EFT versus UV complete models for VBS

Dieter Zeppenfeld (KIT)

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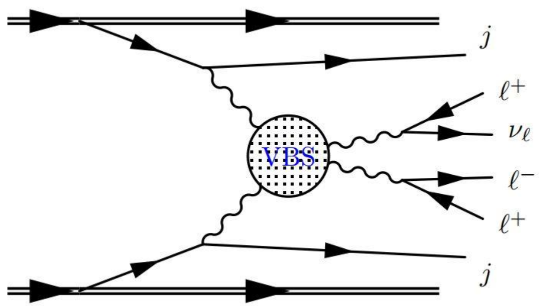
Based on arXiv 2103.16517
(in collaboration with Jannis Lang, Stefan Liebler, and Heiko Schäfer-Siebert)

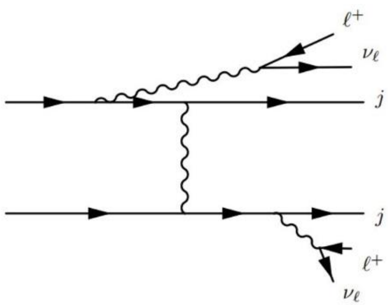
KIT Center Elementary Particle and Astroparticle Physics - KCETA

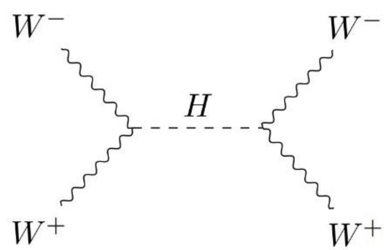
VBS and anomalous quartic gauge couplings (aQGC)

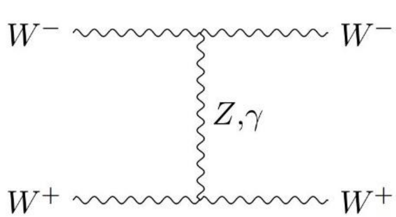


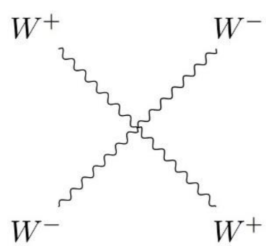
VBS provides rich source of information on dynamics of electroweak gauge bosons and EW symmetry breaking

Signature is VVjj final state with well separated tagging jets: simulate with VBFNLO









Contributions from

- EW radiation
- Higgs exchange

- Triple gauge couplings
- Quartic gauge couplings

Use EFT to describe them

EFT operators for VBS

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

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

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

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

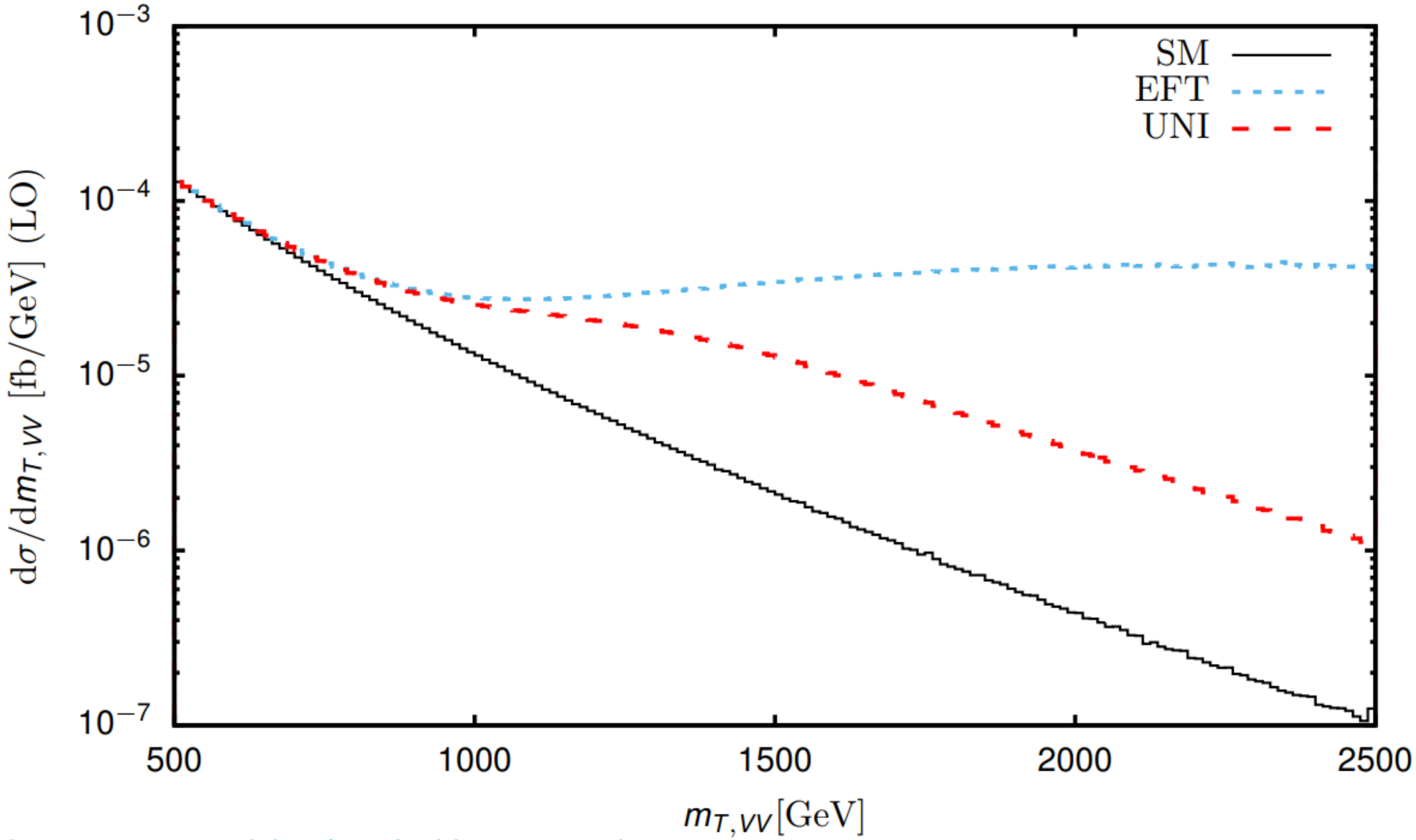
$$+ \frac{f_{S_0}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] + \ldots .$$

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

Problem: unitarity violation within LHC energy range

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

The model(s)

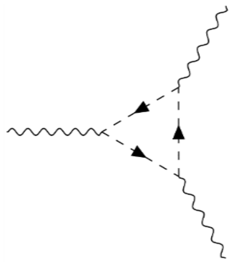
- n_R SU(2) multiplets of isospin J_R of scalars (R=S) or Dirac fermions (R=F) with their SU(2) gauge interactions (no hypercharge couplings)

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

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

- Yukawa couplings of fermions to Higgs doublet absent if no fermion multiplets with J_F ±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 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

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

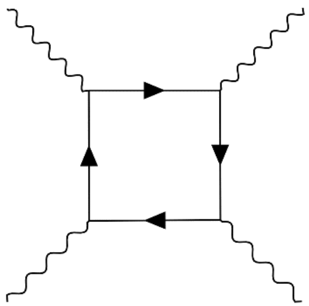


Massive BSM matter fields in isospin J_R multiplets induce EFT operators like

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

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

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



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 limit size of isospin representations

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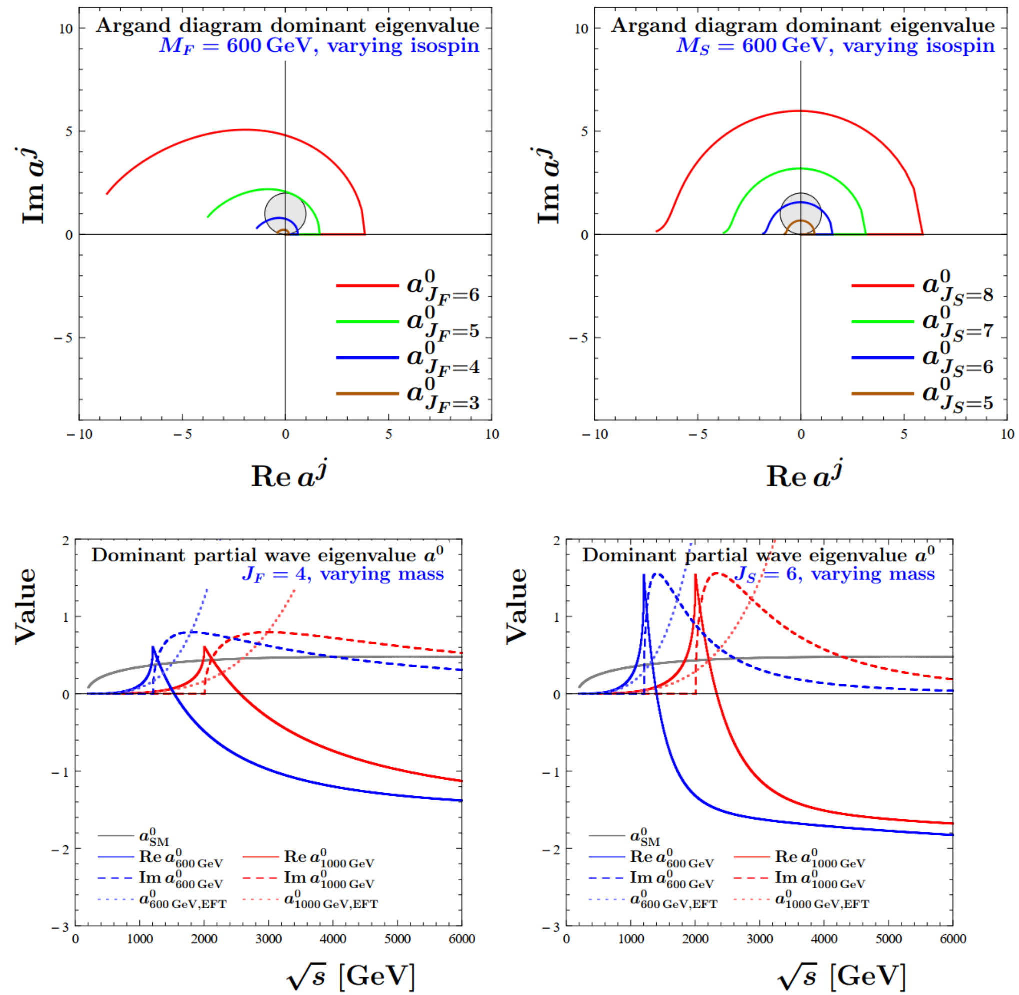
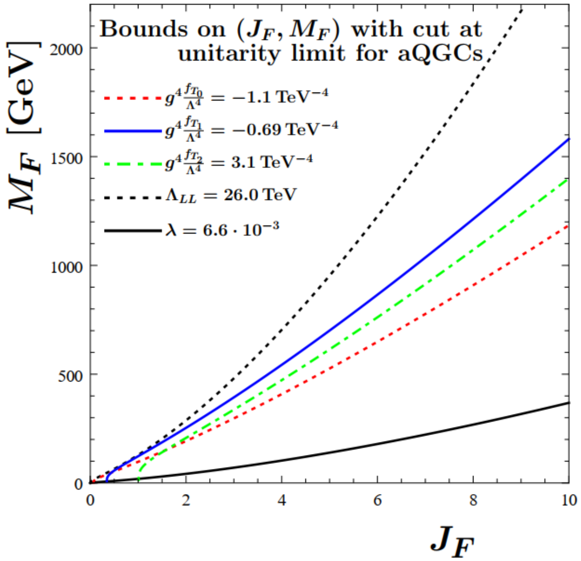
- Argand diagram for dominant VV→VV partial wave amplitude: At large J_R, model becomes non-perturbative

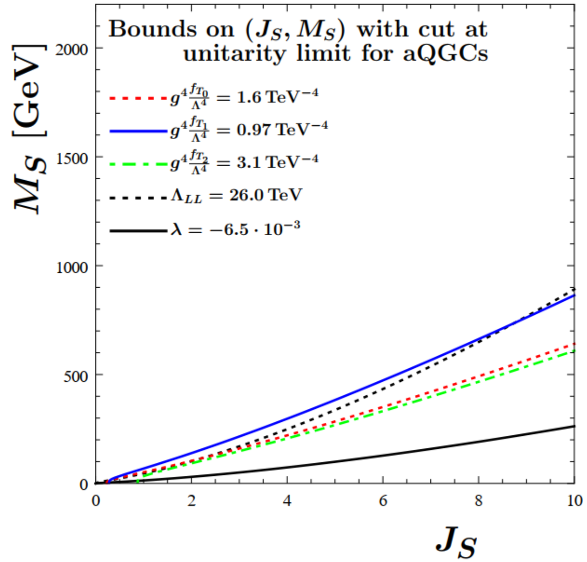


- Energy dependence of dominant partial wave amplitude

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

Constraints from experiment:



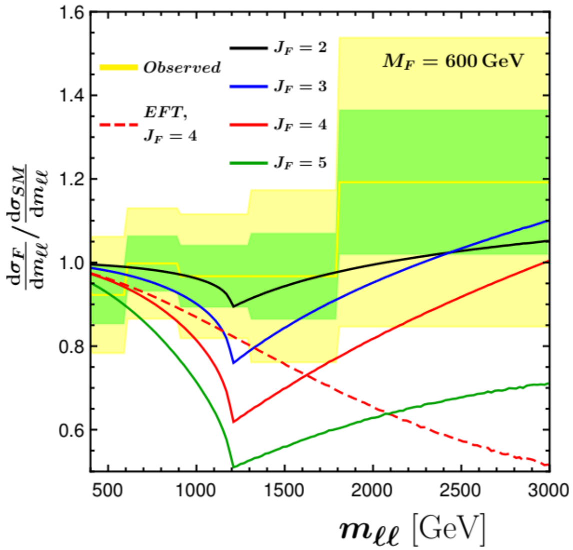


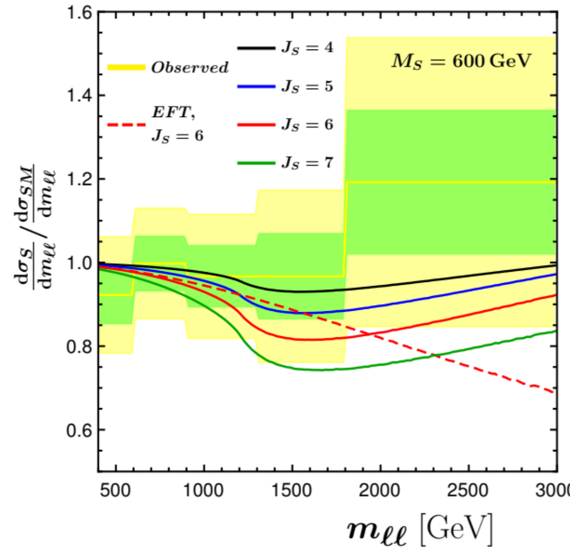
limits on individual Wilson coefficients:

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)





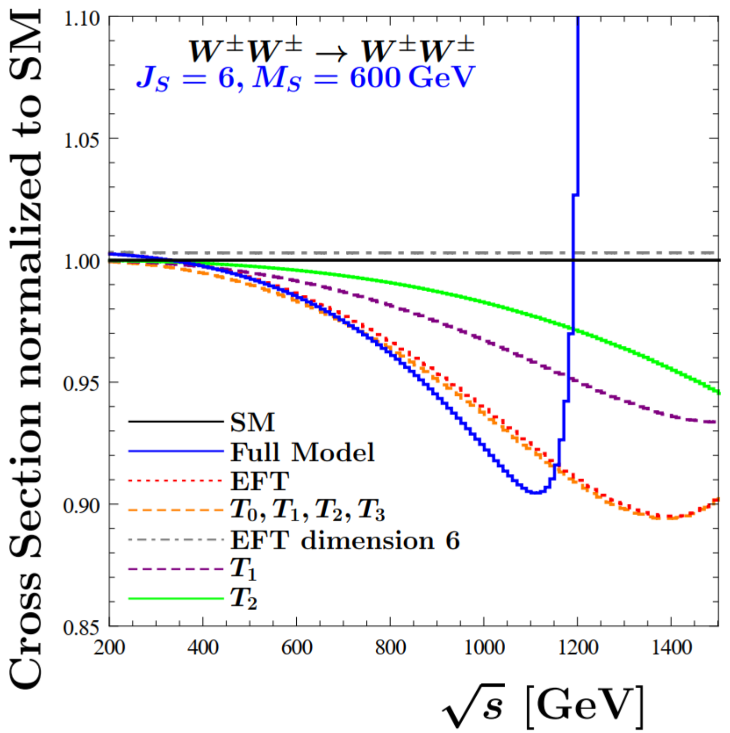
Parameter choices:

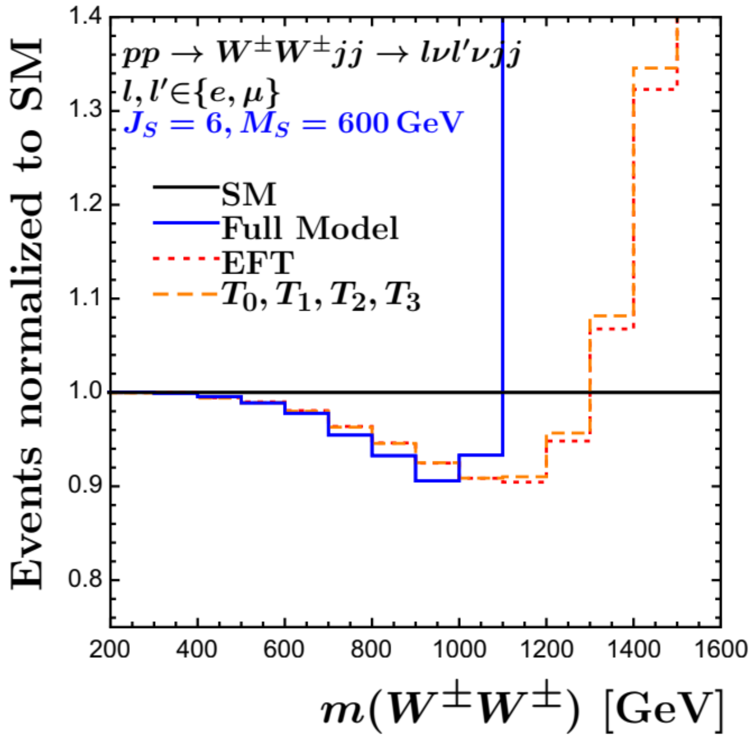
- Use fermion model with $J_F = 4$ and $M_F = 600$ GeV
  or scalar model with $J_S = 6$ and $M_S = 600$ GeV
  for illustration from here on

- 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

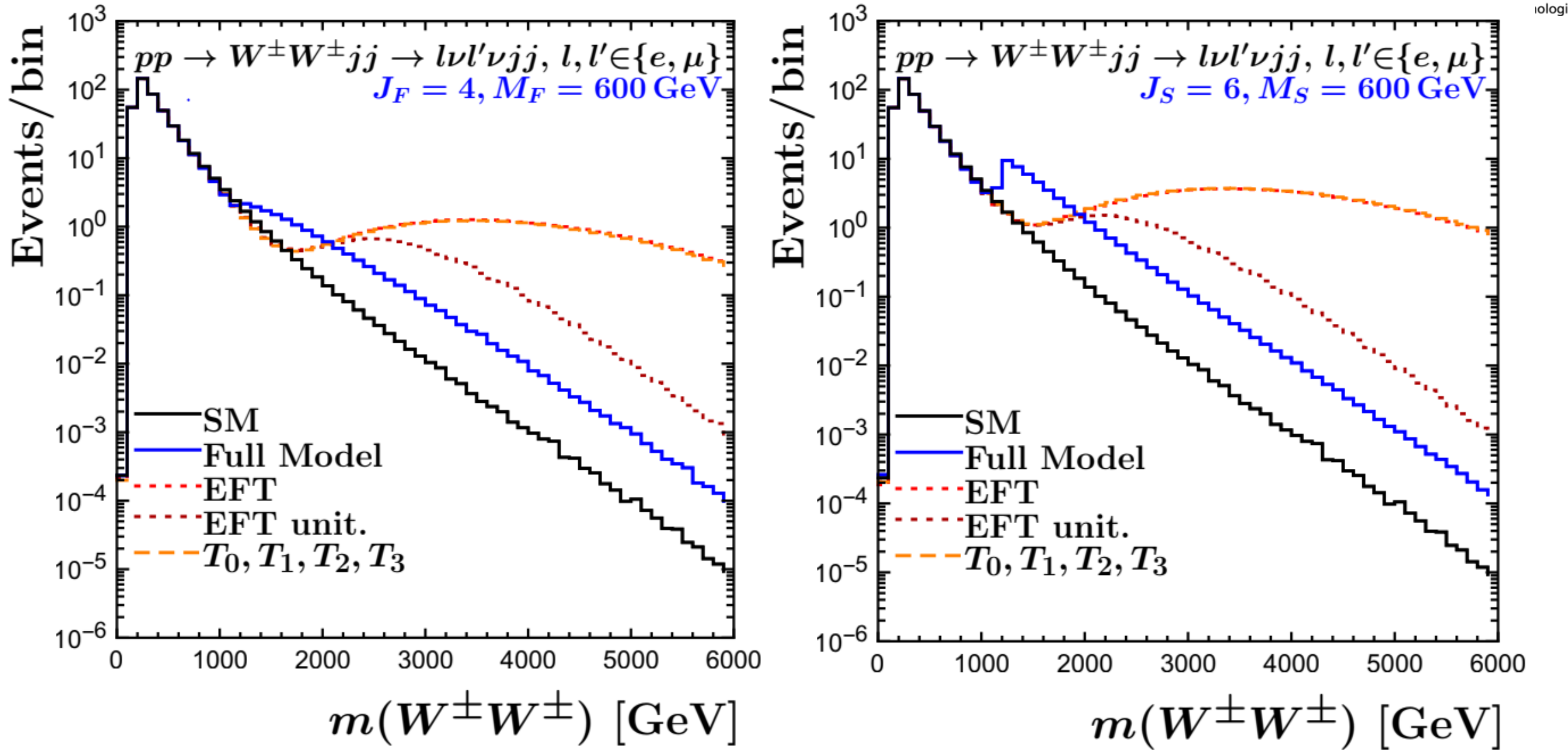
full model vs. EFT ➔ EFT validity range:





- 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

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

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 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 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 →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

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

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

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

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

- 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

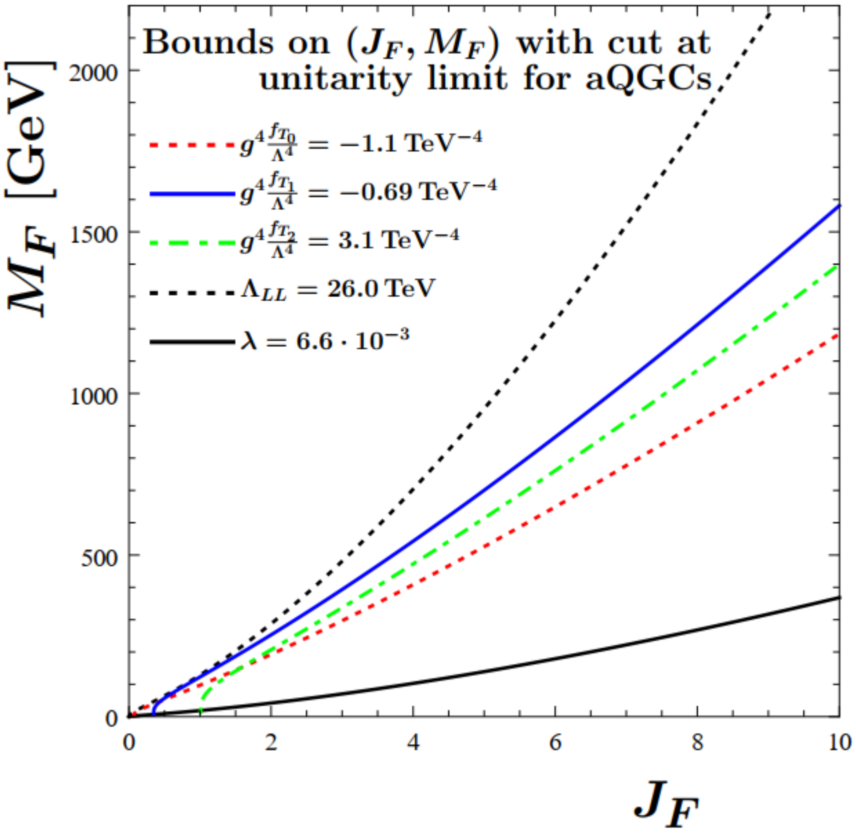
$$\frac{f_{T_0}}{\Lambda^4} = \sum_F n_F \frac{(-14C_{2,F}+1)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}-2)\,T_S}{40320\pi^2 M_S^4}\,,$$

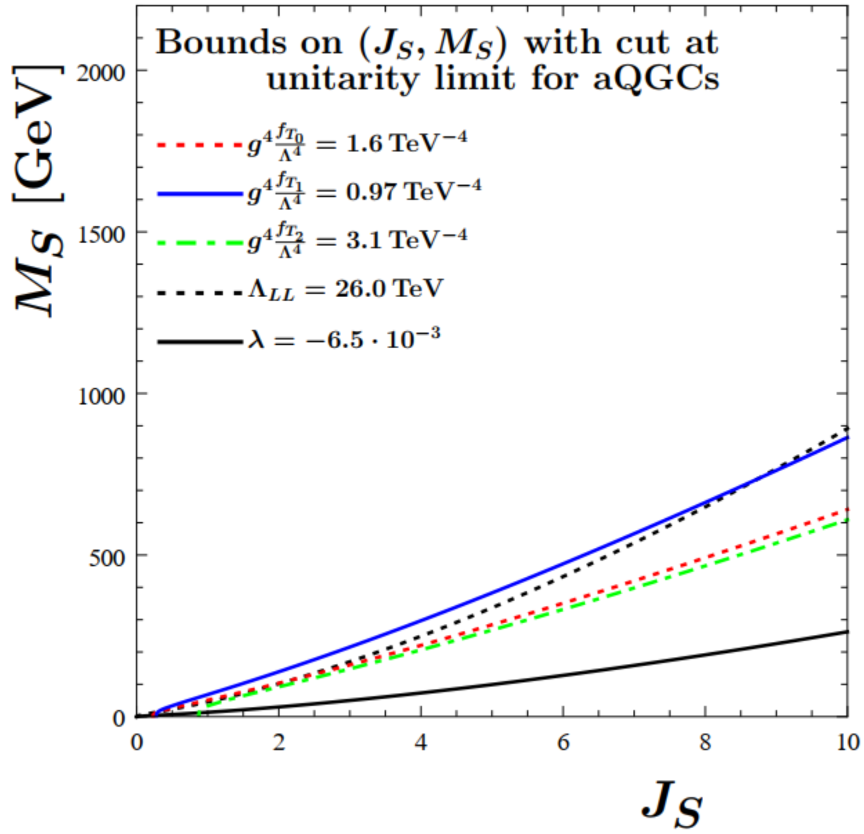
$$\frac{f_{T_1}}{\Lambda^4} = \sum_F n_F \frac{(-28C_{2,F}+13)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(14C_{2,S}-5)\,T_S}{40320\pi^2 M_S^4}\,,$$

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

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

Constraints from experiment: limits on individual Wilson coefficients





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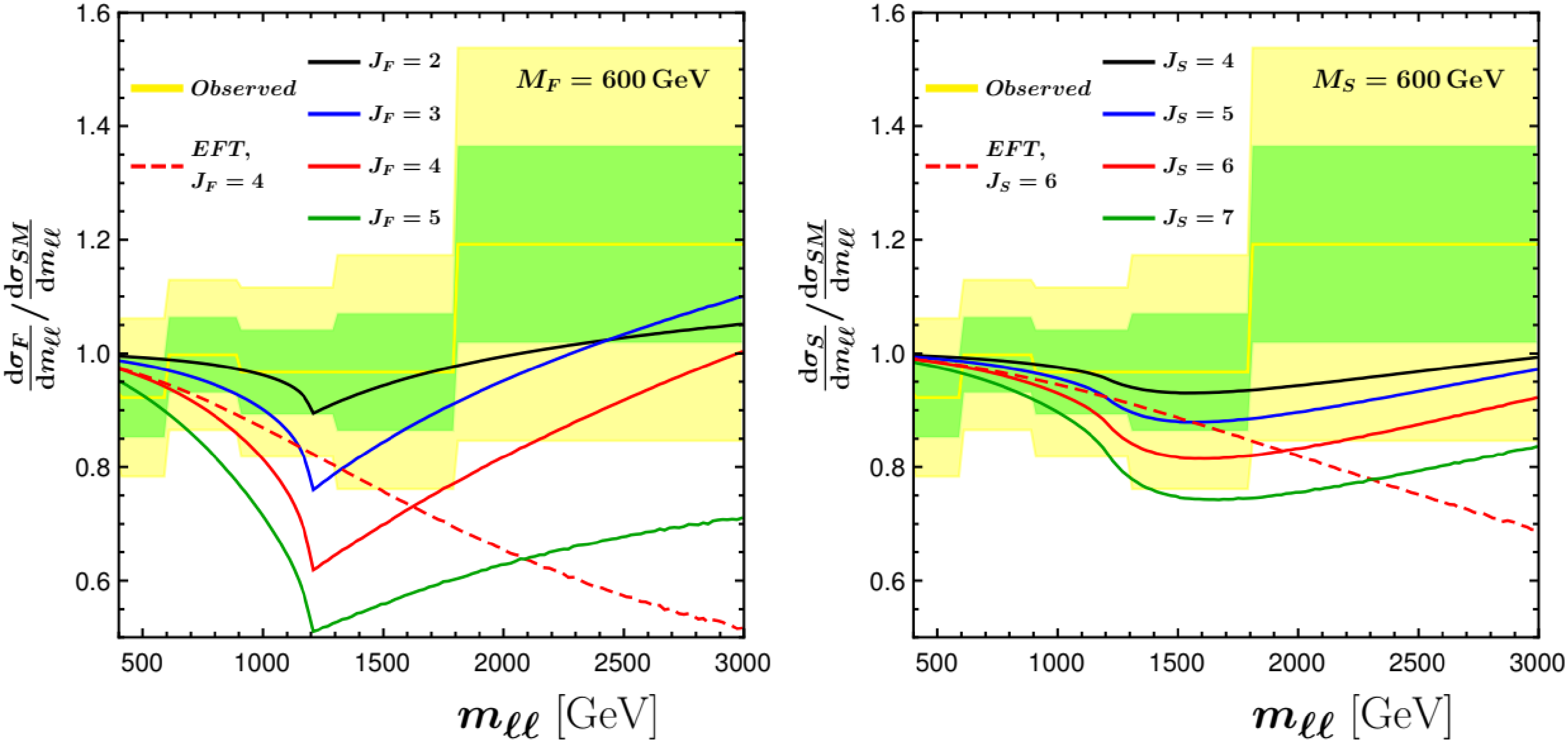
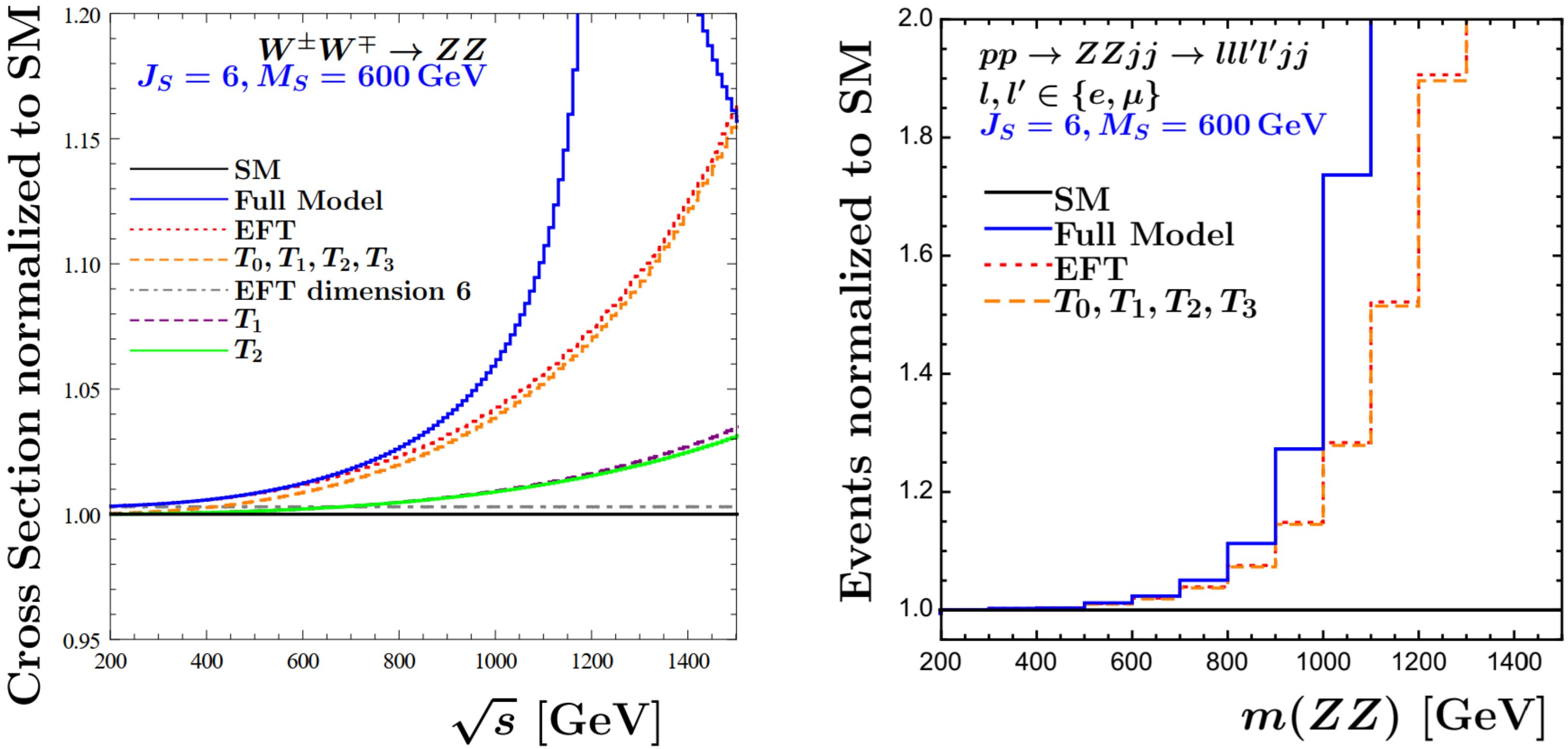


EFT validity range for ZZ production in VBS



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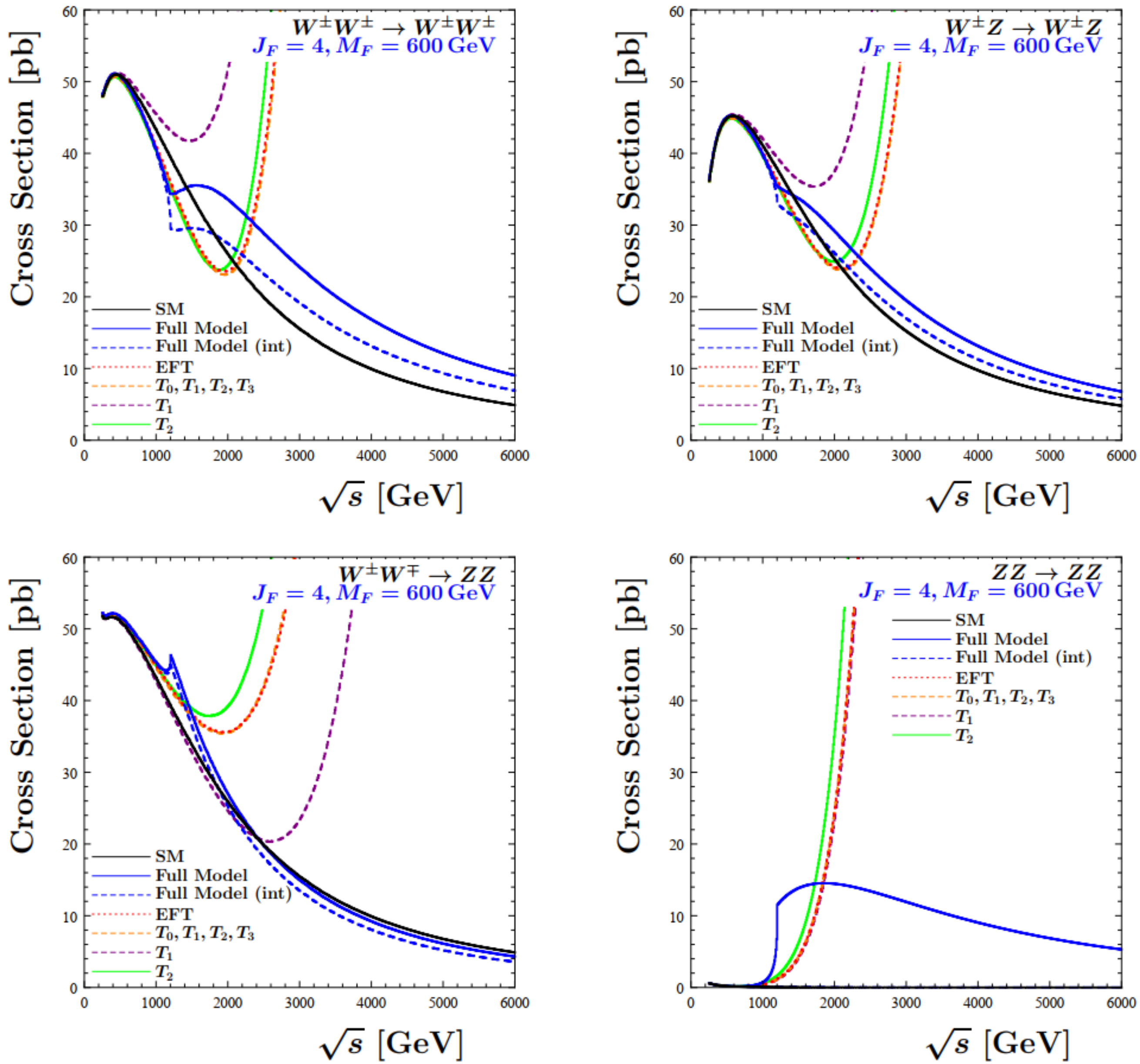
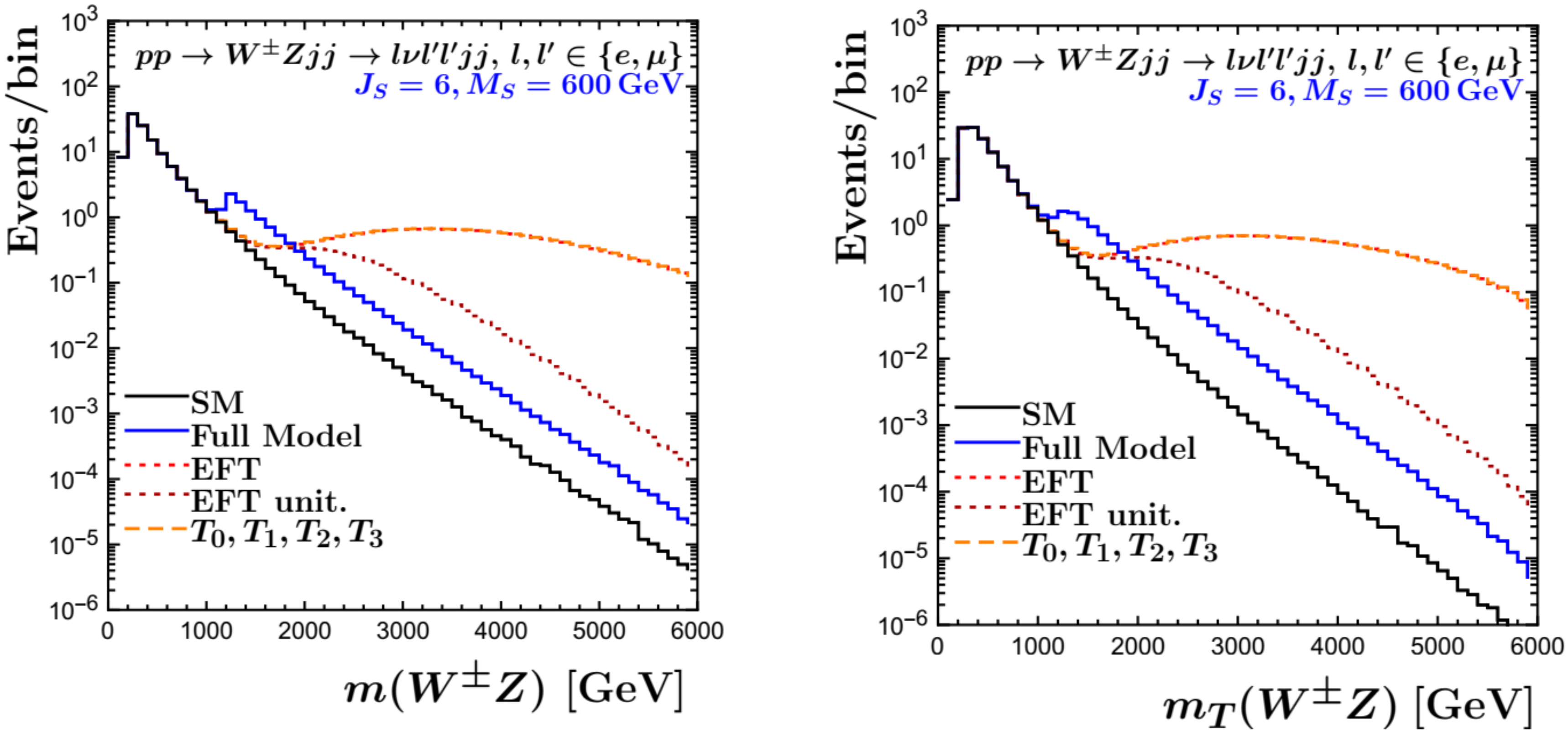


Onshell cross sections

Diboson mass vs transverse mass



Dependence on multiplet mass