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Heavy Vector Triplets

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based on arXiv:1402.4431, 1502.01701 and 2207.05091

Heavy Vector Resonances

- heavy vectors among the most motivated direct searches
- since they appear in many NP models

SPIN 1

Weakly coupled

Z' models,
sequential W' ,…

Strongly coupled

Composite Higgs models

- 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]

→ singlets (work in progress)

→ no coupling to quarks

→ studied here!

→ no coupling to fermions

- simplified model approach

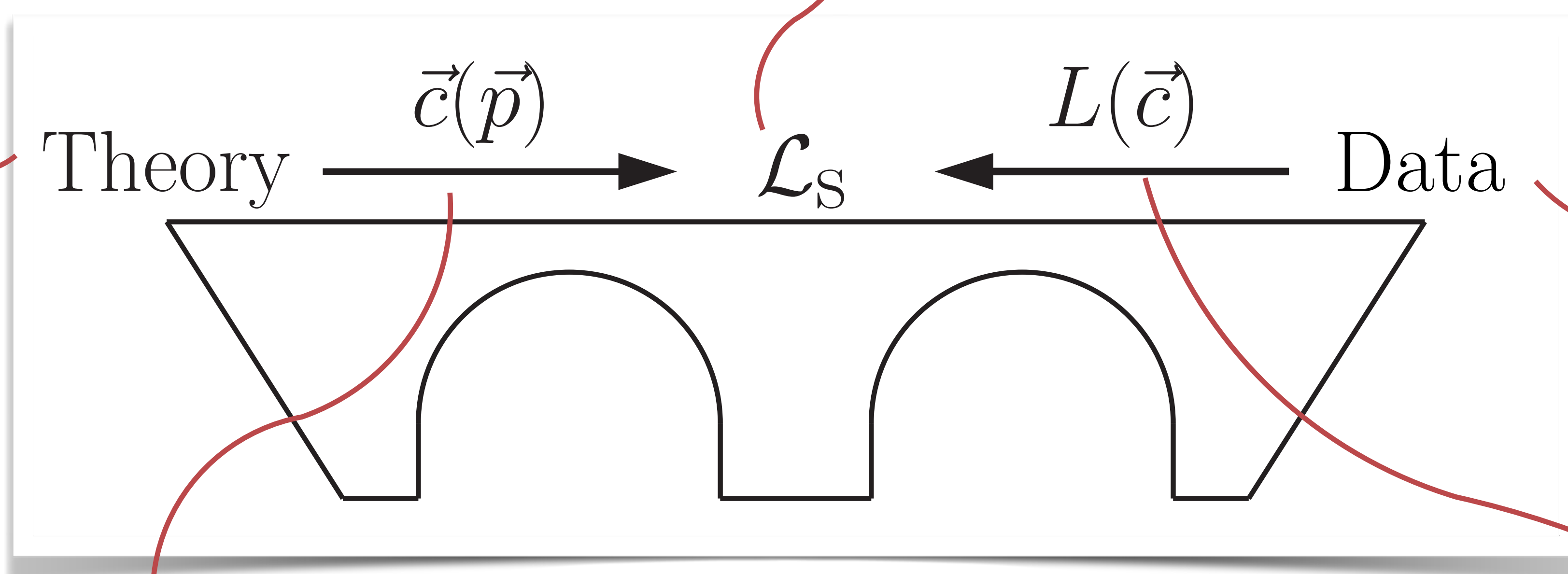
Bridge

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

explicit models

Simplified Lagrangian
can be matched to 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

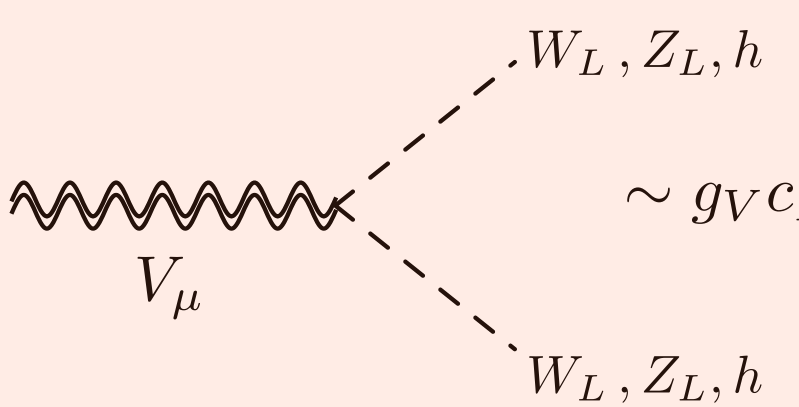
Heavy Vector Triplets

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

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

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

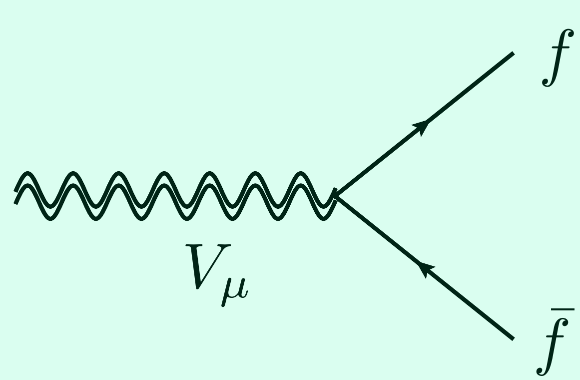
Coupling to SM Vectors



$$\sim g_V c_H$$

Coupling to SM fermions

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



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

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

Heavy Vector Triplets

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- Couplings among vectors
- do not contribute to V decays
- do not contribute to single production
- only effects through (usually small) VW mixing

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

Heavy Vector Triplets

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

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

Weakly coupled model

Strongly coupled model

g_V typical strength of V interactions

Weakly coupled: $g_V \sim g \sim 1$

Strongly coupled: $1 < g_V \leq 4\pi$

c_i dimensionless coefficients

Weakly coupled: $c_H \sim -g^2/g_V^2 \quad \text{and} \quad c_F \sim 1$

Strongly coupled: $c_H \sim \; c_F \sim 1$

HVT Production Rates

- DY and VBF production

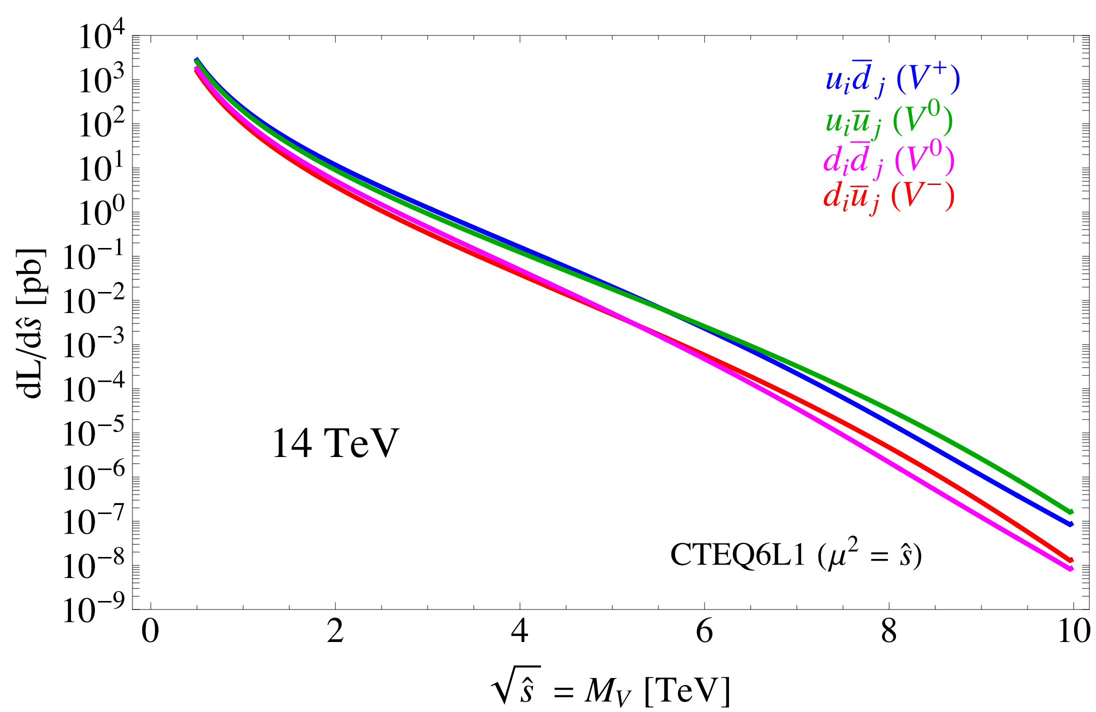
$$\sigma_{DY} = \sum_{i,j \in p} \frac{\Gamma_{V \to ij}}{M_V} \frac{4\pi^2}{3} \frac{dL_{ij}}{d\hat{s}}\bigg|_{\hat{s}=M_V^2} \qquad \sigma_{VBF} = \sum_{i,j \in p} \frac{\Gamma_{V \to W_{L\,i} W_{L\,j}}}{M_V} 48\pi^2 \frac{dL_{W_{L\,i} W_{L\,j}}}{d\hat{s}}\bigg|_{\hat{s}=M_V^2}$$

model dependent

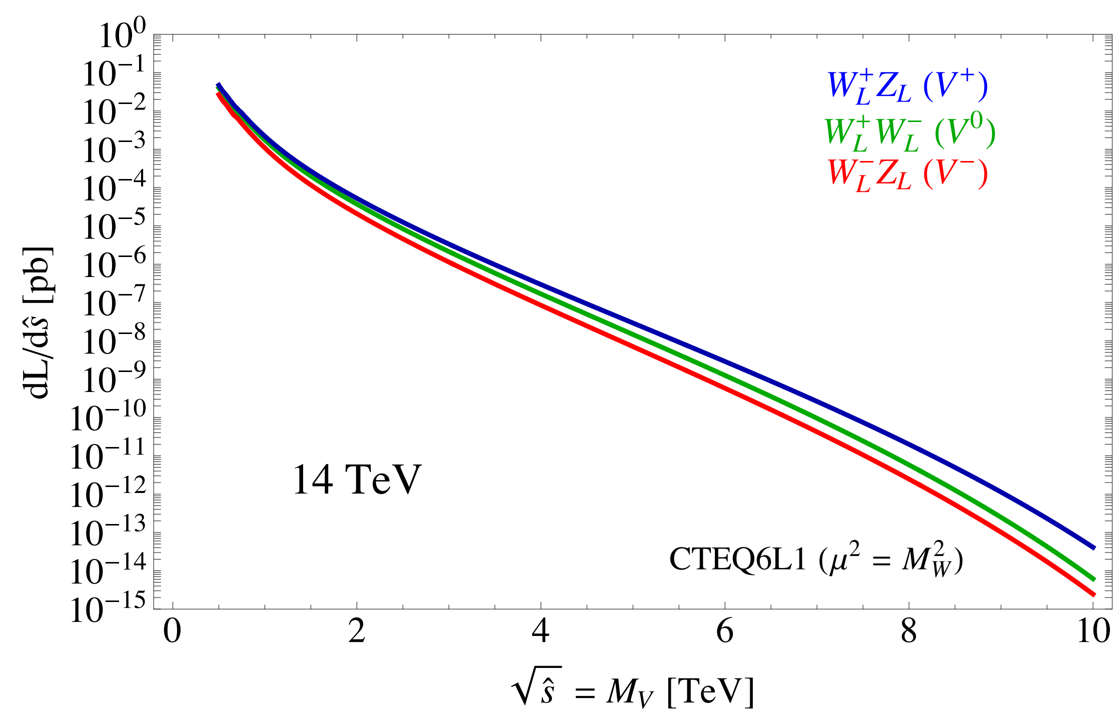
model independent

- can compute production rates analytically
- easily rescale to different points in parameter space

quark initial state



vector boson initial state



HVT Decay Widths

- relevant decay channels: di-lepton, di-quark, di-boson

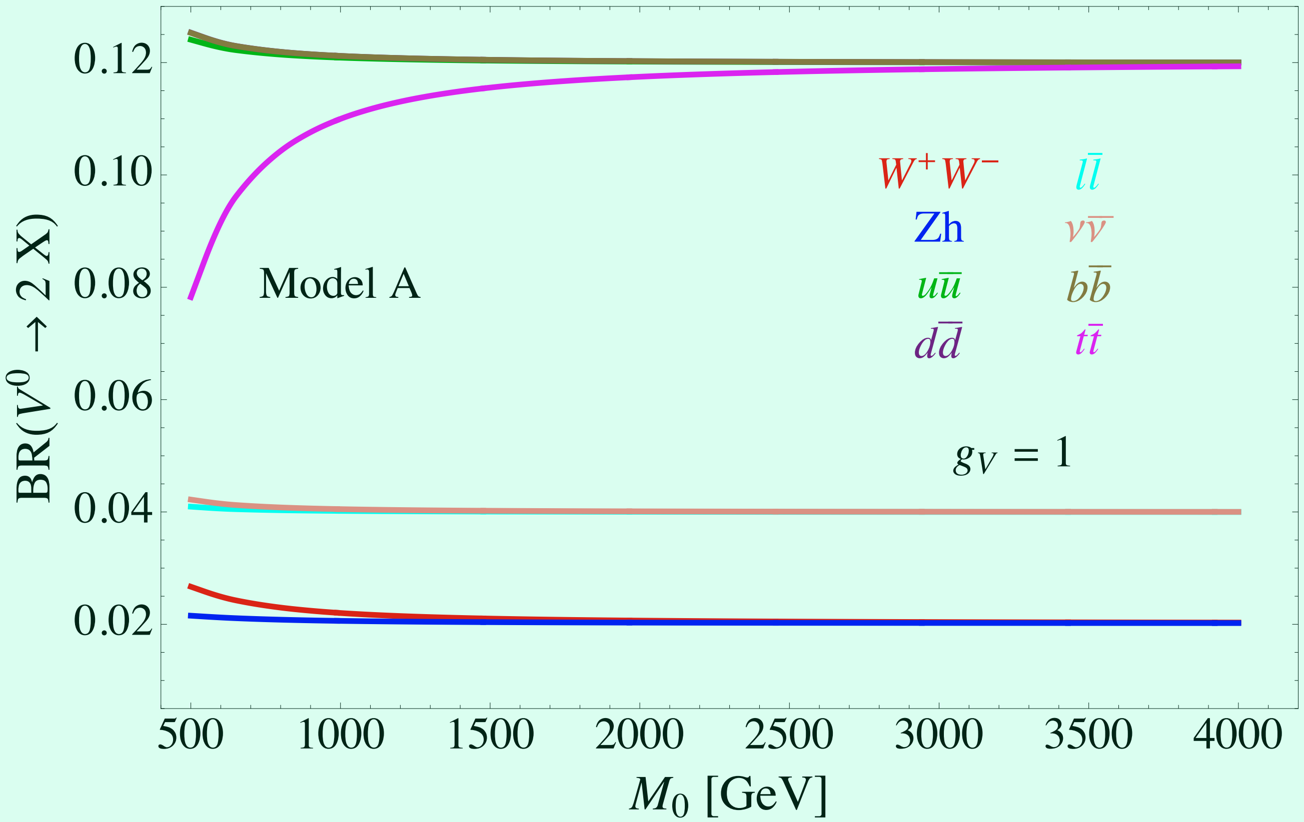
$$\Gamma_{V_\pm \to f\bar{f}'} \simeq 2\,\Gamma_{V_0 \to f\bar{f}} \simeq N_c[f]\left(\frac{g^2 c_F}{g_V}\right)^2 \frac{M_V}{96\pi}\,,$$

$$\Gamma_{V_0 \to W_L^+ W_L^-} \simeq \Gamma_{V_\pm \to W_L^\pm Z_L} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}\left[1+\mathcal{O}(\zeta^2)\right]$$

$$\Gamma_{V_0 \to Z_L h} \simeq \Gamma_{V_\pm \to W_L^\pm h} \simeq \frac{g_V^2 c_H^2 M_V}{192\pi}\left[1+\mathcal{O}(\zeta^2)\right]$$

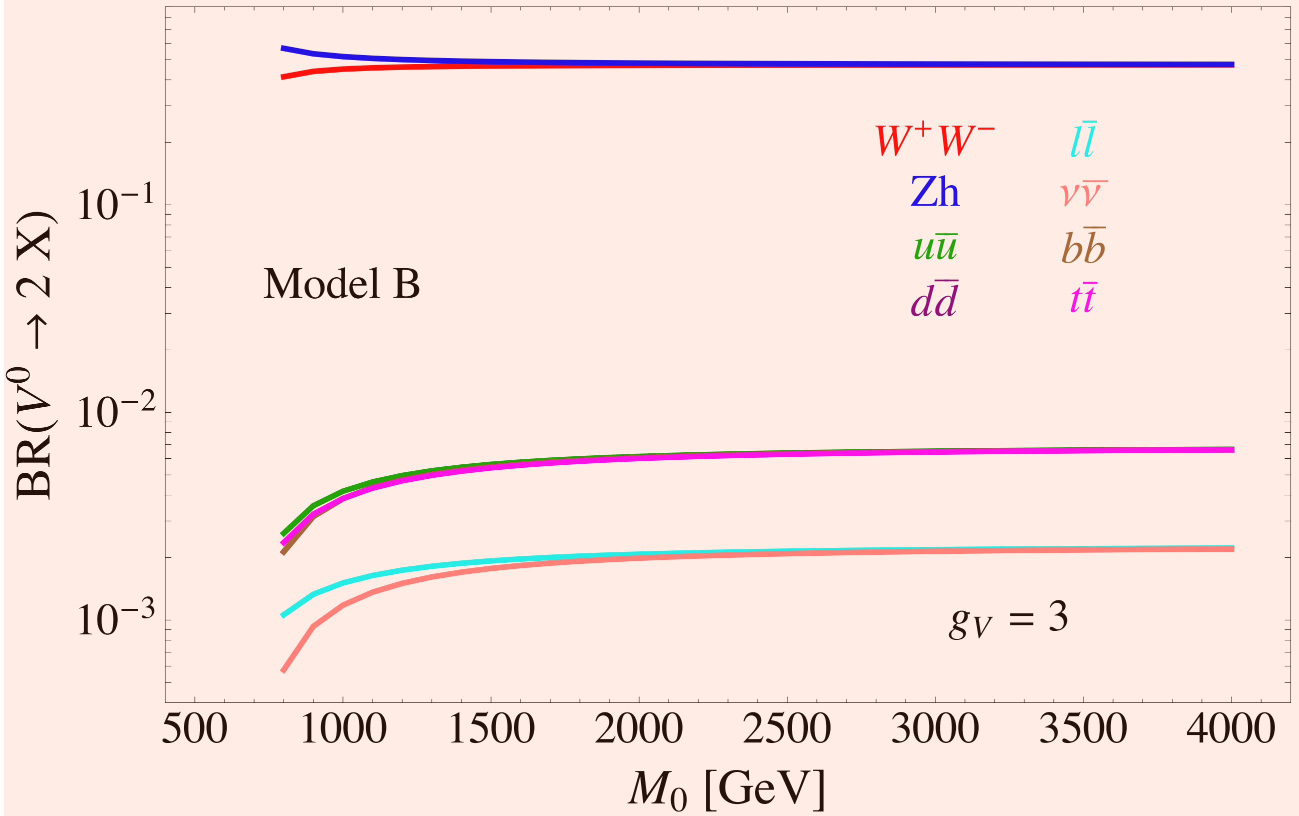
Weakly coupled model

$$g_V c_H \simeq g^2 c_F/g_V \simeq g^2/g_V$$



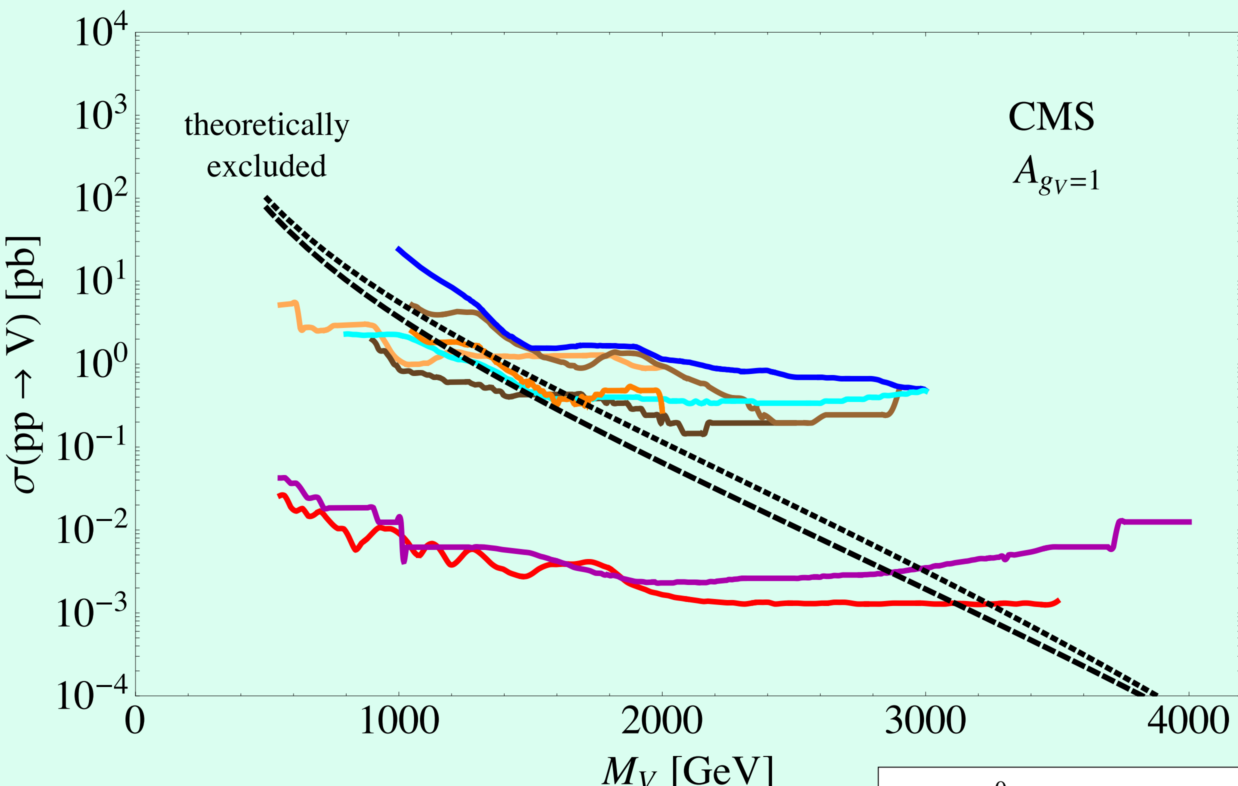
Strongly coupled model

$$g_V c_H \simeq -g_V\,, \qquad g^2 c_F/g_V \simeq g^2/g_V$$

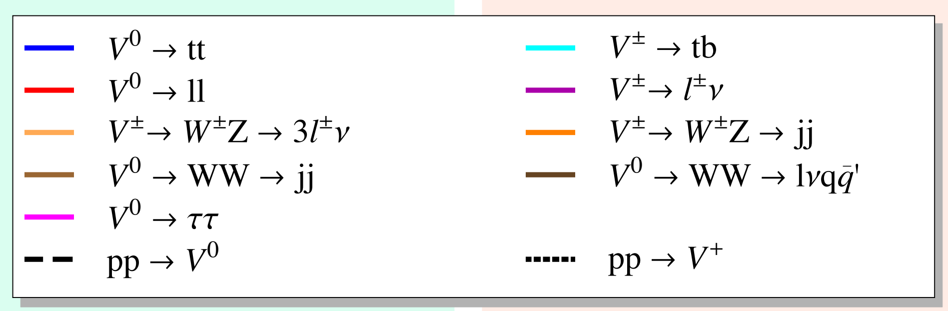


LHC bounds

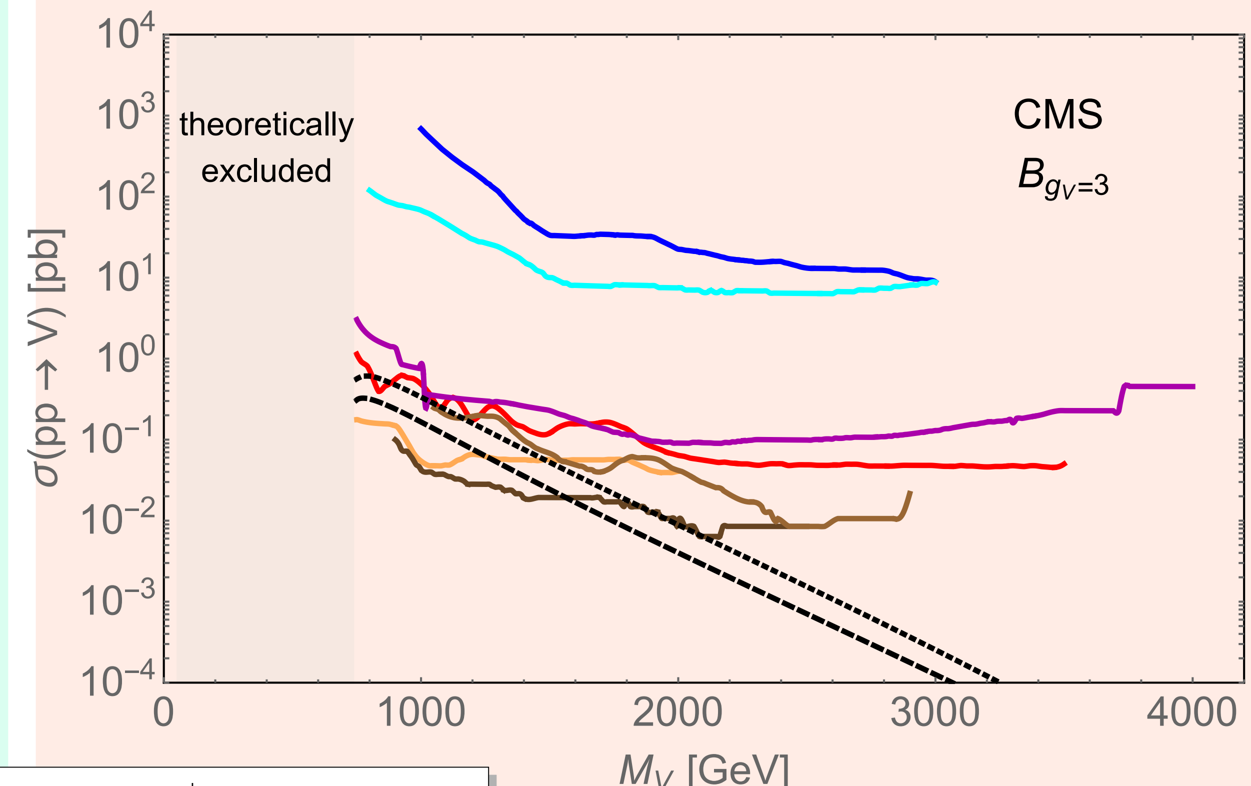
Weakly coupled model



- excluded for masses < 3 TeV
- di-lepton most stringent
- di-boson searches < 1-2 TeV



Strongly coupled model

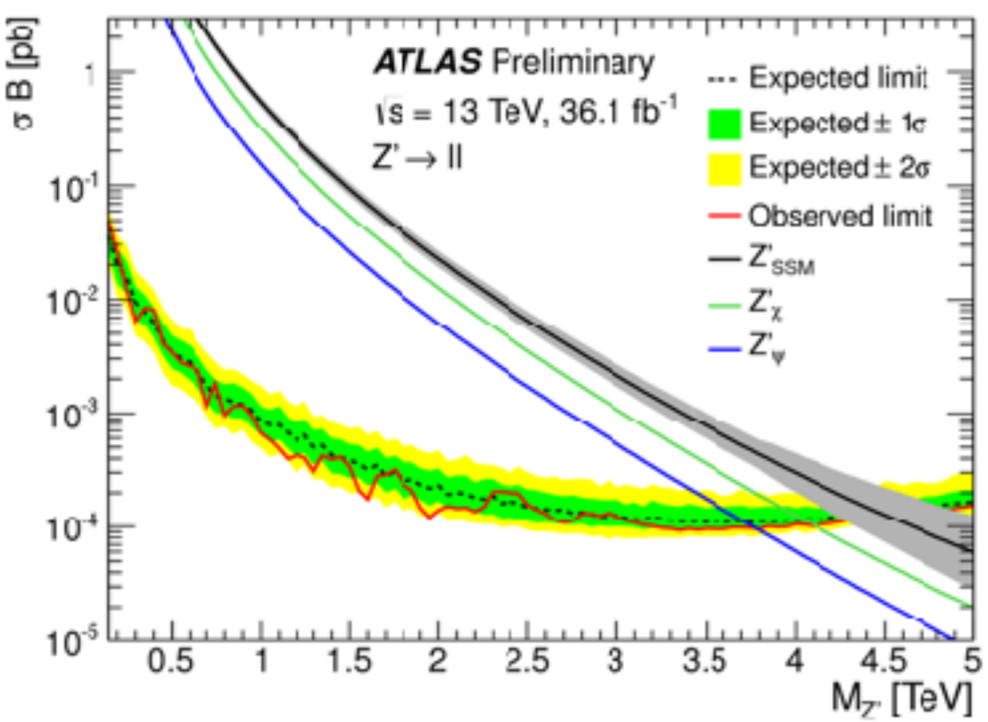


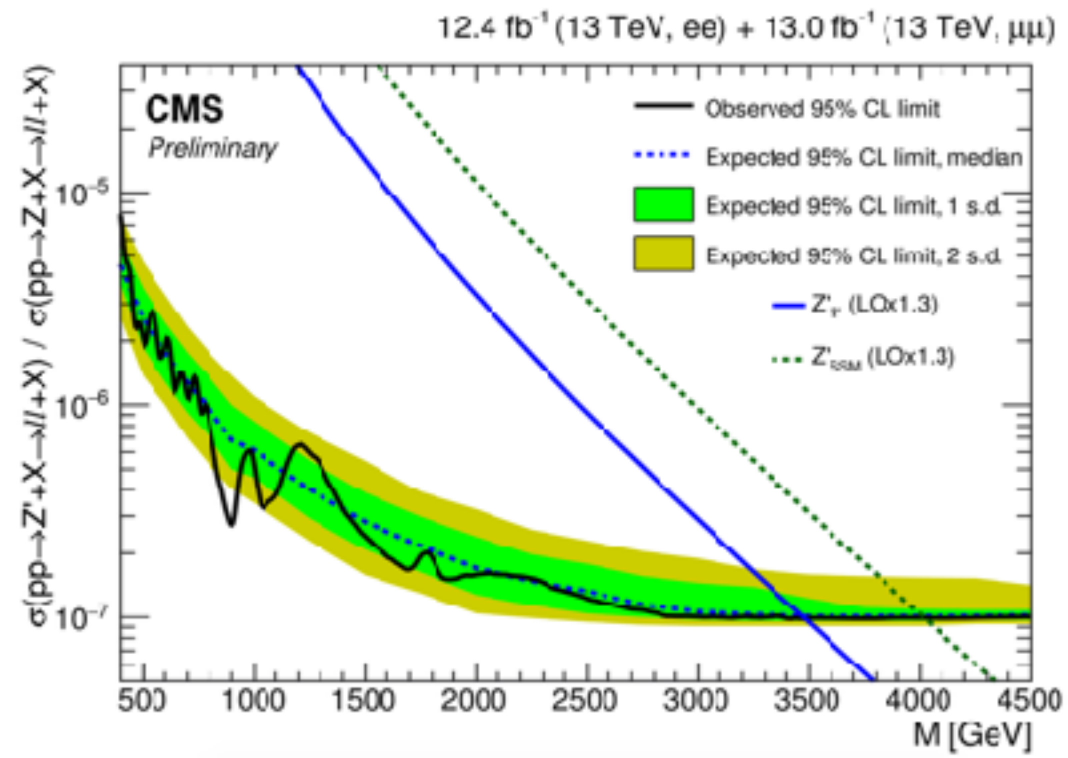
similar bounds for ATLAS

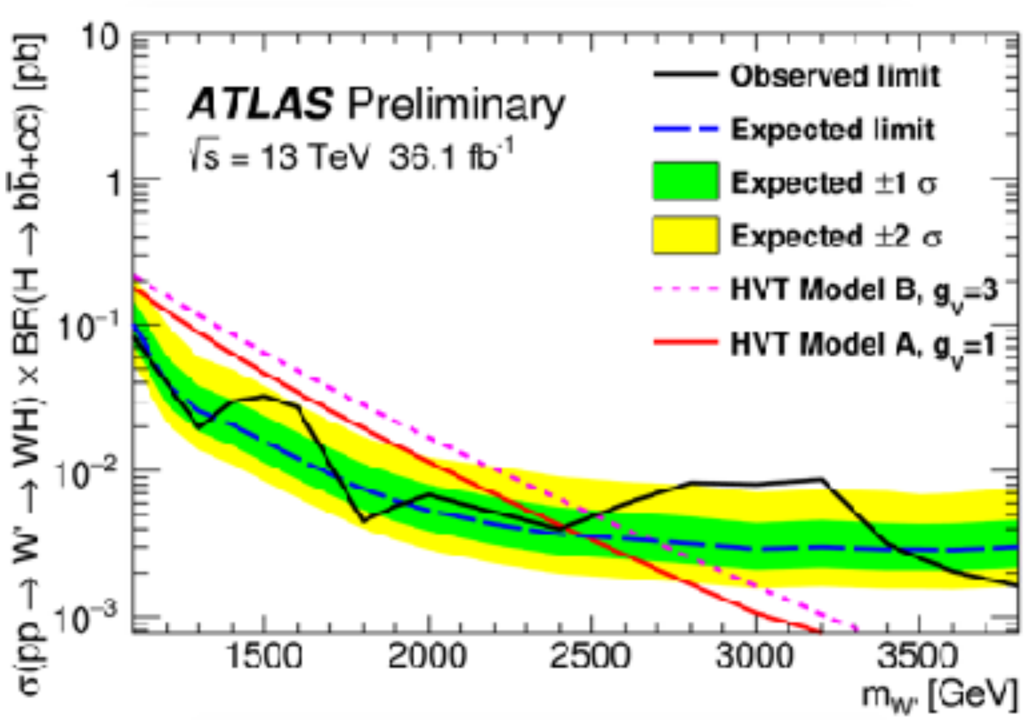
- excluded for masses < 1.5 TeV unconstrained for larger g_V
- di-boson most stringent
- in excluded region G_F , m_Z not reproduced

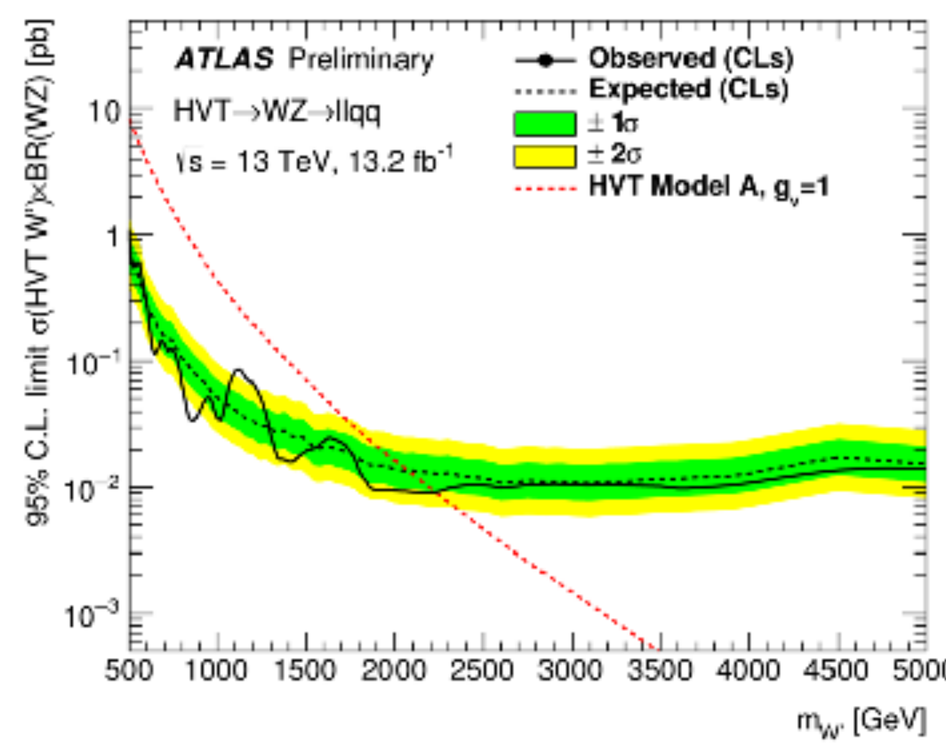
Heavy Vector Resonances

- many searches at 8 and 13 TeV





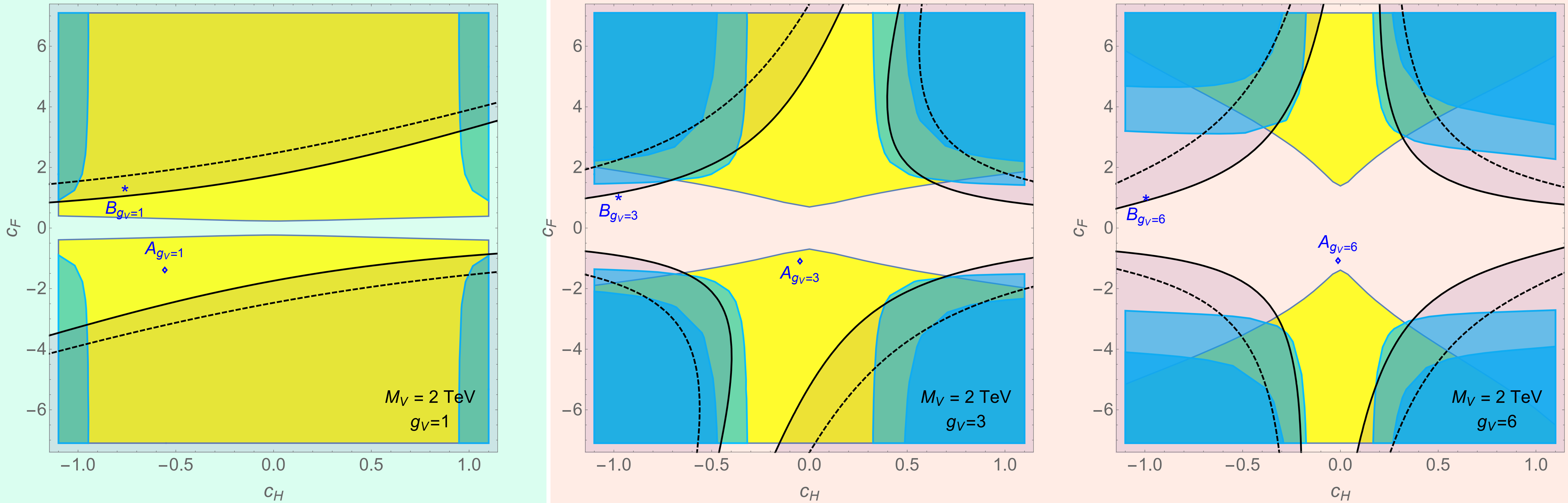




Limits on parameter space

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

- experimental limits converted into (c_H, c_F) plane



- $l\nu$ dominates
- EWPT not competitive
- only $-1 \lesssim c_F \lesssim 1$ allowed

- EWPT become comparable
- di-bosons more and more relevant
- strongly coupled model evades bounds from direct searches

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

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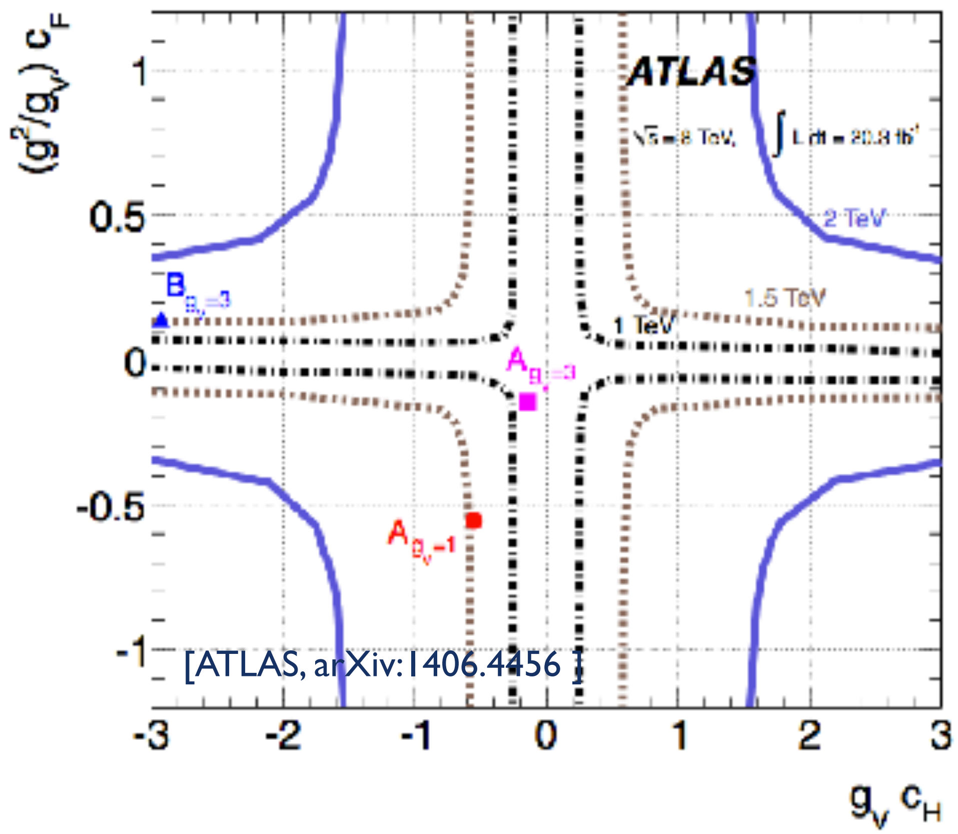
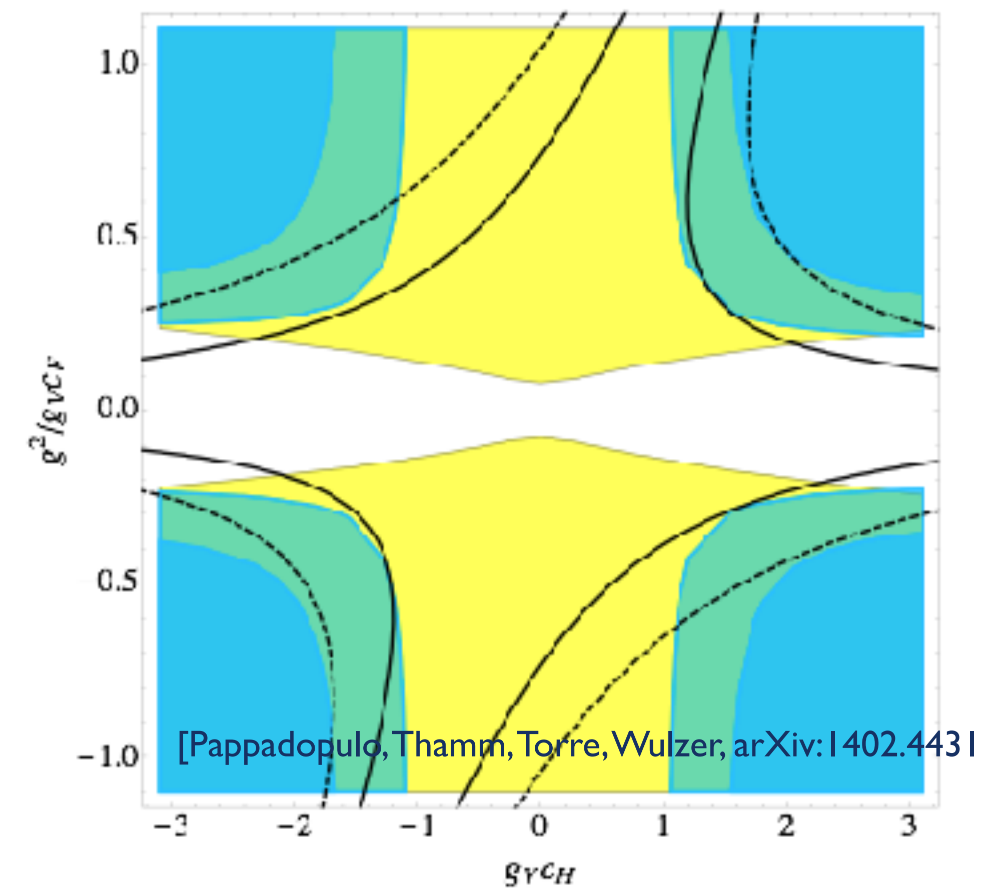
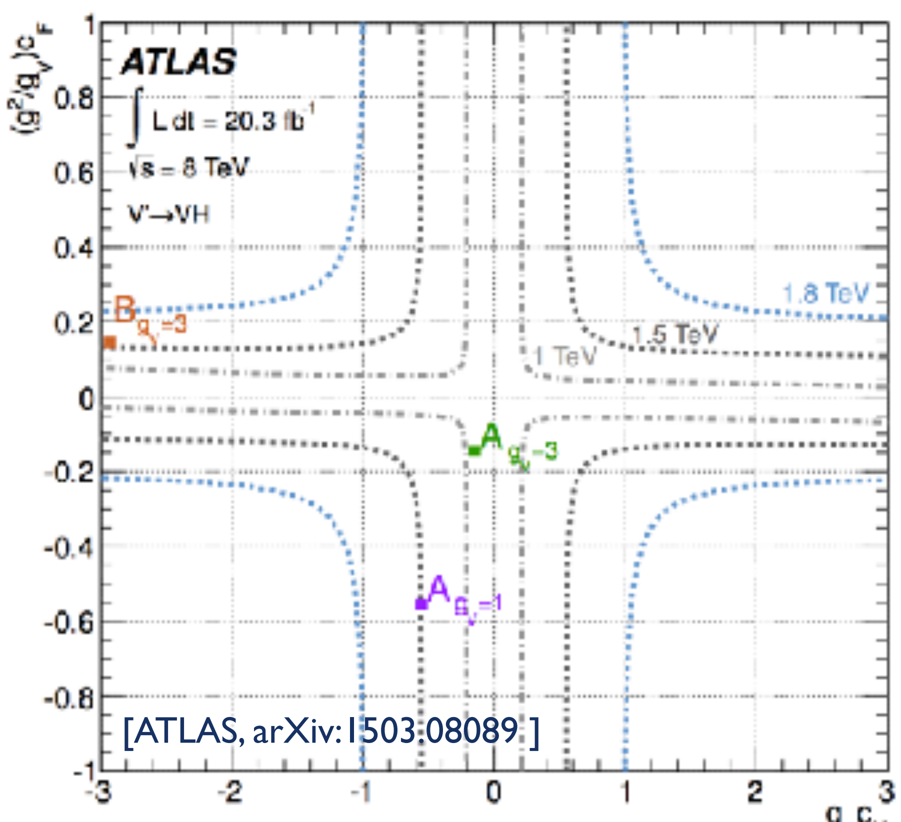
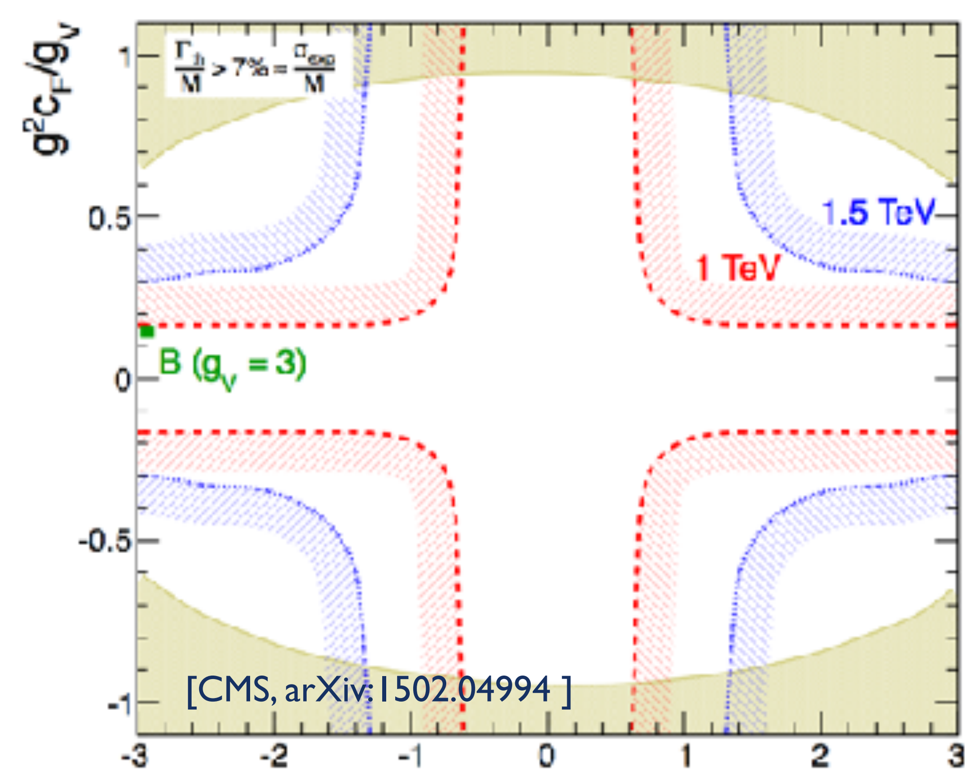


- ATLAS: W’ to WZ





- ATLAS: V’ to HV to (bb)(lep lep)
- CMS: Z’ to HZ to (tau tau)(qq)



Limits on parameter space

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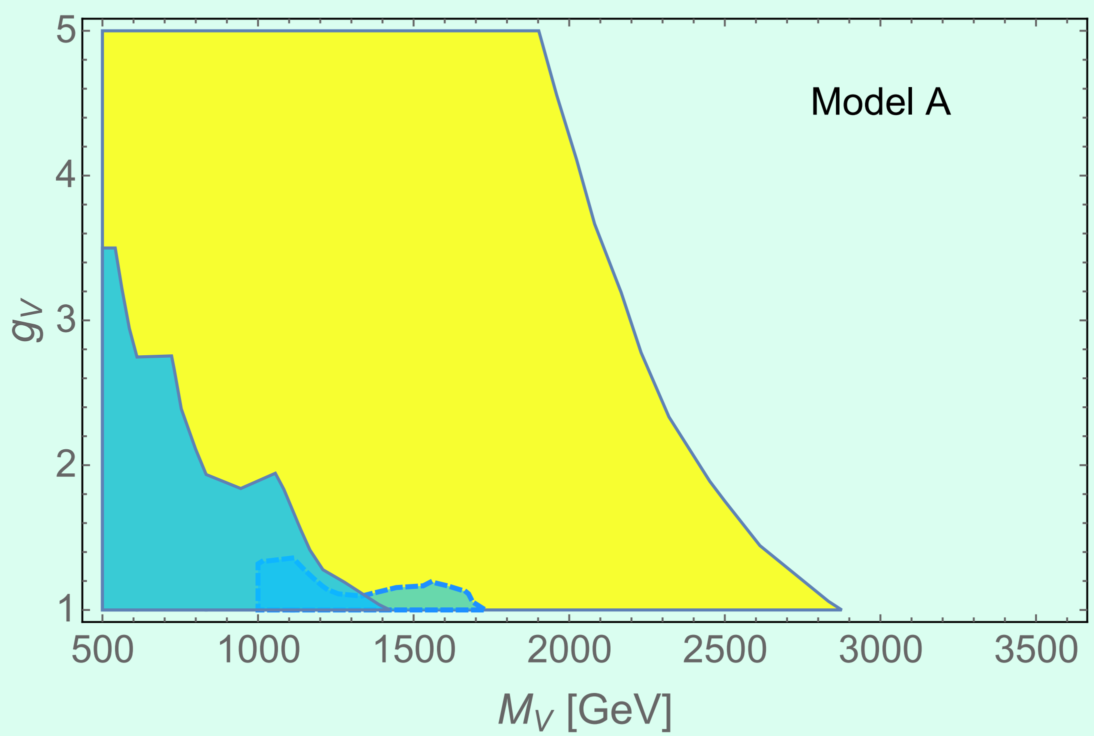
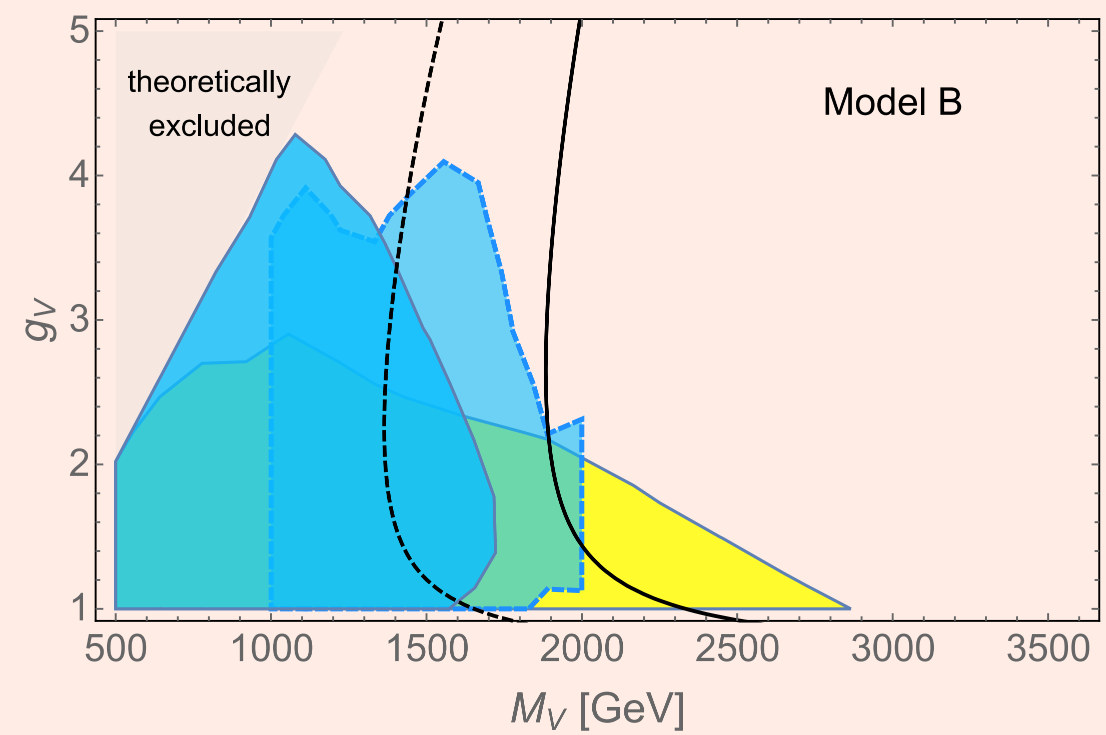
- compare with weakly coupled vectors

Weakly coupled model



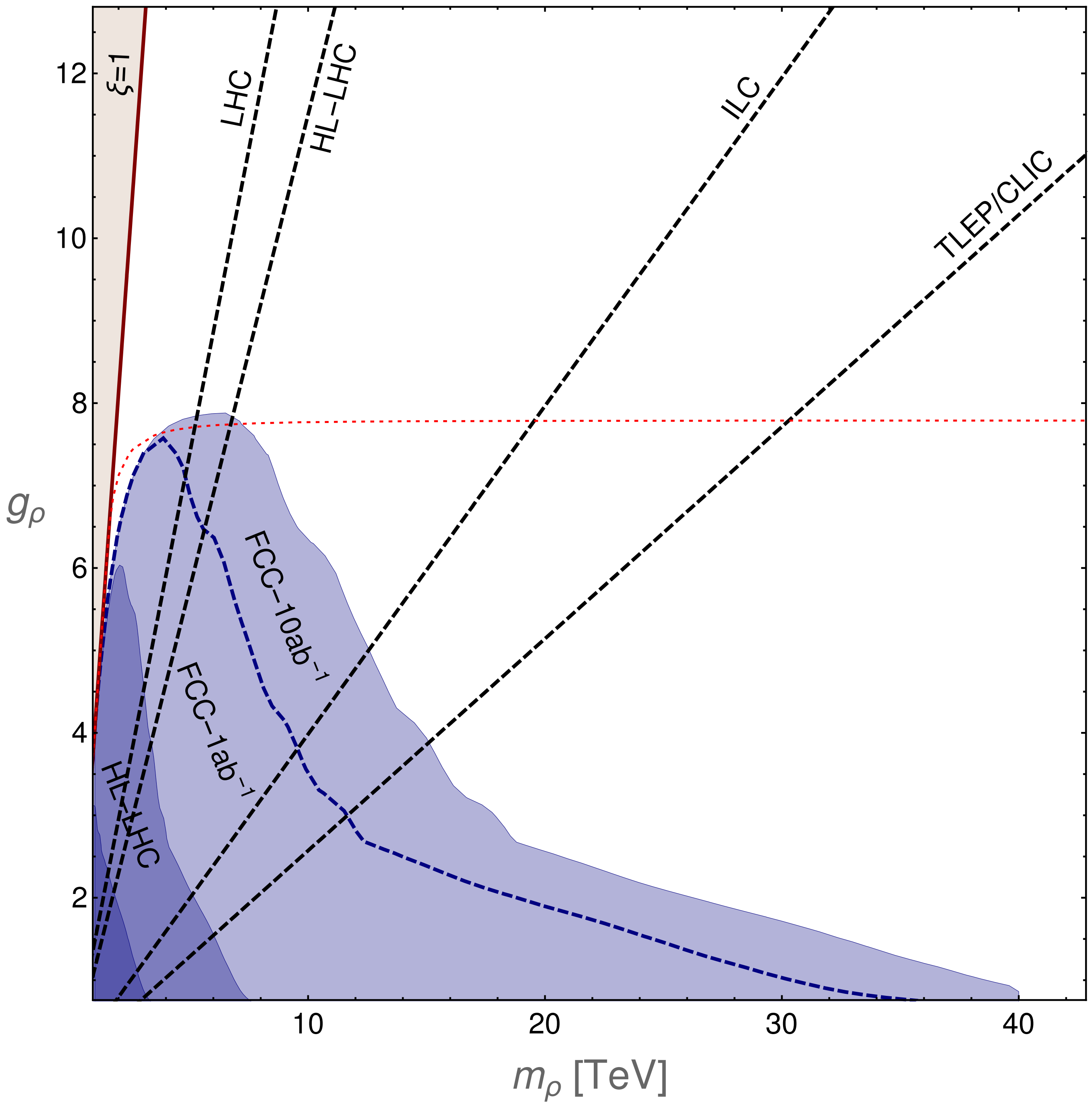
Strongly coupled model



- strongly coupled vectors have weaker bounds

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

HVT at Future Colliders



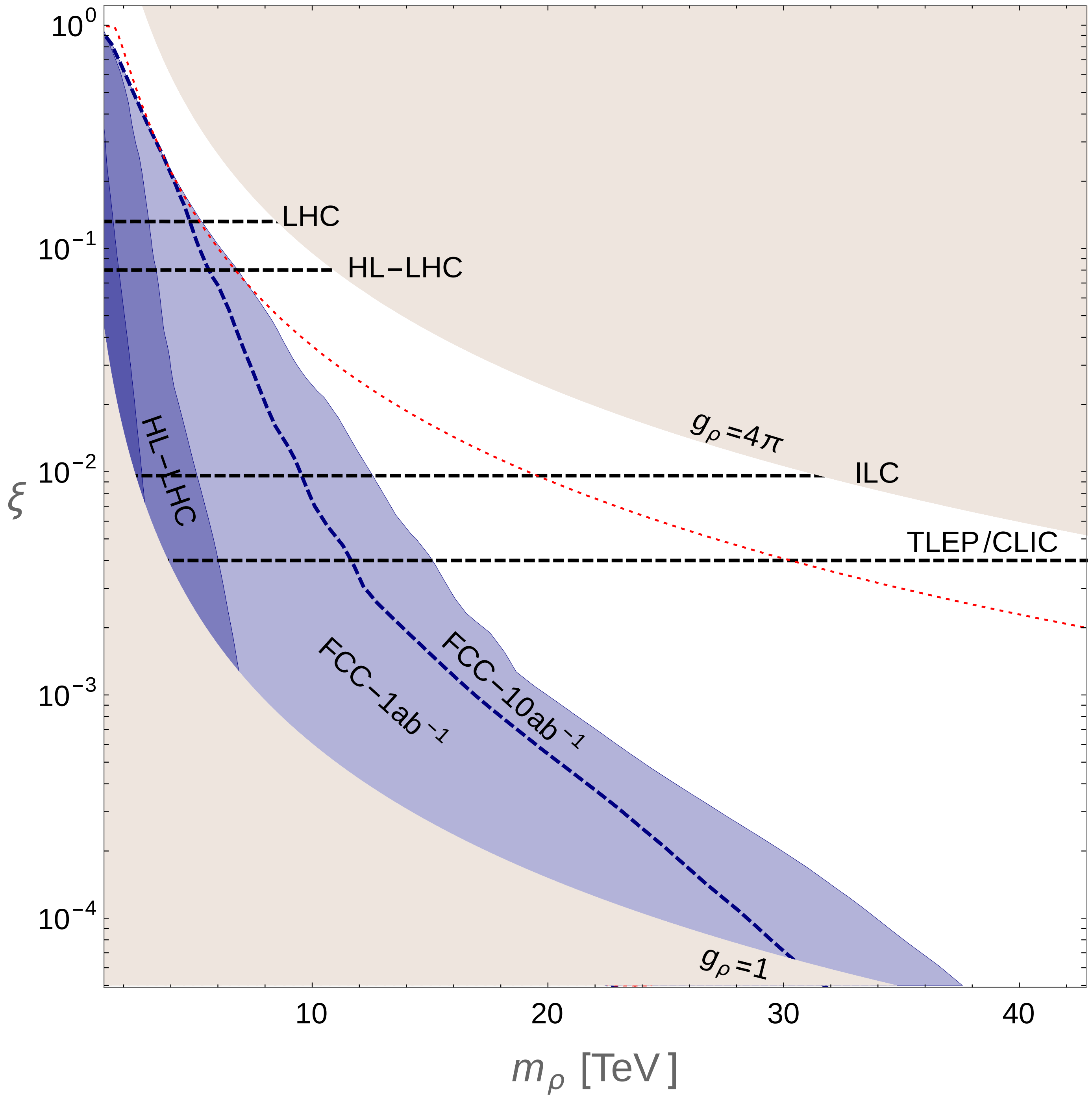
95% C.L.

- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}
  LHC at 14 TeV with 300 fb^{-1}
  HL-LHC at 14 TeV with 3 ab^{-1}
- di-leptons more sensitive for small g_ρ
- di-boson more sensitive for large g_ρ
- increase in $\sqrt{s}$: improves mass reach
- increase in L: improves g_ρ reach
- resonances too broad for large g_ρ

- direct: more effective for small g_ρ
  ineffective for large g_ρ
- indirect: more effective for large

[Thamm, Torre, Wulzer: 1502.01701]

HVT at Future Colliders



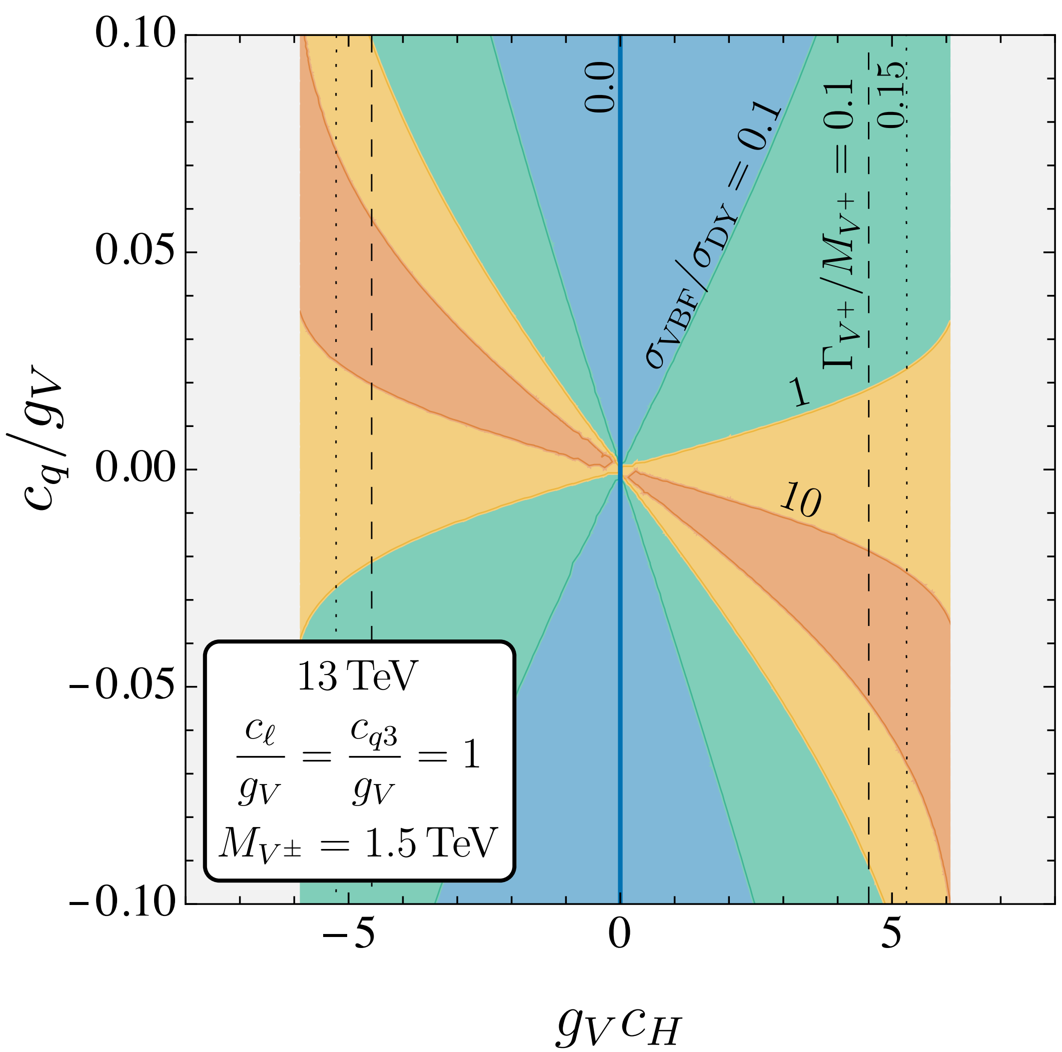
- theoretically excluded $1 \leq g_\rho \leq 4\pi$
- LHC8 at 8 TeV with 20 fb^{-1}
  HL-LHC at 14 TeV with 3 ab^{-1}

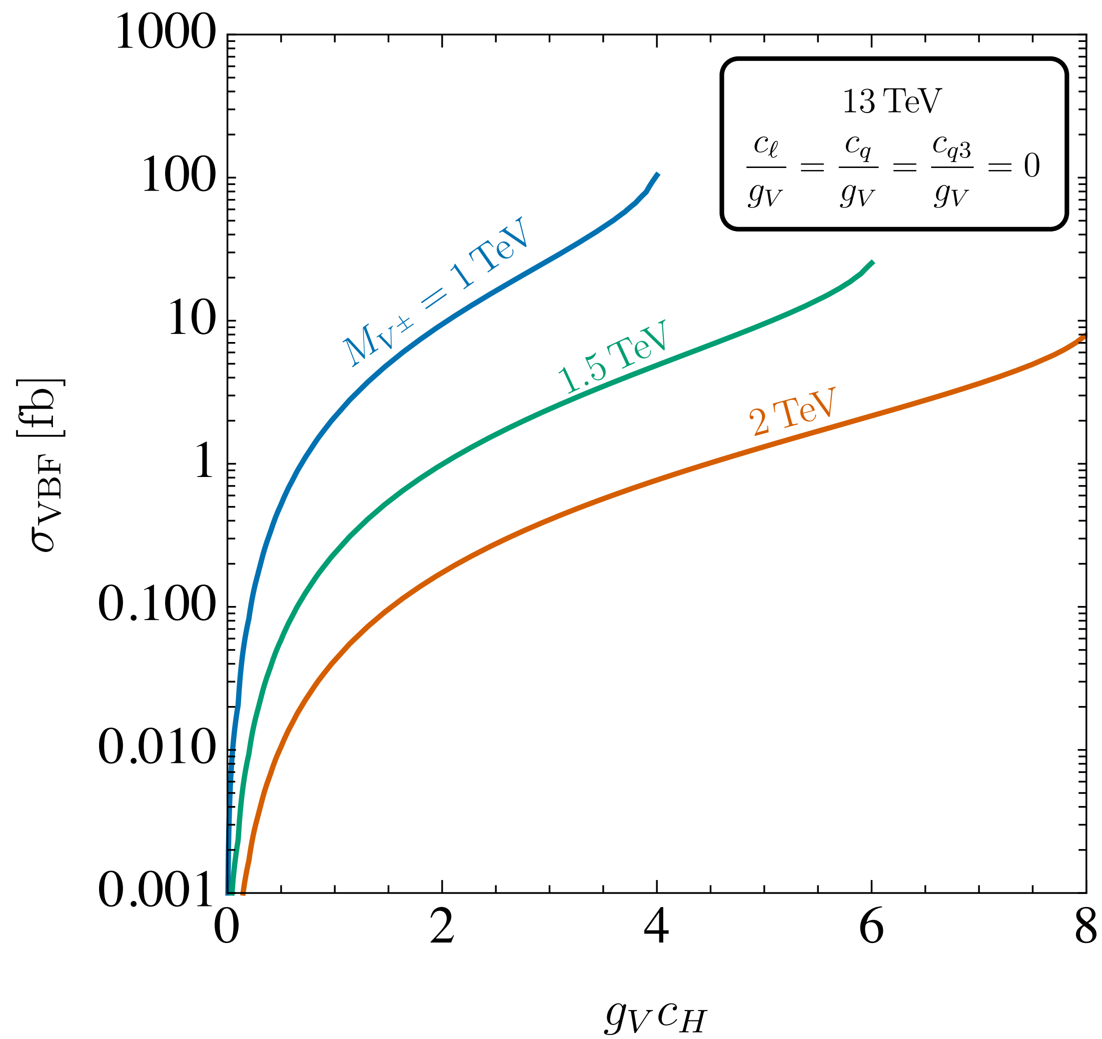
95% C.L.

[Thamm, Torre, Wulzer: 1502.01701]

HVT in VBF

- Some parameter regions can only be accessed via VBF





[Baker, Martonhelyi, Thamm, Torre, arXiv:2207.05091]

HVT in VBF

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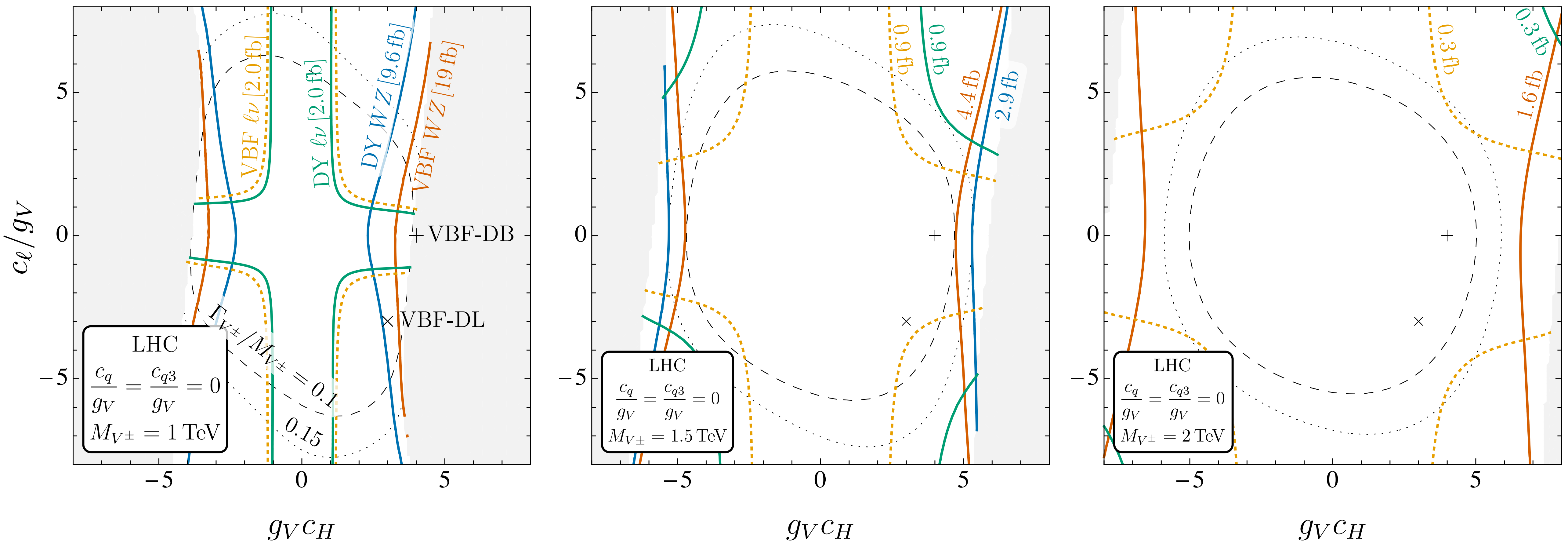
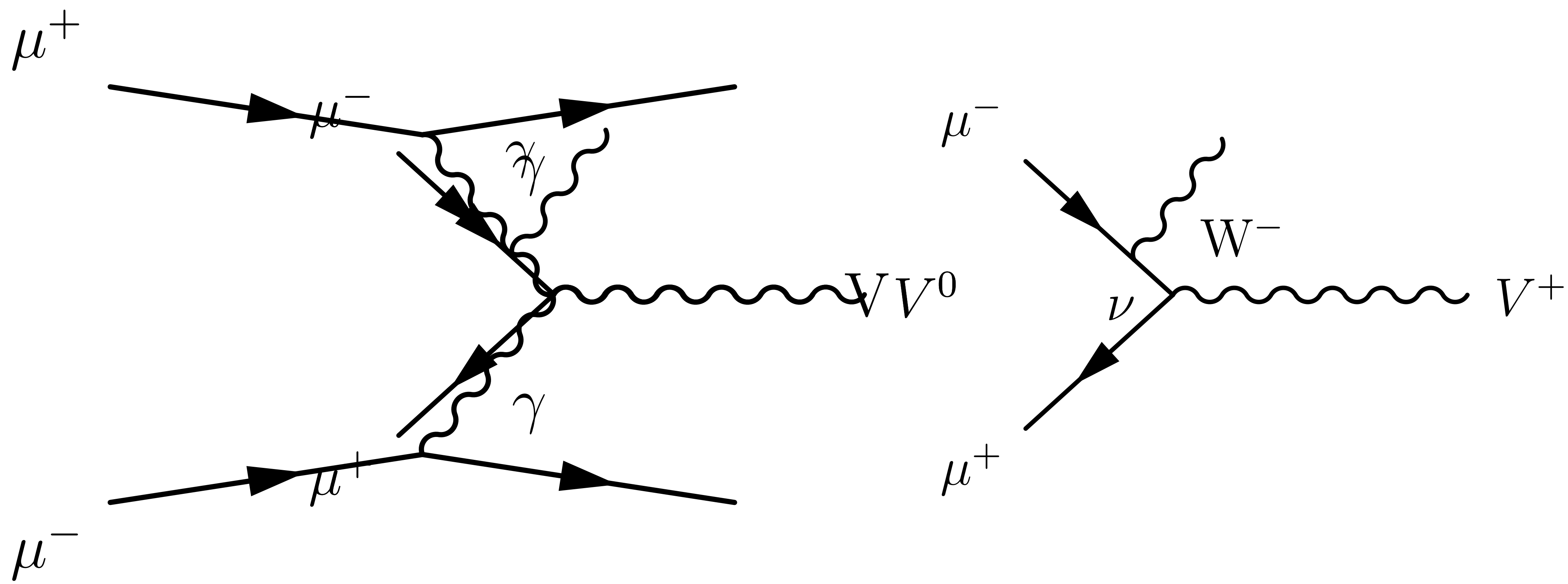


[Baker, Martonhelyi, Thamm, Torre, arXiv:2207.05091]

HVT at the Muon Collider

- Production via
  - Resonance production
  - Radiative return
  - Vector boson fusion



HVT at the Muon Collider

- Decay into all final states
  - Leptons, quarks
  - WW
  - Wh
- HVT is an ideal benchmark
  - Explore several production modes
  - Explore several decay modes

Conclusions

- Model independent framework to study heavy spin-1 triplets
- Captures weakly and strongly coupled extensions of the SM
- HVT is an ideal benchmark for the muon collider