Charged Higgs at a muon collider

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Outlines

- Introduction
- Two Higgs doublet model (2HDM)
- Charged Higgs production at MuC.
- Heavy Higgs Resonance effects on SM processes: $\mu^+\mu^- \to Zh, t\bar{t}, W^+W^-, hh...$
- Conclusions

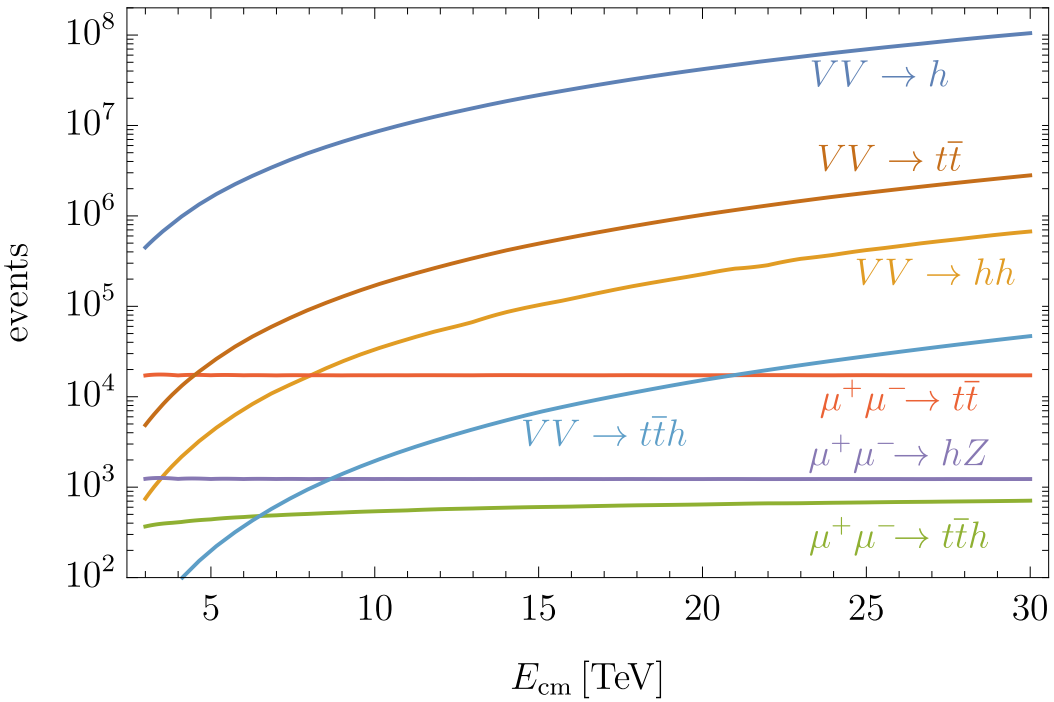
B. Ait Ouazghour, AA , K.Cheung, E. Ghourmin, and L. Rahili, PRD110 (2024);

B. Ait Ouazghour, AA , K.Cheung, E. Ghourmin, and L. Rahili, PRD109 (2024)

B. Ait Ouazghour, AA , K.Cheung, E. Ghourmin, M. Krab and L. Rahili, PRD112 (2025)

Introduction:

- MuC results complementary to the other projects such HL-LHC, FCC-ee, CLIC ...
- At MuC with: $\sqrt{s} = 3$–30 TeV, $\mathcal{L} \approx (\frac{\sqrt{s}}{10\,TeV})^2 \times 10^4$ fb^{-1}
  A total of 1/2million Higgs bosons will be produced at the 3 TeV MuC: It's a Higgs factory



	HL-LHC	HL-LHC+10 TeV	HL-LHC+10 TeV+ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t	3.3	3.1	3.1

1σ sensitivities (in %) from a 10-parameter fit in the κ-framework at a 10 TeV MuC with 10 ab^{-1}, compared with HL-LHC.

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \phi_1^0 + i a_1\right) \end{pmatrix}; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \phi_2^0 + i a_2\right) \end{pmatrix}.$$

The most general potential for 2HDM:

$$\begin{aligned} V(\Phi_1,\Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c}) \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ &+ +\lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \mathrm{h.c.}], \end{aligned}$$

Spectrum: 2 CP-even h and H: $m_h < m_H$, CP-odd A and a pair of charged Higgs $H^\pm$

Decoupling limit of the 2HDM

From the 2 minimization conditions:

$$m_{12}^2 v_2 - m_1^2 v_1 - \frac{1}{2}\lambda_1 v_1^3 - \frac{1}{2}\lambda_{345} v_1 v_2^2 = 0$$
$$m_{12}^2 v_1 - m_2^2 v_2 - \frac{1}{2}\lambda_2 v_2^3 - \frac{1}{2}\lambda_{345} v_1^2 v_2 = 0$$

m_1^2 and m_2^2 can be eliminated in terms of λ_i, v_1 and v_2.
CP-odd and charged Higgs sector:

$$m_{H^\pm}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta} - \frac{1}{2}(\lambda_4+\lambda_5)v^2,$$
$$m_A^2 = \frac{m_{12}^2}{\sin\beta\cos\beta} - \lambda_5 v^2,$$

CP-even Higgses:

$$
\begin{aligned}
M_{11}^2 &= (\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{1}{2}\lambda_{345}\sin^2 2\beta)v^2, \\
M_{12}^2 &= (-\lambda_1 \cos^2\beta + \lambda_2 \sin^2\beta + \lambda_{345}\cos 2\beta)\cos\beta \sin\beta v^2, \\
M_{22}^2 &= \frac{m_{12}^2}{\sin\beta\cos\beta} + \frac{1}{4}(\lambda_1 + \lambda_2 - 2\lambda_{345})\sin^2 2\beta v^2,
\end{aligned}
$$

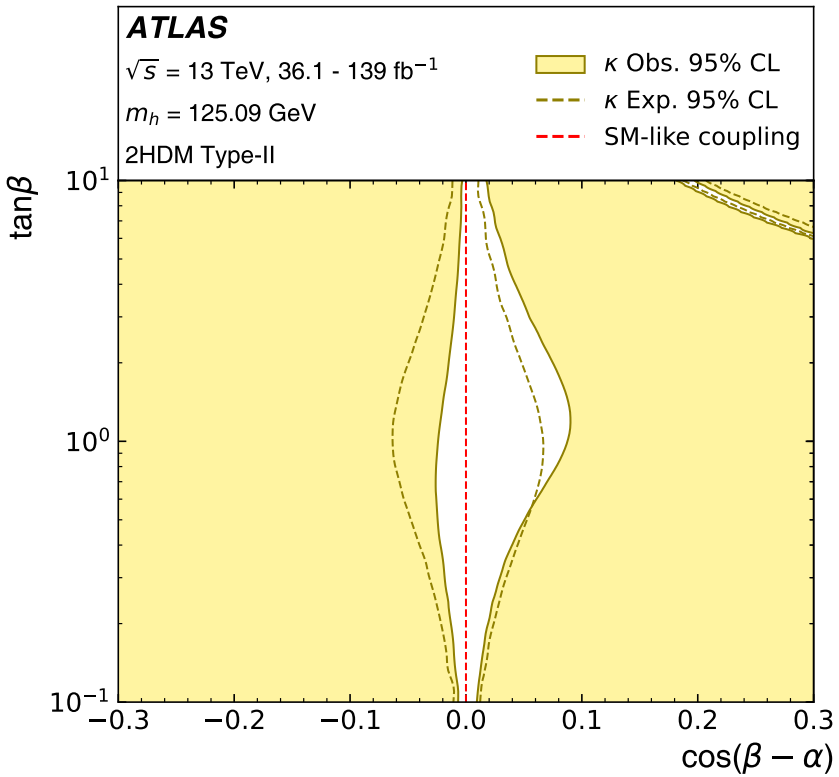
The mixing angle $\alpha - \beta$:

$$
\tan 2(\alpha-\beta) = \frac{2M_{12}^2}{M_{11}^2 - M_{22}^2} \to 0 \quad \textit{for} \quad m_{12}^2 \to \infty\,,
$$

and

$$
\begin{aligned}
m_H^2 &= \cos^2(\alpha-\beta)M_{11}^2 + \sin 2(\alpha-\beta)M_{12}^2 + \sin^2(\alpha-\beta)M_{22}^2, \\
m_h^2 &= \sin^2(\alpha-\beta)M_{11}^2 - \sin 2(\alpha-\beta)M_{12}^2 + \cos^2(\alpha-\beta)M_{22}^2 < m_H^2
\end{aligned}
$$

2HDM at LHC


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_h = 125.09 GeV
2HDM Type-II
κ Obs. 95% CL
κ Exp. 95% CL
SM-like coupling
tanβ
10^1
10^0
10^{-1}
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
cos(β − α)

Yukawa textures

The Yukawa Lagrangian:

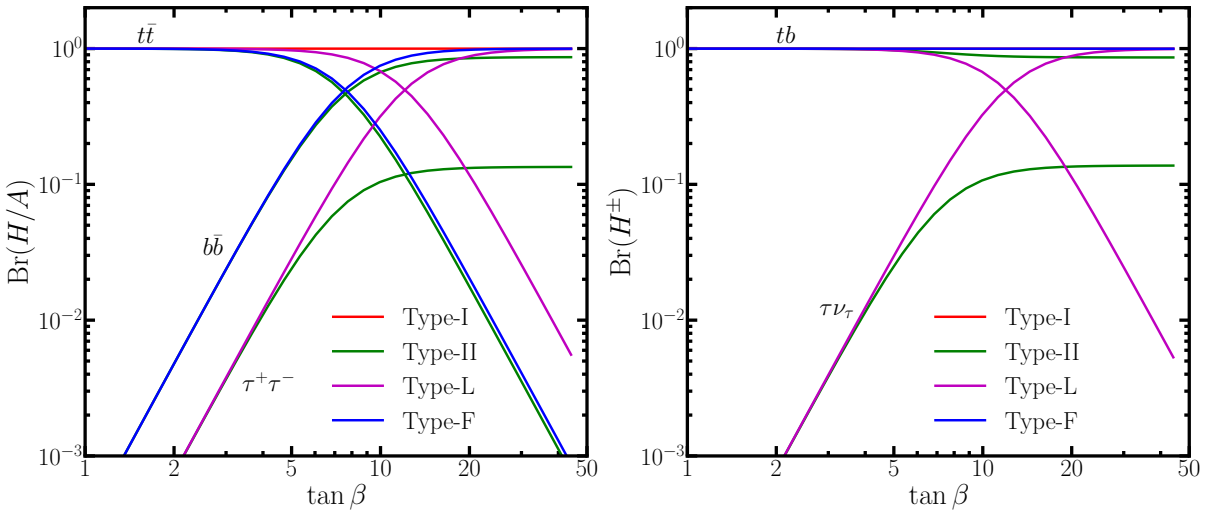
$$-\mathcal{L}_{Yuk} = \sum_{\psi=u,d,l} \left(\frac{m_\psi}{v} \kappa_\psi^h \bar{\psi}\psi h^0 + \frac{m_\psi}{v} \kappa_\psi^H \bar{\psi}\psi H^0 - i \frac{m_\psi}{v} \kappa_\psi^A \bar{\psi}\gamma_5 \psi A^0 \right) +$$

$$\left(\frac{V_{ud}}{\sqrt{2}v} \bar{u}(m_u \kappa_u^A P_L + m_d \kappa_d^A P_R) d H^+ + \frac{m_l \kappa_l^A}{\sqrt{2}v} \bar{\nu}_L l_R H^+ + H.c. \right)$$

	κ_u^H	κ_d^H	κ_l^H	κ_u^A	κ_d^A	κ_l^A
Type-I	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-III	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-IV	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

	κ_u^H	κ_d^H	κ_l^H	κ_u^A	κ_d^A	κ_l^A
Type-I	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-III	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-IV	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

$m_{H,A,H^\pm} = 2$ TeV, $\cos(\beta-\alpha)=0$



T. Han et al PRD **104** (2021)

Constraints

- Stability of the 2HDM potential requires that it should be bounded from below, i.e. that there is no direction in field space along which the potential becomes negatif.

  Deshpande and E. Ma, PRD18'1978

$$\lambda_1 > 0 \quad , \quad \lambda_2 > 0$$
$$\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$$
$$\lambda_3 + min(0, \lambda_4 - \mid \lambda_5 \mid) > -\sqrt{\lambda_1 \lambda_2}$$

- The vacuum of the model is global one if and only if:

  $m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) > 0 \qquad ; \quad k = \sqrt[4]{\frac{\lambda_1}{\lambda_2}}$

  A. Barroso et al JHEP**06** (2013)

- Perturbative unitarity: $V_L^+ V_L^- \to V_L^+ V_L^-$, $h_i\ h_j \to h_i\ h_j$ ...

  S. Kanemura et al PLB313 (1993) , A.A et al PLB490 (2000)

Constraints

- 2HDM spectrum and constraints: 2HDM-Calculator

  [O. Stal et al CPC181 (2010)]

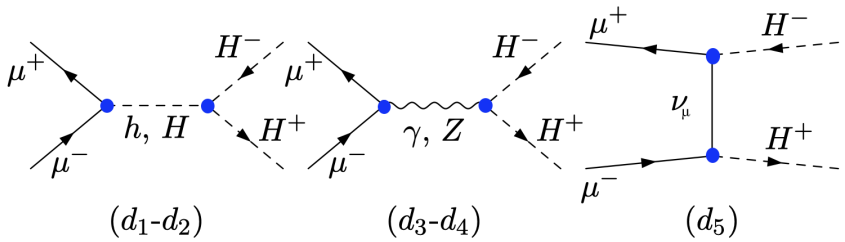
- HiggsBounds and HiggsSignal

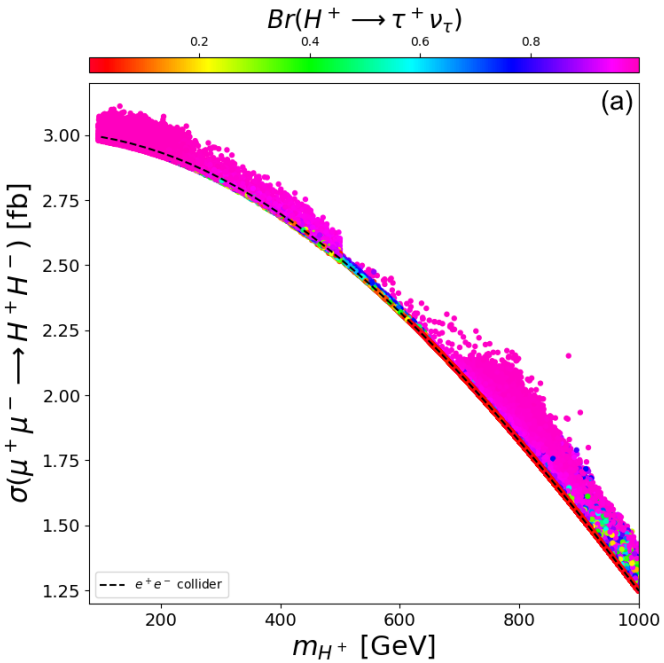
  [P. Bechtle et al CPC181 (2010)] [P. Bechtle et al Eur.Phys.J.C 74]

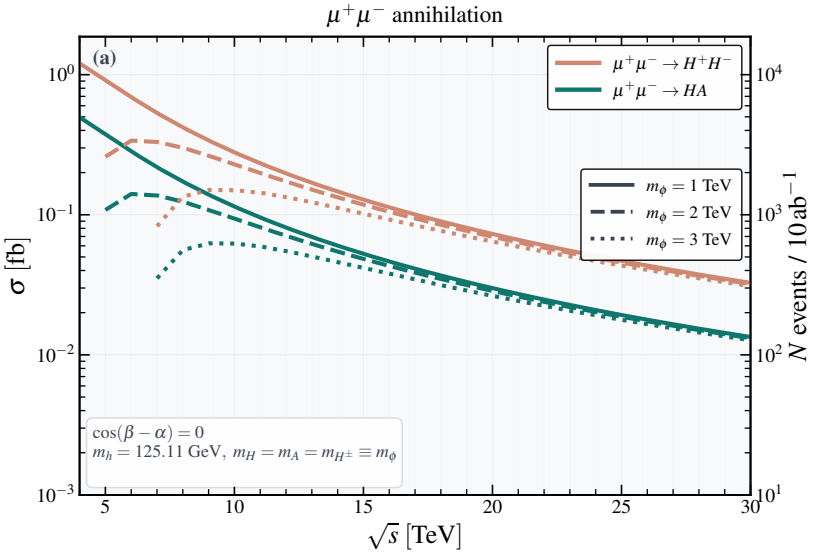
Charged Higgs production

Various direct production modes:

- DY: $\mu^+\mu^- \to H^\pm H^\mp$



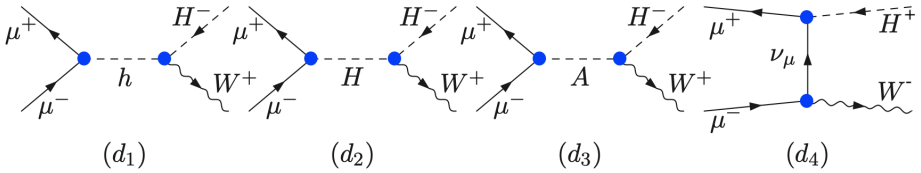


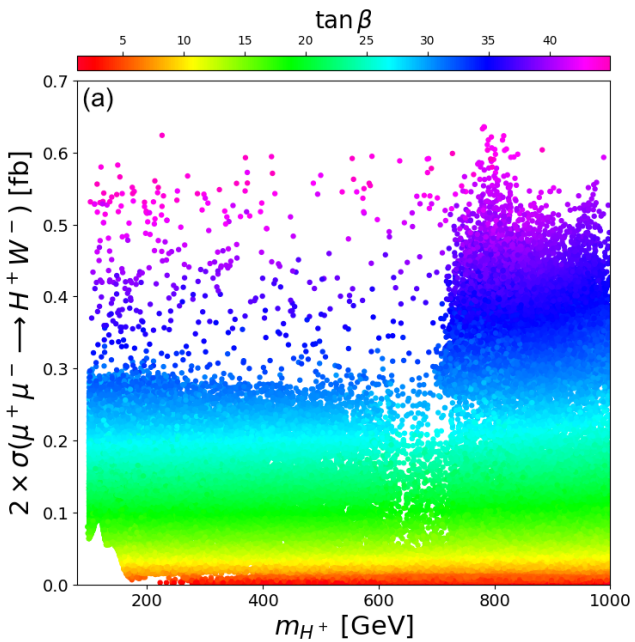


$\sqrt{s} = 3$TeV, 2HDM type X

Charged Higgs production

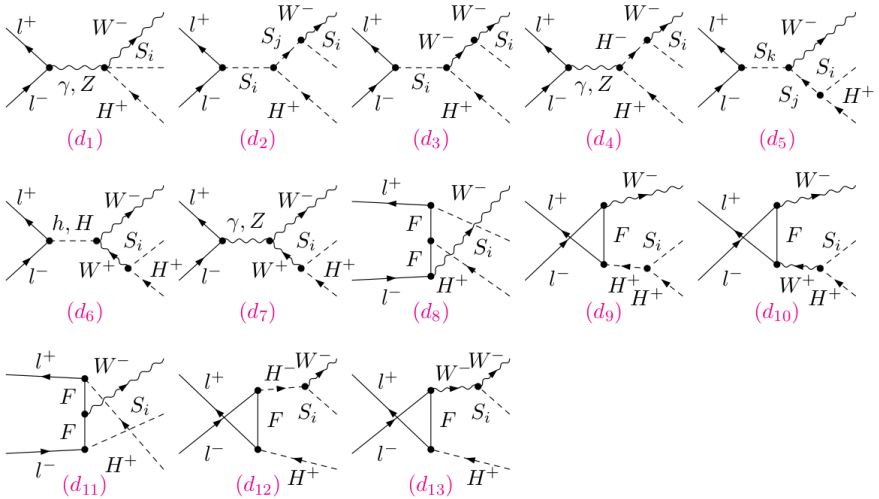
- $\mu^+\mu^- \to W^\pm H^\mp$ offers the possibility of searching for $m_{H^\pm}$ up to $\sqrt{s} - m_W$ in contrast to the pair production which probe up to $\sqrt{s}/2$.
- At e^+e^-, $e^+e^- \to W^\pm H^\mp$ is loop mediated (rather small)
- At MuC: $\mu^+\mu^- \to W^\pm H^\mp$

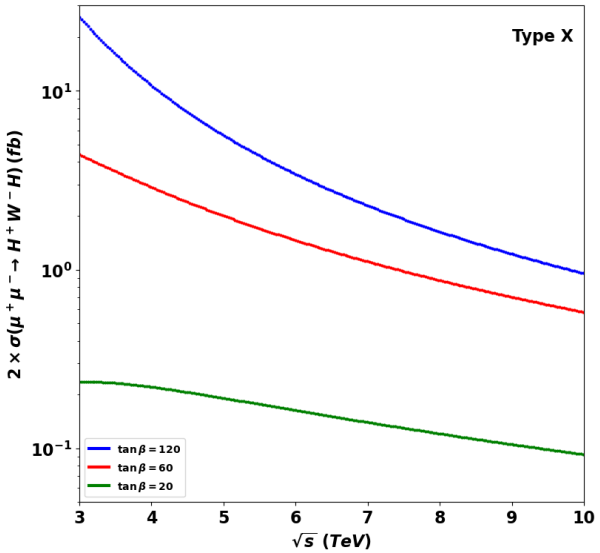


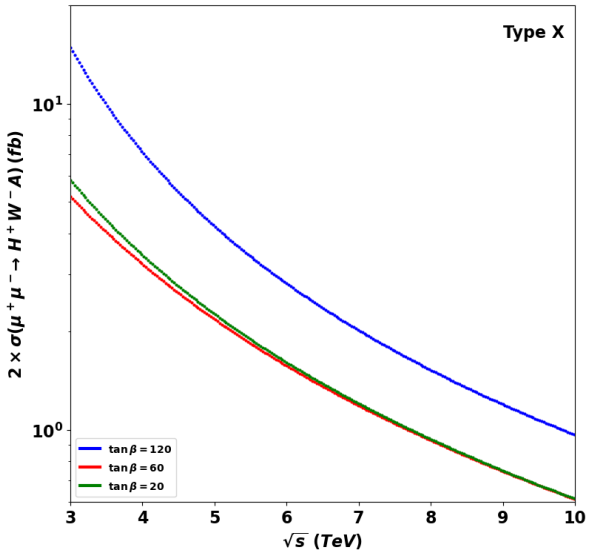


$\sqrt{s} = 3$TeV, 2HDM type X

Charged Higgs production: $\mu^+\mu^- \to W^\pm H^\mp S$

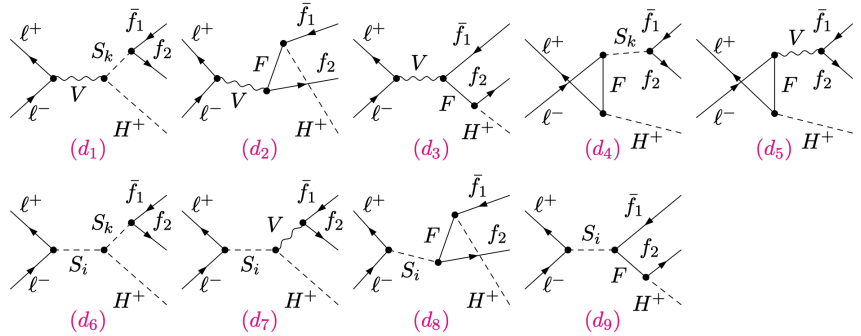


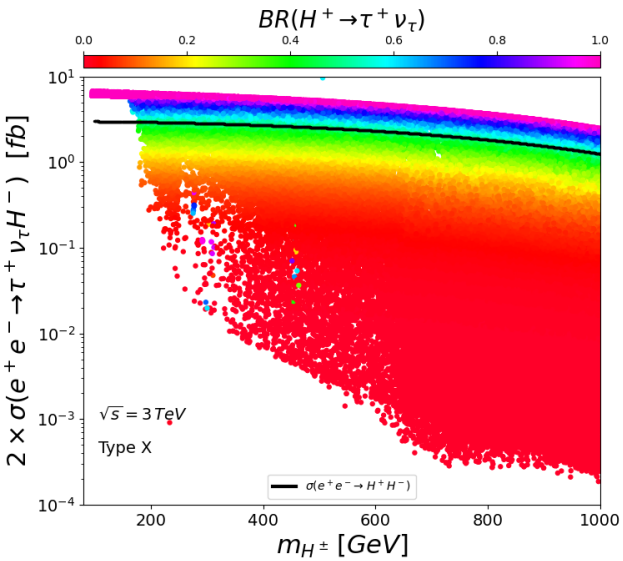


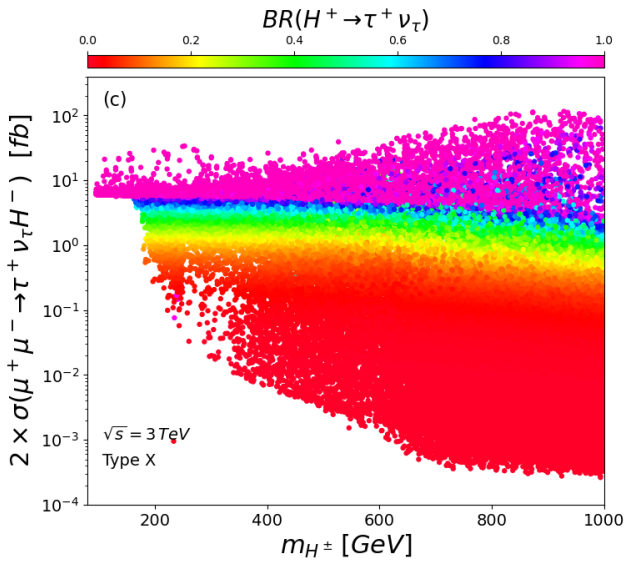


Charged Higgs production

- Production in association with fermions: $\mu^+\mu^- \to H^+\tau\nu$ and $\mu^+\mu^- \to H^+tb$

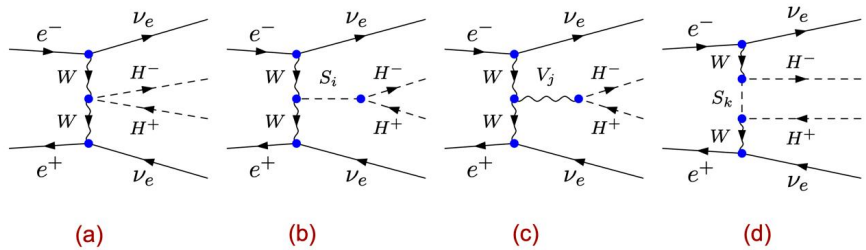


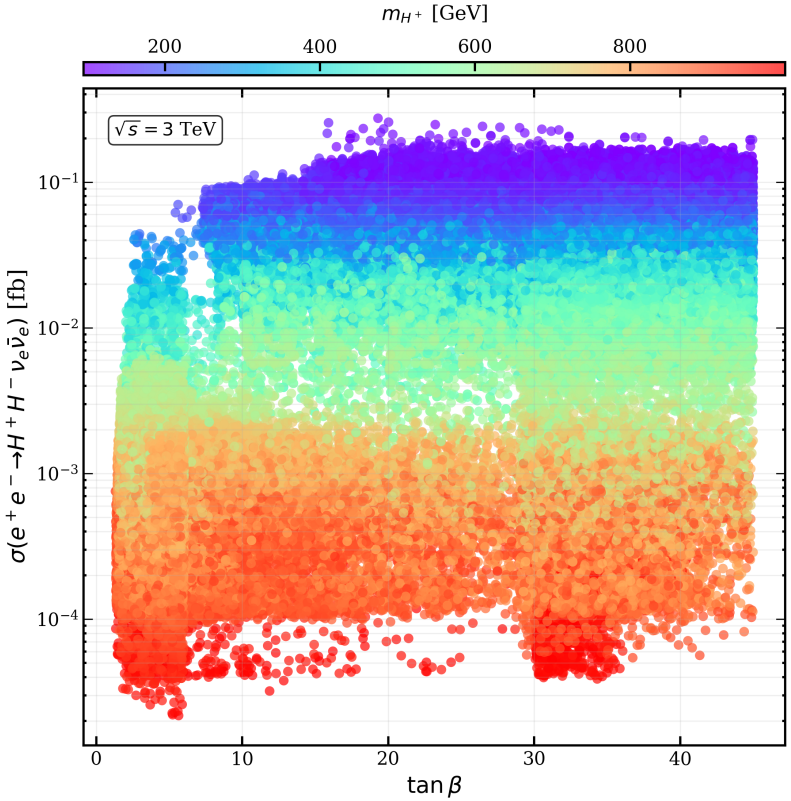




Charged Higgs production

- VBF: $\mu^+\mu^- \to W^*W^* \to \nu\nu H^\pm H^\mp$





Heavy Higgs Resonance effects on SM processes

The parton-level cross section for resonant H/A production is:

$$\sigma(\mu^+\mu^- \to H/A) = \frac{4\pi\Gamma^2_{H/A}\mathrm{Br}(H/A \to \mu^+\mu^-)}{(\hat{s} - m^2_{H/A})^2 + \Gamma^2_{H/A}m^2_{H/A}}$$

- Having $\sqrt{s}$ near H/A resonance, would allow to measure properties of H/A.
- If sufficient precision on beam energy is achieved, one might be able to separate H and A resonances.

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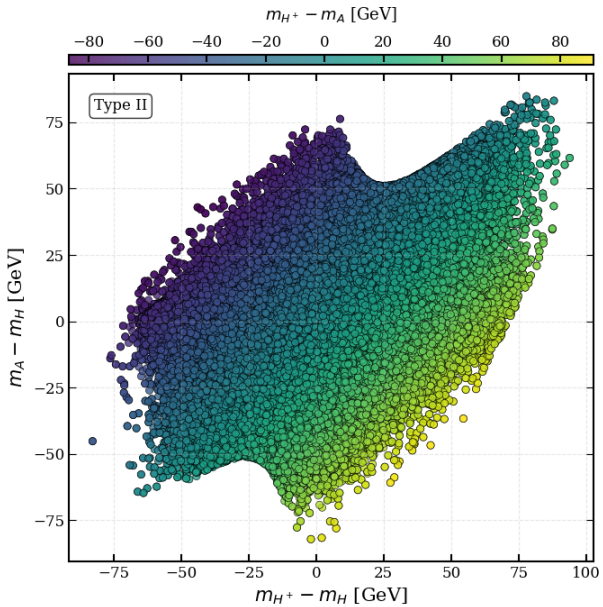
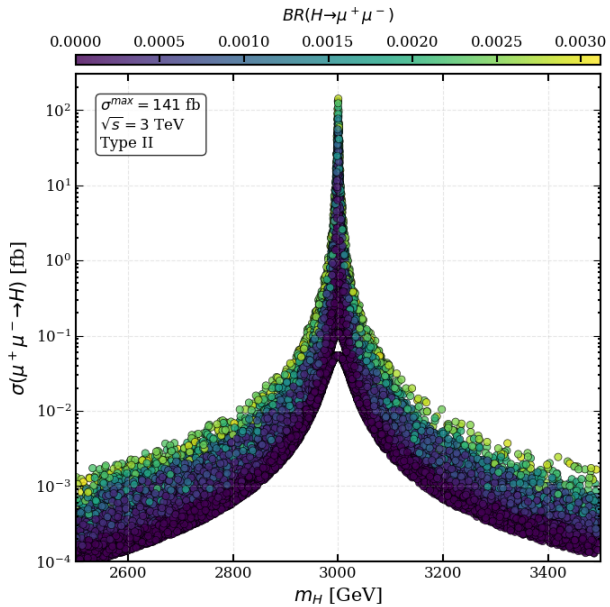
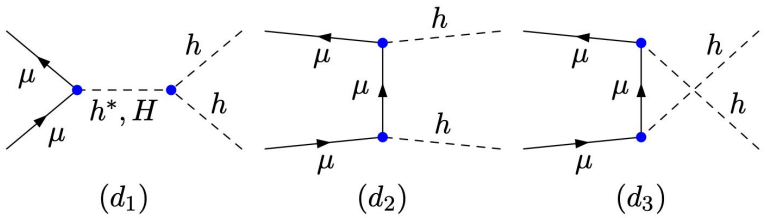
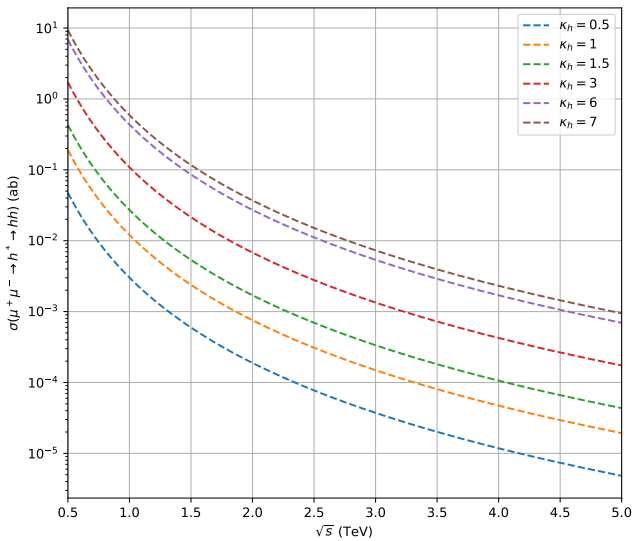


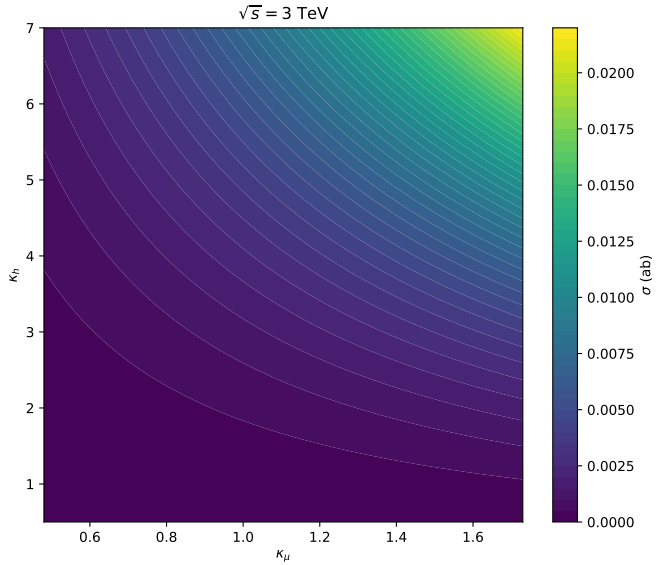


$\mu^+\mu^- \to hh$ in SM

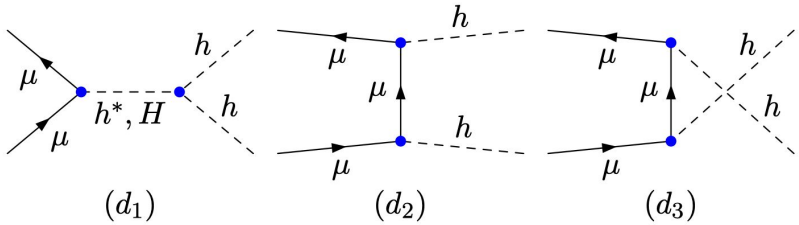


$$hhh = hhh_{SM}\ \kappa_h\ ,\ h\mu^+\mu^- = (h\mu^+\mu^-)_{SM}\ \kappa_\mu$$





$\mu^+\mu^- \to hh$

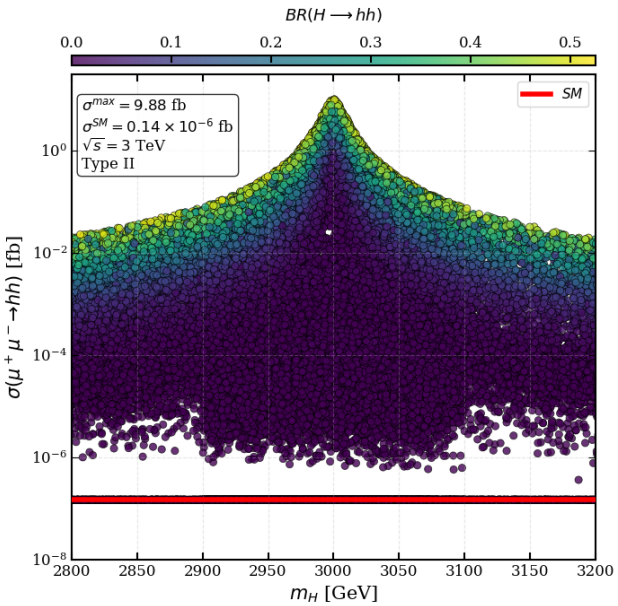


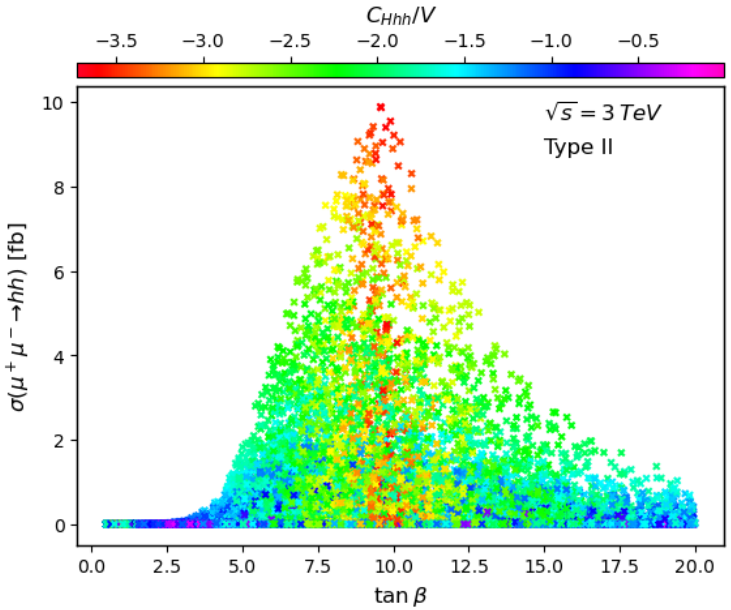
$$\lambda^{2HDM}_{h^0h^0h^0} = \frac{-1}{4v}\left[\frac{(c_{3\alpha-\beta}+3c_{\alpha+\beta})}{s_{2\beta}}m_h^2 - 4c^2_{\beta-\alpha}\frac{c_{\beta+\alpha}}{s_{2\beta}}\widetilde{m}^2_{12}\right] \quad , \quad \widetilde{m}^2_{12} = \frac{m^2_{12}}{s_\beta c_\beta}$$

$$= \frac{-m_h^2}{2v} + \frac{1}{4v}(4\widetilde{m}^2_{12} - 3m_h^2)\delta^2 \quad , \quad \beta-\alpha = \pi/2+\delta$$

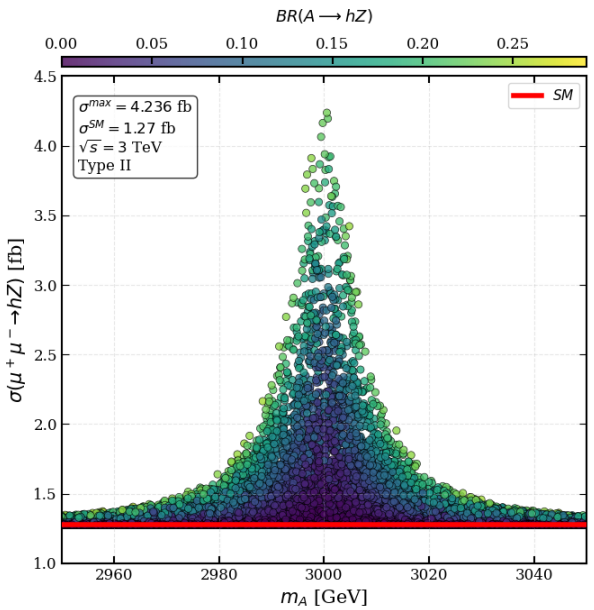
$$\lambda^{2HDM}_{H^0h^0h^0} = \frac{-c_{\beta-\alpha}}{2v}\left[(2m^2_{h^0}+m^2_{H^0})\frac{s_{2\alpha}}{s_{2\beta}} - (3\frac{s_{2\alpha}}{s_{2\beta}}-1)\widetilde{m}^2_{12}\right]$$

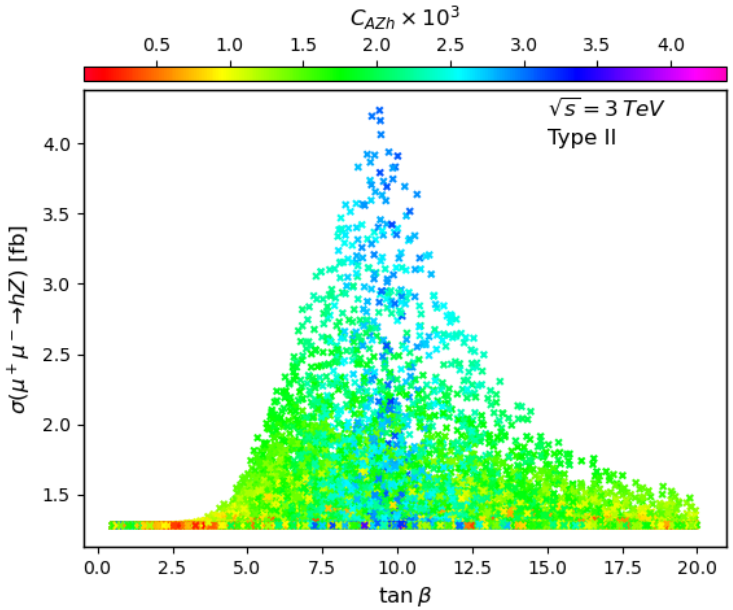
$$= \frac{\delta}{2v}(3\widetilde{m}^2_{12} - 2m_h^2 + 4(\widetilde{m}^2_{12}-m_h^2)\cot(2\beta)\delta + ...)$$


$BR(H \longrightarrow hh)$
0.0
0.1
0.2
0.3
0.4
0.5
SM
$\sigma^{max} = 9.88$ fb
$\sigma^{SM} = 0.14 \times 10^{-6}$ fb
$\sqrt{s} = 3$ TeV
Type II
$\sigma(\mu^+\mu^- \to hh)$ [fb]
m_H [GeV]

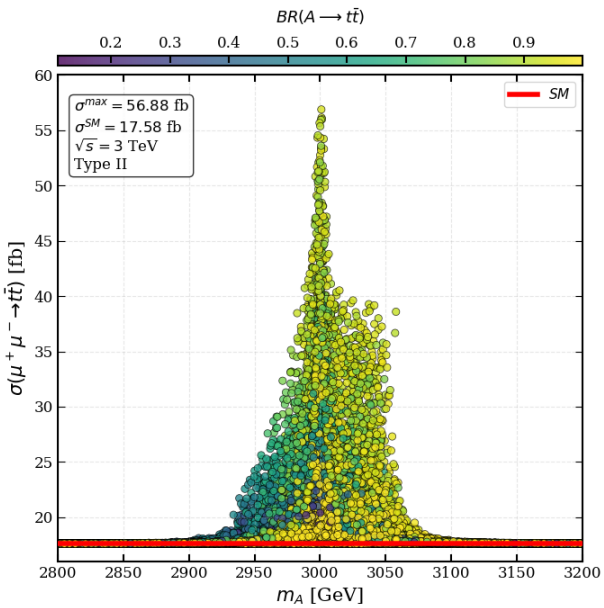

C_{Hhh}/V
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
$\sqrt{s} = 3$ TeV
Type II
$\sigma(\mu^+\mu^- \to hh)$ [fb]
$\tan\beta$

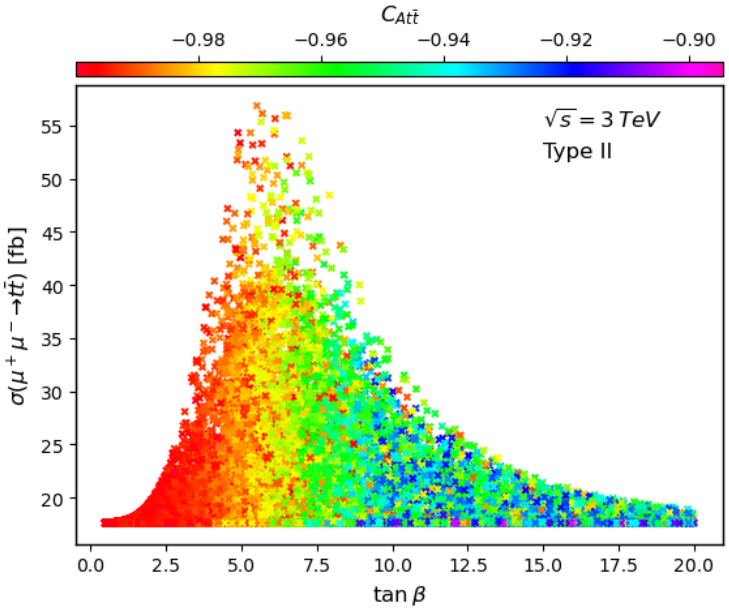
$ZZh \propto s_{\beta-\alpha}$, $AZh \propto c_{\beta-\alpha}$



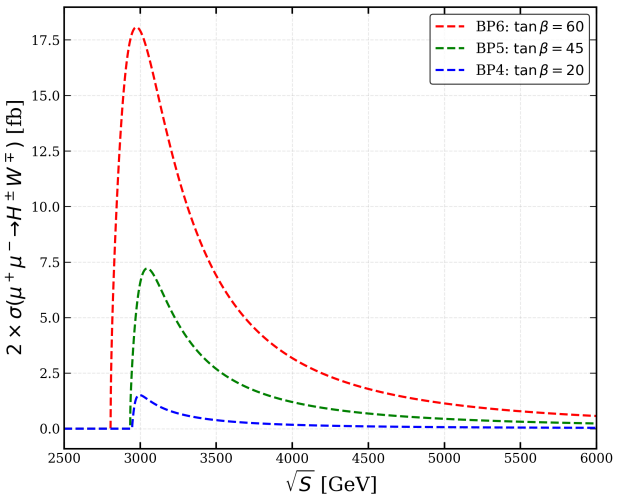


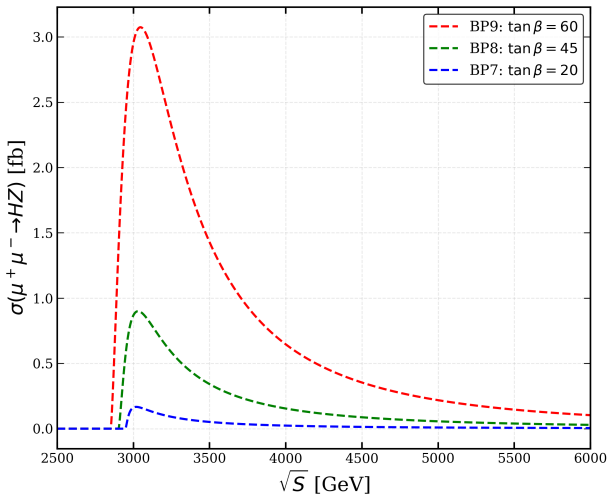
$\mu^+\mu^- \to V^*, S^* \to t\bar{t}$, $V = Z, \gamma$, $S = h, H, A$





$\mu^+\mu^- \to A^*, H^* \to W^\pm H^\mp$, $\mu^+\mu^- \to A^* \to ZH$





Conclusions

- MuC offer new opportunities for direct production of heavy particles (extra Higgses, SUSY particles, new heavy fermions ...)
- Charged Higgs can be copiously produced at the MuC
- Heavy Higgs resonance effects on SM processes: $\mu^+\mu^- \to Zh, t\bar{t}, W^+W^-, hh...$
- At MuC its possible to discriminate between Yukawa textures of the 2HDM