Anomalous Quartic Gauge Couplings at a Muon Collider

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Overview

- Prospects for searches of **anomalous quartic gauge couplings** (aQGCs) at a **future muon collider** using **WW boson pairs** produced from **vector boson scattering** (VBS) and **decaying hadronically** are reported
  - aQGCs could point in the right direction for **new physics models** (BSM)
- Considering two channels: $W^+W^-\nu_\mu\nu_\mu$ and $W^+W^-\mu\mu$ (Fig. 1)
- aQGC searches can be framed generically with **dimension-8 effective field theory** (EFT) operators
- **Muon colliders** have considerable advantages compared to proposed e^+e^- and pp colliders

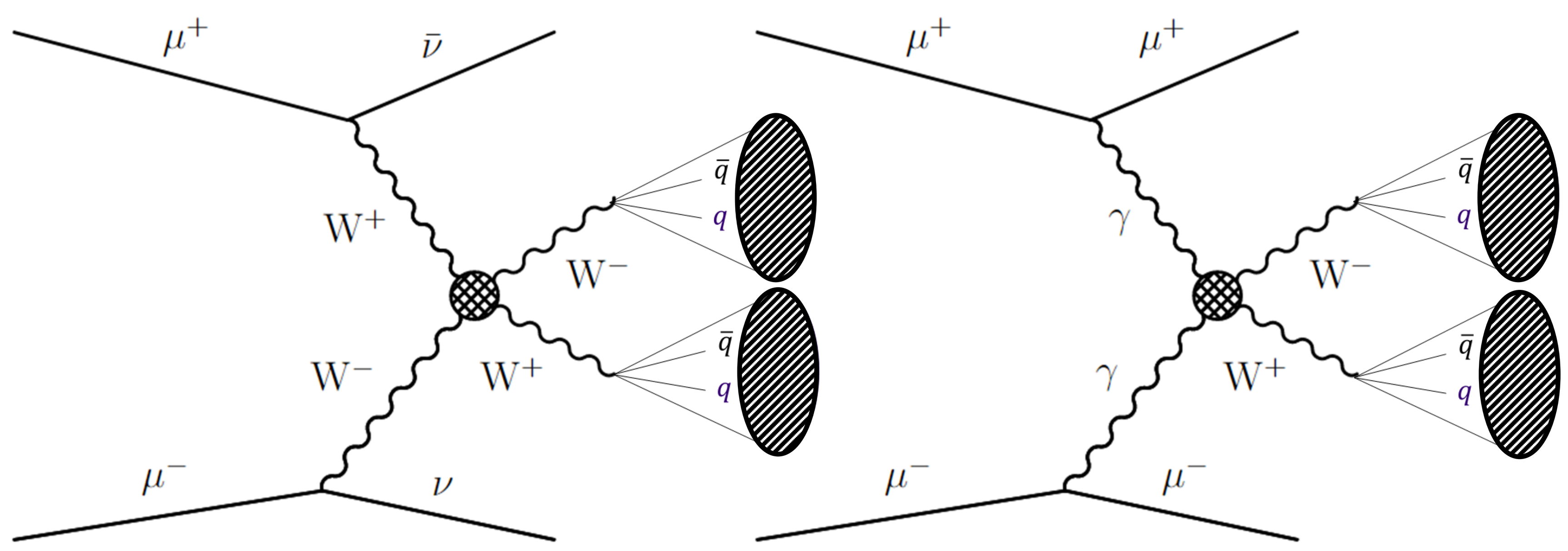

Fig. 1: Representative Feynman diagrams of the $W^+W^-\nu_\mu\nu_\mu$ (left) and $W^+W^-\mu\mu$ (right) processes. New physics (hatched circle) in the EW sector can modify the QGCs. Each W decays hadronically, resulting in one boosted jet.

Why Muon Collider?

- **High energy & luminosity**
- **Clean environment** (but need to consider muon beam decays)
- **"Weak boson collider"** – great opportunity to study VBS processes

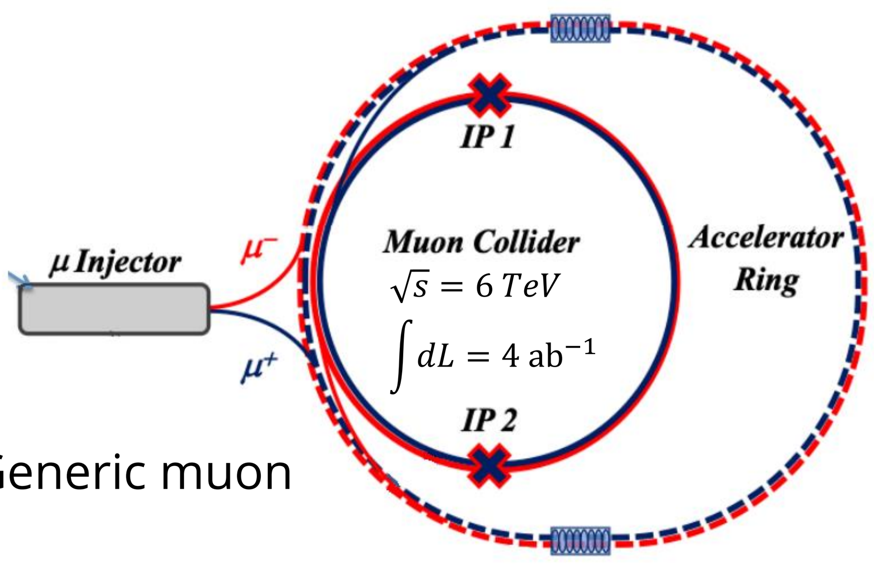

Fig. 2: Generic muon collider

aQGC dimension-8 EFT framework

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \underbrace{\sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i^{(6)}}_{\text{dim-6}} + \underbrace{\sum_i \frac{f_i}{\Lambda^4}\mathcal{O}_i^{(8)}}_{\text{dim-8}} + \cdots$$

- **Expands the standard model** in powers of the energy scale $1/\Lambda$
- **Ten independent dim-8 operators**
- **Violates tree-level unitarity** at sufficiently high energy

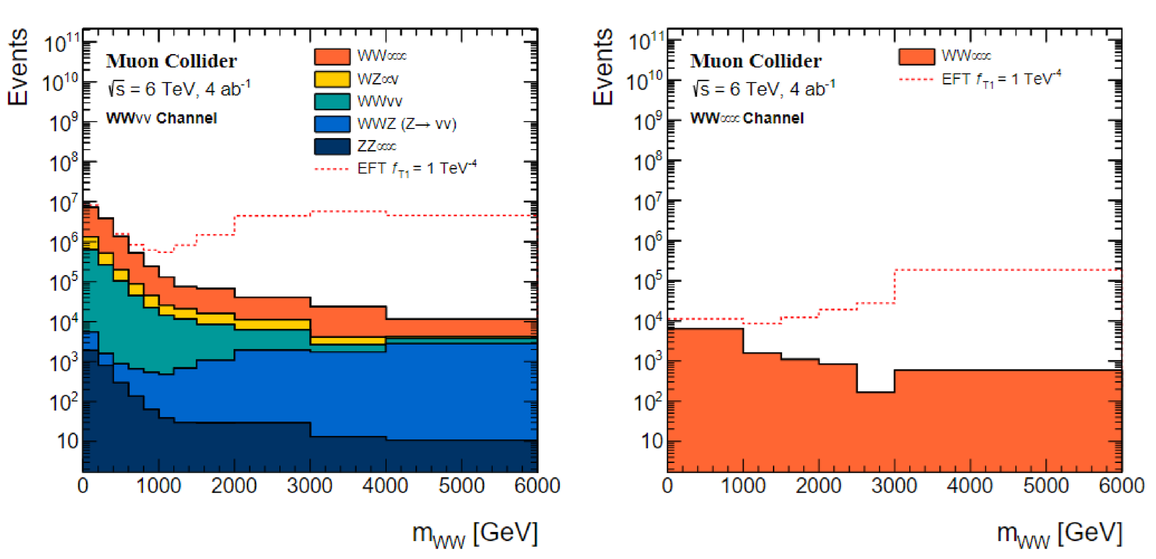

Fig. 3: m_{WW} in the $W^+W^-\nu_\mu\nu_\mu$ (left) and $W^+W^-\mu\mu$ (right) channels after event selection. The dashed lines show the signal predictions for one illustrative aQGC parameter. The overflow is included in the last bin.

Event Simulation

$$\left|A_{SM} + \sum_i c_i A_i\right|^2 = \underbrace{|A_{SM}|^2}_{\text{SM}} + \underbrace{\sum_i c_i 2Re(A_{SM}^* A_i)}_{\text{interference}} + \underbrace{\sum_i c_i^2 |A_i|^2}_{\text{quadratic}} + \cdots$$

- **SM, interference, and quadratic EFT** contributions to the signal process – MadGraph5
- **Background processes** ($WZ\mu\nu$, $ZZ\mu\mu m$, $WW\mu\mu$, and WWZ) – Whizard 3
- **Parton showering and hadronization** – Pythia 8.306
- **Detector effects** – Delphes 3.5
- **Beam induced backgrounds** – not considered

Event Selection

- Targeting hadronically decaying WW pairs with large invariant mass
- Two channels:
- $\boldsymbol{W^+W^-\nu_\mu\nu_\mu}$
  - 0 leptons, large $M_{missing}$, two jets
- $\boldsymbol{W^+W^-\mu\mu}$
  - 2 muons, low $E_{missing}$, two jets

Statistical Analysis

- **Fit f_i/Λ^4 using distribution of invariant mass of WW pair m_{WW}** (Fig. 3)
- $W^+W^-\nu_\mu\nu_\mu$ and $W^+W^-\mu\mu$ considered separately
- **Each EFT operator is fit separately** – all other aQGC parameters are set to 0
- No systematic uncertainties are considered

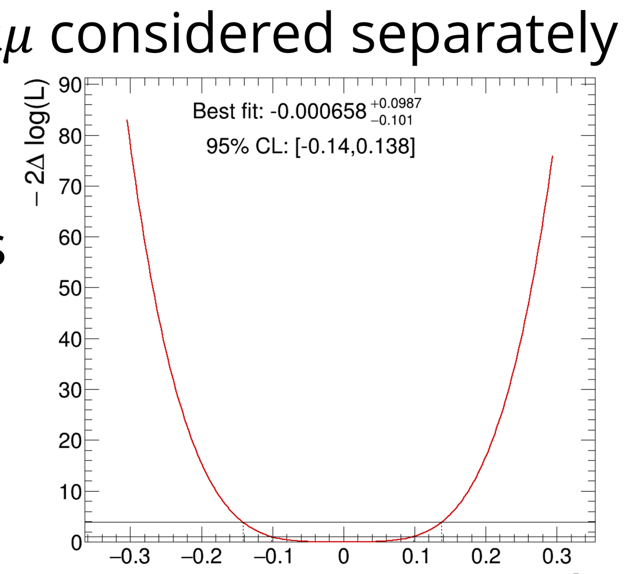

Fig. 4: test statistic vs $\frac{f_{S1}}{\Lambda^4}$ fit on m_{WW}

$WW\nu\nu$	Limits (TeV^{-4})
$f_{M,0}/\Lambda^4$	$[-0.032, 0.035]$
$f_{M,1}/\Lambda^4$	$[-0.088, 0.065]$
$f_{M,7}/\Lambda^4$	$[-0.12, 0.17]$
$f_{S,0}/\Lambda^4$	$[-0.22, 0.20]$
$f_{S,1}/\Lambda^4$	$[-0.14, 0.14]$
$f_{T,0}/\Lambda^4$	$[-0.0062, 0.0030]$
$f_{T,1}/\Lambda^4$	$[-0.0082, 0.0031]$
$f_{T,2}/\Lambda^4$	$[-0.0096, 0.0046]$

$WW\mu\mu$	Limits (TeV^{-4})
$f_{T,0}/\Lambda^4$	$[-0.04, 0.028]$
$f_{T,1}/\Lambda^4$	$[-0.025, 0.0095]$
$f_{T,2}/\Lambda^4$	$[-0.12, 0.068]$
$f_{T,6}/\Lambda^4$	$[-0.034, 0.033]$
$f_{T,7}/\Lambda^4$	$[-0.043, 0.038]$

Fig 3: expected 95% confidence level lower and upper limits on the aQGC parameters f/Λ^4, where f is the Wilson coefficient of the given operator and Λ is the energy scale of new physics.

Future Work

- Unitarity consideration
- Beam induced backgrounds
- Complete BSM model
- Higher center-of-mass energies ($\sqrt{s} = 10, 30$ TeV)

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