Hadronic corrections to neutrino–electron scattering at high momentum transfer

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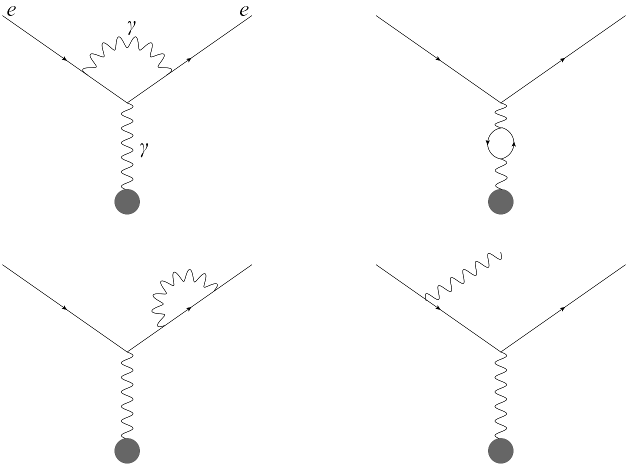
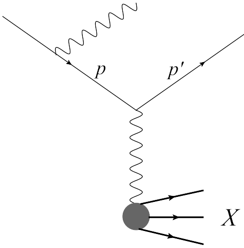
An overview

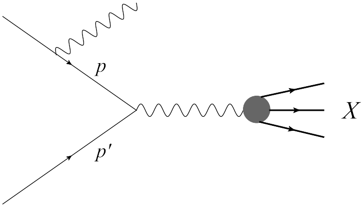
QED radiative corrections



An overview

Processes at high momentum transfer





$t=(p - p')^2$

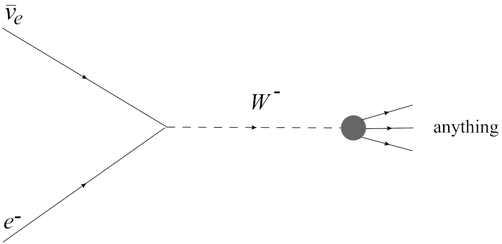
$-t >> m_i^2$

$s=(p + p')^2$

$s >> m_i^2$

The Glashow resonance (1959)

An example of neutrino–electron scattering at high momentum transfer:



$$s = m_W^2 \implies E_{\bar{\nu}} = \frac{m_W^2}{2m_e} \approx 6.3 \times 10^{15} \text{ eV}.$$

Searches for the Glashow resonance

nature

Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

Nature **591**, 220–224(2021) | Cite this article

A Publisher Correction to this article was published on 31 March 2021

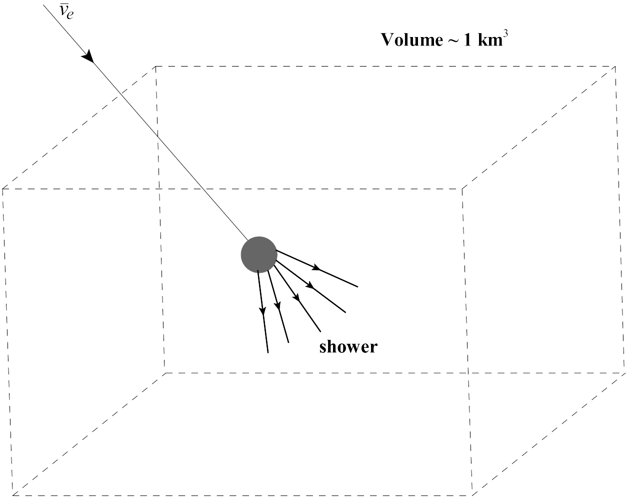
This article has been updated

Abstract

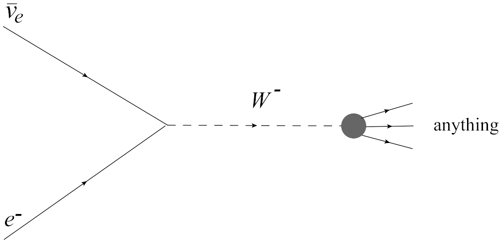
The Glashow resonance describes the resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron[1], peaking at an antineutrino energy of 6.3 petaelectronvolts (PeV) in the rest frame of the electron. Whereas this energy scale is out of reach for currently operating and future planned particle accelerators, natural astrophysical phenomena are expected to produce antineutrinos with energies beyond the PeV scale. Here we report the detection by the IceCube neutrino observatory of a cascade of high-energy particles (a particle shower) consistent with being created at the Glashow resonance. A shower with an energy of 6.05 ± 0.72 PeV (determined from Cherenkov radiation in the Antarctic Ice Sheet) was measured.

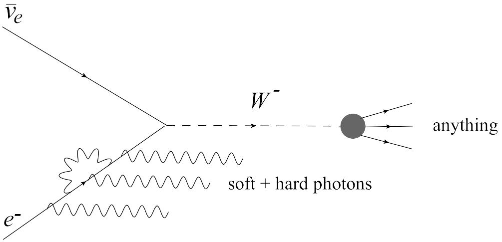
A neutrino-induced shower in a large water detector

Typically, an event inside a km-scale neutrino detector is a mixture of electromagnetic and hadronic components (IceCube, Baikal-GVD).



QED corrections to $\bar{\nu}_e e^-$ annihilation into a W^- boson

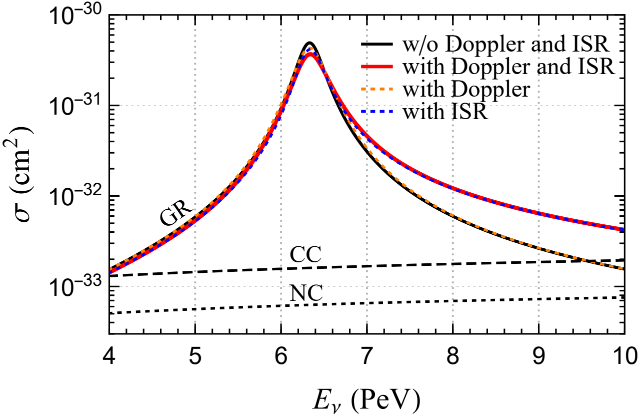




QED corrections to $\bar{\nu}_e e^-$ scattering

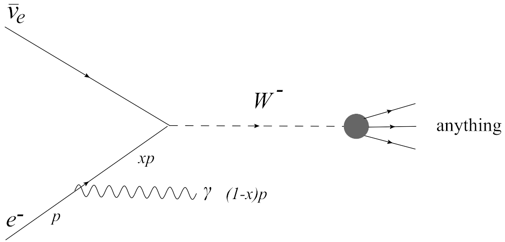
$$\bar{\nu}_e + e^- \to \text{anything}.$$

Soft photons resummed to all orders and $\mathcal{O}(\alpha^3)$ hard photons have been taken into account [Lindner *et al.*, JHEP11(2023)164]:



The initial state radiation (ISR)

The LO process: $\bar{\nu}_e + e^- \to W^- + \gamma$, [Seckel, PRL80(1998)900].

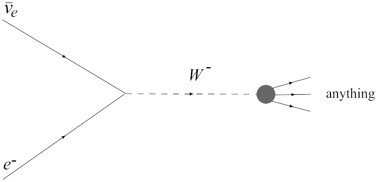


The radiative return: the photon carries away a fraction of the total energy returning thus the process to the resonance pole:

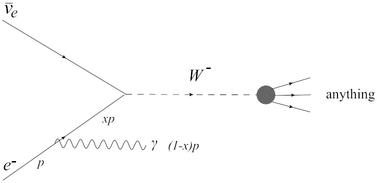
$$s \implies xs = m_W^2.$$

So that, even $\bar{\nu}_e$s of energies above 6.3 PeV are able to excite the resonance.

The behaviour of the cross sections

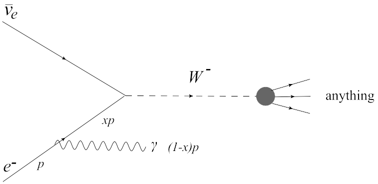


$$\sigma_{BW} \propto \frac{\alpha^2}{(s - m_W^2)^2/m_W^2 + \Gamma^2}$$



$$\sigma_{ISR} \propto \frac{\alpha^2}{s - m_W^2} \log\left(\frac{s - m_W^2}{m_e^2}\right).$$

Another ISR-like mechanisms



$$\sigma_{ISR} \propto \frac{\alpha^2}{s - m_W^2} \log\left(\frac{s - m_W^2}{m_e^2}\right).$$

One may ask:

are there another processes in SM contributing to the $\nu_e e$ scattering with the effect similar to ISR?

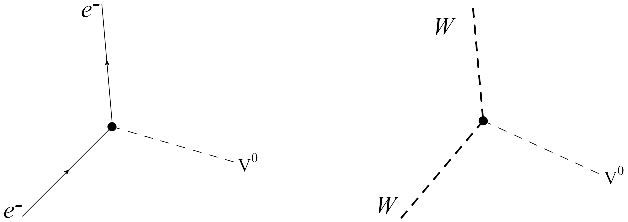
Another ISR-like mechanisms

Two conditions must hold:

1) The particle to carry away the "extra energy" couples to the electron current.

2) The high momentum transfer regime (high mass final states).

The vector meson dominance (VMD) generates the following terms:

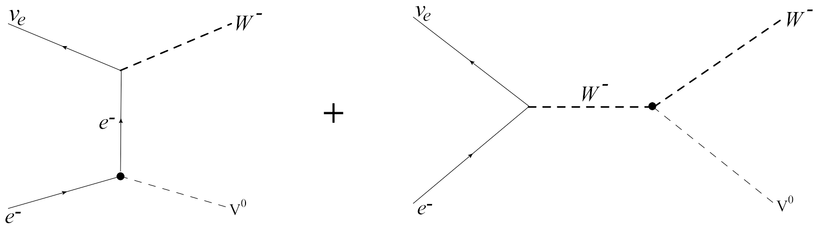


$$V^0 = \rho^0,\, \omega,\, \phi,\, J/\psi, ...$$

Justified by the adequate description of the behaviour of the reaction $e^+e^- \to \pi^+\pi^-$ around $\sqrt{s} = m_\rho$, for example.

We consider the reactions:

$$\bar{\nu}_e e^- \to W^- V^0, \quad V^0 = \rho^0, \omega, \phi, J/\psi, ...$$



$$\sigma_{\bar{\nu}_e e \to WV} \propto \frac{\alpha^3}{s - m_W^2} \log\left(\frac{s - m_W^2}{m_V^2}\right).$$

This provides a mechanism similar to ISR at a higher order in α.

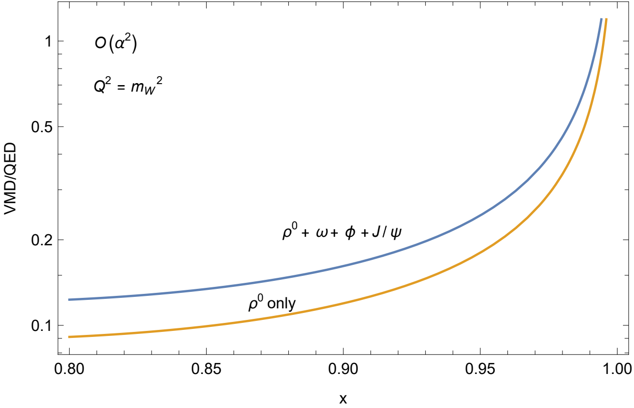
The VMD provides an ISR-like mechanism

Compare the cross sections:

$$\sigma_{ISR} \propto \frac{\alpha^2}{s - m_W^2} \log\left(\frac{s - m_W^2}{m_e^2}\right) \qquad \text{QED,}$$

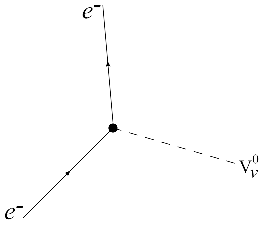
$$\sigma_{\bar{\nu}_e e \to WV} \propto \frac{\alpha^3}{s - m_W^2} \log\left(\frac{s - m_W^2}{m_V^2}\right) \qquad \text{VMD.}$$

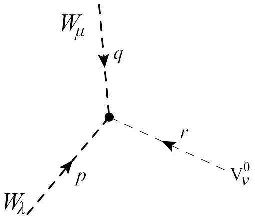
VMD and QED corrections at $\mathcal{O}(\alpha^2)$



The VMD contribution becomes comparable to the QED $\mathcal{O}(\alpha^2)$ corrections as $x \to 1$ (the resonance region).

The Feynman rules in VMD



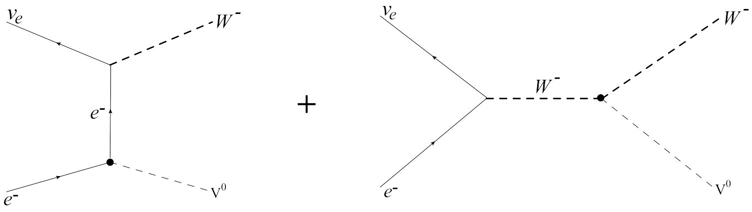


$$i\frac{4\pi\alpha}{f_V}\gamma_\nu$$

$$i\frac{4\pi\alpha}{f_V}[(r-q)_\lambda g_{\mu\nu} + (q-p)_\nu g_{\lambda\mu}$$

$$+(p-r)_\mu g_{\lambda\nu}]$$

The amplitude for $\bar{\nu}_e e^- \to W^- V^0$



$$i\mathcal{M} = i\frac{4\pi\alpha g}{2\sqrt{2}f_V}\bar{v}(p_\nu)(1+\gamma^5)\,T^{\mu\sigma}\,u(p_e)\epsilon^*_\mu(p_V)\epsilon^*_\sigma(p_W),$$

$$T_{\mu\sigma} = \Bigg[\frac{1}{s-m_W^2}[g_{\mu\sigma}(\not{p}_V - \not{p}_W) + \gamma_\sigma(2p_W+p_V)_\mu$$

$$-\gamma_\mu(2p_V+p_W)_\sigma] - \frac{\gamma_\sigma(\not{p}_e - \not{p}_V)\gamma_\mu}{(p_e-p_V)^2}\Bigg].$$

The cross section for $\bar{\nu}_e e^- \to W^- V^0$

Note that $\frac{m_V^2}{m_W^2} \ll 1$ for $V = \rho^0,\ \omega,\ \phi,\ J/\psi$.
A massless meson approximation.

$$\sigma_{\bar{\nu}_e e \to WV} = \frac{\sqrt{32}\pi}{f_V^2} \frac{\alpha^2 G_F}{(1-x)} \left\{ (x + x^3) \log\left(\frac{s(1-x)}{m_V^2} \right) - \frac{1}{3}(5x - 4x^2 + 5x^3) \right\},$$

where $x = \frac{m_W^2}{s}$.

The parameters of VMD

$$\frac{1}{f_\rho^2} = 39.3 \times 10^{-3},$$

$$\frac{1}{f_\omega^2} = 3.5 \times 10^{-3},$$

$$\frac{1}{f_\phi^2} = 5.5 \times 10^{-3},$$

$$\frac{1}{f_{J/\psi}^2} = 7.9 \times 10^{-3}.$$

[Grossman *et al.*, JHEP04(2015)101].

Uncertainties

The results depend on the VMD effective couplings. There may be changes, but not dramatical, $\lesssim 10\ \%$.

QED $\mathcal{O}(\alpha^2)$ corrections

$$f_{QED}(x, Q^2) = \frac{\alpha^2}{8\pi^2}\left[-4(1+x)\log(1-x) + 3(1+x)\log(x) - 4\frac{\log(x)}{1-x} - 5 - x\right]\log^2\left(\frac{Q^2}{m_e^2}\right).$$

[Cacciari *et al.*, EPL17(1992)123].

Universality of the approach

The presented approach is by no means restricted to the neutrino reactions.
One may use this for analysing other processes with electrons provided $Q^2 \gg m_V^2$.

Summary

The reactions $\bar{\nu}_e e^- \to W^- V^0$ ($V^0 = \rho^0, \omega, \phi, J/\psi$) have been studied. The corresponding cross sections are calculated in VMD.

As far as $\mathcal{O}(\alpha^2)$ QED corrections to neutrino–electron scattering at high momentum transfer are concerned, these reactions should also be taken into account.

Thank you!