{u}(k') u(k)] [\bar{u}(p') u(p)] ; \quad [\bar{v}(k') u(k)] [\bar{u}(p') v(p)]$$

$$(k+p)^2 \equiv s$$

$$(k-k')^2 \equiv t$$

$$\longleftrightarrow$$

$$k' \leftrightarrow -p$$

$$(k-k')^2 \equiv t$$

$$(k+p)^2 \equiv s$$

$$|M|^2 = 2e^4 \frac{s^2 + u^2}{t^2}$$

$$2e^4 \frac{t^2 + u^2}{s^2}$$

$$\longleftrightarrow$$

# URL granica

$$\frac{d\sigma(e^+e^- \rightarrow \mu^+\mu^-)}{d\Omega} \Big|_{\text{CM}} = \frac{\alpha^2}{4S} (1 + \cos^2\vartheta)$$

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3S} \approx \frac{22 \text{ nb}}{E_{\text{Snopu}}^2 (\text{GeV}^2)}$$