Vh production via vector boson scattering at lepton colliders in the Feynman-diagram gauge

(Work in progress)

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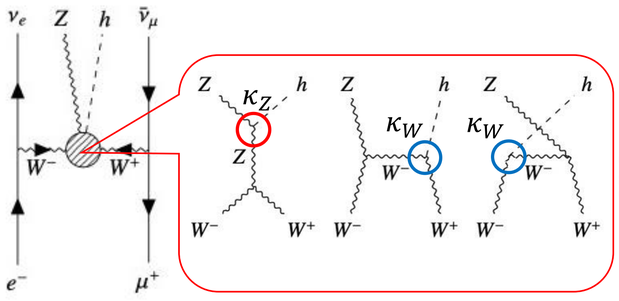
1. Introduction

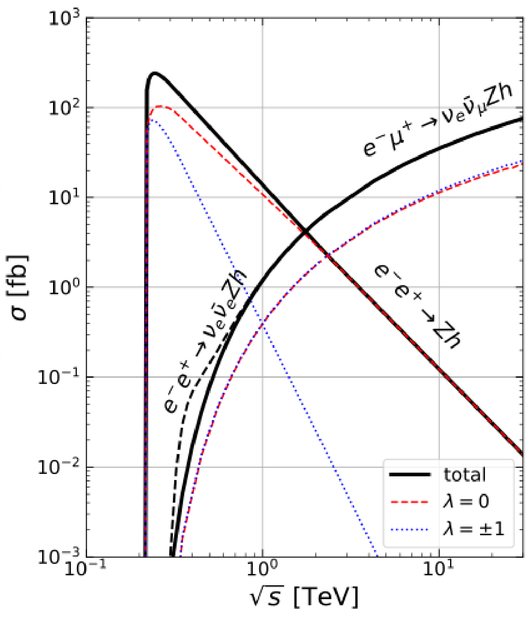
We study the $e^-e^+ \to \nu\bar{\nu}Zh$ process.

・The Vh production via vector boson scattering is included.



(a) VBS

・At high energies, the cross section of $e^-e^+ \to \nu\bar{\nu}Zh$ is larger than $e^-e^+ \to Zh$.



$e^-e^+ \to \nu\bar{\nu}Zh$ is important at high-energy collider experiments to study the Higgs coupling to the weak gauge bosons.

In the longitudinal massive gauge boson scattering, gauge cancellation occurs (energy growth).
→Cancellation of significant digits
It can be avoided!!

"Feynman-Diagram Gauge" [1],[2],[3],[4]

2. Gauge choices

・The treatment of Nambu-Goldstone (NG) bosons depend on gauge choices.
・Before EW symmetry breaking, gauge bosons run at the speed of light (mass 0).

Gauge boson ©2023 SoraKobayashi

EWSB

NG boson

When EW symmetry breaks, NG bosons appear.

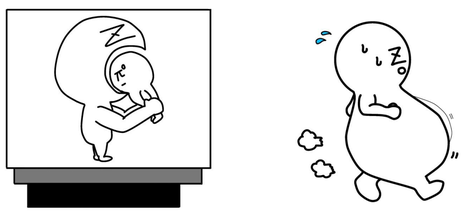
$$q^\mu = (E, 0, 0, q),$$

$$\beta = \frac{q}{E} = \sqrt{1 - \frac{m^2}{E^2}},$$

$$\gamma = \frac{E}{m} = \frac{1}{\sqrt{1-\beta^2}}.$$

Unitary (U) gauge

Gauge bosons eat NG bosons and become fat (run slower = massive).



$\mu, \nu = 0$ to 3,

$$G_{\mu\nu}(q) = \frac{i}{q^2 - m^2 + i\epsilon}\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{m^2}\right)$$

$$\epsilon^\mu(q,0) = \frac{1}{m}(q,0,0,E) = \gamma(\beta,0,0,1)$$

Feynman-Diagram (FD) gauge

Gauge bosons and NG bosons run together (run slower = massive).

$M, N = 0$ to 4,

$$n^\mu = (\mathrm{sgn}(q^0), -\vec{q}/|\vec{q}|)$$

$$G_{MN}(q) = \frac{i}{q^2 - m^2 + i\epsilon}\begin{pmatrix} -g_{\mu\nu} + \frac{q_\mu n_\nu + n_\mu q_\nu}{n\cdot q} & i\frac{m n_\mu}{n\cdot q} \\ -i\frac{m n_\nu}{n\cdot q} & 1 \end{pmatrix}$$

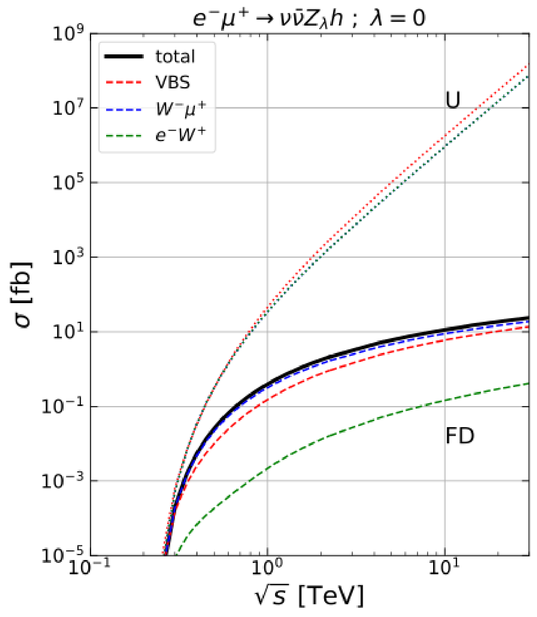
$$\epsilon^M(q,0) = (\tilde{\epsilon}^\mu(q,0),\ i)$$

$$\tilde{\epsilon}^\mu(q,0) = \epsilon^\mu(q,0) - \frac{q^\mu}{Q} = \frac{1}{\gamma(1+\beta)}(-1,0,0,1)$$

3. U vs FD

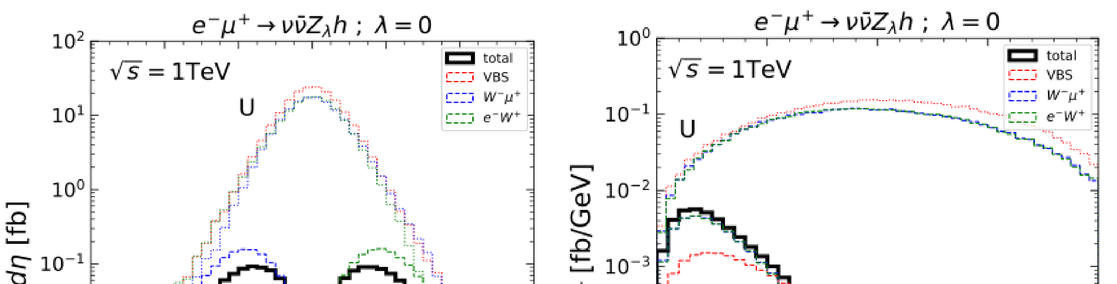
We divide $e^-\mu^+ \to \nu\bar{\nu}Zh$ into 3 categories.

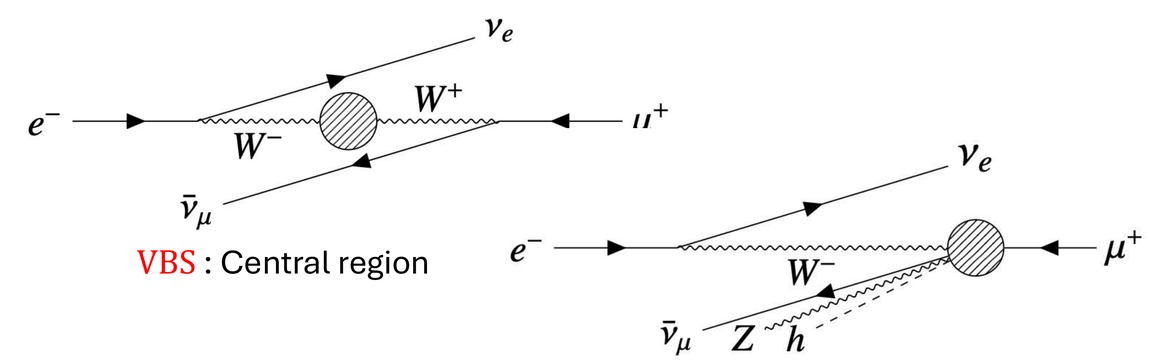
$$\text{total} \propto \left| \text{(a)VBS} + \text{(b)}W^-\mu^+ + \text{(c)}e^-W^+ \right|^2$$



total
$\propto |M_{\mathrm{VBS}} + M_{W^-\mu^+} + M_{e^-W^+}|^2$

VBS $\propto |M_{\mathrm{VBS}}|^2$,
$W^-\mu^+ \propto |M_{W^-\mu^+}|^2$,
$e^-W^+ \propto |M_{e^-W^+}|^2$.





VBS : Central region

$W^-\mu^+$: Backward scattering

U gauge:
・Each category of the amplitudes has energy growth.
→ Large cancellation among the three categories (VBS, $W^-\mu^+$, e^-W^+) at high energies.
・No clue for the physical distribution from each contribution.

FD gauge :
・No such energy growth of each category at all.
・ VBS : Central region,
$W^-\mu^+$: Backward scattering,
e^-W^+: Forward scattering.
→ Naive expectations for the contribution of each category agree.

[1] K. Hagiwara, J. Kanzaki and K. Mawatari, "QED and QCD helicity amplitudes in parton-shower gauge", Eur.Phys.J.C 80 584 (2020)
[1] J. Chen, K. Hagiwara, J. Kanzaki and K. Mawatari, "Helicity amplitudes without gauge cancellation for electroweak processes", Eur.Phys.J.C 83 922 (2023)
[2] J. Chen, K. Hagiwara, J. Kanzaki, K. Mawatari and Y. Zheng , "Helicity amplitudes in light-cone and Feynman-diagram gauges", Eur.Phys.J.Plus 139 332 (2024)
[3] K. Hagiwara, J. Kanzaki, O. Mattelaer, K. Mawatari and Y. Zheng, "Automatic generation of helicity amplitudes in Feynman-Diagram gauge", Phys. ReV. D 110, 056024 (2024)
[4] H.Furusato, K.Mawatari, Y.Suzuki, Y.Zheng, "W pair production at lepton colliders in the Feynman-diagram gauge", Phys. ReV. D 110, 053005 (2024)