New Physics at Future Lepton Colliders

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based on

arXiv:2005.10289

AC, F. De Lillo, F. Maltoni, L. Mantani, O. Mattelaer, R. Ruiz and X. Zhao

to appear in JHEP

Content

- Introduction
- Physics @ μ Colliders
- SM @ μ Collider
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- BSM @ μ Collider
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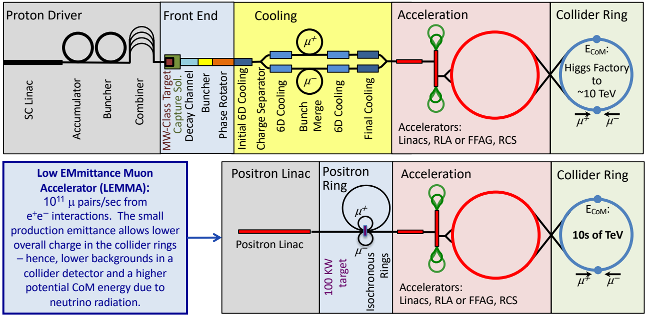
Introduction

μ Collider



J. P. Delahaye *et al.*, arXiv:1901.06150

Muon **A**ccelerator **P**rogram
map.fnal.gov

Low **EM**ittance **M**uon **A**ccelerator
web.infn.it/LEMMA

New results on μ cooling by **MICE** collaboration
Nature 508(2020)53

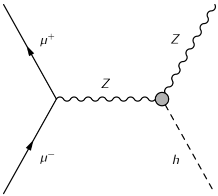
Physics @ μ Collider

Generic Process at μ Collider

Different class of processes are relevant at different $\sqrt{s}$

$\sqrt{s} \lesssim 5$ TeV

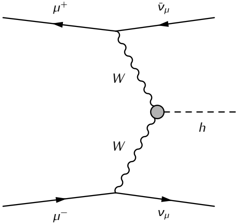
s-channel



$$\sigma \sim \frac{1}{s}$$

$\sqrt{s} \gtrsim 5$ TeV

VBF



$$\sigma \sim \frac{1}{M^2} \log^n \frac{\sqrt{s}}{M}$$

s- and t-channles are sensitive to different new physics

Effective V Approximation

$f_{V_\lambda/\mu}(z, Q^2)$ is the LL likelihood of μ radiating a V with polarization λ and $p_W^z = z\, E_\mu$ and $p_W^T < Q$

$$\sigma(\mu^+\mu^- \xrightarrow{VV\to X} X) \approx f_{V_\lambda/\mu} \otimes f_{V'_{\lambda'}/\mu} \otimes \hat{\sigma}(VV' \to X)$$

$$= \Sigma_{\lambda,\lambda'} \int dz_1 dz_2\; f_{V_\lambda/\mu}(z_1, Q_f) f_{V'_{\lambda'}/\mu}(z_2, Q_f) \hat{\sigma}_{\lambda\lambda'}(s_{VV'})$$

Dawson('84);Kane,Repko,Rolnick('84);Altarelli,Mele,Pirolli('86);Kunszt,Soper('87);+...

$$f_{V_T}(z, Q_f^2, \lambda = \pm) = \frac{C}{16\pi^2} \frac{(g_V \mp g_A)^2 + (g_V \pm g_A)^2(1-z)^2}{z} \log\left(\frac{Q_f^2}{M_V^2}\right)$$

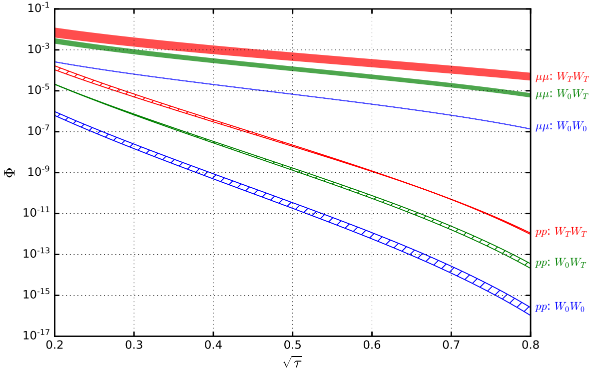
$$f_{V_L}(z, Q_f^2) = \frac{C}{4\pi^2}(g_V^2 + g_A^2)\left(\frac{1-z}{z}\right)$$

Ws PDF: μ vs q

$$\Phi^{pp}_{VV'}(\tau, Q_f) = \frac{1}{1+\delta_{VV'}} \int_\tau^1 \frac{d\xi}{\xi} \int_{\tau/\xi}^1 \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2} \sum_{q,q'}$$

$$(f_{V/q}(z_2) f_{V'/q'}(z_1) f_{q/p}(\xi) f_{q'/p}(\frac{\tau}{\xi z_1 z_2}) + f_{V/q}(z_2) f_{V'/q'}(z_1) f_{q/p}(\frac{\tau}{\xi z_1 z_2}) f_{q'/p}(\xi))$$

$$\Phi^{\mu\mu}_{VV'}(\tau, Q_f, \lambda_1, \lambda_2) \equiv \int_\tau^1 \frac{d\xi}{\xi} f_{V/\mu}(\xi, Q_f^2, \lambda_1)\, f_{V'/\mu}(\frac{\tau}{\xi}, Q_f^2, \lambda_2)$$



$$\sqrt{\tau} = \frac{M}{\sqrt{s}} = \frac{1}{2}$$

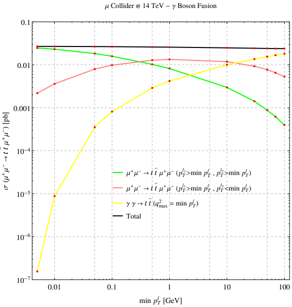
$$\Downarrow$$

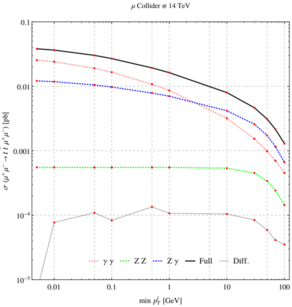
$$\frac{\Phi^{\mu\mu}_{WW}}{\Phi^{pp}_{WW}} \gtrsim 10^4$$

EPA

Neutral VBF production of $t\bar{t}$

$$f_\gamma^{(l)} = \frac{\alpha}{2\pi}\left[2m_l^2 z\left(\frac{1}{q^2_{max}} - \frac{1}{q^2_{min}}\right) + \frac{1+(1-z)^2}{z}\log\frac{q^2_{min}}{q^2_{max}}\right]$$





$$\sigma_{\gamma\gamma}(t\bar{t}) = 2.5\cdot 10^{-2}\ pb \qquad \sigma_{Z/\gamma\, Z/\gamma}(t\bar{t}) = 3.7\cdot 10^{-2}\ pb$$

$$\sigma_{WW}(t\bar{t}) = 2.1\cdot 10^{-2}\ pb$$

with massive μ one can go to $p_T^l \to 0$

PRELIMINARY RESULTS

MadGraph5_aMC@NLO and μ Collider

Generating processes at a μ Collider in MadGraph5_aMC@NLO (e.g. top pair-production)

- ✔ `mu+ mu- > mu+ mu- t t~` , `mu+ mu- > vm vm~ t t~`
- ✔ `a a > t t~ with lpp 4: photon from muon`
- ✔ `w+ w- > t t~ , w from muon` – in development
- ✔ `z z > t t~ , z from muon` – in development

SM @ μ Collider

μ Collider: SM Processes

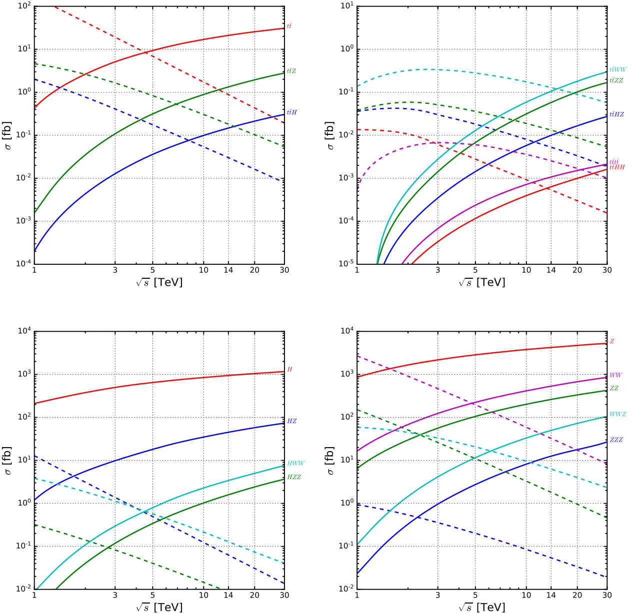
σ [fb]	$\sqrt{s} = 1$ TeV VBF	$\sqrt{s} = 1$ TeV s-ch.	$\sqrt{s} = 3$ TeV VBF	$\sqrt{s} = 3$ TeV s-ch.	$\sqrt{s} = 14$ TeV VBF	$\sqrt{s} = 14$ TeV s-ch.	$\sqrt{s} = 30$ TeV VBF	$\sqrt{s} = 30$ TeV s-ch
$t\bar{t}$	$4.3\cdot10^{-1}$	$1.7\cdot10^{2}$	$5.1\cdot10^{0}$	$1.9\cdot10^{1}$	$2.1\cdot10^{1}$	$8.8\cdot10^{-1}$	$3.1\cdot10^{1}$	$1.9\cdot10^{-1}$
$t\bar{t}Z$	$1.6\cdot10^{-3}$	$4.6\cdot10^{0}$	$1.1\cdot10^{-1}$	$1.6\cdot10^{0}$	$1.3\cdot10^{0}$	$1.8\cdot10^{-1}$	$2.8\cdot10^{0}$	$5.4\cdot10^{-2}$
$t\bar{t}H$	$2.0\cdot10^{-4}$	$2.0\cdot10^{0}$	$1.3\cdot10^{-2}$	$4.1\cdot10^{-1}$	$1.5\cdot10^{-1}$	$3.0\cdot10^{-2}$	$3.1\cdot10^{-1}$	$7.9\cdot10^{-3}$
$t\bar{t}WW$	$4.8\cdot10^{-6}$	$1.4\cdot10^{-1}$	$2.8\cdot10^{-3}$	$3.4\cdot10^{-1}$	$1.1\cdot10^{-1}$	$1.3\cdot10^{-1}$	$3.0\cdot10^{-1}$	$5.8\cdot10^{-2}$
$t\bar{t}ZZ$	$2.3\cdot10^{-6}$	$3.8\cdot10^{-2}$	$1.4\cdot10^{-3}$	$5.1\cdot10^{-2}$	$5.8\cdot10^{-2}$	$1.3\cdot10^{-2}$	$1.7\cdot10^{-1}$	$5.4\cdot10^{-3}$
$t\bar{t}HZ$	$7.1\cdot10^{-7}$	$3.6\cdot10^{-2}$	$3.5\cdot10^{-4}$	$3.0\cdot10^{-2}$	$1.0\cdot10^{-2}$	$5.3\cdot10^{-3}$	$2.7\cdot10^{-2}$	$1.9\cdot10^{-3}$
$t\bar{t}HH$	$7.2\cdot10^{-8}$	$1.4\cdot10^{-2}$	$3.4\cdot10^{-5}$	$6.1\cdot10^{-3}$	$6.4\cdot10^{-4}$	$5.4\cdot10^{-4}$	$1.6\cdot10^{-3}$	$1.5\cdot10^{-4}$
$t\bar{t}t\bar{t}$ (i)	$5.1\cdot10^{-8}$	$5.4\cdot10^{-4}$	$6.8\cdot10^{-5}$	$6.7\cdot10^{-3}$	$1.1\cdot10^{-3}$	$2.5\cdot10^{-3}$	$2.1\cdot10^{-3}$	$1.0\cdot10^{-3}$
H	$2.1\cdot10^{2}$	-	$5.0\cdot10^{2}$	-	$9.4\cdot10^{2}$	-	$1.2\cdot10^{3}$	-
HH	$7.4\cdot10^{-2}$	-	$8.2\cdot10^{-1}$	-	$4.4\cdot10^{0}$	-	$7.4\cdot10^{0}$	-
HHH	$3.7\cdot10^{-6}$	-	$3.0\cdot10^{-4}$	-	$7.1\cdot10^{-3}$	-	$1.9\cdot10^{-2}$	-
HZ	$1.2\cdot10^{0}$	$1.3\cdot10^{1}$	$9.8\cdot10^{0}$	$1.4\cdot10^{0}$	$4.5\cdot10^{1}$	$6.3\cdot10^{-2}$	$7.4\cdot10^{1}$	$1.4\cdot10^{-2}$
HHZ	$1.5\cdot10^{-4}$	$1.2\cdot10^{-1}$	$9.4\cdot10^{-3}$	$3.3\cdot10^{-2}$	$1.4\cdot10^{-1}$	$3.7\cdot10^{-3}$	$3.3\cdot10^{-1}$	$1.1\cdot10^{-3}$
$HHHZ$	$1.5\cdot10^{-8}$	$4.1\cdot10^{-4}$	$4.7\cdot10^{-6}$	$1.6\cdot10^{-4}$	$1.9\cdot10^{-4}$	$1.6\cdot10^{-5}$	$5.1\cdot10^{-4}$	$5.4\cdot10^{-6}$
HWW	$8.9\cdot10^{-3}$	$3.8\cdot10^{0}$	$3.0\cdot10^{-1}$	$1.1\cdot10^{0}$	$3.4\cdot10^{0}$	$1.3\cdot10^{-1}$	$7.6\cdot10^{0}$	$4.1\cdot10^{-2}$
$HHWW$	$7.2\cdot10^{-7}$	$1.3\cdot10^{-2}$	$2.3\cdot10^{-4}$	$1.1\cdot10^{-2}$	$9.1\cdot10^{-3}$	$2.8\cdot10^{-3}$	$2.9\cdot10^{-2}$	$1.2\cdot10^{-3}$
HZZ	$2.7\cdot10^{-3}$	$3.2\cdot10^{-1}$	$1.2\cdot10^{-1}$	$8.2\cdot10^{-2}$	$1.6\cdot10^{0}$	$8.8\cdot10^{-3}$	$3.7\cdot10^{0}$	$2.5\cdot10^{-3}$
$HHZZ$	$2.4\cdot10^{-7}$	$1.5\cdot10^{-3}$	$9.1\cdot10^{-5}$	$9.8\cdot10^{-4}$	$3.9\cdot10^{-3}$	$2.5\cdot10^{-4}$	$1.2\cdot10^{-2}$	$9.5\cdot10^{-5}$
WW	$1.6\cdot10^{1}$	$2.7\cdot10^{3}$	$1.2\cdot10^{2}$	$4.7\cdot10^{2}$	$5.3\cdot10^{2}$	$3.2\cdot10^{1}$	$8.5\cdot10^{2}$	$8.3\cdot10^{0}$
ZZ	$6.4\cdot10^{0}$	$1.5\cdot10^{2}$	$5.6\cdot10^{1}$	$2.6\cdot10^{1}$	$2.6\cdot10^{2}$	$1.8\cdot10^{0}$	$4.2\cdot10^{2}$	$4.6\cdot10^{-1}$
WWZ	$1.1\cdot10^{-1}$	$5.9\cdot10^{1}$	$4.1\cdot10^{0}$	$3.3\cdot10^{1}$	$5.0\cdot10^{1}$	$6.3\cdot10^{0}$	$1.0\cdot10^{2}$	$2.3\cdot10^{0}$
ZZZ	$2.3\cdot10^{-2}$	$9.3\cdot10^{-1}$	$9.6\cdot10^{-1}$	$3.5\cdot10^{-1}$	$1.2\cdot10^{1}$	$5.4\cdot10^{-2}$	$2.7\cdot10^{1}$	$1.9\cdot10^{-2}$

generated with `MadGraph5_aMC@NLO`

μ Collider: SM Processes

heavier final state → larger $\sqrt{s}$ for t-channel to win

possible exceptions, e.g. HZZ vs HWW, ZZZ vs WWZ



μ Collider: SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum C_i \mathcal{O}_i$$

Operators	Limit on C_i TeV^{-2}		Operators	Limit on C_i TeV^{-2}	
	Individual	Marginalised		Individual	Marginalised
$\mathcal{O}_{\varphi D}$	[-0.021,0.0055]	[-0.45,0.50]	$\mathcal{O}_{t\varphi}$	[-5.3,1.6]	[-60,10]
$\mathcal{O}_{\varphi d}$	[-0.78,1.44]	[-1.24,16.2]	$\mathcal{O}_{tB}$	[-7.09,4.68]	–
$\mathcal{O}_{\varphi B}$	[-0.0033,0.0031]	[-0.13,0.21]	$\mathcal{O}_{tW}$	[-0.4,0.2]	[-1.8,0.9]
$\mathcal{O}_{\varphi W}$	[-0.0093,0.011]	[-0.50,0.40]	$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10]	–
$\mathcal{O}_{\varphi WB}$	[-0.0051,0.0020]	[-0.17,0.33]	$\mathcal{O}_{\varphi Q}^{(3)}$	[-0.9,0.6]	[-5.5,5.8]
$\mathcal{O}_{W}$	[-0.18,0.18]	–	$\mathcal{O}_{\varphi t}$	[-6.4,7.3]	[-13,18]
$\mathcal{O}_{\varphi}$	–	–			

current limits taken from Buckley et.al.;Butter et.al.;Ellis,Murphy,Sanz,You;Hartland et.al.

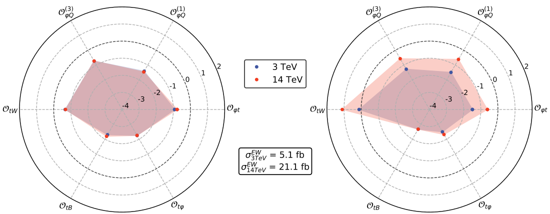
μ Collider: SMEFT

$$\sigma = \sigma_{SM} + \sum c_i\, \sigma^i_{int} + \sum c_{i,j} \sigma^{i,j}_{sq}$$

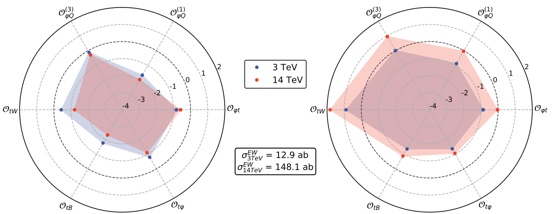
$$r_i = c_i \frac{\sigma^i_{int}}{\sigma_{SM}}$$

$$r_{i,i} = c^2_{i,i} \frac{\sigma^{i,i}_{sq}}{\sigma_{SM}}$$

$VBF \to t\bar{t}$

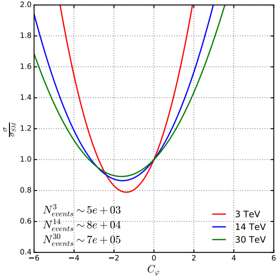


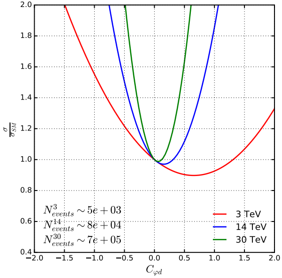
$VBF \to t\bar{t}H$



μ Collider: SMEFT

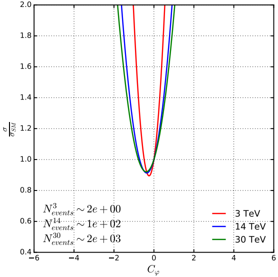
HH

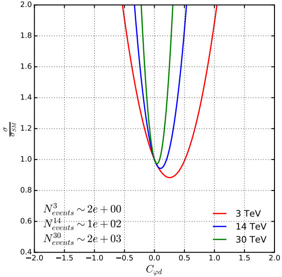




not much gain from $\sqrt{s} = 14 \to 30$ TeV

HHH

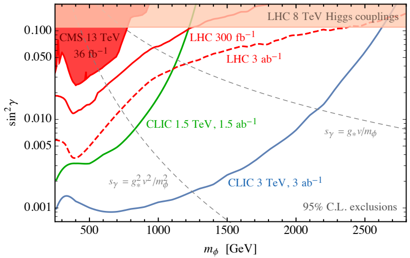


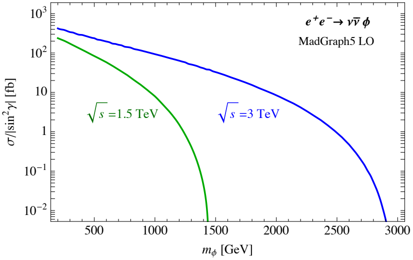


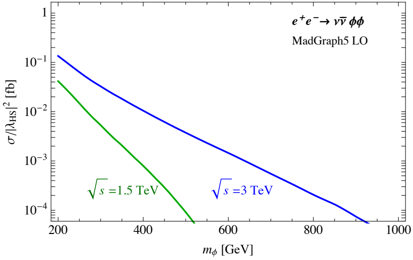
$\sigma(HHH)$ too low @ 3 TeV

BSM @ μ Collider

BSM @ High-Energy Lepton Collider



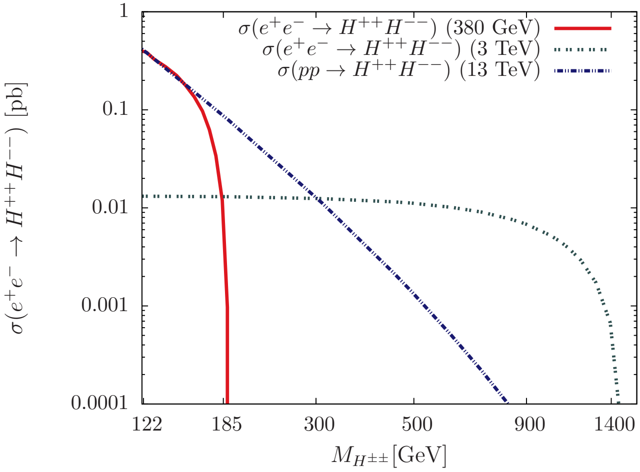




D.Buttazzo, D.Redigolo, F.Sala and A.Tesi
JHEP **11** (2018), 144

Only Low-Energy Results
($\sqrt{s} \leq 3$ TeV)

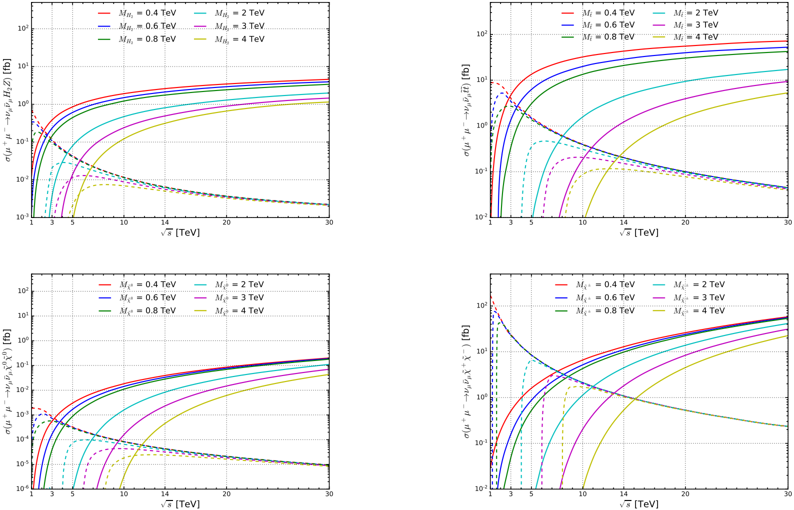
BSM @ High-Energy Lepton Collider



P.Agrawal, M.Mitra, S.Niyogi, S.Shil and M.Spannowsky
Phys. Rev. D **98** (2018) no.1, 015024

Which BSM Model?

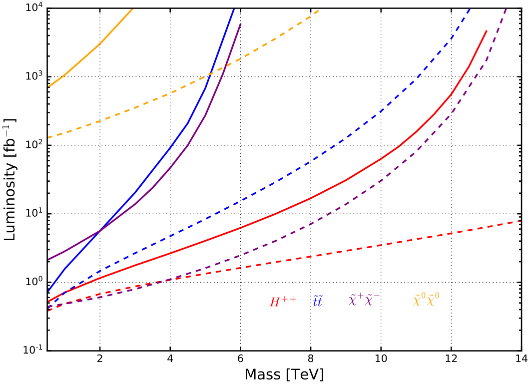
VBF for various BSM Models



$$\frac{\sigma^{VBF}}{\sigma^{s-ch.}} \sim \frac{s}{m_X^2} \log^2 \frac{s}{m_V^2} \log \frac{s}{m_X^2}$$

New Physics Reach (via VBF) @ μ Collider

$$\mathcal{L} \equiv \frac{\#\,events}{\sigma}$$



Luminosity required for 25 events, with assumed zero background

Conclusions

- proposed FC are either precision or discovery machines
- multi-TeV μ-collider $\rightarrow$ VV collider
- for SM/EFT μ-collider is a precision machine
- multi-TeV μ-collider is suitable for BSM discovery
- needs R & D from THEO and EXP

Thanks

Backup Slides

SM + Singlet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\sigma\,\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\,\sigma^2 - \frac{\lambda_\sigma}{4!}\sigma^4 - \frac{\kappa_\sigma}{2}\sigma^2\,\Phi^\dagger\Phi.$$

$$\langle\sigma\rangle = v_s$$

$$\lambda_{hhh} = -\frac{3m_h^2}{v\,v_s}(v_s\cos^3\theta + v\sin^3\theta)$$

$$\lambda_{sss} = \frac{3m_s^2}{v\,v_s}(v\cos^3\theta - v_s\sin^3\theta)$$

$$\lambda_{hss} = -\frac{(m_h^2 + 2m_s^2)}{2v\,v_s}\sin 2\theta(v\cos\theta + v_s\sin\theta)$$

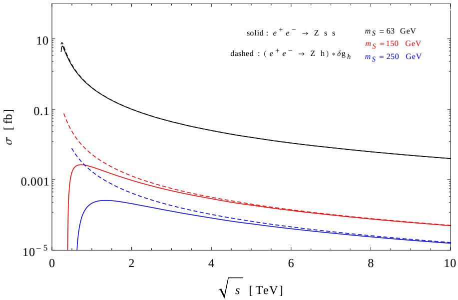
$$\lambda_{hhs} = \frac{(2m_h^2 + m_s^2)}{2v\,v_s}\sin 2\theta(v_s\cos\theta - v\sin\theta)$$

SM + Singlet: Inert Pair Production vs. Loop Corrections

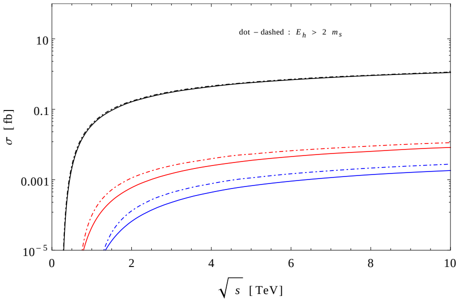
$$\delta g_h = -\frac{\kappa_\sigma^2 v^2}{16\pi^2 m_h^2}\left(1 - 4m_S^2 \frac{\tan^{-1}\sqrt{\frac{m_h^2}{(4m_S^2 - m_h^2)}}}{\sqrt{m_h^2(4m_S^2 - m_h^2)}}\right)$$

Heinemann,Nir, Phys.Usp. 62 (2019) no.9, 920-930

s-channel



VBF



2HDM

$$V = \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 + \left(\mu_3 \Phi_1^\dagger \Phi_2 + \text{H.c.} \right) + \lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left(\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{H.c.} \right)$$
$$+ \Phi_1^\dagger \Phi_1 \left(\lambda_6 \left(\Phi_1^\dagger \Phi_2 \right) + \text{H.c.} \right) + \Phi_2^\dagger \Phi_2 \left(\lambda_7 \left(\Phi_1^\dagger \Phi_2 \right) + \text{H.c.} \right)$$

$$\Phi_1 \equiv \begin{pmatrix} -ih_1^+ \\ \frac{h_1^0 + ia_1 + v}{\sqrt{2}} \end{pmatrix} \quad \text{and} \quad \Phi_2 \equiv \begin{pmatrix} h_2^+ \\ \frac{h_2^0 + ia_2}{\sqrt{2}} \end{pmatrix}$$

$$\begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

where h is identified as the observed, SM-like Higgs boson with $m_h \approx 125$ GeV and H is heavier with $m_H > m_h$

GM Model

$$\Phi = \begin{pmatrix} \varphi^{0*} & \varphi^{+} \\ -\varphi^{+*} & \varphi^{0} \end{pmatrix} \quad , \quad X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

$$\begin{aligned} V(\Phi, X) = & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) \\ & + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\ & - M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab} \end{aligned}$$

Custodial Limit

$$\langle\chi^0\rangle = \langle\xi^0\rangle \equiv v_X$$

$$(\sqrt{2}G_F)^{-1} = v_\varphi^2 + 8v_X^2$$

μ Collider: Pros and Cons

μ vs. e
(circular collider)

Pros 👍

- ✔ reduced synchrotron radiation
- ✔ increased $\mathcal{L}$
- ✔ cool physics

Cons 👎

- ✘ μ decay
- ✘ ν radiation
- ✘ lots of R&D (is it a real cons)