

# (New) Physics at a multi-TeV $\mu$ Collider

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EPS-HEP Conference 2021

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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:2108.XXXXX

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

# Content

- ➡ SM+BSM @  $\mu$  Collider
  - ➡ New Physics Reach @  $\mu$  Collider
  - ➡ Simple SM Extension @  $\mu$  Collider
- ➡ EVA implementation in MadGraph5\_aMC@NLO
- ➡ Conclusions

# $\mu$ Collider: Interest is Growing...

—	2107.12442	—	2104.03267	—	2012.02769
—	2106.01393	—	2103.14043	—	2011.03055
—	2105.11500	—	2102.08386	—	2009.11287
—	2105.11462	—	2101.10469	—	2008.12204
—	2105.09116	—	2101.10334 – next talk	—	2007.15684
—	2105.06879	—	2101.04956	—	2007.14300
—	2104.05770	—	2012.14818	—	2006.16277
—	2104.05720 – next talk	—	2012.03928	—	2003.13628

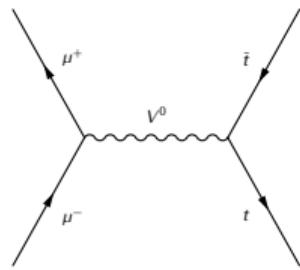
...definitely a non-exhaustive list...

# SM+BSM @ $\mu$ Collider

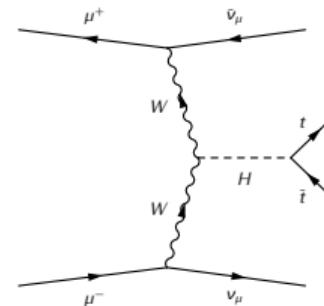
# Generic Process at $\mu$ Collider

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

$\sqrt{s} \lesssim 5$  TeV  
s-channel



$\sqrt{s} \gtrsim 5$  TeV  
VBF



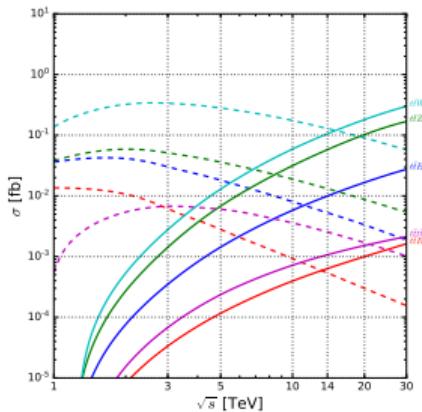
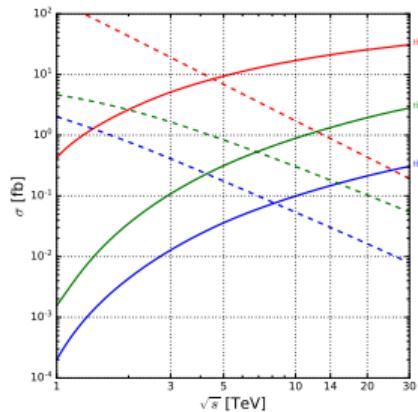
$$\sigma \sim \frac{1}{s}$$

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

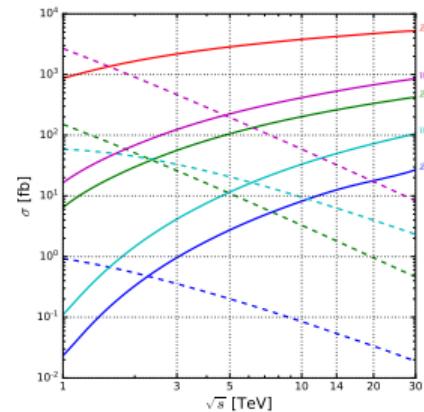
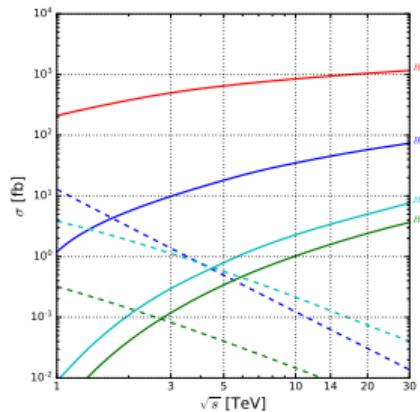
s- and t-channels are sensitive to different (new) physics

# $\mu$ Collider: SM Processes

solid lines  
 $VBF \equiv \mu^+ \mu^- \rightarrow X v_\mu \bar{v}_\mu$

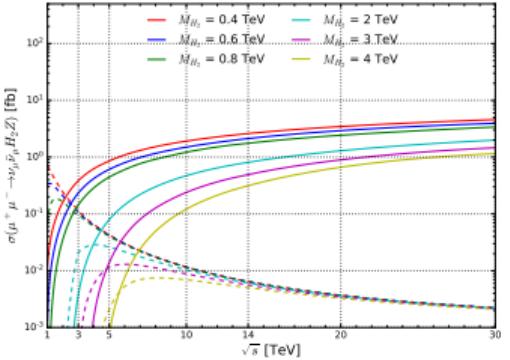
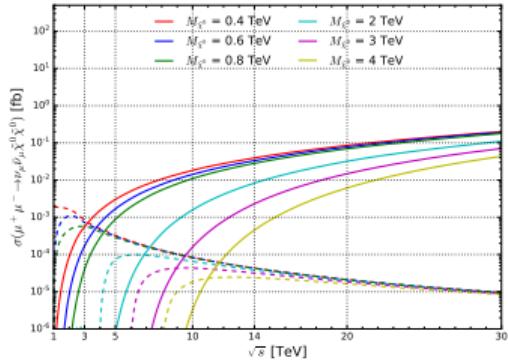
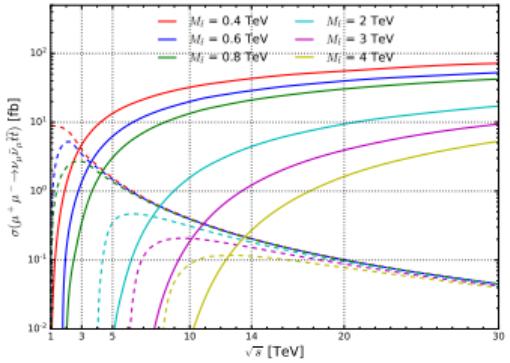
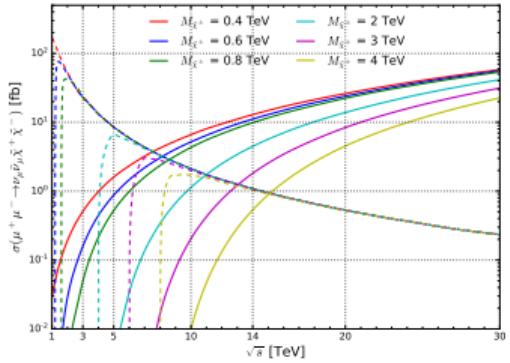


dashed lines  
 $s\text{-channel} \equiv \mu^+ \mu^- \rightarrow X$



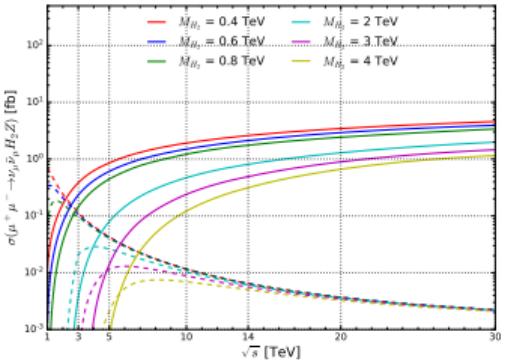
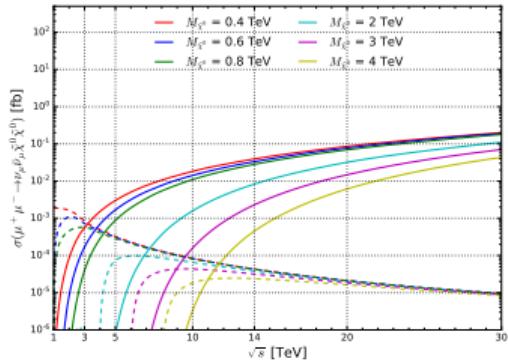
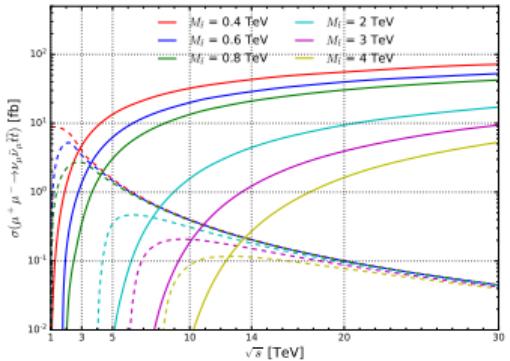
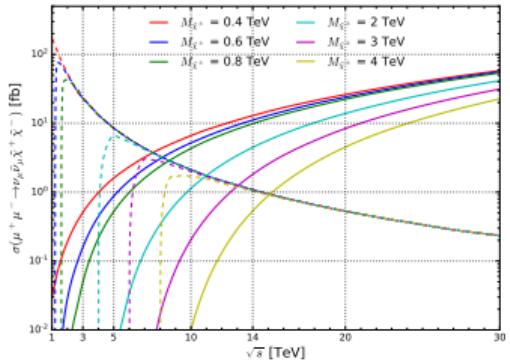
heavier final state  $\rightarrow$  larger  $\sqrt{s}$  for t-channel to win  
possible exceptions, e.g.  $HZZ$  vs  $HWW$ ,  $ZZZ$  vs  $WWZ$

# VBF for various BSM Models



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

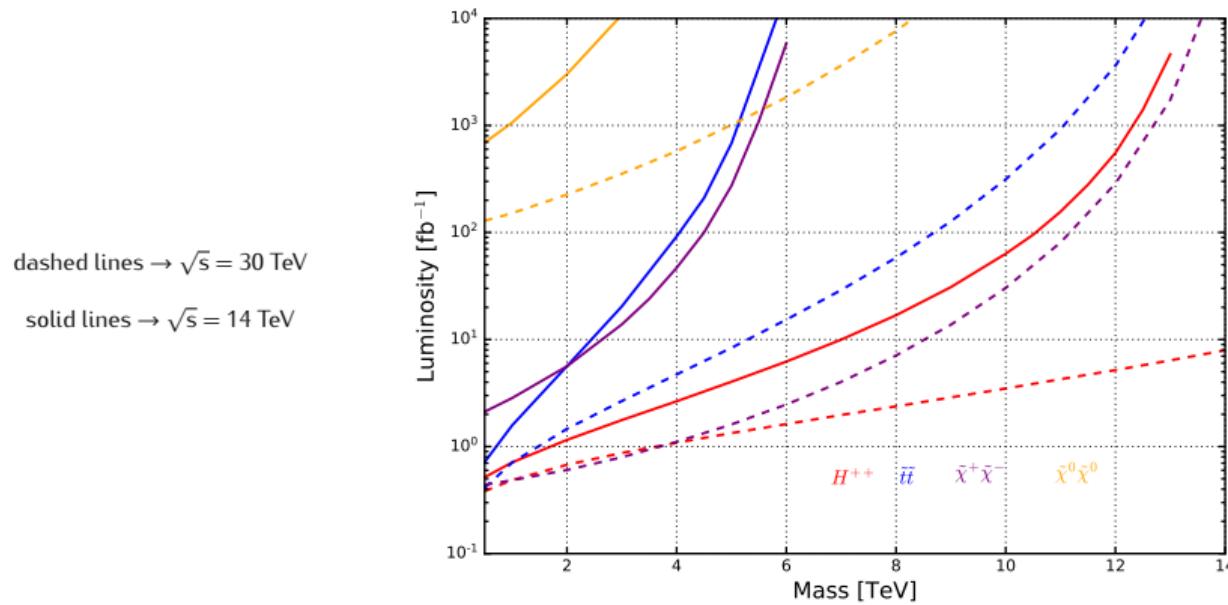
# VBF for various BSM Models



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

# New Physics Reach (via VBF) @ $\mu$ Collider

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



Luminosity required for 25 events, with assumed zero background

# pNG Dark Matter

Is a Miracle-less WIMP Ruled Out?

Jason Arakawa, Tim M.P. Tait (Jan 26, 2021)  
e-Print: [2101.11031 \[hep-ph\]](#)

[pdf](#) [DOI](#) [cite](#) [23 citations](#)

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](#)

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](#)

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: Examples of Vanishing Direct Detection #1

Cross Section

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: *JHEP* 04 (2020) 015, *JHEP* 04 (2020) 015 • e-Print: [1912.04008 \[hep-ph\]](#)

[pdf](#) [DOI](#) [cite](#) [15 citations](#)

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](#)

# SM + Complex Triplet

## Scalar Sector

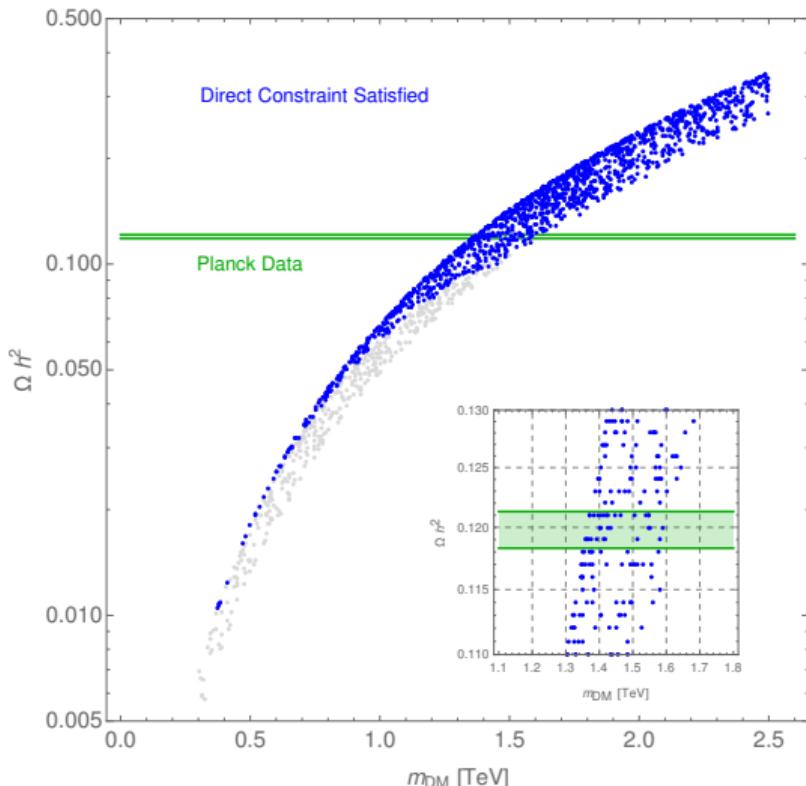
$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi_0 \end{pmatrix} \quad T = \frac{1}{\sqrt{2}} \begin{pmatrix} t_0 & \sqrt{2}t_1^+ \\ \sqrt{2}t_2^- & -t_0 \end{pmatrix}$$

## Massive Vector Bosons

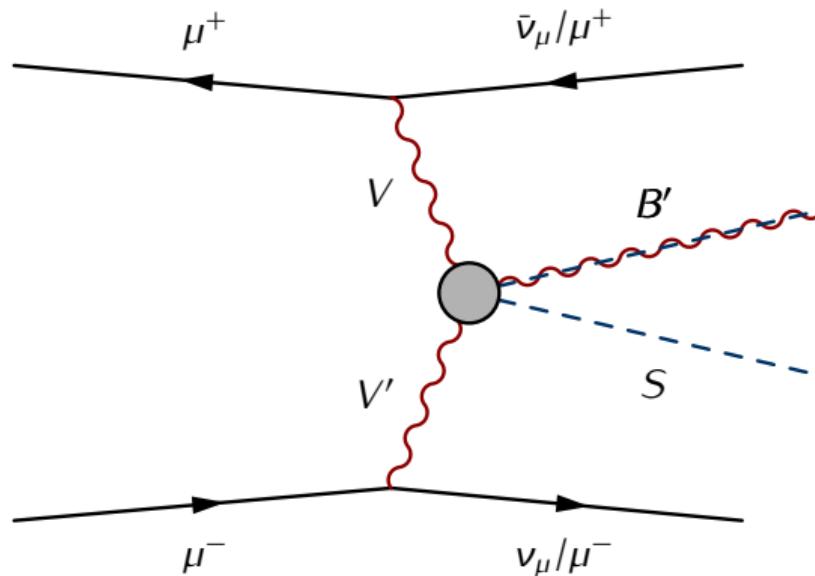
$$m_W = \frac{1}{2} g_2 \sqrt{v^2 + 4v_T^2} \quad m_Z = \frac{1}{2} \sqrt{(g_1^2 + g_2^2)} v$$

↓

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

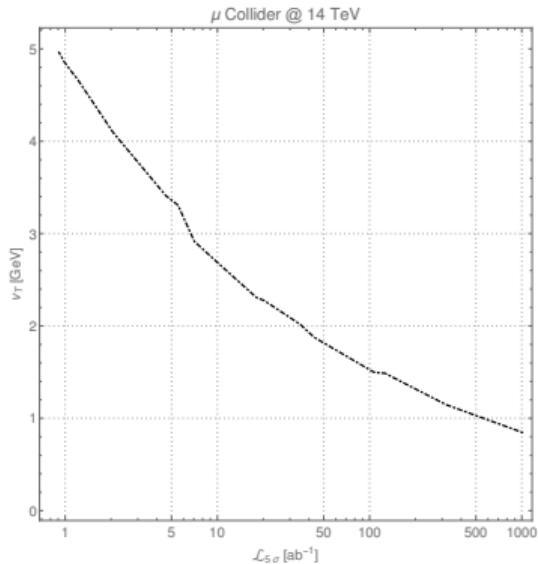
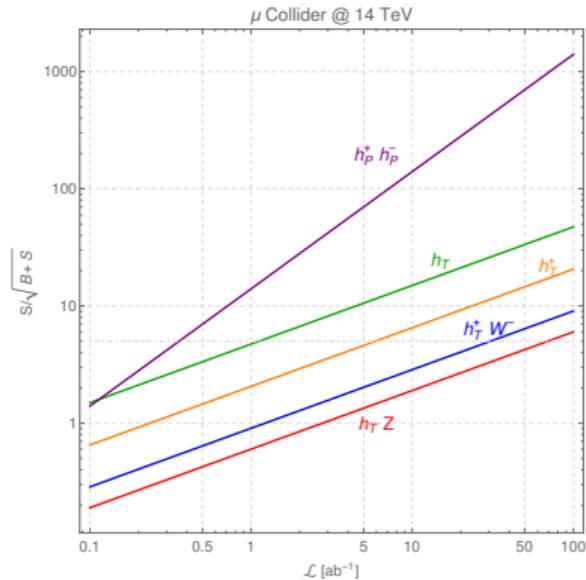


# Dark Matter and Collider Phenomenology



$S$  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

$$M_{W^+W^-} = m_{h_T} \text{ or } M_{W^\pm Z} = m_{h_T^\pm}$$

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

PHYSICAL REVIEW D 103, L031301 (2021)

Letter

## 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  
© North-Holland Publishing Company

## 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  $W^+$  and  $Z$  gauge bosons of the Weinberg-Salam model. The  $W^+$  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, ( $\sqrt{s} \geq 20$  TeV), and greatly simplify calculations involving vector bosons in the intermediate state of a scattering process. As

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

Tao Han<sup>●,\*</sup>, Yang Ma<sup>●,†</sup>, and Keping Xie<sup>●,‡</sup>  
PITT PACC, Department of Physics and Astronomy, University of Pittsburgh,  
3941 O'Hara Street, Pittsburgh, Pennsylvania 15260, USA

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 $\mu$ Collider

Generating processes at a  $\mu$  Collider in MadGraph5\_aMC@NLO (e.g. top pair-production)

- ✓  $\mu^+ \mu^- \rightarrow \mu^+ \mu^- t \bar{t}$ ,  $\mu^+ \mu^- \rightarrow \nu \bar{\nu} t \bar{t}$
- ✓  $a a \rightarrow t \bar{t}$  with lpp 4: photon from muon
- ✓  $w^+ w^- \rightarrow t \bar{t}$ , w from muon - soon
- ✓  $z z \rightarrow t \bar{t}$ , 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

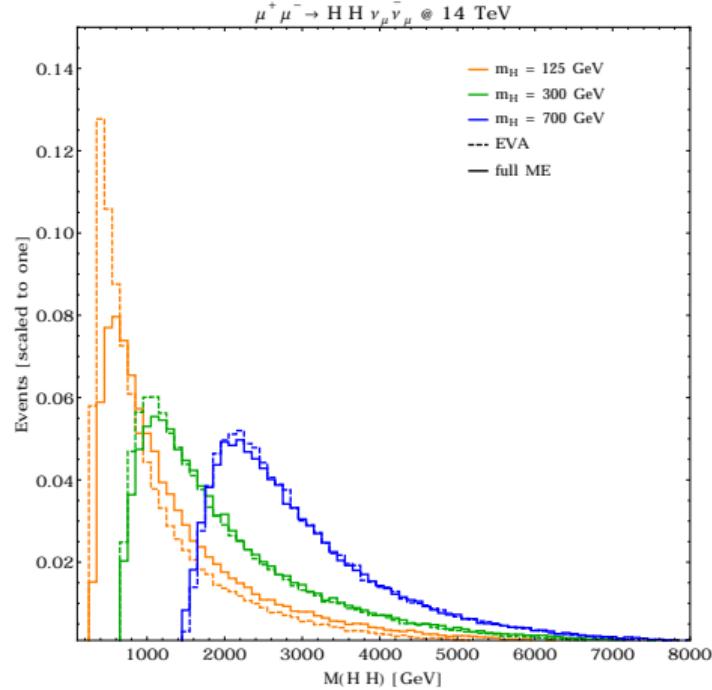
eva_fx_to_vm =      fLpol*eva_fL_to_vm(gg2,gL2,mv2,x,mu2,ievo)
&           + (1d0-fLpol)*eva_fR_to_vm(gg2,gR2,mv2,x,mu2,ievo)
return
end
/* ****
double precision function eva_fx_to_v0(gg2,gL2,gR2,fLpol,mv2,x,mu2,ievo)
implicit none
integer ievo
double precision gg2,gL2,gR2,fLpol,mv2,x,mu2
double precision 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)
-----
```

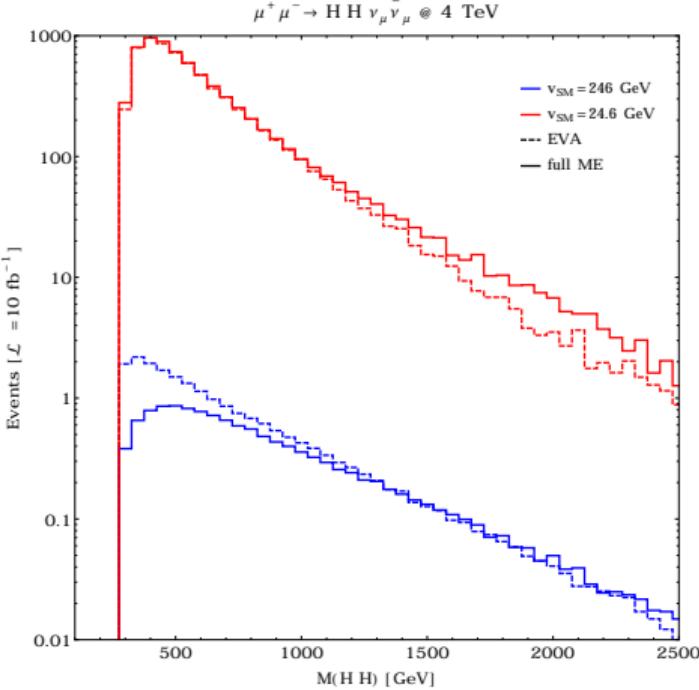
from  $2 \rightarrow n+2$  to  $2 \rightarrow n$

**WARNING: preliminary results!**

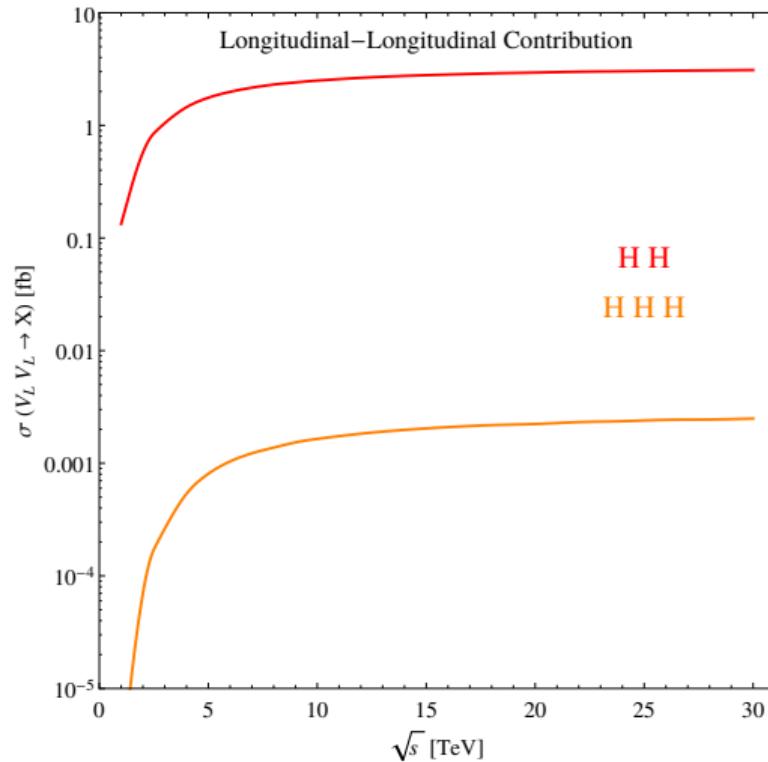
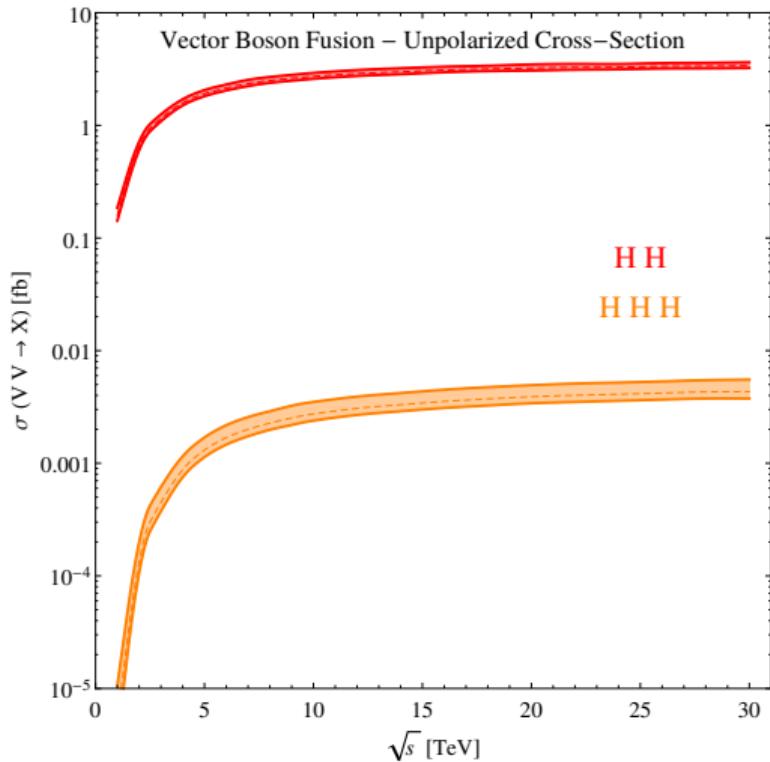
# Higgs pair production



better agreement if  
 $m_H \gtrsim 300 \text{ GeV}$

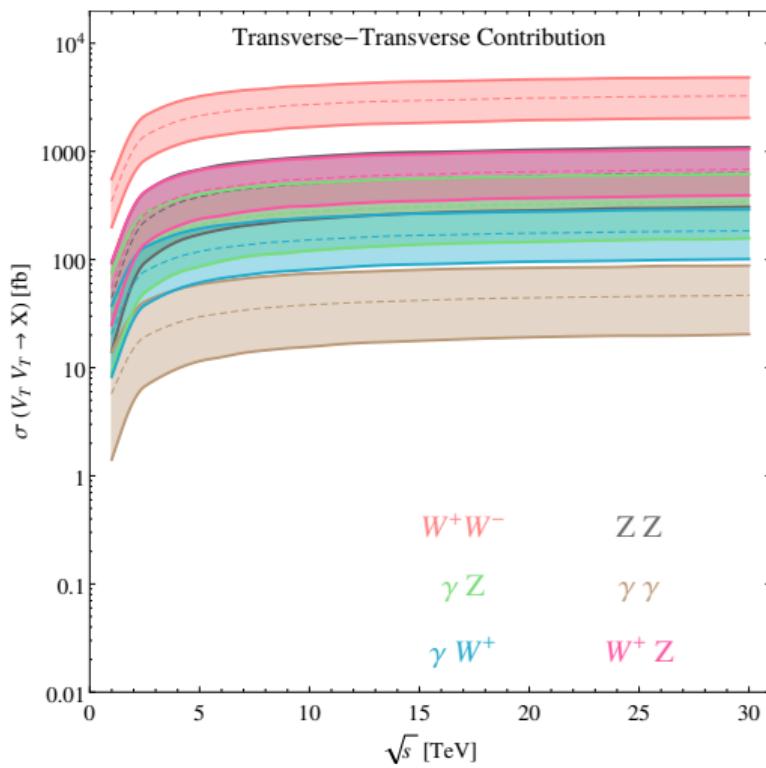
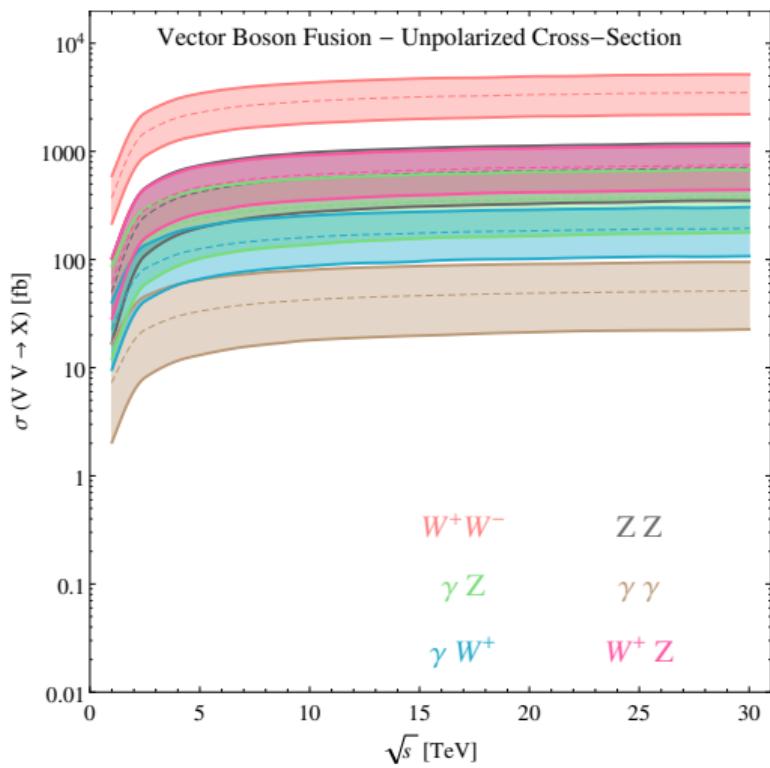


better agreement if  
 $v_{SM} \ll 246 \text{ GeV}$



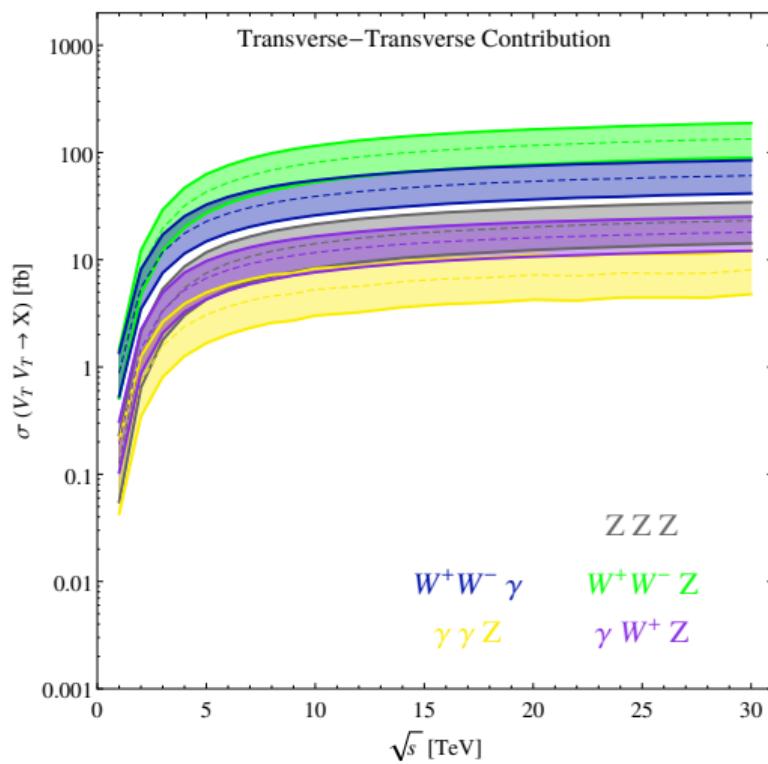
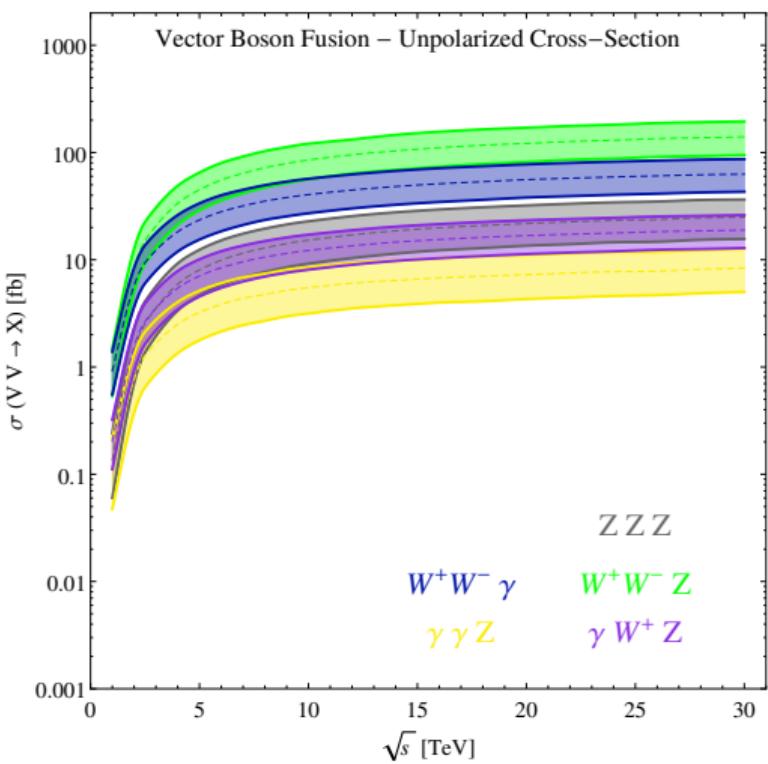
$$VV' \rightarrow nH$$

dominated by longitudinally polarized  $V$



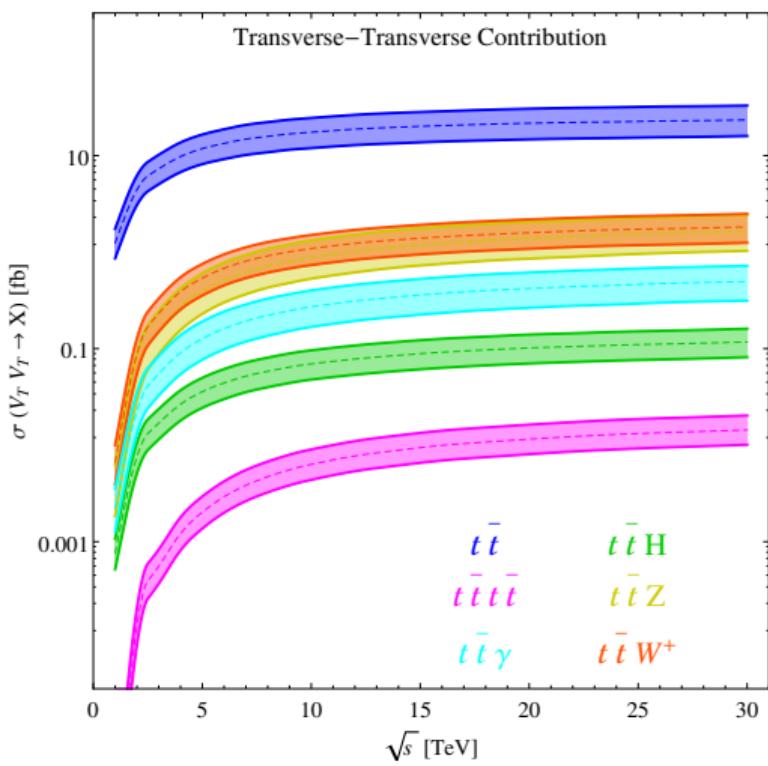
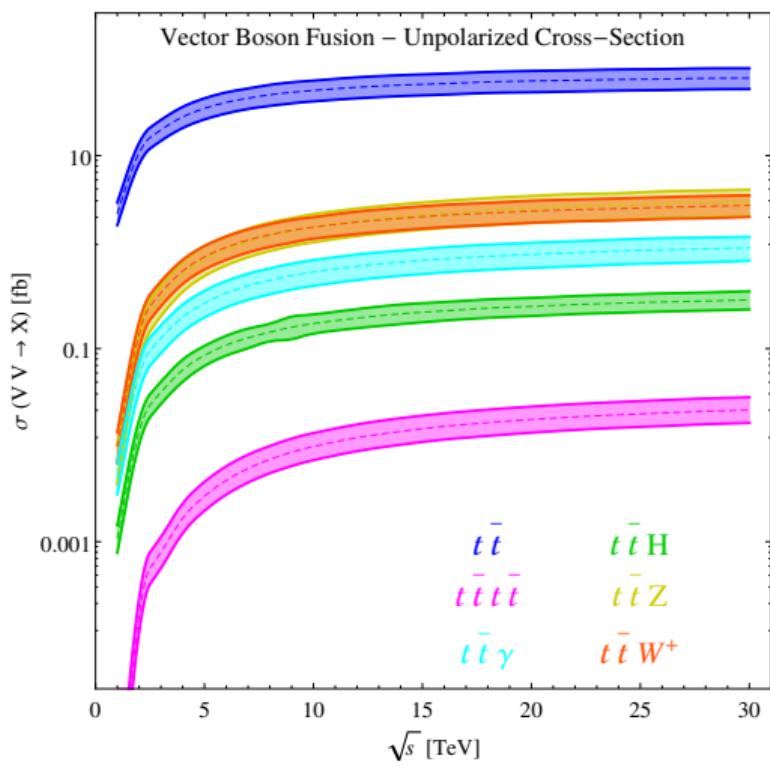
$$VV' \rightarrow mV$$

driven by  $V_T$



$$VV' \rightarrow mV$$

driven by  $V_T$



$$VV' \rightarrow t\bar{t} + X$$

relevant contribution from all polarizations

# Conclusions

- THEO and EXP interest in multi-TeV  $\mu$  collider
- for SM and/or BSM  $\mu$  collider at very-high energies is a vector bosons collider ( $\mu\mu \rightarrow X \Rightarrow VV' \rightarrow X$ )
- 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

# $\mu$ Collider: Pros and Cons

$\mu$  vs.  $e$   
(circular collider)

Pros 

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

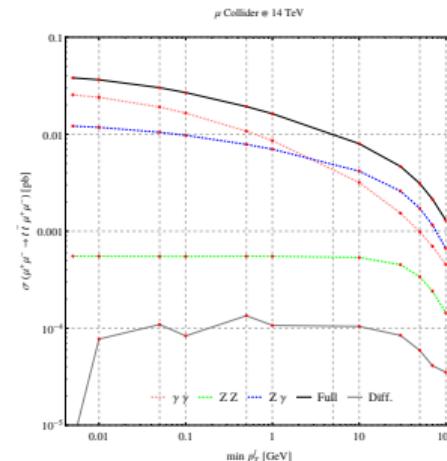
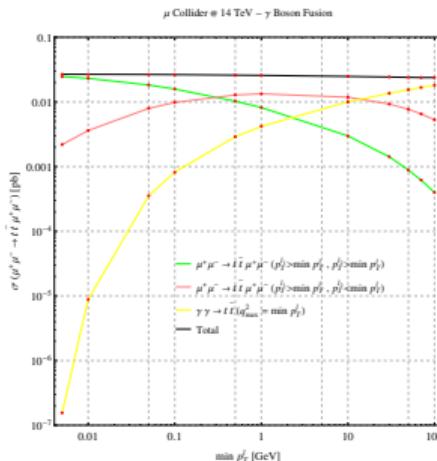
Cons 

- ✗  $\mu$  decay
- ✗  $\nu$  radiation
- ✗ lots of R&D (true cons?)

# EPA

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

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



$$\sigma_{\gamma\gamma}(t\bar{t}) = 2.5 \cdot 10^{-2} \text{ pb}$$

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

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

with massive  $\mu$  one can go to  $p_T^I \rightarrow 0$

## SM + Singlet

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

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

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

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

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

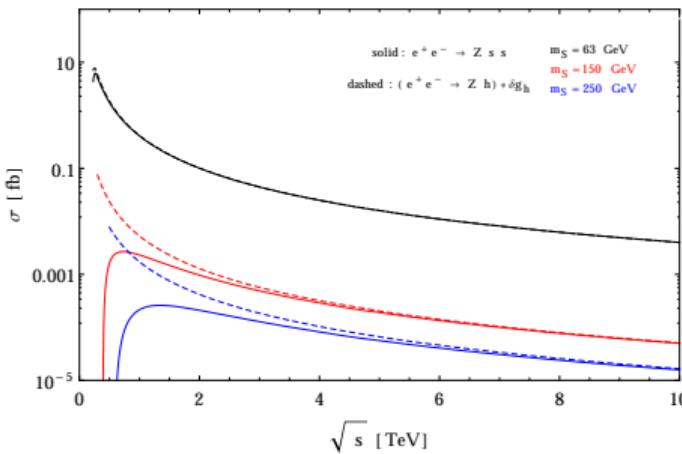
$$\lambda_{hs} = \frac{(2m_h^2 + m_s^2)}{2v v_s} \sin 2\theta (v_s \cos \theta - v \sin \theta)$$

# SM + Singlet: Inert Pair Production vs. Loop Corrections

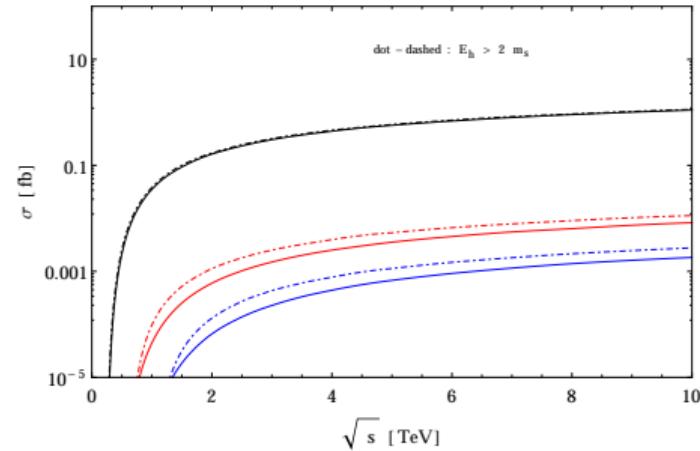
$$\delta g_h = -\frac{\kappa_\sigma^2 v^2}{16\pi^2 m_h^2} \left( 1 - 4m_S^2 \frac{\tan^{-1} \sqrt{\frac{m_h^2}{(4m_S^2 - m_h^2)}}}{\sqrt{m_h^2 (4m_S^2 - m_h^2)}} \right)$$

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s-channel



VBF



## SM + Complex Triplet: Scalar Spectrum

$$V = V_1 + V_2$$

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

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

# SM + Complex Triplet: Scalar Spectrum

After EWSB

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

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

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

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

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

# Physical Pseudoscalar: Features

$a_P$  is a pure pseudoscalar state



no interaction with fermions (triplet!)

pseudoscalar nature



no loop-level coupling with massless  
gauge bosons

no interaction with massive gauge  
bosons



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

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

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

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

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

# CTSM at Hadron Colliders

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