BSM at Future μ Collider

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Winter 2021 topical meeting on VBS: VBS at Snowmass

January 29th 2021

based on

arXiv:2005.10289

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

JHEP 09 (2020) 080

arXiv:2010.02597

P. Bandyopadhyay, AC

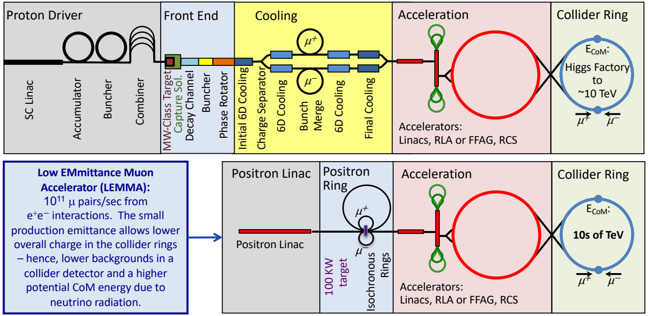
Phys.Rev.D 103 (2021) 1

Content

- Introduction
- SM @ μ Collider
- BSM @ μ Collider
  - New Physics Reach @ μ Collider
- Simple SM Extension @ μ Collider
- Conclusions

Introduction

μ Collider



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

Muon Accelerator Program
map.fnal.gov

Low EMittance Muon Accelerator
web.infn.it/LEMMA

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

μ Collider: Interest is Growing...

- 2101.10334
- 2101.10469
- 2101.04956
- 2012.14818
- 2012.03928
- 2012.02769
- 2011.03055
- 2009.11287
- 2008.12204
- 2007.15684
- 2007.14300
- 2006.16277
- 2003.13628
- 1910.04170

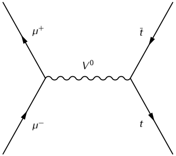
...definitely a non-exhaustive list...

Generic Process at μ Collider

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

$\sqrt{s} \lesssim 5$ TeV

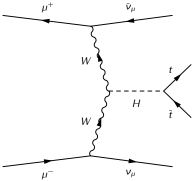
s-channel



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

$\sqrt{s} \gtrsim 5$ TeV

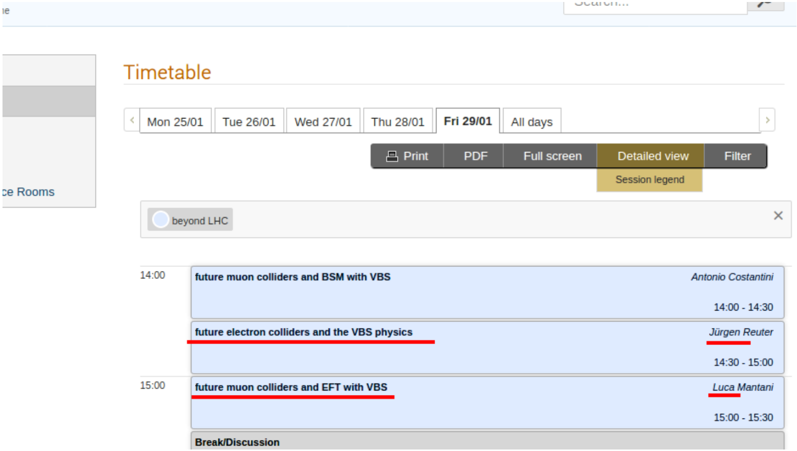
VBF



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

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

more details in Jürgen's and Luca's Talk!



SM @ μ Collider

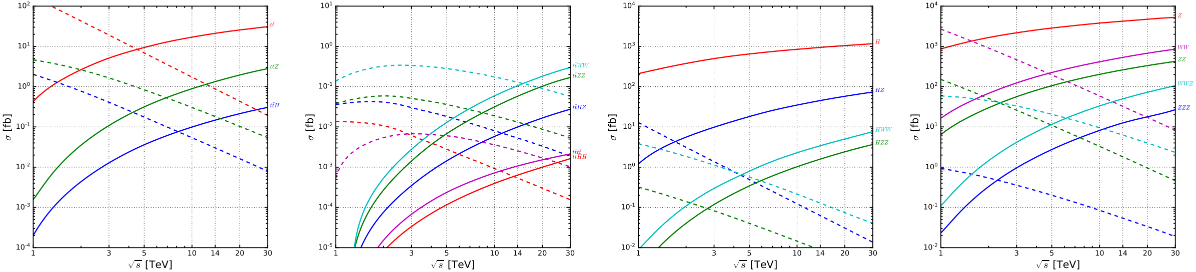
μ Collider: SM Processes

$$\mathrm{VBF} \equiv W^+W^- \to X \qquad \mathrm{s-ch.} \equiv \mu^+\mu^- \to X$$

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

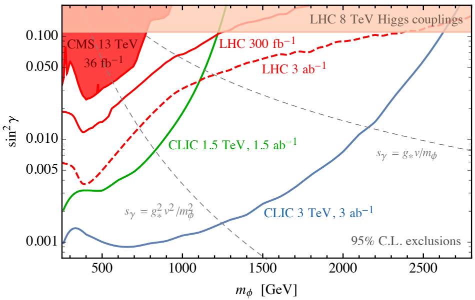


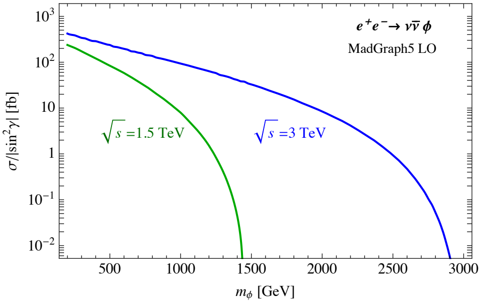
heavier final state → larger $\sqrt{s}$ for t-channel to win

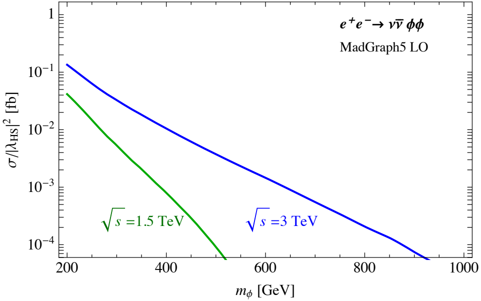
possible exceptions, e.g. HZZ vs HWW, ZZZ vs WWZ

BSM @ μ Collider

BSM @ High-Energy Lepton Collider





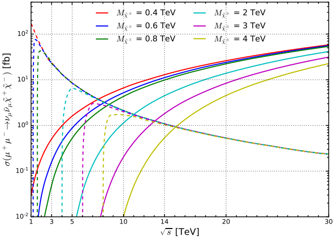


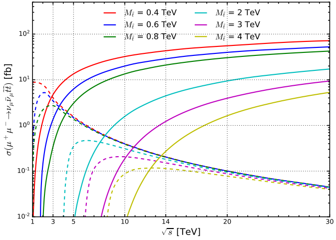
D.Buttazzo, D.Redigolo, F.Sala and A.Tesi
JHEP **11** (2018), 144

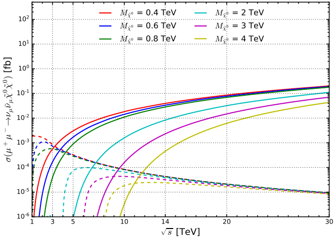
Only Low-Energy Results
($\sqrt{s} \leq 3$ TeV)

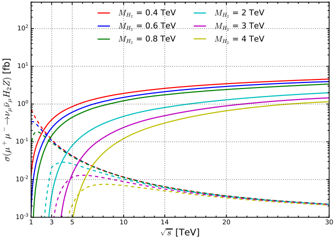
Which BSM Model?

VBF for various BSM Models



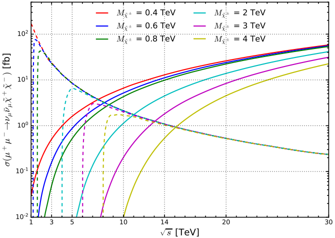


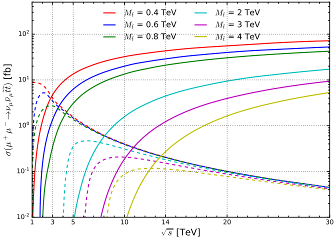


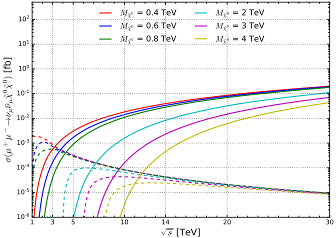


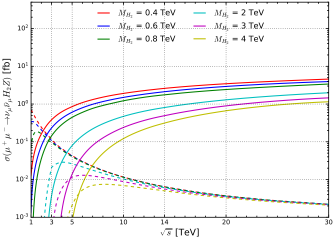
results are qualitatively similar for SM+Singlet, 2HDM, GM Model, VLQ Models, MSSM, Heavy Neutrino Models, etc.

VBF for various BSM Models









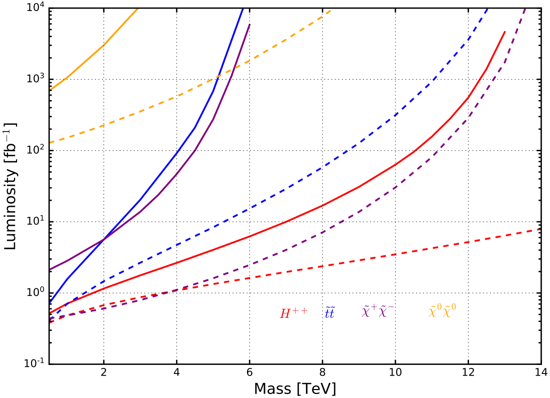
$$\frac{\sigma^{VBF}}{\sigma^{s-ch.}} \sim \frac{s}{m_X^2} \log^2 \frac{s}{m_V^2} \log \frac{s}{m_X^2}$$

New Physics Reach (via VBF) @ μ Collider

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

dashed lines → $\sqrt{s} = 30$ TeV

solid lines → $\sqrt{s} = 14$ TeV



Luminosity required for 25 events, with assumed zero background

Simple SM Extension @ μ Collider

SM + Complex Triplet

Scalar Sector

$$\Phi = \begin{pmatrix} \varphi^+ \\ \phi_0 \end{pmatrix} \qquad T = \frac{1}{\sqrt{2}} \begin{pmatrix} t_0 & \sqrt{2}\, t_1^+ \\ \sqrt{2}\, t_2^- & -t_0 \end{pmatrix}$$

Massive Vector Bosons

$$m_W = \frac{1}{2} g_2 \sqrt{v^2 + 4v_T^2} \qquad m_Z = \frac{1}{2} \sqrt{\left(g_1^2 + g_2^2\right)} v$$

$$\Downarrow$$

$$v_T \lesssim 5\ \text{GeV}$$

SM + Complex Triplet: Scalar Spectrum

$$V = V_1 + V_2$$

$$\begin{aligned} V_1 &= \mu^2 \Phi^\dagger \Phi + \frac{\lambda_H}{2} \Phi^\dagger \Phi \Phi^\dagger \Phi + m_T^2 \,\mathtt{tr}[T^\dagger T] + \frac{\lambda_T}{2} \mathtt{tr}[T^\dagger T] \mathtt{tr}[T^\dagger T] + \frac{\lambda_{T'}}{2} \mathtt{tr}[T^\dagger T T^\dagger T] \\ &\quad + \frac{\lambda_{HT}}{2} \Phi^\dagger \Phi \,\mathtt{tr}[T^\dagger T] + \kappa_{HT} \left(\mathtt{tr}[\Phi^\dagger T \Phi] + \mathtt{h.c.} \right) \end{aligned}$$

$$\begin{aligned} V_2 &= \Big(m_T'^2 \,\mathtt{tr}[T\, T] + \frac{\lambda_T^{(2)}}{2} \mathtt{tr}[T\, T\, T\, T] + \frac{\lambda_T^{(3)}}{2} \mathtt{tr}[T^\dagger T\, T\, T] \\ &\quad + \frac{\lambda_{HT}^{(2)}}{2} \Phi^\dagger \Phi \,\mathtt{tr}[T\, T] \Big) + \mathtt{h.c.} \end{aligned}$$

SM + Complex Triplet: Scalar Spectrum

After EWSB

$$m_{a_P}^2 = \kappa_{HT}\frac{v^2}{2v_T} - 4m_T'^2 - \lambda_{HT}^{(2)}v^2 - (4\lambda_T^{(2)} + \lambda_T^{(3)})v_T^2 \qquad \leftarrow \text{pure state}$$

$$m_{h_T^\pm}^2 = \kappa_{HT}\left(\frac{v^2}{2\,v_T} + 2\,v_T\right)$$

$$m_{h_P^\pm}^2 = \kappa_{HT}\frac{v^2}{2\,v_T} - 4m_T'^2 - \lambda_{HT}^{(2)}v^2 - (2\lambda_T^{(2)} + \lambda_T^{(3)} + \frac{\lambda_{T'}}{2})v_T^2 \qquad \leftarrow \text{pure state}$$

$$m_{h_D}^2 = \lambda_H v^2 - 2\kappa_{HT}\,v_T + 2\left(\lambda_{HT} + 2\lambda_{HT}^{(2)} - 2\lambda_H\right)v_T^2$$

$$m_{h_T}^2 = \frac{\kappa_{HT}}{2v_T}\left(v^2 + 4v_T^2\right) + \left(4\lambda_H - 2\lambda_{HT} - 4\lambda_{HT}^{(2)} + \lambda_T + \frac{\lambda_{T'}}{2} + 2(\lambda_T^{(2)} + \lambda_T^{(3)})\right)v_T^2$$

Physical Pseudoscalar: Features

a_P is a pure pseudoscalar state

$\Downarrow$

no interaction with fermions (triplet!)

$\Downarrow$

no loop-level coupling with massless gauge bosons

pseudoscalar nature

$\Downarrow$

no interaction with massive gauge bosons

$\Downarrow$

pNG Dark Matter candidate

3-point vertices are $a_P W^{\pm} h_P^{\mp}$, $a_P a_P h_{D/T}$, ... (purity must be conserved in each vertex)

pNG Dark Matter: other Examples

Probing pseudo-Goldstone dark matter at the LHC #1

Katri Huitu (Helsinki U.), Niko Koivunen (Helsinki U.), Oleg Lebedev (Helsinki U.), Subhadeep Mondal (Helsinki U.), Takashi Toma (Kyoto U.) (Dec 14, 2018)

Published in: *Phys.Rev.D* 100 (2019) 1, 015009 • e-Print: 1812.05952 [hep-ph]

pdf DOI cite 23 citations

Is a Miracle-less WIMP Ruled Out?

Jason Arakawa, Tim M.P. Tait (Jan 26, 2021)

e-Print: 2101.11031 [hep-ph]

pdf cite

Direct and indirect probes of Goldstone dark matter #1

Tommi Alanne (Heidelberg, Max Planck Inst.), Matti Heikinheimo (Helsinki U. and Helsinki Inst. of Phys.), Venus Keus (Helsinki U. and Helsinki Inst. of Phys.), Niko Koivunen (Helsinki U. and Helsinki Inst. of Phys.), Kimmo Tuominen (Helsinki U. and Helsinki Inst. of Phys.) (Dec 14, 2018)

Published in: *Phys.Rev.D* 99 (2019) 7, 075028 • e-Print: 1812.05996 [hep-ph]

pdf DOI cite 15 citations

Pseudo-Nambu-Goldstone dark matter and two-Higgs-doublet models

Xue-Min Jiang (Zhongshan U. and Yunnan U.), Chengfeng Cai (Zhongshan U.), Zhao-Huan Yu (Zhongshan Yu-Pan Zeng (Zhongshan U.), Hong-Hao Zhang (Zhongshan U.) (Jul 22, 2019)

Published in: *Phys.Rev.D* 100 (2019) 7, 075011 • e-Print: 1907.09684 [hep-ph]

pdf DOI cite 7 citations

Pseudo-Nambu-Goldstone dark matter from gauged $U(1)_{B-L}$ symmetry #1

Yoshihiko Abe (Kyoto U.), Takashi Toma (McGill U.), Koji Tsumura (Kyushu U.) (Jan 12, 2020)

Published in: *JHEP* 05 (2020) 057 • e-Print: 2001.03954 [hep-ph]

pdf DOI cite 7 citations

Pseudo Nambu-Goldstone Dark Matter: Examples of Vanishing Direct Detection Cross Section #1

Dimitrios Karamitros (NCBJ, Warsaw) (Jan 28, 2019)

Published in: *Phys.Rev.D* 99 (2019) 9, 095036 • e-Print: 1901.09751 [hep-ph]

pdf DOI cite

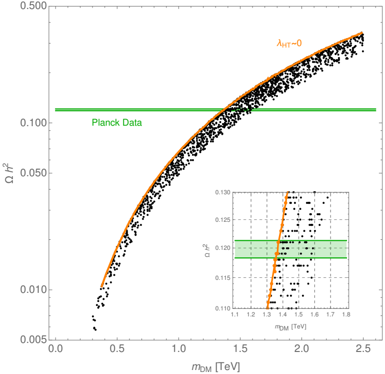
Global fit of pseudo-Nambu-Goldstone Dark Matter #1

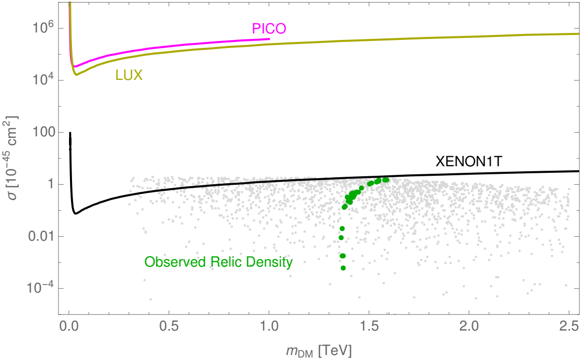
Chiara Arina (Louvain U., CP3), Ankit Beniwal (Louvain U., CP3), Céline Degrande (Louvain U., CP3), Jan Heisig (Louvain U., CP3), Andre Scaffidi (Melbourne U.) (Dec 9, 2019)

Published in: JHEP04 (2020) 015, *JHEP* 04 (2020) 015 • e-Print: 1912.04008 [hep-ph]

pdf DOI cite 15 citations

Dark Matter and Collider Phenomenology

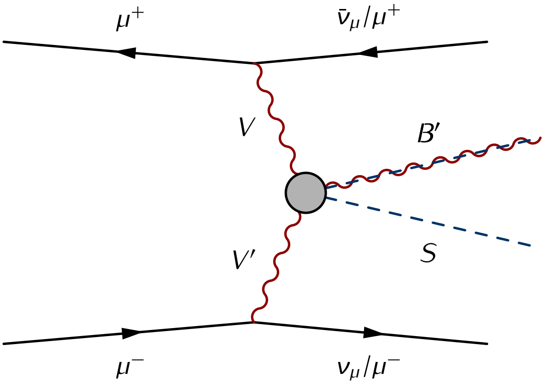




generated with MadDM

$$m_{h_D} = 125.18 \pm 0.16 \text{ GeV} \qquad |\mathcal{R}^S_{11}| \geq 99/100$$

Dark Matter and Collider Phenomenology



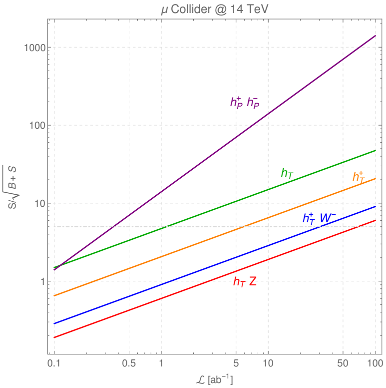
S is a scalar boson, B' can be either a scalar or a massive vector boson, V, V' are vector bosons

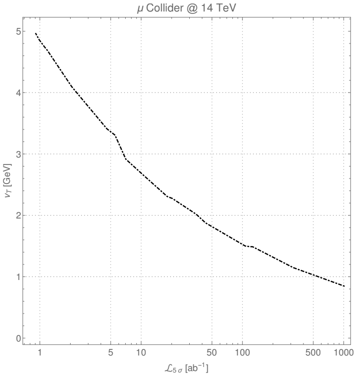
Dark Matter and Collider Phenomenology

Production modes	σ [fb]			
	$\sqrt{s} = 14$ TeV		$\sqrt{s} = 30$ TeV	
	BP1	BP2	BP1	BP2
$\mu^+\mu^- \to h_T\ \nu_\mu\bar{\nu}_\mu$	$1.8 \cdot 10^{-2}$	$6.2 \cdot 10^{-1}$	$2.9 \cdot 10^{-2}$	$9.6 \cdot 10^{-1}$
$\mu^+\mu^- \to h_T^+\ \mu^-\bar{\nu}_\mu$	$5.3 \cdot 10^{-3}$	$1.8 \cdot 10^{-1}$	$8.4 \cdot 10^{-3}$	$2.8 \cdot 10^{-1}$
$\mu^+\mu^- \to h_T\ h_T\ \nu_\mu\bar{\nu}_\mu$	$1.9 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$4.8 \cdot 10^{-2}$	$5.1 \cdot 10^{-2}$
$\mu^+\mu^- \to a_P\ a_P\ \nu_\mu\bar{\nu}_\mu$	$1.8 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$4.7 \cdot 10^{-2}$	$5.0 \cdot 10^{-2}$
$\mu^+\mu^- \to h_T^+\ h_T^-\ \nu_\mu\bar{\nu}_\mu$	$1.3 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$3.4 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$
$\mu^+\mu^- \to h_P^+\ h_P^-\ \nu_\mu\bar{\nu}_\mu$	$1.3 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$3.4 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$
$\mu^+\mu^- \to h_D\ h_T\ \nu_\mu\bar{\nu}_\mu$	$1.6 \cdot 10^{-4}$	$5.7 \cdot 10^{-3}$	$3.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$
$\mu^+\mu^- \to h_D\ h_T^+\ \mu^-\bar{\nu}_\mu$	$4.8 \cdot 10^{-5}$	$1.6 \cdot 10^{-3}$	$1.1 \cdot 10^{-4}$	$3.8 \cdot 10^{-3}$
$\mu^+\mu^- \to h_T\ Z\ \nu_\mu\bar{\nu}_\mu$	$7.7 \cdot 10^{-4}$	$2.6 \cdot 10^{-2}$	$1.7 \cdot 10^{-3}$	$5.6 \cdot 10^{-2}$
$\mu^+\mu^- \to h_T\ W^+\mu^-\bar{\nu}_\mu$	$4.1 \cdot 10^{-4}$	$1.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-3}$	$3.4 \cdot 10^{-2}$
$\mu^+\mu^- \to h_T^+\ Z\ \mu^-\bar{\nu}_\mu$	$1.4 \cdot 10^{-4}$	$4.8 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	$1.2 \cdot 10^{-2}$
$\mu^+\mu^- \to h_T^+\ W^-\ \nu_\mu\bar{\nu}_\mu$	$9.7 \cdot 10^{-4}$	$3.2 \cdot 10^{-2}$	$1.9 \cdot 10^{-3}$	$6.1 \cdot 10^{-2}$

generated with `MadGraph5_aMC@NLO`

Dark Matter and Collider Phenomenology





background is $VBF_{W^+W^-}$ or $VBF_{W^\pm Z}$ or $VBF_{W^+W^-Z}$
with
$M_{W^+W^-} = m_{h_T}$ or $M_{W^\pm Z} = m_{h_T^\pm}$

exclusion plot
from VBF production of h_T

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

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

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

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

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

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

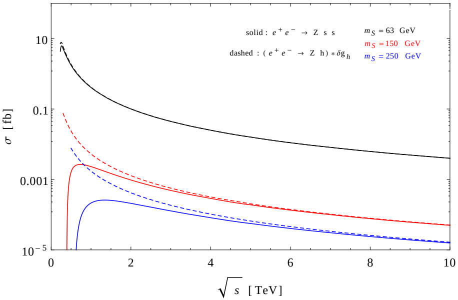
$$\lambda_{hhs} = \frac{(2m_h^2 + m_s^2)}{2v\,v_s}\sin 2\theta(v_s\cos\theta - v\sin\theta)$$

SM + Singlet: Inert Pair Production vs. Loop Corrections

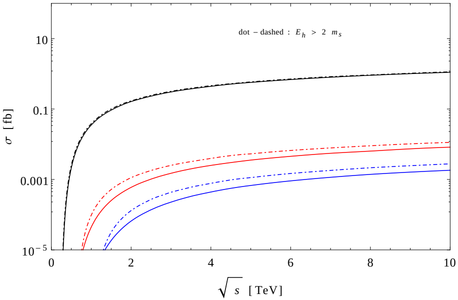
$$\delta g_h = -\frac{\kappa_\sigma^2 v^2}{16\pi^2 m_h^2}\left(1 - 4m_S^2 \frac{\tan^{-1}\sqrt{\frac{m_h^2}{(4m_S^2 - m_h^2)}}}{\sqrt{m_h^2(4m_S^2 - m_h^2)}}\right)$$

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 $\mathscr{L}$
- ✔ cool physics

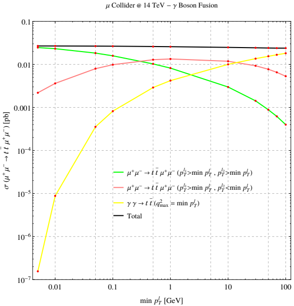
Cons 👎

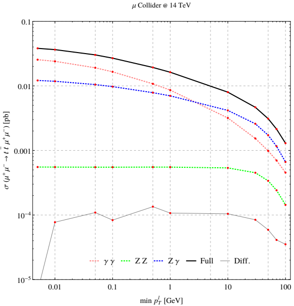
- ✘ μ decay
- ✘ ν radiation
- ✘ lots of R&D (true cons?)

EPA

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

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





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

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

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

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

CTSM: Mass Matrices

$$m^S = \begin{pmatrix} \lambda_H v^2 & (\lambda_{HT} + 2\lambda_{HT}^{(2)})\frac{v\, v_T}{2} - \kappa_{HT}\, v \\ \cdot & \frac{1}{2v_T}(\kappa_{HT}\, v^2 + (2\lambda_T + \lambda_{T'} + 2(\lambda_T^{(2)} + \lambda_T^{(3)}))v_T^3) \end{pmatrix}$$

$$m^P = \begin{pmatrix} \frac{1}{4}v^2\, \xi_Z (g_2 \cos\theta_w + g_1 \sin\theta_w)^2 & 0 \\ \cdot & \kappa_{HT}\frac{v^2}{2v_T} - 4m_T'^2 - \lambda_{HT}^{(2)} v^2 - (4\lambda_T^{(2)} + \lambda_T^{(3)})v_T^2 \end{pmatrix}$$

$$m^C = \begin{pmatrix} \frac{1}{4}g_2^2\xi_W v^2 + 2\kappa_{HT}\, v_T & \frac{v}{2\sqrt{2}}(2\kappa_{HT} - g_2^2\xi_W v_T) & \frac{v}{2\sqrt{2}}(2\kappa_{HT} - g_2^2\xi_W v_T) \\ \cdot & \frac{\kappa_{HT}\, v^2}{2v_T} + \frac{v_T^2}{2}g_2^2\xi_W - \tilde{m} & \frac{v_T^2}{2}g_2^2\xi_W + \tilde{m} \\ \cdot & \cdot & \frac{\kappa_{HT}\, v^2}{2v_T} + \frac{v_T^2}{2}g_2^2\xi_W - \tilde{m} \end{pmatrix}$$

$\tilde{m} = 2m_T'^2 + \lambda_{HT}^{(2)}/2\, v^2 + (\lambda_T^{(2)} + \lambda_T^{(3)}/2 - \lambda_{T'}/4)v_T^2$

CTSM at Hadron Colliders

Production modes	σ [fb]			
	$\sqrt{s} = 14$ TeV		$\sqrt{s} = 100$ TeV	
	BP1	BP2	BP1	BP2
$p\,p \to h_T$	$6.7 \cdot 10^{-7}$	$2.7 \cdot 10^{-5}$	$8.4 \cdot 10^{-5}$	$3.2 \cdot 10^{-3}$
$p\,p \to h_T^{\pm}$	$8.2 \cdot 10^{-7}$	$3.2 \cdot 10^{-5}$	$9.5 \cdot 10^{-5}$	$3.5 \cdot 10^{-3}$
$p\,p \to h_T\,h_T$	$2.3 \cdot 10^{-7}$	$1.6 \cdot 10^{-8}$	$4.3 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$
$p\,p \to a_P\,a_P$	$2.2 \cdot 10^{-7}$	$1.1 \cdot 10^{-9}$	$4.2 \cdot 10^{-4}$	$1.8 \cdot 10^{-6}$
$p\,p \to h_T^{+}\,h_T^{-}$	$3.9 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$1.3 \cdot 10^{0}\cdot$	$1.4 \cdot 10^{0}$
$p\,p \to h_P^{+}\,h_P^{-}$	$3.9 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$1.3 \cdot 10^{0}\cdot$	$1.4 \cdot 10^{0}$
$p\,p \to h_D\,h_T$	$1.5 \cdot 10^{-5}$	$5.4 \cdot 10^{-4}$	$5.1 \cdot 10^{-3}$	$1.8 \cdot 10^{-1}$
$p\,p \to h_D\,h_T^{\pm}$	$1.7 \cdot 10^{-6}$	$6.7 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$4.1 \cdot 10^{-3}$
$p\,p \to h_T\,Z$	$1.3 \cdot 10^{-6}$	$5.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$	$3.7 \cdot 10^{-3}$
$p\,p \to h_T\,W^{\pm}$	$1.9 \cdot 10^{-6}$	$7.3 \cdot 10^{-5}$	$1.2 \cdot 10^{-4}$	$4.3 \cdot 10^{-3}$
$p\,p \to h_T^{\pm}\,Z$	$1.9 \cdot 10^{-6}$	$7.5 \cdot 10^{-5}$	$1.2 \cdot 10^{-4}$	$4.4 \cdot 10^{-3}$
$p\,p \to h_T^{+}\,W^{-}$	$2.4 \cdot 10^{-5}$	$9.1 \cdot 10^{-4}$	$4.2 \cdot 10^{-2}$	$1.5 \cdot 10^{0}$
$p\,p \to h_T\,p\,p'$	$3.1 \cdot 10^{-7}$	$1.4 \cdot 10^{-5}$	$7.9 \cdot 10^{-5}$	$3.9 \cdot 10^{-3}$
$p\,p \to h_T^{\pm}\,p\,p'$	$3.6 \cdot 10^{-7}$	$1.4 \cdot 10^{-5}$	$8.5 \cdot 10^{-5}$	$3.1 \cdot 10^{-3}$

generated with `MadGraph5_aMC@NLO`