Vector-Boson-Fusion at multi-TeV μ Colliders

Antonio Costantini

antonio.costantini@bo.infn.it

VBScan Meeting

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Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

based on

arXiv:2005.10289

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

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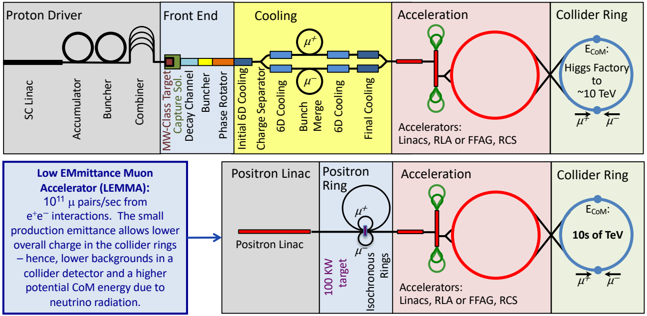
Introduction

μ Collider



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

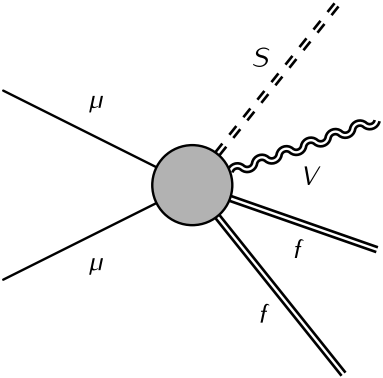
Muon **A**ccelerator **P**rogram
map.fnal.gov

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

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

Physics @ μ Collider

Generic Process at μ Collider



$$\mu\mu \to n\, f\, f + m\, V + k\, S$$

This is a $2 \to (n, m, k)$ process

Generic Process at μ Collider

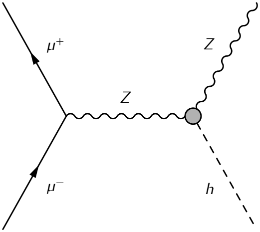
Different class of processes are relevant at different $\sqrt{s}$

Generic Process at μ Collider

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

$\sqrt{s} \lesssim 1$ TeV

s-channel

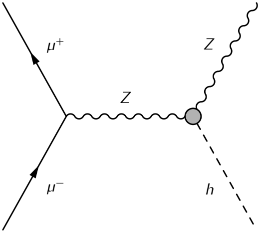


Generic Process at μ Collider

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

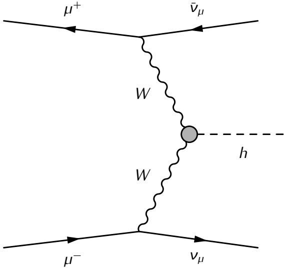
$\sqrt{s} \lesssim 1$ TeV

s-channel



$\sqrt{s} \gtrsim 1$ TeV

VBF



μ PDF

Effective W Approximation

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

$$\sigma(\mu^+\mu^- \xrightarrow{WW\to X} X) \approx f_{W^+/\mu^+} \otimes f_{W^-/\mu^-} \otimes \hat{\sigma}(W^+W^- \to X)$$

$$= \Sigma_{\lambda,\lambda'} \int dz_1 dz_2\, f_{W_\lambda^+/\mu^+}(z_1, \mu_f) f_{W_\lambda^-/\mu^-}(z_2, \mu_f) \hat{\sigma}_{\lambda\lambda'}(s_{WW})$$

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

μ PDF

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

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

μ PDF

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

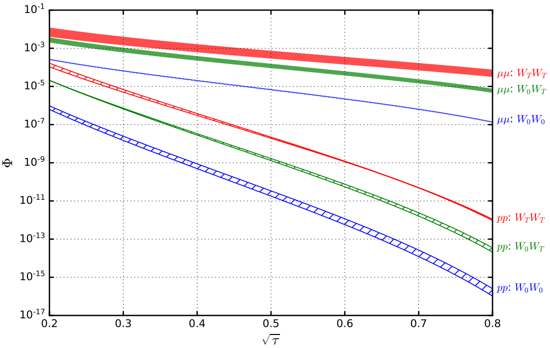
$$f_{V_L}(z, Q_f^2) = \frac{C}{4\pi^2}(g_V^2 + g_A^2)\left(\frac{1-z}{z}\right)$$

$$\Phi_{W^+W^-}(\tau, Q_f, \lambda_1, \lambda_2) \equiv \int_\tau^1 \frac{d\xi}{\xi} f_{W^-/\mu^-}(\xi, Q_f^2, \lambda_1)\, f_{W^+/\mu^+}(\frac{\tau}{\xi}, Q_f^2, \lambda_2)$$

Ws PDF: μ vs q

$$\Phi_{VV'}(\tau,Q_f) = \frac{1}{1+\delta_{VV'}}\int_\tau^1 \frac{d\xi}{\xi}\int_{\tau/\xi}^1 \frac{dz_1}{z_1}\int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2}\sum_{q,q'}$$
$$(f_{V/q}(z_2)f_{V'/q'}(z_1)f_{q/p}(\xi)f_{q'/p}(\frac{\tau}{\xi z_1 z_2}) + f_{V/q}(z_2)f_{V'/q'}(z_1)f_{q/p}(\frac{\tau}{\xi z_1 z_2})f_{q'/p}(\xi))$$

$$\Phi_{W^+W^-}(\tau,Q_f,\lambda_1,\lambda_2) \equiv \int_\tau^1 \frac{d\xi}{\xi} f_{W^-/\mu^-}(\xi,Q_f^2,\lambda_1)\, f_{W^+/\mu^+}(\frac{\tau}{\xi},Q_f^2,\lambda_2)$$



μ Collider vs. p Collider

Given a muon collider cross section σ_μ the equivalent proton energy is defined by

$$\sigma_p = \sigma_\mu$$

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Parton Luminosity

$$\sigma(pp \to X) = \int_{\tau_0}^{1} d\tau \sum_{ij} \Phi_{ij}(\tau, Q_f)\, \hat{\sigma}(ij \to X)$$

$$\Phi_{ij}(\tau, Q_f) \equiv \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{d\xi}{\xi} \left(f_{i/p}(\xi, Q_f^2)\, f_{j/p}\left(\frac{\tau}{\xi}, Q_f^2\right) + (i \leftrightarrow j) \right)$$

μ Collider vs. p Collider: single production

Resonance with mass M

$$\sigma_p(s_p) = \int_{\tau_0}^{1} d\tau \sum_{ij} \Phi_{ij}(\tau, Q_f)[\hat{\sigma}]_p \, \delta\left(\tau - \frac{M^2}{s_p}\right)$$

$$\sigma_\mu(s_\mu) = [\hat{\sigma}]_\mu$$

with $s_\mu = M^2$

μ Collider vs. p Collider: single production

Resonance with mass M

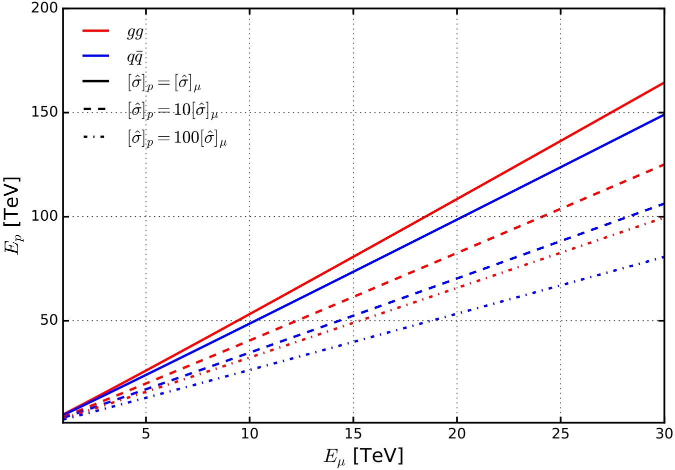
$$\sigma_p(s_p) = \int_{\tau_0}^{1} d\tau \sum_{ij} \Phi_{ij}(\tau, Q_f)[\hat{\sigma}]_p \, \delta\left(\tau - \frac{M^2}{s_p}\right)$$

$$\sigma_\mu(s_\mu) = [\hat{\sigma}]_\mu$$

with $s_\mu = M^2$

$$\sigma_p = \sigma_\mu \quad \Rightarrow \quad \sum_{ij} \Phi_{ij}\left(\frac{s_\mu}{s_p}, \frac{\sqrt{s_\mu}}{2}\right) = \frac{[\hat{\sigma}]_\mu}{[\hat{\sigma}]_p} \equiv \frac{1}{\beta}$$

μ Collider vs. p Collider: single production



μ Collider vs. p Collider: pair production

Pair Production

$$\sigma_p(s_p) = \frac{1}{s_p}\int_{\tau_0}^{1} d\tau \frac{1}{\tau}\sum_{ij}\Phi_{ij}(\tau, Q_f)[\hat{\sigma}\hat{s}]_p$$

$$\sigma_\mu(s_\mu) = \frac{1}{s_\mu}[\hat{\sigma}\hat{s}]_\mu$$

with μ collider at threshold

μ Collider vs. p Collider: pair production

Pair Production

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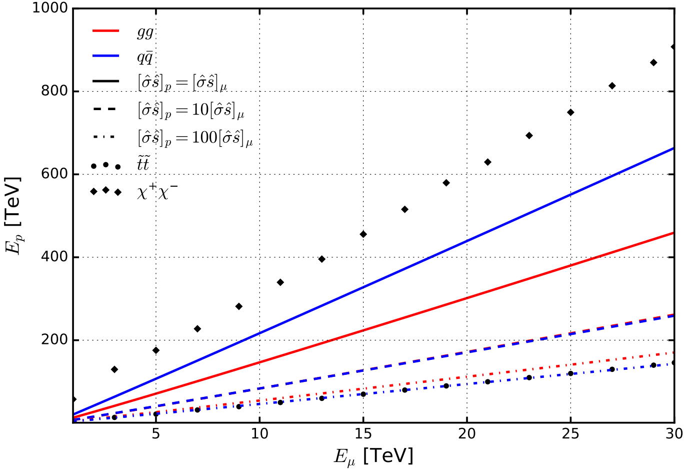
$$\sigma_\mu(s_\mu) = \frac{1}{s_\mu}[\hat{\sigma}\hat{s}]_\mu$$

with μ collider at threshold

$$\sigma_p = \sigma_\mu \quad \Rightarrow \quad \frac{s_\mu}{s_p}\int_{\frac{s_\mu}{s_p}}^{1} d\tau \ \frac{1}{\tau} \ \sum_{ij}\Phi_{ij}\left(\tau, \frac{\sqrt{s_\mu}}{2}\right) \ = \ \frac{[\hat{\sigma}\hat{s}]_\mu}{[\hat{\sigma}\hat{s}]_p} \ \equiv \ \frac{1}{\beta}$$

μ Collider vs. p Collider: pair production



SM @ μ Collider

μ Collider: SM Processes

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

generated with `MadGraph5_aMC@NLO`

μ Collider: SM Processes

VBF > s-channel

	σ [fb]	$\sqrt{s}$ [TeV]		σ [fb]	$\sqrt{s}$ [TeV]
$t\bar{t}$	$8.4 \cdot 10^{0}$	4.5	$t\bar{t}ZZ$	$2.2 \cdot 10^{-2}$	8.4
$t\bar{t}Z$	$5.3 \cdot 10^{-1}$	6.9	$t\bar{t}HZ$	$7.0 \cdot 10^{-3}$	11
$t\bar{t}H$	$7.6 \cdot 10^{-2}$	8.2	$t\bar{t}HH$	$5.9 \cdot 10^{-4}$	13
$t\bar{t}WW$	$1.2 \cdot 10^{-1}$	15	$t\bar{t}t\bar{t}$	$1.6 \cdot 10^{-3}$	22
HZ	$4.3 \cdot 10^{0}$	1.7	$HHWW$	$4.3 \cdot 10^{-3}$	9.2
HHZ	$2.1 \cdot 10^{-2}$	4.2	HZZ	$9.4 \cdot 10^{-2}$	2.7
$HHHZ$	$4.7 \cdot 10^{-5}$	6.9	$HHZZ$	$5.9 \cdot 10^{-4}$	5.7
HWW	$6.6 \cdot 10^{-1}$	4.5			
WW	$2.1 \cdot 10^{2}$	4.8	WWZ	$1.6 \cdot 10^{1}$	6.2
ZZ	$3.9 \cdot 10^{1}$	2.4	ZZZ	$4.8 \cdot 10^{-1}$	2.3

μ Collider: SM Processes

VBF > s-channel

	σ [fb]	$\sqrt{s}$ [TeV]		σ [fb]	$\sqrt{s}$ [TeV]
$t\bar{t}$	$8.4 \cdot 10^{0}$	4.5	$t\bar{t}ZZ$	$2.2 \cdot 10^{-2}$	8.4
$t\bar{t}Z$	$5.3 \cdot 10^{-1}$	6.9	$t\bar{t}HZ$	$7.0 \cdot 10^{-3}$	11
$t\bar{t}H$	$7.6 \cdot 10^{-2}$	8.2	$t\bar{t}HH$	$5.9 \cdot 10^{-4}$	13
$t\bar{t}WW$	$1.2 \cdot 10^{-1}$	15	$t\bar{t}t\bar{t}$	$1.6 \cdot 10^{-3}$	22
HZ	$4.3 \cdot 10^{0}$	1.7	$HHWW$	$4.3 \cdot 10^{-3}$	9.2
HHZ	$2.1 \cdot 10^{-2}$	4.2	HZZ	$9.4 \cdot 10^{-2}$	2.7
$HHHZ$	$4.7 \cdot 10^{-5}$	6.9	$HHZZ$	$5.9 \cdot 10^{-4}$	5.7
HWW	$6.6 \cdot 10^{-1}$	4.5			
WW	$2.1 \cdot 10^{2}$	4.8	WWZ	$1.6 \cdot 10^{1}$	6.2
ZZ	$3.9 \cdot 10^{1}$	2.4	ZZZ	$4.8 \cdot 10^{-1}$	2.3

A μ collider with $\sqrt{s} \sim$ few TeV is essentially a **W-Boson** collider!

μ Collider: EFT

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

μ Collider: EFT

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

Relevant operators for the **Higgs** and **top quark** EW sector

$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}_{tW}$	$i\left(\bar{Q}\sigma^{\mu\nu}\,\tau_I\, t\right)\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{tB}$	$i\left(\bar{Q}\sigma^{\mu\nu}\, t\right)\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\varphi\right)\left(\bar{Q}\,\gamma^\mu\,\tau^I Q\right)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\,\varphi\right)\left(\bar{Q}\,\gamma^\mu\, Q\right)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\,\varphi\right)\left(\bar{t}\,\gamma^\mu\, t\right)$
$\mathcal{O}_\varphi$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$		

μ Collider: EFT

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

Relevant operators for the **Higgs** and **top quark** EW sector

$\mathcal{O}_W$	$\varepsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{tW}$	$i\left(\bar{Q}\sigma^{\mu\nu}\tau_I\, t\right)\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{tB}$	$i\left(\bar{Q}\sigma^{\mu\nu}\, t\right)\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi) B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$
$\mathcal{O}_{\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$		

$$R(c_i) \equiv \frac{\sigma}{\sigma_{SM}} = 1 + c_i \frac{\sigma^i_{Int}}{\sigma_{SM}} + c^2_{i,i}\frac{\sigma^{i,i}_{Sq}}{\sigma_{SM}} = 1 + r_i + r_{i,i}$$

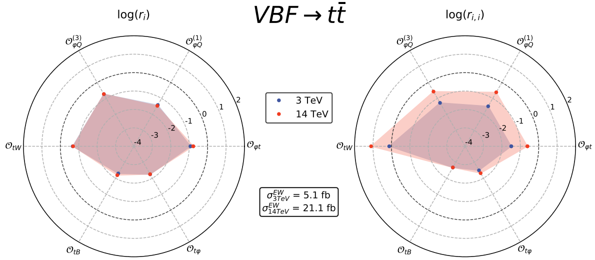
μ Collider: EFT

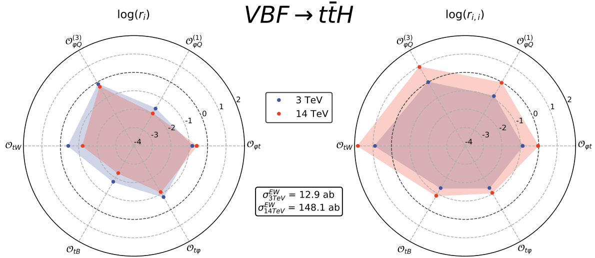
Bound on the operators

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

Buckley et.al.;Butter et.al.;Ellis,Murphy,Sanz,You;Hartland et.al.

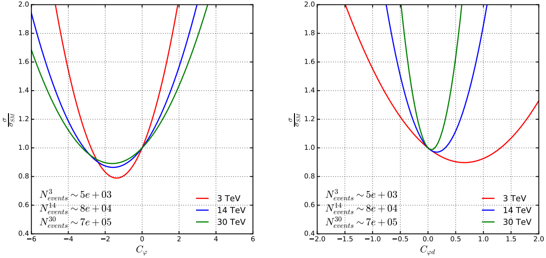
μ Collider: EFT



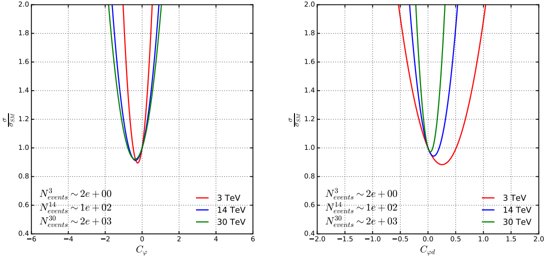


μ Collider: EFT

VBF *hh* sensitivity ratios

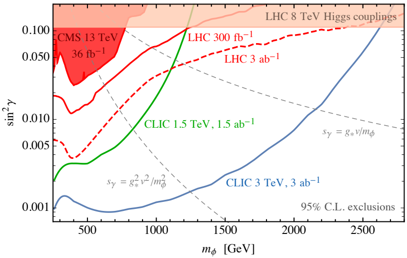


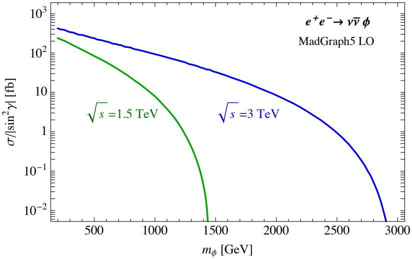
VBF *hhh* sensitivity ratios

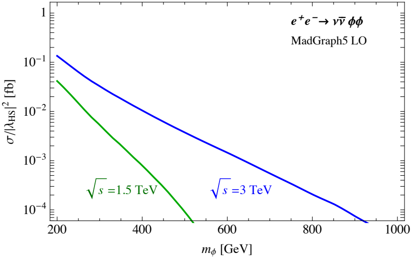


BSM @ μ Collider

BSM @ High-Energy Lepton Collider

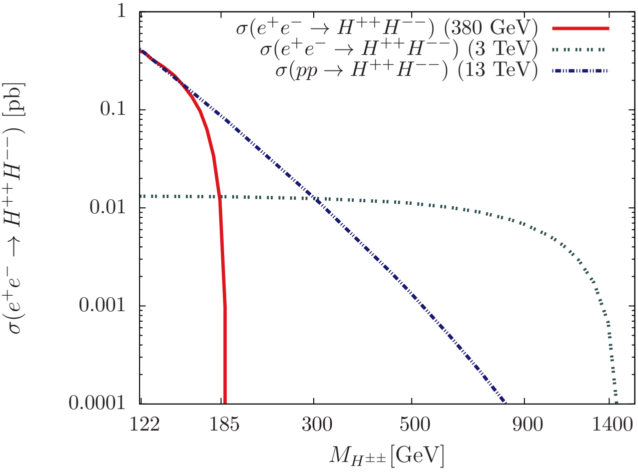






D.Buttazzo, D.Redigolo, F.Sala and A.Tesi
JHEP **11** (2018), 144

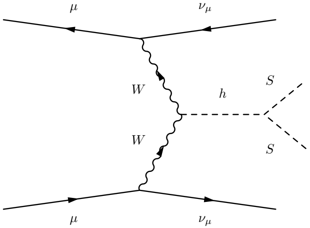
BSM @ High-Energy Lepton Collider

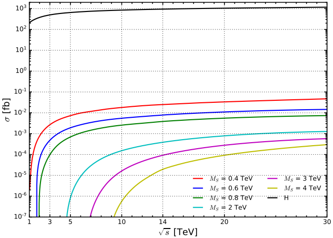


P.Agrawal, M.Mitra, S.Niyogi, S.Shil and M.Spannowsky
Phys. Rev. D **98** (2018) no.1, 015024

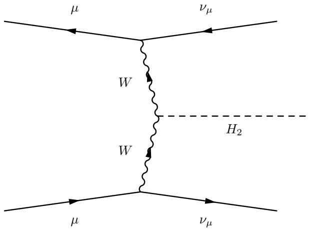
μ Collider: BSM Processes (neutral scalars)

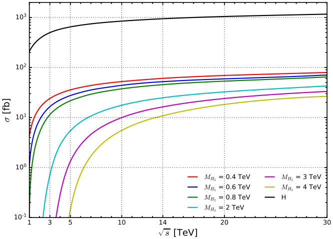
SM+inert singlet





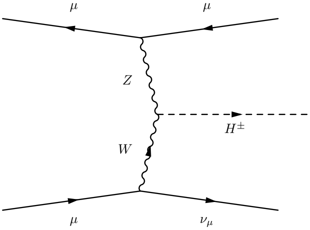
2HDM

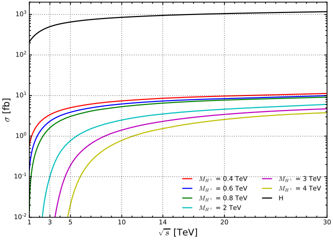


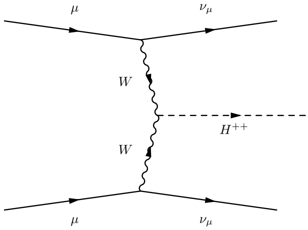


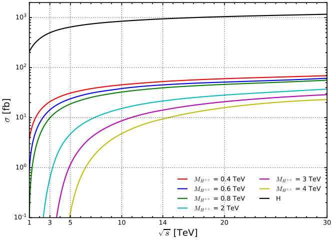
μ Collider: BSM Processes (charged scalars)

Georgi-Machacek model



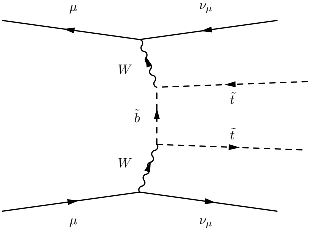


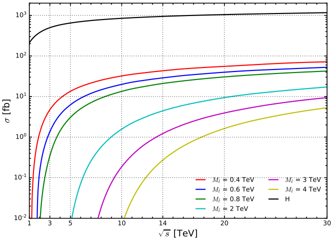


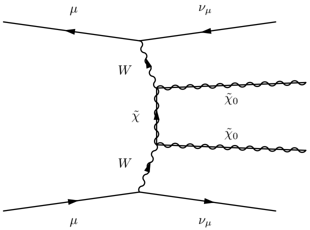


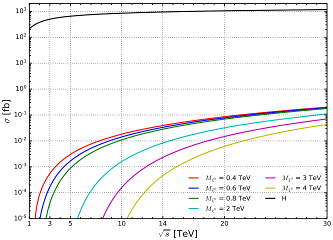
μ Collider: BSM Processes (sparticles)

MSSM

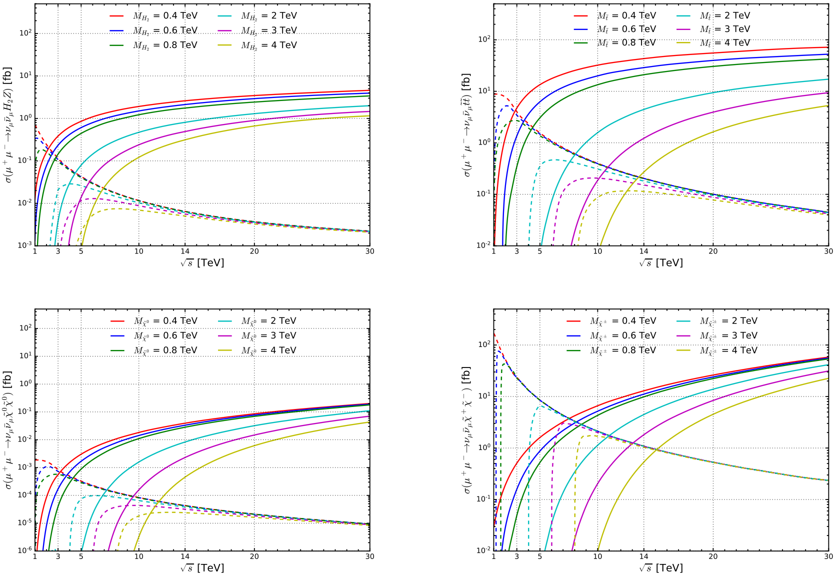






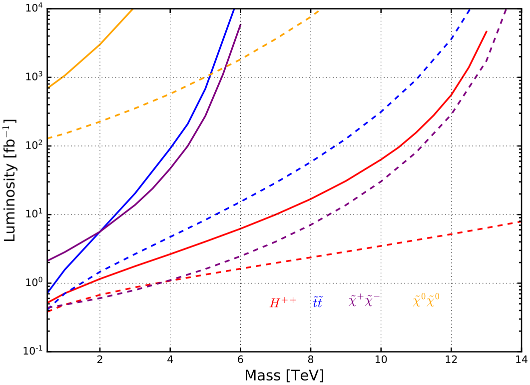


BSM @ μ Collider: VBF vs s-channel



New Physics Reach (via VBF) @ μ Collider

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



Luminosity required for 25 events, with assumed zero background

Conclusions

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

Thanks

Backup Slides

SM + Singlet

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

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

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

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

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

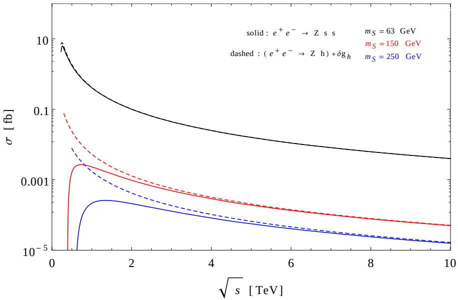
$$\lambda_{hhs} = \frac{(2m_h^2 + m_s^2)}{2v\,v_s}\sin 2\theta(v_s\cos\theta - v\sin\theta)$$

SM + Singlet: Inert Pair Production vs. Loop Corrections

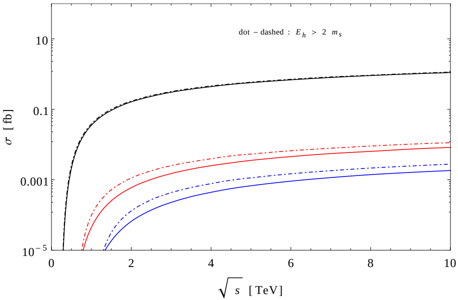
$$\delta g_h = -\frac{\kappa_\sigma^2 v^2}{16\pi^2 m_h^2}\left(1 - 4m_S^2 \frac{\tan^{-1}\sqrt{\frac{m_h^2}{(4m_S^2 - m_h^2)}}}{\sqrt{m_h^2\,(4m_S^2 - m_h^2)}}\right)$$

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

s-channel



VBF



2HDM

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

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

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

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

GM Model

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

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

Custodial Limit

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

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

μ Collider: Pros and Cons

μ vs. e
(circular collider)

Pros 👍

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

Cons 👎

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