Heavy Vectors at the LHC and Future Colliders

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Based on 1402.4431, 1502.01710, 2207.05091, 2404…

In collaboration with M. Baker, D. Pappadopulo, T. Martonhelyi, R. Torre, A. Wulzer

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BNL

Outline

1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
4. Heavy vectors at future colliders
5. Conclusions

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Theory Motivation

Heavy vectors appear in many new physics models

SPIN 1

Weakly coupled

Z' models,
W_R extensions, …

Strongly coupled

ρ_R in composite
Higgs models

[1010.6058, 1011.5918, 1103.2761, 1109.0890, PRD 22 (1980) 727, Phys Rept 183 (1989) 193-381, 9504216, 0610104, 0801.1345, 0909.1320, 0911.1450, 1102.3672, 1304.6700, PRD 40 (1989) 1569-1585, 0207290, 0704.0235, 1010.5809, 1110.0713, 0709.0007, 0810.1497, 0911.0059, 1109.1570, 1205.4032, 1208.0268, 1402.4431, 2207.05091,…]

They have been studied and searched for extensively

Simplified model approach

- Captures features of weakly and strongly coupled explicit models

Theory Motivation

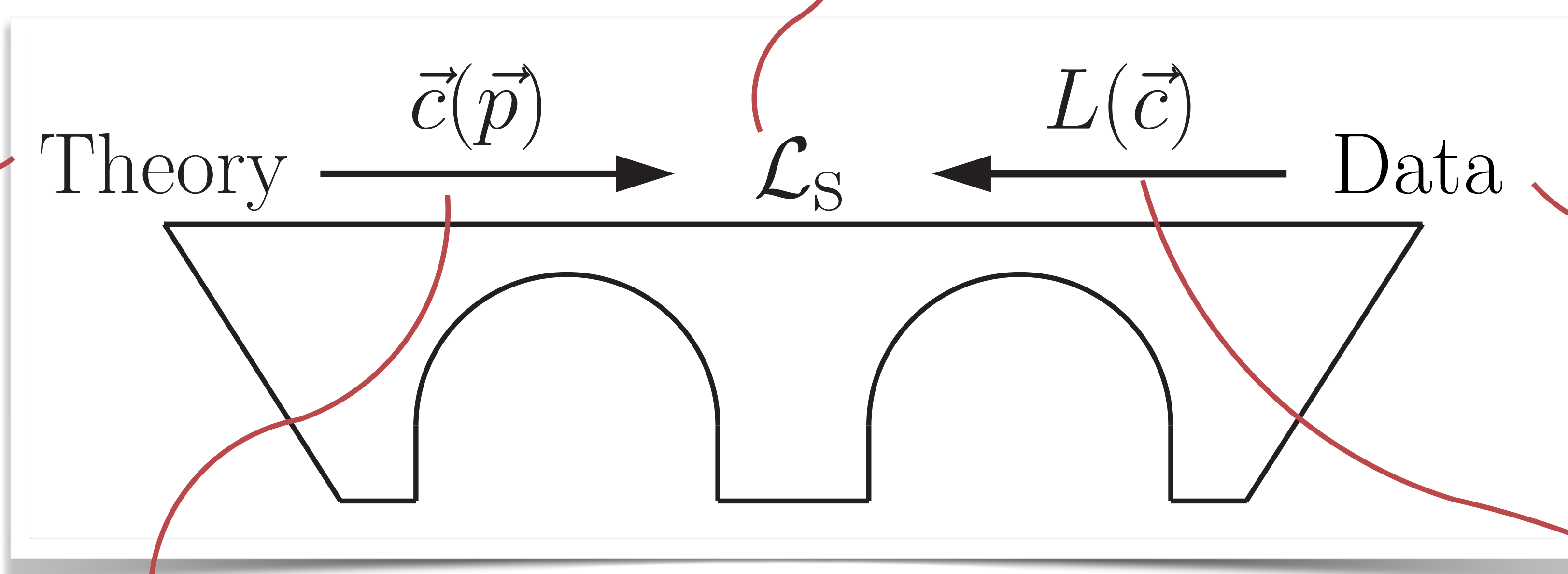
Bridge

- bounds are extremely general
- can be easily used in everyone's favourite model

Simplified Lagrangian
can be matched to explicit models

explicit models

limit on
$\sigma \times BR$



Simplified Lagrangian parameters c
fixed in terms of explicit model
parameters p

translate limits into bounds on
simplified model parameters

Theory Motivation

Heavy vectors appear in many new physics models

SPIN 1

Weakly coupled

Z' models,
W_R extensions ,…

Strongly coupled

ρ_R in composite
Higgs models

They have been studied and searched for extensively

Simplified model approach

- Captures features of weakly and strongly coupled explicit models
- Production via vector boson fusion had never been studied
- Updated LHC limits
- Compare projections for different future colliders

Theory Motivation

Various colourless vectors

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\mathcal{B}_\mu$	$\mathbf{1}$	$\mathbf{1}$	0
$\mathcal{B}_\mu^1$	$\mathbf{1}$	$\mathbf{1}$	1
$\mathcal{L}_\mu$	$\mathbf{1}$	$\mathbf{2}$	$-3/2$
$\mathcal{W}_\mu$	$\mathbf{1}$	$\mathbf{3}$	0
$\mathcal{W}_\mu^1$	$\mathbf{1}$	$\mathbf{3}$	1

[del Aguila, de Blas, Perez-Victoria, arXiv:1005.3998]

Heavy vector singlets (HVS)

[Baker, Martonhelyi, Thamm, Torre: 2404…]

No coupling to quarks

Heavy vector triplets (HVT)

[Pappadopulo, Thamm, Torre, Wulzer: 1402.4441]
[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

No coupling to fermions

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Outline

1. Theory motivation
2. Heavy vector triplets
    - Simplified model Lagrangian
    - Drell-Yan and VBF production
    - Decay
    - Limits on simplified parameter space
3. Heavy vector singlets
4. Heavy vectors at future colliders
5. Conclusions

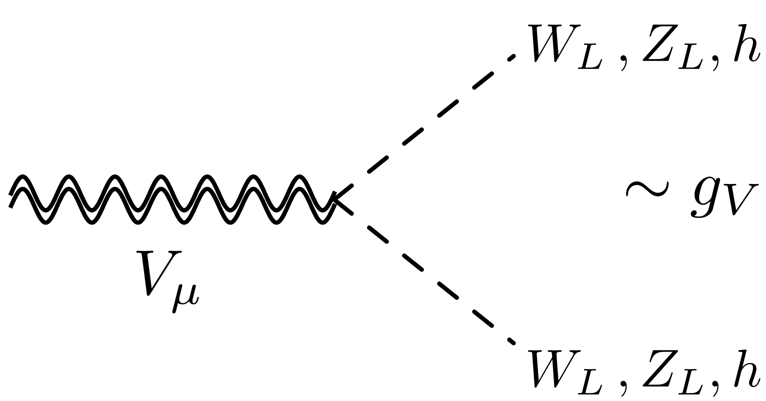
HVT - Simplified Model Lagrangian

Simplified Model for Heavy Vector Triplets

$$
\begin{aligned}
\mathcal{L}_V \;=\;& -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a} \\
& + i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a} \\
& + \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c
\end{aligned}
$$

$$V = (V^+, V^-, V^0)$$

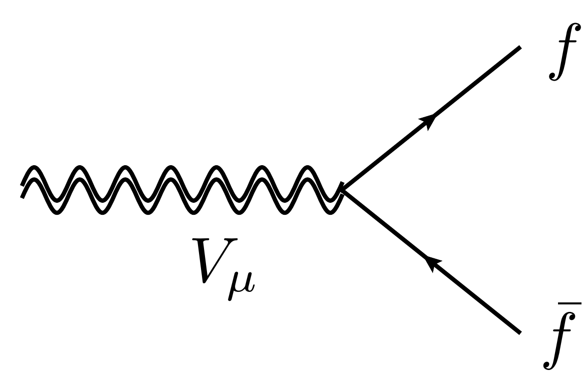
Coupling to SM vectors



$$\sim g_V c_H$$

Coupling to SM fermions

$$J_F^{\mu\,a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$$



$$\sim \frac{g^2}{g_V} c_F$$

$$c_F V \cdot J_F \;\rightarrow\; c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3$$

[Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]

HVT - Simplified Model Lagrangian

Simplified Model for Heavy Vector Triplets

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a} \qquad V = (V^+, V^-, V^0)$$

$$+\, i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a}$$

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

- Couplings among vectors
- Do not contribute to single production
- Do not contribute to V decays
- Only effect through (usually small) VW mixing

- → irrelevant for phenomenology → only need (c_H, c_F)

[Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]

HVT - Simplified Model Lagrangian

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$$+ i\, g_V c_H V_\mu^a H^\dagger \tau^a \overset{\leftrightarrow}{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a}$$

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

g_V typical strength of V interactions

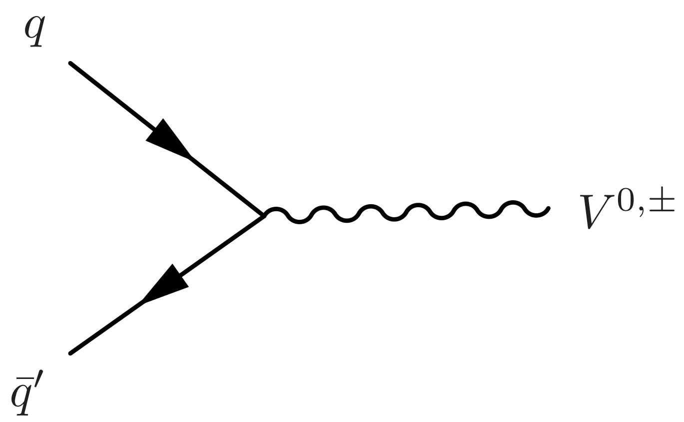
c_i dimensionless coefficients

Weakly coupled model	Strongly coupled model
$g_V \sim g \sim 1$	$1 < g_V \leq 4\pi$
$c_H \sim -g^2/g_V^2 \quad \text{and} \quad c_F \sim 1$	$c_H \sim \; c_F \sim 1$

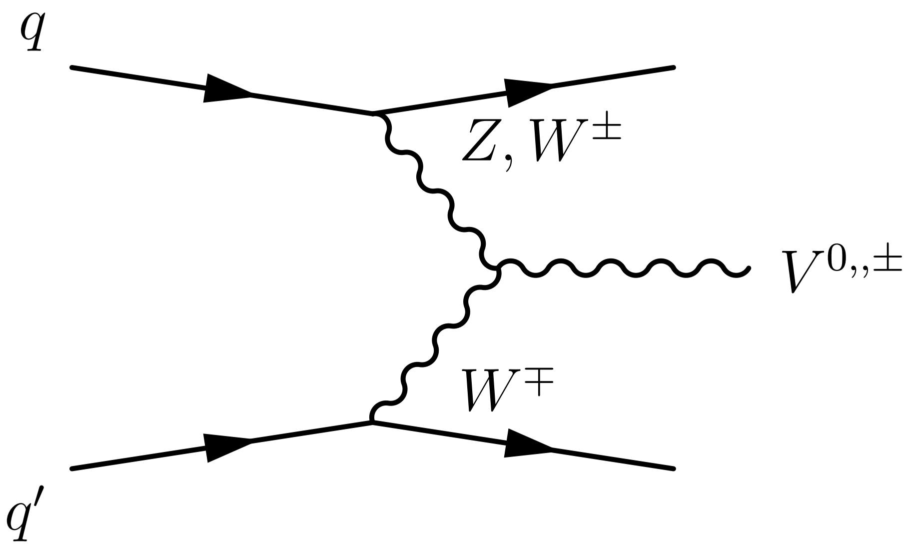
[Pappadopulo, Thamm, Torre, Wulzer: 1402.4431]

HVT - Production

Drell-Yan production



Vector boson fusion



HVT - Production

Narrow width approximation: $\Gamma_{\text{tot}} \lesssim 0.15\, M_V$

Production cross-section of narrow resonance:

$$\sigma(pp \to V + X) = \sum_{i,j \in p} \frac{\Gamma_{V \to ij}}{M_V} \frac{16\pi^2(2J+1)}{(2S_i+1)(2S_j+1)} \frac{C}{C_i C_j} \frac{dL_{ij}}{d\hat{s}}\bigg|_{\hat{s}=M_V^2}$$

Drell-Yan

$$\text{DY} = \frac{4\pi^2}{3}$$

Vector boson fusion

$$\text{VBF} = 48\pi^2$$

Ratio

$$\frac{\text{VBF}}{\text{DY}} = 36$$

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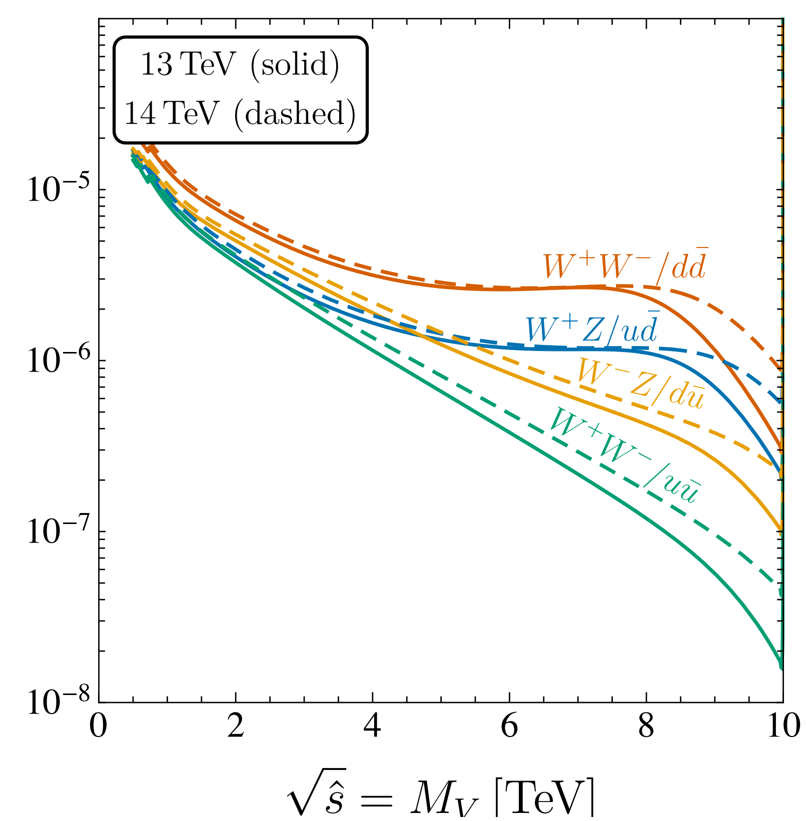
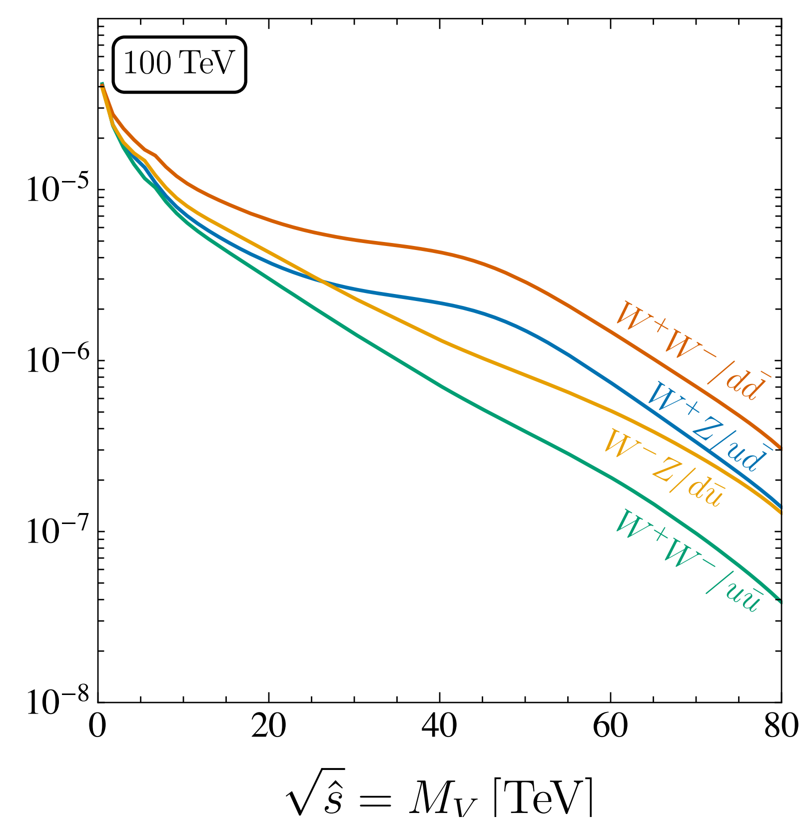
Ratio of VBF to DY parton luminosity





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Partial widths

$$\Gamma_{V^\pm \to W_L^\pm Z_L} \simeq \Gamma_{V^0 \to W_L^+ W_L^-} \simeq \Gamma_{V^\pm \to W_L^\pm h} \simeq \Gamma_{V^0 \to Z_L h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}$$

$$\Gamma_{V^\pm \to q\bar{q}'} \simeq 2\Gamma_{V^0 \to q\bar{q}} \simeq \frac{g^2 M_V}{16\pi} \frac{g^2}{g_V^2} c_q^2$$

Ratio

$$\frac{\Gamma_{V^\pm \to W_L^\pm Z_L}}{\Gamma_{V^\pm \to q\bar{q}'}} \simeq \frac{1}{2} \frac{\Gamma_{V^0 \to W_L^+ W_L^-}}{\Gamma_{V^0 \to q\bar{q}}} = \frac{1}{12} \frac{g_V^4}{g^4} \frac{c_H^2}{c_q^2}$$

$$\frac{c_H}{c_q} \sim 3, \frac{c_q}{g_V} \lesssim 0.05$$

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Partial widths

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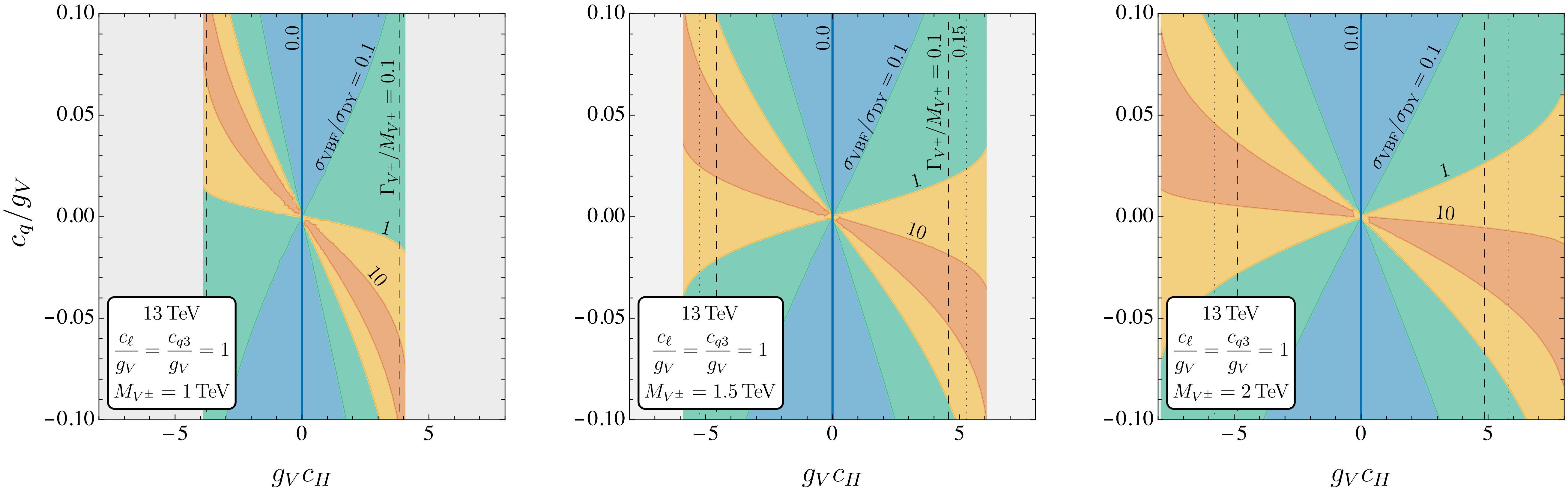
$$\Gamma_{V^\pm\to q\bar{q}'} \simeq 2\Gamma_{V^0\to q\bar{q}} \simeq \frac{g^2 M_V}{16\pi}\frac{g^2}{g_V^2}\left[c_q^2\left(1 - c_H^2\frac{g^2}{g_V^2}\zeta^4\right) + 2c_q c_H \zeta^2\left(1 + \frac{g^2}{g_V^2}\zeta^2\right) + c_H^2\zeta^4\right]$$

Putting everything together - Ratio for $c_q = 0$

$$\frac{\text{VBF}}{\text{DY}} \sim 0.4 \text{ at 1 TeV} \qquad \frac{\text{VBF}}{\text{DY}} \sim 3.2 \text{ at 2 TeV}$$

HVT - Production

Ratio of VBF to DY production cross-section

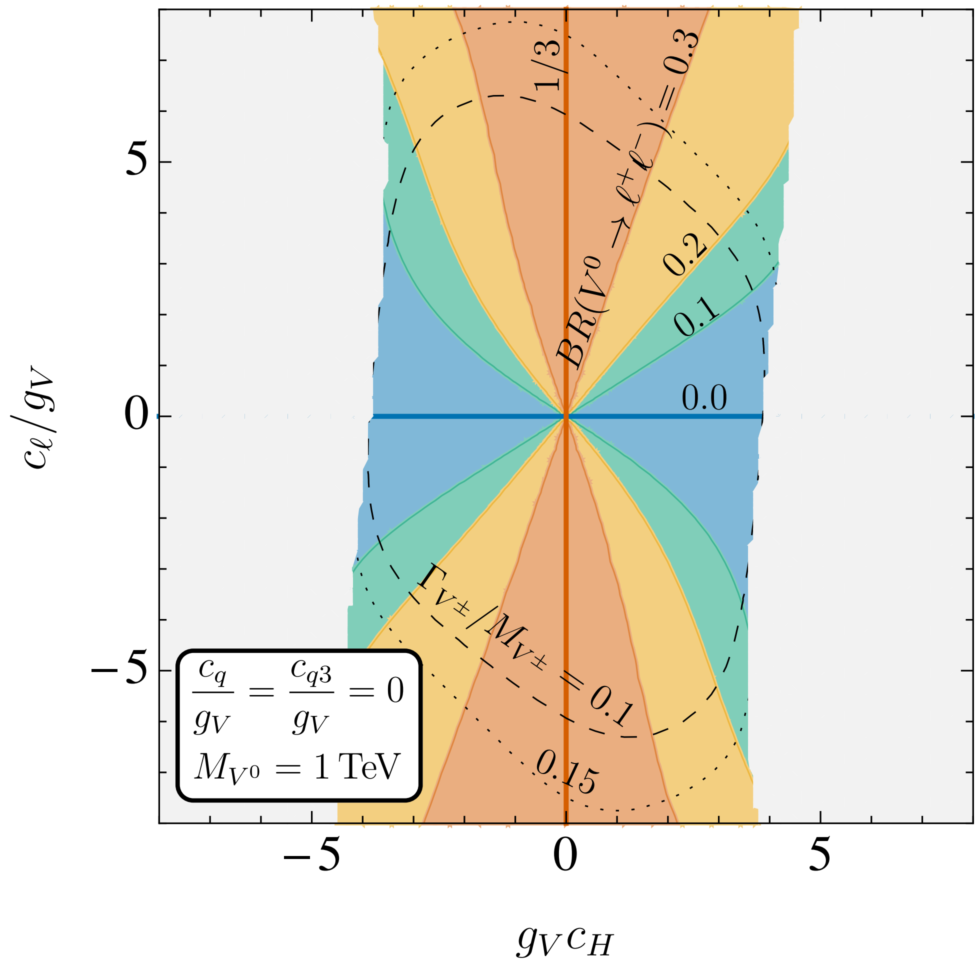


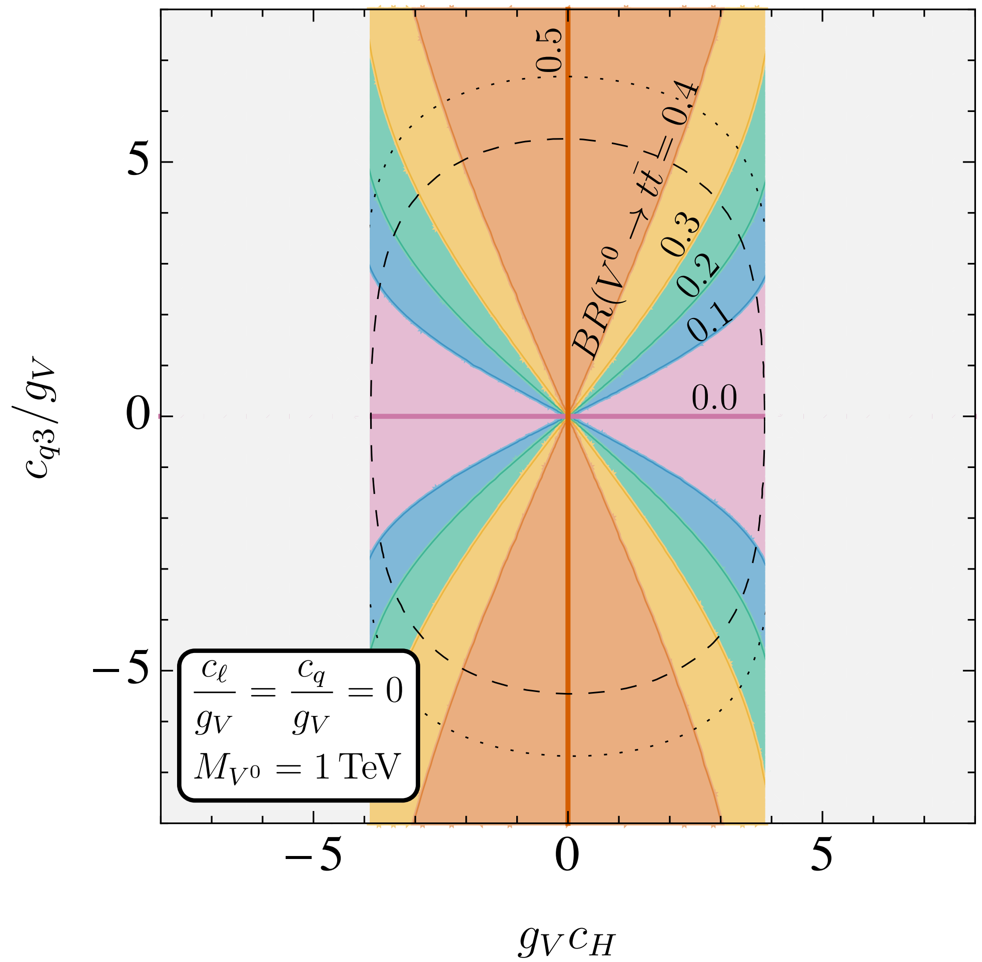
[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

HVT - Decay

Branching ratios

Di-boson decay > di-jet decay
Di-jet generally irrelevant for VBF studies
Di-lepton and 3rd generation quarks enter with independent couplings





[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

HVT - Limits on simplified parameter space

Benchmark parameter points

- VBF-DB (Di-Boson) Benchmark
  $g_V c_H = 4,\ c_\ell / g_V = 0,\ c_q / g_V = c_{q3} / g_V = 0$
- VBF-DL (Di-Lepton) Benchmark
  $g_V c_H = 3,\ c_\ell / g_V = -3,\ c_q / g_V = c_{q3} / g_V = 0$

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

VBF benchmark in CMS and ATLAS papers: $g_V = 1,\ c_H = 1,\ c_\ell = 0,\ c_q = c_{q3} = 0$

- Smaller production cross-section than VBF-DB
- $c_q = 0$ does not imply vanishing DY

HVT - Limits on simplified parameter space

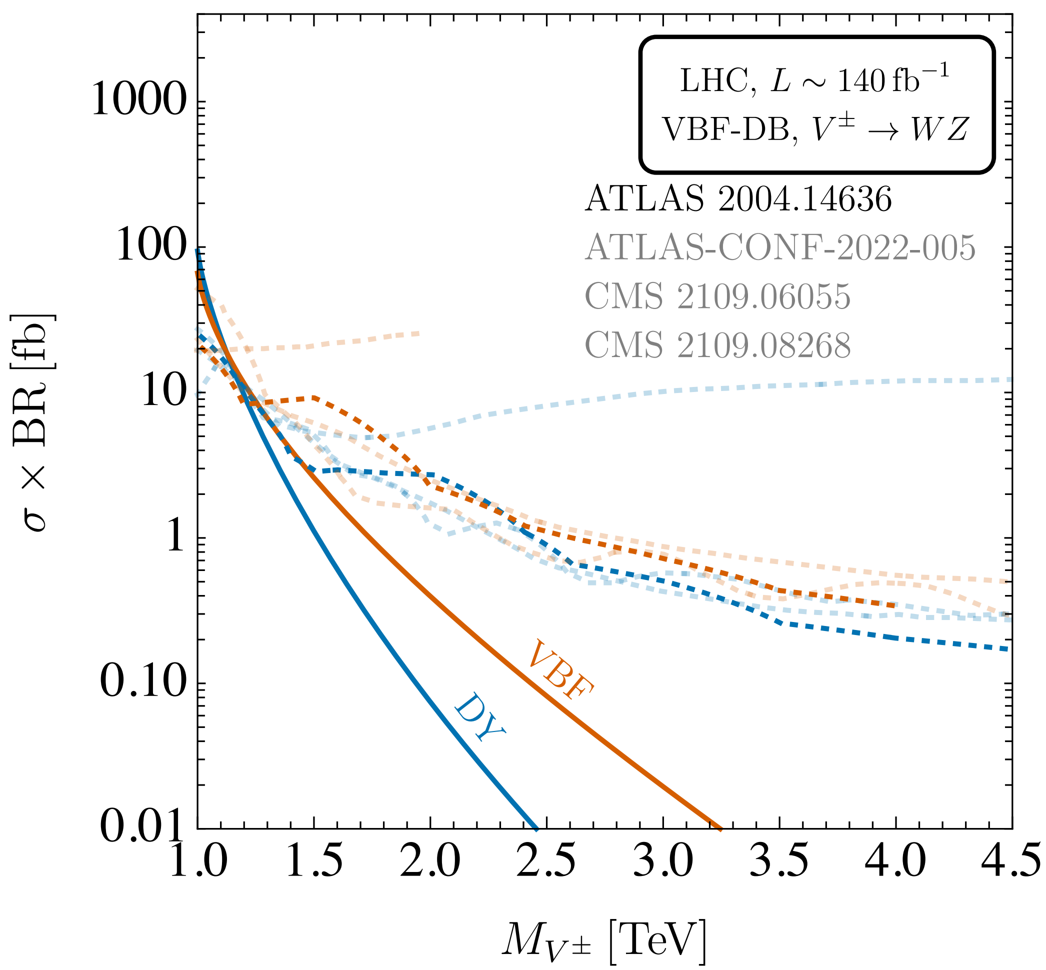
Existing ATLAS and CMS searches considering DY and VBF production at $L = 140\,\text{fb}^{-1}$

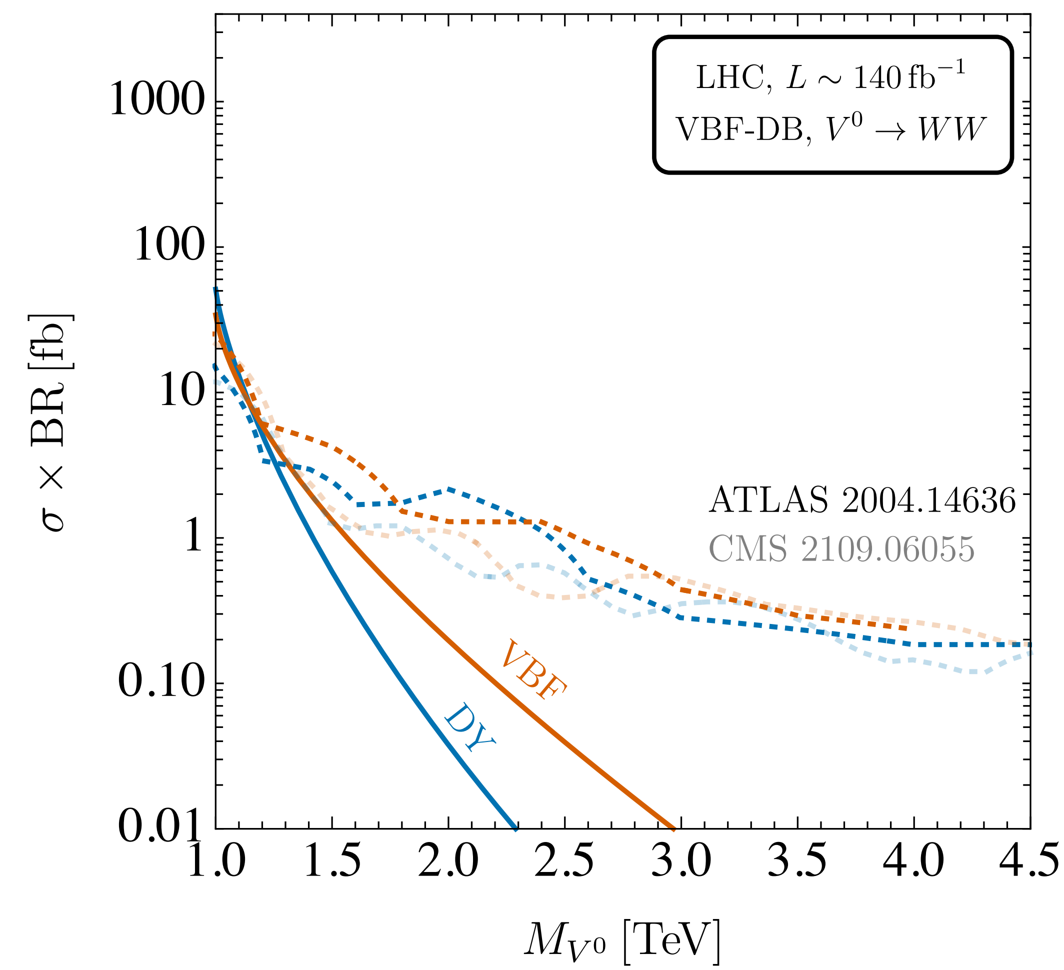
Channel	Reference
$WZ \to \ell\nu\ell'\ell'$	[34]
$Zh \to$ leptons hadrons	[45]
$WW, WZ \to$ leptons hadrons	[35, 43, 44]
$\ell\ell$	[48, 49]
$\ell\nu$	[50, 51]
$\tau\nu$	[52]

HVT - Limits on simplified parameter space

Existing ATLAS and CMS searches considering DY and VBF production at $L = 140\,\text{fb}^{-1}$

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]



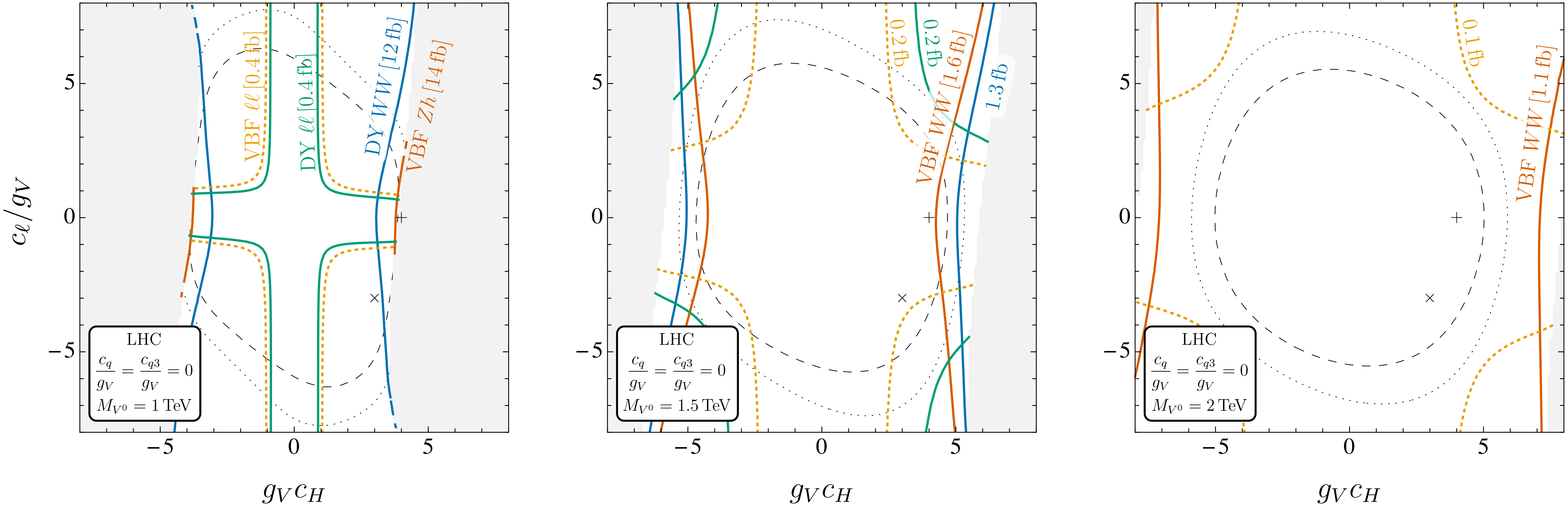


Currently, similar limits but VBF more promising in the future

HVT - Limits on simplified parameter space

Existing ATLAS and CMS searches considering DY and VBF production at $L = 140\,\mathrm{fb}^{-1}$

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

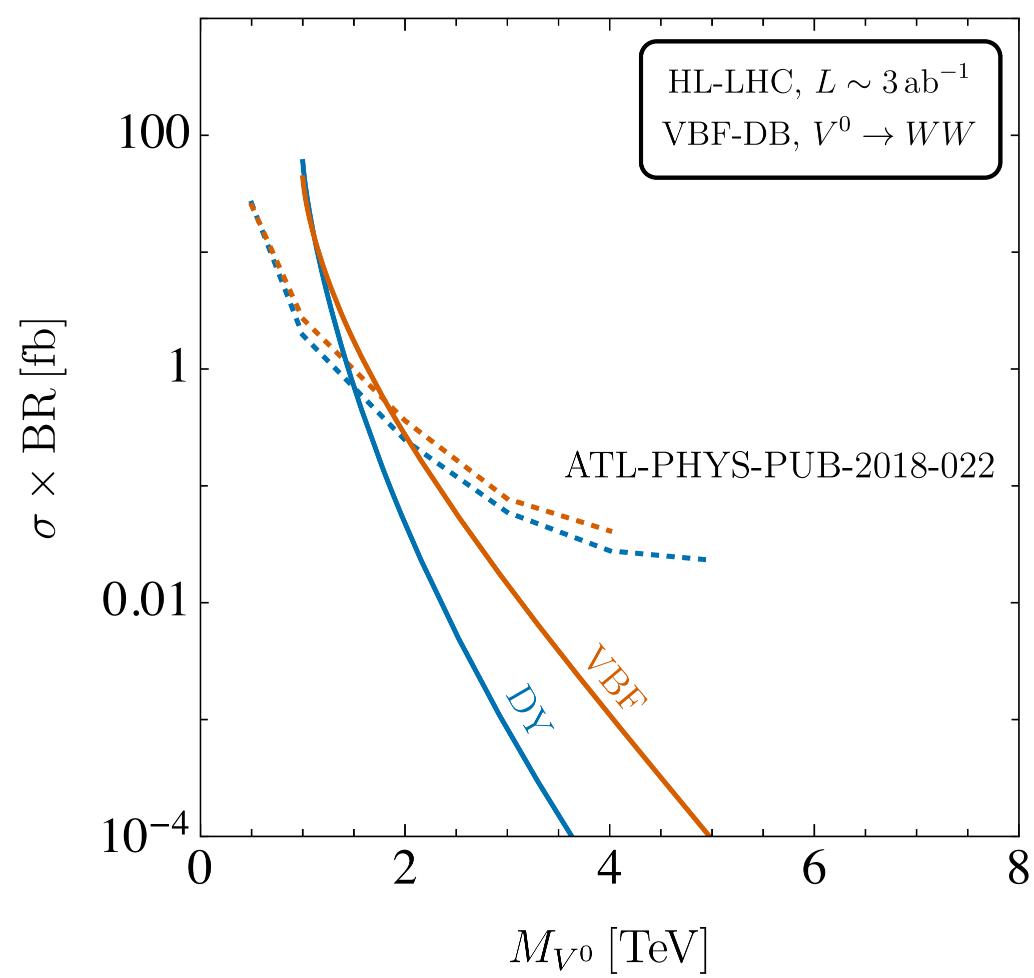


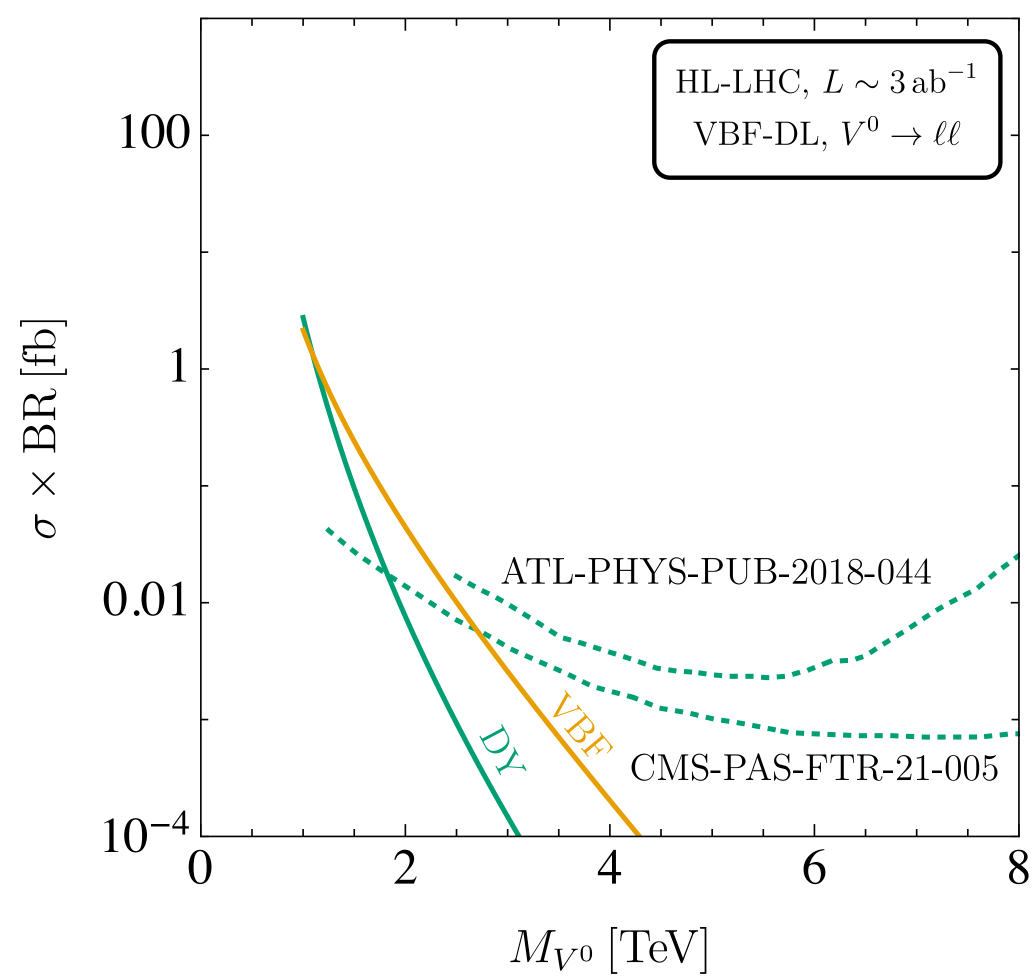
VBF outperforms DY at 1.5 TeV and is only sensitive probe at larger masses

HVT - Limits on simplified parameter space

Projections for HL-LHC at 14 TeV with $3\,\mathrm{ab}^{-1}$

[Baker, Martonhelyi, Thamm, Torre: 2207.05091]

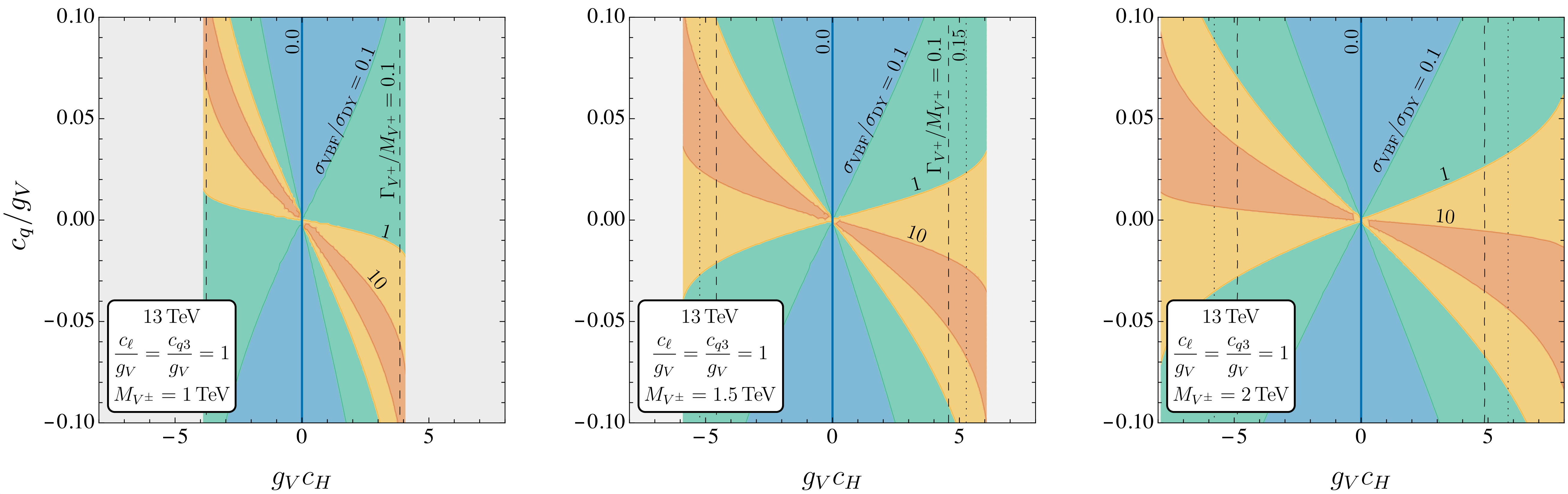




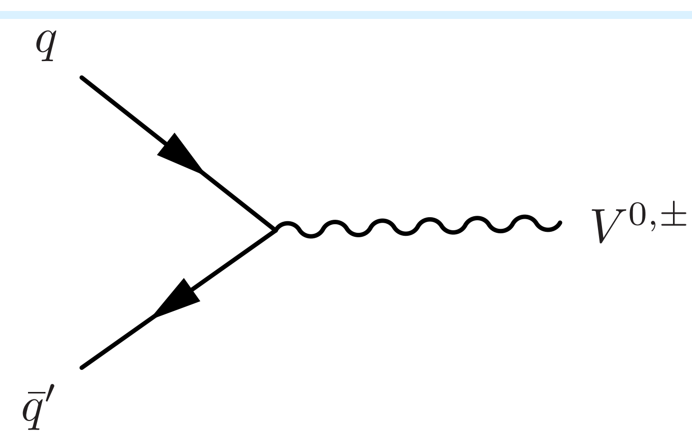
Significantly higher mass reach in VBF than DY

HVT - Production

Ratio of VBF to DY production cross-section

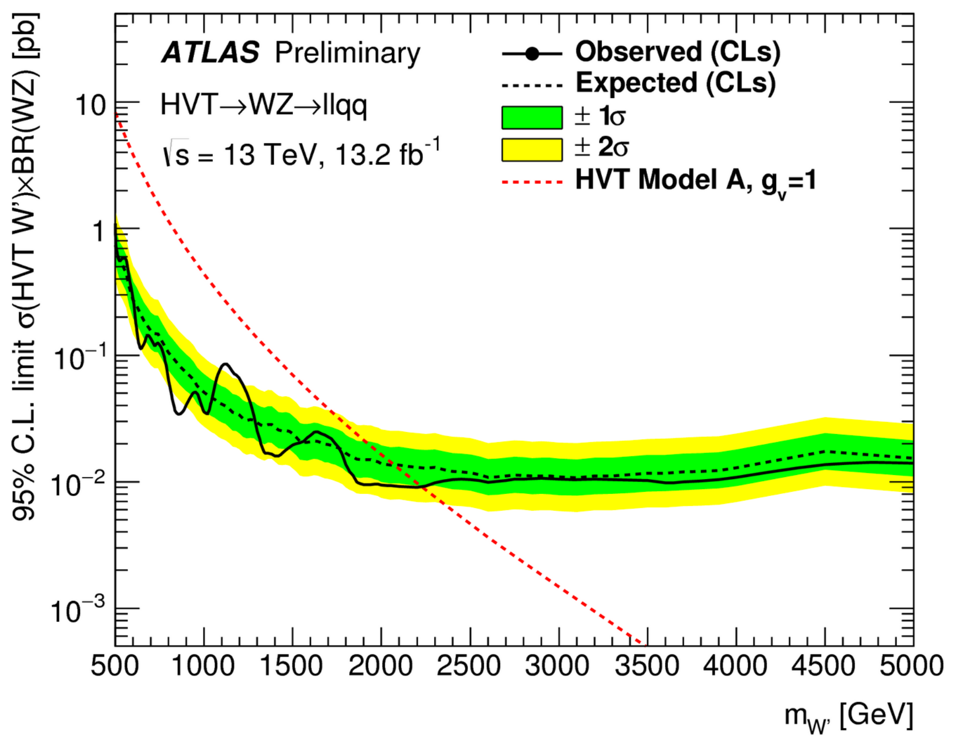


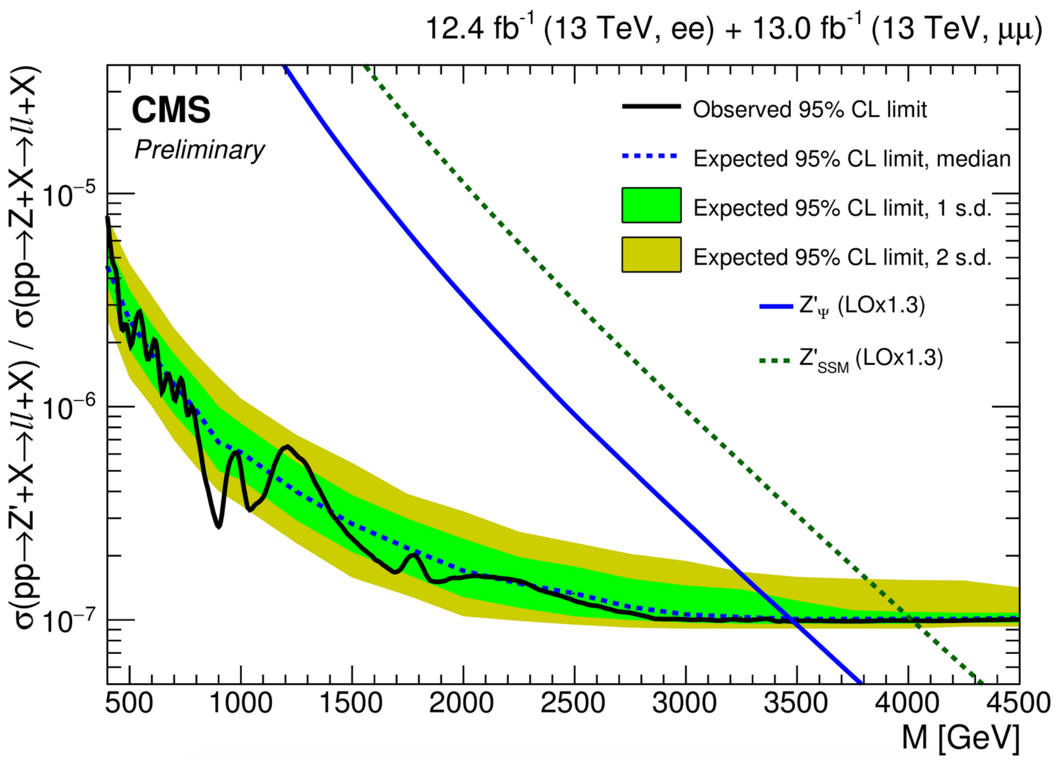
Drell-Yan production



HVT - Limits on simplified parameter space

Take experimental searches to put limits on simplified model parameter space





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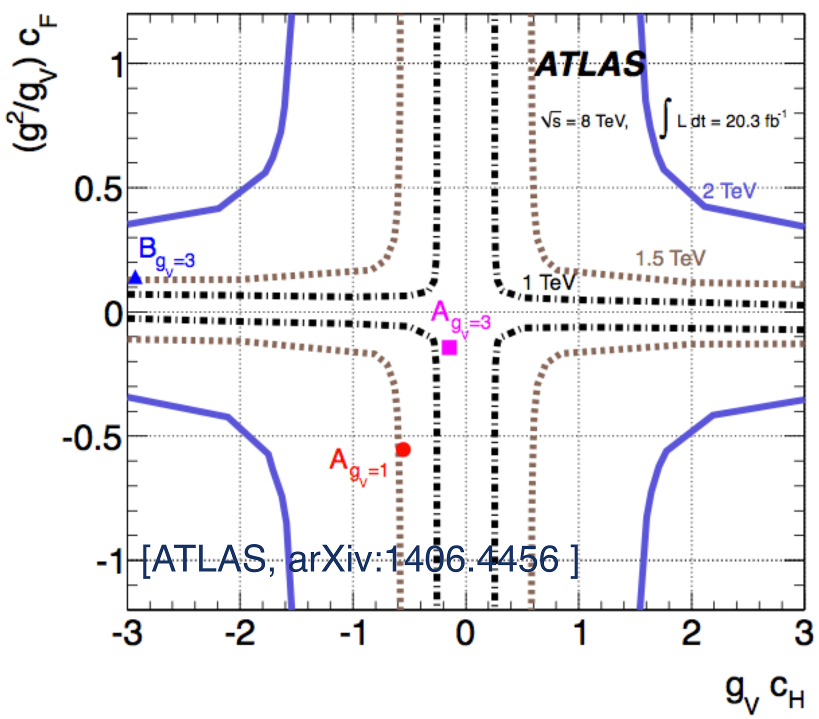
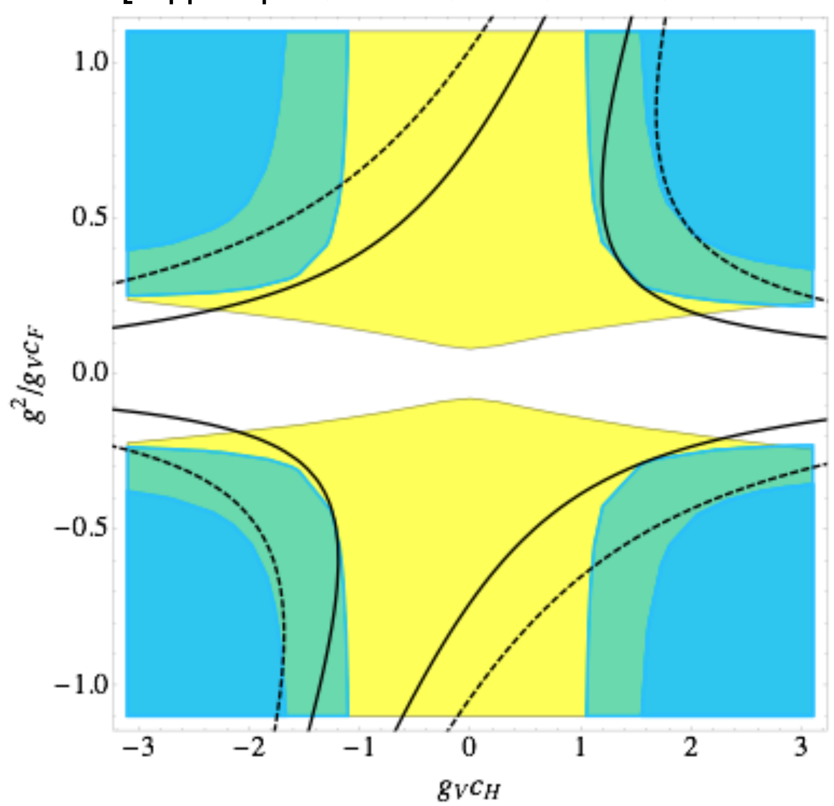
ATLAS: W' to WZ

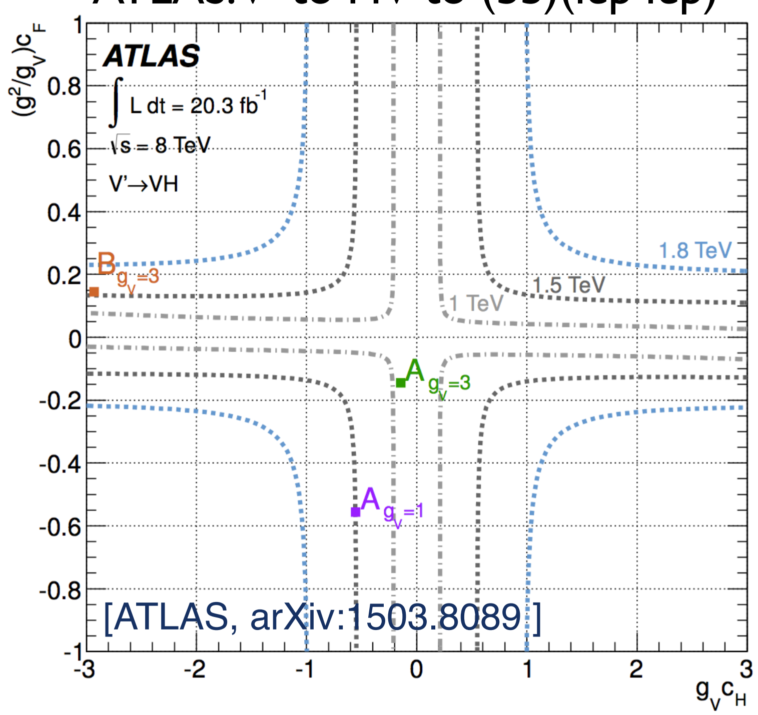


yellow: CMS $\ell^+\nu$ analysis
dark blue: CMS $WZ \to 3\ell\nu$
light blue: CMS $WZ \to jj$
black: bounds from EWPT

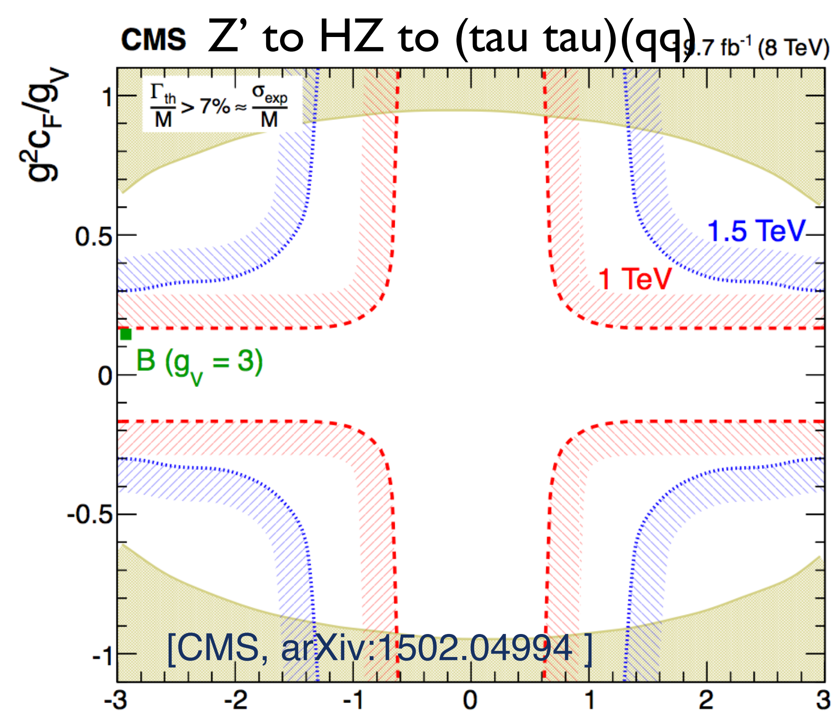
[Pappadopulo, Thamm, Torre, Wulzer, arXiv:1402.4431]



ATLAS: V' to HV to (bb)(lep lep)



Z' to HZ to (tau tau)(qq)



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    - Simplified model Lagrangian
    - Drell-Yann production and decay
    - Limits on simplified parameter space
    - Matching onto explicit models
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HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

$$\begin{aligned}\mathcal{L}_{\mathcal{V}^+} &= -\frac{1}{2} D_{[\mu}\mathcal{V}^+_{\nu]} D^{[\mu}\mathcal{V}^{-\,\nu]} + m^2_{\mathcal{V}^+}\mathcal{V}^+_\mu \mathcal{V}^{-\mu} \\ &\quad -i\frac{g_V}{\sqrt{2}} c^+_H \mathcal{V}^+_\mu H^\dagger \overleftrightarrow{D}^\mu \tilde{H} + \frac{g_V}{\sqrt{2}} c^+_q \mathcal{V}^+_\mu J^\mu_q + \text{h.c.} \\ &\quad +2g_V^2 c^+_{VVHH} \mathcal{V}^+_\mu \mathcal{V}^{-\,\mu} H^\dagger H + ig' c^+_{VVB} B_{\mu\nu} \mathcal{V}^{+\,\mu}\mathcal{V}^{-\,\nu}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\mathcal{V}^0} &= -\frac{1}{4}\partial_{[\mu}\mathcal{V}^0_{\nu]}\partial^{[\mu}\mathcal{V}^{0\,\nu]} + \frac{m^2_{\mathcal{V}^0}}{2}\mathcal{V}^0_\mu \mathcal{V}^{0\,\mu} \\ &\quad +i\frac{g_V}{2} c^0_H \mathcal{V}^0_\mu H^\dagger \overleftrightarrow{D}^\mu H + \sum_{\Psi=Q,L,U,D,E} \frac{g_V}{2} c^0_\Psi \mathcal{V}^0_\mu J^\mu_\Psi \\ &\quad +g_V^2 c^0_{VVHH} \mathcal{V}^0_\mu \mathcal{V}^{0\,\mu} H^\dagger H\,,\end{aligned}$$

$$\mathcal{L}_{\text{mix}} = ig_V c^+_{VVV} D_{[\mu}\mathcal{V}^-_{\nu]}\mathcal{V}^{0\,\mu}\mathcal{V}^{+\,\nu} + \text{h.c.} + ig_V c^0_{VVV}\partial_{[\mu}\mathcal{V}^0_{\nu]}\mathcal{V}^{+\,\mu}\mathcal{V}^{-\,\nu}$$

HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

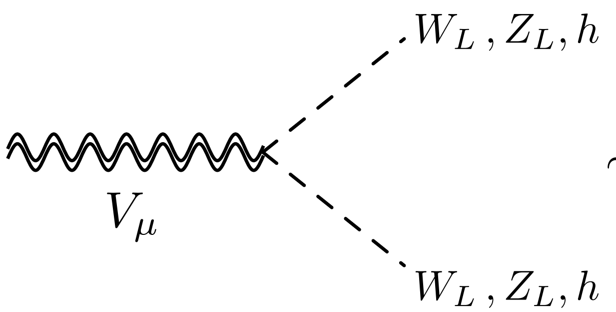
$$\mathcal{L}_{\mathcal{V}^+} = -\frac{1}{2} D_{[\mu} \mathcal{V}^+_{\nu]} D^{[\mu} \mathcal{V}^{-\,\nu]} + m^2_{\mathcal{V}^+} \mathcal{V}^+_\mu \mathcal{V}^{-\mu}$$
$$-i \frac{g_V}{\sqrt{2}} c^+_H \mathcal{V}^+_\mu H^\dagger \overleftrightarrow{D}^\mu \tilde{H} + \frac{g_V}{\sqrt{2}} c^+_q \mathcal{V}^+_\mu J^\mu_q + \text{h.c.}$$
$$+2 g_V^2 c^+_{VVHH} \mathcal{V}^+_\mu \mathcal{V}^{-\,\mu} H^\dagger H + i g' c^+_{VVB} B_{\mu\nu} \mathcal{V}^{+\,\mu} \mathcal{V}^{-\,\nu}$$

$$J^\mu_q = \sum_{i=1}^{3} \bar{U}^i \gamma^\mu D^i$$

$$\mathcal{L}_{\mathcal{V}^0} = -\frac{1}{4} \partial_{[\mu} \mathcal{V}^0_{\nu]} \partial^{[\mu} \mathcal{V}^{0\,\nu]} + \frac{m^2_{\mathcal{V}^0}}{2} \mathcal{V}^0_\mu \mathcal{V}^{0\,\mu}$$
$$+i \frac{g_V}{2} c^0_H \mathcal{V}^0_\mu H^\dagger \overleftrightarrow{D}^\mu H + \sum_{\Psi=Q,L,U,D,E} \frac{g_V}{2} c^0_\Psi \mathcal{V}^0_\mu J^\mu_\Psi$$
$$+g_V^2 c^0_{VVHH} \mathcal{V}^0_\mu \mathcal{V}^{0\,\mu} H^\dagger H \,,$$

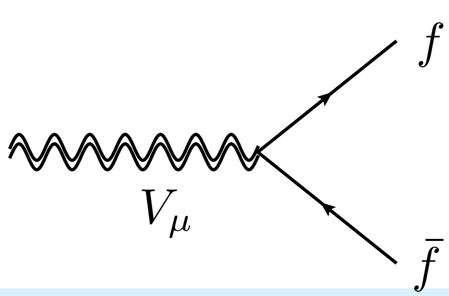
$$J^\mu_\Psi = \sum_{i=1}^{3} \bar{\Psi}^i \gamma^\mu \Psi^i$$

Coupling to SM vectors



$\sim g_V c^+_H, g_V c^0_H$

Coupling to SM fermions



$\sim g_V c^+_q, g_V c^0_\Psi$

HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

$$\begin{aligned}\mathcal{L}_{\mathcal{V}^+} &= -\frac{1}{2}D_{[\mu}\mathcal{V}^+_{\nu]}D^{[\mu}\mathcal{V}^{-\,\nu]} + m^2_{\mathcal{V}^+}\mathcal{V}^+_\mu\mathcal{V}^{-\mu} \\ &\quad -i\frac{g_V}{\sqrt{2}}c^+_H\mathcal{V}^+_\mu H^\dagger \overleftrightarrow{D}^\mu \tilde{H} + \frac{g_V}{\sqrt{2}}c^+_q\mathcal{V}^+_\mu J^\mu_q + \text{h.c.} \\ &\quad +2g_V^2 c^+_{VVHH}\mathcal{V}^+_\mu\mathcal{V}^{-\,\mu}H^\dagger H + ig' c^+_{VVB}B_{\mu\nu}\mathcal{V}^{+\,\mu}\mathcal{V}^{-\,\nu}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\mathcal{V}^0} &= -\frac{1}{4}\partial_{[\mu}\mathcal{V}^0_{\nu]}\partial^{[\mu}\mathcal{V}^{0\,\nu]} + \frac{m^2_{\mathcal{V}^0}}{2}\mathcal{V}^0_\mu\mathcal{V}^{0\,\mu} \\ &\quad +i\frac{g_V}{2}c^0_H\mathcal{V}^0_\mu H^\dagger \overleftrightarrow{D}^\mu H + \sum_{\Psi=Q,L,U,D,E}\frac{g_V}{2}c^0_\Psi\mathcal{V}^0_\mu J^\mu_\Psi \\ &\quad +g_V^2 c^0_{VVHH}\mathcal{V}^0_\mu\mathcal{V}^{0\,\mu}H^\dagger H\,,\end{aligned}$$

$$\mathcal{L}_{\text{mix}} = ig_V c^+_{VVV}D_{[\mu}\mathcal{V}^-_{\nu]}\mathcal{V}^{0\,\mu}\mathcal{V}^{+\,\nu} + \text{h.c.} + ig_V c^0_{VVV}\partial_{[\mu}\mathcal{V}^0_{\nu]}\mathcal{V}^{+\,\mu}\mathcal{V}^{-\,\nu}$$

- irrelevant for phenomenology → only need (c_H, c_F)

HVS - Simplified Model Lagrangian

Simplified Model for Heavy Vector Singlets

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Weakly coupled model

Strongly coupled model

g_V typical strength of V interactions

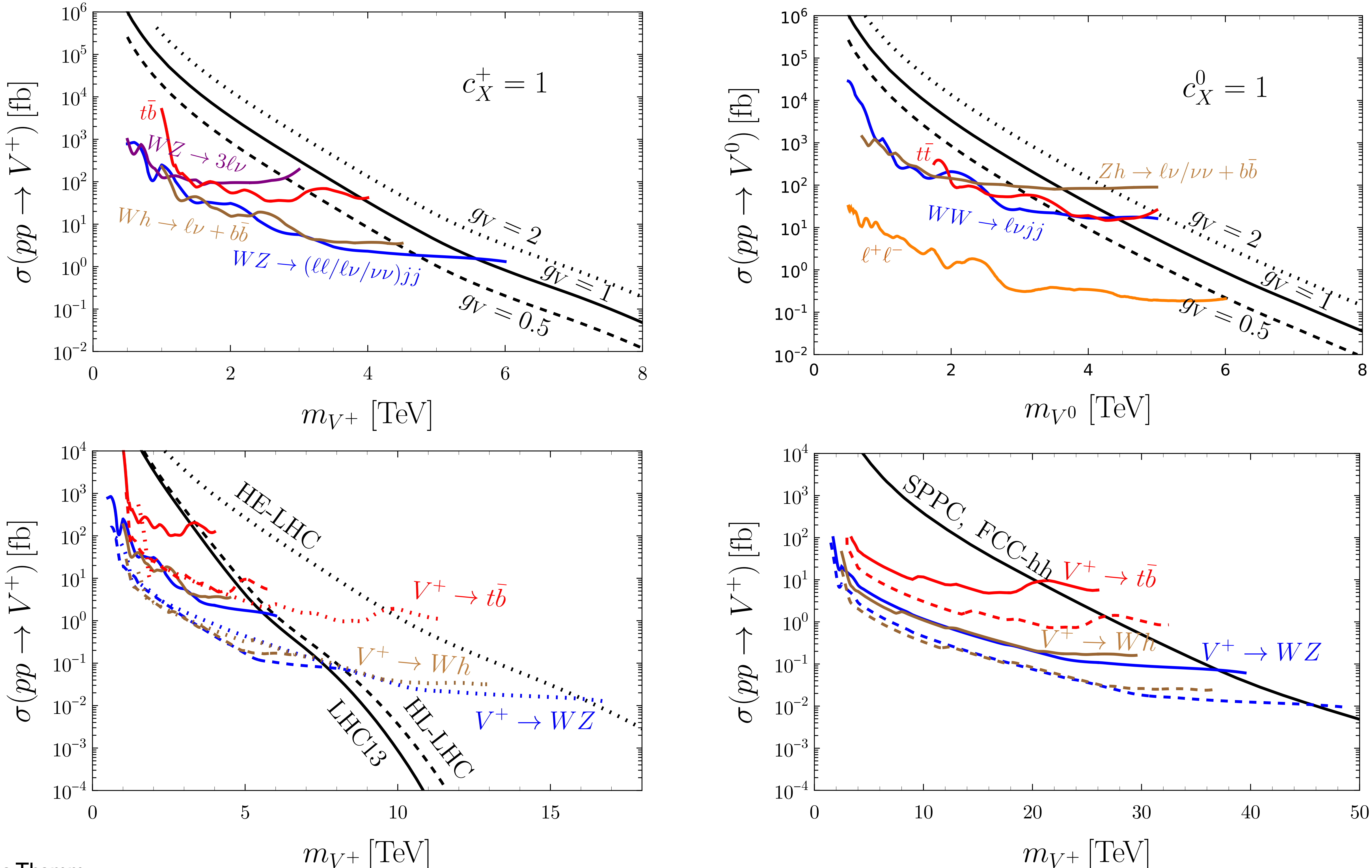
$g_V \sim g \sim 1$

$1 < g_V \leq 4\pi$

c_i dimensionless coefficients

HVS - Limits on simplified parameter space

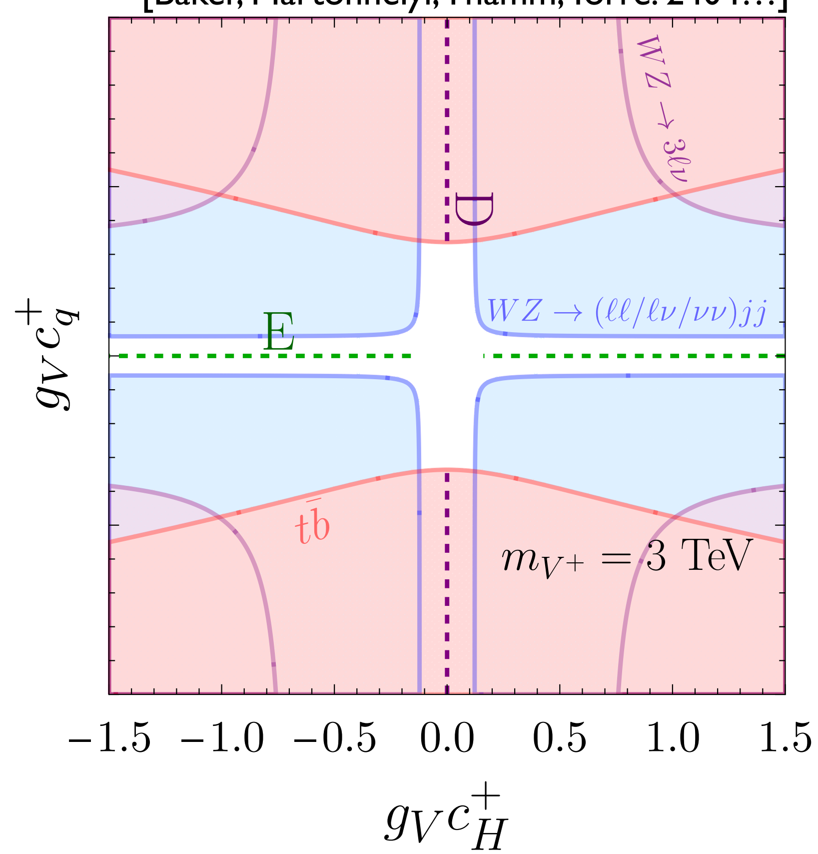
Experimental searches



HVS - Limits on simplified parameter space

Experimental limits on simplified parameter space

[Baker, Martonhelyi, Thamm, Torre: 2404…]



HVS - Limits on simplified parameter space

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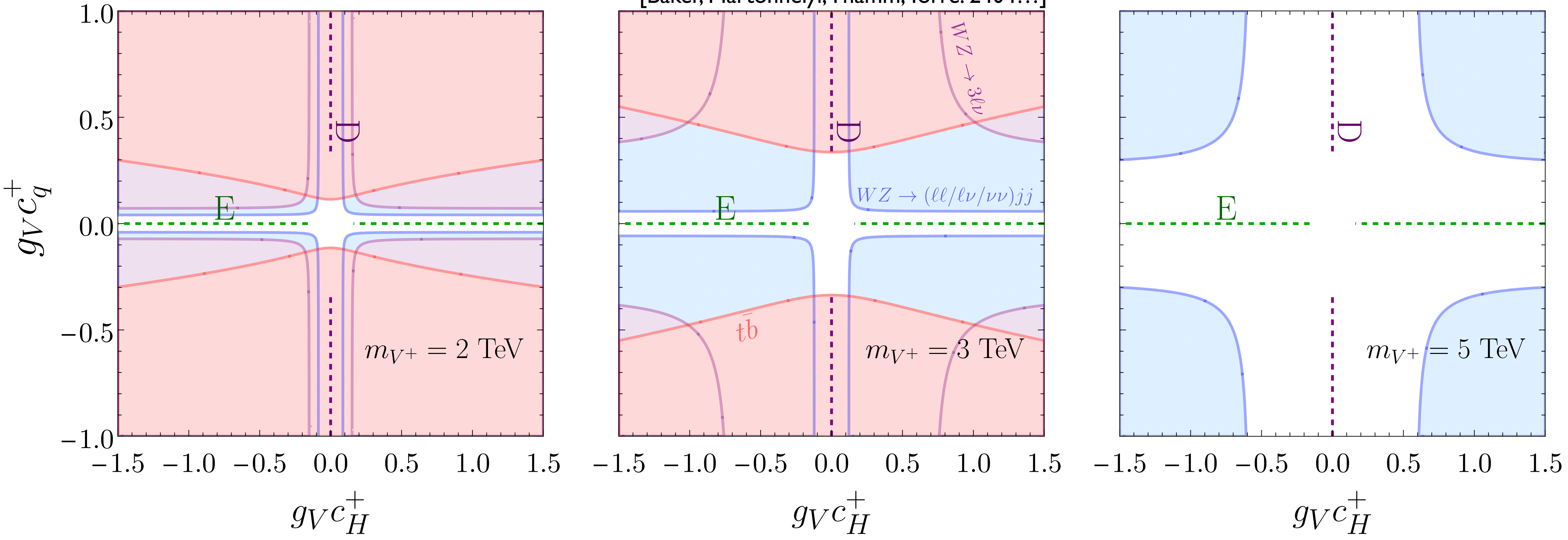
[Baker, Martonhelyi, Thamm, Torre: 2404…]



Simplified model works very well for the charged singlet

HVS - Limits on simplified parameter space

Experimental limits on simplified parameter space

Simplified model for neutral singlets has many 7 parameters
For singlet production and decay they only enter in certain combinations

$$(c_u^{\text{eff}})^2 = (c_Q^0)^2 + (c_U^0)^2,$$
$$(c_d^{\text{eff}})^2 = (c_Q^0)^2 + (c_D^0)^2,$$
$$(c_e^{\text{eff}})^2 = (c_L^0)^2 + (c_E^0)^2,$$
$$c_n^{\text{eff}} = c_L^0,$$

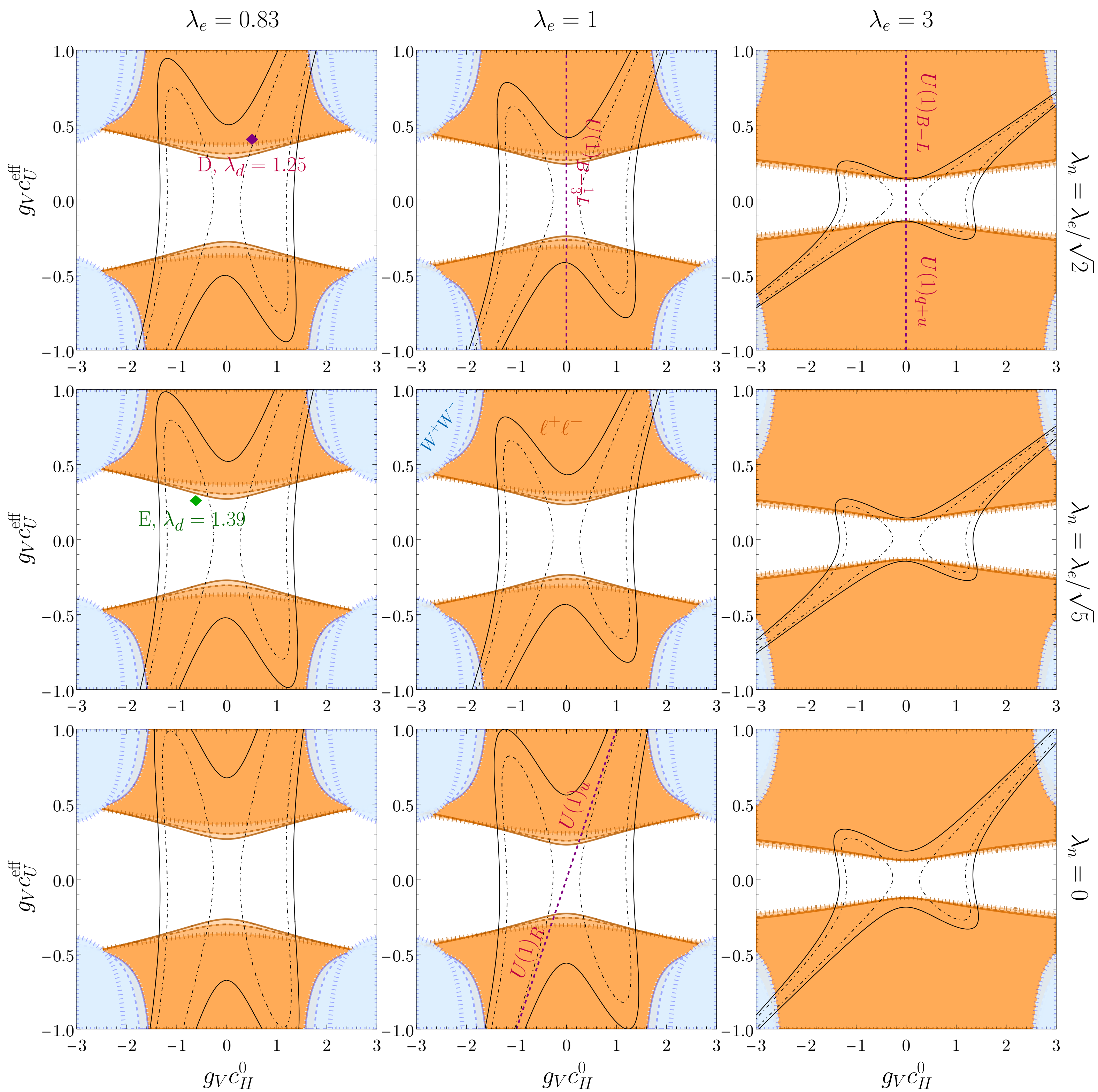
Reduce number of free parameters to 4
Also define

$$\lambda_d = \frac{c_d^{\text{eff}}}{c_u^{\text{eff}}}, \qquad \lambda_e = \frac{c_e^{\text{eff}}}{c_u^{\text{eff}}}, \qquad \lambda_n = \frac{c_n^{\text{eff}}}{c_u^{\text{eff}}}$$

HVS - Limits on simplified parameter space

[Baker, Martonhelyi, Thamm, Torre: 2404…]

Experimental limits on simplified parameter space



Orange: ATLAS $\ell^+\ell^-$
Blue: ATLAS WW
Black: bounds from EWPT

HVS - Matching onto explicit models

1. New $U(1)_X$ gauge extensions

Gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$
Associated gauge boson is V^0 (often called Z')
Matching fixes all parameters except g_V, m_V^0

	Model C		
	$U(1)_{B-xL}$	$U(1)_R$	$U(1)_{q+xu}$
g_V	g_X	g_X	g_X
$m_{\mathcal{V}^0}$	$m_{\mathcal{V}^0}$	$m_{\mathcal{V}^0}$	$m_{\mathcal{V}^0}$
c_Q^0	$\frac{2}{3}$	0	$\frac{2}{3}$
c_U^0	$\frac{2}{3}$	$-\frac{2}{3}$	2x/3
c_D^0	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2(2-x)}{3}$
c_L^0	$-2x$	0	-2
c_E^0	$-2x$	$\frac{2}{3}$	$-\frac{2(2+x)}{3}$
c_H^0	0	$-\frac{2}{3}$	$\frac{2(x-1)}{3}$
c_{VVHH}^0	0	$\frac{4}{9}$	$\frac{4(x-1)^2}{9}$

HVS - Matching onto explicit models

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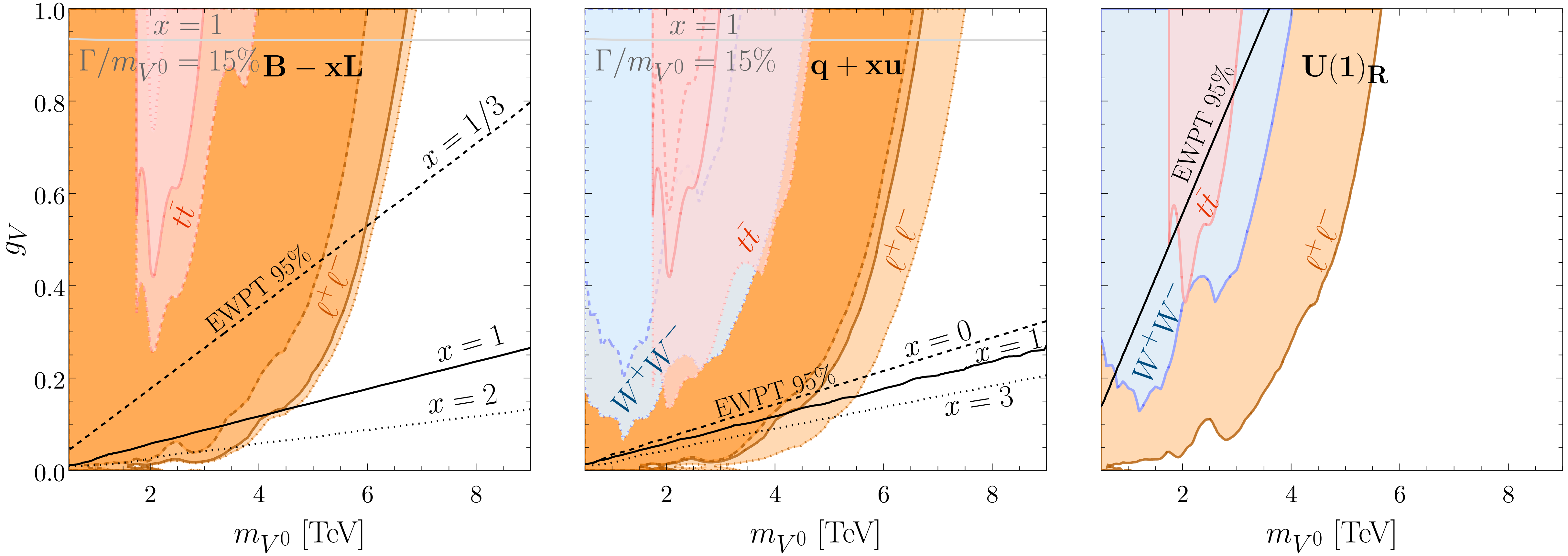
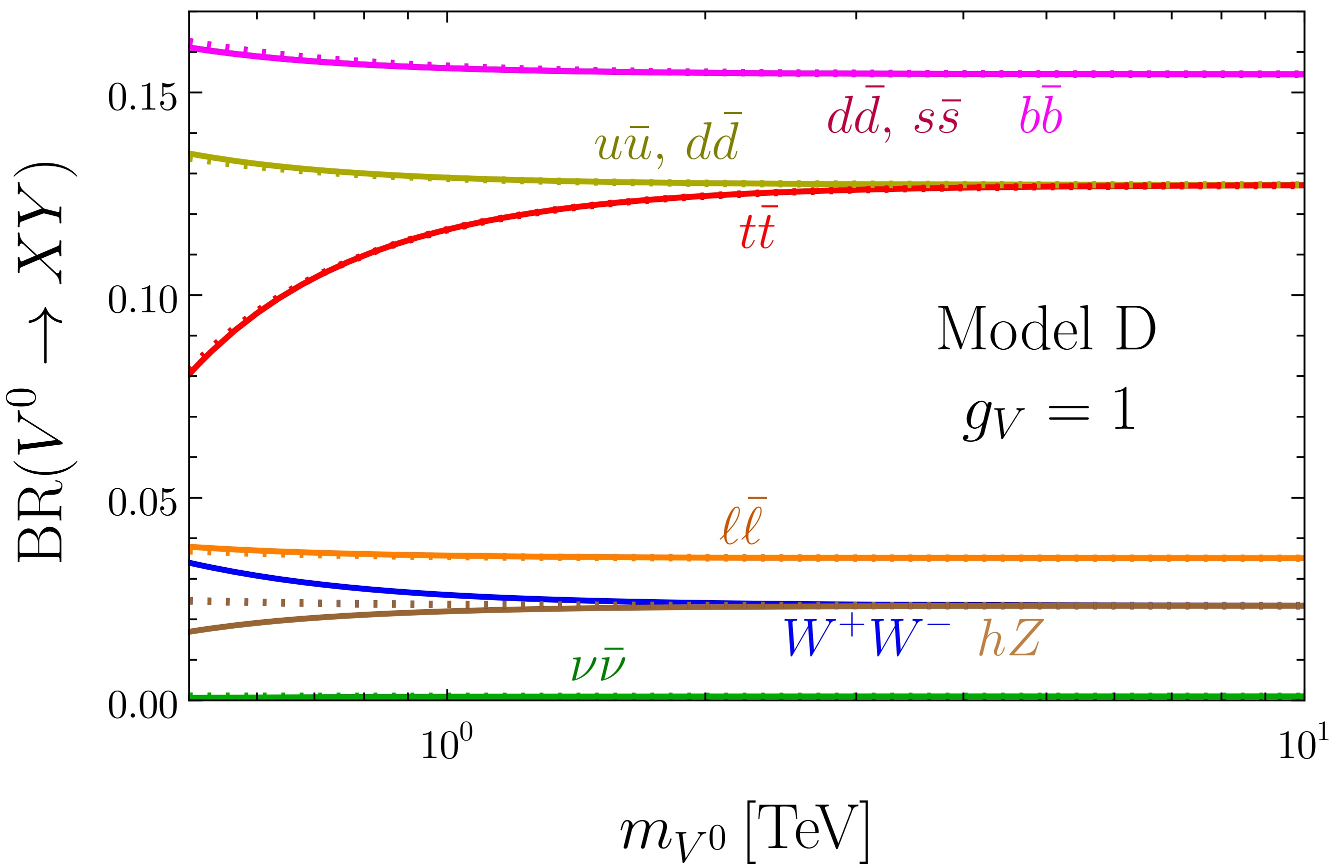


HVS - Matching onto explicit models

2. New non-abelian gauge extensions

Gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$
Associated gauge bosons are V^0, $V^\pm$ (often called W_R, X)
Matching fixes all parameters except g_V, m_V^0



HVS - Matching onto explicit models

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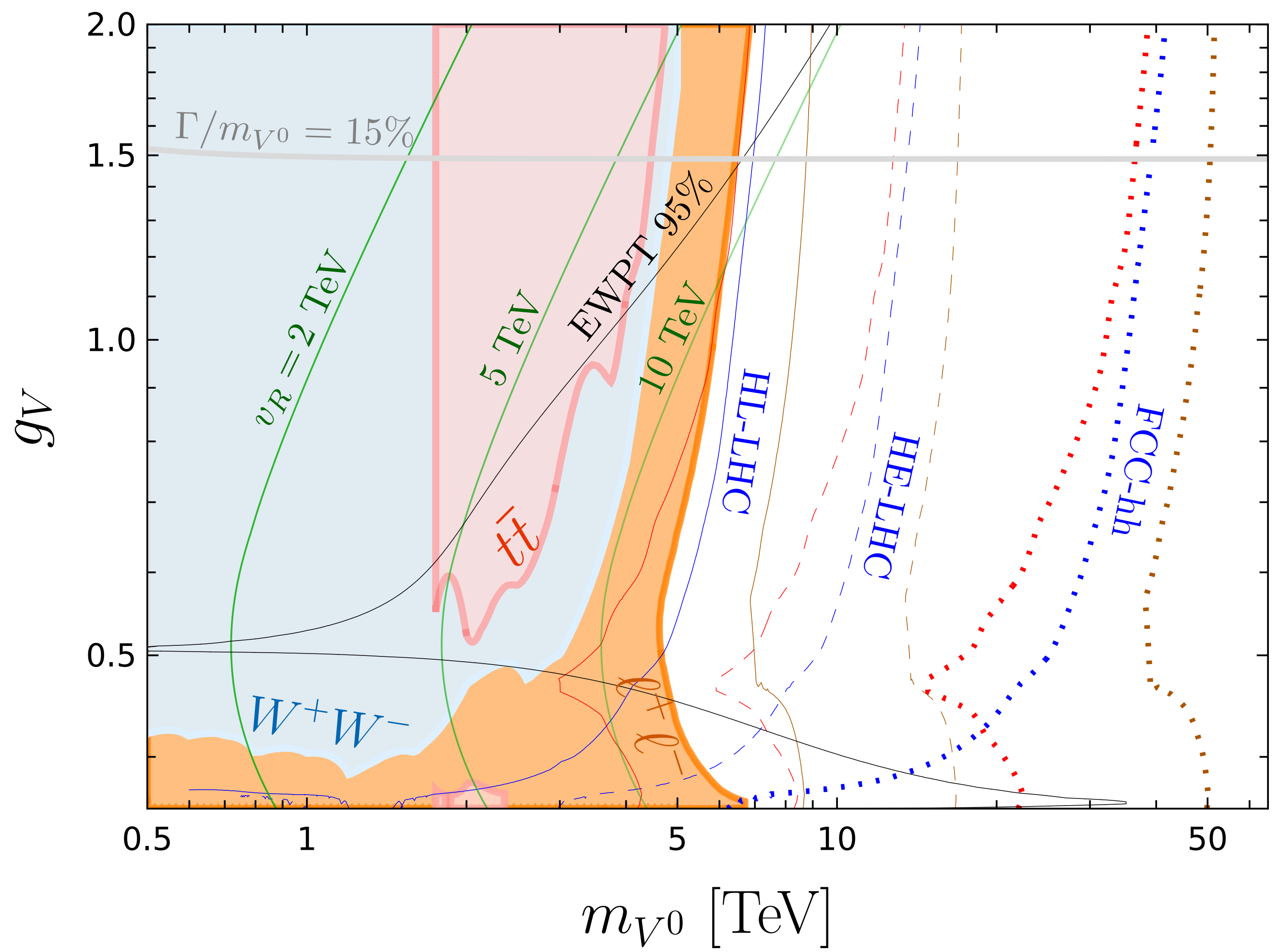
[Baker, Martonhelyi, Thamm, Torre: 2404…]

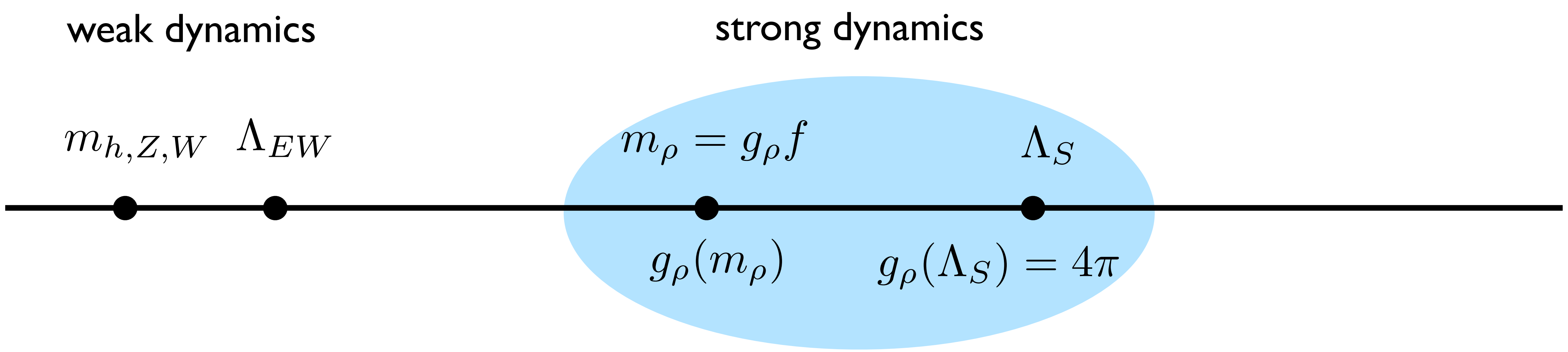


HVS - Matching onto explicit models

[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]

3. Minimal composite Higgs model

Strongly coupled heavy sector at scale

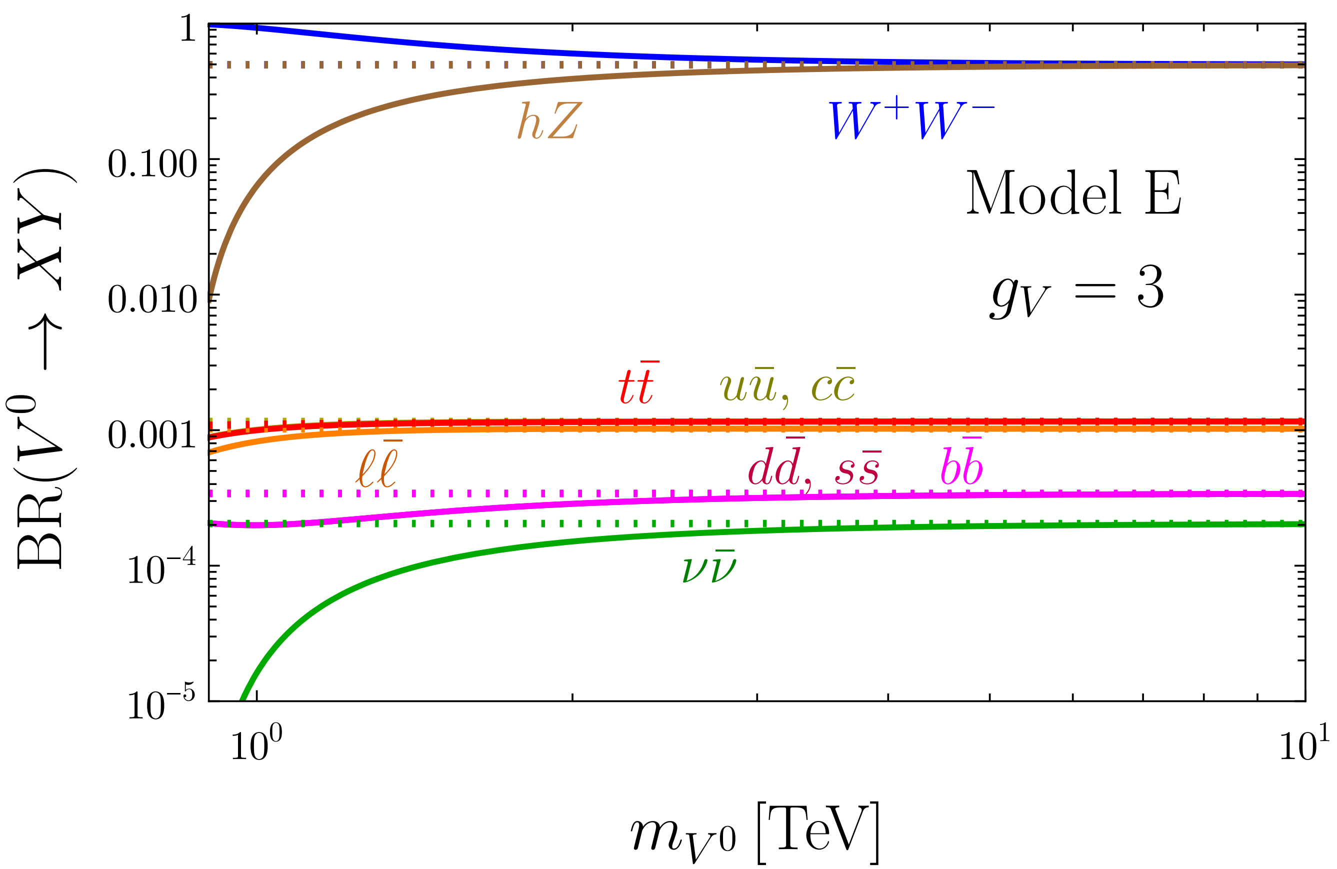


- Spontaneous breaking of global symmetry
- Higgs arises as a pseudo-Nambu-Goldstone boson
- Above Λ_S H no longer elementary d.o.f. → solves hierarchy problem

HVS - Matching onto explicit models

3. Minimal composite Higgs model

Global symmetry breaking pattern: $SO(5)/SO(4)$
Associated gauge bosons are $V^0, V^\pm$ (often called ρ_R)
Matching fixes all parameters except g_V, m_V^0



HVS - Matching onto explicit models

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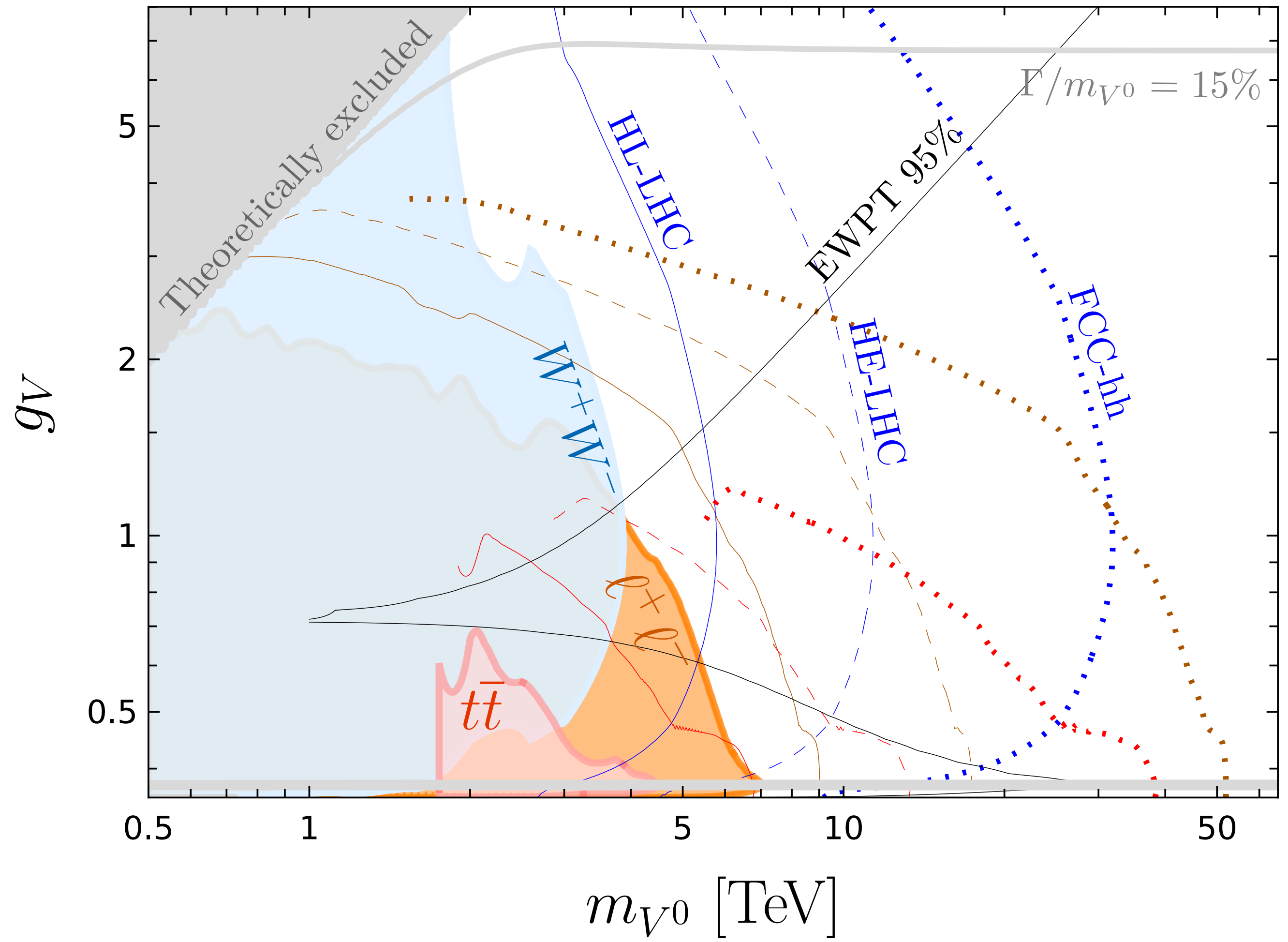


Outline

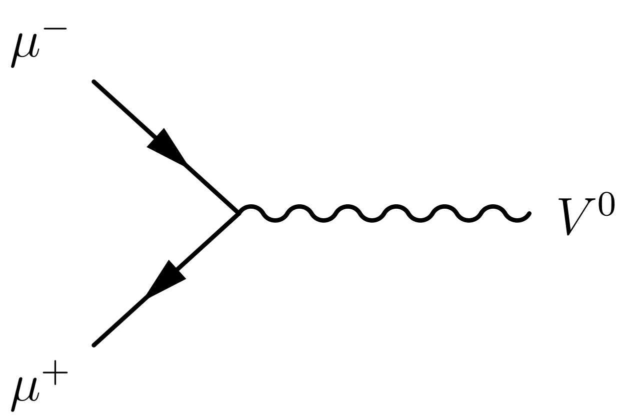
1. Theory motivation
2. Heavy vector triplets
3. Heavy vector singlets
4. Heavy vectors at future colliders
5. Conclusions

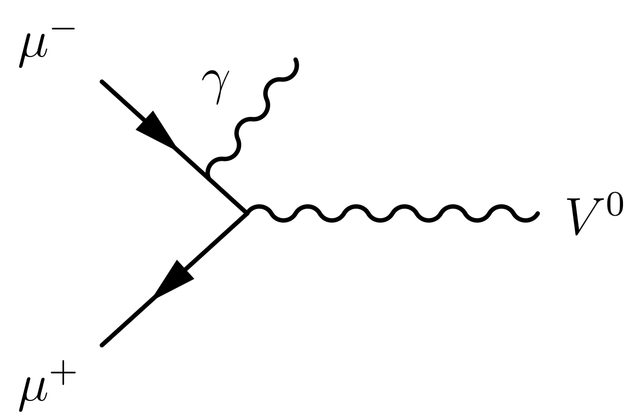
HVT - Future Colliders

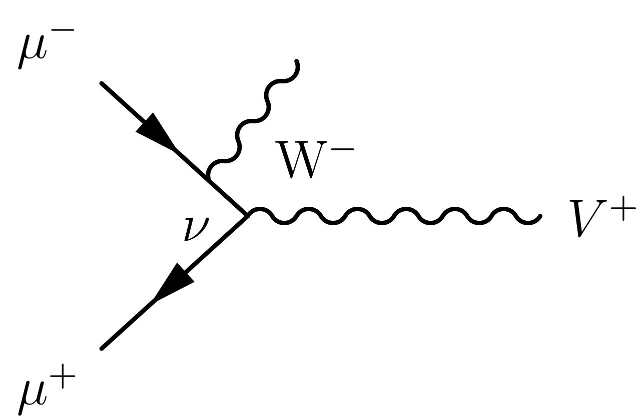
Muon collider - 10 TeV

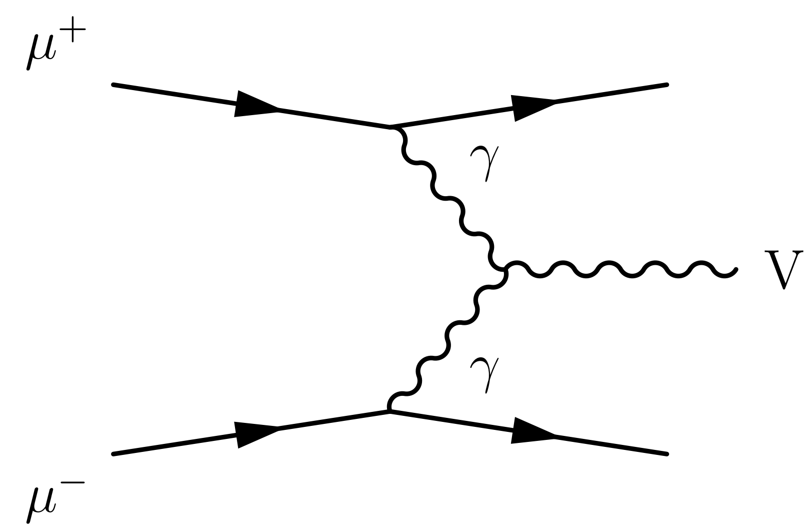
Production via

- Resonance production
- Radiative return
- Vector boson fusion





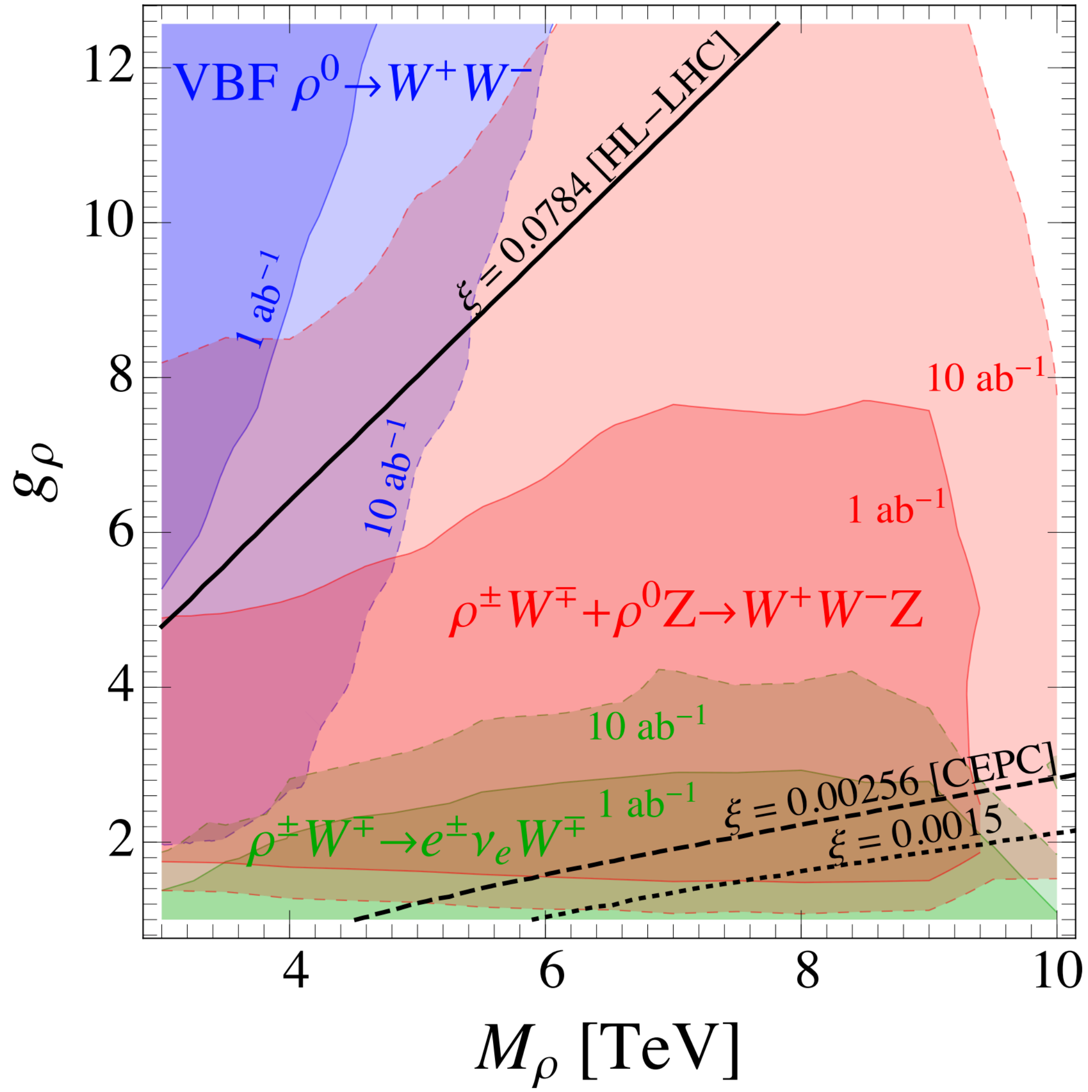




HVT - Future Colliders

Muon collider - 10 TeV

[Liu, Wang, Xie: 2312.09117]



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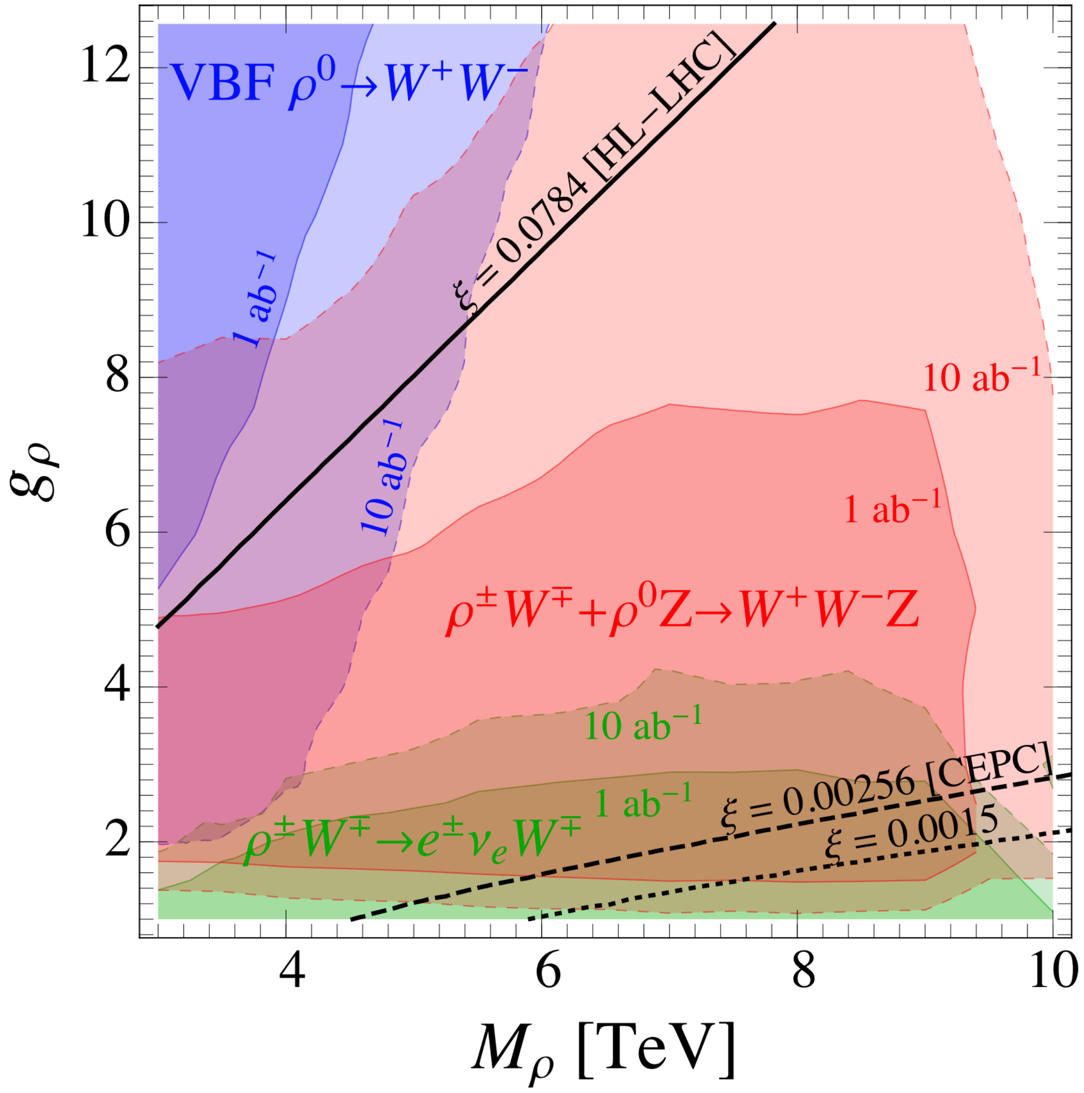
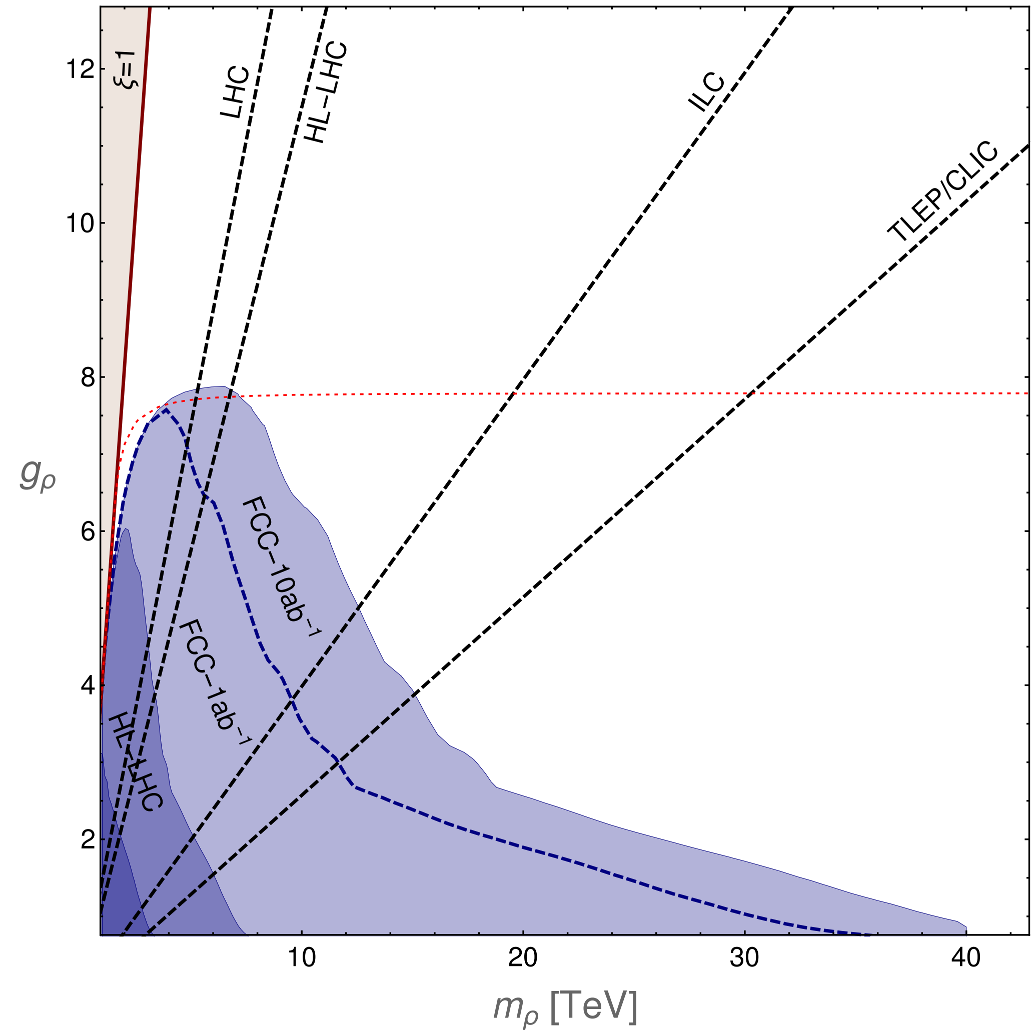


[Thamm, Torre, Wulzer: 1502.01710]



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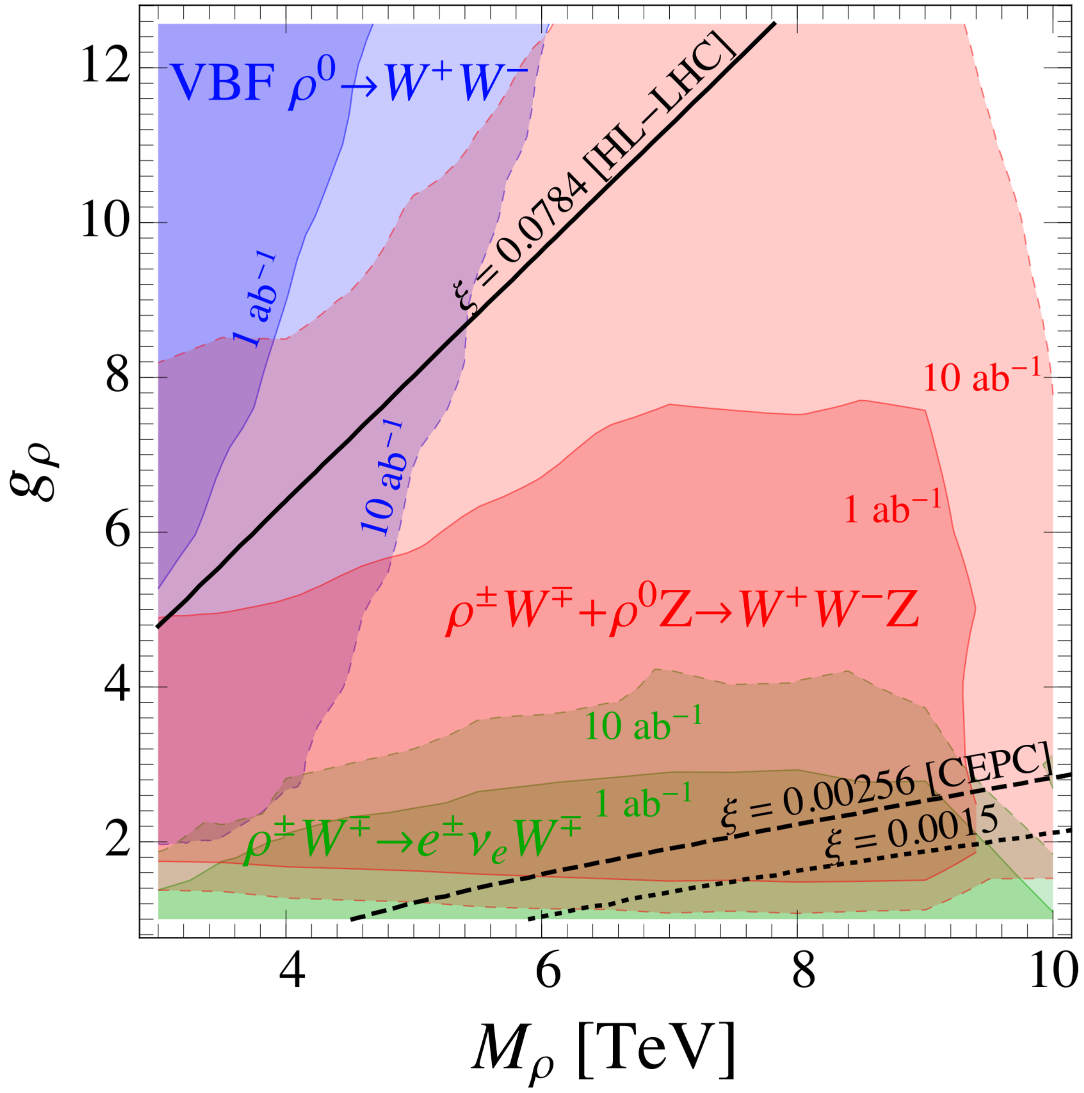
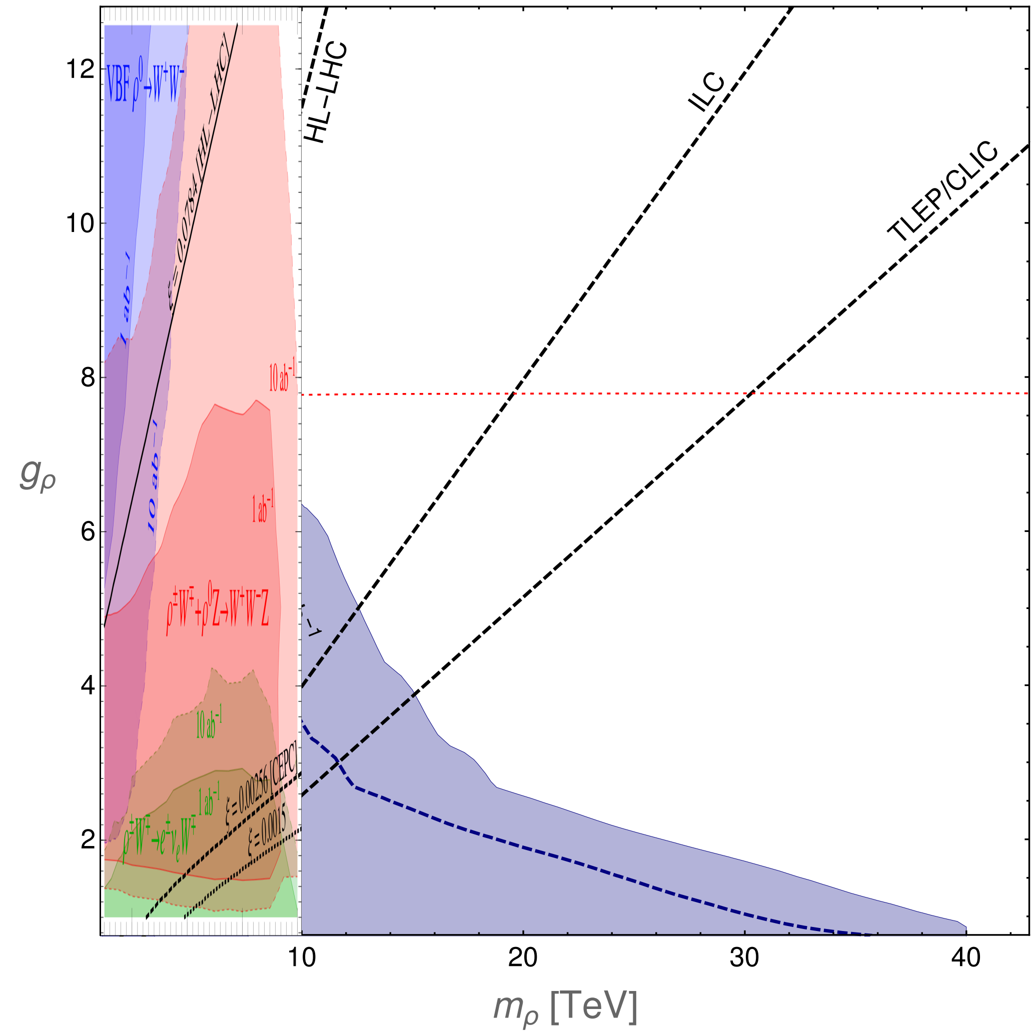


[Thamm, Torre, Wulzer: 1502.01710]



Outline

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Conclusions

- Simplified models are very versatile for vector triplets and singlets
- Vector boson fusion can be a dominant production mode
- Collider probes complementary to electroweak precision tests
- Future colliders can close the gap between them

Thank you!