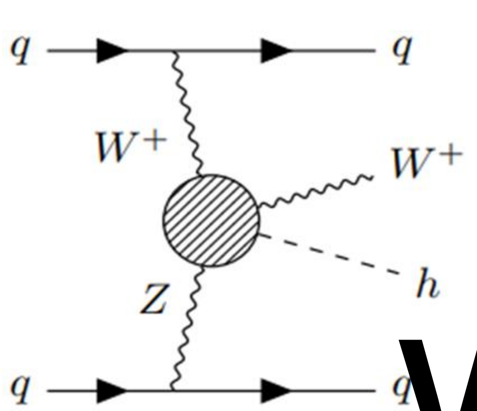
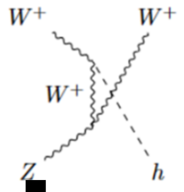
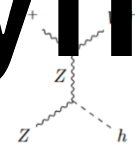
Nov 23, Flavor Physics Workshop 2023

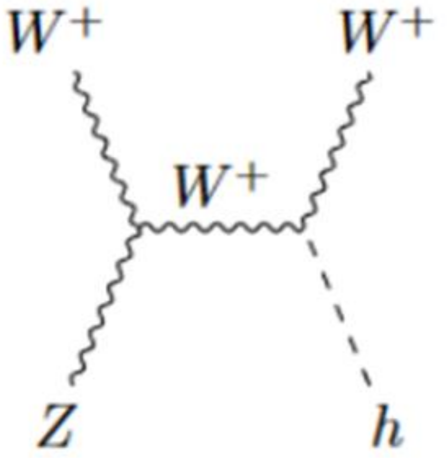


Vector-Boson-Fusion WH production in the Feynman-Diagram gauge





(**Work in progress**)



Hiroyuki Furusato (M2) Iwate University

Kentarou Mawatari
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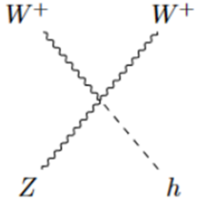
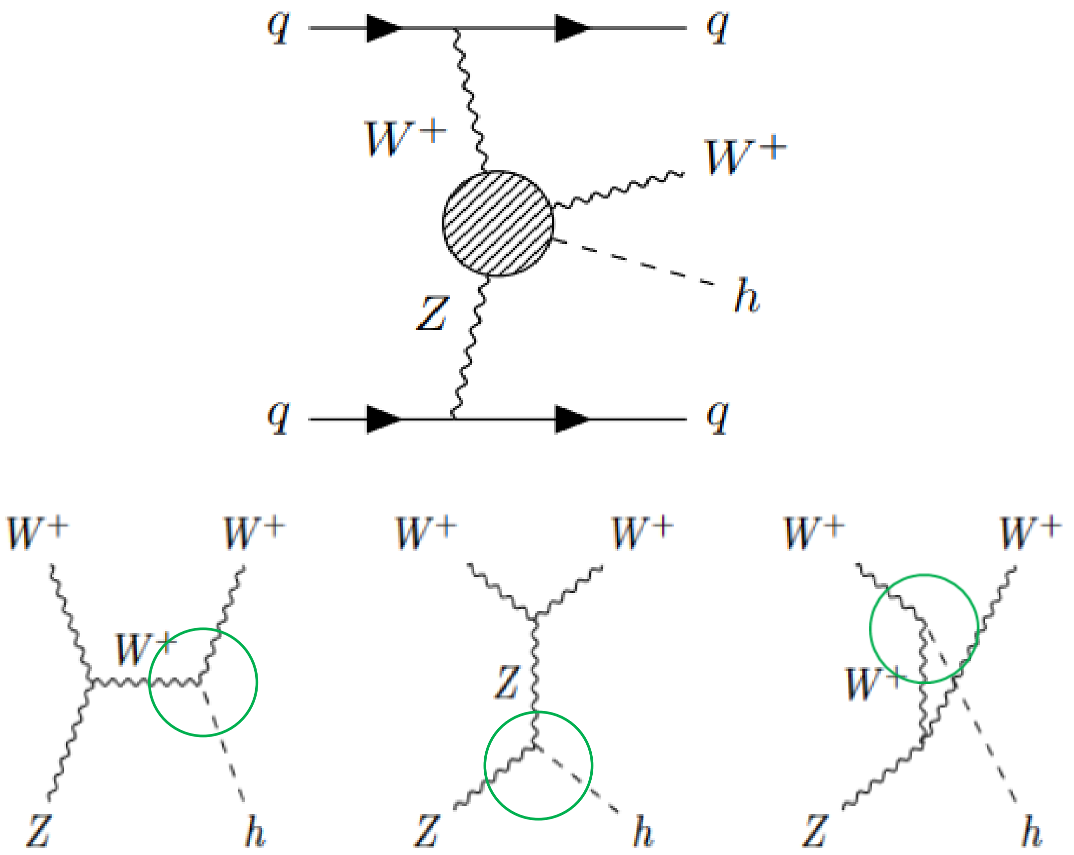
Shouta Suzuki (M1)



Determining the relative sign of the Higgs boson couplings to W and Z bosons using VBF WH production with the ATLAS detector

ATLAS-CONF-2023-057



Recently ATLAS reported a study for the "$pp \to Whjj$" process.

This is an important process where the hWW and hZZ couplings can be determined simultaneously. We may be able to get some hint of the origin of "Spontaneous Electroweak Symmetry Breaking".

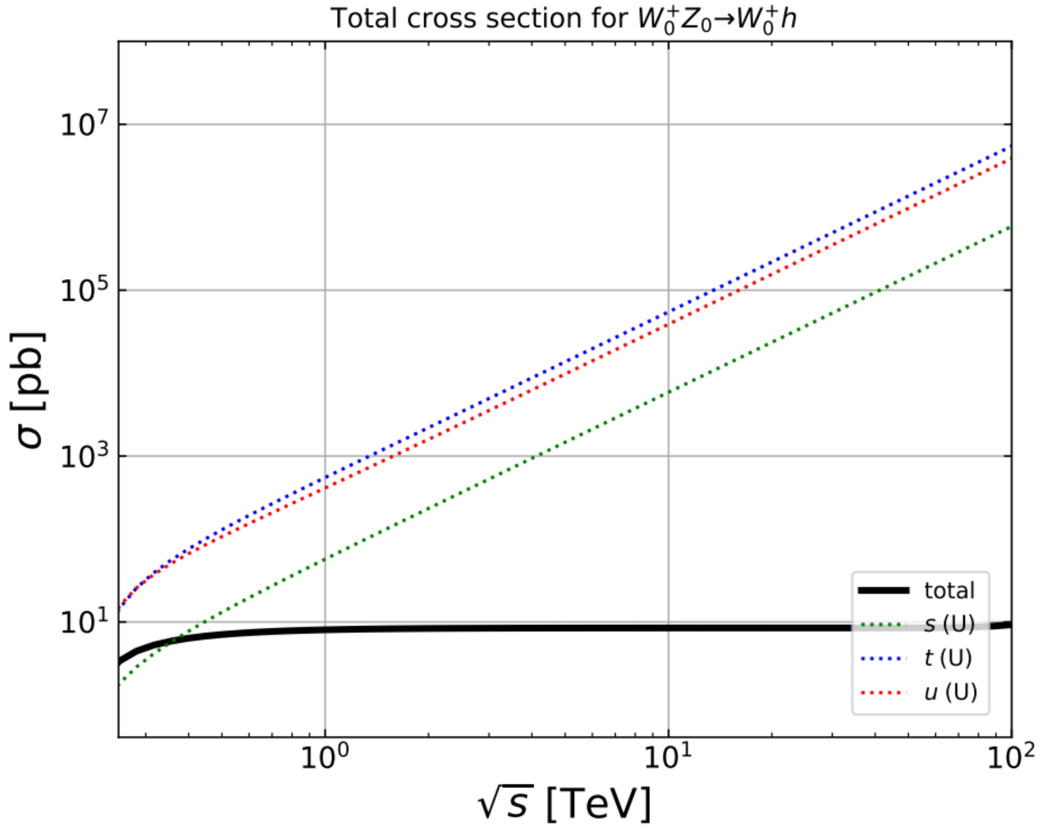
In this talk, we focus on the subprocess "$W^+Z \to W^+h$".

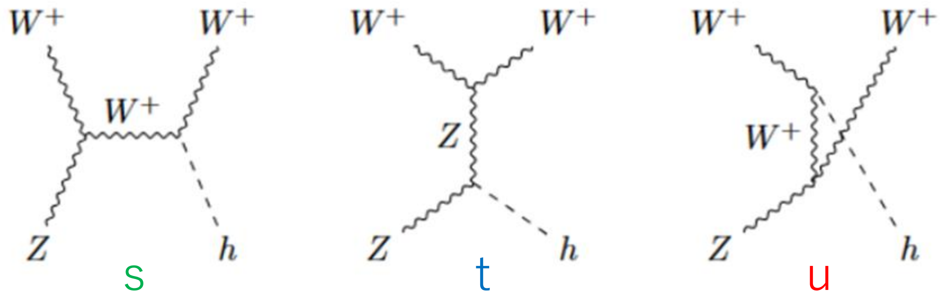
Gauge cancellation for longitudinal gauge-boson scatterings

For scatterings of longitudinal gauge bosons, large gauge cancellation occurs among amplitudes, especially at high energies because of polarization vector $\varepsilon^{\mu}(p,0) \propto E$. A big problem of cancellation of significant digits in the numerical calculation.

Recently a new gauge fixing was proposed which does not lead unphysical gauge cancelation!!

“Feynman Diagram (FD) Gauge”





J. Chen, K. Hagiwara, J. Kanzaki and K. Mawatari,
“Helicity amplitudes without gauge cancellation for electroweak processes”, Eur.Phys.J.C 83 (2023) 10, 922.

Unitary (U) gauge vs Feynman Diagram (FD) gauge

U gauge (Covariant R_ξ gauge with $\xi \to \infty$)

Only weak gauge bosons (Nambu-Goldstone bosons are decoupled.)

- propagator $(\mu, \nu = 0, 1, 2, 3)$

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

- polarization vector

$$\epsilon^\mu(p, \pm)$$
$$\epsilon^\mu(p, 0)$$

FD gauge (Non-covariant light-cone gauge with $n^\mu = \left(\mathrm{sgn}(q^0), -\frac{\vec{q}}{|\vec{q}\,|}\right)$)

Quantum states of weak gauge bosons and Nambu-Goldstone bosons

- 5×5 propagator $(M, N = 0, 1, 2, 3, 4)$

$$P^{\mathrm{FD}}_{MN} = \frac{i}{q^2 - m^2 + i\epsilon}\begin{pmatrix} -\tilde{g}_{\mu\nu} & im\frac{n_\mu}{n\cdot q} \\ -im\frac{n_\nu}{n\cdot q} & 1 \end{pmatrix}$$

$$-\tilde{g}_{\mu\nu} = -g_{\mu\nu} + \frac{n_\mu q_\nu + q_\mu n_\nu}{n \cdot q}$$

- 5 component polarization vector

$$\epsilon^M(p, \pm) = (\epsilon^\mu(p, \pm), 0)$$
$$\epsilon^M(p, 0) = (\tilde{\epsilon}^\mu(p, 0), i)$$
$$\tilde{\epsilon}^\mu(p, 0) = \epsilon^\mu(p, 0) - \frac{p^\mu}{m}$$

In the following, we present the (differential) cross section of

$$W^+Z \to W^+h$$

for longitudinal gauge bosons in the U and FD gauges if we see some differences.

$P^{\mathrm{U}}_{\mu\nu}$

$\epsilon^\mu(p,\pm)$

$\epsilon^\mu(p,0)$

VS

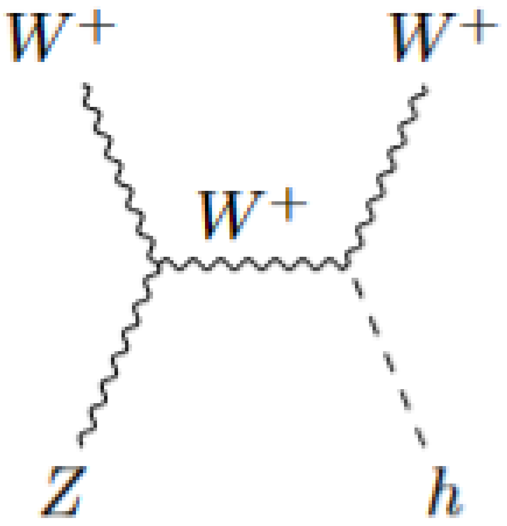
P^{FD}_{MN}

$(\epsilon^\mu(p,\pm),0)$

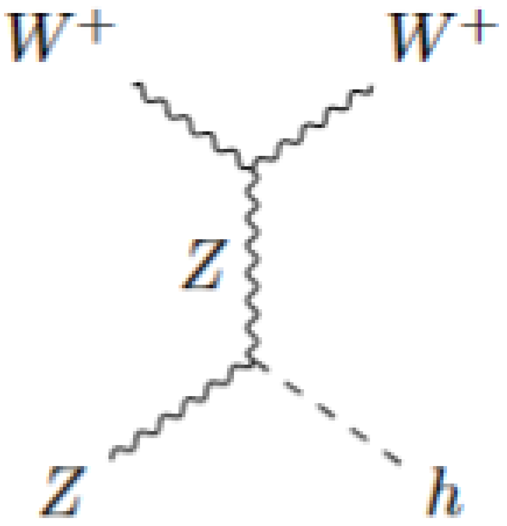
$(\tilde{\epsilon}^\mu(p,0),i)$

Feynman diagrams in the U gauge

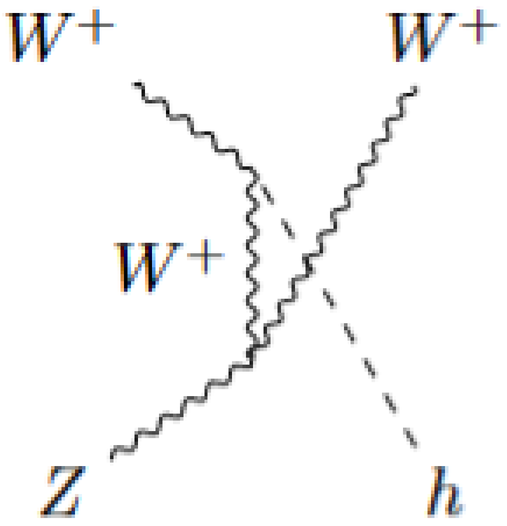
$$W^+(p_1,\lambda_1)+Z(p_2,\lambda_2)\rightarrow W^+(p_3,\lambda_3)+h(p_4)$$



s-channel

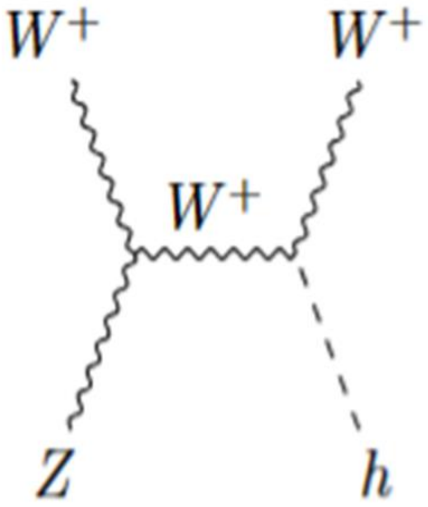


t-channel

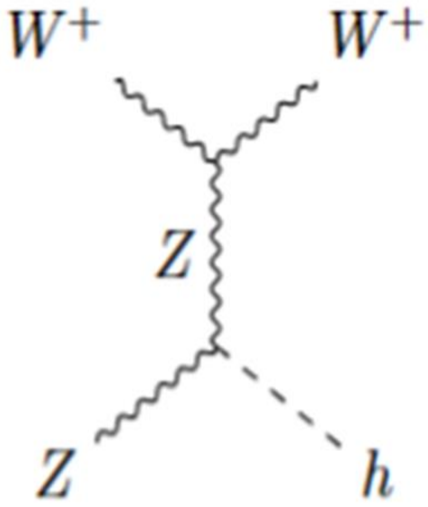


u-channel

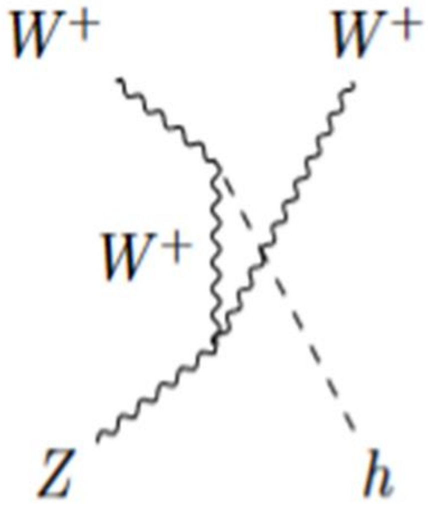
Feynman diagrams in the FD gauge



s-channel

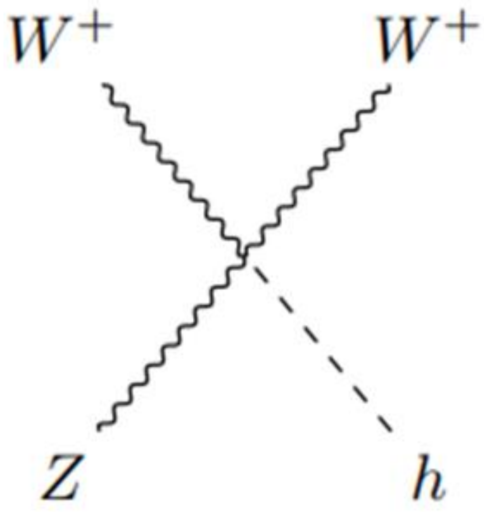


t-channel



u-channel

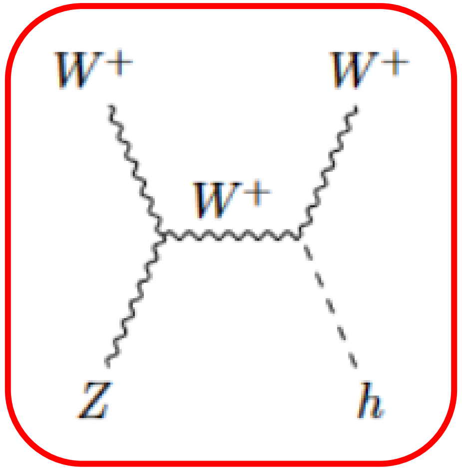
$+$

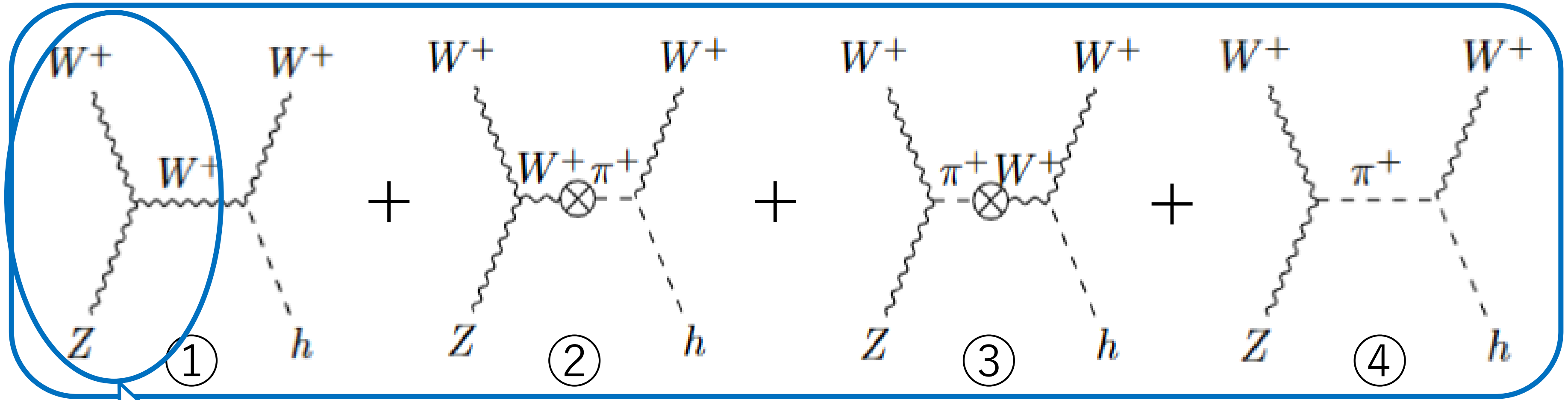


contact (c)-channel

$$+ i\frac{g}{2}(s_W^2 g_Z Z - eA)(W^+\pi^- - W^-\pi^+)(v+H)$$

Ex. the s-channel amplitude for $\lambda_1 = \lambda_2 = \lambda_3 = +1$ in the U and FD gauges

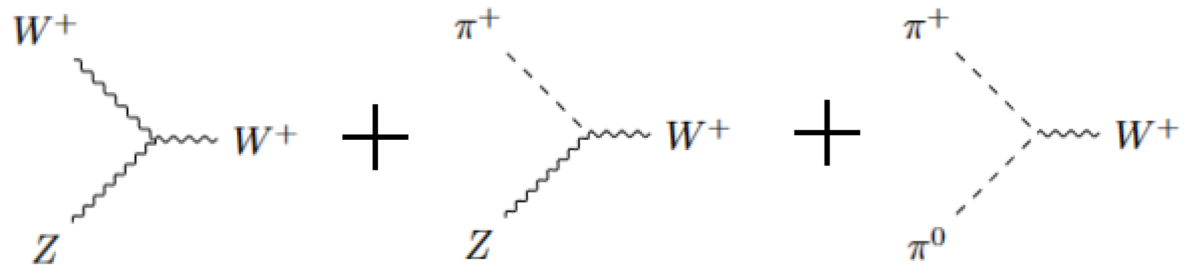




$$\mathcal{M}_s^{\mathrm{U}}(+,+,+) = J^{\mu}_{s\,++} P^{\mathrm{U}}_{s\,\mu\nu} J^{\nu}_{s\,+}$$

$$= J^{\mu}_{s\,++} \frac{i}{q^2 - m^2 + i\epsilon} \left(-g_{\mu\nu} + \right.$$

for $\lambda_1 = \lambda_2 = \lambda_3 = 0$



$$\mathcal{M}_s^{\mathrm{FD}}(+,+,+) = J^{M}_{s\,++} P^{\mathrm{FD}}_{s\,MN} J^{N}_{s\,+}$$

$$= J^{\mu}_{s\,++} \frac{i}{q^2 - m^2 + i\epsilon} \left(-g_{\mu\nu} + \frac{n_\mu q_\nu + q_\mu n_\nu}{n \cdot q} \right) J^{\nu}_{s\,+} \quad \cdots ①$$

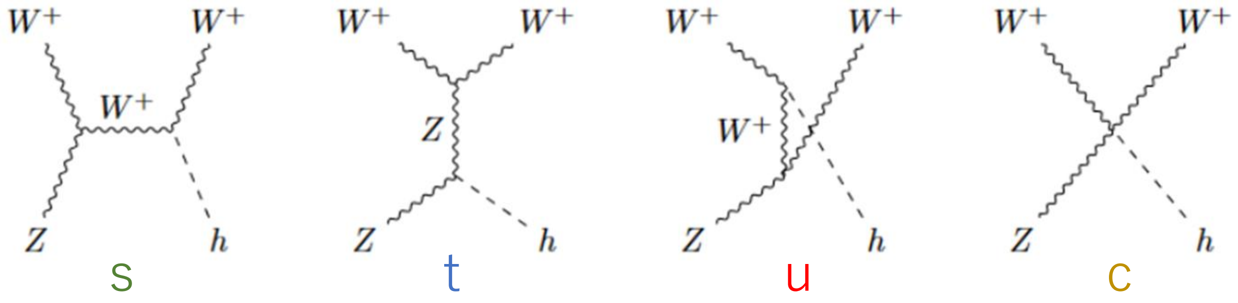
$$+ J^{\mu}_{s\,++} \frac{i}{q^2 - m^2 + i\epsilon} \left(im \frac{n_\mu}{n \cdot q} \right) J^{4}_{s\,+} \quad \cdots ②$$

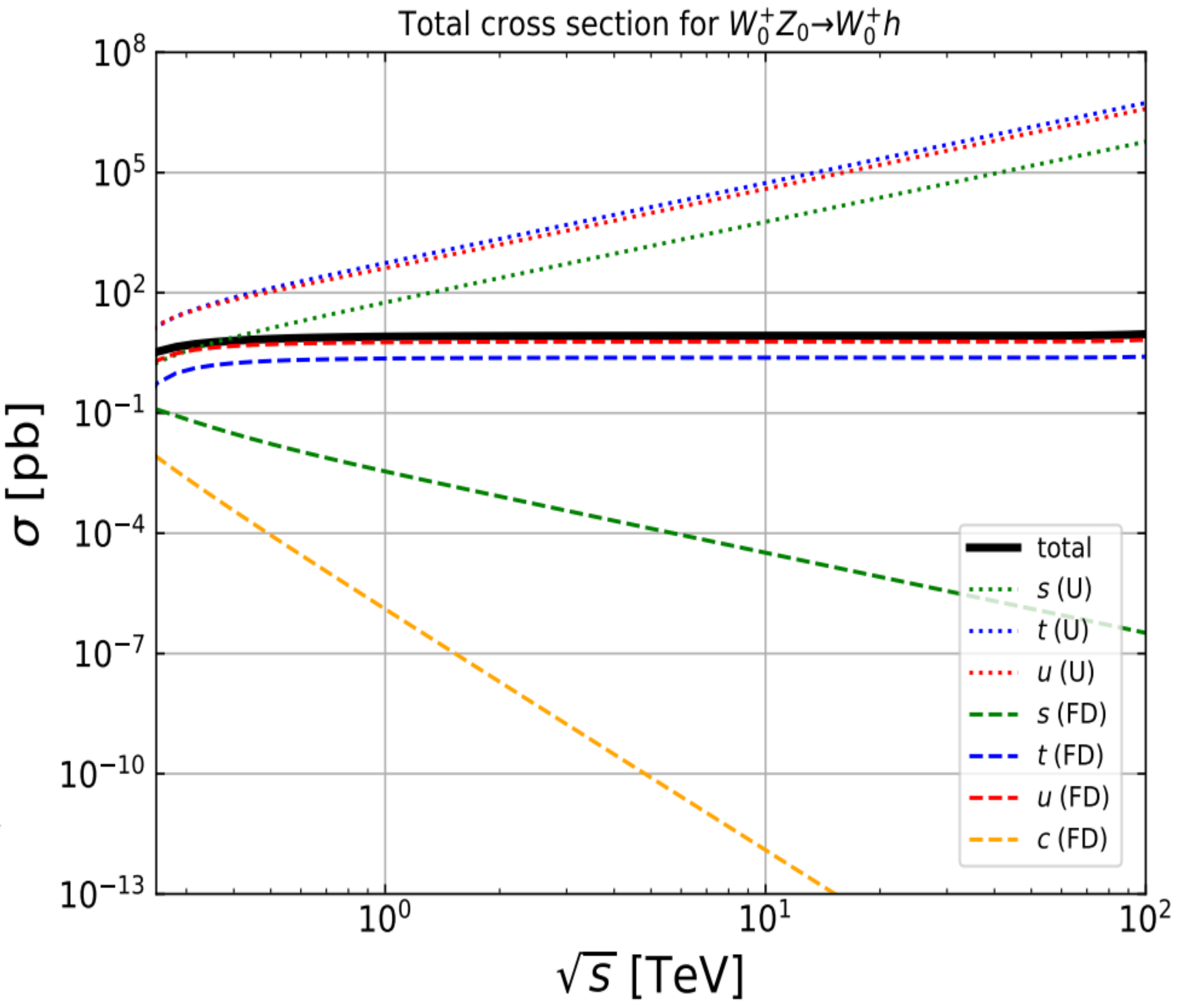
$$+ J^{4}_{s\,++} \frac{i}{q^2 - m^2 + i\epsilon} \left(-im \frac{n_\nu}{n \cdot q} \right) J^{\nu}_{s\,+} \quad \cdots ③$$

$$+ J^{4}_{s\,++} \frac{i}{q^2 - m^2 + i\epsilon} J^{4}_{s\,+} \quad \cdots ④$$

Comparison of cross sections in the U gauge and FD gauge

- **<u>The solid black line</u>** is the physical observable (obtained by summing the amplitudes of all channels (s, t, u, c) together and squaring them.)
- <u>Dotted lines</u> (U gauge) and <u>dashed lines</u> (FD gauge) are non-physical quantities (obtained by squaring the individual amplitudes s, t, u, c).
- Whichever one is chosen, the physical cross section (**<u>solid black</u>**) remains the same as expected.
  →That is, Gauge invariant.
- However, the contribution from each amplitude is quite different between the gauges!

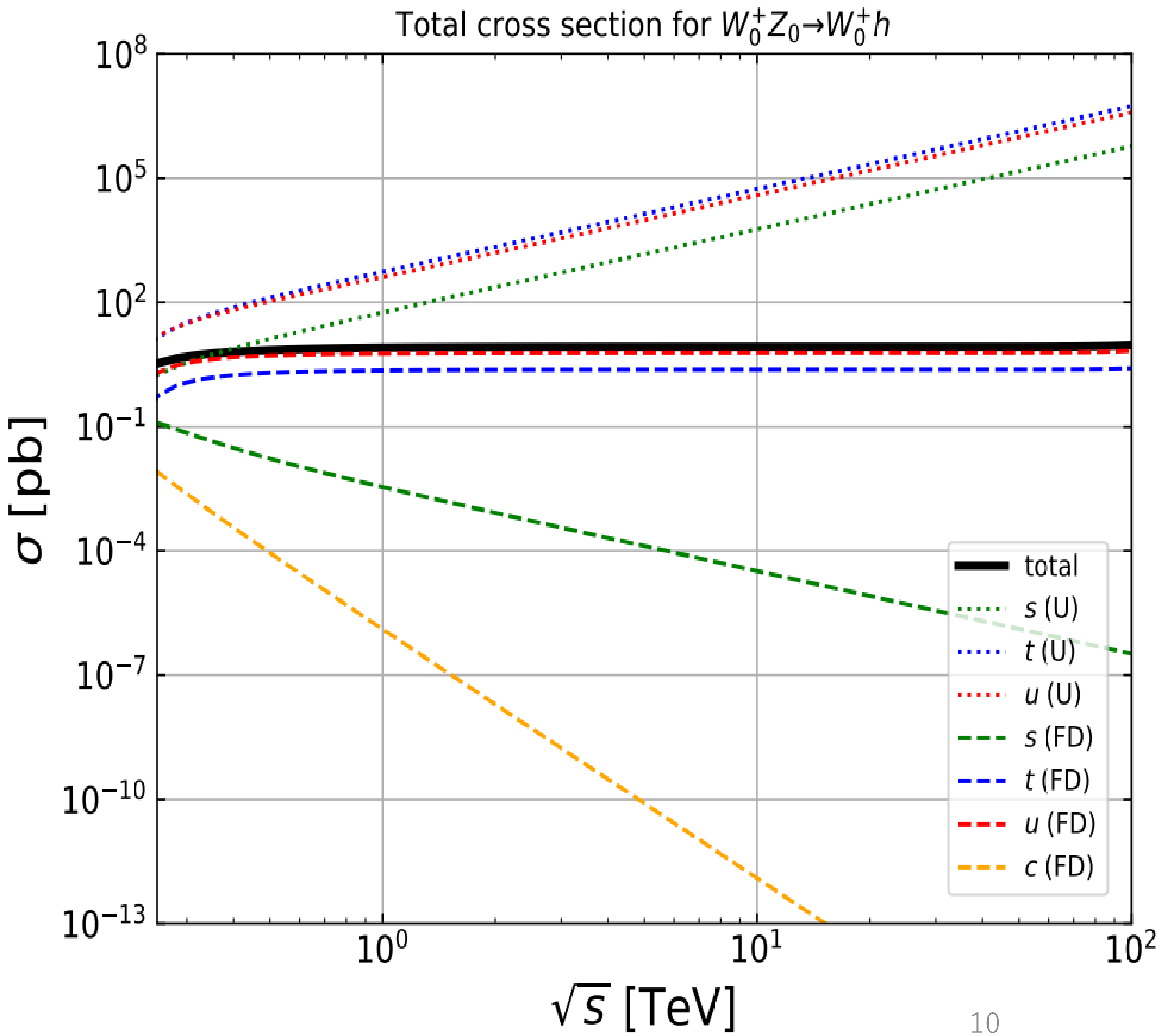




Total cross section for $\lambda_1 = \lambda_2 = \lambda_3 = 0$

- U gauge :
  - Each amplitude has energy growth.
  - Large cancellation between the three amplitudes (s, t, u) at high energies.

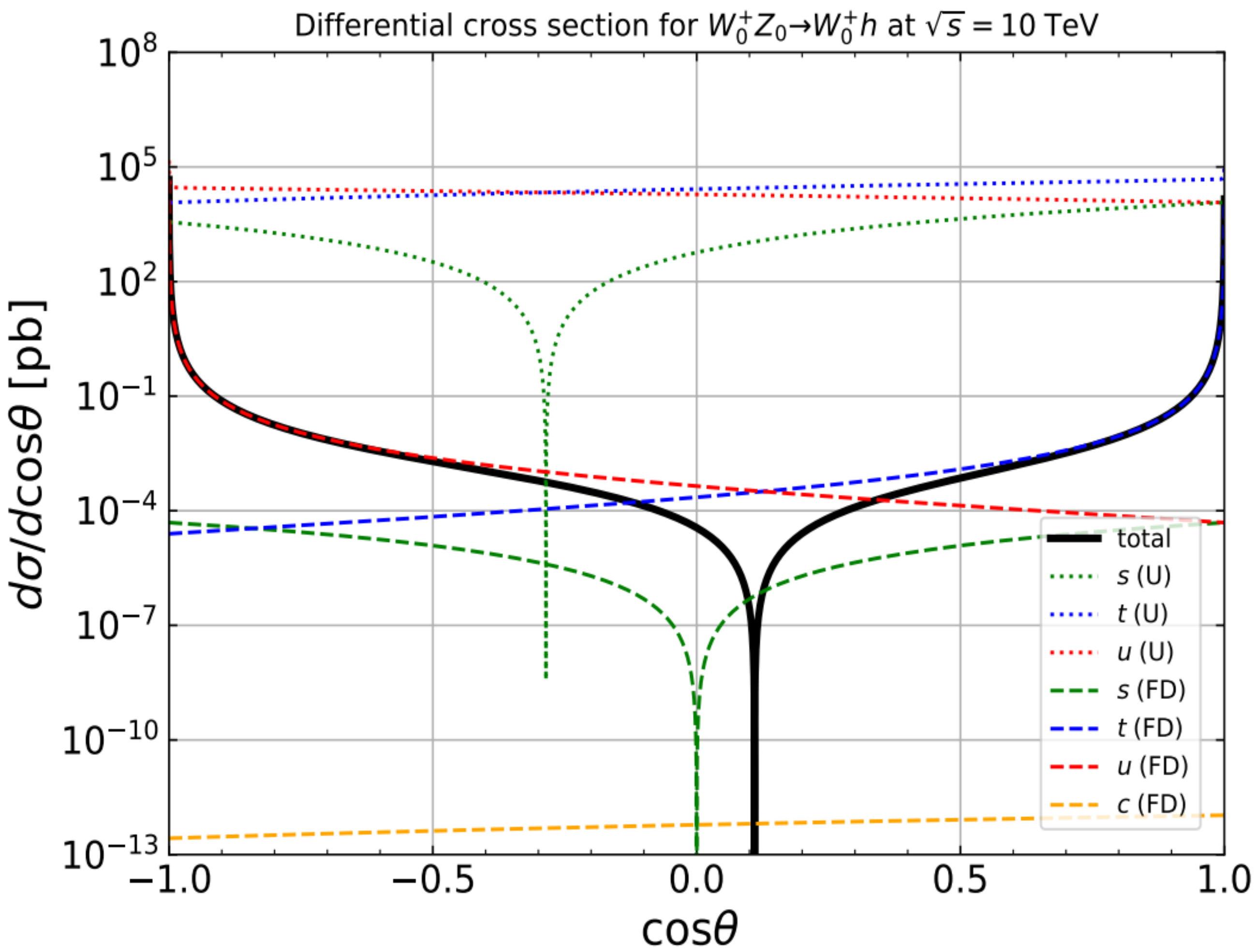
- FD gauge :
  - No such energy growth of each amplitude at all, i.e. no such gauge cancellation.
  - u and t are the main contributors.
  - At higher energies, s and c become smaller.



Angular Distribution for $\lambda_1 = \lambda_2 = \lambda_3 = 0$

- U gauge :
  - No clue for the physical distribution from each contribution.

- FD gauge :
  - Clear indication to the physical distribution from each contribution.
  - Forward scattering $(\cos\theta = 1)$ ： t is dominant.
  - Backward scattering $(\cos\theta = -1)$ ： u is dominant.



The FD gauge allows us to interpret the property of each Feynman amplitude and the interference among them.

Summary

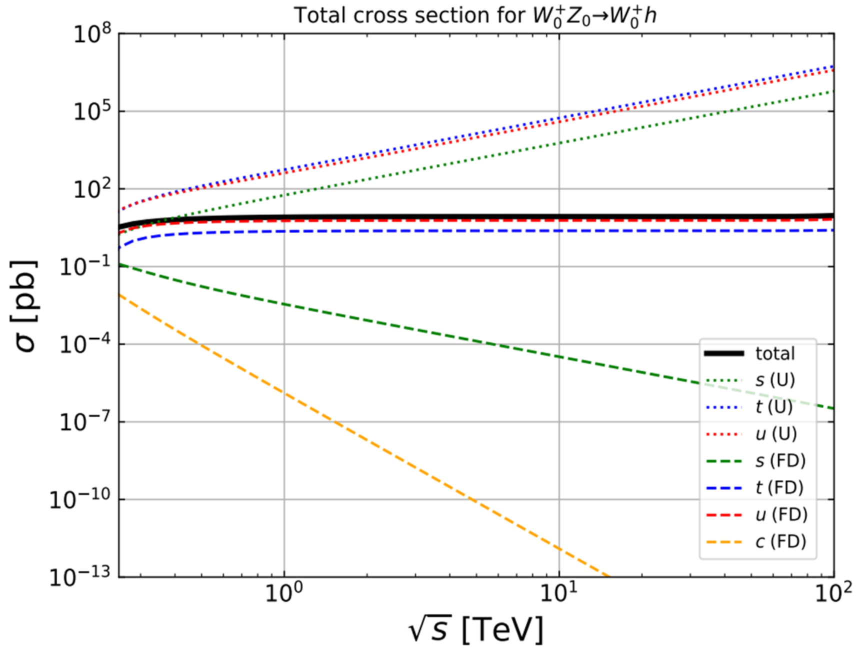
We studied $pp \to Whjj$, especially the $W^+Z \to W^+h$ subprocess for longitudinally polarized gauge bosons.
We found

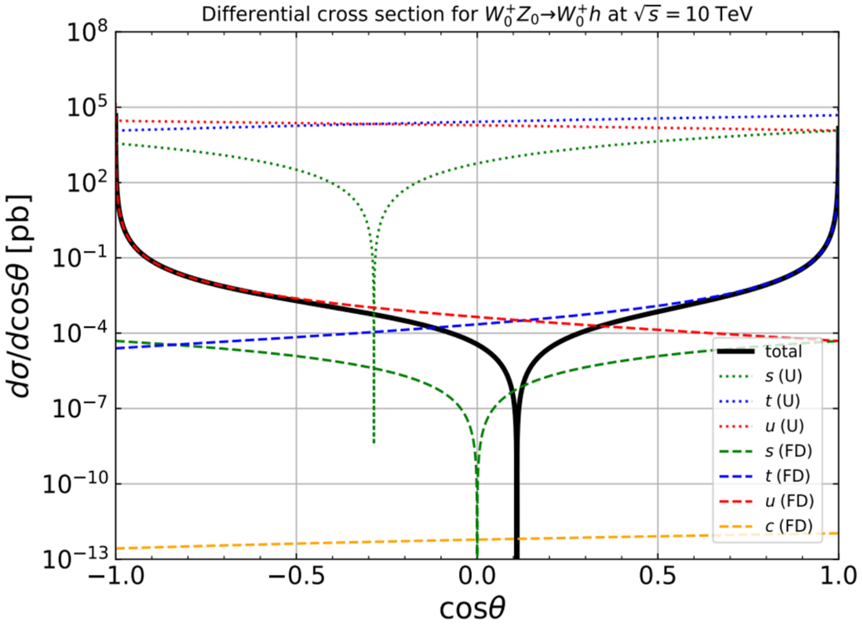
in the U gauge

- huge gauge cancellation is needed at high energies.

in the FD

- no such cancellation.
- it is possible to see which are the dominant contributions and to interpret the property of the individual amplitudes.





Iwate Collider School 2024

26 February - 2 March, 2024

Appi highland, Iwate, Japan

Registration fee

FREE and local expenses will be supported.
(No support for travel fees.)

Eligibility

Mainly for graduate students and postdoc fellows
(Max. 25 participants in person)

Venue

ANA Crowne Plaza Resort Appi Kogen

Application submission deadline

8 December, 2023

Website

https://ics.sgk.iwate-u.ac.jp/

Contact

ics2024@iwate-u.ac.jp

Overview

Students will learn a variety of topics in collider physics via lectures and tutorials. Long lunch break for skiing and discussions are planned.

Lecturers:

- Celine Degrande (Louvain, Belgium)
- Rikkert Frederix (Lund, Sweden)
- Fabio Maltoni (Louvain, Belgium)
- Olivier Mattelaer (Louvain, Belgium)
- Marco Zaro (Milan, Italy) etc.

Organizers:

- Kaoru Hagiwara (KEK)
- Daniel Jeans (KEK)
- Fabio Maltoni (UC Louvain / Bologna)
- Kentarou Mawatari (Chair, Iwate U.)
- Shinya Narita (Iwate U.)
- Yajuan Zheng (Iwate U.)

~Iwate Collider School 2023~

B Goldstone boson couplings in the SM

In this appendix, we present all the Goldstone-boson couplings of the SM explicitly, because not only the magnitude but also the relative signs of all the gauge-boson and the corresponding Goldstone-boson couplings should be kept exact in order to keep the BRST invariance of the amplitudes. The Goldstone bosons appear in the four sector of the SM Lagrangian, the Higgs potential $\mathcal{V}_H$, the Higgs gauge interactions $\mathcal{K}_H$, the gauge-fixing term $\mathcal{L}_{GF}$, and the Yukawa term $\mathcal{L}_Y$. We show all of them explicitly below.

The minimal SM has just one $SU(2)_L$ doublet Higgs field $\phi(x)$. The Lagrangian of the Higgs field is given by

$$\mathcal{L}_H = \mathcal{K}_H - \mathcal{V}_H \tag{B.1}$$

with

$$\mathcal{K}_H = (D^\mu\phi)^\dagger(D_\mu\phi), \tag{B.2}$$

$$\mathcal{V}_H = \frac{\lambda}{4}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)^2, \tag{B.3}$$

$$\mathcal{V}_H = \frac{m_H^2}{2}\left[H + \frac{H^2 + (\pi^1)^2 + (\pi^2)^2 + (\pi^3)^2}{2v}\right]^2, \tag{B.12}$$

$$\mathcal{K}_H = \frac{1}{2}(\partial H)^2 + (\partial\pi^+)(\partial\pi^-) + \frac{1}{2}(\partial\pi^0)^2 \tag{B.15a}$$

$$+ \left[\frac{g^2}{4}W^+W^- + \frac{g_Z^2}{4}\frac{Z^2}{2}\right]\left[(v+H)^2 + (\pi^0)^2\right] \tag{B.15b}$$

$$+ \frac{g_Z}{2}Z\left[(\partial\pi^0)(v+H) - (\partial H)\pi^0\right] \tag{B.15c}$$

$$+ \frac{g}{2}[W^+(\partial\pi^-) + W^-(\partial\pi^+)](v+H) \tag{B.15d}$$

$$- i\frac{g}{2}[W^+(\partial\pi^-) - W^-(\partial\pi^+)]\pi^0 \tag{B.15e}$$

$$+ i\frac{g}{2}(s_W^2 g_Z Z - eA)(W^+\pi^- - W^-\pi^+)(v+H) \tag{B.15f}$$

$$+ \frac{g}{2}(s_W^2 g_Z Z - eA)(W^+\pi^- + W^-\pi^+)\pi^0 \tag{B.15g}$$

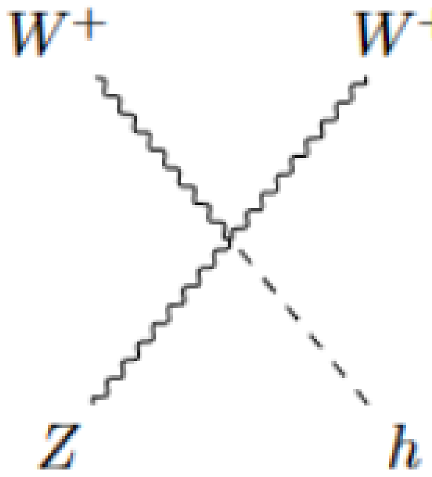
$$- \frac{g}{2}\left[(W^+\pi^- + W^-\pi^+)(\partial H) + i(W^+\pi^- - W^-\pi^+)(\partial\pi^0)\right] \tag{B.15h}$$

$$- i\left[\left(\frac{1}{2} - s_W^2\right)g_Z Z + eA\right]\left[(\partial\pi^+)\pi^- - (\partial\pi^-)\pi^+\right] \tag{B.15i}$$

$$+ \left[\frac{g^2}{2}W^+W^- + \left(\left(\frac{1}{2} - s_W^2\right)g_Z Z + eA\right)^2\right]\pi^+\pi^-, \tag{B.15j}$$

J. Chen, K. Hagiwara, J. Kanzaki and K. Mawatari,
"Helicity amplitudes without gauge cancellation for electroweak processes", Eur.Phys.J.C 83 (2023) 10, 922.

Contact channel



$$\mathcal{L}_H = \mathcal{K}_H - \mathcal{V}_H$$

with

$$\mathcal{K}_H = (D^\mu \phi)^\dagger (D_\mu \phi),$$

$$\mathcal{V}_H = \frac{\lambda}{4}\left(\phi^\dagger \phi - \frac{v^2}{2}\right)^2,$$

$$D_\mu = \partial_\mu + i\frac{g}{\sqrt{2}}(T^+ W_\mu^+ + T^- W_\mu^-) + i g_Z (T^3 - Q s_W^2) Z_\mu + ieQ A_\mu$$

$$\mathcal{K}_H = \frac{1}{2}(\partial H)^2 + (\partial \pi^+)(\partial \pi^-) + \frac{1}{2}(\partial \pi^0)^2 \qquad \text{(B.15a)}$$

$$+ \left[\frac{g^2}{4} W^+ W^- + \frac{g_Z^2}{4}\frac{Z^2}{2}\right]\left[(v+H)^2 + (\pi^0)^2\right] \qquad \text{(B.15b)}$$

$$+ \frac{g_Z}{2} Z\left[(\partial \pi^0)(v+H) - (\partial H)\pi^0\right] \qquad \text{(B.15c)}$$

$$+ \frac{g}{2}[W^+(\partial \pi^-) + W^-(\partial \pi^+)](v+H) \qquad \text{(B.15d)}$$

$$- i\frac{g}{2}[W^+(\partial \pi^-) - W^-(\partial \pi^+)]\pi^0 \qquad \text{(B.15e)}$$

$$+ i\frac{g}{2}(s_W^2 g_Z Z - eA)(W^+ \pi^- - W^- \pi^+)(v+H) \qquad \text{(B.15f)}$$

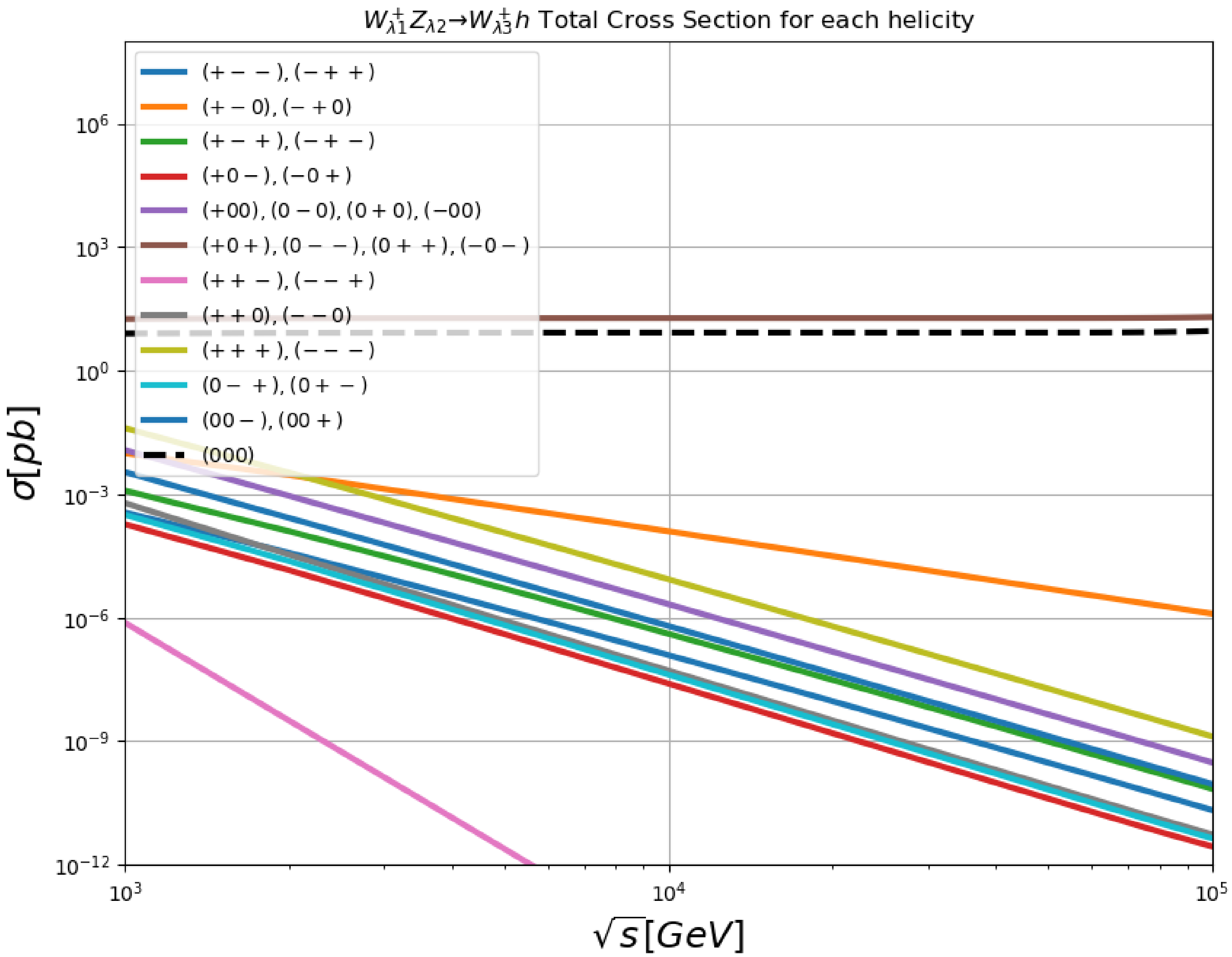
$$+ \frac{g}{2}(s_W^2 g_Z Z - eA)(W^+ \pi^- + W^- \pi^+)\pi^0 \qquad \text{(B.15g)}$$

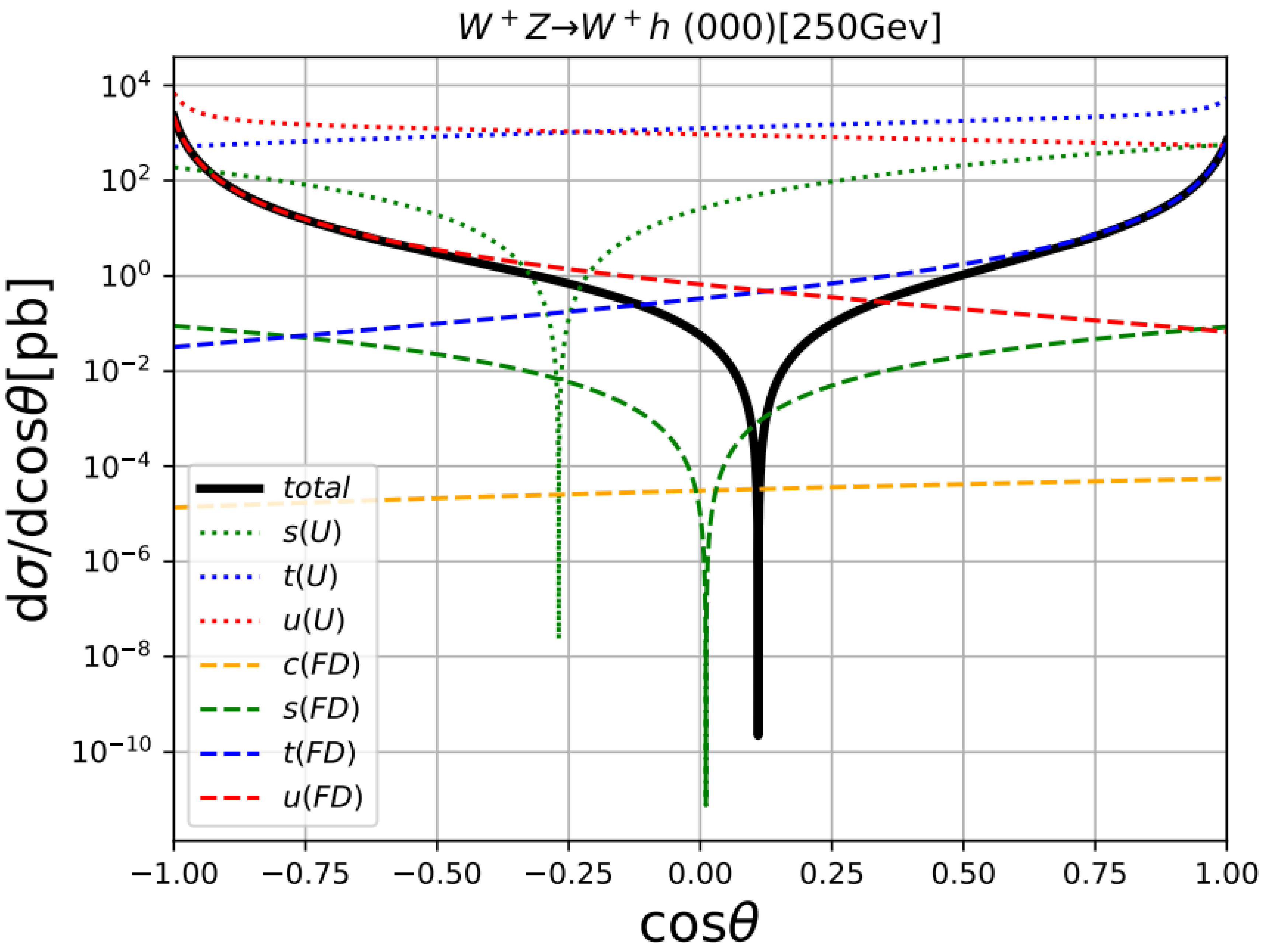
$$- \frac{g}{2}\left[(W^+ \pi^- + W^- \pi^+)(\partial H) + i(W^+ \pi^- - W^- \pi^+)(\partial \pi^0)\right] \qquad \text{(B.15h)}$$

$$- i\left[\left(\frac{1}{2} - s_W^2\right) g_Z Z + eA\right]\left[(\partial \pi^+)\pi^- - (\partial \pi^-)\pi^+\right] \qquad \text{(B.15i)}$$

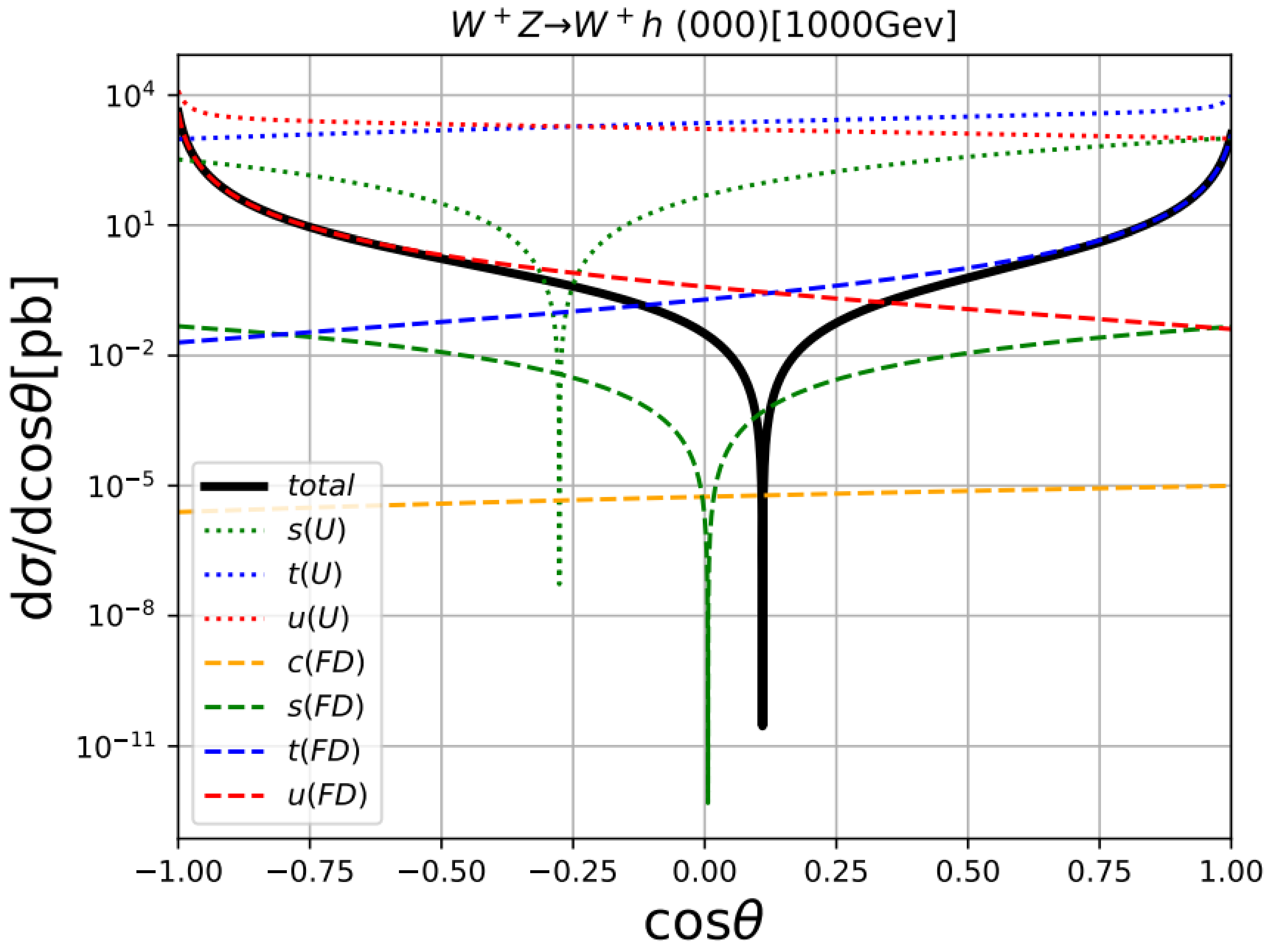
$$+ \left[\frac{g^2}{2} W^+ W^- + \left(\left(\frac{1}{2} - s_W^2\right) g_Z Z + eA\right)^2\right]\pi^+ \pi^-, \qquad \text{(B.15j)}$$

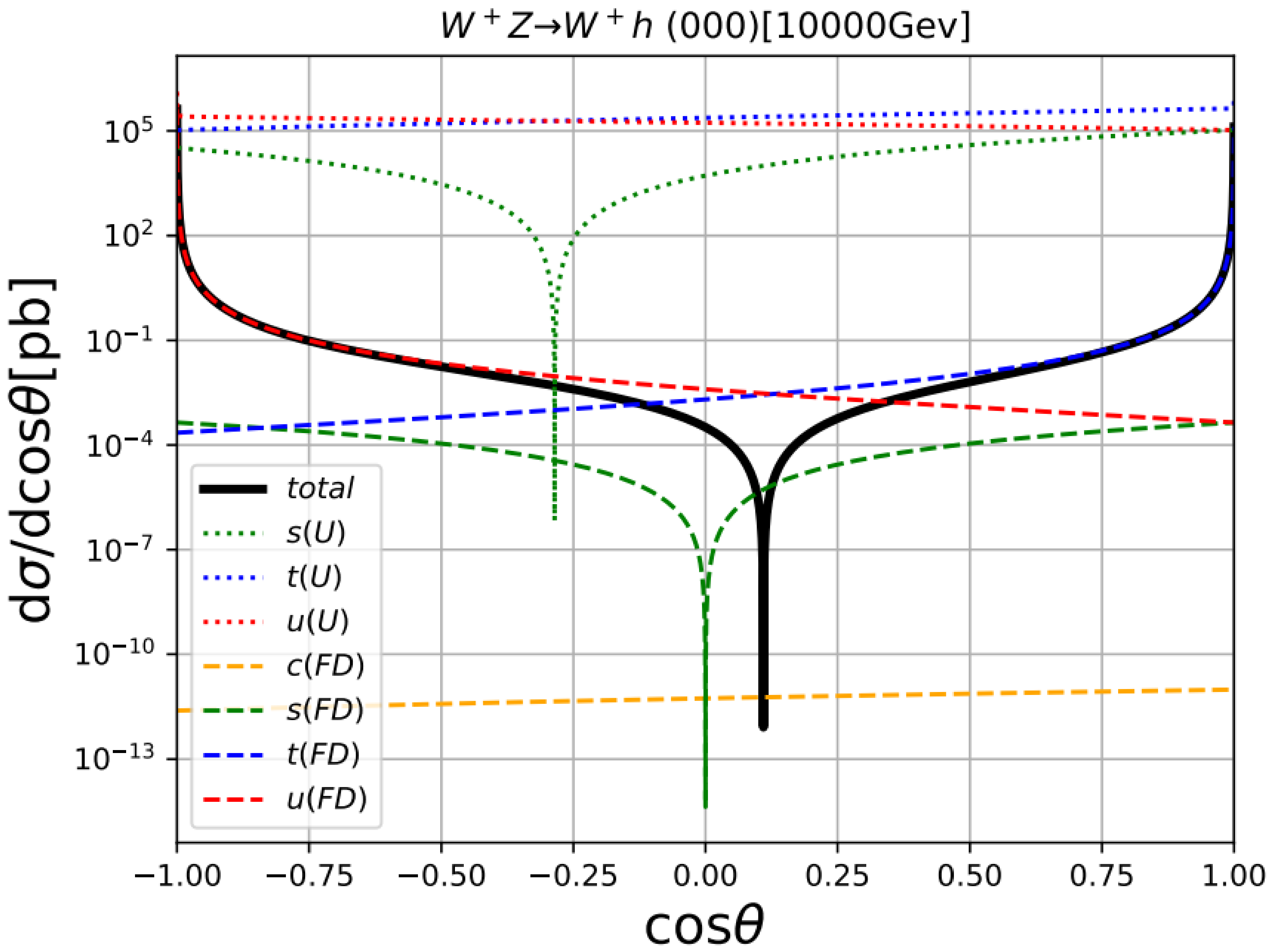
Total cross section for each helicity





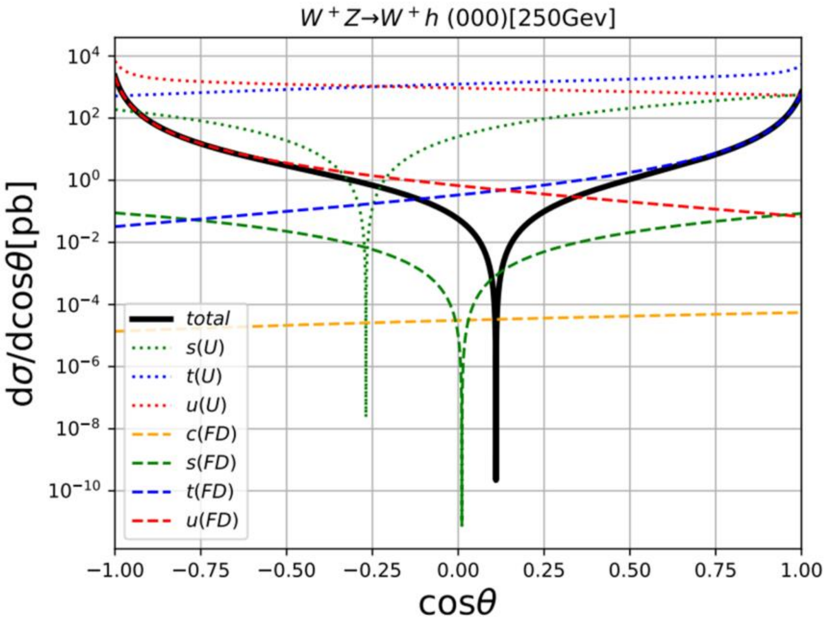
$W^+Z \to W^+h$ (000)[250Gev]
$d\sigma/d\cos\theta$[pb]
$\cos\theta$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
total
$s(U)$
$t(U)$
$u(U)$
$c(FD)$
$s(FD)$
$t(FD)$
$u(FD)$

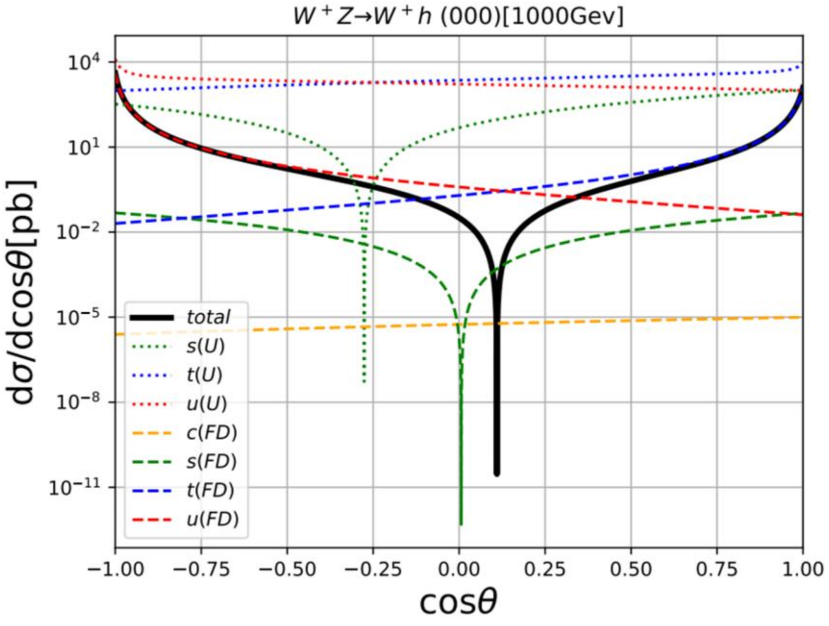

$W^+Z \to W^+h$ (000)[1000Gev]
10^{4}
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
dσ/dcosθ[pb]
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
cosθ
total
s(U)
t(U)
u(U)
c(FD)
s(FD)
t(FD)
u(FD)

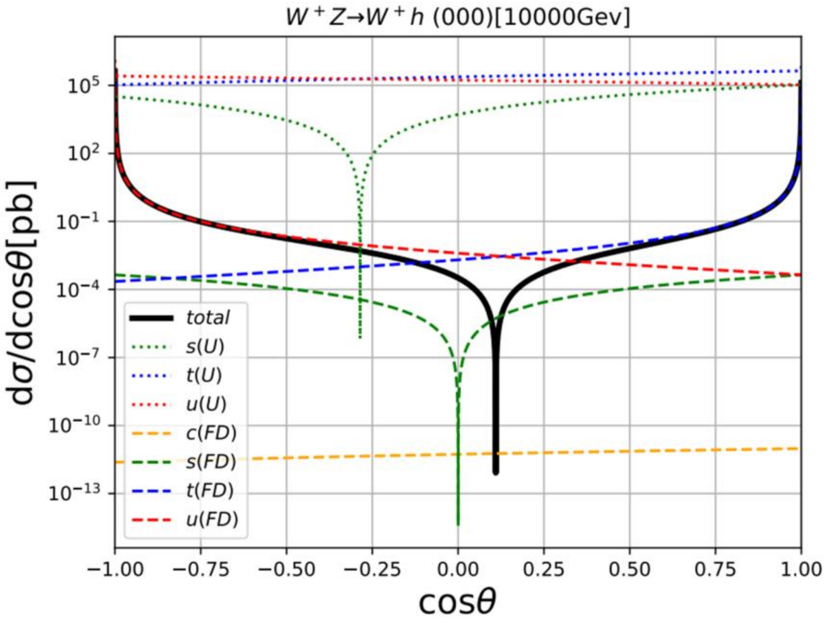


$W^+Z \to W^+h$ (000)[10000Gev]
$d\sigma/d\cos\theta$[pb]
$\cos\theta$
10^5
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
total
s(U)
t(U)
u(U)
c(FD)
s(FD)
t(FD)
u(FD)

Comparison of differential cross section at 250, 1000,10000 GeV







Define 4-momentum, polarization vector, α and β (for calculation of Helicity amplitude)

$$W^+(p_1,\lambda_1)+Z(p_2,\lambda_2)\to W^+(p_3,\lambda_3)+h(p_4).$$

$$\alpha = 1+\alpha_i = 1+\frac{m_W^2-m_Z^2}{s},$$
$$\alpha' = 1-\alpha_i = 1+\frac{m_Z^2-m_W^2}{s},$$
$$\alpha'' = 1+\alpha_f = 1+\frac{m_W^2-m_h^2}{s},$$
$$\alpha''' = 1-\alpha_f = 1+\frac{m_h^2-m_W^2}{s},$$

$$\beta_i = \bar\beta\left(\frac{m_W^2}{s},\frac{m_Z^2}{s}\right),\quad \beta_f = \bar\beta\left(\frac{m_W^2}{s},\frac{mh^2}{s}\right)$$

$$\bar\beta(a,b) = (1+a^2+b^2-2a-2b-2ab)^{\frac{1}{2}}$$

$$p_1^\mu = \sqrt{s}\Big(\alpha,0,0,\beta_i\Big),$$
$$p_2^\mu = \sqrt{s}\Big(\alpha',0,0,-\beta_i\Big),$$
$$p_3^\mu = \sqrt{s}\Big(\alpha'',\beta_f\sin\theta,0,\beta_f\cos\theta\Big),$$
$$p_4^\mu = \sqrt{s}\Big(\alpha''',-\beta_f\sin\theta,0,-\beta_f\cos\theta\Big).$$

$$\epsilon^\mu(P_1,\pm)=\frac{1}{\sqrt2}\begin{pmatrix}0\\ \mp1\\ -i\\ 0\end{pmatrix},\quad \epsilon^\mu(P_1,0)=\frac{\sqrt{s}}{2m_W}\begin{pmatrix}\beta_i\\ 0\\ 0\\ \alpha\end{pmatrix},\quad \tilde\epsilon^\mu(P_1,0)=\frac{\sqrt{s}}{2m_W}\begin{pmatrix}\beta_i-\alpha\\ 0\\ 0\\ \alpha-\beta_i\end{pmatrix},$$

$$\epsilon^\mu(P_2,\pm)=\frac{1}{\sqrt2}\begin{pmatrix}0\\ \mp1\\ +i\\ 0\end{pmatrix},\quad \epsilon^\mu(P_2,0)=\frac{\sqrt{s}}{2m_Z}\begin{pmatrix}\beta_i\\ 0\\ 0\\ -\alpha'\end{pmatrix},\quad \tilde\epsilon^\mu(P_2,0)=\frac{\sqrt{s}}{2m_Z}\begin{pmatrix}\beta_i-\alpha'\\ 0\\ 0\\ -\alpha'+\beta_i\end{pmatrix},$$

$$\epsilon^{\mu*}(P_3,\pm)=\frac{1}{\sqrt2}\begin{pmatrix}0\\ \mp\cos\theta\\ +i\\ \sin\theta\end{pmatrix},\quad \epsilon^{\mu*}(P_3,0)=\frac{\sqrt{s}}{2m_W}\begin{pmatrix}\beta_f\\ \alpha''\sin\theta\\ 0\\ \alpha''\cos\theta\end{pmatrix},\quad \tilde\epsilon^{\mu*}(P_3,0)=\frac{\sqrt{s}}{2m_W}\begin{pmatrix}\beta_f-\alpha''\\ (\alpha''-\beta_f)\sin\theta\\ 0\\ (\alpha''-\beta_f)\cos\theta\end{pmatrix}.$$

Feynman Diagram for $W^{+}Z \to W^{+}h$

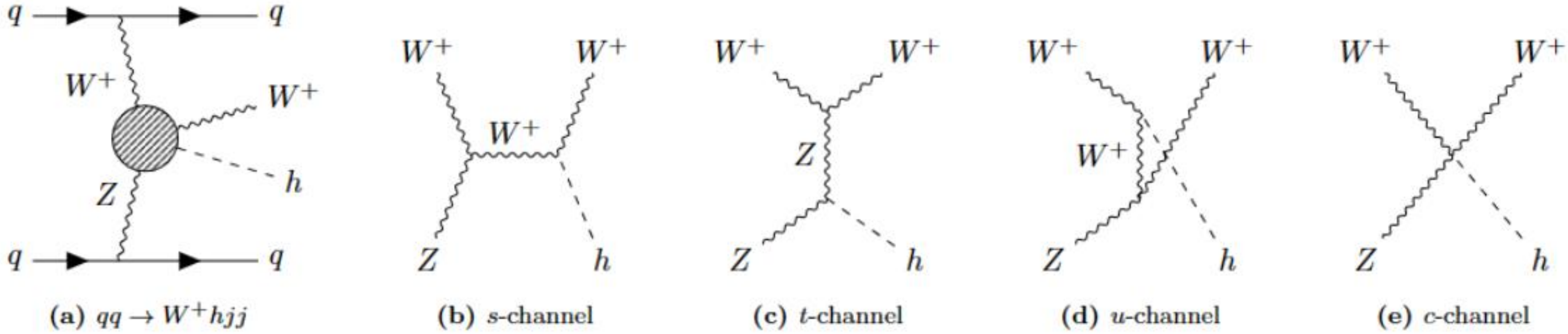


図 1: Feynman diagrams for VBF Wh production (2a), and its $W^{+}Z \to W^{+}h$ subprocesses in the FD gauge (2b-2e).

Amplitude in Unitary Gauge

$$\mathcal{M}^{\lambda_1}_{s\lambda_2\lambda_3} = \epsilon_\mu(P_1, \lambda_1)\epsilon_\nu(P_2, \lambda_2)\Gamma^{\mu\nu\alpha}_{WWZ} D_{\alpha\beta}(q_s)\Gamma^{\rho\beta}_{WWh}\epsilon^*_\rho(P_3, \lambda_3)$$

$$\mathcal{M}^{\lambda_1}_{t\lambda_2\lambda_3} = \epsilon^*_\rho(P_3, \lambda_3)\Gamma^{\mu\alpha\rho}_{WWZ}\epsilon_\mu(P_1, \lambda_1) D_{\alpha\beta}(q_t)\Gamma^{\nu\beta}_{ZZh}\epsilon_\nu(P_2, \lambda_2)$$

$$\mathcal{M}^{\lambda_1}_{u\lambda_2\lambda_3} = \epsilon_\mu(P_1, \lambda_1)\epsilon_\nu(P_2, \lambda_2)\Gamma^{\mu\nu\alpha}_{WWZ} D_{\alpha\beta}(q_u)\Gamma^{\rho\beta}_{WWh}\epsilon^*_\rho(P_3, \lambda_3)$$