Obscurum Higgs @ Colliders

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HEP Seminars @ IITH

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Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

based on

arXiv:2010.02597

P. Bandyopadhyay, AC

Phys.Rev.D 103 (2021) 1

arXiv:2005.10289

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

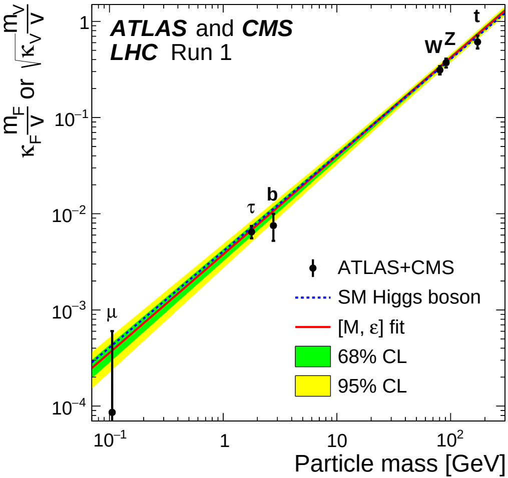
JHEP 09 (2020) 080

Content

- Introduction
- Simple SM Extension
- Phenomenology of cTSM
  - Dark Matter
  - Long-Lived Particles
  - Collider Signatures
- Conclusions

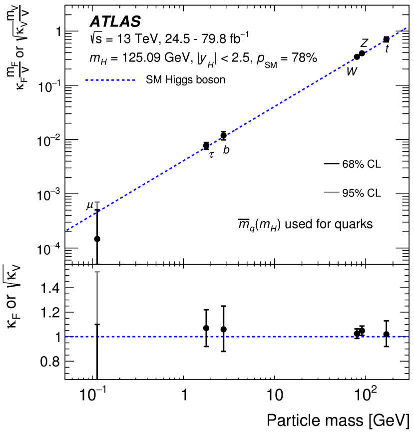
Introduction

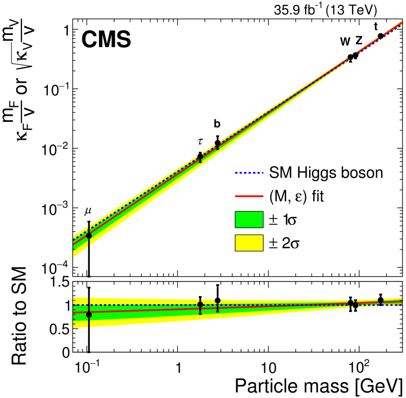
The Higgs Boson @ LHC - (Run 1)



ATLAS and CMS, JHEP 08 (2016) 045

The Higgs Boson @ LHC - (Run 2)





ATLAS and CMS (Sopczak), PoS FFK2019 (2020) 006

Still Need for...

...BSM Physics

Simple SM Extension

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

$$V = V_1 + V_2$$

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

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

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 U.), 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

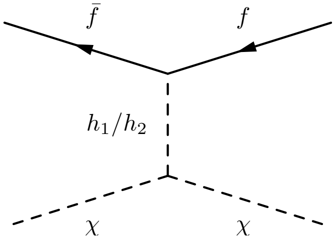
Chiara Arina (Louvain U., CP3), Ankit Beniwal (Louvain U., CP3), Céline Degrande (Louvain U., CP3), Jan Heisig (Louvain U., CP3), Andre Scaffidi (Melbourne U.) (Dec 9, 2019)

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

pdf DOI cite 15 citations

Why pNG Dark Matter?

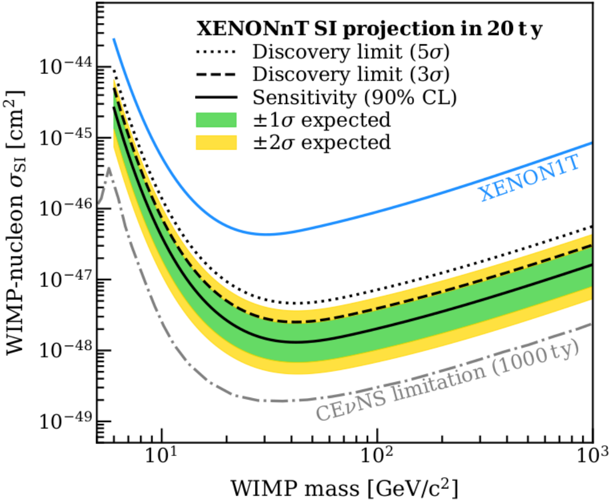
Tree-level amplitude for $\chi N \to \chi N$



$$\mathcal{A}_{ff} \propto \sin\theta\cos\theta \left(\frac{m_{h_2}^2}{t - m_{h_2}^2} - \frac{m_{h_1}^2}{t - m_{h_1}^2} \right) \sim \sin\theta\cos\theta\, t\, \frac{m_{h_2}^2 - m_{h_1}^2}{m_{h_1}^2 m_{h_2}^2} \sim 0$$

cancellation spoiled at loop level and/or with higher-order breaking terms

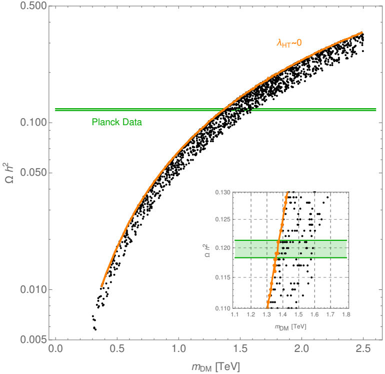
Why pNG Dark Matter?

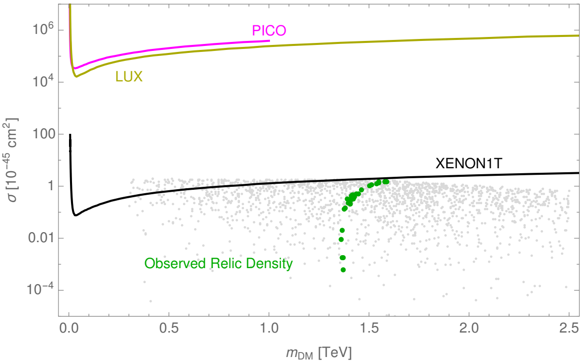


XENON collaboration, JCAP 11 (2020) 031

Phenomenology of cTSM

Dark Matter Phenomenology: Relic Density and Direct Detection





generated with `MadDM`

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

$$\mu_{\gamma\gamma} = \Gamma^{SM}_{h\to\gamma\gamma}/\Gamma_{\phi\to\gamma\gamma} \longrightarrow \mu^{ATLAS}_{\gamma\gamma} = 0.99^{+0.15}_{-0.14}\,, \quad \mu^{CMS}_{\gamma\gamma} = 1.10^{+0.20}_{-0.18}$$

Long-Lived Charged Particle

Pure charged Higgs $h_P^\pm$ only possible decay is

$$h_P^\pm \to a_P \, (W^\pm)^*$$

with

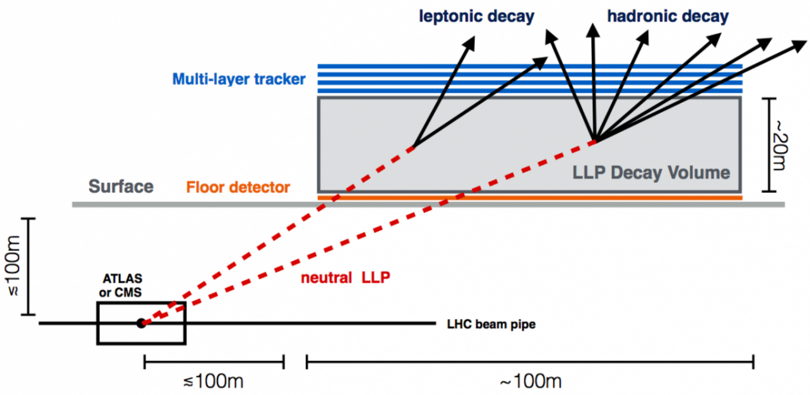
$$\frac{d\Gamma}{dx_1\, dx_2}(h_P^\pm \to a_P W^{*\pm} \to a_P f f') = \frac{9}{8\pi^3} G_F^2 \, m_W^4 \, m_{h_P^\pm} \, F_{a_P W^\pm}(x_1, x_2)$$

$$\Downarrow$$

$$\tau_{h_P^\pm} = \mathcal{O}(10^{15})\, \mathrm{GeV}^{-1} = \mathcal{O}(1)\, \mathrm{m}$$

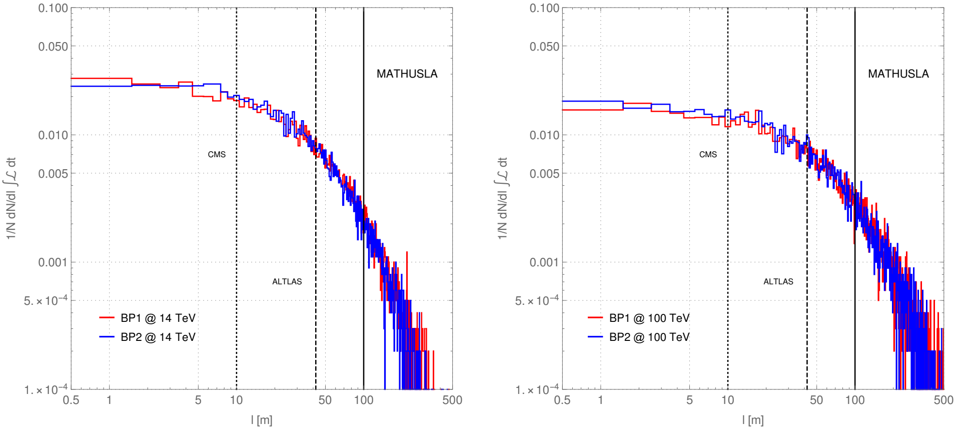
$h_P^\pm$ is a long-lived state

Long-Lived Charged Particle



Beacham, Exploring the Lifetime Frontier at the LHC and Beyond

Long-Lived Charged Particle

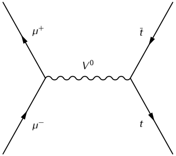


Generic Process at μ Collider

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

$\sqrt{s} \lesssim 5$ TeV

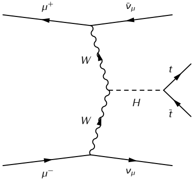
s-channel



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

$\sqrt{s} \gtrsim 5$ TeV

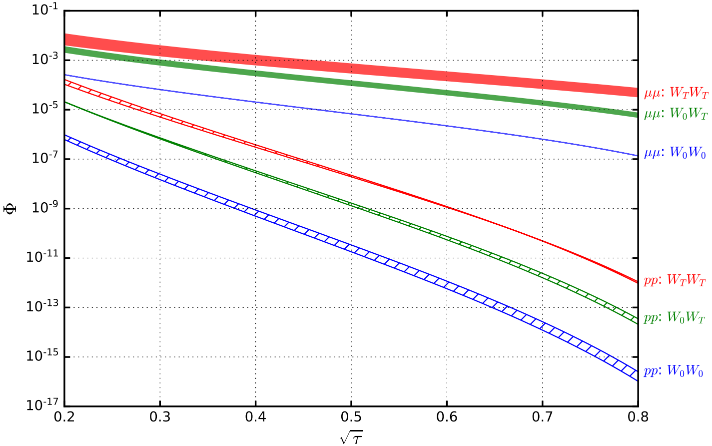
VBF



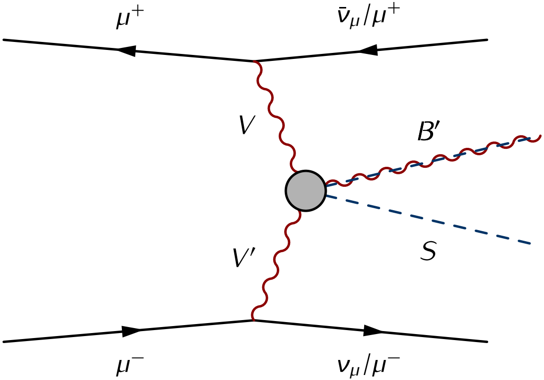
$$\sigma \sim \frac{1}{M^2} \log^n \frac{\sqrt{s}}{M}$$

Lepton vs. Hadron Colliders

$$\Phi_{W^+_{\lambda_1} W^-_{\lambda_2}}(\tau, \mu_f) = \int_\tau^1 \frac{d\xi}{\xi} \; f_{W_{\lambda_1}/\mu}(\xi, \mu_f) \, f_{W_{\lambda_2}/\mu}\left(\frac{\tau}{\xi}, \mu_f\right)$$



cTSM @ multi-TeV μ Collider



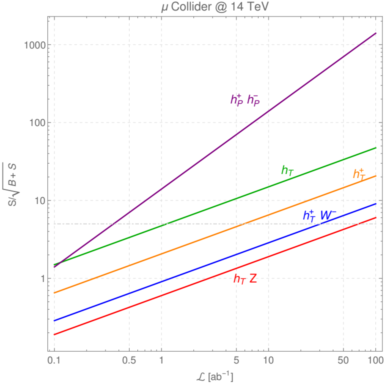
S is a scalar boson, B' can be either a scalar or a massive vector boson, V, V' are vector bosons

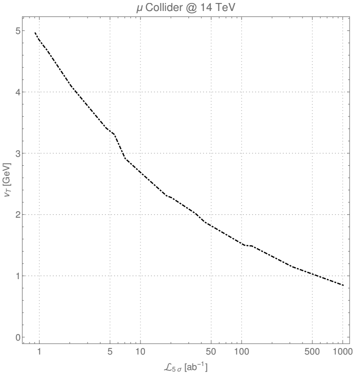
cTSM @ multi-TeV μ Collider

Production modes	σ [fb]			
	$\sqrt{s} = 14$ TeV		$\sqrt{s} = 30$ TeV	
	BP1	BP2	BP1	BP2
$\mu^+\mu^- \to h_T\ \nu_\mu\bar{\nu}_\mu$	$1.8\cdot10^{-2}$	$6.2\cdot10^{-1}$	$2.9\cdot10^{-2}$	$9.6\cdot10^{-1}$
$\mu^+\mu^- \to h_T^+\ \mu^-\bar{\nu}_\mu$	$5.3\cdot10^{-3}$	$1.8\cdot10^{-1}$	$8.4\cdot10^{-3}$	$2.8\cdot10^{-1}$
$\mu^+\mu^- \to h_T\ h_T\ \nu_\mu\bar{\nu}_\mu$	$1.9\cdot10^{-2}$	$2.0\cdot10^{-2}$	$4.8\cdot10^{-2}$	$5.1\cdot10^{-2}$
$\mu^+\mu^- \to a_P\ a_P\ \nu_\mu\bar{\nu}_\mu$	$1.8\cdot10^{-2}$	$2.0\cdot10^{-2}$	$4.7\cdot10^{-2}$	$5.0\cdot10^{-2}$
$\mu^+\mu^- \to h_T^+\ h_T^-\ \nu_\mu\bar{\nu}_\mu$	$1.3\cdot10^{-2}$	$1.4\cdot10^{-2}$	$3.4\cdot10^{-2}$	$3.6\cdot10^{-2}$
$\mu^+\mu^- \to h_P^+\ h_P^-\ \nu_\mu\bar{\nu}_\mu$	$1.3\cdot10^{-2}$	$1.4\cdot10^{-2}$	$3.4\cdot10^{-2}$	$3.6\cdot10^{-2}$
$\mu^+\mu^- \to h_D\ h_T\ \nu_\mu\bar{\nu}_\mu$	$1.6\cdot10^{-4}$	$5.7\cdot10^{-3}$	$3.7\cdot10^{-4}$	$1.3\cdot10^{-2}$
$\mu^+\mu^- \to h_D\ h_T^+\ \mu^-\bar{\nu}_\mu$	$4.8\cdot10^{-5}$	$1.6\cdot10^{-3}$	$1.1\cdot10^{-4}$	$3.8\cdot10^{-3}$
$\mu^+\mu^- \to h_T\ Z\ \nu_\mu\bar{\nu}_\mu$	$7.7\cdot10^{-4}$	$2.6\cdot10^{-2}$	$1.7\cdot10^{-3}$	$5.6\cdot10^{-2}$
$\mu^+\mu^- \to h_T\ W^+\mu^-\bar{\nu}_\mu$	$4.1\cdot10^{-4}$	$1.4\cdot10^{-2}$	$1.0\cdot10^{-3}$	$3.4\cdot10^{-2}$
$\mu^+\mu^- \to h_T^+\ Z\ \mu^-\bar{\nu}_\mu$	$1.4\cdot10^{-4}$	$4.8\cdot10^{-3}$	$3.6\cdot10^{-4}$	$1.2\cdot10^{-2}$
$\mu^+\mu^- \to h_T^+\ W^-\ \nu_\mu\bar{\nu}_\mu$	$9.7\cdot10^{-4}$	$3.2\cdot10^{-2}$	$1.9\cdot10^{-3}$	$6.1\cdot10^{-2}$

generated with `MadGraph5_aMC@NLO`

cTSM @ multi-TeV μ Collider





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

- astonishing tests of the SM at the LHC but....BSM is still needed
- simple extensions of the SM scalar sector can address DM pheno
- interplay between collider and cosmological experiments
- multi-TeV μ-collider is suitable for both precision AND discovery
- multi-Higgs model can shed light on EWSB

Thanks

Backup Slides

SM + Singlet

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

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

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

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

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

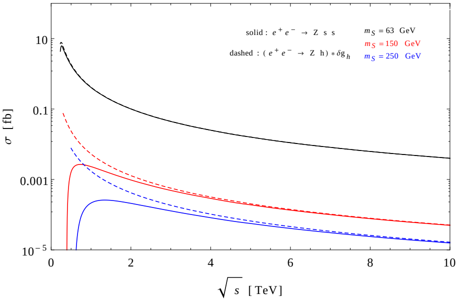
$$\lambda_{hhs} = \frac{(2m_h^2 + m_s^2)}{2v \, v_s} \sin 2\theta (v_s \cos\theta - v \sin\theta)$$

SM + Singlet: Inert Pair Production vs. Loop Corrections

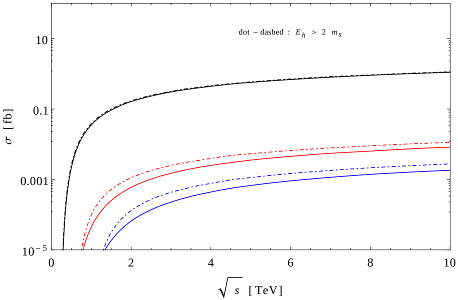
$$\delta g_h = -\frac{\kappa_\sigma^2 v^2}{16\pi^2 m_h^2}\left(1 - 4m_S^2 \frac{\tan^{-1}\sqrt{\frac{m_h^2}{(4m_S^2 - m_h^2)}}}{\sqrt{m_h^2(4m_S^2 - m_h^2)}}\right)$$

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

s-channel



VBF



2HDM

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

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

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

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

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

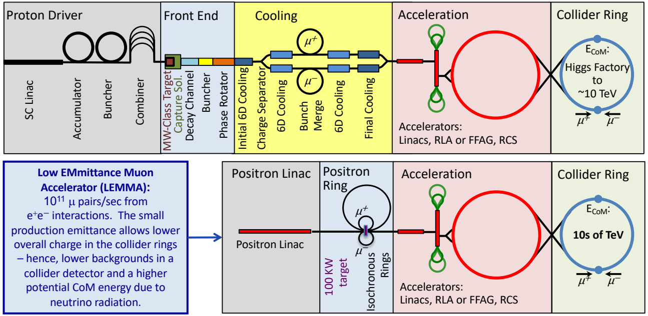
$$(\sqrt{2}G_F)^{-1} = v_\varphi^2 + 8v_X^2$$

cTSM @ Hadron Colliders

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

generated with `MadGraph5_aMC@NLO`

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

μ Collider: Interest is Growing...

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

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

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 (true cons?)

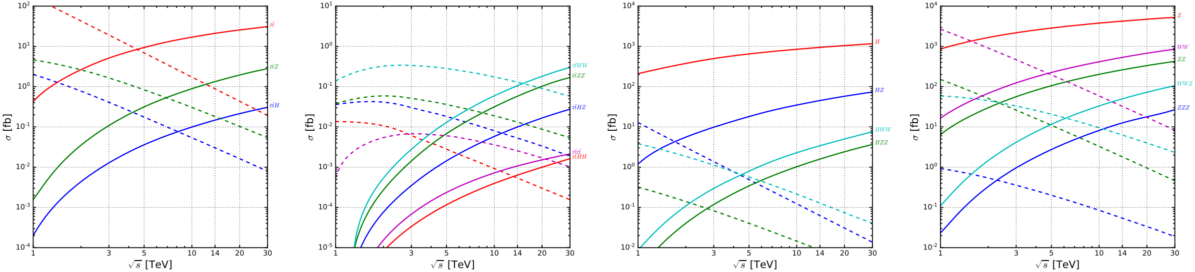
μ Collider: SM Processes

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

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`

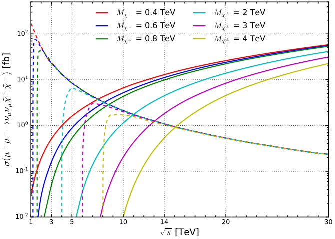
μ Collider: SM Processes

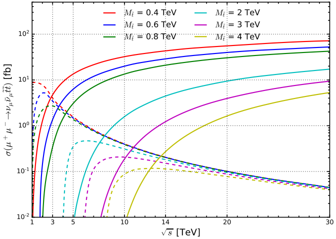


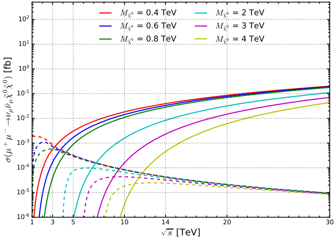
heavier final state → larger $\sqrt{s}$ for t-channel to win

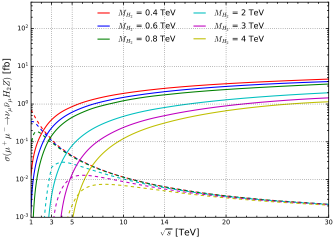
possible exceptions, e.g. HZZ vs HWW, ZZZ vs WWZ

VBF for various BSM Models



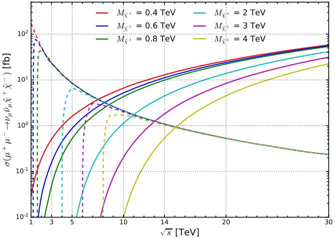


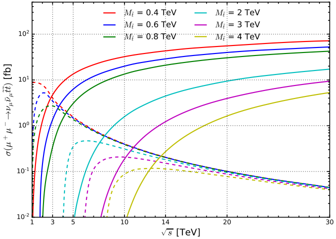


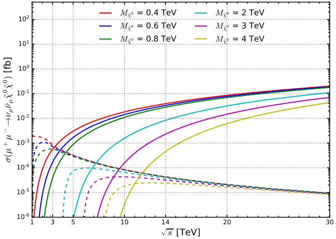


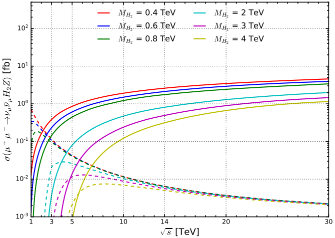
results are qualitatively similar for
SM+Singlet, 2HDM, GM Model, VLQ Models,
MSSM, Heavy Neutrino Models, etc.

VBF for various BSM Models









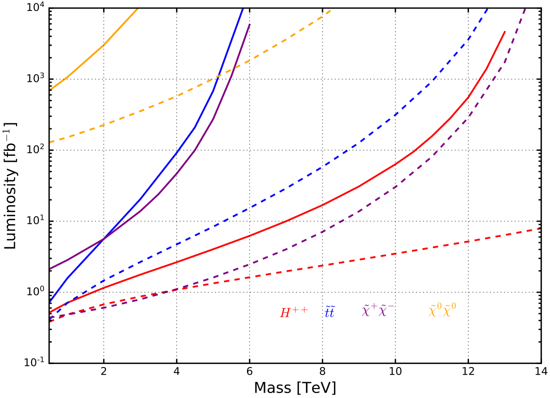
$$\frac{\sigma^{VBF}}{\sigma^{s-ch.}} \sim \frac{s}{m_X^2}\log^2\frac{s}{m_V^2}\log\frac{s}{m_X^2}$$

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