Anomalous Quartic Gauge couplings at a Muon Collider

Elham E Khoda

University of Washington, Seattle

on behalf of

Brad Abbot[1], Aram Apyan[2], Bianca Azartash-Namin[1], Veena Balakrishnan[1] Jeffrey Berryhill[3], Shih-Chieh Hsu[4], Sergo Jindariani[3], Mayuri Kawale[1], Elham E Khoda[4], Ryan Parsons[1], Alexander Schuy[4], Michael Strauss[1], John Stupak[1]

[1] University of Oklahoma, [2]Brandeis University, [3]Fermilab, [4]University of Washington

Snowmass CSS, Seattle

July 20, 2022

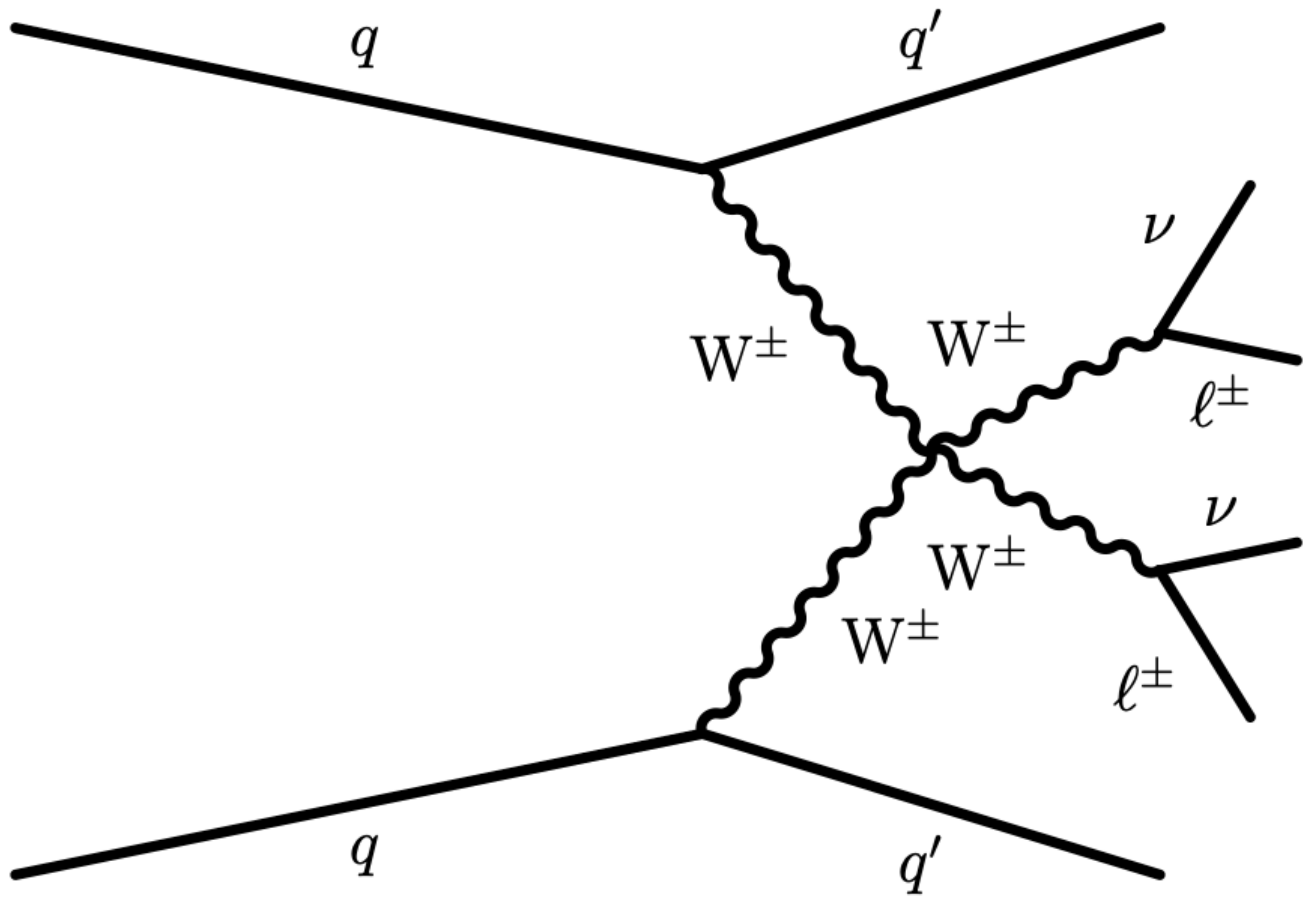
Accelerated AI Algorithms for Data-Driven Discovery

UNIVERSITY of WASHINGTON

Vector Boson Scattering

Vector Boson Scattering (VBS): $VV \rightarrow VV$ scattering

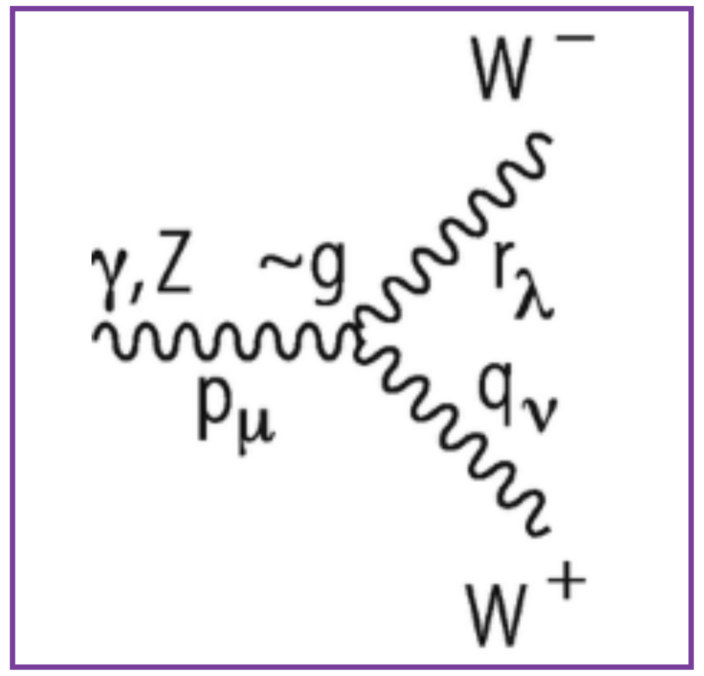
- Key measurements to fully explore EWSB and probe for BSM models
- $V_L V_L \rightarrow V_L V_L$ scattering unitarized by the interference with amplitudes involving Higgs bosons

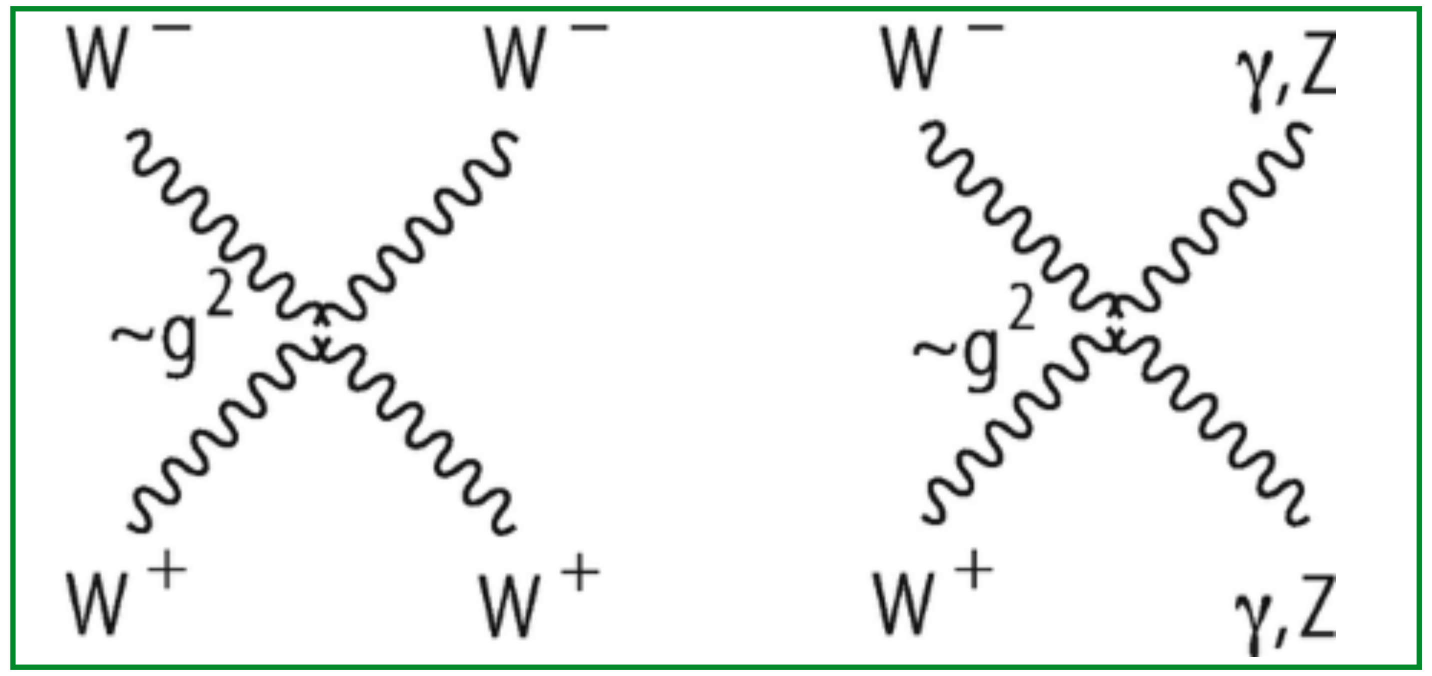


Window for new physics

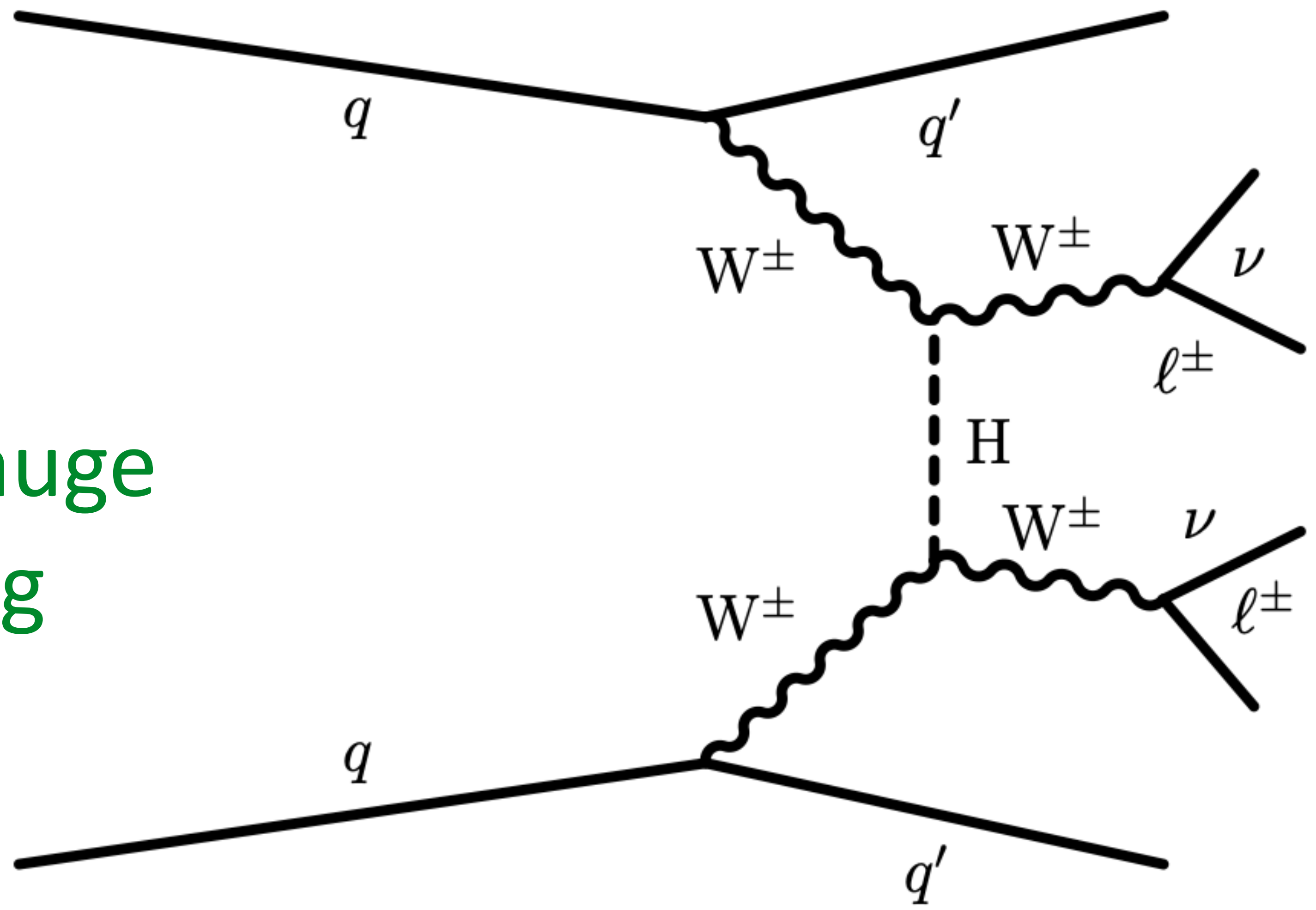
- Anomalous triple and quartic gauge boson couplings

Triple Gauge Coupling





Quartic Gauge Coupling

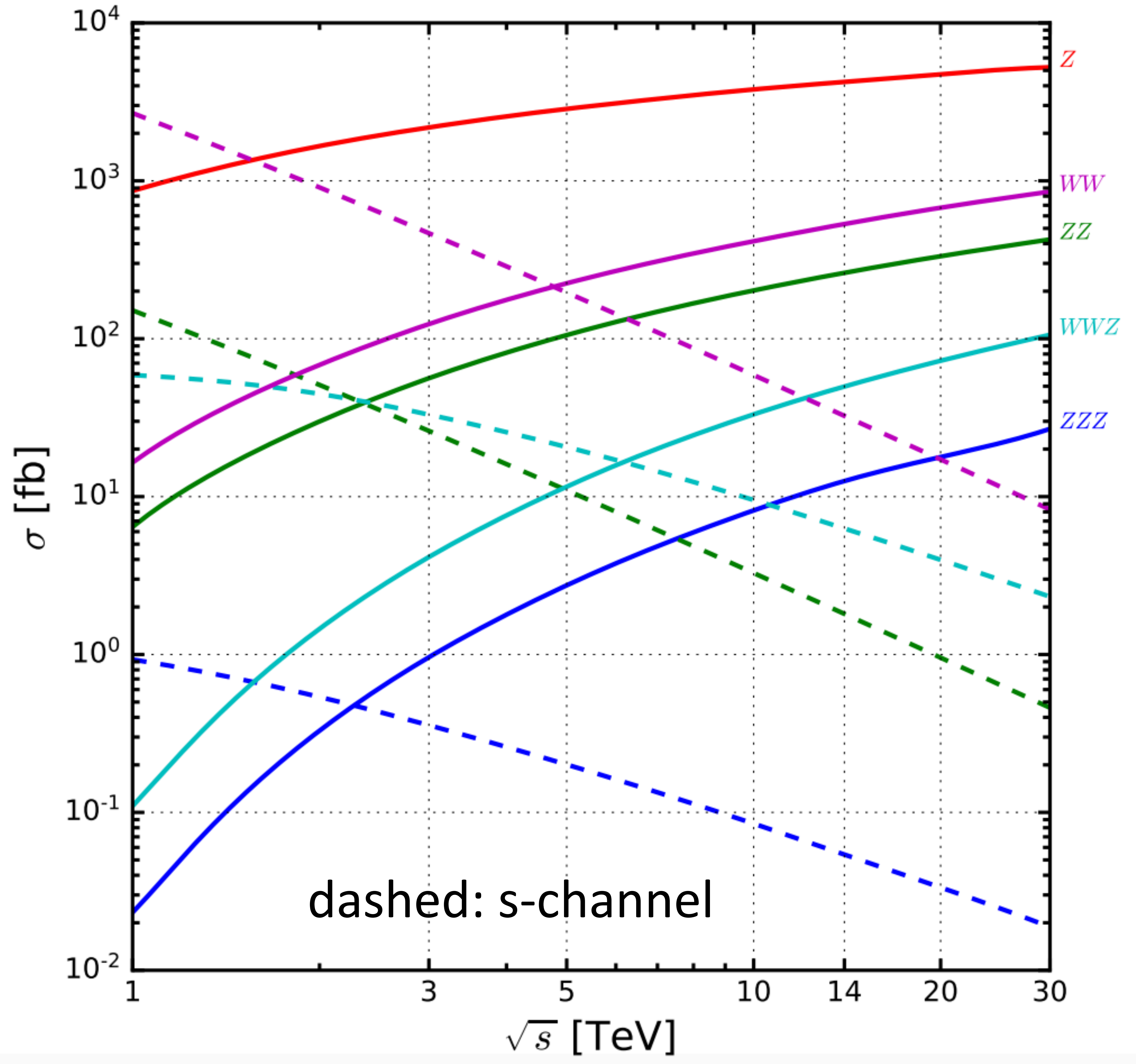


Muon Collider as a "Weak Boson Collider"

- Muon collider provides a clean environment
- More energy efficient than the hadron colliders

High energy muon colliders

- At few ~TeV it is a high luminosity boson collider
- Perfect for fully exploring VBS
- Production cross sections grow as logs while the corresponding s-channel decrease as ~1/s



arXiv:2005.10289

Introduction

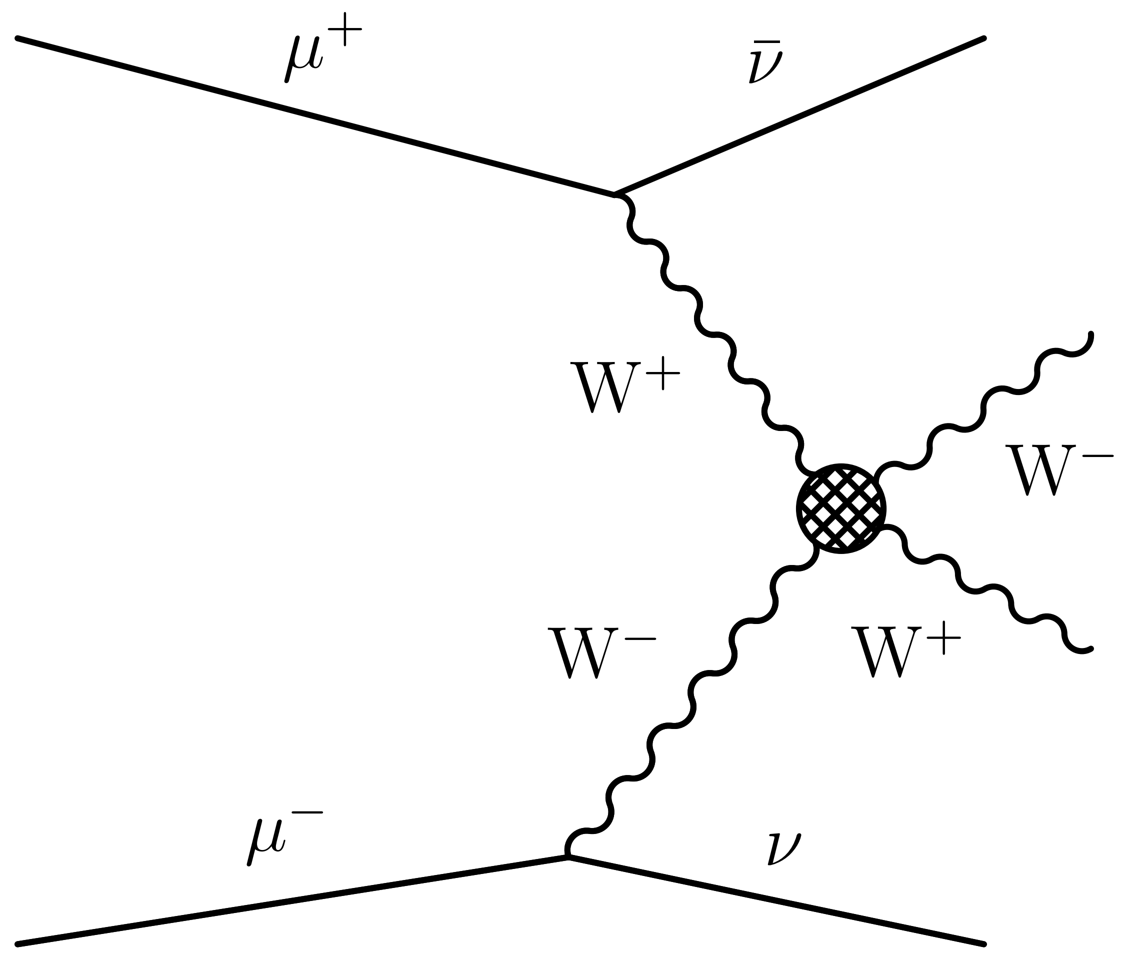
- Goal is to study anomalous quartic gauge couplings (aQGCs) at a muon collider with VBS WW final state
- In this study, we consider $\sqrt{s} = 6$ TeV
- Target luminosity 4 ab^{-1}

Snowmass White paper

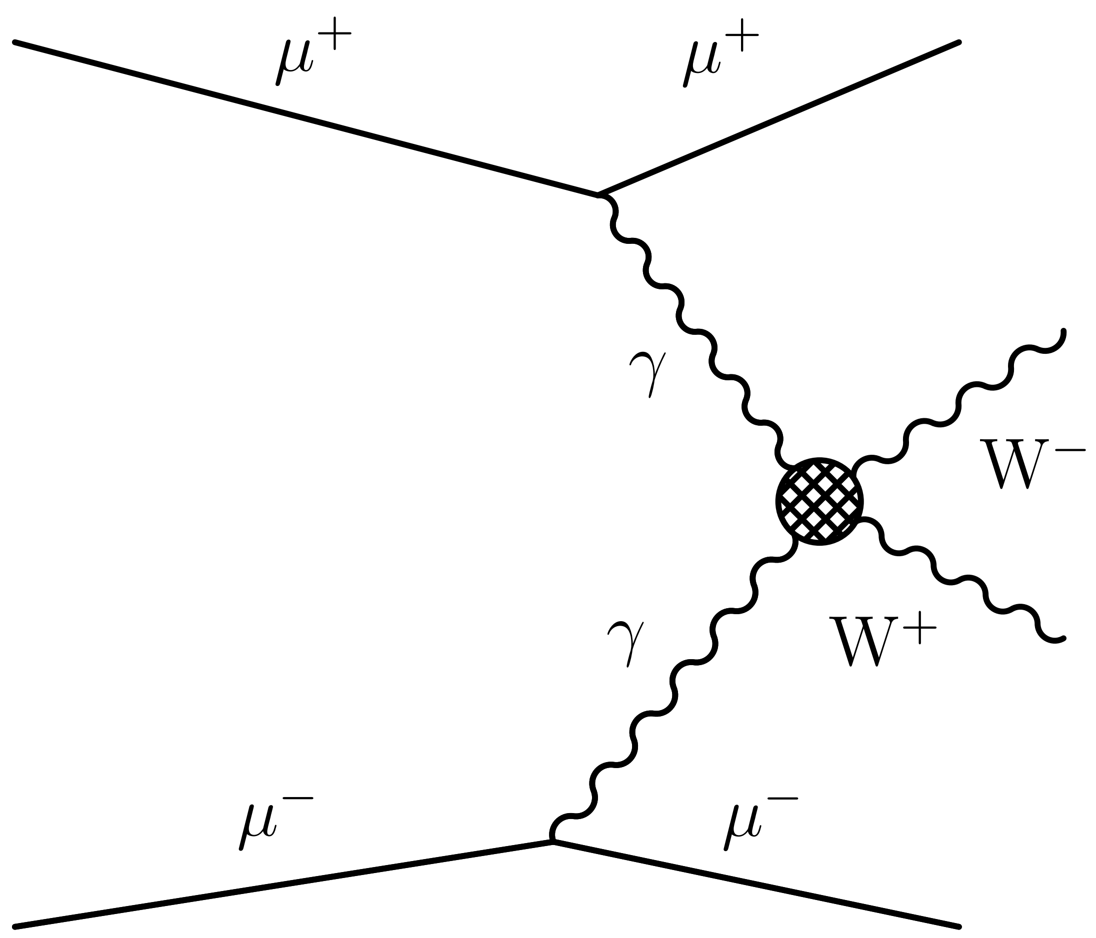
arXiv:2203.08135

- Studying the full-hadronic channels with two final states:
  - $WW\nu\nu$ and $WW\mu\mu$

$WW\nu\nu$ Channel



$WW\mu\mu$ Channel



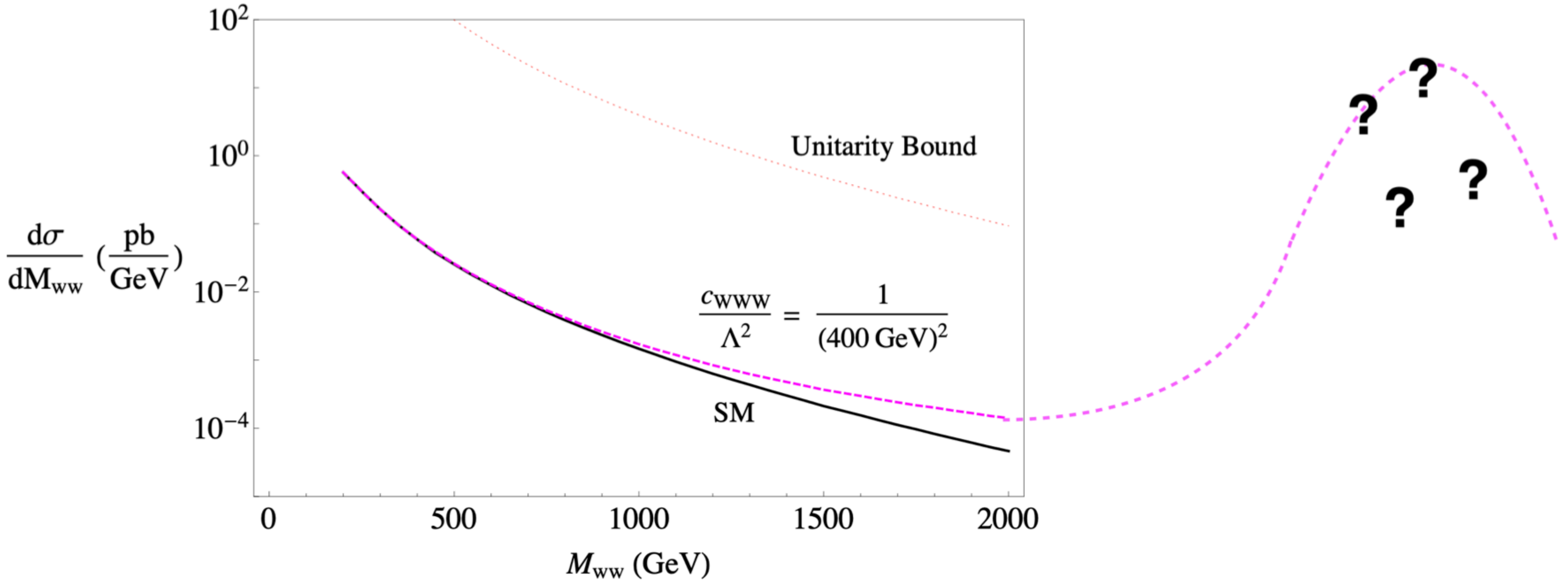
Effective Field Theory and aQGC

Hints for new physics using Effective Field Theory (EFT) approach

SMEFT

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

- SM: f_i = 0 for all i
- Any anomalous couplings (triple and quartic) can be be visible via non-zero f_i
- Goal is to set limit on the coefficients f_i



arXiv:1205.4231

aQGC via EFT dimension-8 operators

Looking at dimension-8 operators

- Grouped into 3 categories, S-type operators, T-type operators, M-type operators

$$\mathcal{O}_{S_0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_2} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\nu \Phi)^\dagger D^\mu \Phi \right]$$

We can set limits on

$S_0, S_1, M_0, M_1, M_6, M_7, T_0, T_1, T_2$ ($WW\nu\nu$ analysis)

$S_0, S_1, M_0 - M_7, T_0, T_0 - T_7$ ($WW\mu\mu$ analysis)

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Total amplitude:

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

WW$\nu\nu$ channel: Backgrounds

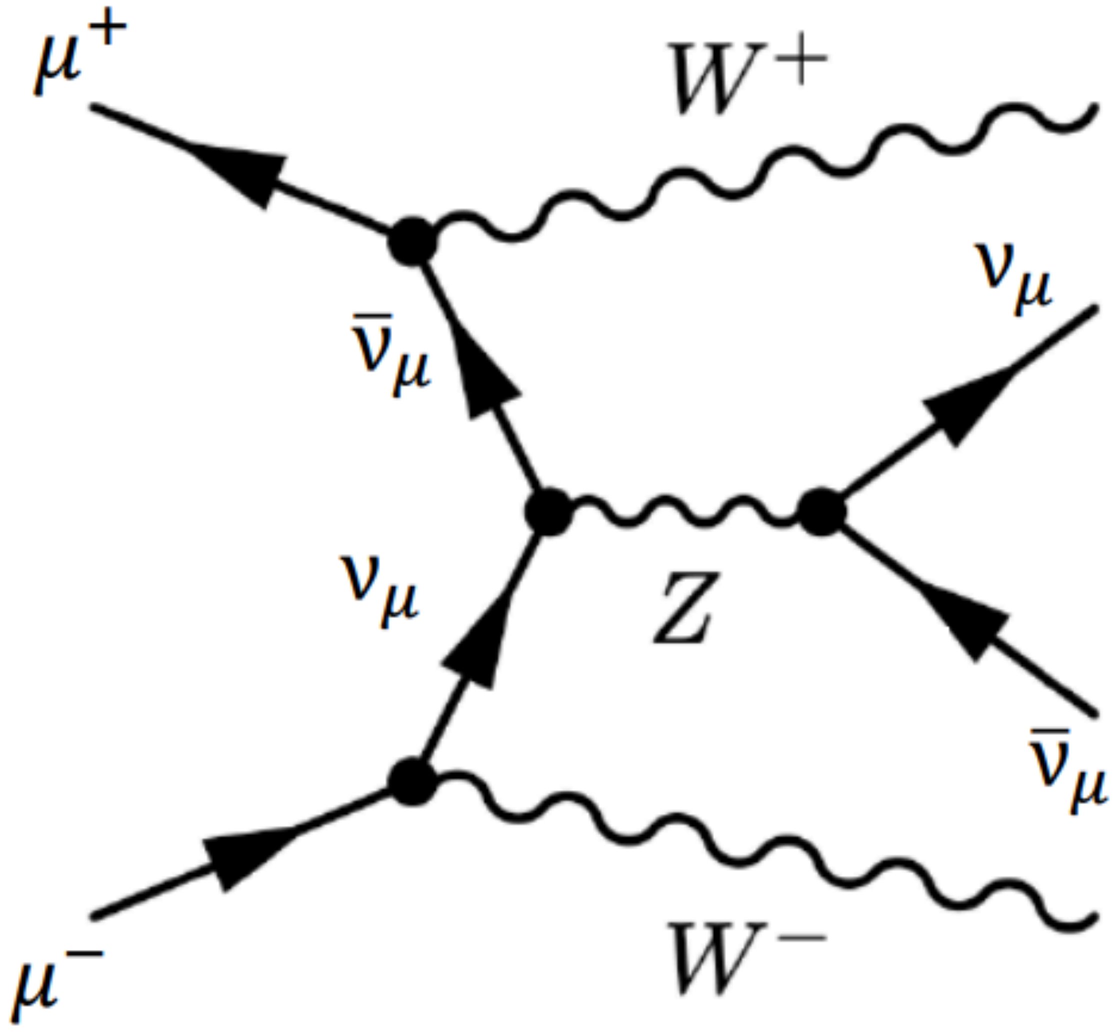
The Major backgrounds are SM-$WW\nu\nu$, $WW\mu\mu$, WWZ $(Z \to \nu\nu)$, $WZ\mu\nu$ and $ZZ\nu\nu$

- **Background samples:** Wizard + Pythia 8 + Delphes (muon config)
- **EFT Signal samples:** MadGraph + Pythia 8 + Delphes (muon config)

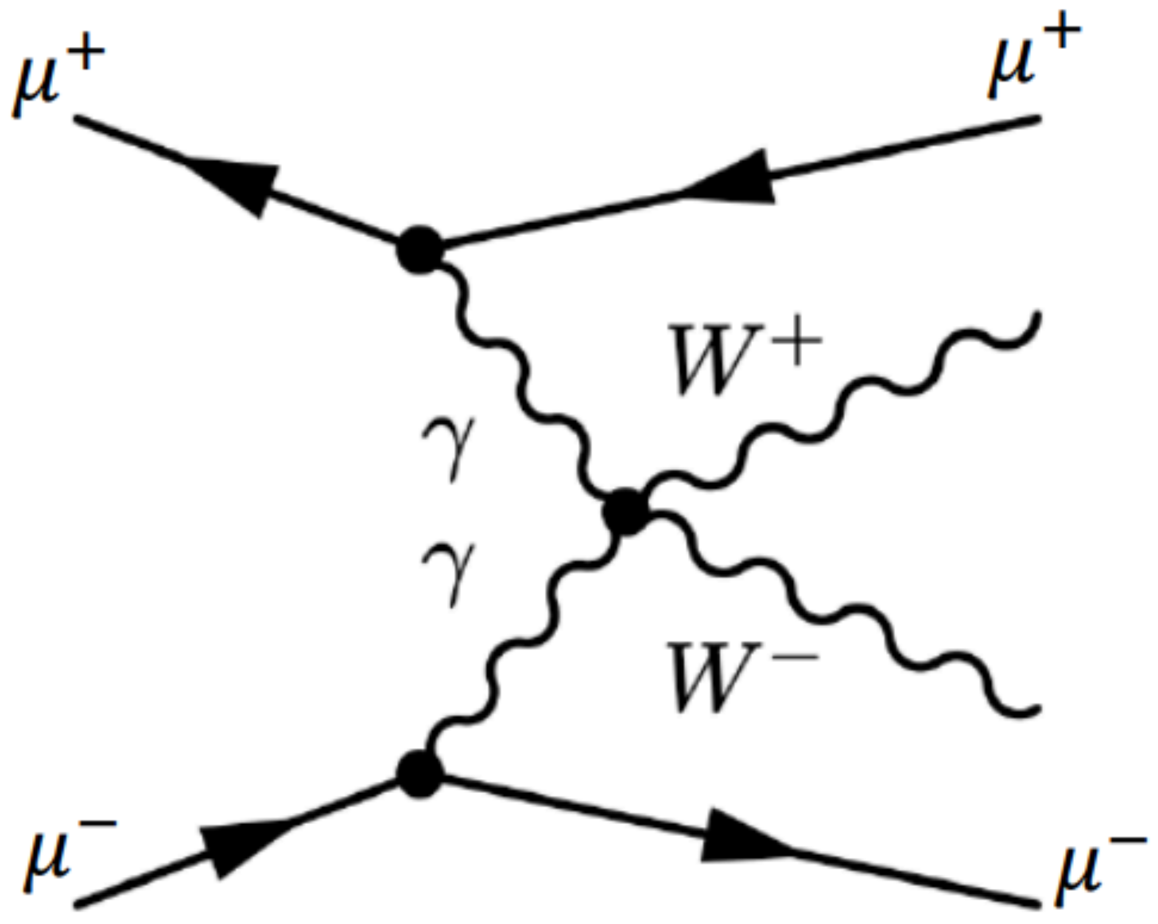
Generate the Interference and Quadratic terms separately

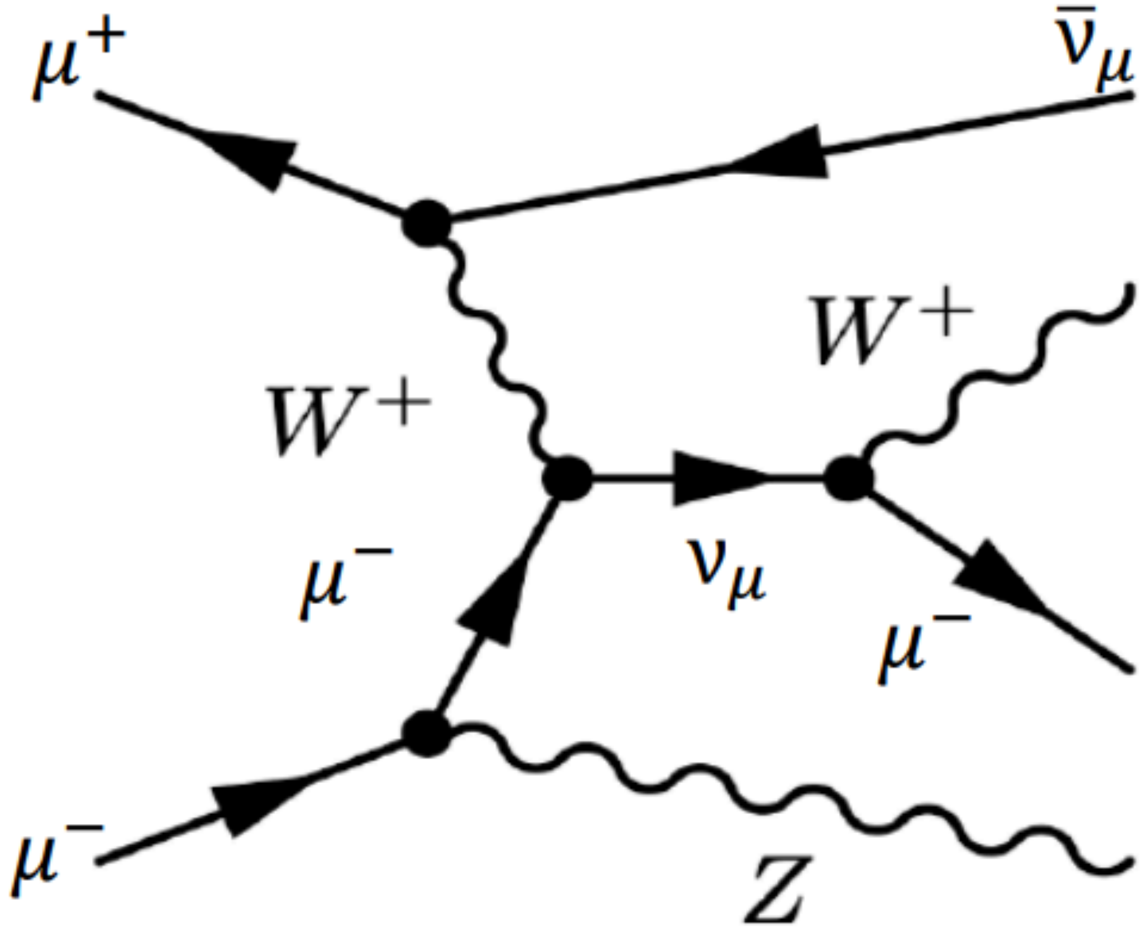
$$\left|A_{SM} + \sum_i c_i A_i\right|^2 = \underbrace{|A_{SM}|^2}_{\text{SM}} + \underbrace{\sum_i c_i 2Re(A^*_{SM} A_i)}_{\text{interference}} + \underbrace{\sum_i c_i^2 |A_i|^2}_{\text{quadratic}} + \cdots$$

WWZ $(Z \to \nu\nu)$



$WW\mu\mu$





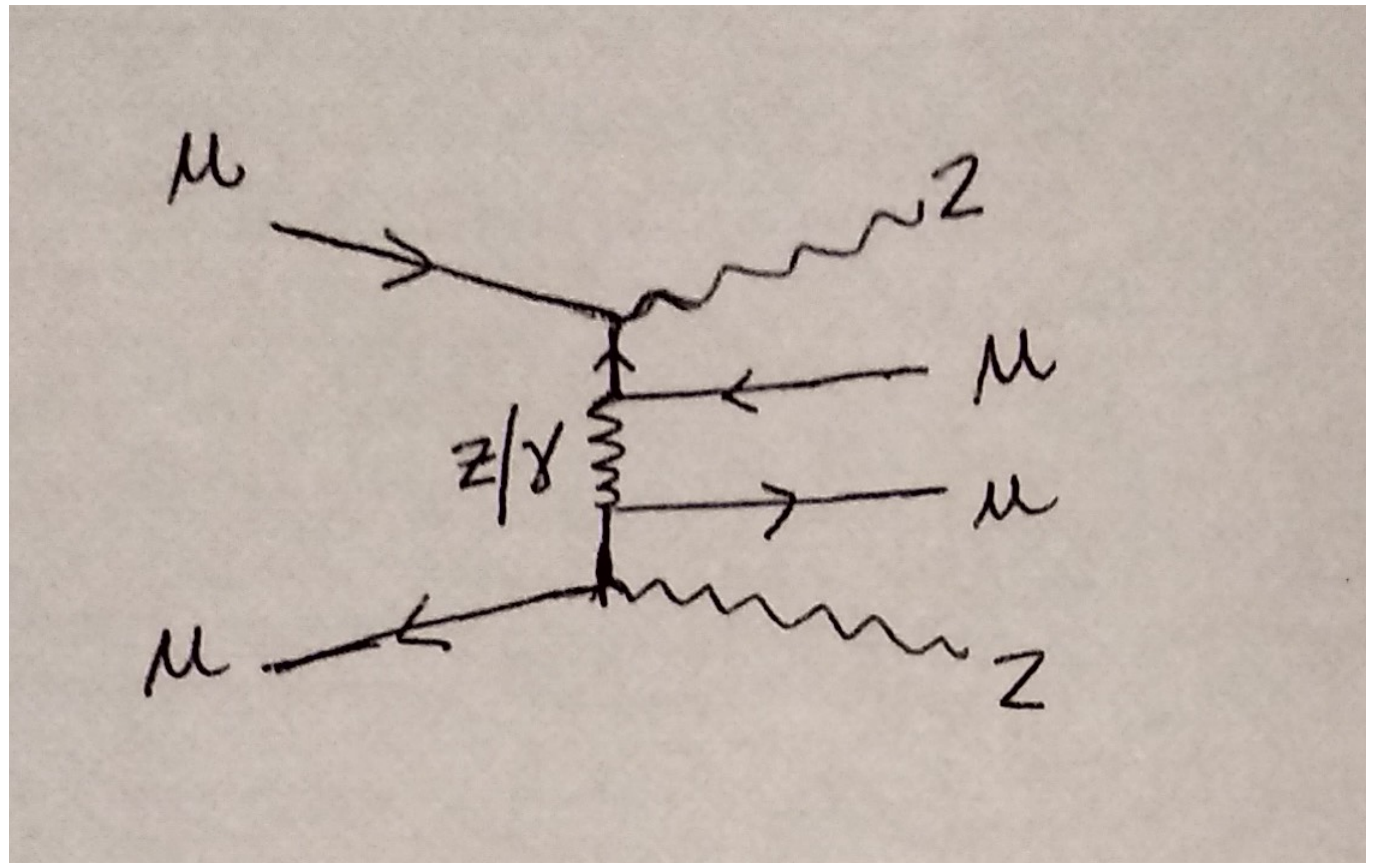
WW$\mu\mu$ channel: Backgrounds

The Major backgrounds are SM-$WW\mu\mu$, ZZZ / WZW (triboson), and 4V production

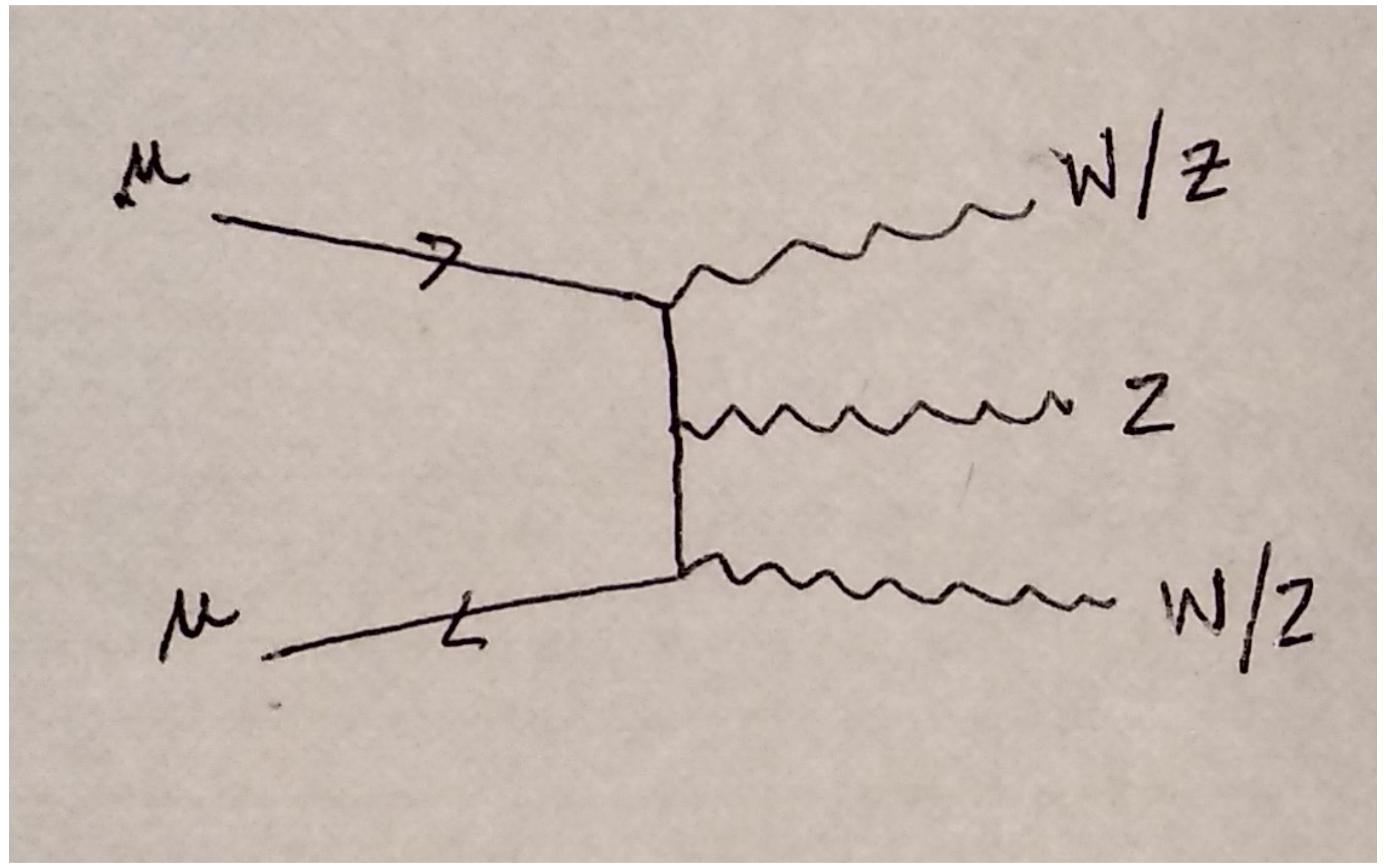
- **Background samples:** MadGraph + Pythia 8 + Delphes (muon config)
- **EFT Signal samples:** MadGraph + Pythia 8 + Delphes (muon config)

  Generate the Interference and Quadratic terms separately

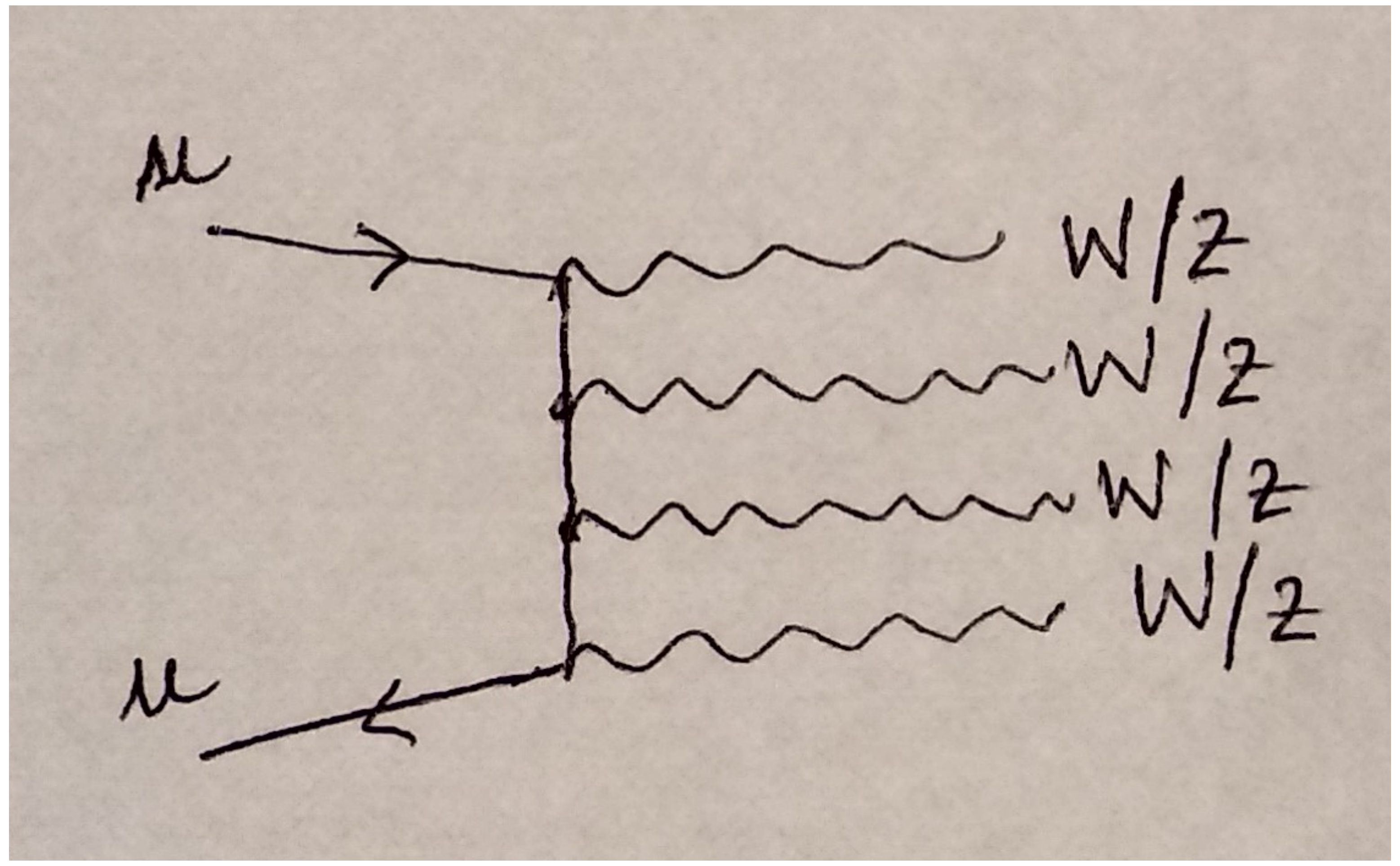
$ZZ\mu\mu$



Triboson: ZZZ / WZW



Quadboson: 4V



WW$\nu\nu$ channel: Event Selection

We studied the Fully Hadronic channel

Jet reconstruction: VLC jets with R=1.0 using inclusive algorithms

1. Exactly 0 lepton

Important to reduce the large photon-induced backgrounds

2. >= 2 jets with $m_{\text{jet}} > 50$ GeV

The Ws are being reconstructed as jets

$$m_{\text{miss}} = \sqrt{(\sqrt{s} - \underbrace{E_{\text{WW}}}_{\text{WW pair energy}})^2 - |\underbrace{\vec{p}_{\text{WW}}}_{\text{WW pair momentum}}|^2},$$

3. Missing mass > 200 GeV

Reduce $WW(Z \to \nu\nu)$, which should have m_{miss} ~91 GeV

4. cos θj < 0.8

Suppress t-channel exchanges, which leads to the vector bosons being close to the beam pipe

WW$\mu\mu$ channel: Event Selection

We studied the Fully Hadronic channel

Jet reconstruction: VLC jets with R=1.0 using inclusive algorithms

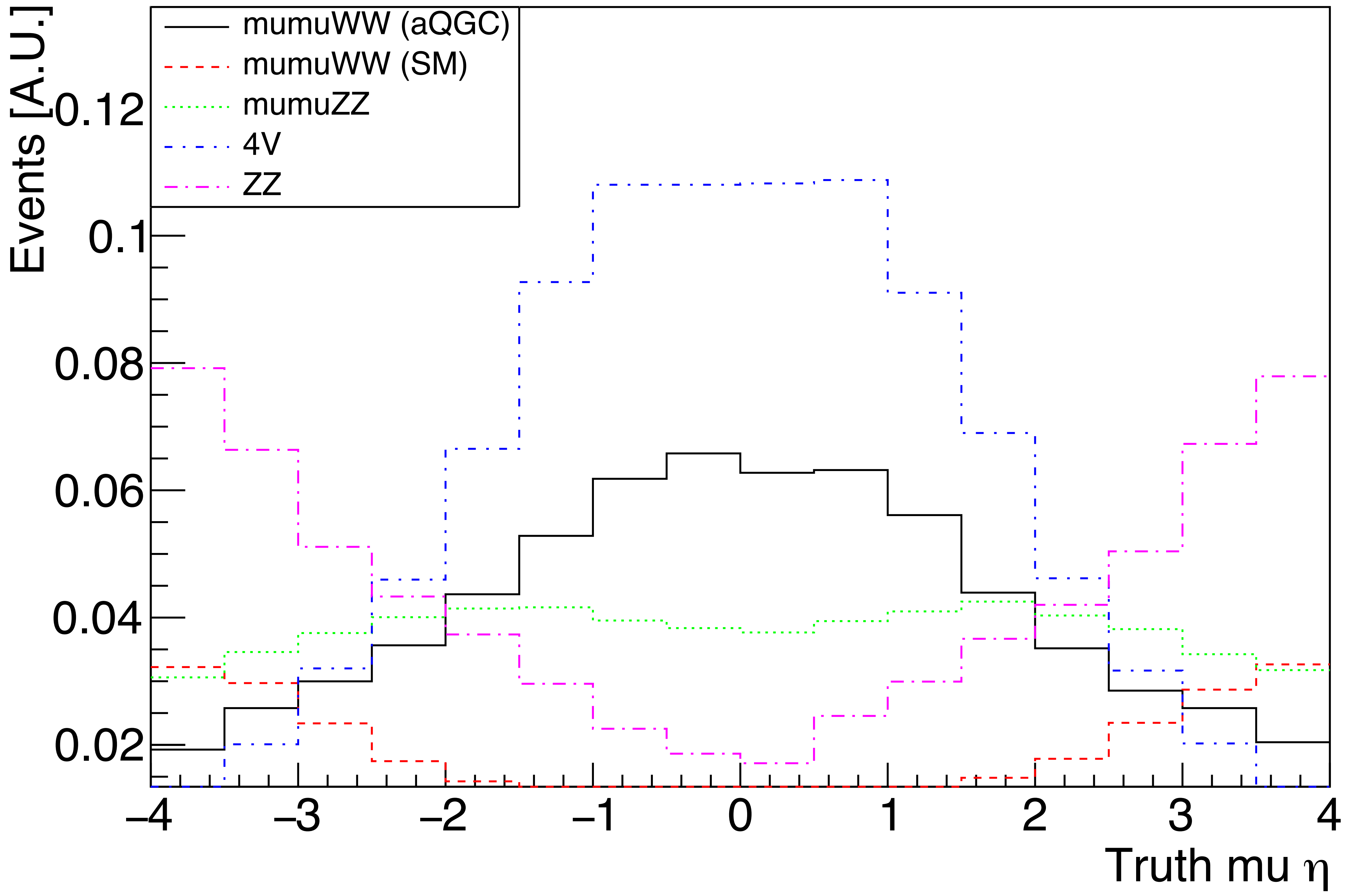
1. Exactly 2 oppositely charged muons

2. Mass of the muon pair ($m_{\mu\mu}$) > 106 GeV

Reduce contribution from the Z boson decay

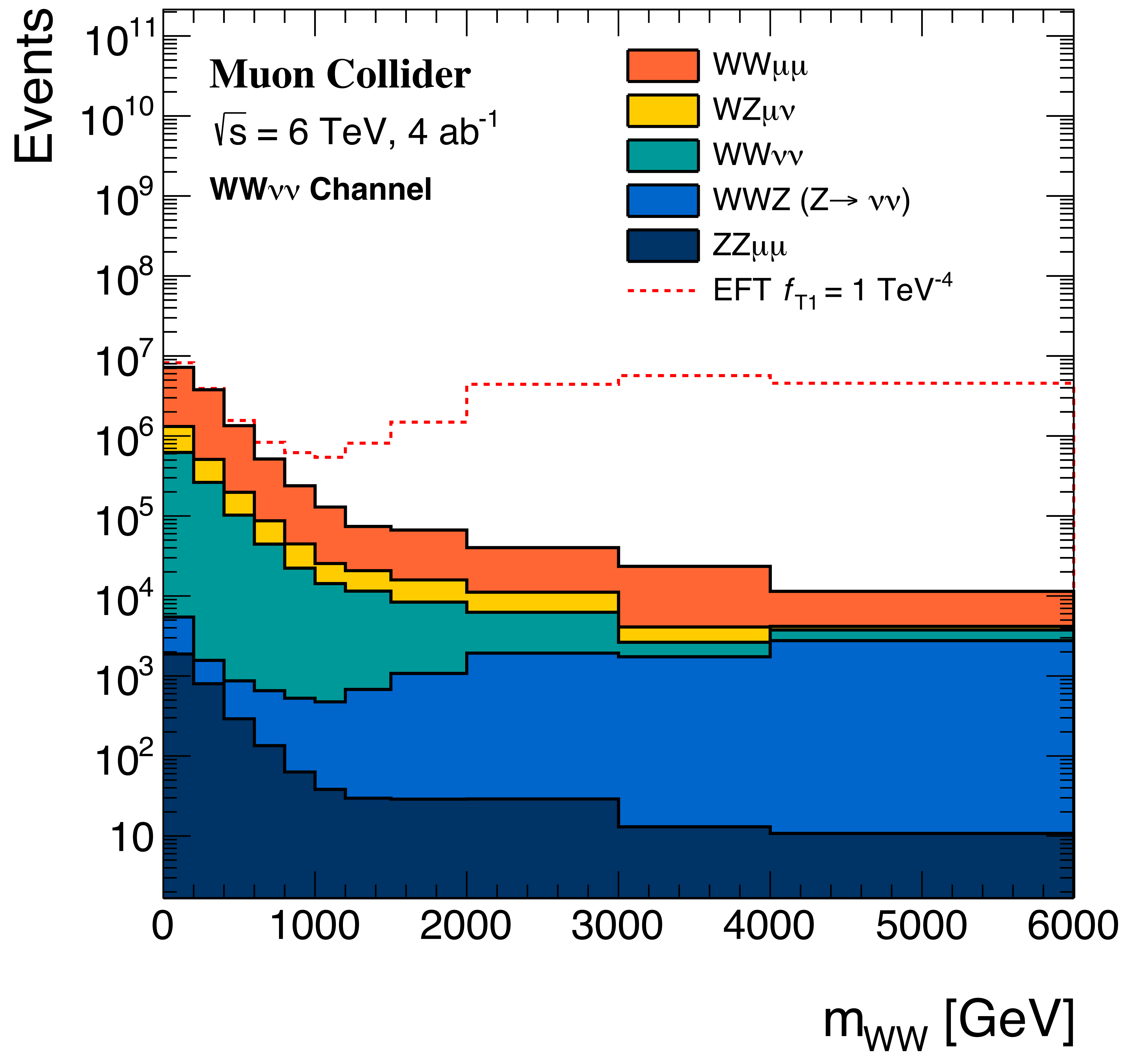
3. Exactly 2 jets, 50 GeV < m_{jet} < 100 Ge

Reduce low energy events

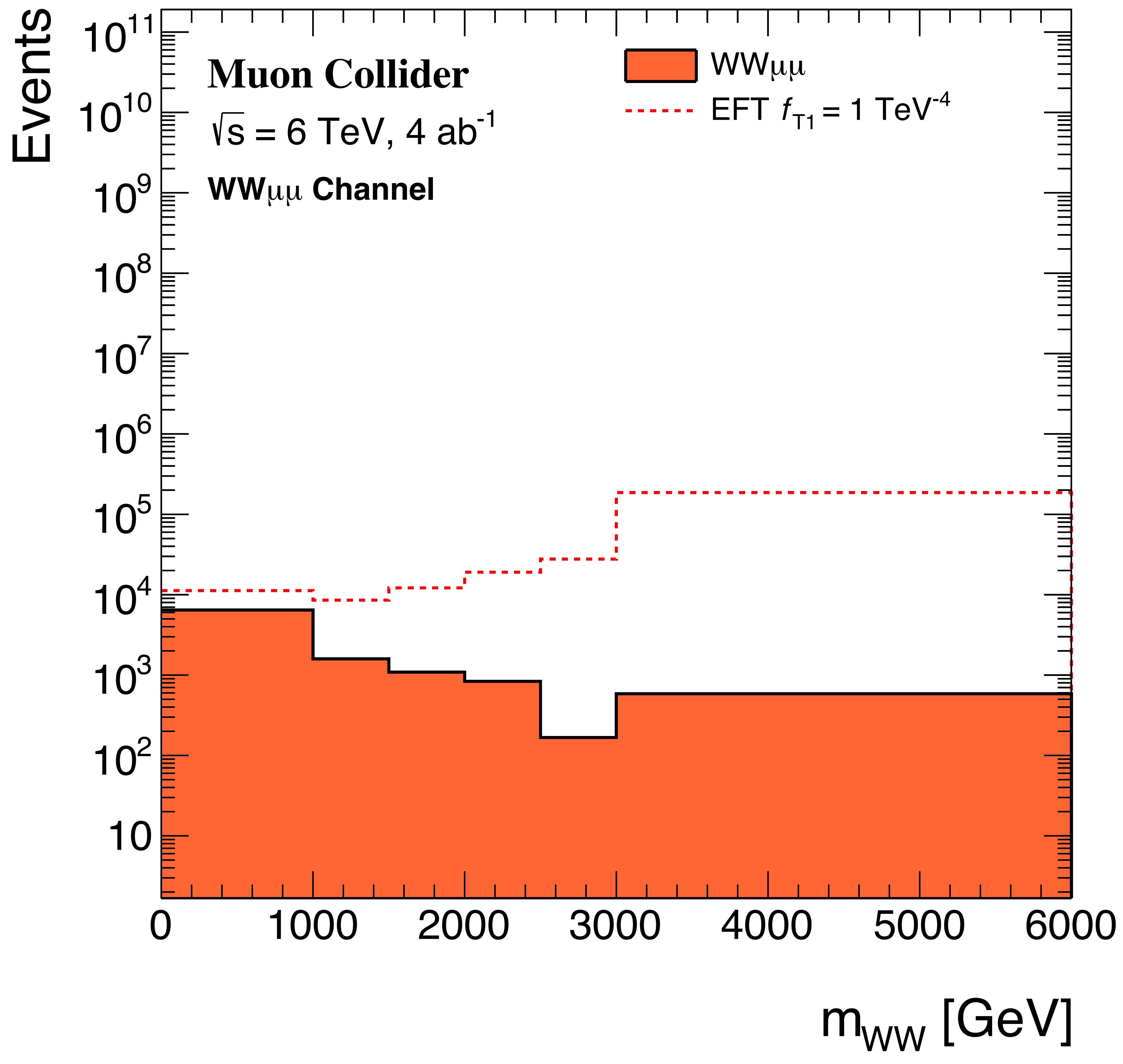


Mass of the W-pair

$WW\nu\nu$ Channel



$WW\mu\mu$ Channel



Limits on dim-8 EFT operators

- Tested one at a time, no cross operator term

$WW\nu\nu$ Channel

$\mathrm{WW}\nu\nu$	Limits (TeV^{-4})
$f_{\mathrm{M},0}/\Lambda^4$	$[-0.032, 0.035$
$f_{\mathrm{M},1}/\Lambda^4$	$[-0.088, 0.065$
$f_{\mathrm{M},7}/\Lambda^4$	$[-0.12, 0.17]$
$f_{\mathrm{S},0}/\Lambda^4$	$[-0.22, 0.20]$
$f_{\mathrm{S},1}/\Lambda^4$	$[-0.14, 0.14]$
$f_{\mathrm{T},0}/\Lambda^4$	$[-0.0062, 0.003$
$f_{\mathrm{T},1}/\Lambda^4$	$[-0.0082, 0.003$
$f_{\mathrm{T},2}/\Lambda^4$	$[-0.0096, 0.004$

$WW\mu\mu$ Channel

$\mathrm{WW}\mu\mu$	Limits (TeV^{-4})
$f_{\mathrm{T},0}/\Lambda^4$	$[-0.02, 0.01]$
$f_{\mathrm{T},1}/\Lambda^4$	$[-0.03, 0.01]$
$f_{\mathrm{T},2}/\Lambda^4$	$[-0.06, 0.02]$
$f_{\mathrm{T},6}/\Lambda^4$	$[-0.01, 0.01]$
$f_{\mathrm{T},7}/\Lambda^4$	$[-0.02, 0.01]$

LHC Constraints on different dim-8 operators

arXiv:2204.10034

coefficient	constraint	coefficient	constraint	coefficient	constraint
f_{S_0}/Λ^4	$[-2.7, 2.7]$ [24]	f_{M_0}/Λ^4	$[-0.69, 0.70]$ [24]	f_{T_0}/Λ^4	$[-0.12, 0.11]$ [24]
f_{S_1}/Λ^4	$[-3.4, 3.4]$ [24]	f_{M_1}/Λ^4	$[-2.0, 2.1]$ [24]	f_{T_1}/Λ^4	$[-0.12, 0.13]$ [24]
f_{S_2}/Λ^4	-	f_{M_2}/Λ^4	$[-2.8, 2.8]$ [25]	f_{T_2}/Λ^4	$[-0.28, 0.28]$ [24]
		f_{M_3}/Λ^4	$[-4.4, 4.4]$ [25]	f_{T_5}/Λ^4	$[-0.5, 0.5]$ [25]
		f_{M_4}/Λ^4	$[-5, 5]$ [25]	f_{T_6}/Λ^4	$[-0.4, 0.4]$ [25]
		f_{M_5}/Λ^4	$[-8.3, 8.3]$ [25]	f_{T_7}/Λ^4	$[-0.9, 0.9]$ [25]
		f_{M_7}/Λ^4	$[-3.4, 3.4]$ [25]	f_{T_8}/Λ^4	$[-0.43, 0.43]$ [26]
				f_{T_9}/Λ^4	$[-0.92, 0.92]$ [26]

- The analysis presented in Snowmass white-paper was a quick proof-of-principle study
- 6 TeV Muon collider is expected to set better limits than the LHC

EFT validity and unitarity bound

- Use VBF@NLO utility to calculate the $\sqrt{s}$ of $VV \to VV$ process at which tree-level unitarity would be violated without a form factor

- Calculated the energy at which the tree-level unitarity would be violated for our bounds in the $WW\nu\nu$ channel

WW$\nu\nu$	Limits (TeV^{-4})	Unitarity bound (TeV)
$f_{\mathrm{M},0}/\Lambda^4$	$[-0.032, 0.035]$	$[5.5, 5.4]$
$f_{\mathrm{M},1}/\Lambda^4$	$[-0.088, 0.065]$	$[6.1, 6.5]$
$f_{\mathrm{M},7}/\Lambda^4$	$[-0.12, 0.17]$	$[6.7, 6.1]$
$f_{\mathrm{S},0}/\Lambda^4$	$[-0.22, 0.20]$	$[4.4, 4.4]$
$f_{\mathrm{S},1}/\Lambda^4$	$[-0.14, 0.14]$	$[4.0, 4.0]$
$f_{\mathrm{T},0}/\Lambda^4$	$[-0.0062, 0.0030]$	$[5.8, 6.0]$
$f_{\mathrm{T},1}/\Lambda^4$	$[-0.0082, 0.0031]$	$[6.1, 6.7]$
$f_{\mathrm{T},2}/\Lambda^4$	$[-0.0096, 0.0046]$	$[6.8, 7.0]$

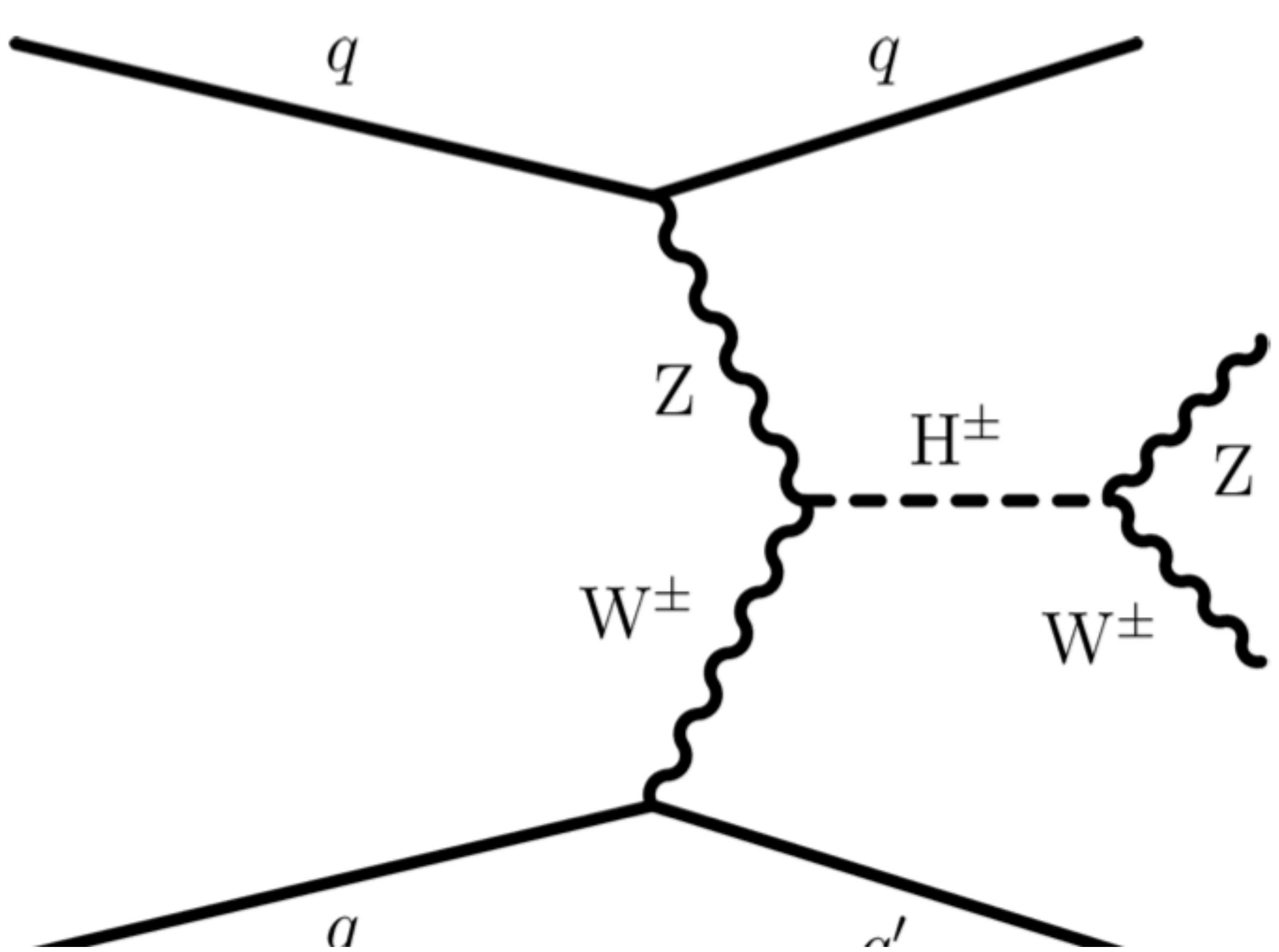
Does not violate unitarity

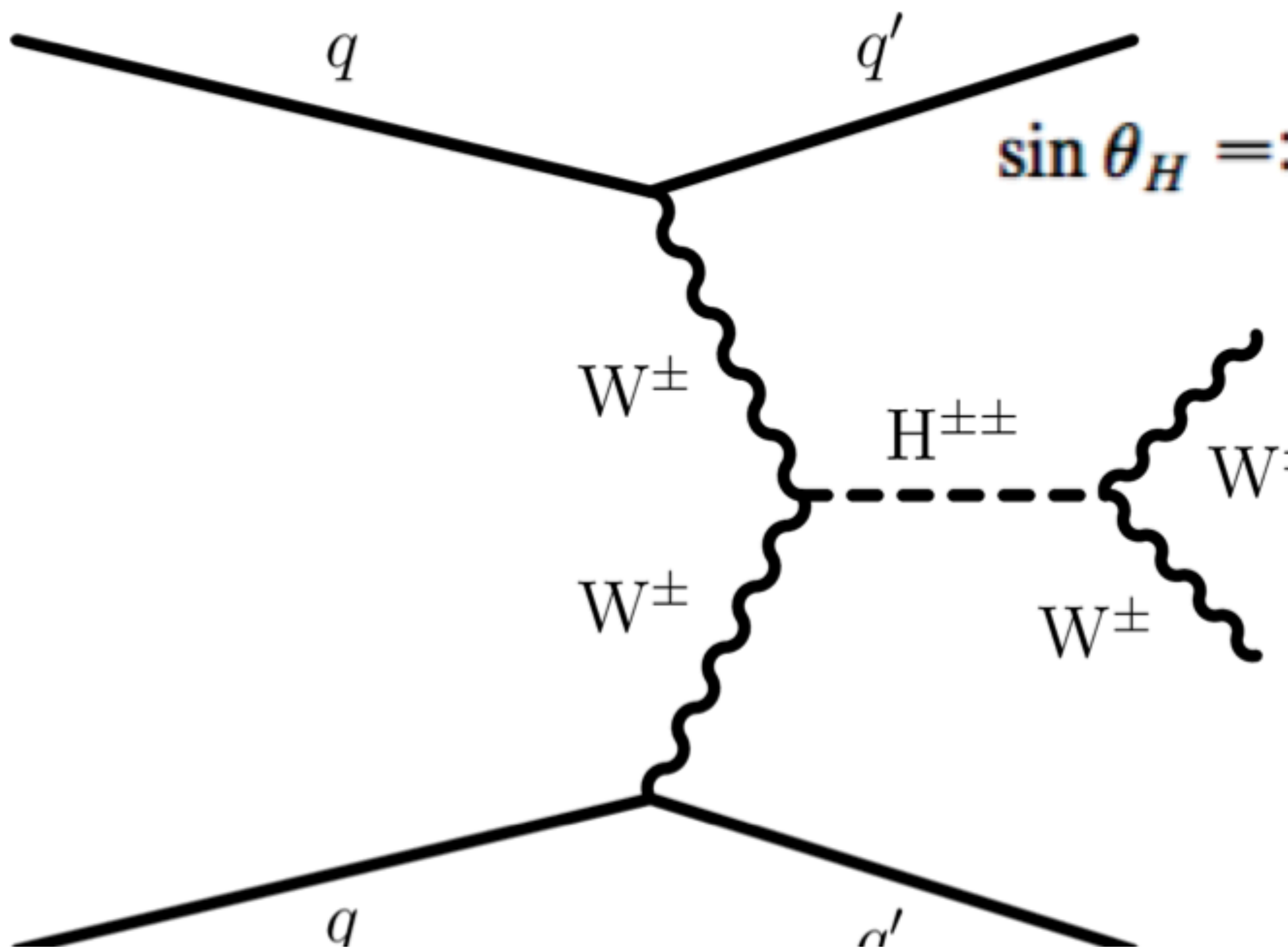
BSM Benchmark: Georgi-Machacek Model

Future steps: BSM interpretation with Georgi-Machacek model

- One real and one complex triplet
- Tree level H^{+} WZ coupling
- Presence of doubly charged Higgs: H^{++}

Easy to compare with LHC limits





$$\sin\theta_H =: s_H = \frac{2\sqrt{2}v_{\Xi}}{v_{\mathrm{SM}}}$$

Summary and Outlook

- **Multiboson processes such as VBS is active area of study**
  - Window to new physics
  - Very interesting at the lepton colliders

Snowmass White paper
arXiv:2203.08135

- **We studied WW at a Muon collider with $\sqrt{s} = 6$ TeV**
  - $\sqrt{s} = 10$ TeV and 30 TeV is being studied
  - Beam induced background is ignored in this study

- We are including a BSM interpretation to do a fair comparison with LHC results

Parameters for Snowmass physics studies at muon collider

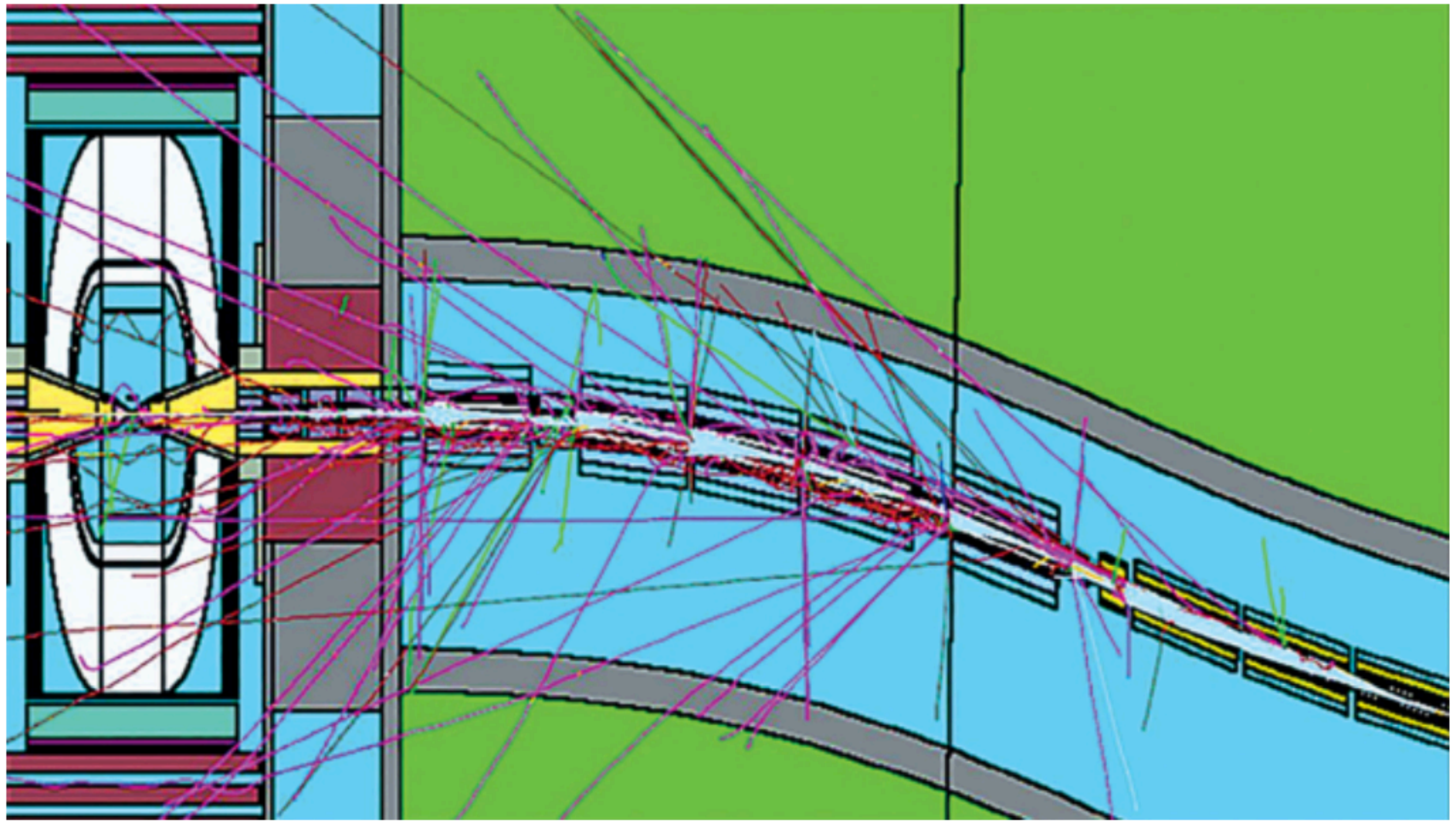
COM Energy	**125 GeV**	1.5 TeV	**3 TeV**	6 TeV	**10 TeV**	14 TeV	**30 TeV**
Total Luminosity (ab-1)	0.020	0.25	1.0	4.0	10	10	10

Thank You

BackUp

Beam Induced Backgrounds

Large amount of beam induced backgrounds from muon decays
Depends on beam energy and on the design of interaction region
High occupancy in the first layers of detector tracking system->need to asses the detector performance
Dedicated study at Snowmass on the performance of reconstructed objects in the presence of beam induced backgrounds



Credit: N V Mokhov

Muon Collider: Conceptual Design