EFT effects in VBS: lessons from UV complete models

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Based on arXiv 2103.16517
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Outline of seminar

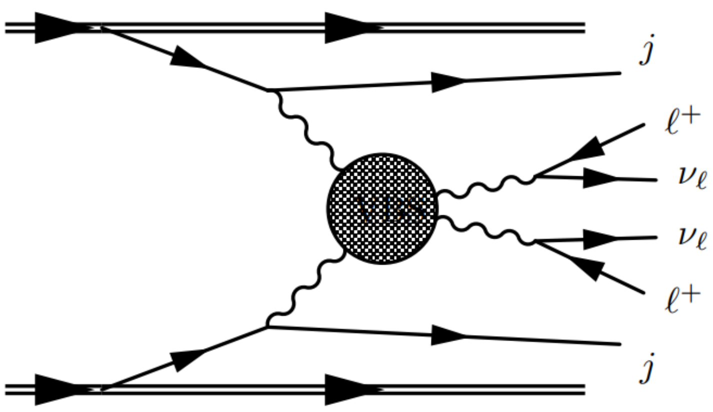
- Vector boson scattering (VBS) and fusion (VBF)
- EFT parameterization of BSM effects →Eboli basis
- Unitarity considerations and EFT
- Operators with field strengths are loop induced

- UV complete model(s) with fermions or scalars and their EFT
- Constraints from experiments
- Constraints from unitarity
- VBF cross sections: onshell and at LHC

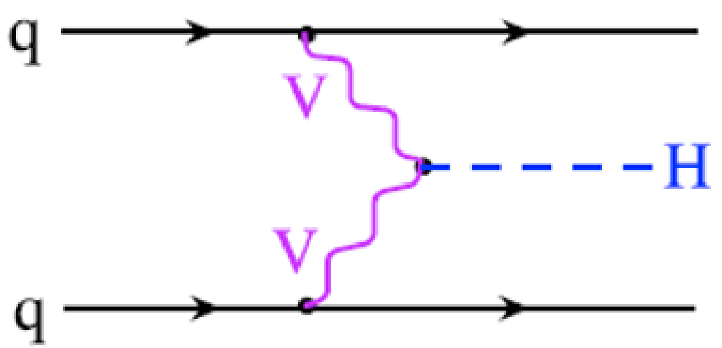
- Conclusions

Introduction

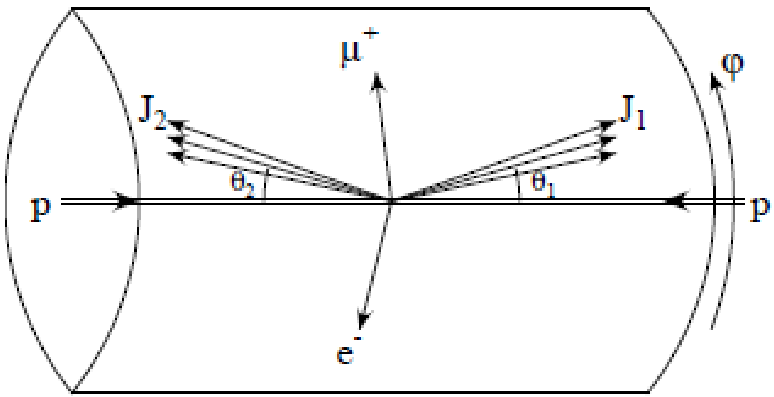
- Vector boson scattering (VBS)
  - Basic process: VV→VV
  - accompanied by 2 quark jets = tagging jets
  - Observe decay leptons of weak bosons or hadronic V decay

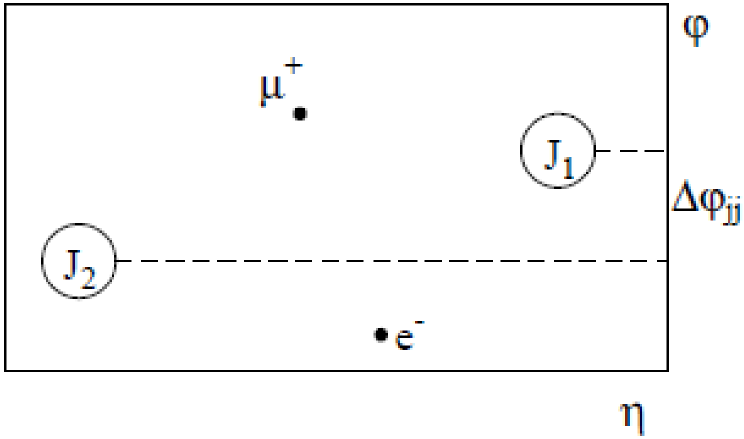


- Vector boson fusion (VBF)
  - Important Higgs production mode, e.g. H→tau+tau-
  - Determine HVV coupling from production cross section
  - Relatively low background



VBF and VBS signature





Characteristics:

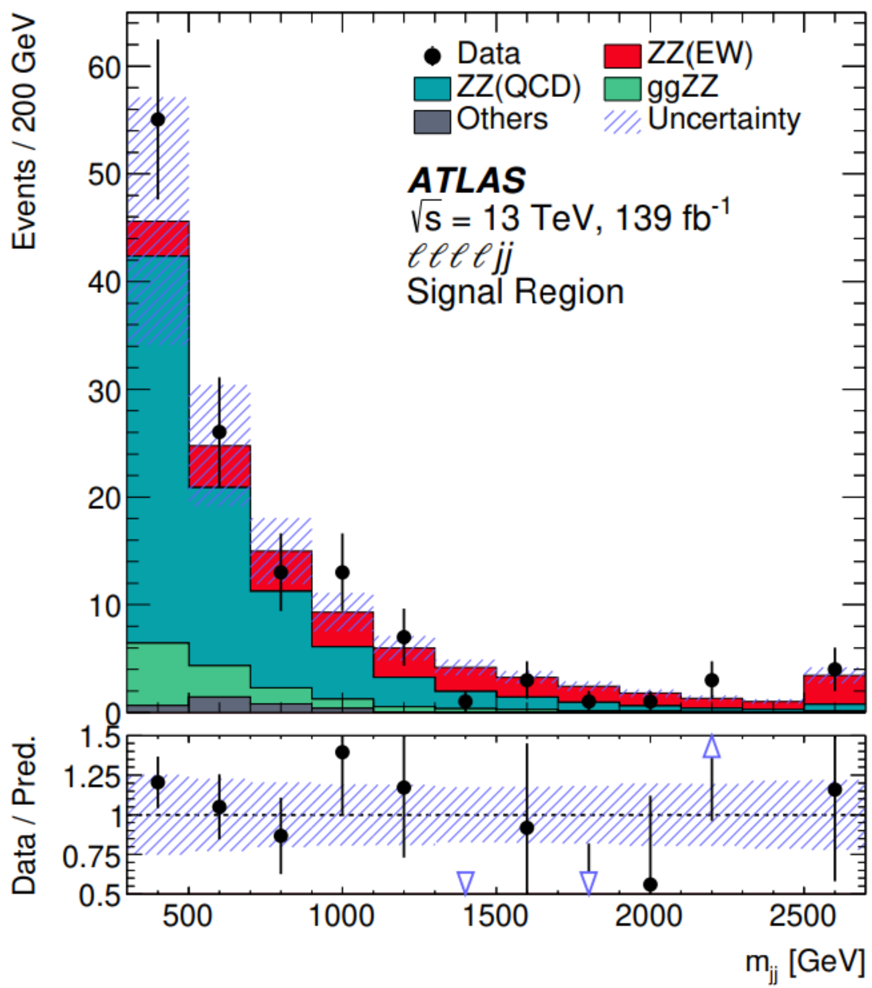
- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
  $\Longrightarrow$ Enhance signal contributions by "VBF cuts", e.g.

$$m_{jj} > 500\,\text{GeV} \qquad \Delta y_{jj} = |y_{j_1} - y_{j_2}| > 2.5$$

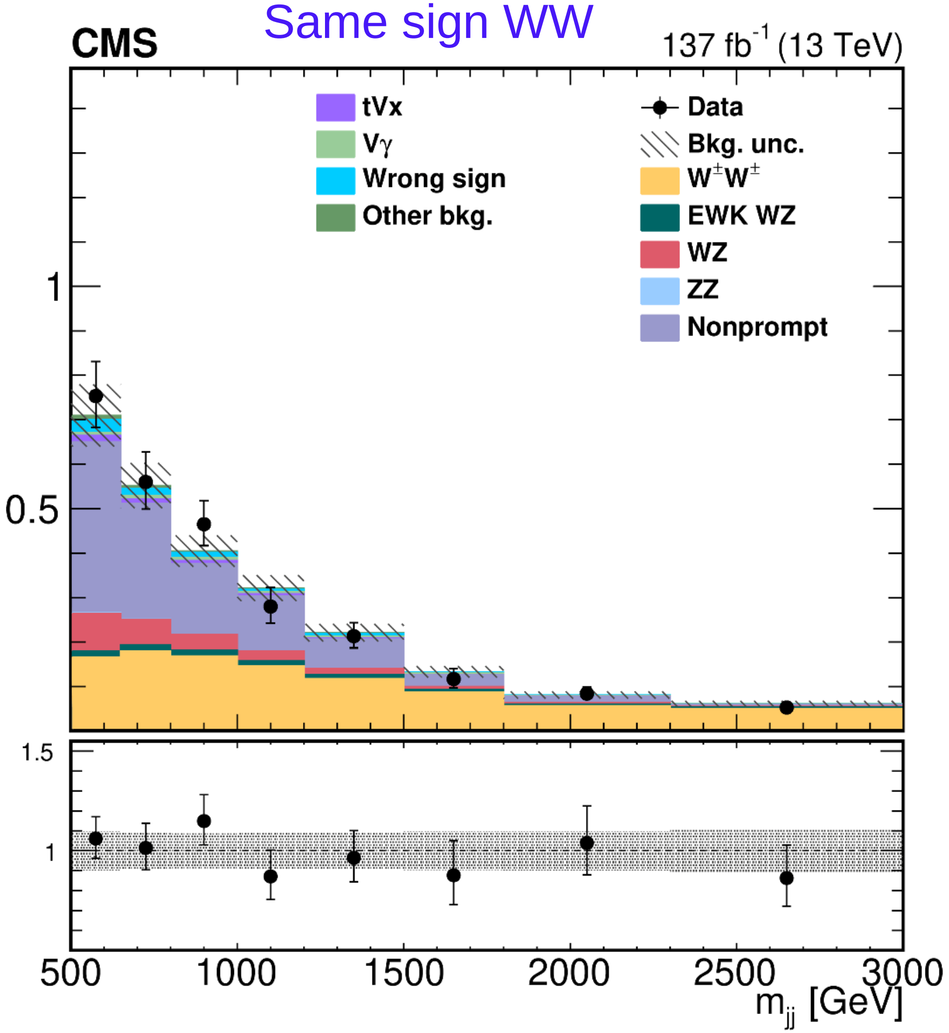
- Higgs/V/VV decay products between tagging jets

VBF signature provides good background rejection

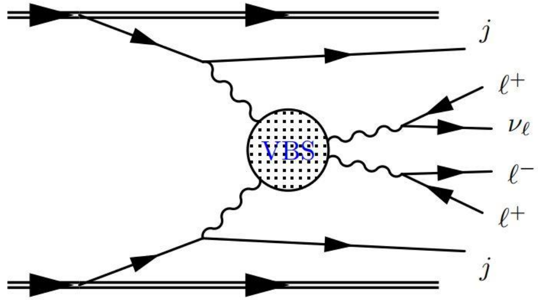
ZZjj, ZZ → 4 leptons



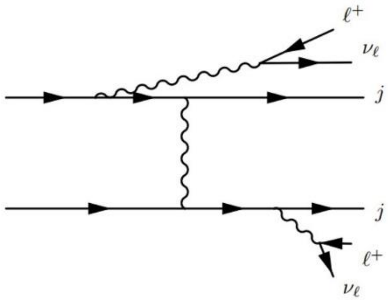
Same sign WW

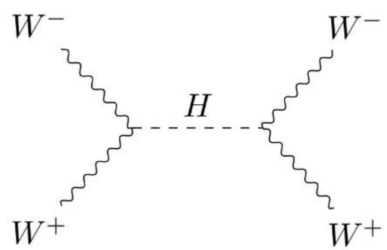


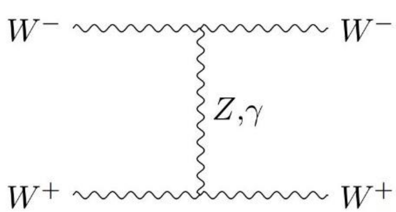
VBS and anomalous quartic gauge couplings (aQGC)

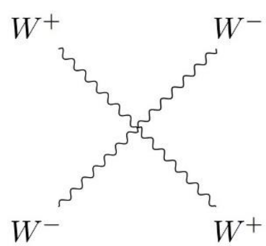


VBS provides rich source of information on dynamics of electroweak gauge bosons and EW symmetry breaking









Contributions from

- EW radiation
- Higgs exchange

- Triple gauge couplings
- Quartic gauge couplings

Use EFT to parameterize them

EFT operators for VBS

$$\mathcal{L}_{EFT} = \sum_{d=6}^{\infty} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} = \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} O_i^{(8)} + \ldots$$

$$= \frac{f_{WWW}}{\Lambda^2} \mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu} \hat{W}^{\nu}{}_{\rho} \hat{W}^{\rho}{}_{\mu}\right) + \ldots$$

$$+ \frac{f_{T_0}}{\Lambda^4} \mathrm{Tr}\left(\hat{W}^{\mu\nu} \hat{W}_{\mu\nu}\right) \mathrm{Tr}\left(\hat{W}^{\alpha\beta} \hat{W}_{\alpha\beta}\right) + \ldots$$

$$+ \frac{f_{M_0}}{\Lambda^4} \mathrm{Tr}\left[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}\right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right] + \ldots$$

$$+ \frac{f_{S_0}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi\right] + \ldots .$$

Extensively used tool for describing BSM effects in vector boson scattering….

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

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

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

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

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

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

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

$$B_{\mu\nu} = \frac{i}{2} g' (\partial_\mu B_\nu - \partial_\nu B_\mu) .$$

Field strength ←→ transverse polarizations

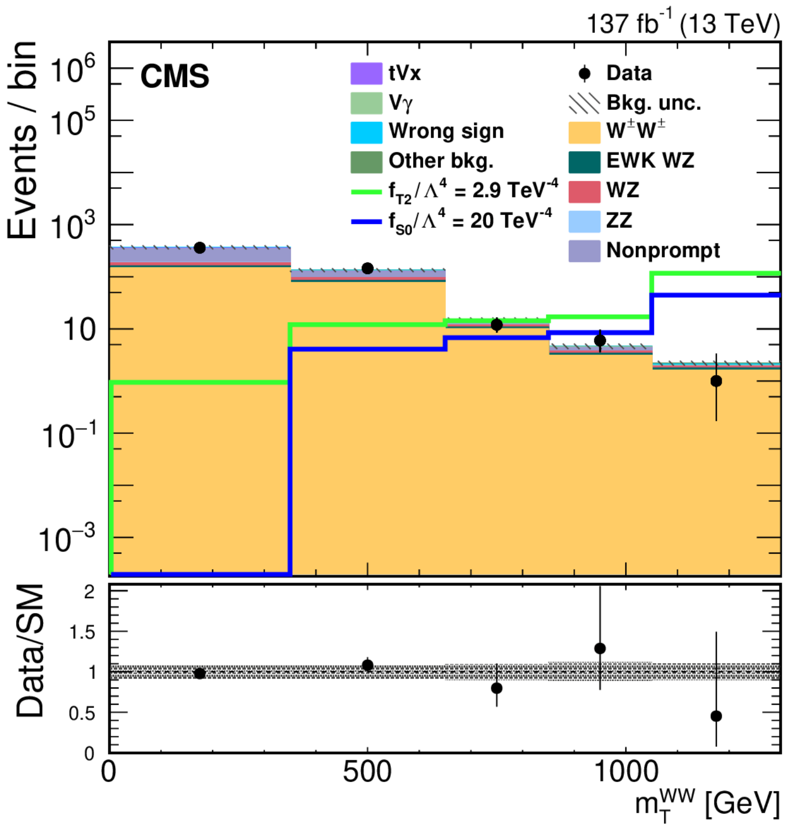
Transverse operators

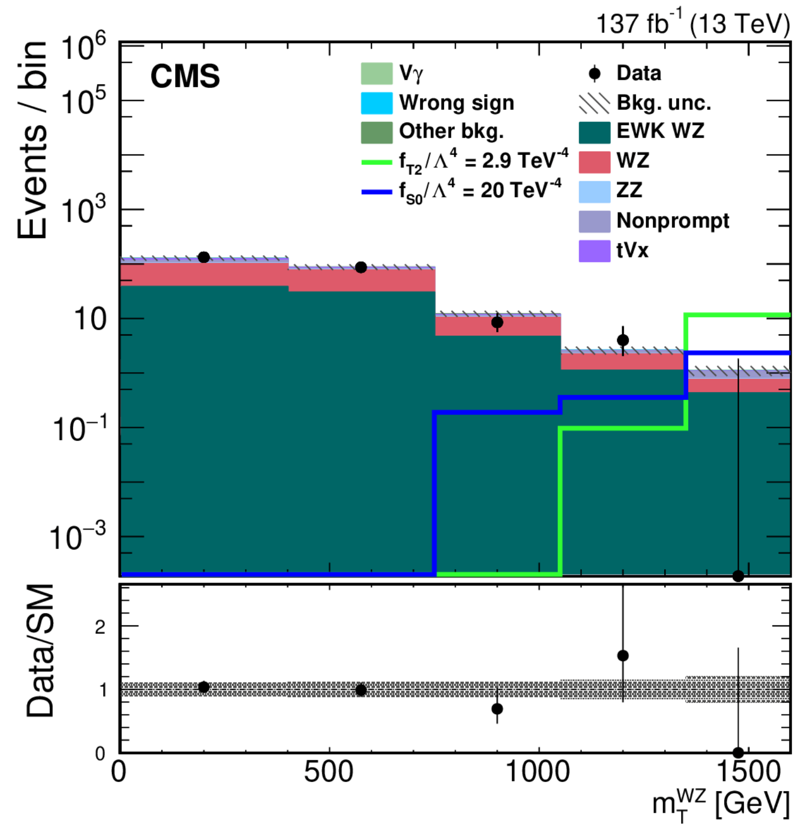
$$
\begin{aligned}
\mathcal{O}_{T_0} &= \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] \\
\mathcal{O}_{T_1} &= \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] \\
\mathcal{O}_{T_2} &=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

Mixed: transverse-longitudinal

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

Main interest: properties of VV final state





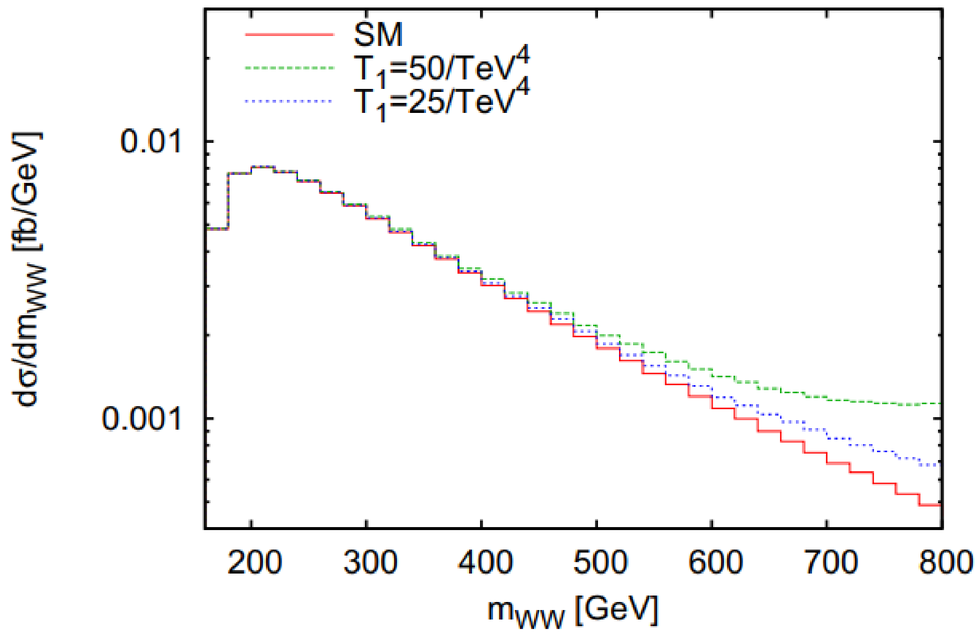
Here: transverse mass of leptons+missing pT system for ssWW and WZ

Problem: unitarity violation within LHC energy range

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

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

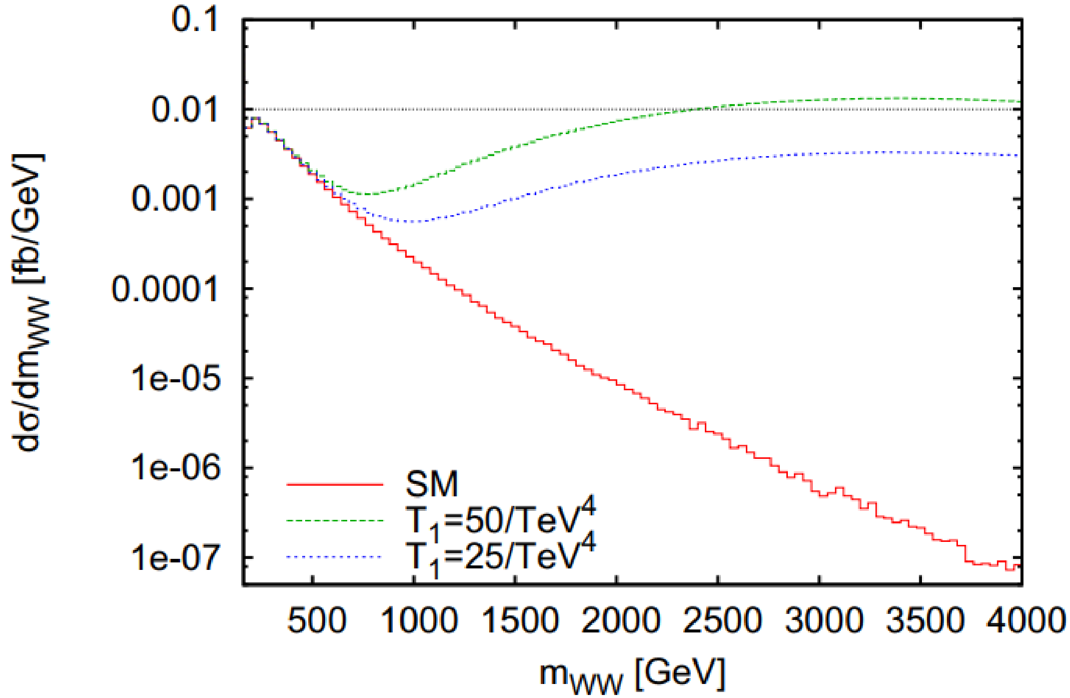
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- 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

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

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

- 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

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

Partial wave decomposition and unitarity relation

- S-matrix unitarity

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

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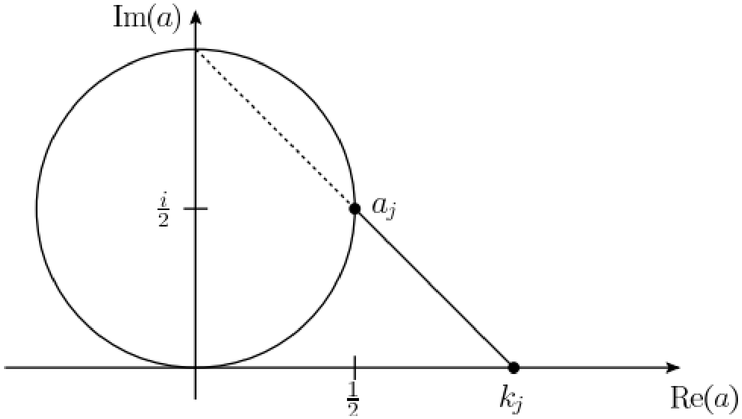
- Partial wave unitarity relation

$$2\mathrm{Im}(\mathcal{A}^j_{\lambda_3\lambda_4\leftarrow\lambda_1\lambda_2}) = \sum_n \sum_{\lambda_1',\lambda_2'} \mathcal{A}^{j\,*}_{\lambda_1'\lambda_2'\leftarrow\lambda_3\lambda_4}\mathcal{A}^j_{\lambda_1'\lambda_2'\leftarrow\lambda_1\lambda_2}$$

K matrix unitarization

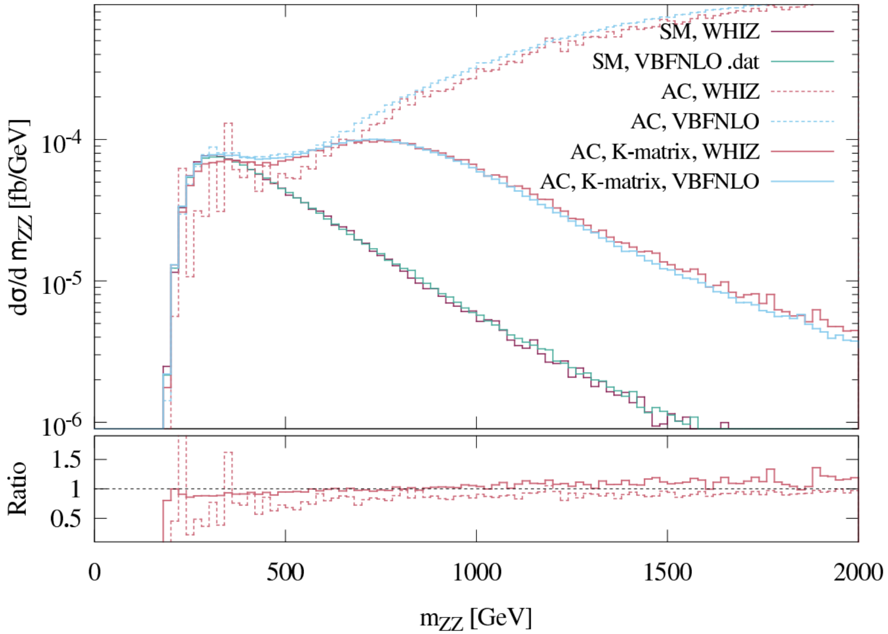


Project amplitude k_j, which exceeds (tree-level) unitarity, back onto Argand circle
$\rightarrow$ K matrix unitarized amplitude a_j

[VBFNLO implementation: Löschner, Perez;

following: Alboteanu, Kilian, Reuter]

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



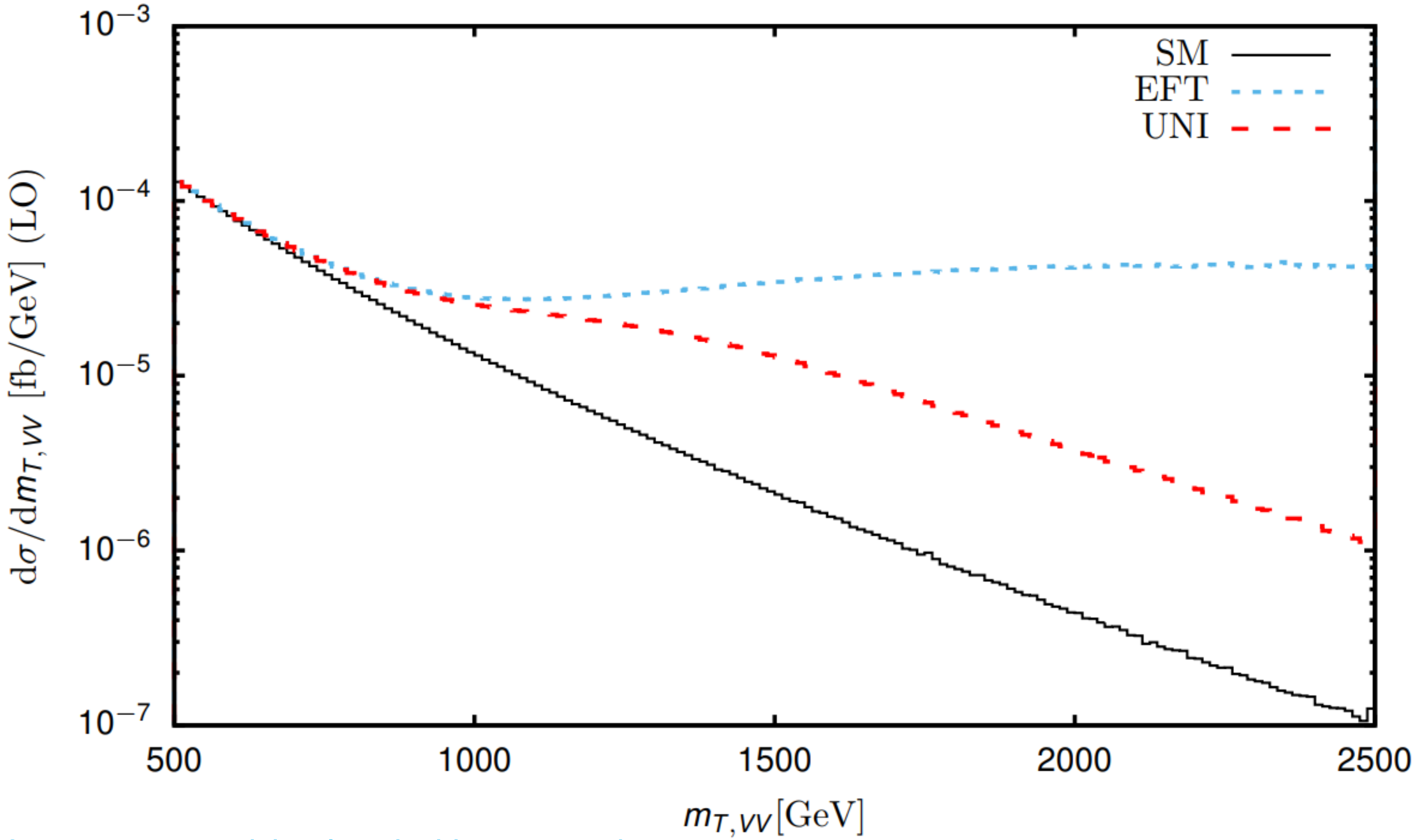
Example: VBF-ZZ (e+e-μ+μ-)
good agreement between both codes for longitudinal ops. at LO

Can generate distributions also at NLO QCD via VBFNLO

Extension to mixed and transverse operators: T_u model of arXiv:1807.02707 (work with Genessis Perez and Marco Sekulla)

Example: dim-8 effects with/out unitarization

$$qq \to W^+Zjj \to l^+l^-l^+\nu_l jj,$$



EFT for S0 operator (simulated with VBFNLO)

Tu-model unitarization applied to WZ→WZ matrix elements (see arXiv 1807.02707 for details)

Questions to ask … and path to answers

- How realistic is EFT description (with or without unitarization) as a function of energy (m_{VV})? What is the validity range of the EFT?
- Are there relations between Wilson coefficients?
- What experimental strategy is most promising to discover BSM effects in VBS? (as opposed to merely setting limits)
- Can VBS be first place to see BSM physics?

Study EFT as approximation to a UV complete model

- At our disposal: gauge theory with extra scalars, fermions, gauge fields
- Consider transverse operators as simplest case: dimension 6 and 8 operators which contain SU(2) field strength, no Higgs couplings
- Field strength tensor naturally (and only) generated at loop level:
  Need loops of extra fields with SU(2) charges ($U(1)_Y$ neglected for simplicity)
- UV complete model should be perturbatively treatable
- → predictions beyond validity range of EFT with small set of parameters:
  mass and isospin of extra multiplets

Origins of operators with field strengths

- Only term with field strength in renormalizable Lagrangian is

$$\mathscr{L} = -\frac{1}{4} W^j_{\mu\nu} W^{j\mu\nu}$$

- j = 1,2,3 is W or Z. Embedding SU(2) in larger gauge group G gives coupling to heavy new gauge bosons via $W^j_{\mu\nu} \sim f^{jkl} W^k_\mu W^l_\nu + \ldots$ with k,l>3 → pair of heavy gauge bosons couple to W/Z field strength at each BSM vertex → contribution only at loop level
- Particles in loop can be heavy gauge bosons, fermions or scalars. Fermion example: EFT approximation to gg→H three-point function
- Fermions or scalars can be in large isospin multiplets, which enhance loop contributions by huge group factors
- For extra gauge bosons, reducing adjoint representation of G to SU(2) irreps only allows isospin ½ or 0 for the extra heavy gauge bosons → no enhanced group factors in loops
- → consider only BSM fermions and scalars in following

The model(s)

- n_R SU(2) multiplets of isospin J_R of scalars (R=S) or Dirac fermions (R=F) with their SU(2) gauge interactions (no hypercharge couplings)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu H)^2 - \frac{m_H^2}{2}H^2 - \frac{1}{2}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right) + \frac{m_W^2}{2}\left(\sum_{a=1}^{3} W_\mu^a W^{a\mu}\right)\left(1+\frac{H}{v}\right)^2$$
$$+ \bar{\Psi}\left(i\gamma_\mu D^\mu - M_F\right)\Psi + (D^\mu\Phi)^\dagger(D_\mu\Phi) - {M_S}^2\Phi^\dagger\Phi\,.$$

- Yukawa couplings of fermions to Higgs doublet absent if no fermion multiplets with $J_F \pm 1/2$ are present
- Yields *natural dark matter models* for $J_R \geq 2$
- Very small splitting induced by SU(2)xU(1) breaking in SM (order 160 MeV to few GeV) ➔ Pair production at LHC hard to detect due to tiny phase space for β-decay within SU(2) multiplet
- Refinements like extra (confining) gauge interactions, several multiplets, hypercharge contributions, Higgs couplings keep our results as LO approximation → very generic class of models

Consider loop contributions to n-point functions

- n=2: gauge boson propagator
- n=3: triple gauge boson vertex functions
- n=4: boxes with 4 external weak bosons

- UV divergences are simple renormalizations of SM parameters (gauge coupling and W wave function renormalization)

- Match first few terms in p^2/M_R^2 expansion to EFT

Dim-6 and dim-8 operators needed for matching of hypercharge Y=0 multiplets

- Dim-6

$$O_{WWW} = \mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu}\hat{W}^{\nu}{}_{\rho}\hat{W}^{\rho}{}_{\mu}\right)\,,$$

aTGC …

$$O_{DW} = \mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}^\alpha, \hat{W}_{\mu\nu}]\right)$$

Propagator correction …

- Dim-8

$$O_{T_0} = \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\alpha\beta}\right)$$

$$O_{T_1} = \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\mu\nu}\right)$$

$$O_{T_2} = \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\nu\alpha}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\beta\mu}\right)$$

$$O_{T_3} = \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}_{\nu\alpha}\hat{W}_{\beta\mu}\right)$$

aQGC …

$$O_{DWW W_0} = \mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu}{}_{\nu}][\hat{D}^\alpha, \hat{W}^{\nu}{}_{\rho}]\hat{W}^{\rho}{}_{\mu}\right)$$

$$O_{DWW W_1} = \mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}_\beta, \hat{W}_{\mu\nu}]\hat{W}^{\alpha\beta}\right)$$

aTGC …

$$O_{D2W} = \mathrm{Tr}\left([\hat{D}_\alpha, [\hat{D}^\alpha, \hat{W}^{\mu\nu}]][\hat{D}_\beta, [\hat{D}^\beta, \hat{W}_{\mu\nu}]]\right)$$

Propagator correction …

Full dim6+8 EFT considered

$$
\begin{aligned}
\mathcal{L}_{EFT} = f_{WW}\,\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right) + \frac{f_{DW}}{\Lambda^2}\mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}^\alpha, \hat{W}_{\mu\nu}]\right) \\
+ \frac{f_{WWW}}{\Lambda^2}\mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu}\hat{W}^{\nu}{}_{\rho}\hat{W}^{\rho}{}_{\mu}\right) + \frac{f_{D2W}}{\Lambda^4}\mathrm{Tr}\left([\hat{D}_\alpha, [\hat{D}^\alpha, \hat{W}^{\mu\nu}]][\hat{D}_\beta, [\hat{D}^\beta, \hat{W}_{\mu\nu}]]\right) \\
+ \frac{f_{DWWW_0}}{\Lambda^4}\mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu}{}_{\nu}][\hat{D}^\alpha, \hat{W}^{\nu}{}_{\rho}]\hat{W}^{\rho}{}_{\mu}\right) \\
+ \frac{f_{DWWW_1}}{\Lambda^4}\mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}_\beta, \hat{W}^{\mu\nu}]\hat{W}^{\alpha\beta}\right) \\
+ \frac{f_{T_0}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\alpha\beta}\right) + \frac{f_{T_1}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\mu\nu}\right) \\
+ \frac{f_{T_2}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu}\hat{W}^{\nu}{}_{\alpha}\right)\mathrm{Tr}\left(\hat{W}^{\alpha}{}_{\beta}\hat{W}^{\beta}{}_{\mu}\right) + \frac{f_{T_3}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}_{\nu\alpha}\hat{W}_{\beta\mu}\right) .
\end{aligned}
$$

Wilson coefficients with
$$C_{2,R} = J_R(J_R+1)$$
$$T_R = \frac{1}{3}\left[J_R(J_R+1)(2J_R+1)\right]$$

- Propagator and higher

$$\frac{f_{DW}}{\Lambda^2} = \sum_F n_F \frac{T_F}{120\pi^2 M_F^2} + \sum_S n_S \frac{T_S}{960\pi^2 M_S^2}\,,$$
$$\frac{f_{D2W}}{\Lambda^4} = \sum_F n_F \frac{T_F}{1120\pi^2 M_F^4} + \sum_S n_S \frac{T_S}{13440\pi^2 M_S^4}$$

- aTGC and higher

$$\frac{f_{WWW}}{\Lambda^2} = \sum_F n_F \frac{13T_F}{360\pi^2 M_F^2} + \sum_S n_S \frac{T_S}{360\pi^2 M_S^2}\,,$$
$$\frac{f_{DWWW_0}}{\Lambda^4} = \sum_F n_F \frac{2T_F}{105\pi^2 M_F^4} + \sum_S n_S \frac{T_S}{1120\pi^2 M_S^4}$$
$$\frac{f_{DWWW_1}}{\Lambda^4} = \sum_F n_F \frac{T_F}{630\pi^2 M_F^4} + \sum_S n_S \frac{T_S}{4032\pi^2 M_S^4}$$

- aQGC and higher

$$\frac{f_{T_0}}{\Lambda^4} = \sum_F n_F \frac{(-14C_{2,F}+1)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}-2)\,T_S}{40320\pi^2 M_S^4}\,,$$
$$\frac{f_{T_1}}{\Lambda^4} = \sum_F n_F \frac{(-28C_{2,F}+13)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(14C_{2,S}-5)\,T_S}{40320\pi^2 M_S^4}\,,$$
$$\frac{f_{T_2}}{\Lambda^4} = \sum_F n_F \frac{(196C_{2,F}-397)\,T_F}{25200\pi^2 M_F^4} + \sum_S n_S \frac{(14C_{2,S}-23)\,T_S}{50400\pi^2 M_S^4}\,,$$
$$\frac{f_{T_3}}{\Lambda^4} = \sum_F n_F \frac{(98C_{2,F}+299)\,T_F}{25200\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}+16)\,T_S}{50400\pi^2 M_S^4}\,.$$

- Loop suppressed, but $(J_R)^3$ enhanced for trilinear couplings, $(J_R)^5$ for aQGC

Constraints from experiment:

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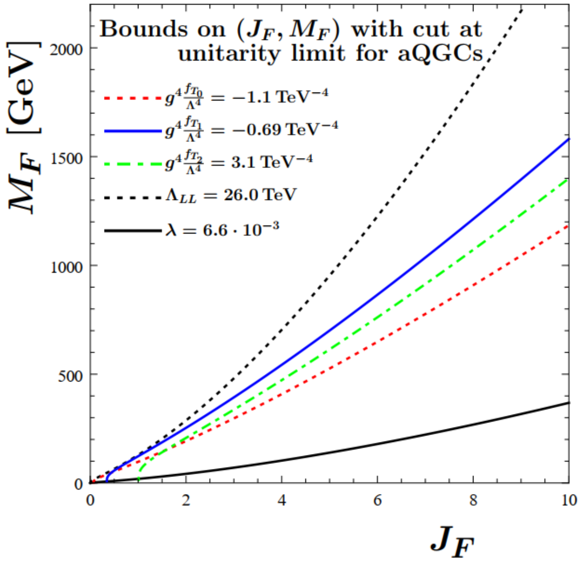
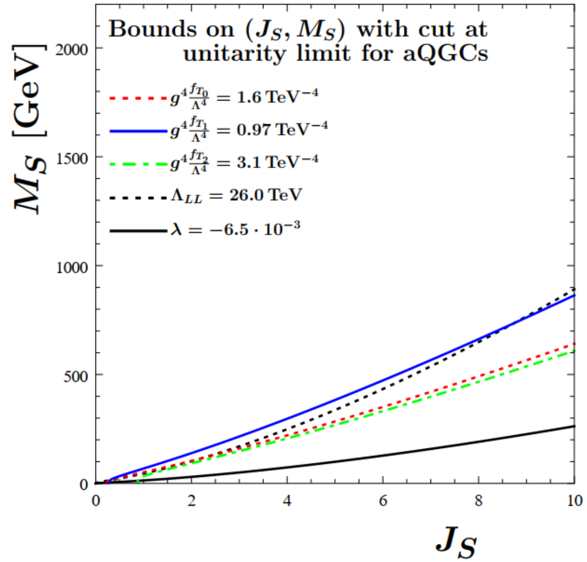


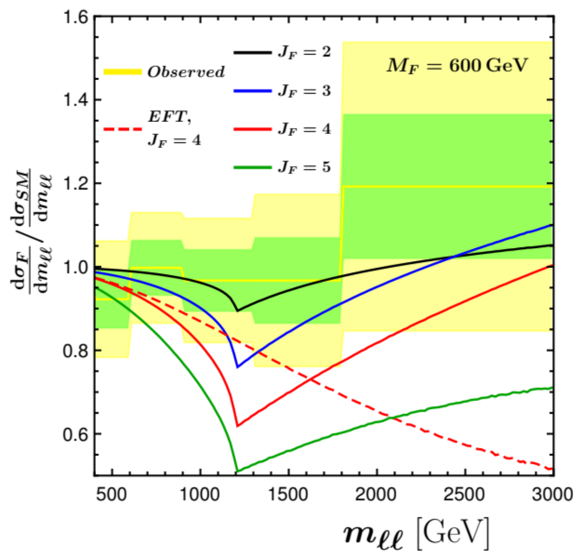


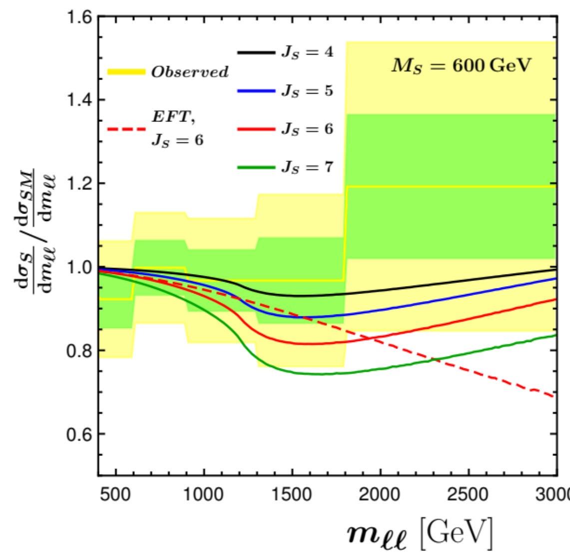
limits on individual Wilson coefficients:

No serious competition to VBS from aTGC measurements in VV production

(Assume wide EFT validity range)

Deviation in Drell-Yan cross section, normalized to SM expectation
(1- and 2-σ error bands adapted from CMS: arXiv:2103.02708)





Unitarity considerations limit size of isospin representations

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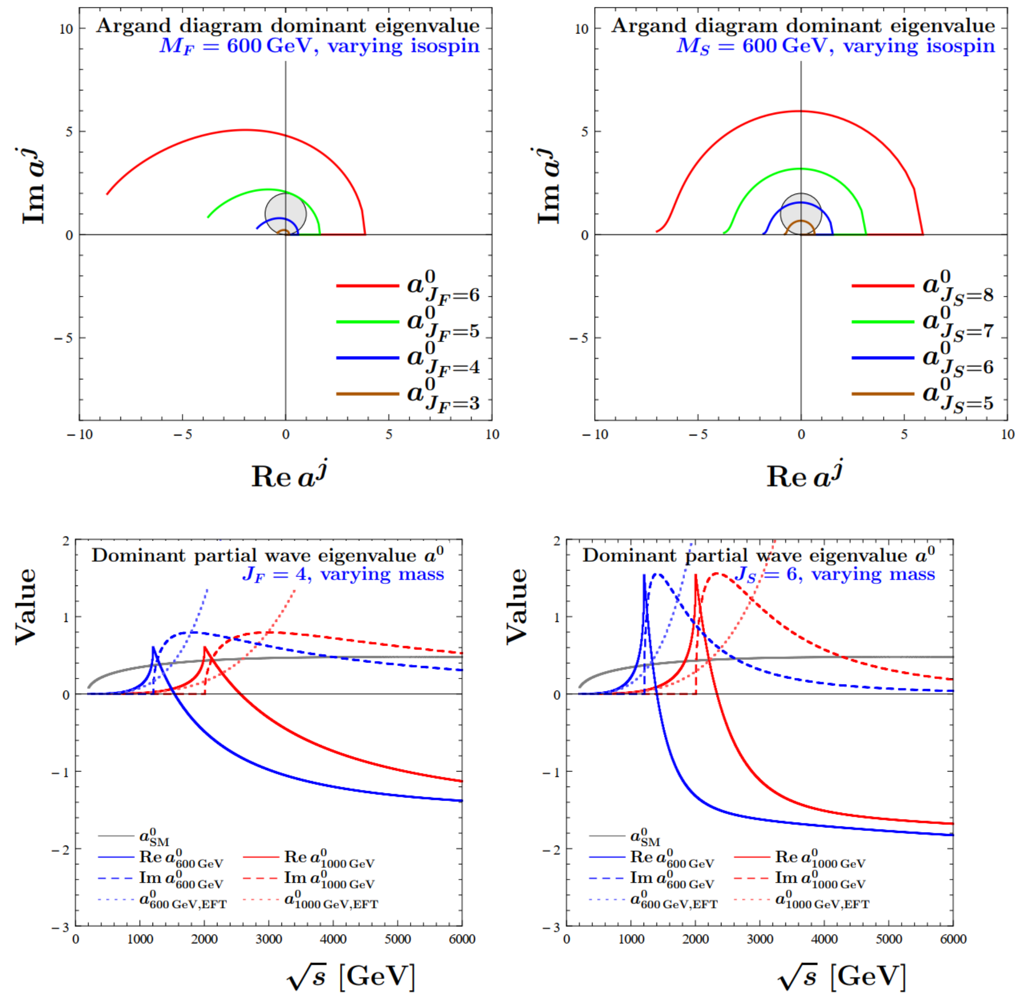
- Argand diagram for dominant VV→VV partial wave amplitude: At large J_R, model becomes non-perturbative



- Energy dependence of dominant partial wave amplitude

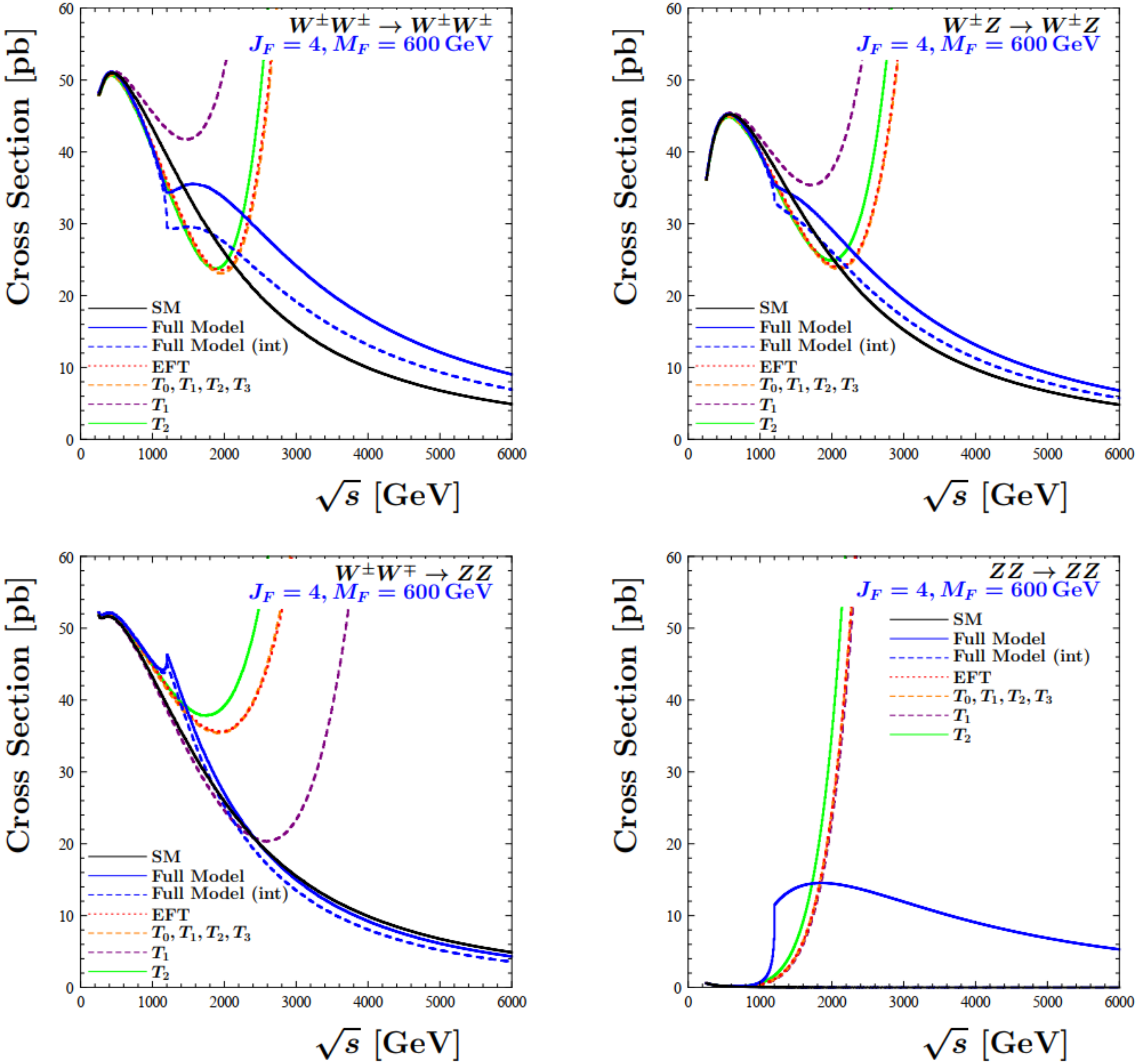
Consider $J_F \leq 4$ and $J_S \leq 6$ as range of perturbative domain

Parameter choices:

- Use fermion model with $J_F = 4$ and $M_F = 600$ GeV
  or scalar model with $J_S = 6$ and $M_S = 600$ GeV
  for illustration from here on

- Parameter choices are optimistic for sake of sizable VBS signals

- $J_F \leq 3$ better accomodates Drell-Yan constraints
- $J_S \leq 5$ better fits in the perturbative domain (as estimated from unitarity)
- Qualitative results, below, do not depend on this



Onshell cross sections for $J_F = 4$

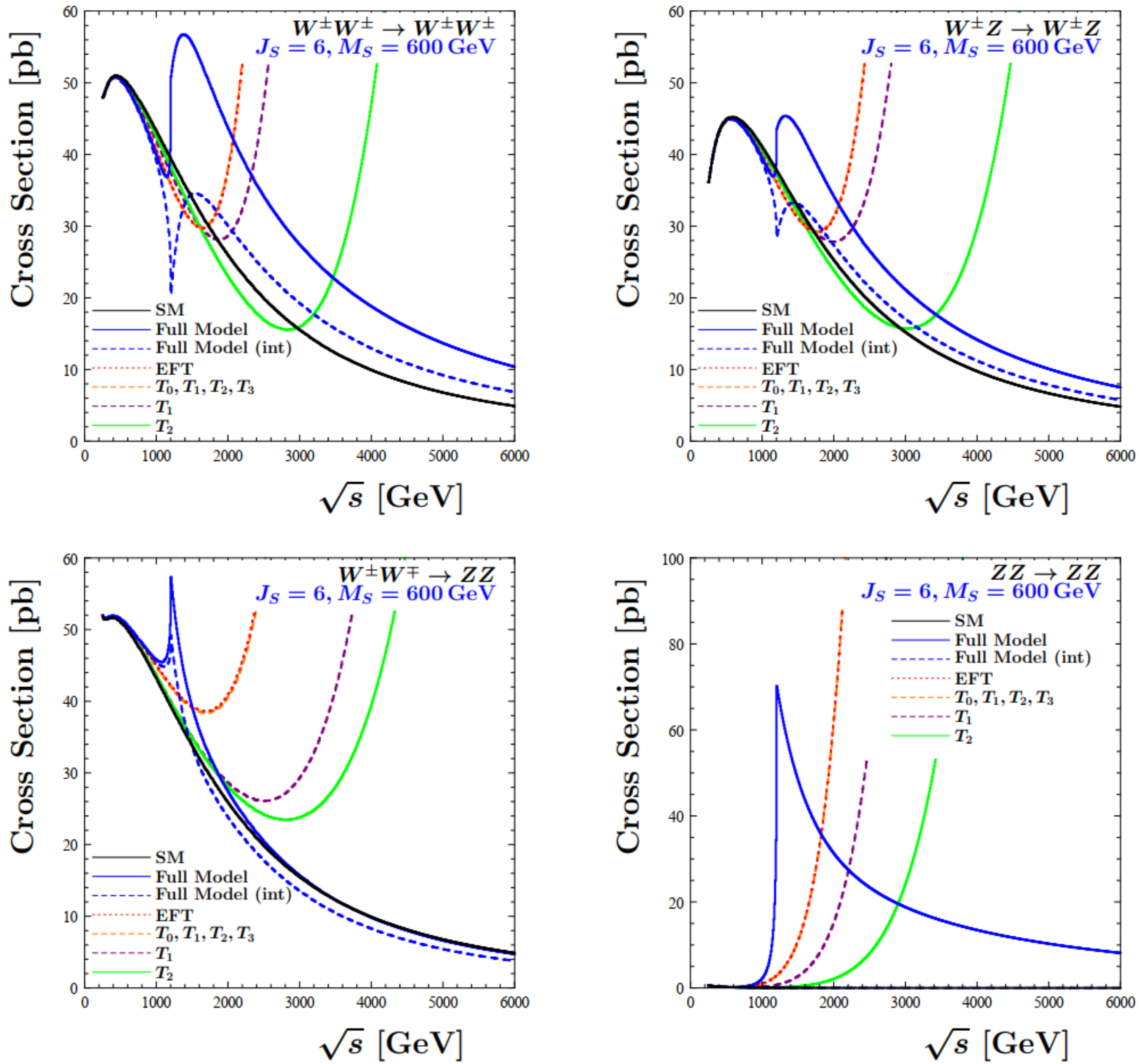
Comparison of:

full model vs

full model - no g^8 term

full EFT

individual dim 8 terms



Onshell cross sections for $J_S = 6$

Comparison of:

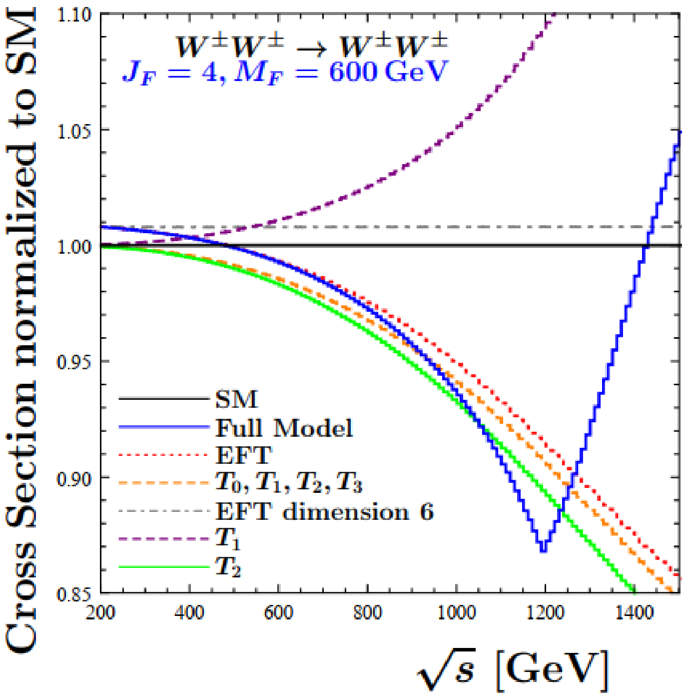
full model vs

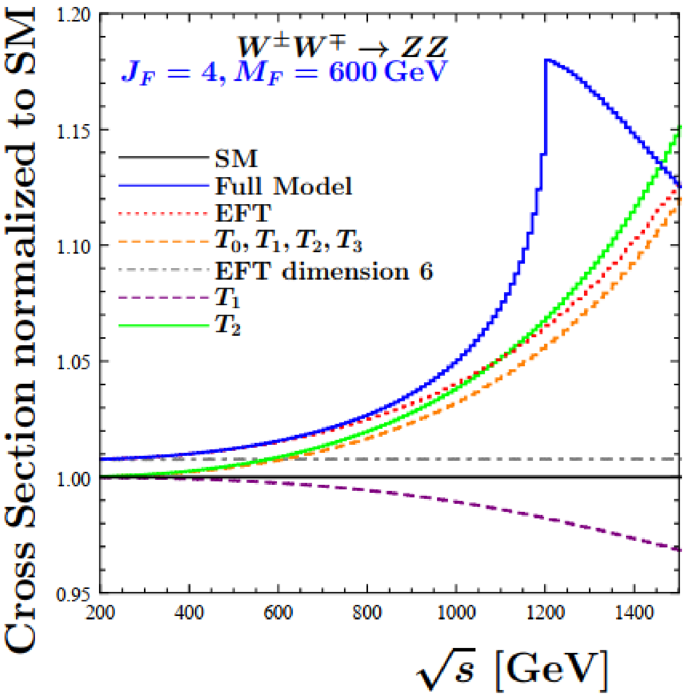
full model - no g^8 term

full EFT

individual dim 8 terms

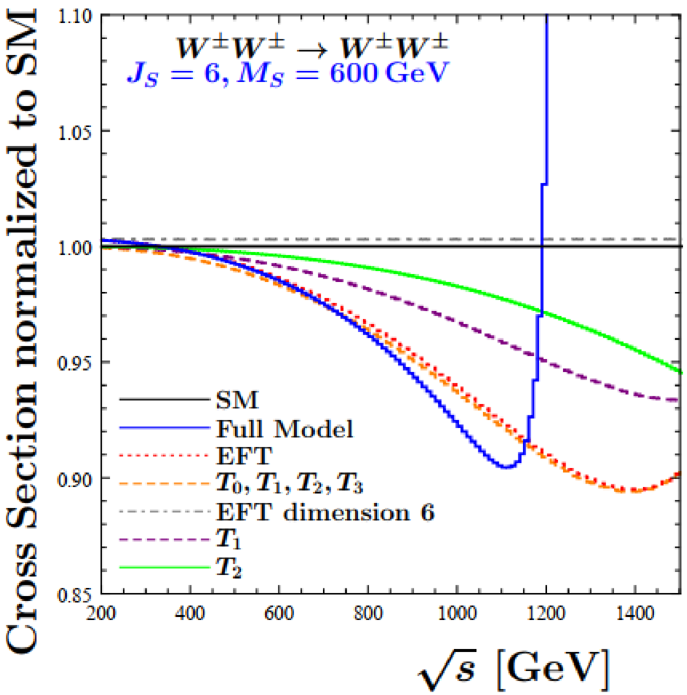
Onshell cross section in low energy region…

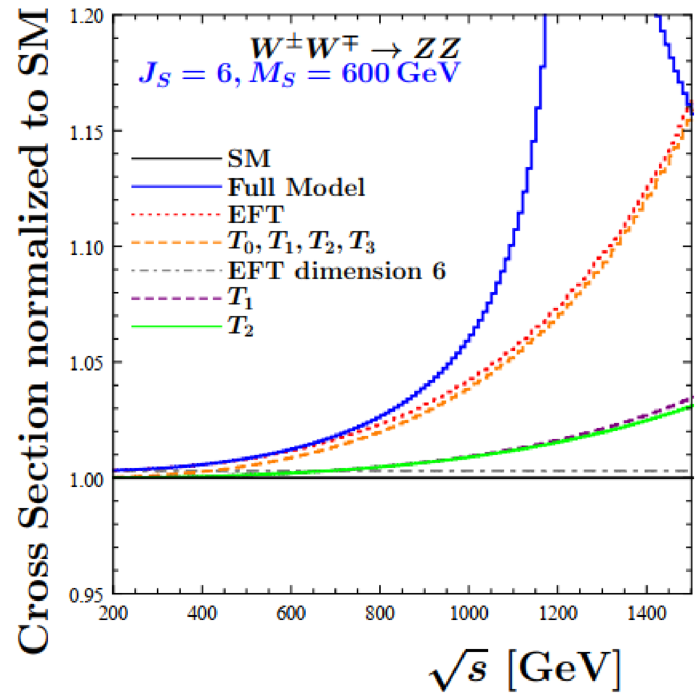




- Dimension 6 operator contributions are negligible due to mere J_R^3 growth and cancellations
- Good agreement between full model and dim-8 EFT below threshold
- Combination of all dim-8 operators is crucial

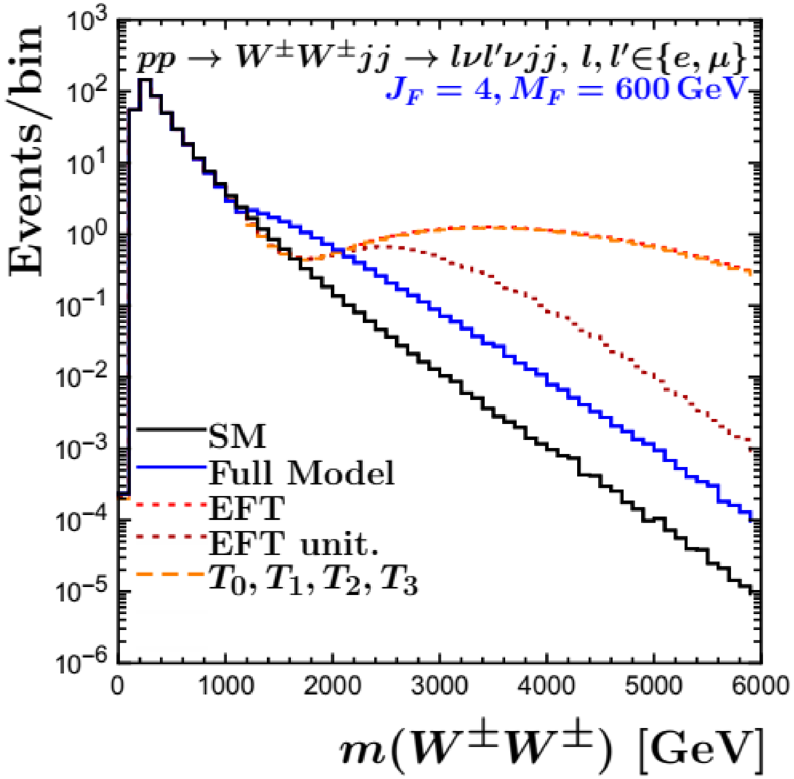
…. and for scalars in the loop

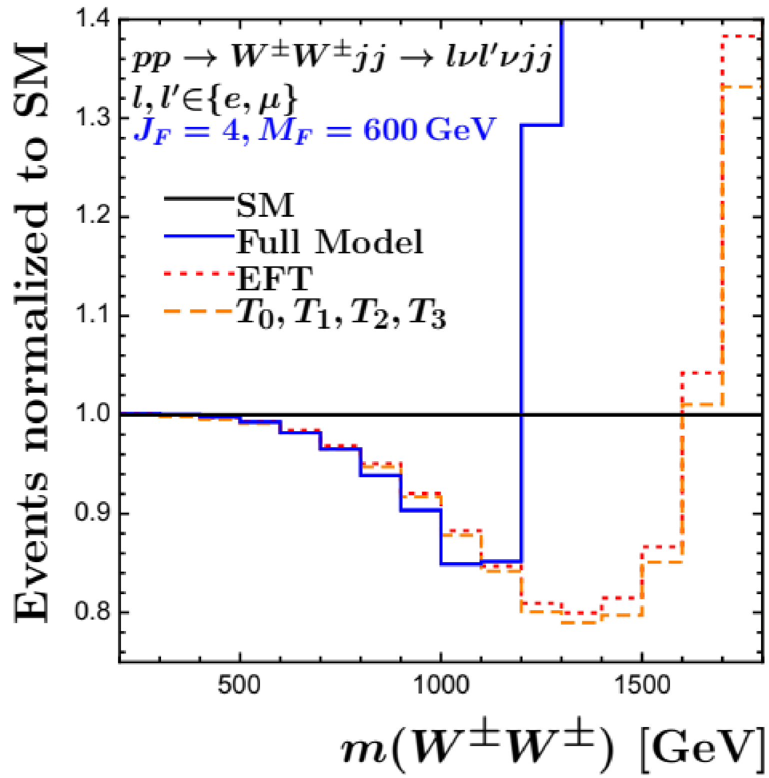




- Dimension 6 operator contributions again negligible
- Good agreement between full model and dim-8 EFT well below threshold
- Deviations from SM below 10% in EFT validity region

Full LHC cross sections simulations with VBFNLO

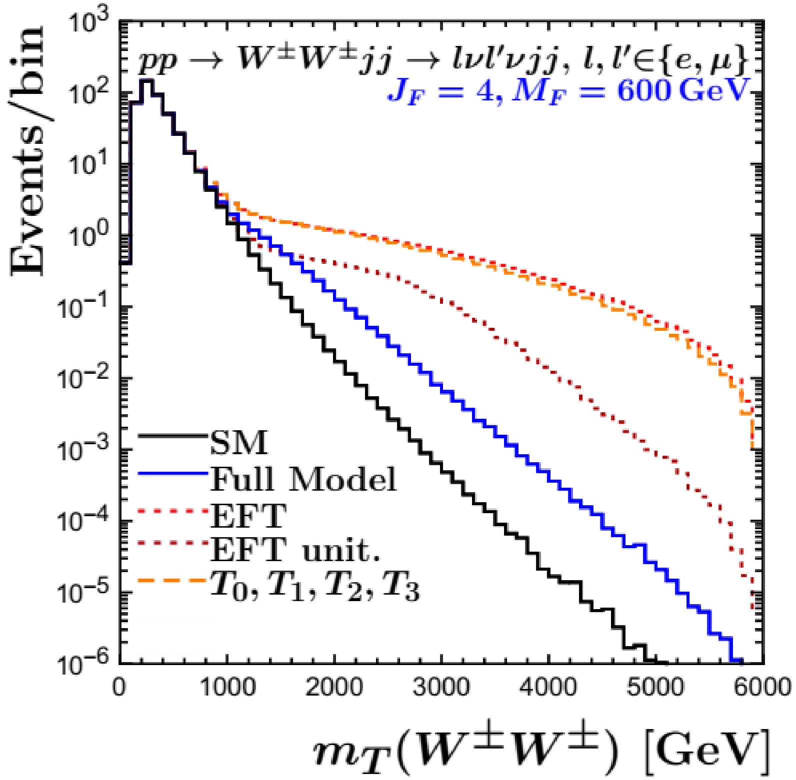


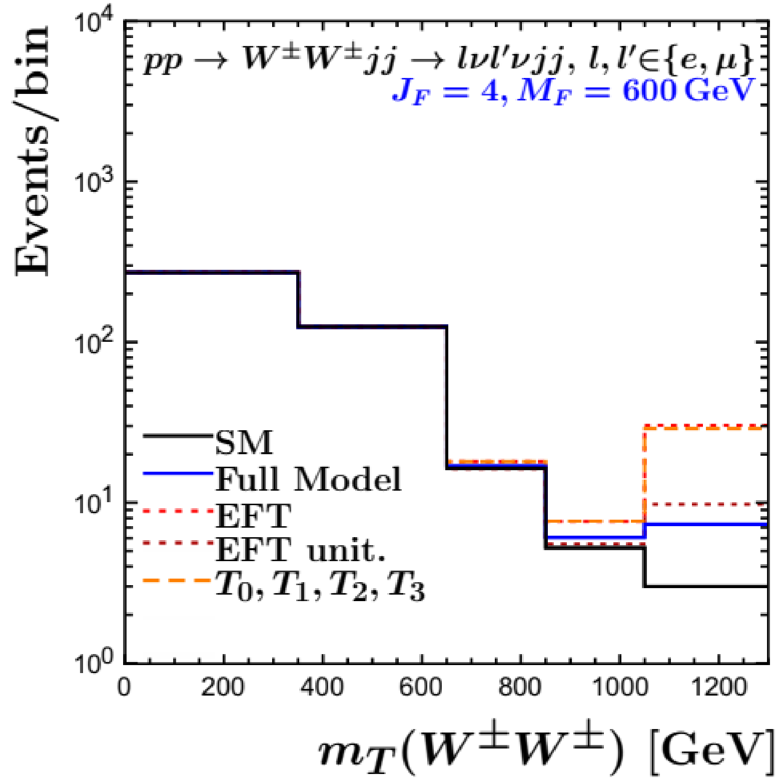


Sizable deviations from SM well above threshold, for high isospin fermions

Disclaimer: VBFNLO implementation is so far approximate,
based on on-shell VV→ VV amplitudes

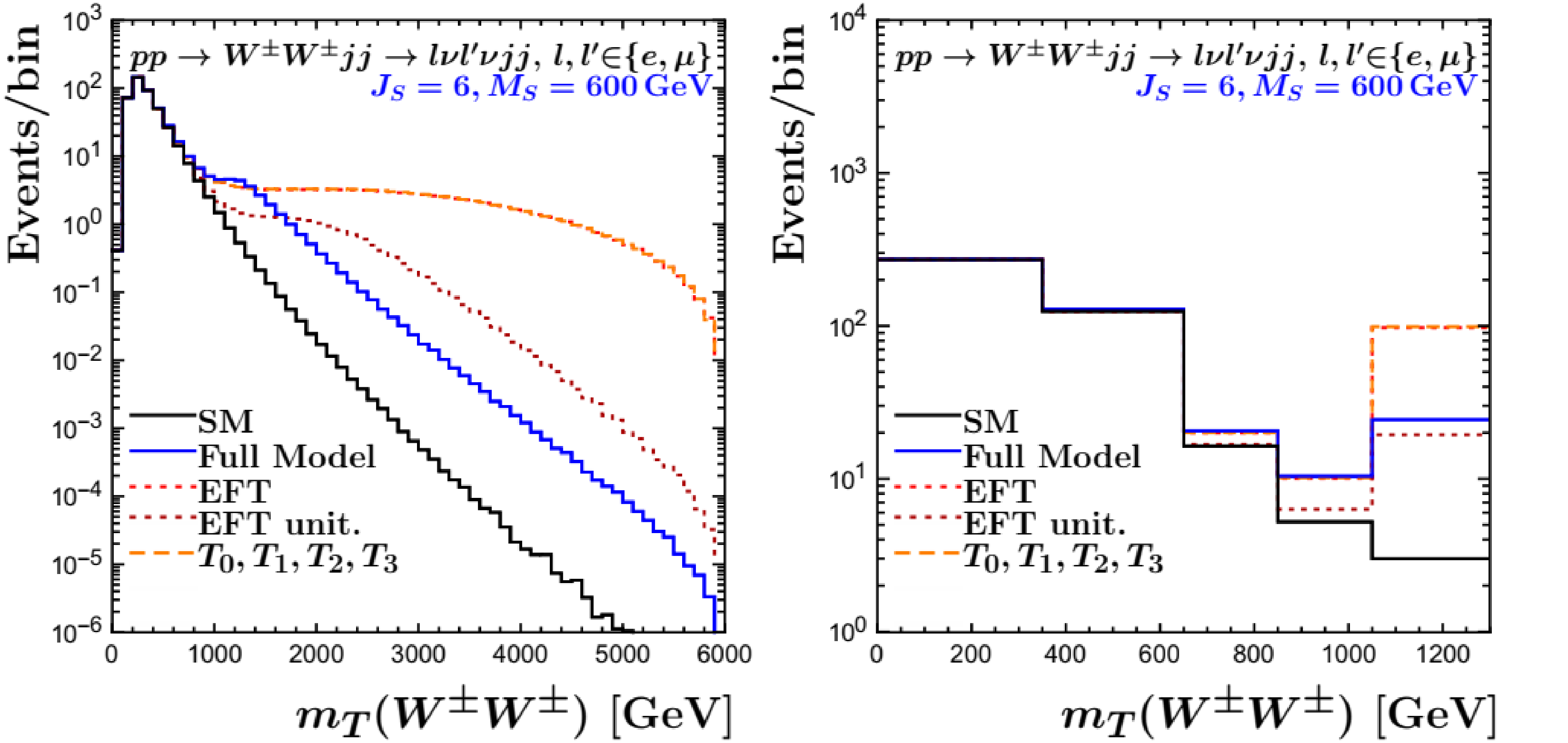
Transverse mass distribution of leptons + pTmiss





Only transverse mass can be reconstructed experimentally for same sign W pairs

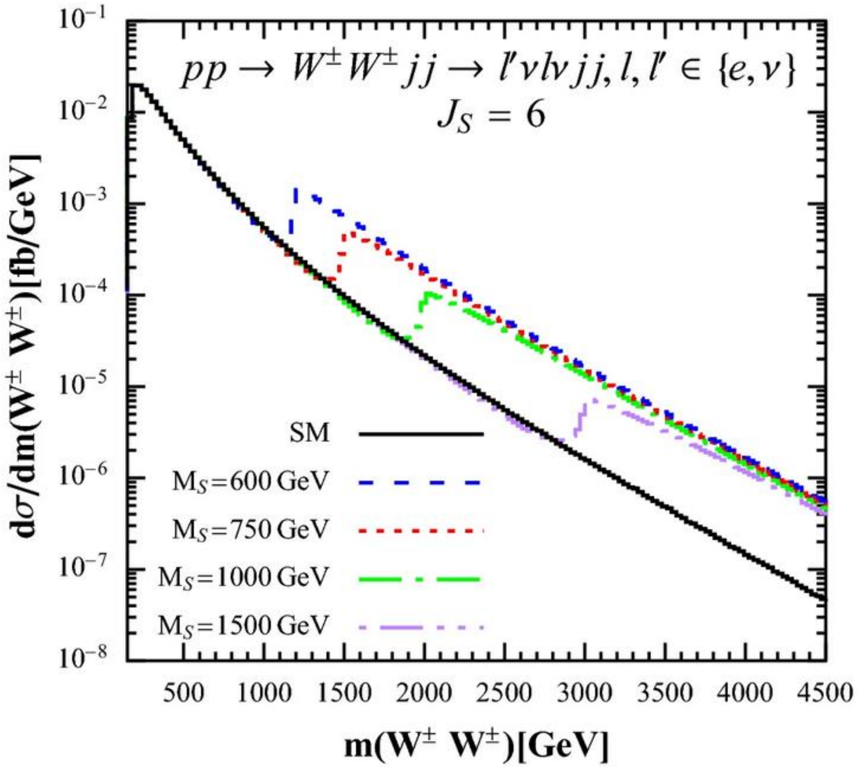
Transverse mass in ssWW for scalar case

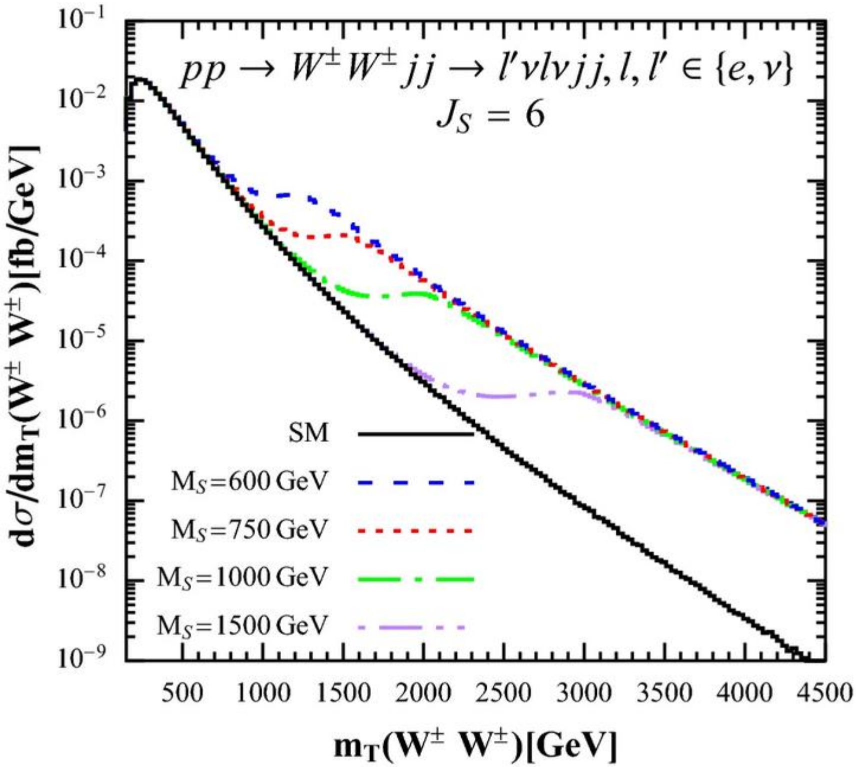


Right hand plot shows binning of CMS publication:

- Unitarized EFT: BSM effects mostly in last bin
- Full model: visible effects extend to lower transverse mass

Changing the mass of the heavy multiplets





Conclusions

- There are many UV-complete models which generate EFT operators with field strength tensors at low energy
- They require existence of extra SU(2) scalar or fermion (or gauge boson) multiplets which generate these EFT operators via 1-loop contributions
- Sizable effects in VBS require very high multiplicity of BSM fields, like SU(2) nonets (quintets may do): rarely expected in BSM models
- Model is generic: existence of additional SU(2) multiplets in loops is also necessary condition for EFT operators with W field strength
- Further complexity does not change basic result, e.g.
  - Additional confining gauge interaction of multiplets expected to average out (analogous to quark-hadron duality in QCD)
  - Perturbative coupling of two multiplets to Higgs doublet field generates modest multiplet splitting (suppressed by $(v/M_R)^2$) which smears out threshold structure

Conclusions continued…

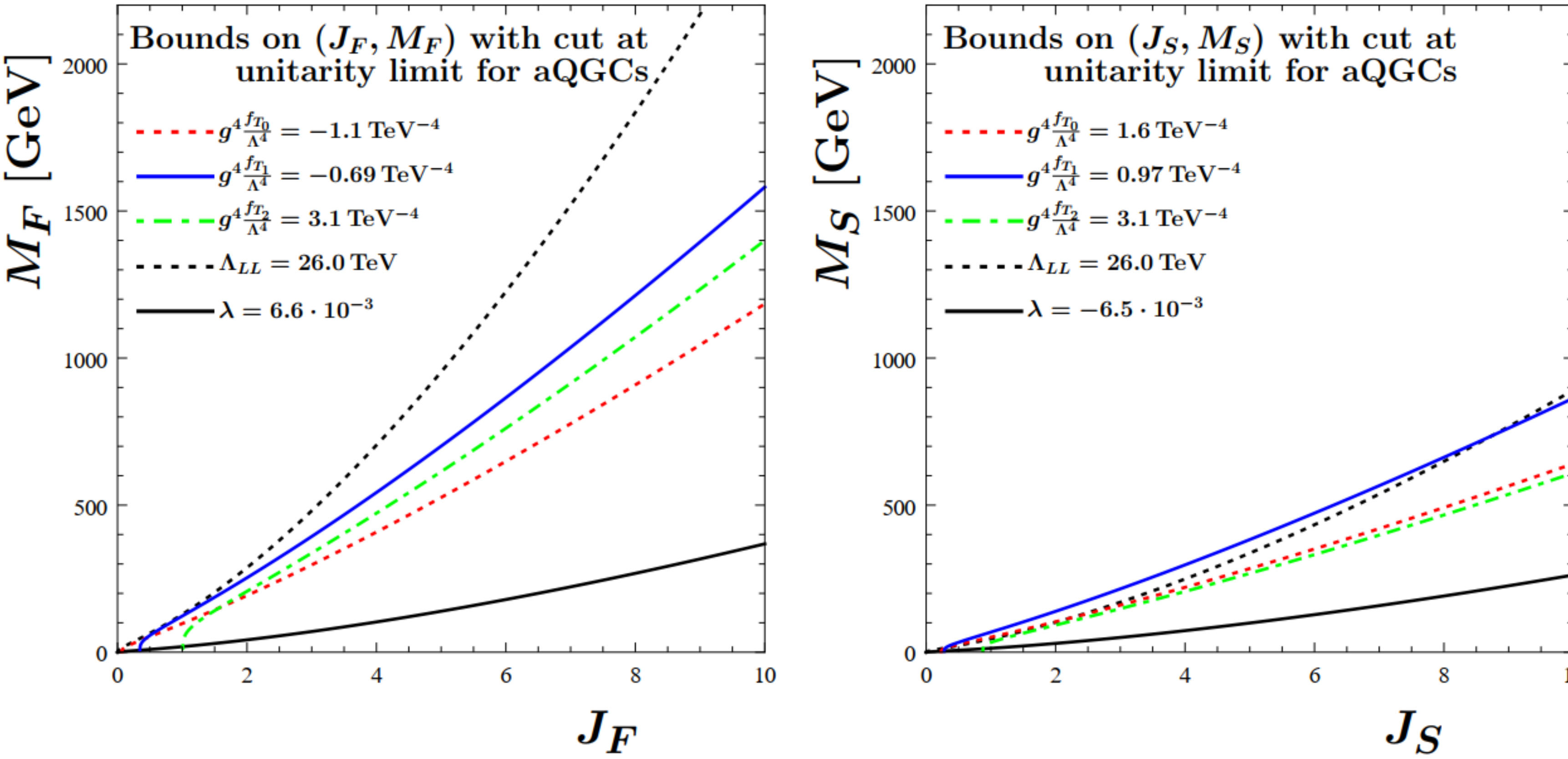
- VBS signal is most dramatic close to threshold, not at highest energy
  => do not concentrate efforts on highest energy bin

- VBS is competitive with other searches for this type of model:
  - $q\bar{q} \to VV$ is not as sensitive due to mere J_R^3 growth and cancellations
  - Direct search for the extra multiplets is hampered by compressed spectra
  - Drell-Yan process is most likely competitor

- EFT as tool for describing BSM effects is of only limited use in describing processes with vast dynamic range such as VBS at the LHC
  => use models discussed here as alternative benchmark for VBS studies

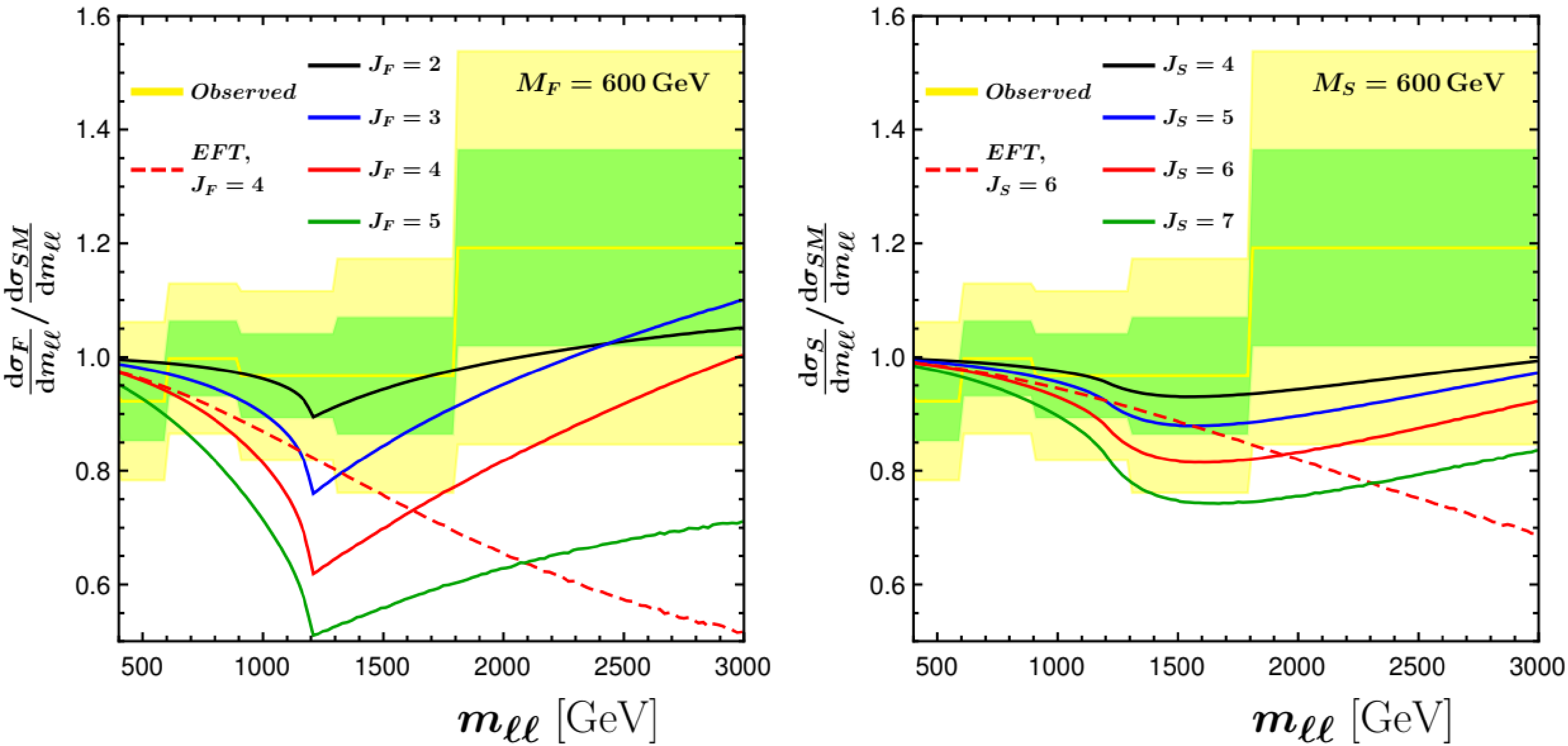
Backup

Constraints from experiment: limits on individual Wilson coefficients

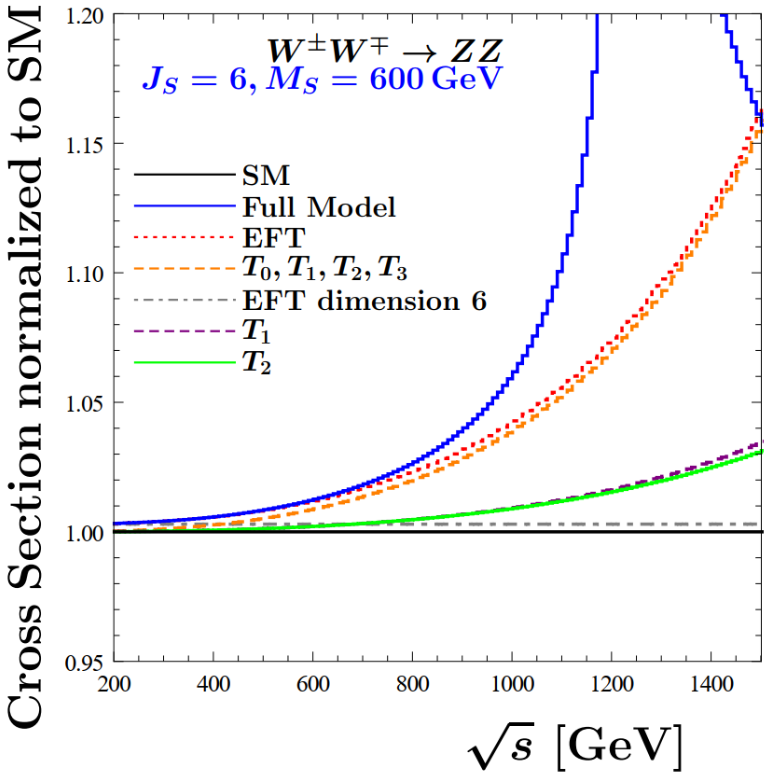


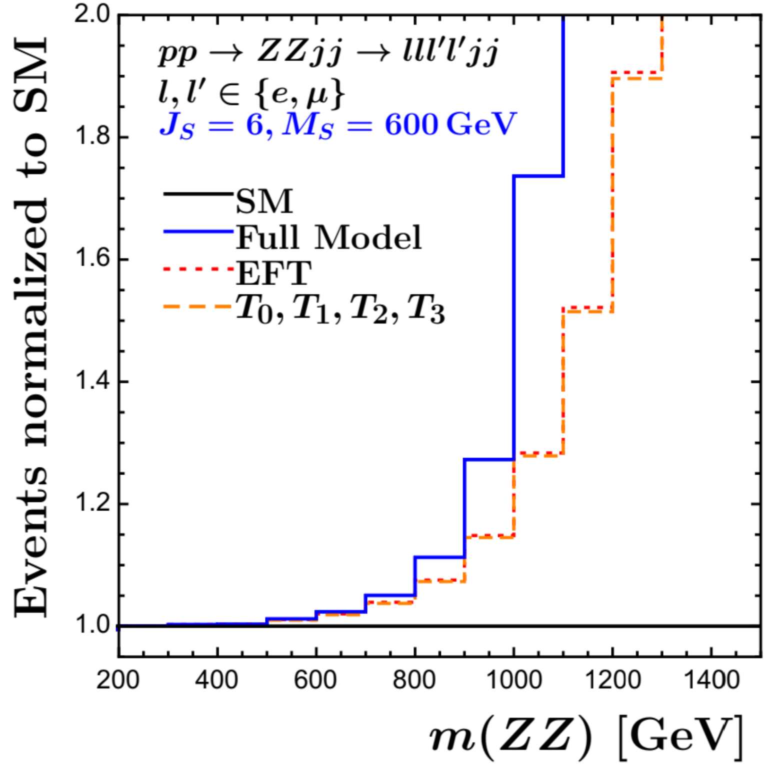
Constraints from experiment:

Deviation in Drell-Yan cross section, normalized to SM expectation (1- and 2-σ error bands adapted from CMS: arXiv:2103.02708)

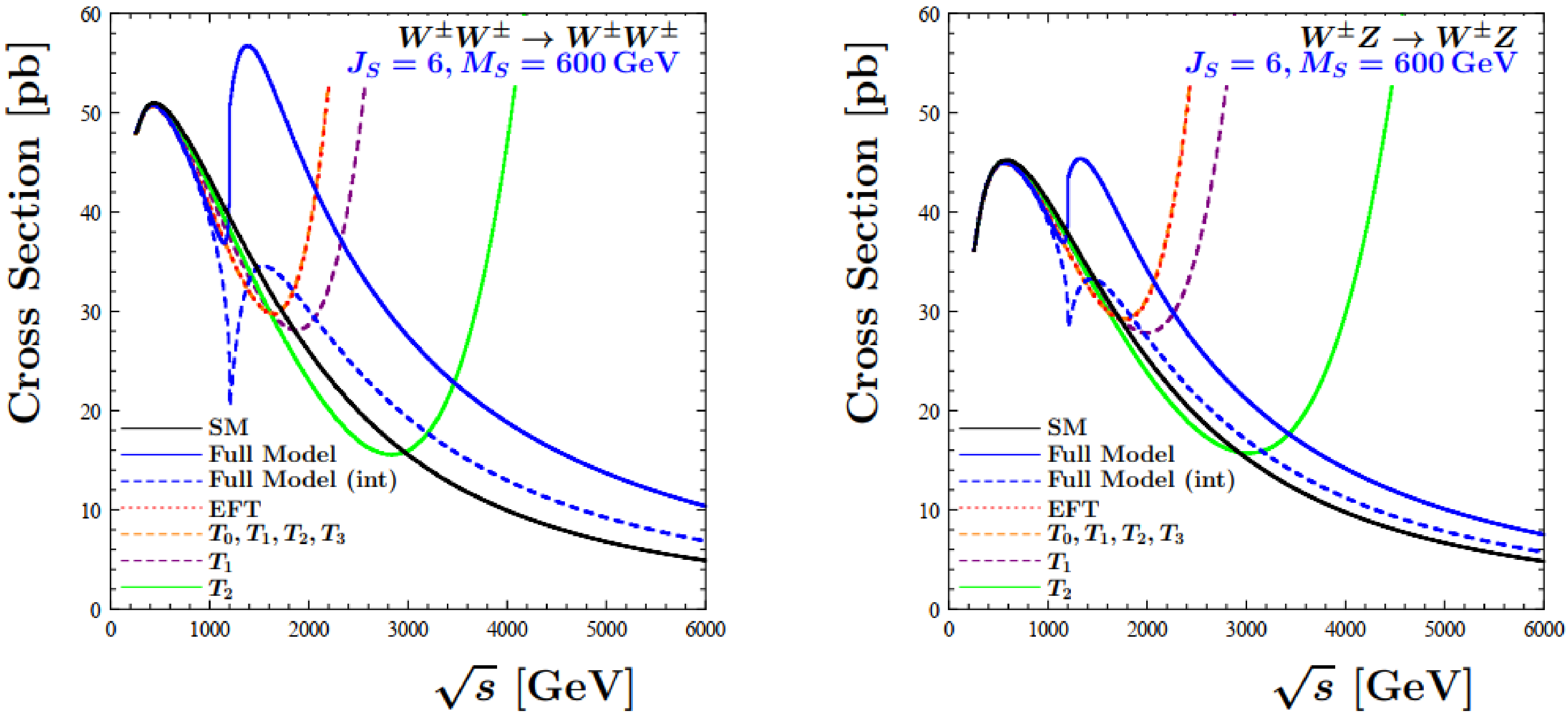


EFT validity range for ZZ production in VBS

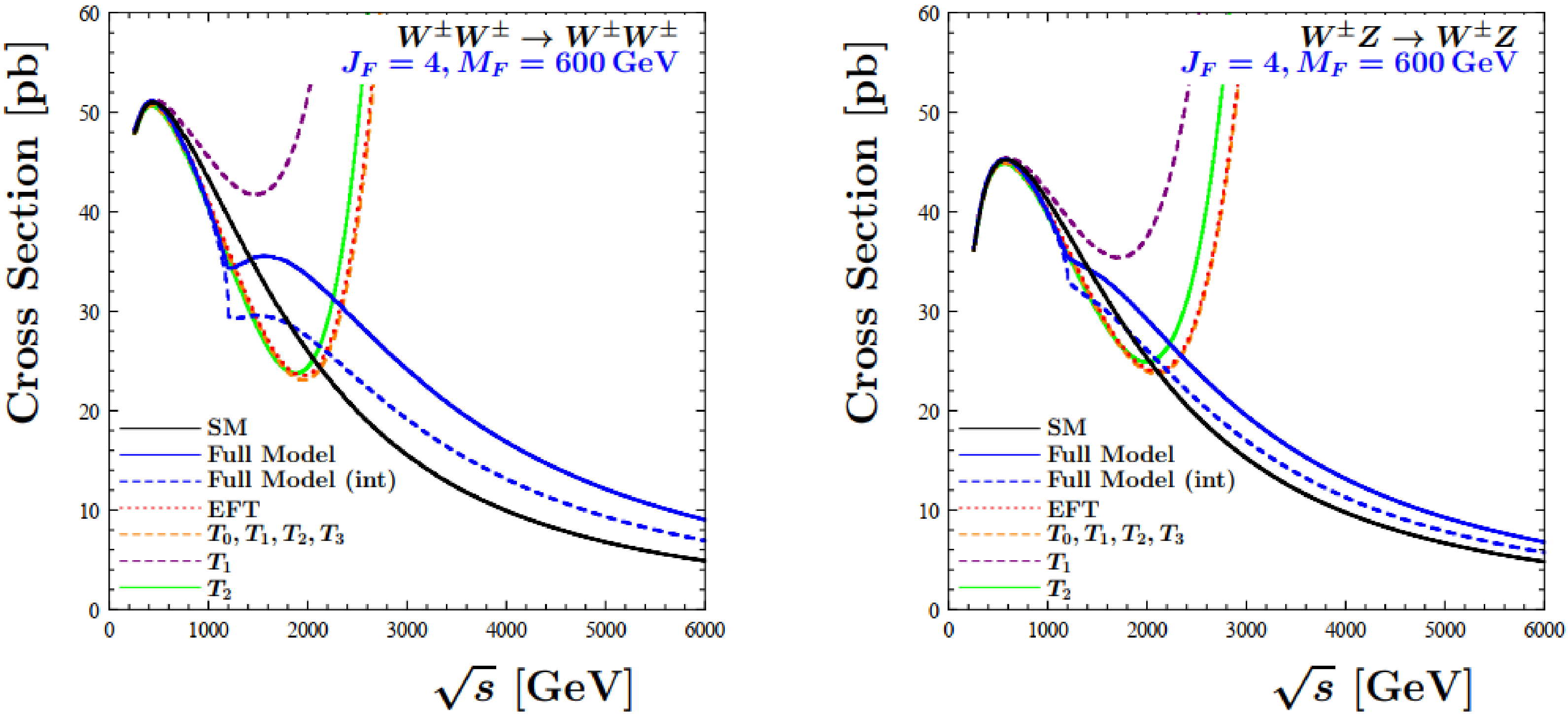




- EFT is valid only well below threshold at 2 M_S =1200 GeV (as expected)
- Deviations from SM barely reach 10% within EFT validity range, even for J_S= 6
- Because of J_R^5 vs J_R^3 growth, dim-8 terms are much more important than dim-6



$W^\pm W^\pm \to W^\pm W^\pm$
$J_S = 6, M_S = 600\,\text{GeV}$
Cross Section [pb]
$\sqrt{s}$ [GeV]
SM
Full Model
Full Model (int)
EFT
T_0, T_1, T_2, T_3
T_1
T_2
$W^\pm Z \to W^\pm Z$
$J_S = 6, M_S = 600\,\text{GeV}$
Cross Section [pb]
$\sqrt{s}$ [GeV]
SM
Full Model
Full Model (int)
EFT
T_0, T_1, T_2, T_3
T_1
T_2


$W^\pm W^\pm \to W^\pm W^\pm$
$J_F = 4, M_F = 600$ GeV
Cross Section [pb]
$\sqrt{s}$ [GeV]
SM
Full Model
Full Model (int)
EFT
T_0, T_1, T_2, T_3
T_1
T_2
$W^\pm Z \to W^\pm Z$
$J_F = 4, M_F = 600$ GeV
Cross Section [pb]
$\sqrt{s}$ [GeV]
SM
Full Model
Full Model (int)
EFT
T_0, T_1, T_2, T_3
T_1
T_2

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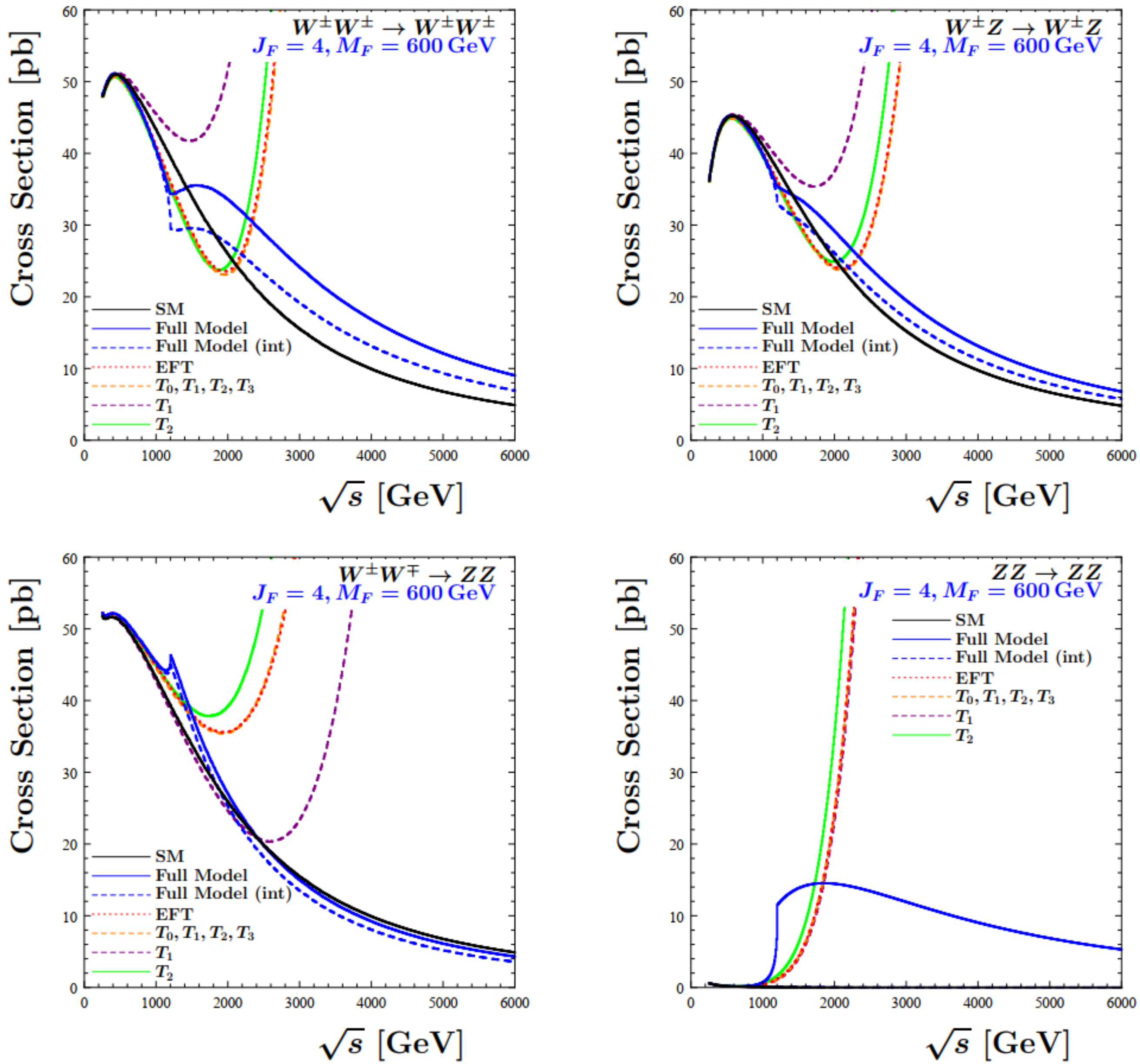
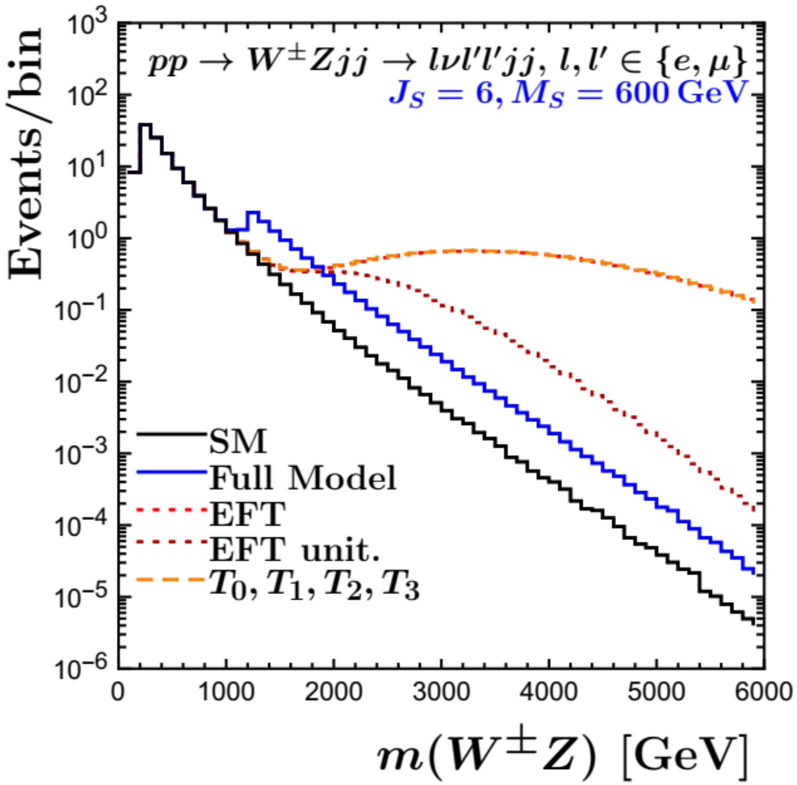
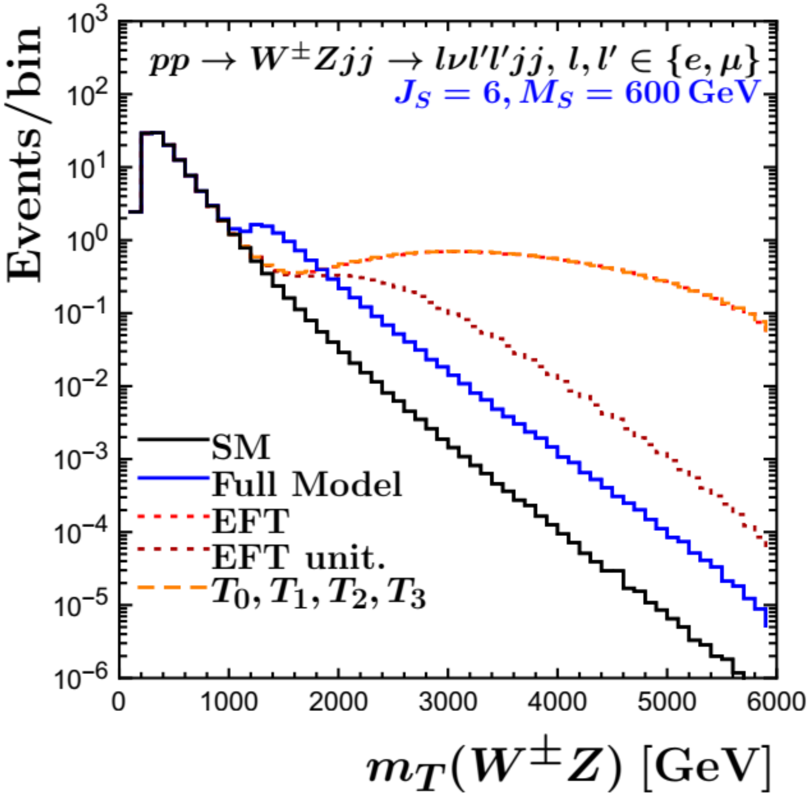
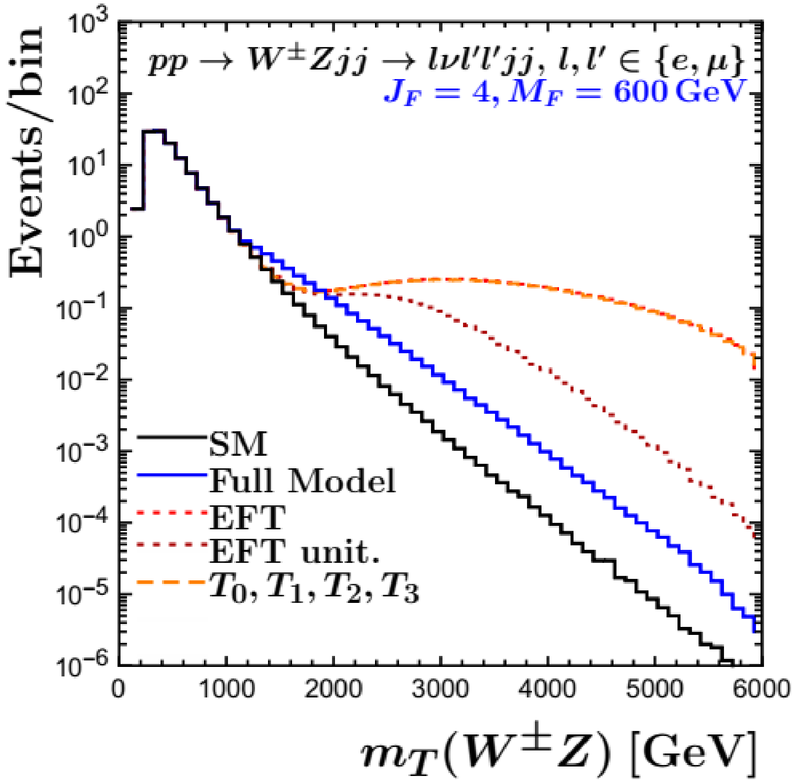


Onshell cross sections

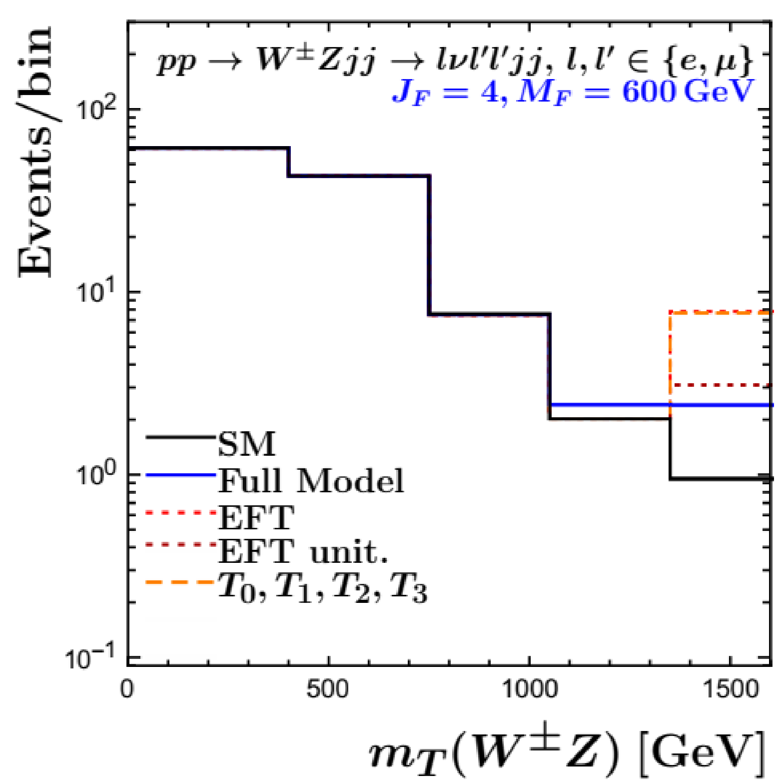
Diboson mass vs transverse mass



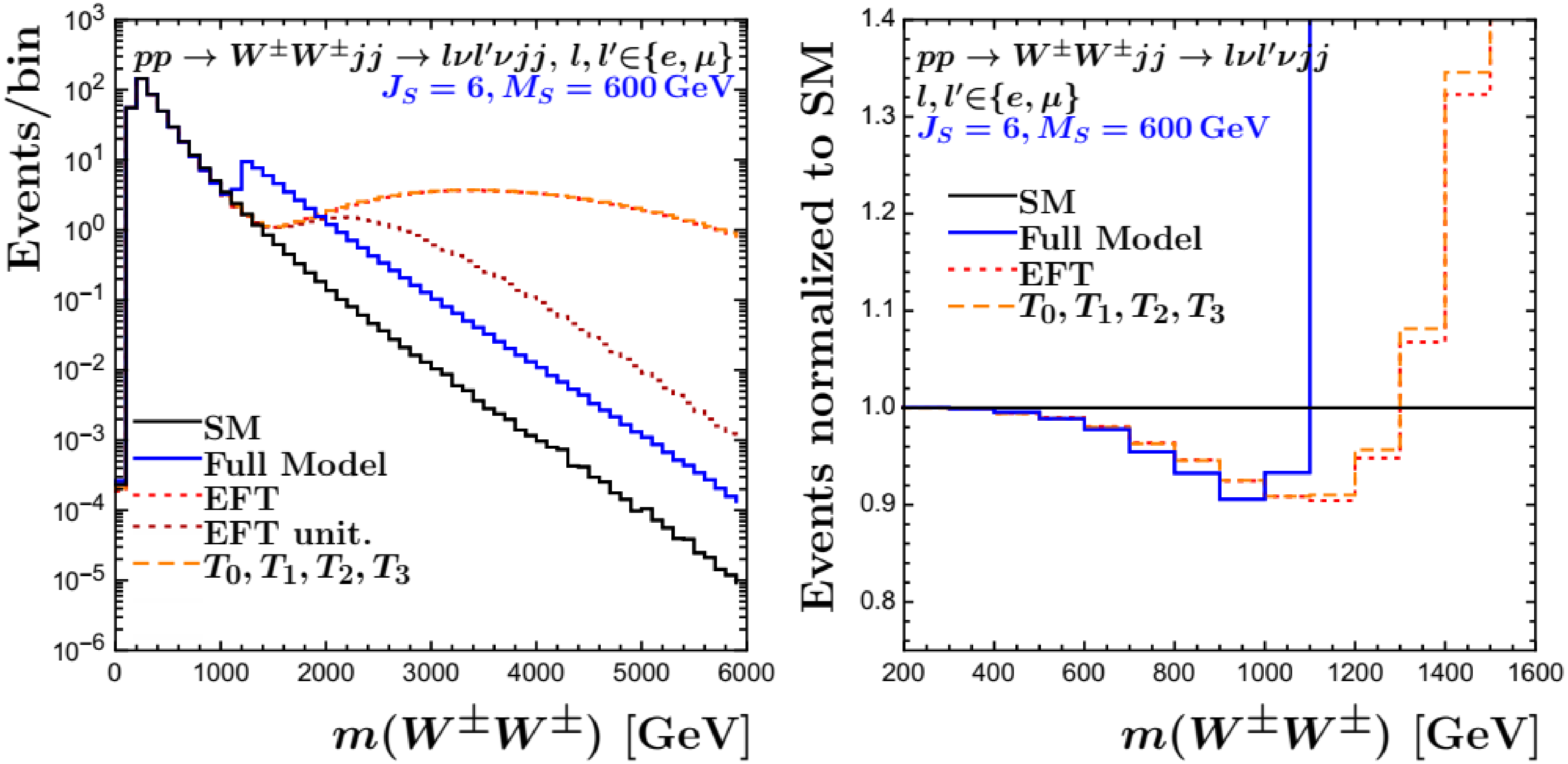




$pp \to W^\pm Zjj \to l\nu l'l'jj,\ l,l' \in \{e,\mu\}$
$J_F = 4, M_F = 600\,\mathrm{GeV}$
Events/bin
SM
Full Model
EFT
EFT unit.
T_0, T_1, T_2, T_3
$m_T(W^\pm Z)$ [GeV]



$pp \to W^\pm Zjj \to l\nu l'l'jj,\ l,l' \in \{e,\mu\}$
$J_F = 4, M_F = 600\,\mathrm{GeV}$
Events/bin
SM
Full Model
EFT
EFT unit.
T_0, T_1, T_2, T_3
$m_T(W^\pm Z)$ [GeV]

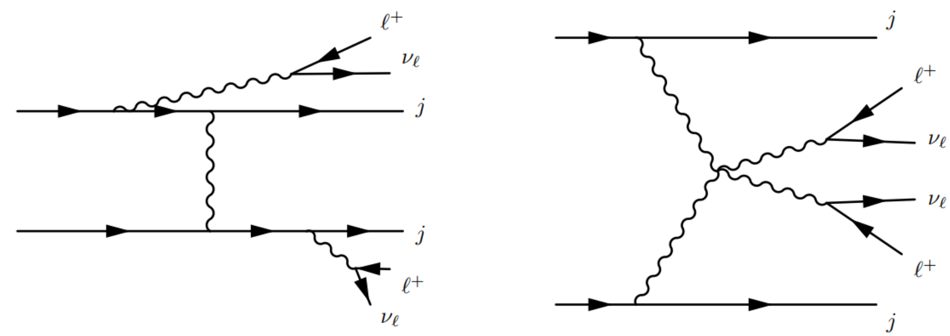

Events/bin
$pp \to W^\pm W^\pm jj \to l\nu l'\nu jj,\ l, l' \in \{e, \mu\}$
$J_S = 6, M_S = 600$ GeV
SM
Full Model
EFT
EFT unit.
T_0, T_1, T_2, T_3
$m(W^\pm W^\pm)$ [GeV]
Events normalized to SM
$pp \to W^\pm W^\pm jj \to l\nu l'\nu jj$
$l, l' \in \{e, \mu\}$
$J_S = 6, M_S = 600$ GeV
SM
Full Model
EFT
T_0, T_1, T_2, T_3
$m(W^\pm W^\pm)$ [GeV]

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 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

$$\begin{aligned}D^{\mu\nu}_V(q) &= \frac{-\mathrm{i}}{q^2 - m_V^2 + i\,m_V\,\Gamma_V}\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)\\ &\equiv \frac{-\mathrm{i}}{q^2 - m_V^2 + i\,m_V\,\Gamma_V}\sum_\lambda \epsilon^{*\mu}_J(q,\lambda)\epsilon^{\nu}_{\mathcal{M}}(q,\lambda)\end{aligned}$$

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

Relative importance of terms (thesis Jannis Lang)

$\mathcal{M}_i$	$2\mathrm{Re}\,(\mathcal{M}_{SM}\mathcal{M}_i)$	$\frac{s}{\Lambda^2} \to [\frac{(2m_W)^2}{M_F^2}, 1]$	$\lvert\mathcal{M}_i\rvert^2$	$\frac{s}{\Lambda^2} \to [\frac{(2m_W)^2}{M_F^2}, 1]$
$\mathcal{M}_{f_{WWW}}$	$\frac{g^2}{16\pi^2}\frac{s}{\Lambda^2}J_R^3$	$[0.01616, 0.34481]$	$\left(\frac{g^2}{16\pi^2}\right)^2\frac{s^2}{\Lambda^4}J_R^6$	$[0.00026, 0.11889]$
$\mathcal{M}_{f_{T_i}}$	$\frac{g^2}{16\pi^2}\frac{s^2}{\Lambda^4}J_R^5$	$[0.01893, 8.62022]$	$\left(\frac{g^2}{16\pi^2}\right)^2\frac{s^4}{\Lambda^8}J_R^{10}$	$[0.00036, 74.3081]$
$\mathcal{M}_{f_{WWW}^2}$	$\left(\frac{g^2}{16\pi^2}\right)^2\frac{s^2}{\Lambda^4}J_R^6$	$[0.00026, 0.11889]$	$\left(\frac{g^2}{16\pi^2}\right)^4\frac{s^4}{\Lambda^8}J_R^{12}$	$[6.8 \cdot 10^{-8}, 0.01414]$
$\mathcal{M}_{SM}^{NLO}$	$\frac{g^2}{16\pi^2}$	$[0.00276, 0.00276]$	$\left(\frac{g^2}{16\pi^2}\right)^2$	$[7.6 \cdot 10^{-6}, 7.6 \cdot 10^{-6}]$
$\mathcal{M}_{f_{WWW}}^{NLO}$	$\left(\frac{g^2}{16\pi^2}\right)^2\frac{s}{\Lambda^2}J_R^3$	$[0.00004, 0.00095]$	$\left(\frac{g^2}{16\pi^2}\right)^4\frac{s^2}{\Lambda^4}J_R^6$	$[2.0 \cdot 10^{-9}, 9.0 \cdot 10^{-7}]$
$\mathcal{M}_{f_{T_i}}^{NLO}$	$\left(\frac{g^2}{16\pi^2}\right)^2\frac{s^2}{\Lambda^4}J_R^5$	$[0.00005, 0.02378]$	$\left(\frac{g^2}{16\pi^2}\right)^4\frac{s^4}{\Lambda^8}J_R^{10}$	$[2.7 \cdot 10^{-9}, 0.00057]$

Table 5.1.: Counting of additional factors in EFT perturbative expansion of the cross section arising from one-loop calculation/matching (factor $\frac{g^2}{16\pi^2}$) and EFT expansion (factor $\frac{s}{\Lambda^2}$). The powers of isospin J_R follow from the representation factor of the NP fields, leading to an enhanced coupling and, therefore, enhanced contribution to the cross section. The explicit values are estimated for $g = 0.66$, $J_R = J_F = 5$, $\Lambda = M_F = 750\,\mathrm{GeV}$ and the estimated limits of the EFT validity region given by the kinematic threshold $s = (2m_W)^2$ as lower bound and the NP energy scale Λ as higher bound.