Heavy Vectors @ Future Colliders

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Mostly based on 2407.11117

Why heavy vectors

- Simplest SM extension providing resonant signatures (in analogy with the SM DY, di-boson, di-jet, etc. processes)
- Appear in large classes of BSM models
- Perfect "benchmark" to study "direct reach" of future High Energy Hadron Colliders
- Perfect "benchmark" to study "indirect reach" of future High Luminosity Lepton Colliders (and Hadron Colliders)

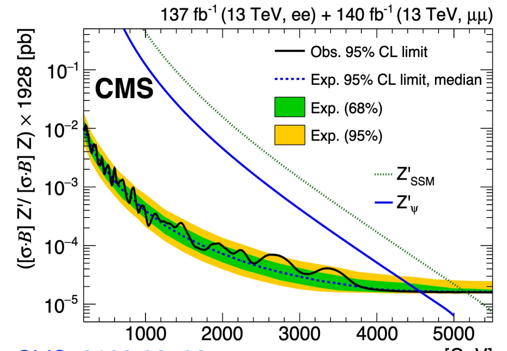
Signatures and searches

Channel	Reference	Main background	Extrapolation
$\ell\ell$	[63–67]	DY $\ell\ell$	✓
$\tau\tau$	[68, 69]	di-jet, jet + τ	×
jj	[39, 40]	multi-jet	×
$b\bar{b}$	[70]	multi-jet	×
$t\bar{t}$	[71–73]	$t\bar{t}$	✓
$WW \to jj$	[45–49]	multi-jet	×
$WW \to \ell\nu jj$	[50–53]	W+jets, $t\bar{t}$ (50% in certain signal regions)	○
$Zh \to \ell\ell/\nu\nu b\bar{b}$	[61]	2-ℓ: $Z + (b\bar{b})$ (75%), $t\bar{t}$ (25%) / 0-ℓ: $t\bar{t}$	✓
$Zh \to jj\bar{b}b$	[62]	multi-jet	×

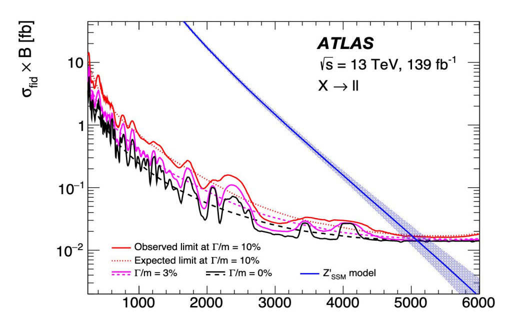
Baker et al., 2407.11117

Channel	Reference	Main background	Extrapolation
jj	[39, 40]	multi-jet	×
$t\bar{b}$	[41–43]	multi-jet	×
$WZ \to 3\ell\nu$	[44]	DY WZ	✓
$WZ \to jj$	[45–49]	multi-jet	×
$WZ \to \ell\nu jj$	[50–53]	W/Z+jets	×
$WZ \to \ell\ell jj$	[50, 54–56]	W/Z+jets	×
$WZ \to \nu\nu jj$	[54, 57, 58]	W/Z+jets, $t\bar{t}$ in certain control regions	○
$W\gamma$	[59, 60]	γ+jet, $\gamma + W$	×
$Wh \to \ell\nu\bar{b}b$	[52, 61]	$t\bar{t}$	✓
$Wh \to jj\bar{b}b$	[62]	multi-jet	×

Examples:



CMS, 2103.02708



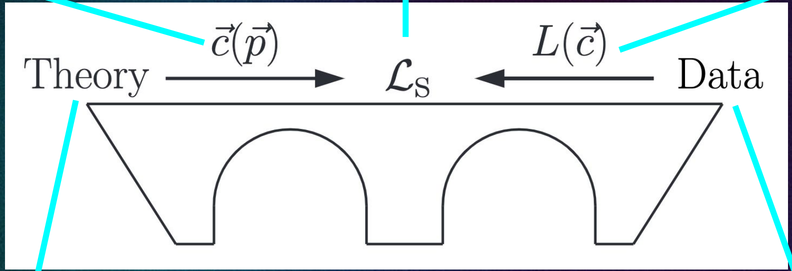
ATLAS, 1903.06248

"Bridging" theory and data

Pappadopulo et al., 1402.4431

Simplified model

Explicit model parameters



Simplified model parameters

BSM model

Narrow Resonance Searches

Simplified models

- Heavy Vector Triplet

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a}$$
$$+\, i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F$$
$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V^b_\mu V^c_\nu\,.$$

Pappadopulo et al., 1402.4431

- Heavy Vector Singlets

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

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

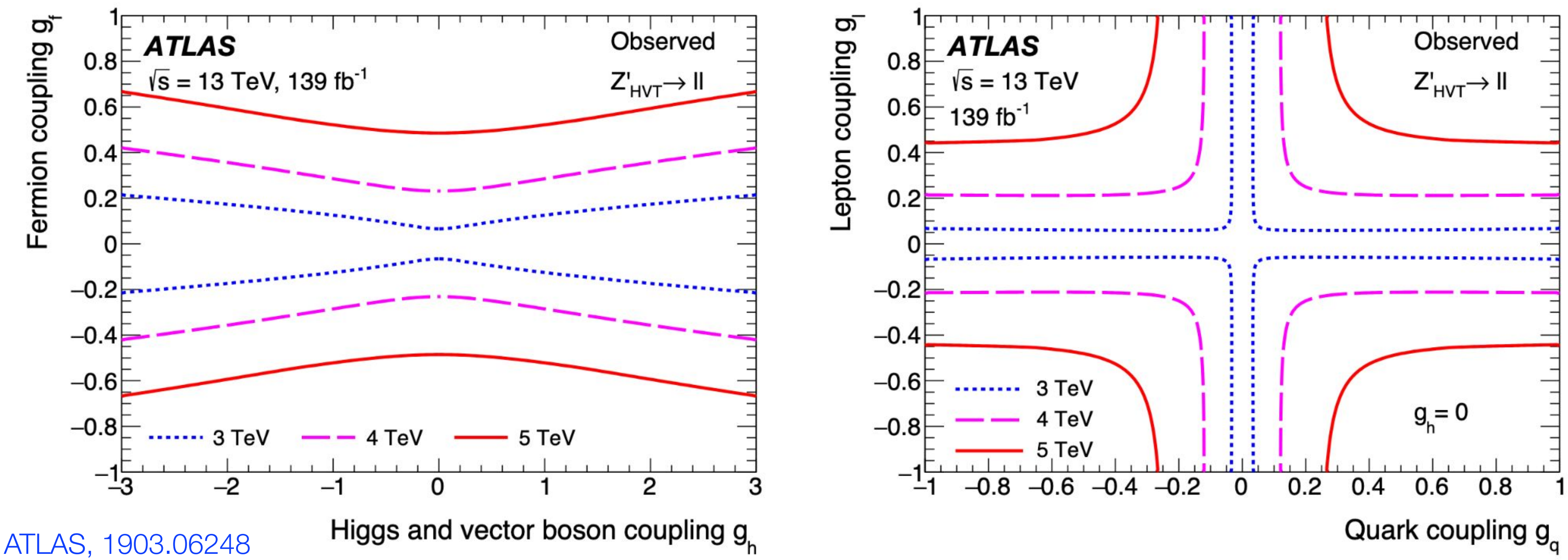
$$\mathcal{L}_{\text{mix}} = (i g_V c^+_{VVV} D_{[\mu} \mathcal{V}^-_{\nu]} \mathcal{V}^{0\,\mu} \mathcal{V}^{+\,\nu} + \text{h.c.}) + i g_V c^0_{VVV} \partial_{[\mu} \mathcal{V}^0_{\nu]} \mathcal{V}^{+\,\mu} \mathcal{V}^{-\,\nu}$$

Baker et al., 2407.11117

Simplified models

- Heavy Vector Triplet
  - Under mild assumptions entirely described by one mass and two couplings $(m_V, g_V c_H, c_F/g_V)$
- Heavy Vector Singlets
  - Charged singlet similar to triplet but does not couple to leptons $(m_{\mathcal{V}^+}, g_V c_H^+, g_V c_q^+)$
  - Neutral singlet has many more couplings making it more complicated $(m_{\mathcal{V}^0}, g_V c_H^0, g_V c_Q^0, g_V c_L^0, g_V c_U^0, g_V c_D^0, g_V c_E^0)$

Limits



ATLAS, 1903.06248

Projecting limits at FC

To extrapolate the limit on CSxBR we look at the scaling of background and not signal

Thamm et al., 1502.01701
Buttazzo et al., 1505.05488

$$B(s_0, L_0, m_0) = B(s, L, m)$$

$$\Downarrow$$

$$\sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m; \sqrt{s}) = \frac{L_0}{L} \sum_{\{i,j\}} c_{ij} \frac{d\mathcal{L}_{ij}}{d\hat{s}}(m_0; \sqrt{s_0})$$

Assumptions on FC

	Collisions	$\sqrt{s}$ [TeV]	L [ab^{-1}]	References
HL-LHC	pp	14	3	[115]
HE-LHC	pp	27	15	[110]
SPPC	pp	100	3	[113]
FCC-hh	pp	100	20	[112]

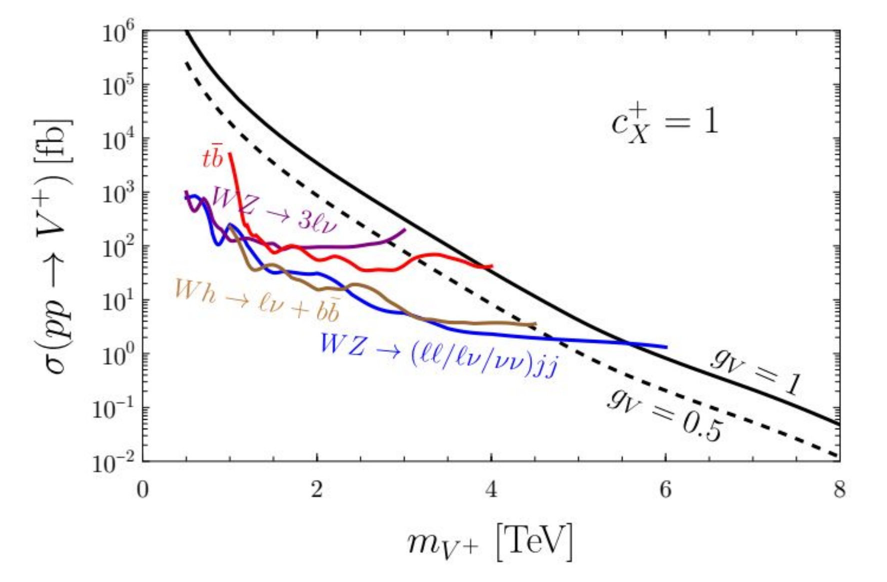
Indirect bounds

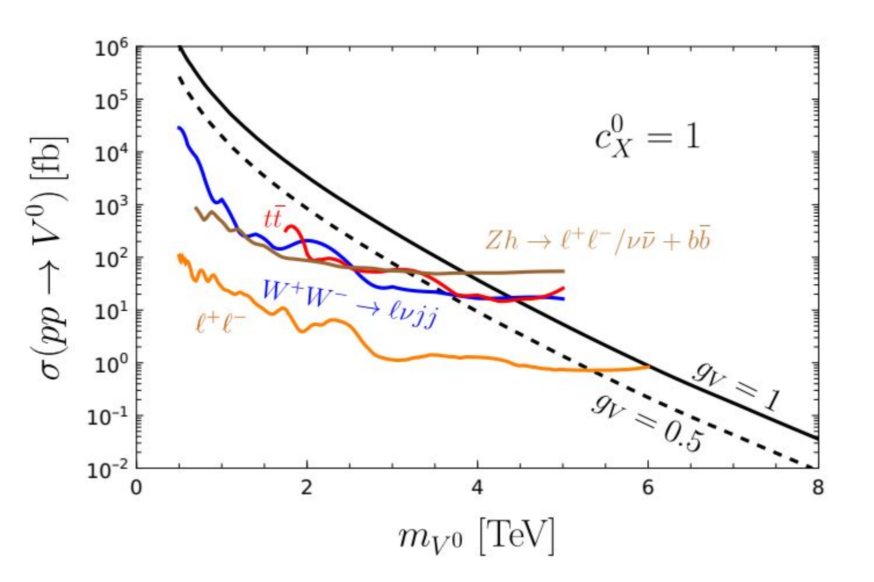
Assuming no flavor mixing and universal couplings, indirect bounds mostly come from Electroweak Precision Observables (EWPO)

- Old approach: S, T, U, W, Y, etc. (used here)
- More modern approach: match to the SMEFT and compute the bounds on the Wilson coefficients of the relevant operators (work in progress)

LHC bounds

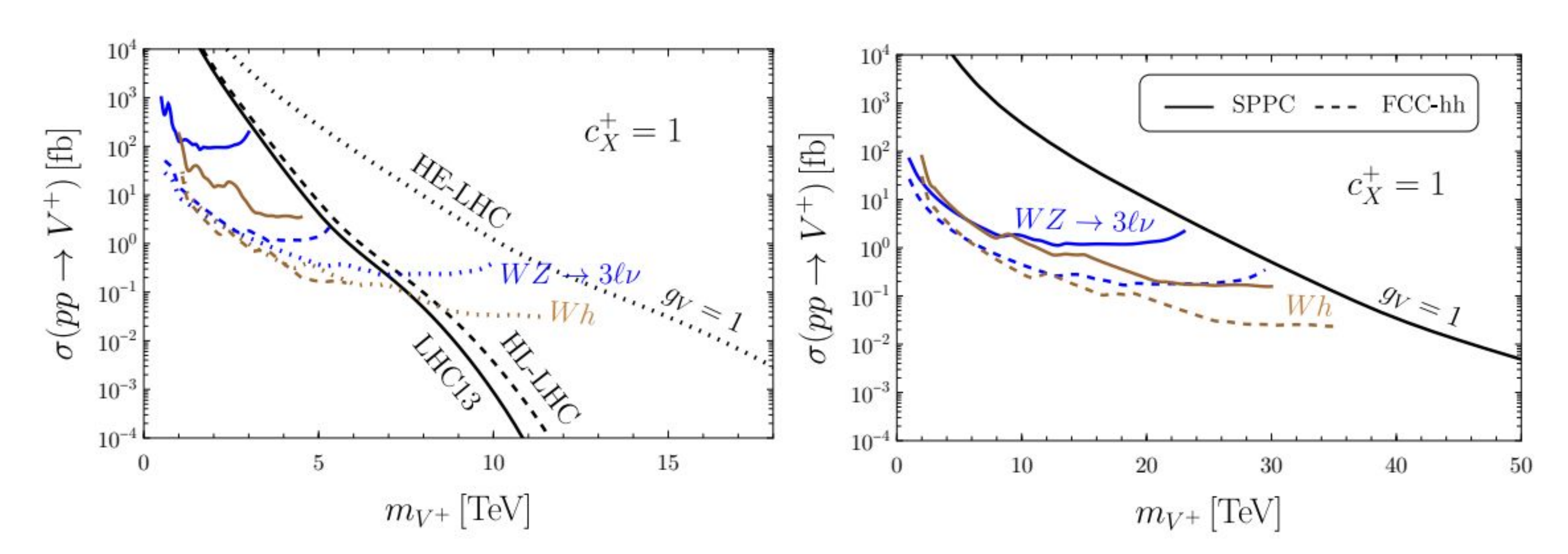
Universal coupling: all c coefficients set to one





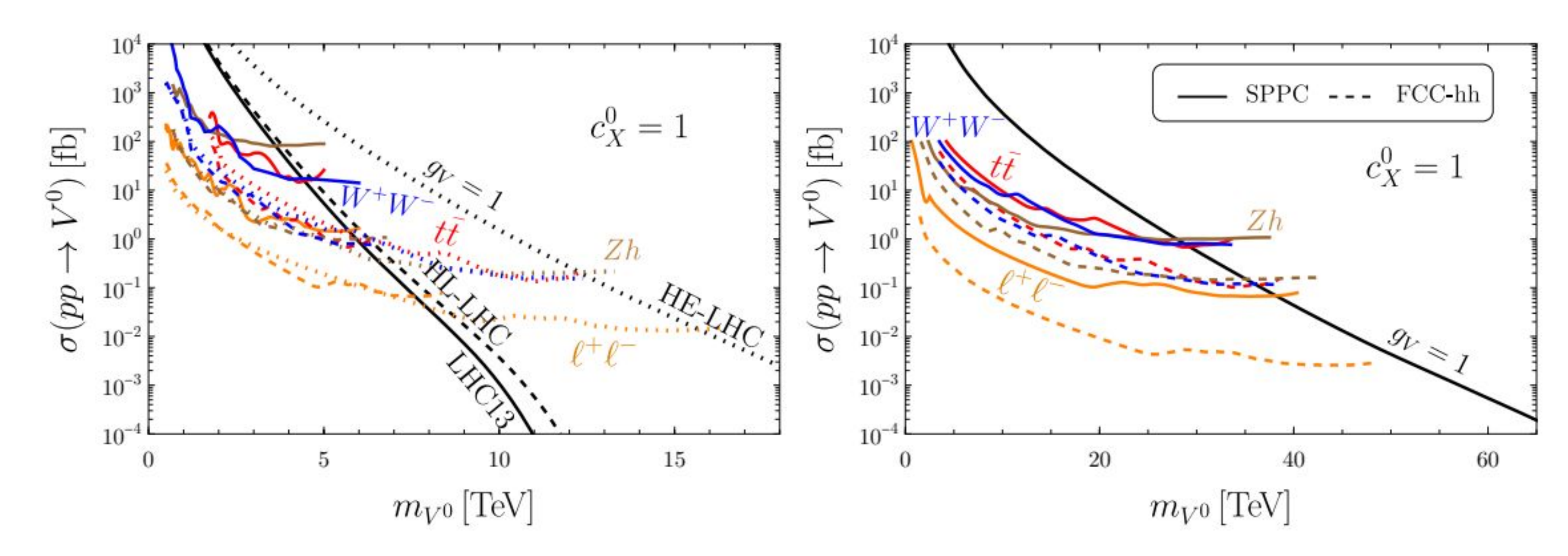
Projections: charged channel

Universal coupling: all c coefficients set to one



Projections: neutral channel

Universal coupling: all c coefficients set to one

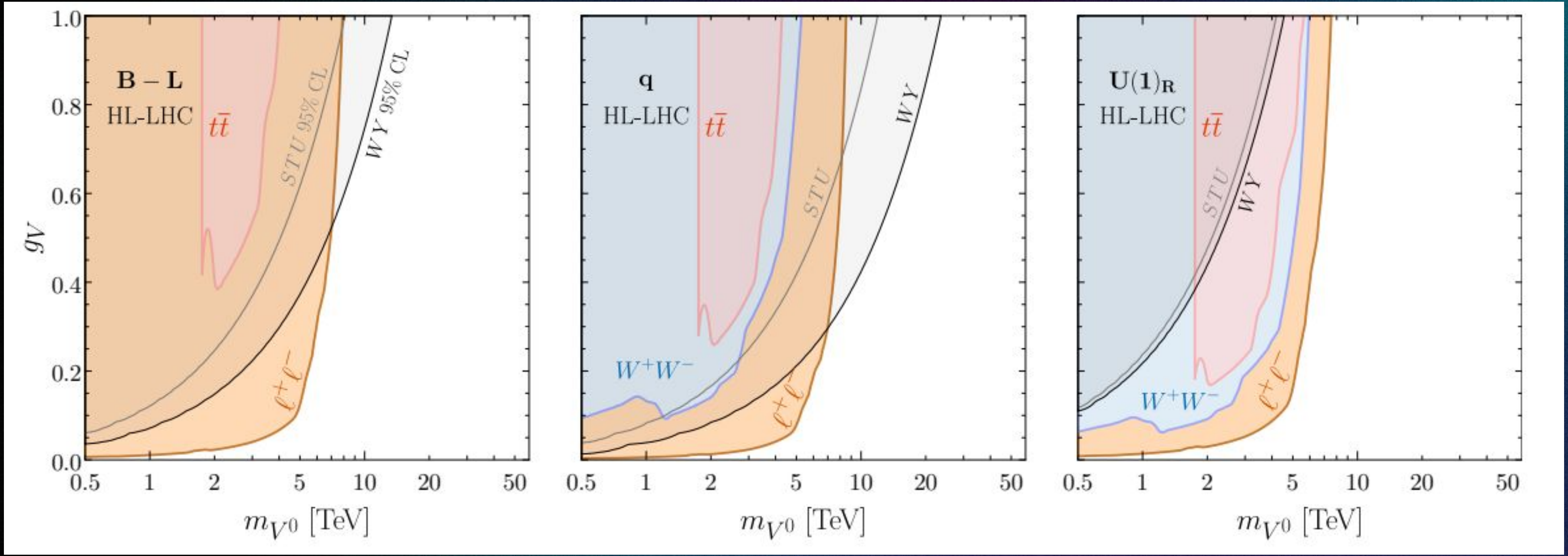


Explicit models

We considered three extensions of the SM giving rise to HVS

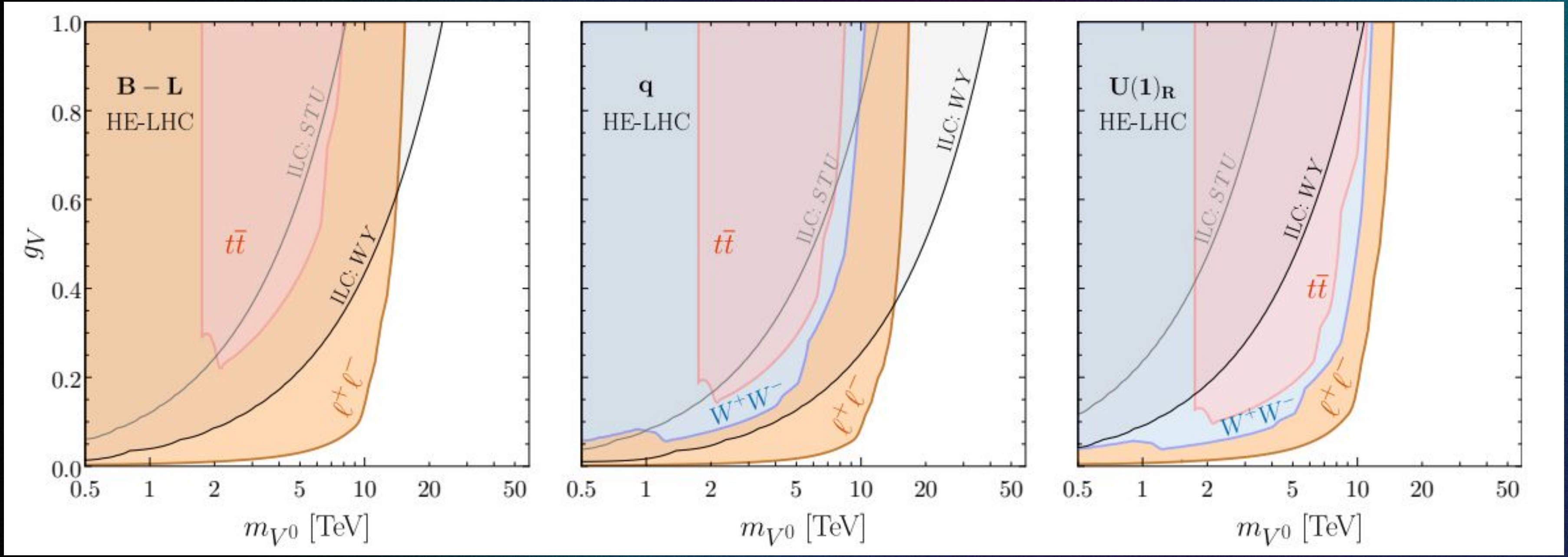
- U(1) extensions (usual Z' model)
- Weakly coupled non-abelian gauge extension (with RH triplet)
- Strongly couplet RH triplet from Minimal CH models

U(1) models



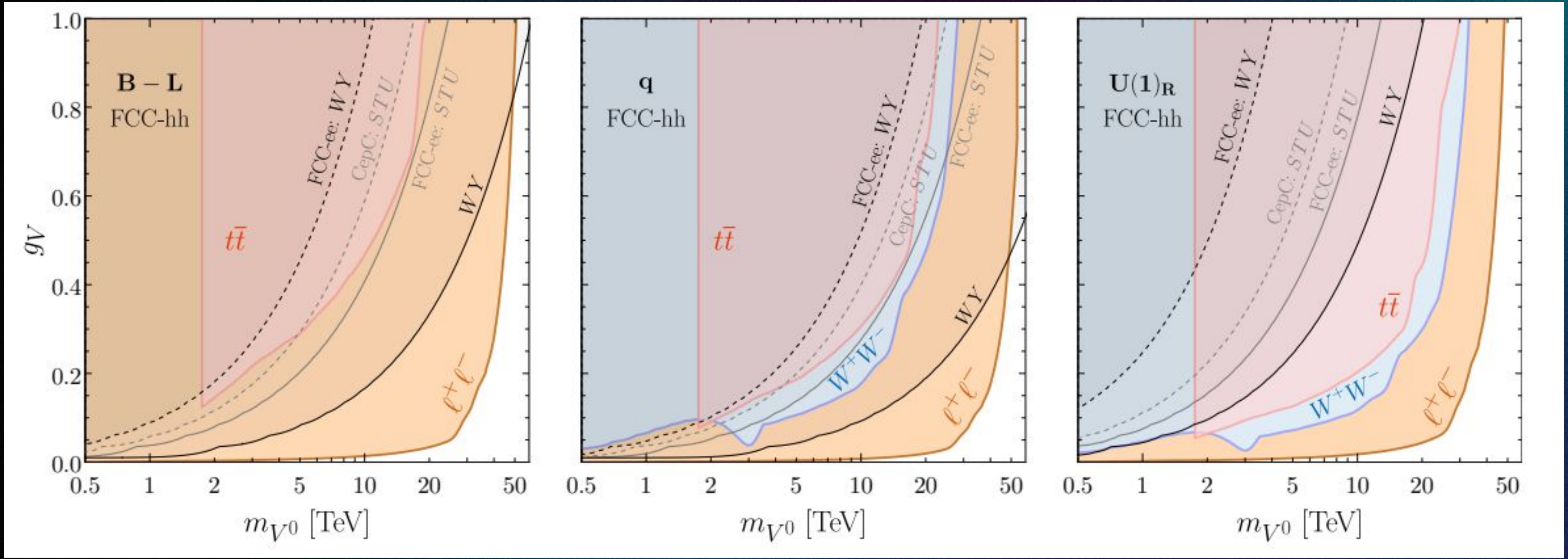
B – L
HL-LHC
$t\bar{t}$
STU 95% CL
WY 95% CL
$\ell^+\ell^-$
g_V
m_{V^0} [TeV]
q
HL-LHC
$t\bar{t}$
WY
STU
W^+W^-
$\ell^+\ell^-$
m_{V^0} [TeV]
$\mathbf{U(1)_R}$
HL-LHC
$t\bar{t}$
STU
WY
W^+W^-
$\ell^+\ell^-$
m_{V^0} [TeV]

U(1) models



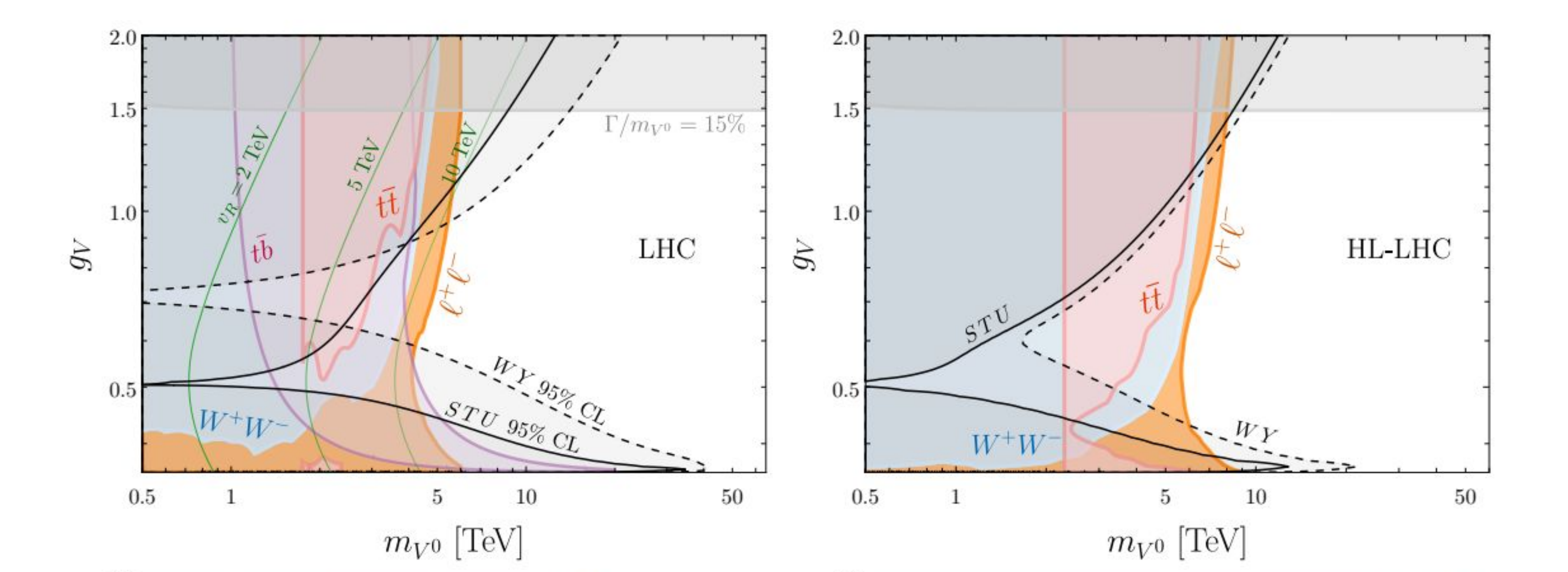
B − L
HE-LHC
q
HE-LHC
$\mathbf{U(1)_R}$
HE-LHC
ILC: STU
ILC: WY
$t\bar{t}$
$\ell^+\ell^-$
W^+W^-
g_V
m_{V^0} [TeV]

U(1) models

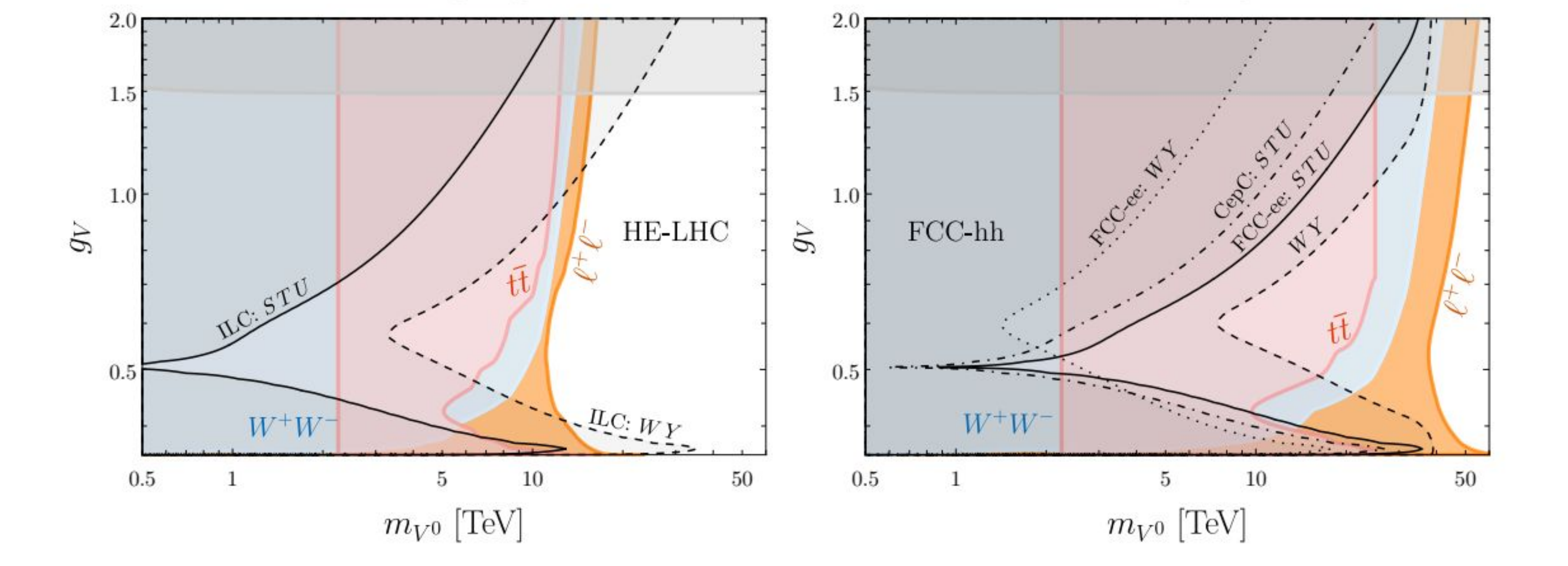


B − L
FCC-hh
q
FCC-hh
U(1)R
FCC-hh
$t\bar{t}$
W^+W^-
$\ell^+\ell^-$
FCC-ee: WY
CepC: STU
FCC-ee: STU
WY
g_V
m_{V^0} [TeV]

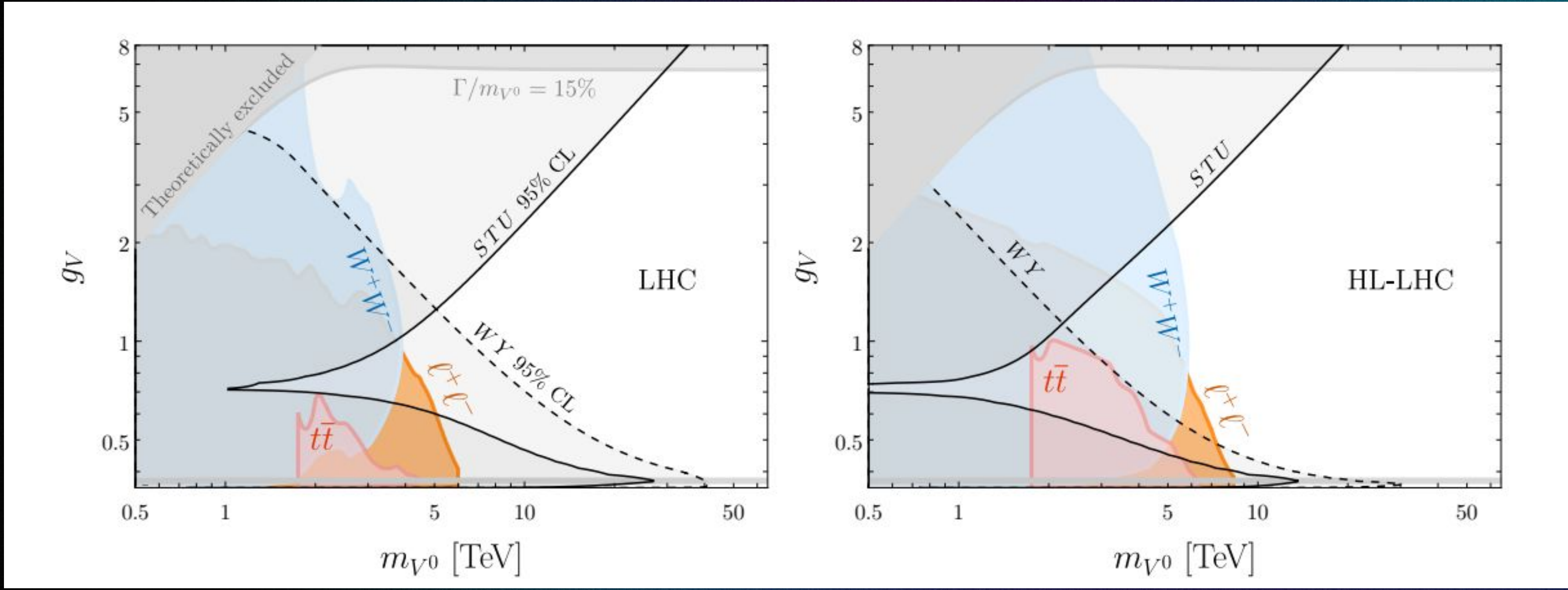
Non-abelian Weakly Coupled



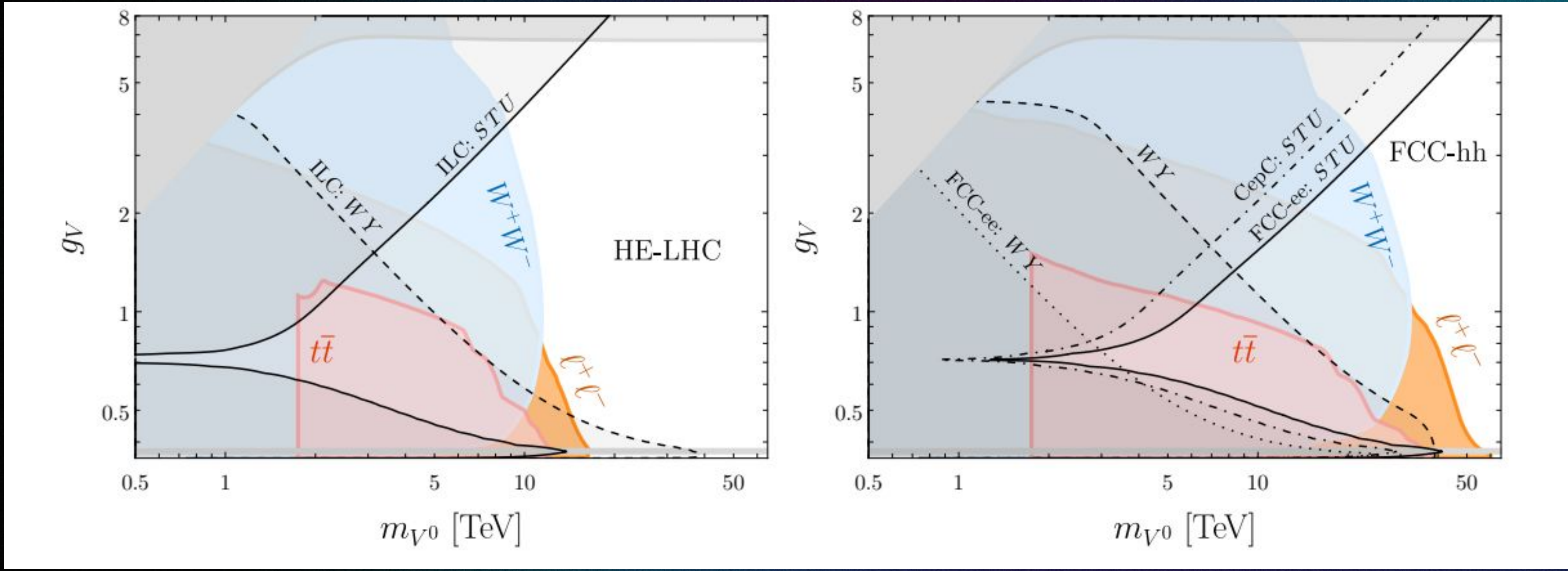
Non-abelian Weakly Coupled



Non-abelian Strongly Coupled



Non-abelian Strongly Coupled



Matching HVT to SMEFT

$$\mathcal{L}^{\text{HVT}}_{\text{SMEFT}} = C_H \mathcal{O}_H + C_{H\Box}\mathcal{O}_{H\Box} + C_{eH}\mathcal{O}_{eH} + C_{uH}\mathcal{O}_{uH} + C_{dH}\mathcal{O}_{dH} + C_{ll}\mathcal{O}_{ll} + C^{(3)}_{lq}\mathcal{O}^{(3)}_{lq} + C^{(3)}_{qq}\mathcal{O}^{(3)}_{qq} + C^{(3)}_{Hl}\mathcal{O}^{(3)}_{Hl} + C^{(3)}_{Hq}\mathcal{O}^{(3)}_{Hq}\,,$$

$$C_H = -\frac{\lambda g_V^2 c_H^2}{M_V^2}\,,\quad C_{H\Box} = -\frac{3 g_V^2 c_H^2}{8 M_V^2}\,,\quad C_{fH} = -\frac{g_V^2 c_H^2}{4 M_V^2} Y_f\,,$$

$$C^{(3)}_{qq} = -\frac{g^4 c_F^2}{8 g_V^2 M_V^2}\delta_{f_1 f_2}\delta_{f_3 f_4}\,,\quad C^{(3)}_{lq} = -\frac{g^4 c_F^2}{4 g_V^2 M_V^2}\delta_{f_1 f_2}\delta_{f_3 f_4}\,,$$

$$C_{ll} = -\frac{g^4 c_F^2}{8 g_V^2 M_V^2}\left(2\delta_{f_1 f_4}\delta_{f_2 f_3} - \delta_{f_1 f_2}\delta_{f_3 f_4}\right)\,,$$

$$C^{(3)}_{Hl} = C^{(3)}_{Hq} = -\frac{g^2 c_H c_F}{4 M_V^2}\,.$$

Matching HVS to SMEFT

$$\mathcal{L}^{\mathcal{V}^\pm}_{\text{SMEFT}} = \left\{ O_{H\Box}, O_H, O_{eH}, O_{uH}, O_{dH}, O_{HD}, O^{(1)}_{ud}, O^{(3)}_{ud}, O_{Hud} \right\}$$

$$\mathcal{L}^{\mathcal{V}^0}_{\text{SMEFT}} = \{ O_{\Psi\Psi'},\ O_{HD}, O_{H\Box}, O_{H\Psi} \}$$

$$C_{H\Box} = \frac{C_H}{4\lambda} = -\frac{C_{HD}}{2} = \frac{C_{eH}}{Y_e} = \frac{C_{uH}}{Y_u} = \frac{C_{dH}}{Y_d} = -\frac{g_V^2 c_H^{+2}}{M^2_{\mathcal{V}^+}},$$

$$\frac{C^{(8)}_{ud}}{2} = 3C^{(1)}_{ud} = -\frac{g_V^2 c_F^{+2}}{2M^2_{\mathcal{V}^+}}, \quad C_{Hud} = \frac{g_V^2 c_H^+ c_q^+}{M^2_{\mathcal{V}^+}}.$$

$$C_{\Psi\Psi'} = -\frac{g_V^2 c^0_\Psi c^0_{\Psi'}}{8M^2_{\mathcal{V}^0}}, \quad \frac{C_{HD}}{4} = C_{H\Box} = -\frac{g_V^2 c_H^{0\,2}}{8M^2_{\mathcal{V}^0}}, \quad C_{H\Psi} = -\frac{i g_V^2 c^0_H c^0_\Psi}{4M^2_{\mathcal{V}^0}}$$

Conclusion

- New heavy vectors are a generic prediction of several extensions of the SM
- Study them through renormalizable Simplified Models is well motivated and allows to catch general features
- The relevance of direct vs indirect reach strongly depends on model assumptions (e.g. abelian vs non-abelian)
- General complementarity between the two

Thank you!