Теория фундаментальных взаимодействий

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HARD PHOTONS IN PROTON-ANTIPROTON ANNIHILATION TO A LEPTON PAIRFOR PANDA EXPERIMENT

We consider the process of proton-antiproton annihilation into lepton pair which allows one to measure proton form factors in time-like region of momentum transfer $q^2 > 4M_p^2$, where M_p is the proton mass (figure 1). Our aim is to contribute to theoretical support for PANDA/FAIR facility [1] which plan to study the process of scattering of antiproton beam with wide range of momentum (from 1,5 GeV/c up to 15 GeV/c) of static target made of hydrogen or heavy nuclei. Besides proton form factor measurements in time-like region this setup in principle allows one to measure proton form factor below threshold $0 < q^2 < 4M_p^2$ [2, 3].

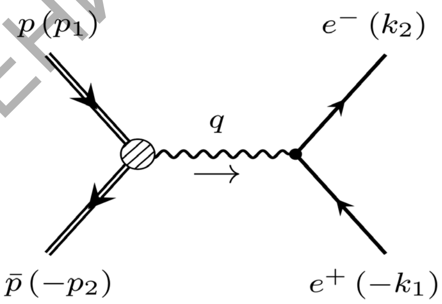

Figure 1 – Antiproton-proton annihilation in Born approximation

In Born approximation this process has the following form [4]:

$$\frac{d\sigma_B}{d\cos\theta} = \frac{\pi\alpha^2}{2s\beta}\left\{|G_M|^2\left(1+\cos^2\theta\right) + |G_E|^2\left(1-\beta^2\right)\left(1-\cos^2\theta\right)\right\},$$

where θ is the scattering angle (angle between directions of initial antiproton and final electron), $\alpha=1/137$ is the fine structure constant, s is the total invariant mass, β is the initial antiproton velocity and $G_{E,M}$ are the electric and magnetic form factors which describe electromagnetic structure of the proton.

In the next perturbation order one has additional contributions:

$$d\sigma \sim |\mathcal{M}_B|^2 + 2\,\mathsf{Re}\,(\mathcal{M}_B \mathcal{M}_V^*) + |\mathcal{M}_\gamma|^2 = |\mathcal{M}_B|^2\,(1 + \delta_V + \delta_\gamma)$$

which is usually called "radiative corrections" (figure 2).

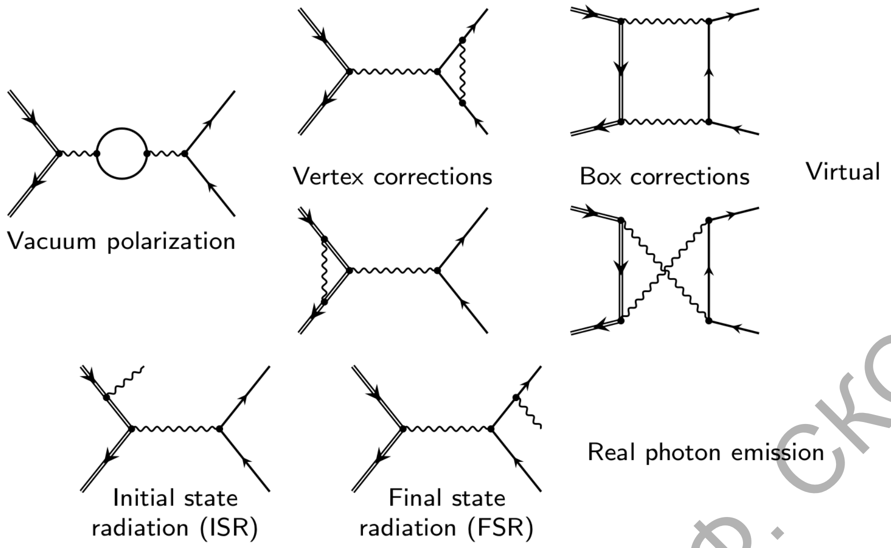

Figure 2 – Radiative corrections

These corrections describe additional terms with virtual particles (denoted with index V) and terms with real photon emission (index γ). Virtual photon contributions are infra-red divergent and we regularize them using "fictitious" photon mass λ. In order to cancel this divergence one need to consider real photon emission which will also depend on λ. The sum of these two contributions is independence of λ and finite. Virtual corrections part has the form:

$$\frac{d\sigma_{B+V}}{d\cos\theta} = \frac{\alpha^2}{4s\beta}\left(2-\beta^2\sin^2\theta\right)\left|\frac{1}{1-\Pi(s)}\right|^2 + \\ + \frac{\alpha^3}{2\pi s\beta}\left\{\left[\left(2-\beta^2\sin^2\theta\right)\mathsf{Re}\left(F_e^{(2)}+F_1^{(2)}\right)+2\,\mathsf{Re}\,F_2^{(2)}\right] + \\ + \frac{I(t,u,s)}{s}\right\},$$

where $\Pi(s)$ is the vacuum polarization operator, $F_{1,2,e}^{(2)}$ are corrections to vertex parts and $I(t,u,s)$ is the two proton "box" contribution. Real photon emission can be divided into charge even and charge odd parts. Even part of soft photon emission has the form [5]:

$$\frac{d\sigma_{\text{even}}^{\text{soft}}}{d\cos\theta} = \frac{\alpha}{\pi}\frac{d\sigma_B}{d\cos\theta}\left\{-2\left[\ln\frac{2\omega}{\lambda} - \frac{1}{2\beta}L_\beta\right] - 2\ln\frac{\omega m}{\lambda E} \right. \\ \left. + \; 2\frac{1+\beta^2}{2\beta}\left[\ln\frac{2\omega}{\lambda}L_\beta - \frac{1}{4}L_\beta^2 + \Phi(\beta)\right] + 2\left[\ln\frac{2\omega}{\lambda}L_e - \frac{1}{4}L_e^2 - \frac{\pi^2}{6}\right]\right\}$$

where function $\Phi(\beta)$ has the form:

$$\Phi(\beta) = \frac{\pi^2}{12} + L_\beta \ln \frac{1+\beta}{2\beta} + \ln \frac{2}{1+\beta} \ln(1-\beta) + \frac{1}{2} \ln^2(1+\beta) - \frac{1}{2} \ln^2 2 +$$
$$- \mathsf{Li}_2(\beta) + \mathsf{Li}_2(-\beta) - \mathsf{Li}_2\left(\frac{1-\beta}{2}\right), \qquad \Phi(1) = -\frac{\pi^2}{6},$$
$$L_\beta \equiv \ln \frac{1+\beta}{1-\beta} \qquad\qquad L_e = \ln \tfrac{s}{m_e^2}$$

Charge odd part of soft photon emission was revised and has the form:

$$\frac{d\sigma_{\text{odd}}^{\text{soft}}}{d\sigma_0} = -\frac{\alpha}{2\pi^2} \left(\left(m_e^2 + M_p^2 - t\right) R(s,t) - \left(m_e^2 + M_p^2 - u\right) R(s,u) \right),$$

where

$$R(s,t) = 2\pi \left(2A(s,t) \ln \frac{2\omega}{\lambda} + C(s,t) \right),$$

$$A(s,t) = \frac{1}{\sqrt{\lambda(t, m_e^2, M_p^2)}} \ln \left| \frac{t - m_e^2 - M_p^2 - \sqrt{\lambda(t, m_e^2, M_p^2)}}{t - m_e^2 - M_p^2 + \sqrt{\lambda(t, m_e^2, M_p^2)}} \right|,$$

$$C(s,t) = \frac{1}{\sqrt{\lambda(t, m_e^2, M_p^2)}} \sum_{i,j=1}^{4} \epsilon_i \delta_j U_{ij}(\eta_0, \eta_1, y_i, y_j),$$

$$\eta_0 = \sqrt{1 - m_e^2/E^2}, \qquad \eta_1 = \sqrt{1 - M_p^2/E^2} + \sqrt{-t}/E,$$

$$y_i = \delta_i - \frac{t + m_e^2 - M_p^2 + \epsilon_i \delta_i \sqrt{\lambda(t, m_e^2, M_p^2)}}{2E\sqrt{-t}}.$$

Soft photon realm in the formulae above was defined with the condition that photon energy should be smaller then some small quantity ω. Modern experiments use Monte-Carlo generators to study hardware setup and one no longer needs for soft photon approximation. We calculated hard photon emission which has rather complicated form and will not be presented here. We only show schematically the structure of hard photon emission cross section:

$$d\sigma_\gamma = \frac{\alpha^3}{\pi^2 s\beta} \int \left(\mathcal{M}_{\text{ISR}} + \mathcal{M}_{\text{FSR}}\right)\left(\mathcal{M}_{\text{ISR}} + \mathcal{M}_{\text{FSR}}\right)^+ \cdot \theta(p_0 - \omega) \cdot \theta_P \cdot d\Phi_3,$$

where we took into account initial state radiation (ISR) and final state radiation (FSR). These contributions are integrated over phase space of final photon $d\Phi_3$ taking into account energy cut of photon hardness using first θ function. Second θ function represents the possibility to include any experiment specific conditions into our integration. One important test of our calculation is the following: when one sum over all possible photon energies and angles (i.e. integrates over whole energy range of final photon) then cross section should not depend on parameter ω since it will cancel in the sum of soft and hard photon emissions. This cancellation one can see on figure 3.

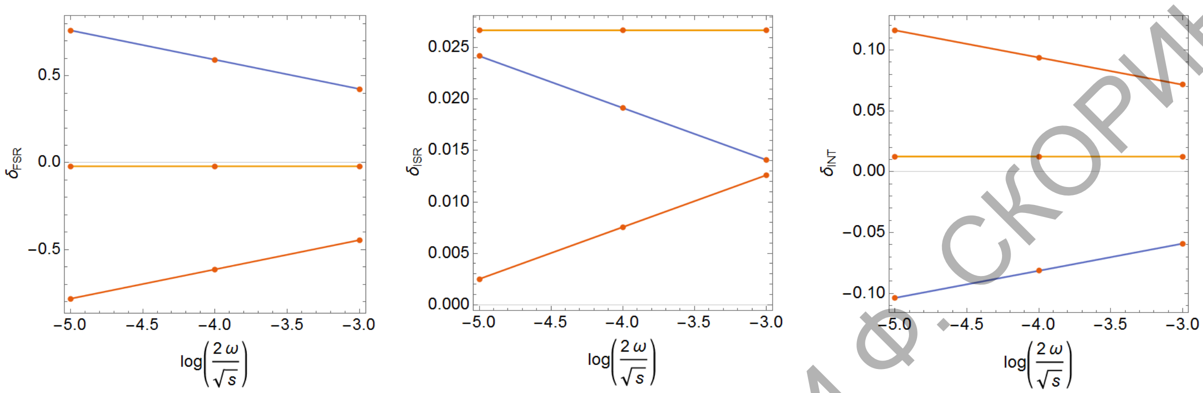

Figure 3 – Dependence of ISR, FSR and their interference of real photon softness parameter ω. One contribution on the plot is real hard photon emission. Another is virtual+soft photon emission. And their sum is flat horizontal line independent of ω

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