Resonant channels in interactions of neutrinos with photons

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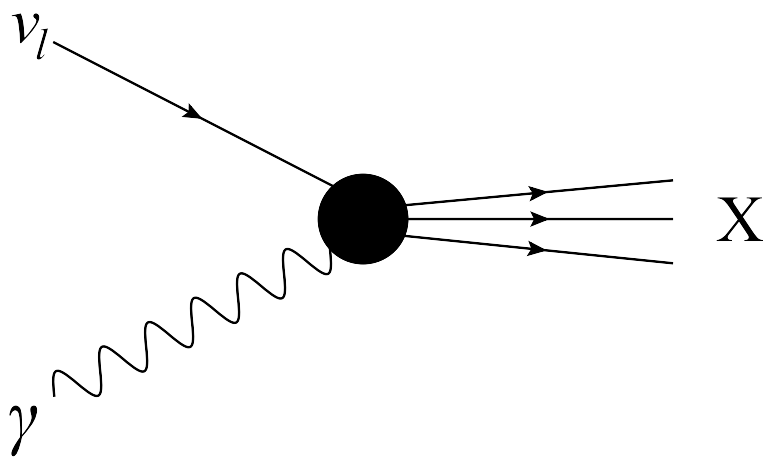
Based on

I.A., PLB 741 (2015) 295; PLB 756 (2016) 247;
MPLA 35 (2020) 2050101; EPL 129 (2020) 11003.

Introduction and Motivation:

Do neutrinos interact with photons in the Standard Model?



They do.

And not only through loop effects, but also at tree level.

This subject has already entered textbooks on particle physics.
See, for example, the famous "Leptons and Quarks" by L.B. Okun.

Introduction and Motivation:

Why are neutrinos special objects to study?

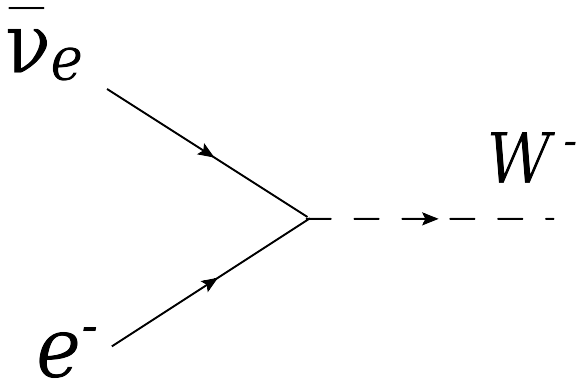
1. Neutrinos are the only known particles that had forced us to extend the Standard Model (non-conservation of the family lepton number – neutrino oscillations).

2. Difficulties associated with neutrino experiments still leave numerous "white spots".

3. Apart from new physics phenomena, there are fundamental predictions of the Standard Model not yet discovered experimentally. For example, the cosmic neutrino background and the Glashow resonance.

The Glashow resonance

Annihilation of an electron antineutrino with an electron into an on-mass-shell W^- boson: $\bar{\nu}_e + e^- \to W^-$ (Glashow, 1959).



The resonant enhancement of the $\bar{\nu}_e e^-$ scattering cross section at the pole $s = m_W^2$:

$$\sigma_{\bar{\nu}_e e} = 24\pi \frac{\Gamma_{\bar{\nu}_e e}\Gamma}{(s - m_W^2)^2 + m_W^2 \Gamma^2}.$$

The Glashow resonance

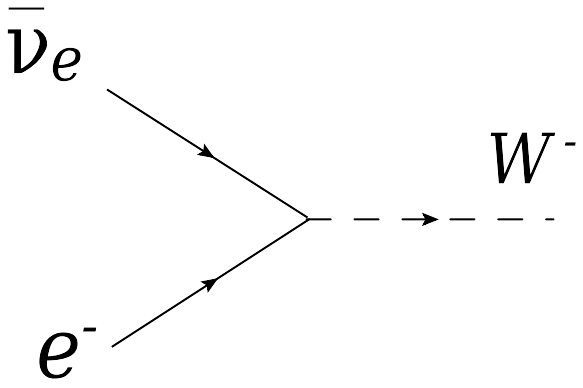
It should be emphasized that the problem is not about a plain rediscovery of the W boson, but about the observation of a special channel in the neutrino sector in the resonance region.

For the other massive weak boson, Z^0, the corresponding channel has already been observed and well studied:

$$e^+ + e^- \to Z^0 \ \ (observed).$$

$$\bar{\nu}_e + e^- \to W^- \ \ (never\ observed).$$

The Glashow resonance: $\bar{\nu}_e + e^- \rightarrow W^-$ (Glashow, 1959).

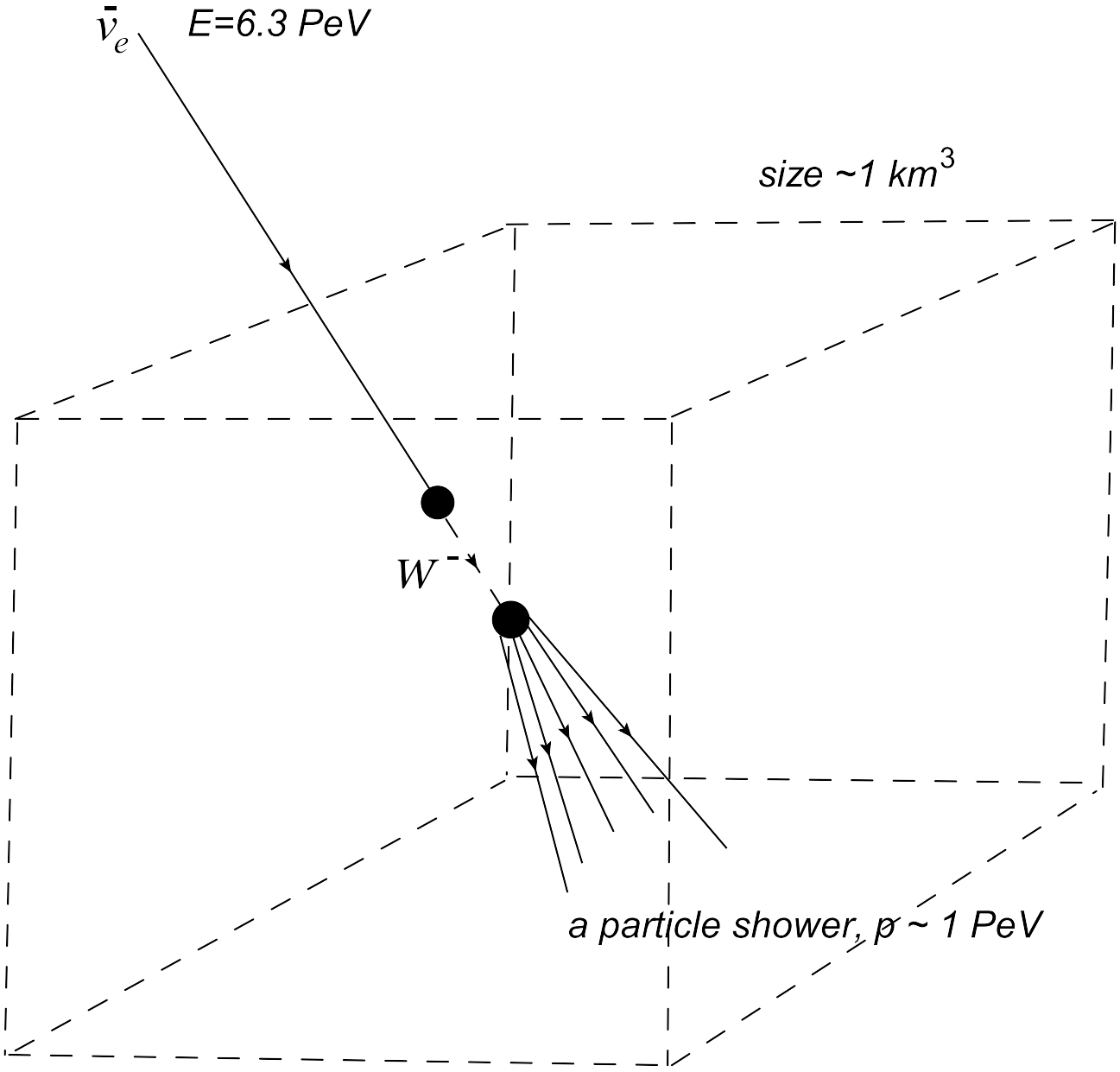


Annihilation of cosmic antineutrinos on electrons contained in a detector:

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

Searches for the resonance at the IceCube Neutrino Observatory.

Experimental 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.

Experimental searches for the Glashow resonance

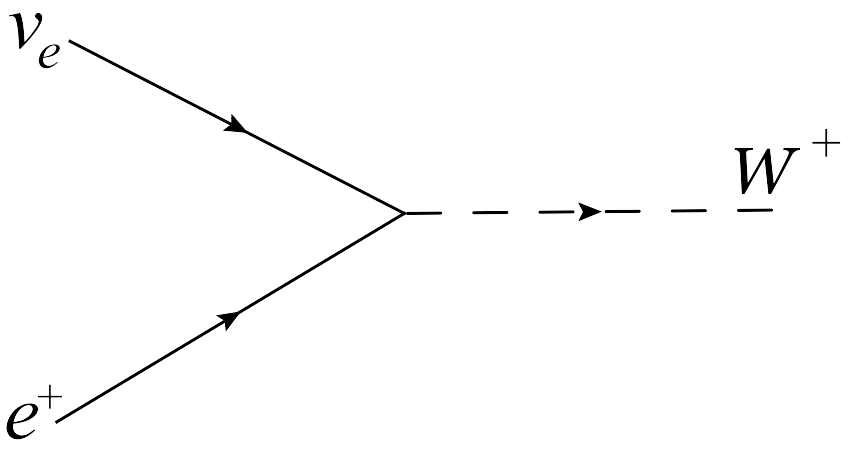
IceCube has detected several events in the PeV region that can, in principle, be initiated by the Glashow resonance.

But the statistics is still insufficient to make a decisive conclusion about the observation of the resonance.

The CP conjugate of the Glashow resonance

What about the following reaction:

$$\nu_e + e^+ \to W^+?$$



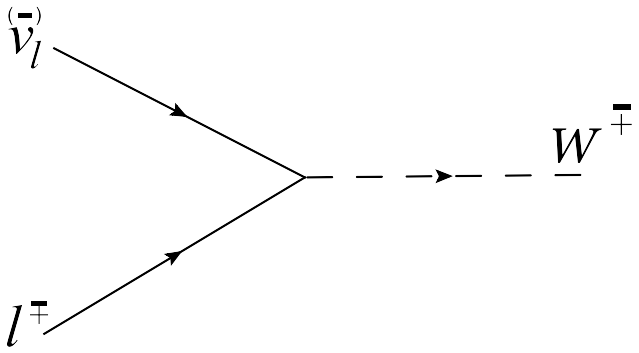
Where can one get a target with positrons?

The Glashow resonance with other leptons

Going farther, one may wonder whether it is possible to probe the lepton universality for the resonance:

$$\nu_\mu + \mu^+ \to W^+, \;\; \nu_\tau + \tau^+ \to W^+.$$

$$\bar{\nu}_\mu + \mu^- \to W^-, \;\; \bar{\nu}_\tau + \tau^- \to W^-.$$



Targets with μ and τ are also needed.

The idea of the radiative return

The direct measurement of the hadronic cross section needs dedicated experiments. This disadvantage can be avoided using the radiative return (Chen and Zerwas, PRD 11 (1975) 58):

$$\sigma(e^+e^- \to \text{hadrons} + \gamma)(s, Q^2) = H \cdot \sigma(e^+e^- \to \text{hadrons})(Q^2).$$

Since H is a known function, measuring $\sigma(e^+e^- \to \text{hadrons} + \gamma)$ one actually evaluate $\sigma(e^+e^- \to \text{hadrons})$.

For example, the very accurate extraction of the pion form factor by the KLOE Collaboration (PLB 606 (2005) 12).

The case of a narrow resonance in QED

If $\Gamma \ll m_R$ then

$$\sigma_{ee\to R}(s) = 12\pi \frac{\Gamma_{ee\to R}\Gamma}{(s-m_R^2)^2 + m_R^2\Gamma^2} \longrightarrow C \cdot \delta(s - m_R^2).$$

$$e^- + \gamma \to e^- + R.$$

$$\sigma_{e\gamma\to eR}(s) = \int_0^1 f_{\gamma/e}(x,s)\sigma_{ee\to R}(xs)dx.$$

Due to the narrowness of the resonance, the integration is very simple:

$$\boxed{\sigma_{e\gamma\to eR}(s) = C \cdot f_{\gamma/e}(m_R^2/s)}$$

The case of a narrow resonance in QED

If $\Gamma \ll m_R$ in

$$e^- + \gamma \to e^- + R,$$

the narrow resonance projects out the structure function of the photon into the cross section $\sigma_{e\gamma \to eR}(s)$:

$$\boxed{\sigma_{e\gamma \to eR}(s) = C' \cdot \frac{m_R^2}{s} f_{\gamma/e}\left(\frac{m_R^2}{s}\right)}$$

Thus, such a behaviour of the cross section of a reaction indicates the presence of a resonant mechanism.

A narrow resonance in the electroweak theory

The widths of $W^{\pm}$ bosons are relatively narrow, $\Gamma/m_W \approx 2.6 \times 10^{-2}$, so that the $\delta(s - m_W^2)$-approximation holds.

Consider the following reaction (Seckel, PRL 80 (1998) 900):

$$\nu_e + \gamma \to e^- + W^+.$$

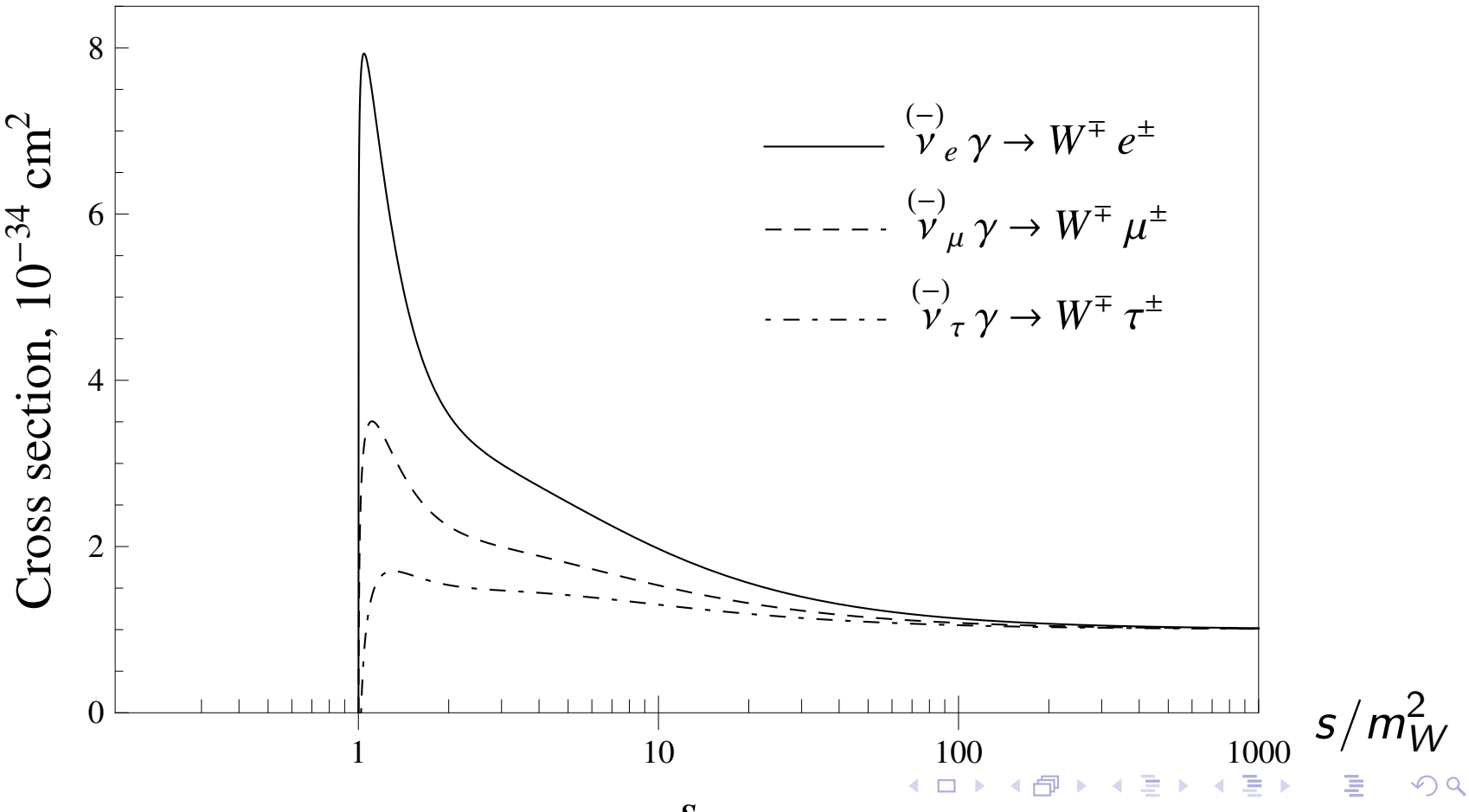
It turns out that the corresponding cross section in the leading logarithmic order behaves as (I.A., PLB 741 (2015) 295)

$$\sigma_{\nu_e \gamma \to eW}(s) = C' \cdot \frac{m_W^2}{s} f_{\gamma/e}\left(\frac{m_W^2}{s}\right).$$

This is a clear indication that the reaction above proceeds through a resonant mechanism of the production of W^+.

The CP conjugate of the Glashow resonance "hides" in $\nu_e \gamma \to e^- W^+$

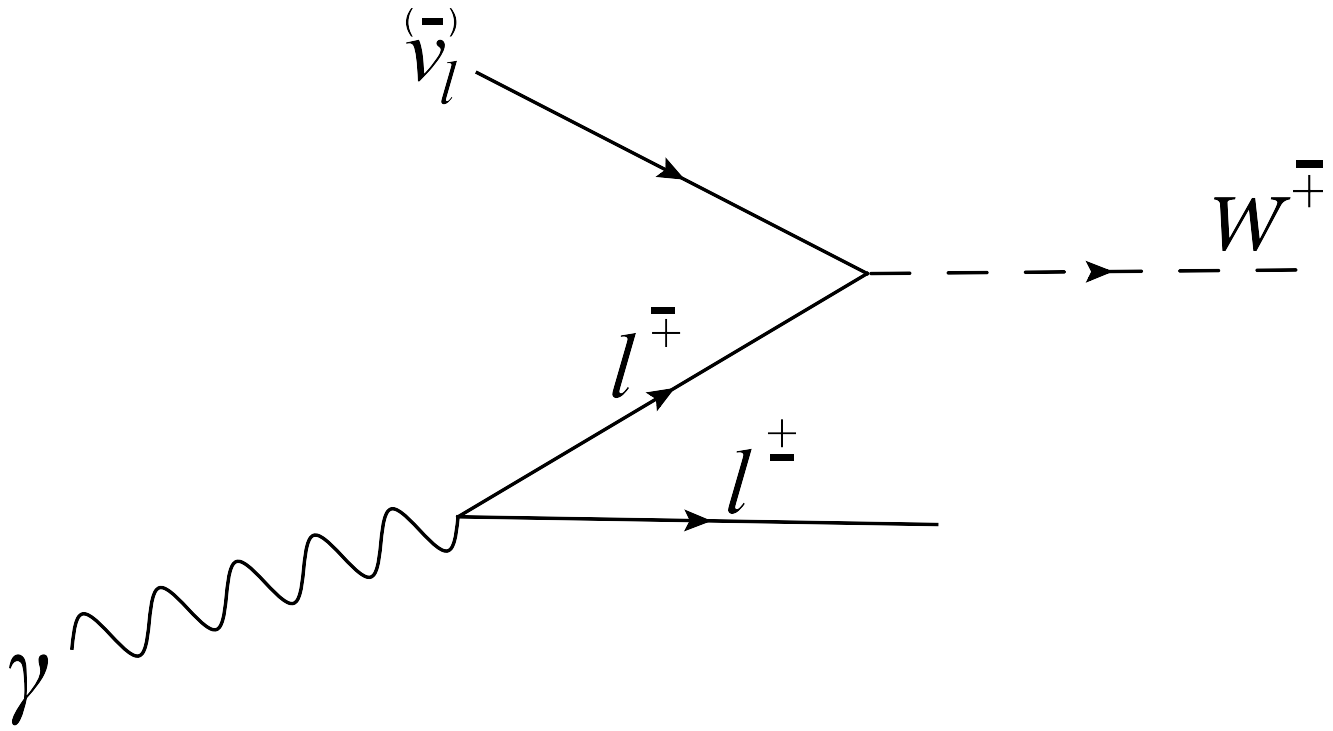
$$\sigma_{\nu_l \gamma \to l W}(s) = C' \cdot \frac{m_W^2}{s} f_{\gamma/l}\left(\frac{m_W^2}{s}\right)$$



The photon as a source of the target leptons

$$\sigma_{\nu_l\gamma\to lW}(s) = C' \cdot \frac{m_W^2}{s} f_{\gamma/l}\left(\frac{m_W^2}{s}\right)$$

A clear interpretation of the underlying resonant mechanism:

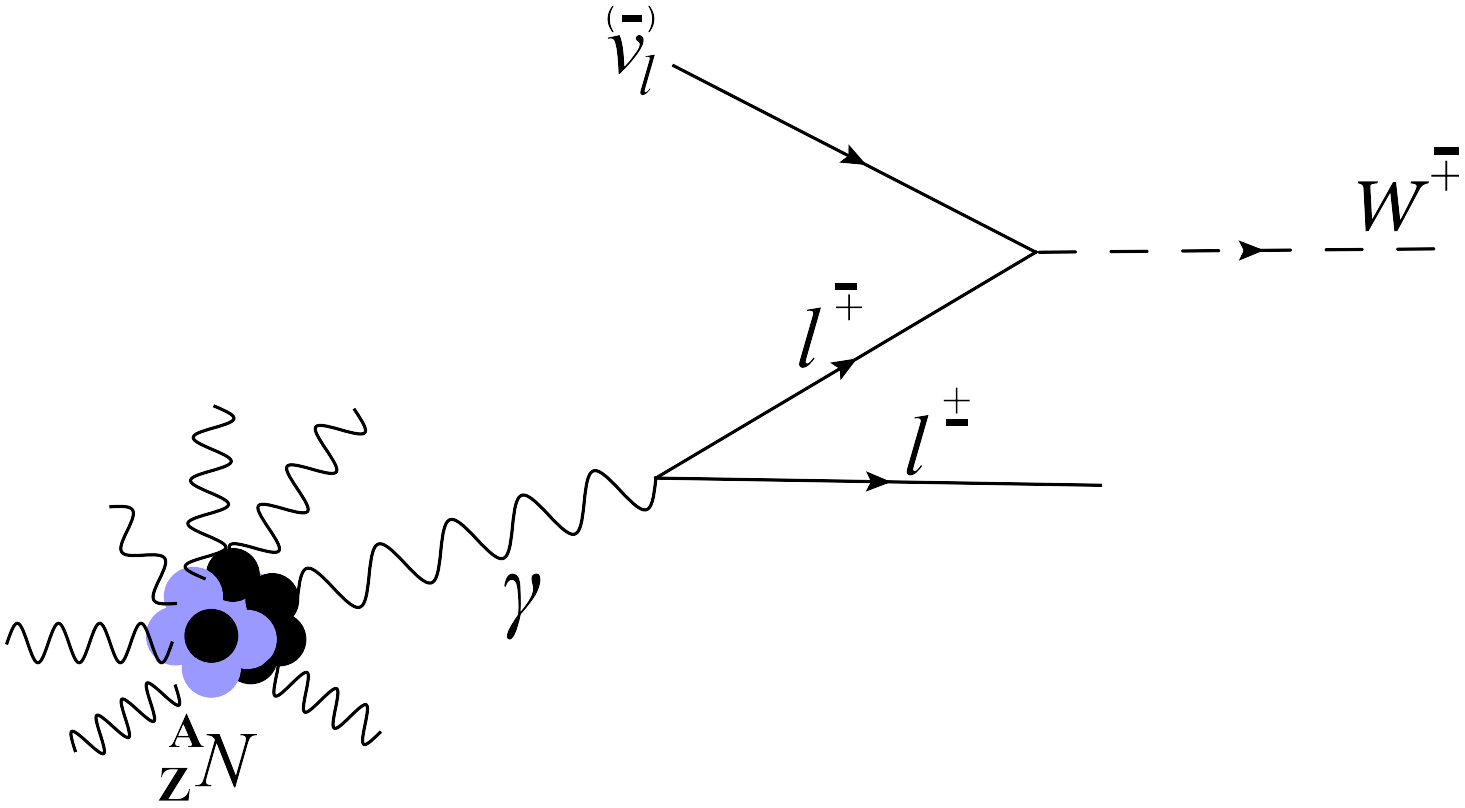


$l = e, \mu, \tau$

Neutrino–nucleus scattering

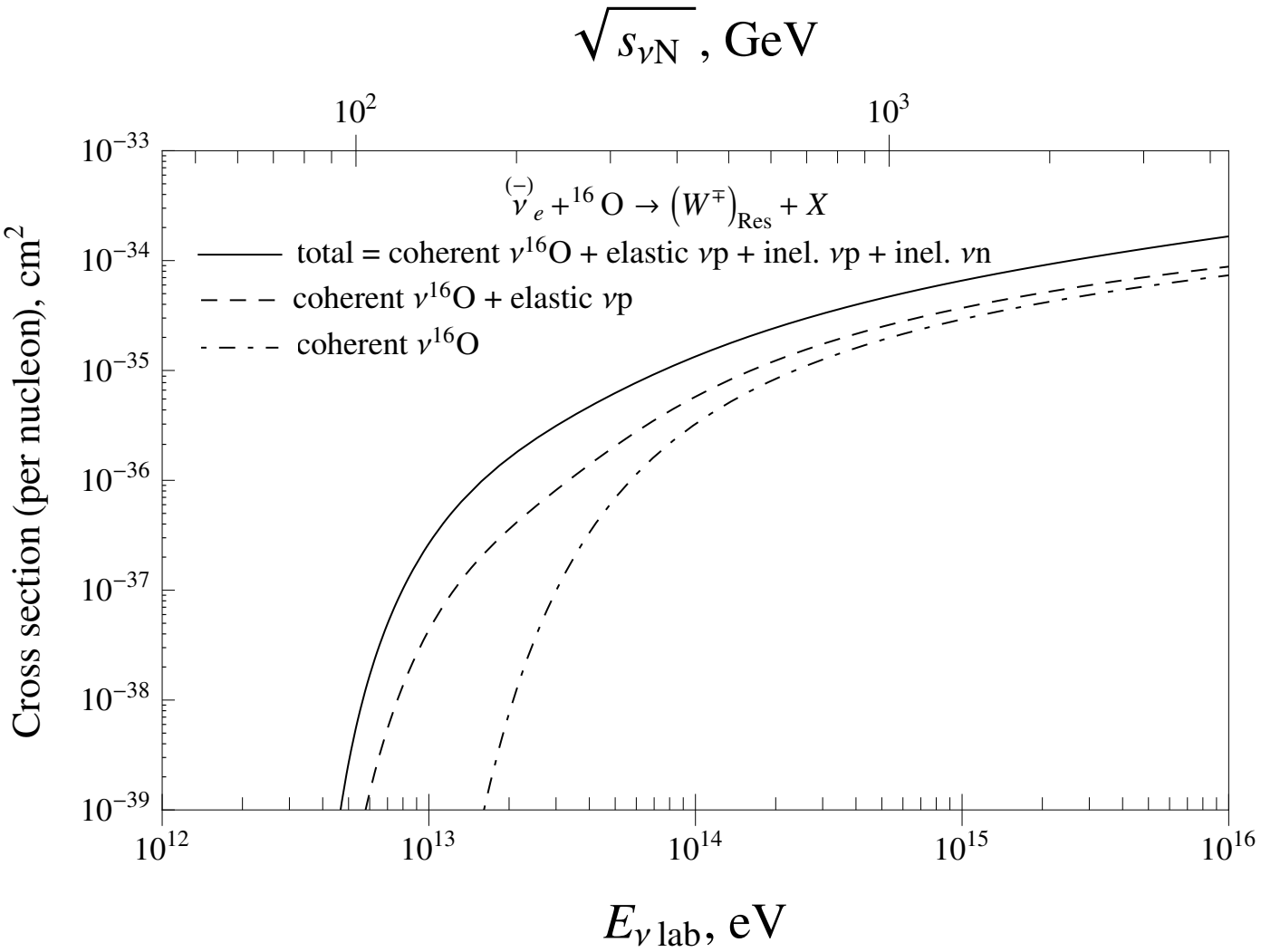
An atomic nucleus provides a source of the Weizsäcker–Williams equivalent photons, so that the Glashow resonance should appear in high energy neutrino–nucleus scattering (I.A., PLB 756 (2016) 247):

$$\bar{\nu}_e + {}^A_Z N \to {}^A_Z N + e^+ + W^- .$$



In km-scale neutrino telescopes, water serves as a target and oxygen is abundant in their volumes. IceCube, Baikal NT1000, KM3NeT.

$$\bar{\nu}_e + {}^{16}\mathrm{O} \to {}^{16}\mathrm{O} + e^+ + W^-.$$

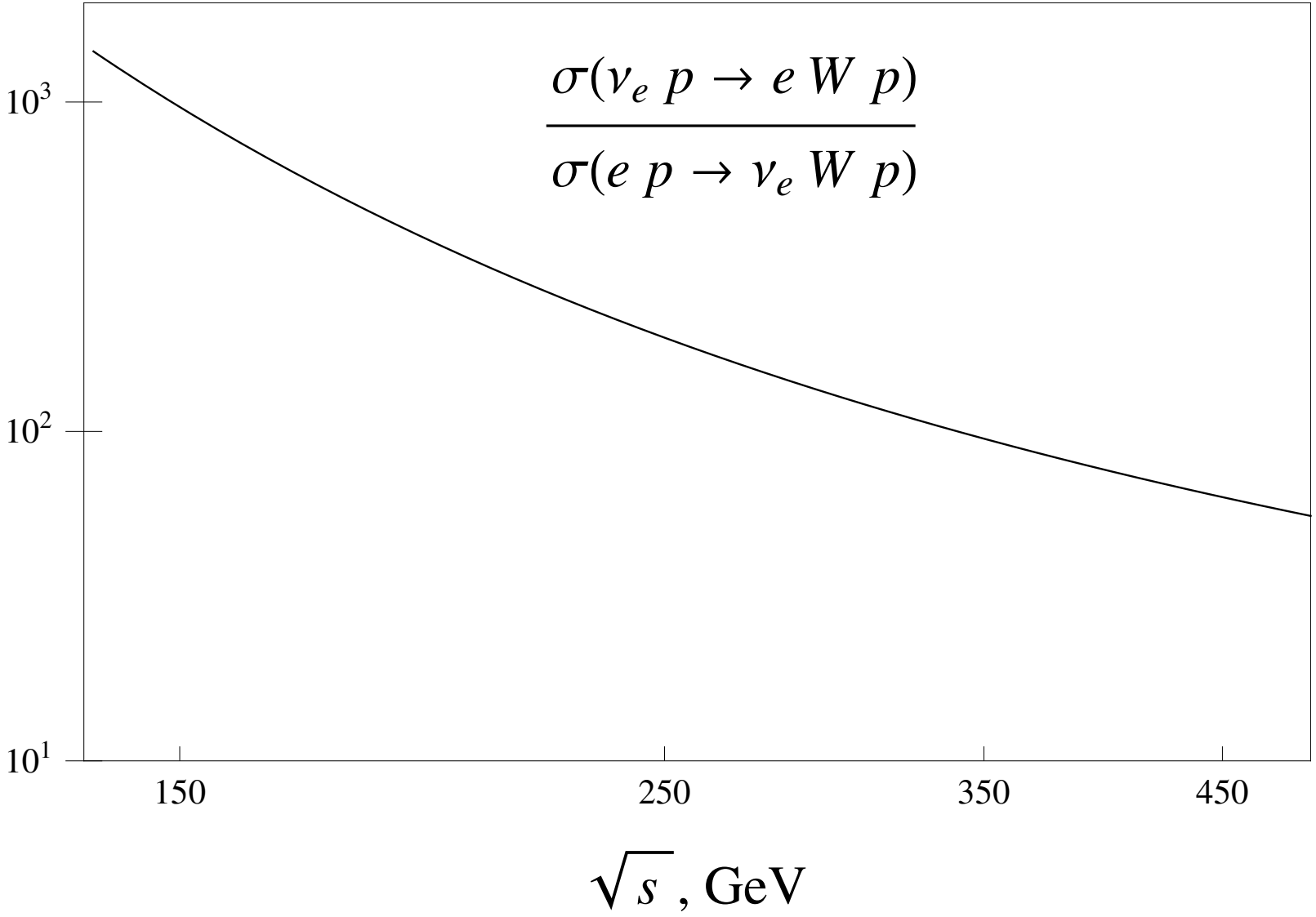


Compare two cross sections within the Standard Model:

$$\sigma(\nu_e\, p \to e\, W\, p),$$

$$\sigma(e\, p \to \nu_e W\, p).$$

Actually, there is a resonant enhancement of the cross section in a relatively wide range of neutrino energies (I.A.,PLB 756(2016)247).



Summary

1. Resonant channels in $\nu\gamma$ interactions within the standard electroweak theory are considered.

2. As an example, it is shown that the reactions $\nu_l + \gamma \to l + W$ proceed through the Glashow resonance.

3. The resonant scenario can be probed for all the three neutrino flavors, ν_e, ν_μ, ν_τ, as well as for their CP conjugates.

4. The corresponding cross sections for the excitations of the resonance on ^{16}O are calculated. The results may be useful for interpreting experimental data at large volume neutrino telescopes as IceCube, Baikal NT1000 and KM3NeT.

5. The presented mechanism can be easily applied to other models with scalar and/or vector narrow resonances.

References

Details can be found in

I.A., PLB 741 (2015) 295; PLB 756 (2016) 247;
MPLA 35 (2020) 2050101; EPL 129 (2020) 11003.

Thank you!