Two boson interaction in high energy physics with dipole formalism

Phd student Gabriel Zardo Becker
Advisor Dr. Emmanuel Gräve de Oliveira

Federal University of Santa Catarina - (UFSC)
High Energy Physics Group of UFSC - (HEP)
Fundamental Interactions Research Group (GRIF)
National Institute of Science and Technology - Nuclear Physics and Applications (INCT-FNA)

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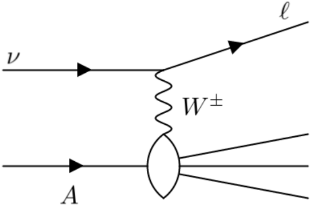
Summary

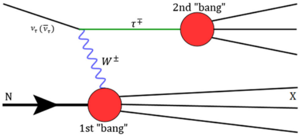
Introduction

Weak Interaction in Cosmic Rays

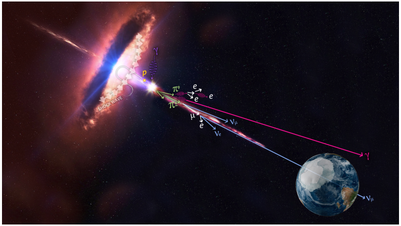
The weak interaction commonly was more useful in neutrino physics by cosmic ray experiments



Deep inelastic neutrino scattering



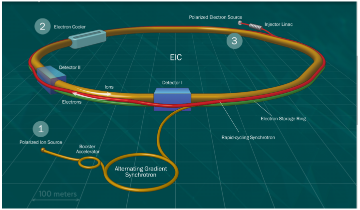
Clean signal from τ decay in Ice Cube [1].



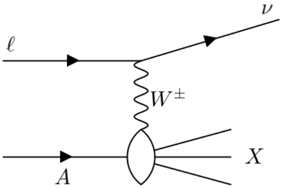
Credit image: IceCube/NASA

Future colliders detect neutrinos

Important implications for QCD, astroparticle physics and physics of BSM [2].



EIC, LHC, and FCC of FPF [1,2].



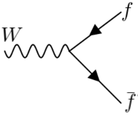
DIS by W boson

- Neutrino(anti) flux and lepton current with $6 \leq \eta$ and $E_\nu \leq 10^4$GeV
- FASERν estimates detection: $10^5\ \nu_e$, $10^6\ \nu_\mu$, and $10^3\ \nu_\tau$

Neutrino-Proton Deep Inelastic Scattering

Light-Cone Wave Function of a W Boson

Using the light-cone coordinates and the feynman rules, we can write the massive wave function of a W boson with the vertex:

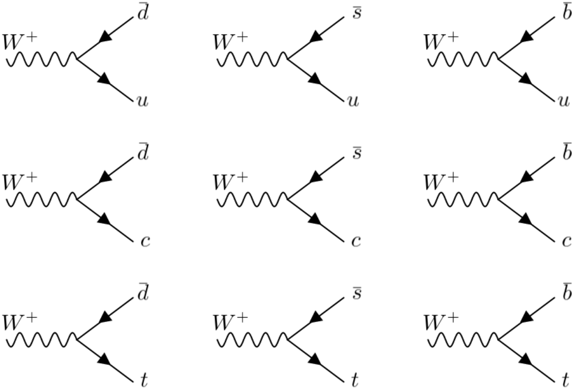


$$
\begin{aligned}
|\Psi_L^{W^+}(z,\vec{r})|^2 &= \frac{2\alpha_W N_c V_{q\bar{q}'}}{(2\pi)^2 Q^2} \left\{ \left[\left[2Q^2 z(1-z) + (m-\mu)\left[(1-z)m - z\mu\right] \right]^2 \right.\right. \\
&+ \left. \left[2Q^2 z(1-z) + (m+\mu)\left[(1-z)m + z\mu\right] \right]^2 \right] K_0^2(\epsilon r) \\
&+ \left. \left[(m-\mu)^2 + (m+\mu)^2 \epsilon^2 K_1^2(\epsilon r) \right] \right\} , \qquad (1) \\
|\Psi_T^{W^+}(z,\vec{r})|^2 &= \frac{4\alpha_W N_c V_{q\bar{q}'}}{(2\pi)^2} \left\{ \left[(1-z)^2 m^2 + z^2 \mu^2 \right] K_0^2(\epsilon r) \right. \\
&+ \left. \left[(1-z)^2 + z^2 \right] \epsilon^2 K_1^2(\epsilon r) \right\} . \qquad (2)
\end{aligned}
$$

Where the $V_{q\bar{q}'}$ is the CKM matrix and $\epsilon^2 = z(1-z)Q^2 + zm^2 + (1-z)\mu^2$

Flavour Contributions

Including all flavour contributions $N_f = 6$:

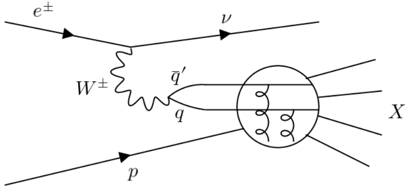


W^+ boson fluctuates into different dipole flavours.

Proton Structure Function W Boson

Unlike F_2^p for the photon-proton interaction, with the W boson we have different flavors investigating the structure of the proton.

$$F_2^p = \sum_{T,L} \sum_{q,\bar{q}'}^{N_f} \frac{Q^2}{4\pi^2} \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}^{W^+ \to q\bar{q}'}(\mathbf{r}, z; Q^2)|^2 \sigma_{dip}(\mathbf{r}, \xi) = \frac{Q^2}{4\pi^2} \left(\sigma_T^{W^+ p} + \sigma_L^{W^+ p} \right)$$

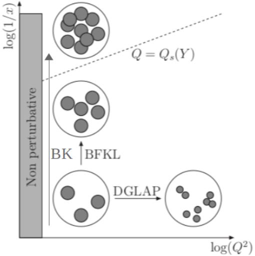


Reaction: $e^\pm p \to \nu p W^\pm \to \nu X$

With W boson mass $M_w = 80.4\text{GeV}$.

Scattering Amplitude Models

The dipole-proton scattering amplitude models carry the QCD information of the interaction that describes the transition of dilute → saturation region

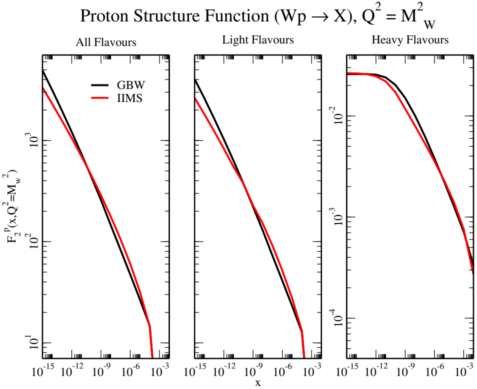


Saturation regime

- GBW (Golec-Biernat-Wüsthoff) [14].
- IIMS (Iancu-Itakura-Munier-Soyez) [15].
- rcBK (Running coupling of BK equation [16])

Proton Structure Function (F_2^p)

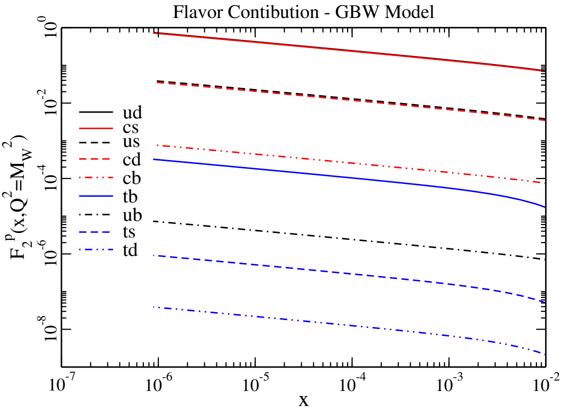
Using the virtuality in mass scale of W boson, $Q^2 = M_w^2$



Different models and flavors to low-x are verified.

Flavour contribution in (F_2^p)

All flavour contributions are shown separately with $Q^2 = M_w^2$.

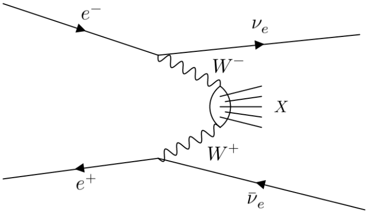


Different flavours of quarks from W interaction.

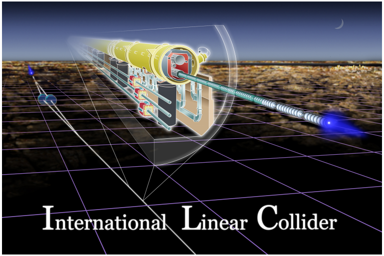
Two W Boson Interaction

W^+W^- boson interaction

60% of WW interaction cross section is the hadronic final state and it dominates the backgroud [7].



Reaction:
$e^+e^- \to \bar{\nu}_e\nu_e W^+W^- \to \bar{\nu}_e\nu_e X$



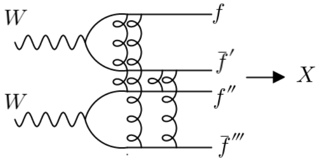
Prediction to ILC and CLIC.

Monte Carlo and Parton Model are the main approach used to describe $W^+W^- \to X$ that do not include the QCD evolution with energy.

W^+W^- like two hadron interaction

The W^+W^- cross section can be written by dipole-dipole interaction which includes QCD interactions from the (non-linear) equations of evolution with energy

$$\sigma_{i,j}^{W^+W^-}(W^2, Q_{1,2}^2) = \sum_{f,\bar{f}'}^{N_f} \int_0^1 dz_{1,2} \int d^2\mathbf{r}_{1,2} |\Psi_i^{W^+\to f\bar{f}'}(z_1, \mathbf{r}_1)|^2 |\Psi_j^{W^-\to \bar{f}f'}(z_2, \mathbf{r}_2)|^2 \sigma_{dd}^{f,\bar{f}'}(r_{1,2}, \xi)$$



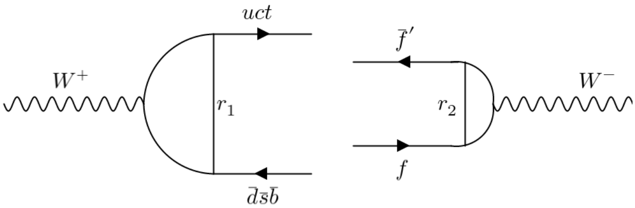
WW into dipole-dipole

The momentum fraction of two flavour partons is $\xi = x\left(1 + \frac{(m_f + m_{f'})^2}{Q^2}\right)$ and the $(i, j = T, L)$ is the polarized wave state.

Dipole-Dipole Cross Section Prescription

Prescription IKT: Based in dipole-proton scattering amplitude and using the Heavyside function (Θ) [12].

$$\widehat{\sigma}^{dd}(r_1, r_2, x) = 2\pi r_1^2 T(r_2, x_2)\Theta(r_1 - r_2) + 2\pi r_2^2 T(r_1, x_1)\Theta(r_2 - r_1)$$



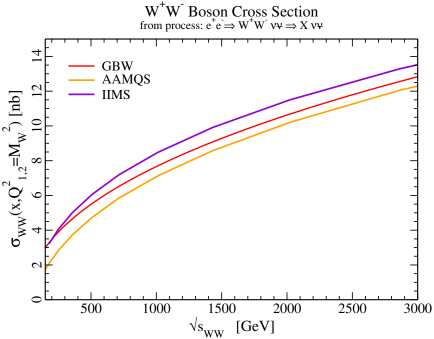
W^+W^- interaction for the Heavyside case $r_1 > r_2$.

- **Free parameter:** $0 \leq r_{1,2} \leq r_{max} = \frac{1}{\Lambda}$, where $\Lambda \approx \Lambda_{QCD}$.
- **x-correction:** $\sigma^{dd} = \widehat{\sigma}^{dd}(1-\xi)^{2\eta_s - 1}$, for $\eta_s = N_f = 6$

WW Boson Cross Section (σ_{WW})

Using the virtuality as mass scale to both W bosons, $Q^2_{1,2} = M^2_w$, with the sum of all polarized contributions:

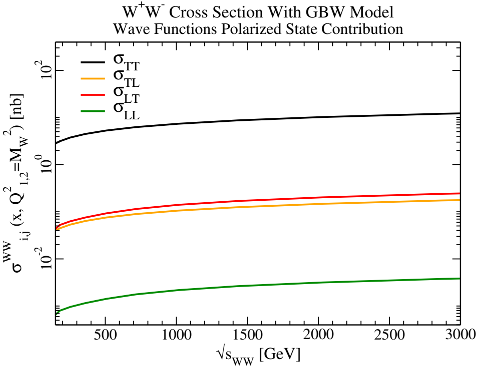
$$\sigma^{W^+W^-}_{total}(W^2, Q^2_{1,2}) = \sigma^{W^+W^-}_{LL} + \sigma^{W^+W^-}_{TT} + \sigma^{W^+W^-}_{LT} + \sigma^{W^+W^-}_{TL}$$



Analysis of different models for low-x.

Polarized WW Boson interaction

The polarized contribution of both W bosons are shown

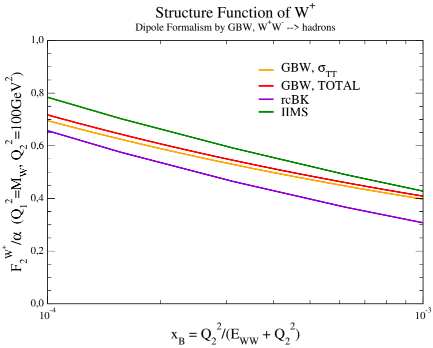


Polarization contribution of W^+W^- cross section.

W Structure Function

The parton distribution inside of W^+ boson ($Q_1^2 = M_W$) and investigated by W^- boson ($Q_2^2 = 100\text{GeV}^2$)

$$F_2^W/\alpha_s = \frac{Q^2}{4\pi^2}\left(\sigma_{TT}^{W^+W^-} + \sigma_{TL}^{W^+W^-}\right)$$



W Structure Function

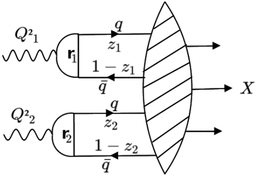
Two γ Interaction

Light-Cone Wave function to $\gamma \to q\bar{q}$

The squared modulus of the wave function of a photon with its transverse (T) and longitudinal (L) polarization states is given by [7]:

$$|\Psi_i(r,z;Q^2)|^2 = \frac{2N_c\alpha_{em}}{4\pi^2}\sum_q e_q^2 \begin{cases} [z^2+(1-z)^2]\bar{Q}_q^2 K_1^2(\bar{Q}_q r) + m_q^2 K_0^2(\bar{Q}_q r) & , i = T \\ 4Q^2 z^2 (1-z)^2 K_0^2(\bar{Q}_q r) & , i = L \end{cases}$$

$$\sigma_{gluon}^{\gamma^{(*)}\gamma^{(*)}}(W^2, r_{1,2}, Q_{1,2}^2) = \sum_{i,j}^{T,L}\sum_{a,b=1}^{N_f}\int_0^1 d^2\mathbf{r}_{1,2}\int_0^1 dz_{1,2}|\Psi_i^a(z_{1,2},\mathbf{r}_{1,2},Q_{1,2}^2)|^2\sigma_{a,b}^{dd}(r_{1,2},Y)$$

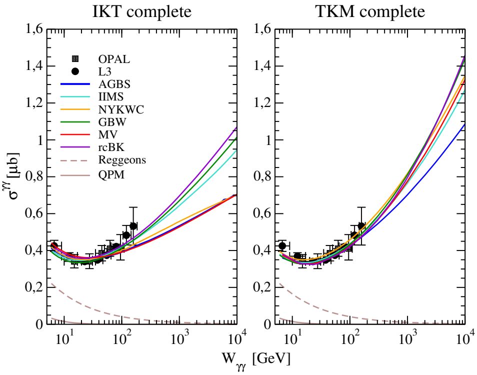


Two γ interaction by QCD.

Hadron production from real photons $\gamma\gamma \to X$

The polarized contribution of both W bosons are shown

$$\sigma^{\gamma^{(*)}\gamma^{(*)}}_{total}(W^2, Q^2_{1,2}) = \sigma^{\gamma^{(*)}\gamma^{(*)}}_{gluon}(W^2, Q^2_{1,2}) + \sigma^{\gamma^{(*)}\gamma^{(*)}}_{R}(W^2, Q^2_{1,2}) + \sigma^{\gamma^{(*)}\gamma^{(*)}}_{QPM}(W^2, Q^2_{1,2})$$



Cross section of two real photons.

Conclusions & Forthcoming Projects

Conclusions & Forthcoming Projects

Conclusions:

- We demonstrate the application of the dipole formalism (with saturation physics) to describe weak interactions in colliders: Wp and WW.
- We analyze both the polarization states of the bosons and the contribution of each flavor of quarks.
- Predictions of hadron production from two W boson interaction with energy evolution equation.
- We consider the interaction between bosons similar to the interaction between hadrons.
- We analyze the hadronic structure of bosons.

Forthcoming Projects: We are already calculating observables of all two-boson interaction types by dipole-dipole cross section:

$$\gamma\gamma, WW, ZZ, gg, W\gamma, Z\gamma, g\gamma, WZ, Wg, Zg \to X$$

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Thank you for your attention

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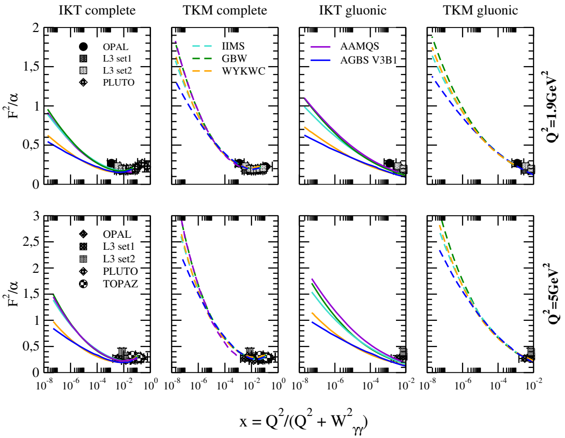
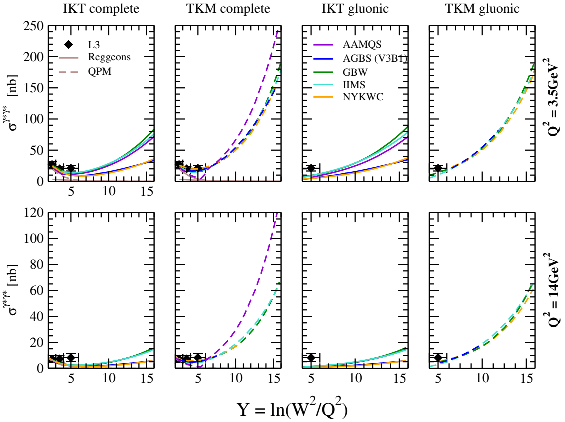
γ Strucure Function



Photon Structure Function.

Virtual Cross Section from $\gamma\gamma$



Virtual Cross Section.