Heavy Vectors: Bounds and Hopes

Based on **JHEP 1409 (2014) 060** and **arXiv:1506.0868**,
with A.Thamm and R. Torre

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Introduction

New heavy spin-1 resonances emerge in different contexts

New gauge forces

e.g.

Z's , LR models, W's, …

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"Composite" Vectors

Significant pheno. differences, but common framework

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The **Composite Higgs** picture for high energy physics

Two sectors exist at some Very High (>>TeV) scale Λ_{VH}:

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SM **minus** Higgs

$W_\mu^\alpha, B_\mu, f_{L,R}, \ldots$

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No fundamental Higgs.

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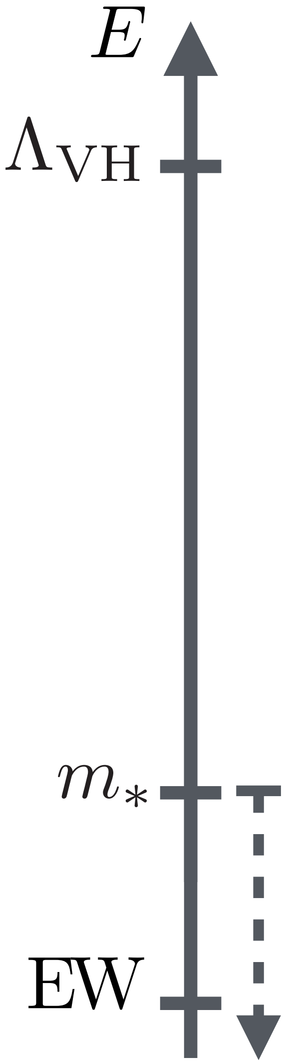

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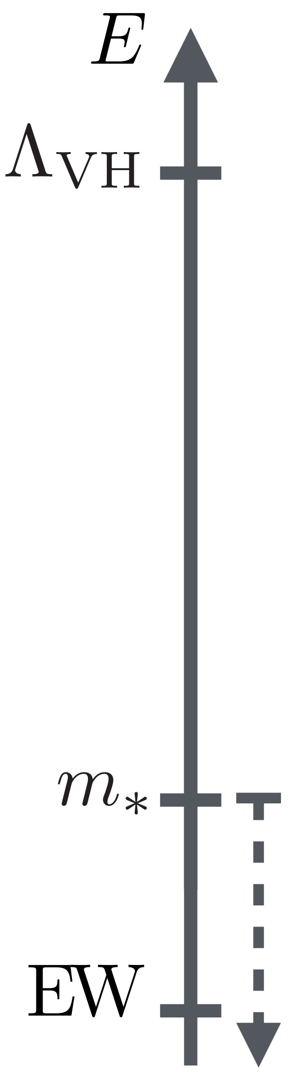

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According to the general tuning formula …

$$\Delta \geq \left(\frac{\Lambda_{\rm SM}}{500\,\mathrm{GeV}}\right)^2 = \left(\frac{m_*}{500\,\mathrm{GeV}}\right)^2$$

… **Naturalness** requires m_* to be below around the TeV.

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The **Composite Higgs** picture, some more details

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SM **gauge fields:** $W_\mu^\alpha, \, B_\mu$**.**

Coupled by **gauging.**

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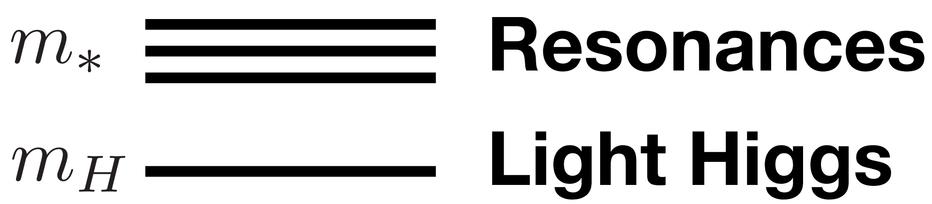

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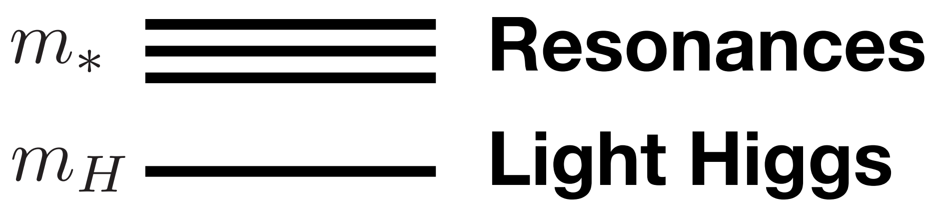

The Higgs particle is **not** a **generic** “hadron”:

1. $m_H \ll m_* \sim \text{TeV}$
2. Has ~ SM couplings

Behaves as coming from the SM Higgs **doublet**

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m_H **Light Higgs**

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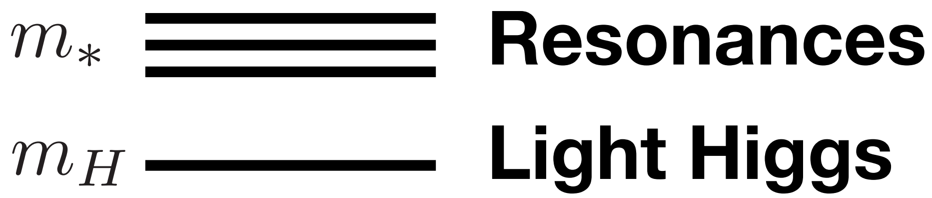

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Goldstone nature not assumed in this talk. Only **doublet**

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If Partial Compositeness, the **CS carries QCD color:**

$$\mathcal{G} \supset \mathrm{SU}(3)_c \Rightarrow J_\mu^{\mathcal{G}} \supset \mathbf{8}$$ **= KK-gluon**

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CS interactions obey a **power-counting rule:**

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Notice: $g < g_* < 4\pi$. **Strongest** coupling in the theory

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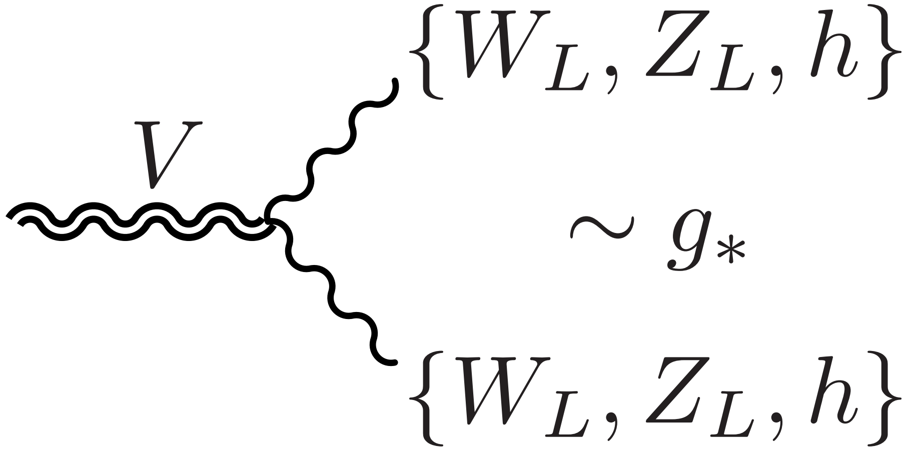
by Equivalence Theorem



strong coupling to vector bosons and Higgs

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Instead, V interaction with W is:

$$\frac{m_*^4}{g_*^2}\frac{g_* g}{m_*^4} D_{[\mu} V_{\nu]}^a W_a^{\mu\nu} = \frac{g}{g_*} D_{[\mu} V_{\nu]}^a W_a^{\mu\nu}$$

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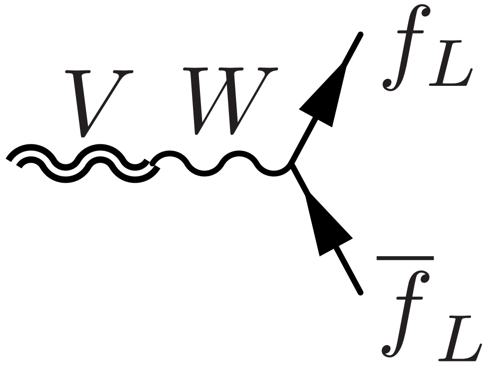
a V—W **mixing**, generates couplings such as



$$\sim \frac{g}{g_*} \cdot g = \frac{g^2}{g_*}$$

weak universal fermion couplings

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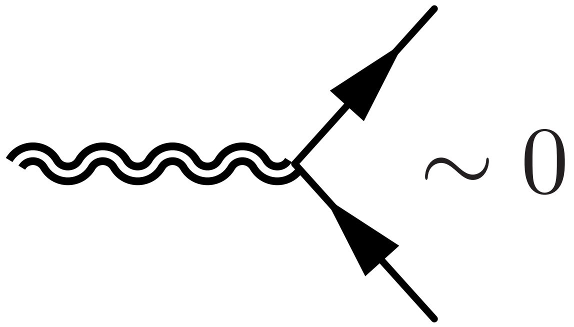

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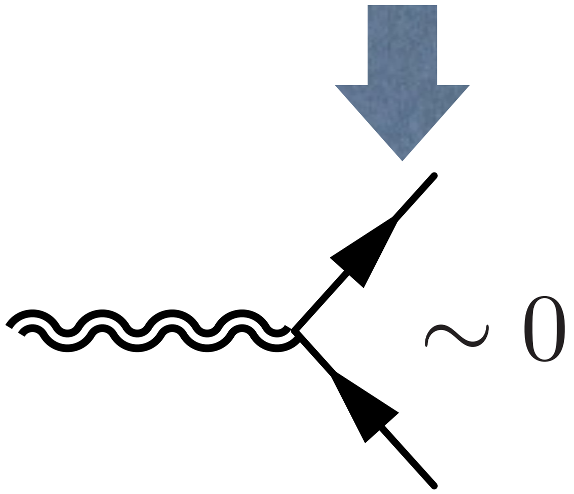

Sizeable direct coupling instead possible to $t,\ b$.

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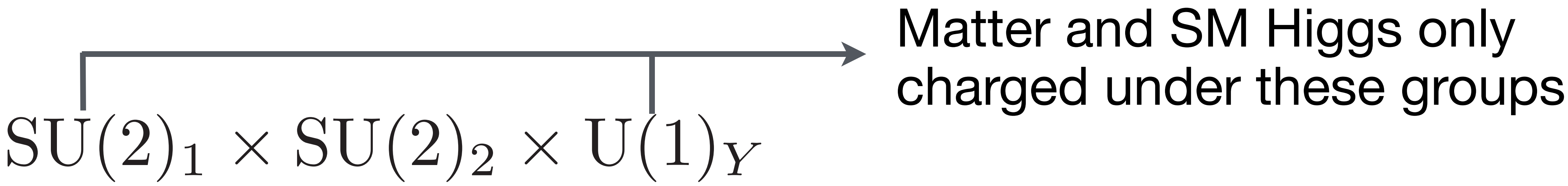
A popular “Elementary” model: (**Barger et.al.,** Phys.Rev. D22 (1980) 727)



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Matter and SM Higgs only charged under these groups

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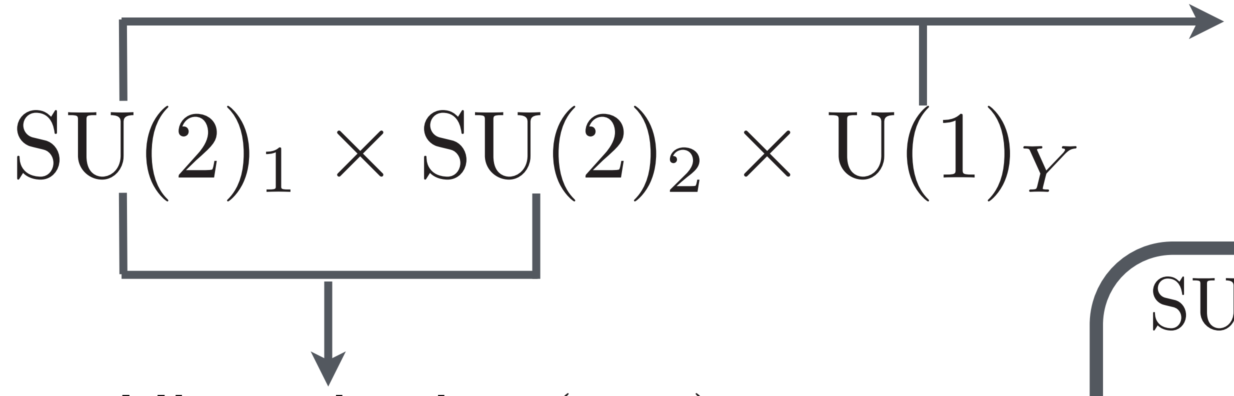

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Heavy Higgs in the $(\mathbf{2},\mathbf{2})$ breaks this to diagonal

$$\mathrm{SU}(2)_L = [\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2]_D$$

$$W = \frac{g_2 W_1 + g_1 W_2}{\sqrt{g_1^2 + g_2^2}} \qquad \frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

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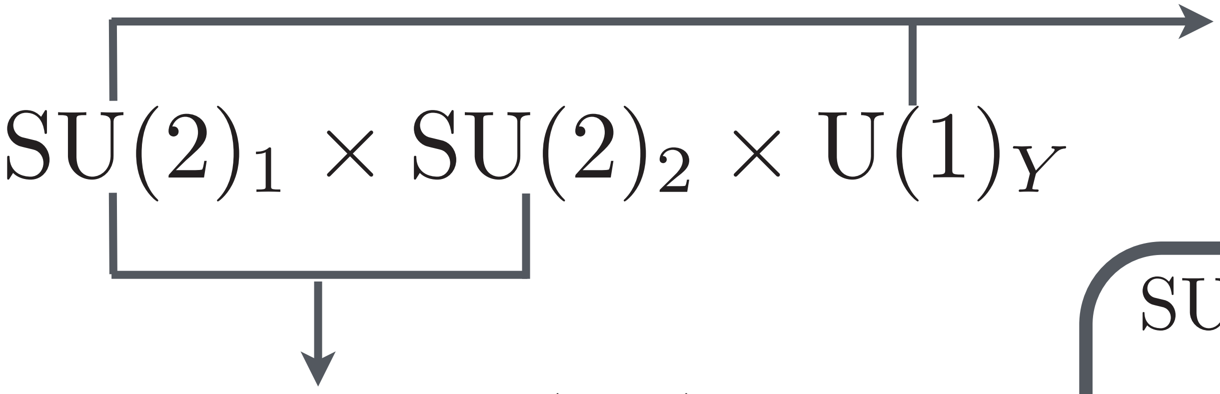

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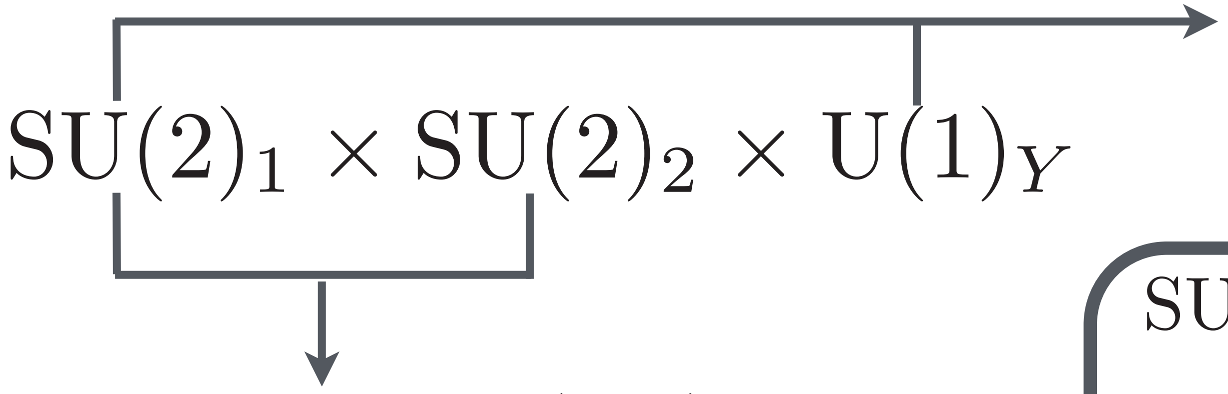

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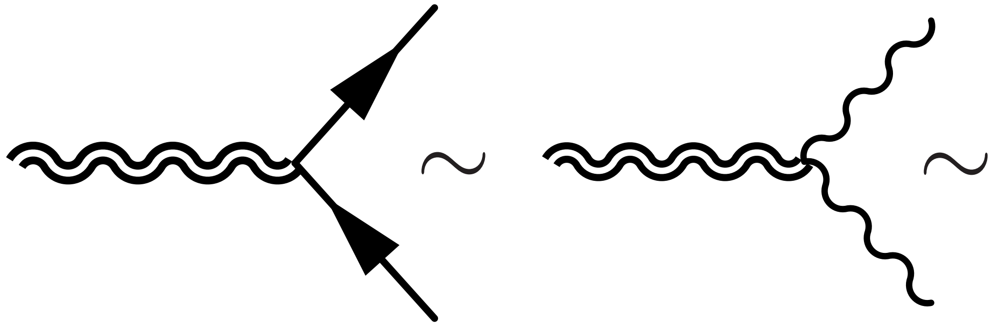

$\sim$ $\sim g \cdot \frac{g_1}{g_2}$

Higgs and fermions with same couplings. Potentially weak.

The HVT Framework

Elementary or Composite, general Triplet Lagrangian is:

(kinetic mixing eliminated by field redefinition)

$$-\frac{1}{4}D_{[\mu}V^a_{\nu]}D^{[\mu}V^{\nu]\,a}+\frac{m_V^2}{2}V^a_\mu V^{\mu\,a}$$

$$+\,i\,g_V c_H V^a_\mu H^\dagger\tau^a \overleftrightarrow{D}^\mu H+\frac{g^2}{g_V}c_F V^a_\mu J^{\mu\,a}_F$$

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

The HVT Framework

Elementary or Composite, general Triplet Lagrangian is:

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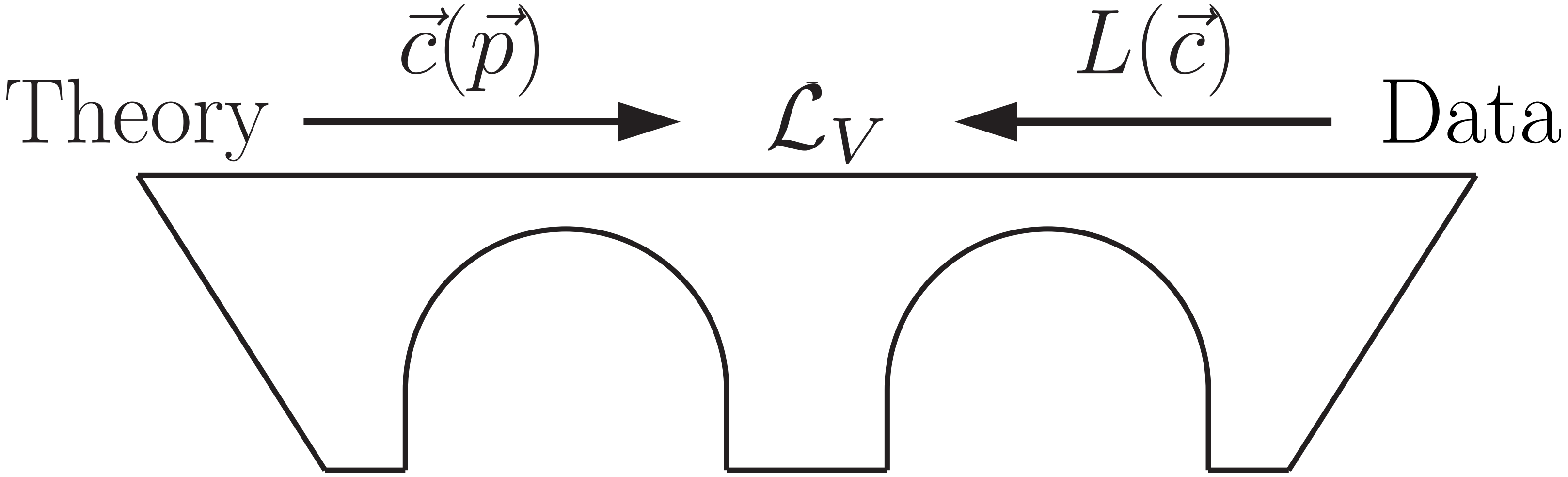

$$\text{Theory} \xrightarrow{\vec{c}(\vec{p})} \mathcal{L}_V \xleftarrow{L(\vec{c})} \text{Data}$$

Limits (or discoveries!) on HVT parameters immediately translated in any explicit model.

The HVT Framework

Elementary or Composite, general Triplet Lagrangian is:

(kinetic mixing eliminated by field redefinition)

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

Basic phenomenological viability (e.g. $\delta\rho < 1\%$) implies:

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$$

$$
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$$

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

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

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3. $\Gamma[V_0 \to W^+W^-] \simeq \Gamma[V_0 \to Zh] \simeq \Gamma[V_\pm \to W^\pm Z] \simeq \Gamma[V_\pm \to W^\pm h]$
4. Terms in the **last line** have **little impact** on the phenomenology

The HVT Framework

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$$-\frac{1}{4} D_{[\mu} V_{\nu]}^a D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a}$$

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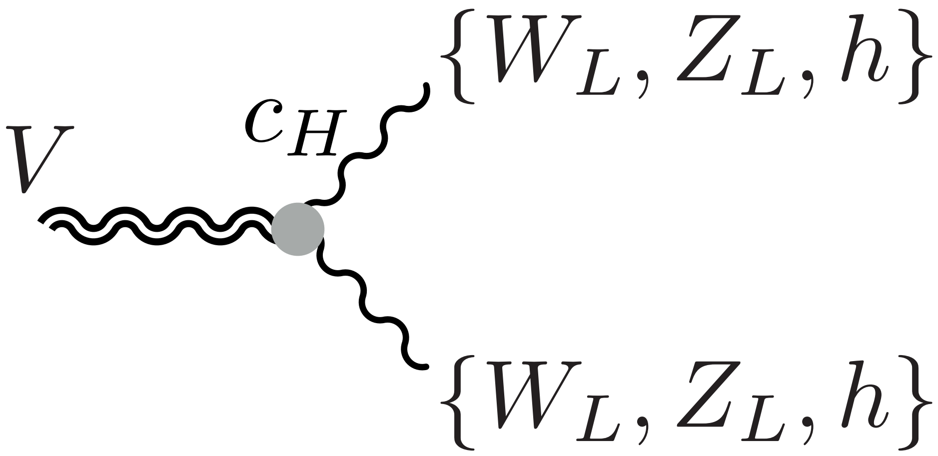
$$+\cancel{\frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW}\, \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c}$$

Controls decay to longitudinal W,Z and Higgs:



Correlated VB and Higgs channels

The HVT Framework

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(kinetic mixing eliminated by field redefinition)

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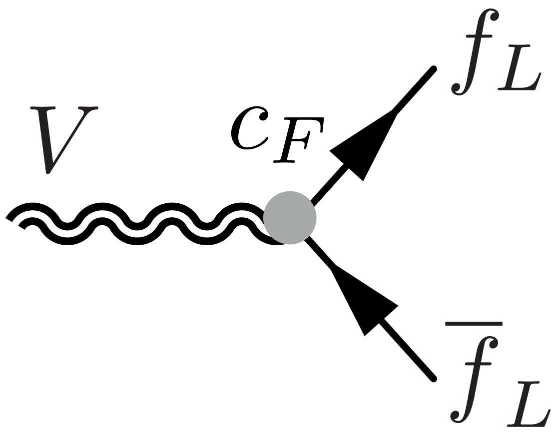
~~$$+\frac{g_V}{2}c_{VVV}\,\epsilon_{abc}V_\mu^a V_\nu^b D^{[\mu}V^{\nu]\,c}+g_V^2 c_{VVHH}V_\mu^a V^{\mu\,a}H^\dagger H-\frac{g}{2}c_{VVW}\epsilon_{abc}W^{\mu\nu\,a}V_\mu^b V_\nu^c$$~~

Controls **production, 2-lepton, 2-jet** and **3rd fam. decays**



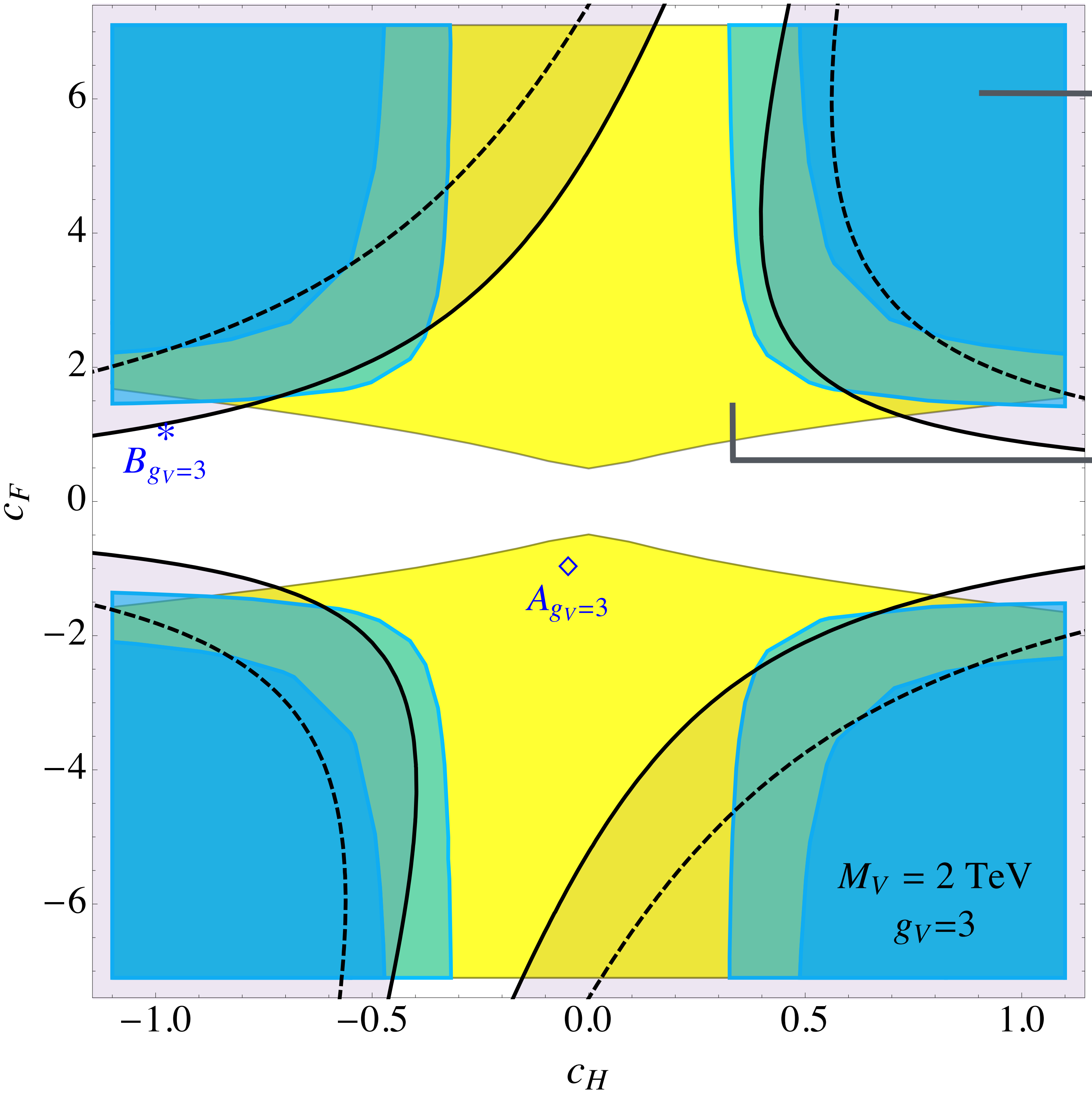
in full generality:

$$c_F \to \{c_l, c_q, c_3\}$$

Equal in what follows, but 3rd fam. deserves further studies

The HVT Framework

Example: (our recast)



WZ final state hadronic and leptonic searches.

2-lepton (lν) search

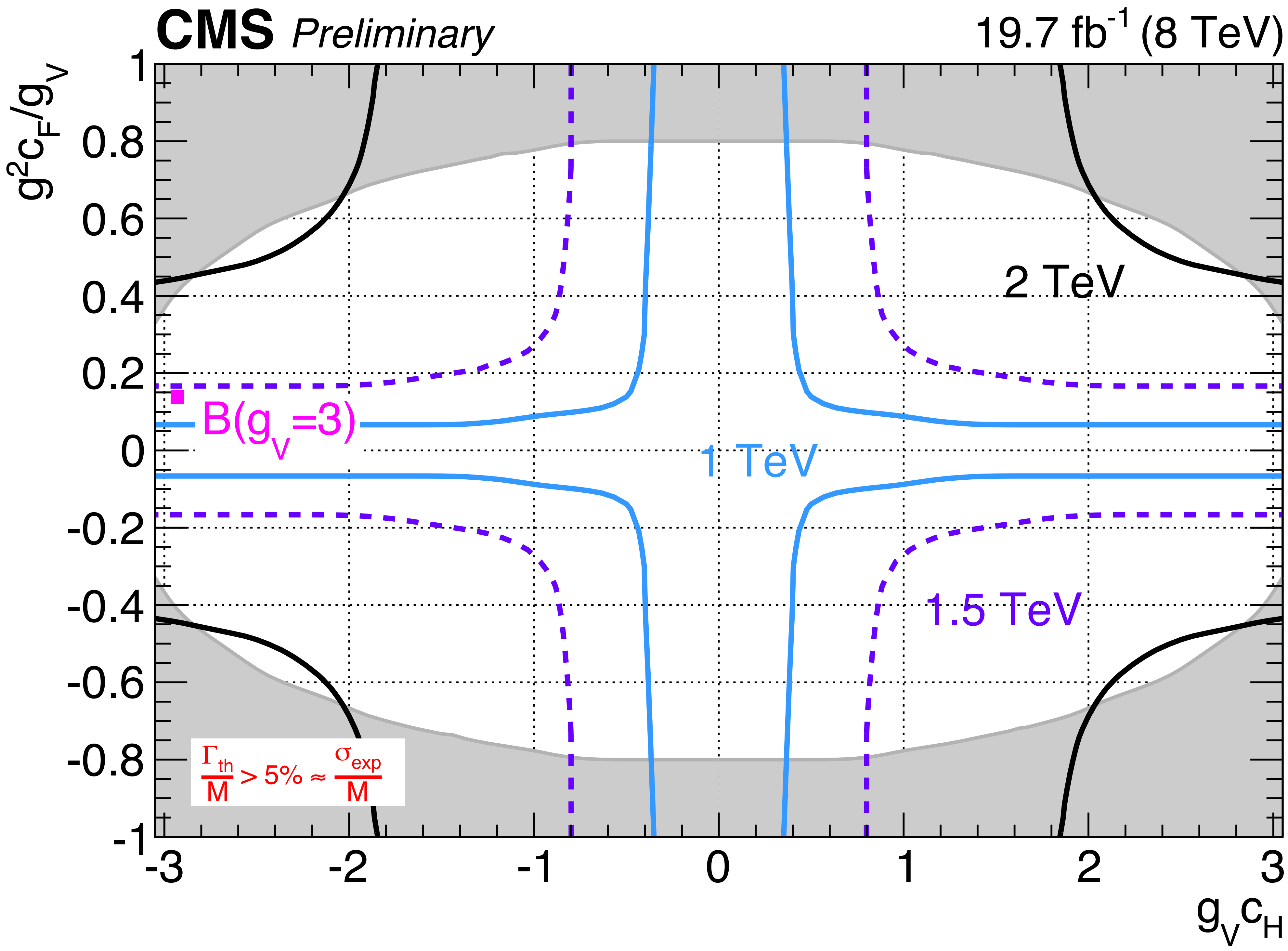
Model A = Elementary

Model B = Composite

(Contino et. al. **JHEP 1110 (2011) 081**)

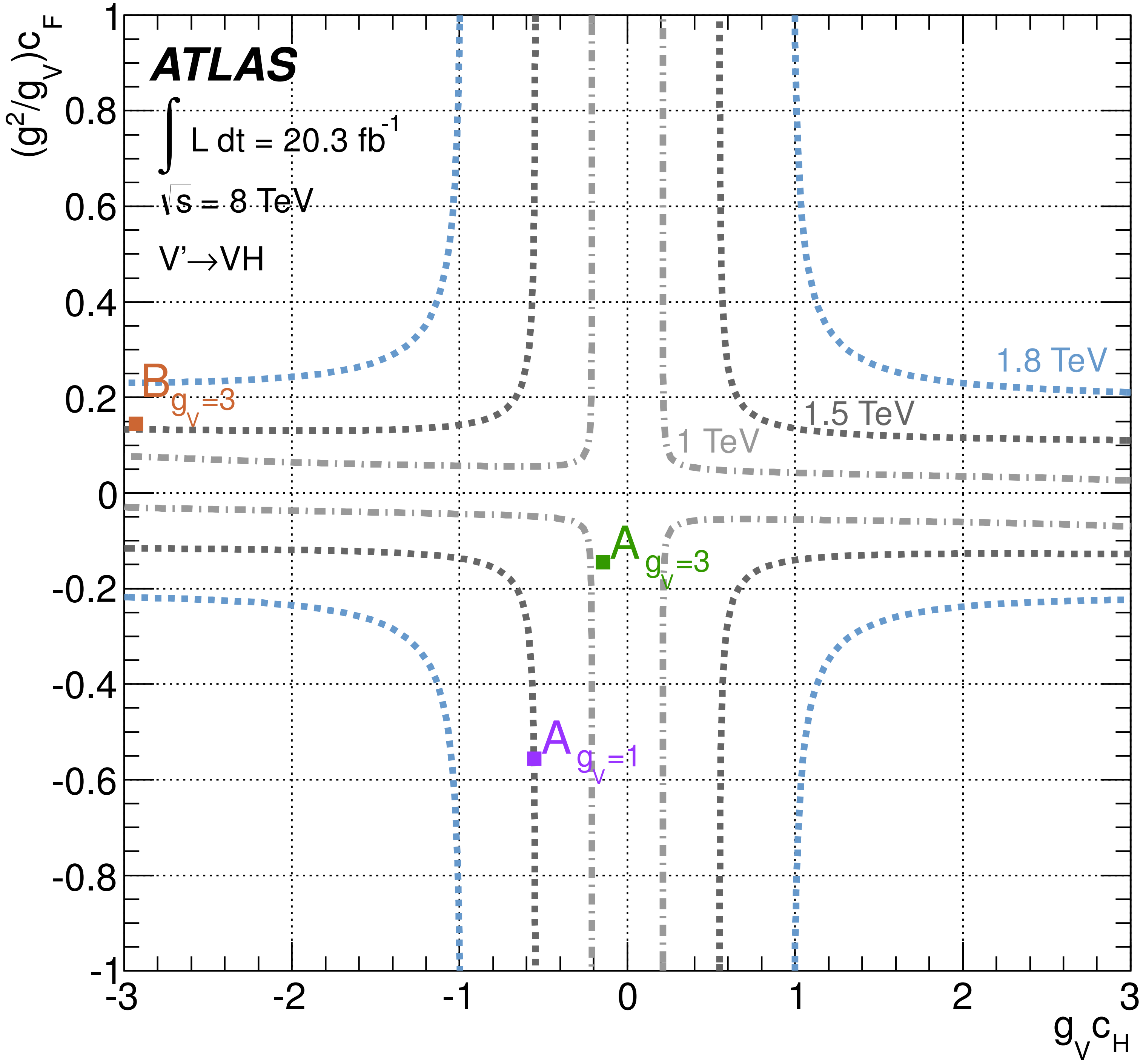
The HVT Framework

From the collaborations: $W_{lep}H_{b\bar{b}}$ (CMS PAS EXO-14-010)



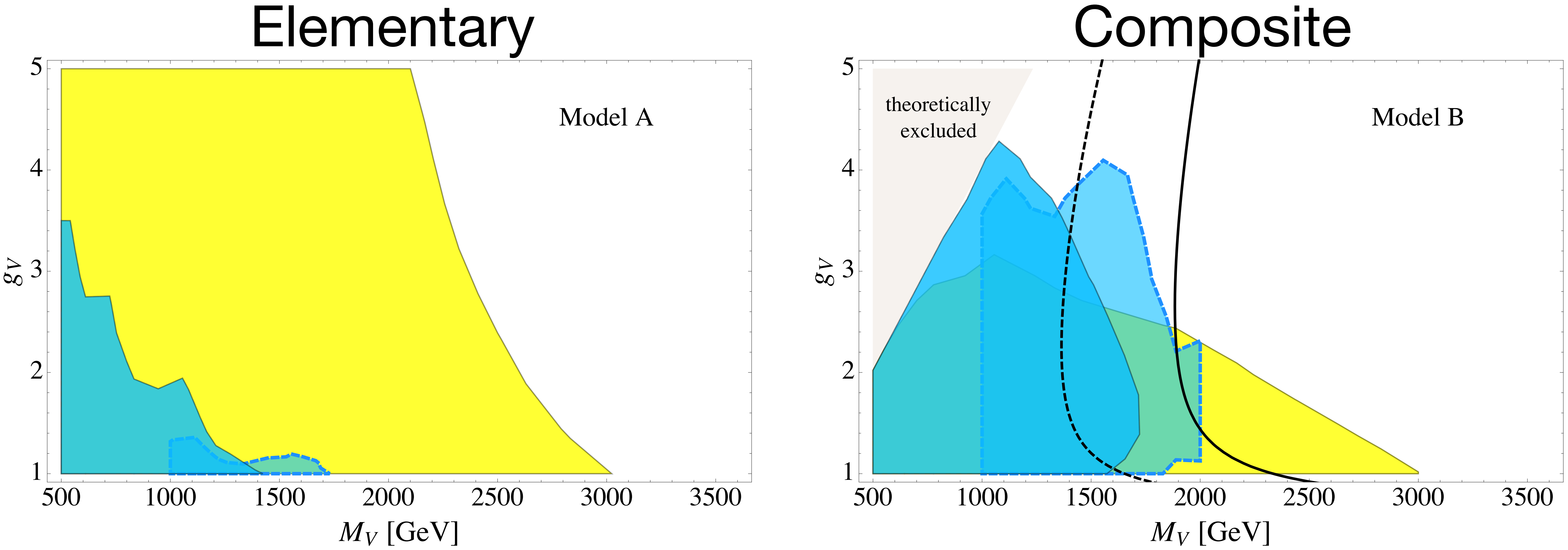
The HVT Framework

From the collaborations: $W_{lep}/Z_{lep}H_{b\bar{b}}$ (ATLAS 1503.08089)



The HVT Framework

Elementary/Composite comparison



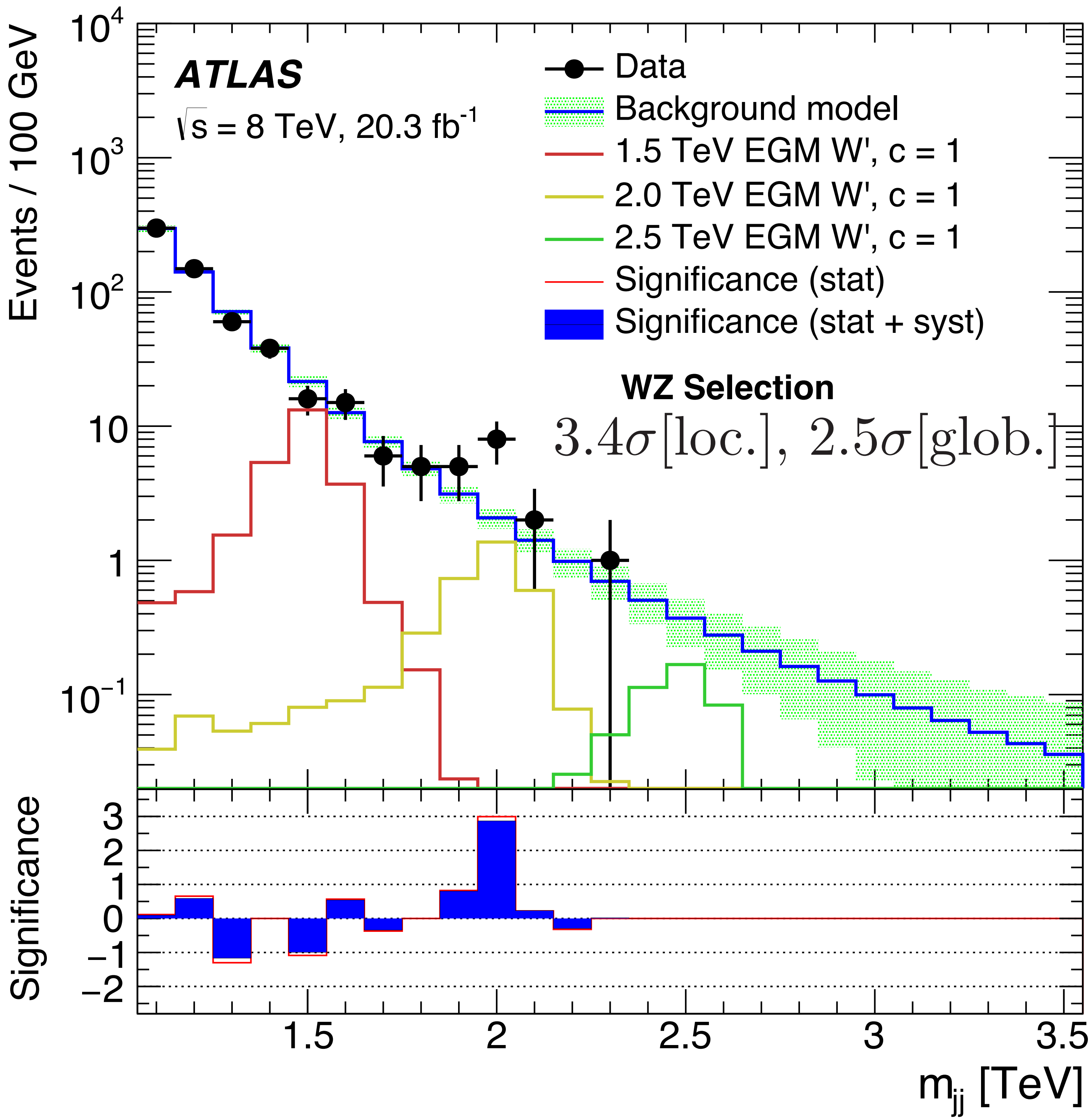
“Natural” region poorly explored in the Composite case

Hopes

Could a triplet explain this?

Boosted hadronic vector bosons, 1W + 1Z selection.

Not even try with the Elementary triplet (2-lep bound). Try Model B



$3.4\sigma[\text{loc.}],\ 2.5\sigma[\text{glob.}]$

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Could a triplet explain this?

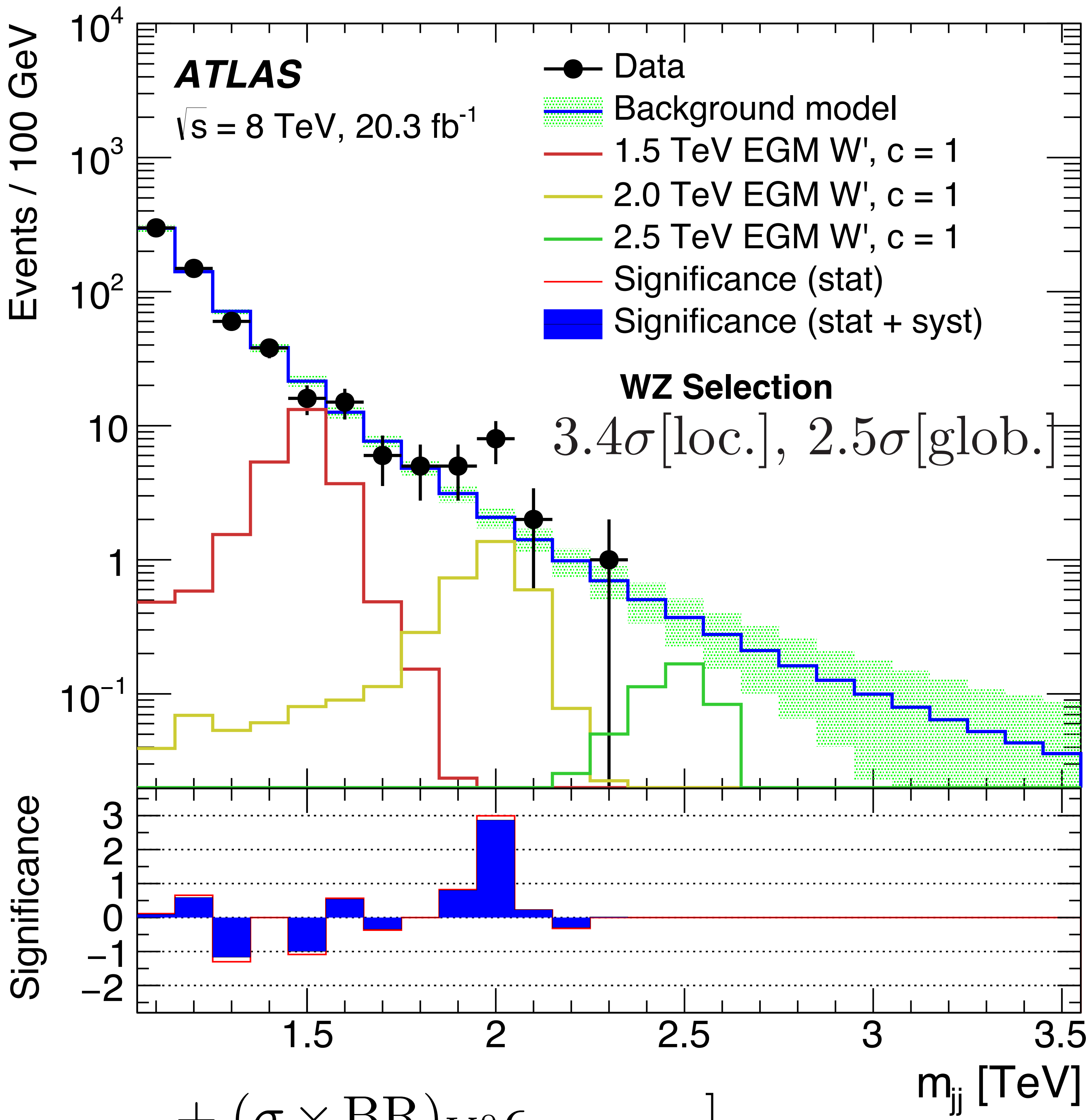
Boosted hadronic vector bosons, 1W + 1Z selection.

Not even try with the Elementary triplet (2-lep bound). Try Model B

Accounting for events in excess, with their stat. error, requires:

m_V [TeV]	g_V	$(\sigma\times\mathrm{BR})_{V^\pm}$ [fb]	$(\sigma\times\mathrm{BR})_{V^0}$ [fb]
1.8	$3.95^{+1.65}_{-0.88}$	4.51	2.04
1.9	$3.37^{+1.63}_{-0.83}$	4.63	2.09
2.0	$2.81^{+1.54}_{-0.82}$	4.79	2.16

Mass-range chosen on the basis of jet-jet mass uncertainty



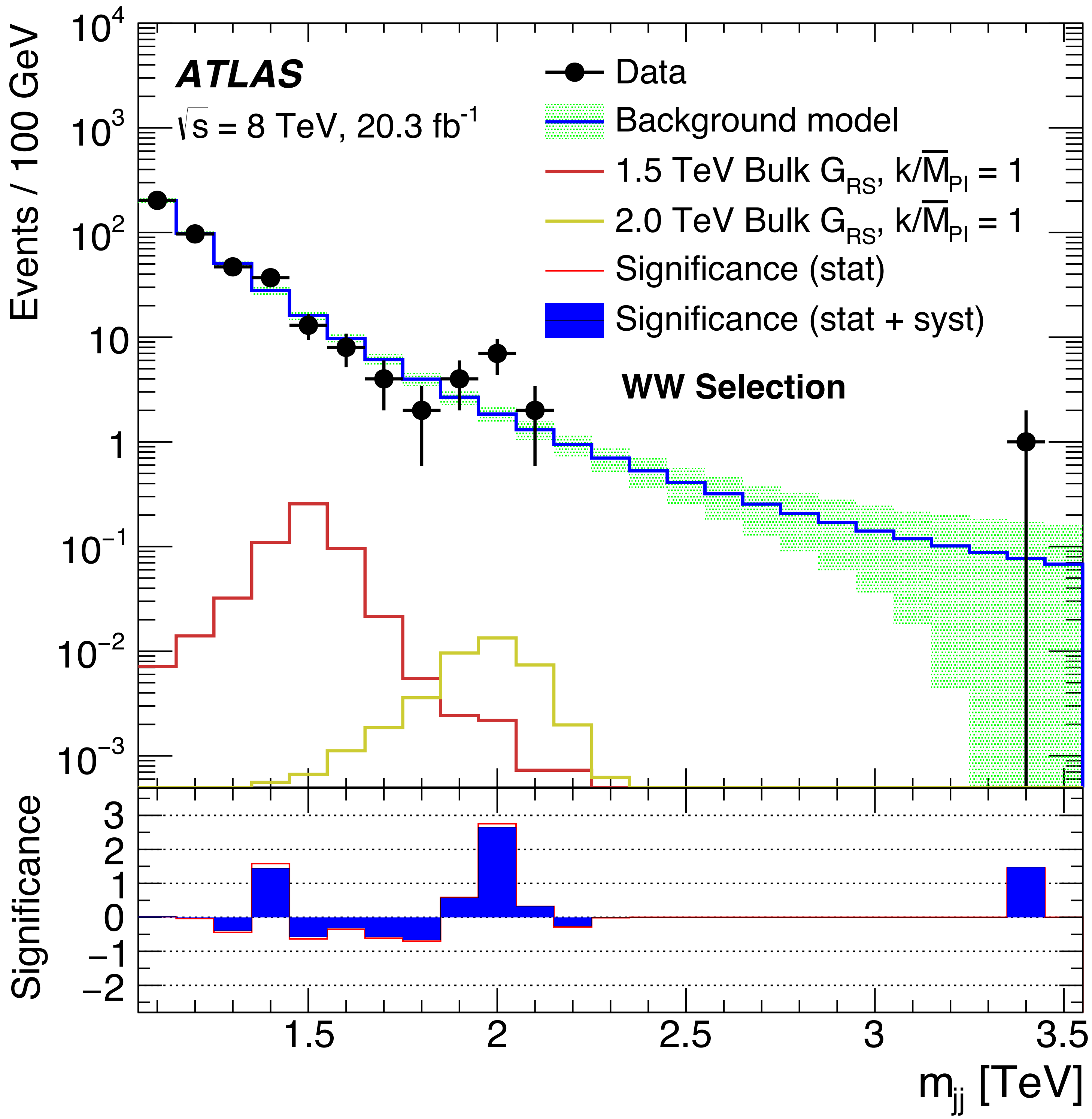
$3.4\sigma[\mathrm{loc.}],\ 2.5\sigma[\mathrm{glob.}]$

$$S_{WZ} = \mathcal{L}\,\mathcal{A}\left[(\sigma\times\mathrm{BR})_{V^\pm}\epsilon_{WZ\to WZ} + (\sigma\times\mathrm{BR})_{V^0}\epsilon_{WW\to WZ}\right]$$

Hopes

Could a triplet explain this?

Compatible with other selections (less performant, mainly WZ sign.)

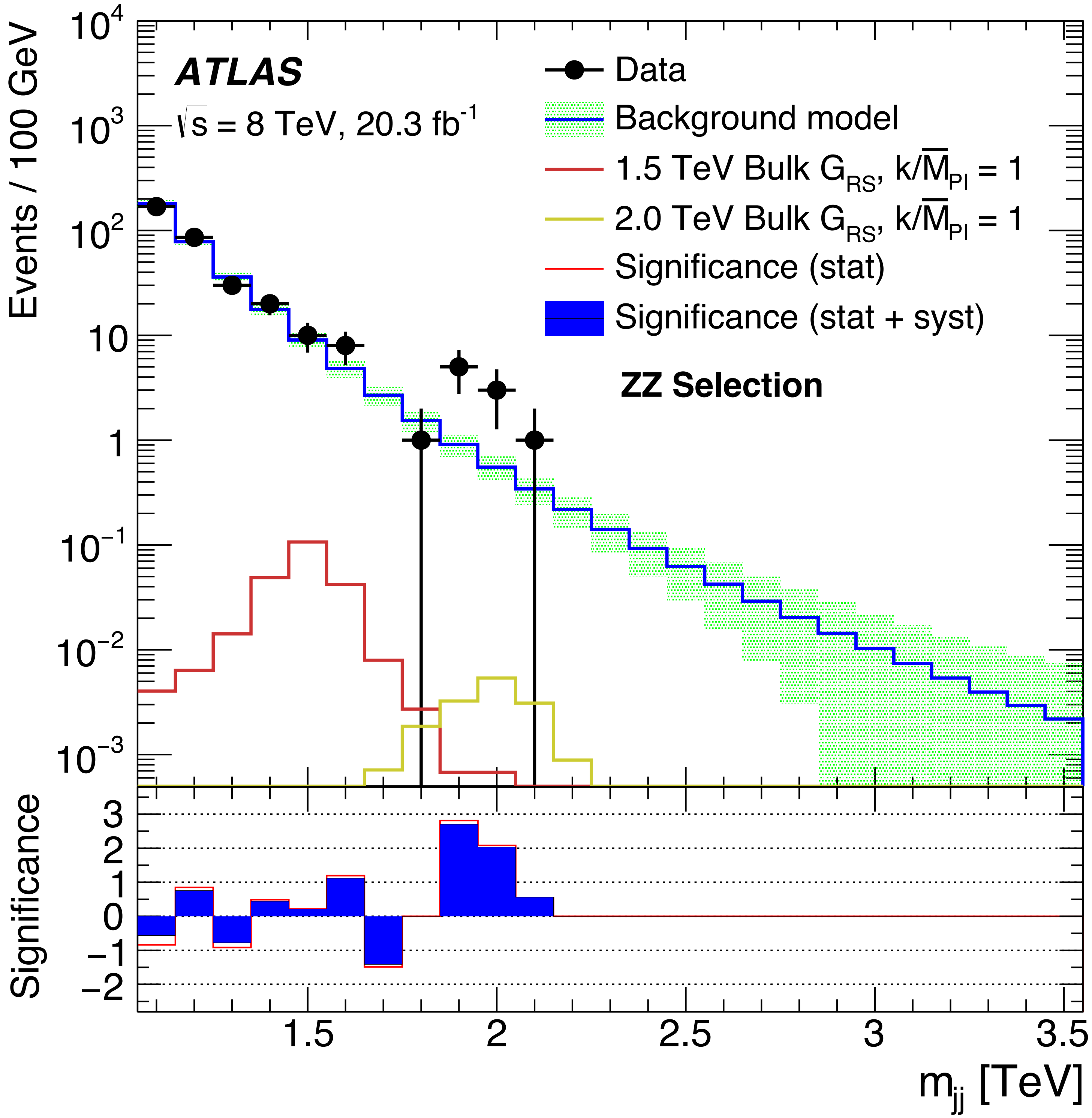


Hopes

Could a triplet explain this?

Compatible with other selections (less performant, mainly WZ sign.)

Combination impossible with ATLAS public results



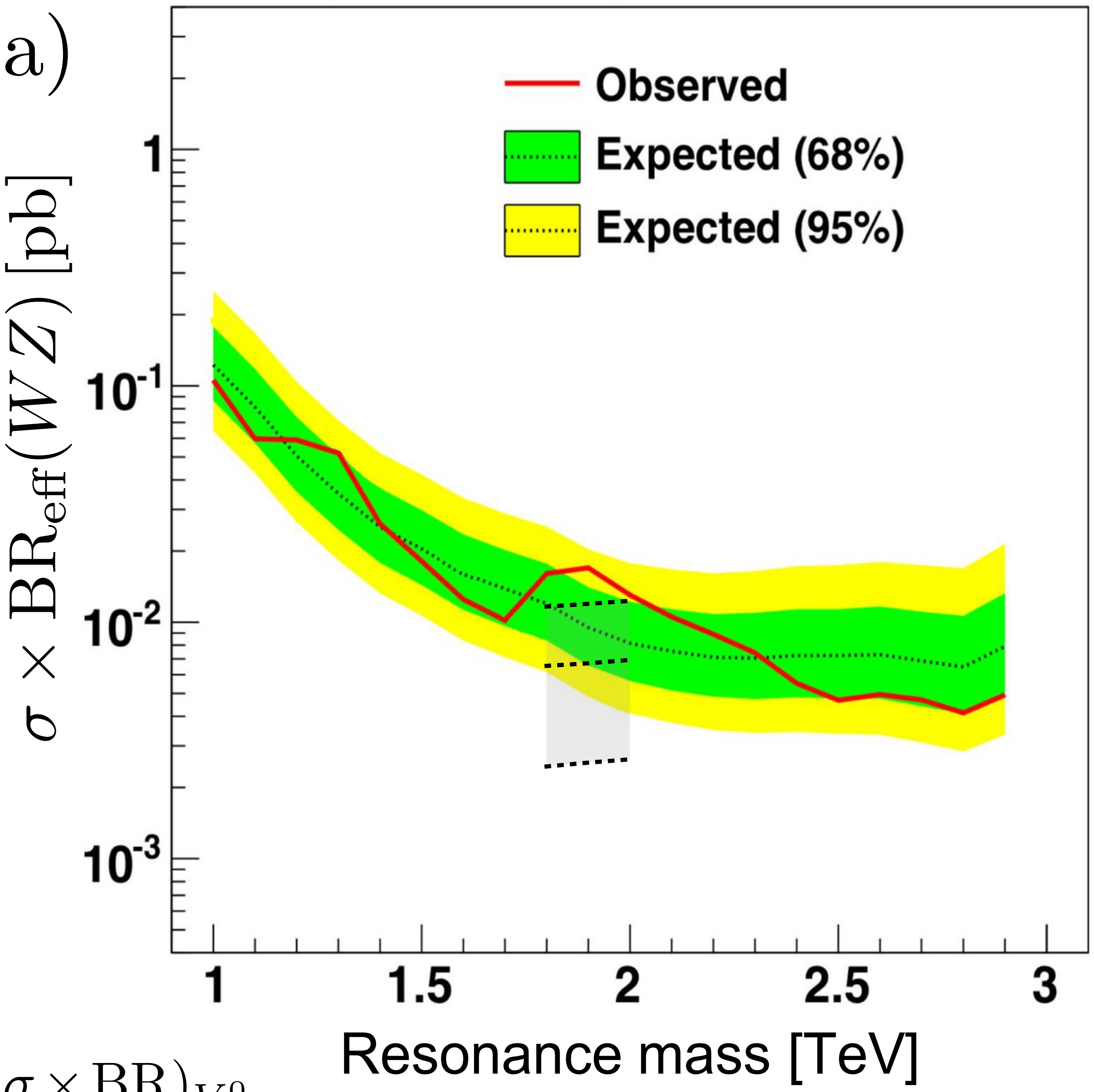
Hopes

Other di-boson searches exclude the putative signal?

CMS boosted W/Z. No attempt to distinguish. Assume same accept.

Signal can account for the "CMS excess" ($< 2\,\sigma$)

a)



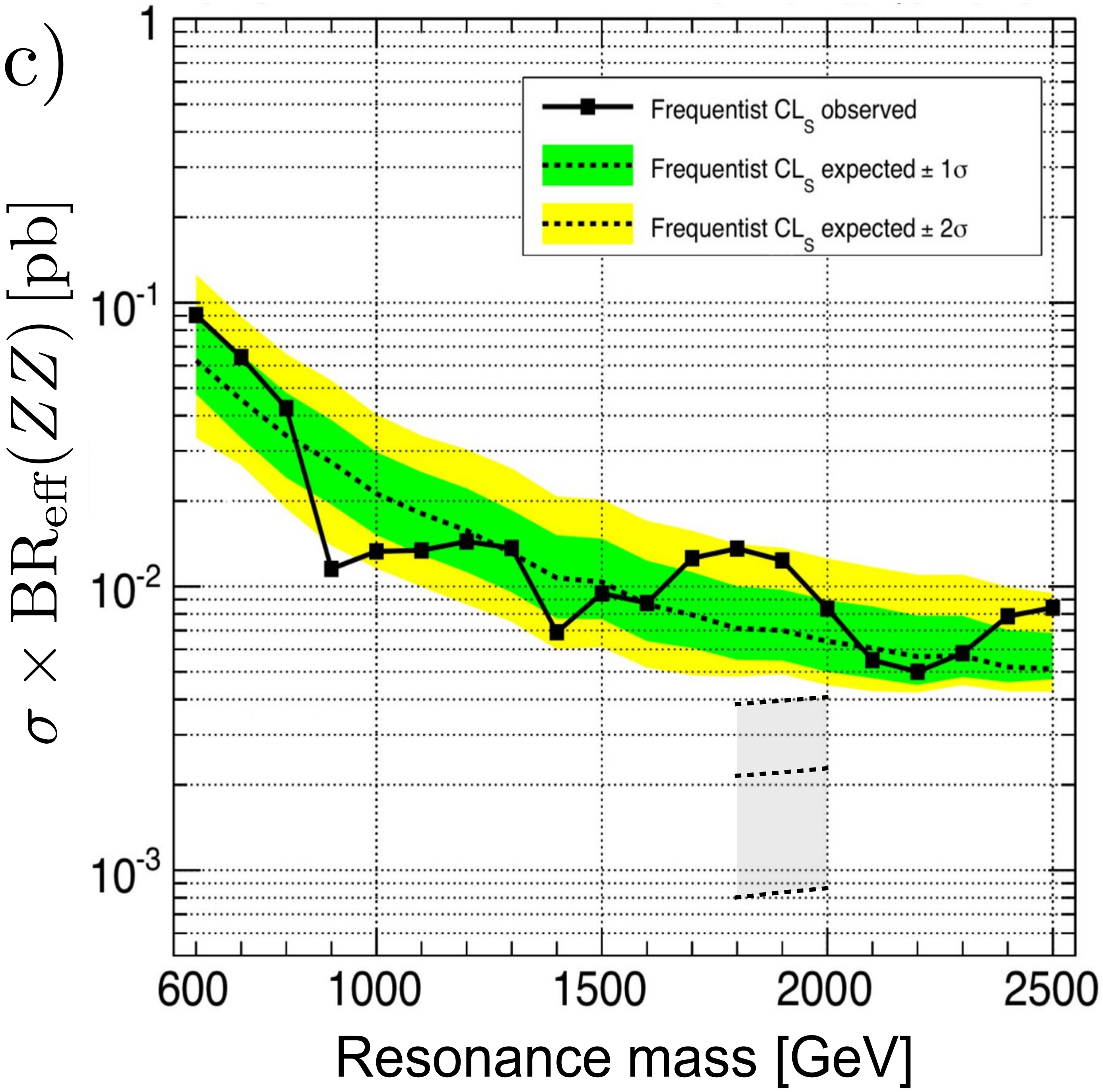
$$(\sigma \times \mathrm{BR})_{\mathrm{eff}} = (\sigma \times \mathrm{BR})_{V^{\pm}} + \frac{\mathrm{BR}_{W \to \mathrm{had}}}{\mathrm{BR}_{Z \to \mathrm{had}}} (\sigma \times \mathrm{BR})_{V^0}$$

Hopes

Other di-boson searches exclude the putative signal?

CMS $Z_{\mathrm{lep.}} + Z_{\mathrm{had.}}$. Reinterpretation of the Graviton limit

Notice important combinatorial factor of 1/2



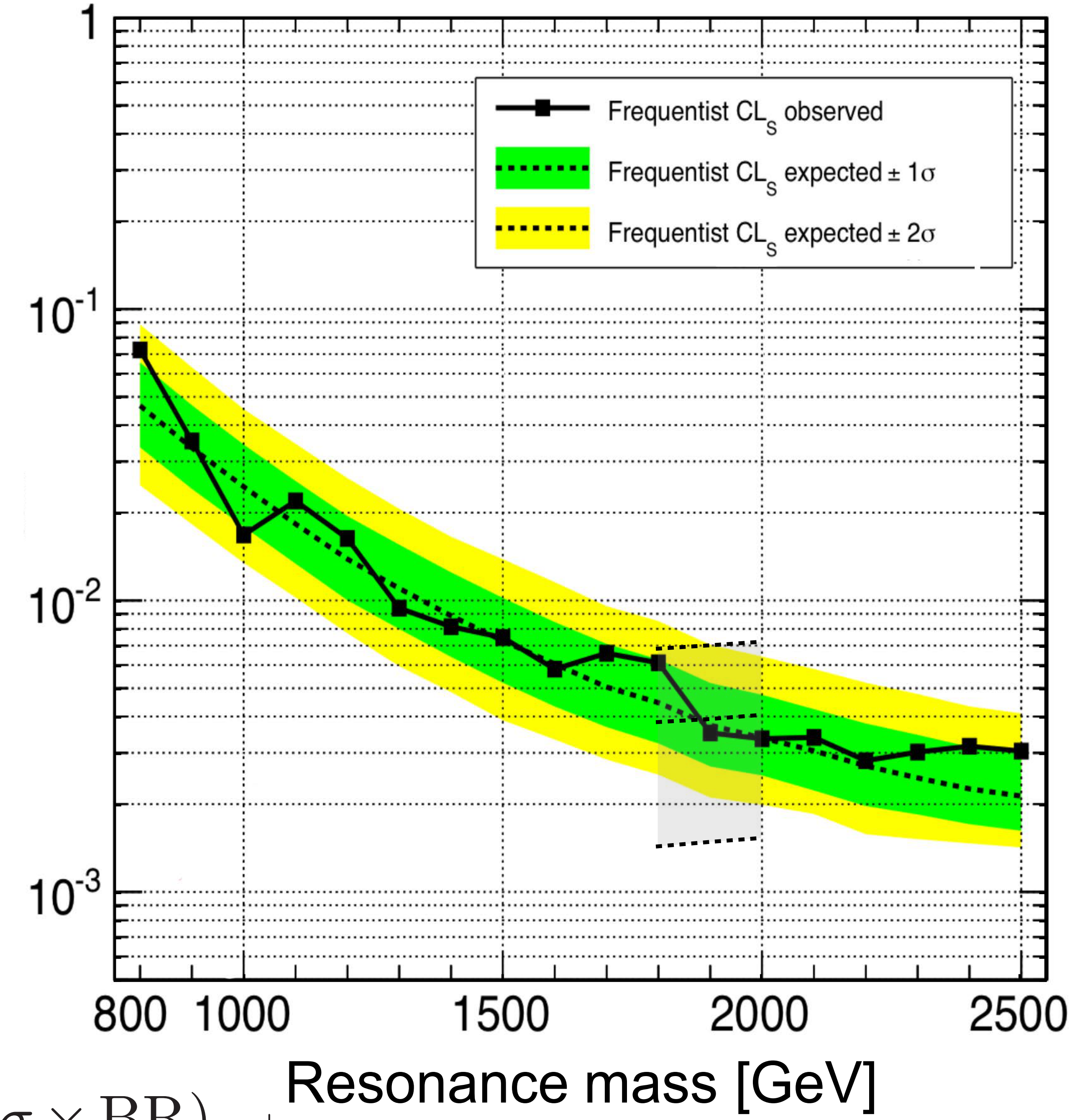
$$(\sigma \times \mathrm{BR})_{\mathrm{eff}} = \frac{\mathrm{BR}_{W\to \mathrm{had}}}{2\,\mathrm{BR}_{Z\to \mathrm{had}}}(\sigma \times \mathrm{BR})_{V^{\pm}}$$

Hopes

Other di-boson searches exclude the putative signal?

CMS $W_{\text{lep.}} + Z_{\text{had.}}$ is the most constraining one.

Signal not excluded mainly because of combinatorial 1/2

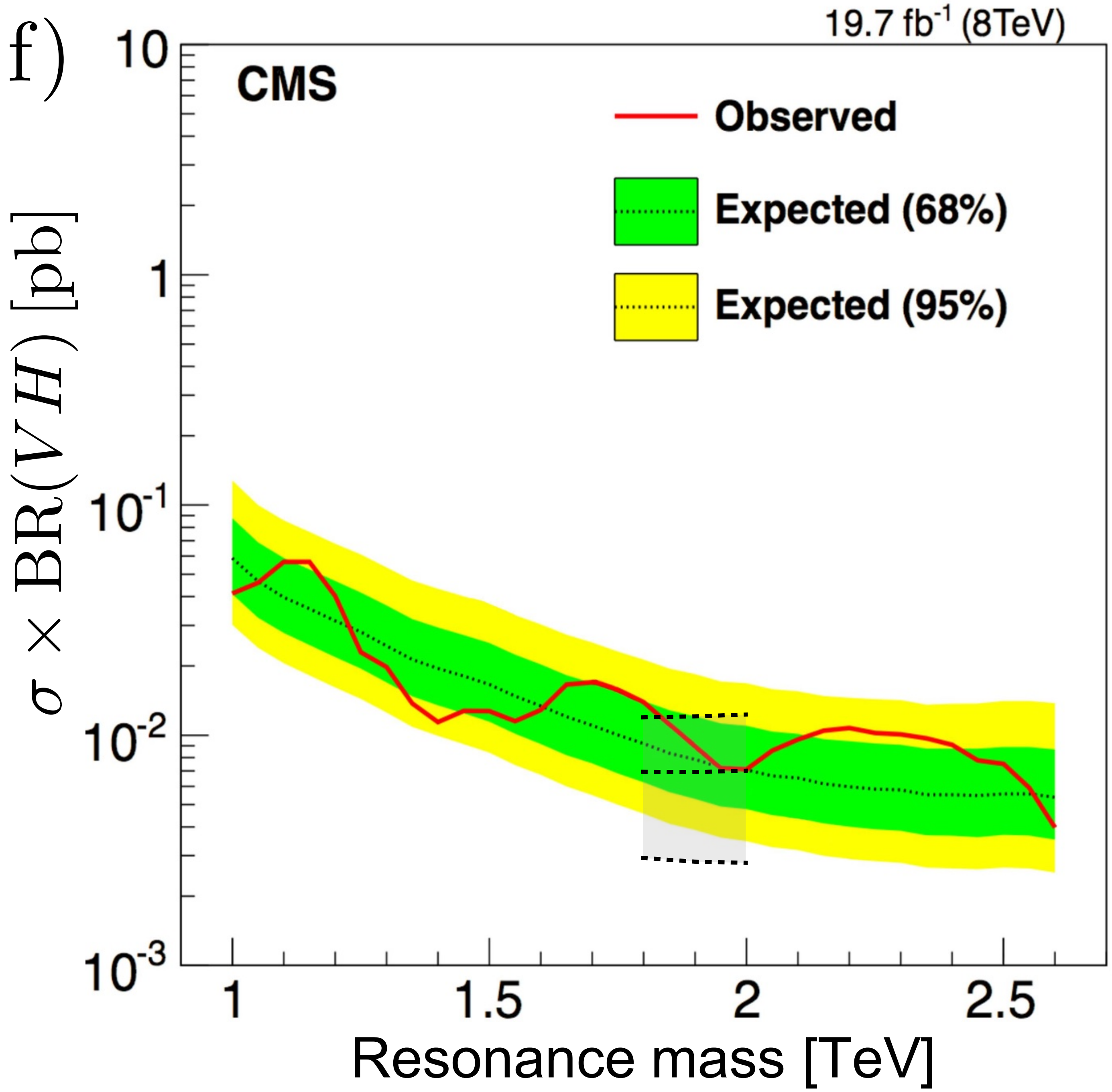


$$(\sigma \times \mathrm{BR})_{\text{eff}} = (\sigma \times \mathrm{BR})_{V^0} + \frac{\mathrm{BR}_{Z\to\text{had}}}{\mathrm{BR}_{W\to\text{had}}} \frac{\epsilon_{\not{b}}}{2} (\sigma \times \mathrm{BR})_{V^\pm}$$

Hopes

Final states with the Higgs:

CMS combination of several channels in the HVT framework

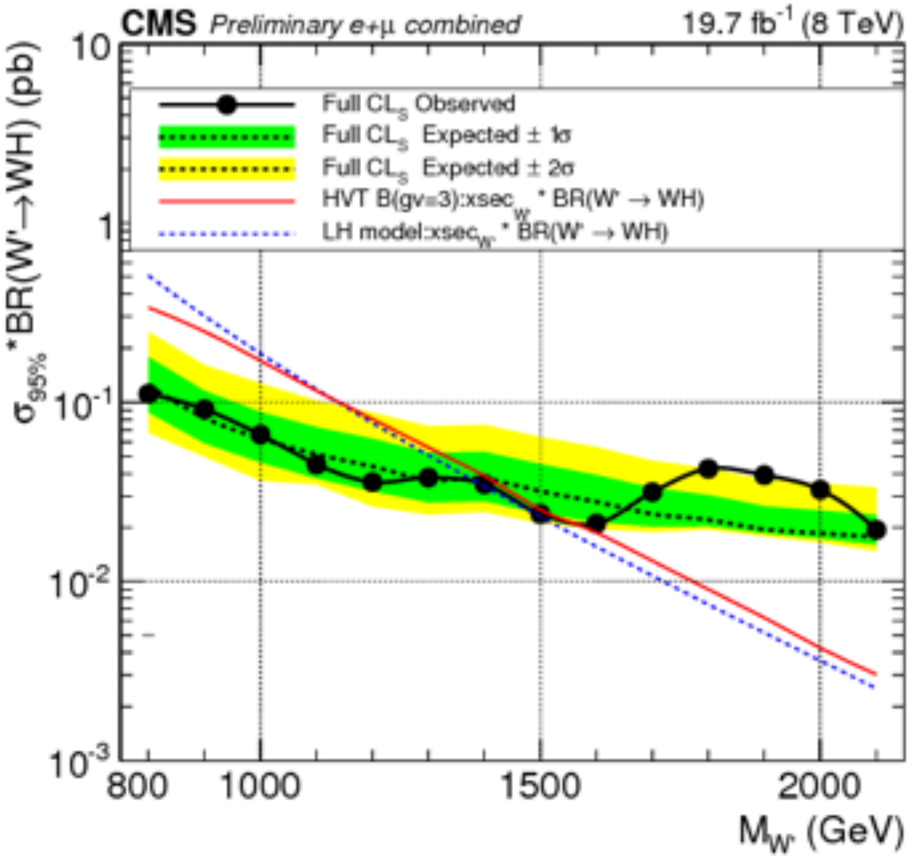


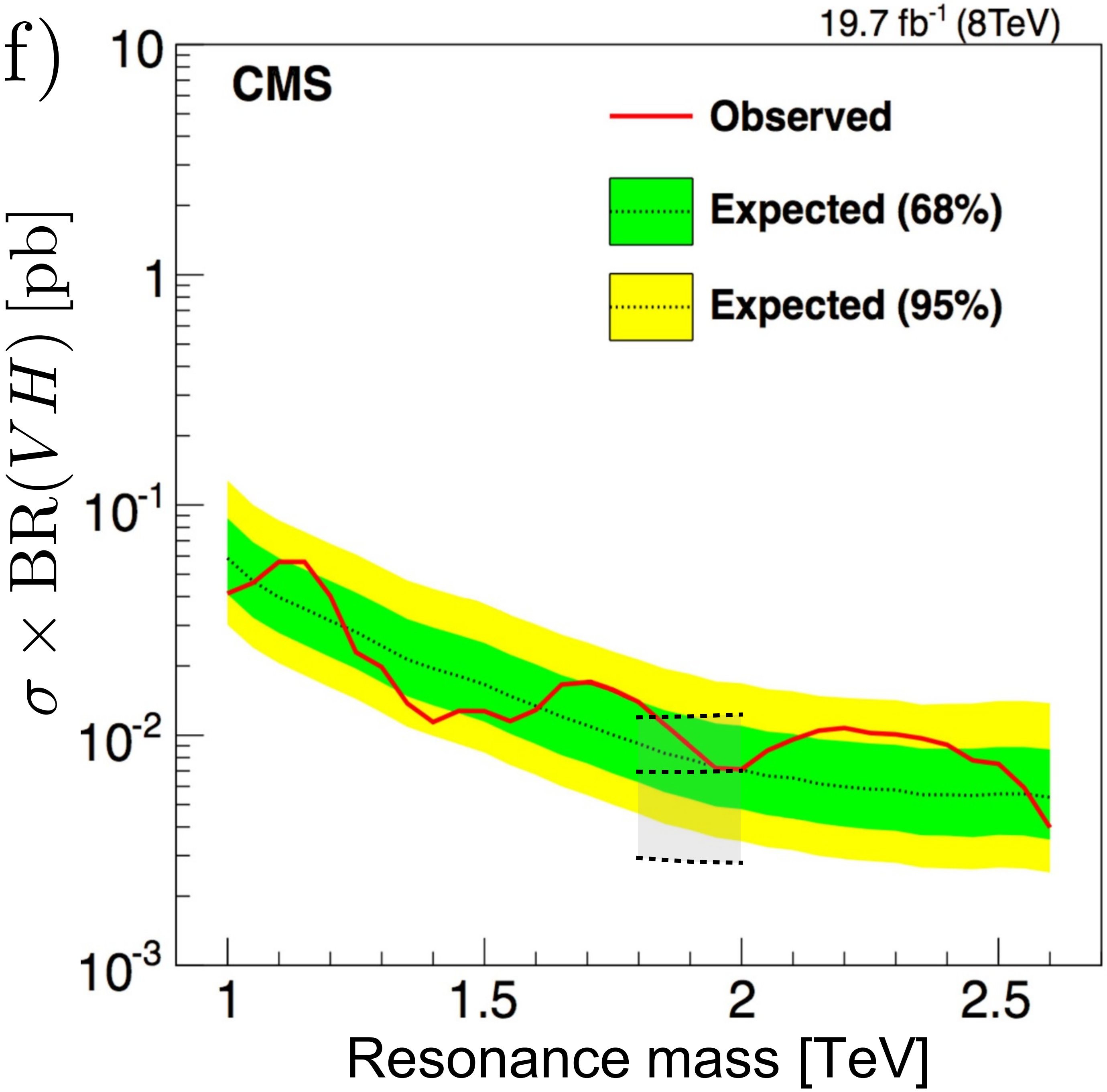
Hopes

Final states with the Higgs:

CMS combination of several channels in the HVT framework

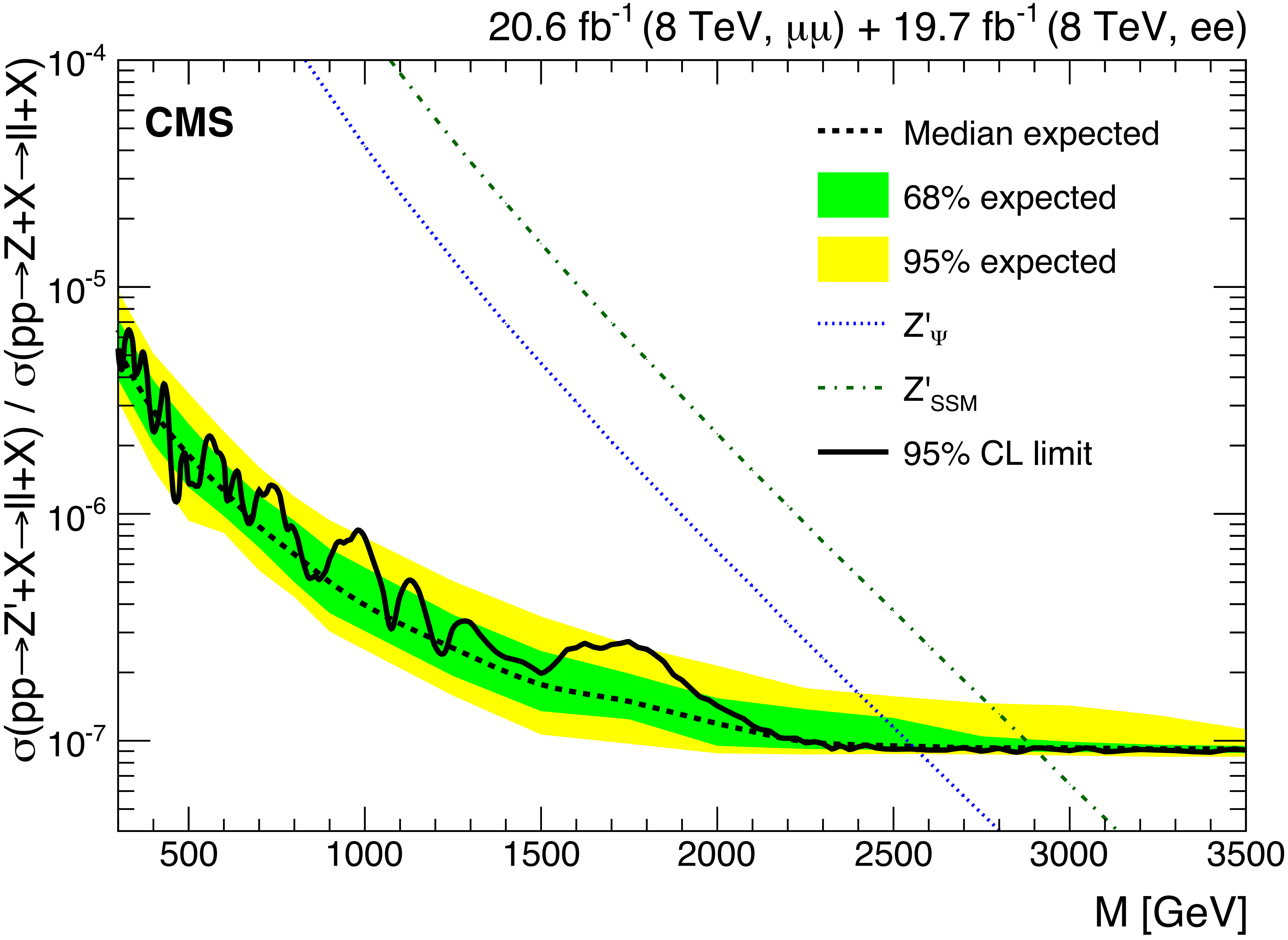
Combination does not include $W_{\text{lep.}} + h_{\text{had.}}$ with $\sim 2\,\sigma$





Hopes

Dileptons are well under control.
Model might account for CMS excess. Not for 2-j excess.



Conclusions

- The HVT framework:
  - Defines a comprehensive search strategy for triplets at the LHC
  - Contributes to liberate our field from benchmark models plague!
- Composite HVT are robust signatures of CH scenario
  - Relevant for “Naturalness”, or “Un-Naturalness”, searches
  - Poorly constrained by run-1 data
- ATLAS excess:
  - Can be accounted for by Natural and plausible New Physics
  - To be confirmed or disproven in the next few months

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New physics might be still waiting for us at 13TeV.
Run-2 has started and we must take the best out of it.
Not yet time to **“relax”**.