

# The Glashow Resonance in Neutrino–Nucleus Scattering

Ibragim Alikhanov

Baksan Neutrino Observatory INR RAS  
Baksan Valley, Russia

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# Outline

1. Introduction
2. GR in  $\nu\gamma$  scattering: The Standard Model
3. GR in  $\nu\gamma$  scattering: The parton model
4. Experimental consequences for  $\nu N$  scattering
5. Conclusions

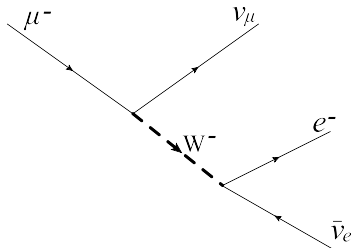
## Resonant Scattering of Antineutrinos

SHELDON L. GLASHOW\*

*Institute for Theoretical Physics, Copenhagen, Denmark*

(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process  $\bar{\nu} + e \rightarrow \bar{\nu} + \mu^-$  near the energy at which the intermediary may be produced. If the boson is assumed to have  $K$ -meson mass, the resonance occurs at an incident antineutrino energy of  $\sim 2 \times 10^{12}$  ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.



muon decay

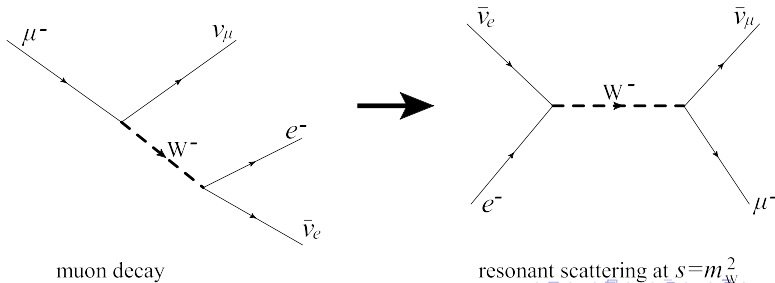
## Resonant Scattering of Antineutrinos

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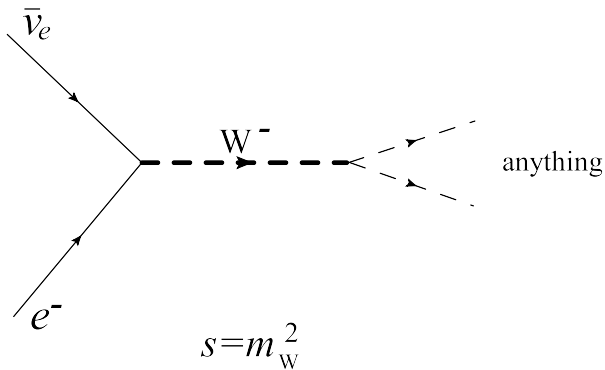
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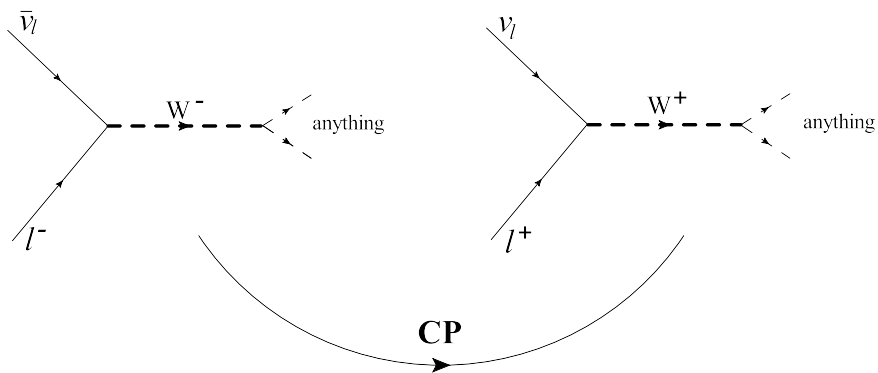


# The Glashow Resonance



# The Glashow Resonance

$$l = e, \mu, \tau$$



The  $s$ -channel reaction  $\bar{\nu}_e + e^- \rightarrow W^-$  takes a unique place.

Electrons are present in matter while positrons, muons and tau leptons are not.

The Glashow resonance can be observed in large volume neutrino telescopes. The incident neutrino energy in the laboratory reference frame is very high:

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

The IceCube Neutrino Telescope –a kilometer-scale detector at the South Pole– investigates this energy region but no convincing evidence for the Glashow resonance is found to date.

So far the Glashow resonance is not experimentally observed.

The Glashow resonance still remains an important prediction and its observation would be a crucial test of the Standard Electroweak Theory.



# Exclusive single W boson production in $\nu\gamma$ scattering

CP invariant interaction

$$\nu_l + \gamma \longrightarrow l^- + W^+$$

$$\bar{\nu}_l + \gamma \longrightarrow l^+ + W^-$$

**CP**

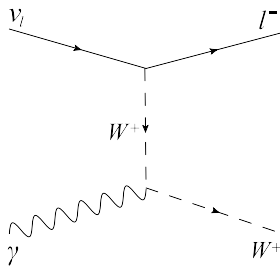
$$|\mathbf{M}(\nu_l + \gamma \longrightarrow l^- + W^+)|^2 = |\mathbf{M}(\bar{\nu}_l + \gamma \longrightarrow l^+ + W^-)|^2$$

**CP**

# The Standard Model

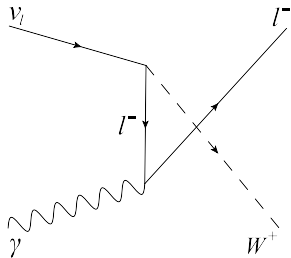
$$\nu_l + \gamma \longrightarrow l^- + W^+$$

$M =$



t-channel

+



u-channel

D. Seckel, Phys. Rev. Lett. 80 (1998) 900.

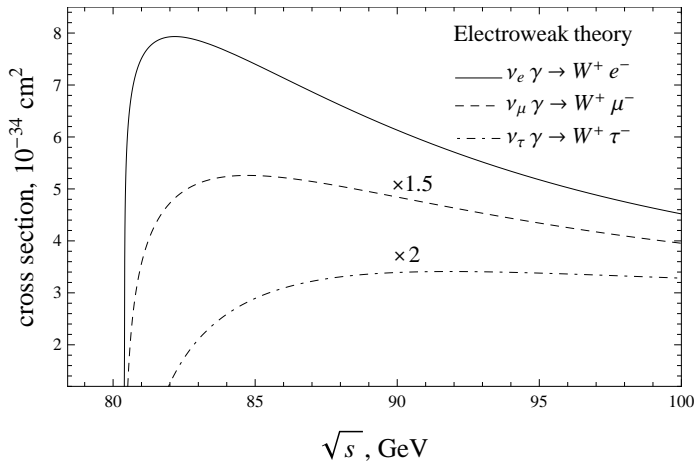
The LO cross section for  $\nu_l \gamma \rightarrow W^+ l^-$ :

$$\sigma_l = \sqrt{2}\alpha G_F \left\{ 2 \left( 1 - \frac{m_W^2}{s} \right) \left( 1 + \frac{2m_W^4}{s^2} - \frac{m_W^4}{s^2} \ln \left[ \frac{s}{m_W^2} \right] \right) + \frac{m_W^2}{s} \left( 1 - \frac{2m_W^2}{s} + \frac{2m_W^4}{s^2} \right) \ln \left[ \frac{(s - m_W^2)^2}{m_l^2 s} \right] \right\}.$$

[D. Seckel, Phys. Rev. Lett. 80 (1998) 900]

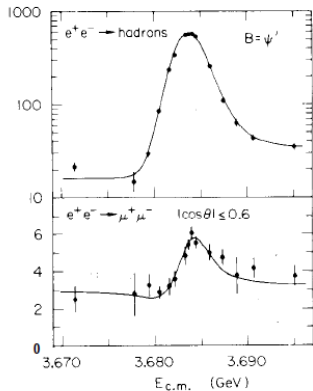
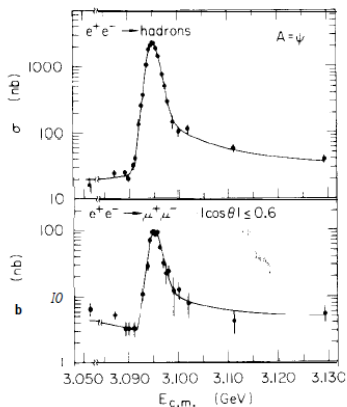
[I. Alikhanov, Phys. Lett. B 710 (2012) 149]

The LO cross section for  $\nu_l \gamma \rightarrow W^+ l^-$ :

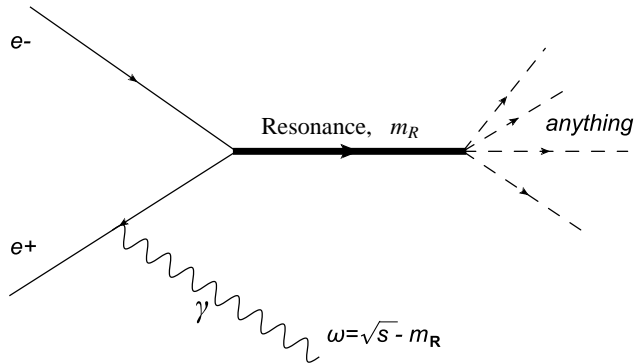


$$e^+e^- \rightarrow J/\Psi, \Psi(2S)$$

B. Richter, Nobel Lecture, 1976

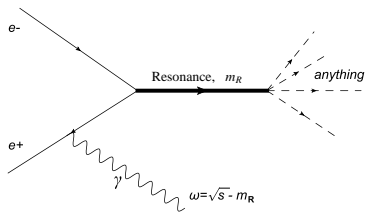


# Initial state radiation in $e^+e^-$ annihilation into a resonance

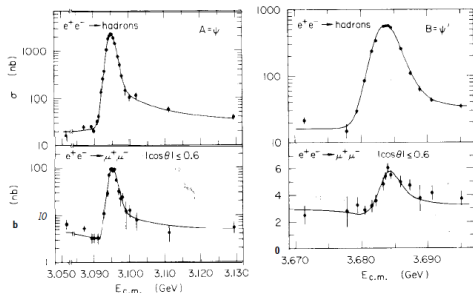


A "radiative tail" appears to the right of the resonance maximum. The emitted photon carries away the energy excess and turns thus back the electron–positron pair to the resonance energy. The suppression due to the extra factor  $\alpha$  is compensated by the resonance denominator.

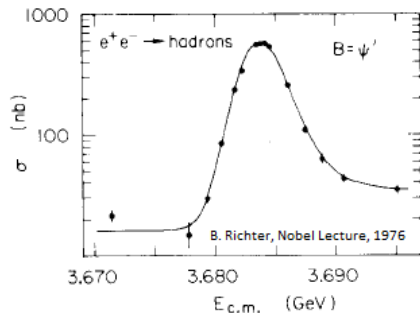
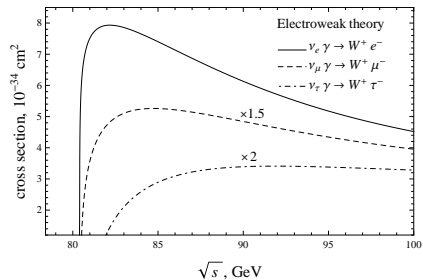
[Ioffe B.L., Khoze V.A., Lipatov L.N., Hard processes 1. Phenomenology Quark–parton model, 1984]



B. Richter, Nobel Lecture, 1976

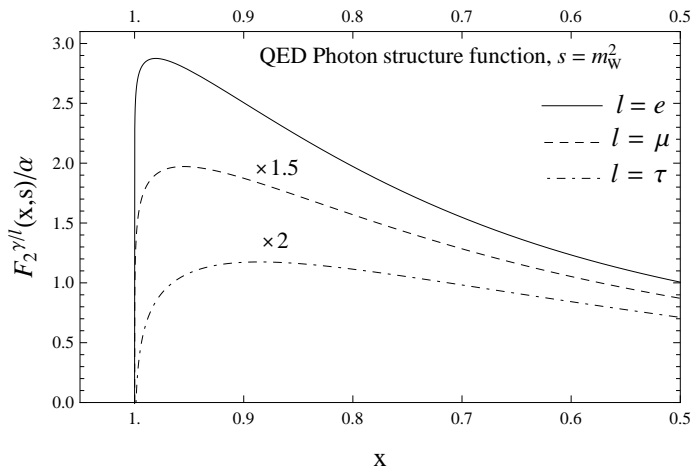


# Initial state lepton emission in $\nu_l \gamma \rightarrow W^+ l^-$ ?



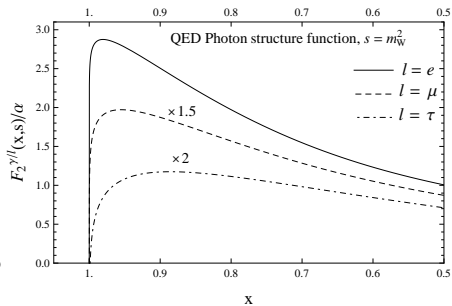
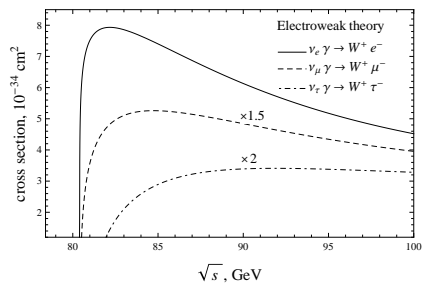


# The photon structure function

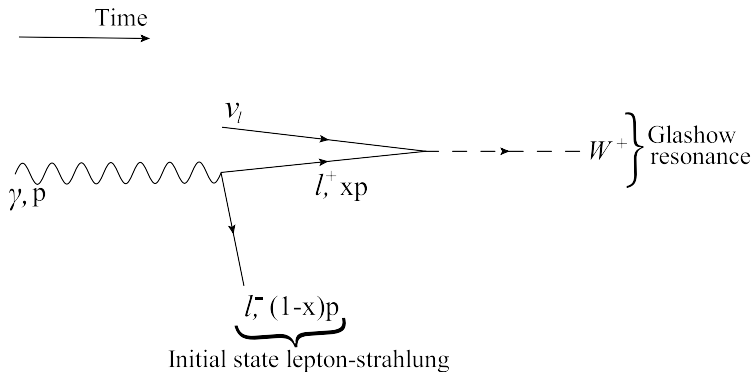


[R. Nisius, Phys. Rept. 332 (2000) 165]

# The photon structure function



# $\nu_l \gamma \rightarrow W^+ l^-$ in the parton model



$$\sigma_l = \int_0^1 \frac{dx}{x} F_2^{\gamma/l}(x, s) \sigma_{\nu l \rightarrow W}(xs).$$

$\nu_l \gamma \rightarrow W^+ l^-$  in the parton model

$$\sigma_l = \int_0^1 \frac{dx}{x} F_2^{\gamma/l}(x, s) \sigma_{\nu_l \rightarrow W}(xs).$$

In the narrow width approximation:

$$\sigma_{\nu_l \rightarrow W}(xs) = 2\sqrt{2}\pi G_F \tau \delta(x - \tau), \quad \tau = m_W^2/s,$$

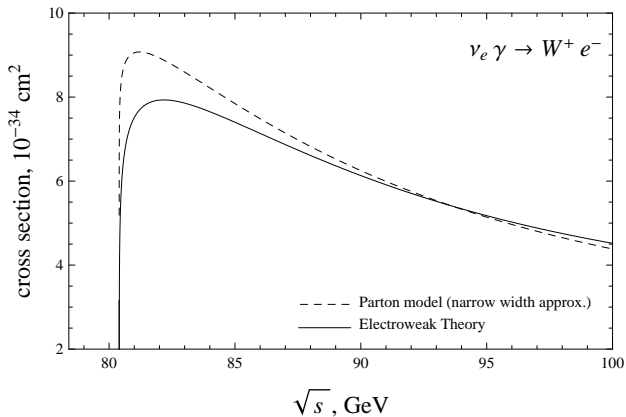
$$\sigma_l = 2\sqrt{2}\pi G_F F_2^{\gamma/l}(\tau, s).$$

The Glashow resonances project out the corresponding structure functions of the photon  $F_2^{\gamma/l}(x, s)$  in the cross sections  $\sigma_l$ .

# $\nu_e \gamma \rightarrow W^+ e^-$ in the parton model

$$\sigma_e = 2\sqrt{2}\pi G_F F_2^{\gamma/e}(\tau, s).$$

For example,

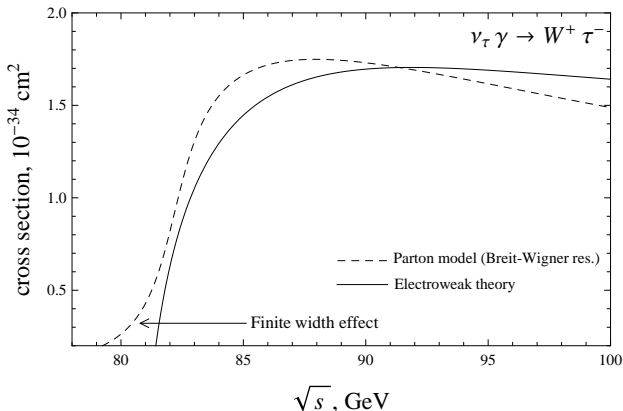






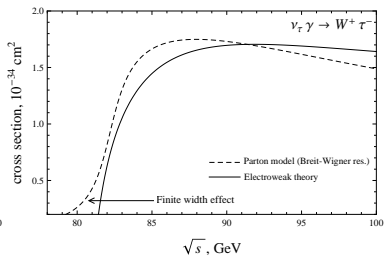
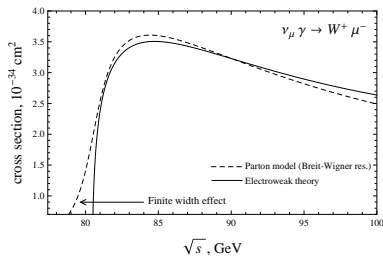
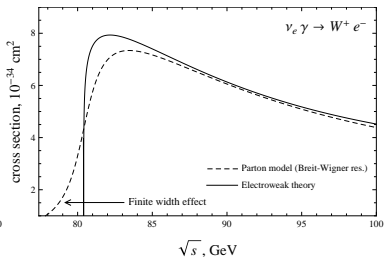
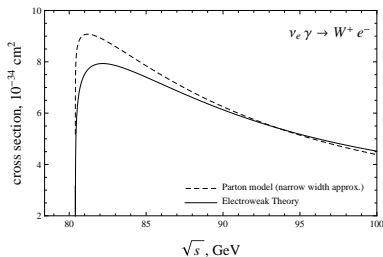
The Breit–Wigner formula provides a more realistic description than the narrow width approximation:

$$\sigma_{\tau} = 24\pi\Gamma_{W\rightarrow\nu\tau}\Gamma \int_0^1 \frac{dx}{x} \frac{F_2^{\gamma/\tau}(x, s)}{(xs - m_W^2)^2 + m_W^2\Gamma^2},$$





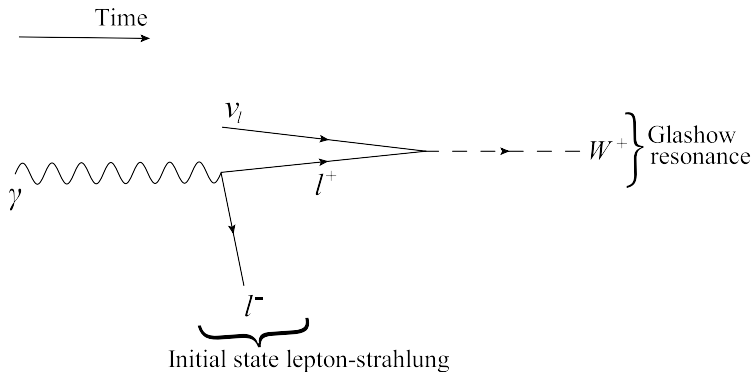
# $\nu_l \gamma \rightarrow l^- W^+$ in the parton model



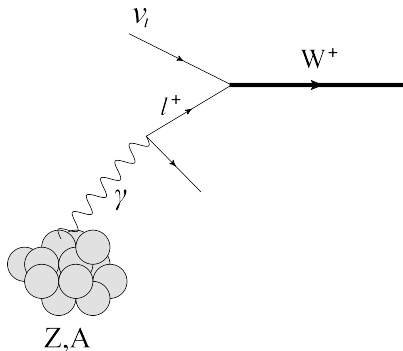
The Standard Model strongly suggests that the reactions  $\nu_l \gamma \rightarrow l^- W^+$  proceed through initial state lepton emission.

Hypothesis: **The on-shell  $W$  bosons in  $\nu_l \gamma \rightarrow l^- W^+$  are the Glashow resonances.**

$$\nu_l + \gamma \longrightarrow l^- + W^+$$



Knowing the neutrino–photon scattering cross sections one can find the cross sections for neutrino–nucleus scattering by using the equivalent photon approximation



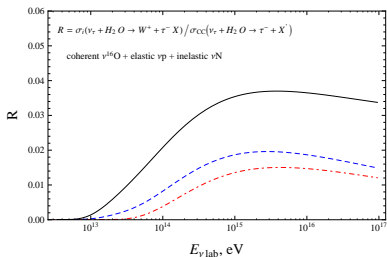
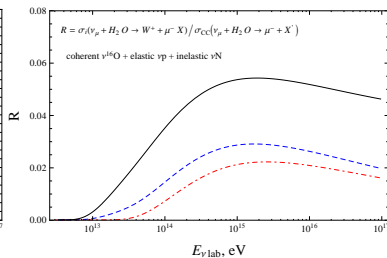
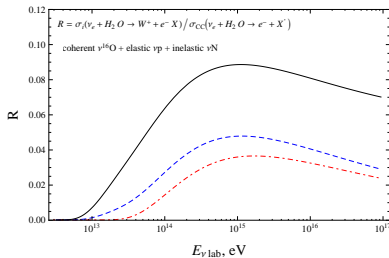
$$\sigma_{\nu N} = \int dx \sigma_{\nu\gamma}(xs) f^{\gamma/N}(x)$$

## Production of the Glashow resonances by neutrinos in water/ice detectors.

The following contributions are taken into account:

1. Coherent neutrino–nucleus scattering.
2. Elastic neutrino–proton scattering.
3. Inelastic neutrino–proton and neutrino–neutron interactions.

The results are presented in the form of ratios of the obtained cross sections per nucleon to the standard neutrino–nucleon cross sections.



The Glashow resonance may have already been produced in the IceCube neutrino detector at energies far below  $6.3 \times 10^{15}$  eV.

The event rate distribution:

$$\frac{dN}{dE_\nu} = nt\Omega \sum_{l=e,\mu,\tau} \sigma_{Nl} \Phi_{\nu_l + \bar{\nu}_l}, \quad (1)$$

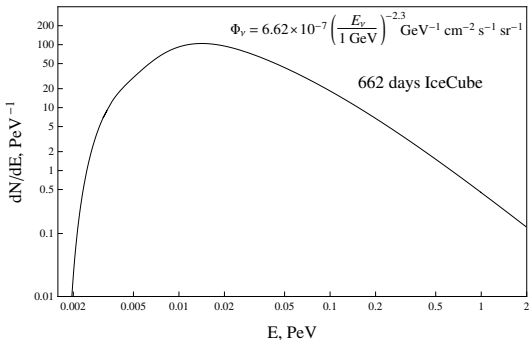
where  $n$  is the number of target nuclei in the effective volume of the detector,  $t$  is the time of exposure,  $\Omega$  is the solid angle,  $\Phi_{\nu_l + \bar{\nu}_l}$  is the flux of neutrinos and antineutrinos of flavor  $l$ .

The number of events at the IceCube:

$$\Phi_{\nu+\bar{\nu}} = 6.62 \times 10^{-7} (E_{\nu})^{-2.3} \text{ GeV}^{1.3} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},$$

1:1:1 neutrino flavor ratio.

L. A. Anchordoqui *et al.*, arXiv:1312.6587.



A few Glashow resonance events should have been detected by the IceCube

# Conclusions

1. Exclusive single  $W$  boson production production in  $\nu\gamma$  scattering at  $s \approx m_W^2$  is analyzed.
2. Two independent approaches within the Standard Model are used.
3. It is shown that the Standard Model strongly suggests that the  $W$  boson production proceeds through initial state charged lepton emission.
4. Hypothesis: the on-shell  $W$  bosons in  $\nu\gamma \rightarrow Wl$  are the Glashow resonances.
5. The Glashow resonance can be probed not only for  $\bar{\nu}_e$  but also for the other neutrino flavors,  $\nu_\mu$  and  $\nu_\tau$ .
6. The Glashow resonance should have already been produced in the IceCube neutrino detector at  $E_\nu \sim 100 \text{ TeV}$ .



Details of calculations as well as a more complete list of references  
can be found in arXiv:1402.6678.

Thank You!