Resonant pp → W^+Zjj events at the LHC from a unitarized study of the EChL

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R. Delgado, A. Dobado, D. Espriu, **CGG**, M.J. Herrero, X. Marcano & J.J. Sanz-Cillero

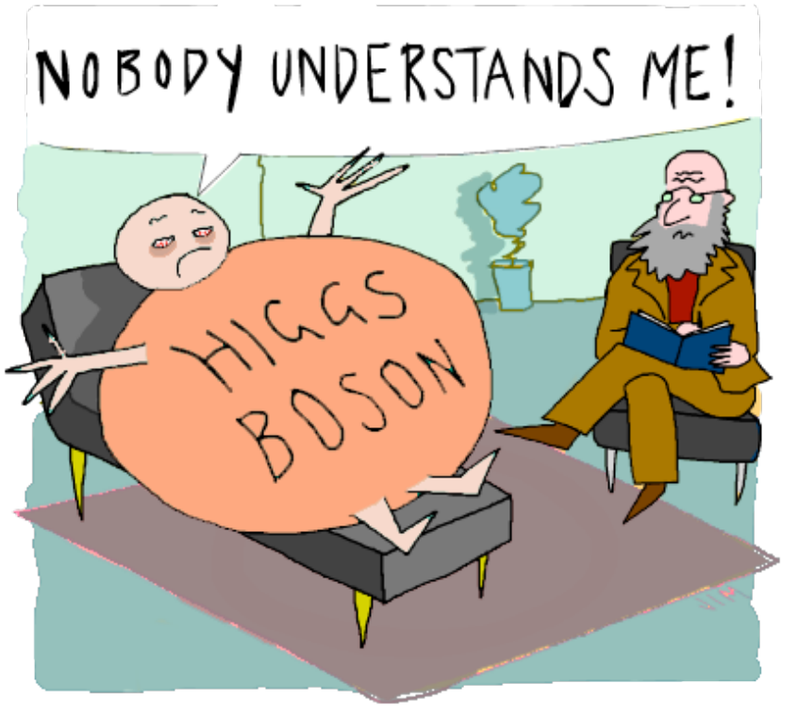
53rd Rencontres de Moriond - EW 2018

Motivation

What is the dynamical generation of EWSB?

Effective Theories for EWSB

- Describe **dynamical generation of EWSB**
  - → Strong Dynamics?
    - → Resonances predicted!
- **Model independent**



Vector Boson Scattering @ the LHC

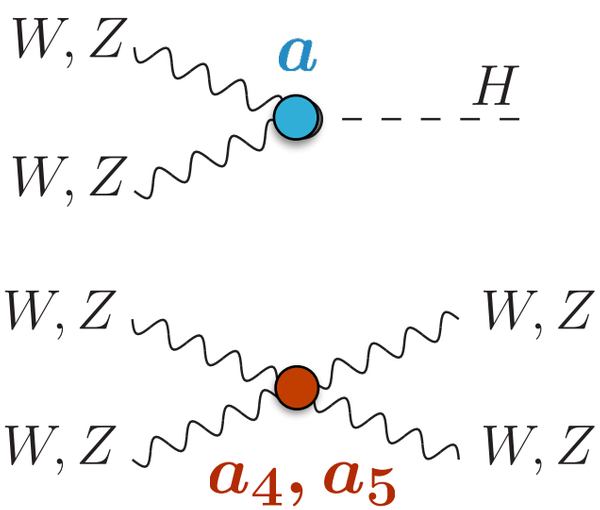
- New Pheno in EWSB sector → **New Pheno** in EW boson interactions
- **Vector Boson Scattering** (VBS) very sensitive to **New Physics**
- **Searches for VBS** planned @ the **LHC**!

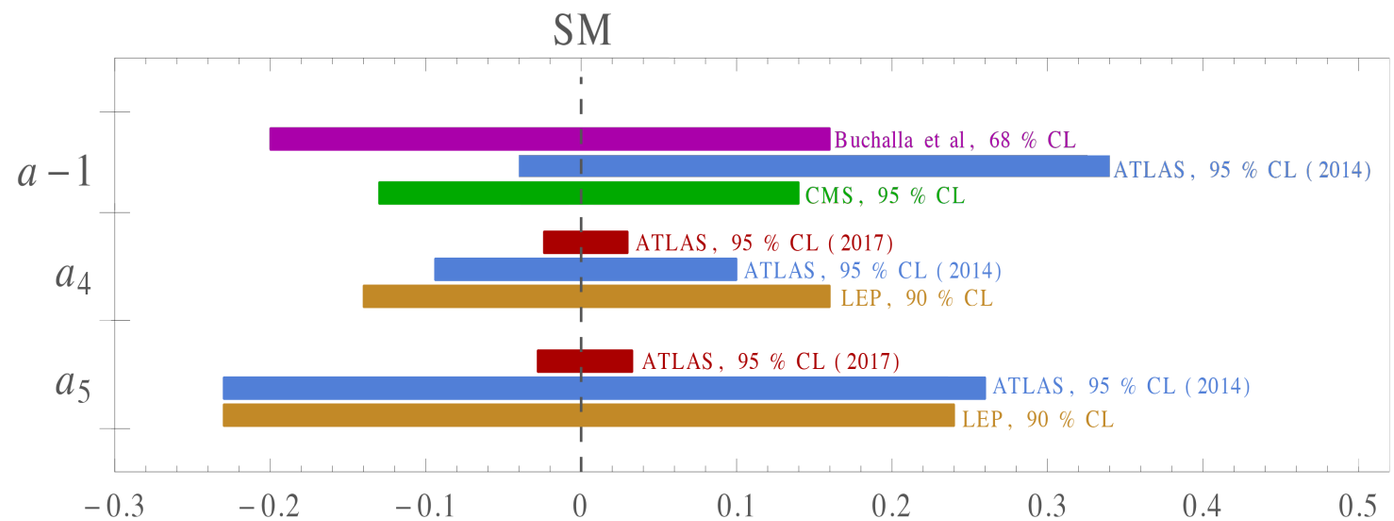
The Electroweak Chiral Lagrangian & the IAM

[A. C. Longhitano, 1980; T. Appelquist et al., 1980]

EChL copy of ChPT in QCD

- **EChL** symmetries: Gauge → $SU(2)_L \times U(1)_Y$ and EW Chiral → $SU(2)_L \times SU(2)_R$
- New interactions in EW sector → Controlled by ***chiral*** parameters a a_4 a_5





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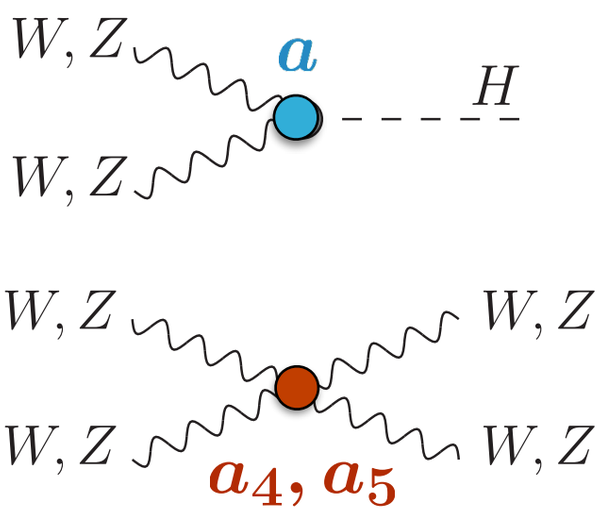

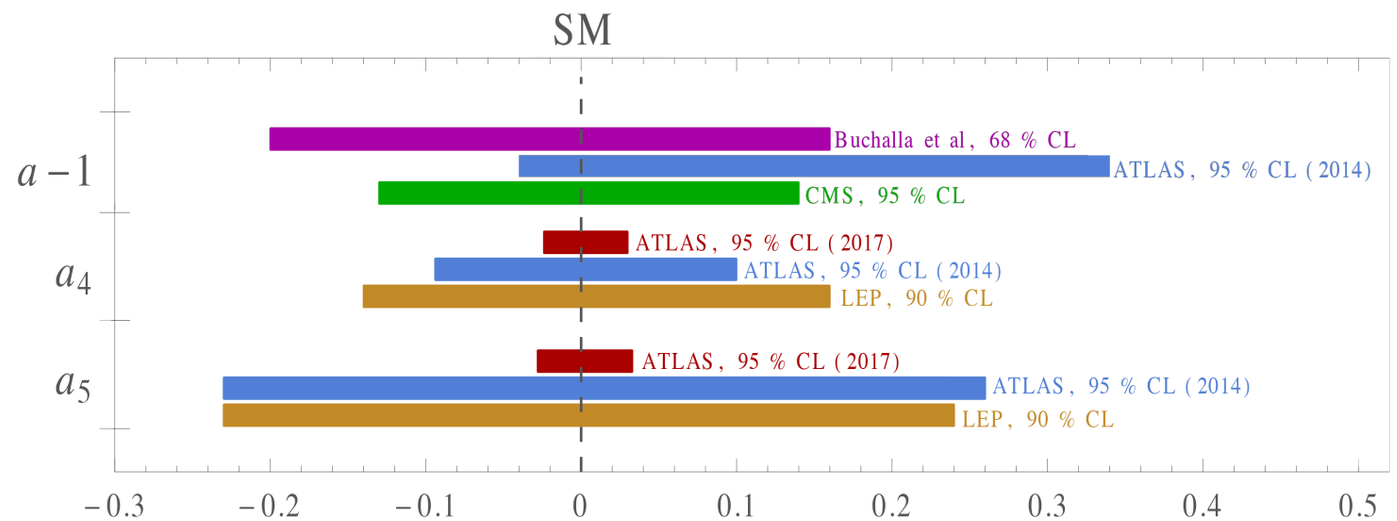

- Expansion in powers of p —typically→ **Violation of Unitarity**
- Unitarization via the **Inverse Amplitude Method** (IAM) → generates **resonances** dynamically

[Tran N. Truong, Phys. Rev. Lett. 61 (1988)2526]

Unitarized Partial Waves

$$a_{IJ}^{\mathrm{IAM}}(s) = \frac{(a_{IJ}^{(0)}(s))^2}{a_{IJ}^{(0)} - a_{IJ}^{(1)}}$$

$M_V,\ \Gamma_V$ depend on a a_4 a_5

We select vector scenarios

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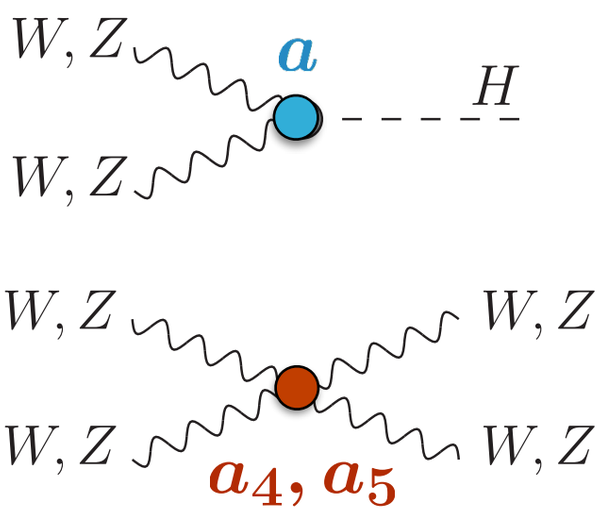

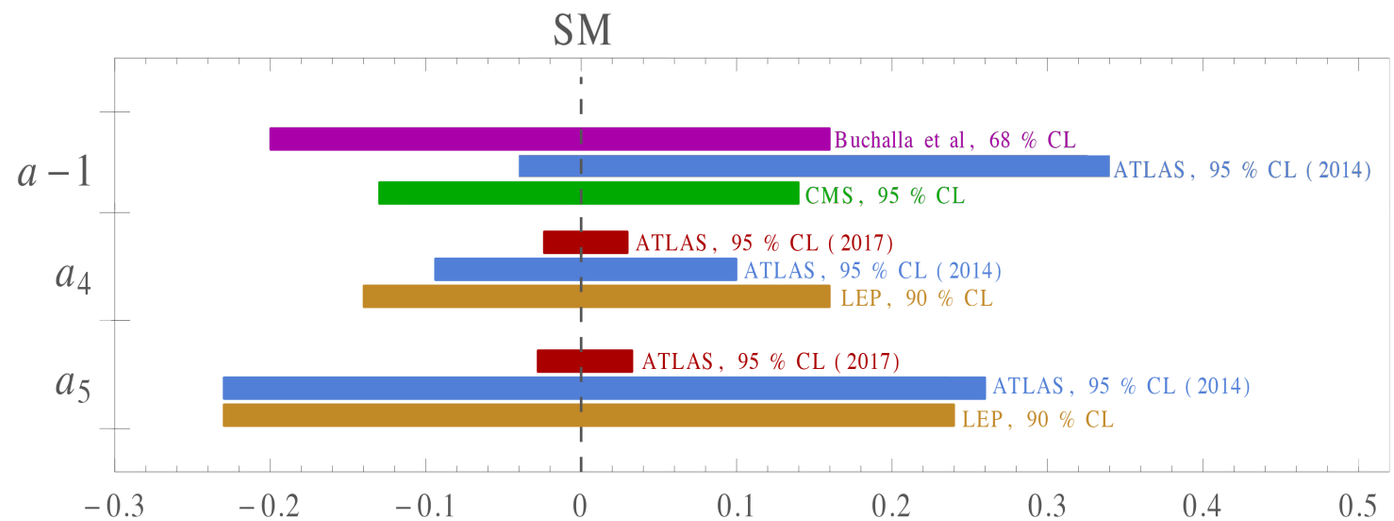

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Difficult to Implement in Monte Carlo!

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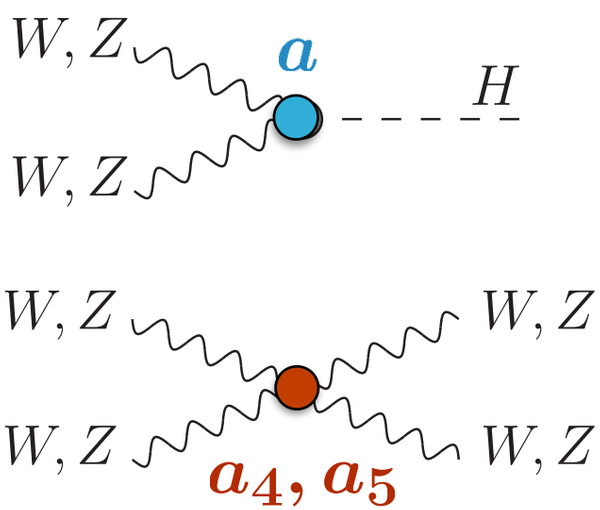

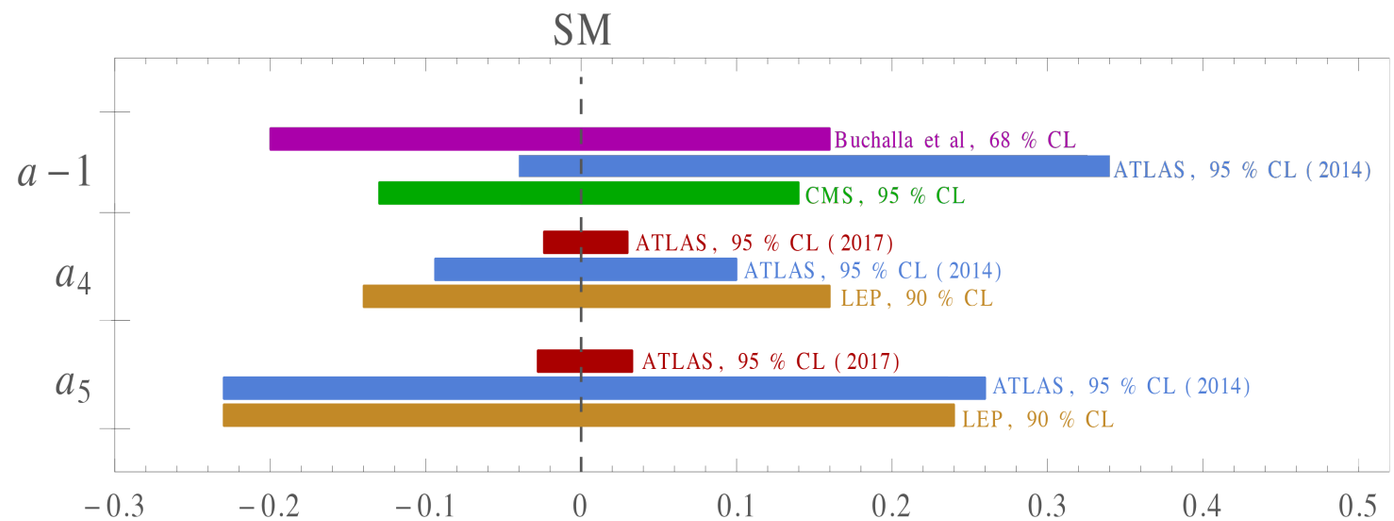

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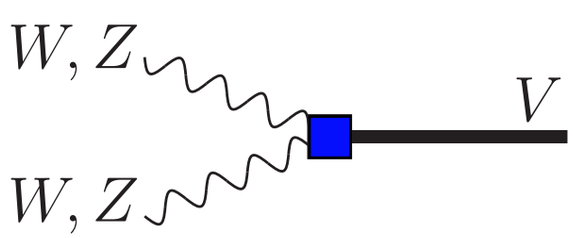
$M_V,\ \Gamma_V$ depend on a a_4 a_5

We select vector scenarios

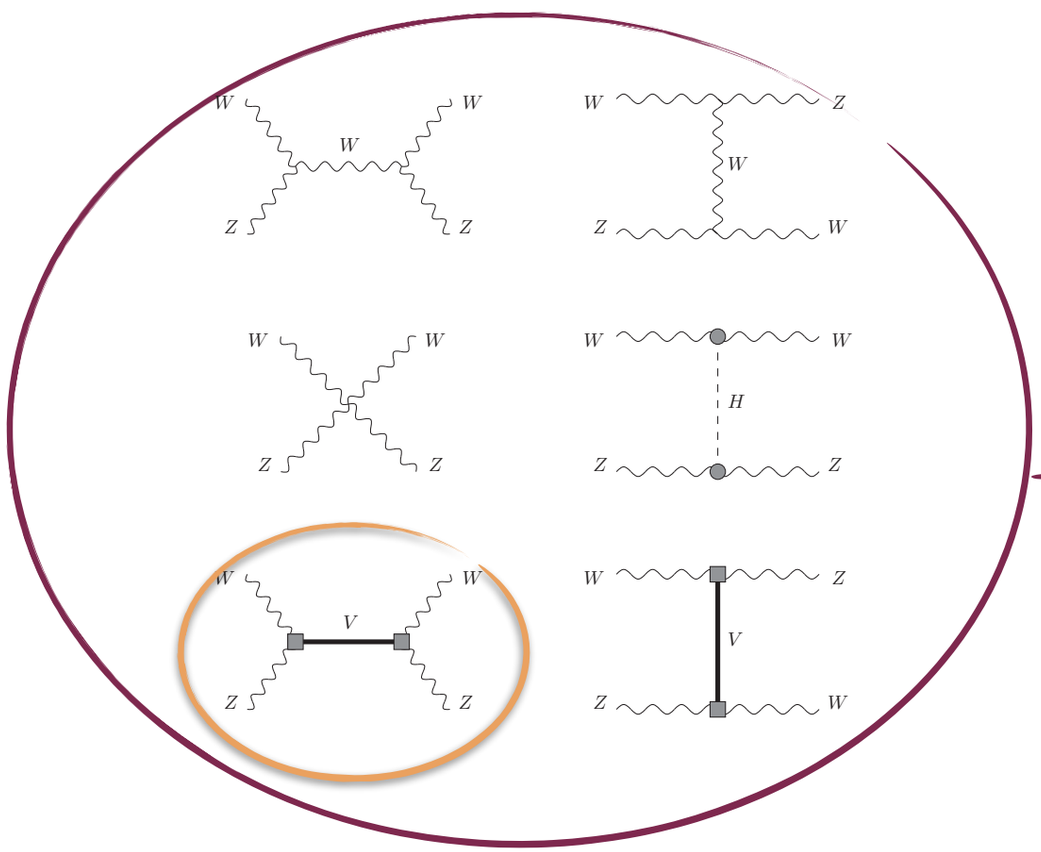
Efective vertex to mimic the IAM vector resonances!

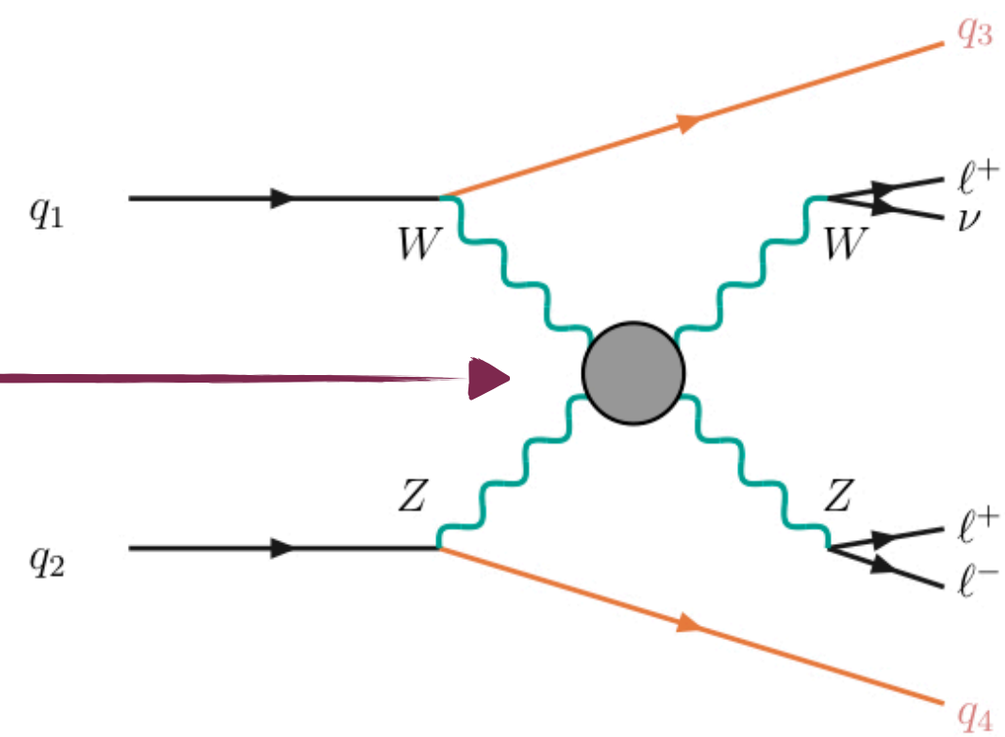


→ introduced in MG5

Vector Resonances in the W⁺Z channel @ LHC

- We study **charged vector resonances**, V , from a triplet, $V^{\pm}, V^{0}$
- **W⁺Z** channel very promising
  - Mediated only by V
  - No severe QCD backgrounds
  - Clean leptonic signal
- Signals $pp \to W^{+} Z j j$ $\quad pp \to \ell_1^{+} \ell_1^{-} \ell_2^{+} \not{E}_T j j$ $\quad pp \to J J j j$

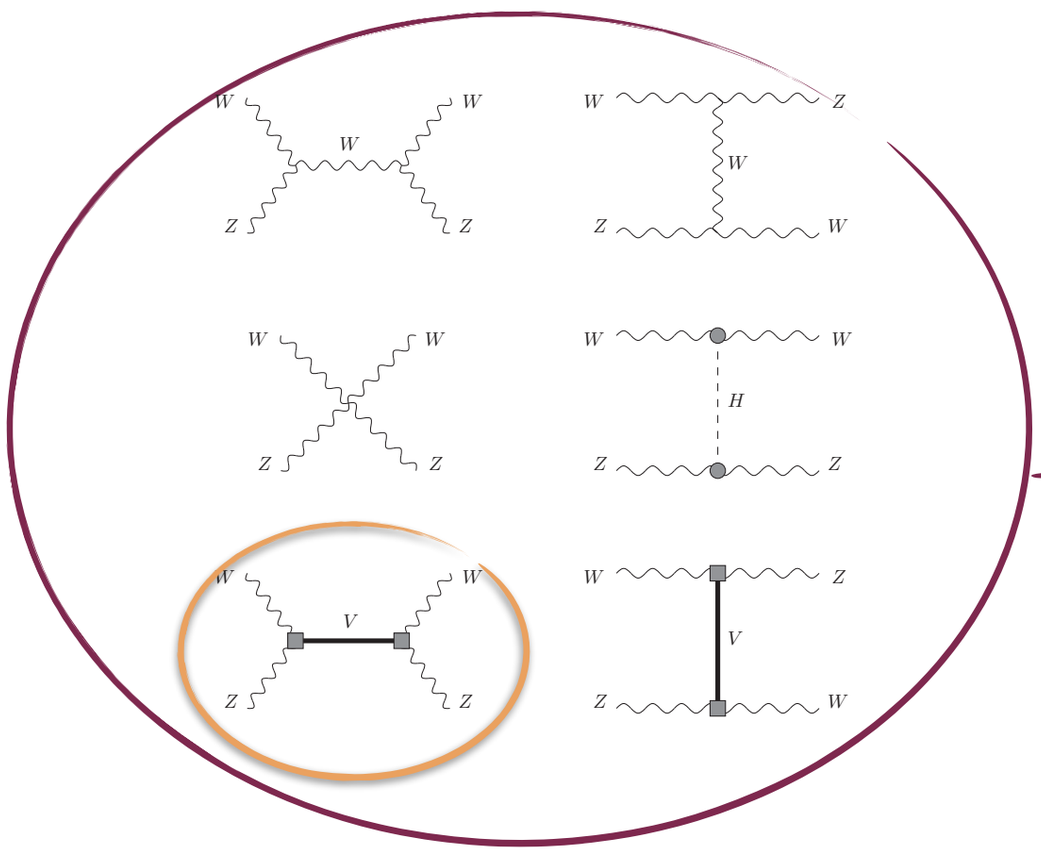


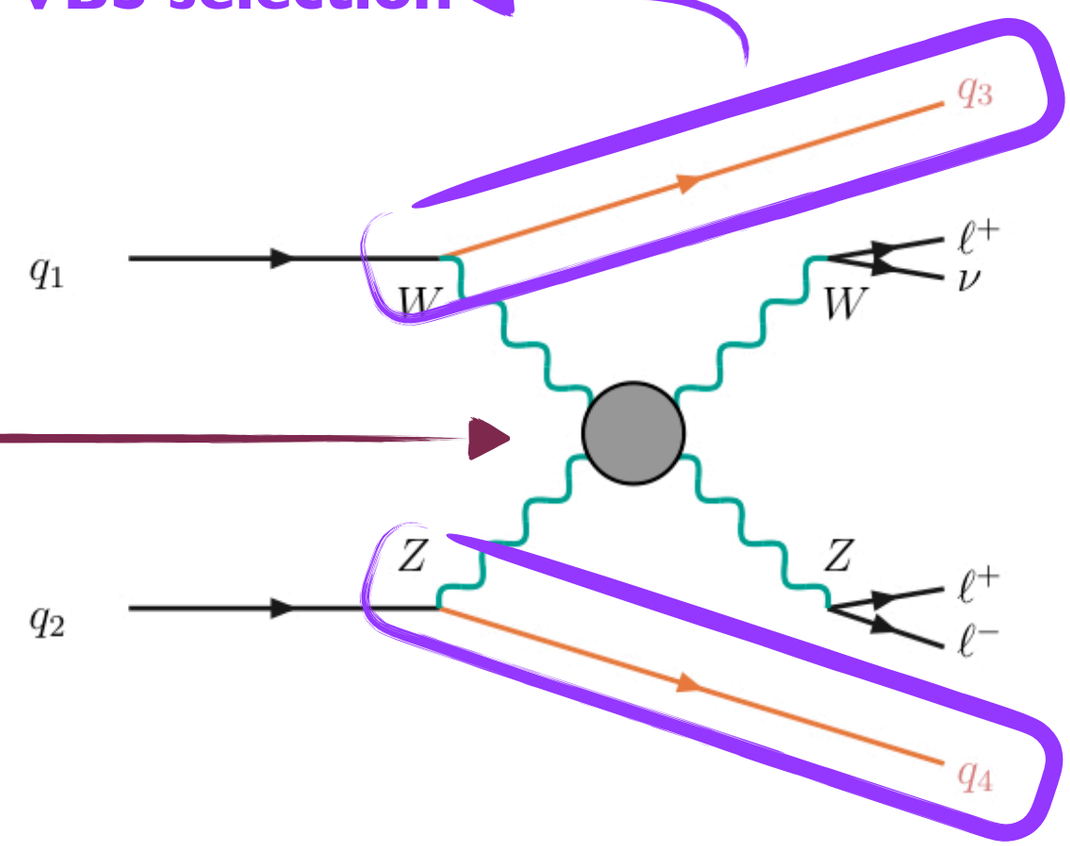


Vector Resonances in the W^+Z channel @ LHC

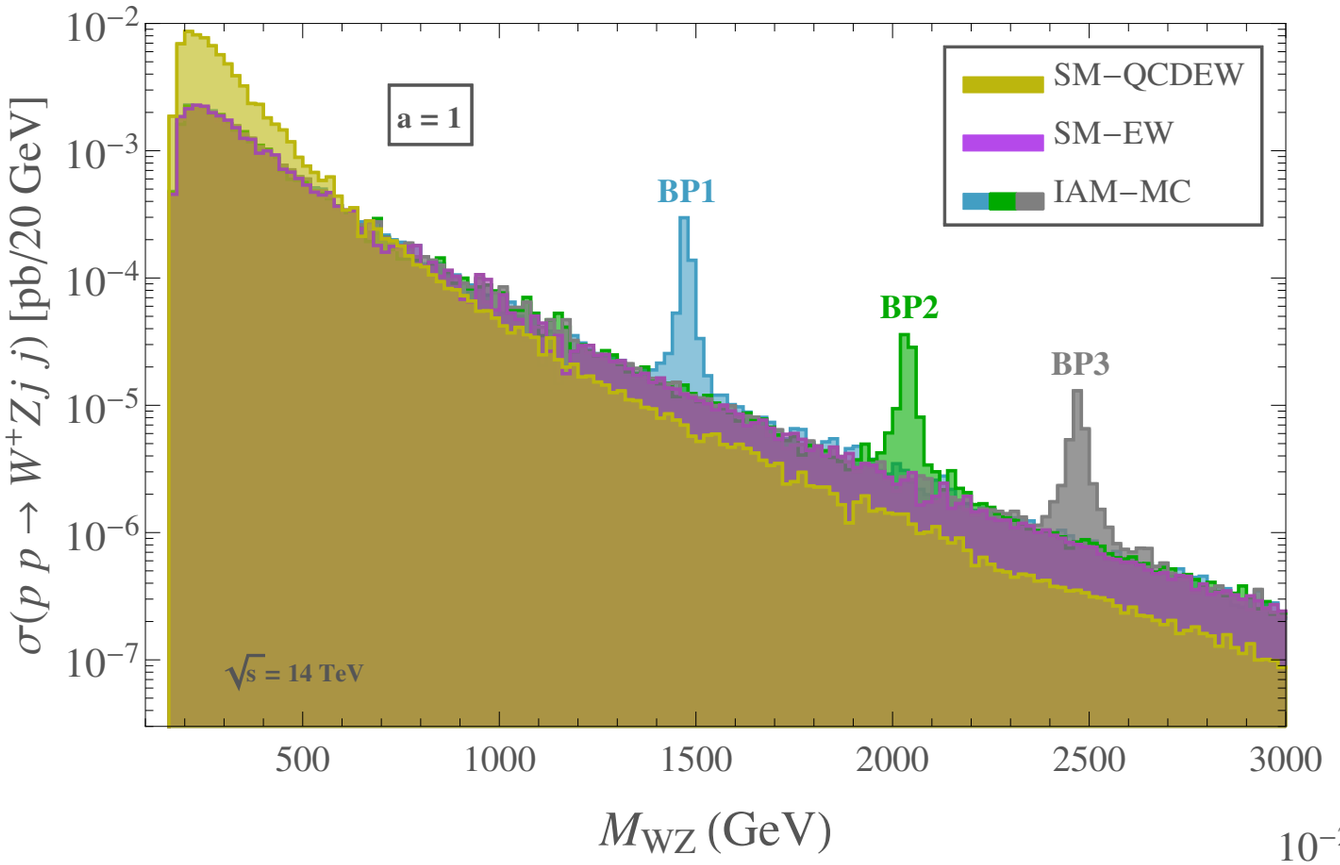
- We study **charged vector resonances**, V , from a triplet, $V^{\pm}, V^0$
- **W^+Z** channel very promising
  - Mediated only by V
  - No severe QCD backgrounds
  - Clean leptonic signal
- Signals $pp \to W^+ Zjj$ $\quad pp \to \ell_1^+ \ell_1^- \ell_2^+ \not{E}_T jj$ $\quad pp \to JJjj$

Key to VBS selection



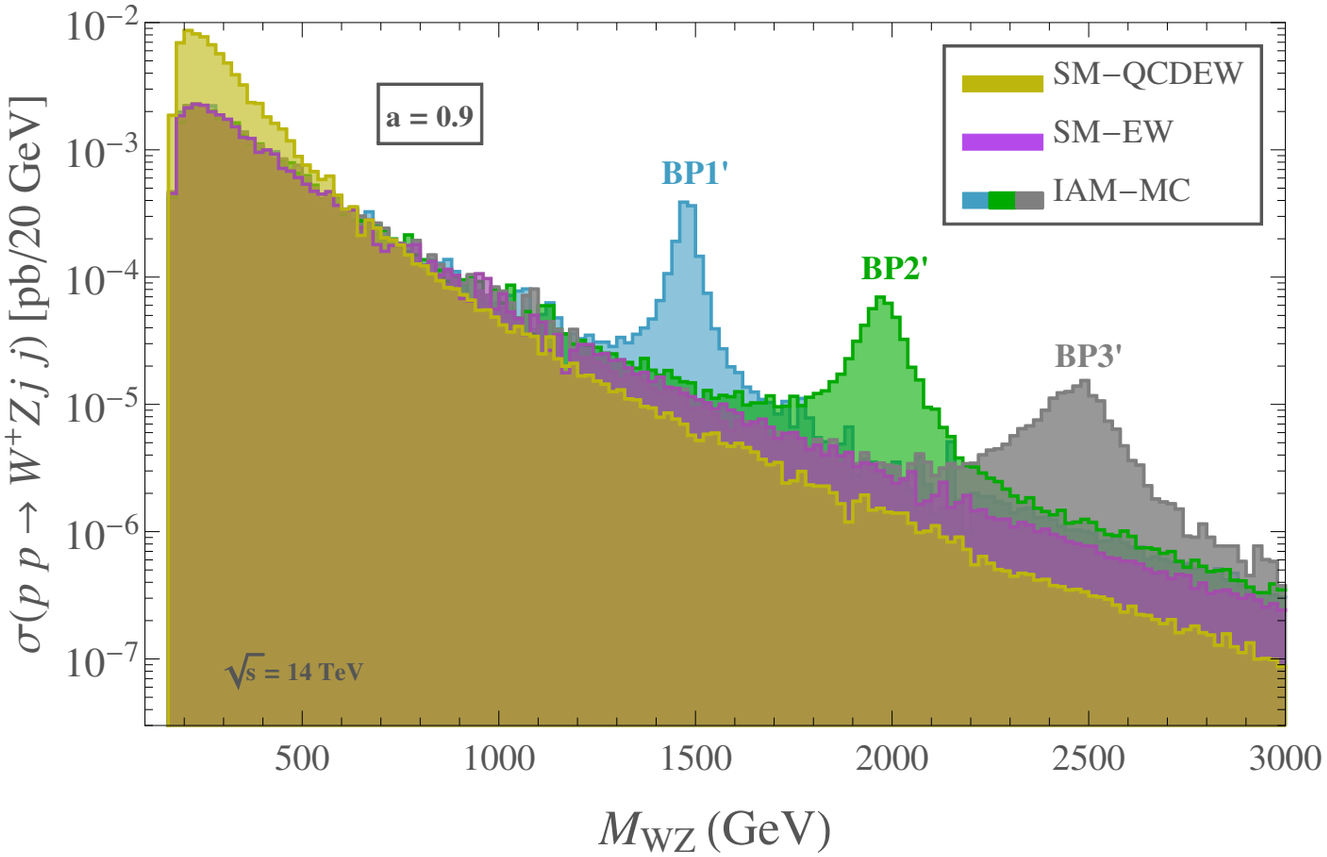


Results for W^+Zjj final state

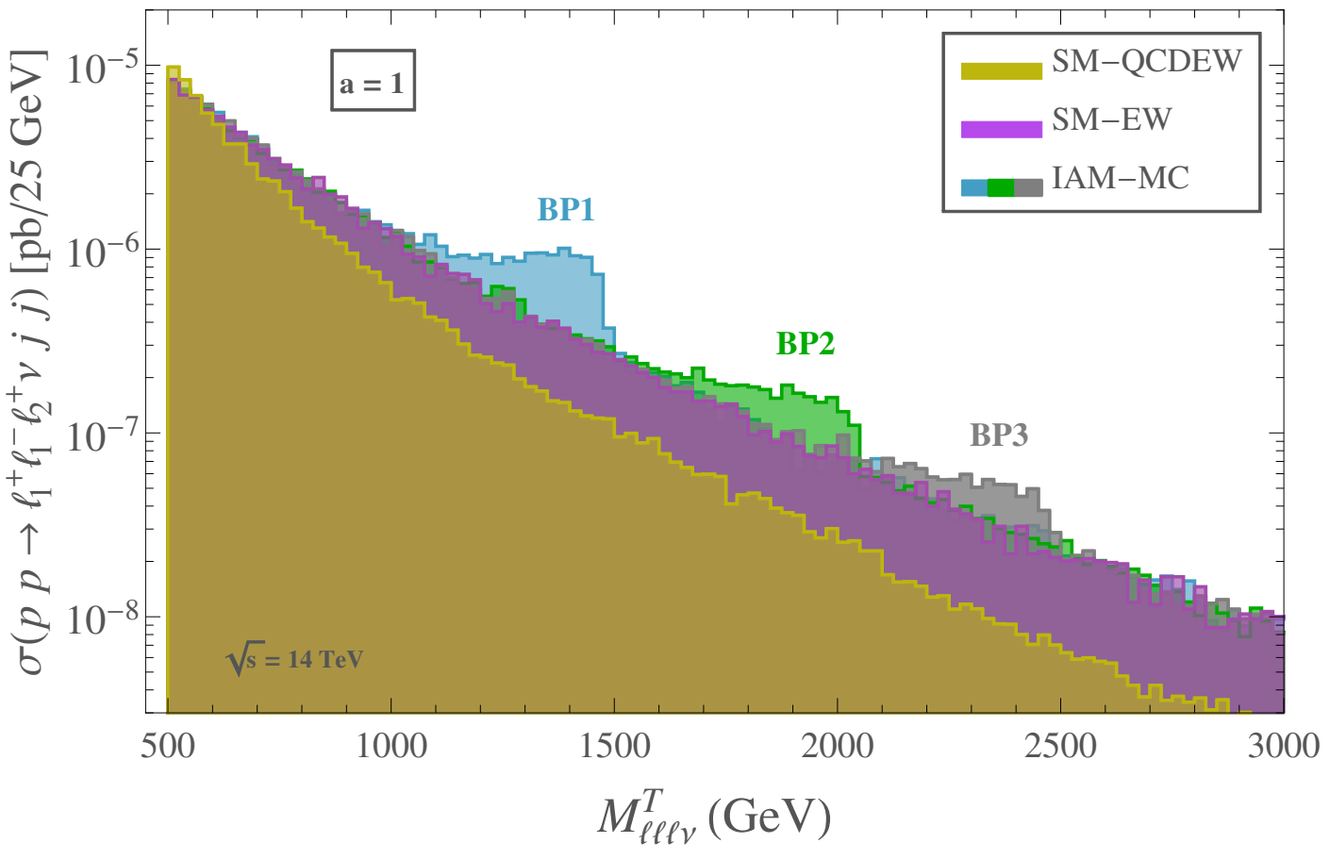


- Very **clear resonant peaks** on top of SM background

- Many **events available** for LHC luminosities if W & Z are well reconstructed

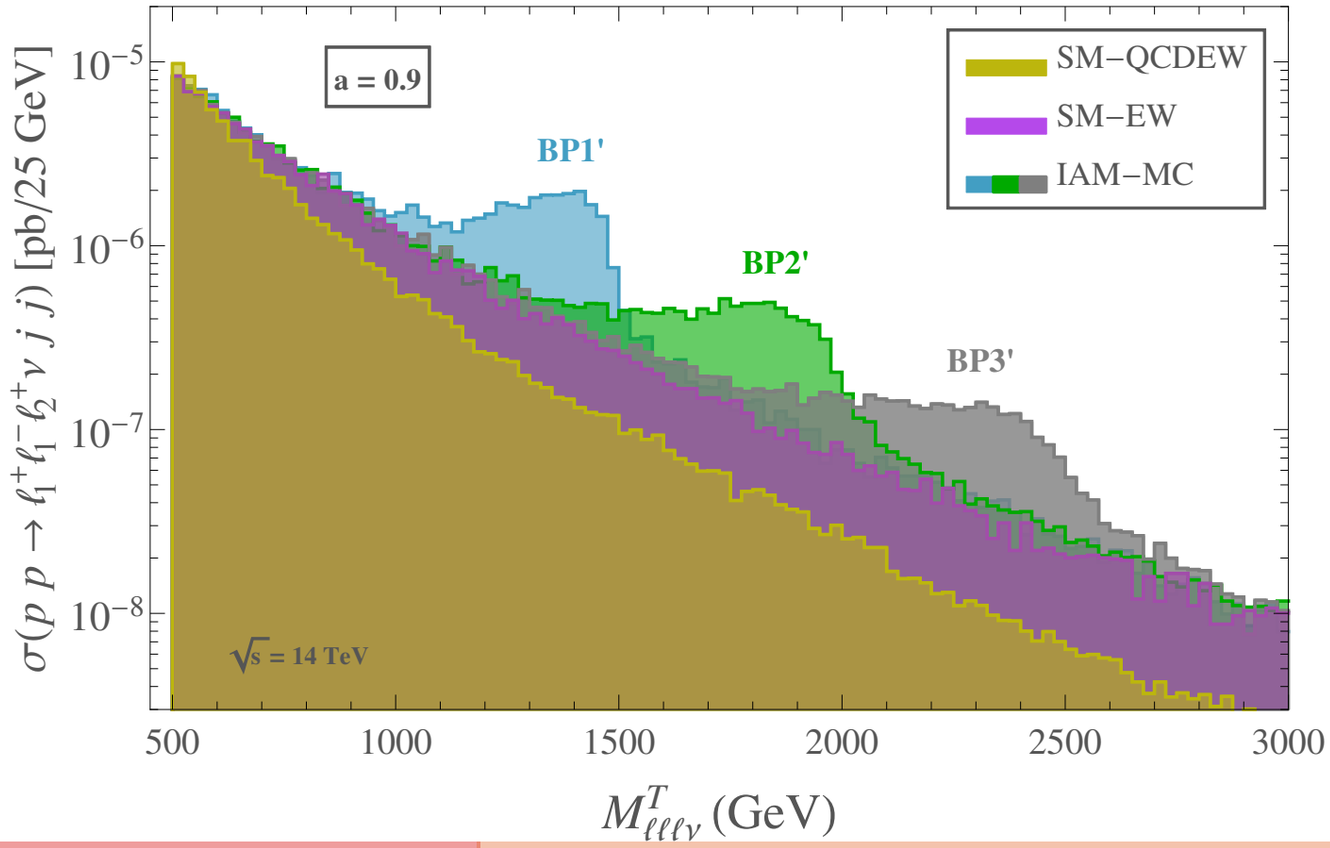


Results for $\ell^+\ell^-\ell'^+\nu$ jj final state



- Some scenarios are **still** very **visible** above SM background

- Very clean signal in the leptonic channel



Sensitivity to a in W+Zjj final state

- Given M_V:
  significance **increases** with $(a-1)$
- Given $(a-1)$:
  significance **decreases** with M_V

LHC sensitive to $a \in [0.9, 1]$ for $M_V \in [1.5, 2.5]$ TeV and $\mathcal{L} = 300\ \mathrm{fb}^{-1}$

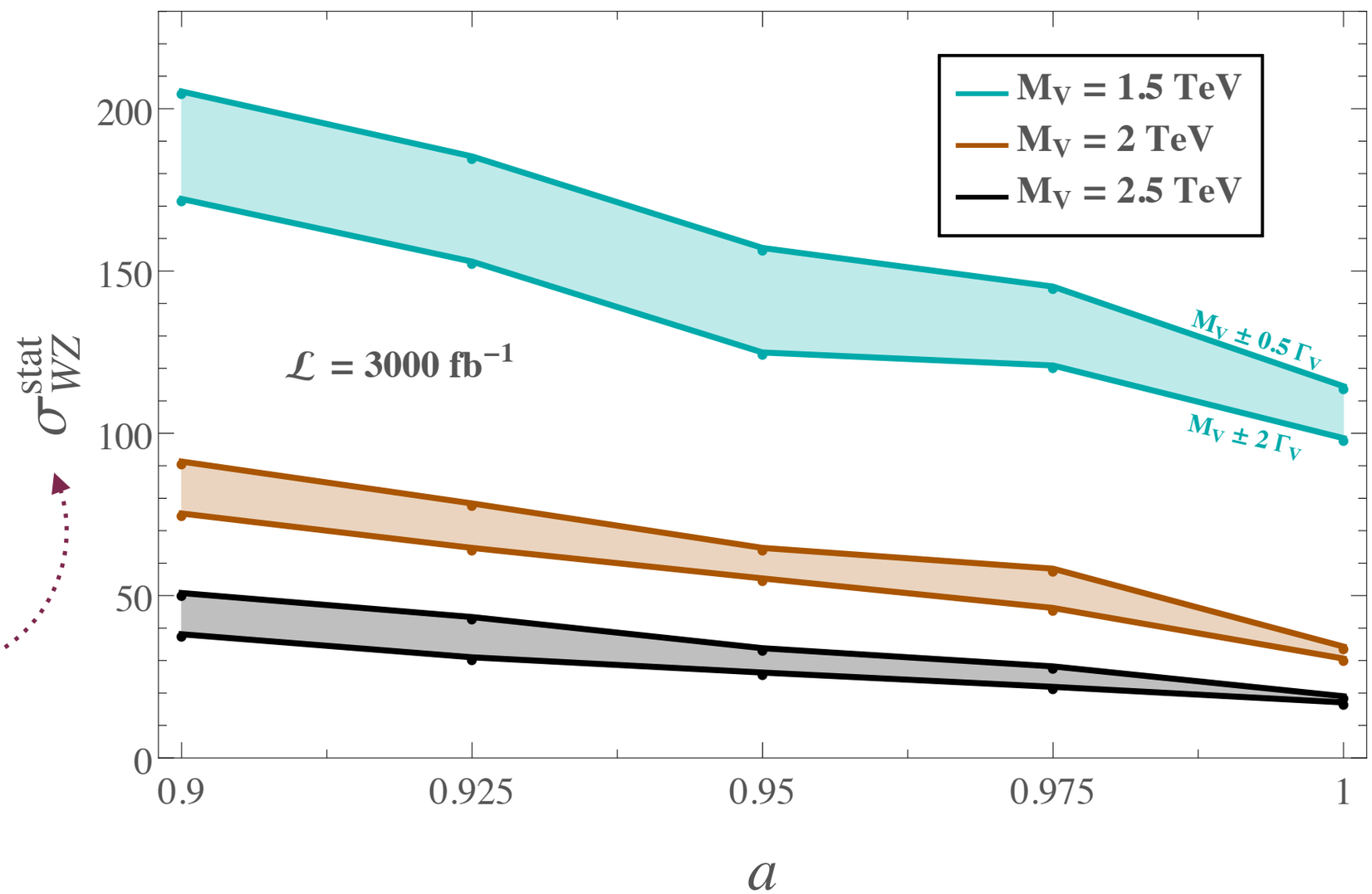
Signal & Background definitions

$$S = N_{\mathrm{ev}}^{\mathrm{IAM-MC}} - N_{\mathrm{ev}}^{\mathrm{SM(QCD+EW)}}$$

$$B = N_{\mathrm{ev}}^{\mathrm{SM(QCD+EW)}}$$

stat. significance

$$\sigma^{\mathrm{stat}} = \frac{S}{\sqrt{B}}$$



Sensitivity to a in other channels

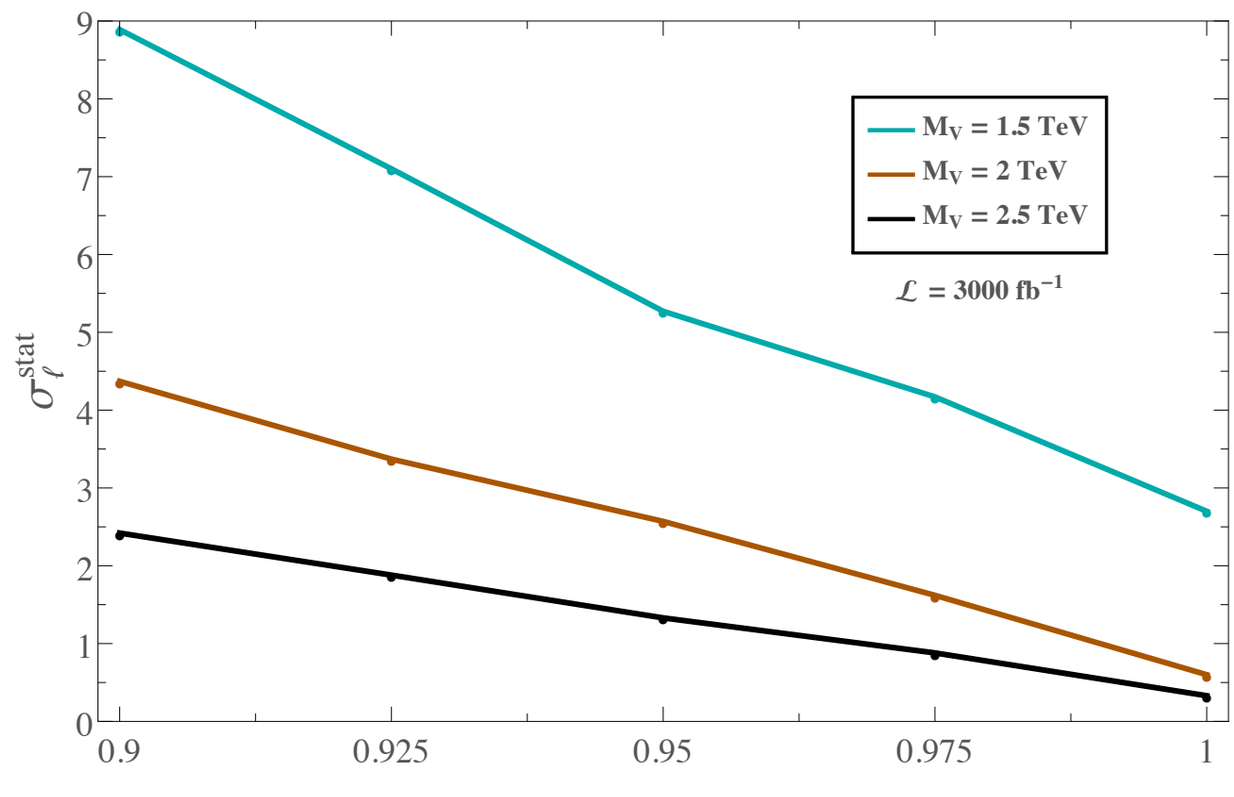
$pp \to \ell_1^+ \ell_1^- \ell_2^+ \not{E}_T jj$ $\quad \mathcal{L} = 3000\ \text{fb}^{-1}$

$a \in [0.9, 1] \longleftrightarrow M_V = 1.5\ \text{TeV}$

$a \in [0.94, 1] \longleftrightarrow M_V = 2\ \text{TeV}$

Poor sensitivity for $M_V = 2.5\ \text{TeV}$

- Clean and controlled
- Requires High Luminosity



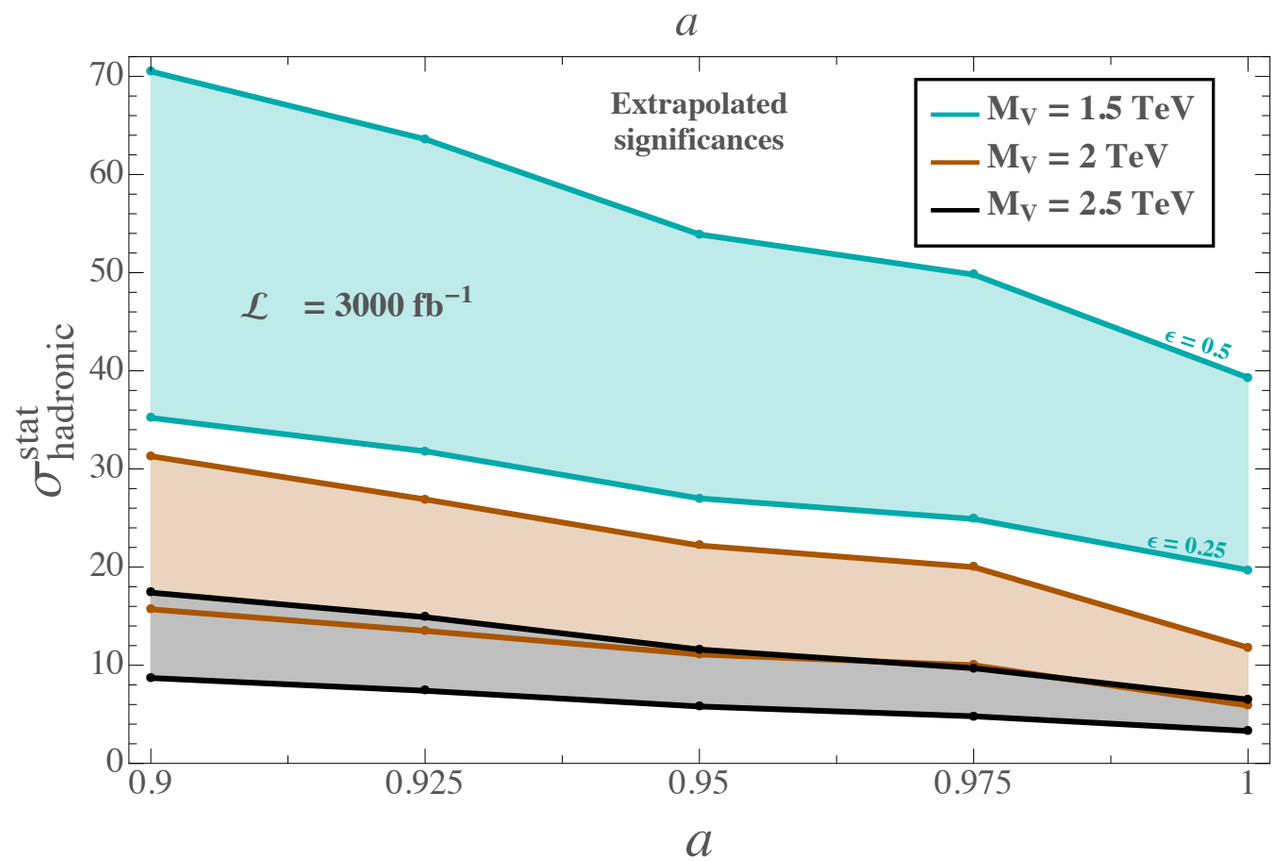
$pp \to JJjj$ **ESTIMATES** $\quad \mathcal{L} = 300\ \text{fb}^{-1}$

$a \in [0.9, 1] \longleftrightarrow M_V = 1.5\ \text{TeV}$

$a \in [0.975, 1] \longleftrightarrow M_V = 2\ \text{TeV}$

$a \in [0.925, 1] \longleftrightarrow M_V = 2.5\ \text{TeV}$

- Very high significances!
- Depends on reconstruction efficiency



Conclusions

- **VBS** optimal place to **test deviations** introduced by the **EChL**

- **Dynamically generated vector resonances** from unitarized EChL can be seen **@ LHC**
  - → Very high statistical significance in WZ final state
  - → Promising results in leptonic channel for some scenarios and HL-LHC
  - → High sensitivity in final states with fat jets

- Study Resonances of 1.5 - 2.5 TeV → broad **sensitivity** to **EChL params**
  - → Depending on:
    - final state
    - luminosity

- Improving selection cuts + study other distributions might improve the results

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THANK YOU!

- Improving selection cuts + study other distributions might improve the results

Back up Slides

The Electroweak Chiral Lagrangian

- Symmetries: **Gauge** → $SU(2)_L \times U(1)_Y$ and **EW Chiral** → $SU(2)_L \times SU(2)_R$

  EChL copy of ChPT in QCD

- **Light d.o.f. :** $w^{\pm}, z$ $\quad W^{\pm}, Z$ $\quad h$

- Building blocks:

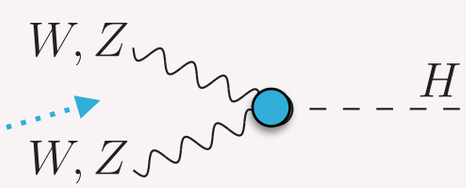
$$D_\mu U = D_\mu\left(e^{\frac{i w^a \tau^a}{v}}\right) \qquad \hat{W}_{\mu\nu}, \hat{B}_{\mu\nu} \qquad \mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 \qquad \mathcal{V}_\mu = (D_\mu U)U^\dagger$$

$\mathscr{L}_{EChL} = \mathscr{L}_2 + \mathscr{L}_4$ Relevant terms & chiral parameters for VBS

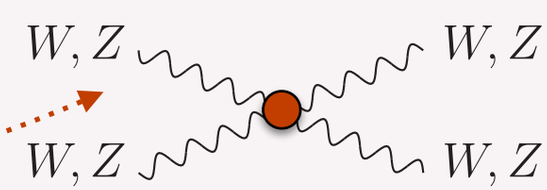
[A. C. Longhitano, 1980; T. Appelquist et al., 1980]

$b = a^2$

$$\mathcal{L}_2 = \frac{v^2}{4}\left[1 + 2a\frac{H}{v} + b\frac{H^2}{v^2}\right]\mathrm{Tr}\left(D^\mu U^\dagger D_\mu U\right) + \frac{1}{2}\partial^\mu H\,\partial_\mu H + \ldots,$$



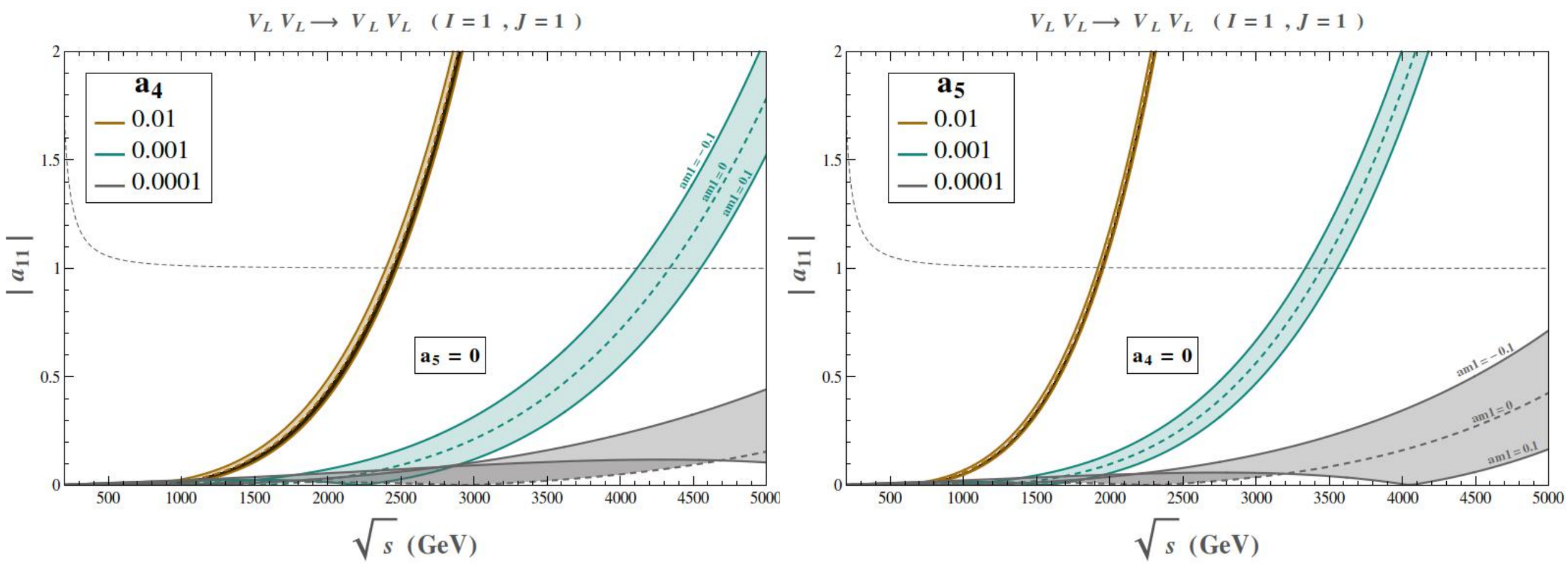
$$\mathcal{L}_4 = a_4\left[\mathrm{Tr}(\mathcal{V}_\mu\mathcal{V}_\nu)\right]\left[\mathrm{Tr}(\mathcal{V}^\mu\mathcal{V}^\nu)\right] + a_5\left[\mathrm{Tr}(\mathcal{V}_\mu\mathcal{V}^\mu)\right]\left[\mathrm{Tr}(\mathcal{V}_\nu\mathcal{V}^\nu)\right]$$



Unitarity Violation

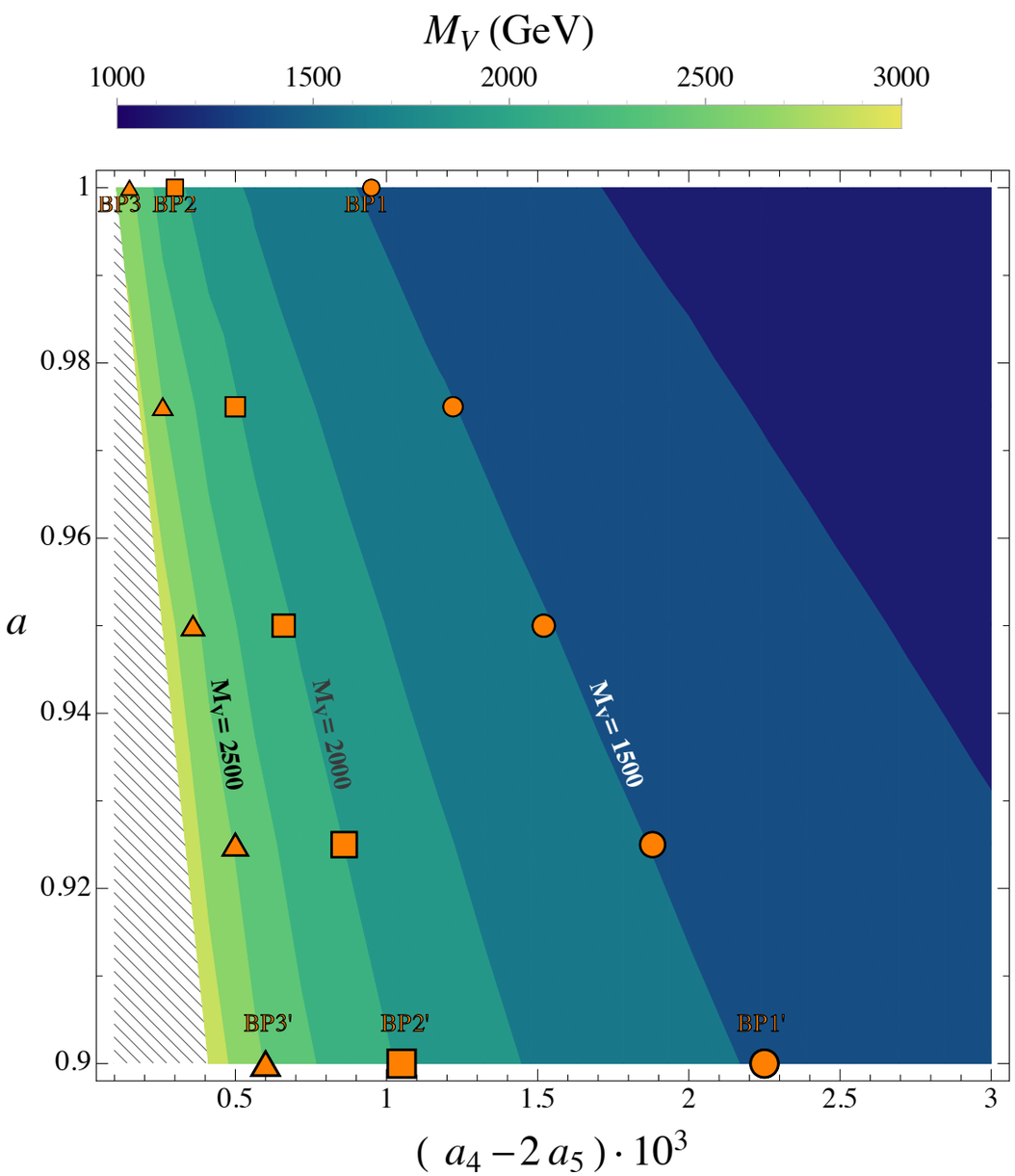
- Energy at which unitarity violation occurs is very sensitive to chiral param. values

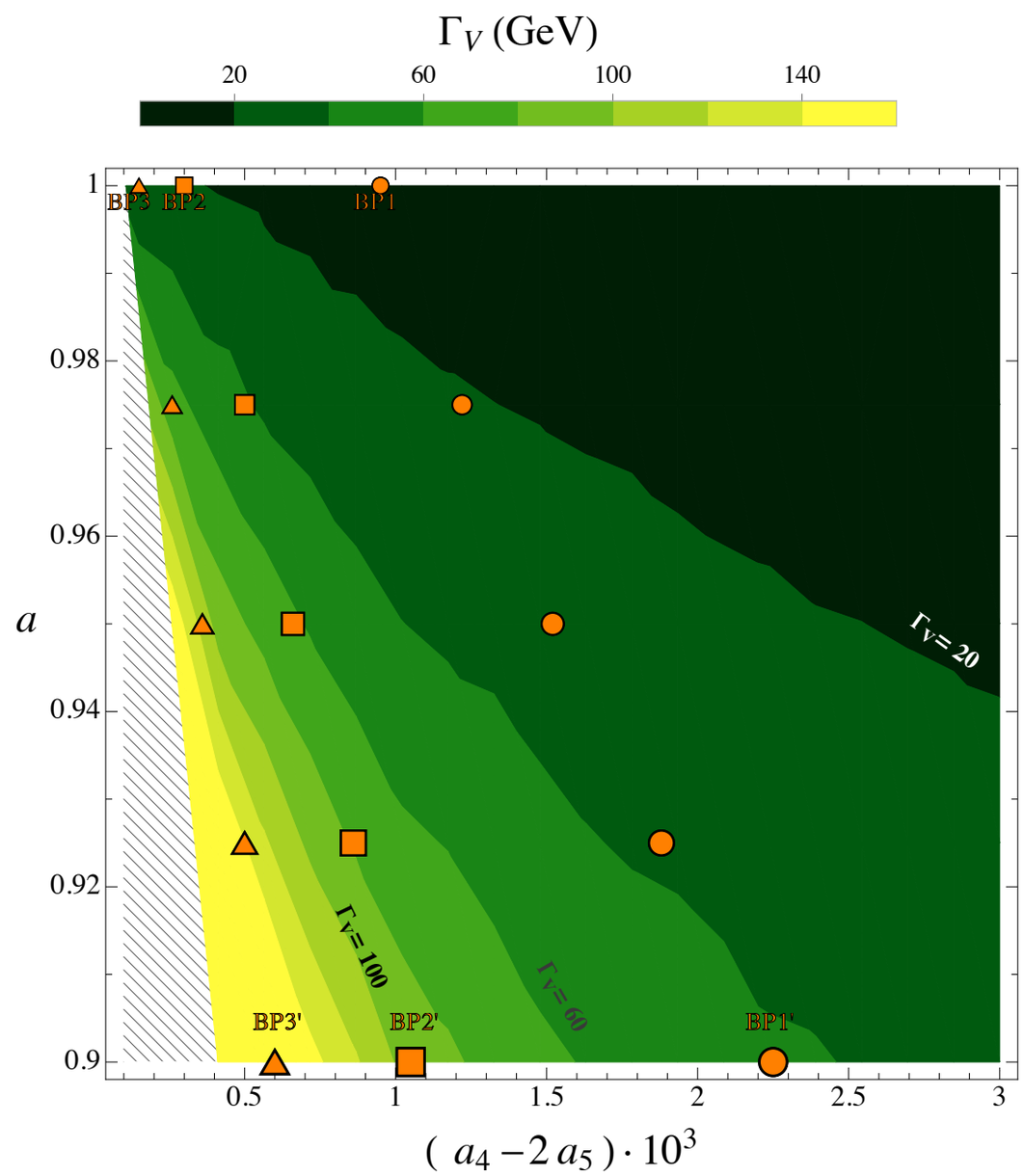
- At tree level, for the values considered $a \in [0.9, 1],\ a_4, a_5 \in [10^{-3}, 10^{-4}]$ (allowed by exp.) unitarity violation happens at the few TeV scale



Selection of Scenarios

- 5 different values of a for three lines of fixed mass value M_V
- Resonance properties M_V, Γ_V depend on chiral parameters

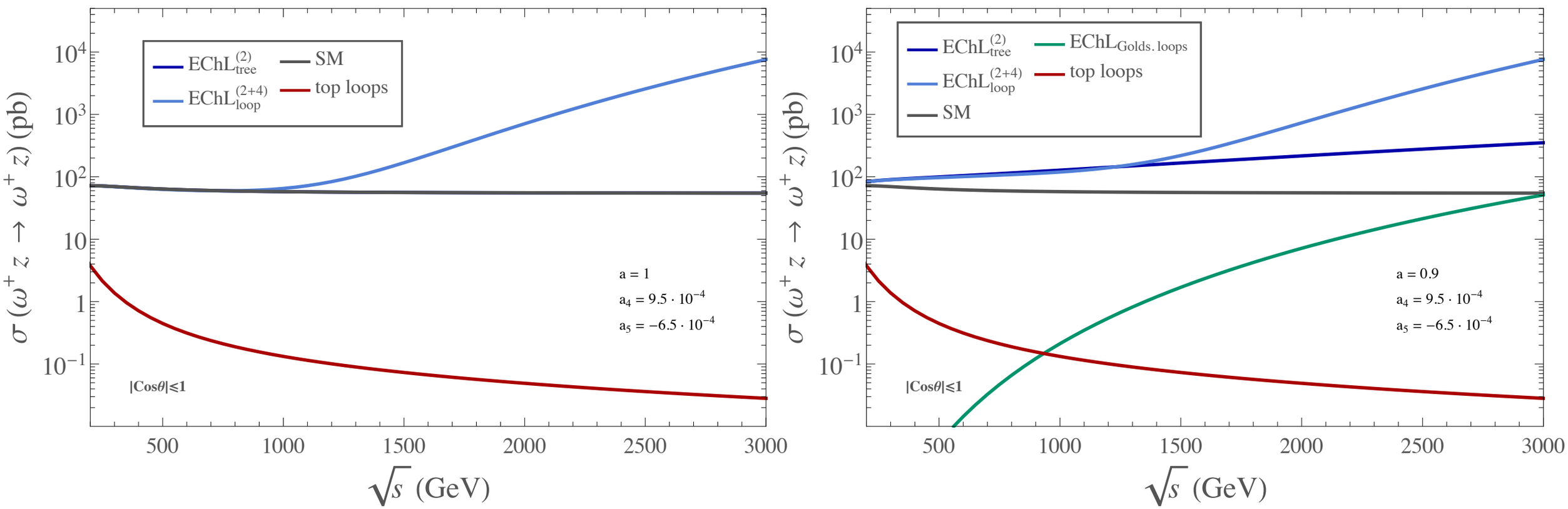




Properties of resonances: top contribution

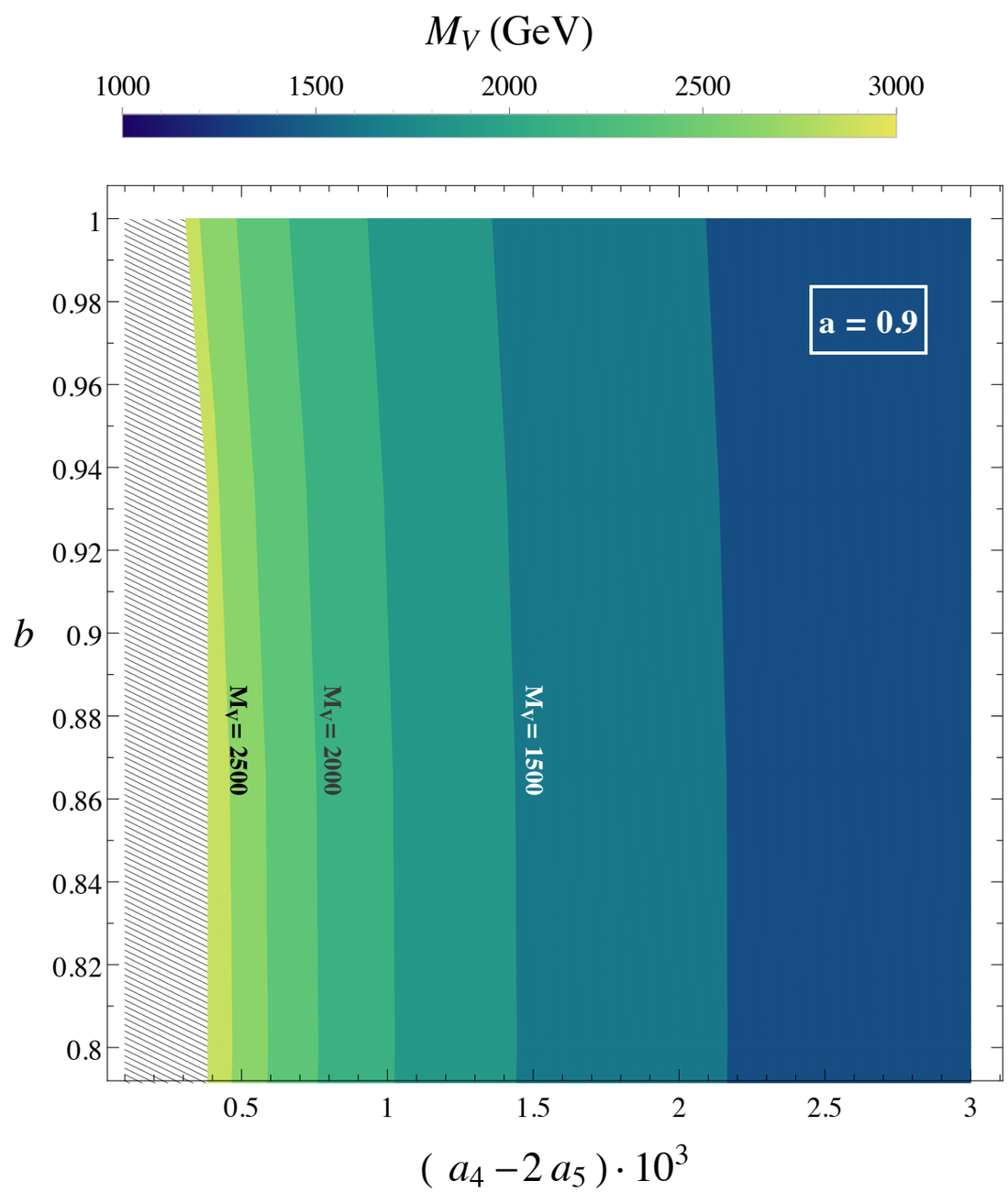
[S. Dawson, G. Valencia, Phys. Lett. B 246 (1990) 156]

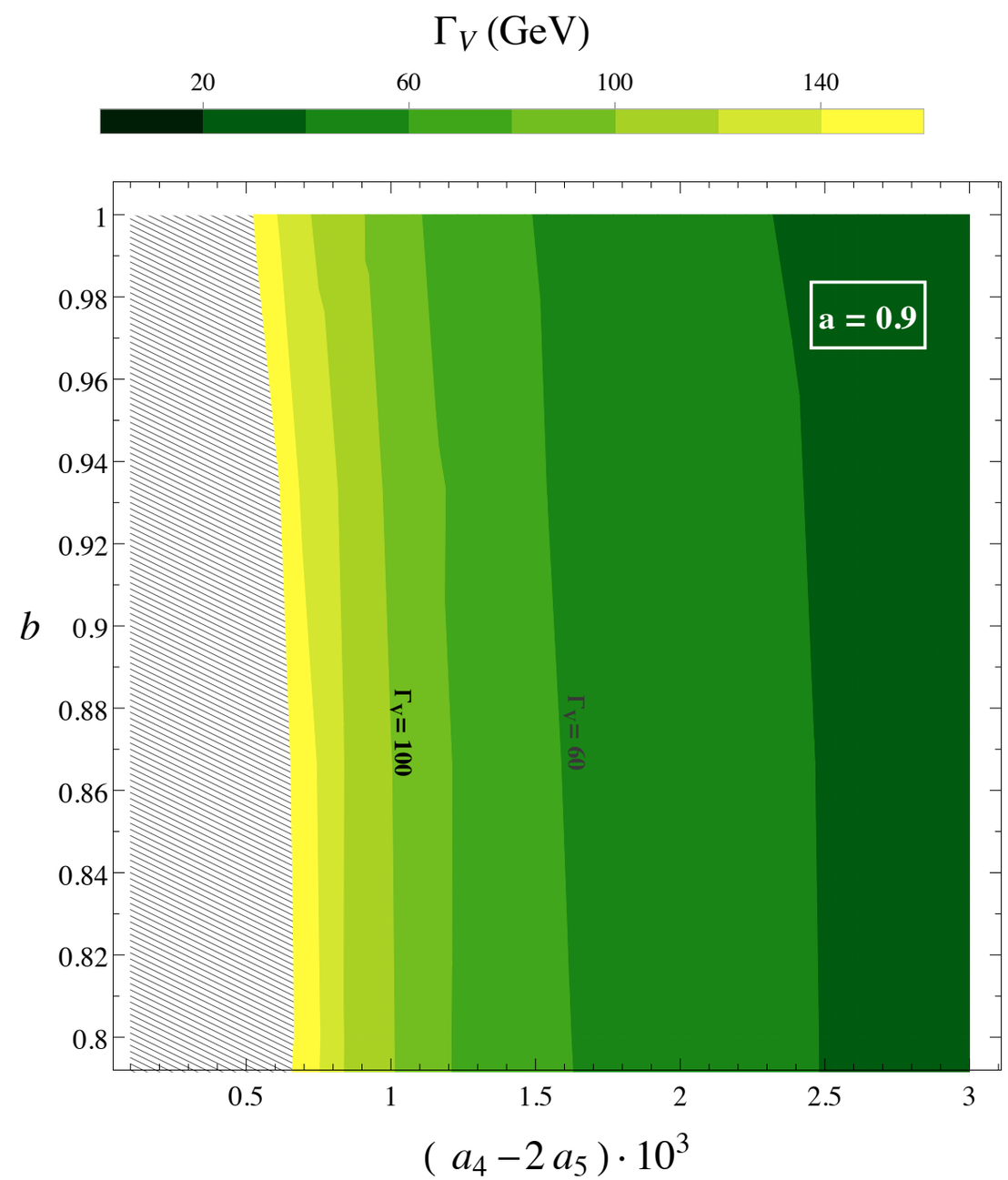
- Top loop contribution decreases with energy
- Negligible with respect to Goldstone boson loops above 1 TeV
- Subleading effects on resonance properties



Properties of resonances: the b parameter

- Indirect constraints: $b \in [0, 2]$ [R.L. Delgado, A. Dobado et al., Phys. Rev. Lett. 114 (2015) 221803]
- Relaxing condition $b = a^2$ does not modify properties of resonances





Our model: IAM-MC for resonant WZ scattering

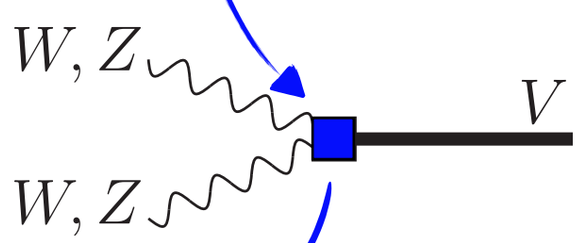
- MG5 → Prediction for resonance observables in W^+Z → Works with FR as input

Chiral inv. Lagrangian to mimic IAM vector resonances

$$\mathscr{L}_V = \frac{i2g_V}{v^2}\left[m_W^2 V^{0\,\mu\nu} W_\mu^+ W_\nu^- + m_W\, m_Z\, V^{+\,\mu\nu} W_\mu^- Z_\nu + m_W\, m_Z\, V^{-\,\mu\nu} Z_\mu W_\nu^+\right] + \dots$$

From Proca Lagrangian [G. Ecker, et al., Phys. Lett. B223, 425 (1989)]

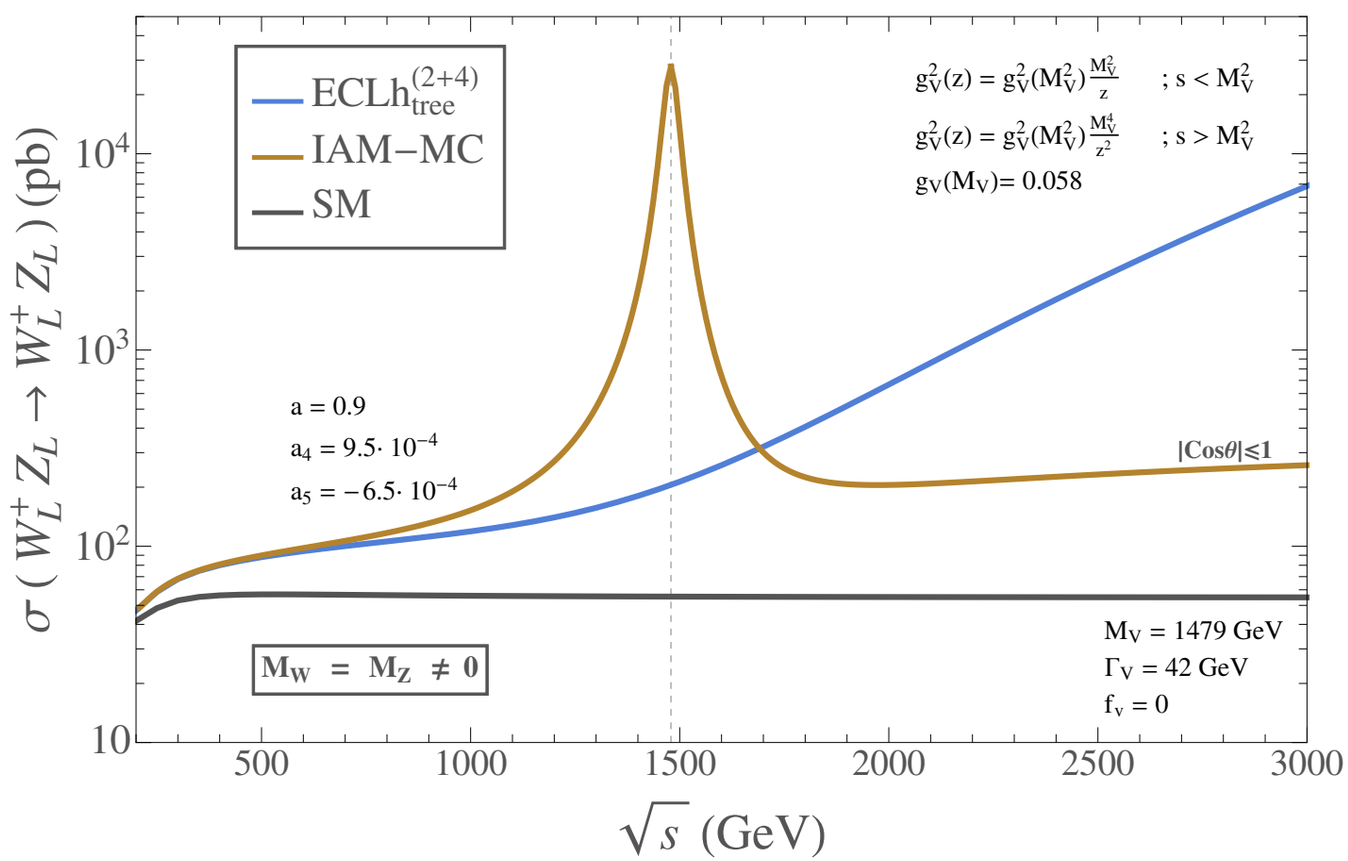
$$\mathscr{L}_{\mathrm{IAM-MC}} = \mathscr{L}_2 + \mathscr{L}_V$$



Agreement with IAM unitarized Partial Waves

g_V ↔ **Form Factor**

- EChL $\mathscr{L}_4$ recovered for $s < M_V^2$
- $g_V(M_V^2) \equiv g_V(a, b, a_4, a_5) \sim 10^{-2}$
- Froissart unitarity bound for $s > M_V^2$



VBS Event Selection

- **VBS kinematics** very characteristic
- **extra jets** key to select VBS efficiently

$|\eta_{W,Z}| < 2$

WZ final state

$2 < |\eta_j| < 5$
$\eta_{j_1} \cdot \eta_{j_2} < 0$
$m_{jj} > 500$ GeV
$p_T^j > 20$ GeV

leptonic final state

$M_Z - 10 \text{ GeV} < m_{\ell_Z^+ \ell_Z^-} < M_Z + 10 \text{ GeV}$
$M_{WZ}^T \equiv M_{\ell\ell\ell\nu}^T > 500$ GeV
$\not{E}_T > 50$ GeV
$p_T^\ell > 40$ GeV

Transverse invariant mass

$$M_{WZ}^T = \sqrt{\left(\sqrt{M^2(\ell\ell\ell) + p_T^2(\ell\ell\ell)} + |\not{p}_T|\right)^2 - (\vec{p_T}(\ell\ell\ell) + \vec{\not{p}_T})^2}$$