Vector resonances from a unitarized EChL in Vector Boson Scattering at the LHC

Claudia García-García
Instituto de Física Teórica, Universidad Autónoma de Madrid/CSIC

claudia.garcia@uam.es

April 16th, 2018

HEFT 2018, Mainz

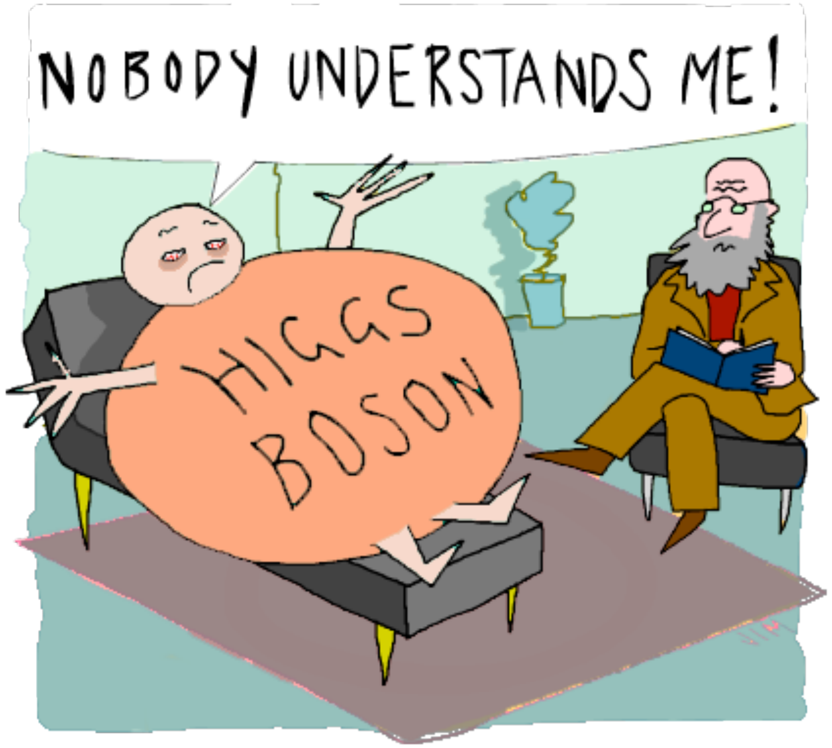
Based on JHEP 1711 (2017) 098, [arXiv:1707.04580]
R. L. Delgado, A. Dobado, D. Espriu, **CGG**, M.J. Herrero, X. Marcano & J.J. Sanz-Cillero

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]

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. :**
  - → **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 ⟶ $\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2$

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

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. :**

  ⟶ **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 $D_\mu, W_{\mu\nu},$ & $B_{\mu\nu}$

  ⟶ **Higgs singlet** under Chiral symmetry $\longrightarrow$ $\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2$

- Building blocks:

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

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

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. :**

  → **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 ⟶ $\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2$

- Building blocks:

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

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

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

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

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

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. :**
  - → **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 $\longrightarrow$ $\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2$

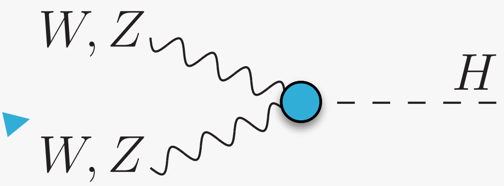
- Building blocks:

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

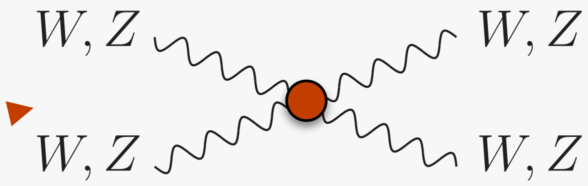
$\mathscr{L}_{EChL} = \mathscr{L}_2 + \mathscr{L}_4$ **Relevant terms & chiral parameters for VBS**

$b = a^2$

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



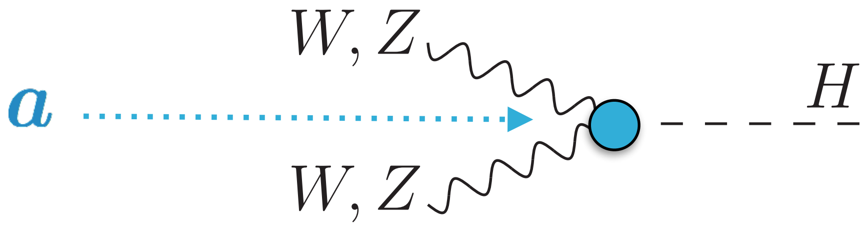
$$\mathcal{L}_4 = a_4\Big[\mathrm{Tr}\big(\mathcal{V}_\mu \mathcal{V}_\nu\big)\Big]\Big[\mathrm{Tr}\big(\mathcal{V}^\mu \mathcal{V}^\nu\big)\Big] + a_5\Big[\mathrm{Tr}\big(\mathcal{V}_\mu \mathcal{V}^\mu\big)\Big]\Big[\mathrm{Tr}\big(\mathcal{V}_\nu \mathcal{V}^\nu\big)\Big] + \dots$$

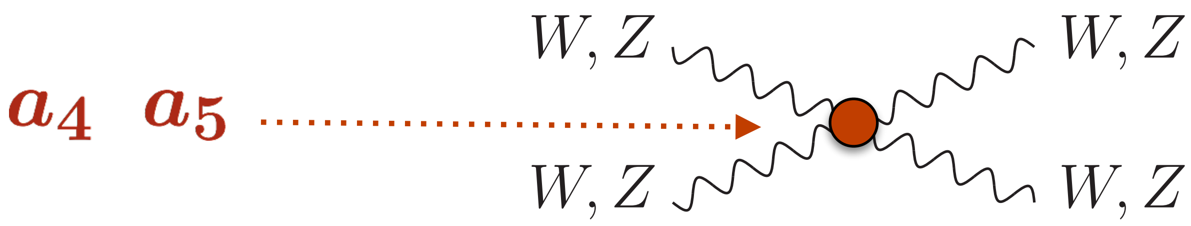


[A. C. Longhitano, 1980; T. Appelquist et al., 1980]

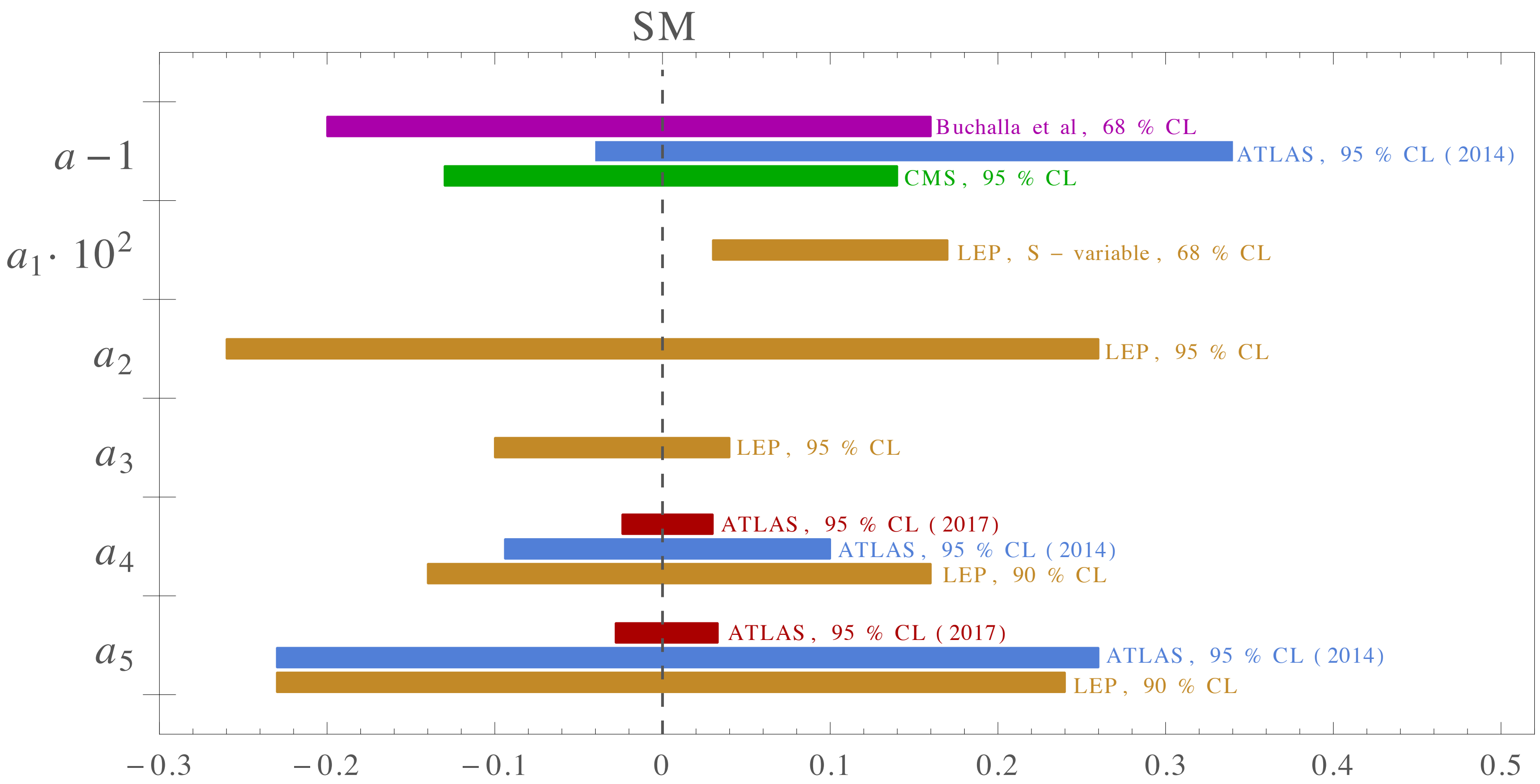
Relevant Chiral Parameters

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





- Constraints



Considered intervals

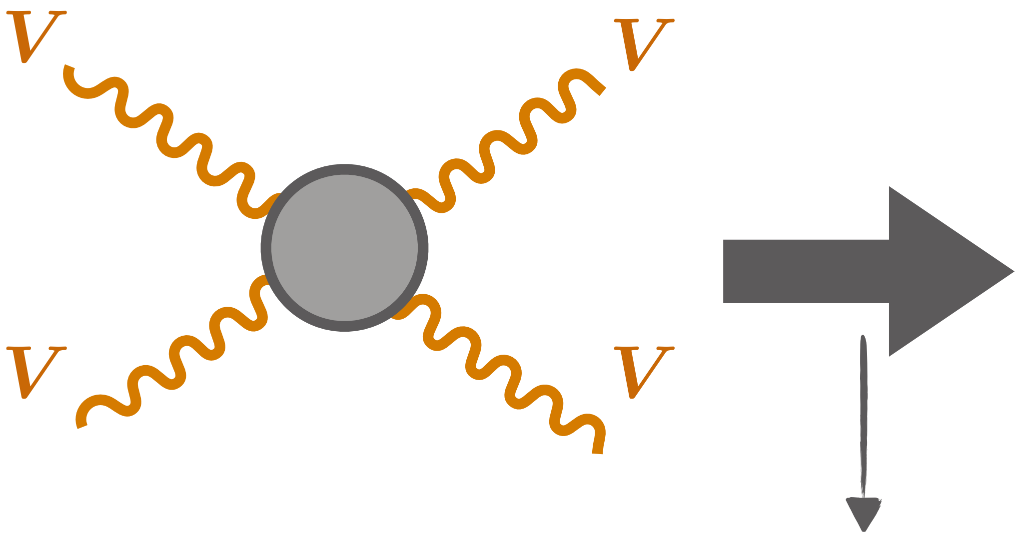
$$a \in [0.9, 1]$$

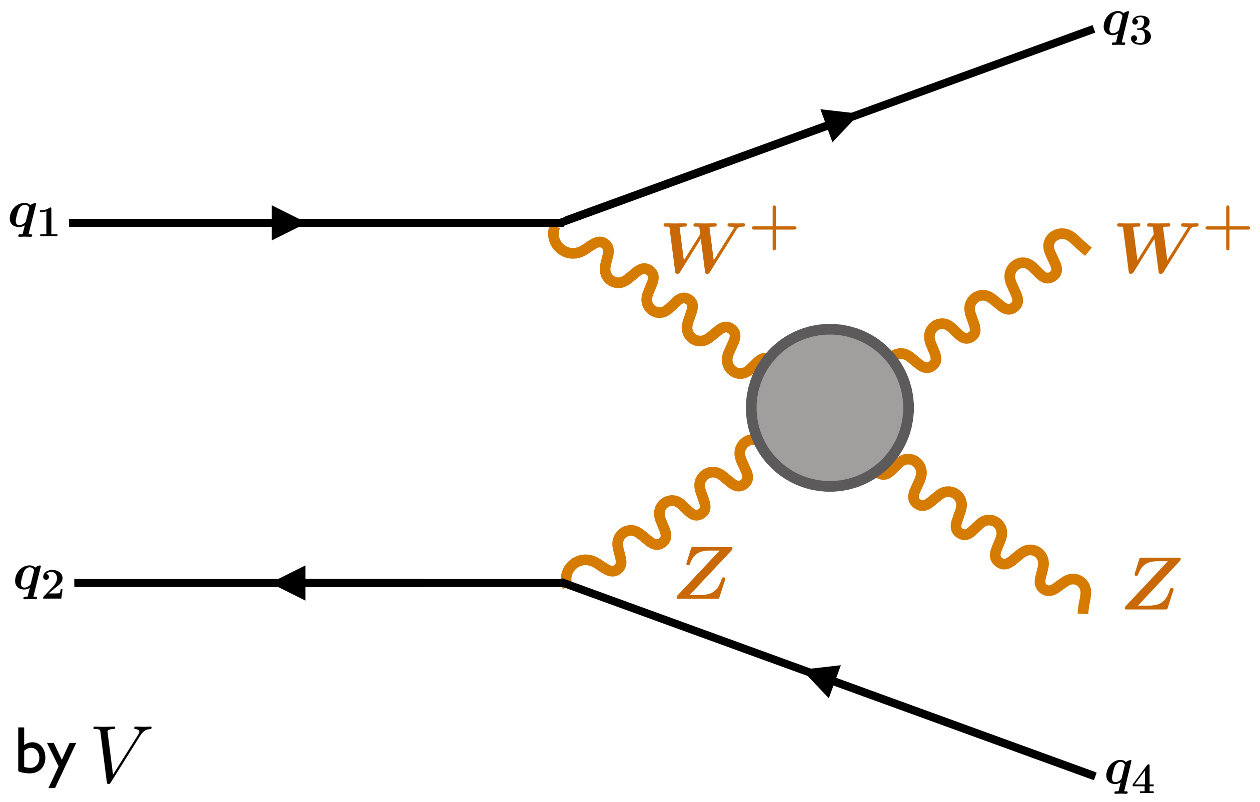
$$a_4, a_5 \in [10^{-3}, 10^{-4}]$$

Resonance mass
in TeV range

W⁺Z resonant scattering @ the LHC

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

Energy at which occurs depends on

- Expansion in powers of p $\xrightarrow{\text{typically}}$ **Violation of Unitarity** $\longrightarrow$ $(a-1), a_4, a_5$

Dynamical Generation of Resonances: the IAM

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

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD

  generates **resonances** dynamically

Dynamical Generation of Resonances: the IAM

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

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD

  generates **resonances** dynamically

Unitarized Partial Waves

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

Dynamical Generation of Resonances: the IAM

- Expansion in powers of *p* $\xrightarrow{\text{typically}}$ **Violation of Unitarity** → $(a-1), a_4, a_5$

  Energy at which occurs depends on

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD

  generates **resonances** dynamically

Unitarized Partial Waves

$$a_{IJ}^{\mathrm{IAM}} = \frac{\left(a_{IJ}^{(0)}\right)^2}{\boxed{a_{IJ}^{(0)} - a_{IJ}^{(1)}}} \longrightarrow \text{Poles}$$

Dynamical Generation of Resonances: the IAM

- Expansion in powers of p $\xrightarrow{\text{typically}}$ **Violation of Unitarity** → $(a-1), a_4, a_5$

  Energy at which occurs depends on

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD

  generates **resonances** dynamically

Unitarized Partial Waves

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

→ Poles → **Resonances**

scalar, vector…

Dynamical Generation of Resonances: the IAM

- Expansion in powers of *p* —typically→ **Violation of Unitarity** → $(a-1)$, a_4, a_5

  Energy at which occurs depends on

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD

  generates **resonances** dynamically

Unitarized Partial Waves

$$a_{IJ}^{\text{IAM}} = \frac{\left(a_{IJ}^{(0)}\right)^2}{\boxed{a_{IJ}^{(0)} - a_{IJ}^{(1)}}}$$

→ Poles → **Resonances** scalar, vector… → M, Γ depend on a b a_4 a_5

Dynamical Generation of Resonances: the IAM

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

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD; generates **resonances** dynamically

Unitarized Partial Waves

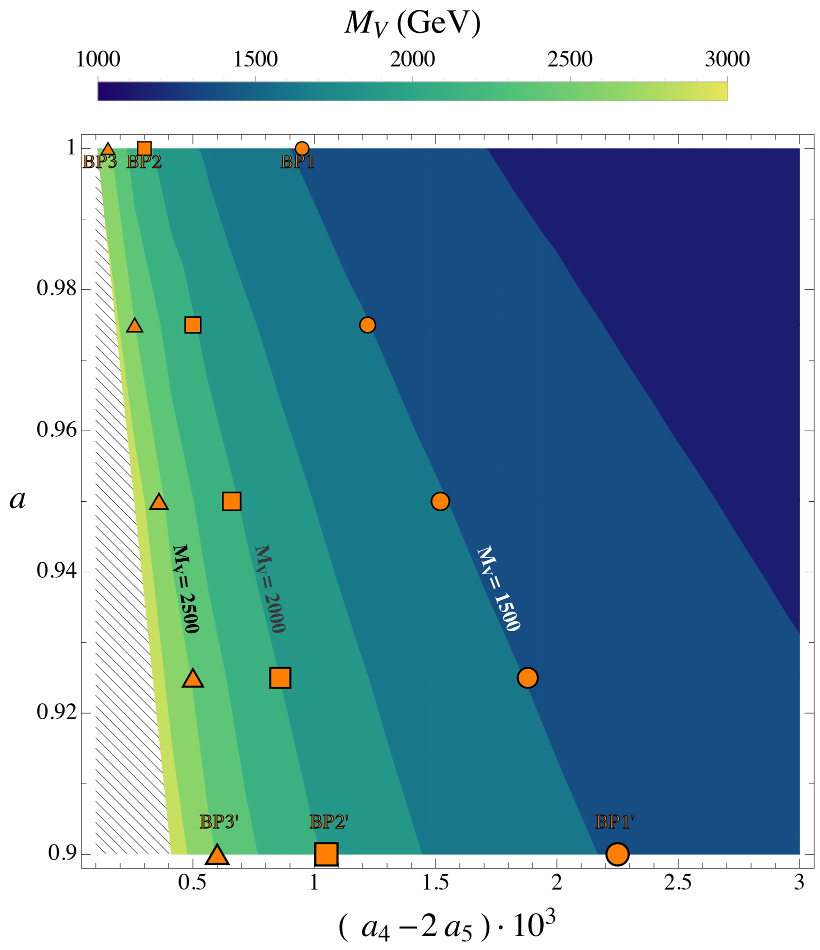
$$a_{IJ}^{\mathrm{IAM}} = \frac{\left(a_{IJ}^{(0)}\right)^2}{\boxed{a_{IJ}^{(0)} - a_{IJ}^{(1)}}}$$

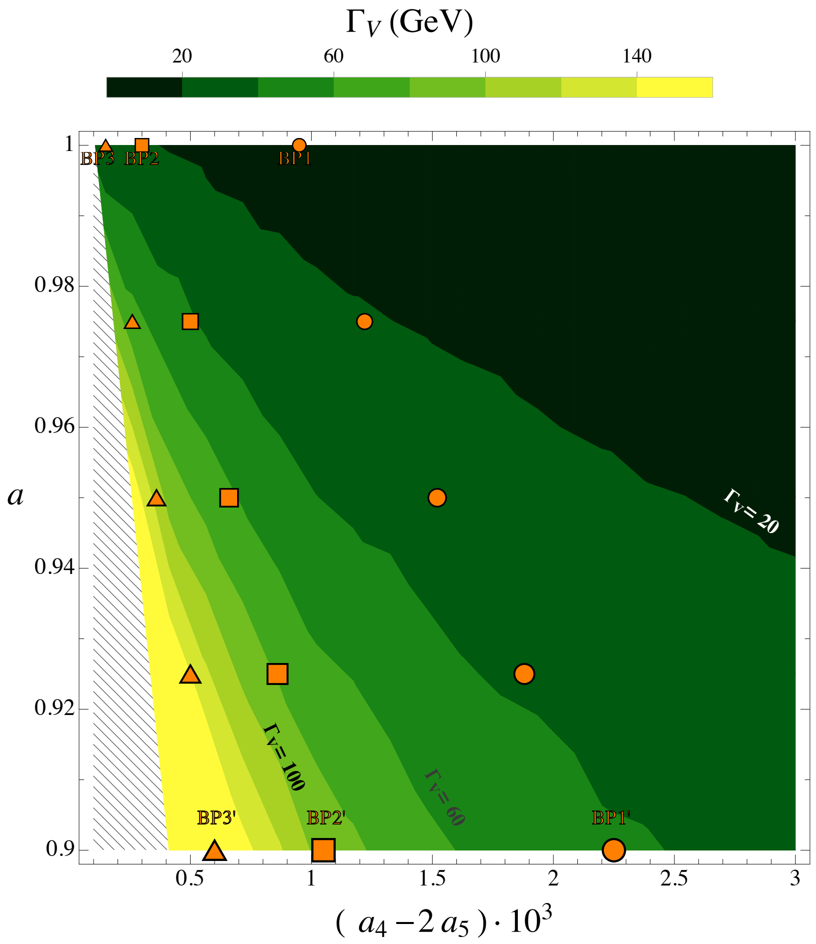
→ Poles → **Resonances** scalar, vector… → M, Γ depend on a b a_4 a_5

- We select **vector** scenarios

- Relevant combination $(a_4 - 2a_5)$

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





Dynamical Generation of Resonances: the IAM

- Expansion in powers of p → typically → **Violation of Unitarity** → $(a-1)$, a_4, a_5

  Energy at which occurs depends on

- Unitarization via the **Inverse Amplitude Method** (IAM) → good results in QCD

  generates **resonances** dynamically

Unitarized Partial Waves

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

→ Poles → **Resonances** scalar, vector… → M, Γ depend on a b a_4 a_5

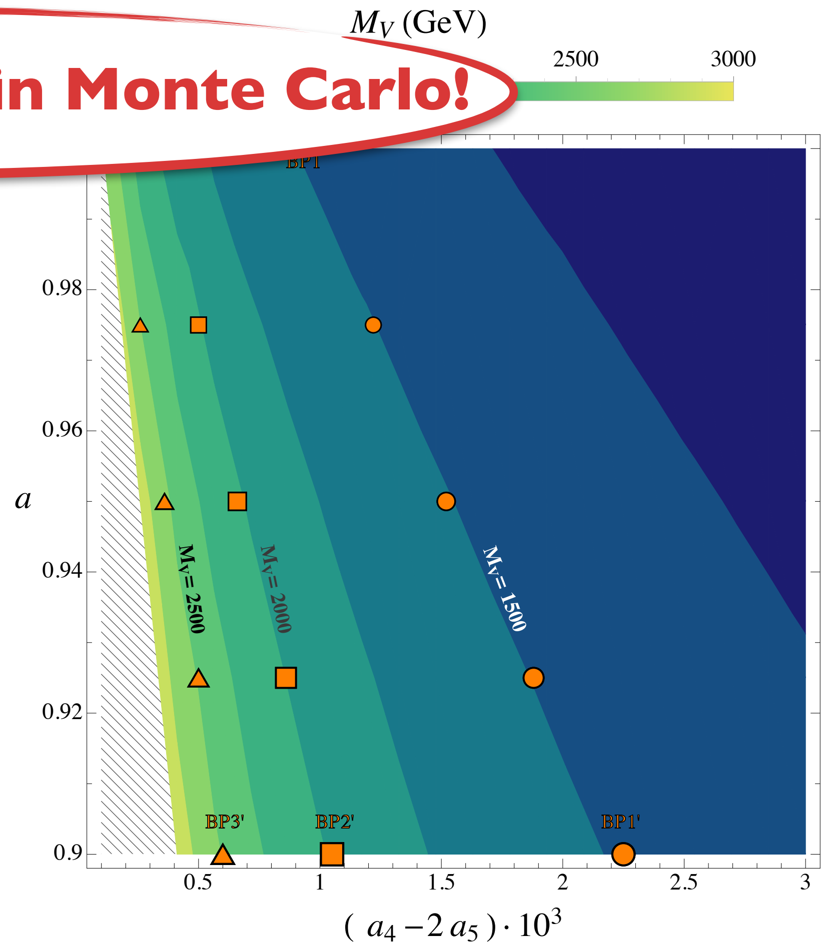
Difficult to Implement in Monte Carlo!

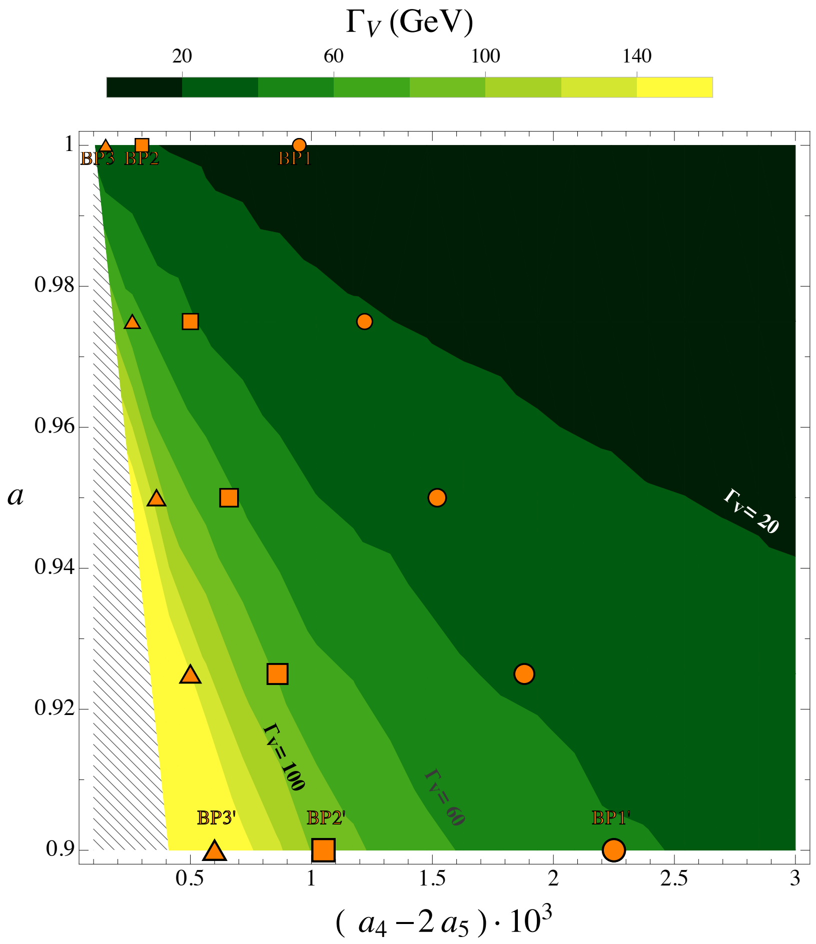
- We select **vector** scenarios

- Relevant combination

  $(a_4 - 2a_5)$

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





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)]

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

Computed from IAM pole
(also Γ_V)

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

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

Couples V mainly to W_L, Z_L

Couples V mainly to W_T, Z_T
Controls unphysical mixing between V and W, Z

$$\downarrow$$

$$f_V = 0$$

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

Computed from IAM pole
(also Γ_V)

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

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

Couples V mainly to W_L, Z_L

Unitary gauge
Rotation to mass basis

Couples V mainly to W_T, Z_T
Controls unphysical mixing between V and W, Z

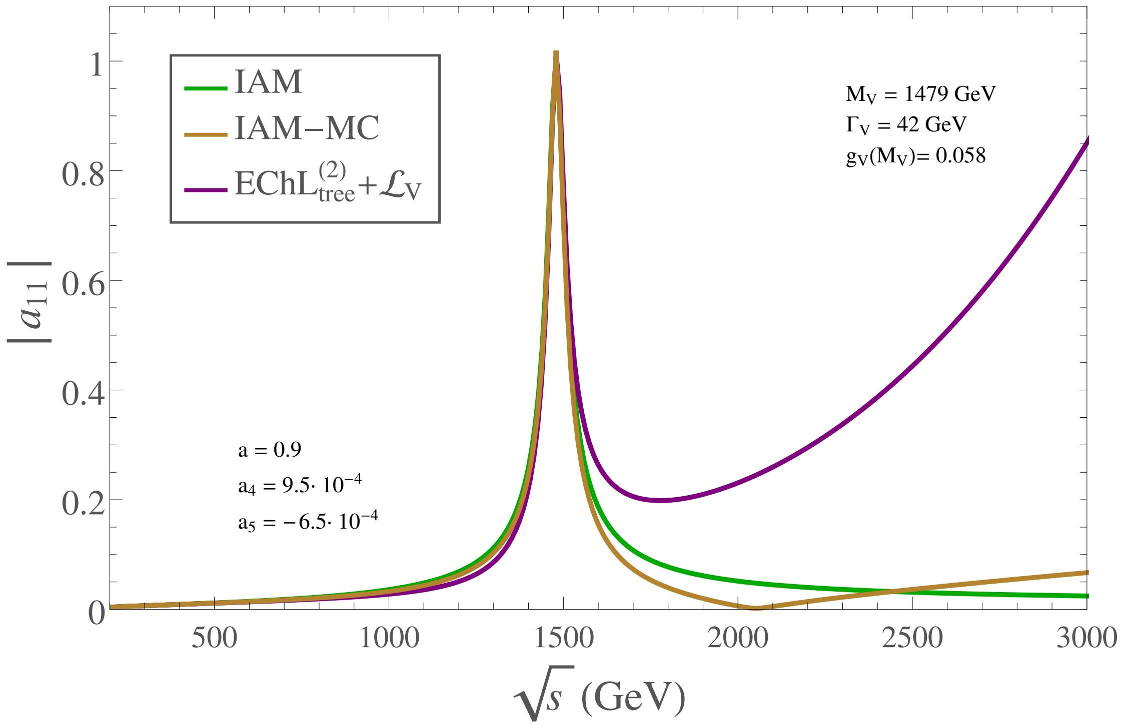
$$f_V = 0$$

$$\mathcal{L}_V = -\frac{1}{4}\Big(2V^+_{\mu\nu}V^{-\mu\nu} + V^0_{\mu\nu}V^{0\mu\nu}\Big) + \frac{1}{2}M_V^2\Big(2V^+_\mu V^{-\mu} + V^0_\mu V^{0\mu}\Big)$$
$$+\frac{i2g_V}{v^2}\Big[m_W^2 V^{0\ \mu\nu}W^+_\mu W^-_\nu + m_W\, m_Z\, V^{+\ \mu\nu}W^-_\mu Z_\nu + m_W\, m_Z\, V^{-\ \mu\nu}Z_\mu W^+_\nu\Big]$$

Our model: IAM-MC for resonant WZ scattering

- Proca Lagrangian with constant g_V violates unitarity

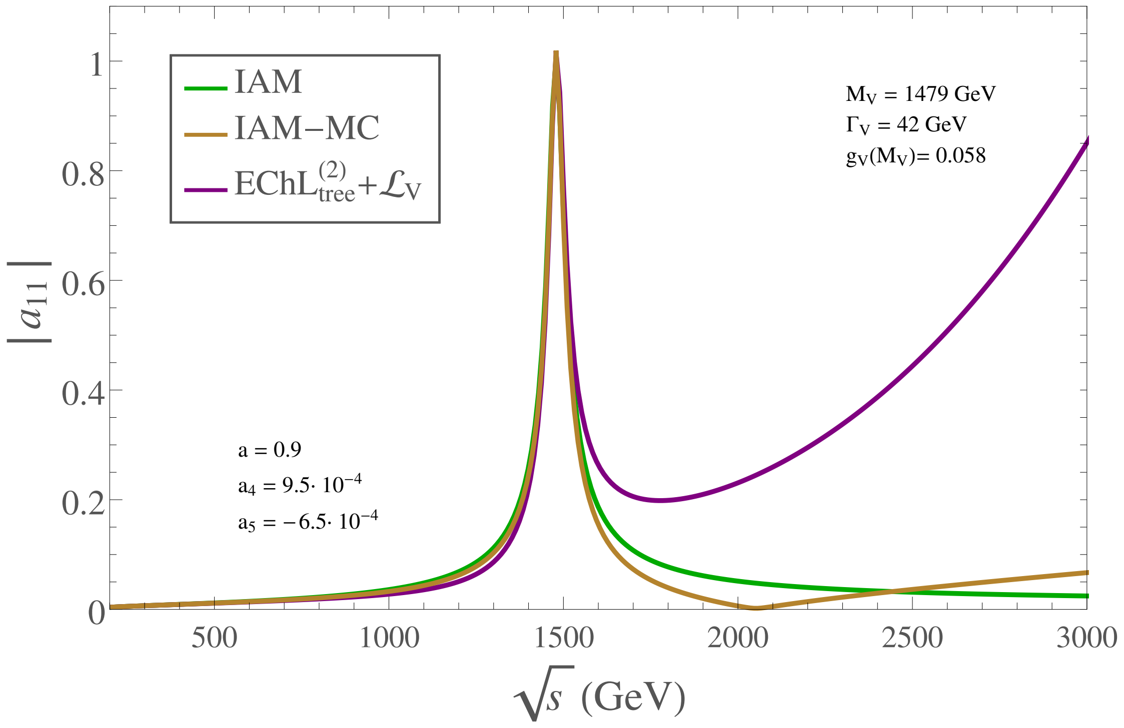
→



Our model: IAM-MC for resonant WZ scattering

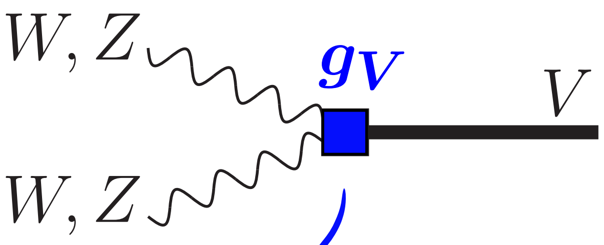
- Proca Lagrangian with constant g_V violates unitarity

→



- g_V promoted to form factor

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

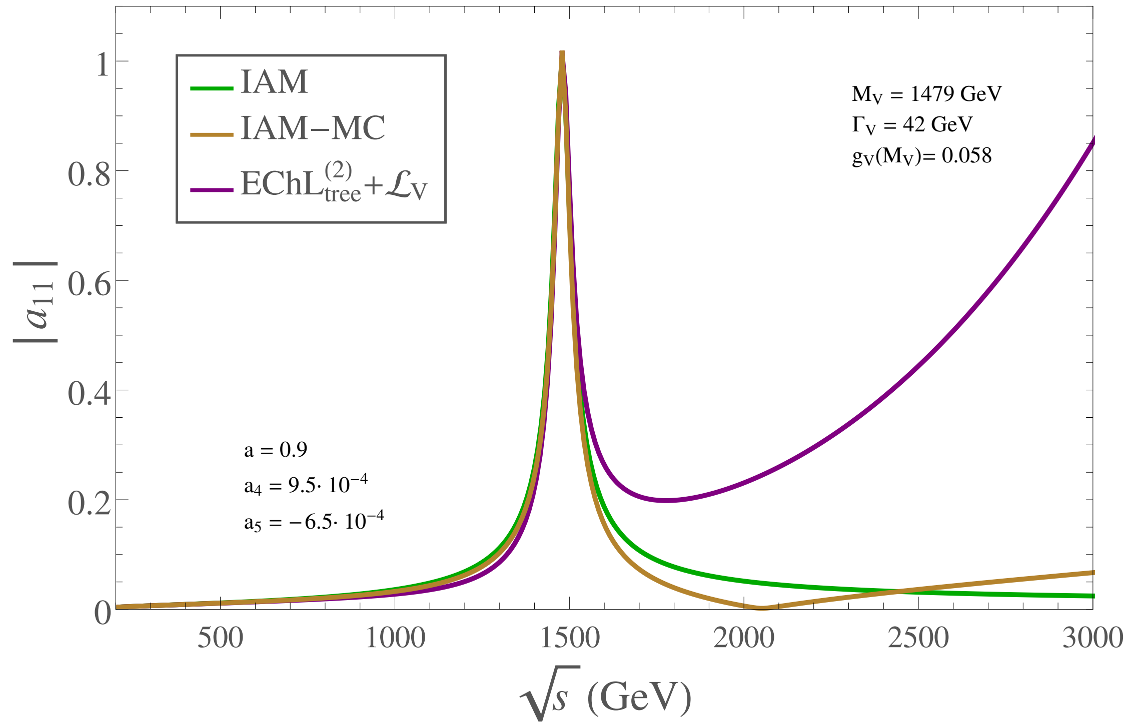


g_V ⟷ **Form Factor**

Our model: IAM-MC for resonant WZ scattering

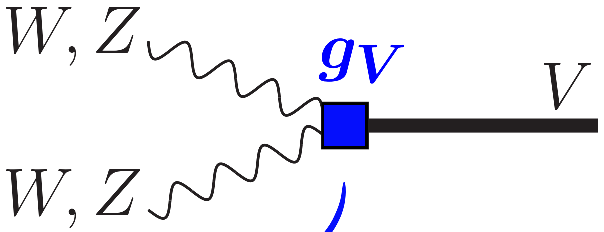
- Proca Lagrangian with constant g_V violates unitarity

→



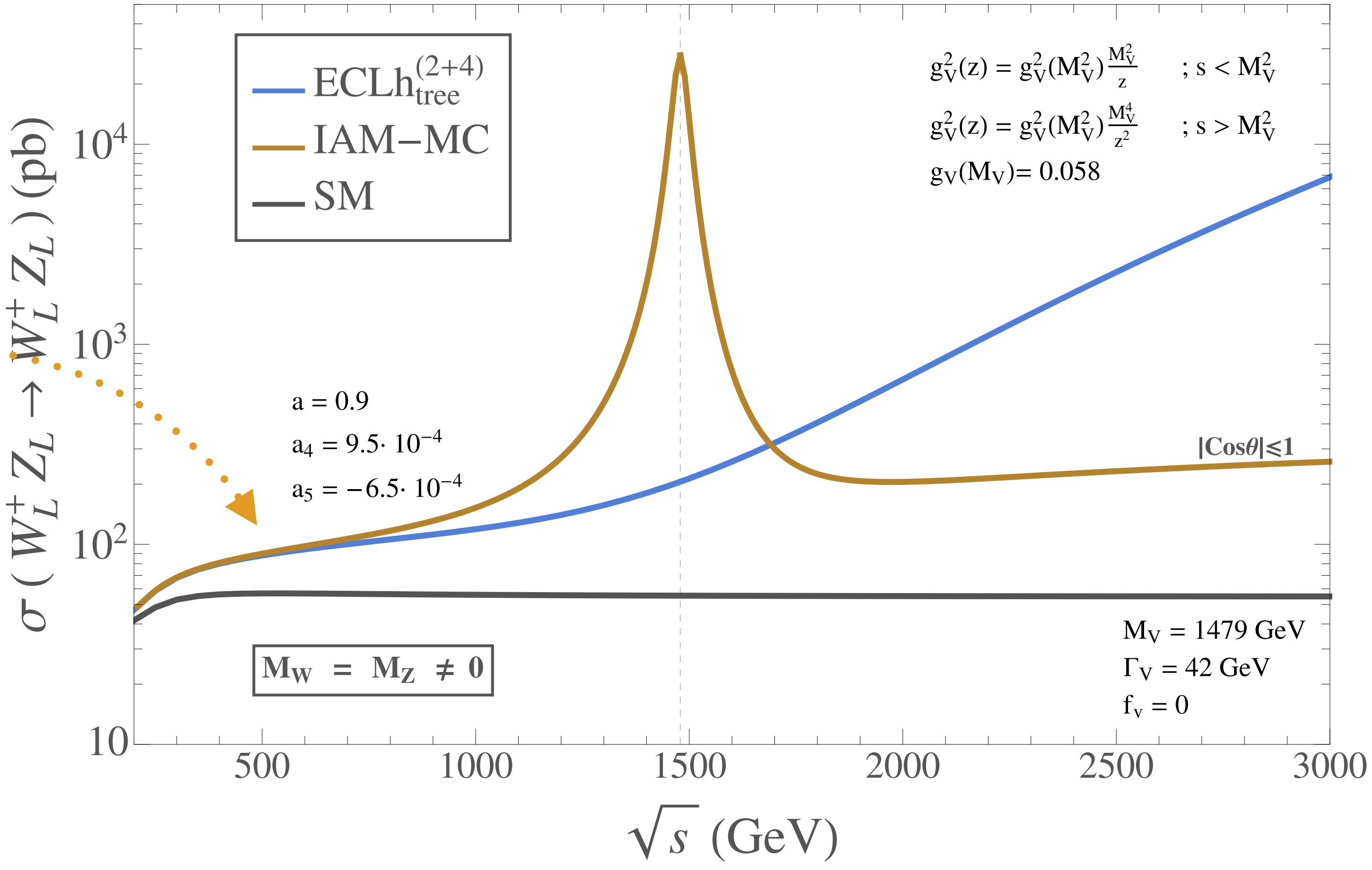
- g_V promoted to form factor

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



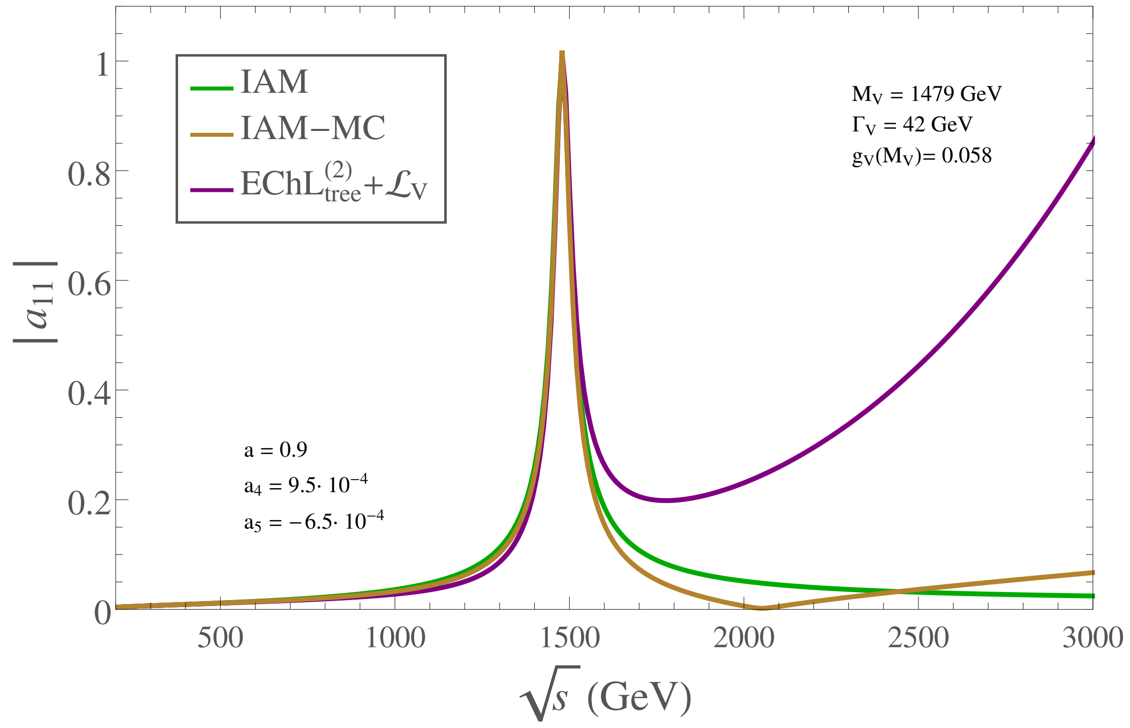
g_V ⟷ **Form Factor**

- EChL $\mathscr{L}_4$ recovered for $s < M_V^2$



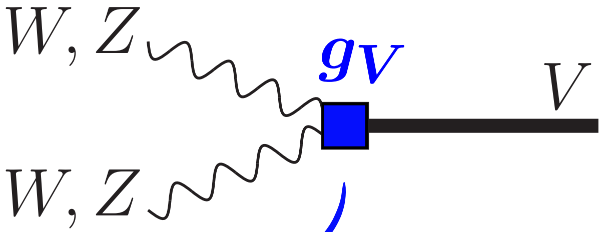
Our model: IAM-MC for resonant WZ scattering

- Proca Lagrangian with constant g_V violates unitarity →



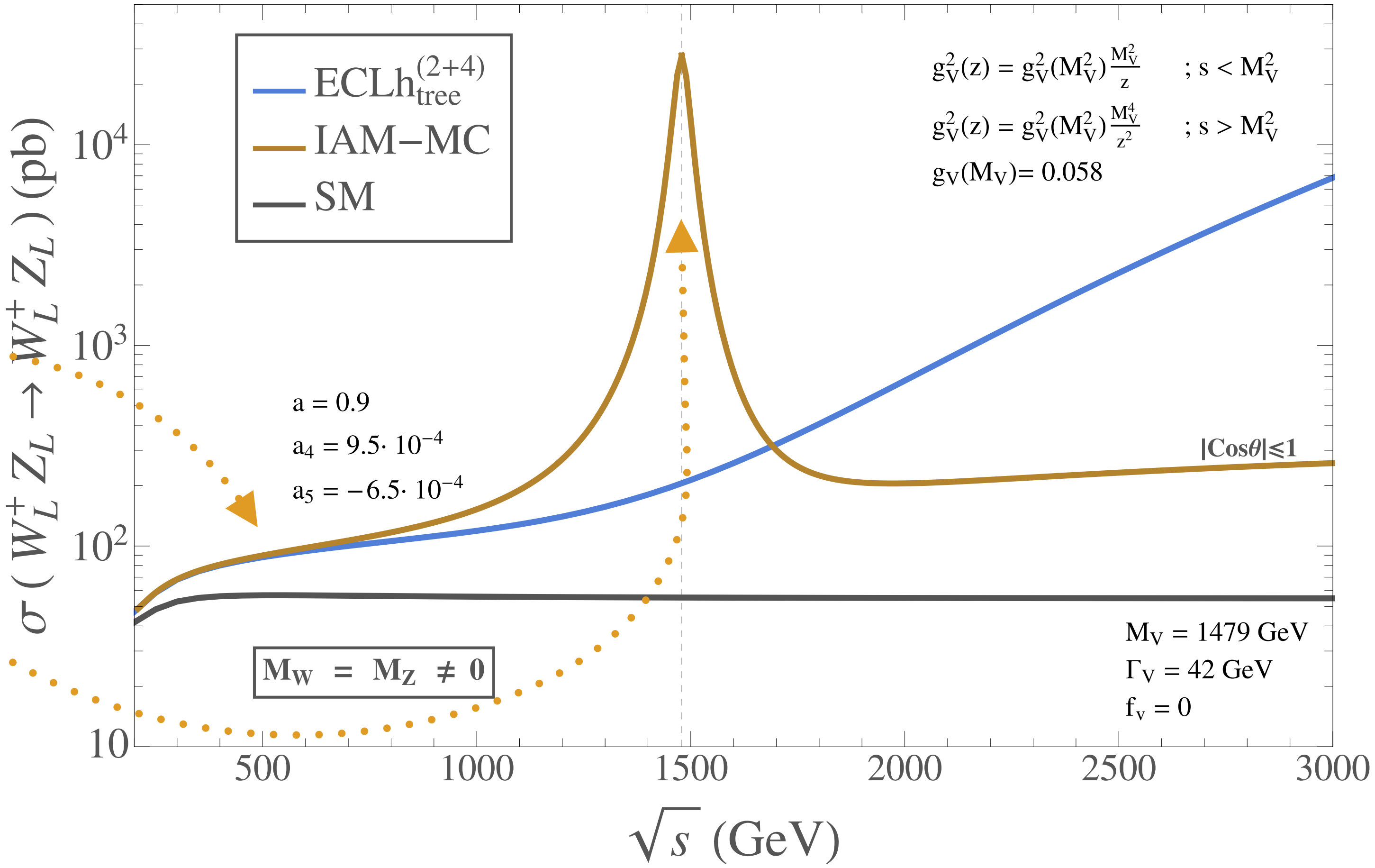
- g_V promoted to form factor

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



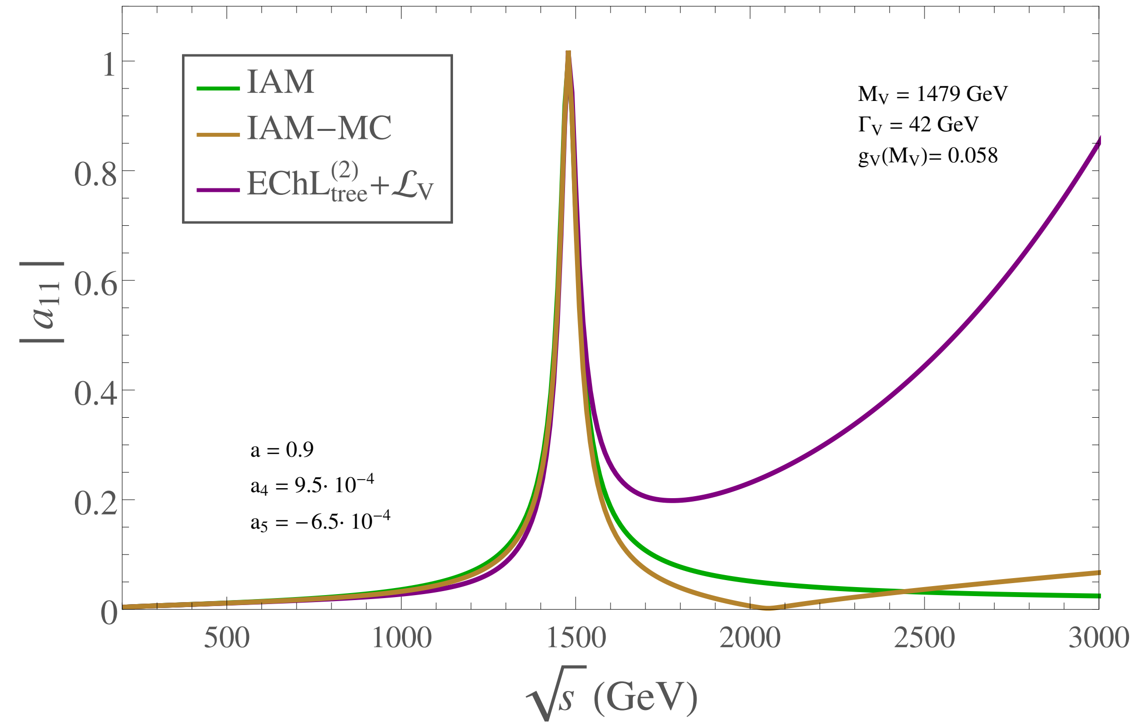
g_V ⟷ Form Factor

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



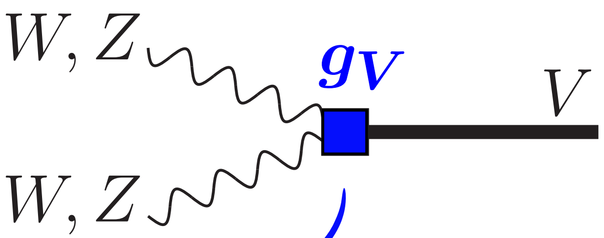
Our model: IAM-MC for resonant WZ scattering

- Proca Lagrangian with constant g_V violates unitarity



- g_V promoted to form factor

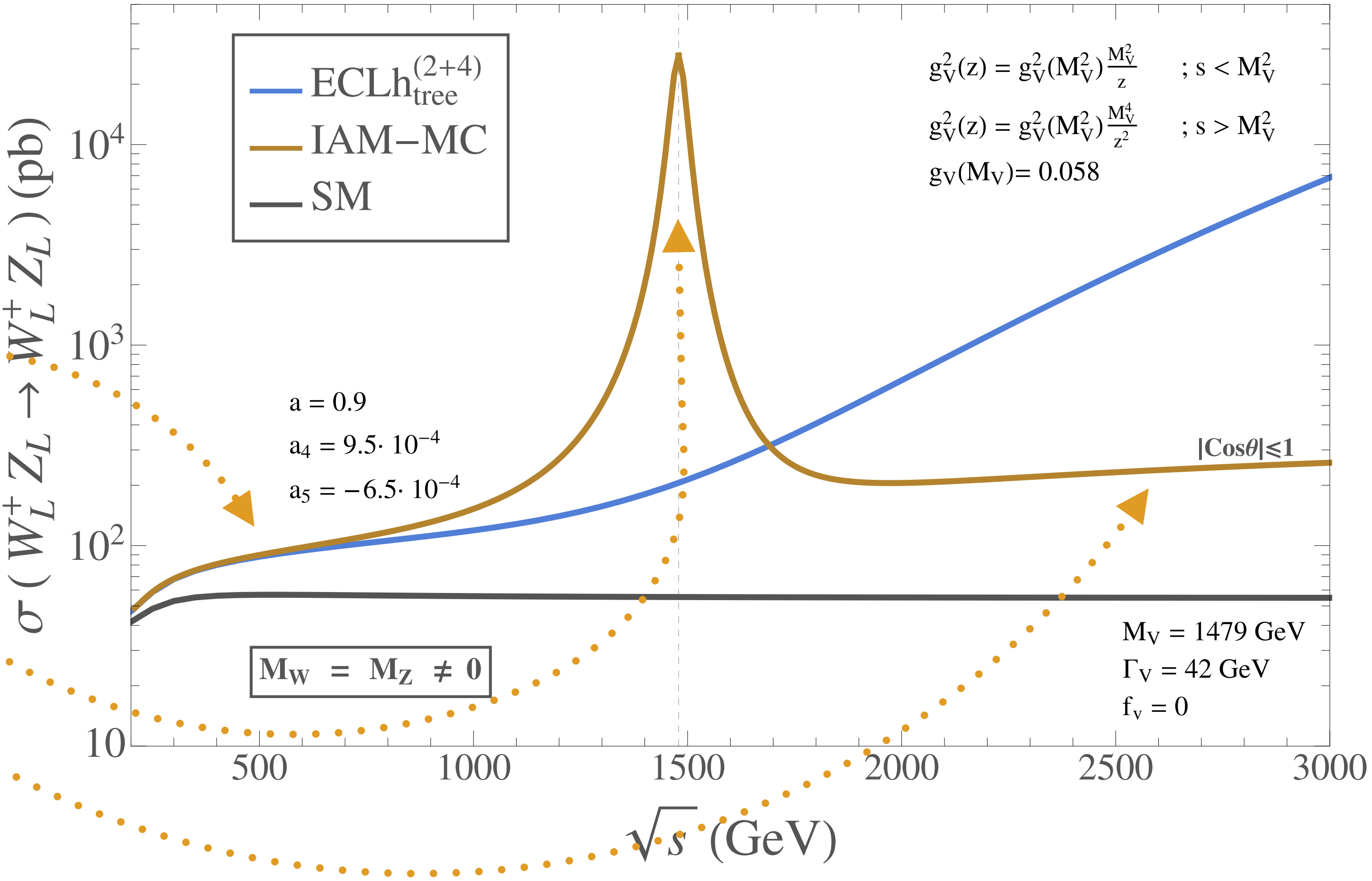
$$\mathscr{L}_{\rm IAM-MC} = \mathscr{L}_2 + \mathscr{L}_V$$



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 $s > M_V^2$

  [M. Froissart, Phys. Rev. 123, 1053 (1961)]

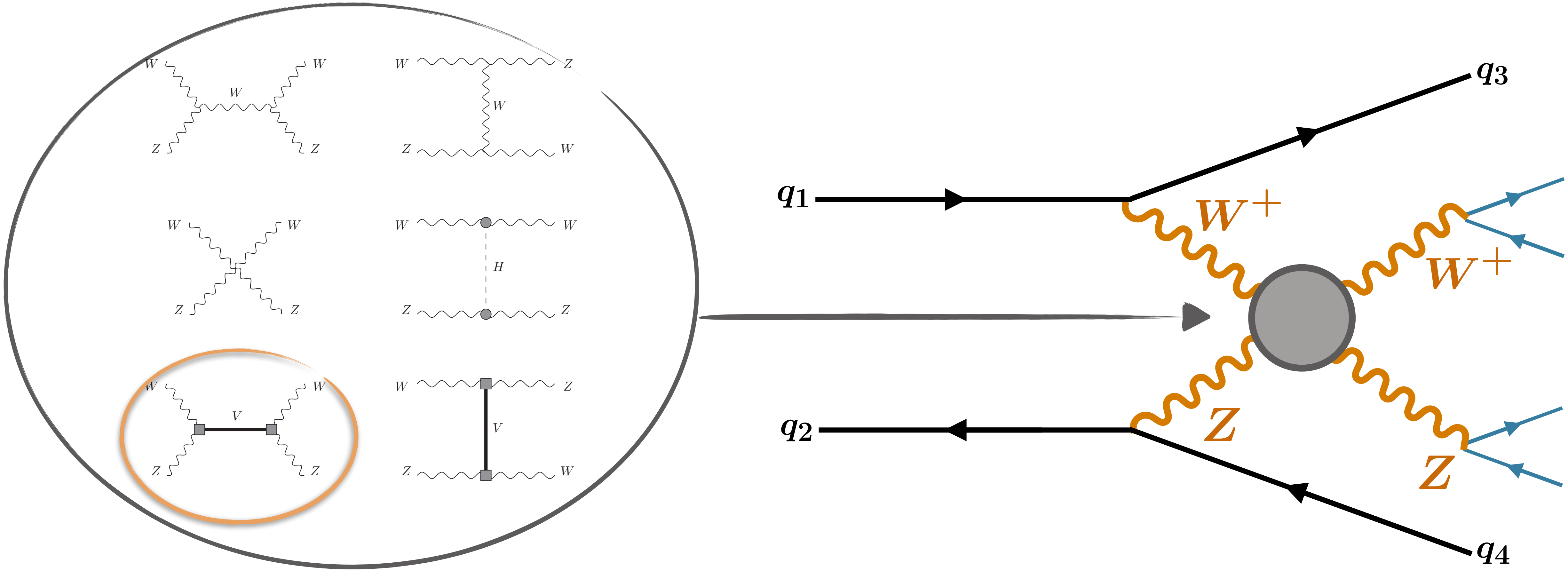


Vector Resonances in the W^+Z channel @ LHC

- We study **charged vector resonances**, V , from a triplet, $V^{\pm}, V^0$

- **W^+Z** channel very promising
  - Mediated only by V
  - No severe QCD backgrounds
  - Clean leptonic signal

- Signals $pp \to W^+Zjj$ $pp \to \ell_1^+\ell_1^-\ell_2^+ \not{E}_Tjj$ $pp \to JJjj$



MG effective vertex

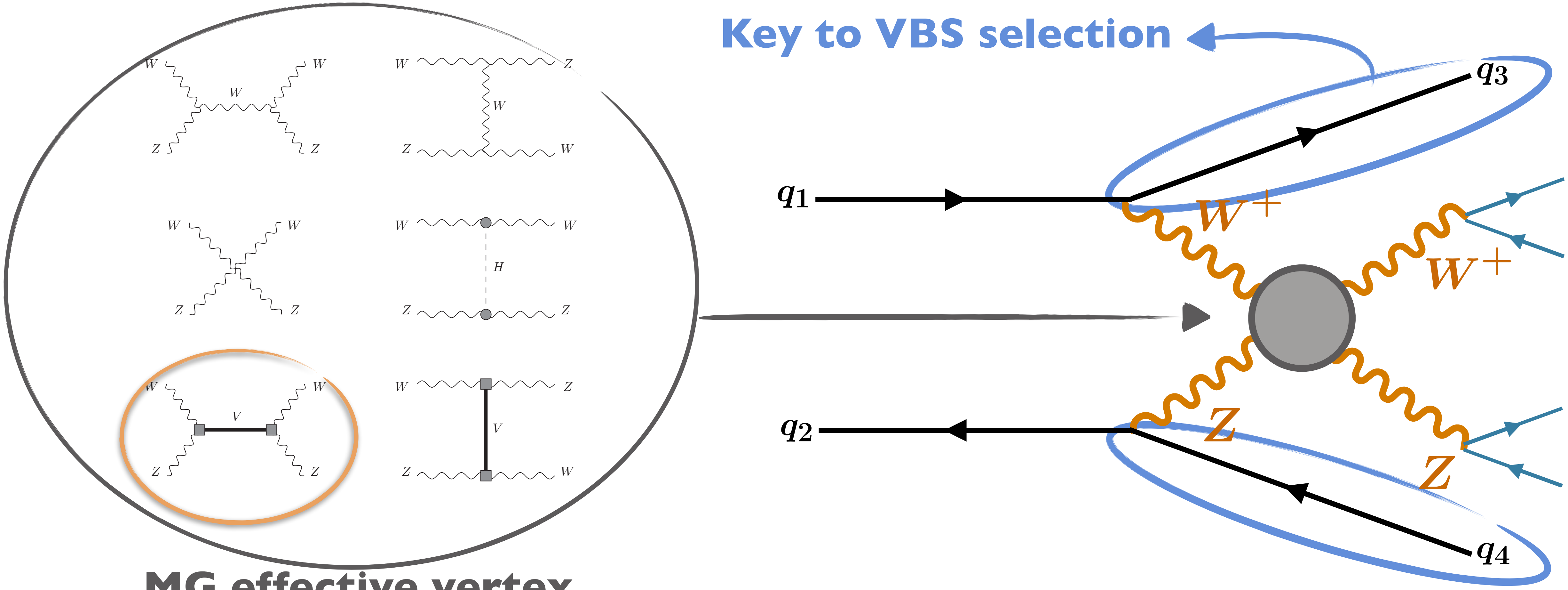
Vector Resonances in the W^+Z channel @ LHC

- 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

$$pp \to W^+Zjj$$

$$pp \to \ell_1^+\ell_1^-\ell_2^+\not{E}_Tjj$$

$$pp \to JJjj$$



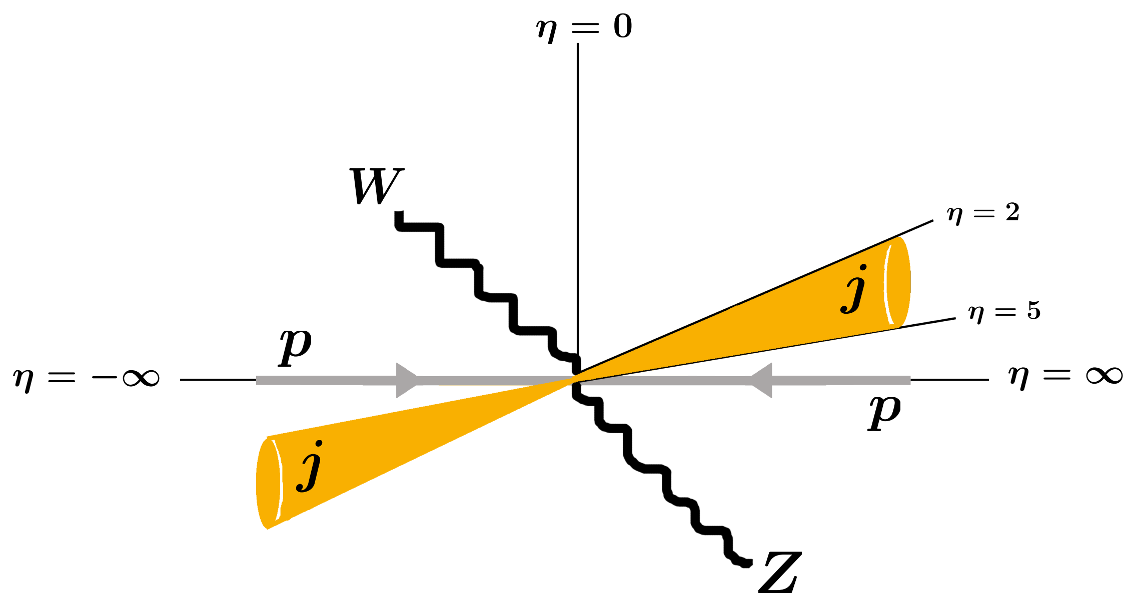
MG effective vertex

VBS Event Selection

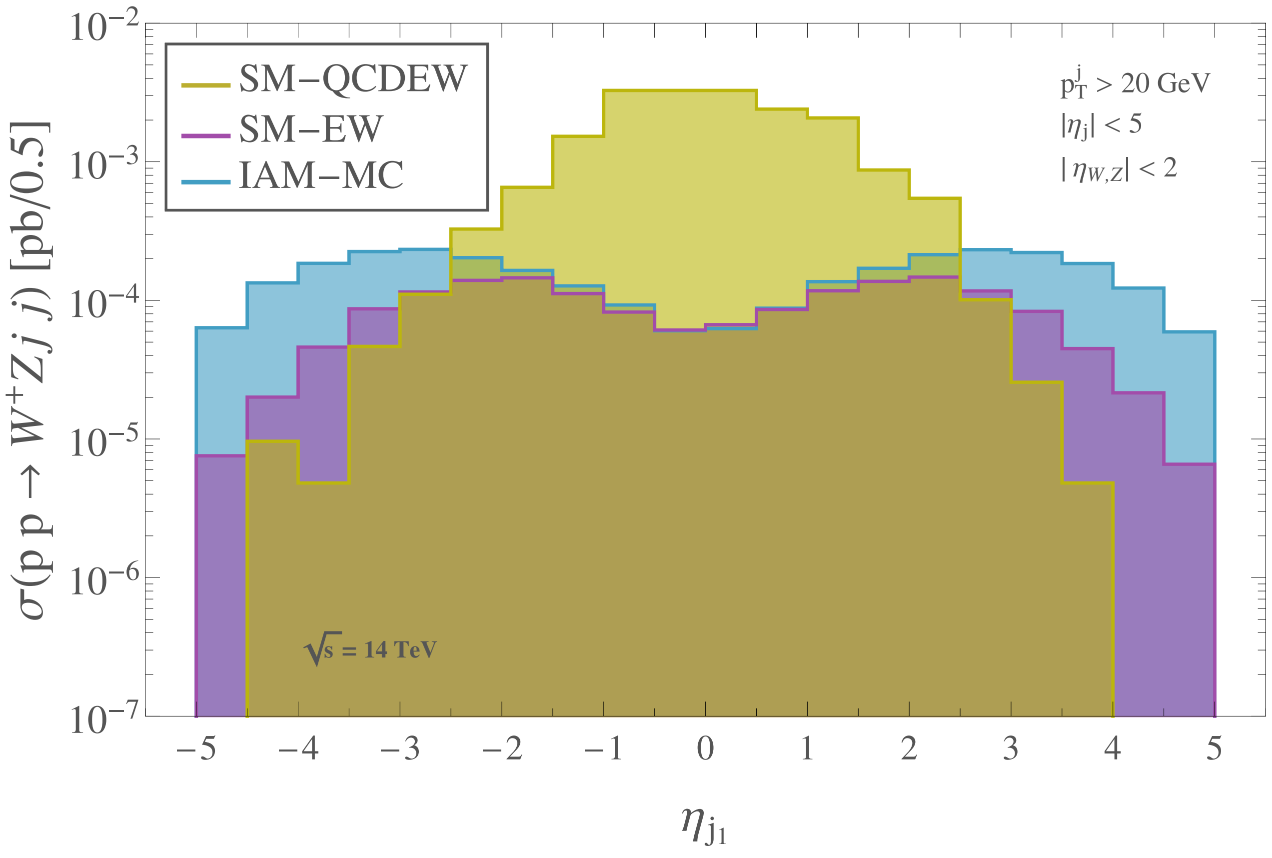
- **VBS kinematics** very characteristic

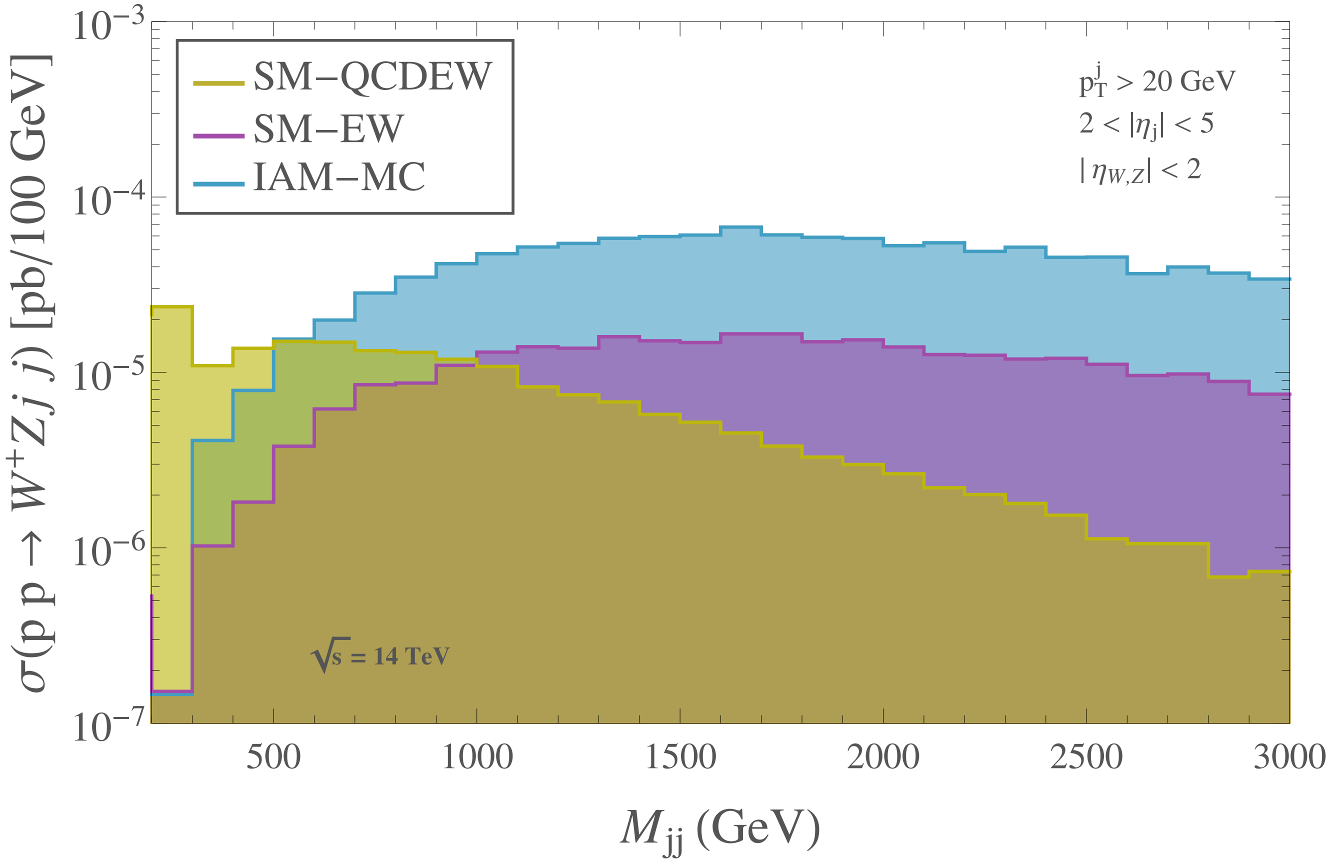
$$2 < |\eta_j| < 5$$
$$\eta_{j_1} \cdot \eta_{j_2} < 0$$
$$m_{jj} > 500 \text{ GeV}$$
$$p_T^j > 20 \text{ GeV}$$

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



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



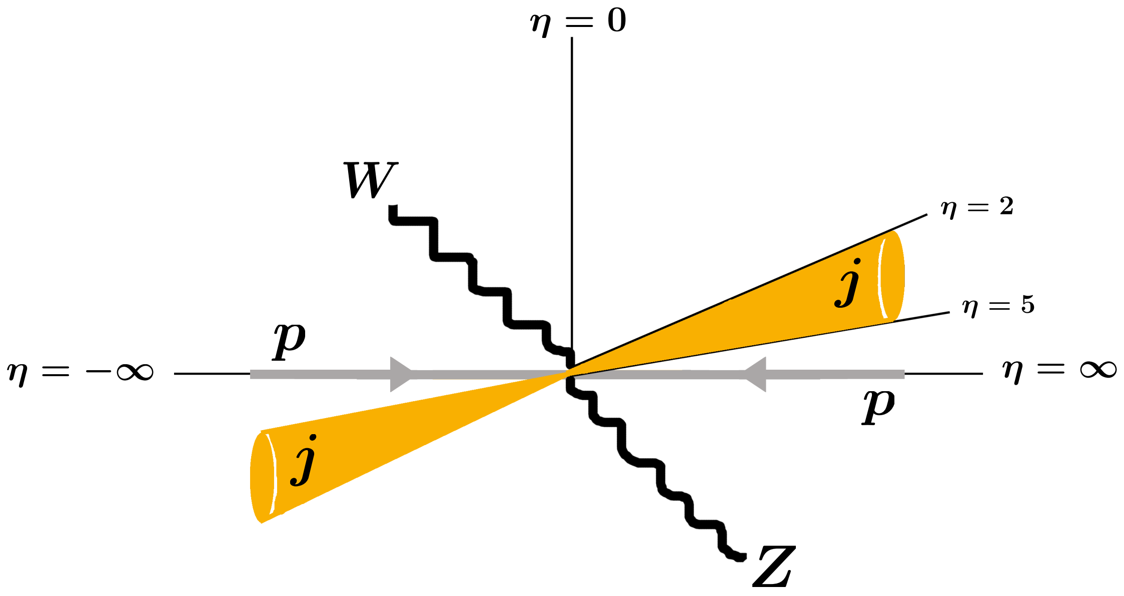


VBS Event Selection

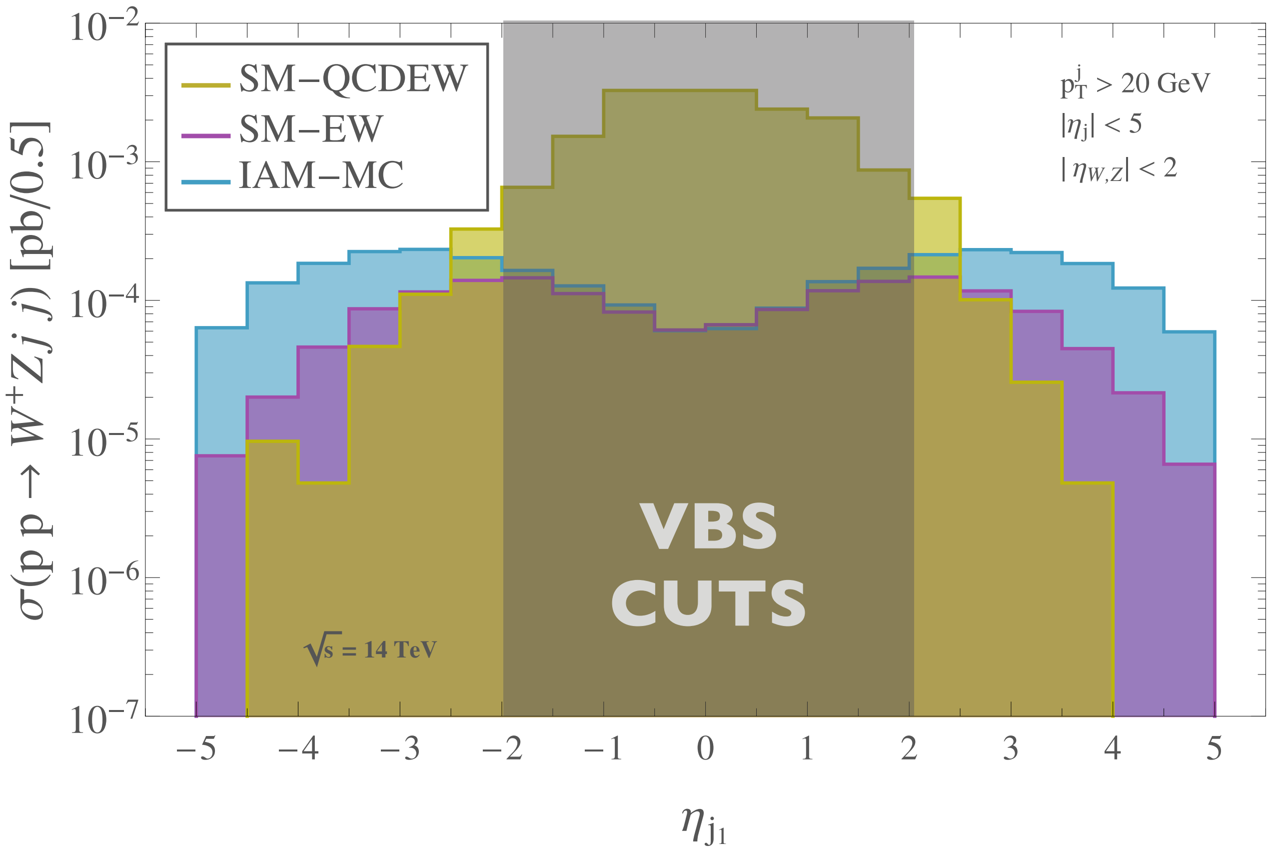
- **VBS kinematics** very characteristic

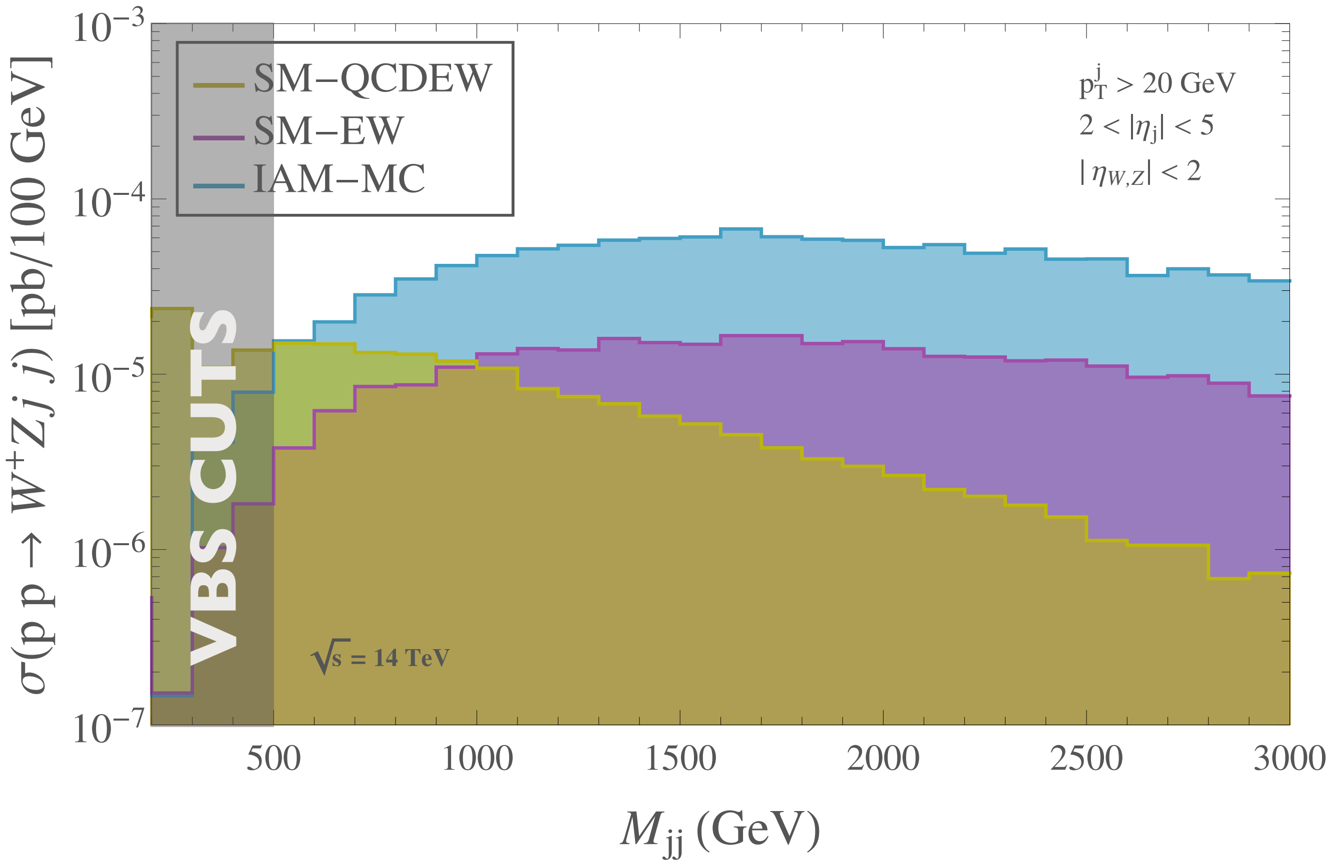
$$2 < |\eta_j| < 5$$
$$\eta_{j_1} \cdot \eta_{j_2} < 0$$
$$m_{jj} > 500 \text{ GeV}$$
$$p_T^j > 20 \text{ GeV}$$

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

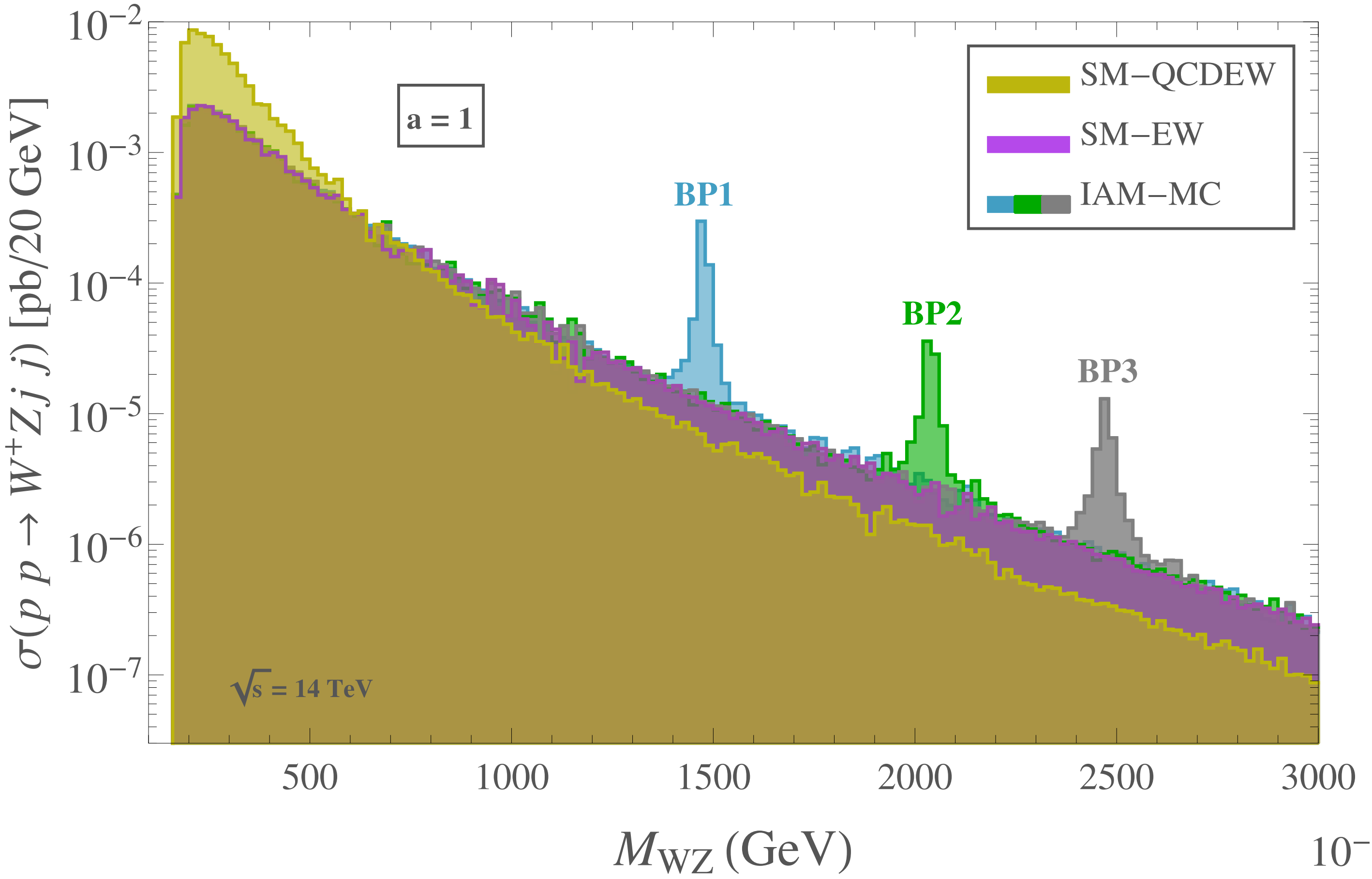


- Very effective in our case: **W^+Zjj**

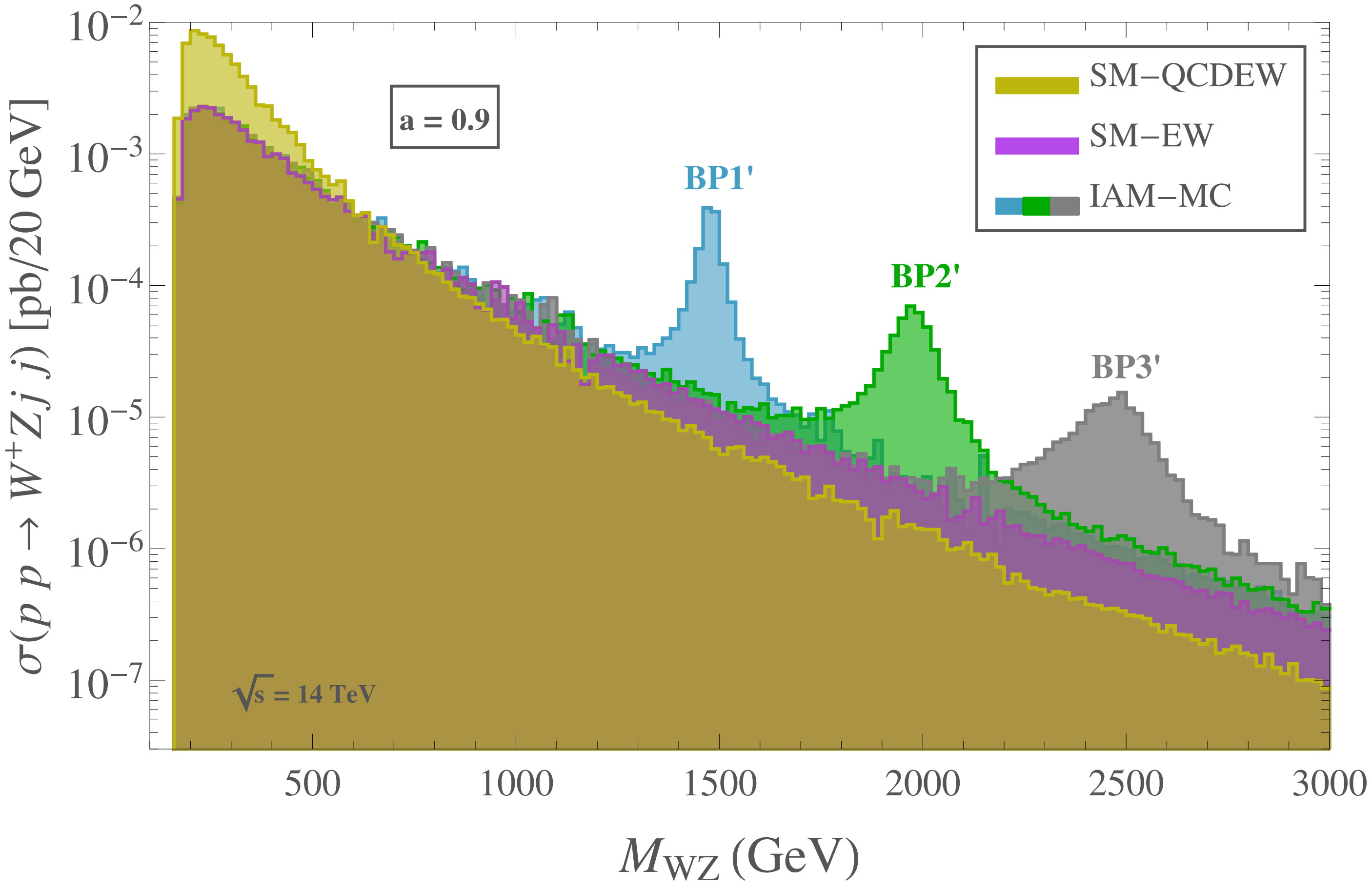




Results for W⁺Zjj: invariant mass distributions



- 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

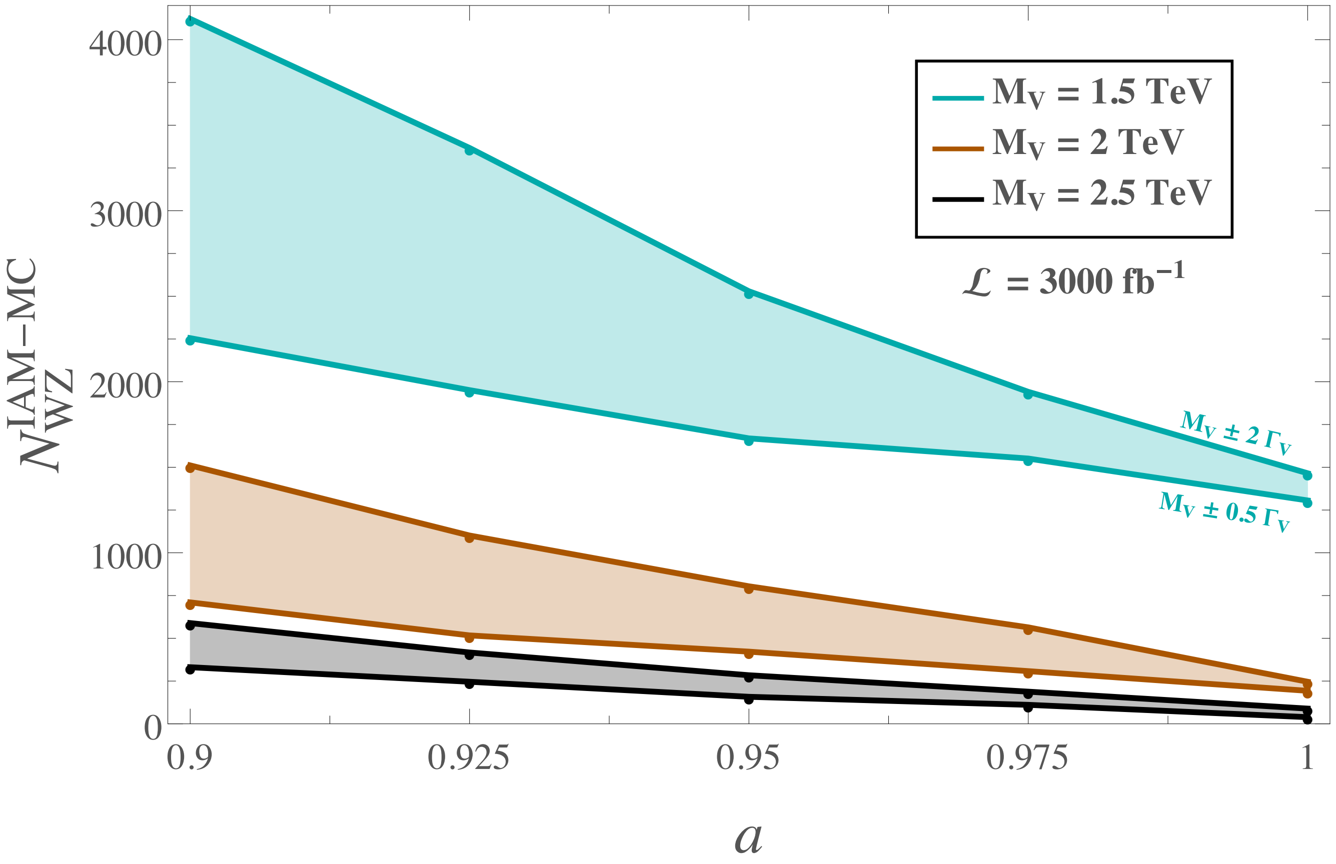
$\pm 0.5\,\Gamma_V$

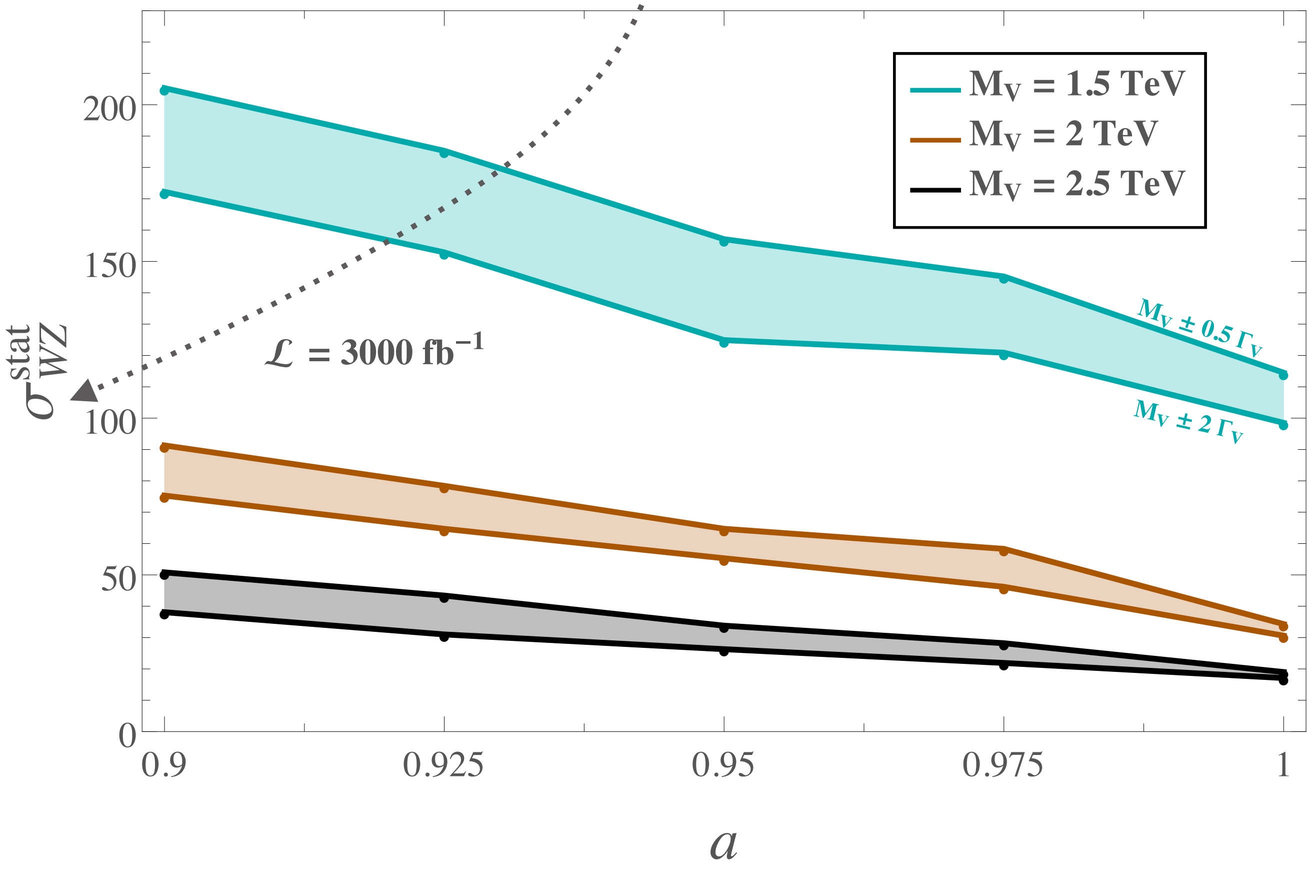
$\pm 2\,\Gamma_V$

→

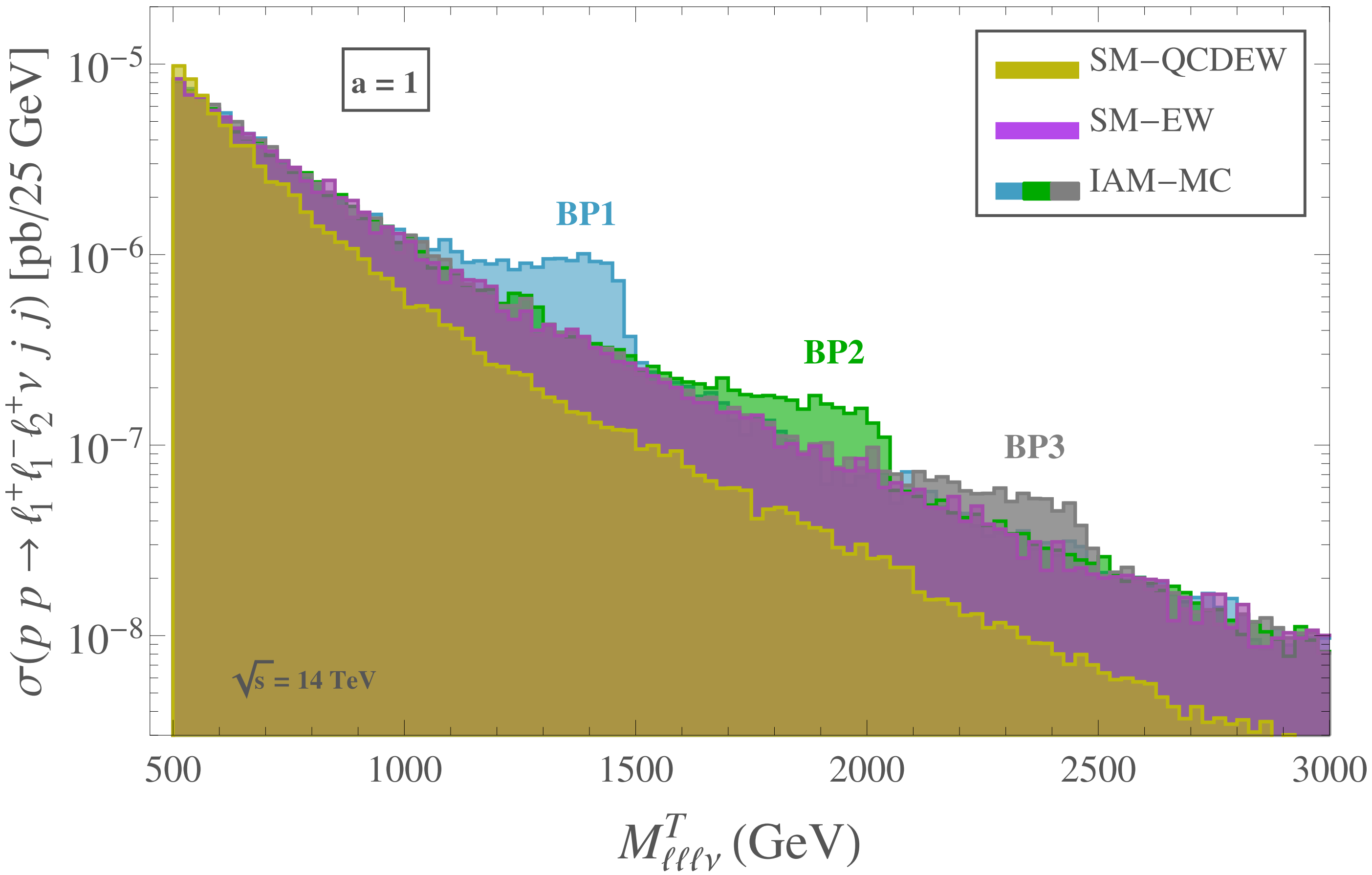
Statistical significance

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



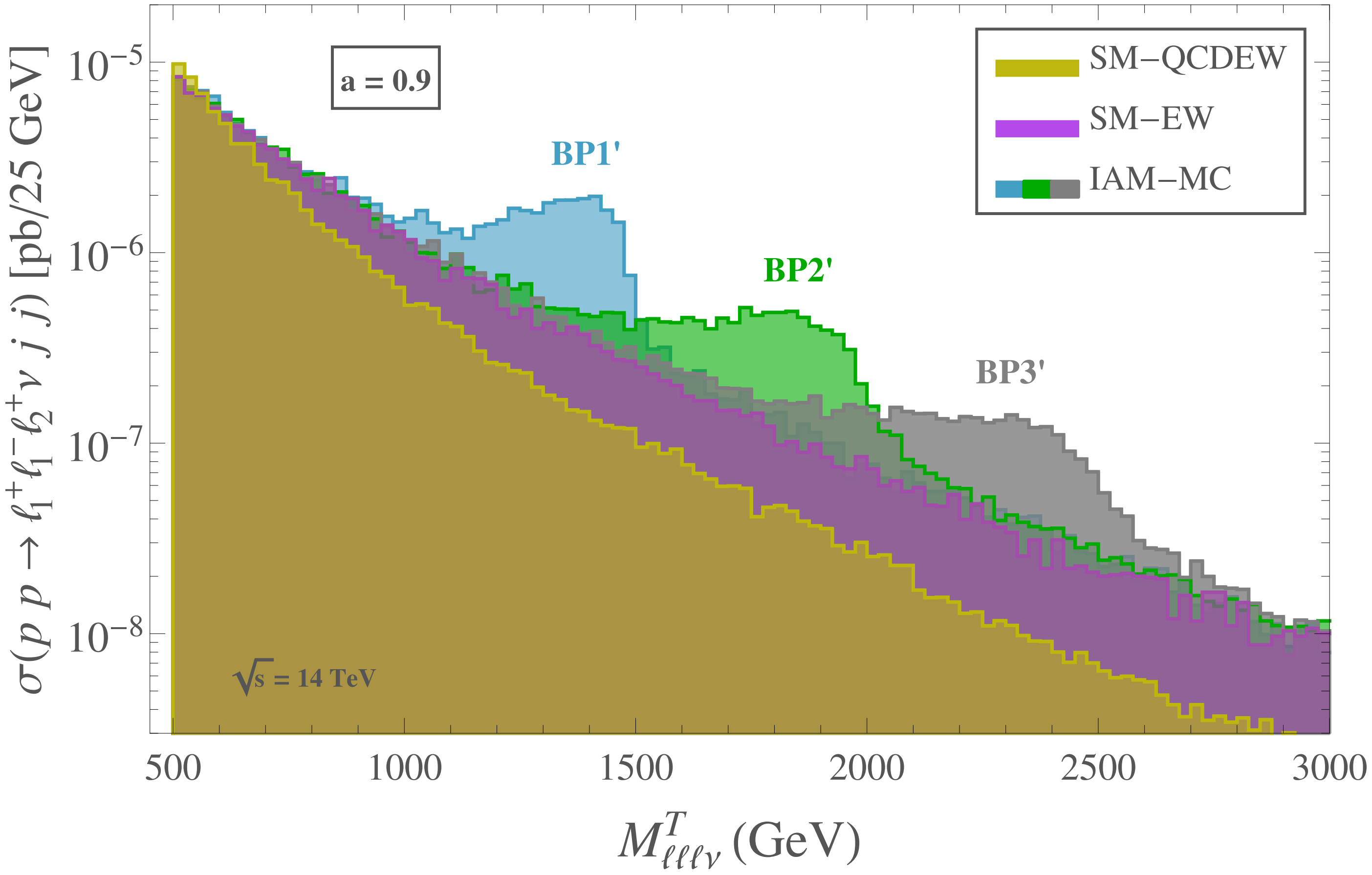


Results for $\ell^+\ell^-\ell'^+\nu$ jj : distributions



- 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

$pp \to \ell_1^+\ell_1^-\ell_2^+ \cancel{E}_T jj$ $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$

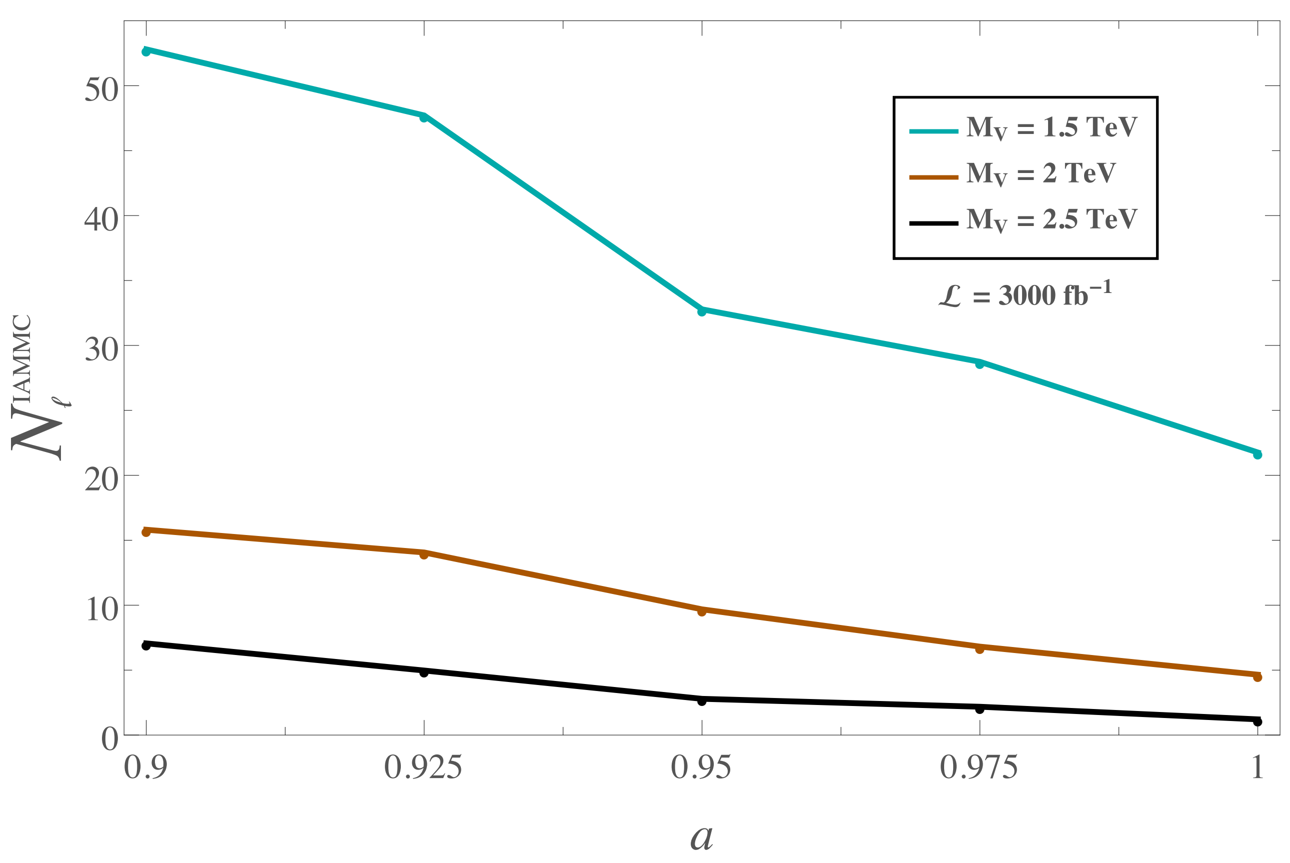
$a \in [0.9, 1] \longleftrightarrow M_V = 1.5$ TeV

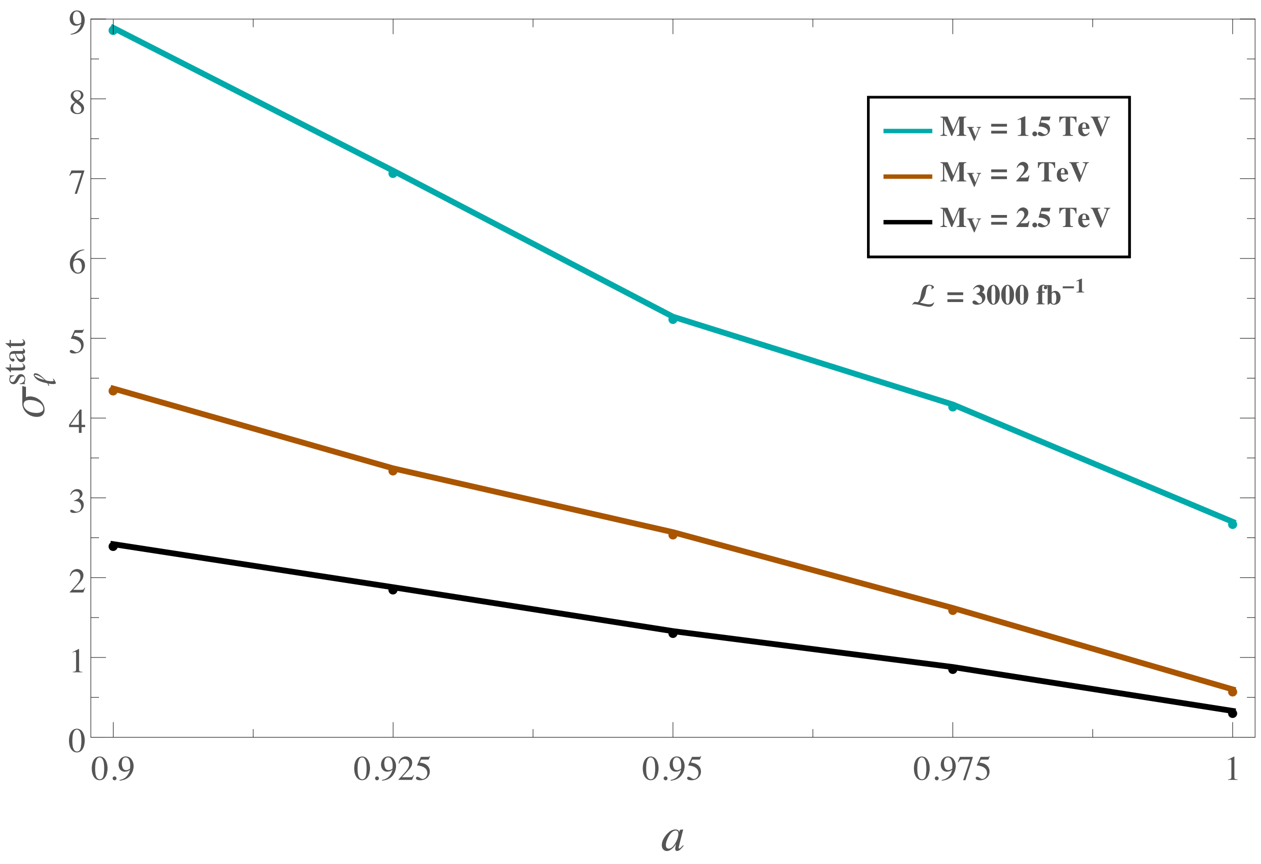
$a \in [0.94, 1] \longleftrightarrow M_V = 2$ TeV

Poor sensitivity for $M_V = 2.5$ TeV

- Clean and controlled
- Requires High Luminosity

Events summed over optimized intervals





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

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

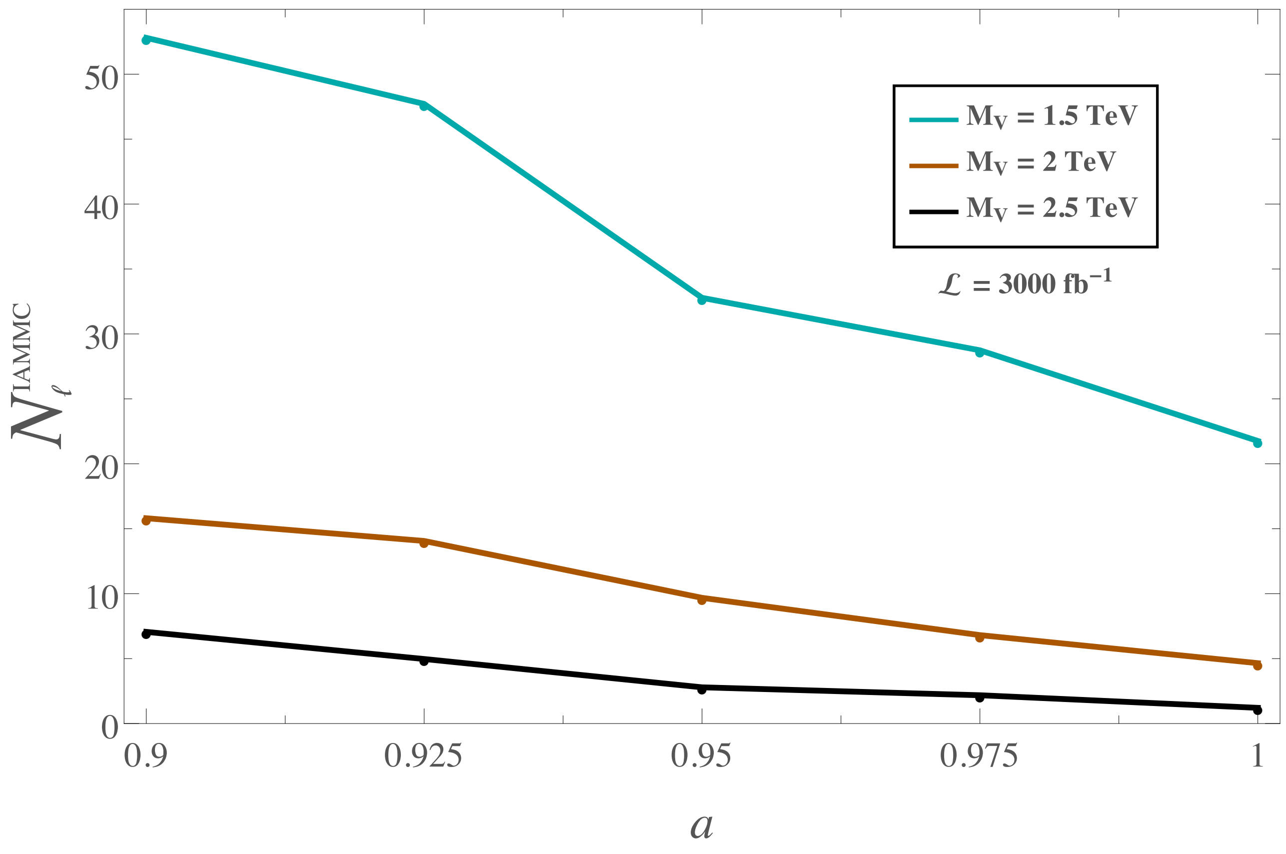
$a \in [0.9, 1]$ ⟷ $M_V = 1.5$ TeV

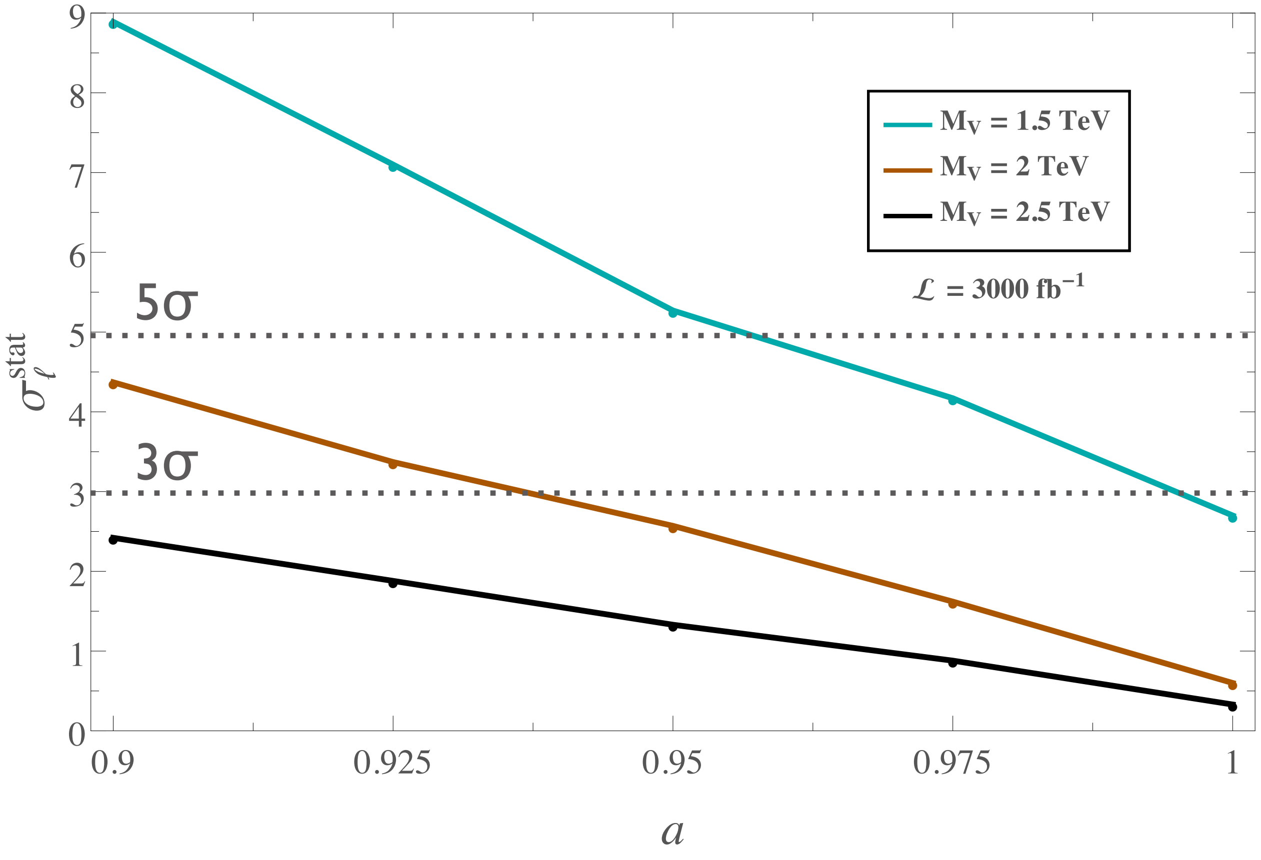
$a \in [0.94, 1]$ ⟷ $M_V = 2$ TeV

Poor sensitivity for $M_V = 2.5$ TeV

- Clean and controlled
- Requires High Luminosity

Events summed over optimized intervals





Estimates for other channels: JJjj

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

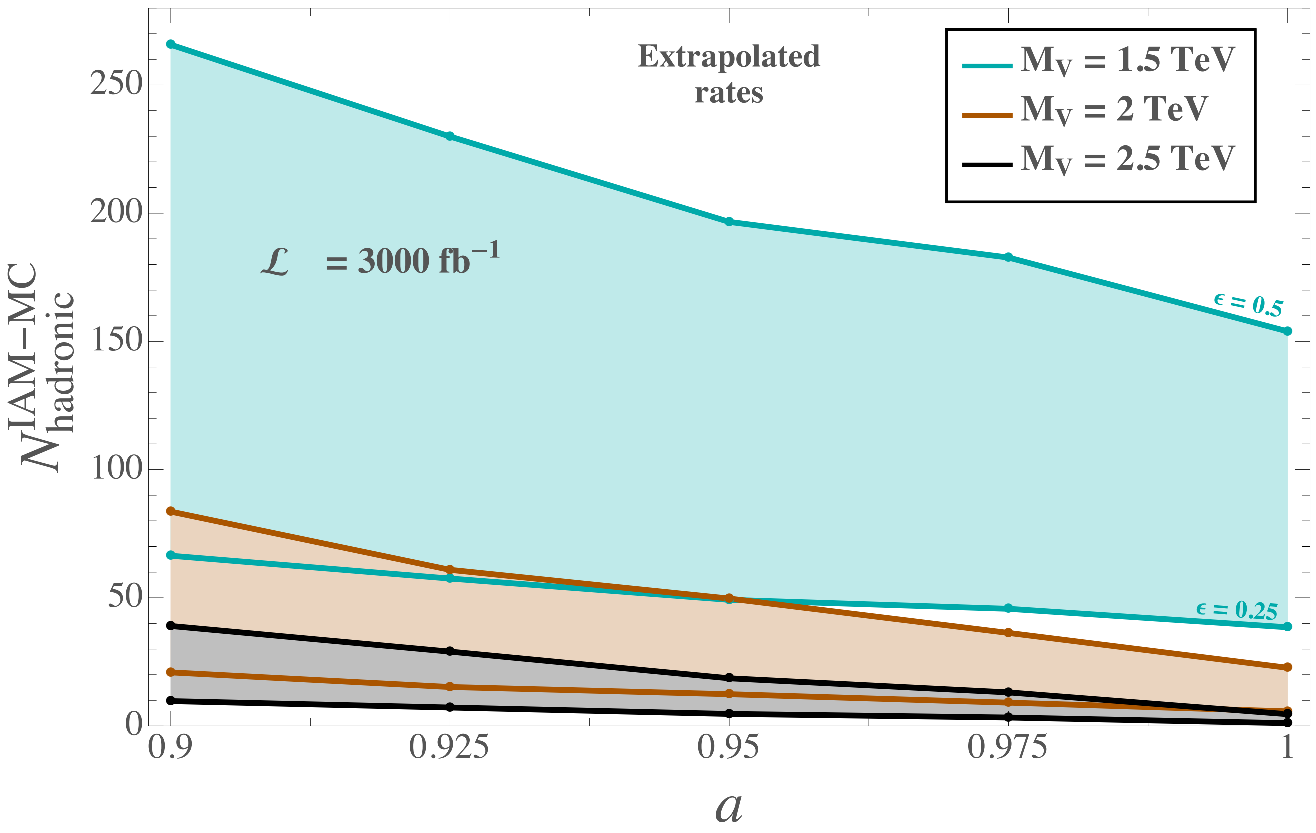
$a \in [0.9, 1] \longleftrightarrow M_V = 1.5\ \mathrm{TeV}$

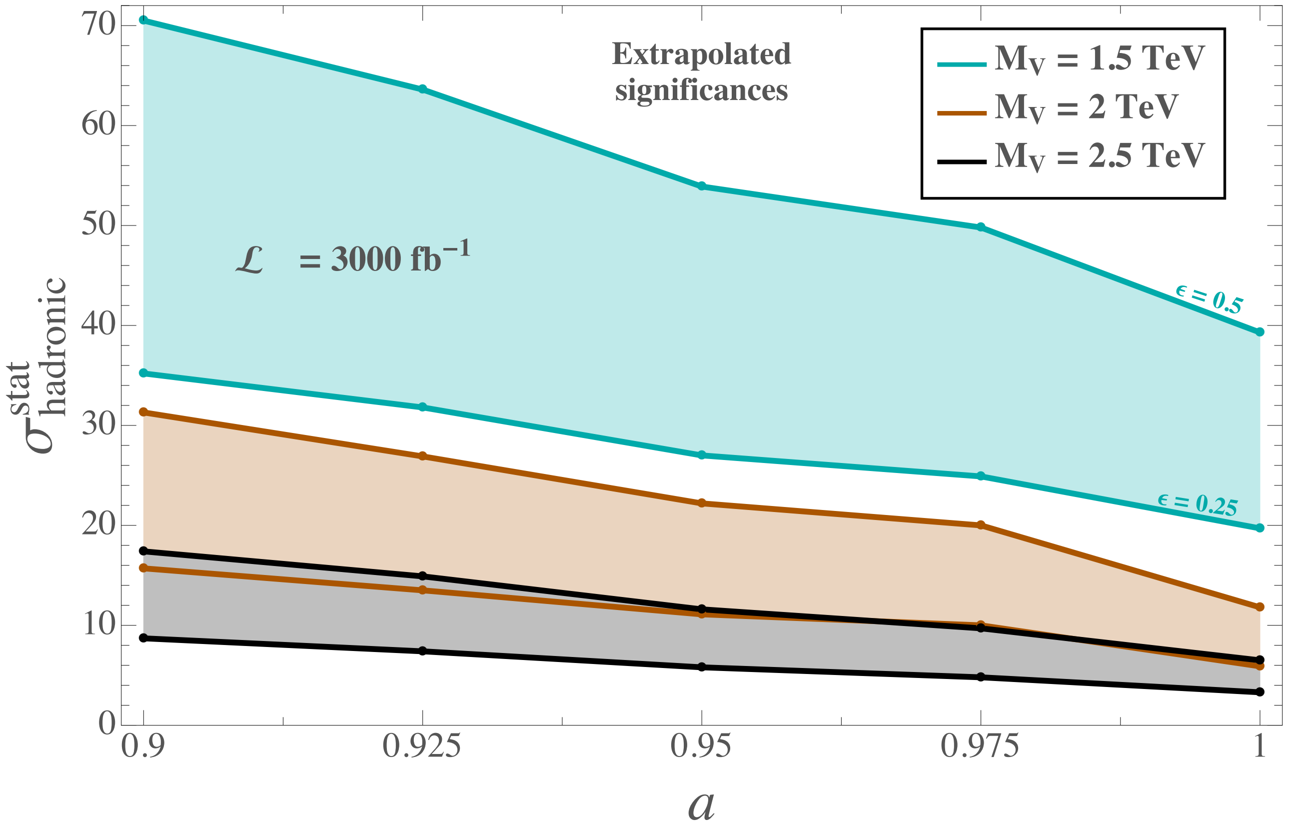
$a \in [0.975, 1] \longleftrightarrow M_V = 2\ \mathrm{TeV}$

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

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

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





Estimates for other channels: JJjj

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

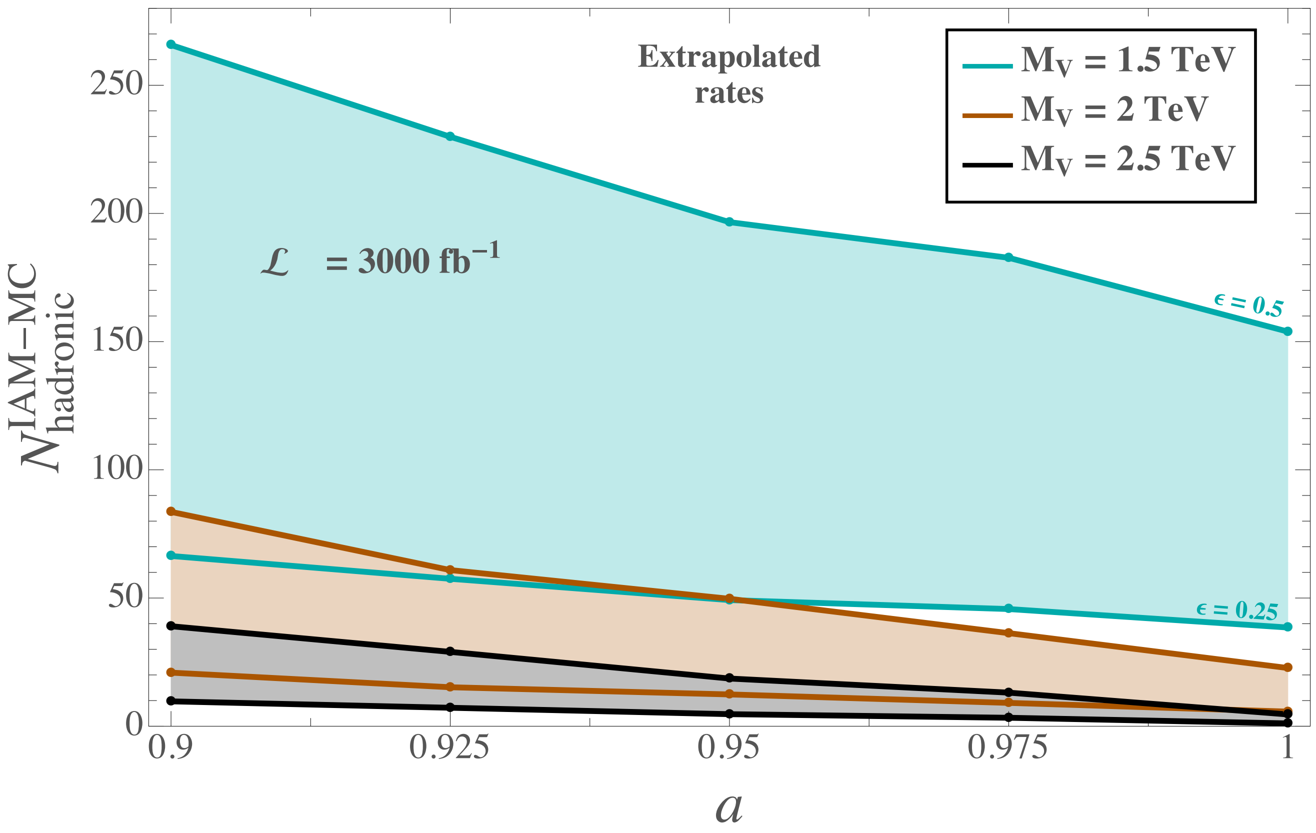
$a \in [0.9, 1] \longleftrightarrow M_V = 1.5\ \mathrm{TeV}$

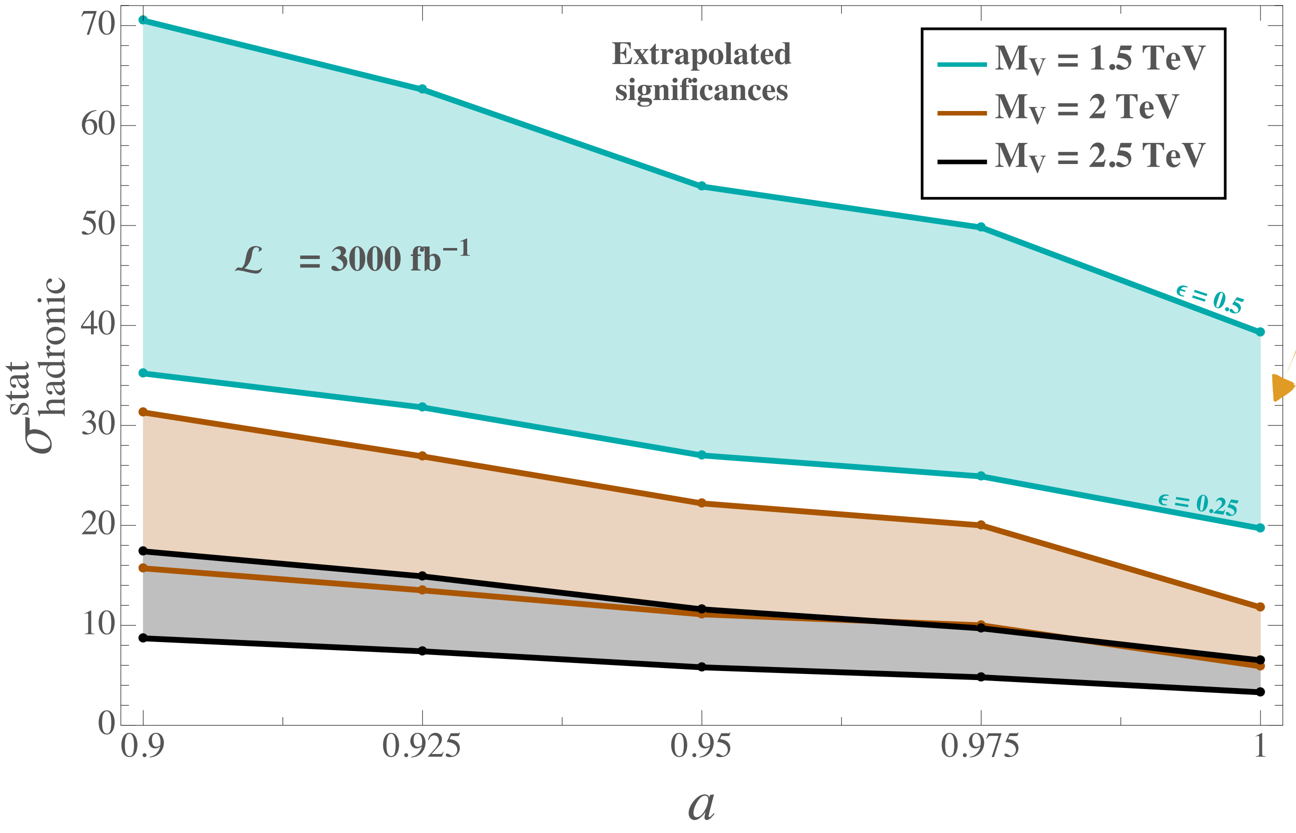
$a \in [0.975, 1] \longleftrightarrow M_V = 2\ \mathrm{TeV}$

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

- Very high significances!
- Very promising channel
  for $\mathcal{L} = 3000\,\mathrm{fb}^{-1} \longrightarrow a \in [0.9, 1]$
- More dedicated study on demand

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





Estimates for other channels: JJjj

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

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

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

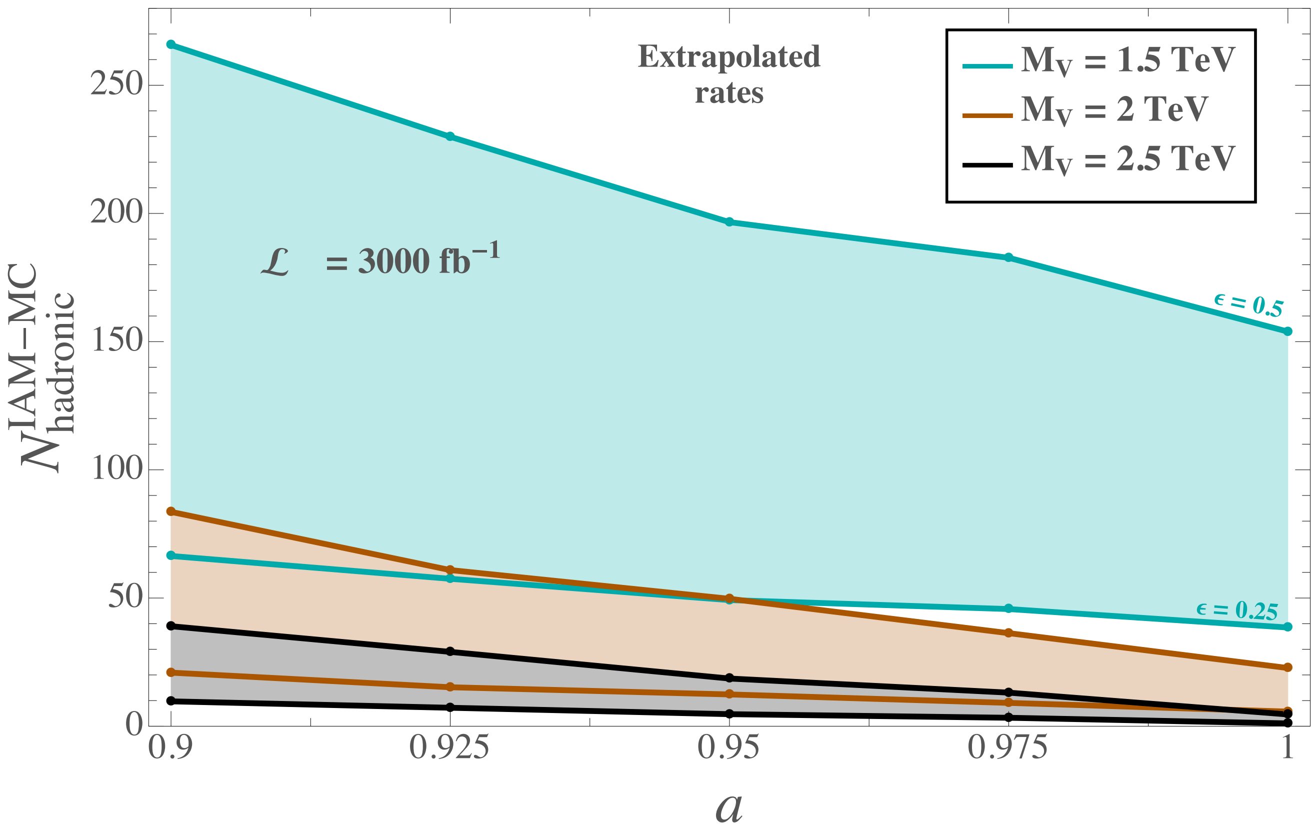
$a \in [0.925, 1] \longleftrightarrow M_V = 2.5\ \text{TeV}$

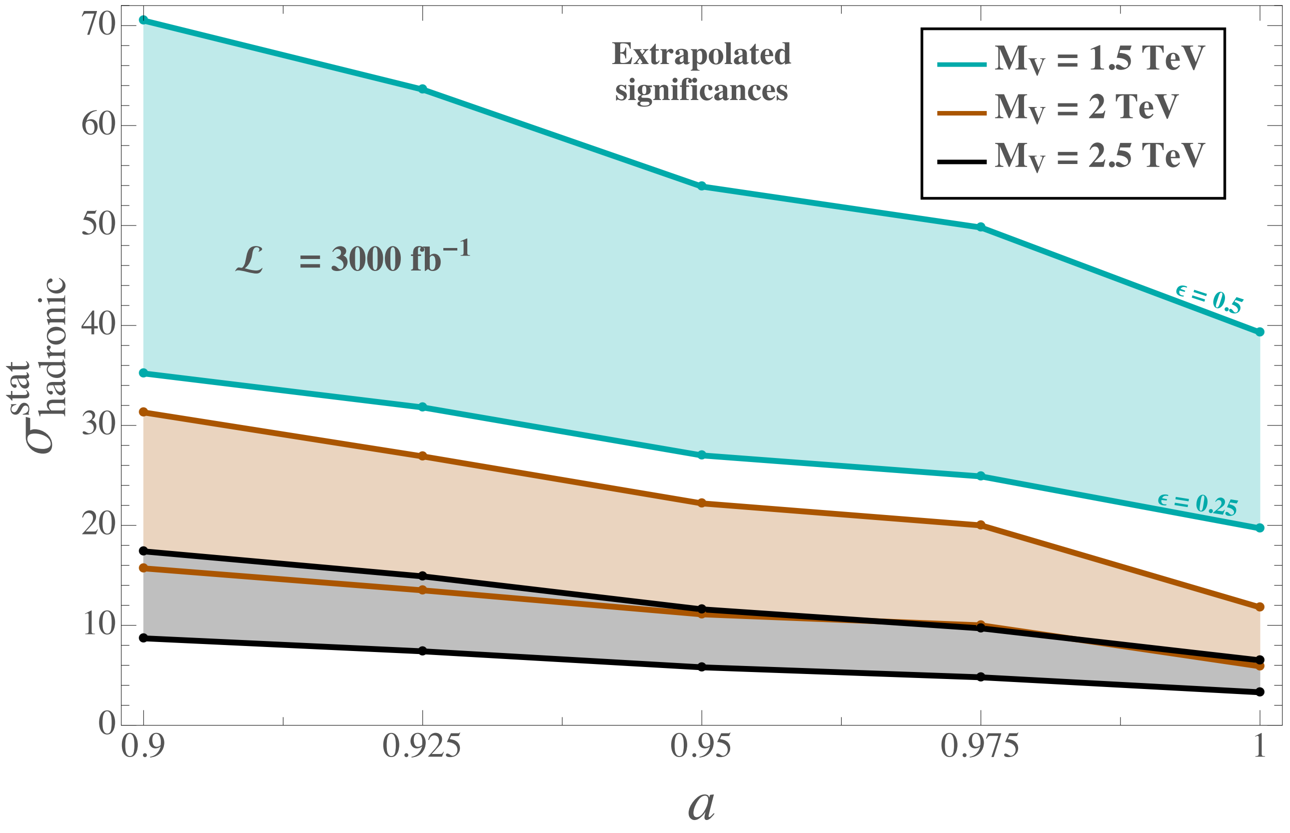
- Very high significances!
- Very promising channel

  for $\mathcal{L} = 3000\,\text{fb}^{-1} \longrightarrow a \in [0.9, 1]$
- More dedicated study on demand

  depends on reconstruction efficiency*

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





* 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

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**

  $a \quad a_4 \quad a_5$

  → Depending on:
  - final state
  - luminosity

THANK YOU!

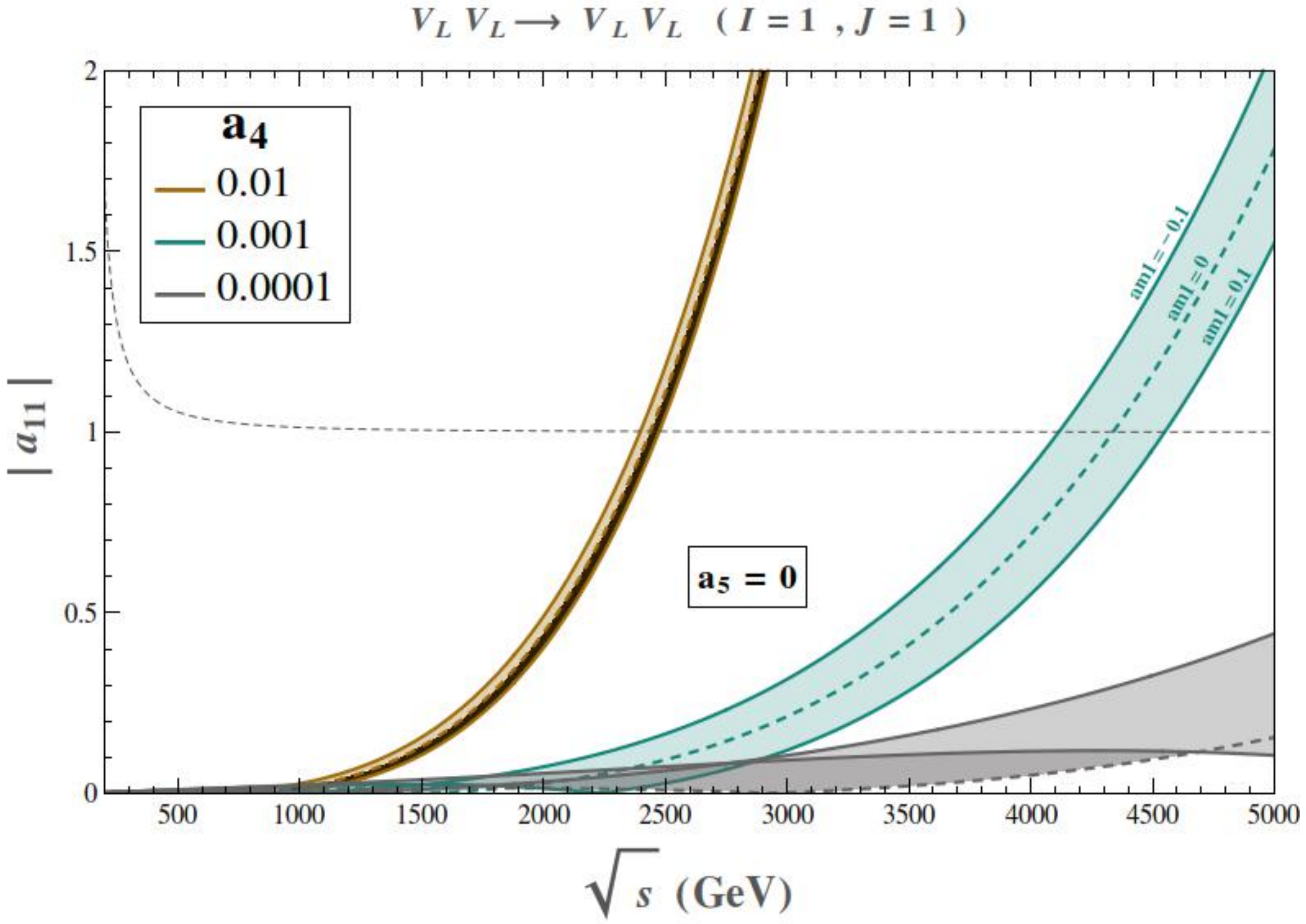
- Improving selection cuts + study other distributions might improve the results

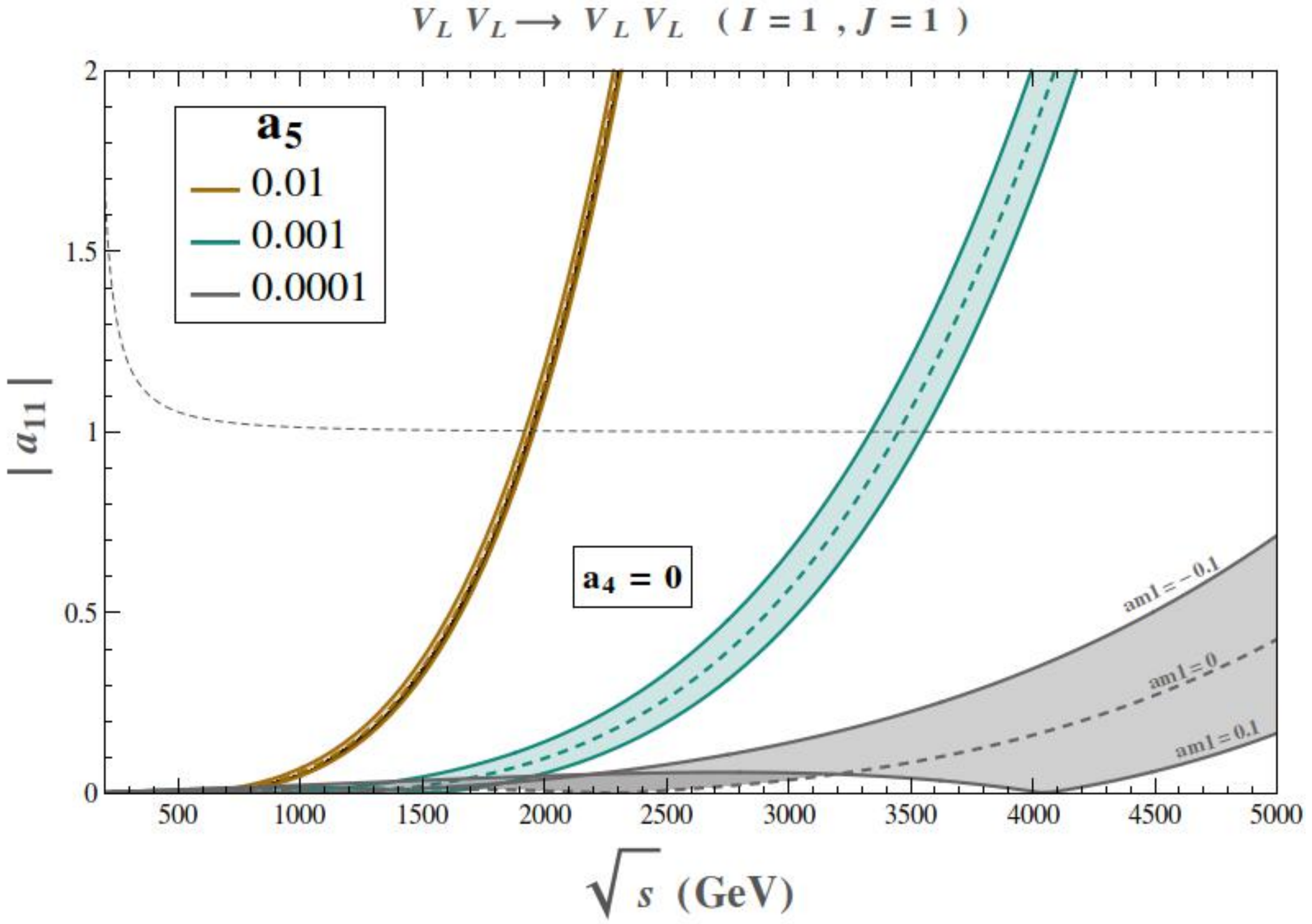
Back up Slides

Unitarity Violation (1)

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

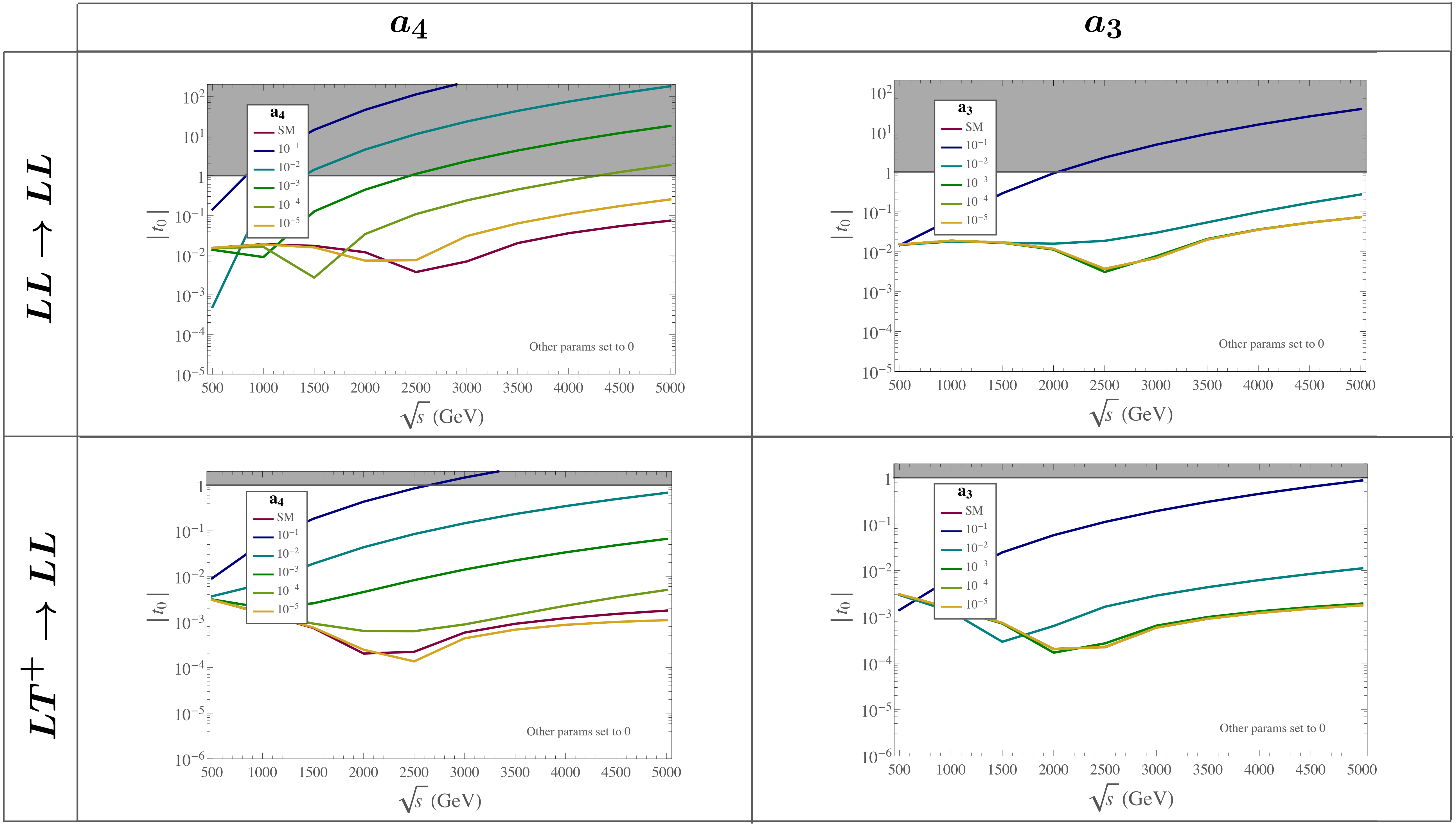
- At tree level, for the values considered $a \in [0.9, 1],\ a_4, a_5 \in [10^{-3}, 10^{-4}]$ unitarity violation happens at the few TeV scale





Unitarity Violation (2)

- Might depend on → Helicity of particles
  Other parameters



Properties of resonances: top contribution

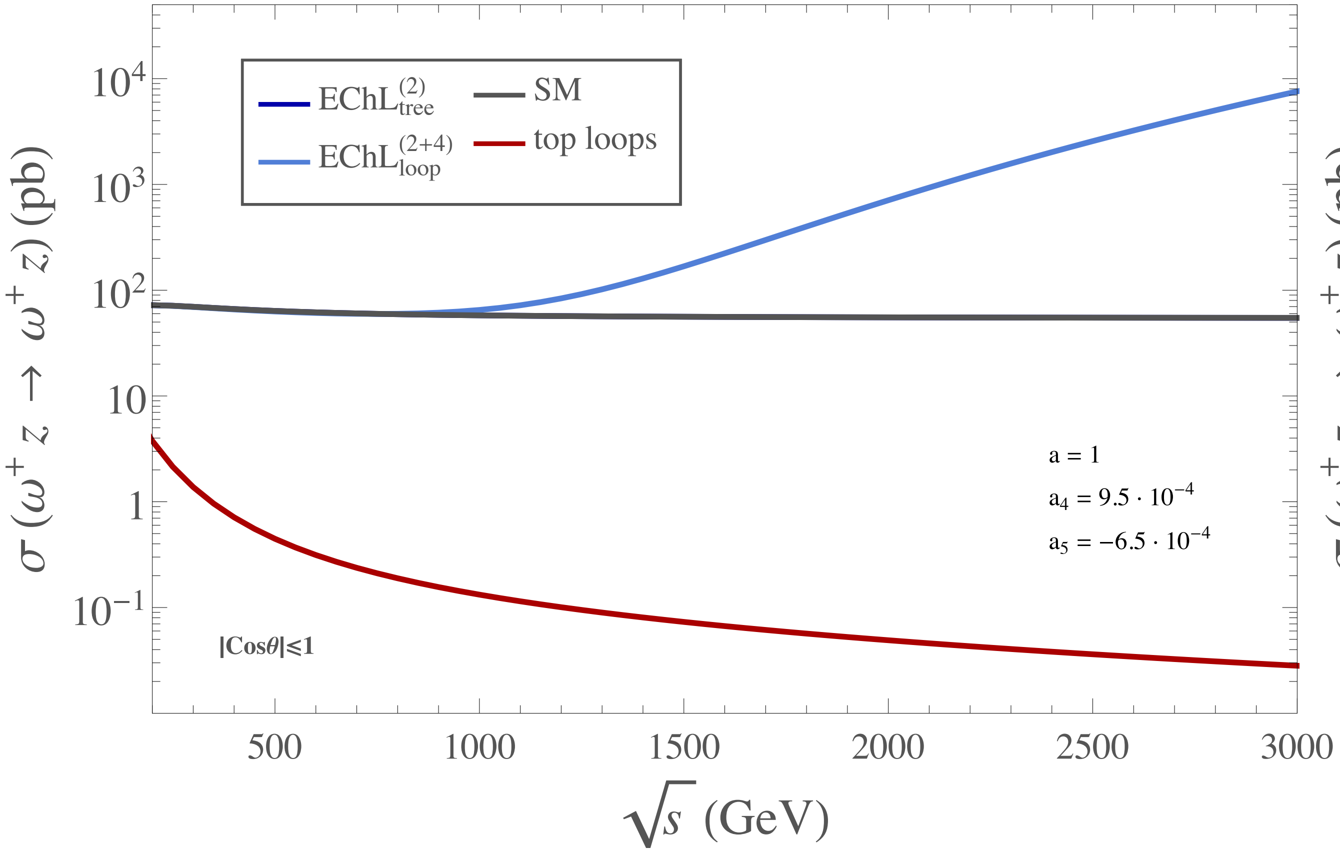
[S. Dawson, G.Valencia, Phys. Lett. B 246 (1990) 156]

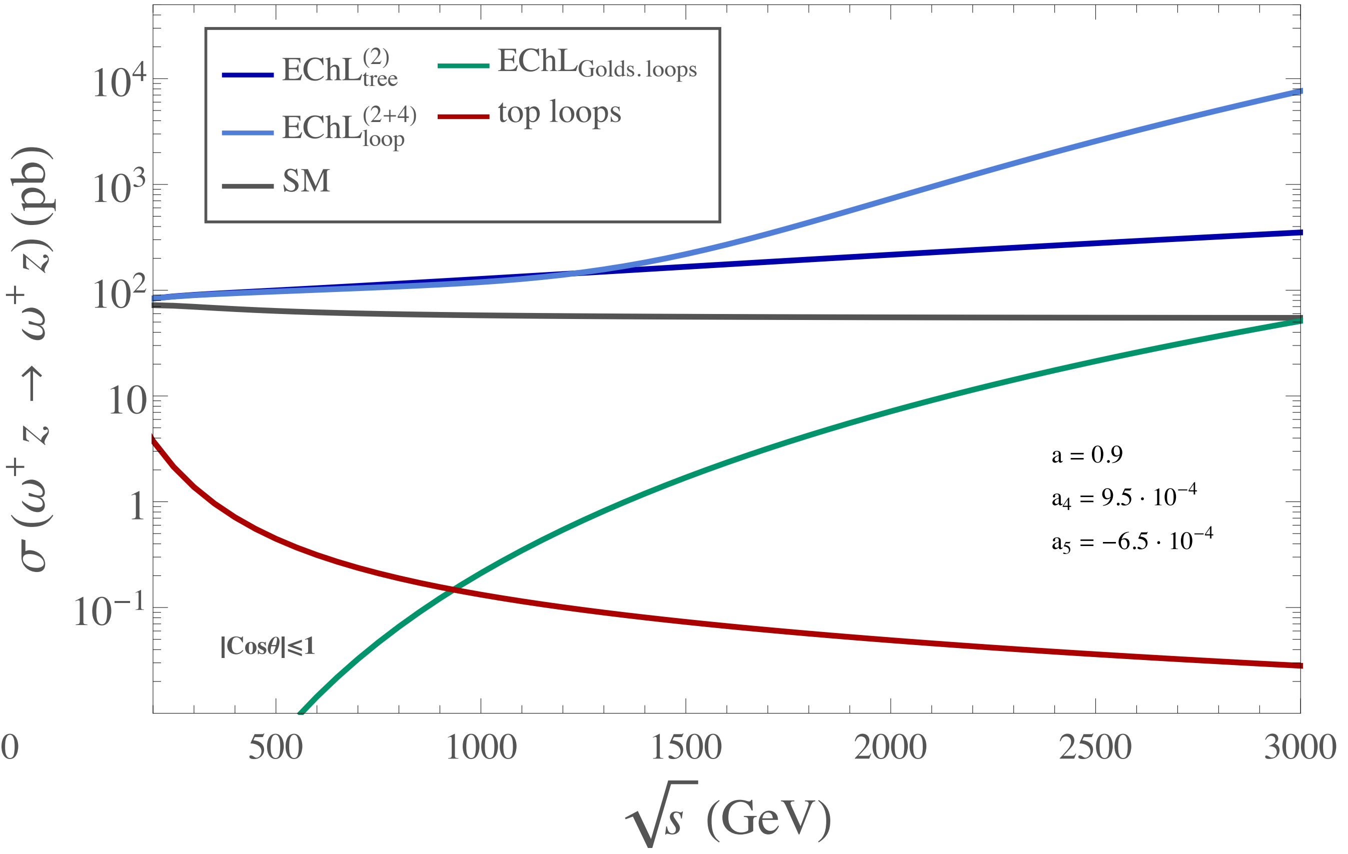
- Top loop contribution decreases with energy

  (Effects of renormalization not taken into account)

- Negligible with respect to Goldstone boson loops above 1 TeV

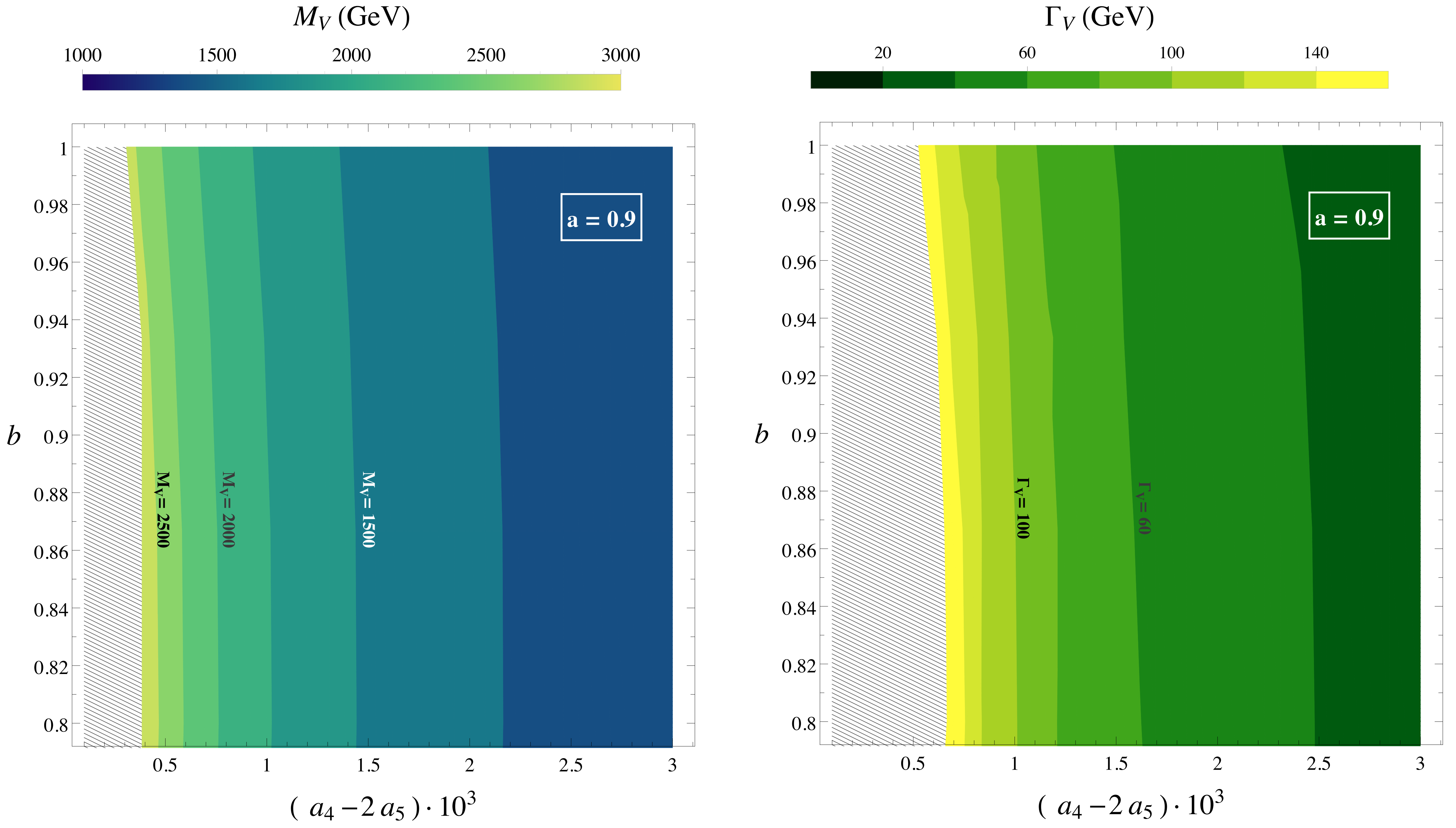
- Subleading effects on resonance properties





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



The IAM-MC g_V

- IAM-MC Form Factor

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

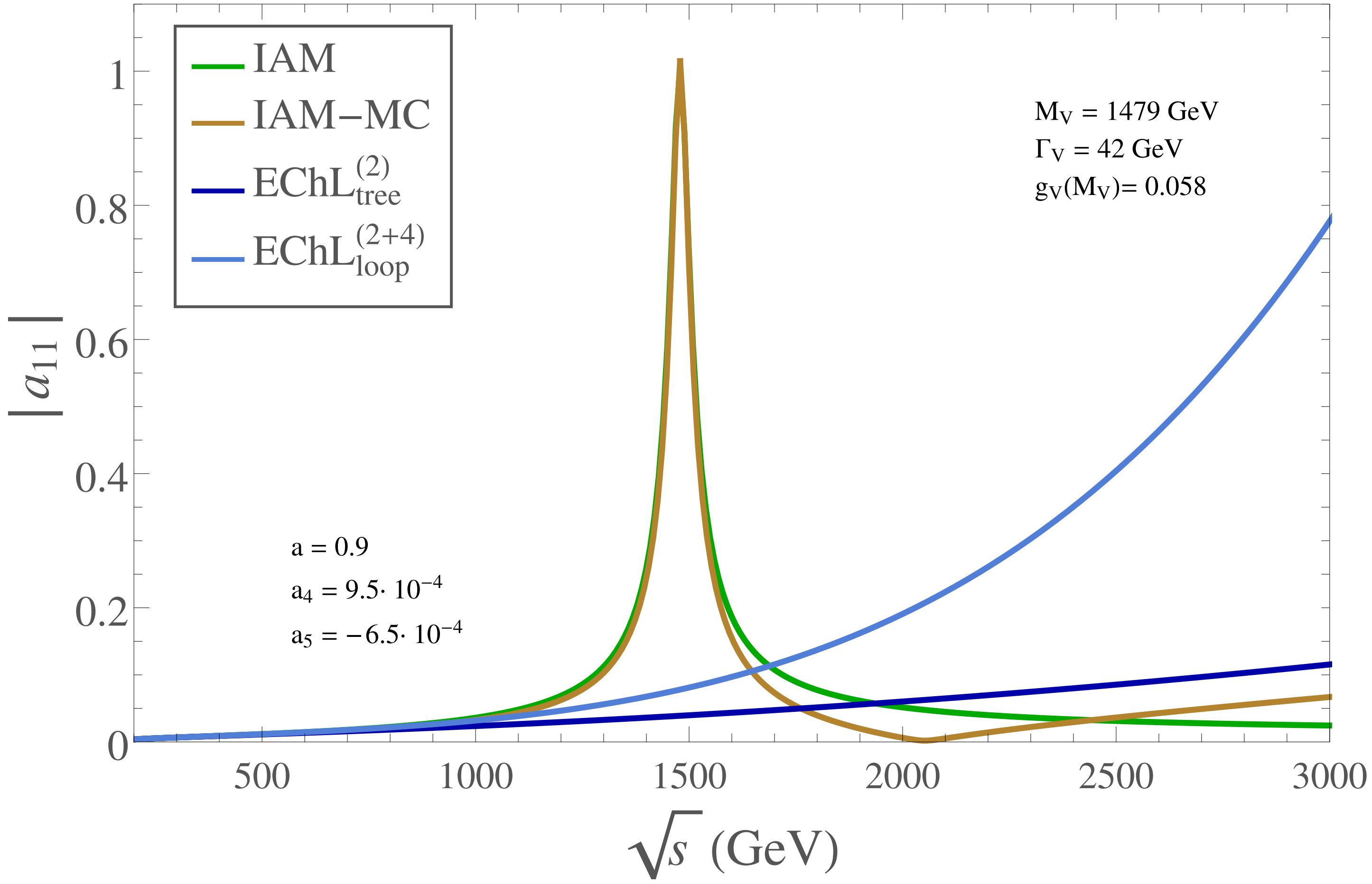
  assumes no other resonances appear

  recovers IAM resonance behavior

IAM-MC Form Factor

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

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

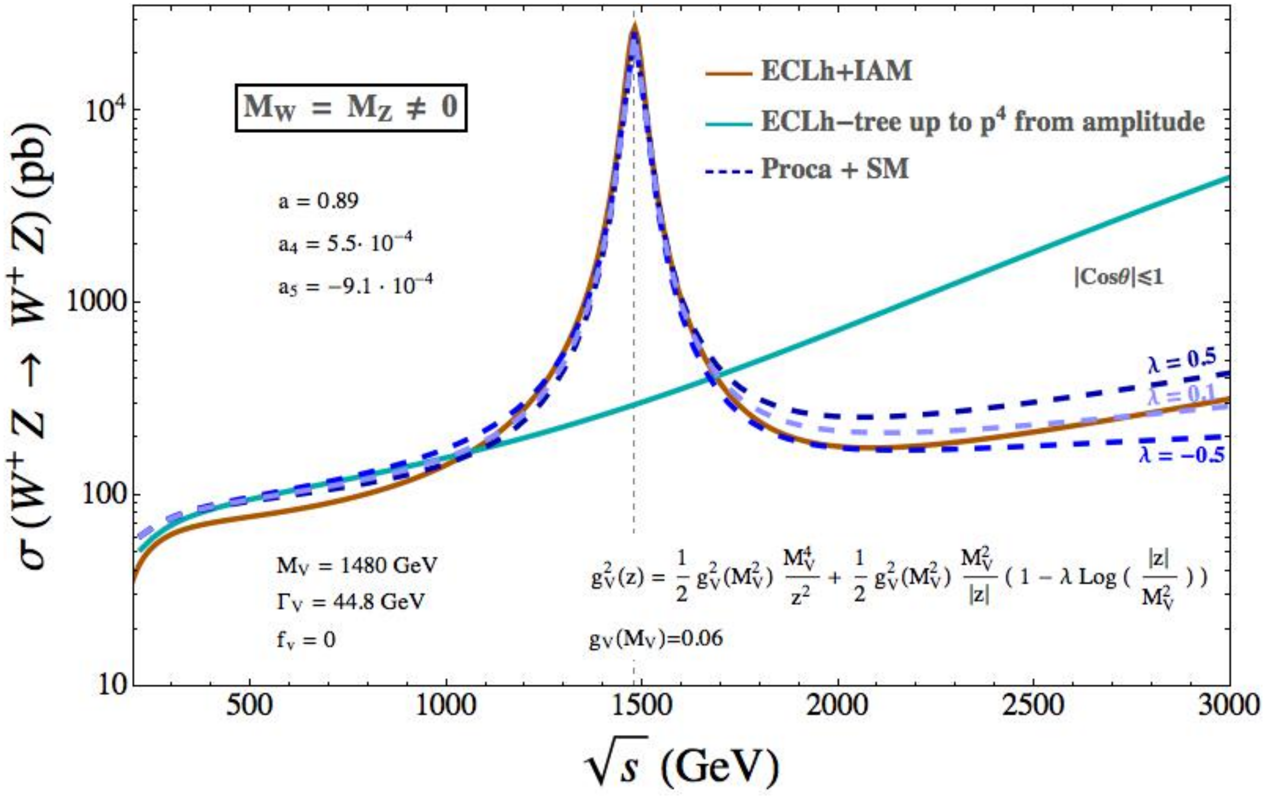


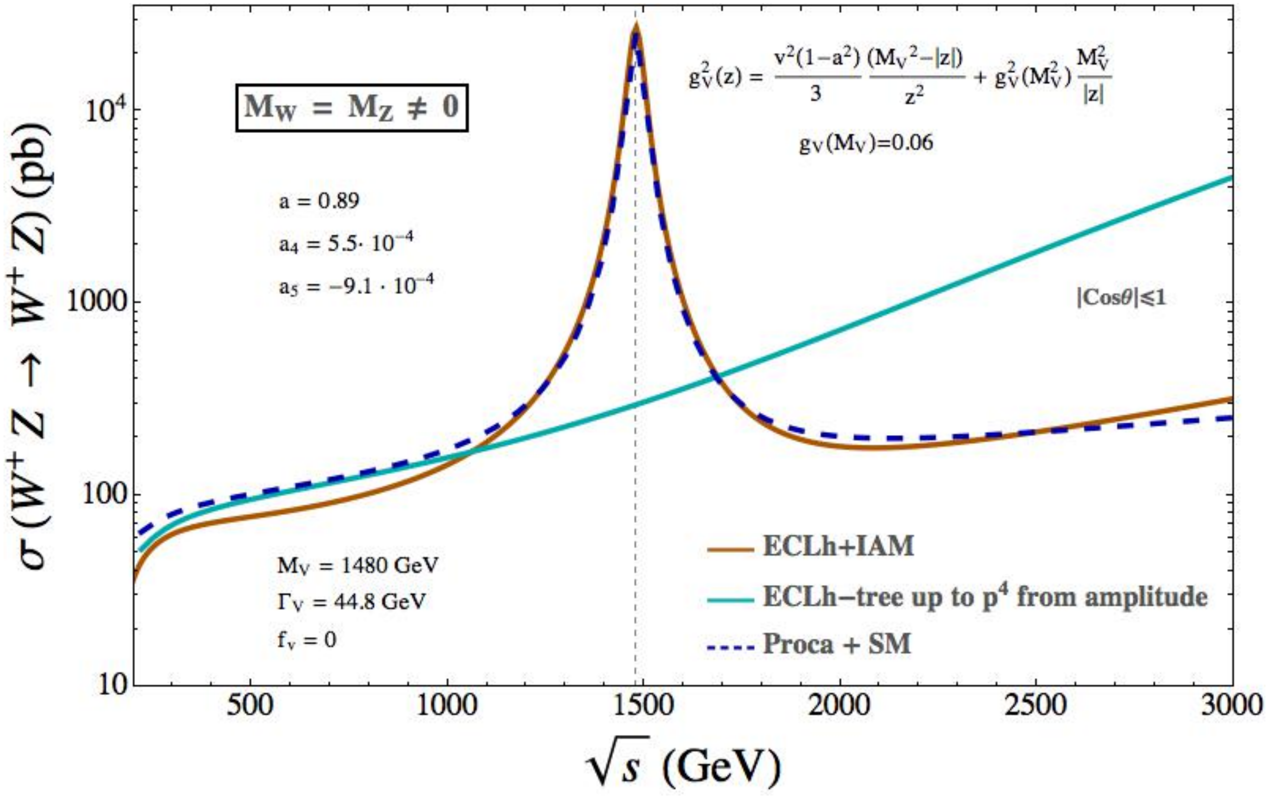
- Other choices of g_V → unphysical/unitarity violating

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 $M, \Gamma \leftrightarrow a \;\; b \;\; a_4 \;\; a_5$

  Different counting → Different weighting of operators

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