(New) Physics at a multi-TeV μ Collider

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Phenomenology 2021 Symposium

Pittsburgh, May 26th 2021

UCLouvain

FREEDOM TO RESEARCH

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

arXiv:2106.XXXXX

AC, F. Maltoni, L. Mantani, O. Mattelaer, R. Ruiz

Content

- Introduction
- SM+BSM @ μ Collider
  - New Physics Reach @ μ Collider
  - Simple SM Extension @ μ Collider
- EVA implementation in `MadGraph5_aMC@NLO`
- Conclusions

Introduction

μ Collider: Interest is Growing...

- 2104.05720 – **Cari's talk**
- 2104.03267
- 2102.08386
- 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

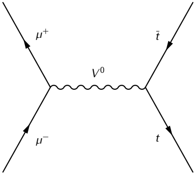
...definitely a non-exhaustive list...

Generic Process at μ Collider

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

$\sqrt{s} \lesssim 5$ TeV

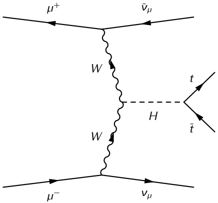
s-channel



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

$\sqrt{s} \gtrsim 5$ TeV

VBF



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

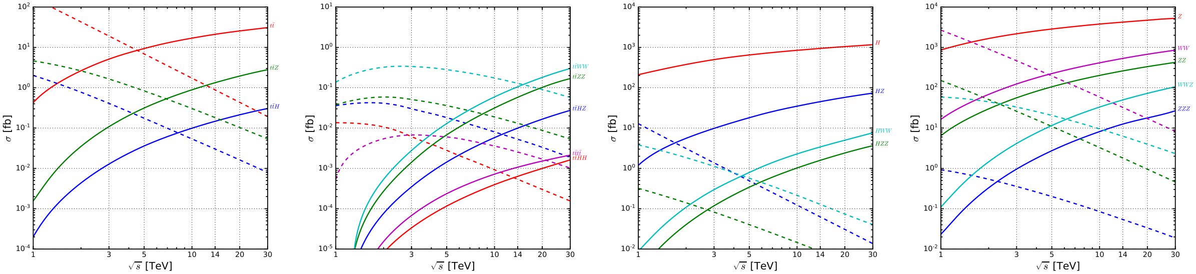
s- and t-channles are sensitive to different (new) physics

SM+BSM @ μ Collider

μ Collider: SM Processes

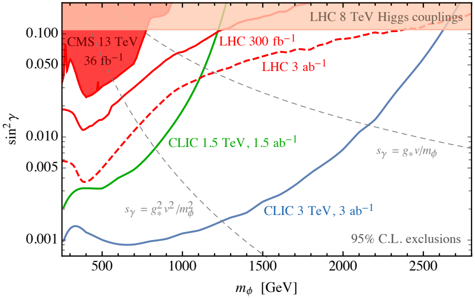
solid lines
VBF $\equiv \mu^+\mu^- \to X\nu_\mu\bar{\nu}_\mu$

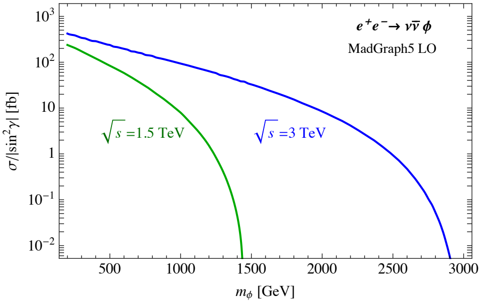
dashed lines
s-channel $\equiv \mu^+\mu^- \to X$

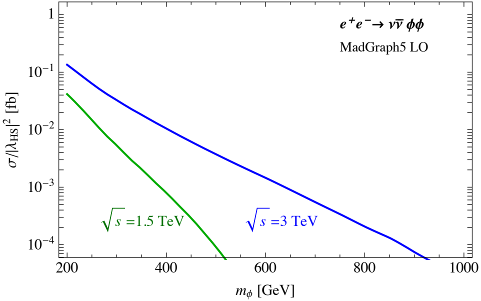


heavier final state $\to$ larger $\sqrt{s}$ for t-channel to win
possible exceptions, e.g. HZZ vs HWW, ZZZ vs WWZ

BSM @ High-Energy Lepton Collider





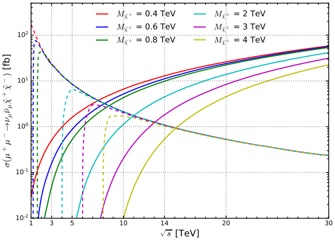


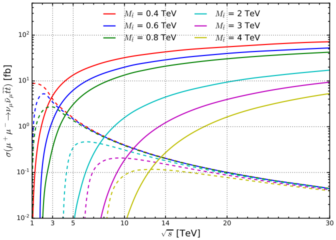
D.Buttazzo, D.Redigolo, F.Sala and A.Tesi
JHEP **11** (2018), 144

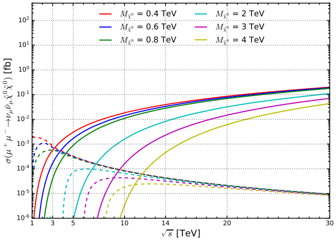
Only Low-Energy Results
($\sqrt{s} \leq 3$ TeV)

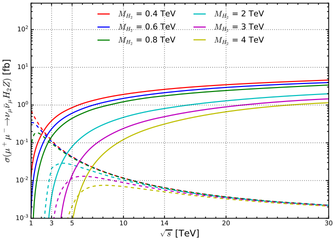
Which BSM Model?

VBF for various BSM Models



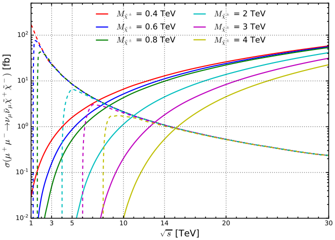


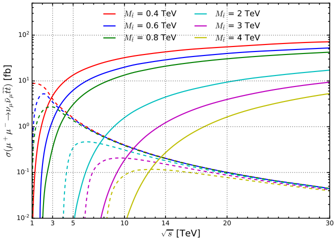


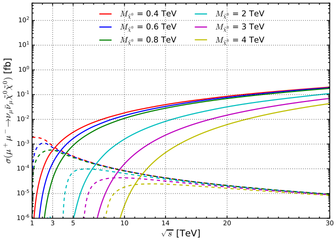


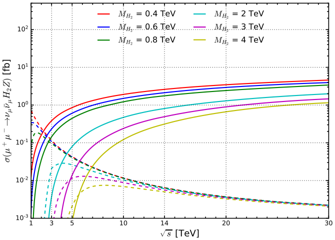
results are qualitatively similar for
SM+Singlet, 2HDM, GM Model, VLQ Models,
MSSM, Heavy Neutrino Models, etc.

VBF for various BSM Models









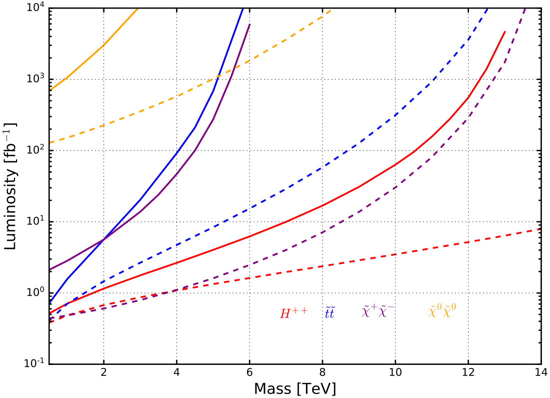
$$\frac{\sigma^{VBF}}{\sigma^{s-ch.}} \sim \frac{s}{m_X^2}\log^2\frac{s}{m_V^2}\log\frac{s}{m_X^2}$$

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

pNG Dark Matter

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

SM + Complex Triplet

Scalar Sector

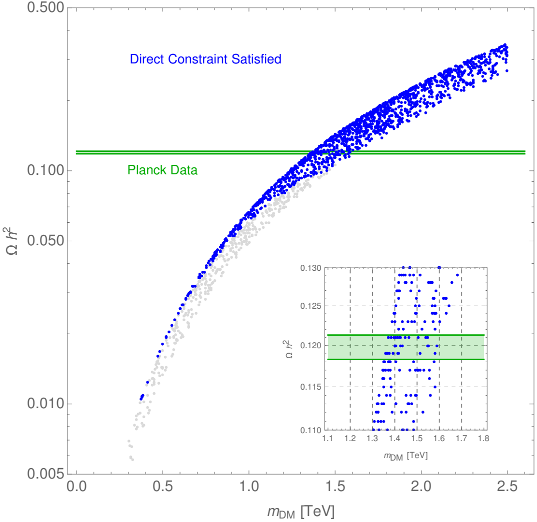
$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi_0 \end{pmatrix} \qquad T = \frac{1}{\sqrt{2}} \begin{pmatrix} t_0 & \sqrt{2}\, t_1^+ \\ \sqrt{2}\, t_2^- & -t_0 \end{pmatrix}$$

Massive Vector Bosons

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

$$\Downarrow$$

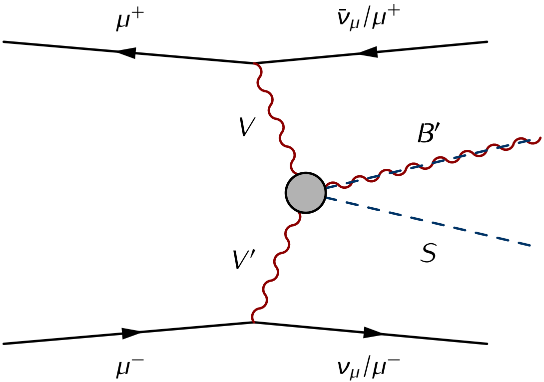
$$v_T \lesssim 5 \text{ GeV}$$



generated with MadDM

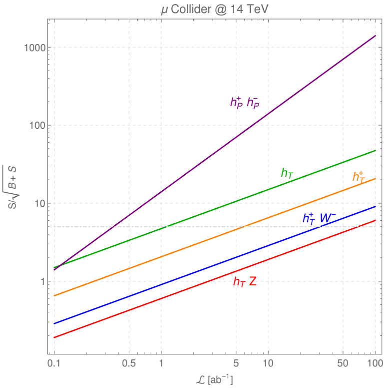
more details about triplet extension(s) in Priyotosh's talk

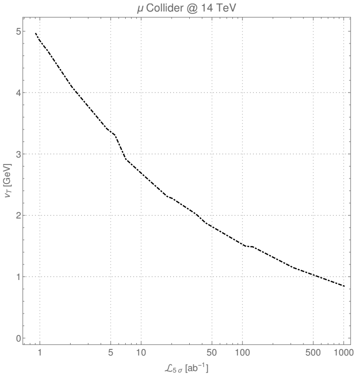
Dark Matter and Collider Phenomenology



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





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

EVA implementation in MadGraph5_aMC@NLO

EVA approximation

Nuclear Physics B287 (1987) 205–224
North-Holland, Amsterdam

HEAVY HIGGS PRODUCTION AT FUTURE COLLIDERS

G. ALTARELLI, B. MELE and F. PITOLLI

Dipartimento di Fisica, Università di Roma "La Sapienza", INFN, Sezione di Roma, Italy

Received 16 October 1986

The WW and ZZ mechanisms for production of heavy Higgs bosons are further studied in detail. The exact analytic distribution $E_k\, d\sigma/d^3k$ with k being the Higgs momentum is derived. In particular, the rapidity and transverse momentum distributions of the Higgs are obtained, which are important for the experimental reconstruction of the Higgs signal through its decay products. The relation between the exact results and some approximations for the total cross

Nuclear Physics B249 (1985) 42–60

THE EFFECTIVE W APPROXIMATION*

Sally DAWSON

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

Received 30 April 1984

We generalize the effective photon approximation to include the massive $W^{\pm}$ and Z gauge bosons of the Weinberg-Salam model. The $W^{\pm}$ and Z bosons are treated as partons in the proton and we present predictions for the structure functions of both transversely and longitudinally polarized W's and Z's. Our results are valid only at high energies, ($\sqrt{s} \gtrsim 20$ TeV), and greatly simplify calculations involving vector bosons in the intermediate state of a scattering process. As

PHYSICAL REVIEW D **103,** L031301 (2021)

Letter

High energy leptonic collisions and electroweak parton distribution functions

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PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, Pennsylvania 15260, USA

(Received 28 August 2020; revised 16 November 2020; accepted 26 January 2021; published 18 February 2021)

In high-energy leptonic collisions well above the electroweak scale, the collinear splitting mechanism of the electroweak gauge bosons becomes the dominant phenomena via the initial state radiation and the final state showering. We point out that at future high-energy lepton colliders, such as a multi-TeV muon collider, the electroweak parton distribution functions (EW PDFs) should be adopted as the proper description for partonic collisions of the initial states. The leptons and electroweak gauge bosons are the EW partons, that evolve according to the unbroken Standard Model (SM) gauge group and that effectively resum potentially large collinear logarithms. We present a formalism for the EW PDFs at the leading-log (LL) accuracy. We calculate semi-inclusive cross sections for some important SM processes at a future multi-TeV muon collider. We conclude that it is appropriate to adopt the EW PDF formalism for future high-energy lepton colliders.

DOI: 10.1103/PhysRevD.103.L031301

Nuclear Physics B296 (1988) 253–289
North-Holland, Amsterdam

ON THE VALIDITY OF THE EFFECTIVE W APPROXIMATION

Zoltan KUNSZT

ETH, Höngg,Zurich, Switzerland

Davison E. SOPER

Institute of Theoretical Science, University of Oregon, Eugene, OR 97403, USA

Received 17 June 1987

We analyze the validity of the effective W approximation in the standard model under the conditions appropriate to a search for a very heavy Higgs boson at the SSC. Specifically, we

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` – soon
- ✔ `z z > t t~ , z from muon` – soon

Gauge Vector Bosons as Partons

$$f_{V_+/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2(1-z)^2}{2z}\log\left[\frac{\mu_f^2}{M_V^2}\right],$$

$$f_{V_-/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2}{2z}\log\left[\frac{\mu_f^2}{M_V^2}\right],$$

$$f_{V_0/f_L}(z,\mu_f^2) = \frac{g_V^2}{4\pi^2}\frac{g_L^2(1-z)}{z},$$

$$f_{V_+/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_-/f_L}(z,\mu_f^2)$$

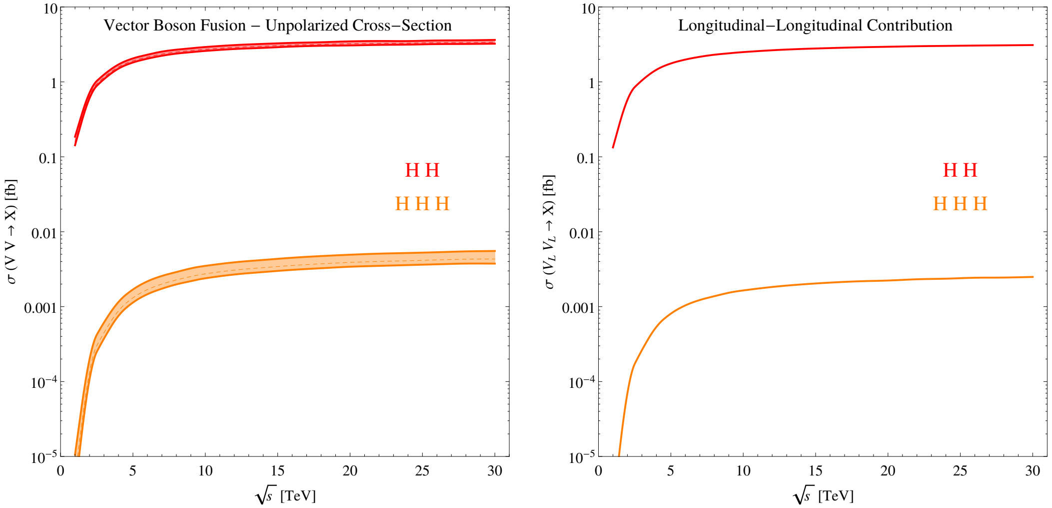
$$f_{V_-/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_+/f_L}(z,\mu_f^2)$$

$$f_{V_0/f_R}(z,\mu_f^2) = \left(\frac{g_R}{g_L}\right)^2 \times f_{V_0/f_L}(z,\mu_f^2)$$

```
/* ******************************************************** *
/* ******************************************************** *
/* ******************************************************** *
/* ******************************************************** *
double precision function eva_fX_to_vp(gg2,gL2,gR2,fLpol,mv2,x,mu2,ievo)
implicit none
integer ievo
double precision gg2,gL2,gR2,fLpol,mv2,x,mu2
double precision eva_fL_to_vp,eva_fR_to_vp

eva_fX_to_vp =       fLpol*eva_fL_to_vp(gg2,gL2,mv2,x,mu2,ievo)
&              + (1d0-fLpol)*eva_fR_to_vp(gg2,gR2,mv2,x,mu2,ievo)
return
end
/* ******************************************************** *
double precision function eva_fX_to_vm(gg2,gL2,gR2,fLpol,mv2,x,mu2,ievo)
implicit none
integer ievo
double precision gg2,gL2,gR2,fLpol,mv2,x,mu2
double precision eva_fL_to_vm,eva_fR_to_vm

eva_fX_to_vm =       fLpol*eva_fL_to_vm(gg2,gL2,mv2,x,mu2,ievo)
&              + (1d0-fLpol)*eva_fR_to_vm(gg2,gR2,mv2,x,mu2,ievo)
return
end
/* ******************************************************** *
double precision function eva_fX_to_v0(gg2,gL2,gR2,fLpol,mv2,x,mu2,ievo)
implicit none
integer ievo
double precision gg2,gL2,gR2,fLpol,mv2,x,mu2
double precision eva_fL_to_v0,eva_fR_to_v0

eva_fX_to_v0 =       fLpol*eva_fL_to_v0(gg2,gL2,mv2,x,mu2,ievo)
&              + (1d0-fLpol)*eva_fR_to_v0(gg2,gR2,mv2,x,mu2,ievo)
```

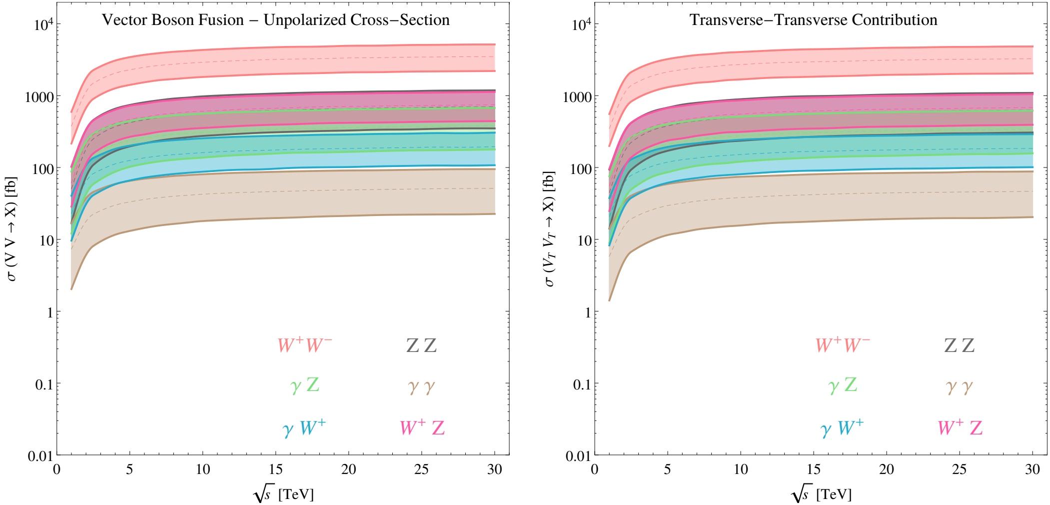
from $2 \to n+2$ to $2 \to n$

WARNING: preliminary results!



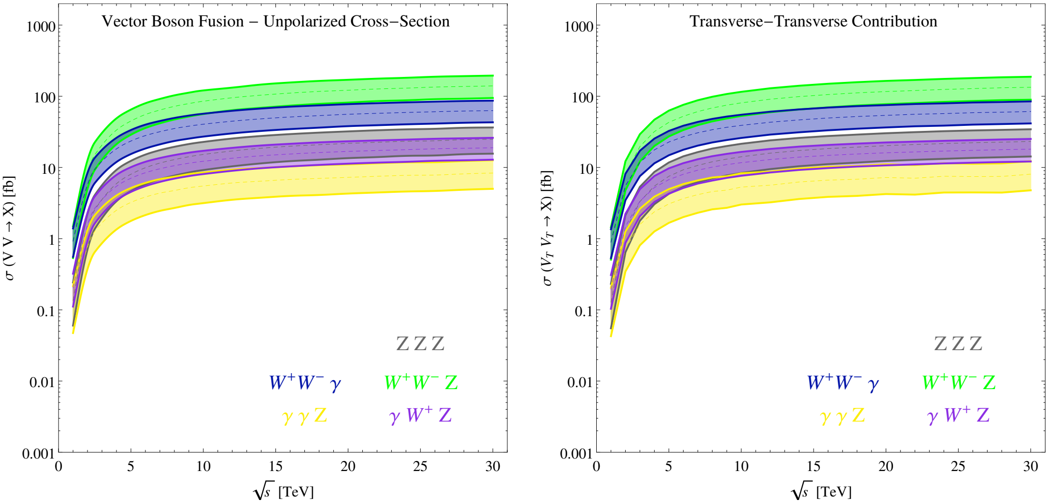
$$V\,V' \to n\,H$$

dominated by longitudinally polarized V



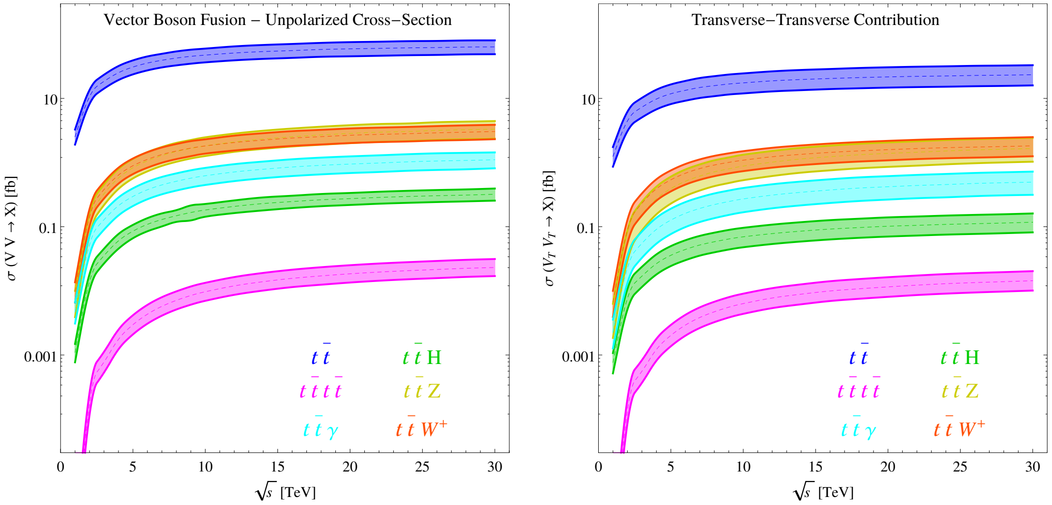
$$V\, V' \to m\, V$$

driven by V_T



$$V\,V' \to m\,V$$

driven by V_T



$$V\,V' \to t\bar{t} + X$$

relevant contribution from all polarizations

Conclusions

- THEO and EXP interest in multi-TeV μ collider

- for SM and/or BSM μ collider at very-high energies is a vector bosons collider ($\mu\mu \to X \implies V V' \to X$)

- EVA implementation in `MadGraph5_aMC@NLO`: to be released soon

- EVA in MonteCarlo $\Rightarrow$ detailed studies of high-multiplicity final states (cross-sections, distributions, ...)

thanks

Backup Slides

μ Collider: Pros and Cons

μ vs. e
(circular collider)

Pros 👍

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

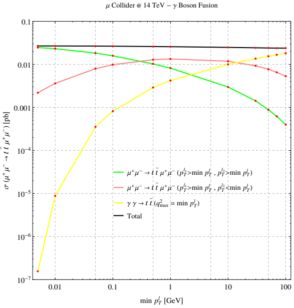
Cons 👎

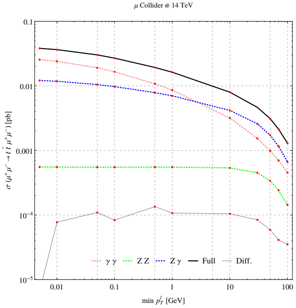
- ✘ μ decay
- ✘ ν radiation
- ✘ lots of R&D (true cons?)

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 $p_T^l \to 0$

SM + Singlet

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

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

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

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

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

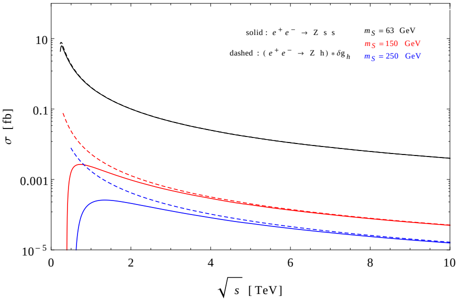
$$\lambda_{hhs} = \frac{(2m_h^2 + m_s^2)}{2v\, v_s}\sin 2\theta (v_s \cos\theta - v \sin\theta)$$

SM + Singlet: Inert Pair Production vs. Loop Corrections

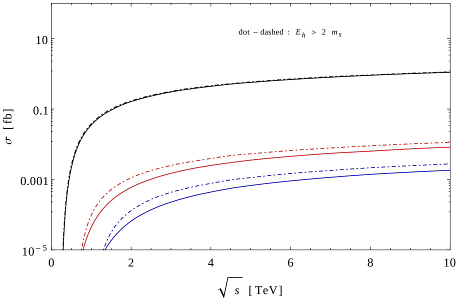
$$\delta g_h = -\frac{\kappa_\sigma^2 v^2}{16\pi^2 m_h^2}\left(1-4m_S^2 \frac{\tan^{-1}\sqrt{\frac{m_h^2}{(4m_S^2-m_h^2)}}}{\sqrt{m_h^2(4m_S^2-m_h^2)}}\right)$$

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

s-channel



VBF



SM + Complex Triplet: Scalar Spectrum

$$V = V_1 + V_2$$

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

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

SM + Complex Triplet: Scalar Spectrum

After EWSB

$$m^2_{a_P} = \kappa_{HT}\frac{v^2}{2v_T} - 4m'^2_T - \lambda^{(2)}_{HT}v^2 - (4\lambda^{(2)}_T + \lambda^{(3)}_T)v^2_T \qquad \leftarrow \text{pure state}$$

$$m^2_{h^\pm_T} = \kappa_{HT}\left(\frac{v^2}{2\,v_T} + 2\,v_T\right)$$

$$m^2_{h^\pm_P} = \kappa_{HT}\frac{v^2}{2\,v_T} - 4m'^2_T - \lambda^{(2)}_{HT}v^2 - (2\lambda^{(2)}_T + \lambda^{(3)}_T + \frac{\lambda_{T'}}{2})v^2_T \qquad \leftarrow \text{pure state}$$

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

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

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)

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`