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Heavy Vector Triplets at the Muon Collider

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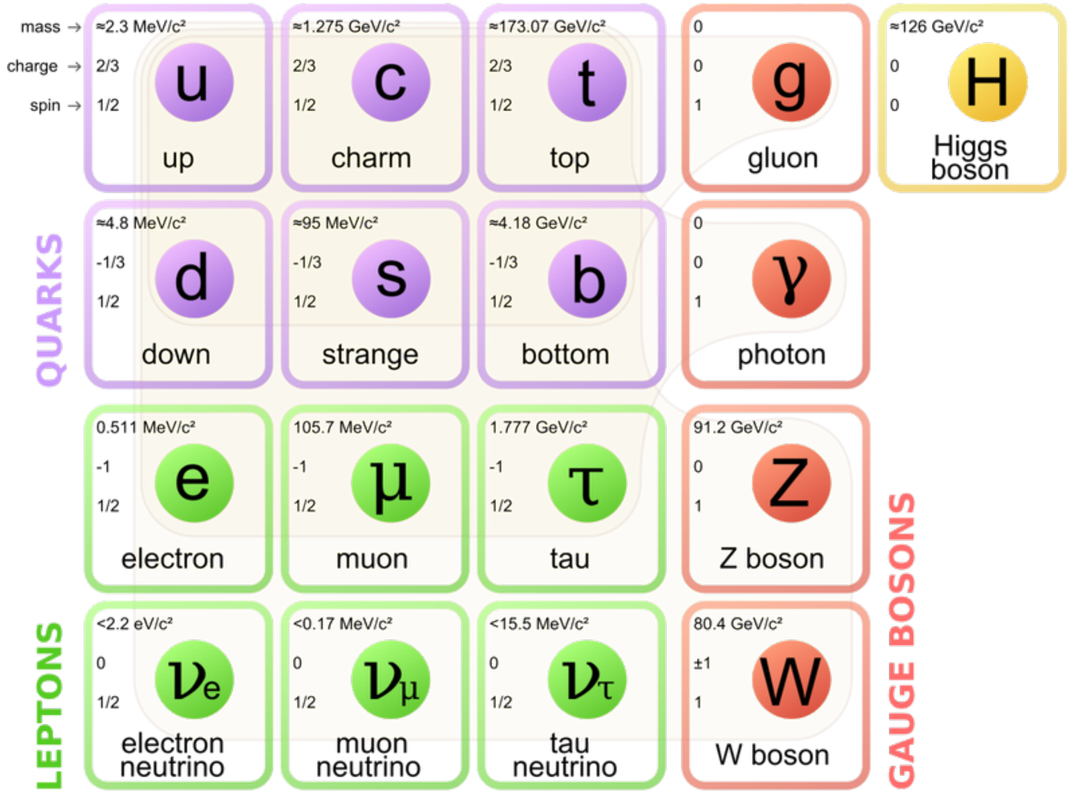
Phenomenology 2026 Symposium

Outline

- A bridge theory
- How to discover HVT at a Muon Collider
- Interference
- Comparison with other colliders

A bridge theory



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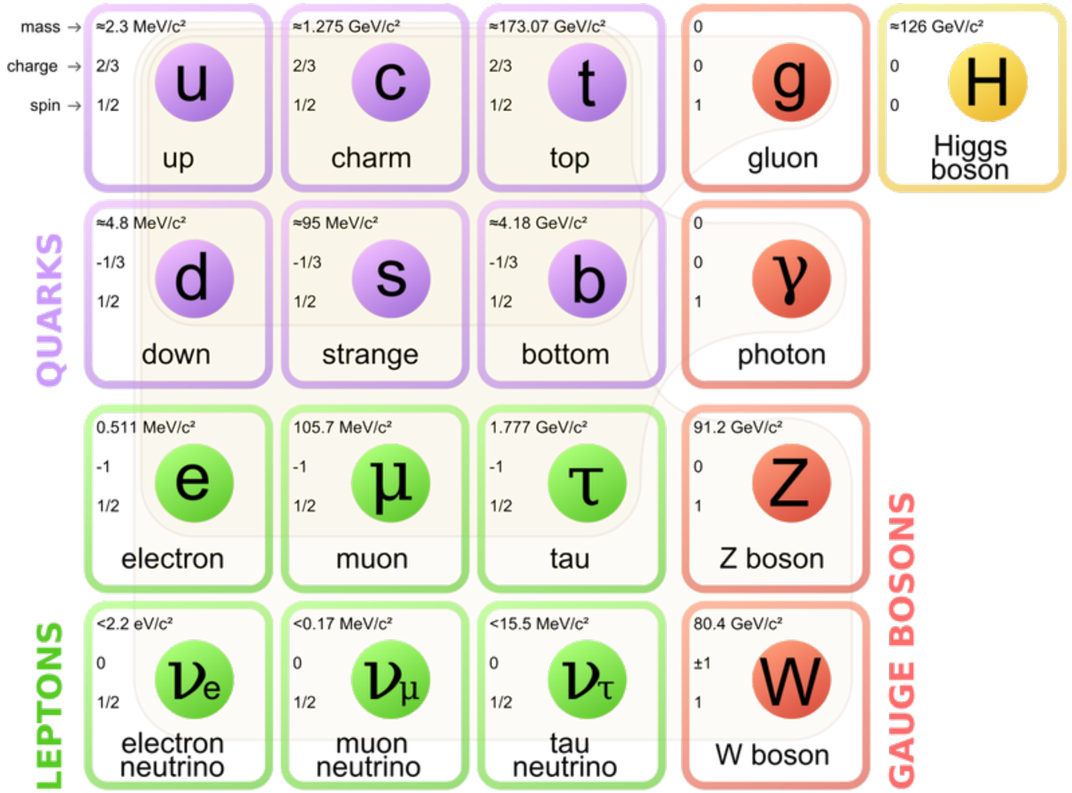
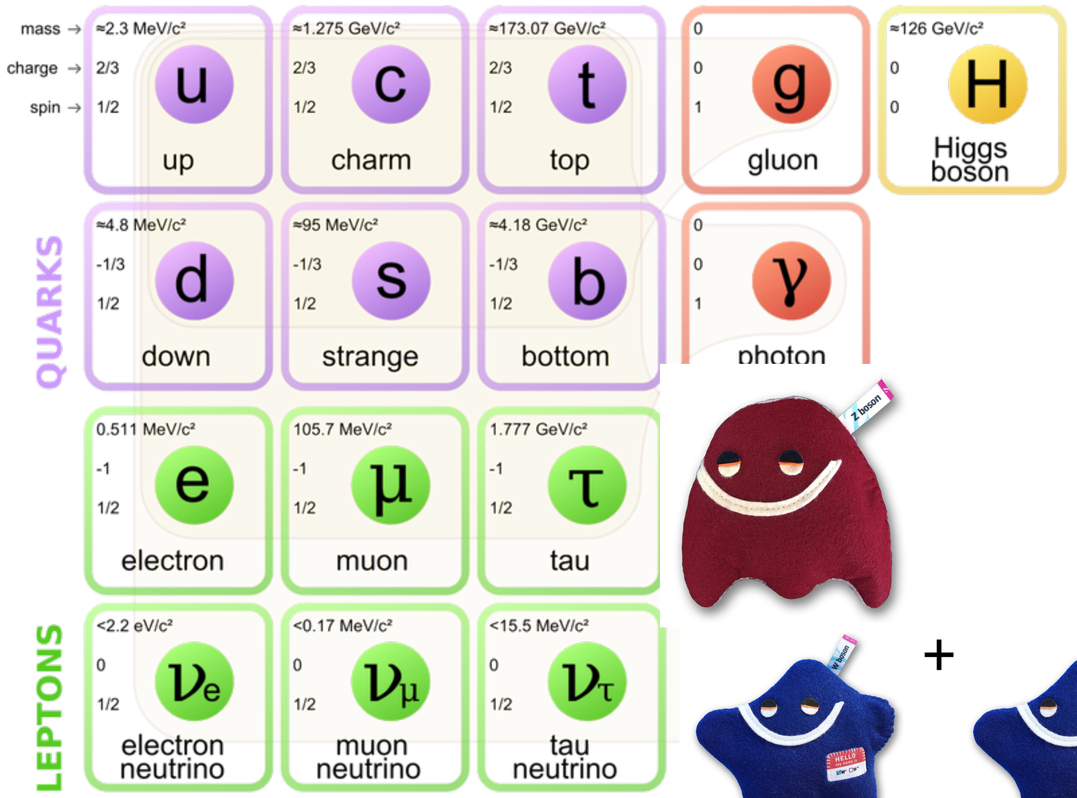
NP

- Extended gauge symmetries
- Composite Higgs models
- Extra dimensions
- …


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
GAUGE BOSONS
LEPTONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson

+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ντ
tau neutrino

Z boson

W boson

+


W boson

-

+


W boson
HELLO
W⁻ and W⁺

+

-


W boson
HELLO
W⁻ and W⁺


Z boson

$$\mathcal{L}_{\mathcal{V}} \supset -\frac{1}{4} D_{[\mu} \mathcal{V}^a_{\nu]} D^{[\mu} \mathcal{V}^{\nu]\, a} + \frac{m_{\mathcal{V}}^2}{2} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a}$$

$$+ i\, g_V c_H \mathcal{V}^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_q \mathcal{V}^a_\mu \sum_q \overline{q_L} \gamma^\mu \tau^a q_L + \frac{g^2}{g_V} c_\ell \mathcal{V}^a_\mu \sum_\ell \overline{\ell_L} \gamma^\mu \tau^a \ell_L$$

$$+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} \mathcal{V}^a_\mu \mathcal{V}^b_\nu D^{[\mu} \mathcal{V}^{\nu]\, c} + g_V^2 c_{VVHH} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\, a} \mathcal{V}^b_\mu \mathcal{V}^c_\nu$$

kinetic

$$\mathcal{L}_{\mathcal{V}} \supset -\frac{1}{4} D_{[\mu} \mathcal{V}^a_{\nu]} D^{[\mu} \mathcal{V}^{\nu]\, a} + \frac{m_{\mathcal{V}}^2}{2} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a}$$

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mass

$$\mathcal{L}_{\mathcal{V}} \supset -\frac{1}{4} D_{[\mu} \mathcal{V}^a_{\nu]} D^{[\mu} \mathcal{V}^{\nu]\, a} + \frac{m_{\mathcal{V}}^2}{2} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a}$$

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$$\mathcal{L}_{\mathcal{V}} \supset -\frac{1}{4} D_{[\mu} \mathcal{V}^a_{\nu]} D^{[\mu} \mathcal{V}^{\nu]\, a} + \frac{m^2_{\mathcal{V}}}{2} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a}$$

Higgs current

$$+ i\, g_V c_H \mathcal{V}^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_q \mathcal{V}^a_\mu \sum_q \overline{q_L} \gamma^\mu \tau^a q_L + \frac{g^2}{g_V} c_\ell \mathcal{V}^a_\mu \sum_\ell \overline{\ell_L} \gamma^\mu \tau^a \ell_L$$

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quarks

$$+ i\, g_V c_H \mathcal{V}^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_q \mathcal{V}^a_\mu \sum_q \overline{q_L} \gamma^\mu \tau^a q_L + \frac{g^2}{g_V} c_\ell \mathcal{V}^a_\mu \sum_\ell \overline{\ell_L} \gamma^\mu \tau^a \ell_L$$

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leptons

$$+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} \mathcal{V}^a_\mu \mathcal{V}^b_\nu D^{[\mu} \mathcal{V}^{\nu]\, c} + g_V^2 c_{VVHH} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a} H^\dagger H - \frac{g}{2} c_{VVVW} \epsilon_{abc} W^{\mu\nu\, a} \mathcal{V}^b_\mu \mathcal{V}^c_\nu$$

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self-interaction

$$\mathcal{L}_{\mathcal{V}} \supset -\frac{1}{4} D_{[\mu} \mathcal{V}^a_{\nu]} D^{[\mu} \mathcal{V}^{\nu]\, a} + \frac{m_{\mathcal{V}}^2}{2} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a}$$

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VVhh

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SM SU(2) current

- Dimension 4 operators
- Compatible with SM symmetry
- Assume CP
- Ignored 4V vertices because pheno irrelevant
- A bridge theory: only list pheno relevant operators
- Not an EFT: HVT is not integrated away

$$\begin{aligned}\mathcal{L}_{\mathcal{V}} \supset & -\frac{1}{4} D_{[\mu} \mathcal{V}^a_{\nu]} D^{[\mu} \mathcal{V}^{\nu]\, a} + \frac{m^2_{\mathcal{V}}}{2} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a} \\ & + i\, g_V c_H \mathcal{V}^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_q \mathcal{V}^a_\mu \sum_q \overline{q_L} \gamma^\mu \tau^a q_L + \frac{g^2}{g_V} c_\ell \mathcal{V}^a_\mu \sum_\ell \overline{\ell_L} \gamma^\mu \tau^a \ell_L \\ & + \frac{g_V}{2} c_{VVV} \epsilon_{abc} \mathcal{V}^a_\mu \mathcal{V}^b_\nu D^{[\mu} \mathcal{V}^{\nu]\, c} + g_V^2 c_{VVHH} \mathcal{V}^a_\mu \mathcal{V}^{\mu\, a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\, a} \mathcal{V}^b_\mu \mathcal{V}^c_\nu\end{aligned}$$

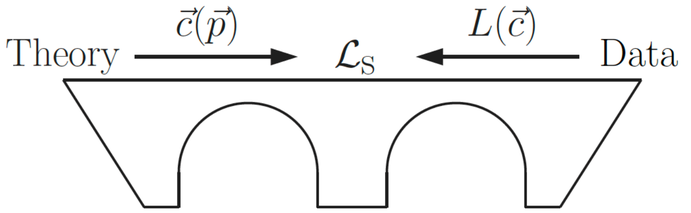


Figure 1.1: Pictorial view of the Bridge Method.

1402.4431

Bridge theory

Bridge theory

"Matching"

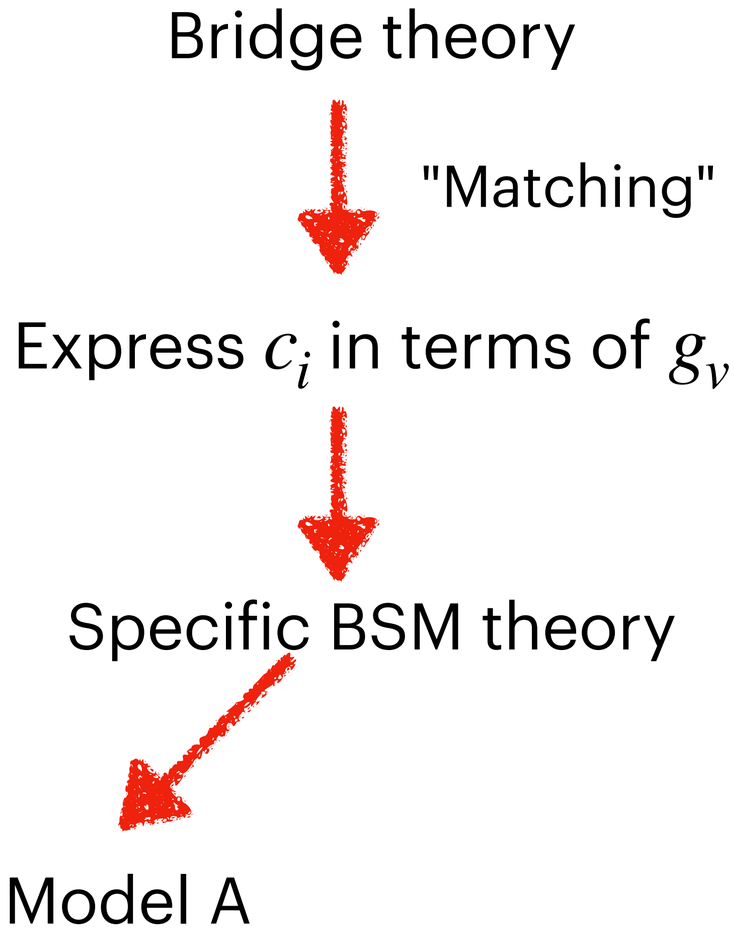
Express c_i in terms of g_v

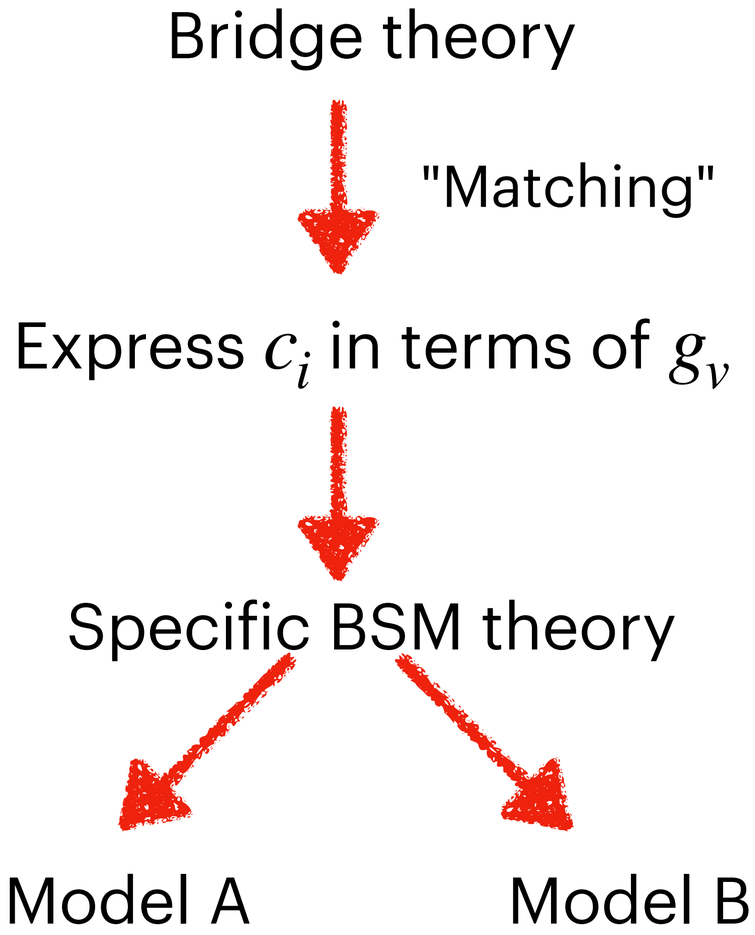
Bridge theory

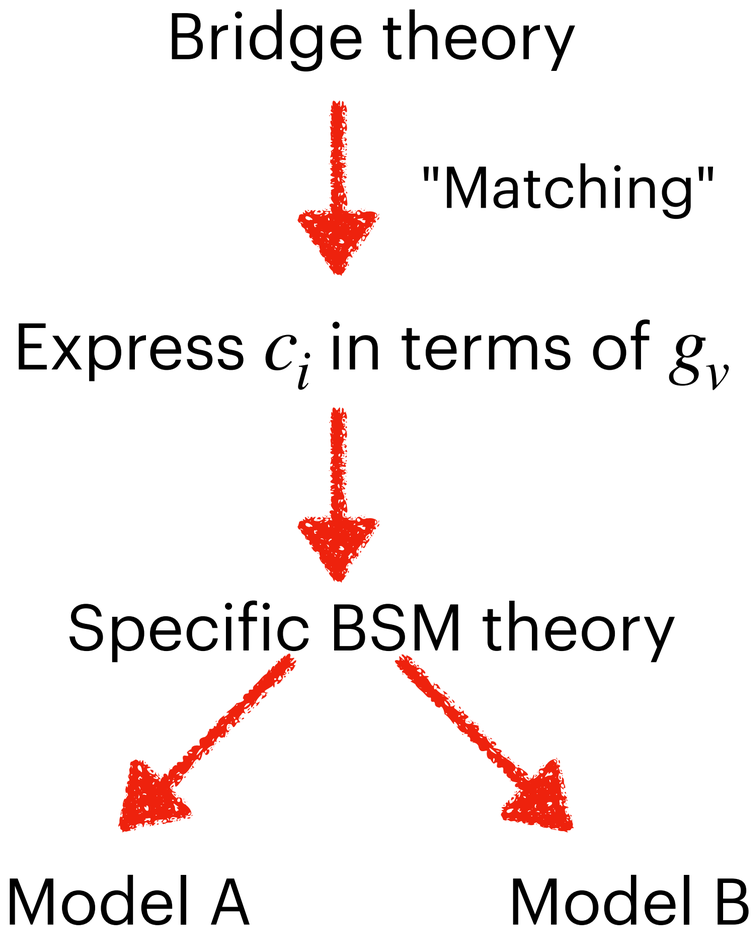
"Matching"

Express c_i in terms of g_v

Specific BSM theory


Bridge theory
"Matching"
Express c_i in terms of g_v
Specific BSM theory
Model A


Bridge theory
"Matching"
Express c_i in terms of g_v
Specific BSM theory
Model A
Model B



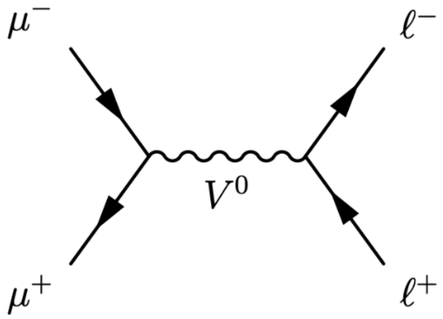
	Model A $su(2)_1 \times su(2)_2$	**Model B** $SO(5)/SO(4)$
g_V	g_2	$\pm g_\rho$
m_V	$\frac{\lvert g_V \rvert u}{k_V}$	$\frac{m_\rho}{k_V}$
c_F	$-\frac{1}{k_V}$	$\frac{1}{k_V}$
c_H	$-\frac{g^2}{g_V^2 k_V}$	$-\frac{1}{k_V}\left(a_\rho^2 - \frac{g^2}{g_V^2}\right)$
c_{VVV}	$-\frac{1}{k_V}\left(1 - \frac{2g^2}{g_V^2}\right)$	$\frac{1}{k_V}\left(1 - \frac{2g^2}{g_V^2}\right)$
c_{VVW}	1	1
c_{VVHH}	$\frac{g^4}{4g_V^4 k_V^2}$	$-\frac{g^2}{2g_V^2 k_V^2}\left(a_\rho^2 - \frac{g^2}{2g_V^2}\right)$

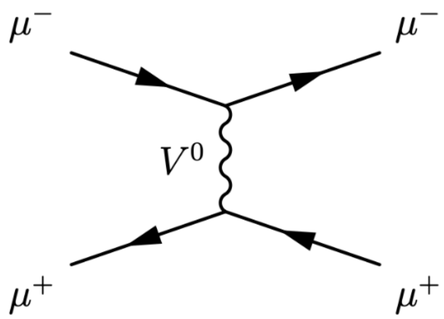
$$a_\rho = 1/\sqrt{2}, k_V = \sqrt{1 - g_w^2/g_V^2}$$

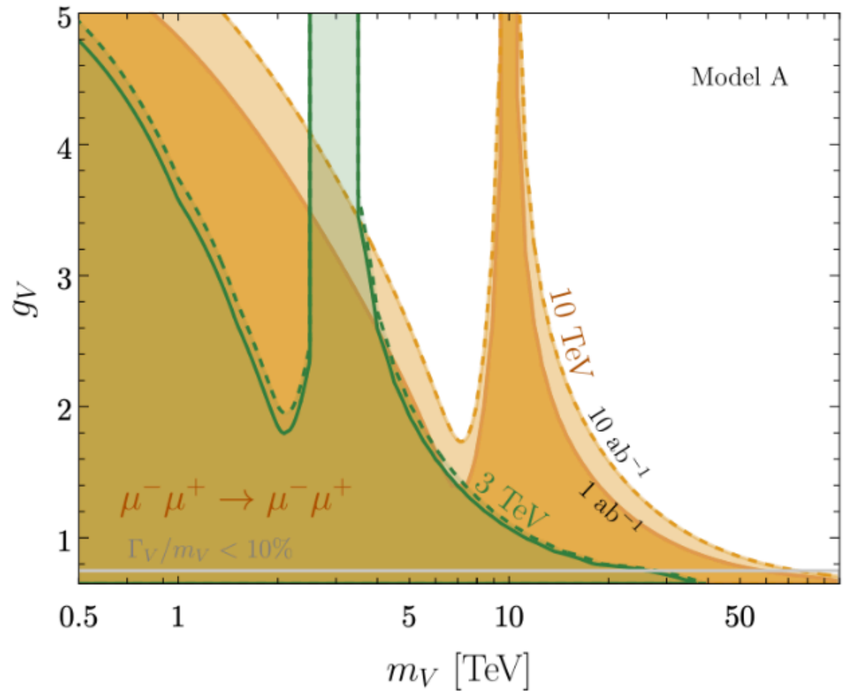
Pheno of HVT at a Muon Collider

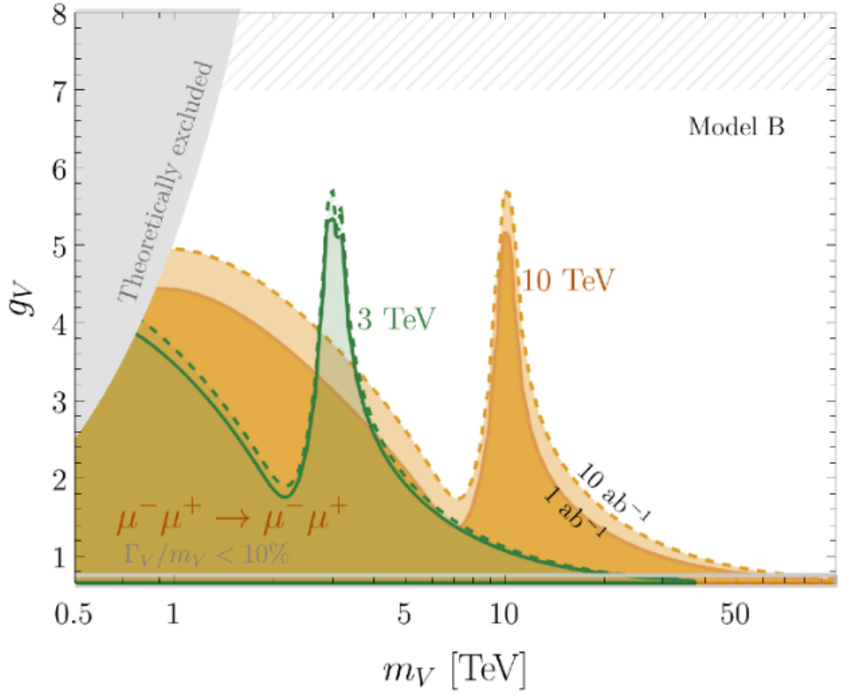
The setup

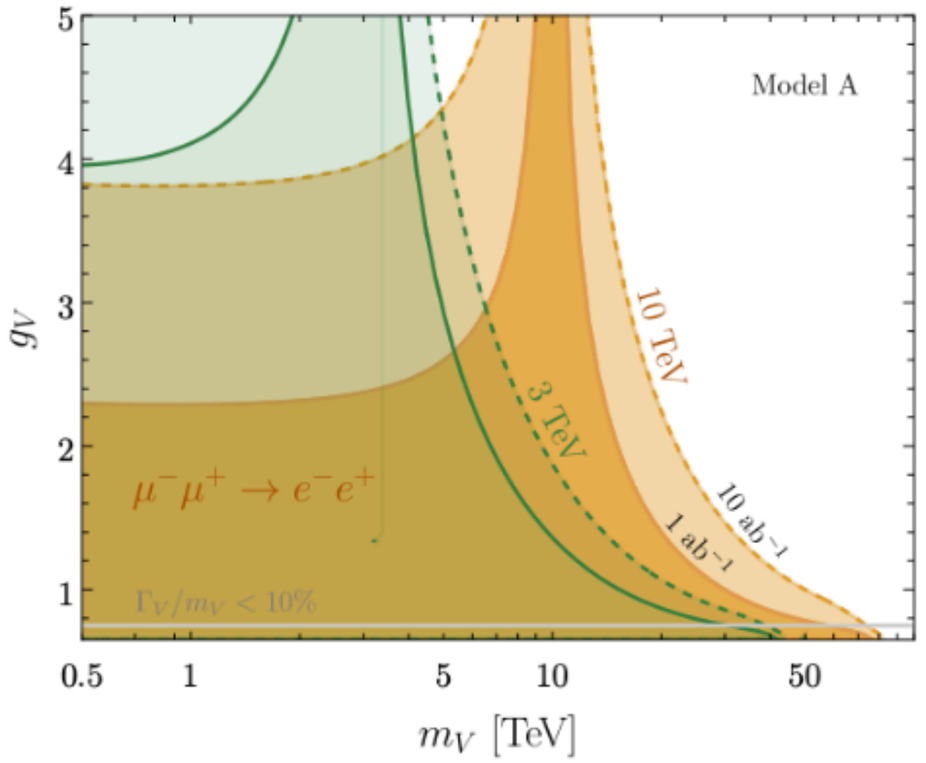
- Can not use Narrow Width Approximation:
  - Can have $\frac{\Gamma}{m_V} > 10\,\%$
  - Can have $m_V \sim \sqrt{s}$
  - Can have non resonant important channels
- Must simulate signal + background + interference
  - MC errors become important
- 3 or 10 TeV MuC, $E_X > 20$ GeV, $|\eta_X| < 2.5$, $\Delta R_{i,j} > 0.4$

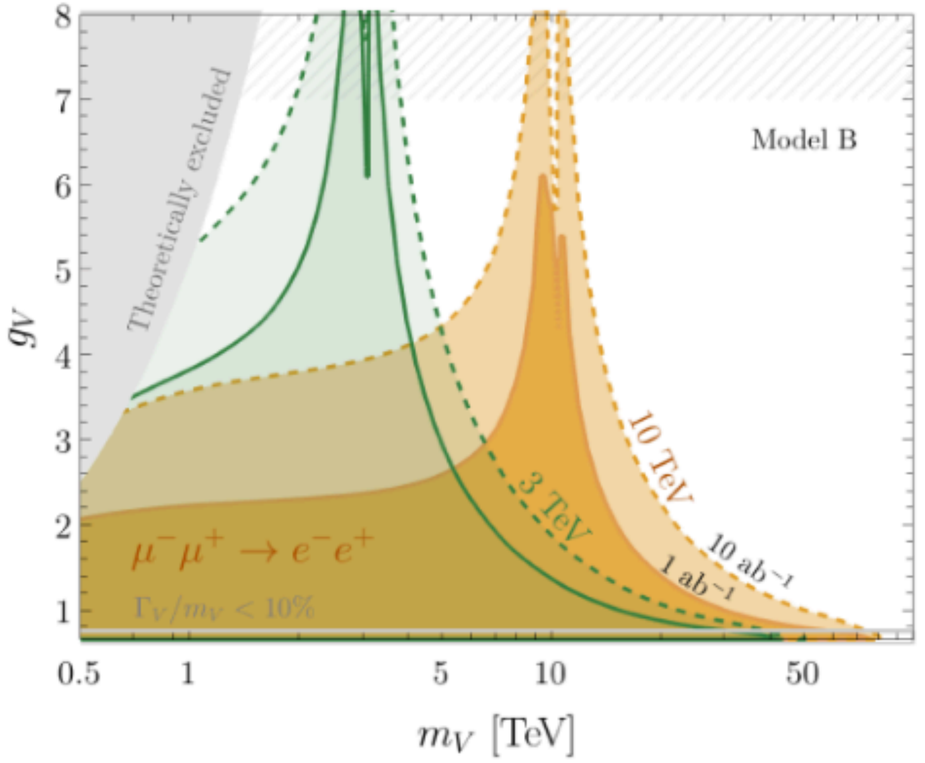

μ^-
ℓ^-
V^0
μ^+
ℓ^+


μ^-
μ^-
V^0
μ^+
μ^+


Model A
g_V
m_V [TeV]
$\mu^-\mu^+ \to \mu^-\mu^+$
$\Gamma_V/m_V < 10\%$
10 TeV
3 TeV
10 ab^{-1}
1 ab^{-1}


Model B
Theoretically excluded
g_V
m_V [TeV]
$\mu^-\mu^+ \to \mu^-\mu^+$
$\Gamma_V/m_V < 10\%$
10 TeV
3 TeV
10 ab^{-1}
1 ab^{-1}


Model A
g_V
m_V [TeV]
$\mu^-\mu^+ \to e^-e^+$
$\Gamma_V/m_V < 10\%$
10 TeV
3 TeV
10 ab^{-1}
1 ab^{-1}
0.5
1
5
10
50
1
2
3
4
5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5
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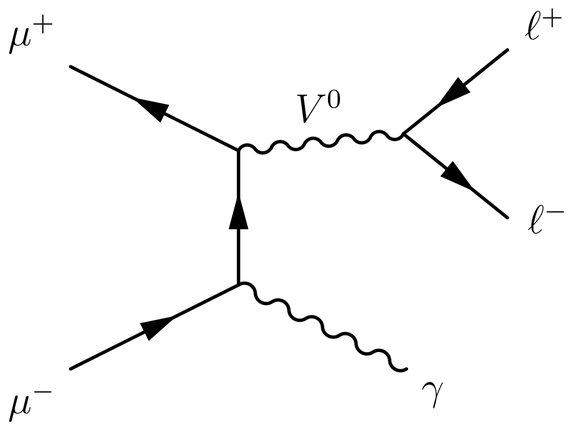
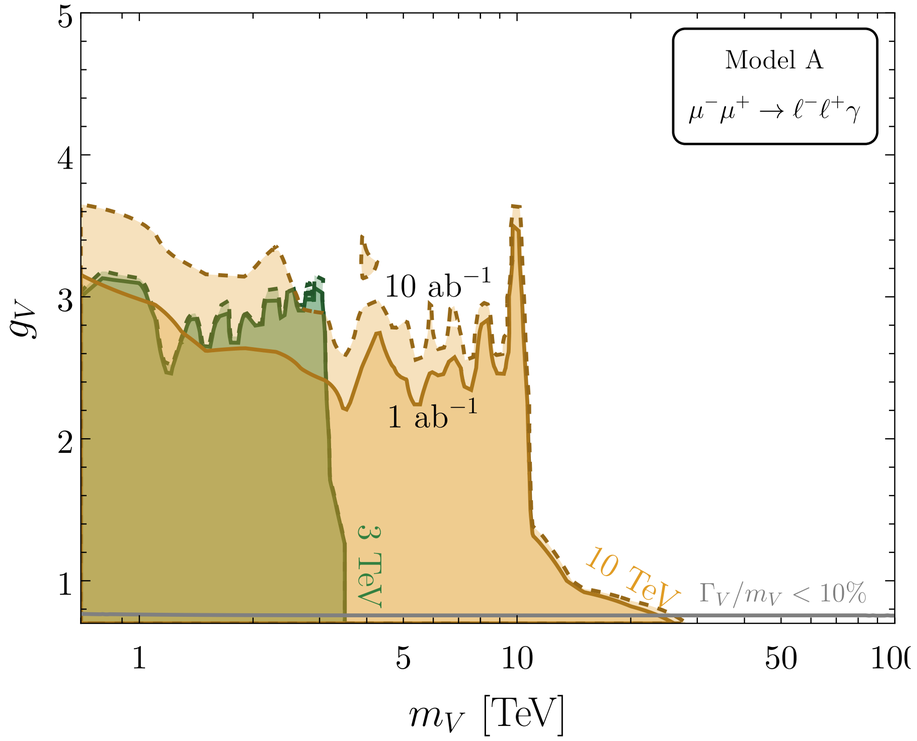
50
1
2
3
4
5
6
7
8


μ^+
ℓ^+
V^0
ℓ^-
μ^-
γ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10 ab^{-1}
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3 TeV
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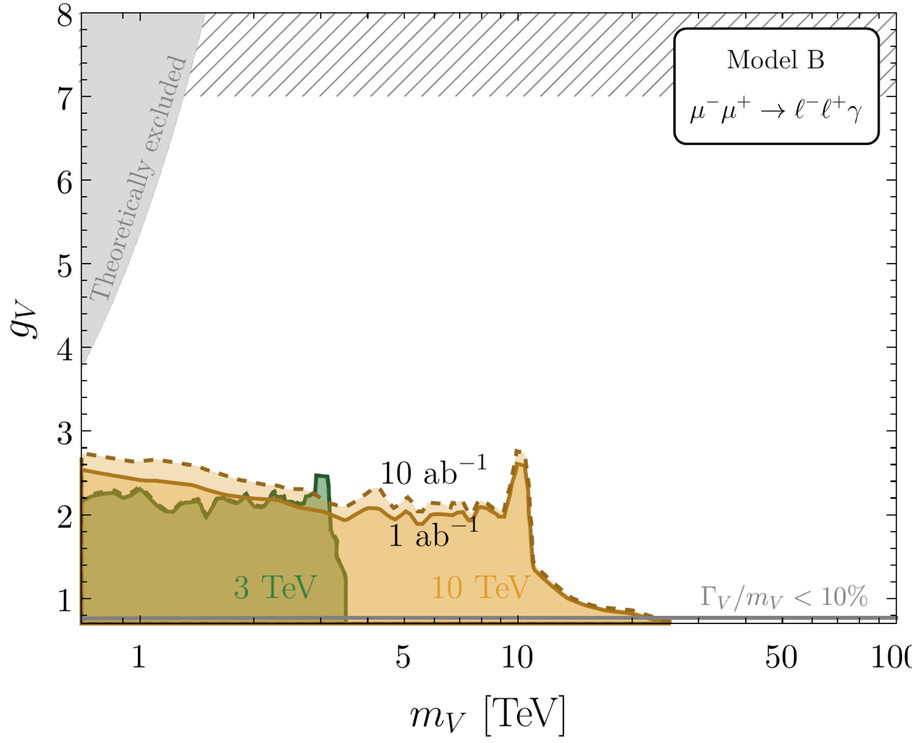
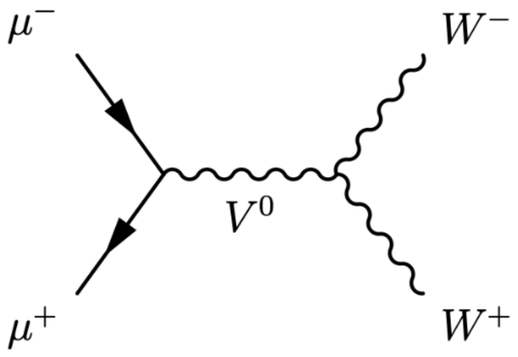
g_V
m_V [TeV]


Model B
$\mu^-\mu^+ \to \ell^-\ell^+\gamma$
Theoretically excluded
10 ab^{-1}
1 ab^{-1}
3 TeV
10 TeV
$\Gamma_V/m_V < 10\%$
g_V
m_V [TeV]



Unitarity

$$|\mathcal{M}|^2_V = \frac{e^6 c_W}{s_W^6}\frac{c_\ell^2}{g_V^2}\frac{s^2 t(s+t)}{m_W^4(s-m_V^2)^2}\theta_C\theta_N \tag{3.10}$$

$$|\mathcal{M}|^2_\gamma = \frac{e^4}{4s_W^4}\frac{t(s+t)}{m_W^4}\left[-8s_W^4\right] \tag{3.11}$$

$$|\mathcal{M}|^2_Z = \frac{e^4}{4s_W^4}\frac{t(s+t)}{m_W^4}\left[-8s_W^4+4s_W^2-1-\frac{2ec_\ell}{g_V s_W c_W}\theta_N-\frac{4es_W^3 c_\ell}{g_V c_W}\theta_N+\frac{6es_W c_\ell}{g_V c_W}\theta_N\right] \tag{3.12}$$

$$|\mathcal{M}|^2_\nu = \frac{e^4}{4s_W^4}\frac{t(s+t)}{m_W^4}\left[-1-\frac{4ec_\ell}{g_V s_W}\theta_C\right] \tag{3.13}$$

$$|\mathcal{M}|^2_{\gamma Z} = \frac{e^4}{4s_W^4}\frac{t(s+t)}{m_W^4}\left[16s_W^4-4s_W^2+\frac{4es_W^3 c_\ell}{g_V c_W}\theta_N-\frac{4es_W c_\ell}{g_V c_W}\theta_N\right] \tag{3.14}$$

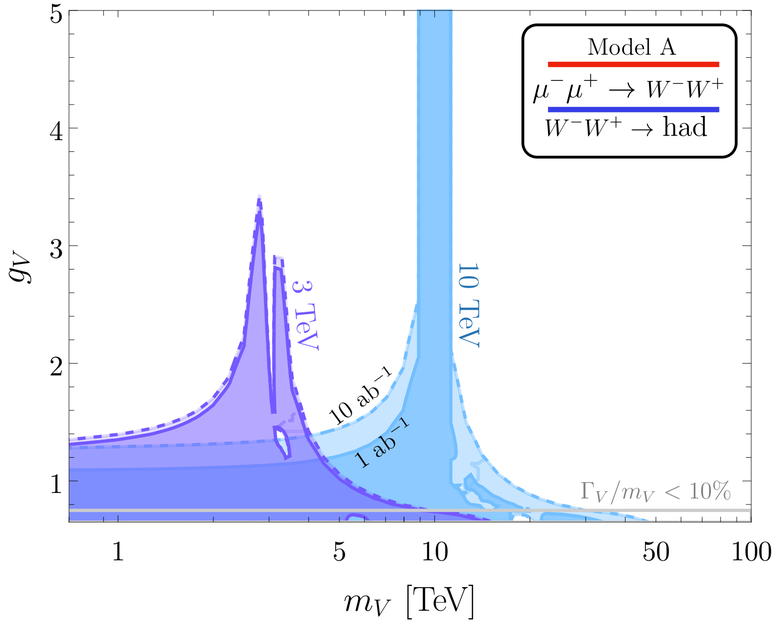
$$|\mathcal{M}|^2_{\gamma\nu} = \frac{e^4}{4s_W^4}\frac{t(s+t)}{m_W^4}\left[4s_W^2+\frac{8ec_\ell s_W}{g_V}\theta_C\right] \tag{3.15}$$

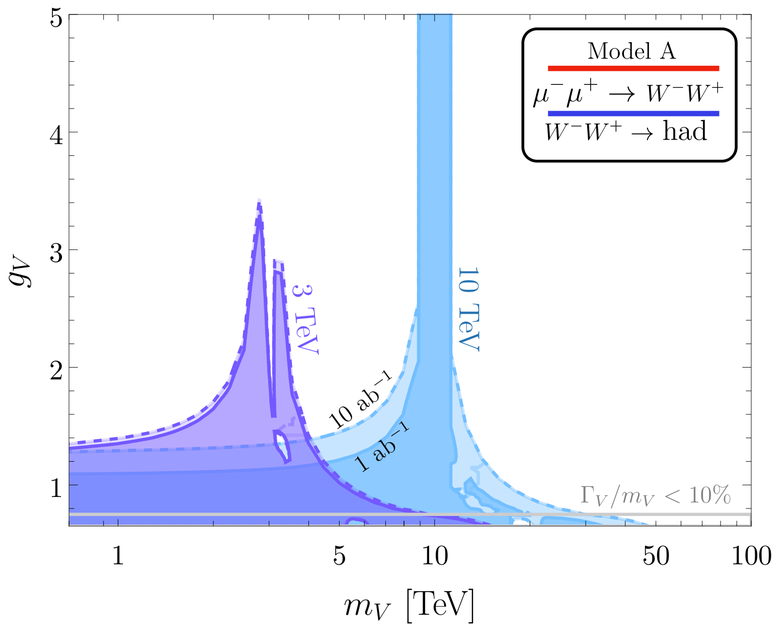
$$|\mathcal{M}|^2_{Z\nu} = \frac{e^4}{4s_W^4}\frac{t(s+t)}{m_W^4}\left[2-4s_W^2-\frac{2es_W c_\ell}{g_V c_W}\theta_N+\frac{2ec_\ell}{g_V c_W s_W}\theta_N-\frac{8ec_\ell s_W}{g_V}\theta_C+\frac{4ec_\ell}{g_V s_W}\theta_C\right] \tag{3.16}$$

$$|\mathcal{M}|^2_{\gamma V} = \frac{e^5}{s_W^5}\frac{c_\ell}{2g_V}\frac{st(s+t)}{m_W^4(s-m_V^2)}\left[4c_W s_W^2\theta_C-2s_W^2\theta_N++2s_W^4\theta_N\right] \tag{3.17}$$

$$|\mathcal{M}|^2_{ZV} = \frac{e^5}{s_W^5}\frac{c_\ell}{2g_V}\frac{st(s+t)}{m_W^4(s-m_V^2)}\left[2c_W\theta_C-4c_W s_W^2\theta_C-\theta_N-2s_W^4\theta_N+3s_W^2\theta_N\right] \tag{3.18}$$

$$|\mathcal{M}|^2_{\nu V} = c_C^3 c_N\frac{e^5}{s_W^5}\frac{c_\ell}{2g_V}\frac{st(s+t)}{m_W^4(s-m_V^2)}\left[-2c_W\theta_C+\theta_N-s_W^2\theta_N\right], \tag{3.19}$$


Model A
$\mu^-\mu^+ \to W^-W^+$
$W^-W^+ \to$ had
3 TeV
10 TeV
10 ab^{-1}
1 ab^{-1}
$\Gamma_V/m_V < 10\%$
g_V
m_V [TeV]
1
2
3
4
5
1
5
10
50
100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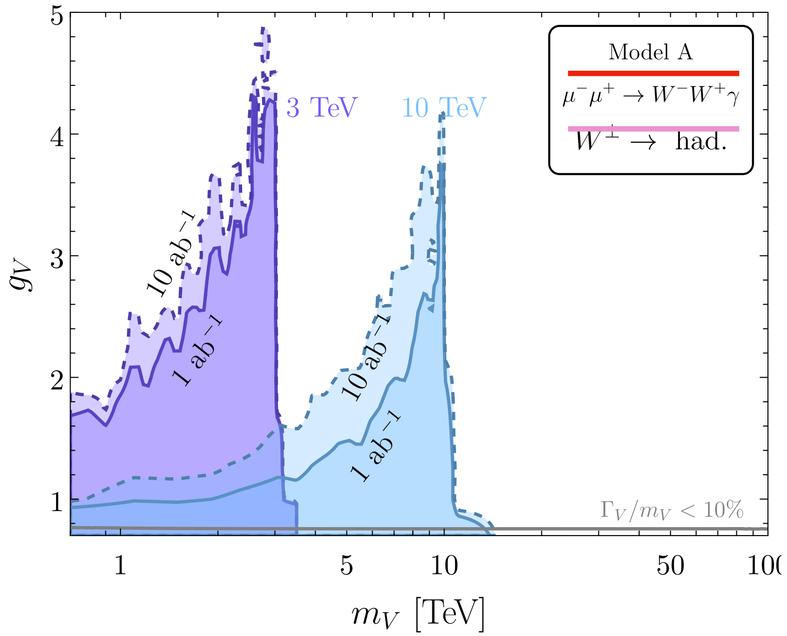
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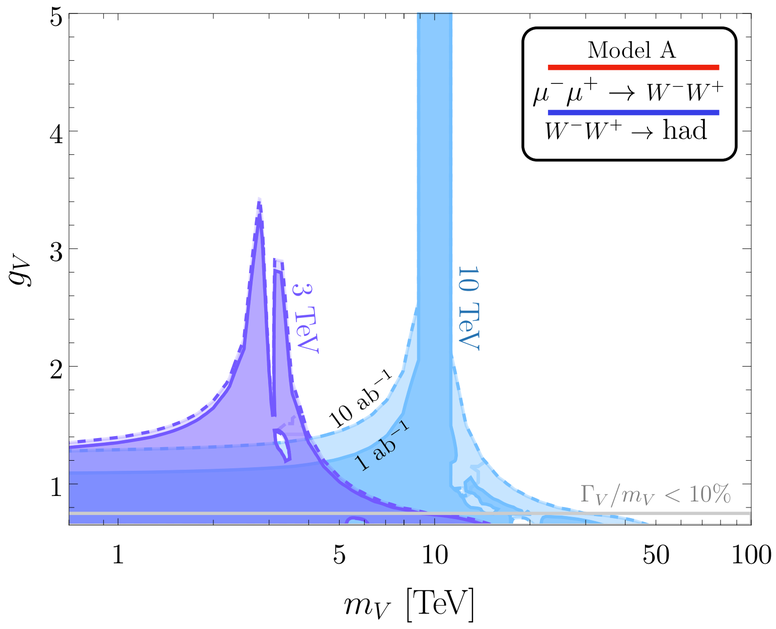
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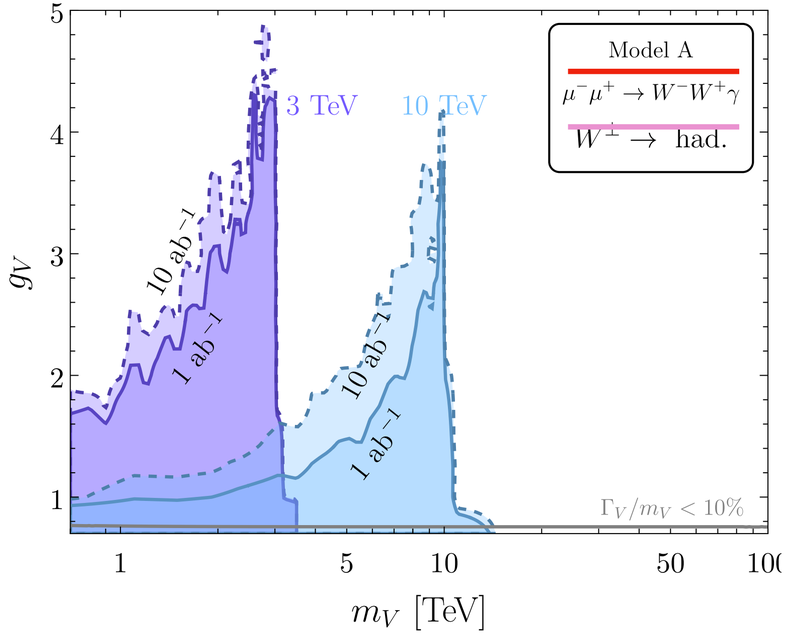
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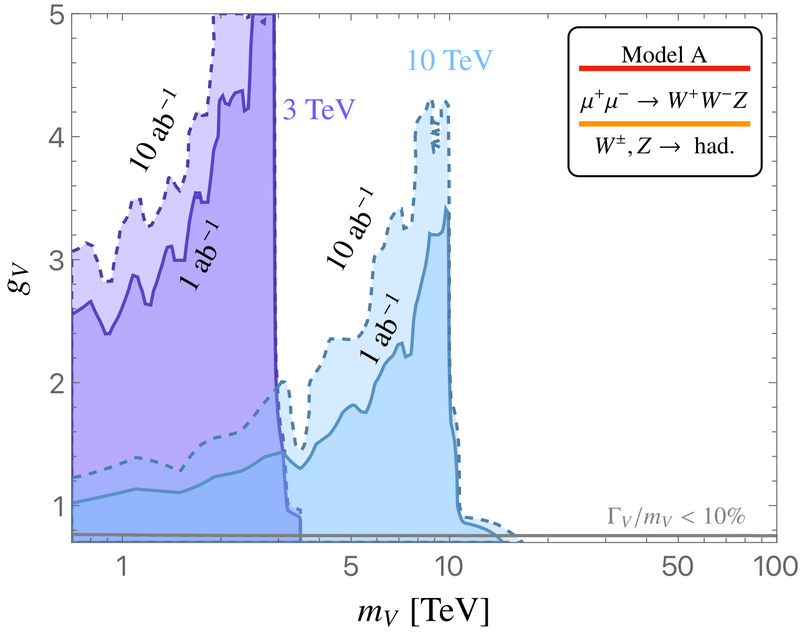
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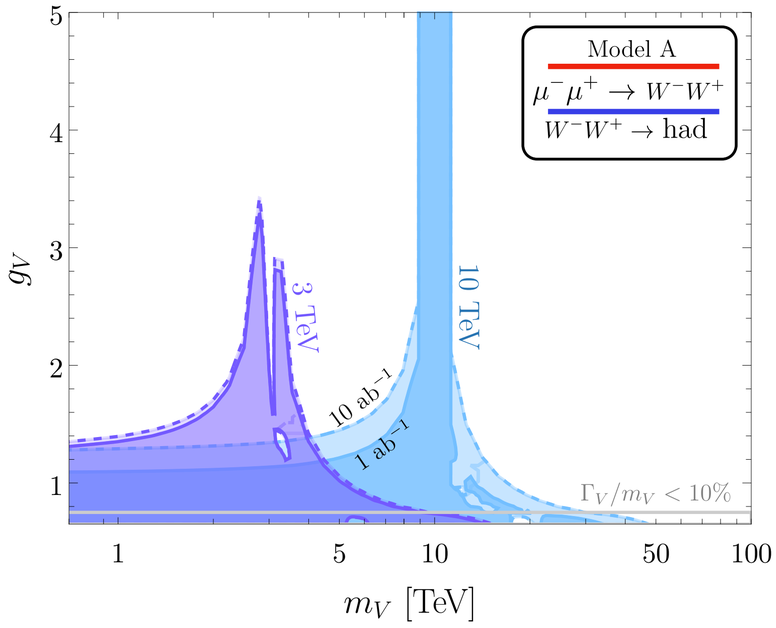
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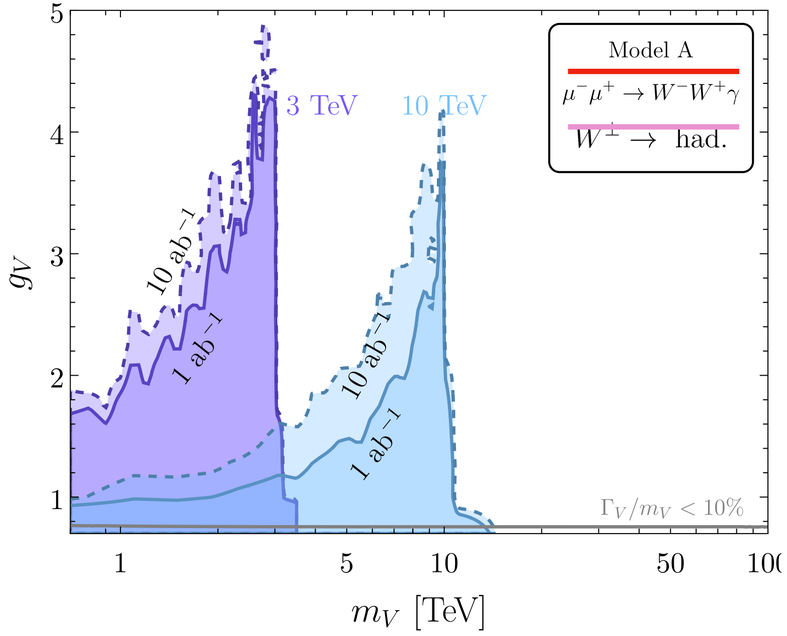
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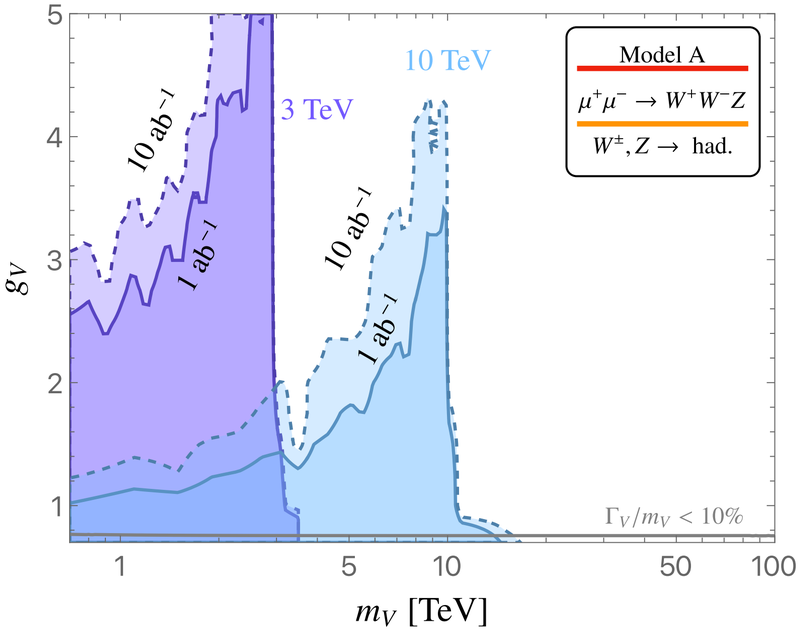
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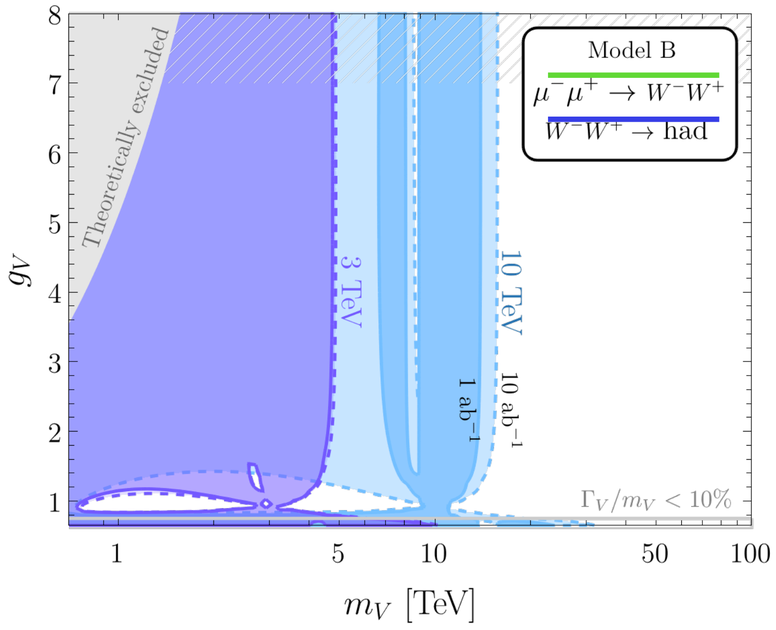
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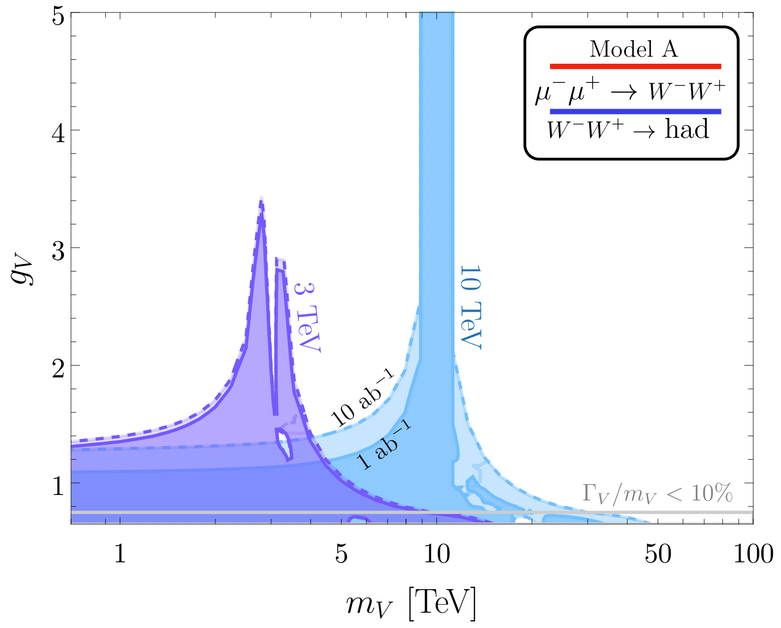
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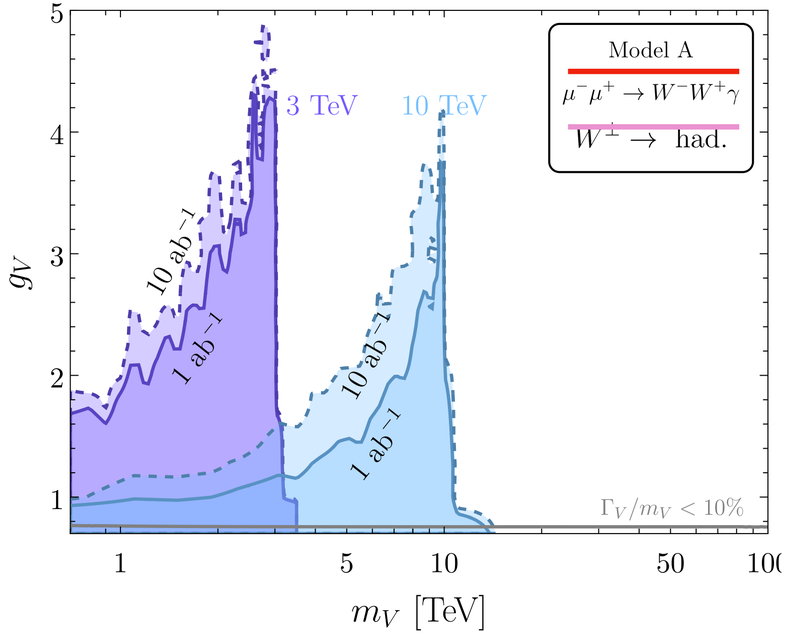
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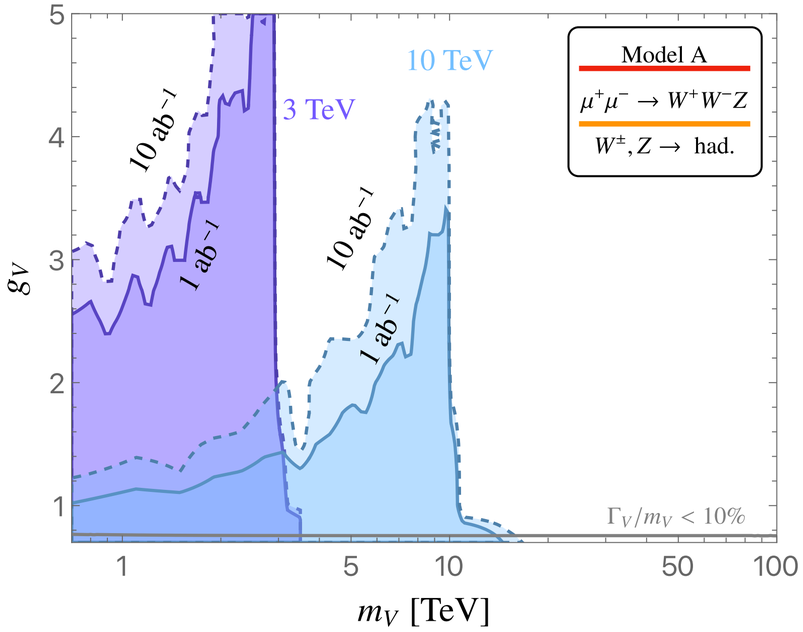
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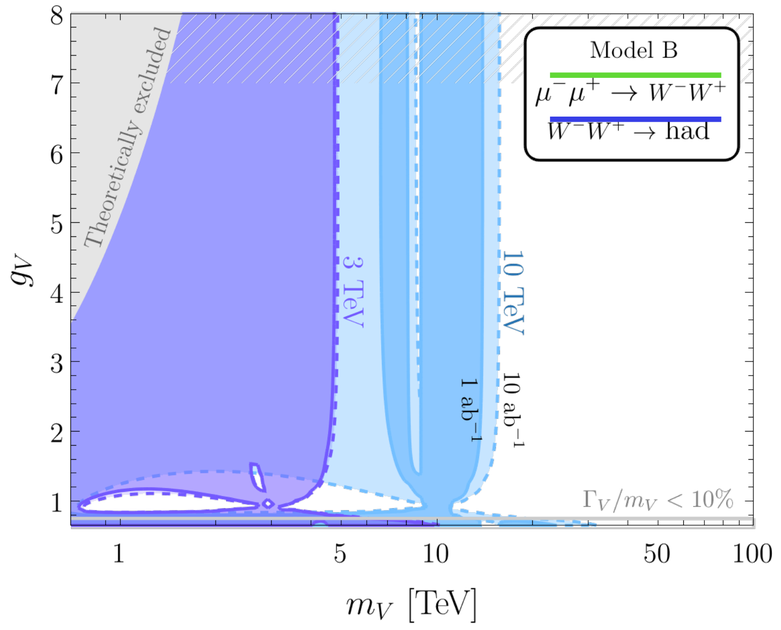
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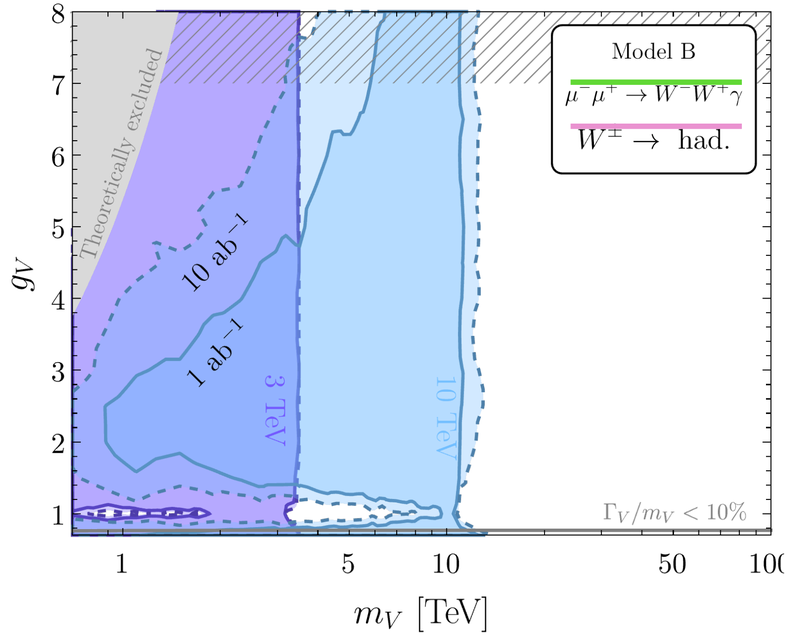
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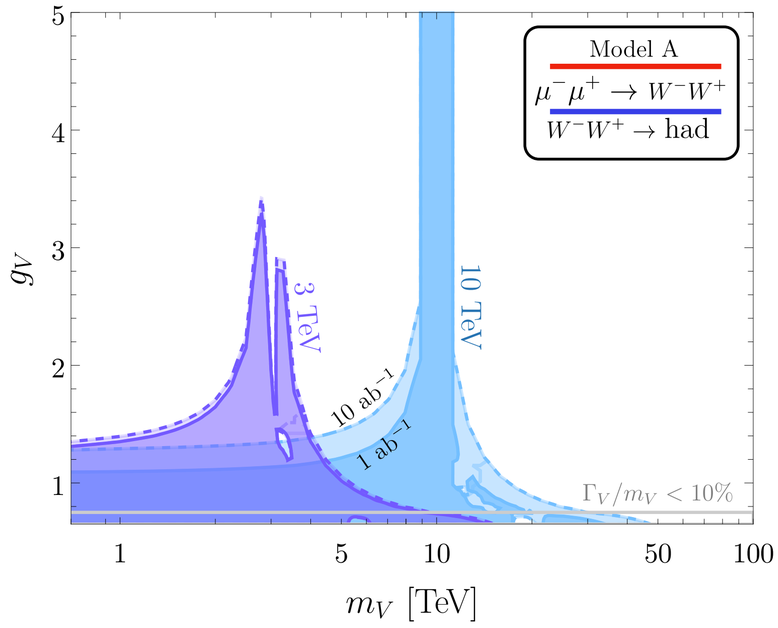
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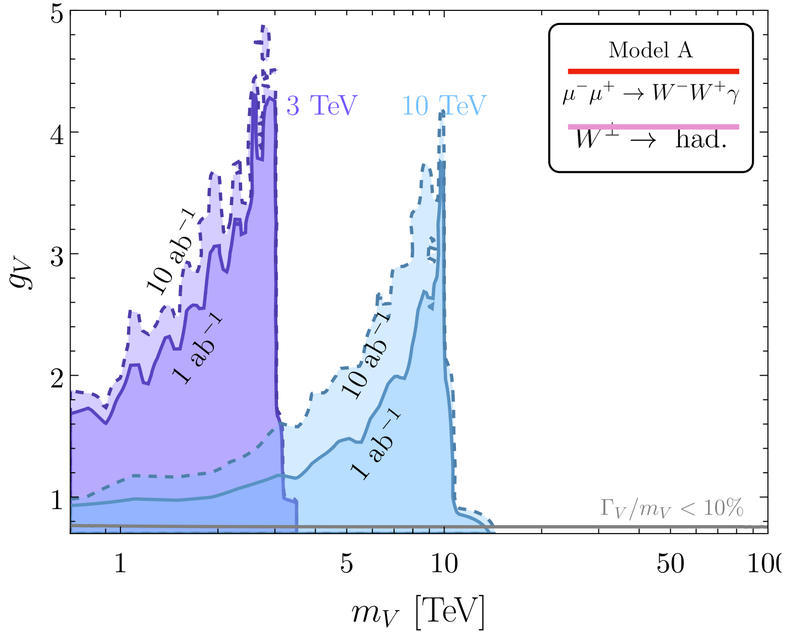
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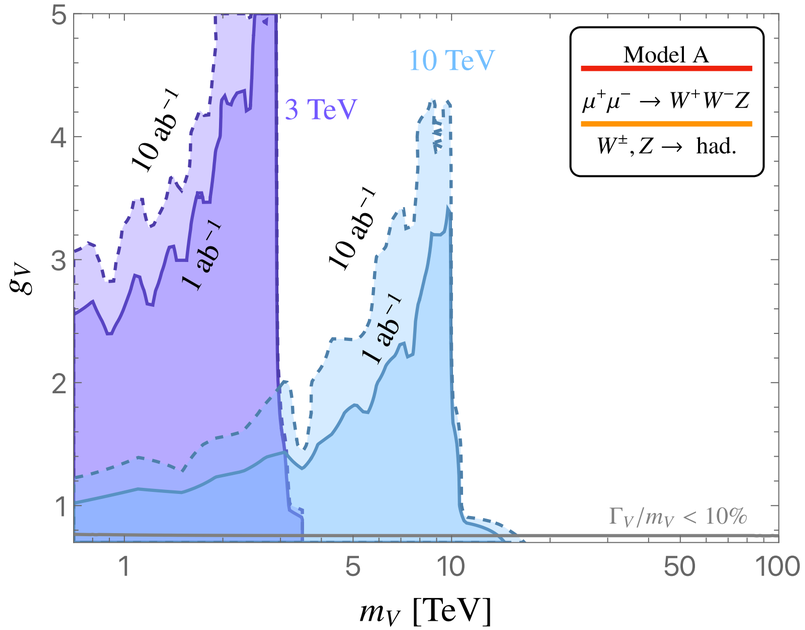
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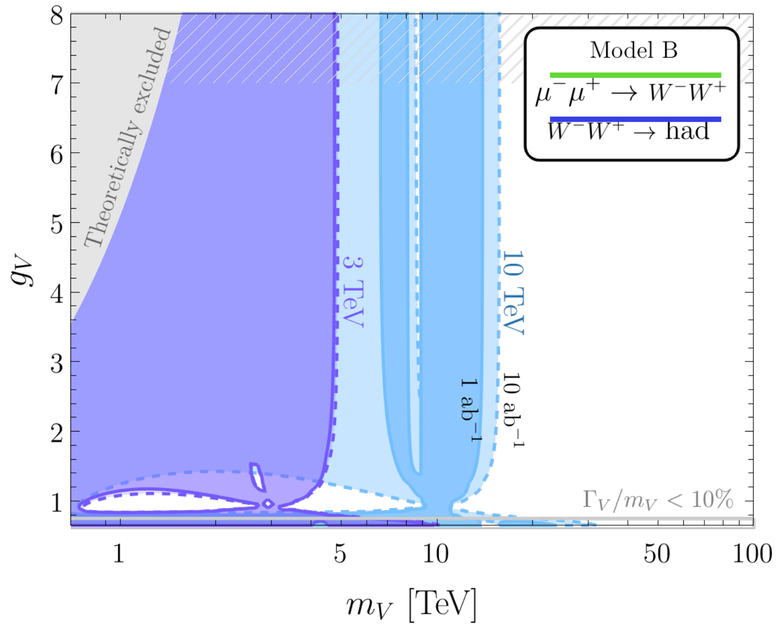
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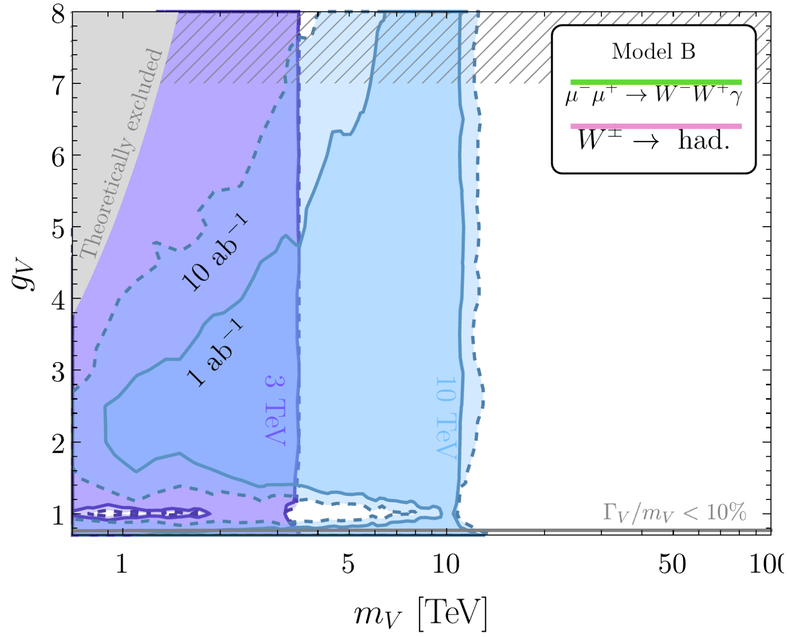
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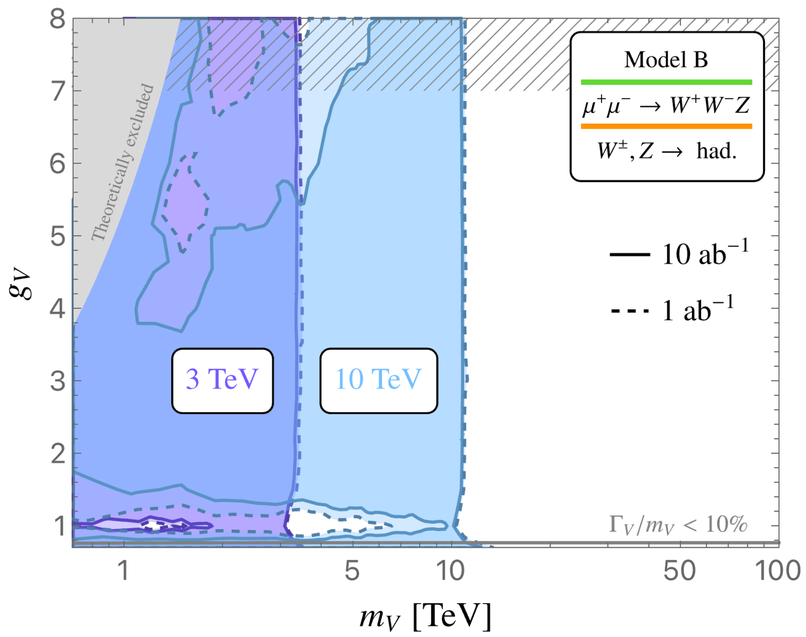
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Theoretically excluded
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3 TeV
10 TeV
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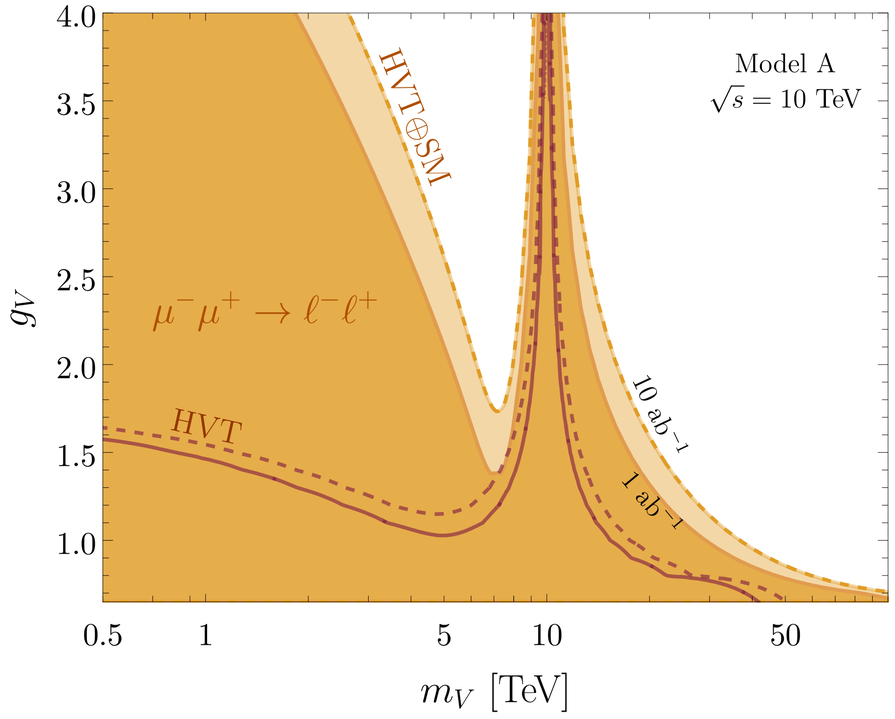
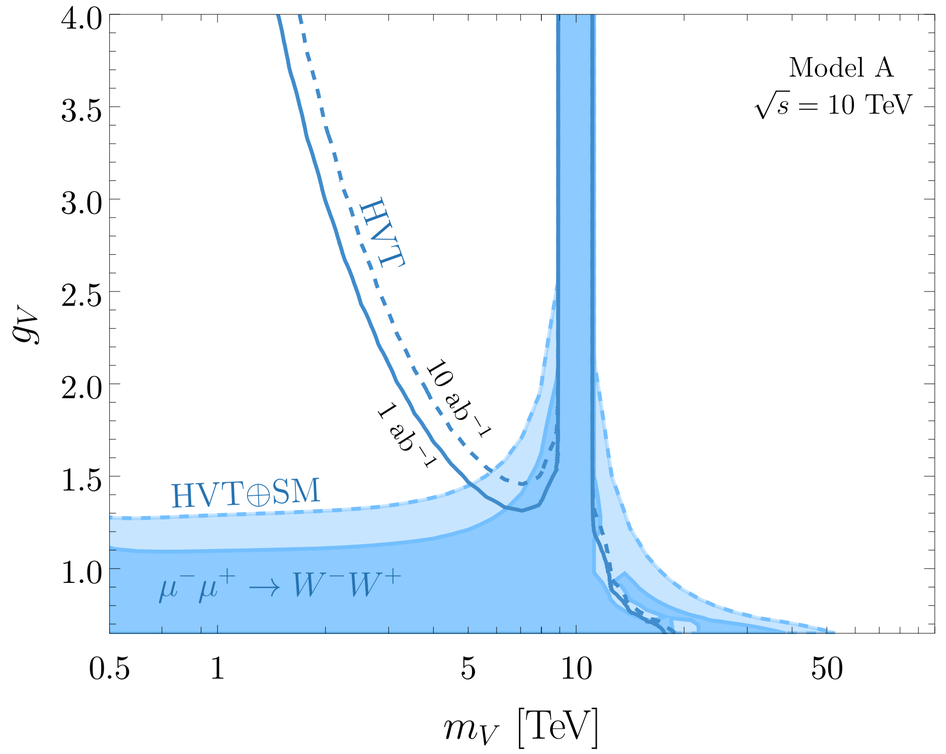
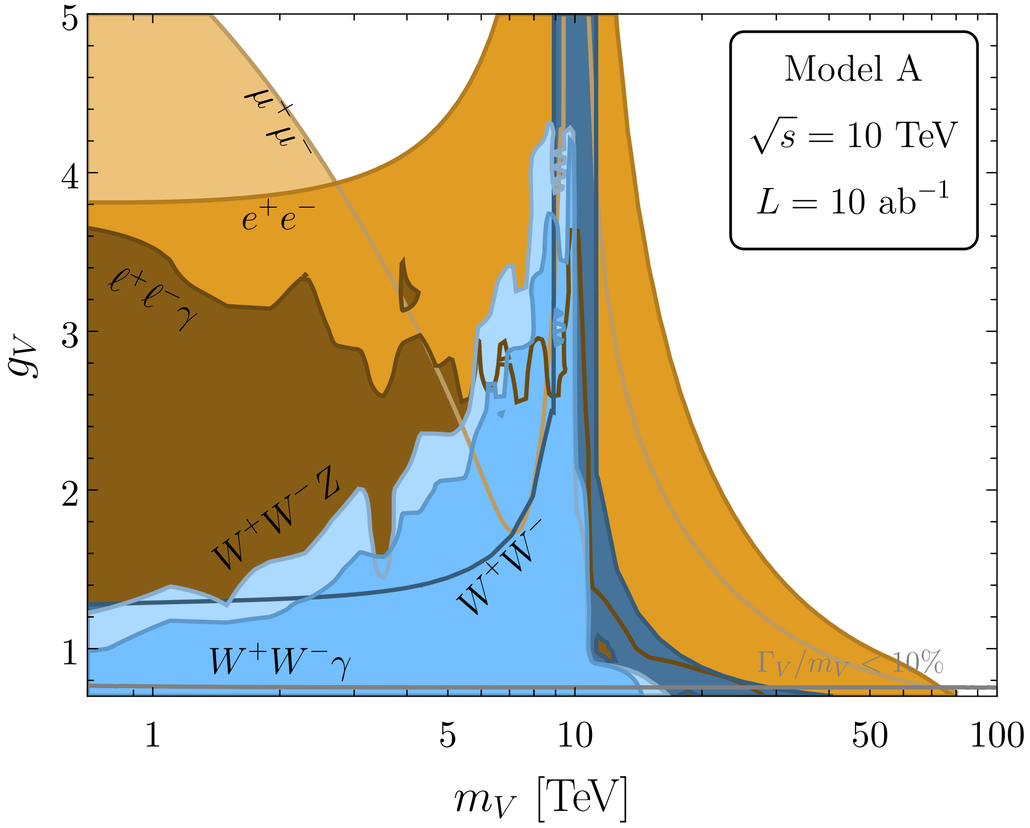
g_V
m_V [TeV]

Impact of interference

$$|\mathscr{M}|^2 = |\mathscr{M}_{\text{SM}} + \mathscr{M}_{\text{BSM}}|^2 = |\mathscr{M}_{\text{SM}}|^2 + \mathscr{M}_{\text{int}} + |\mathscr{M}_{\text{BSM}}|^2$$






Model A
$\sqrt{s} = 10$ TeV
$L = 10$ ab^{-1}
$\mu^+\mu^-$
e^+e^-
$\ell^+\ell^-\gamma$
W^+W^-Z
W^+W^-
$W^+W^-\gamma$
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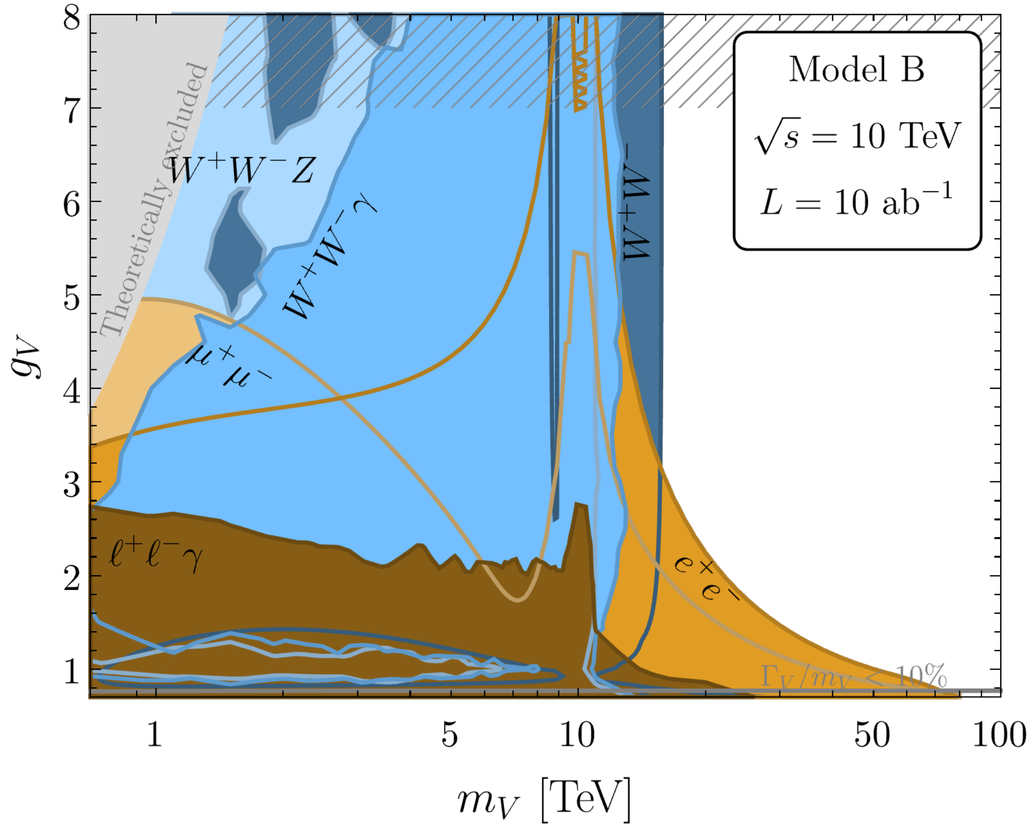
1
2
3
4
5
1
5
10
50
100


Model B
$\sqrt{s} = 10$ TeV
$L = 10$ ab^{-1}
Theoretically excluded
W^+W^-Z
$W^+W^-\gamma$
W^+W^-
$\mu^+\mu^-$
$\ell^+\ell^-\gamma$
e^+e^-
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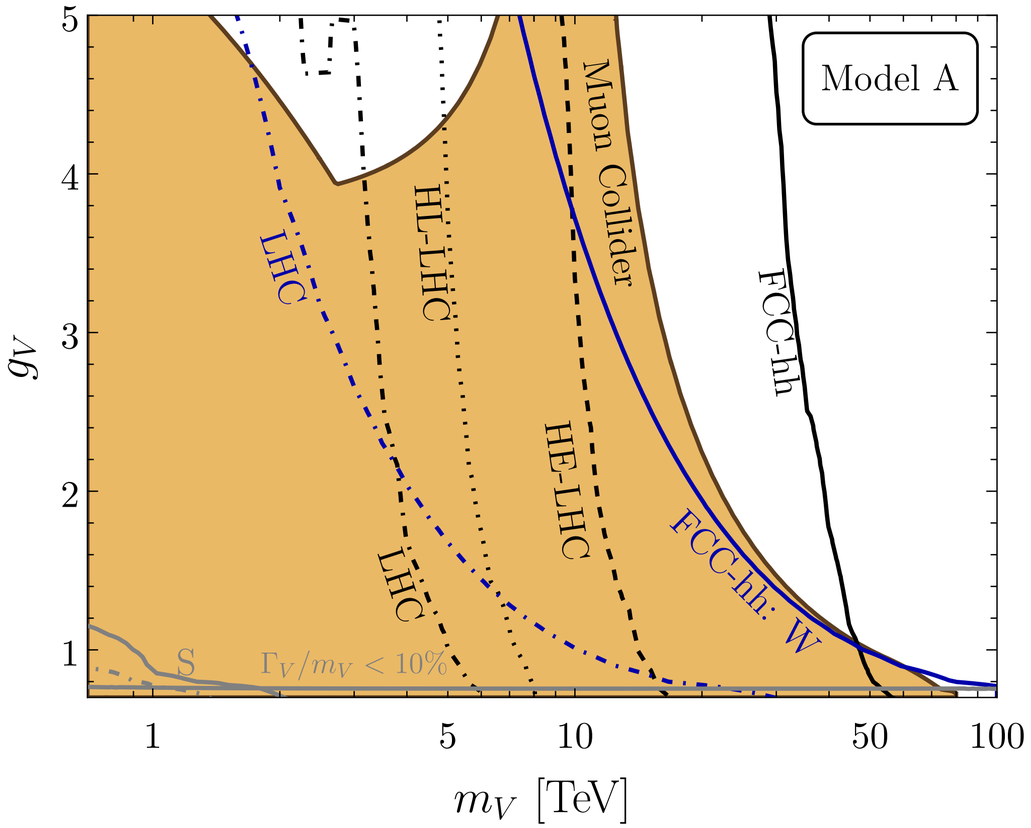
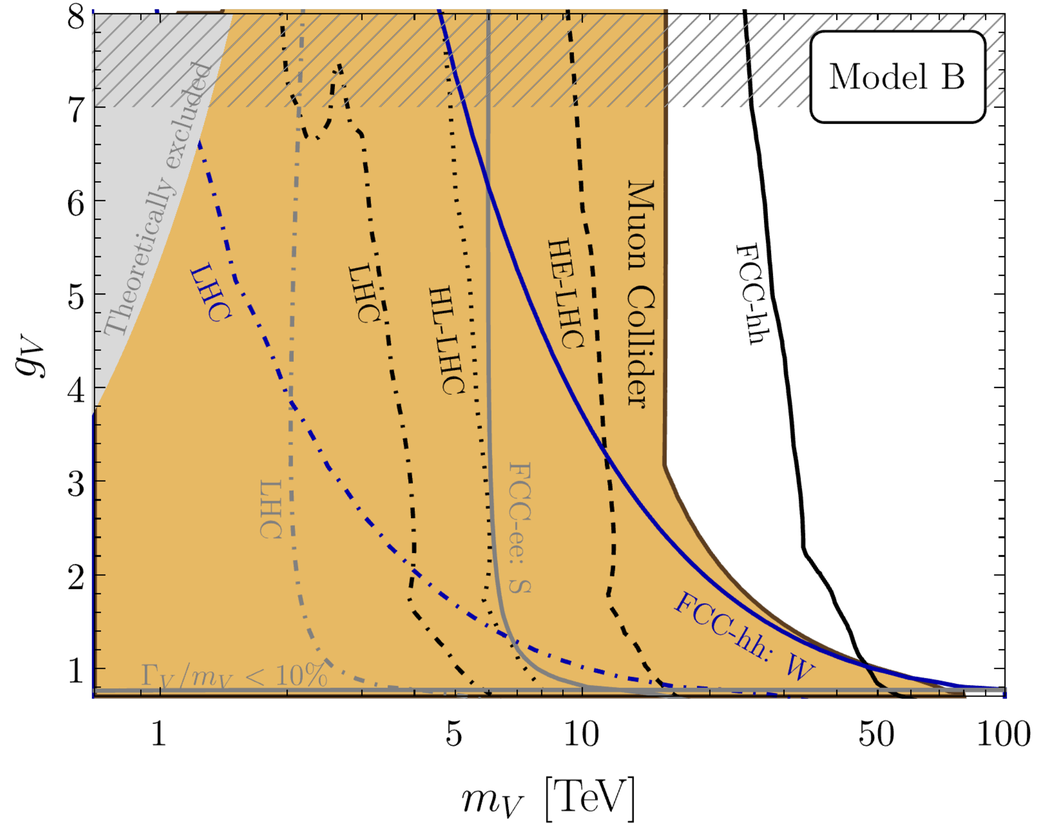
g_V
m_V [TeV]
1
2
3
4
5
6
7
8
1
5
10
50
100

Comparison with future colliders





Conclusions

- HVT can be found already with $2 \to 2$ scatterings
- Must include interference
- ~ all (m_V, g_V) plane excluded
- Overcomes all LHC stages, competitive with FCC

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MONDAY ON YOUR ARXIV FEED!

Thank you!
Questions?

Backup slides

Muon Collider

MuC performance

Requirement	Baseline		Aspirational
	$\sqrt{s} = 3$ TeV	$\sqrt{s} = 10$ TeV	
Angular acceptance	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

From *Interim report for the International Muon Collider Collaboration* 2025

Higgs

- We need to study the Higgs:
  - couplings to itself:
  - couplings to BSM
  - is it composite?
- What would the best machine be? To have h on shell you need
  - An e^+e^- collider of $\sqrt{s} \sim 240$ GeV . Lepton precision
  - A pp collider of $\sqrt{s} \sim 100$ TeV can study 3h vertices.

$$\mathscr{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{m_h^2}{2}h^2 - \lambda_3 h^3 - \lambda_4 h^4$$

- Higgs was found at pp collider:
  - Dirty: richer but unpredictable initial state. Do not control soft gluon emission
- A MuC can:
  - have lepton precision
  - go to high energy
  - emit EW radiation controllably

Muon Collider

- $\sqrt{s} \sim 3$ or 10 TeV $\rightarrow v_\mu \sim (1 - 10^{-10})c$
- Lumi: 1 or 10 ab^{-1} because we are interested in 1 ab cross section
- A MuC of 10 Km has the same effective CoM energy of a pp collider with 100 km ring.
- $\tau_\mu \sim 2.2 \cdot 10^{-6} s$ (but goes up to 0.2 s at 10 TeV)

The strength of a Muon Collider

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- Synergy with neutrino physics because a μ beam will also make a ν beam
- A Higgs factory can probe BSM only in loops. A MuC can probe both Higgs and BSM

HVT

Mixing

- Covariant derivatives give VW terms:
  - $D_{[\mu}\mathscr{V}^{a}_{\nu]} = D_{\mu}\mathscr{V}^{a}_{\nu} - D_{\nu}\mathscr{V}^{a}_{\mu}$

$$D_{\mu}\mathscr{V}^{a}_{\nu} = \partial_{\mu}\mathscr{V}^{a}_{\nu} + g\,\epsilon^{abc}W^{b}_{\mu}\mathscr{V}^{c}_{\nu}$$

- HVT mixes with SM. Let's disentangle

From gauge to mass base

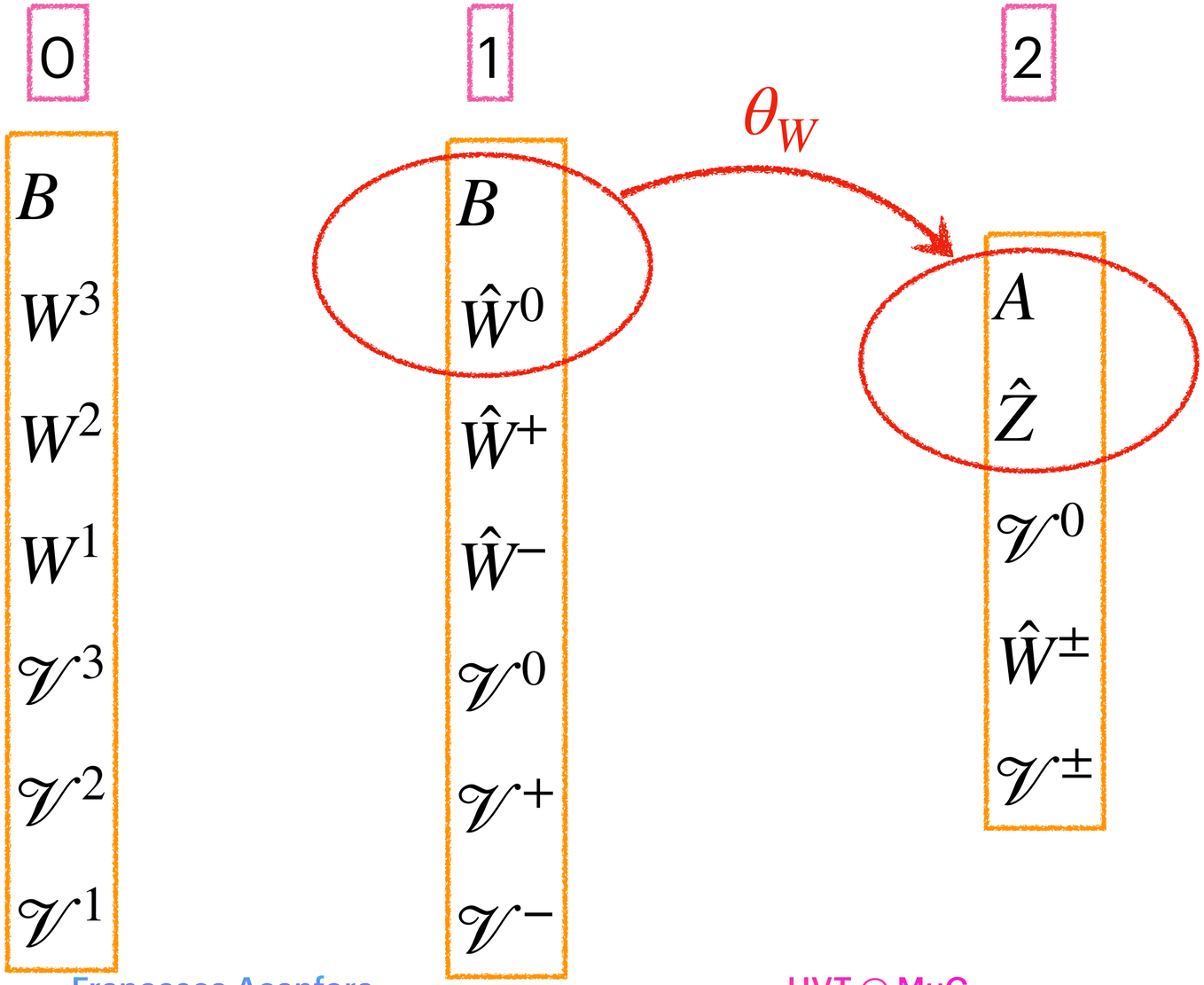
From gauge to mass base

0	1
B	B
W^3	$\hat{W}^0$
W^2	$\hat{W}^+$
W^1	$\hat{W}^-$
$\mathscr{V}^3$	$\mathscr{V}^0$
$\mathscr{V}^2$	$\mathscr{V}^+$
$\mathscr{V}^1$	$\mathscr{V}^-$

From gauge to mass base

0	1	2
B	B	
W^3	$\hat{W}^0$	A
W^2	$\hat{W}^+$	$\hat{Z}$
W^1	$\hat{W}^-$	$\mathcal{V}^0$
$\mathcal{V}^3$	$\mathcal{V}^0$	$\hat{W}^\pm$
$\mathcal{V}^2$	$\mathcal{V}^+$	$\mathcal{V}^\pm$
$\mathcal{V}^1$	$\mathcal{V}^-$	

From gauge to mass base



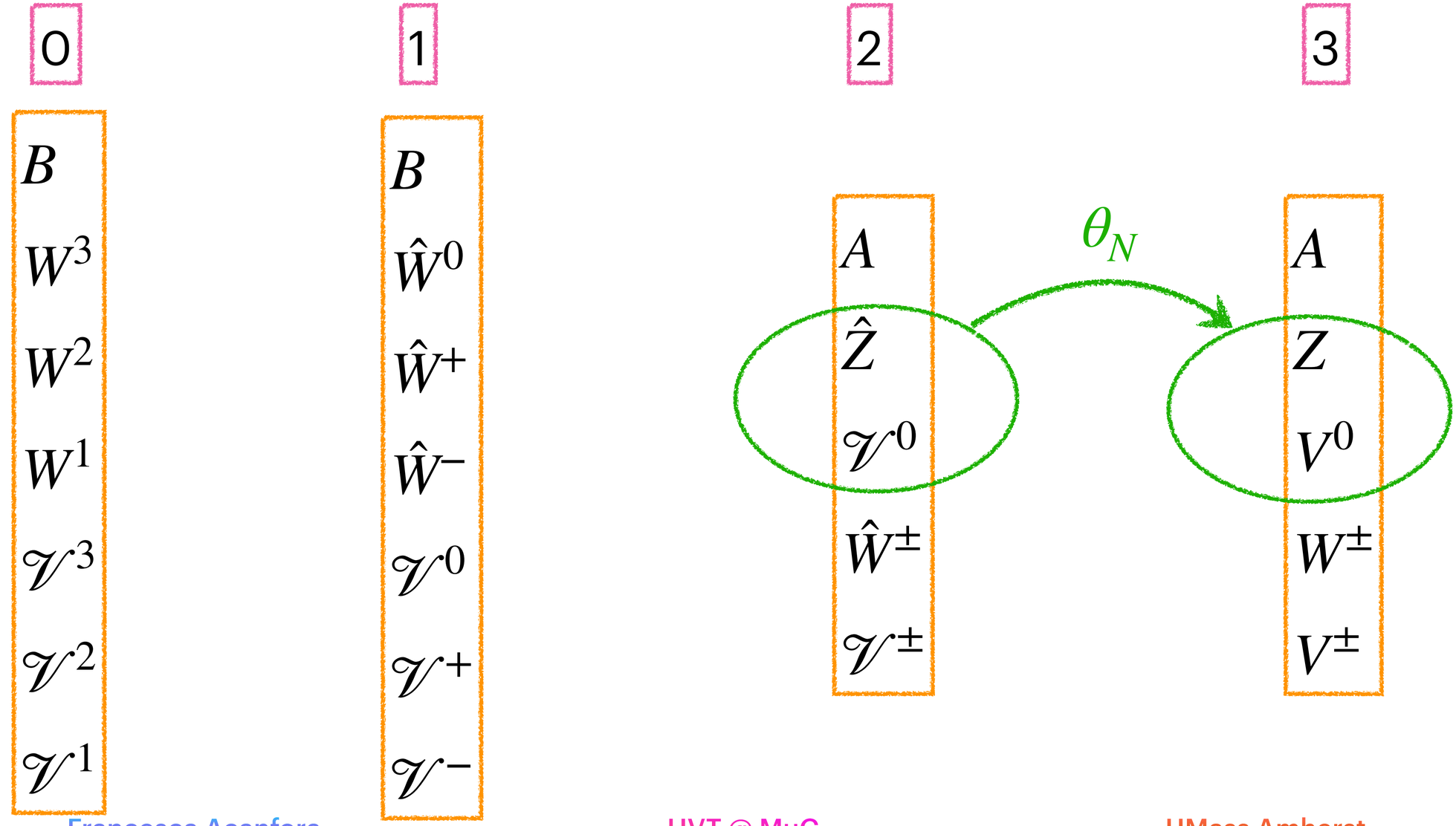
From gauge to mass base

0	1	2
B	B	
W^3	$\hat{W}^0$	A
W^2	$\hat{W}^+$	$\hat{Z}$
W^1	$\hat{W}^-$	$\mathcal{V}^0$
$\mathcal{V}^3$	$\mathcal{V}^0$	$\hat{W}^\pm$
$\mathcal{V}^2$	$\mathcal{V}^+$	$\mathcal{V}^\pm$
$\mathcal{V}^1$	$\mathcal{V}^-$	

From gauge to mass base

0	1	2	3
B	B	A	A
W^3	$\hat{W}^0$	$\hat{Z}$	Z
W^2	$\hat{W}^+$	$\mathcal{V}^0$	V^0
W^1	$\hat{W}^-$	$\hat{W}^\pm$	$W^\pm$
$\mathcal{V}^3$	$\mathcal{V}^0$	$\mathcal{V}^\pm$	$V^\pm$
$\mathcal{V}^2$	$\mathcal{V}^+$		
$\mathcal{V}^1$	$\mathcal{V}^-$		

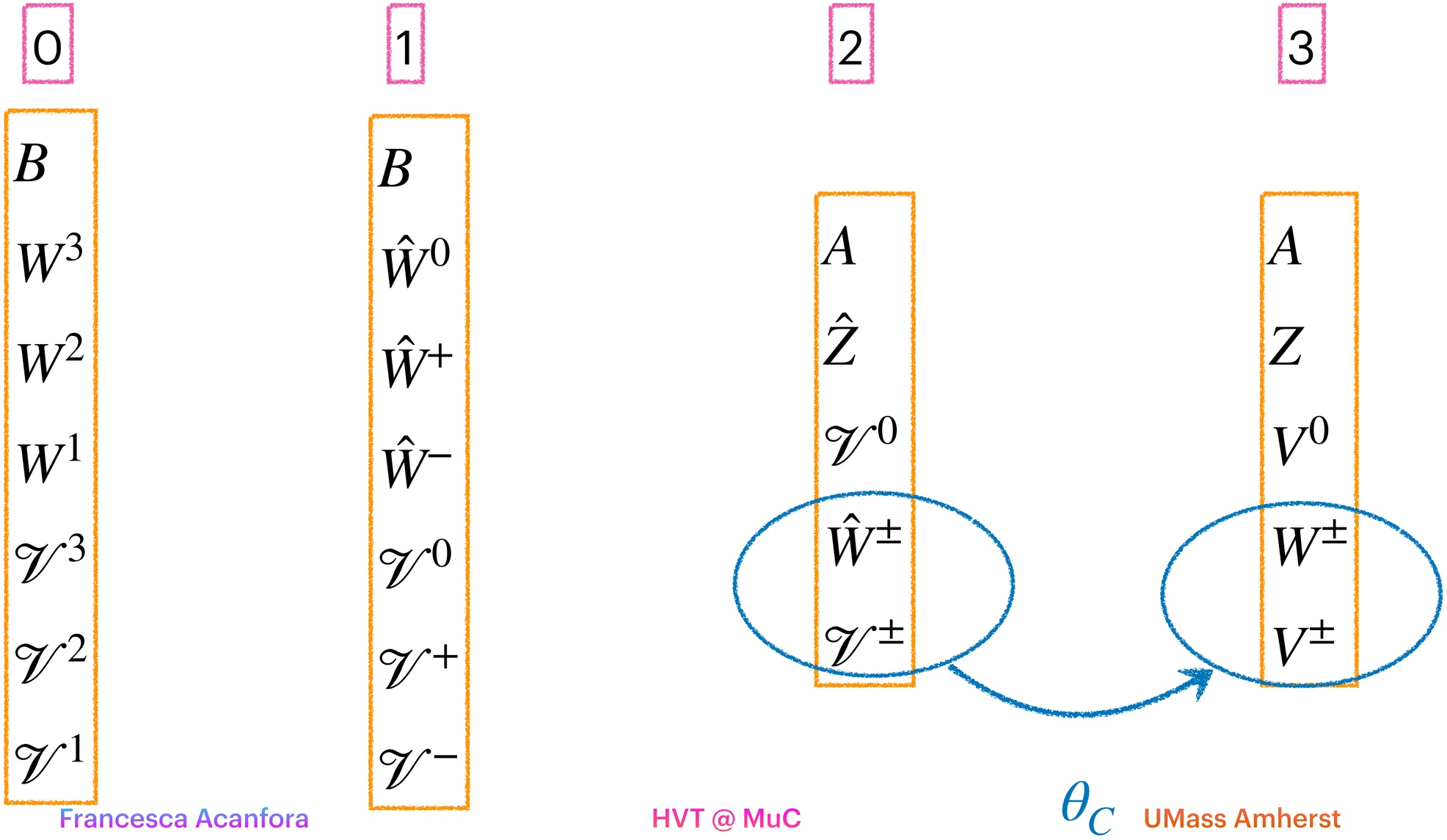
From gauge to mass base



From gauge to mass base

0	1	2	3
B	B	A	A
W^3	$\hat{W}^0$	$\hat{Z}$	Z
W^2	$\hat{W}^+$	$\mathcal{V}^0$	V^0
W^1	$\hat{W}^-$	$\hat{W}^\pm$	$W^\pm$
$\mathcal{V}^3$	$\mathcal{V}^0$	$\mathcal{V}^\pm$	$V^\pm$
$\mathcal{V}^2$	$\mathcal{V}^+$		
$\mathcal{V}^1$	$\mathcal{V}^-$		

From gauge to mass base



θ_C

From gauge to mass base

0	1	2	3
B	B	A	A
W^3	$\hat{W}^0$	$\hat{Z}$	Z
W^2	$\hat{W}^+$	$\mathcal{V}^0$	V^0
W^1	$\hat{W}^-$	$\hat{W}^\pm$	$W^\pm$
$\mathcal{V}^3$	$\mathcal{V}^0$	$\mathcal{V}^\pm$	$V^\pm$
$\mathcal{V}^2$	$\mathcal{V}^+$		
$\mathcal{V}^1$	$\mathcal{V}^-$		

- $\mathscr{V}^{\pm}_{\mu} = \dfrac{\mathscr{V}^{1}_{\mu} \mp i\mathscr{V}^{2}_{\mu}}{\sqrt{2}}, \qquad \mathscr{V}^{0}_{\mu} = \mathscr{V}^{3}_{\mu}$
- Massless photon: $A_{\mu} = c_W B_{\mu} + s_W W^3_{\mu}$
- $\tan\theta_W = \dfrac{g'}{g}$
- $\tan 2\theta_N = g_V c_H \dfrac{\hat{v}}{\hat{m}_V} \dfrac{\hat{m}_Z \hat{m}_V}{\hat{m}_V^2 - \hat{m}_Z^2}$
- $\tan 2\theta_C = g_V c_H \dfrac{\hat{v}}{\hat{m}_V} \dfrac{\hat{m}_W \hat{m}_V}{\hat{m}_V^2 - \hat{m}_W^2}$

- To reproduce SM $\dfrac{\hat{m}_{W,Z}}{\hat{m}_V} \ll 1$
- Custodial symmetry: if $\hat{m}_W \to \hat{m}_Z$ then $\theta_C \to \theta_N$
- $m_W^2 M_+^2 = \cos^2\theta_W m_Z^2 M_0^2$

  i.e. $M_+^2 = M_0^2(1 + \mathcal{O}(\%))$

A small correction to SM masse

- $\hat{m}_Z = \dfrac{e}{2 \sin\theta_W \cos\theta_W}\hat{v}$
- $\hat{m}_W = \cos\theta_W \hat{m}_Z$
- $\hat{m}_V = \sqrt{m_{\mathscr{Y}}^2 + g_V^2 c_{VVHH}\hat{v}^2}$
- $\hat{v} = \dfrac{\mu}{\sqrt{\lambda}}$

$$m_Z^2 = \hat{m}_Z^2\left(1 - c_H^2\zeta^2\right)\left(1 + \mathcal{O}\left(\hat{m}_Z^2/\hat{m}_V^2\right)\right)$$

$$m_W^2 = \hat{m}_W^2\left(1 - c_H^2\zeta^2\right)\left(1 + \mathcal{O}\left(\hat{m}_W^2/\hat{m}_V^2\right)\right)$$

$$\zeta := \frac{g_v\hat{v}}{2\hat{m}_V} \ll 1$$

Model A (weakly coupled)

- Extend the SM with another SU(2):
  $SU(2)_1 \times SU(2)_2 \times U(1)_Y$
- You get two copies of Ws, one going to SM W and one making the HVT
- You break the symmetry down to SM thanks to the real bidoublet
  $\Phi = (2,2)_0$ with vev $\begin{pmatrix} f & 0 \\ 0 & f \end{pmatrix}$

Model B (strongly coupled)

- In general:
  - the Higgs boson is the pNGb of some broken symmetry of a strong new force
  - Feature heavy vector resonances with EW quantum numbers.
- Example: Minimal Composite Higgs Model (MCHM). SO(5) spontaneously broken to SO(4)

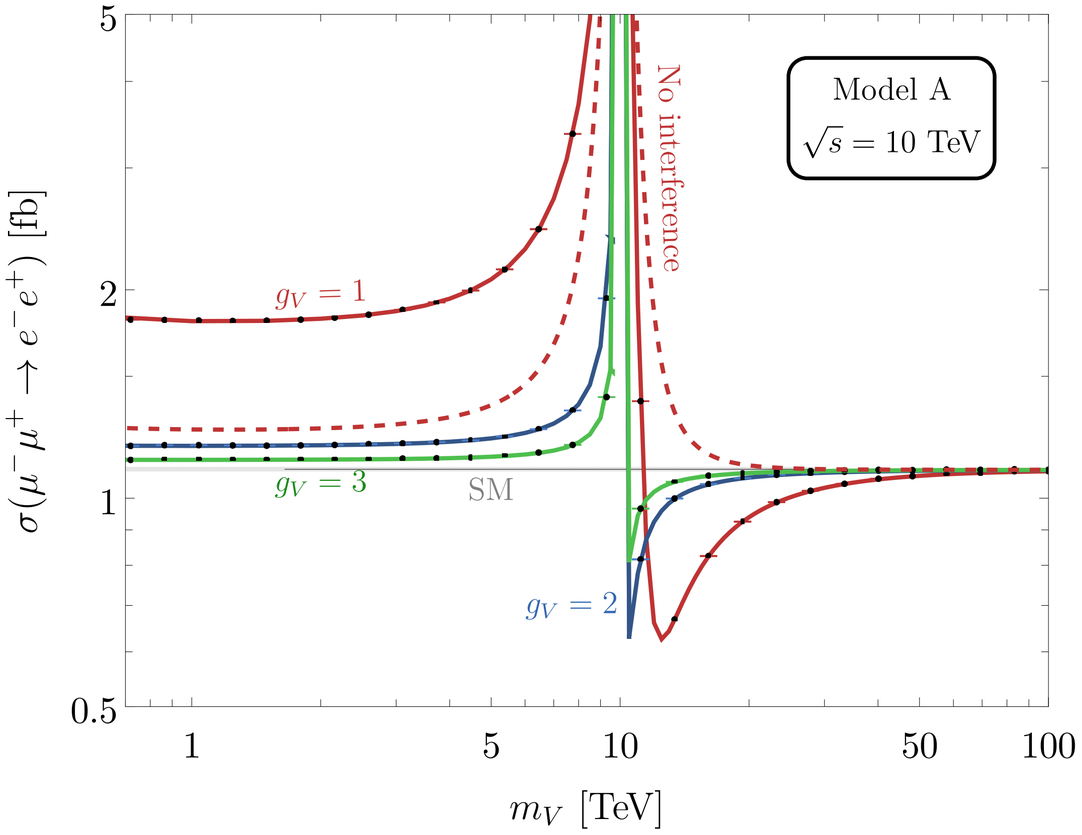
ElectroWeak Precision Tests (EWPT)

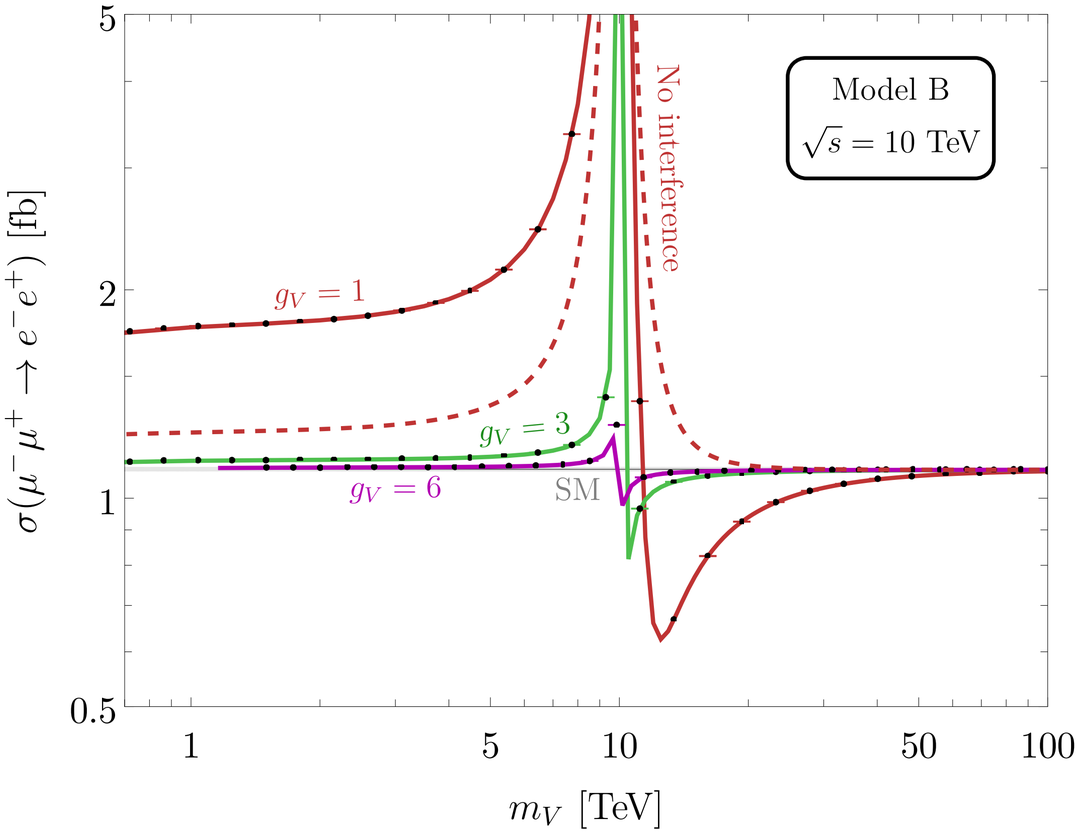
- We introduced a new heavy particle
- At low energies, can integrate away
- Effectively, W and B interactions are modified. Can express with form factors

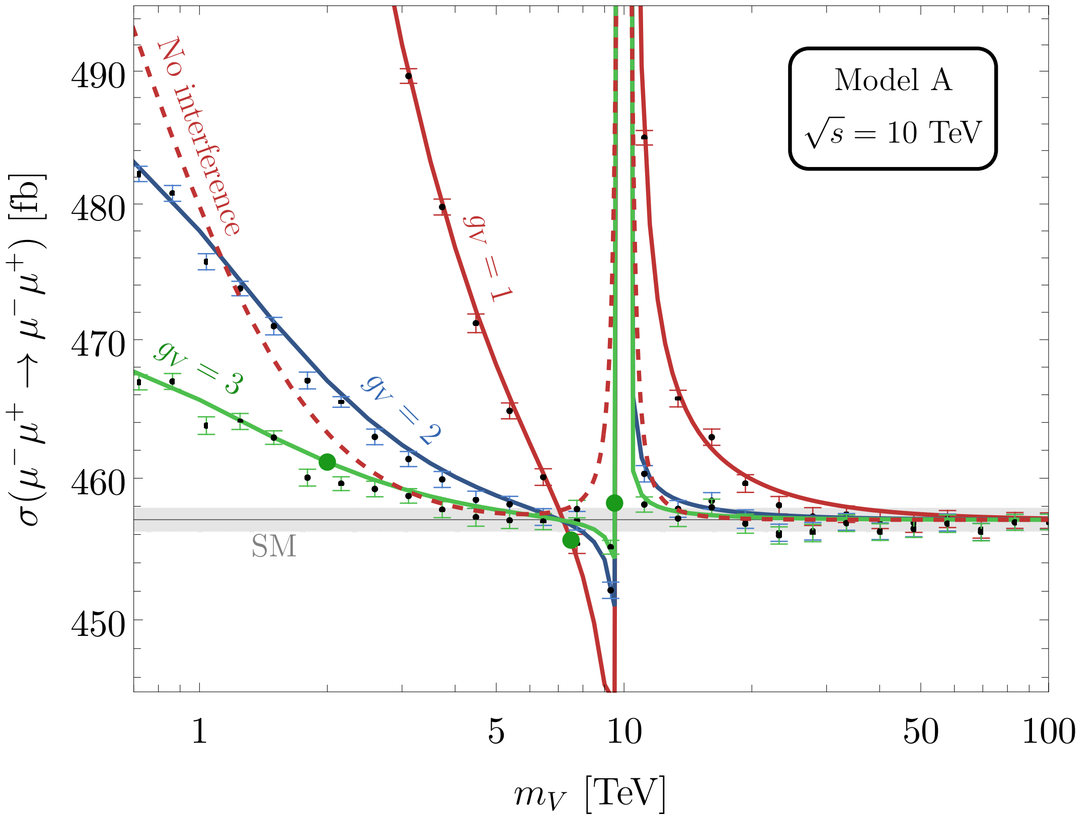
$$\mathscr{L} = -\frac{1}{2} W_\mu^3 \Pi_{33}\left(p^2\right) W^{\mu 3} - \frac{1}{2} B_\mu \Pi_{00}\left(p^2\right) B^\mu - W_\mu^3 \Pi_{30}\left(p^2\right) B^\mu - W_\mu^+ \Pi_\pm\left(p^2\right) W^{\mu -}$$

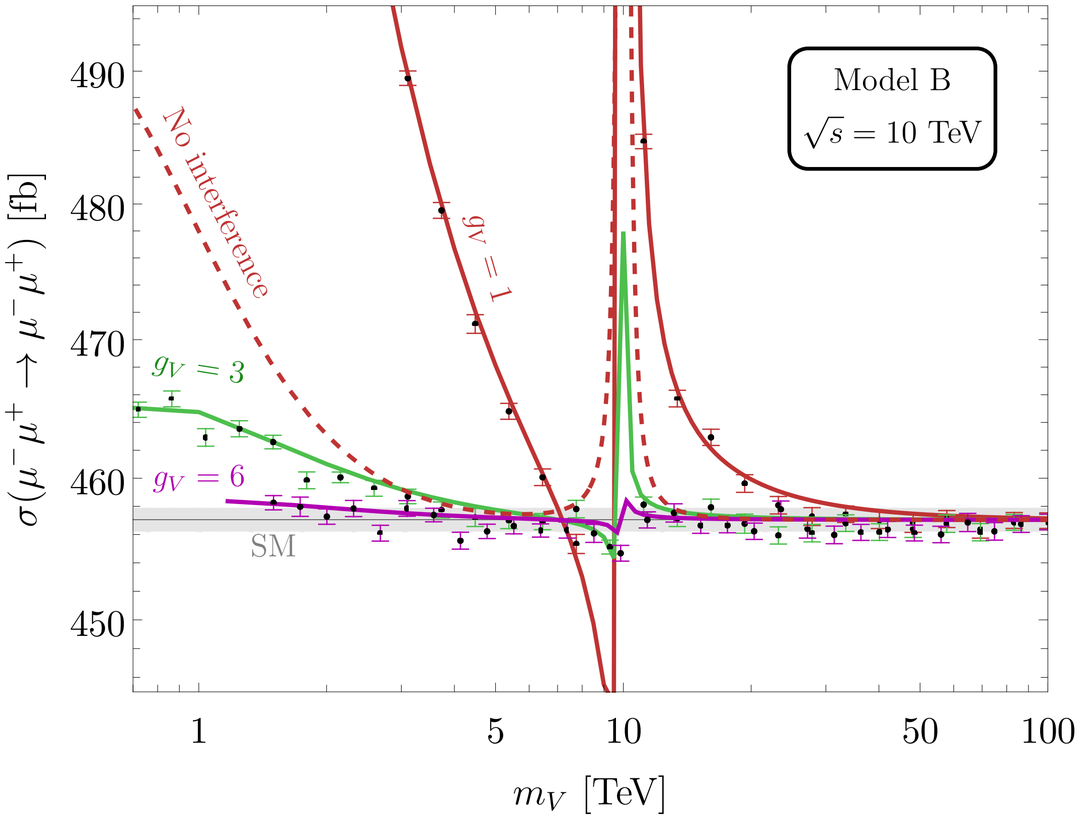
- Π_x are very well measured around $p^2 \sim 0$: need to reconstruct well known values like $M_{W,Z}, \Gamma_{W,Z}, \alpha_{\text{EM}}$

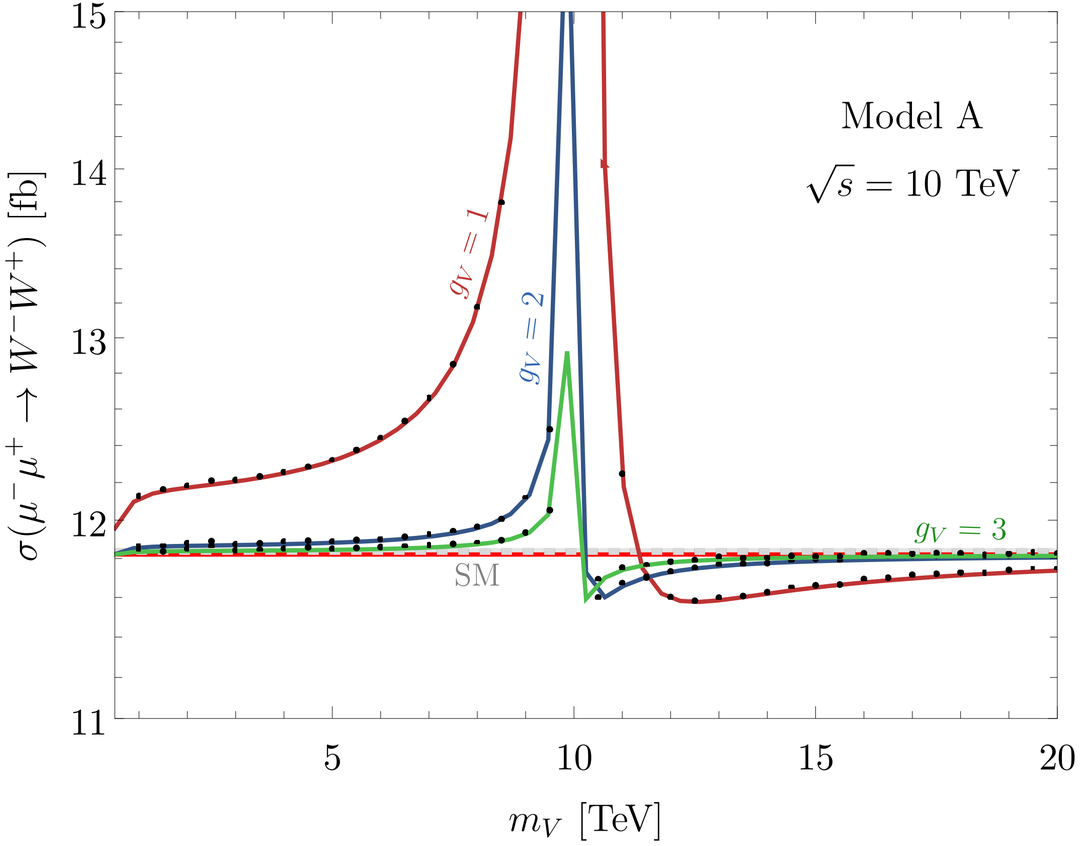
Cross sections

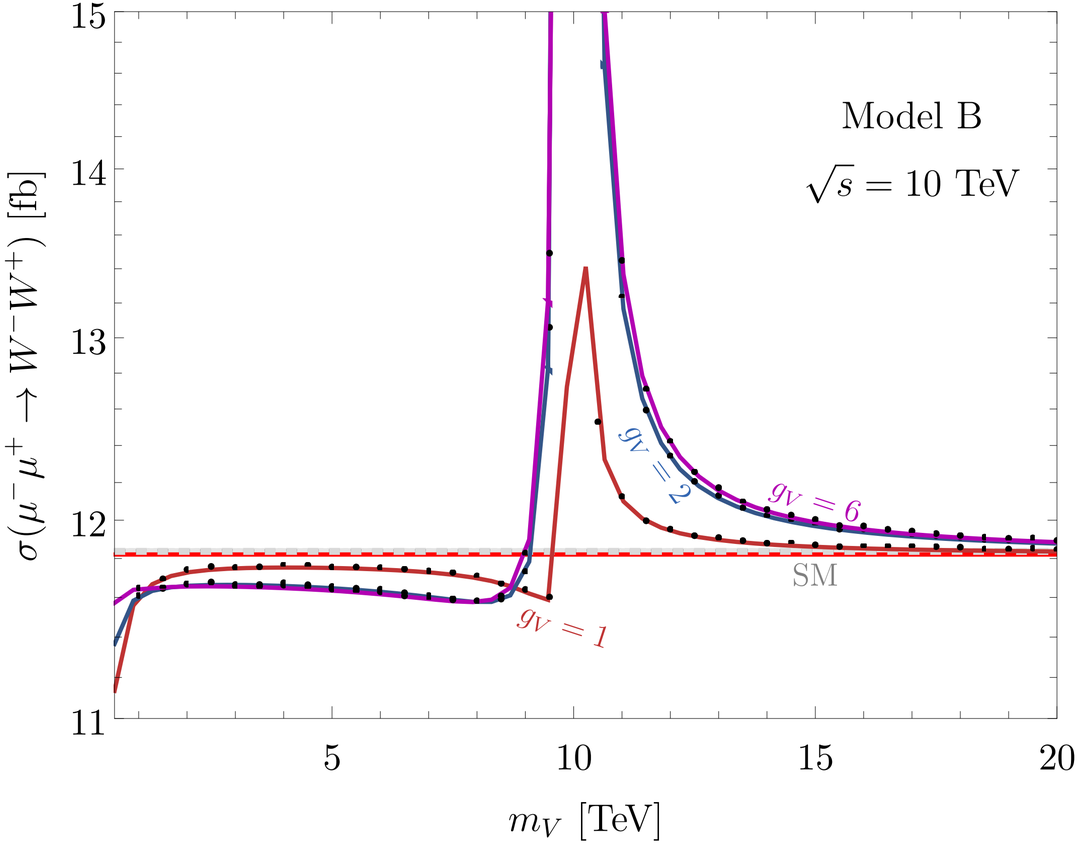

Model A
$\sqrt{s} = 10$ TeV
No interference
$g_V = 1$
$g_V = 3$
SM
$g_V = 2$
$\sigma(\mu^-\mu^+ \to e^-e^+)$ [fb]
m_V [TeV]
5
2
1
0.5
1
5
10
50
100

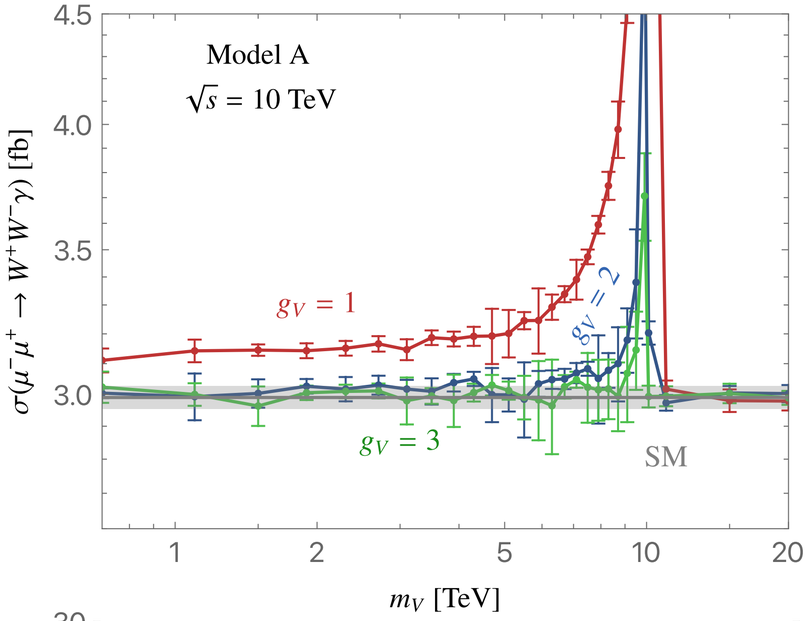

Model B
$\sqrt{s} = 10$ TeV
No interference
$g_V = 1$
$g_V = 3$
$g_V = 6$
SM
$\sigma(\mu^-\mu^+ \to e^-e^+)$ [fb]
m_V [TeV]
5
2
1
0.5
1
5
10
50
100

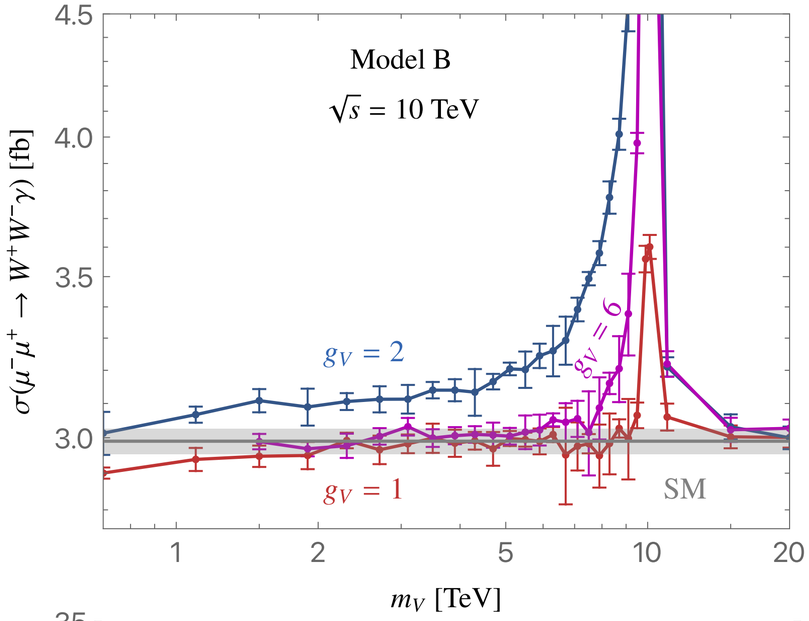

Model A
$\sqrt{s} = 10$ TeV
No interference
$g_V = 1$
$g_V = 2$
$g_V = 3$
SM
$\sigma(\mu^-\mu^+ \to \mu^-\mu^+)$ [fb]
m_V [TeV]
490
480
470
460
450
1
5
10
50
100

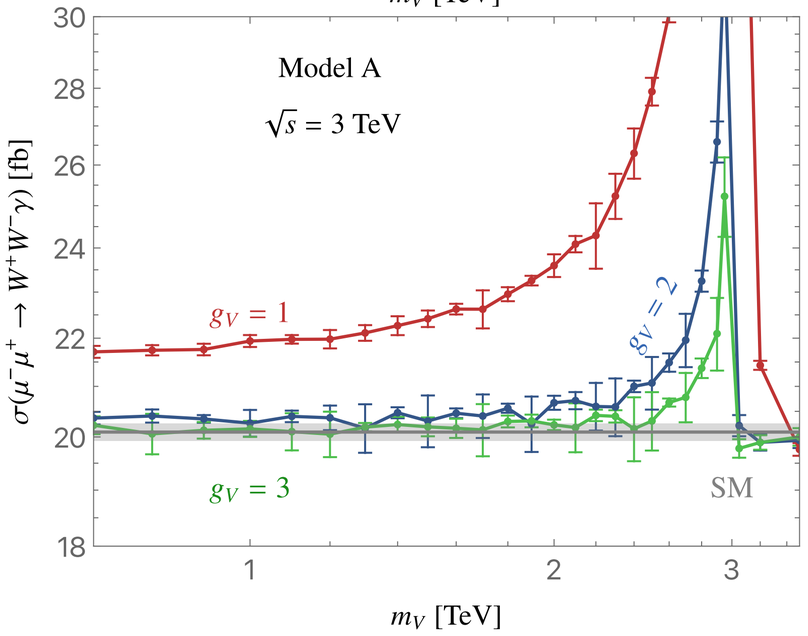

Model B
$\sqrt{s} = 10$ TeV
No interference
$g_V = 1$
$g_V = 3$
$g_V = 6$
SM
$\sigma(\mu^-\mu^+ \to \mu^-\mu^+)$ [fb]
m_V [TeV]
490
480
470
460
450
1
5
10
50
100

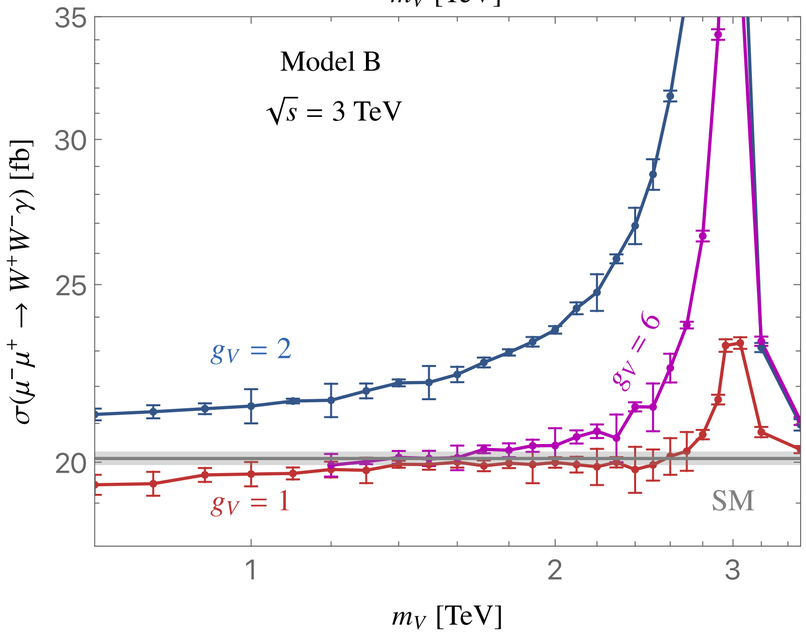

Model A
$\sqrt{s} = 10$ TeV
$g_V = 1$
$g_V = 2$
$g_V = 3$
SM
$\sigma(\mu^-\mu^+ \to W^-W^+)$ [fb]
m_V [TeV]
15
14
13
12
11
5
10
15
20

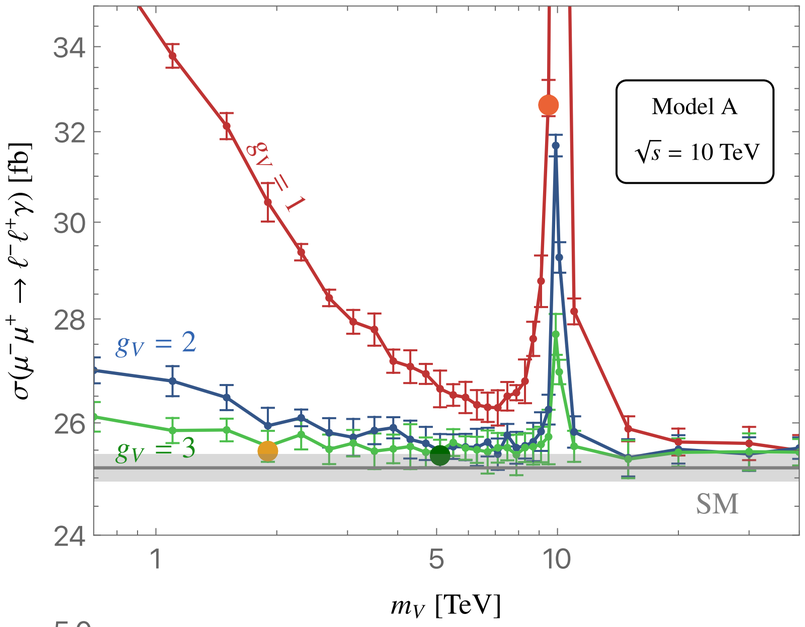

Model B
$\sqrt{s} = 10$ TeV
$g_V = 1$
$g_V = 2$
$g_V = 6$
SM
$\sigma(\mu^-\mu^+ \to W^-W^+)$ [fb]
m_V [TeV]
15
14
13
12
11
5
10
15
20

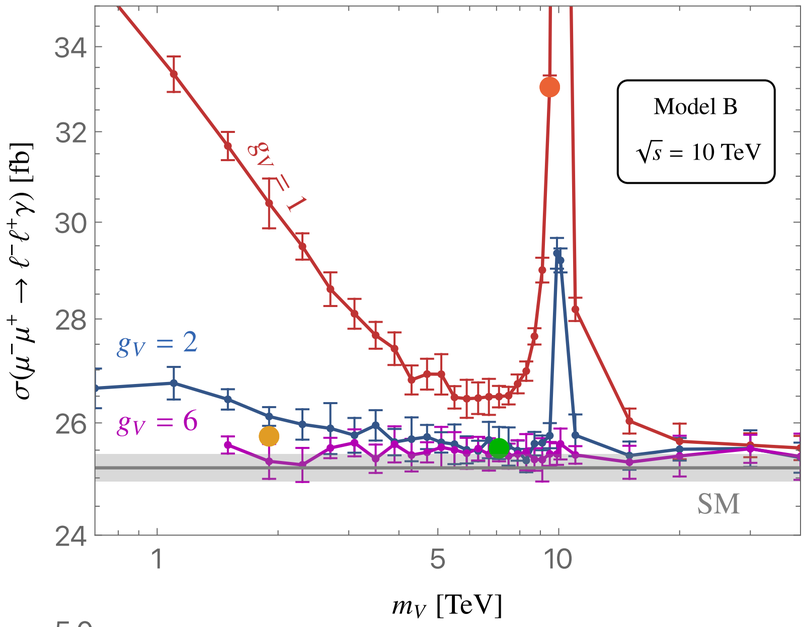

Model A
$\sqrt{s}$ = 10 TeV
g_V = 1
g_V = 2
g_V = 3
SM
$\sigma(\mu^-\mu^+ \to W^+W^-\gamma)$ [fb]
m_V [TeV]

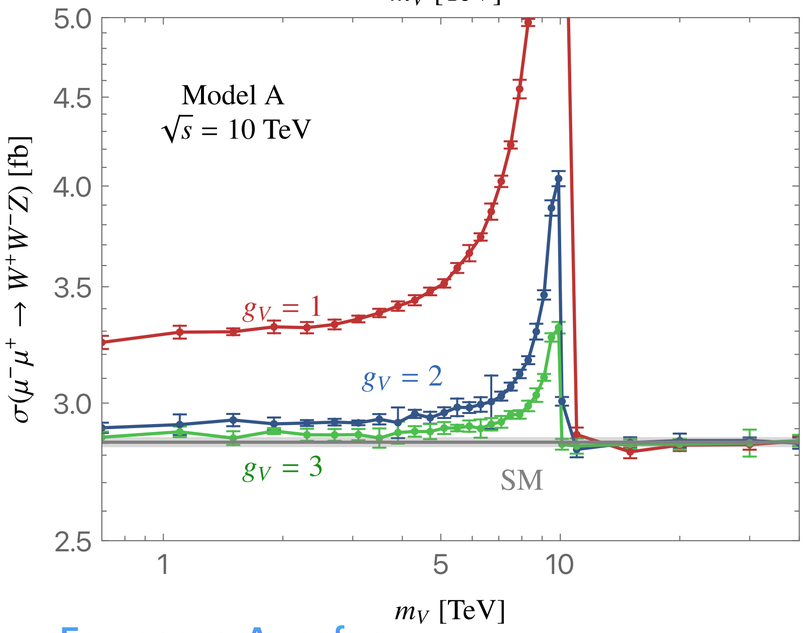

Model B
$\sqrt{s}$ = 10 TeV
g_V = 1
g_V = 2
g_V = 6
SM
$\sigma(\mu^-\mu^+ \to W^+W^-\gamma)$ [fb]
m_V [TeV]

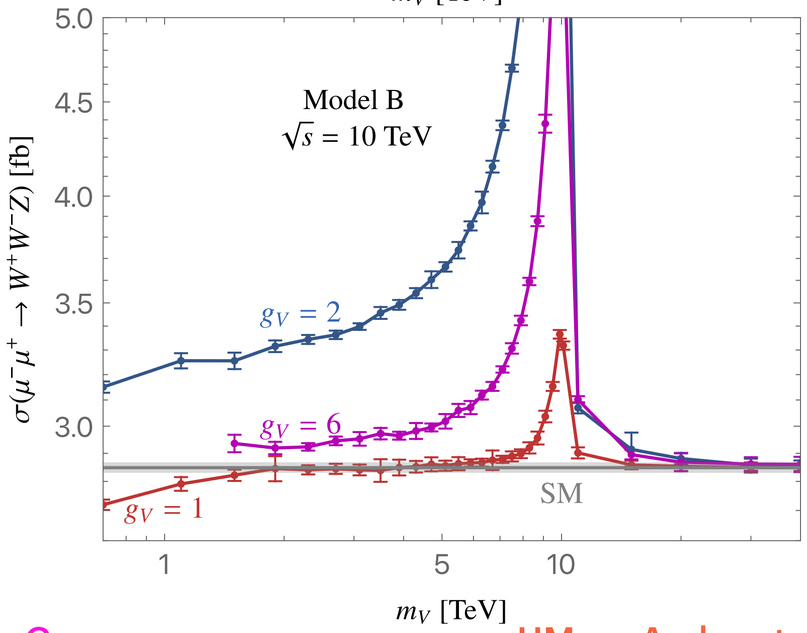

Model A
$\sqrt{s}$ = 3 TeV
g_V = 1
g_V = 2
g_V = 3
SM
$\sigma(\mu^-\mu^+ \to W^+W^-\gamma)$ [fb]
m_V [TeV]


Model B
$\sqrt{s}$ = 3 TeV
g_V = 1
g_V = 2
g_V = 6
SM
$\sigma(\mu^-\mu^+ \to W^+W^-\gamma)$ [fb]
m_V [TeV]

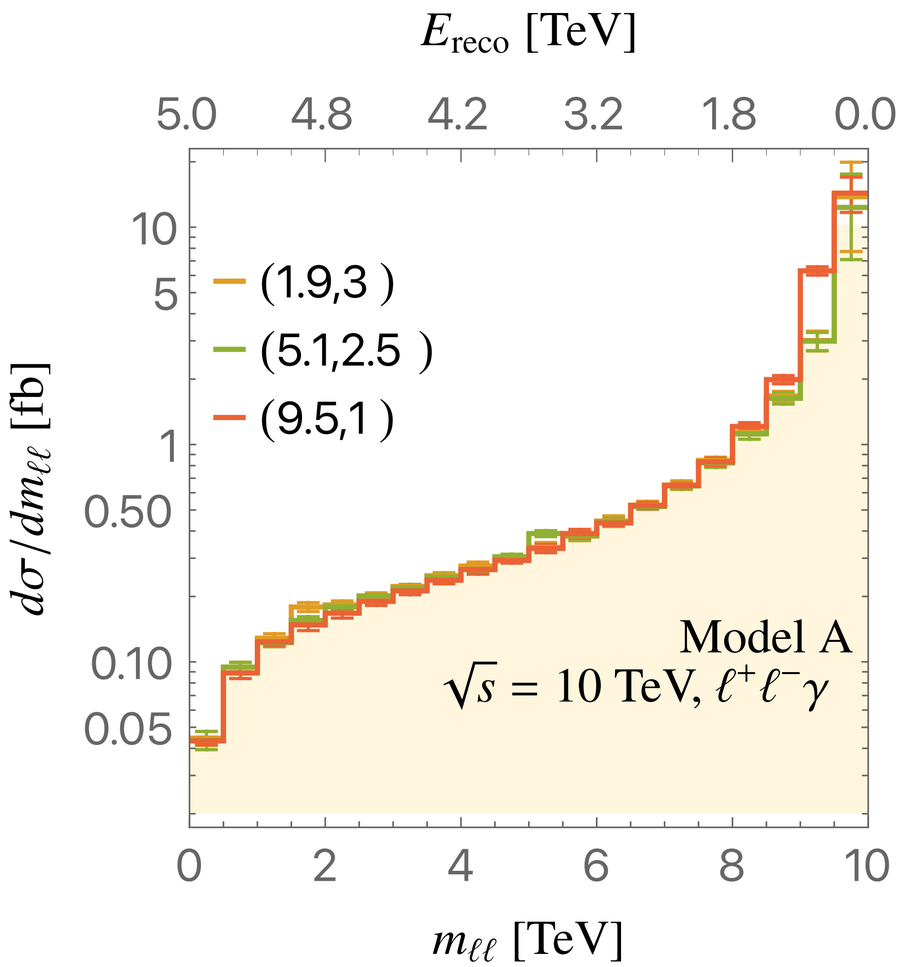

Model A
$\sqrt{s}$ = 10 TeV
$g_V = 1$
$g_V = 2$
$g_V = 3$
SM
$\sigma(\mu^-\mu^+ \to \ell^-\ell^+\gamma)$ [fb]
m_V [TeV]

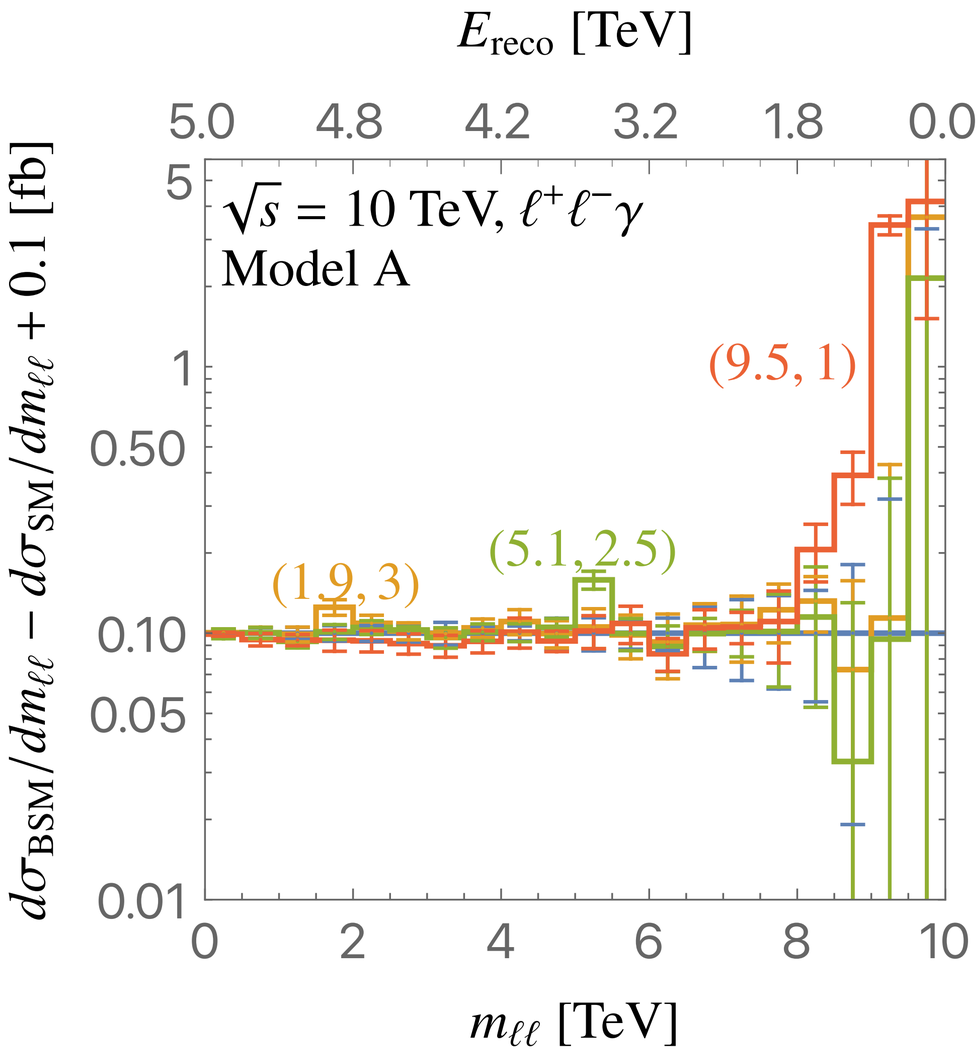

Model B
$\sqrt{s}$ = 10 TeV
$g_V = 1$
$g_V = 2$
$g_V = 6$
SM
$\sigma(\mu^-\mu^+ \to \ell^-\ell^+\gamma)$ [fb]
m_V [TeV]

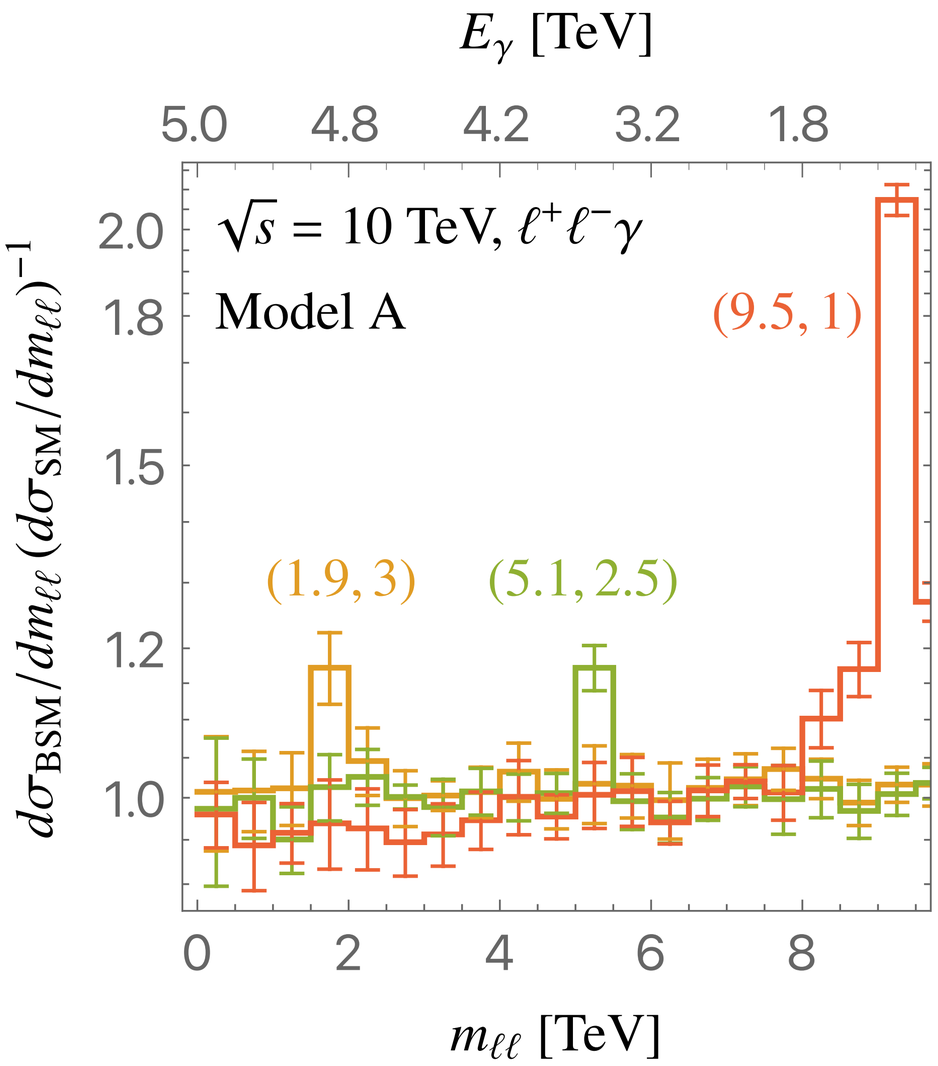

Model A
$\sqrt{s}$ = 10 TeV
$g_V = 1$
$g_V = 2$
$g_V = 3$
SM
$\sigma(\mu^-\mu^+ \to W^+W^-Z)$ [fb]
m_V [TeV]

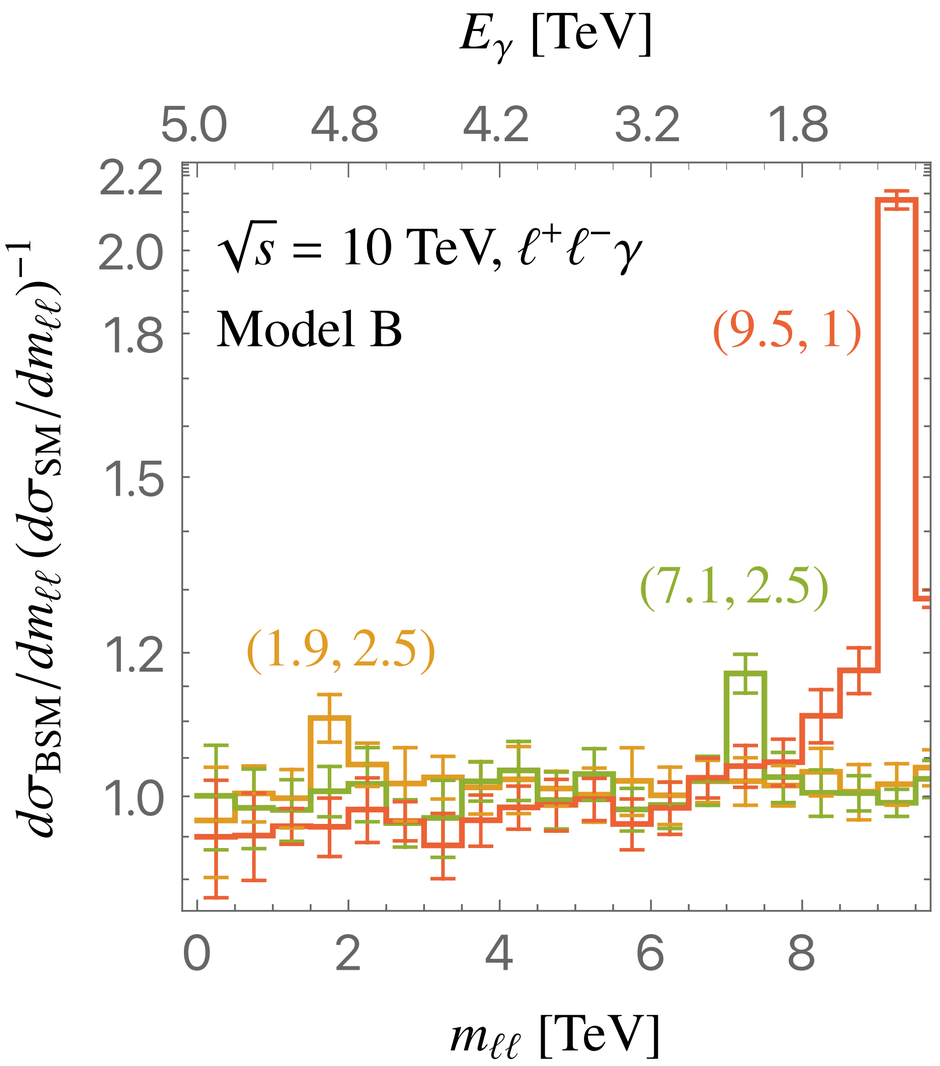

Model B
$\sqrt{s}$ = 10 TeV
$g_V = 2$
$g_V = 6$
$g_V = 1$
SM
$\sigma(\mu^-\mu^+ \to W^+W^-Z)$ [fb]
m_V [TeV]

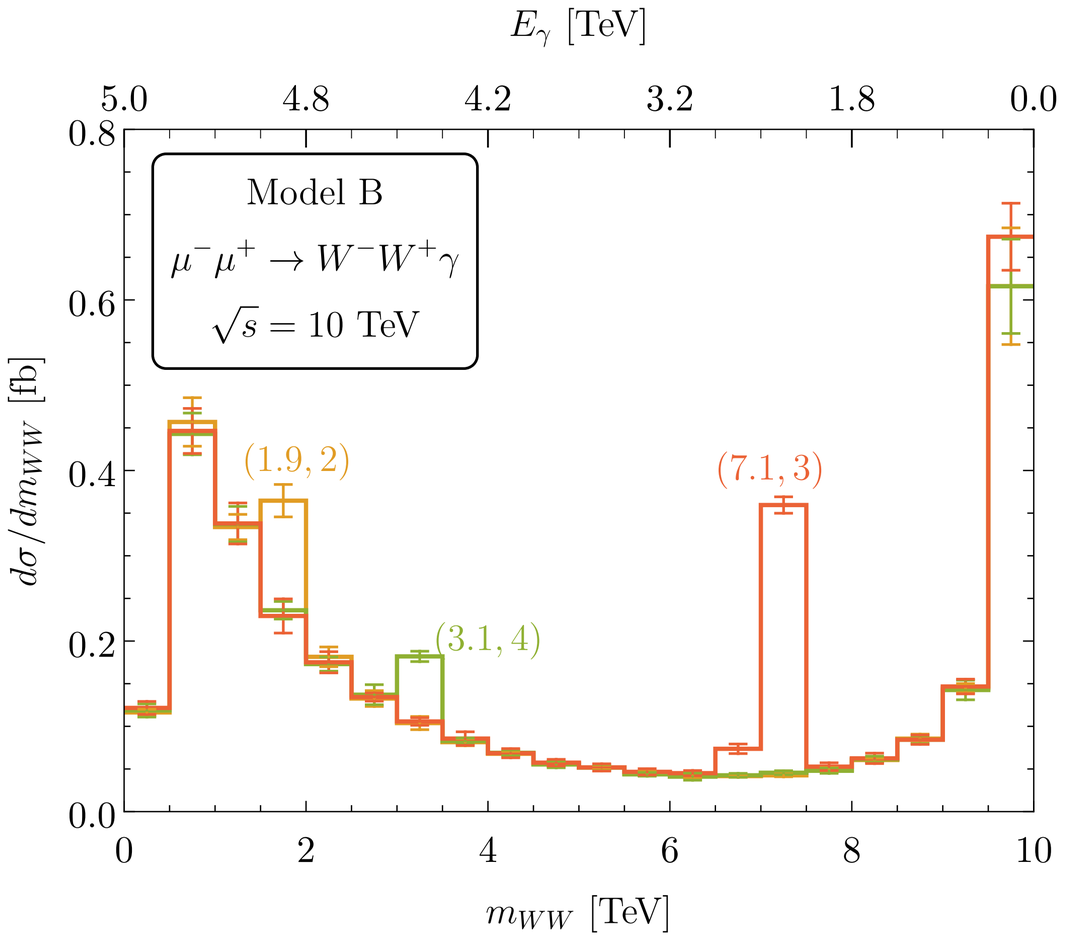
Distributions

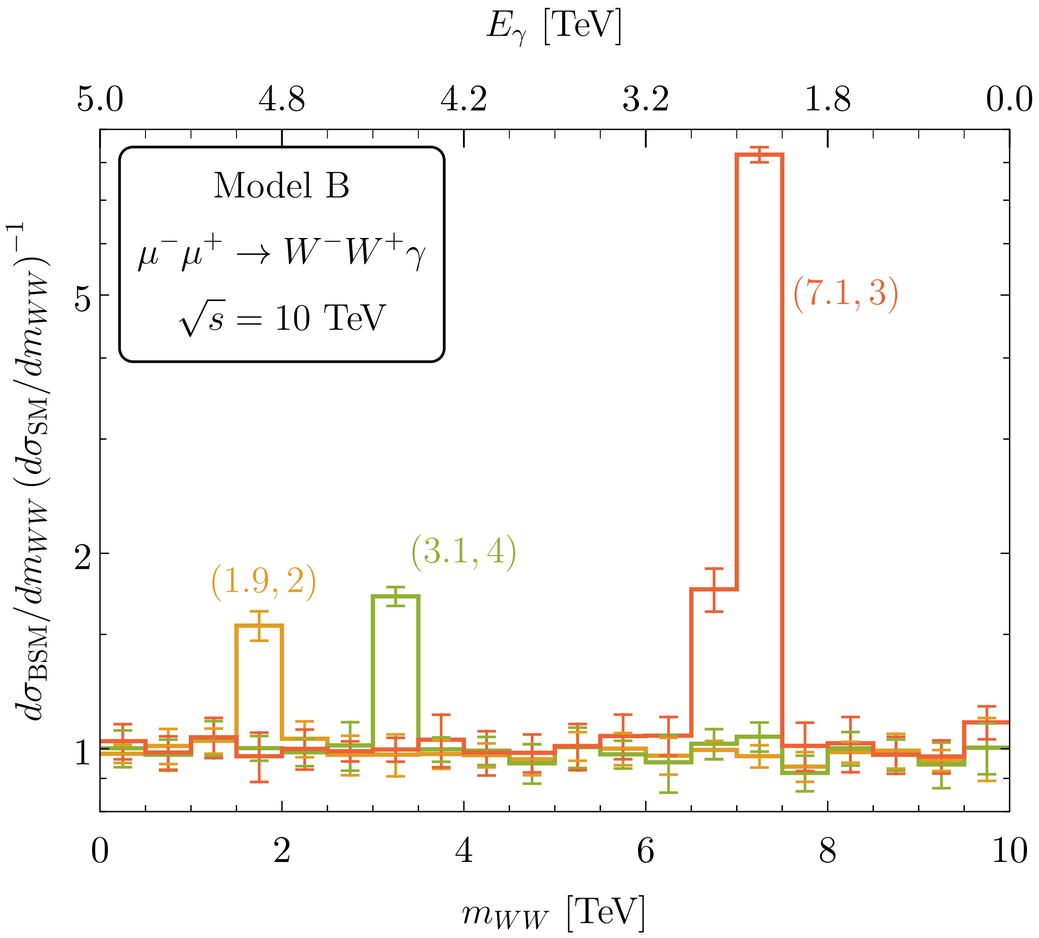

E_{reco} [TeV]
5.0 4.8 4.2 3.2 1.8 0.0
10
5
1
0.50
0.10
0.05
(1.9,3)
(5.1,2.5)
(9.5,1)
Model A
$\sqrt{s}$ = 10 TeV, $\ell^+\ell^-\gamma$
0 2 4 6 8 10
$m_{\ell\ell}$ [TeV]
$d\sigma/dm_{\ell\ell}$ [fb]

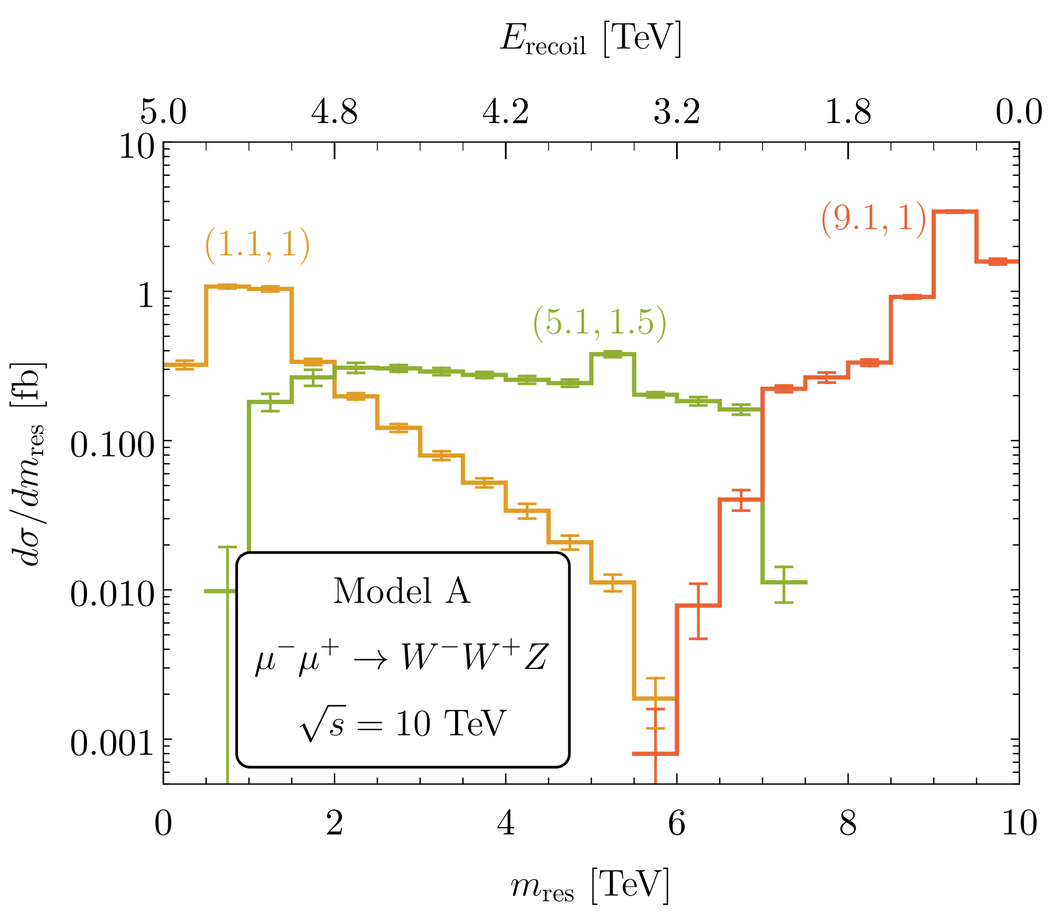

E_{reco} [TeV]
5.0 4.8 4.2 3.2 1.8 0.0
5
1
0.50
0.10
0.05
0.01
$\sqrt{s}$ = 10 TeV, $\ell^+\ell^-\gamma$
Model A
(9.5, 1)
(5.1, 2.5)
(1.9, 3)
0 2 4 6 8 10
$m_{\ell\ell}$ [TeV]
$d\sigma_{\text{BSM}}/dm_{\ell\ell} - d\sigma_{\text{SM}}/dm_{\ell\ell} + 0.1$ [fb]

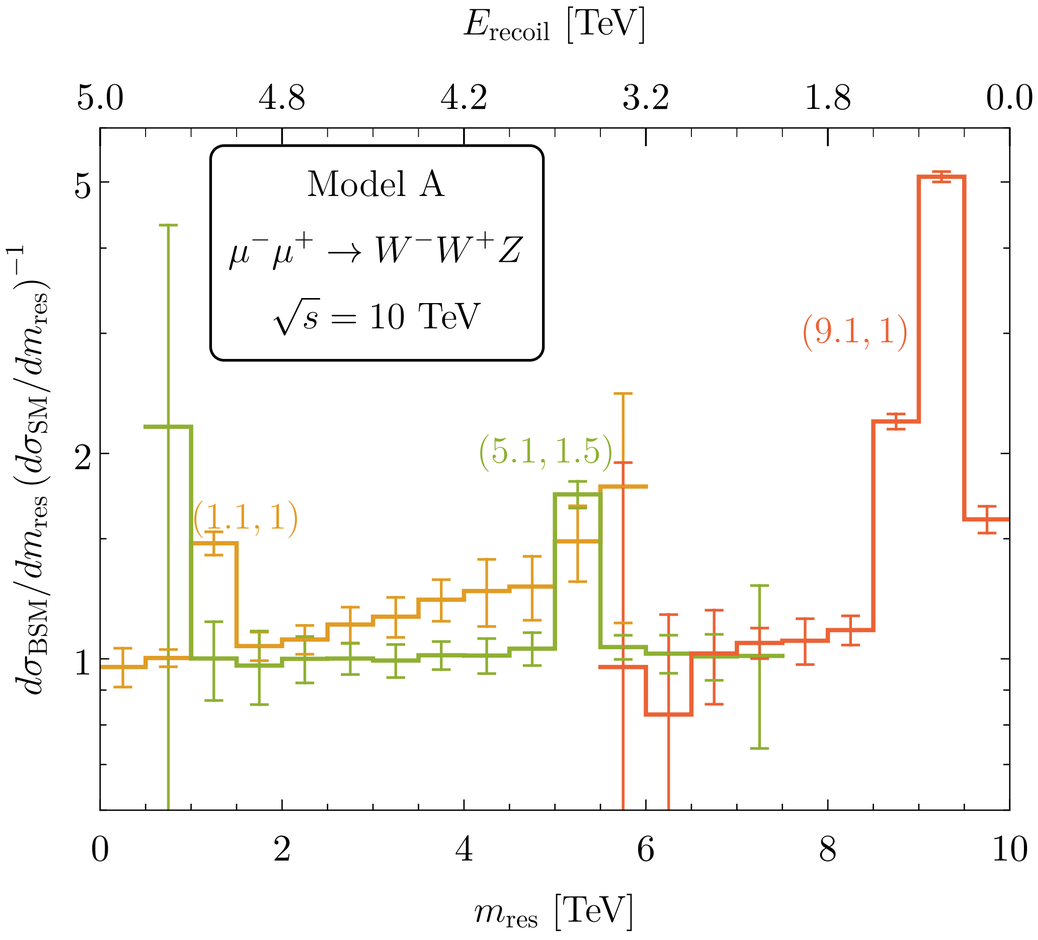

E_γ [TeV]
5.0
4.8
4.2
3.2
1.8
$\sqrt{s}$ = 10 TeV, $\ell^+\ell^-\gamma$
Model A
(9.5, 1)
(1.9, 3)
(5.1, 2.5)
$d\sigma_{\rm BSM}/dm_{\ell\ell}\,(d\sigma_{\rm SM}/dm_{\ell\ell})^{-1}$
2.0
1.8
1.5
1.2
1.0
0
2
4
6
8
$m_{\ell\ell}$ [TeV]


E_γ [TeV]
5.0
4.8
4.2
3.2
1.8
$\sqrt{s}$ = 10 TeV, $\ell^+\ell^-\gamma$
Model B
(9.5, 1)
(7.1, 2.5)
(1.9, 2.5)
$d\sigma_{\rm BSM}/dm_{\ell\ell}\,(d\sigma_{\rm SM}/dm_{\ell\ell})^{-1}$
2.2
2.0
1.8
1.5
1.2
1.0
0
2
4
6
8
$m_{\ell\ell}$ [TeV]


E_γ [TeV]
5.0
4.8
4.2
3.2
1.8
0.0
Model B
$\mu^-\mu^+ \to W^-W^+\gamma$
$\sqrt{s} = 10$ TeV
(1.9, 2)
(3.1, 4)
(7.1, 3)
$d\sigma/dm_{WW}$ [fb]
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
m_{WW} [TeV]


E_γ [TeV]
5.0
4.8
4.2
3.2
1.8
0.0
Model B
$\mu^-\mu^+ \to W^-W^+\gamma$
$\sqrt{s} = 10$ TeV
(1.9, 2)
(3.1, 4)
(7.1, 3)
$d\sigma_{\rm BSM}/dm_{WW}\,(d\sigma_{\rm SM}/dm_{WW})^{-1}$
1
2
5
0
2
4
6
8
10
m_{WW} [TeV]


E_{recoil} [TeV]
5.0
4.8
4.2
3.2
1.8
0.0
10
1
0.100
0.010
0.001
$d\sigma/dm_{\text{res}}$ [fb]
(1.1, 1)
(5.1, 1.5)
(9.1, 1)
Model A
$\mu^-\mu^+ \to W^-W^+Z$
$\sqrt{s} = 10$ TeV
0
2
4
6
8
10
m_{res} [TeV]


E_{recoil} [TeV]
5.0
4.8
4.2
3.2
1.8
0.0
5
2
1
$d\sigma_{\text{BSM}}/dm_{\text{res}}\,(d\sigma_{\text{SM}}/dm_{\text{res}})^{-1}$
Model A
$\mu^-\mu^+ \to W^-W^+Z$
$\sqrt{s} = 10$ TeV
(1.1, 1)
(5.1, 1.5)
(9.1, 1)
0
2
4
6
8
10
m_{res} [TeV]