Searching for new physics in Vector Boson Scattering at the LHC

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Based on JHEP 1711 (2017) 098, [arXiv:1707.04580]

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

Motivation

What is the dynamical generation of EWSB?

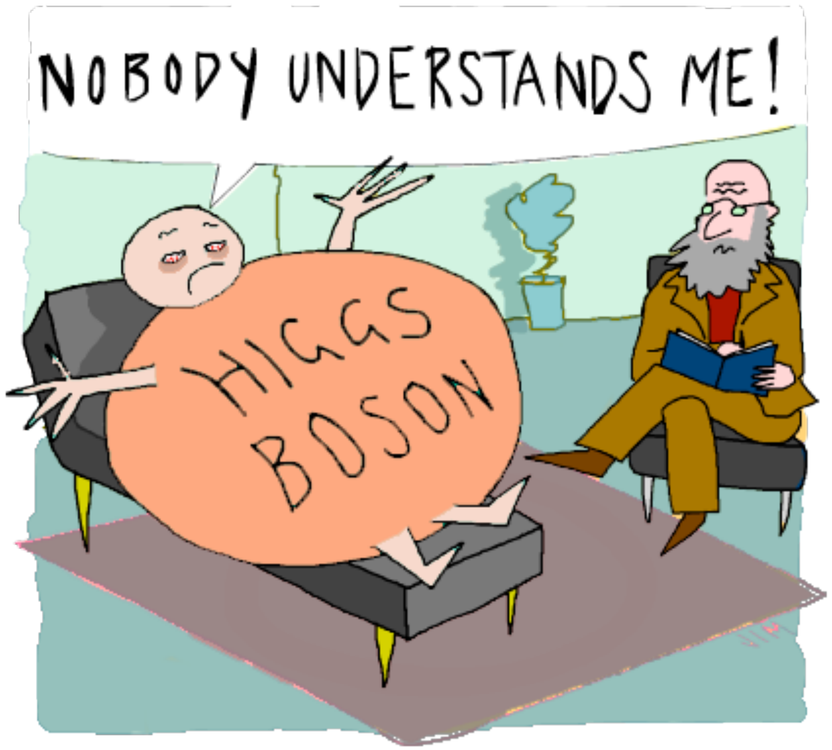
Effective Theories for EWSB

- 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

- 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

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

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  - → **EW GB's** $w^{\pm}, z$ introduced non-linearly $U(w^{\pm}, z) = e^{\frac{i w^a \tau^a}{v}}$

    Equivalence Theorem! $w^{\pm}, z \Leftrightarrow W_L^{\pm}, Z_L$
  - → **EW gauge bosons** $W^{\pm}, Z$ described by D_μ, $W_{\mu\nu}$, & $B_{\mu\nu}$
  - → **Higgs singlet** under Chiral symmetry → $\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2$

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- Building blocks:

$$D_\mu U \qquad \hat{W}_{\mu\nu}, \hat{B}_{\mu\nu} \qquad \mathcal{F}(h) \qquad \mathcal{V}_\mu = (D_\mu U)U^\dagger$$

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

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

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

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$b = a^2$

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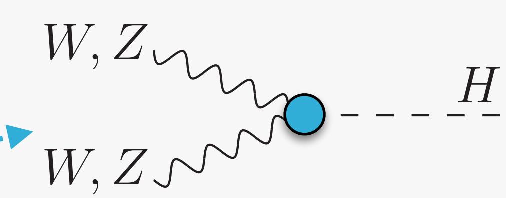

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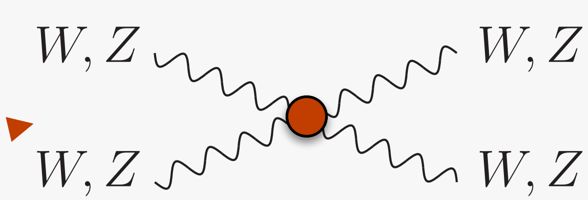

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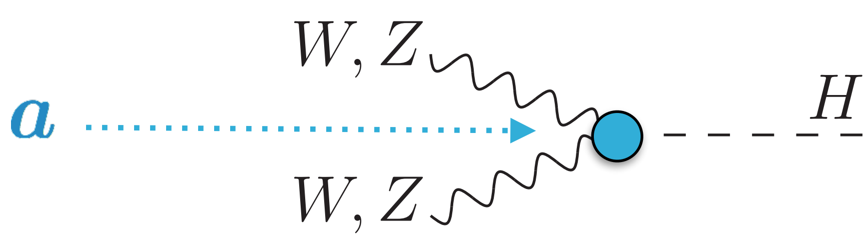
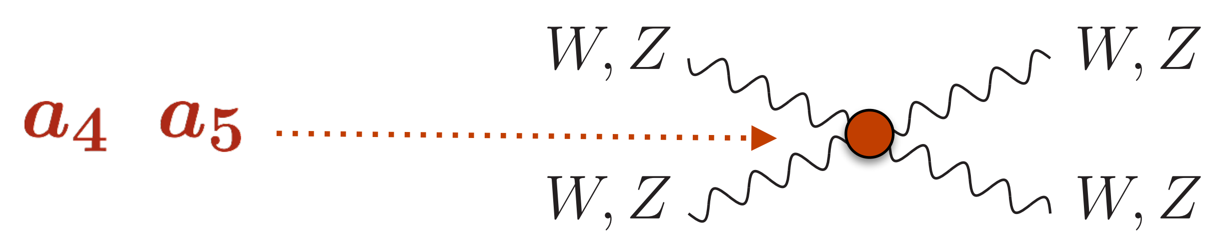
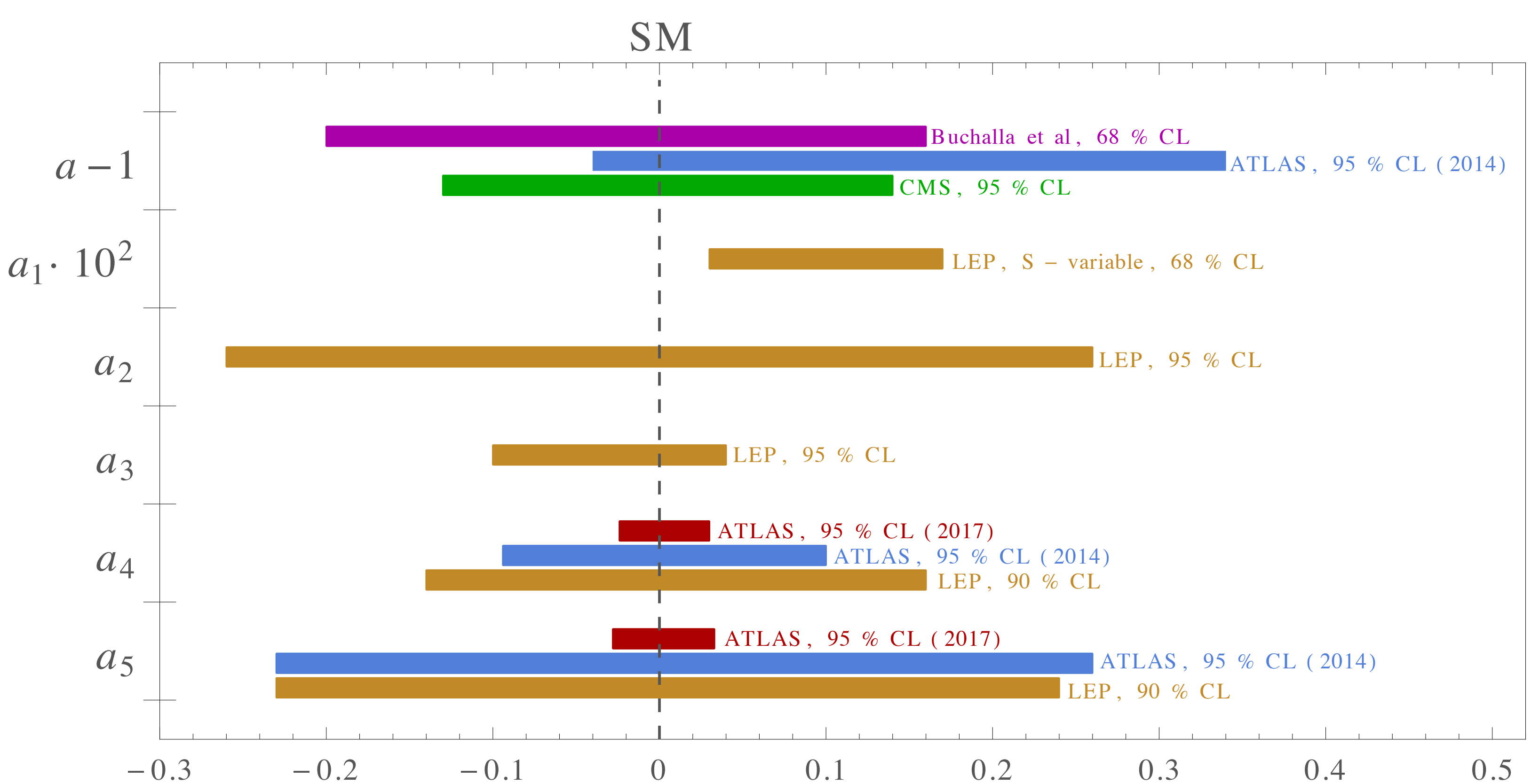
Relevant Chiral Parameters

- Most relevant: a a_4 a_5 → Remain present for $g = g' = 0$





- Constraints



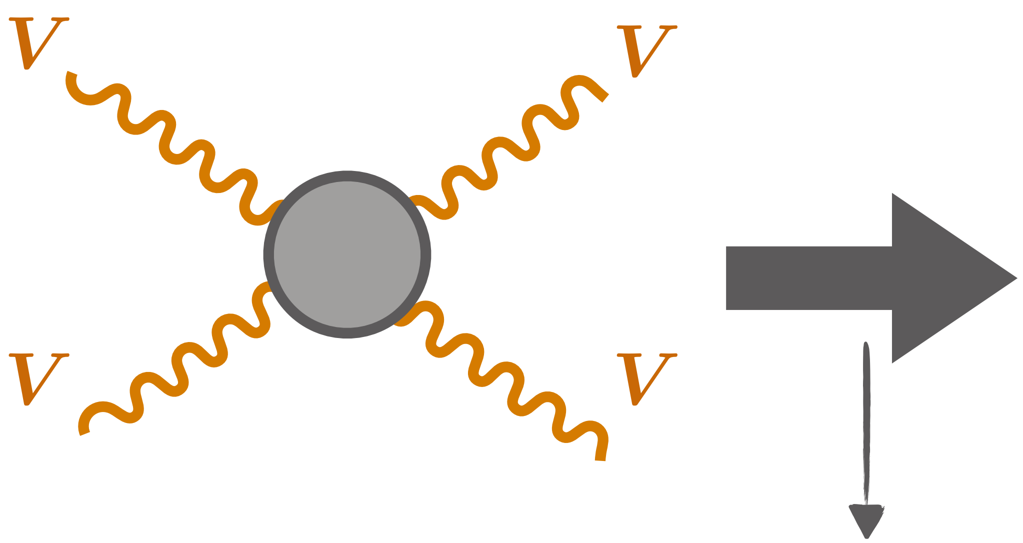
Considered intervals

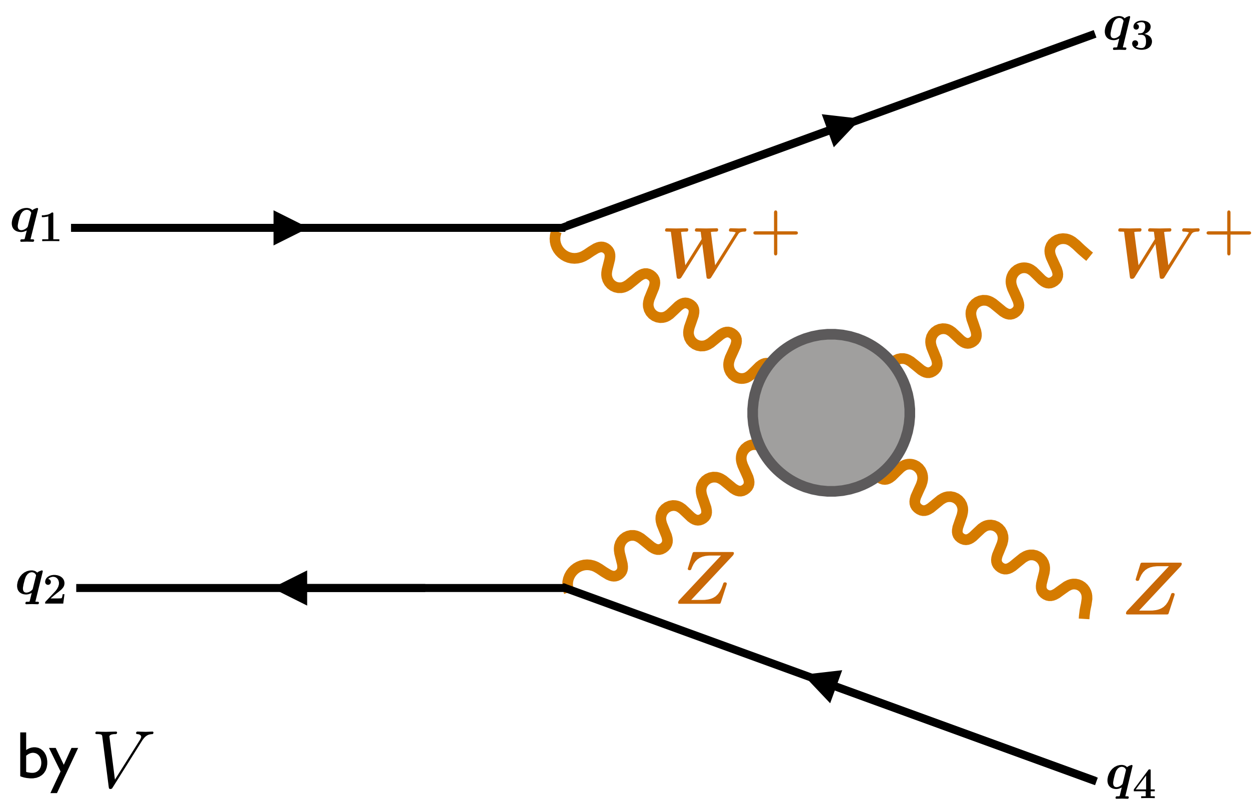
$$a \in [0.9, 1]$$

$$a_4, a_5 \in [10^{-3}, 10^{-4}]$$

Resonance mass in TeV range

Study resonant behavior in W^+Z scattering @ the LHC





Mediated only by V

No severe QCD backgrounds

Requirement of unitarity

No use of Equivalence Theorem

Implementation following: [D. Espriu et al., Phys. Rev. D90, 015035 (2014)]

Dynamical Generation of Resonances: the IAM

- Expansion in powers of p —typically→ **Violation of Unitarity** → Energy at which occurs depends on $(a-1), a_4, a_5$

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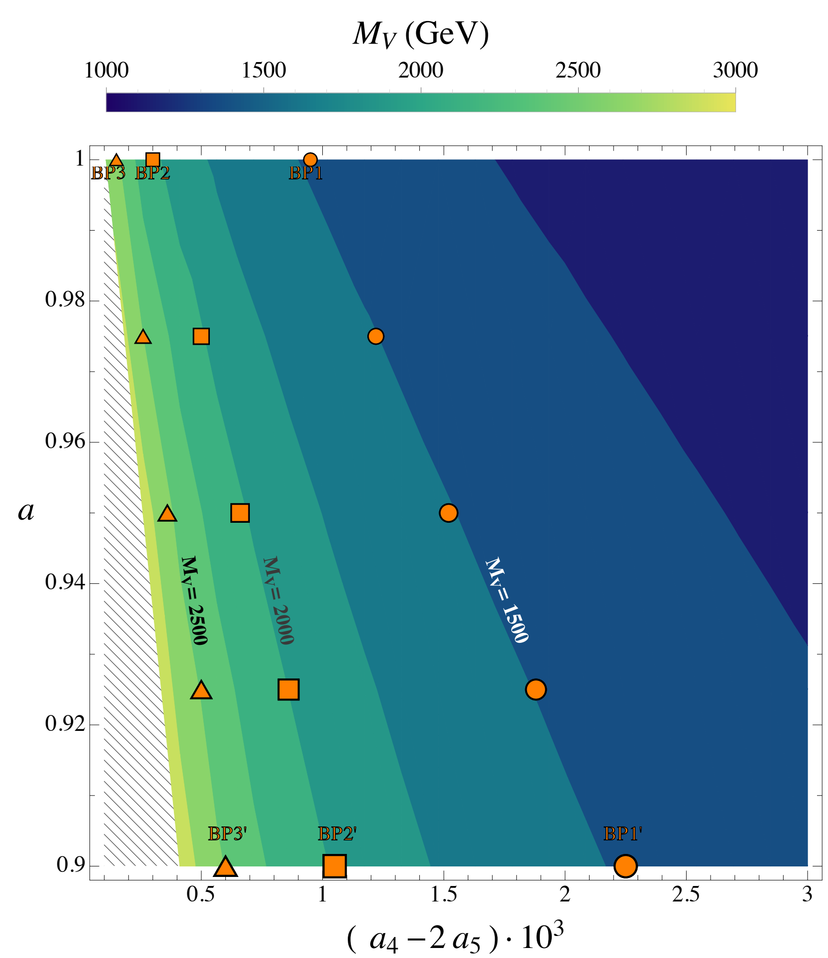
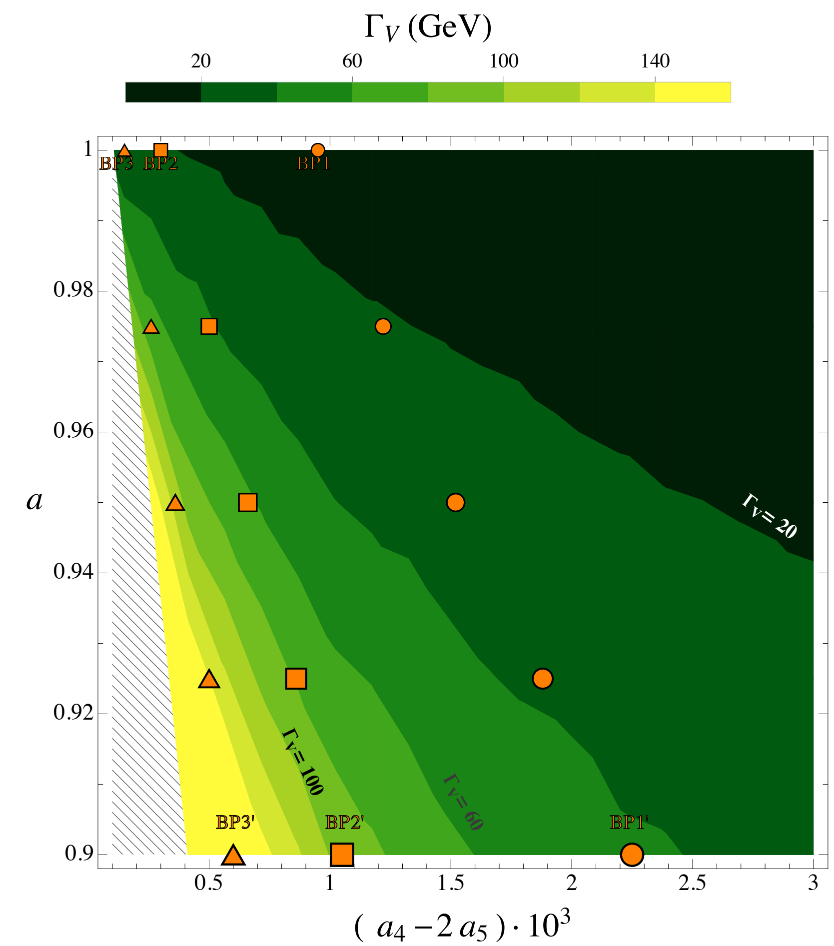
- We select **vector** scenarios

- Relevant combination $(a_4 - 2a_5)$

- 5 values of a for three lines of fixed mass M_V





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Difficult to Implement in Monte Carlo!

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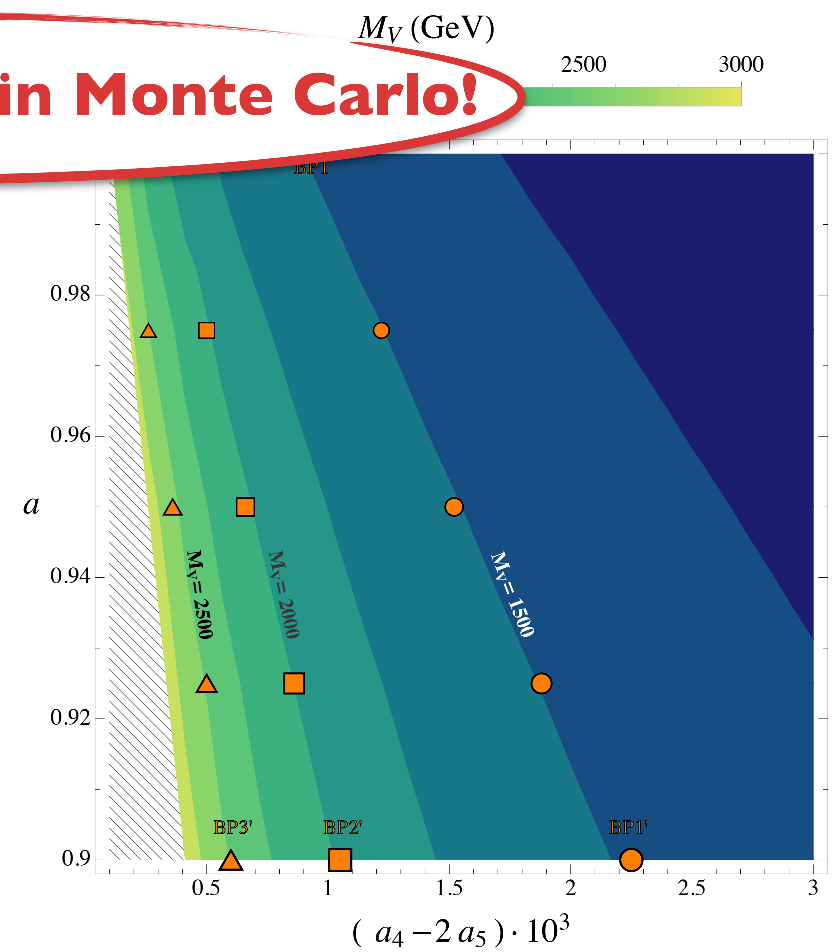

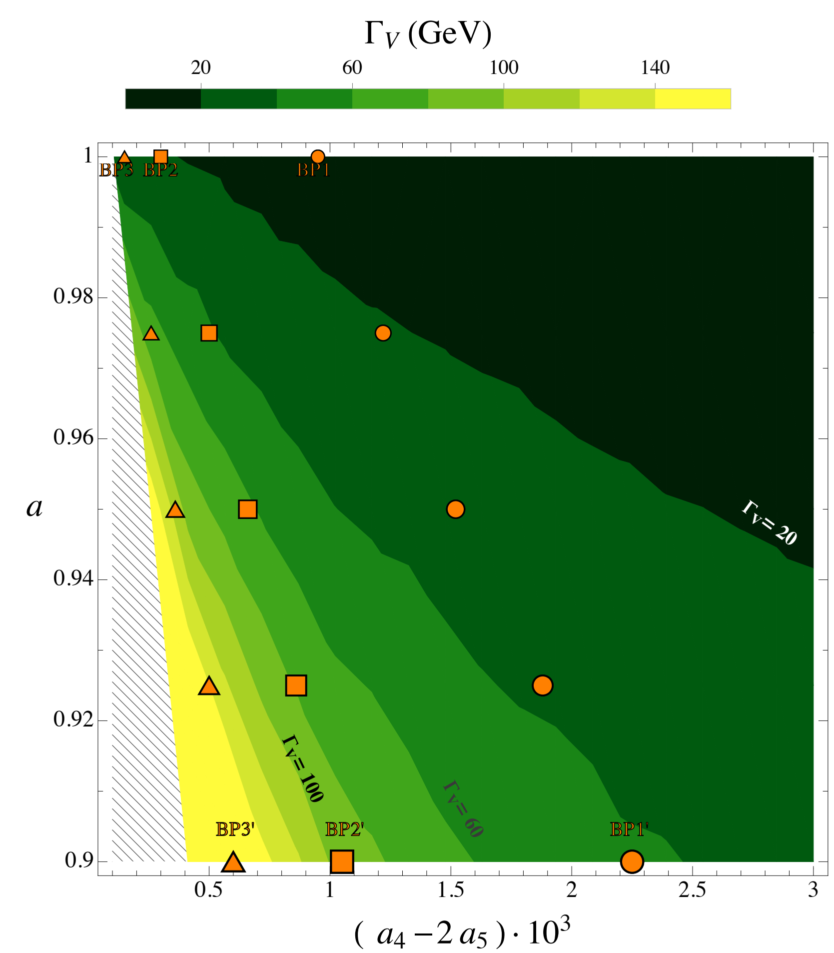

The tool to introduce the resonances

- MadGraph5 → Prediction for resonant observables in W^+Z → Works with FR

Used to mimic IAM vector resonances

EW gauge & Chiral invariant

$$\mathcal{L}_V = -\frac{1}{4}\mathrm{Tr}(\hat{V}_{\mu\nu}\hat{V}^{\mu\nu}) + \frac{1}{2}M_V^2\,\mathrm{Tr}(\hat{V}_\mu\hat{V}^\mu) + \frac{f_V}{2\sqrt{2}}\mathrm{Tr}(\hat{V}_{\mu\nu}f_+^{\mu\nu}) + \frac{ig_V}{2\sqrt{2}}\mathrm{Tr}(\hat{V}_{\mu\nu}\,[u^\mu, u^\nu])$$

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

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Unitary gauge
Rotation to mass basis

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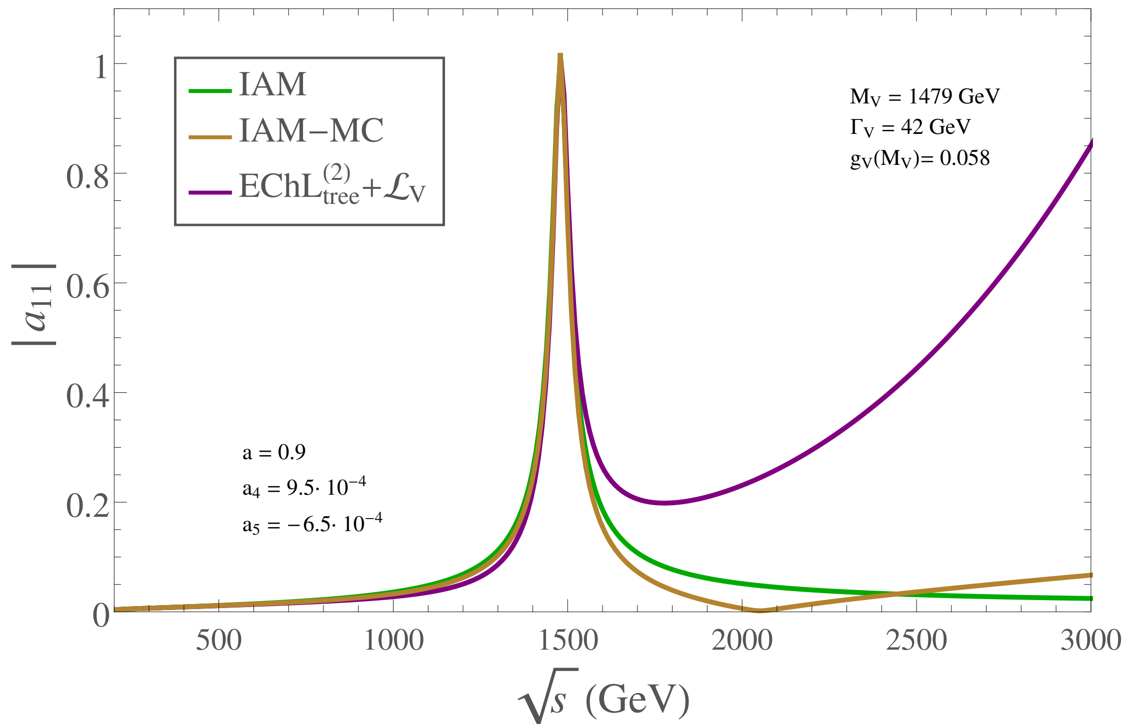
$$+\frac{i2g_V}{v^2}\Big[m_W^2 V^{0\,\mu\nu}W^+_\mu W^-_\nu + m_W m_Z V^{+\,\mu\nu}W^-_\mu Z_\nu + m_W m_Z V^{-\,\mu\nu}Z_\mu W^+_\nu\Big]$$

Our model: IAM-MC for resonant WZ scattering

- Proca Lagrangian with constant g_V violates unitarity



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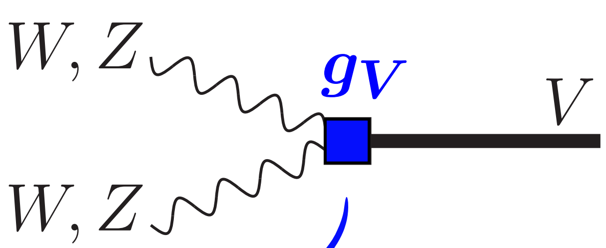

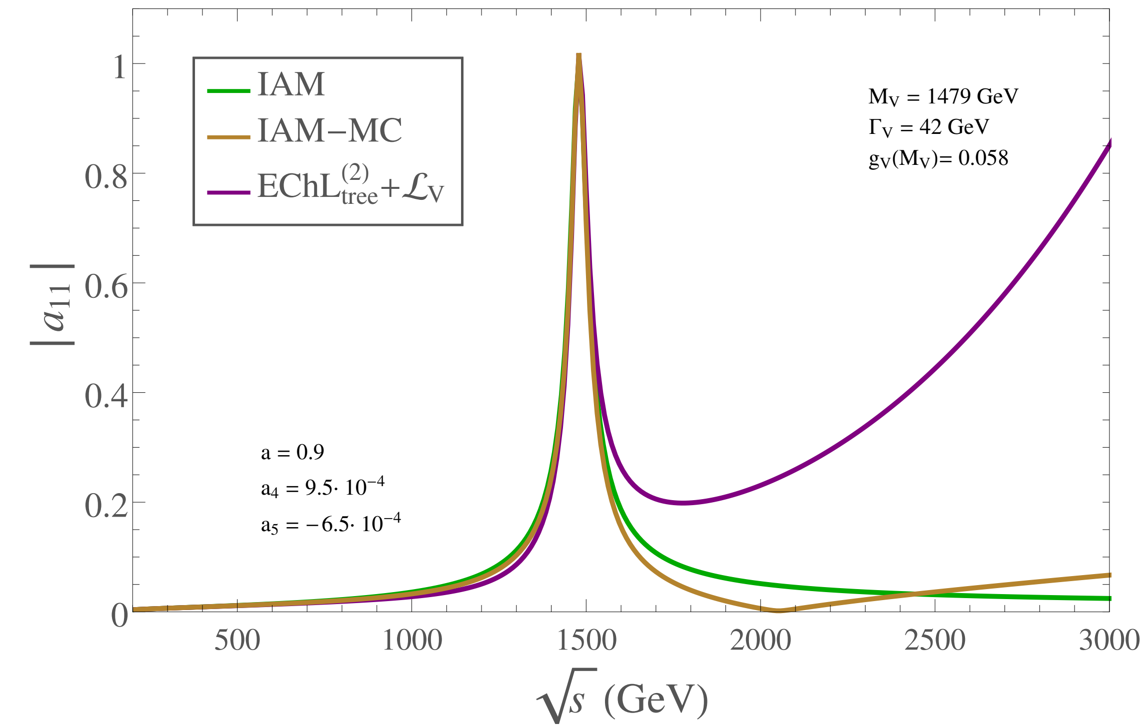

g_V ⟷ **Form Factor**

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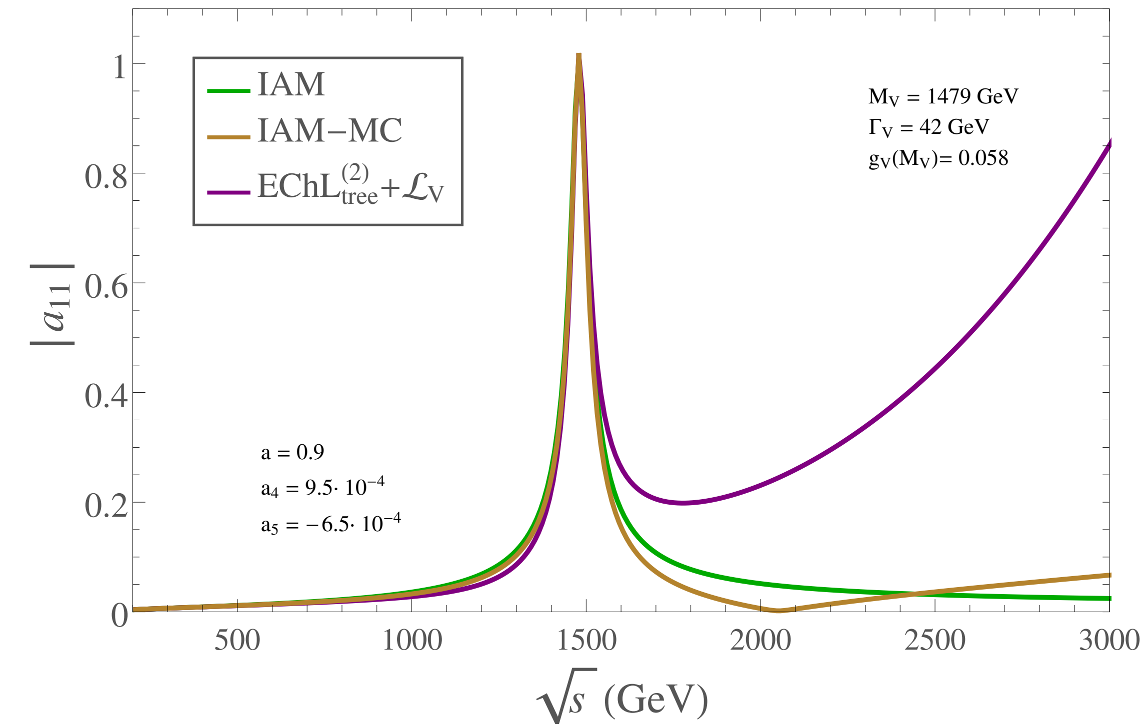

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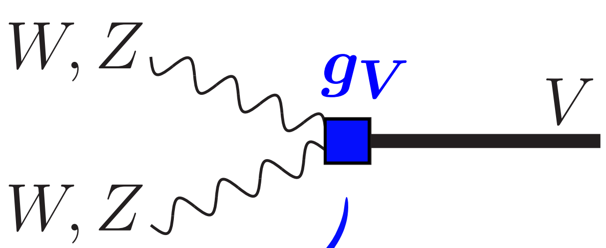

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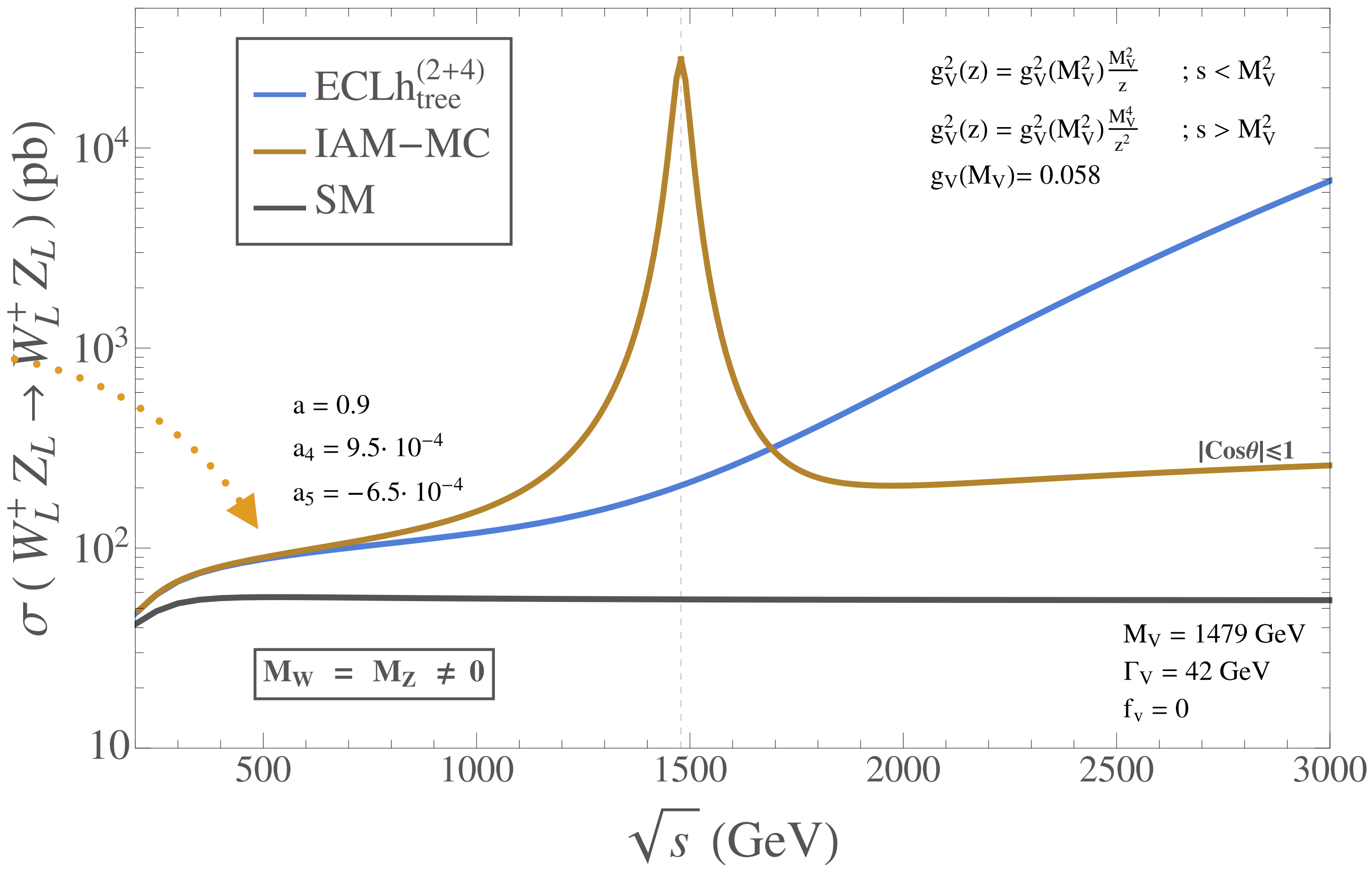

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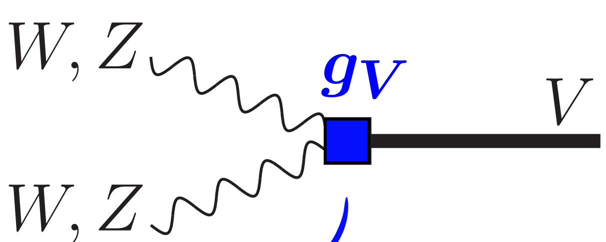

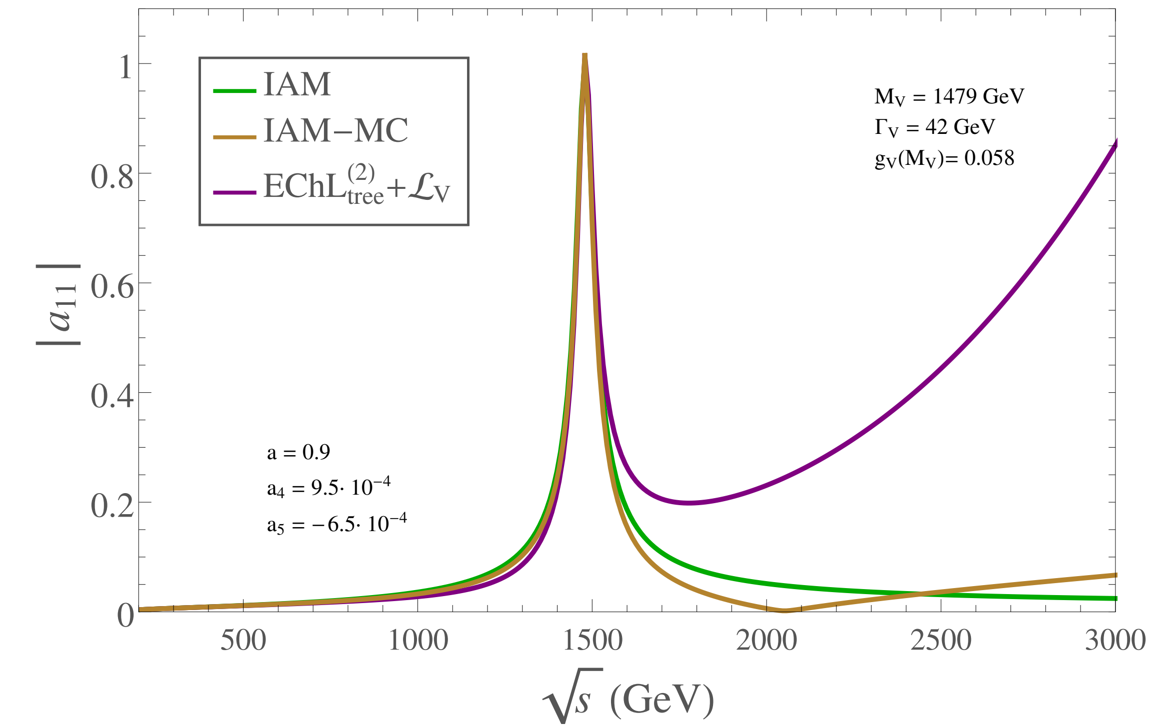

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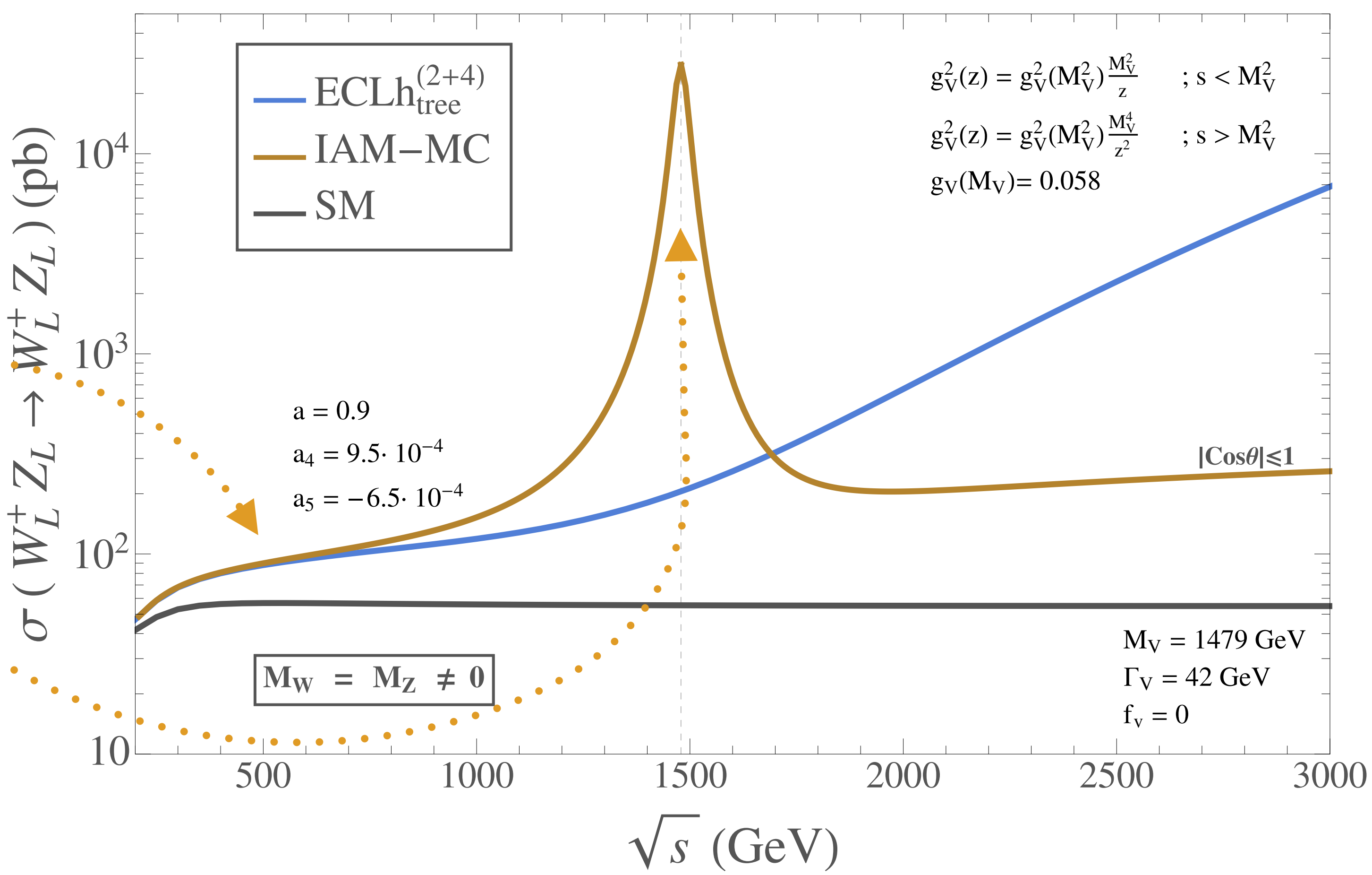

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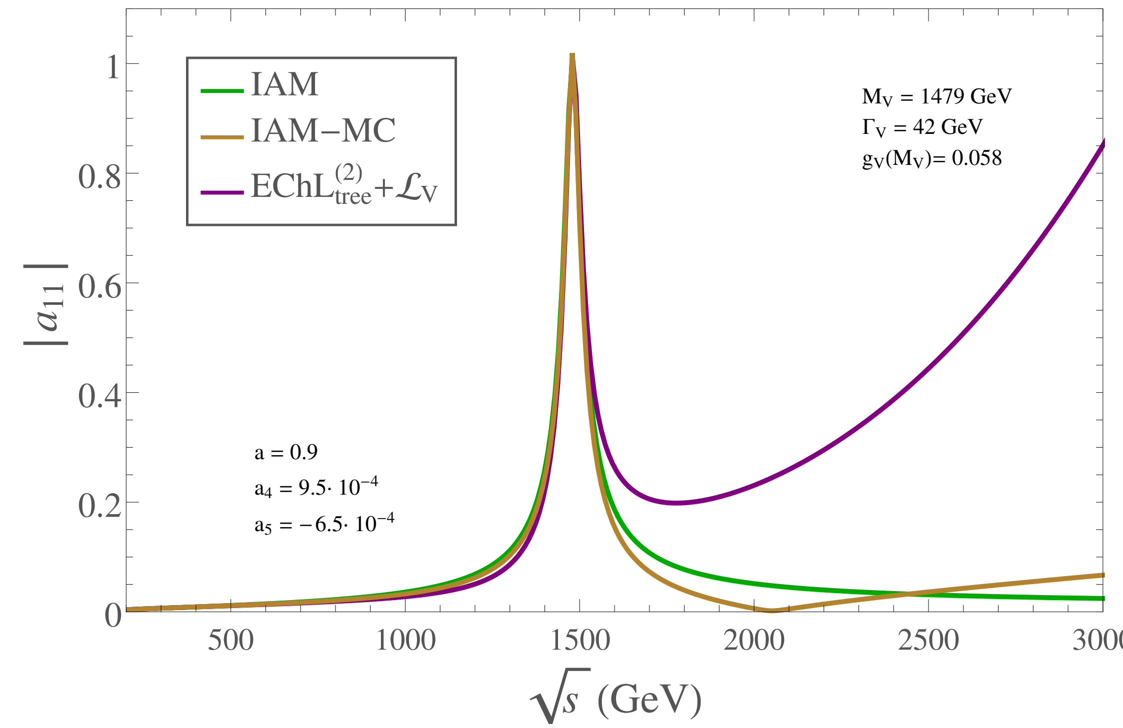

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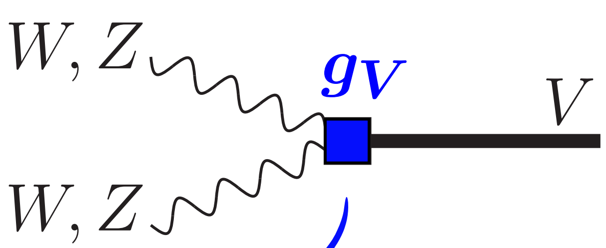

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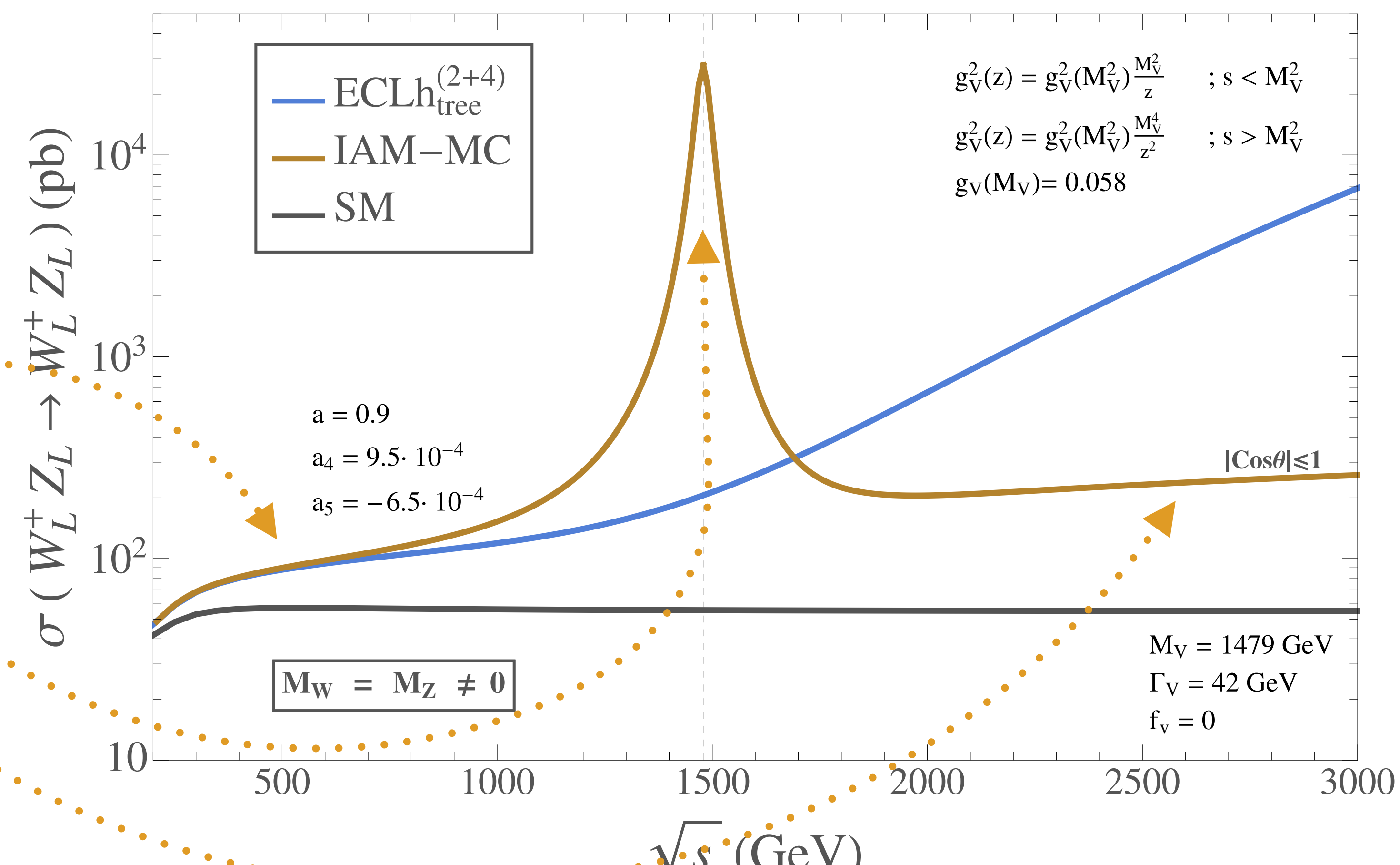
- $g_V(M_V^2) \equiv g_V(a, b, a_4, a_5) \sim 10^{-2}$
- Froissart unitarity bound for $s > M_V^2$
  [M. Froissart, Phys. Rev. 123, 1053 (1961)]



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
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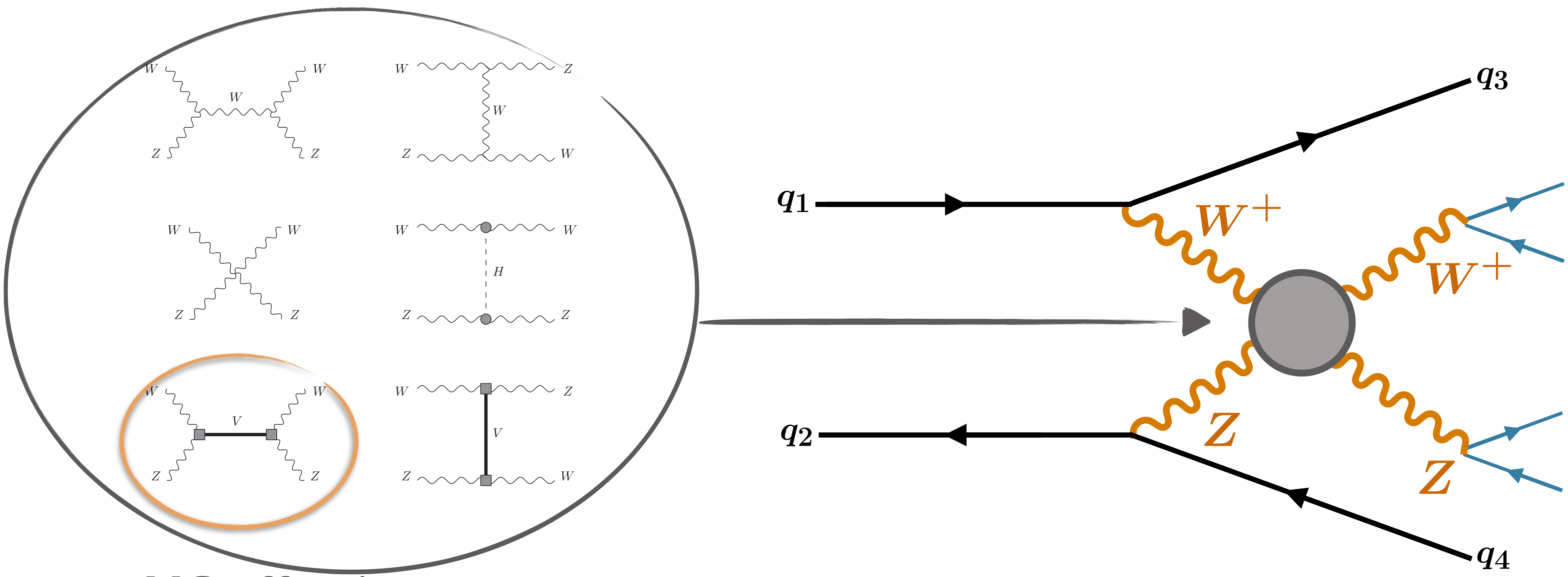
  - Clean leptonic signal
- Signals $pp \to W^+Zjj$ $\quad pp \to \ell_1^+\ell_1^-\ell_2^+ \not{E}_T jj$ $\quad pp \to JJjj$



MG effective vertex

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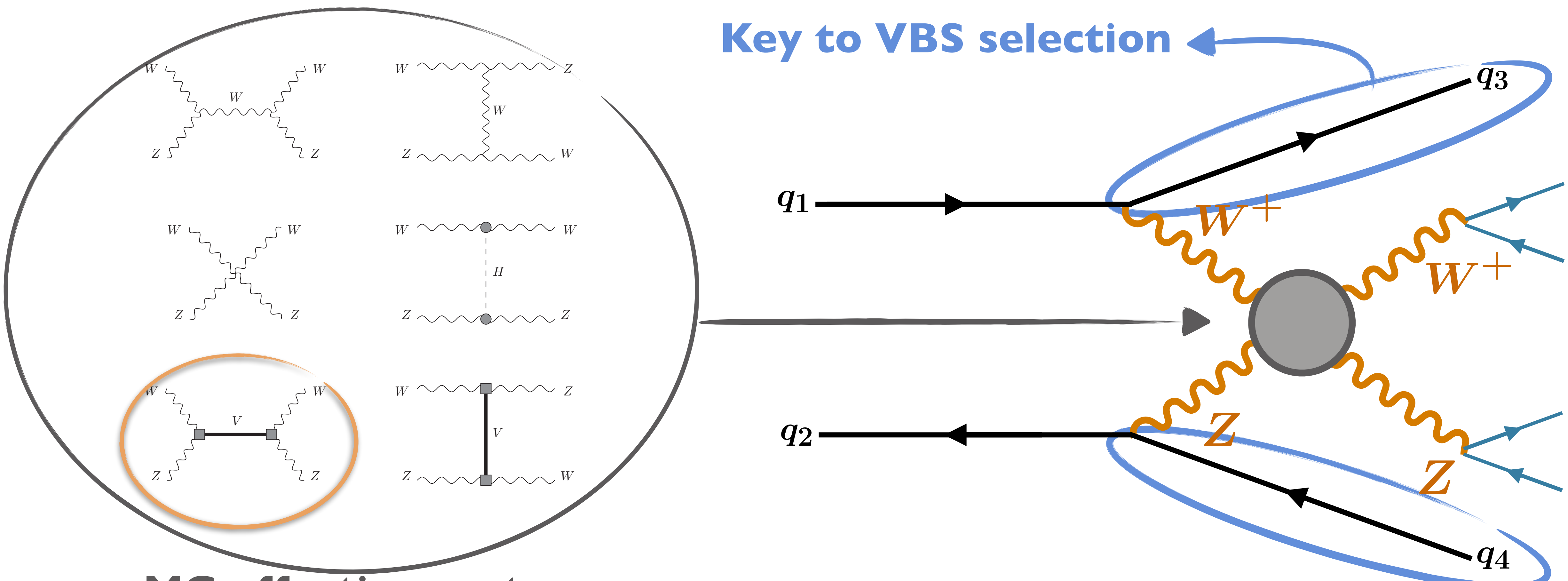

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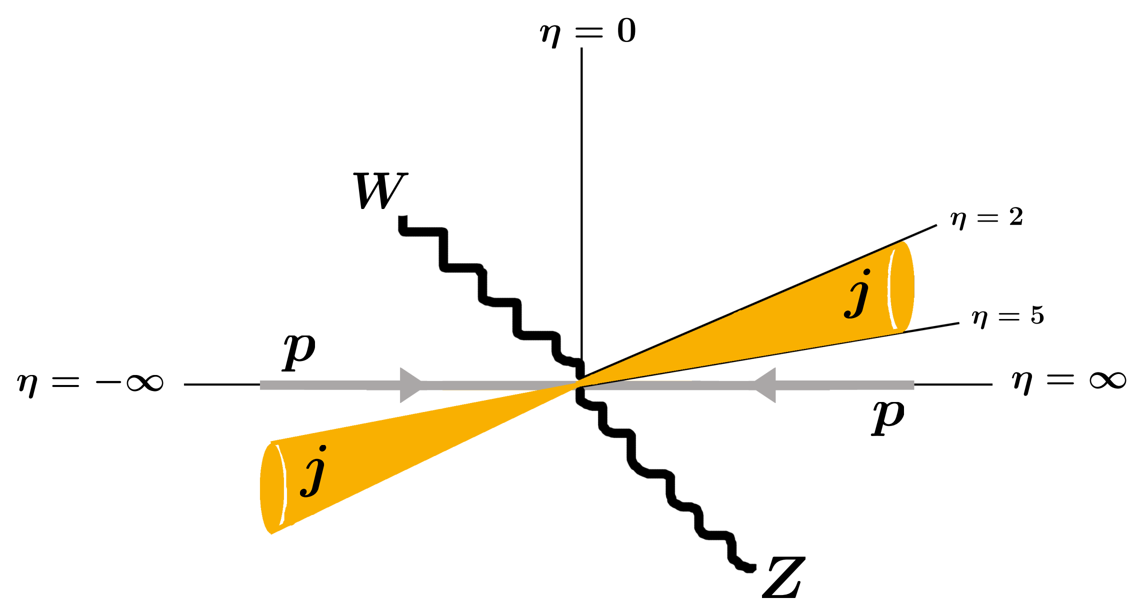
VBS Event Selection

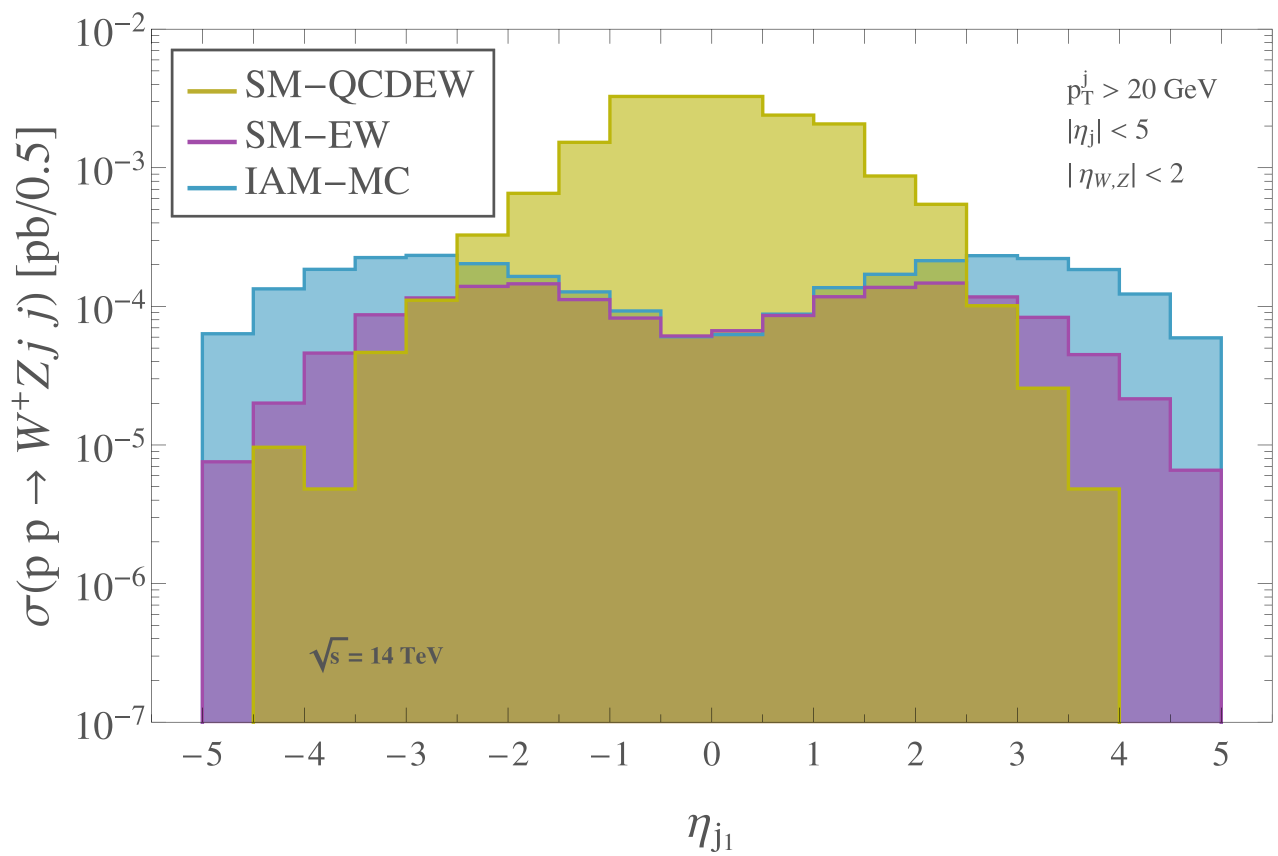
- **VBS kinematics** very characteristic

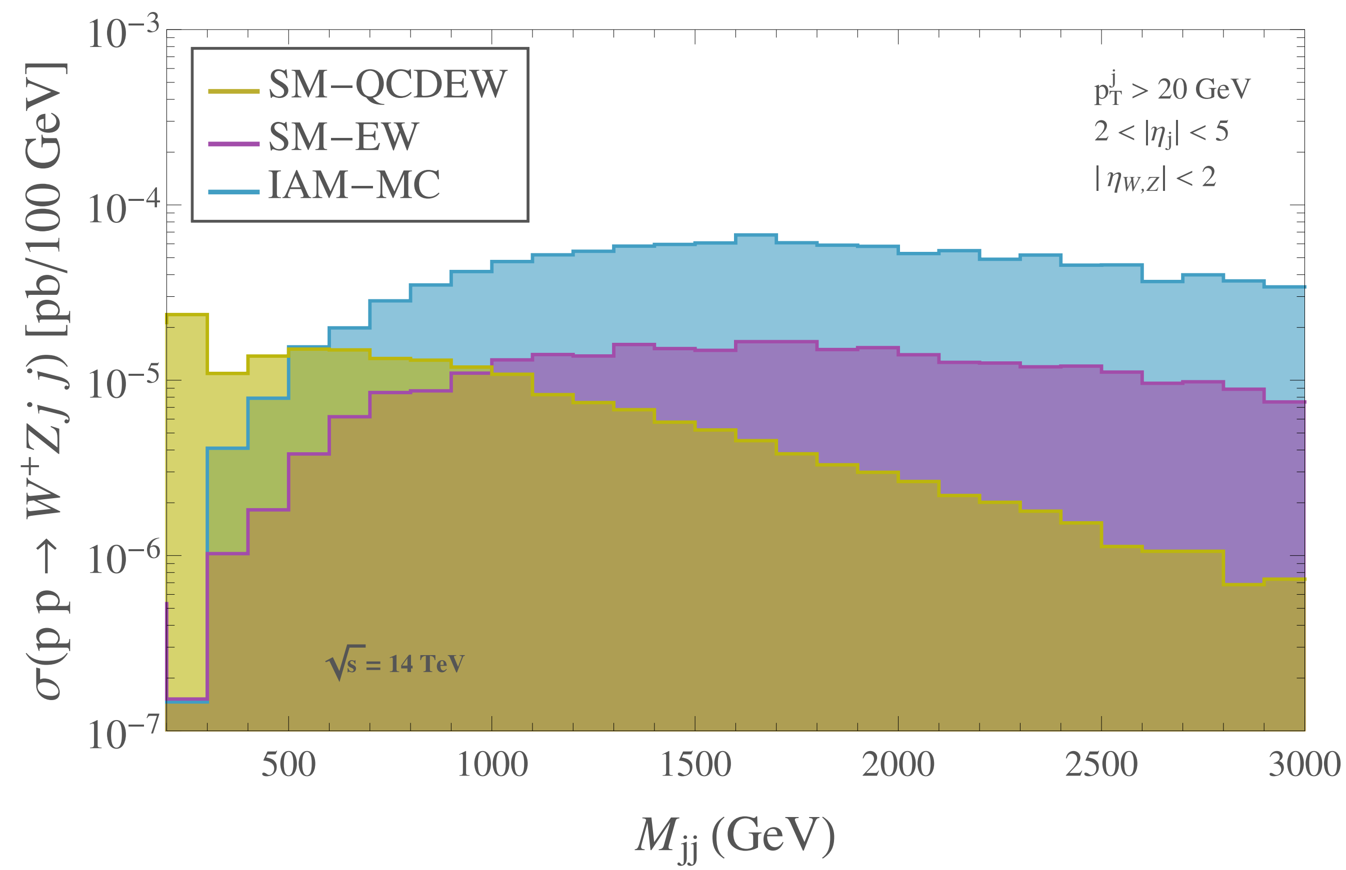
$$2 < |\eta_j| < 5$$
$$\eta_{j_1} \cdot \eta_{j_2} < 0$$
$$m_{jj} > 500\ \mathrm{GeV}$$
$$p_T^j > 20\ \mathrm{GeV}$$

- **Extra jets** key to select VBS efficiently



- Very effective in our case: **W⁺Zjj**



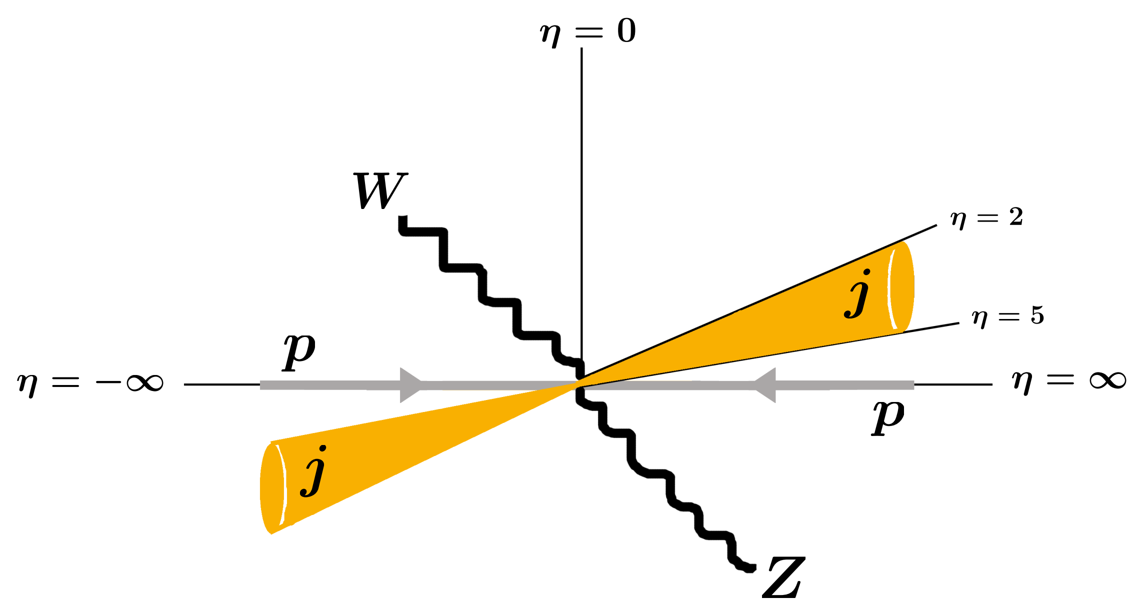


VBS Event Selection

- **VBS kinematics** very characteristic

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

- **Extra jets** key to select VBS efficiently



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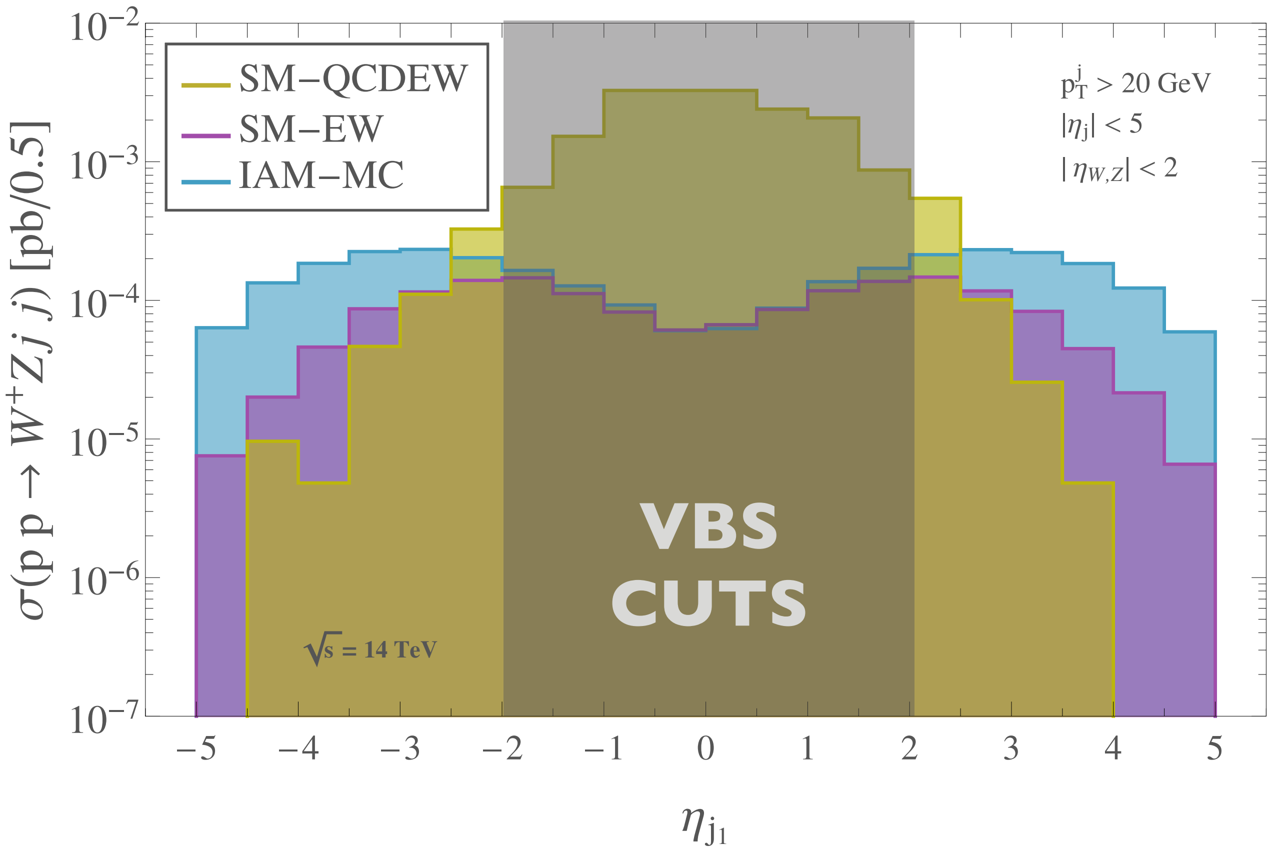
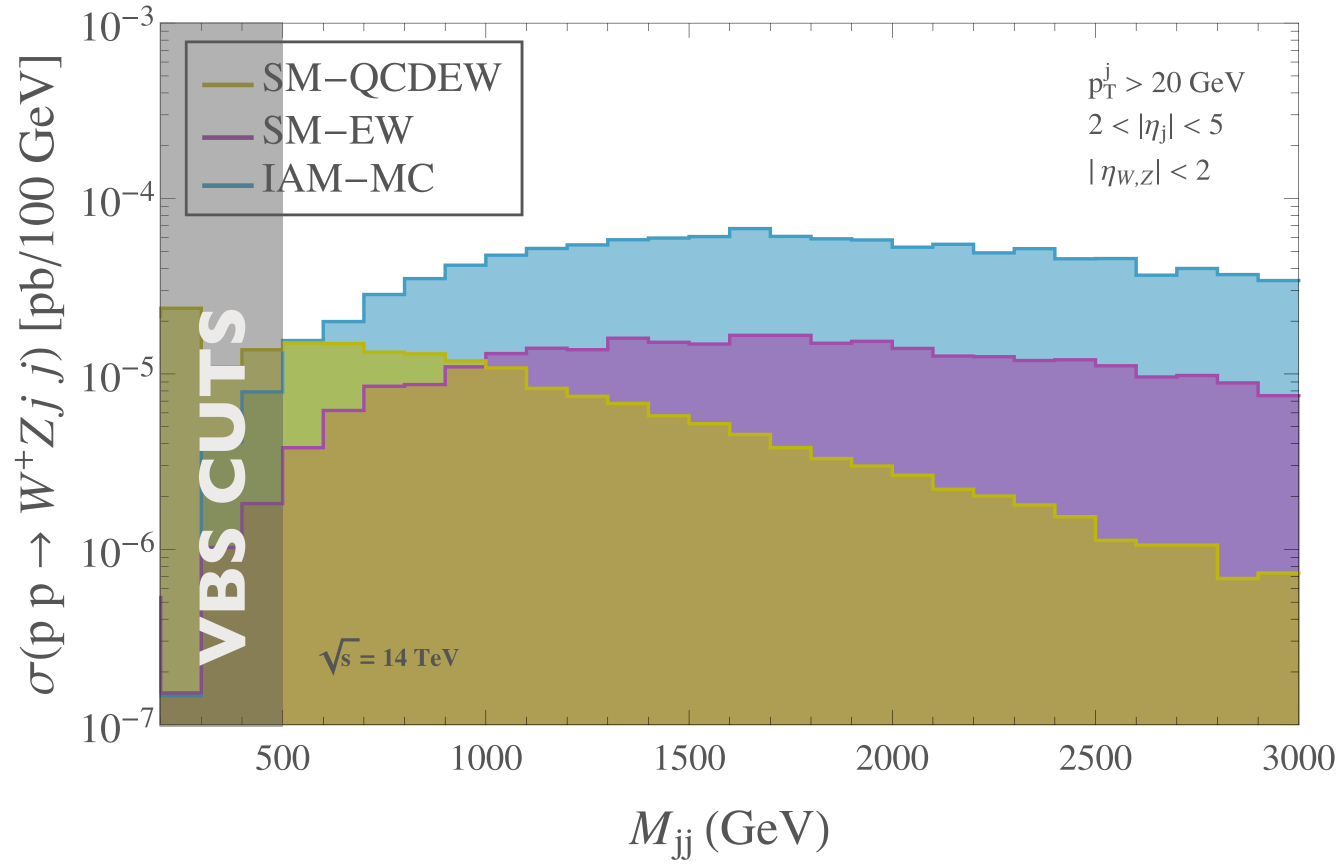
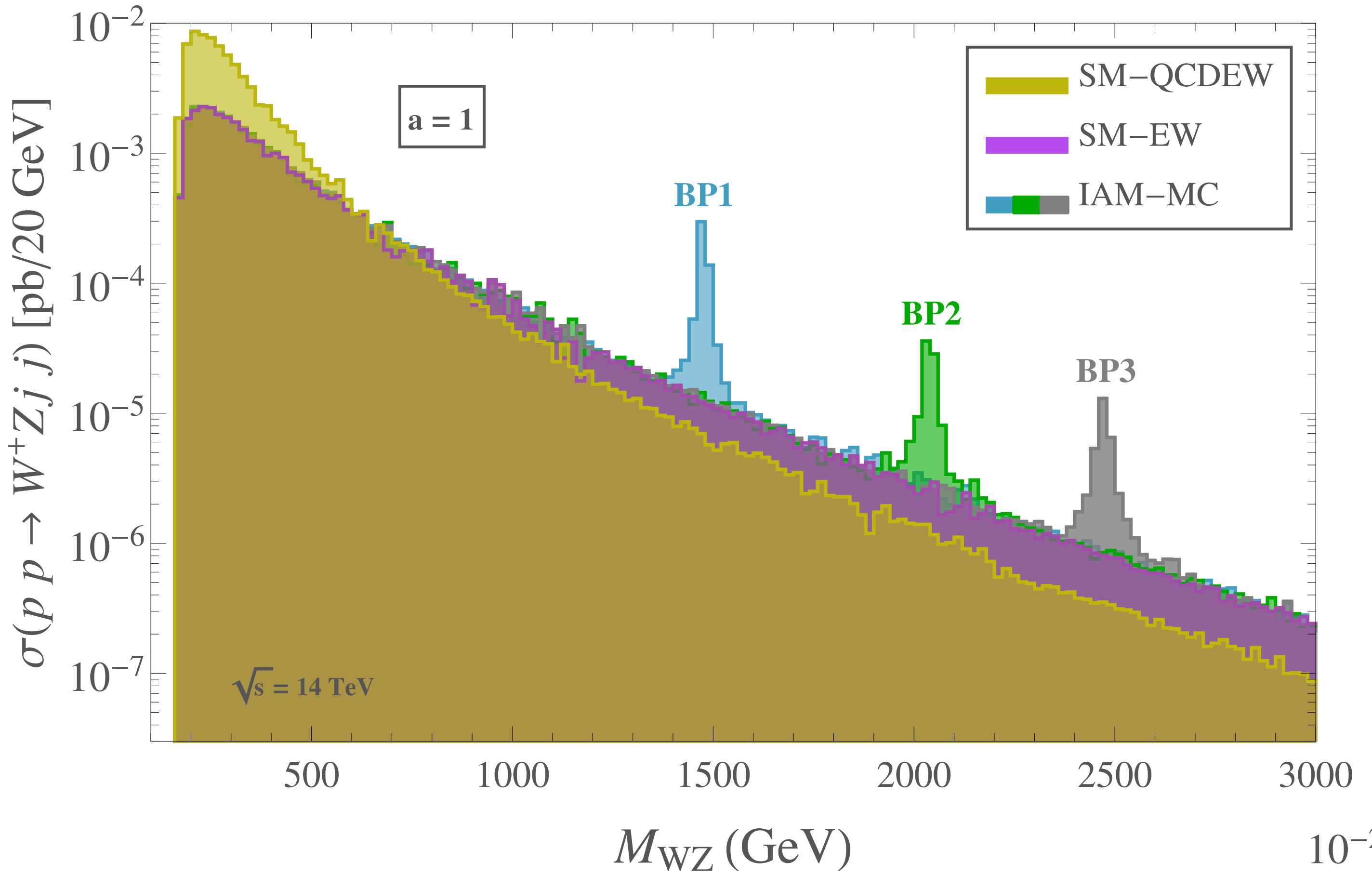
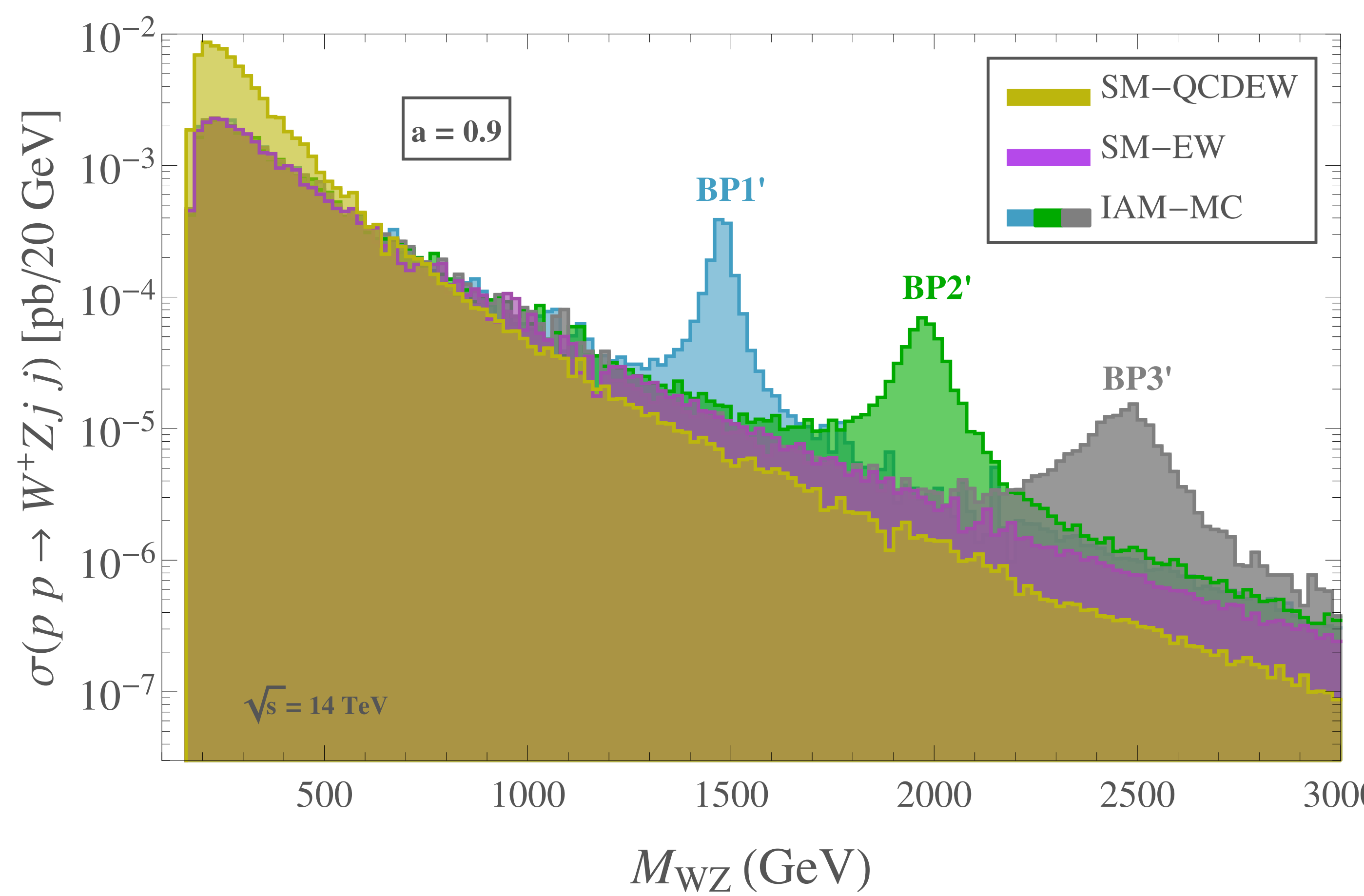




Results for W^+Zjj: invariant mass distributions



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



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

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

Results for W⁺Zjj: statistical significance

- 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 $\mathcal{L} = 300 \text{ fb}^{-1}$

Signal & Background definitions

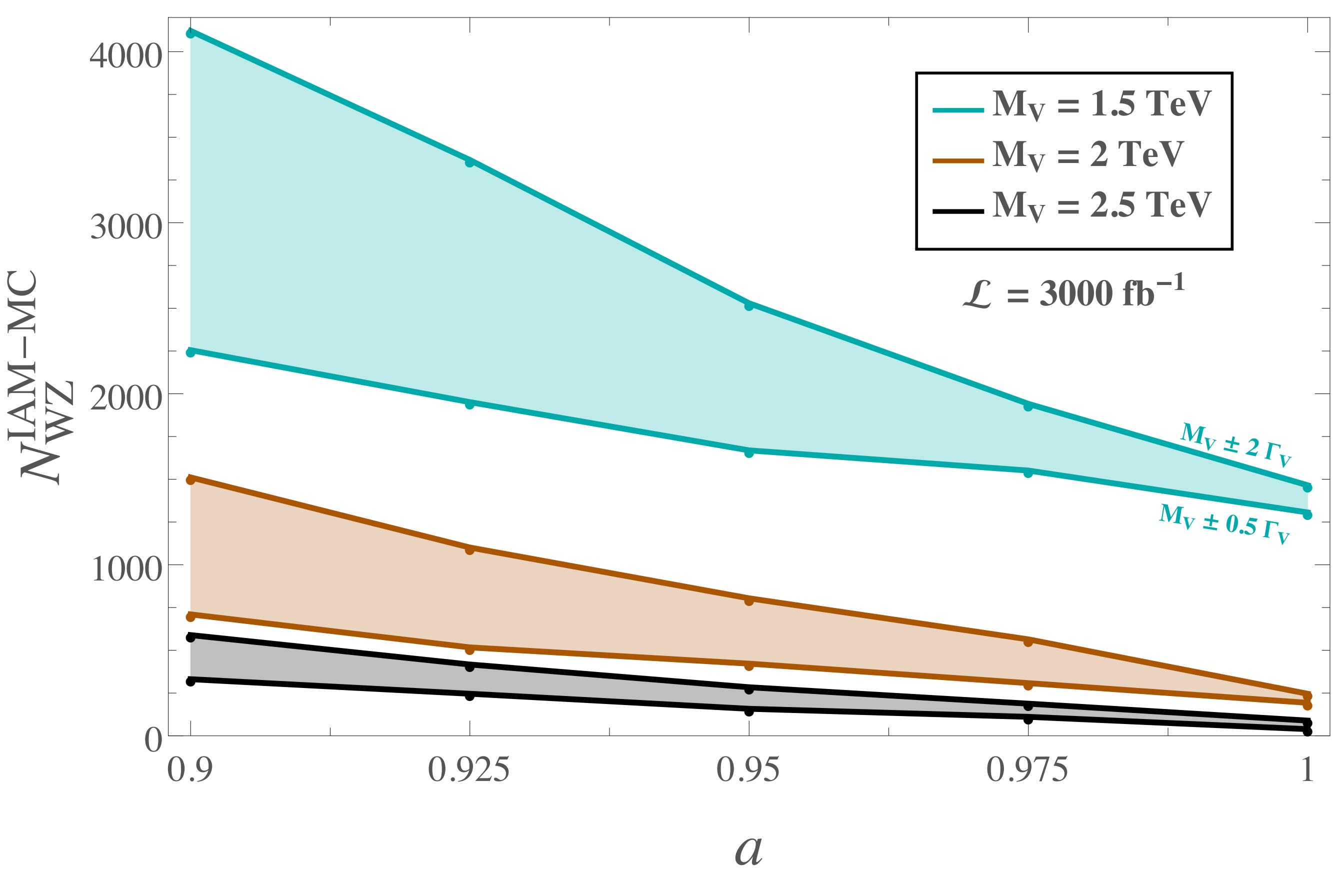
$$S = N_{\text{ev}}^{\text{IAM-MC}} - N_{\text{ev}}^{\text{SM(QCD+EW)}}$$

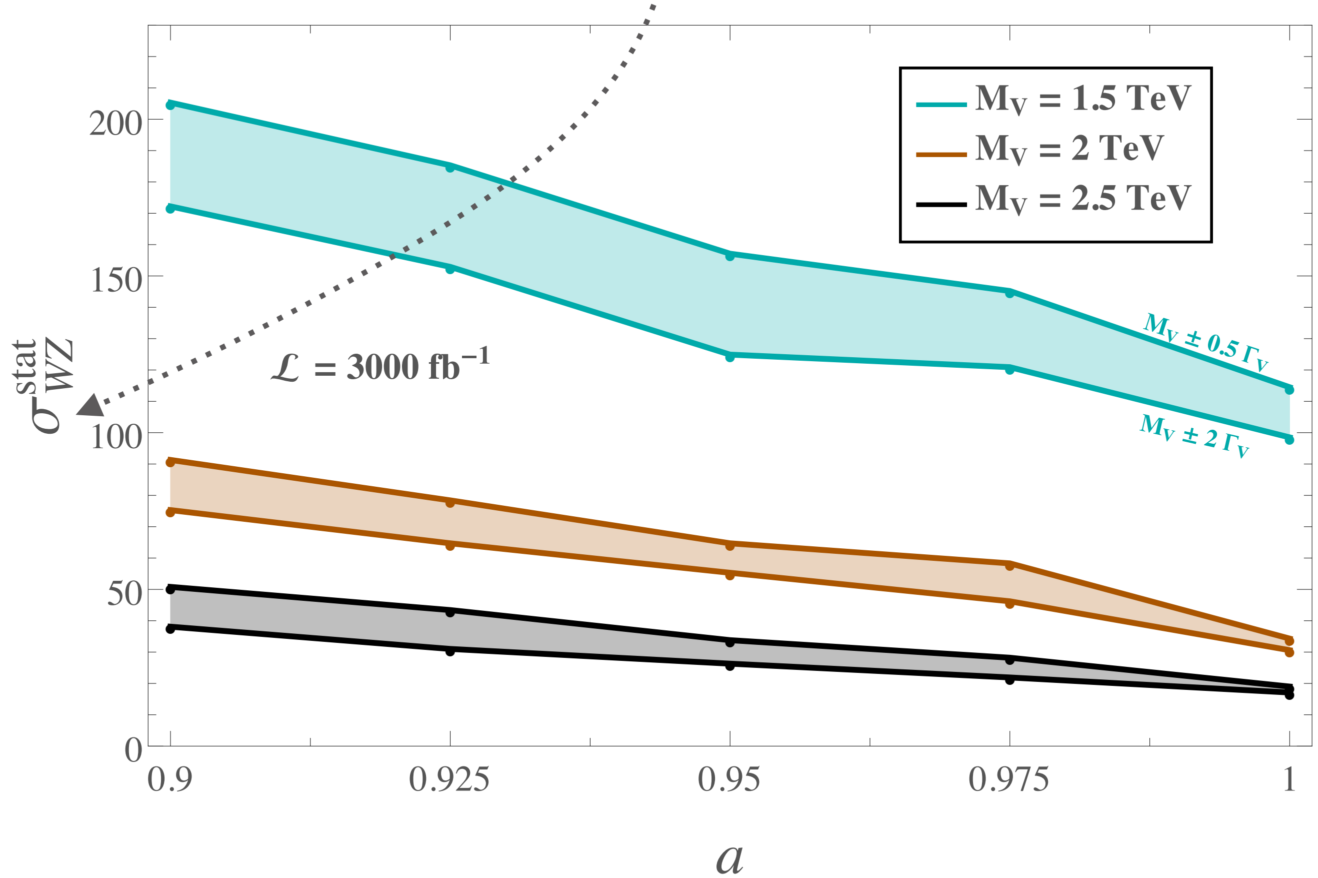
$$B = N_{\text{ev}}^{\text{SM(QCD+EW)}}$$

Summed over $\pm 0.5\,\Gamma_V$, $\pm 2\,\Gamma_V$

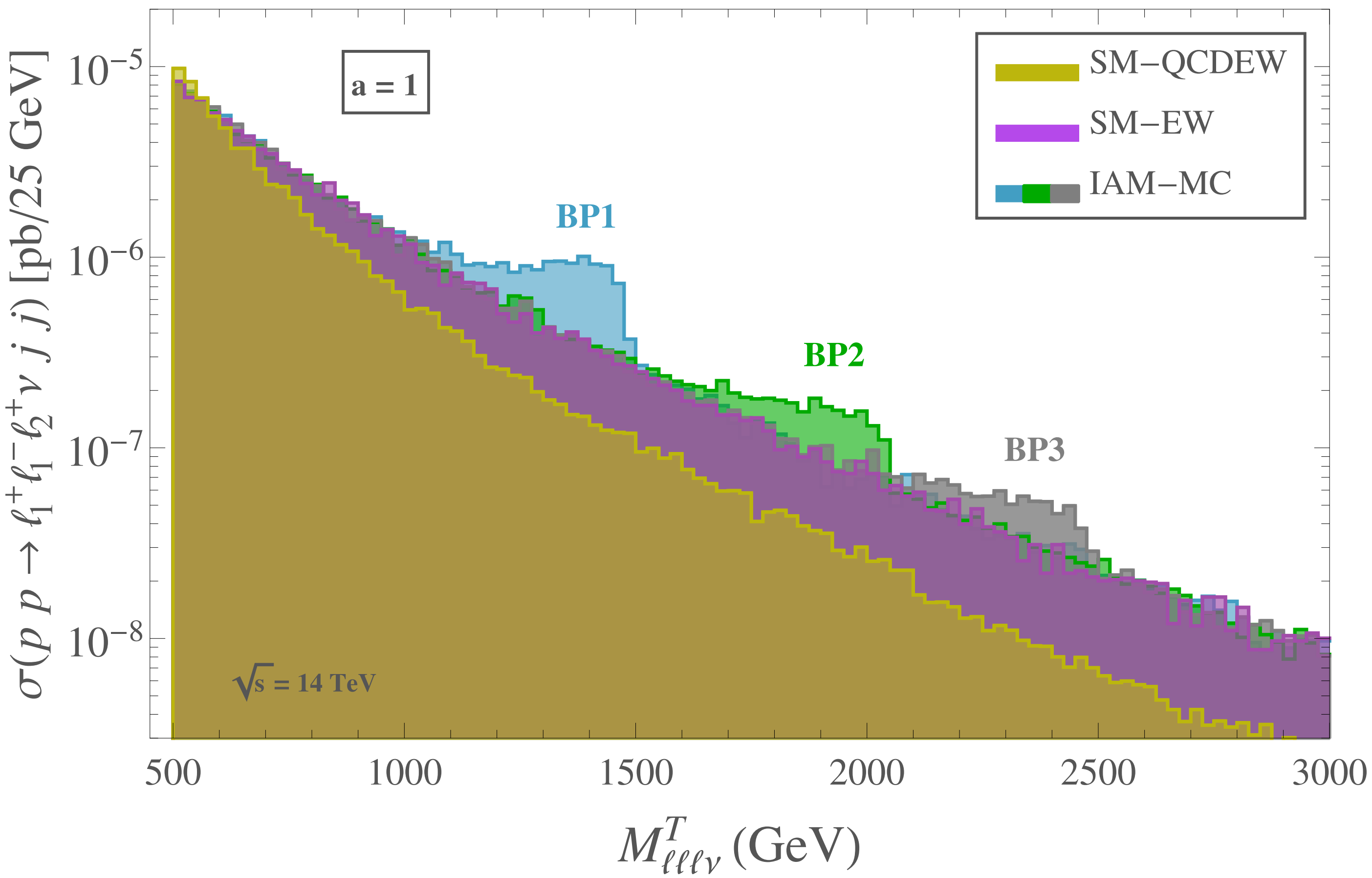
Statistical significance

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

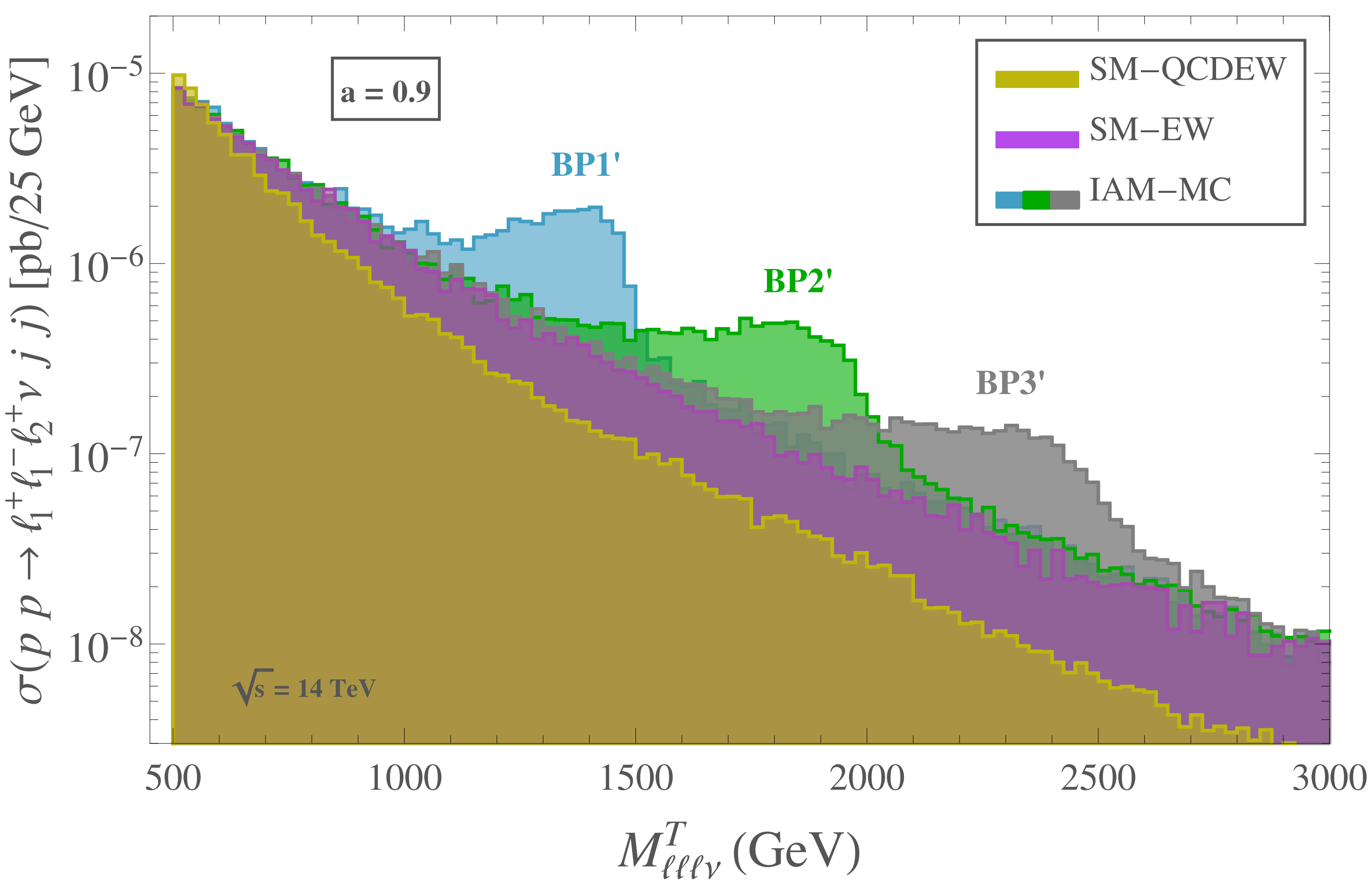




Results for $\ell^+ \ell^- \ell'^+ \nu$ jj : distributions



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



- Very clean signal in the leptonic channel

Cuts:

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

Transverse invariant mass

Results for $\ell^+\ell^-\ell'^+\nu$ jj : significance

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

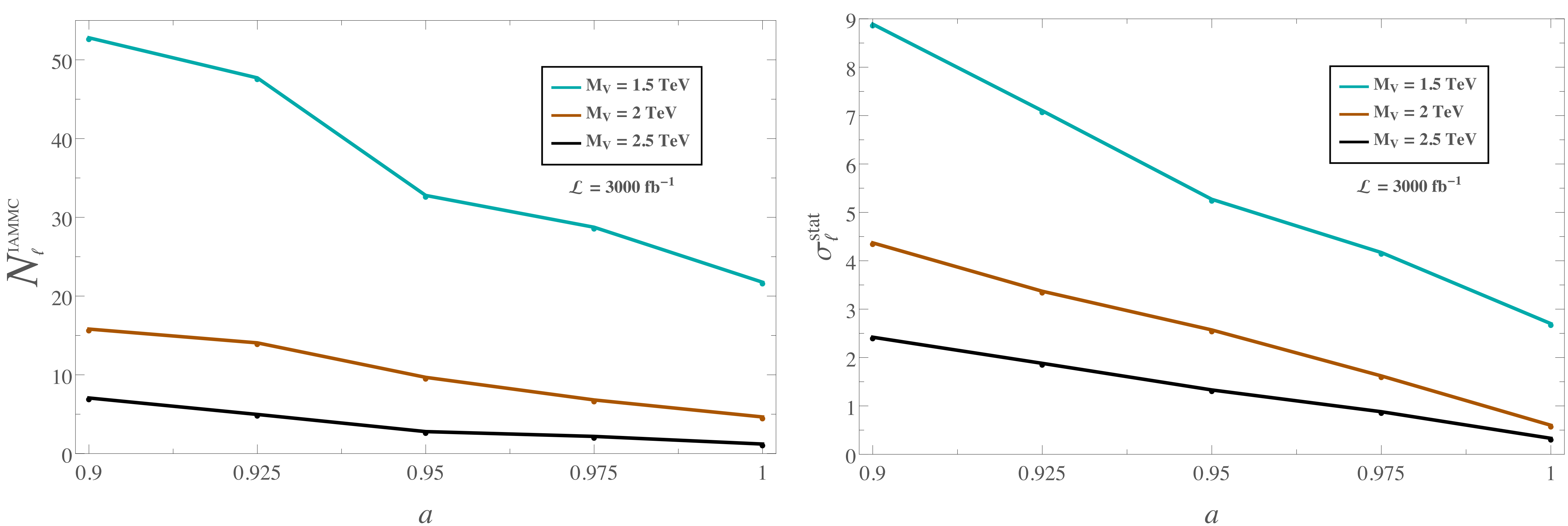
$a \in [0.9, 1]$ ⟷ $M_V = 1.5$ TeV

$a \in [0.94, 1]$ ⟷ $M_V = 2$ TeV

Poor sensitivity for $M_V = 2.5$ TeV

- Clean and controlled
- Requires High Luminosity

Events summed over optimized intervals



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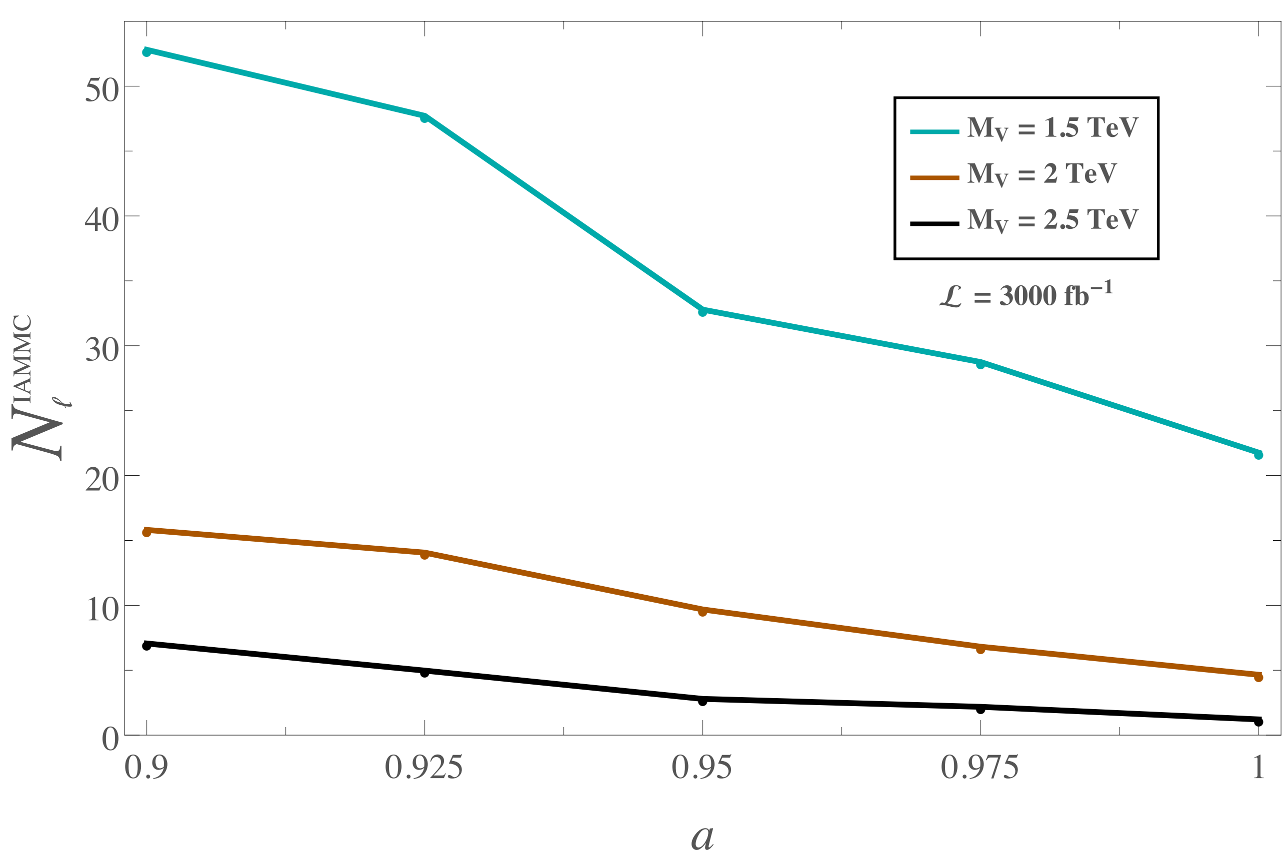
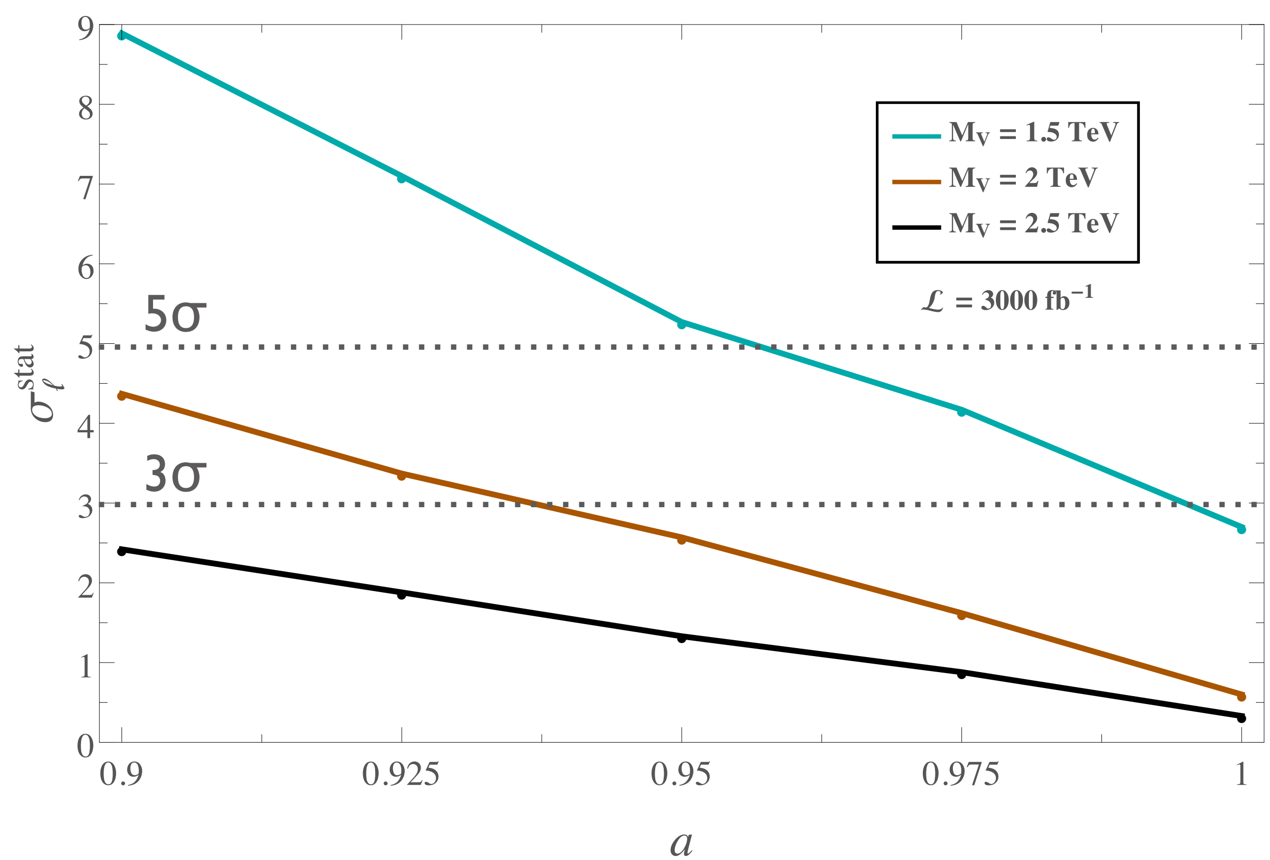




Estimates for other channels: JJjj

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

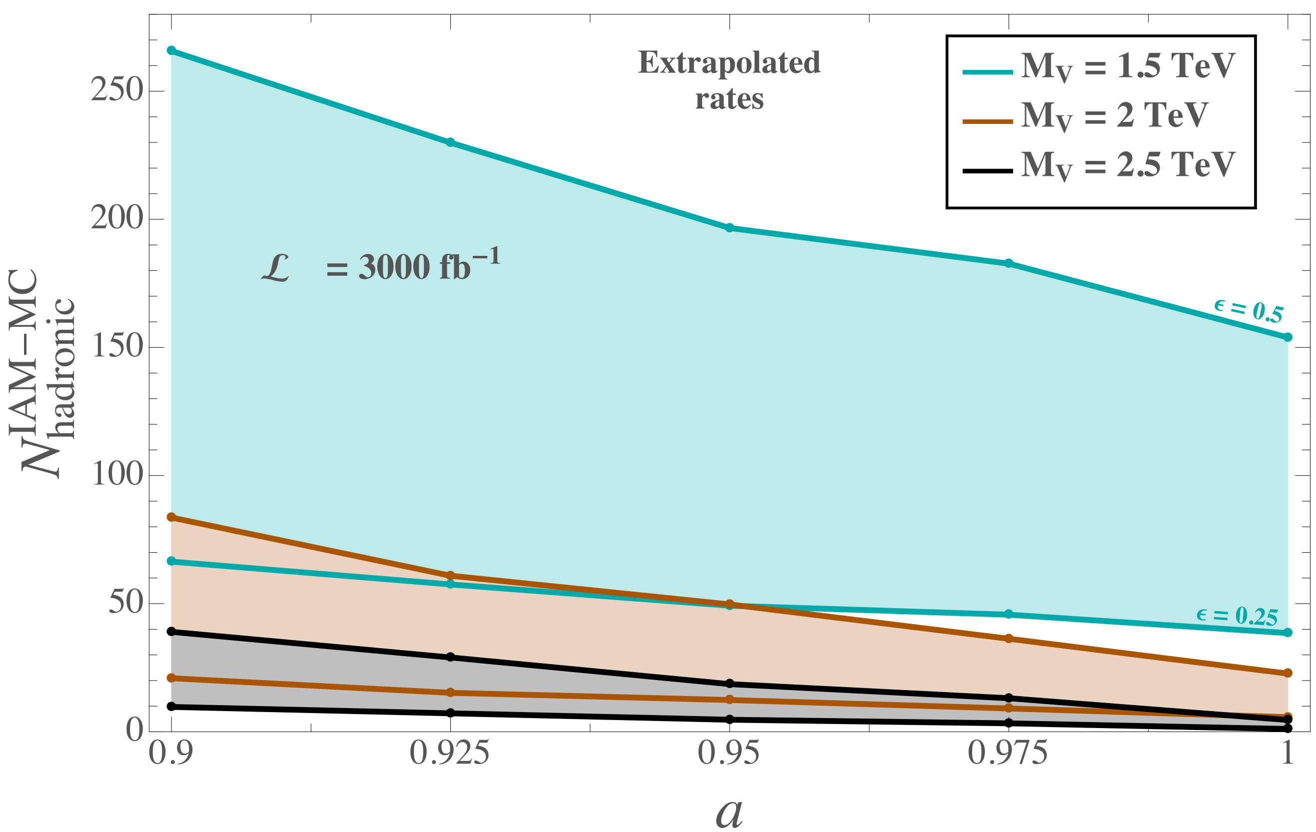
$a \in [0.9, 1] \longleftrightarrow M_V = 1.5$ TeV

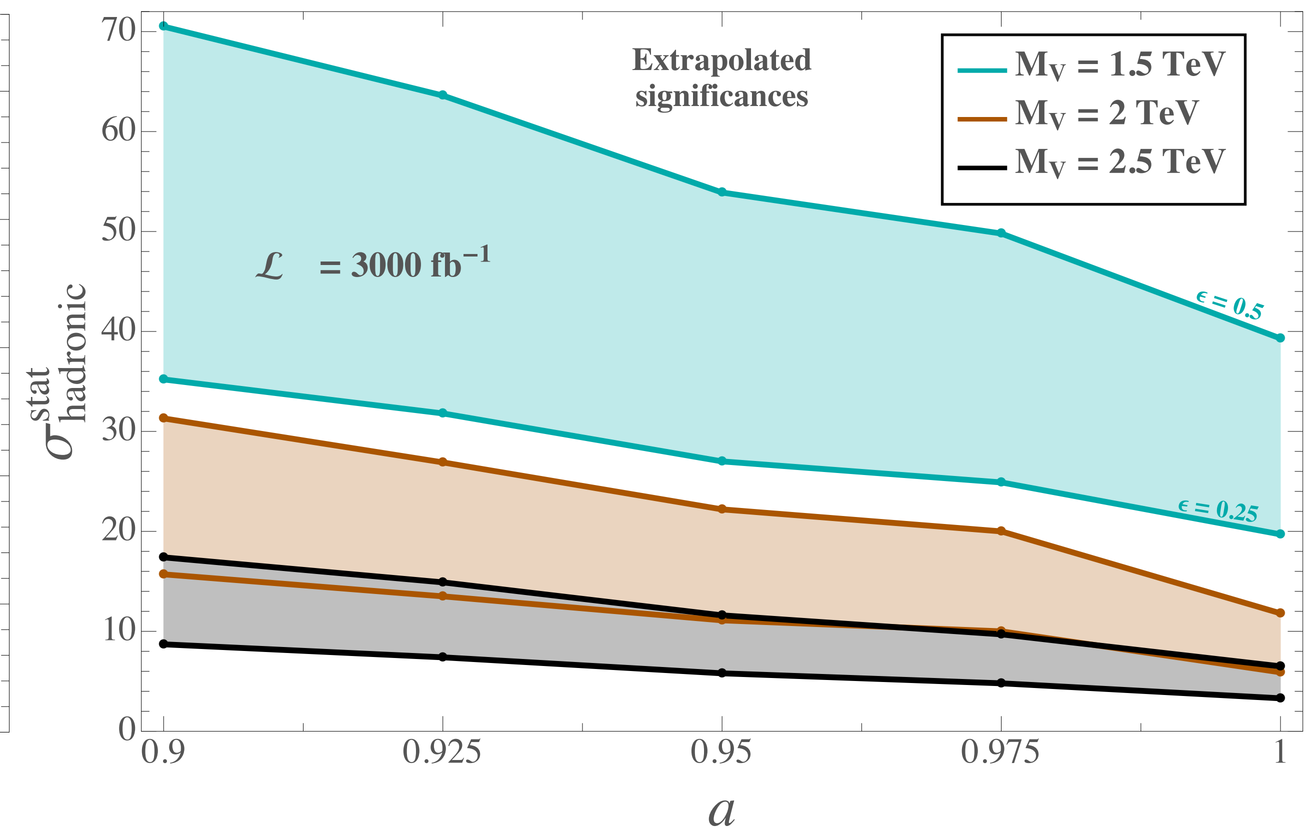
$a \in [0.975, 1] \longleftrightarrow M_V = 2$ TeV

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

- Very high significances!
- Very promising channel
- More dedicated study on demand

Estimates obtained by: $N_{\mathrm{hadronic}}^{\mathrm{IAM-MC}} = N_{WZ}^{\mathrm{IAM-MC}} \times \mathrm{BR}(W \to \mathrm{hadrons}) \times \mathrm{BR}(Z \to \mathrm{hadrons}) \times \epsilon_W \times \epsilon_Z$





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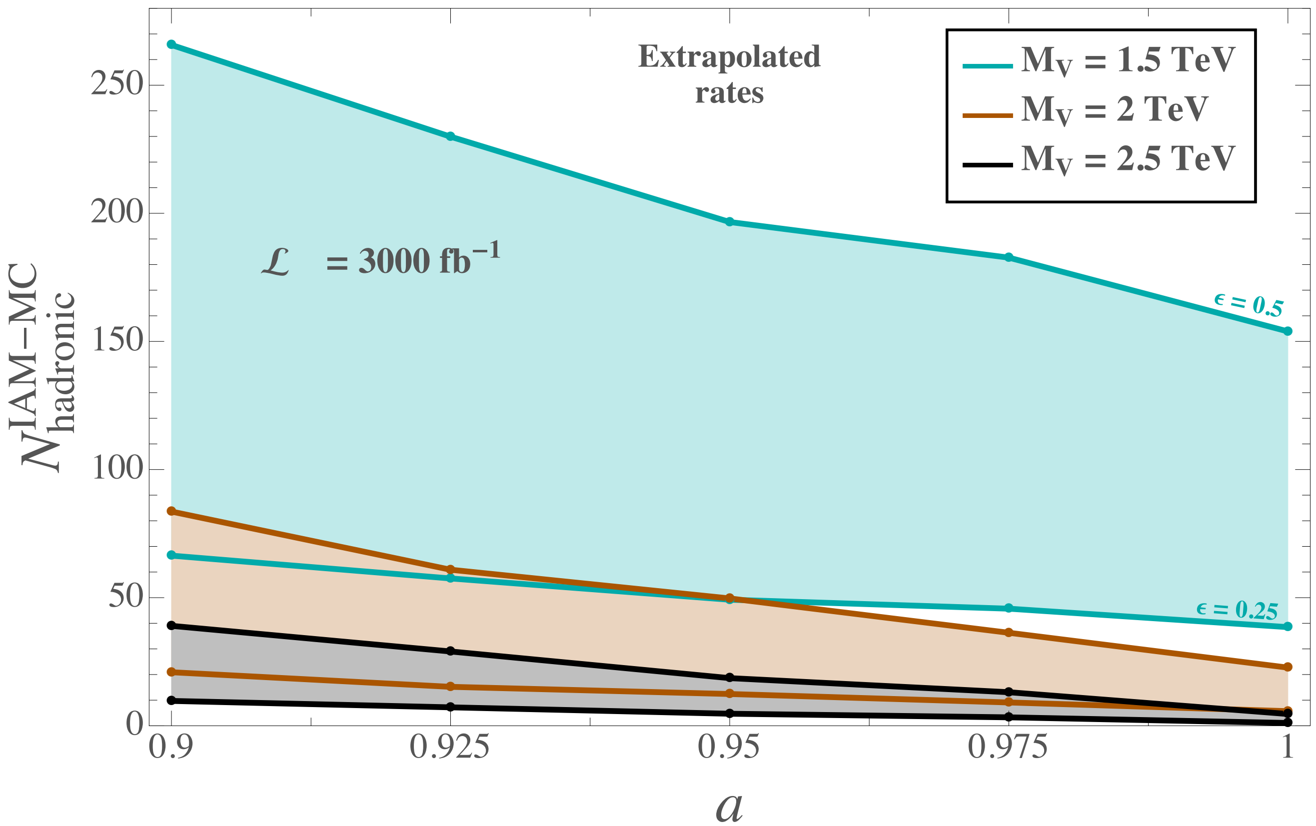

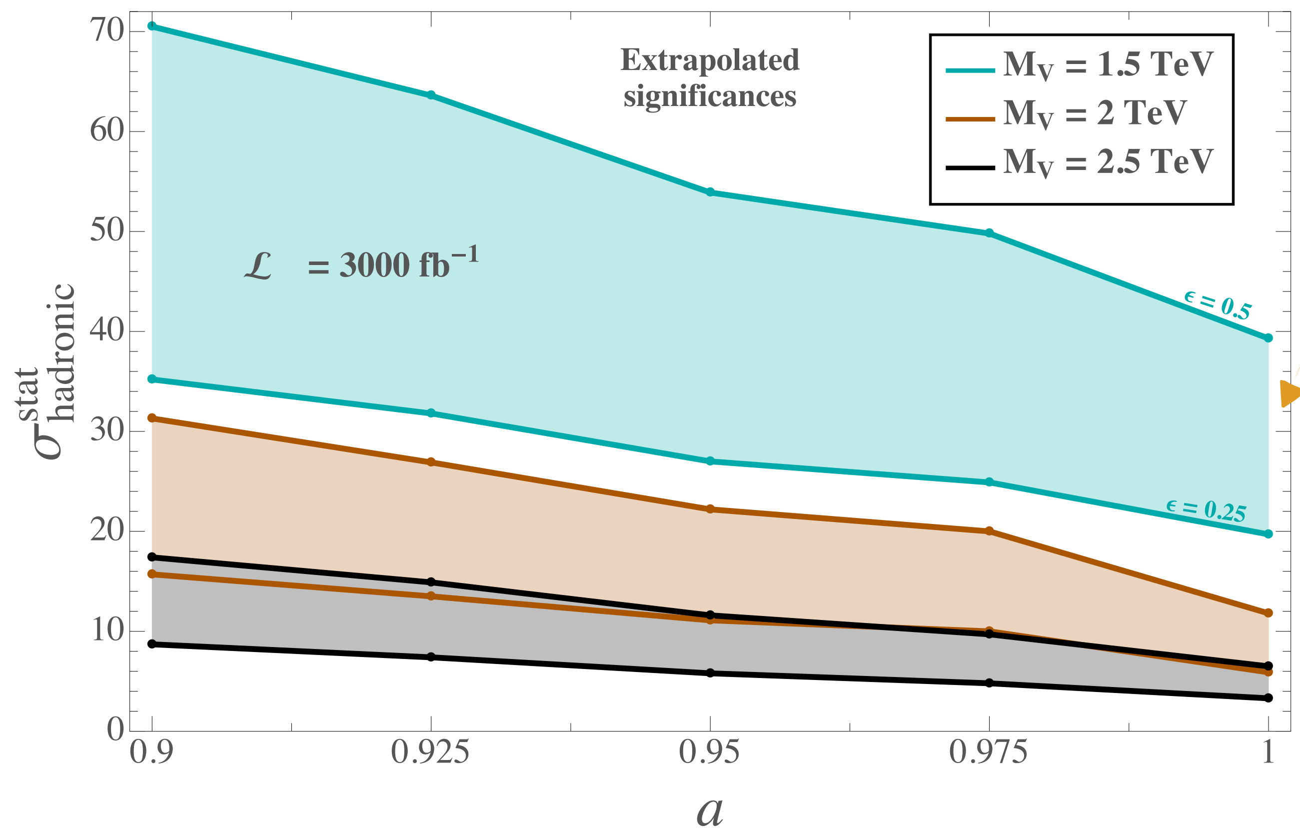

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  for $\mathcal{L} = 3000\ \text{fb}^{-1} \longrightarrow a \in [0.9, 1]$
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  → depends on reconstruction efficiency*

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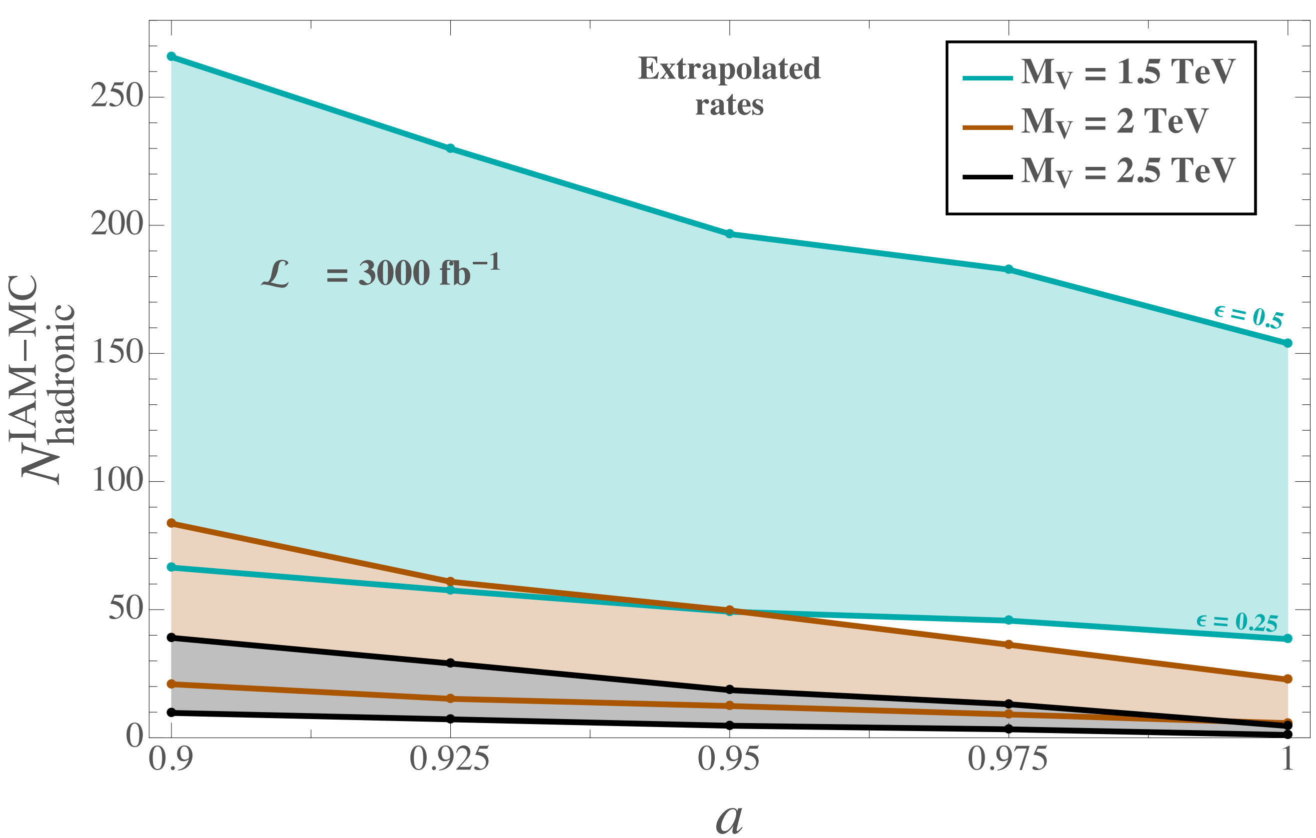

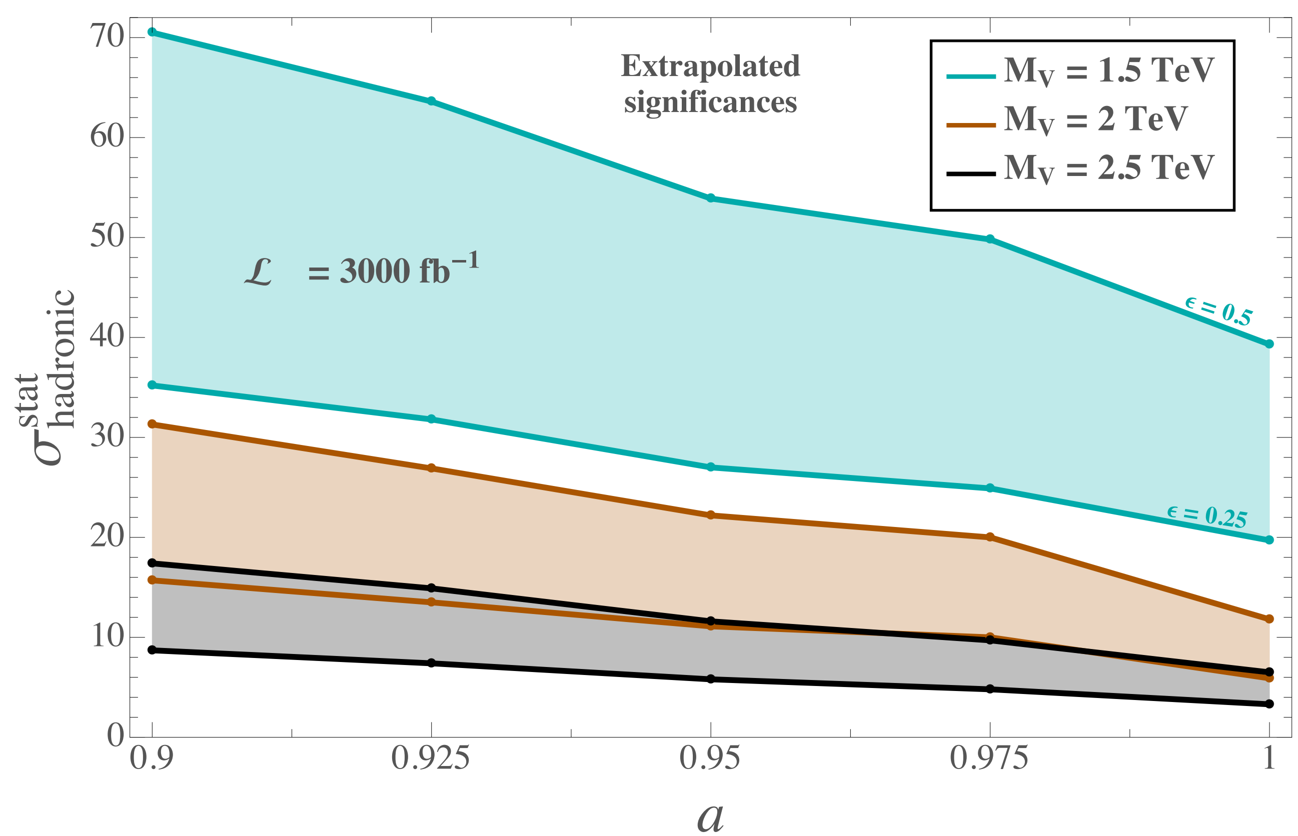

* CMS & ATLAS [JHEP 08, 173 (2014); Tech. Rep. ATL-PHYS-PUB-2015-033; JHEP 12, 055 (2015)]

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** a a_4 a_5
  - → Depending on:
    - final state
    - luminosity

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

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THANK YOU!

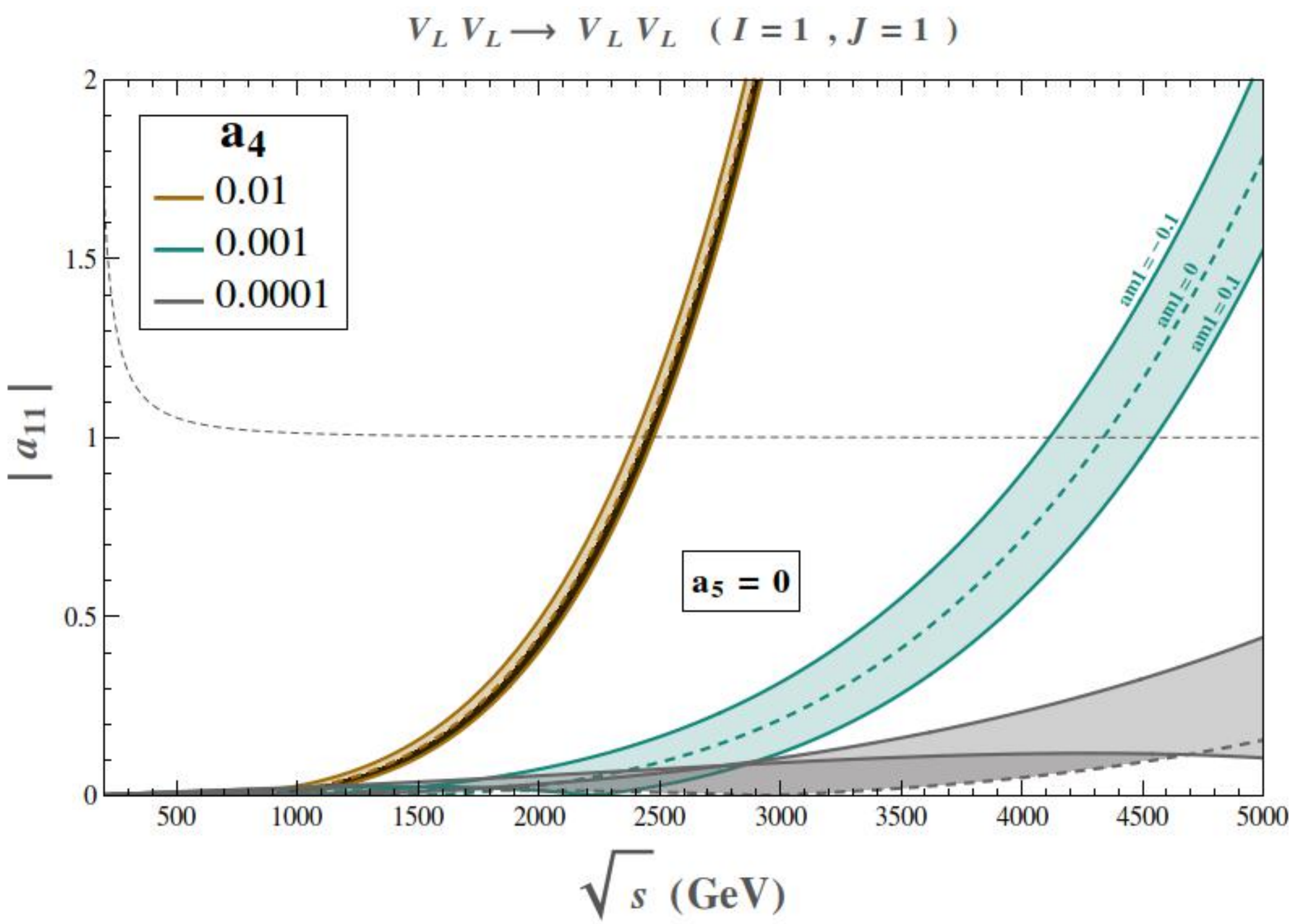
- Improving selection cuts + study other distributions might improve the results

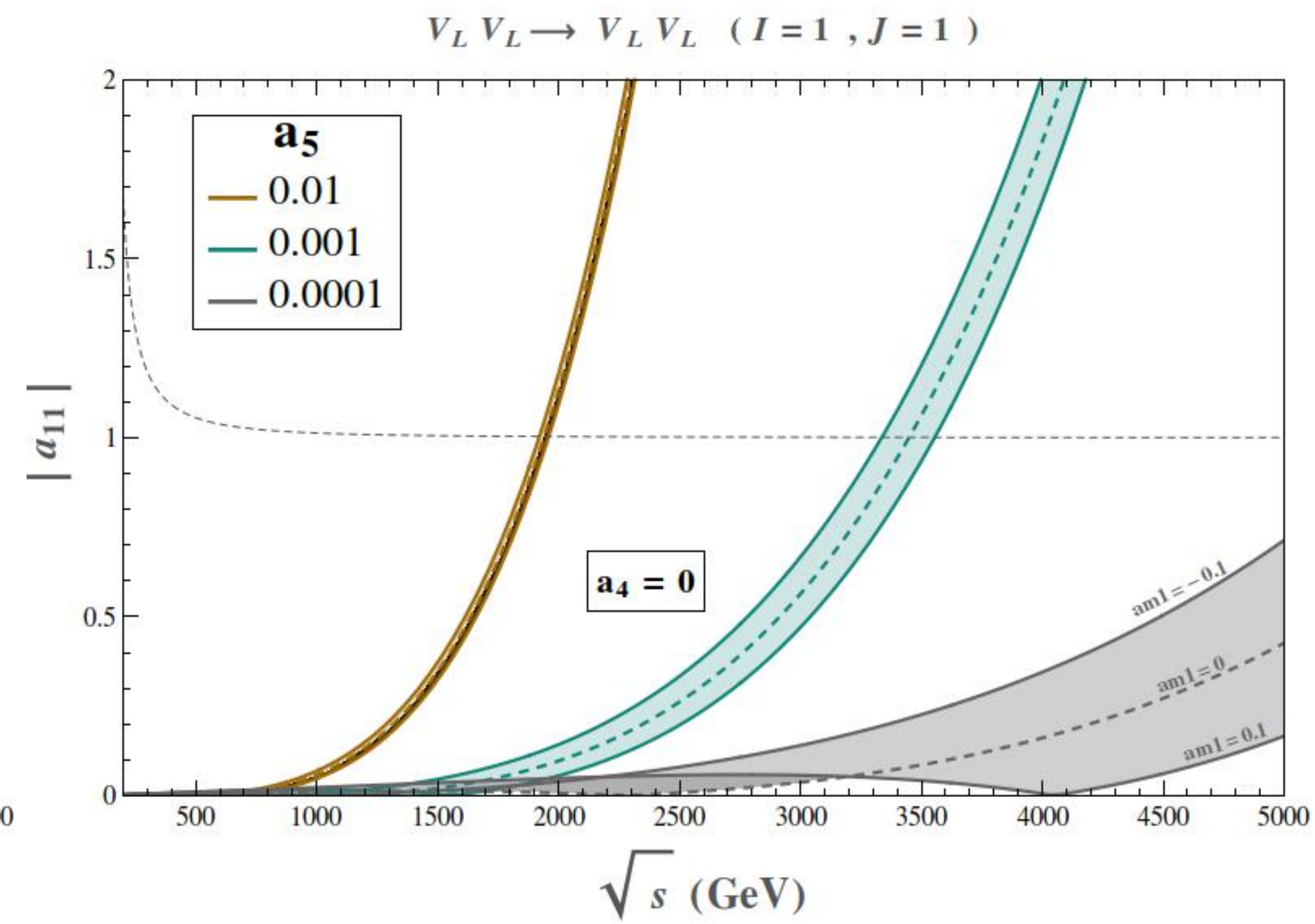
Back up Slides

Unitarity Violation (1)

- Energy at which occurs ⟶ very sensitive to $(a-1), a_4, a_5$

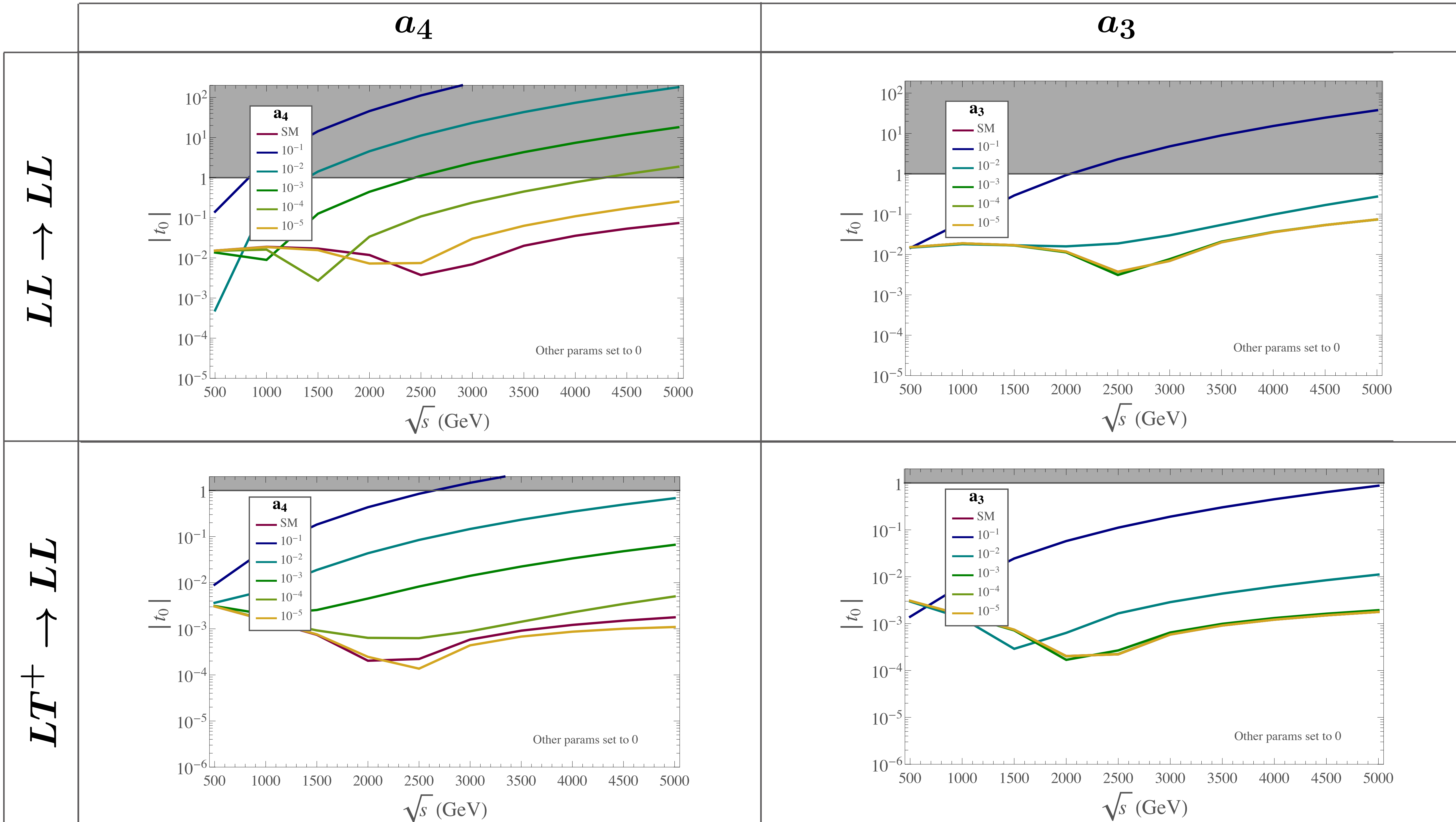
- At tree level, for the values considered $a \in [0.9, 1],\ a_4, a_5 \in [10^{-3}, 10^{-4}]$ unitarity violation happens at the few TeV scale





Unitarity Violation (2)

- Might depend on → Helicity of particles; Other parameters



Properties of resonances: top contribution

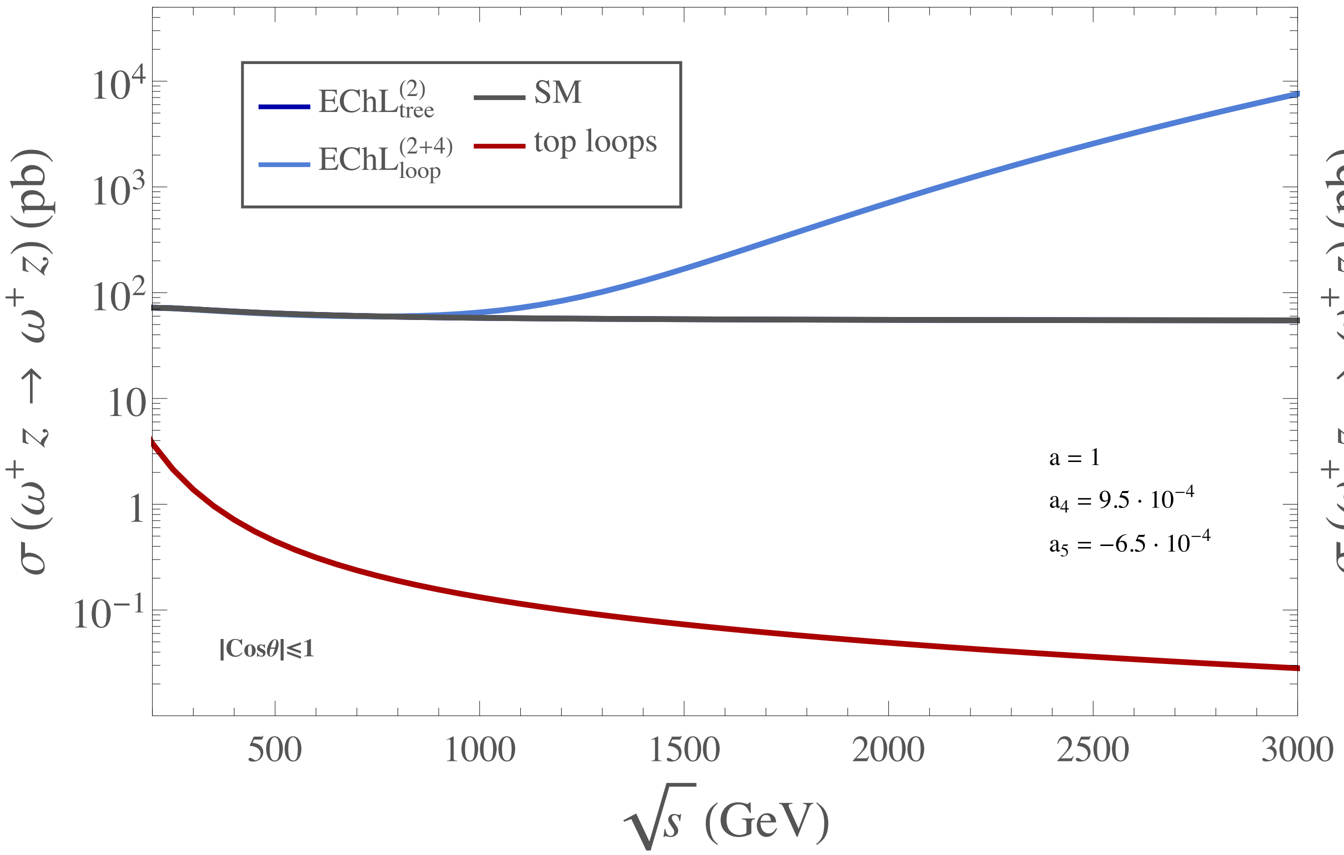
[S. Dawson, G.Valencia, Phys. Lett. B 246 (1990) 156]

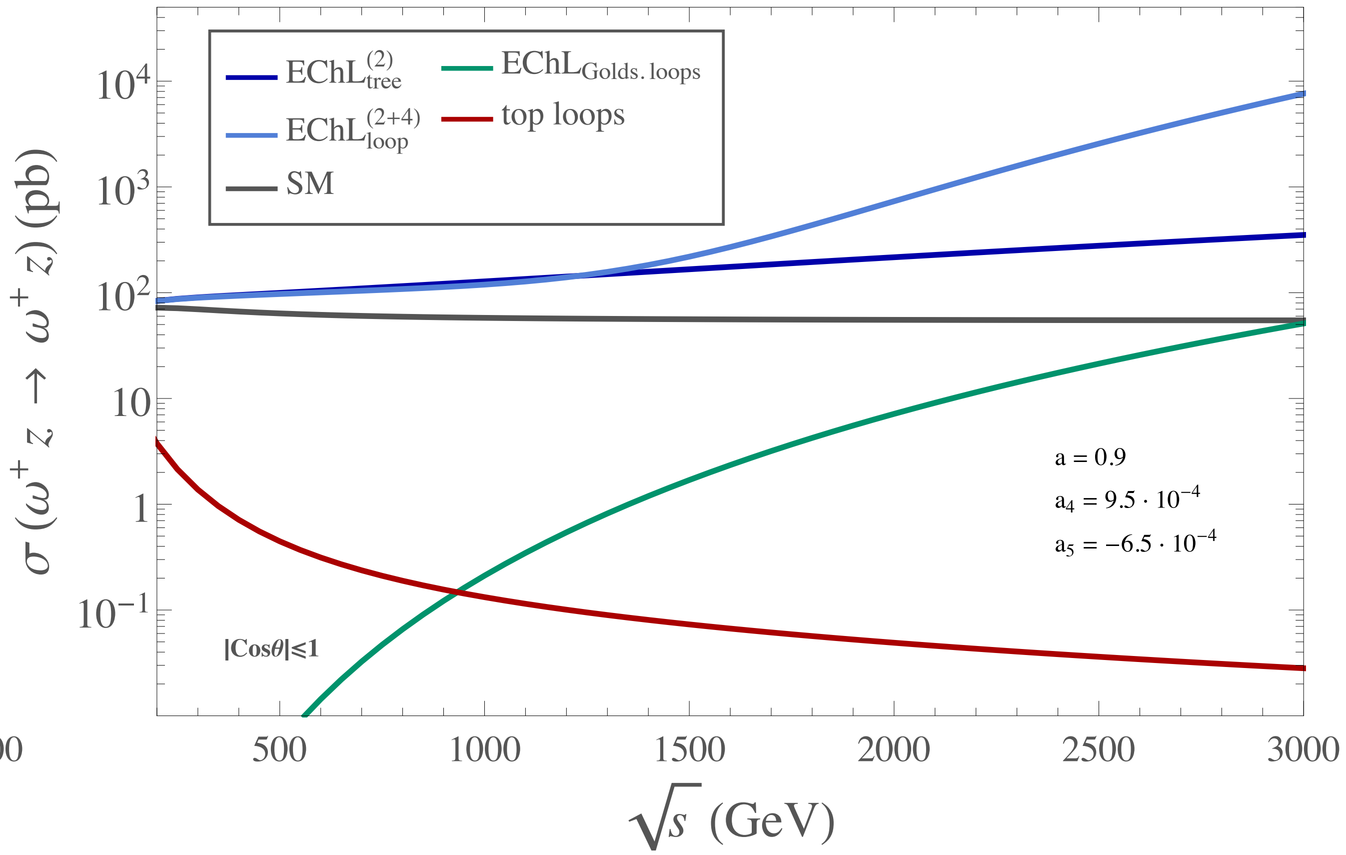
- Top loop contribution decreases with energy

  (Effects of renormalization not taken into account)

- Negligible with respect to Goldstone boson loops above 1 TeV

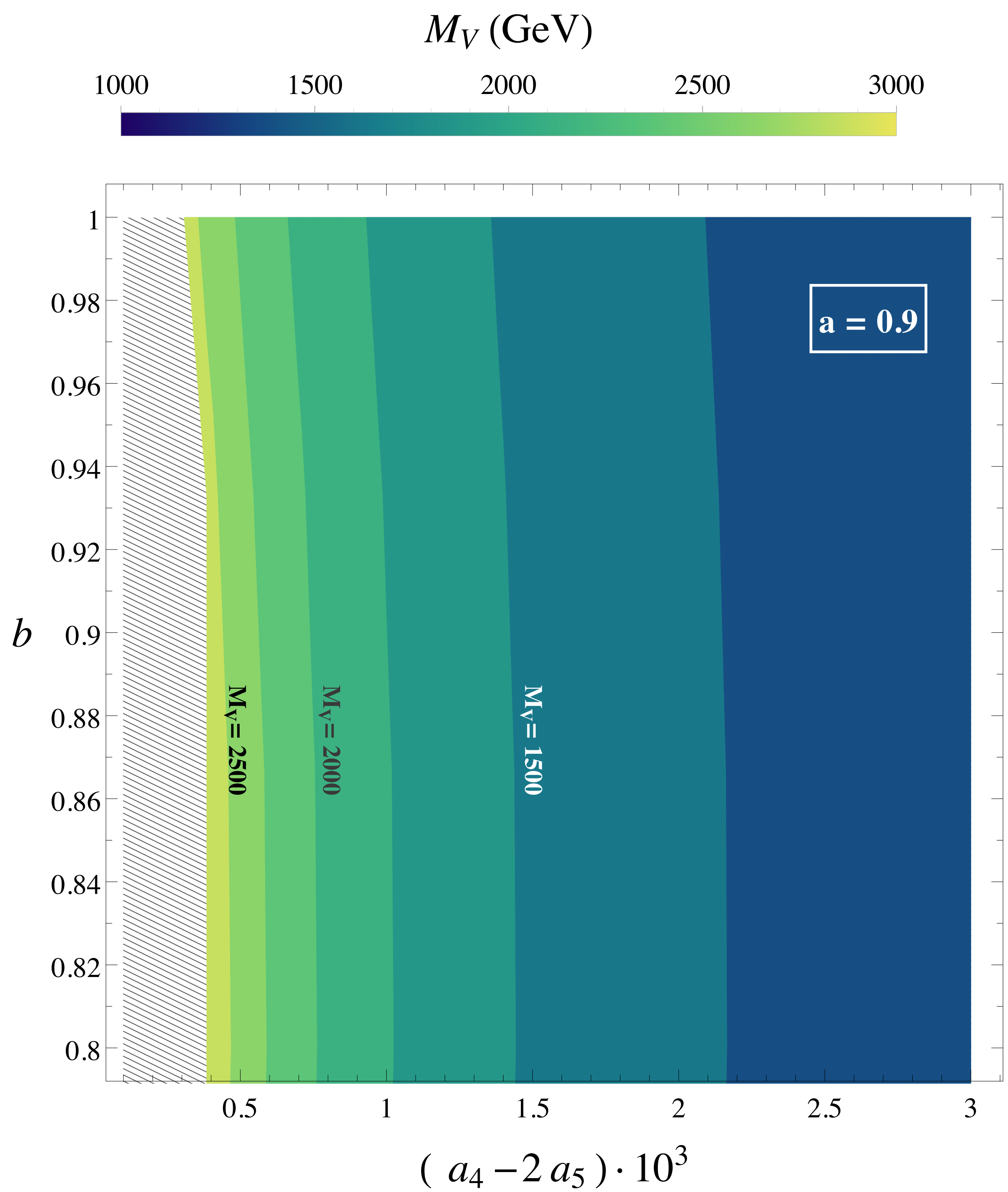
- Subleading effects on resonance properties

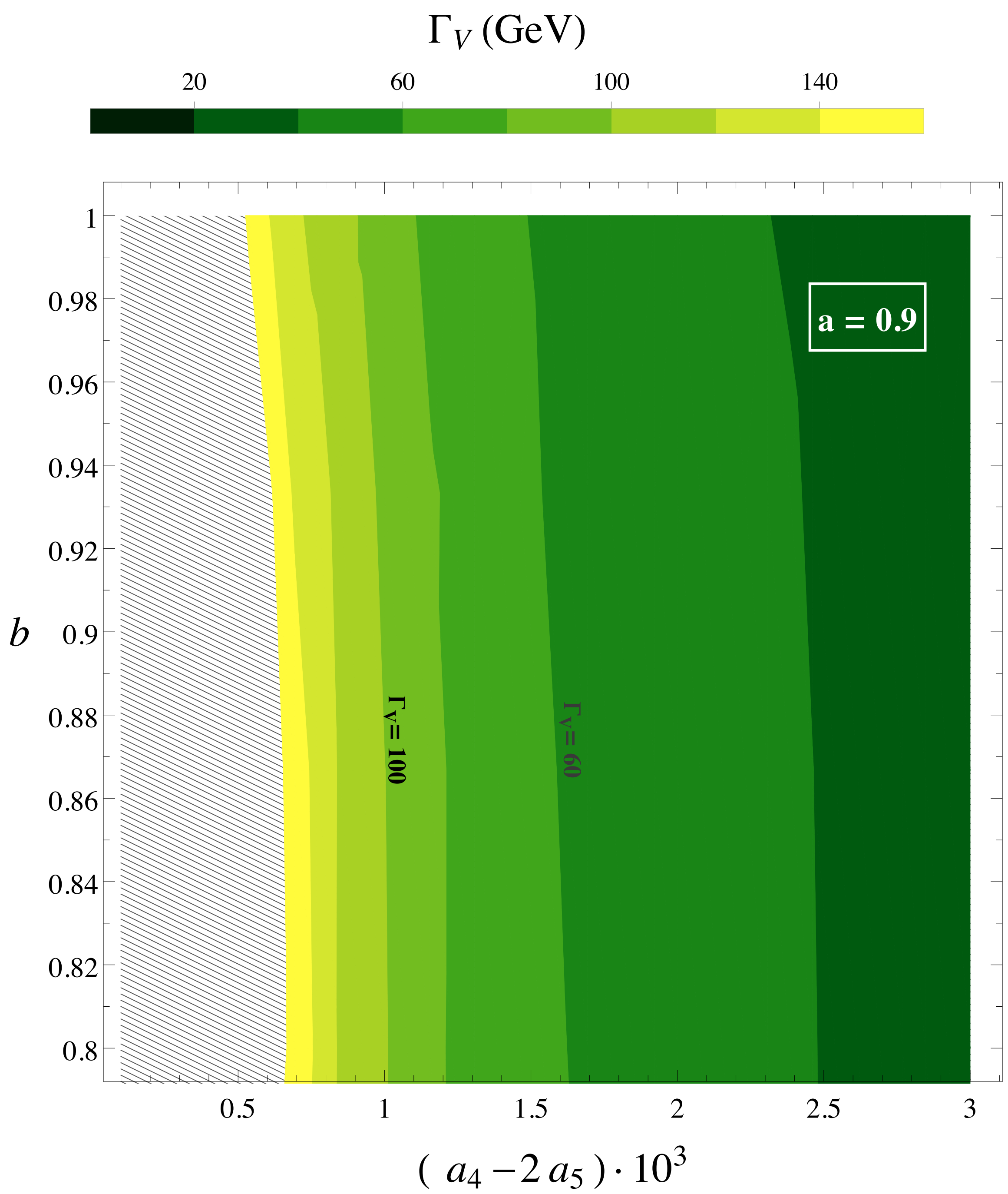




Properties of resonances: the b parameter

- 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





- IAM-MC Form Factor

  respects Froissart bound $\sigma(s) \leq \sigma_0 \log^2\left(\frac{s}{s_0}\right)$

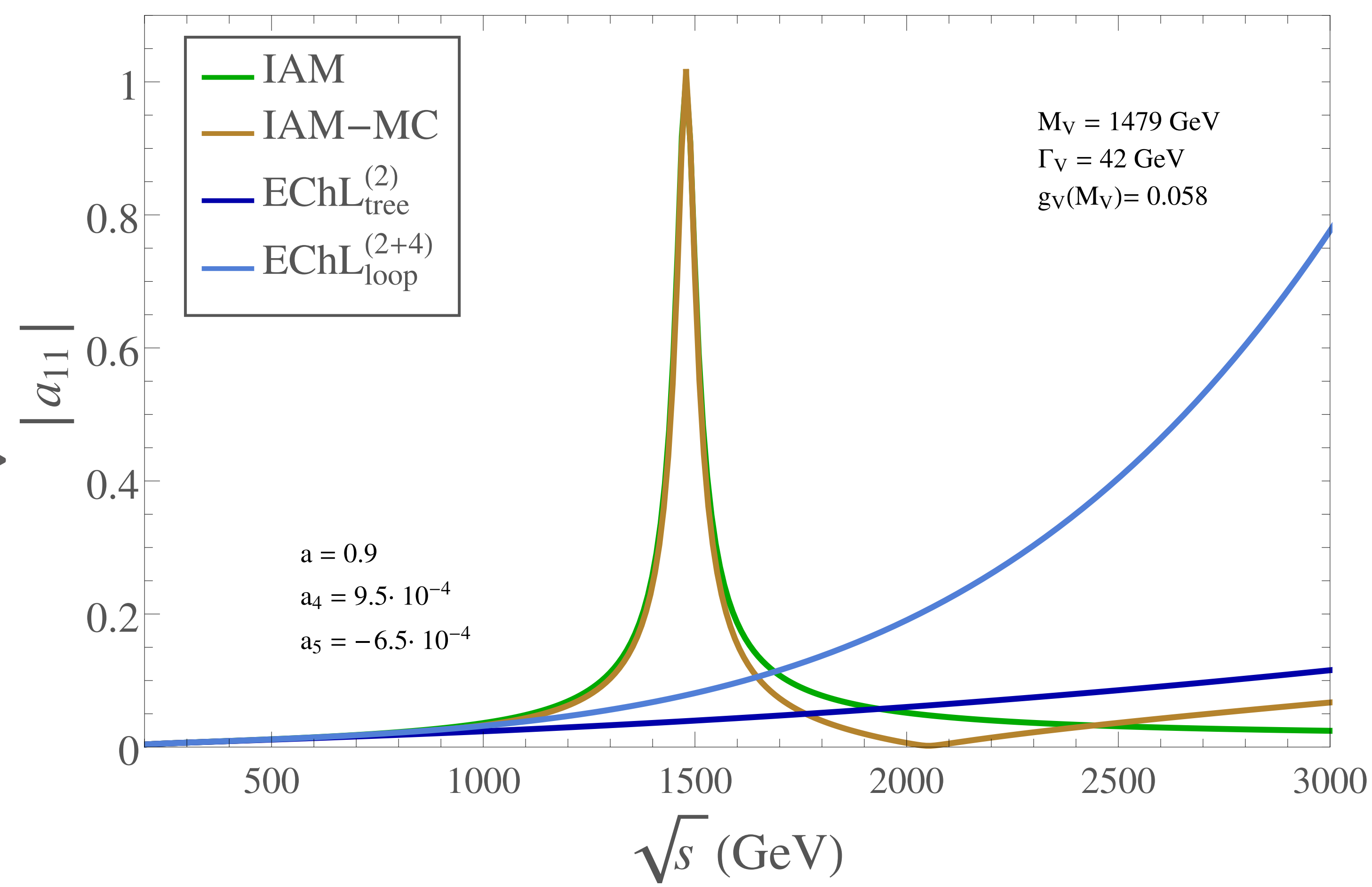
  assumes no other resonances appear

  recovers IAM resonance behavior

IAM-MC Form Factor

$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^2}{z} \quad \text{for } s < M_V^2$$

$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^4}{z^2} \quad \text{for } s > M_V^2$$

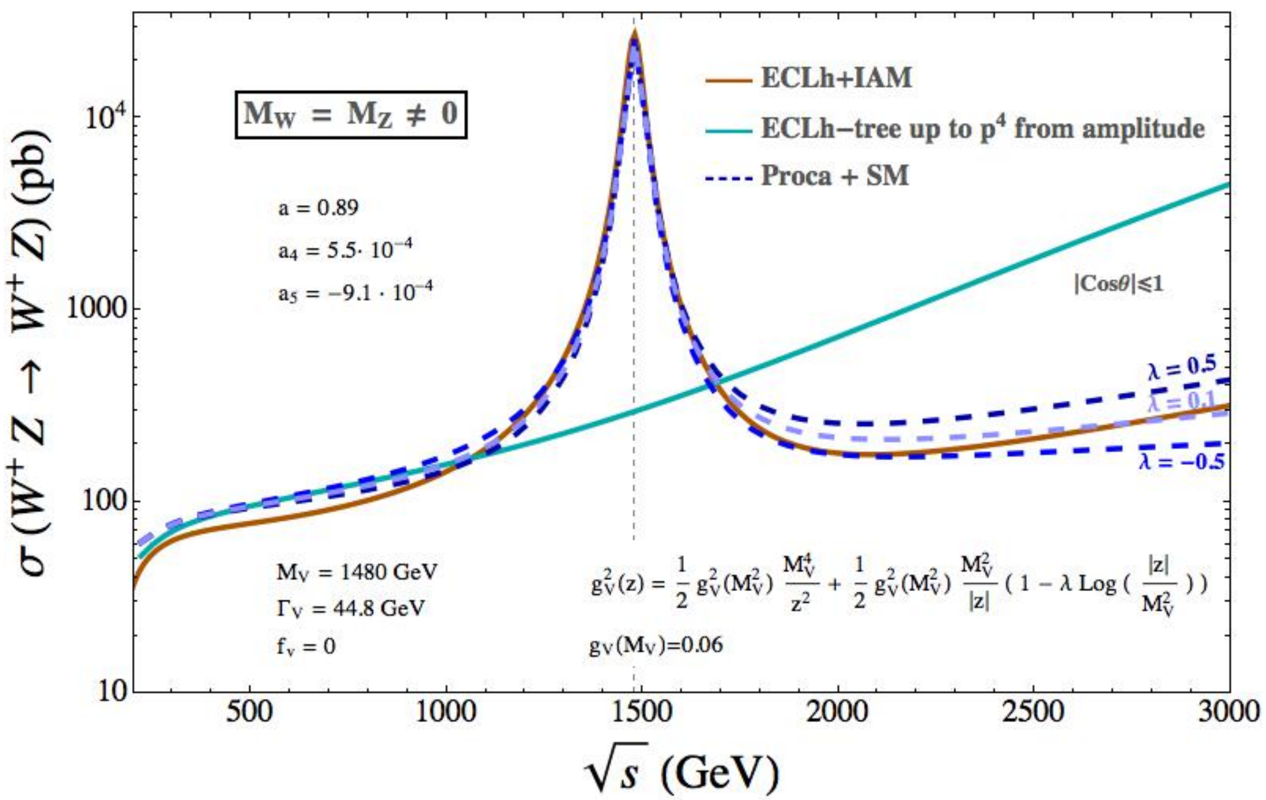


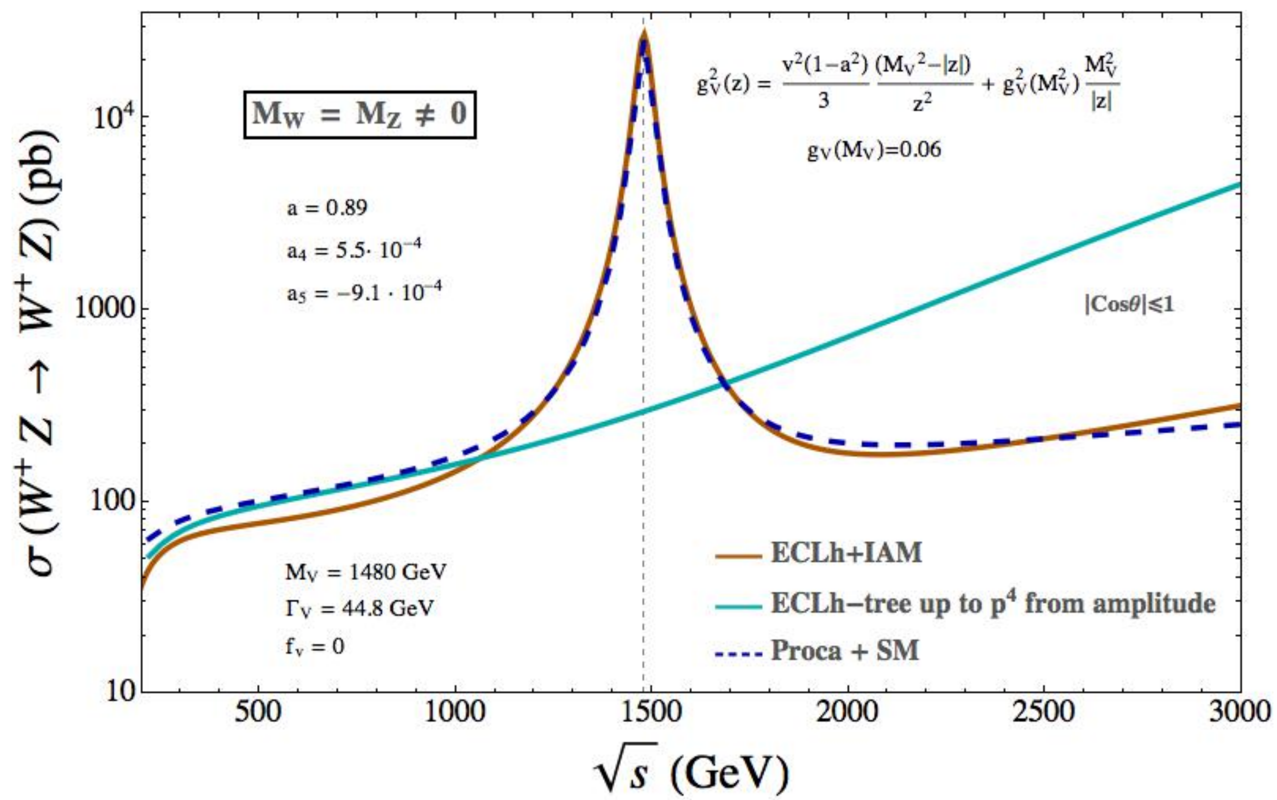
- Other choices of g_V ⟶ unphysical/unitarity violating

Other choices of g_V

- Non IAM-MC choices of g_V ⟶ unphysical/unitarity violating results

Examples:





Crossing-symmetric form factor: $g_V^2(z) = \theta(M_V^2 - z) g_V^2(M_V^2) \frac{M_V^2}{z} + \theta(z - M_V^2) g_V^2(M_V^2) \frac{M_V^4}{z^2}$

⟶ Violates unitarity!

Comparison with the linear case

- Weakly interacting dynamics → No dyn. generated resonances

- In linear Lagrangian:

Introduce resonances directly → Integrate out to relate M, Γ ↔ $\boldsymbol{a}$ $\boldsymbol{b}$ $\boldsymbol{a_4}$ $\boldsymbol{a_5}$

Different counting → Different weighting of operators

Scale suppression → For $a_{4,5} \sim 10^{-4}$ → $F_{S,[0,1]} \sim 10^{-12}\,\mathrm{GeV}^{-4}$