Karlsruher Institut für Technologie

Anomalous quartic gauge couplings and unitarization for VBS

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VBSCan WG1 meeting, Oct. 26, 2018

KIT Center Elementary Particle and Astroparticle Physics - KCETA

Outline of talk:

- Introduction
- Effective Lagrangian for VBS
- Unitarization and off-shell VV→VV
- Results for same sign W scattering
- Conclusions

- For details see **arXiv:1807.02707**

BSM effects in VBS: EFT expansion

- Concentrate on quartic gauge couplings (QGC): trilinear couplings already probed in qq→VV or h→VV at much better statistics
- Dimension 6 operators do affect QGC, but they all also contribute to trilinear WWV or hVV couplings ➔ allowed values after qq→VV or h→VV constraints affect VBS at modest level only
- Consider mainly dimension 8 operators in effective Lagrangian in the following

Going beyond dimension 6

Reason for dimension 8 operators like

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

- Dimension 6 operators only do not allow to parameterize $VVVV$ vertex with arbitrary helicities of the four gauge bosons

For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \to V_L V_L$ scattering

- New physics may appear at 1-loop level for dimension 6 operators but at tree level for some dimension 8 operators

Building blocks: $D_\mu\Phi \equiv \left(\partial_\mu + i\frac{g'}{2}B_\mu + igW_\mu^i\frac{\tau^i}{2}\right)\Phi$ with $\Phi = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}.$

$$W_{\mu\nu} = \frac{i}{2}g\tau^I(\partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk}W_\mu^j W_\nu^k),$$
$$B_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu).$$

Full set of dimension 8 operators (Eboli et al.)

- Distinguish by dominant set of vector boson helicities
- Longitudinal operators: derivatives of Higgs doublet field

$$\mathcal{O}_{S_0} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\mu \Phi \right)^\dagger D^\nu \Phi \right]$$

$$\mathcal{O}_{S_1} = \left[\left(D_\mu \Phi \right)^\dagger D^\mu \Phi \right] \times \left[\left(D_\nu \Phi \right)^\dagger D^\nu \Phi \right]$$

$$\mathcal{O}_{S_2} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\nu \Phi \right)^\dagger D^\mu \Phi \right]$$

Field strength ←→ transverse polarizations

Transverse operators

$$\mathcal{O}_{T_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$\mathcal{O}_{T_1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$\mathcal{O}_{T_2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$
$$\mathcal{O}_{T_5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{O}_{T_6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu},$$
$$\mathcal{O}_{T_7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha},$$
$$\mathcal{O}_{T_8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{O}_{T_9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

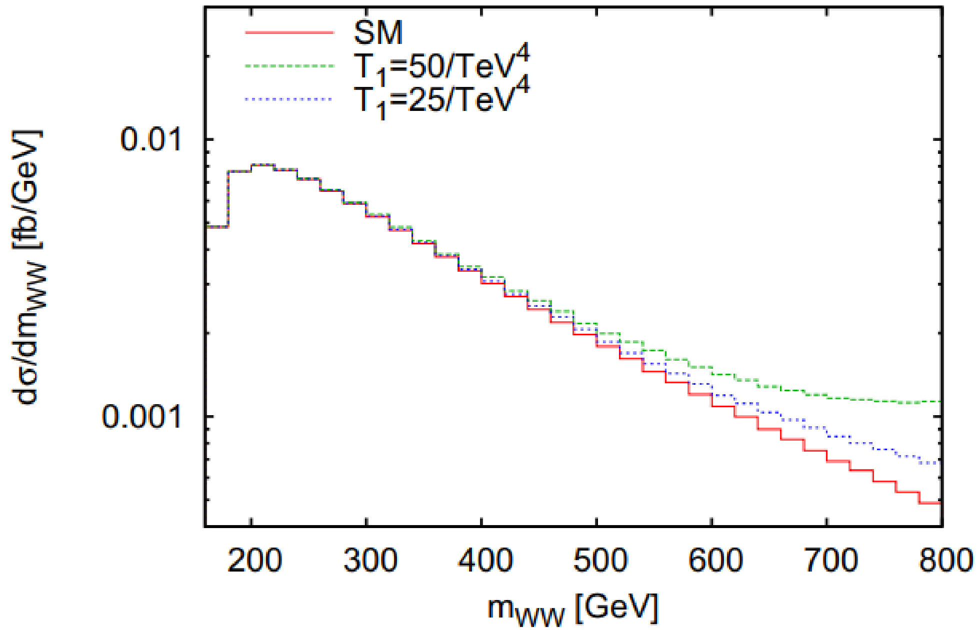
Mixed: transverse-longitudinal

$$\mathcal{O}_{M_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_4} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu},$$
$$\mathcal{O}_{M_5} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu},$$
$$\mathcal{O}_{M_7} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right].$$

$VV \to W^+W^-$ with dimension 8 operators

Effect of $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$

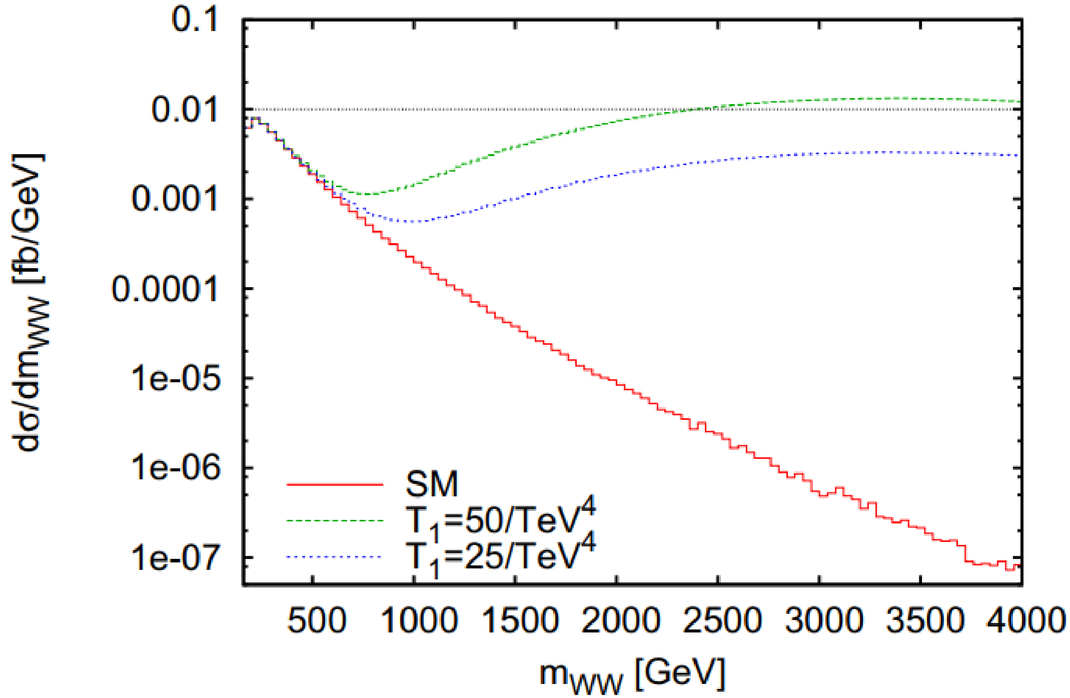
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Small increase in cross section at high WW invariant mass??

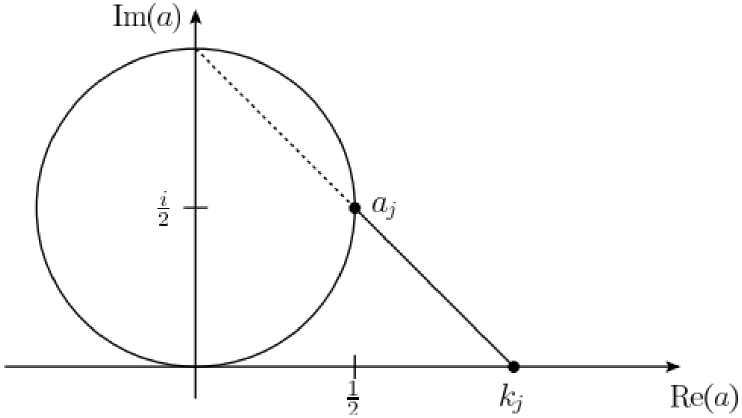
$VV \to W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \to W^+W^- jj \to e^+ \nu_e \mu^- \bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure

K matrix unitarization

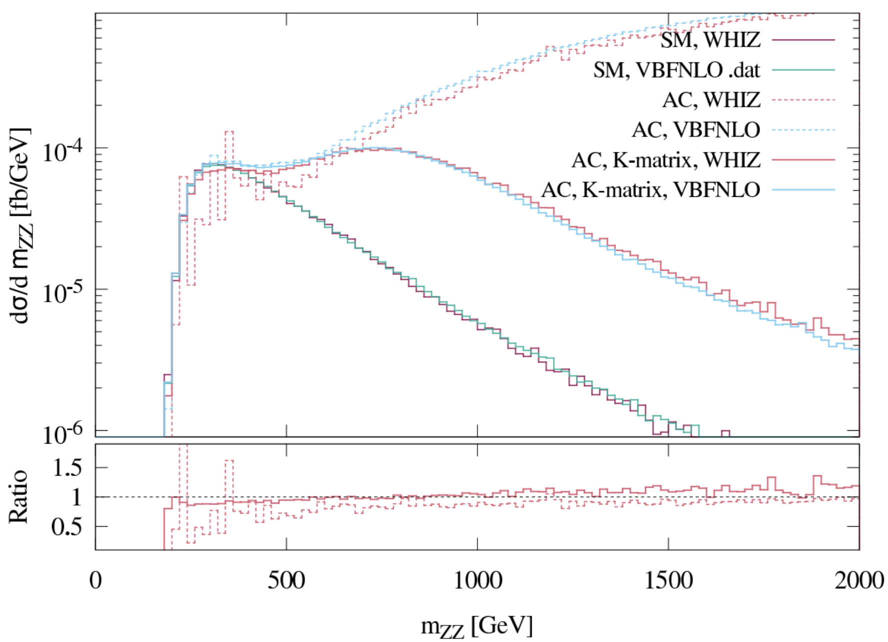


Project amplitude k_j, which exceeds (tree-level) unitarity, back onto Argand circle
→ K matrix unitarized amplitude a_j

[VBFNLO implementation: Löschner, Perez;

following: Alboteanu, Kilian, Reuter]

Comparison with Whizard, which has this method already implemented: [Kilian, Ohl, Reuter, Sekulla, et al.]



Example: VBF-ZZ (e+e-μ+μ-)
good agreement between both codes for longitudinal ops. at LO

→ can now generate distributions also at NLO via VBFNLO

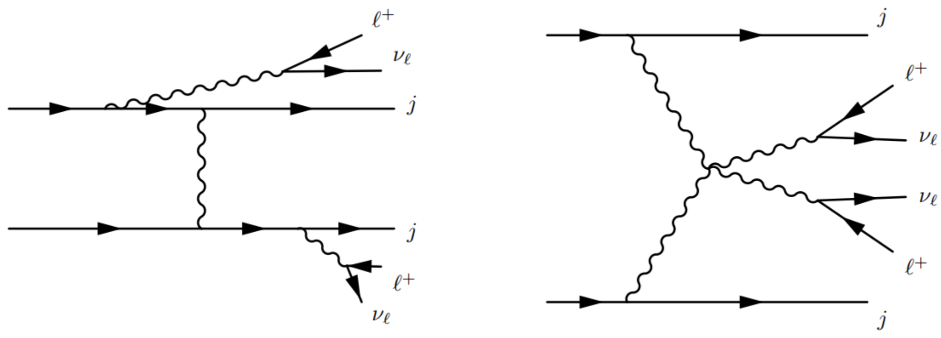
Extension to mixed and transverse operators not straight-forward: work with Genessis Perez and Marco Sekulla

Off-shell VBS amplitude

- Assume new physics in VV→VV only

$$\mathcal{M}_{pp\to 4fjj} = \mathcal{M}^{\rm SM}_{pp\to 4fjj} + \mathcal{M}^{\rm BSM}_{pp\to 4fjj}$$

- SM part alone has vector boson emission, triple gauge couplings, H-exchange etc. which interfere destructively
  → SM piece is unitary and small



(a) Vector boson emission (b) Quartic gauge interaction.

- → unitarize BSM piece only

$$\begin{aligned}\mathcal{M}^{\rm BSM}_{pp\to 4fjj} =& J^{\mu}_{p_1\to jV_1}\; J^{\nu}_{p_2\to jV_2}\; D^{V_1}_{\mu\alpha}(q_1)\; D^{V_2}_{\nu\beta}(q_2)\\ &\times \mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\; D^{V_3}_{\gamma\rho}(q_3)\; D^{V_4}_{\delta\sigma}(q_4)\\ &\times J^{\rho}_{V_3\to\bar{f}f}\; J^{\sigma}_{V_4\to\bar{f}f}\end{aligned}$$

- V-propagators decompose into polarization sums

$$D^{\mu\nu}_V(q) = \frac{-\mathrm{i}}{q^2 - m_V^2 + i\, m_V\, \Gamma_V}\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)$$

$$\equiv \frac{-\mathrm{i}}{q^2 - m_V^2 + i\, m_V\, \Gamma_V}\sum_\lambda \epsilon^{*\mu}_{J}(q,\lambda)\epsilon^{\nu}_{\mathcal{M}}(q,\lambda)$$

- Defines $\mathcal{M}^{VBS}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_1,q_2;q_3,q_4) = \epsilon_{\mathcal{M},\alpha}(q_1,\lambda_1)\epsilon_{\mathcal{M},\beta}(q_2,\lambda_2)\,\mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\,\epsilon^*_{\mathcal{M},\gamma}(q_3,\lambda_3)\epsilon^*_{\mathcal{M},\delta}(q_4,\lambda_4)$

Partial wave decomposition and unitarity relation

- S-matrix unitarity

$$\mathbf{S} = 1 + \mathrm{i}\mathbf{T}\,, \qquad \mathbf{T}_{fi} = (2\pi)^4\delta(P_f - P_i)\,\mathcal{T}_{fi}$$

$$2\mathrm{Im}\mathbf{T} = -\mathrm{i}\left(\mathbf{T} - \mathbf{T}^\dagger\right) = \mathbf{T}^\dagger\mathbf{T} = \mathbf{T}\mathbf{T}^\dagger$$

- Implication for helicity amplitudes

$$\mathcal{M}_{\lambda_3\lambda_4\leftarrow\lambda_1\lambda_2} = \mathcal{T}_{fi}$$

$$\mathcal{T}_{fi} - \mathcal{T}_{if}^* = \mathrm{i}\sum_n \int \underbrace{\frac{d^3\mathbf{q}_{n,3}\,d^3\mathbf{q}_{n,4}}{(2\pi)^3 2q_{n,3}^0 (2\pi)^3 2q_{n,4}^0}(2\pi)^4\delta(P_i - q_{n,3} - q_{n,4})}_{\frac{\lambda^{1/2}(s,q_{n,3}^2,q_{n,4}^2)}{8s(2\pi)^2}d\Omega}\, S_n\, \mathcal{T}_{nf}^*\mathcal{T}_{ni}$$

- Projection onto j<=2 partial waves

$$\mathcal{M}_{\lambda_3\lambda_4\leftarrow\lambda_1\lambda_2}(\Theta,\varphi) = 8\pi\mathcal{N}_{fi}\sum_{j=\max(|\lambda_{12}|,|\lambda_{34}|)}^{j_{\max}}(2j+1)\mathcal{A}^j_{\lambda_3\lambda_4\leftarrow\lambda_1\lambda_2}\, d^j_{\lambda_{12}\lambda_{34}}(\Theta)\, e^{\mathrm{i}\lambda_{34}\varphi}$$

- Partial wave unitarity relation

$$2\mathrm{Im}(\mathcal{A}^j_{\lambda_3\lambda_4\leftarrow\lambda_1\lambda_2}) = \sum_n \frac{\mathcal{N}_{ni}\mathcal{N}_{nf}}{\mathcal{N}_{fi}}\frac{\lambda^{1/2}(s,q_{n,3}^2,q_{n,4}^2)}{s}\, S_n \sum_{\lambda_1',\lambda_2'} \mathcal{A}^{j\,*}_{\lambda_1'\lambda_2'\leftarrow\lambda_3\lambda_4}\mathcal{A}^j_{\lambda_1'\lambda_2'\leftarrow\lambda_1\lambda_2}$$

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Unitarization of tree level amplitude: $T_0 \rightarrow T_u$

- K-matrix (also called T-matrix) procedure for on-shell hermitian T_0

$$\mathbf{T}_L = \left(\mathbb{1} - \frac{\mathrm{i}}{2}\mathbf{T}_0^\dagger\right)^{-1} \frac{1}{2}\left(\mathbf{T}_0 + \mathbf{T}_0^\dagger\right) = \left(\mathbb{1} + \frac{1}{4}\mathbf{T}_0\mathbf{T}_0\right)^{-1} \left(\mathbf{T}_0 + \frac{\mathrm{i}}{2}\mathbf{T}_0\mathbf{T}_0\right)$$

- General virtualities → T_0 not normal for off-shell VV→VV

  Must distinguish

$$\mathbf{A}_{t\leftarrow s} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3, q_4; q_1, q_2)$$
$$\mathbf{A}_{s\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(k_3, k_4; k_1, k_2)$$
$$\mathbf{A}_{t\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3, q_4; k_1, k_2)$$

- Use

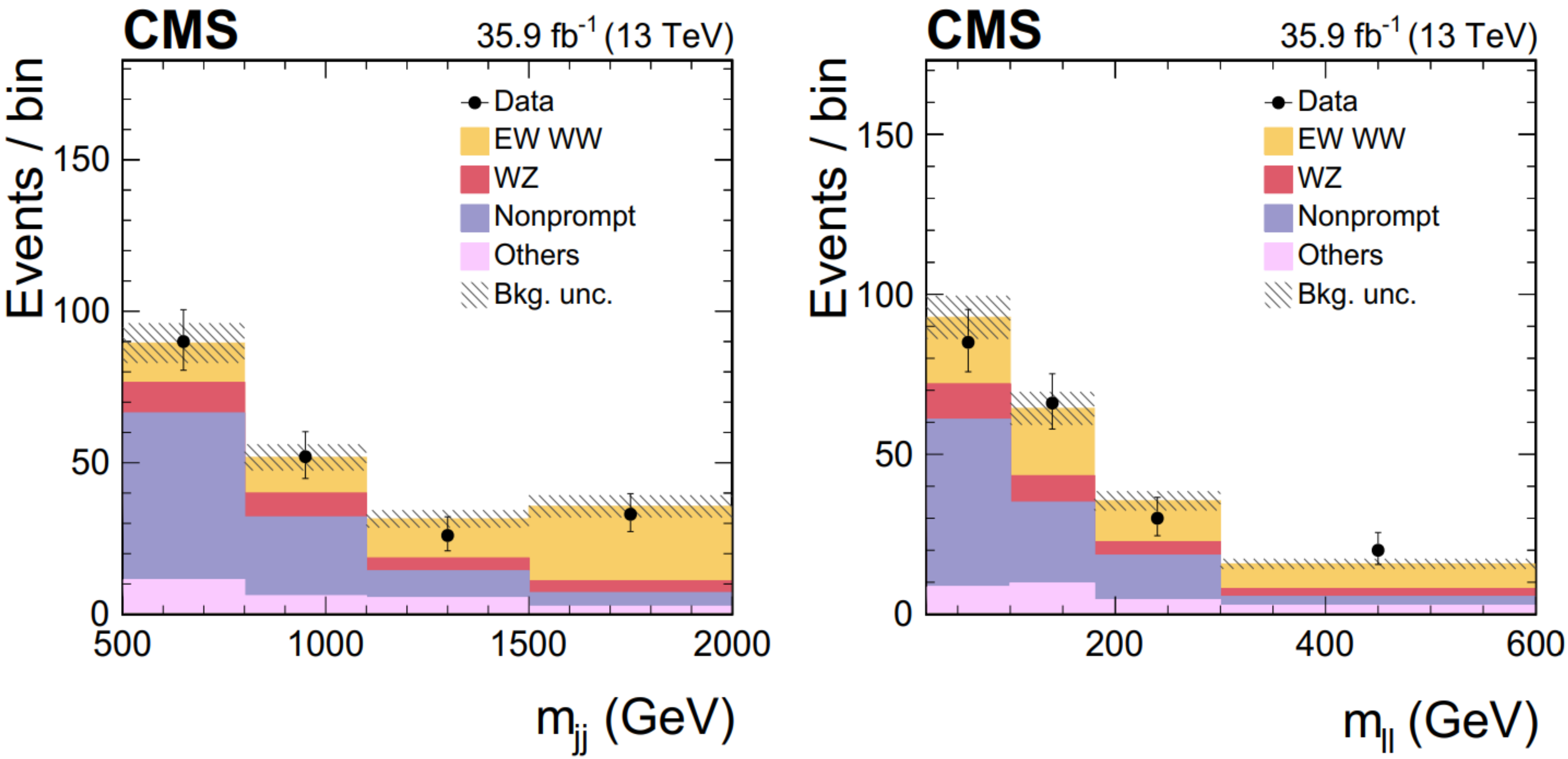
$$\mathbf{A}^{\mathrm{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}\mathbf{A}_{t\leftarrow s}\mathbf{A}_{s\leftarrow t}\right)^{-1} \left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

- Alignment problems avoided by using largest eigenvalue of denominator

$$\mathbf{A}^{\mathrm{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}a^2_{\max}\right)^{-1} \left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

Application to same sign W scattering

- Observed (with modest background) by ATLAS and CMS
- Useful bounds on Wilson coefficients of dim-8 operators



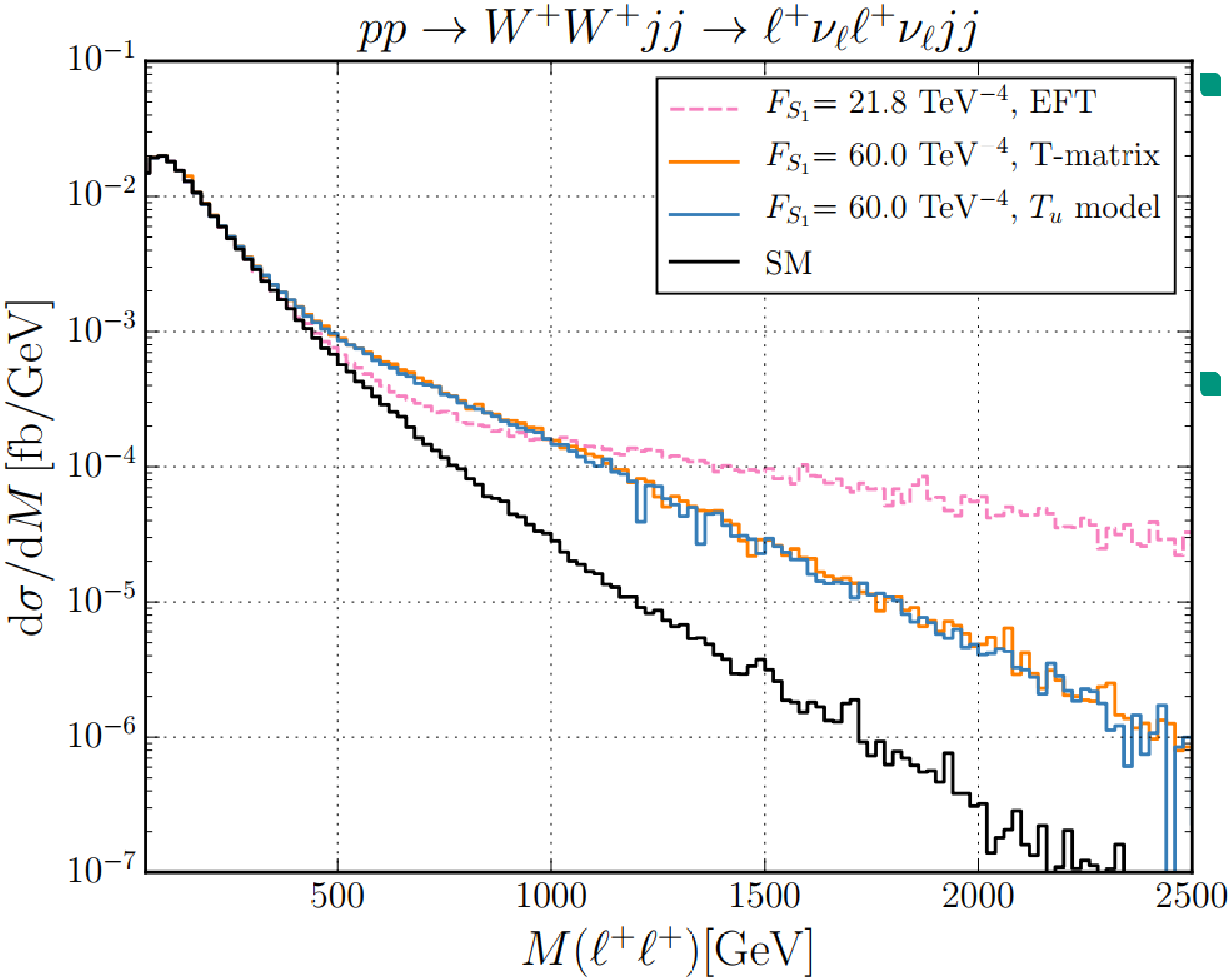
Definition of fiducial VBS cross sections

- Phase space cuts

$$m_{\ell\ell} > 20\,\mathrm{GeV}, \quad m_{jj} > 500\,\mathrm{GeV},$$
$$p_T^{\ell} > 20\,\mathrm{GeV}, \quad p_T^{j} > 30\,\mathrm{GeV}, \quad p_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$$
$$|\eta_\ell| < 2.5, \quad |\eta_j| < 5, \quad \Delta\eta_{jj} > 2.5\,.$$

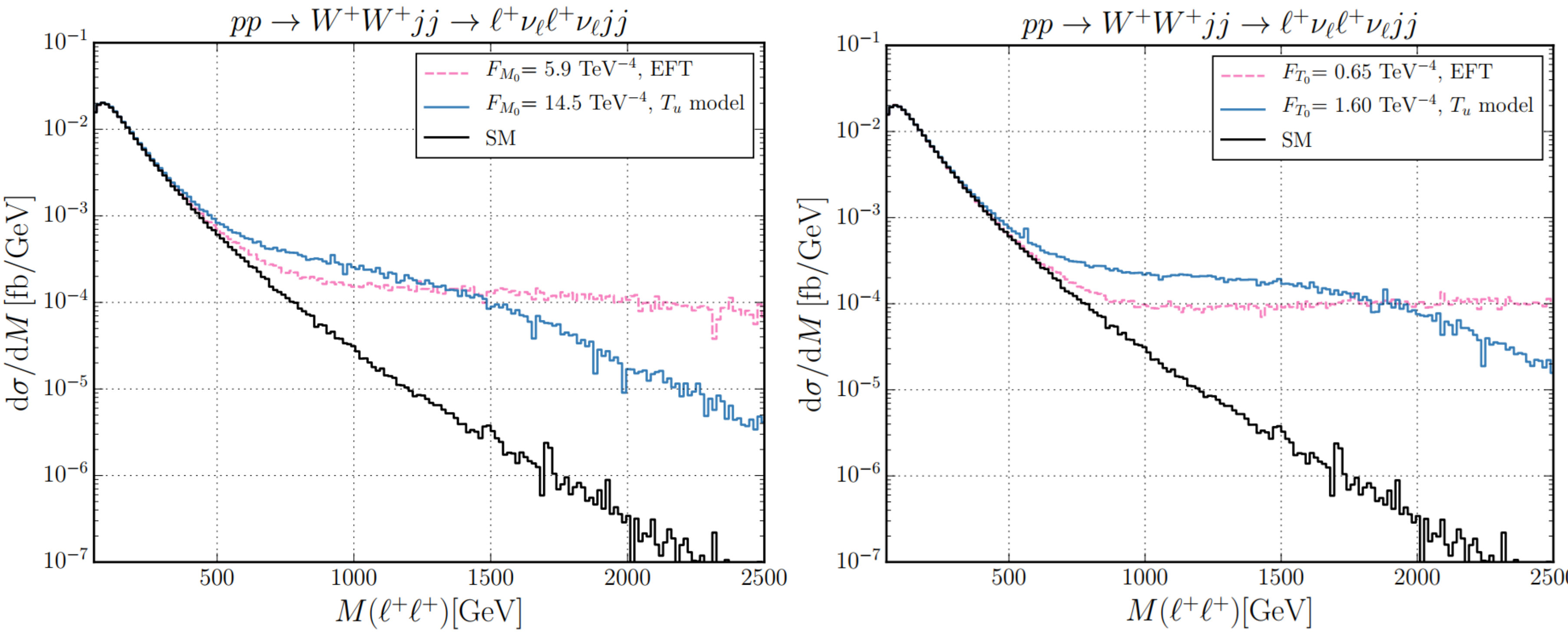
- Jets defined with anti-kT clustering and R=0.4

Comparison to K-matrix



- Excellent agreement between different unitarization methods
- $F_{S_1} = f_{S_1}/\Lambda^4$ coefficients adjusted for unitarized models to reproduce pure EFT cross section ←→ CMS limits on F

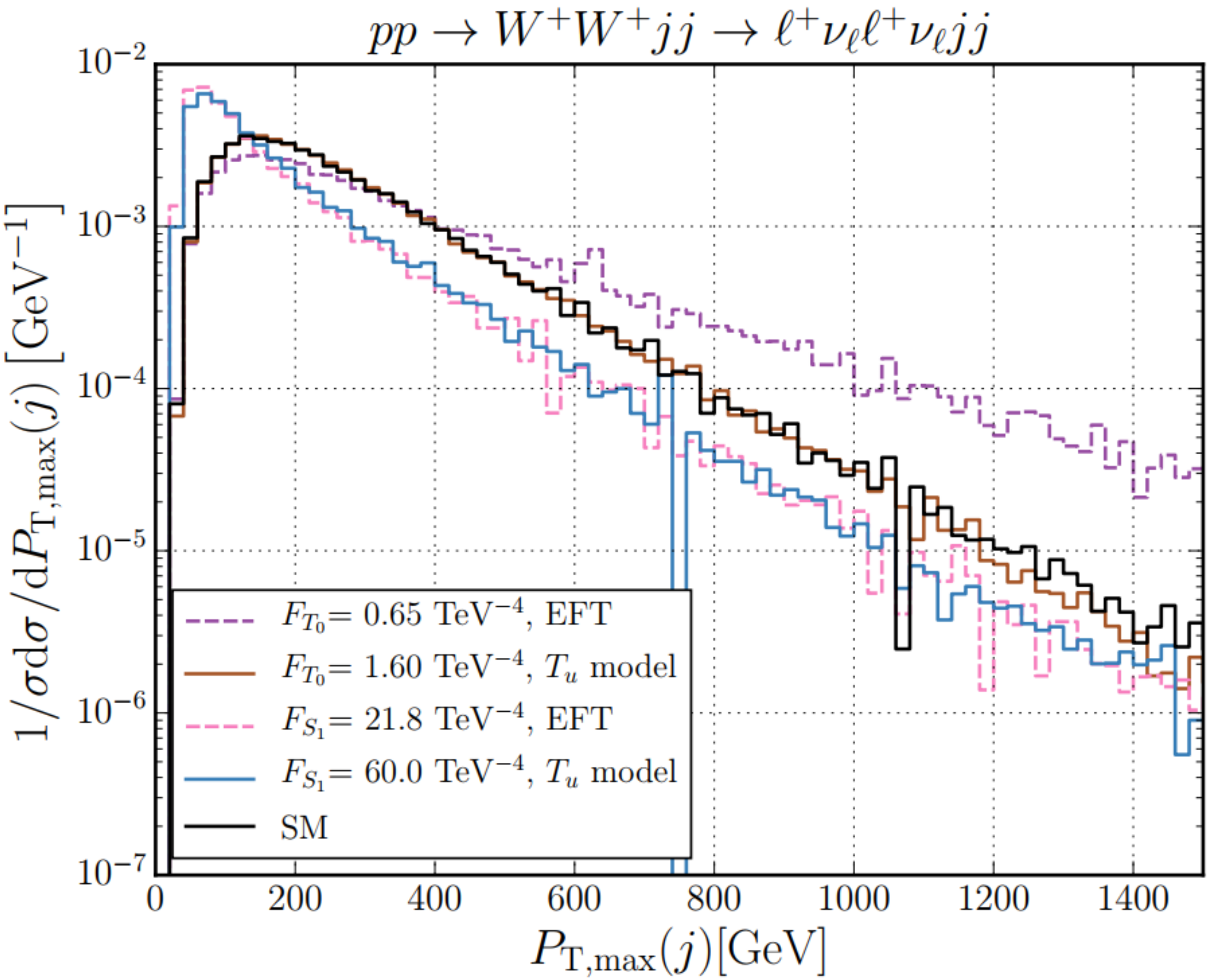
Mixed and transverse operators



Unitarity bound depends on whether j=0,1, or 2 partial waves dominate

Larger deviations allowed for transverse than for longitudinal operators

Incident W polarization: pT(j,max)



- Typical off-shell behavior

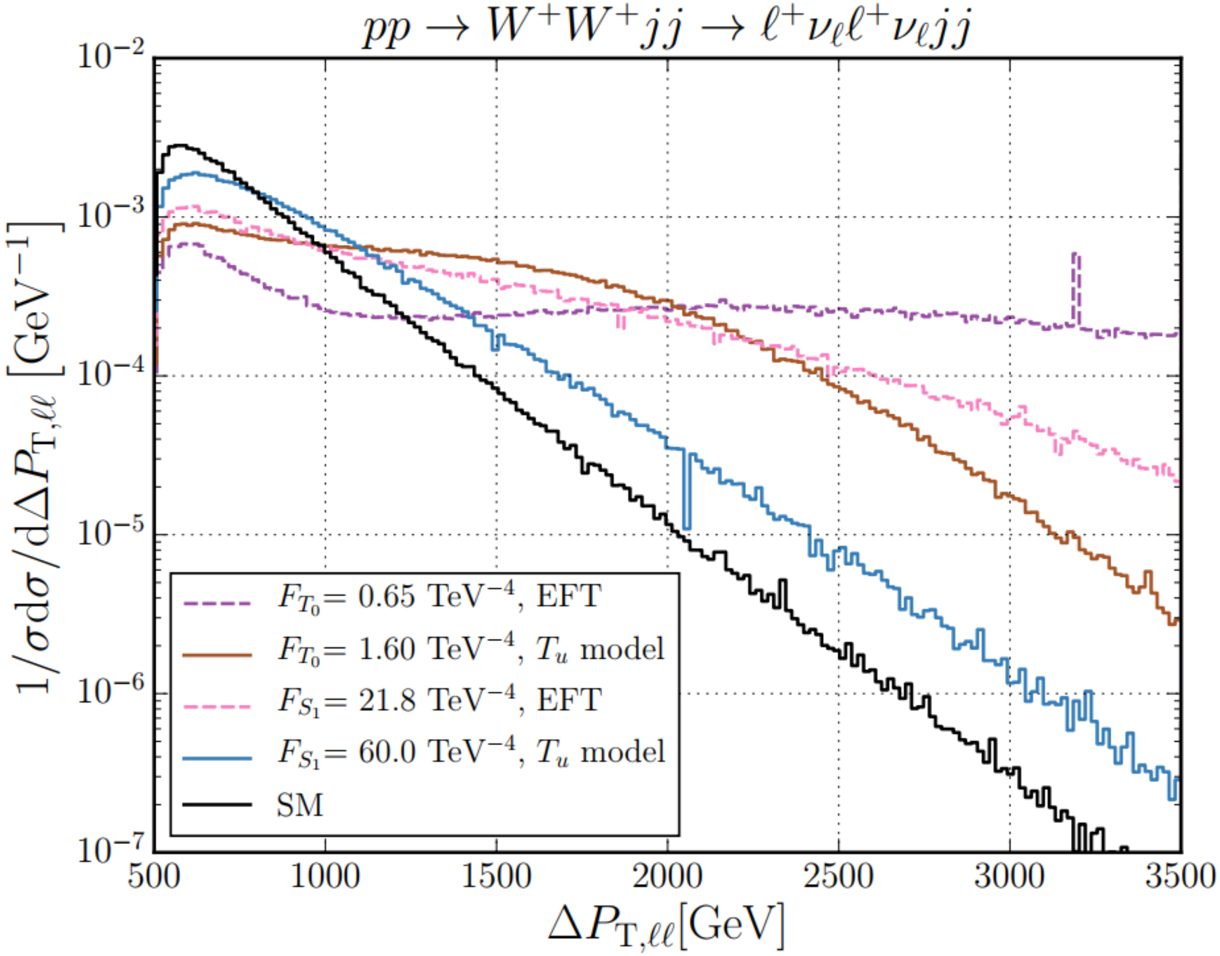
$M \sim [s^2 + (q_1^2 + q_2^2 - q_3^2 - q_4^2)\, s]/\Lambda^4$

- Unitarization suppresses large incident virtualities → pT(j,max) shapes depend on polarization only

- Enhancement at small pT(j,max) is sign for enhanced longitudinal scattering

Lepton transverse momentum correlation

- $\Delta p_{T,\ell\ell} = |\mathbf{p}_{T,\ell_1} - \mathbf{p}_{T,\ell_2}|$ is sensitive to final W-polarization differences



Comments

- Unitarization changes shapes of distributions
- T_u model supresses high VV invariant mass and large incident virtualities: similar to what one expects from loop functions
- Unitarization is not unique → additional model dependence

Conclusions

- VBF and VBS provide powerful tests of electroweak symmetry breaking
- Pure EFT approach to parameterization of BSM effects is insufficient due to large energy reach of LHC and breakdown of unitarity at tree level
- Unitarization models provide improved tools for describing BSM VV scattering

Backup

Off-shell VBS amplitude: details

- Off shell polarization vectors

$$\epsilon^\mu_J(q,\pm) = \mp\frac{1}{\sqrt{2}\sqrt{q_x^2+q_y^2}}\left(0;\frac{q_z q_x}{|\vec{q}|}\mp \mathrm{i}q_y, \frac{q_y q_z}{|\vec{q}|}\pm \mathrm{i}q_x, -\frac{q_x^2+q_y^2}{|\vec{q}|}\right) = \epsilon^\mu_{\mathcal{M}}(q,\pm)$$

$$\epsilon^\mu_J(q,0) = \mathcal{N}_J\left(|\vec{q}|,\, q_0\frac{\vec{q}}{|\vec{q}|}\right), \qquad \mathcal{N}_{\mathcal{M}}\left(|\vec{q}|,\, q_0\frac{\vec{q}}{|\vec{q}|}\right) = \epsilon^\mu_{\mathcal{M}}(q,0)$$

- Normalizaton factors

$$\mathcal{N}_J = \frac{m_V}{q^2}, \qquad \mathcal{N}_{\mathcal{M}} = \frac{1}{m_V} \qquad \mathcal{N}_J\mathcal{N}_{\mathcal{M}} = 1/q^2$$

- Defines off shell tree-level amplitude

$$\mathcal{M}^{VBS}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_1,q_2;q_3,q_4) = \epsilon_{\mathcal{M},\alpha}(q_1,\lambda_1)\epsilon_{\mathcal{M},\beta}(q_2,\lambda_2)\,\mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\,\epsilon^*_{\mathcal{M},\gamma}(q_3,\lambda_3)\epsilon^*_{\mathcal{M},\delta}(q_4,\lambda_4)$$

- Normalization of partial wave amplitudes

$$2\mathrm{Im}(\mathcal{A}^j_{\lambda_3\lambda_4\leftarrow\lambda_1\lambda_2}) = \sum_n \frac{\mathcal{N}_{ni}\mathcal{N}_{nf}}{\mathcal{N}_{fi}}\frac{\lambda^{1/2}(s,q^2_{n,3},q^2_{n,4})}{s} S_n \sum_{\lambda'_1,\lambda'_2} \mathcal{A}^{j*}_{\lambda'_1\lambda'_2\leftarrow\lambda_3\lambda_4}\mathcal{A}^j_{\lambda'_1\lambda'_2\leftarrow\lambda_1\lambda_2}$$

$$\mathcal{N}_{ni} = \frac{s}{\lambda^{1/4}(s,q^2_{n,3},q^2_{n,4})\lambda^{1/4}(s,q_1^2,q_2^2)}\frac{1}{\sqrt{S_nS_i}}$$