Effective field theory versus UV-complete models in VBS

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Talk based on arXiv 2103.16517

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Effective field theory versus UV-complete model: vector boson scattering as a case study

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Abstract

Effective field theories (EFT) are commonly used to parameterize effects of BSM physics in vector boson scattering (VBS). For Wilson coefficients which are large enough to produce presently observable effects, the validity range of the EFT represents only a fraction of the energy range covered by the LHC, however. In order to shed light on possible extrapolations

EFT operators for VBS

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

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

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

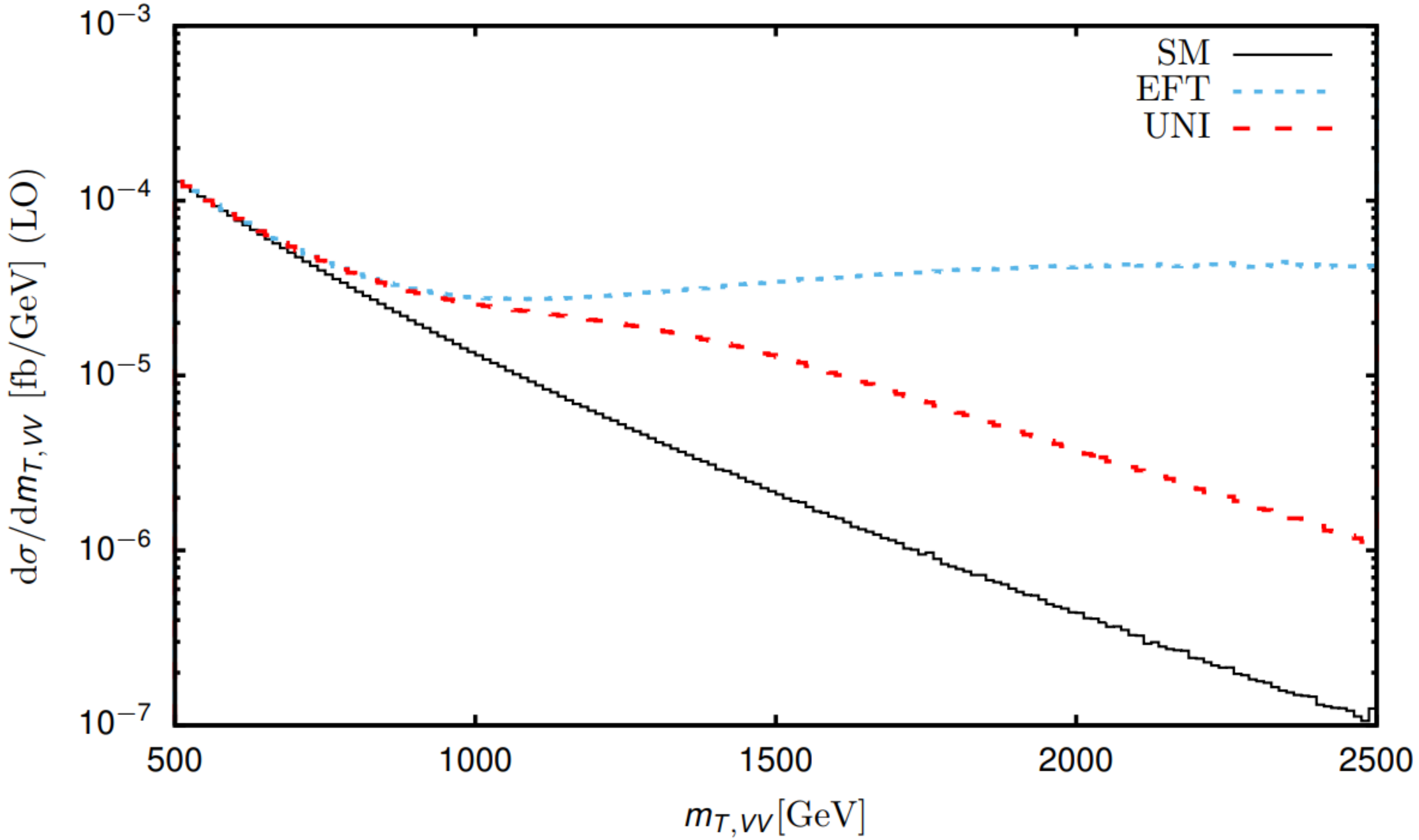
$$+ \frac{f_{M_0}}{\Lambda^4} \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\, \widehat{W}^{\mu\nu}\right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right] + \ldots$$

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

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

Example: dim-8 effects with/out unitarization

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



Many open questions

- How realistic is EFT description (with or without unitarization) as a function of energy (m_{VV})?
- What is the validity range of the EFT?
- 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

- arXiv 2103.16517 considers transverse operators as simplest case: dimension 6 and 8 operators constructed with SU(2) field strength, no Higgs
- 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 must be renormalizable and should be perturbatively treatable
- At our disposal: gauge theory with extra scalars, fermions, and gauge fields

The model(s)

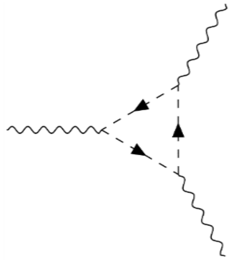
- n_R SU(2) multiplets of isospin J_R of scalars (R=S) or Dirac fermions (R=F) with their SU(2) gauge interactions (no hypercharge couplings)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu H)^2 - \frac{m_H^2}{2} H^2 - \frac{1}{2}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right) + \frac{m_W^2}{2}\left(\sum_{a=1}^{3} W_\mu^a W^{a\mu}\right)\left(1+\frac{H}{v}\right)^2$$

$$+ \bar{\Psi}\left(i\gamma_\mu D^\mu - M_F\right)\Psi + (D^\mu\Phi)^\dagger(D_\mu\Phi) - {M_S}^2\Phi^\dagger\Phi\,.$$

- Yukawa couplings of fermions to Higgs doublet absent if no fermion multiplets with $J_F \pm ½$ 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
- Refinements like extra (confining) gauge interactions, several multiplets, hypercharge contributions keep our results as LO approximation
  → very generic class of models

Matching of 1-loop results to EFT operators with field strength tensors

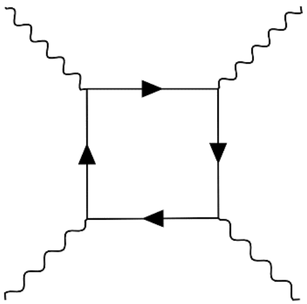


Massive BSM matter fields in isospin J_R multiplets induce EFT operators like

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

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

$\sim \; T_R = \frac{1}{3}\left[J_R(J_R+1)(2J_R+1)\right]$



and also anomalous quartic gauge couplings (aQGC), like

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

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

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

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

$\sim C_{2,R}\, T_R$

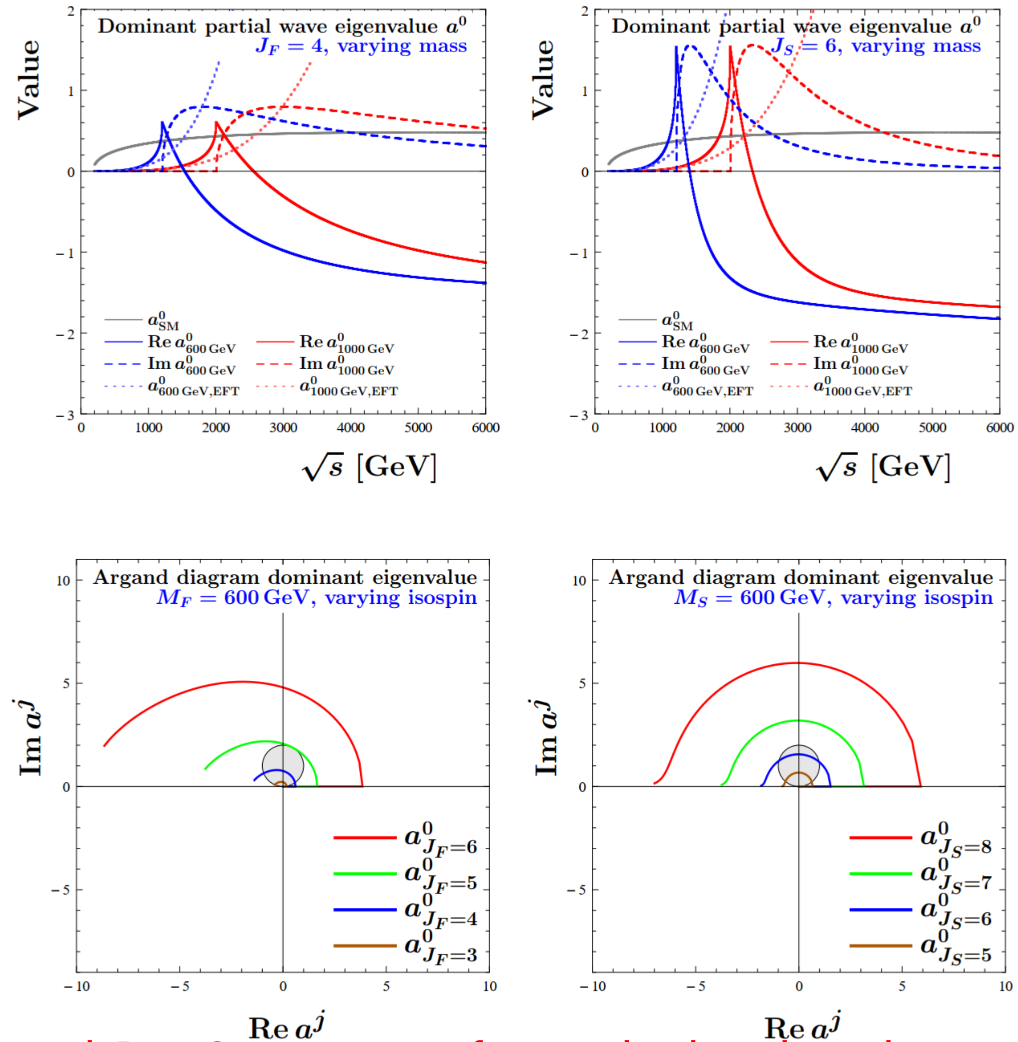
- Loop suppressed, but $(J_R)^3$ enhanced for trilinear couplings, $(J_R)^5$ for aQGC
- Find Wilson coefficients, e.g.

$$\frac{f_{WWW}}{\Lambda^2} = \sum_F n_F \frac{13 T_F}{360\pi^2 M_F^2} + \sum_S n_S \frac{T_S}{360\pi^2 M_S^2}$$

$$\frac{f_{T_1}}{\Lambda^4} = \sum_F n_F \frac{(-28 C_{2,F} + 13)\, T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(14 C_{2,S} - 5)\, T_S}{40320\pi^2 M_S^4}$$

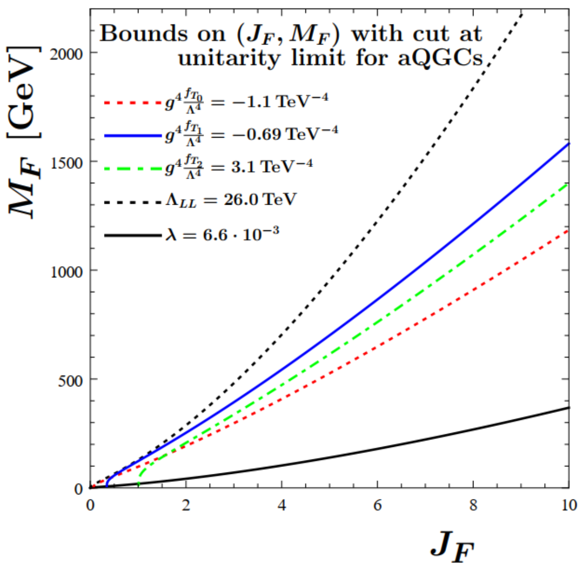
Unitarity considerations for VBS

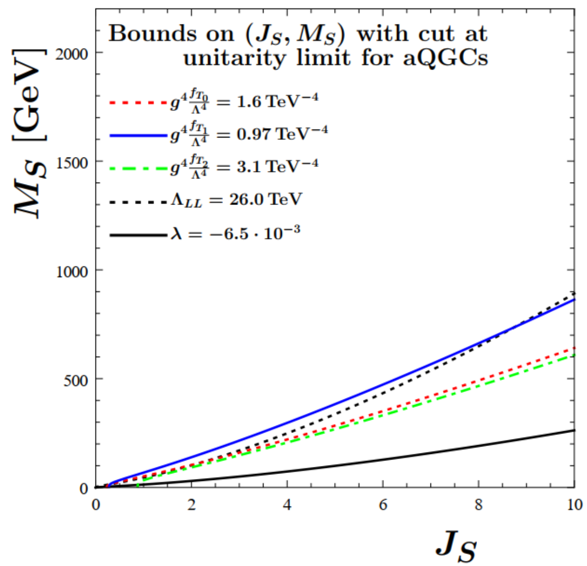
- Energy dependence of dominant VBS partial wave amplitude
- At large J_R, model becomes non-perturbative



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

Constraints from experiment:



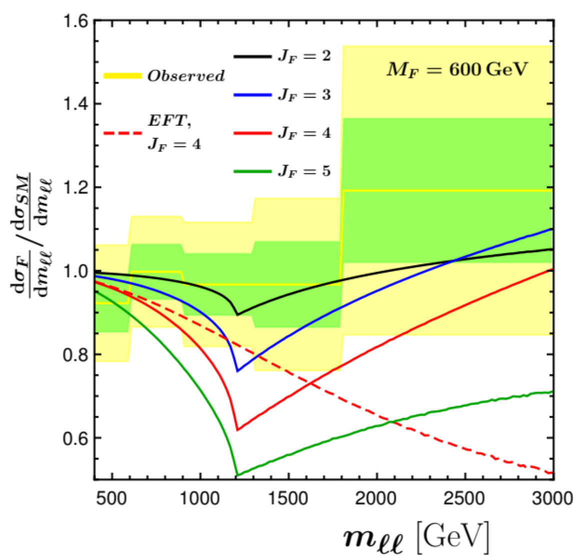


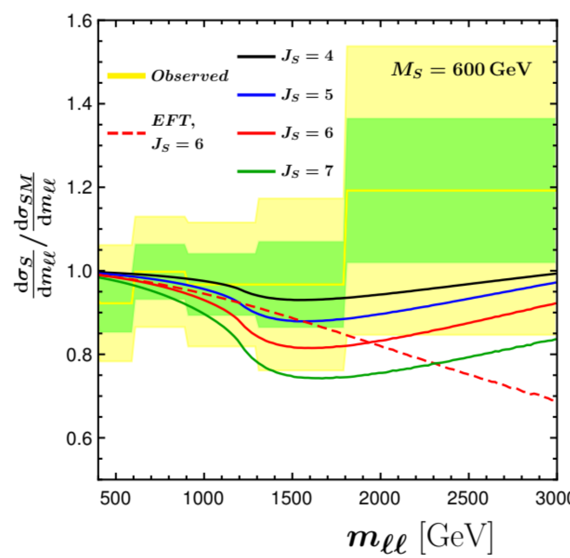
limits on individual Wilson coefficients:

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)





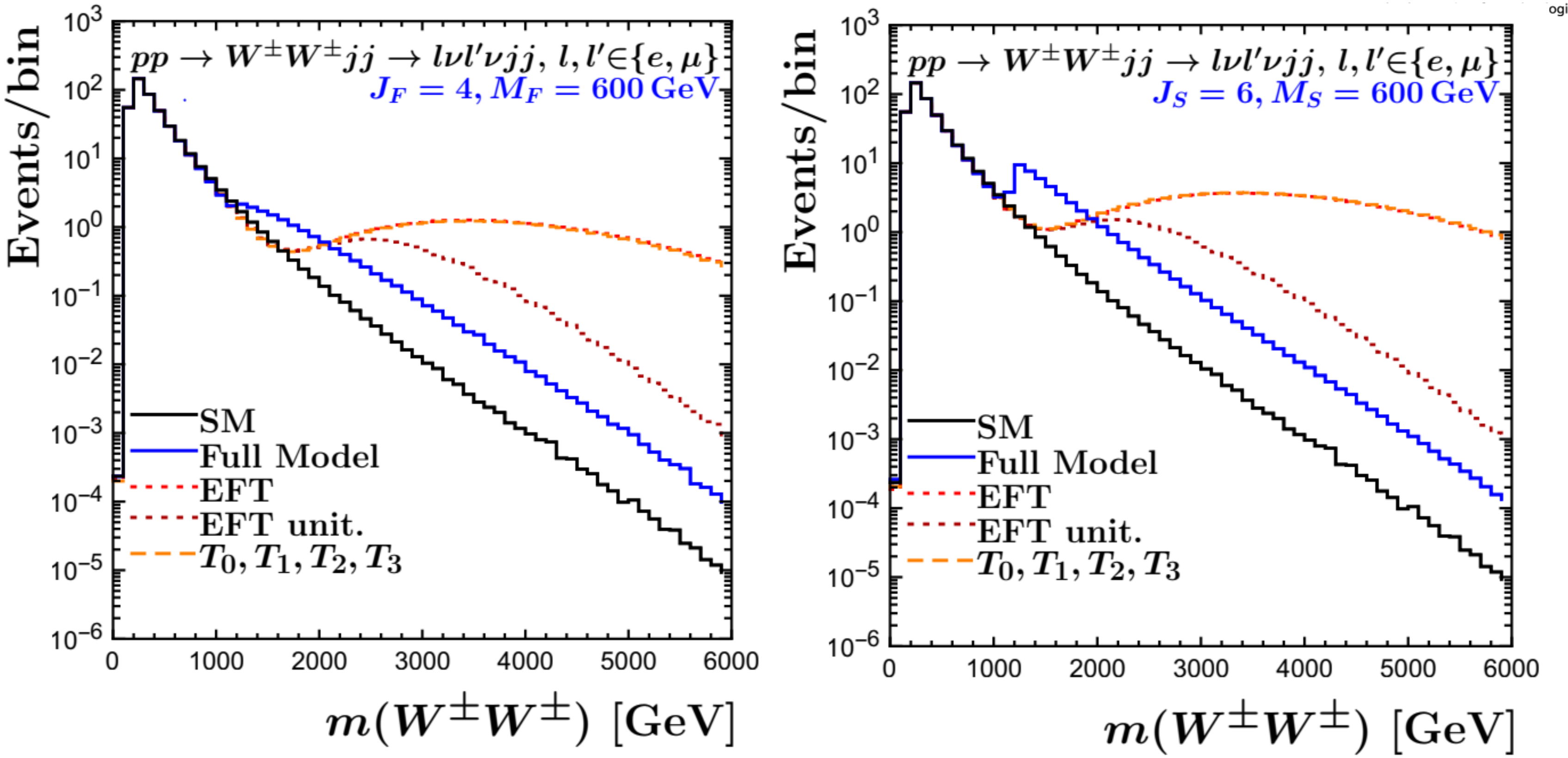
Parameter choices:

- 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

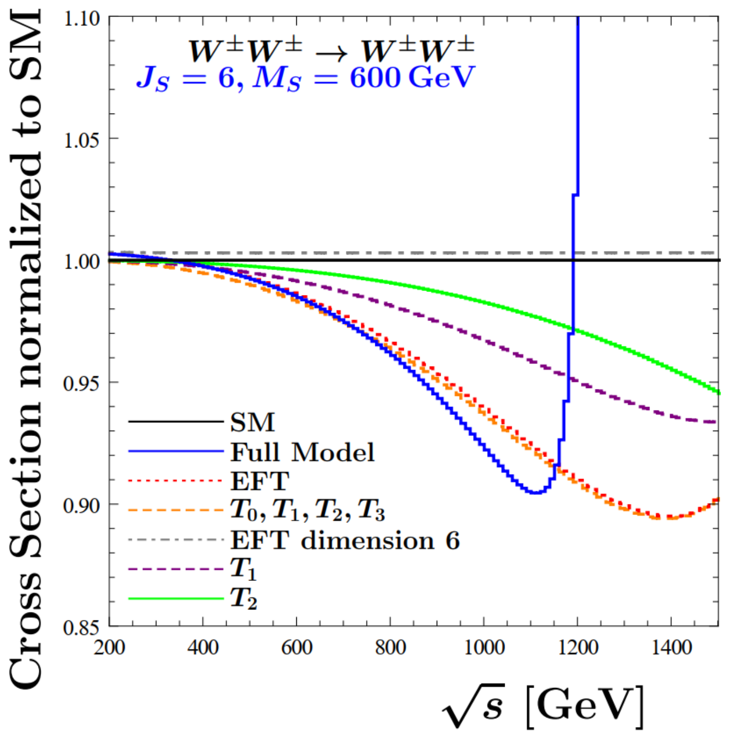
Comparison for LHC: full model – EFT – unitarized EFT

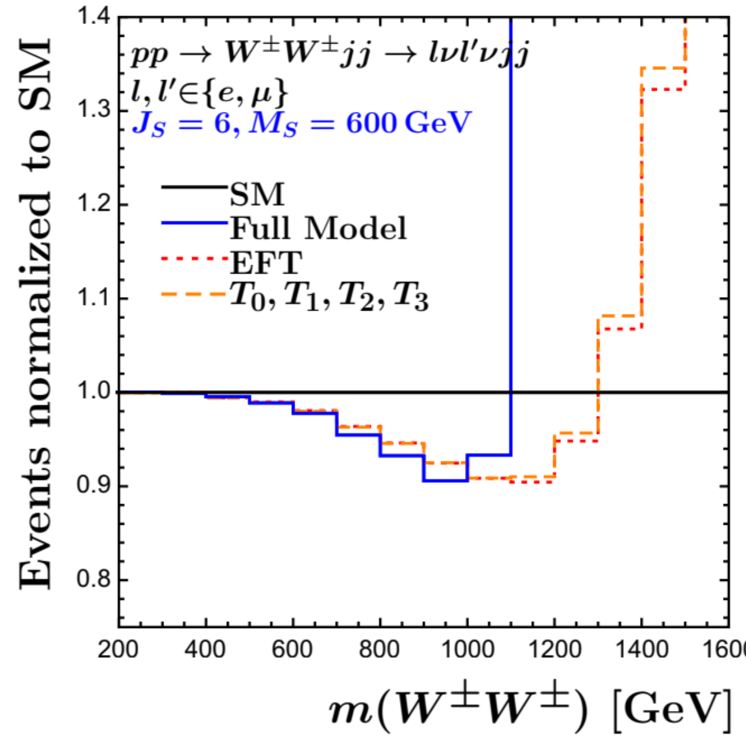


- Bad news: Violent disagreement between full model and EFT approximation
- Good news: Sizable effects are possible at modest invariant mass

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

EFT validity range





- EFT is valid only well below threshold at $2M_S$ =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

Conclusions

- Extra SU(2) scalar or fermion multiplets can generate sizable loop effects in VBS
- This requires very high multiplicity of BSM fields, like SU(2) nonets (quintets may do): rarely expected in BSM models
- Model is generic: any EFT BSM effects with W field strength require loops with additional SU(2) multiplets
- Further complexity does not change basic result, e.g.
  - Additional confining gauge interaction of multiplets averages 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:
  - qq $\rightarrow$VV is not as sensitive due to mere J_R^3 growth
  - 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

Thank you!

Backup

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 …

$$O_{DWW_0} = \mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu}{}_{\nu}][\hat{D}^\alpha, \hat{W}^{\nu}{}_{\rho}]\hat{W}^{\rho}{}_{\mu}\right)$$

$$O_{DWW_1} = \mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}_\beta, \hat{W}_{\mu\nu}]\hat{W}^{\alpha\beta}\right)$$

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

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- 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

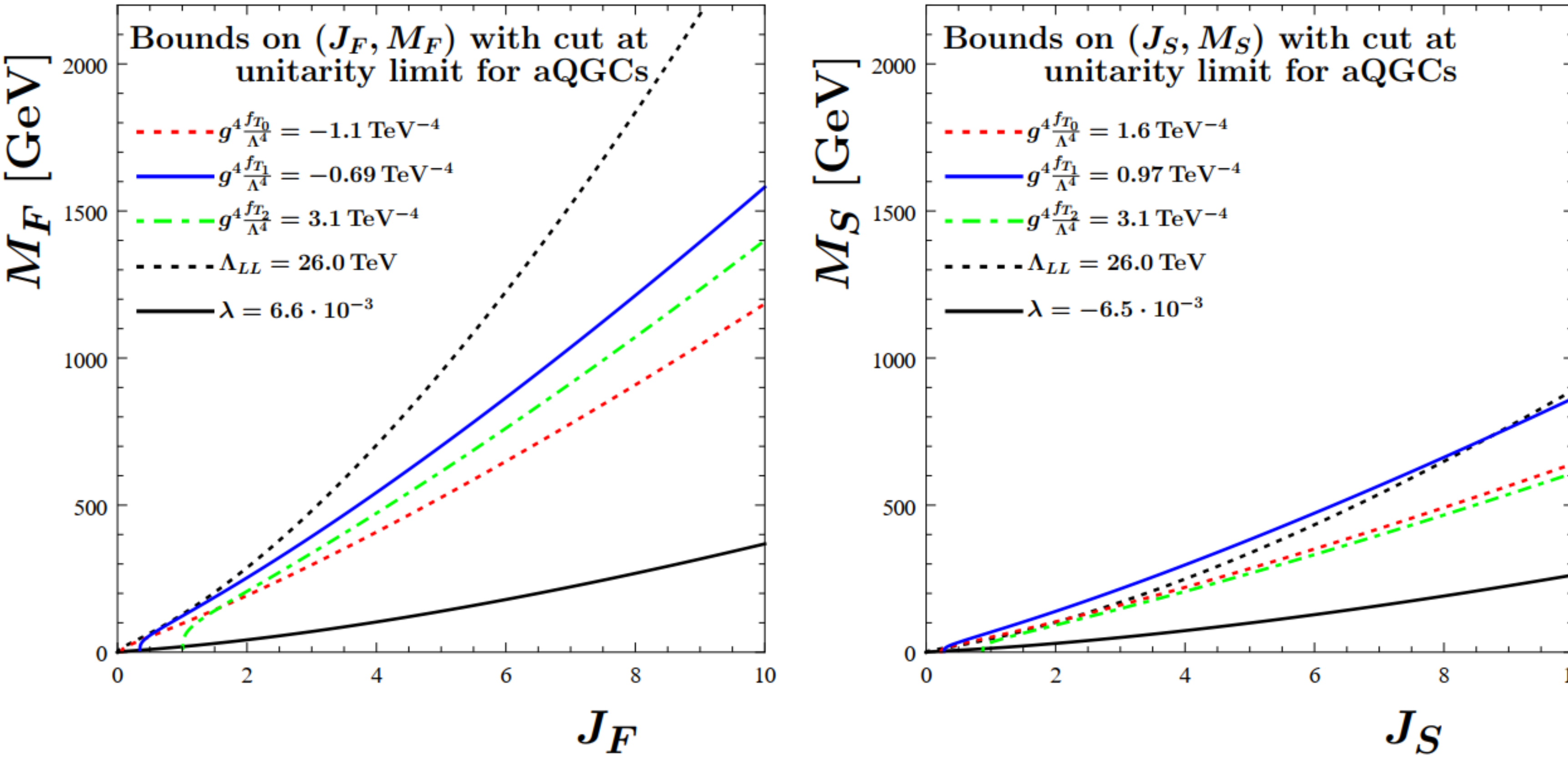
$$\frac{f_{T_0}}{\Lambda^4} = \sum_F n_F \frac{(-14C_{2,F}+1)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}-2)\,T_S}{40320\pi^2 M_S^4},$$

$$\frac{f_{T_1}}{\Lambda^4} = \sum_F n_F \frac{(-28C_{2,F}+13)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(14C_{2,S}-5)\,T_S}{40320\pi^2 M_S^4},$$

$$\frac{f_{T_2}}{\Lambda^4} = \sum_F n_F \frac{(196C_{2,F}-397)\,T_F}{25200\pi^2 M_F^4} + \sum_S n_S \frac{(14C_{2,S}-23)\,T_S}{50400\pi^2 M_S^4},$$

$$\frac{f_{T_3}}{\Lambda^4} = \sum_F n_F \frac{(98C_{2,F}+299)\,T_F}{25200\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}+16)\,T_S}{50400\pi^2 M_S^4}.$$

Constraints from experiment: limits on individual Wilson coefficients



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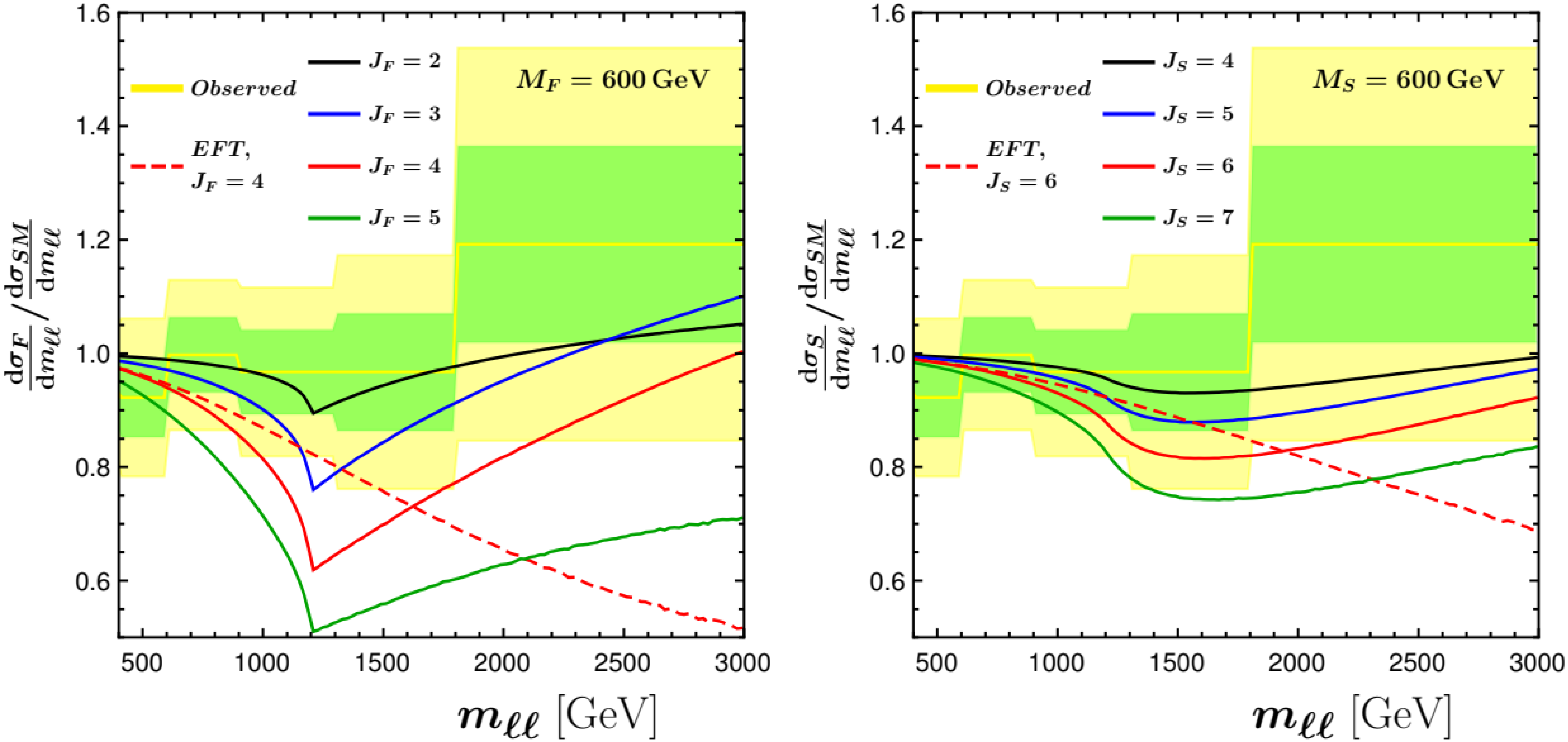
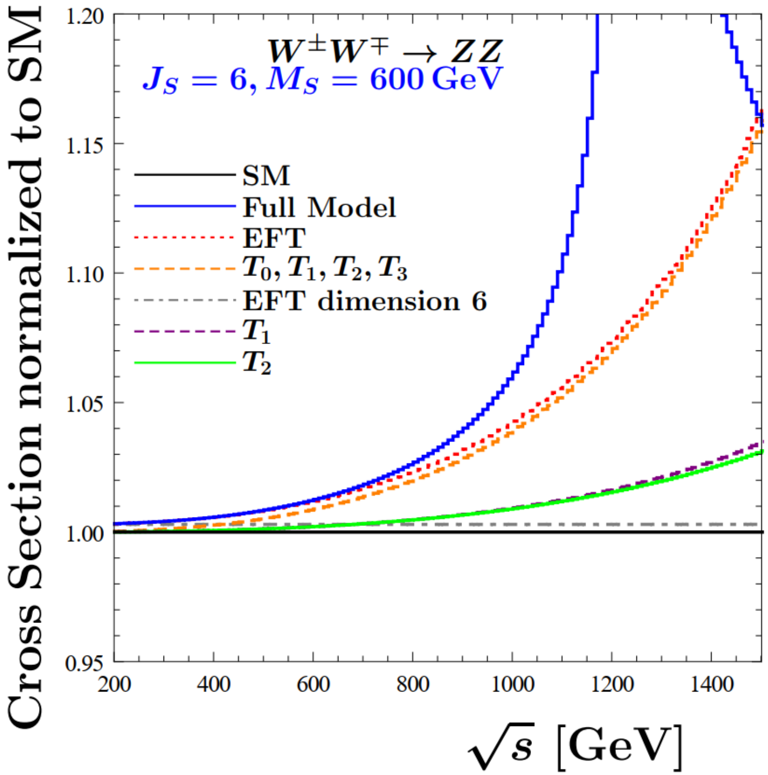
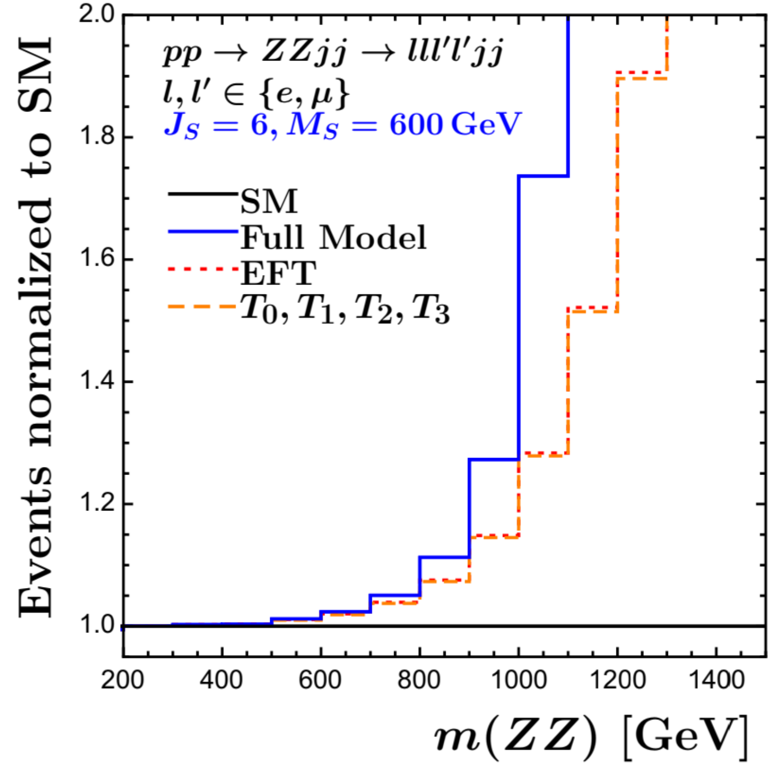
Deviation in Drell-Yan cross section, normalized to SM expectation (1- and 2-σ error bands adapted from CMS: arXiv:2103.02708)



EFT validity range for ZZ production in VBS





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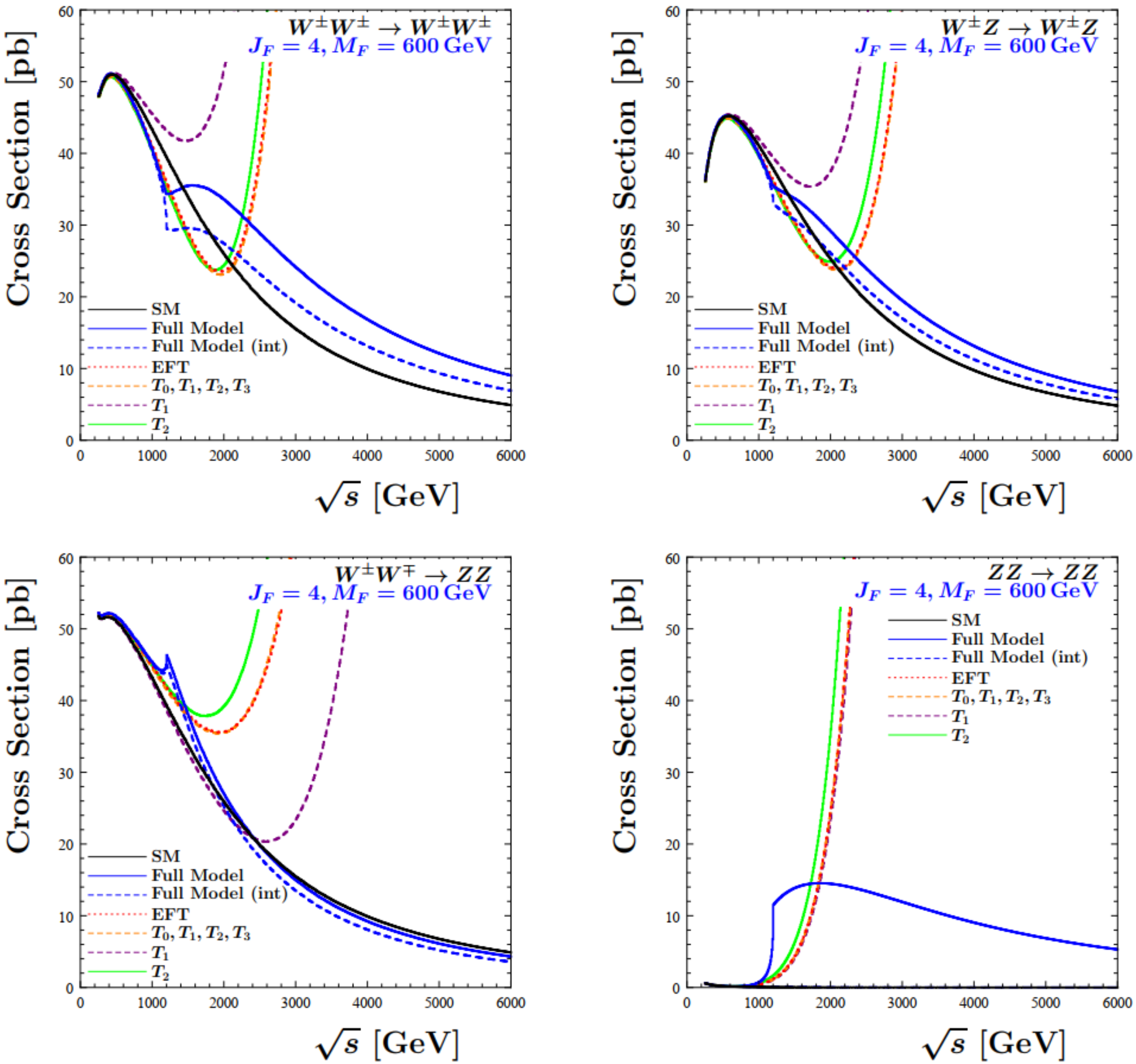
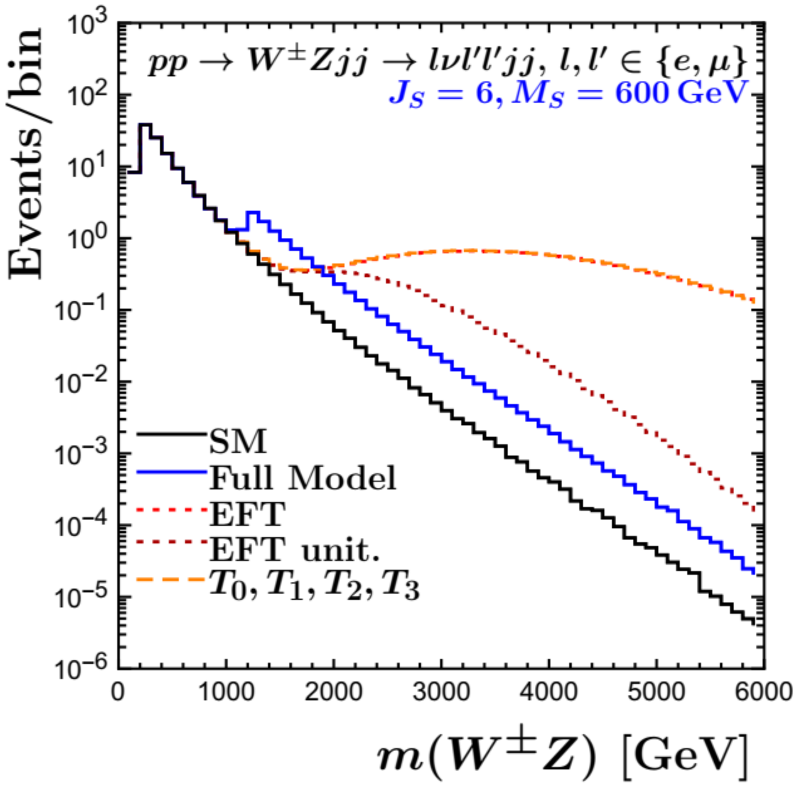
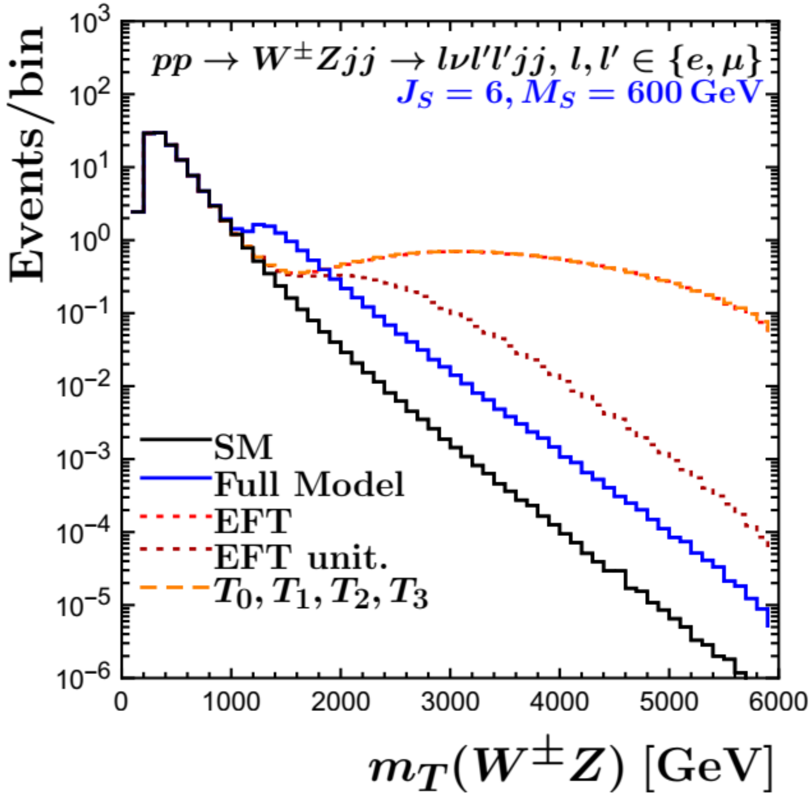


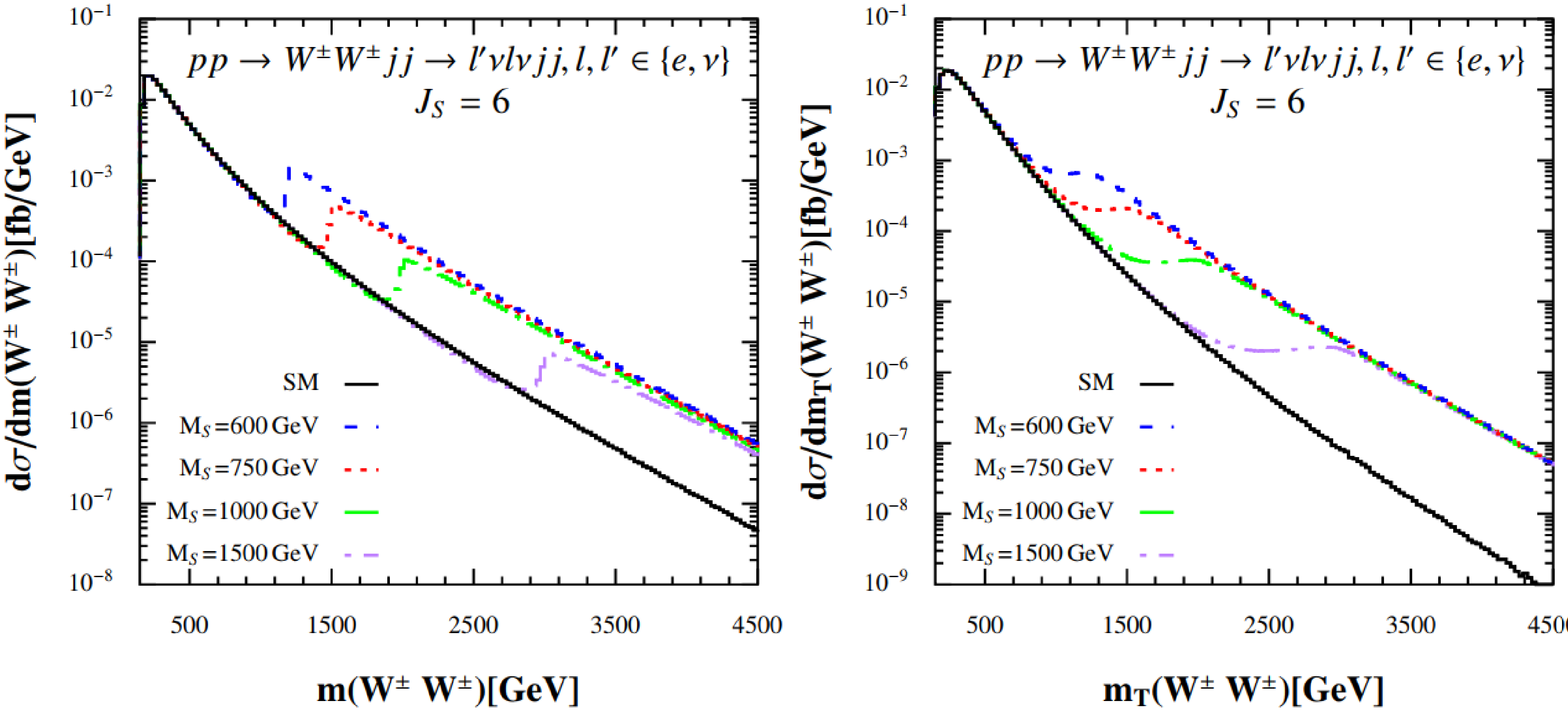
Onshell cross sections

Diboson mass vs transverse mass

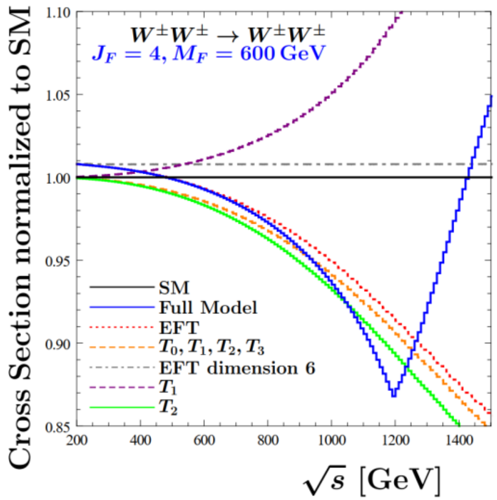




Dependence on multiplet mass

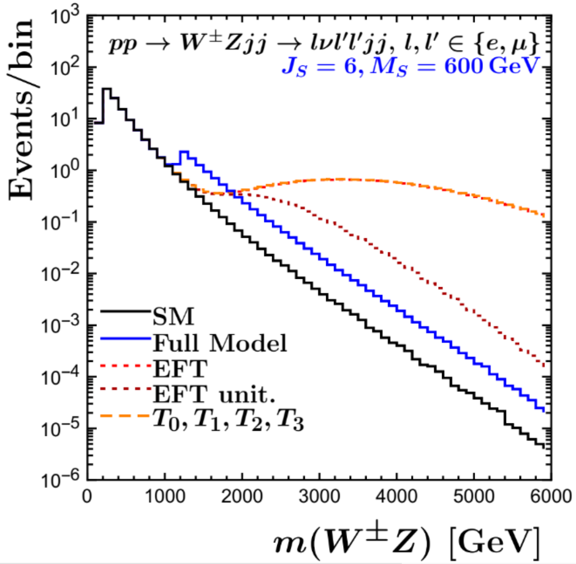


Problem: Validity range of EFT restricted to <1.5 M_R



←Cross section for on-shell WW scattering below threshold (taken as $2M_F$=1200 GeV)

EFT effects below 10% within EFT validity range, even for SU(2) nonents



←Full VBFNLO simulation:

Large effects of extra multiplets are possible above threshold where

- EFT does not describe new physics
- Unitarization does only slightly better, but reduces huge to merely sizable overestimate of cross section