PHENOMENOLOGICAL STUDY OF $\mu^+ \mu^- \to H^\pm W^\mp \gamma/Z$ PRODUCTION AT MUON COLLIDERS

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2. **Two Higgs Doublet Models**
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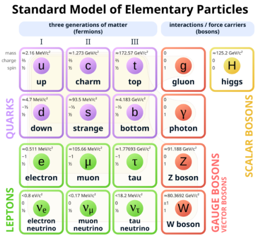
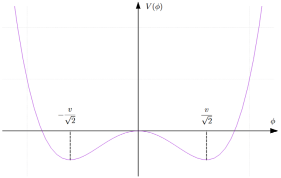
1. The Standard Model

The Standard Model





- **Higgs sector:** Higgs sector extention could explain the LHC data since the minimal SM one Higgs doublet lack theoretical justification.

The Standard Model Lagrangian

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{YM}} + \mathcal{L}_{\text{Yukawa}} + (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi)$$

$$- \underbrace{(\mu^2 |\Phi|^2 + \lambda |\Phi|^4)}_{V(\Phi)}$$

$$\mathcal{L}_{\text{kin}} = i\bar{f} \not{D} f$$

$$\mathcal{L}_{\text{YM}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} - \frac{1}{4} W^b_{\mu\nu} W^{\mu\nu,b} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

- **Gravity:** Can not incorporate space time symmetry of gravity, unification remain unsolved.
- **Neutrino masses:** Can not explain neutrinos oscillation and thus their non zero masses.
- **Dark matter:** Can not provide stable candidates for dark matter.

2. Two Higgs Doublet Model

Lagrangian of Two-Higgs-Doublet Models

Full 2HDM Lagrangian

$$\mathcal{L}_{\mathrm{2HDM}} = \mathcal{L}_{\mathrm{kin}} + \mathcal{L}_{\mathrm{YM}} + \mathcal{L}^{\mathrm{2HDM}}_{Yukawa}(\phi_1,\phi_2) + \mathcal{L}^{\mathrm{2HDM}}_{Higgs-kinetic}(\phi_1,\phi_2) - V_{2HDM}(\phi_1,\phi_2) \quad (1)$$

$$\phi_1(x) = \begin{pmatrix} \omega_1^+(x) \\ \frac{1}{\sqrt{2}}(v_1 + h_1(x) + iz_1) \end{pmatrix}, \; \phi_2(x) = \begin{pmatrix} \omega_2^+(x) \\ \frac{1}{\sqrt{2}}(v_2 + h_2(x) + iz_2) \end{pmatrix} \quad (2)$$

The 2HDM Higgs kinetic term is as follow:

$$\mathcal{L}^{\mathrm{2HDM}}_{Higgs-kinetic}(\phi_1,\phi_2) = |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 \quad (3)$$

The general 2HDM Higgs potential is given by:

$$\begin{aligned} V_{2HDM}(\phi_1,\phi_2) = m_1^2|\phi_1|^2 + \frac{\lambda_1}{2}|\phi_1|^4 + m_2^2|\phi_2|^2 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 \\ +\lambda_4|\phi_1^\dagger\phi_2|^2 + \left(\frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \lambda_6|\Phi_1|^2\Phi_1^\dagger\Phi_2 + \lambda_7|\Phi_2|^2\Phi_2^\dagger\Phi_1 - m_3^2\phi_1^\dagger\phi_2 + \mathrm{h.c}\right) \end{aligned} \quad (4)$$

If only replace the single Higgs doublet in the SM with two Higgs doublets would allow tree level FCNCs between quarks. Z_2 symmetry was introduced.
The 2HDM Yukawa term:

$$\mathcal{L}^{2HDM}_{Yukawa}(\phi_1,\phi_2) \supset \sum_{f=u,d,e} \frac{m_f}{v}[(s_{\beta-\alpha}+\zeta_f c_{\beta-\alpha})\bar{f}fh + (s_{\beta-\alpha}-\zeta_f c_{\beta-\alpha})\bar{f}fH$$
$$-2iI_f\zeta_f\bar{f}\gamma_5 fA] + \frac{\sqrt{2}}{v}[V_{ud}\bar{u}(m_u\zeta_u P_L - m_d\zeta_d P_R)dH^+ - m_e\zeta_e\bar{\nu}P_R eH^+ + \text{h.c}] \quad (5)$$

	ϕ_1	ϕ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	−	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton specific)	+	−	+	+	−	+	−	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Constraints scalar parameters of Two-Higgs-Doublet Models

There are 14 neutral 2-body scattering states:

$$|w_i^+ w_j^-\rangle \ , \ |z_i z_j\rangle \ , \ |h_i h_j\rangle \ , \ |h_i z_j\rangle \ , \ i,j = 1,2. \tag{6}$$

After diagonalize their S matrix yield 12 different eigenvalues, such as:

$$a^0_{1,\pm} = \frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2 + 4(2\lambda_3+\lambda_4)^2}\right] \tag{7}$$

Condition for convergence when computing the higher order loop is $|a^0_{i,\pm}| \leq \frac{1}{2}$ with $i = 1,...6$. The condition for v_1 and v_2 to be global minimum values of $V_{2HDM}(\phi_1,\phi_2)$ and stable VEV are as follow in order:

$$\lambda_1 > 0 \ , \quad \lambda_2 > 0 \ , \quad \sqrt{\lambda_1\lambda_2} + \lambda_3 + MIN(0, \lambda_4+\lambda_5, \lambda_4-\lambda_5) > 0,$$
$$\frac{m_3^2}{s_\beta c_\beta} \geq 0.$$

3. The Processes $\mu^+\mu^- \to H^\pm W^\mp \gamma/Z$ in Two-Higgs-Doublet Models

The Processes $\mu^+\mu^- \to H^\pm W^\mp\gamma/Z$ in 2HDM

This section will display simulation result plotted by MadAnalysis using data from the Monte Carlo event generator MadGraph5_aMC@NLO of the processes $\mu^+\mu^- \to H^\pm W^\mp\gamma/Z$ in Type-I 2HDM.

We then plot several kinematic graphs to investigate the behavior of the scattering product and evaluate the significance of the processes for future muons colliders detection.

Coupling constants of the processes $\mu^+\mu^- \to H^\pm W^\mp \gamma/Z$

The coupling constants of Type-I 2HDM required for caculating the total cross section of the processes $\mu^+\mu^- \to H^\pm W^\mp \gamma/Z$ are laid out on tables below:

Boson-Fermion vertices	Coupling constant
$\mu^+\ \mu^-\ A$	$\frac{-Y_e}{\sqrt{2}}\, c_\beta$
$\mu^+\ \mu^-\ H$	$\frac{Y_e}{\sqrt{2}}\, s_\alpha$
$\mu^+\ \mu^-\ h$	$\frac{-Y_e}{\sqrt{2}}\, c_\alpha$
$\mu^+\ \mu^-\ \gamma$	$-2e$
$\mu^+\ \mu^-\ Z$	$\frac{-e}{2s_W c_W}\,(1-4s_W^2)$
$\mu^+\ \nu_\mu\ H^+$	$-Y_e\, c_\beta$
$\mu^-\ \nu_\mu\ W^-$	$\frac{e(1-\gamma^5)}{s_W 2\sqrt{2}}$

Boson-only vertices	Coupling constant
$H^+H^+\gamma$	e
H^+H^+Z	$\frac{e}{s_W c_W}(\frac{1}{2}-s_W^2)$
$Z\ Z\ H$	$\frac{ve^2}{2s_W^2 c_W^2}\, c_{\beta-\alpha}$
$Z\ Z\ h$	$\frac{ve^2}{2s_W^2 c_W^2}\, s_{\beta-\alpha}$
H^+W^-A	$\frac{e}{s_W 2\sqrt{2}}$
H^+W^-H	$\frac{e}{s_W 2\sqrt{2}}\, s_{\beta-\alpha}$
H^+W^-h	$\frac{e}{s_W 2\sqrt{2}}\, c_{\beta-\alpha}$

$H^+W^-A\,\gamma$	$\frac{e^2}{2s_W}$
$H^+W^-H\,\gamma$	$\frac{e^2}{2s_W}\, s_{\beta-\alpha}$
$H^+W^-h\,\gamma$	$\frac{e^2}{2s_W}\, c_{\beta-\alpha}$
$Z\ A\ H$	$\frac{-e}{s_W c_W 2\sqrt{2}}\, s_{\beta-\alpha}$
$Z\ A\ h$	$\frac{-e}{s_W c_W 2\sqrt{2}}\, c_{\beta-\alpha}$
$W^-W^-\gamma$	e
W^-W^-Z	$\frac{c_W}{s_W}\, e$

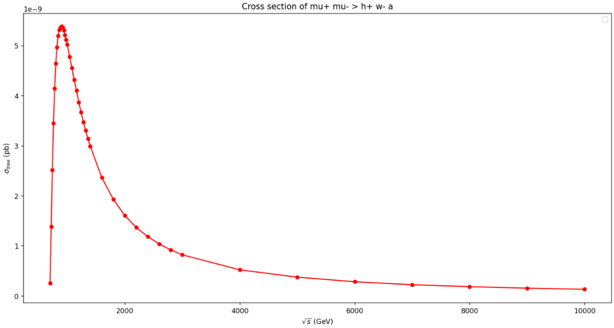
Total Cross-Section

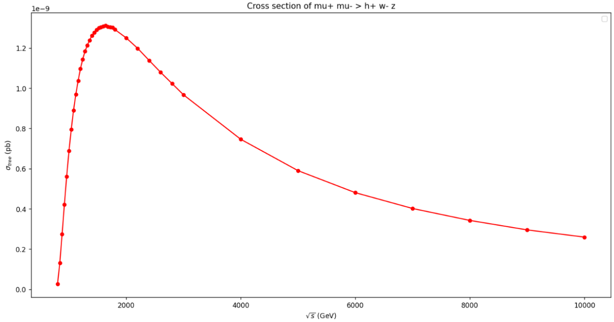
The standard differential cross section fomular for 2-n scattering process is given by:

$$d\sigma = \left(\prod^{m} \frac{d^3 p_m}{(2\pi)^3 2E_m}\right) \frac{1}{4E_A E_B |v_A - v_B|} \times (2\pi)^4 \delta^{(4)} \left(\sum_i^m p_i - k_A - k_B\right) |M(k_A k_B \to p_1 p_2 ... p_m)|^2 , \quad (8)$$

with the integral over the momentum space for 2-3 case as follow:

$$\int d\Pi_m = \left(\prod_m \int \frac{d^3 \mathrm{p}_m}{(2\pi)^3} \frac{1}{2E_m}\right) (2\pi)^4 \delta^{(4)}(p_A + p_B - \sum p_m) = \frac{\sqrt{\lambda(s, q, m_3^2)}}{32\pi^2 s} \frac{\sqrt{\lambda(q, m_1^2, m_2^2)}}{32\pi^2 q} d\cos\theta d\phi d\cos\theta_{12} d\phi_{12} dq. \quad (9)$$





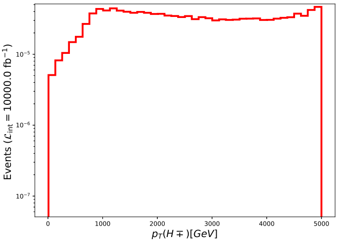
The total cross section dependant on CoM energy in region larger than the threshold energy up to 10 TeV.

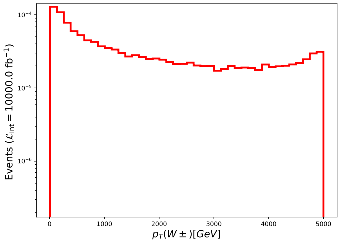
Phenomenological Results

Data of the following kinematic graphs is from simulating the processes at 3 TeV and 10 TeV of CoM energy.

The following plot the kinematic dependent of the cross section on, and thusly the event numbers N expected at values of tranverse momentum p_T and psuedo rapidity η:

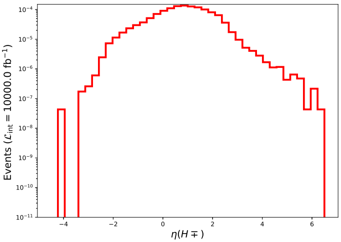
$$p_T = \sqrt{p_x^2 + p_y^2}\ ,\ \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)\ ,\ N_{\text{expected}} = \sigma \times L. \quad (10)$$

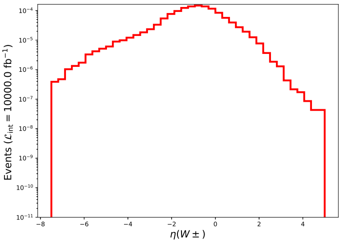


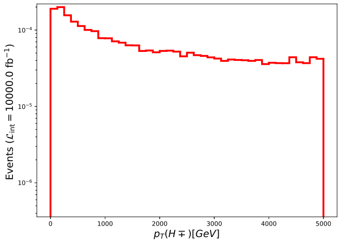


$H^\pm$ kinematic produced with γ at 10 TeV

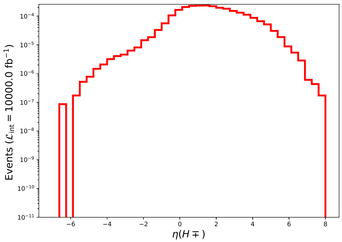
$W^\pm$ kinematic produced with γ at 10 TeV

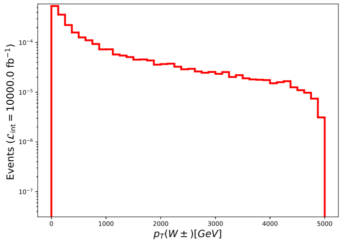




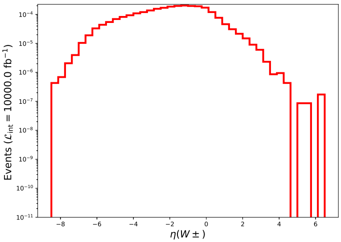


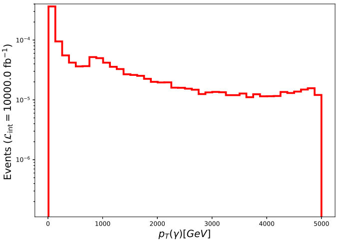
$H^\pm$ kinematic produced with Z at 10 TeV



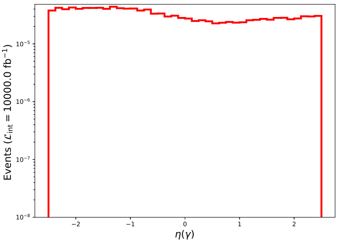


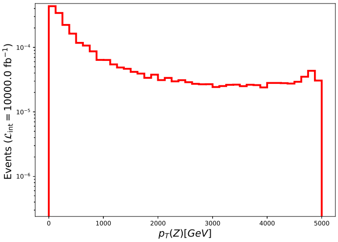
$W^\pm$ kinematic produced with Z at 10 TeV



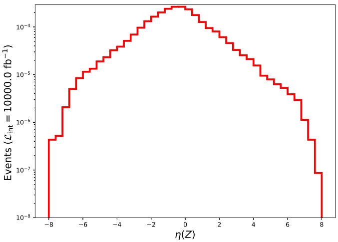


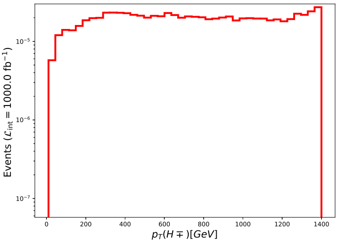
γ kinematic at 10 TeV

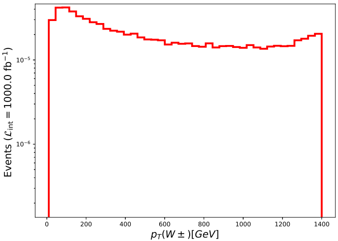




Z kinematic at 10 TeV

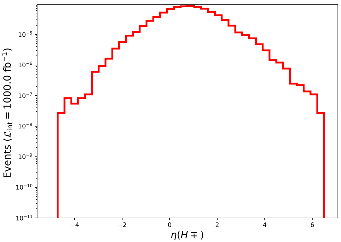


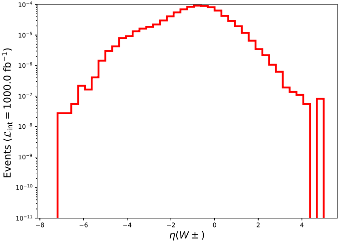


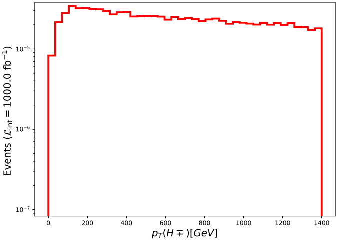


$H^\pm$ kinematic produced with γ at 3 TeV

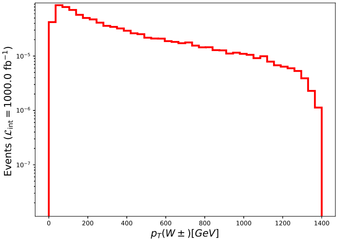
$W^\pm$ kinematic produced with γ at 3 TeV



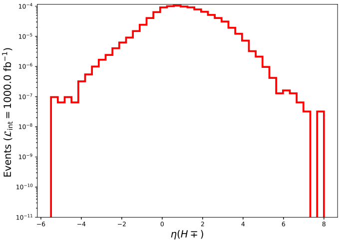


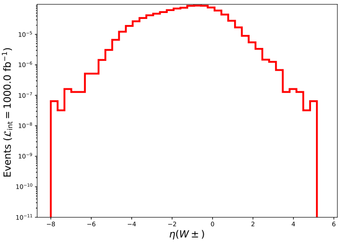


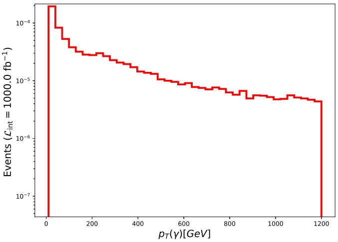
$H^\pm$ kinematic produced with Z at 3 TeV

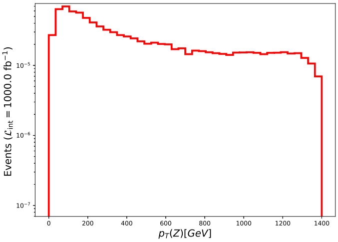


$W^\pm$ kinematic produced with Z at 3 TeV



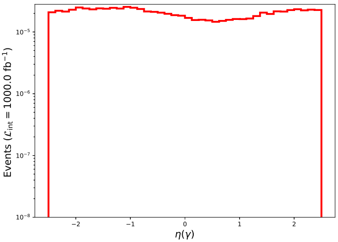


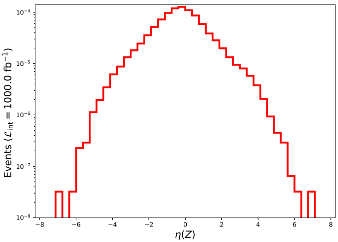




γ kinematic at 3 TeV

Z kinematic at 3 TeV





4. Conclusion

Conclusion

- Investigated the production of charged Higgs conjunction with the electroweak bosons at future muon colliders ($\mu^+\mu^- \to H^\pm W^\mp \gamma/Z$) in Type-I 2HDM.
- Compute numerically the kinematic behavior of the produced particle at hard scattering.
- **Conclusion :** The processes have low expected number of events at high value integrated luminosity (1000 fb^{-1} $\to$ 10000 fb^{-1}), low priority for detection at the future muon colliders.

Thank you