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EFT versus UV complete models: lessons for VBS

Pushing the Limits of Theoretical Physics, May 8-12, 2023, Mainz

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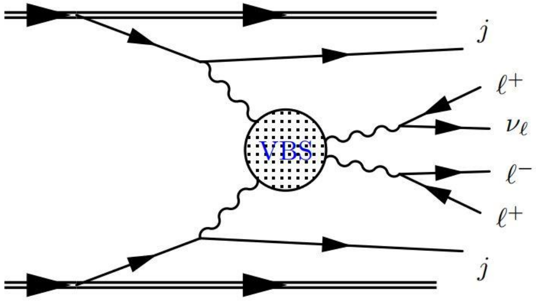
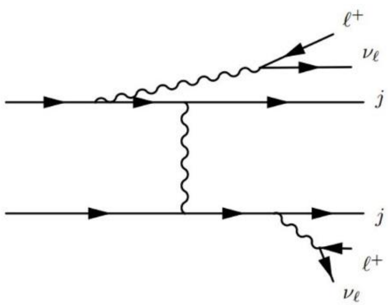
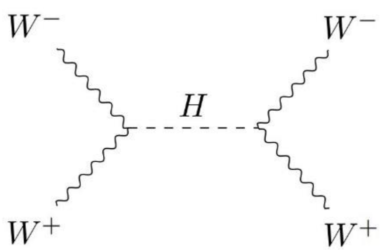
VBS and anomalous quartic gauge couplings (aQGC)

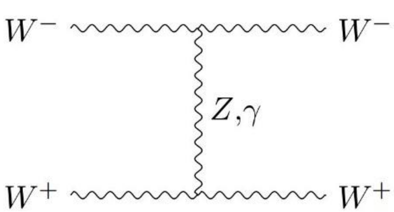


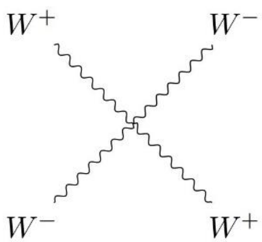
VBS provides rich source of information on dynamics of electroweak gauge bosons and EW symmetry breaking

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

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

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

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

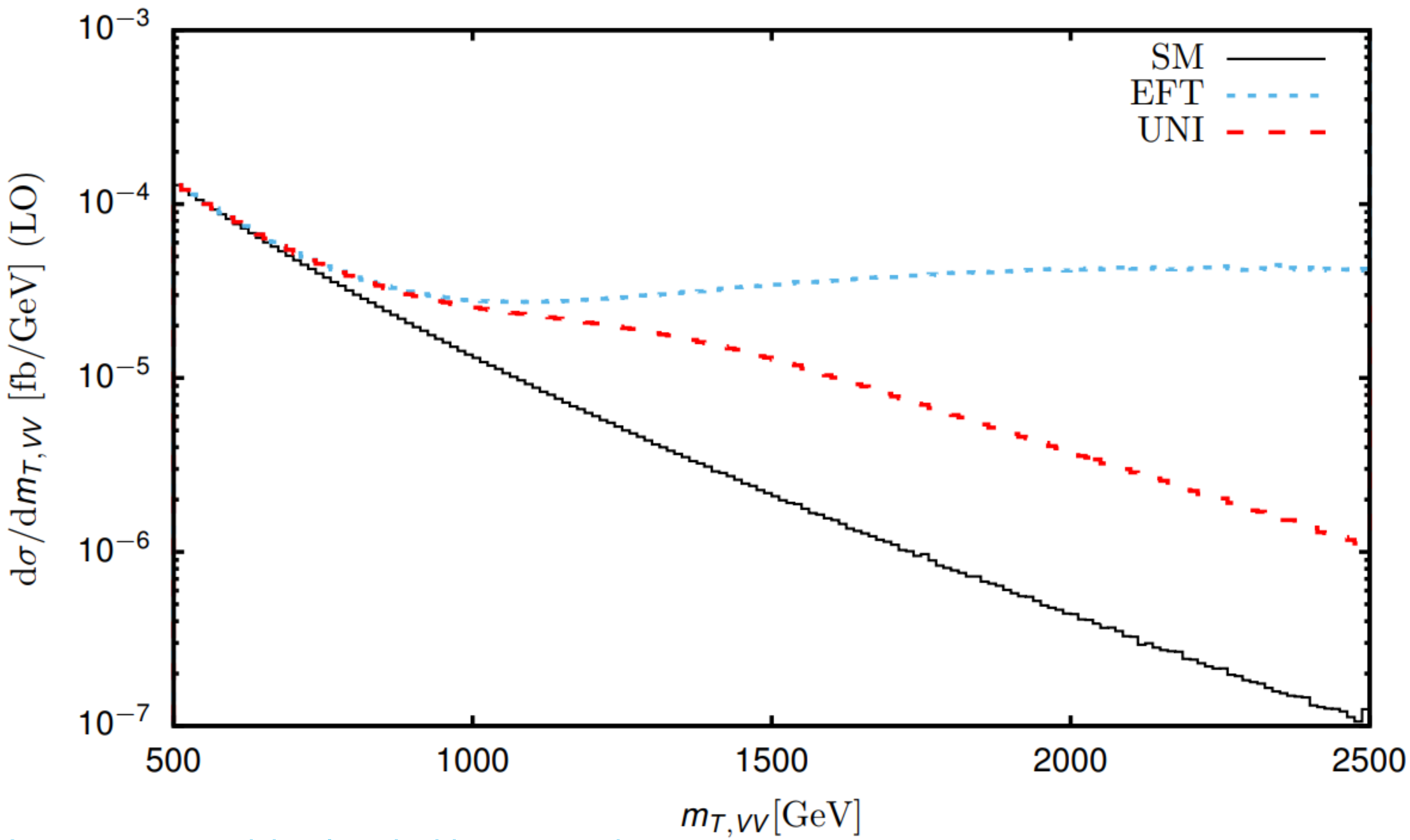
$$+ \frac{f_{M_0}}{\Lambda^4} \mathrm{Tr}\left[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}\right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right] + \ldots$$

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

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)

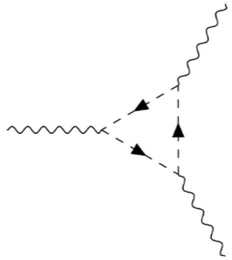
- n_R SU(2) multiplets of isospin J_R of scalars (R=S) or Dirac fermions (R=F) with their SU(2) gauge interactions (no hypercharge couplings)

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

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

- Yukawa couplings of fermions to Higgs doublet absent if no fermion multiplets with $J_F \pm ½$ 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 within SU(2) multiplet
- Refinements like extra (confining) gauge interactions, several multiplets, hypercharge contributions, Higgs couplings keep our results as leading approximation → very generic class of models

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

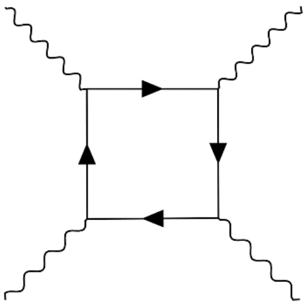


Massive BSM matter fields in isospin J_R multiplets induce EFT operators like

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

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

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



and also anomalous quartic gauge couplings (aQGC), like

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

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

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

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

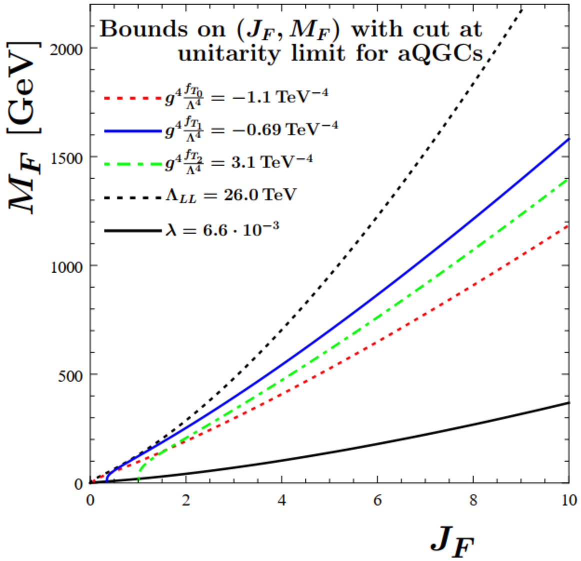
$\sim C_{2,R}\, T_R$

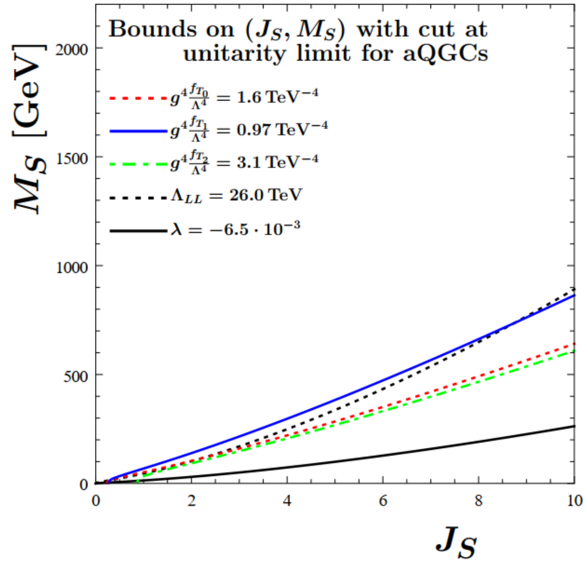
- Loop suppressed, but $(J_R)^3$ enhanced for trilinear couplings, $(J_R)^5$ for aQGC
- Find Wilson coefficients, e.g.

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

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

Constraints from experiment (single multiplet case):



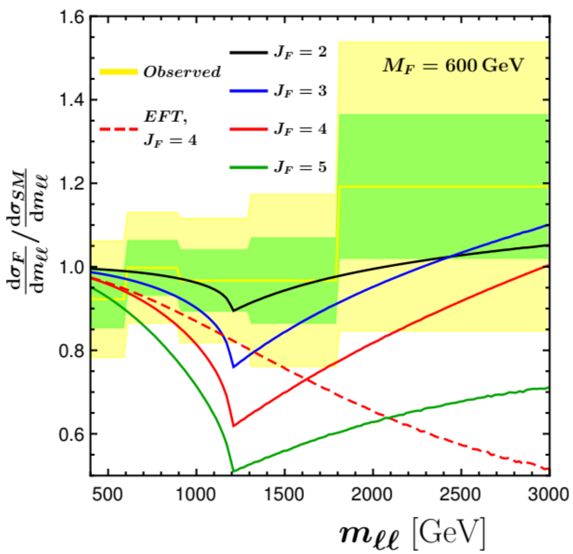


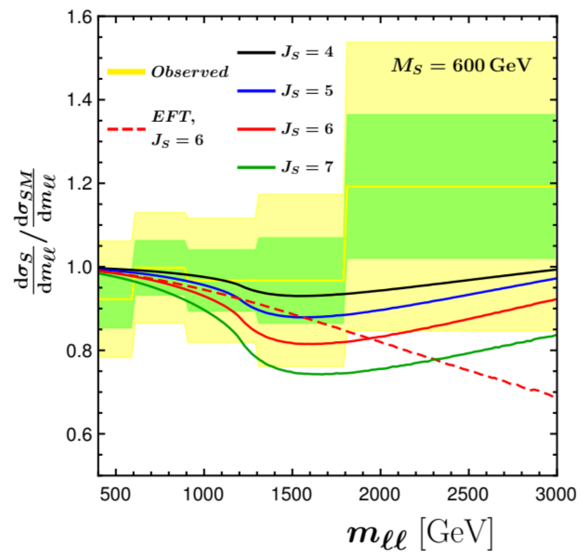
limits on individual Wilson coefficients:

No serious competition to VBS from aTGC measurements in VV production

(Assume wide EFT validity range)

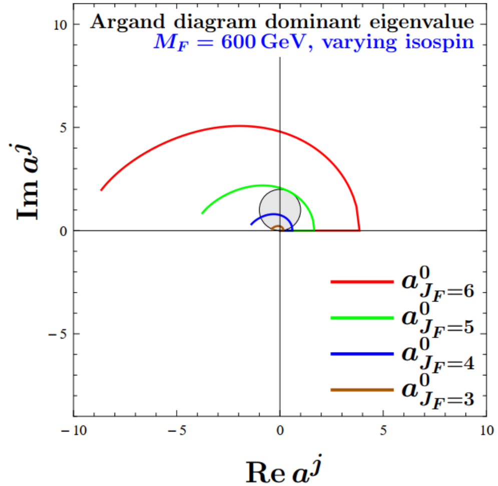
Deviation in Drell-Yan cross section, normalized to SM expectation (1- and 2-σ error bands adapted from CMS: arXiv:2103.02708)

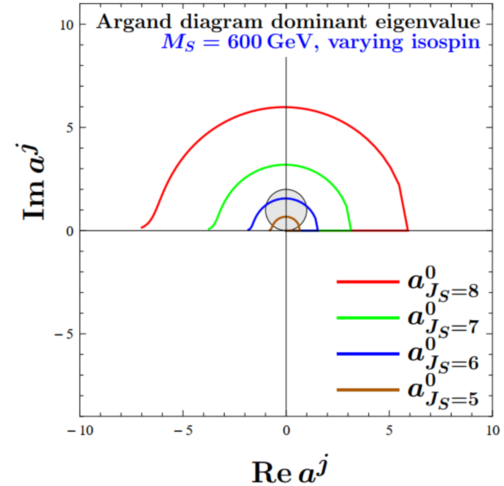




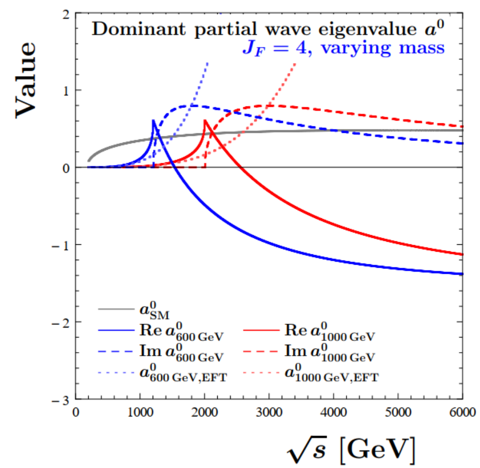
Unitarity considerations limit size of isospin representations

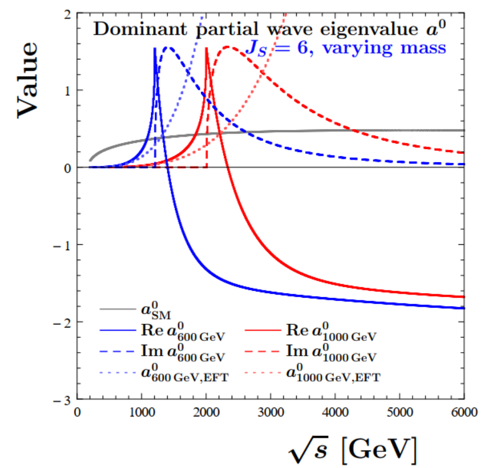
- Argand diagram for dominant VV→VV partial wave amplitude: At large J_R, model becomes non-perturbative





- Energy dependence of dominant partial wave amplitude





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

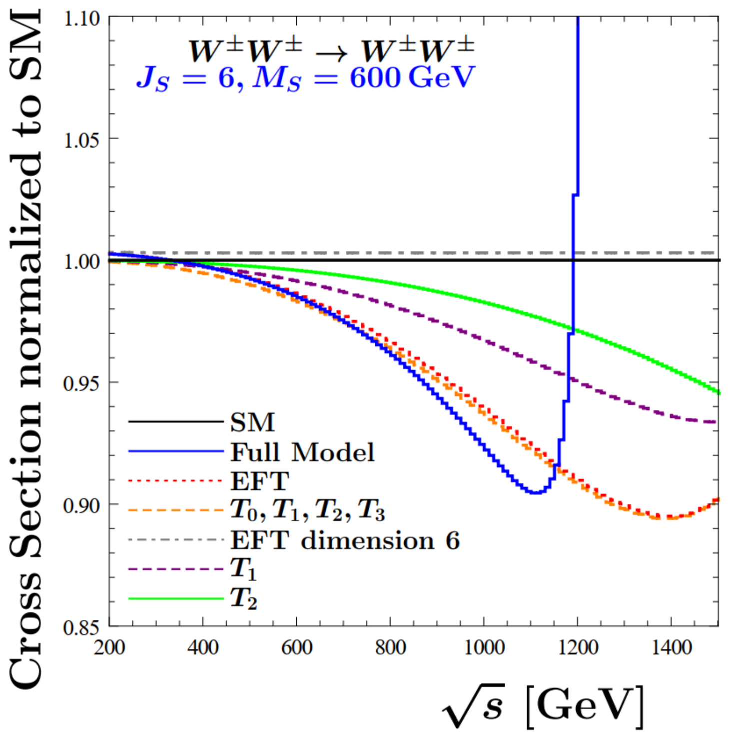
Parameter choices:

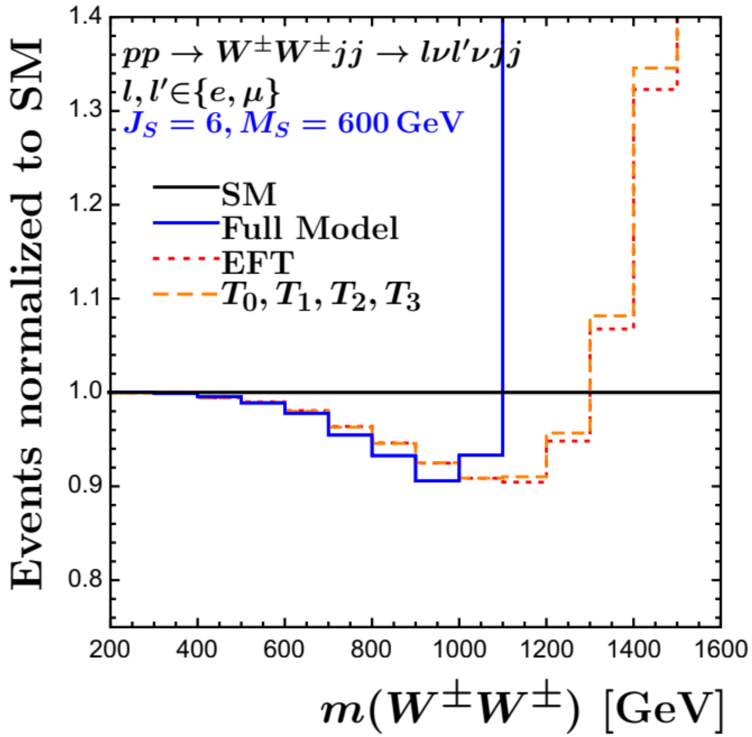
- Use fermion model with $J_F = 4$ and $M_F = 600$ GeV
  or scalar model with $J_S = 6$ and $M_S = 600$ GeV
  for illustration from here on

- 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

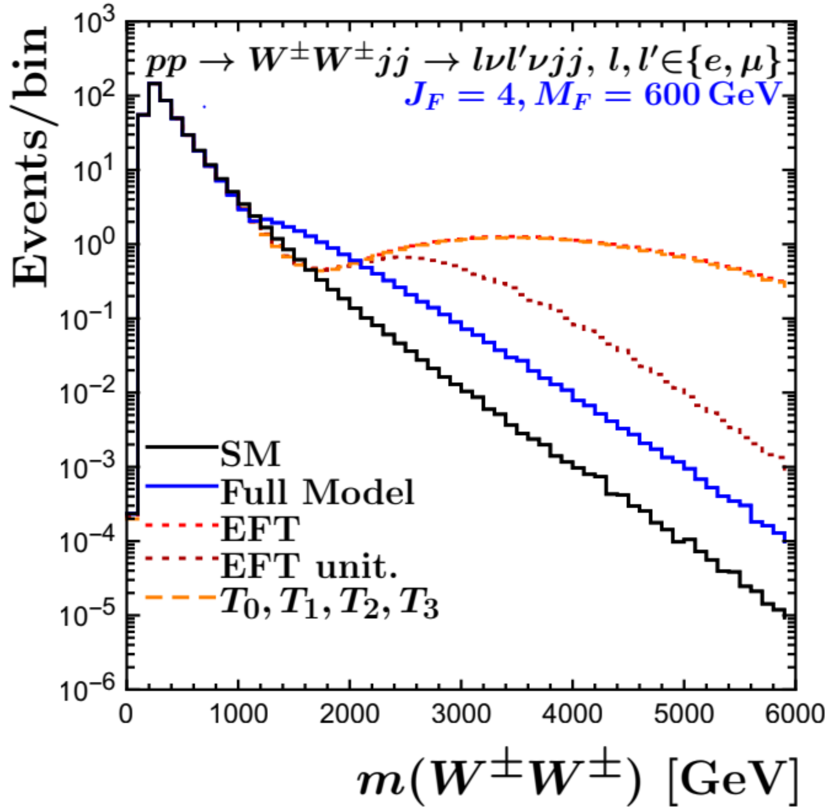
full model vs. EFT → EFT validity range:

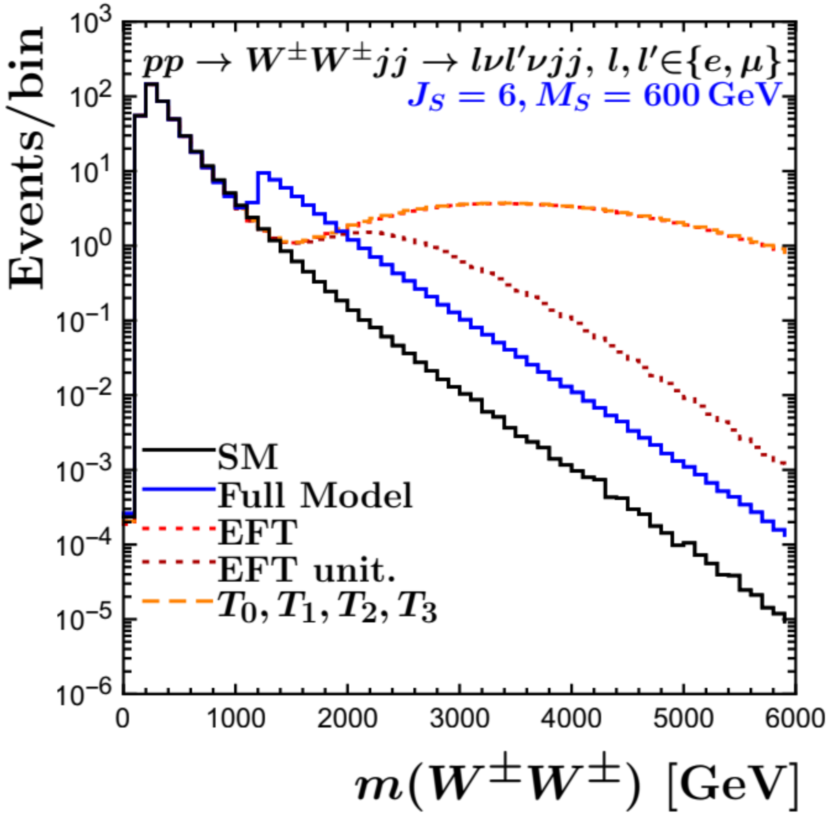




- EFT is valid only well below threshold at $2M_S$ =1200 GeV (as expected)
- Deviations from SM barely reach 10% within EFT validity range, even for J_S= 6
- Because of J_R^5 vs J_R^3 growth, dim-8 terms are much more important than dim-6

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

Extending the model with Higgs couplings:

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- Consider one (J_F,Y=0) and two (J_F – ½,Y=±½) multiplets
- Mass splitting due to sizable Yukawa coupling

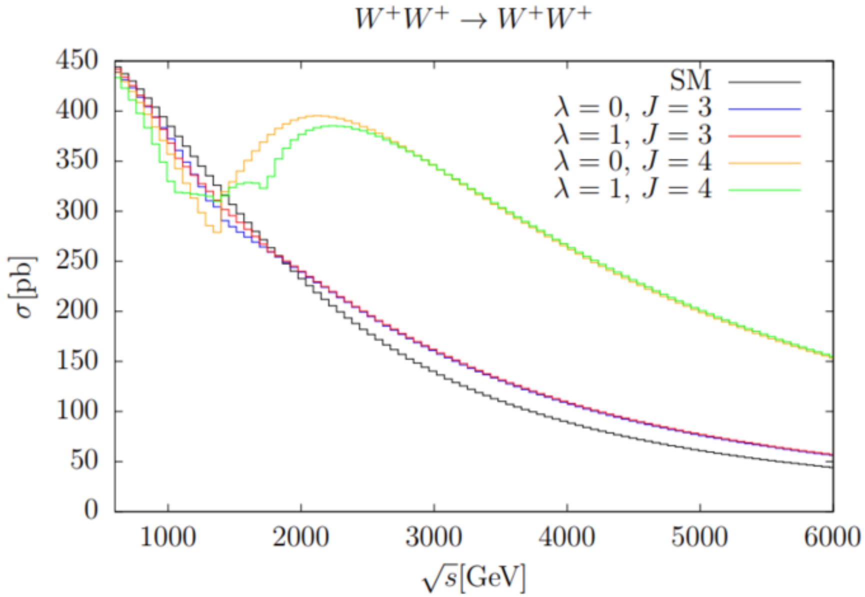
$$+\lambda\bar{\Psi}_j^{Y=0}\Phi\Psi_{j-1/2}^{Y=-1/2}+\lambda\bar{\Psi}_j^{Y=0}\tilde{\Phi}\Psi_{j-1/2}^{Y=1/2}+h.c.$$

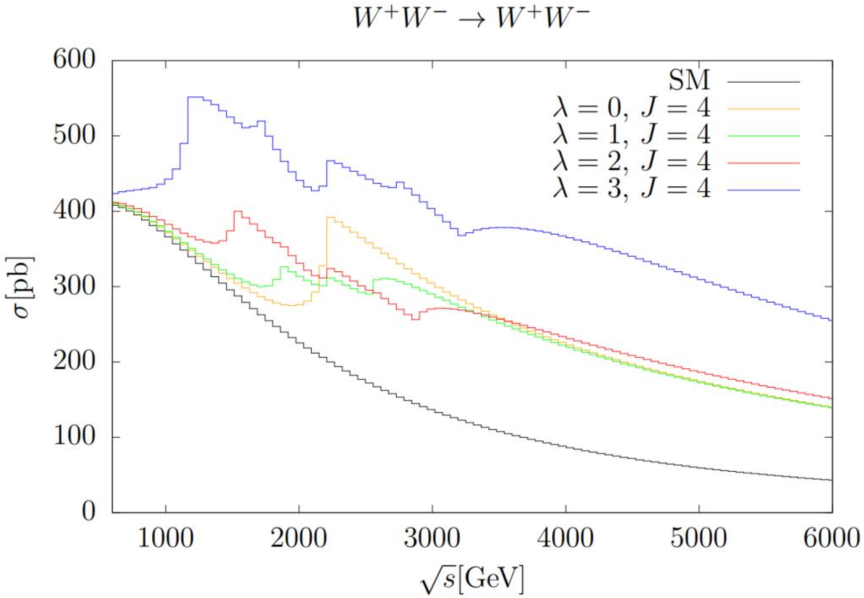
- Generates additional "mixed" dimension-8 operators, e.g.

Table 4.4.: Wilson coefficients for dimensions d=8, for operators with two higgs fields for $J=3$ and $J=4$ (from thesis of Heiko Dietrich-Siebert)

	$\phi^2 D^6$	$\frac{c_{\mathcal{O}}}{\Lambda_{EFT}^4}(J=3)$	$\frac{c_{\mathcal{O}}}{\Lambda_{EFT}^4}(J=4)$
$\mathcal{O}_{HDDD}$	$(D_\mu D_\nu D_\alpha\phi)^\dagger D^\mu D^\nu D^\alpha\phi$	$\frac{\lambda^2}{160\pi^2 m^4}$	$\frac{9\lambda^2}{1120\pi^2 m^4}$
	$\phi^2 D^4 X$		
$\mathcal{O}_{HD4W1}$	$\mathrm{i}(D^\alpha D^\mu\phi)^\dagger\tau^I D_\alpha D^\nu\phi W_{\mu\nu}^I$	$\frac{17g\lambda^2}{720\pi^2 m^4}$	$\frac{17g\lambda^2}{560\pi^2 m^4}$
$\mathcal{O}_{HD4W2}$	$\mathrm{i}((D_\alpha D^\alpha D^\nu\phi)^\dagger\tau^I D^\mu\phi)W_{\mu\nu}^I + h.c.$	$-\frac{g\lambda^2}{48\pi^2 m^4}$	$-\frac{3g\lambda^2}{112\pi^2 m^4}$
	$\phi^2 D^2 X^2$		
$\mathcal{O}_{M0}$	$\frac{1}{2}(D_\alpha\phi)^\dagger D^\alpha\phi W_{\mu\nu}^I W^{I\mu\nu}$	$\frac{14291g^2\lambda^2}{8640\pi^2 m^4}$	$\frac{24791g^2\lambda^2}{6720\pi^2 m^4}$
$\mathcal{O}_{M1}$	$\frac{1}{2}(D_\mu\phi)^\dagger D^\nu\phi W_{\nu\alpha}^I W^{I\alpha\mu}$	$\frac{7891g^2\lambda^2}{4320\pi^2 m^4}$	$\frac{13771g^2\lambda^2}{3360\pi^2 m^4}$
$\mathcal{O}_{M7}$	$\frac{\mathrm{i}}{2}\epsilon_{IJK}((D_\mu\phi)^\dagger\tau^I D^\nu\phi)W_{\nu\alpha}^J W^{K\alpha\mu}$	$\frac{17g^2\lambda^2}{240\pi^2 m^4}$	$\frac{51g^2\lambda^2}{560\pi^2 m^4}$

Comparison to simple model class without Yukawa coupling





- Qualitatively identical to model without Higgs couplings for modest Yukawas
- Huge Yukawa coupling (λ>2) needed to make mixed interactions dominant
- → search for purely transverse operators covers large fraction of parameter space

How UV-complete is the model? A caveat….

- Extra matter field gives large positive contribution to SU(2) β-function

$$\alpha_2(Q^2) = \frac{\alpha_2(m_F^2)}{1 + \frac{\alpha_2(m_F^2)}{4\pi} \beta_0 \log\frac{Q^2}{m_F^2}} \quad \text{with} \quad \beta_0 = \frac{19}{6} - \frac{4}{3}\sum T_R \quad \text{and} \quad T_R = \frac{J_F(J_F+1)(2J_F+1)}{3}$$

- SU(2) gauge coupling diverges at Landau pole, which is well below Planck scale for $J_F \geq 2$ and $J_S \geq 3$:

$$J_F = 4: \qquad Q_{Pole} = 11.4\, m_F$$

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$$J_F = 2: \qquad Q_{Pole} = 10^8\, m_F$$

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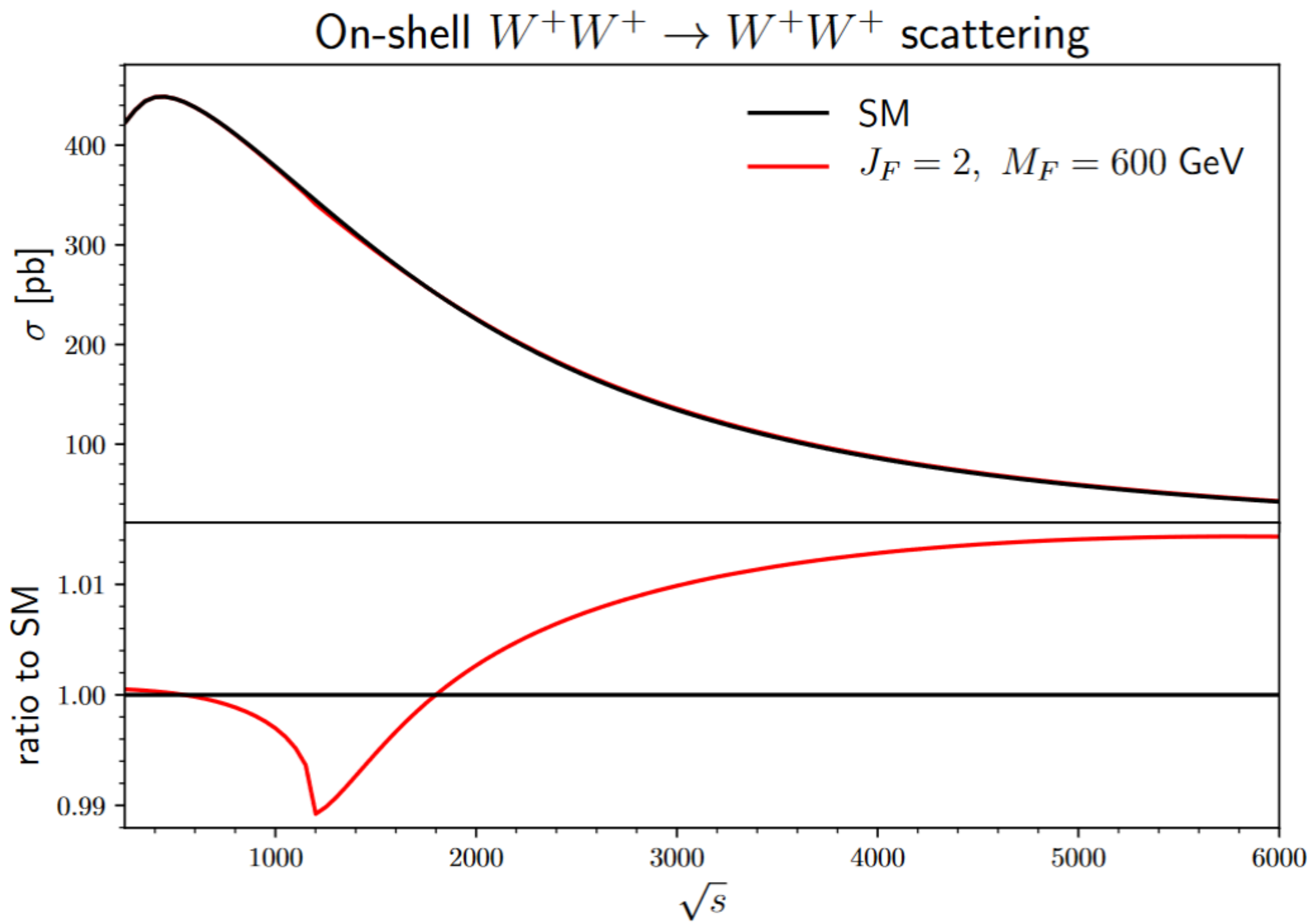
$$J_F = 4: \qquad Q_{Pole} = 11.4\, m_F$$

$$J_F = 3: \qquad Q_{Pole} = 240\, m_F$$

$$J_F = 2: \qquad Q_{Pole} = 10^8\, m_F$$

- Embedding of high J multiplets in larger gauge group makes matters worse since contribution to beta function grows faster than negative Yang-Mills term due to high dimensionality of additional matter multiplets
- UV-completeness up to Planck scale ==> $J_F < 2$ even with only one additional fermion multiplet

JF=2 case provides upper limit on truly UV-complete LHC signal



Would need sub-percent experimental errors to establish such a signal

Consequences for VBS at LHC

- Observation of large loop-induced anomalous couplings (T- and also M-operators) at the LHC kills weak coupling extrapolation of the SM well below the Planck scale. This has major consequences, such as
  1. Contend with nearby Landau pole
  2. No GUT
  3. Lower Planck scale due to extra dimensions
  4. … your idea

- Alternatively: LHC observation of anomalies in (partially) transverse VBS is highly unlikely
  → huge reduction of number of anomalous couplings which need to be considered in VBS analyses: the three S-operators are sufficient as long as experimental uncertainties are above a few per-mille

Summary

- There are many (superficially) 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, which result in nearby Landau pole for SU(2) coupling
- 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.
  - Perturbative coupling of two multiplets to Higgs doublet field generates modest multiplet splitting (suppressed by $(v/M_R)^2$) which smears out threshold structure
  - Additional confining gauge interaction of multiplets averages out (analogous to quark-hadron duality in QCD)
  - Below threshold resonances (analogous to J/ψ) deserve further study

Conclusions

- 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

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

Backup

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

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

$$\mathcal{O}_{S_0} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\mu \Phi \right)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_1} = \left[\left(D_\mu \Phi \right)^\dagger D^\mu \Phi \right] \times \left[\left(D_\nu \Phi \right)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_2} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\nu \Phi \right)^\dagger D^\mu \Phi \right]$$

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

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

Mixed: transverse-longitudinal

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

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

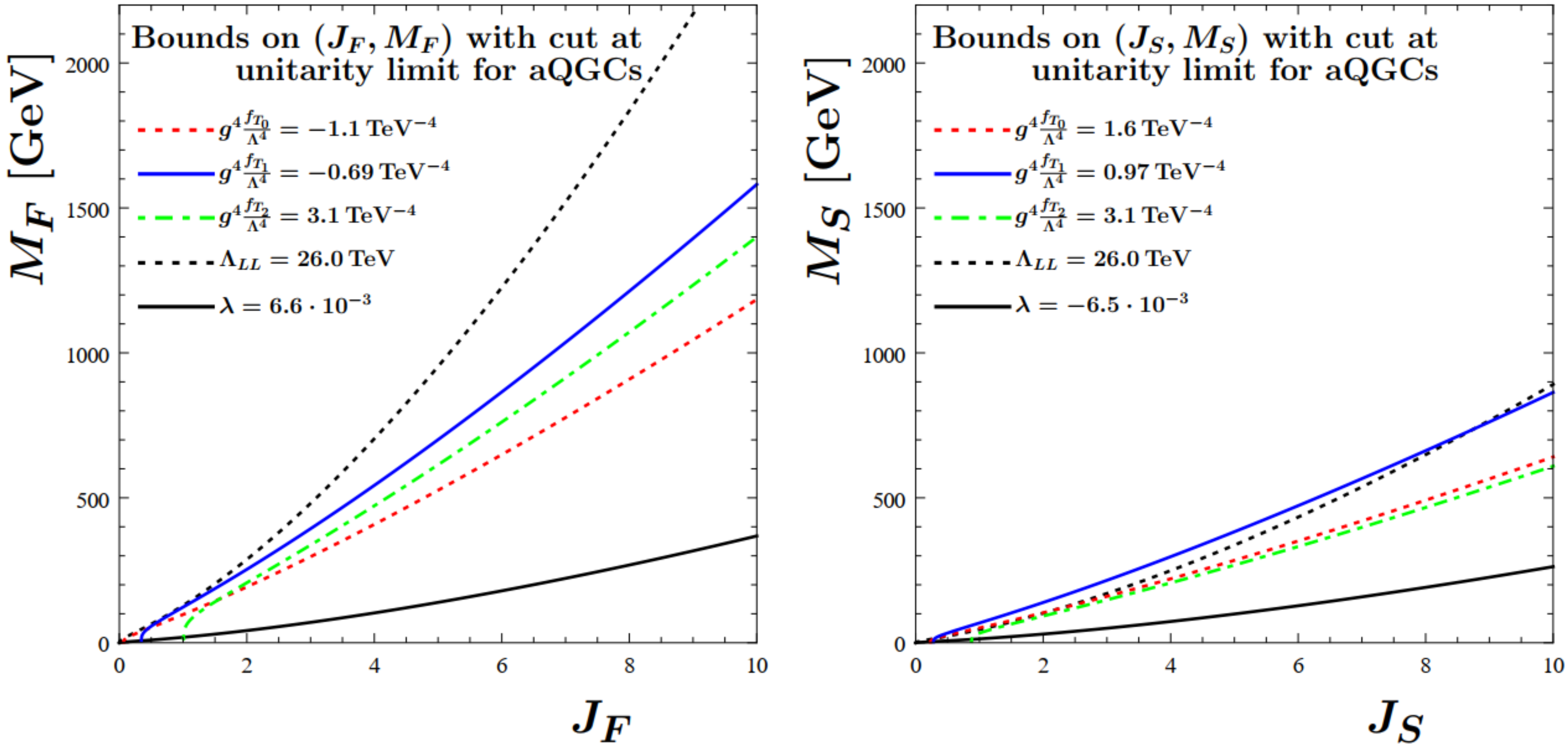
$$\frac{f_{T_0}}{\Lambda^4} = \sum_F n_F \frac{(-14C_{2,F}+1)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}-2)\,T_S}{40320\pi^2 M_S^4}\,,$$

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

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

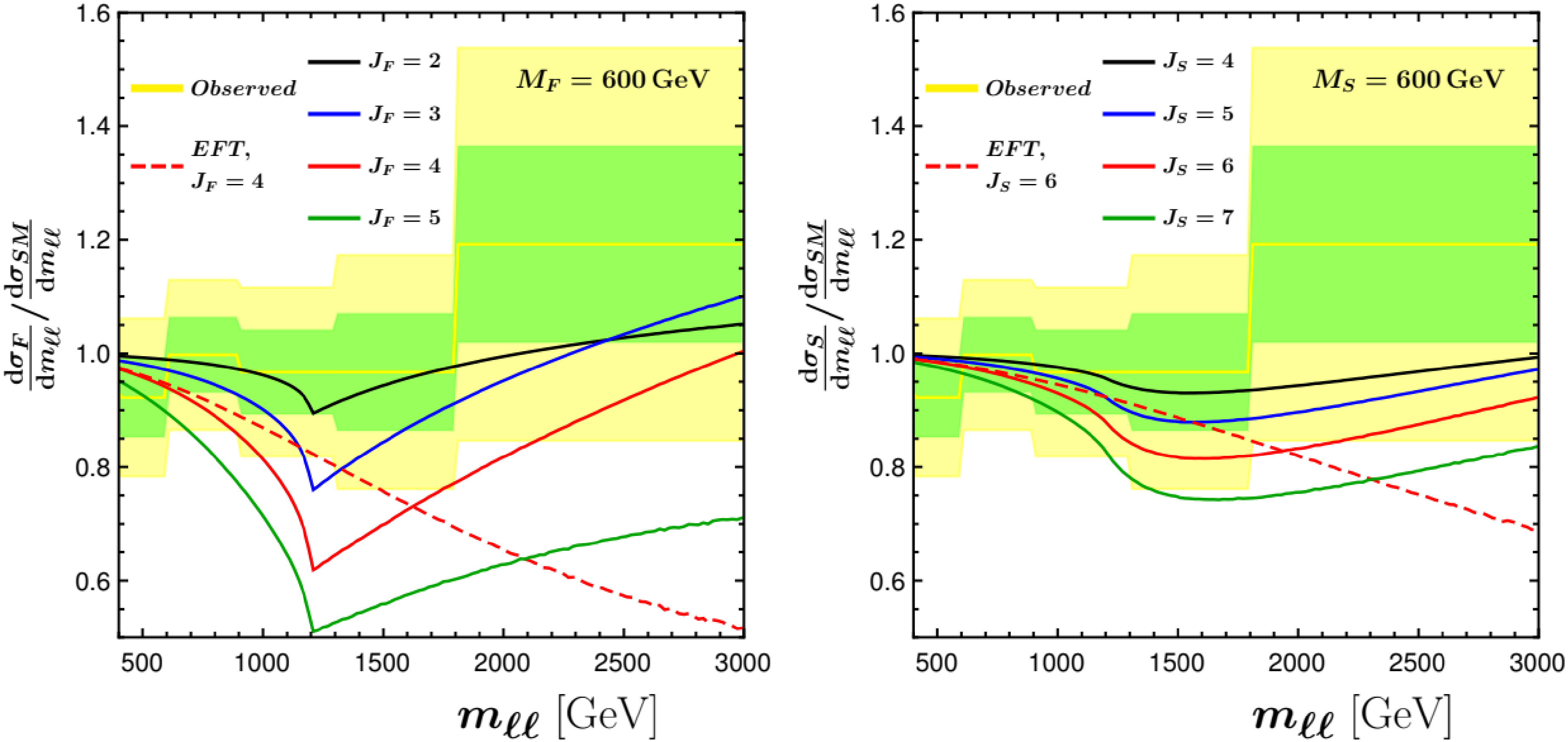
$$\frac{f_{T_3}}{\Lambda^4} = \sum_F n_F \frac{(98C_{2,F}+299)\,T_F}{25200\pi^2 M_F^4} + \sum_S n_S \frac{(7C_{2,S}+16)\,T_S}{50400\pi^2 M_S^4}\,.$$

Constraints from experiment:
limits on individual Wilson coefficients

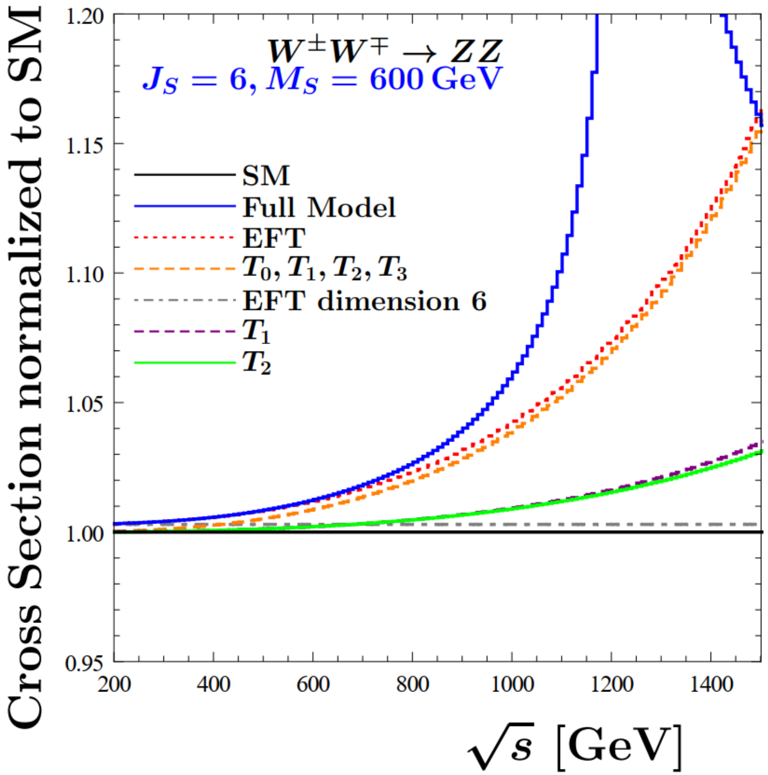


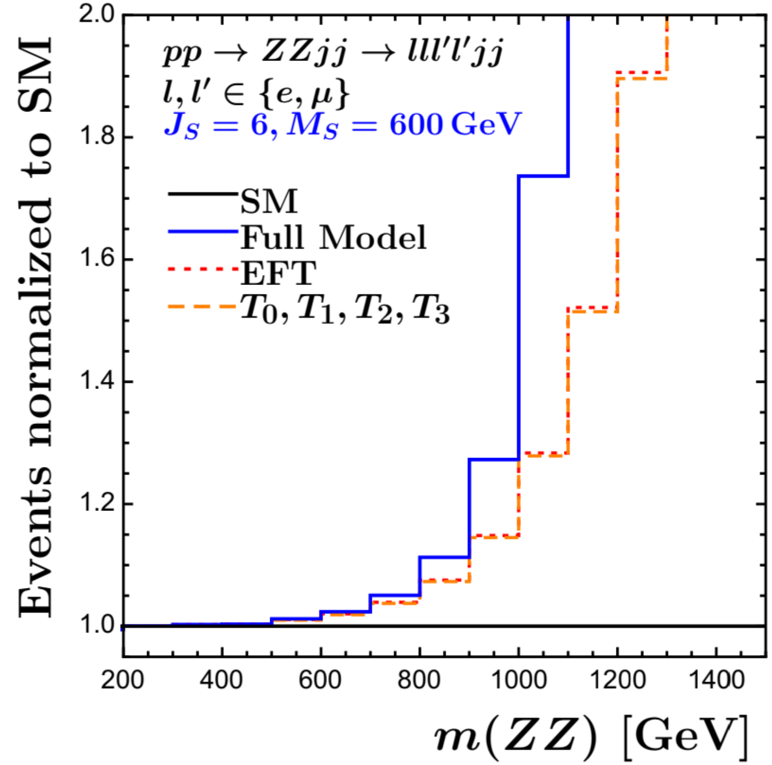
Constraints from experiment:

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

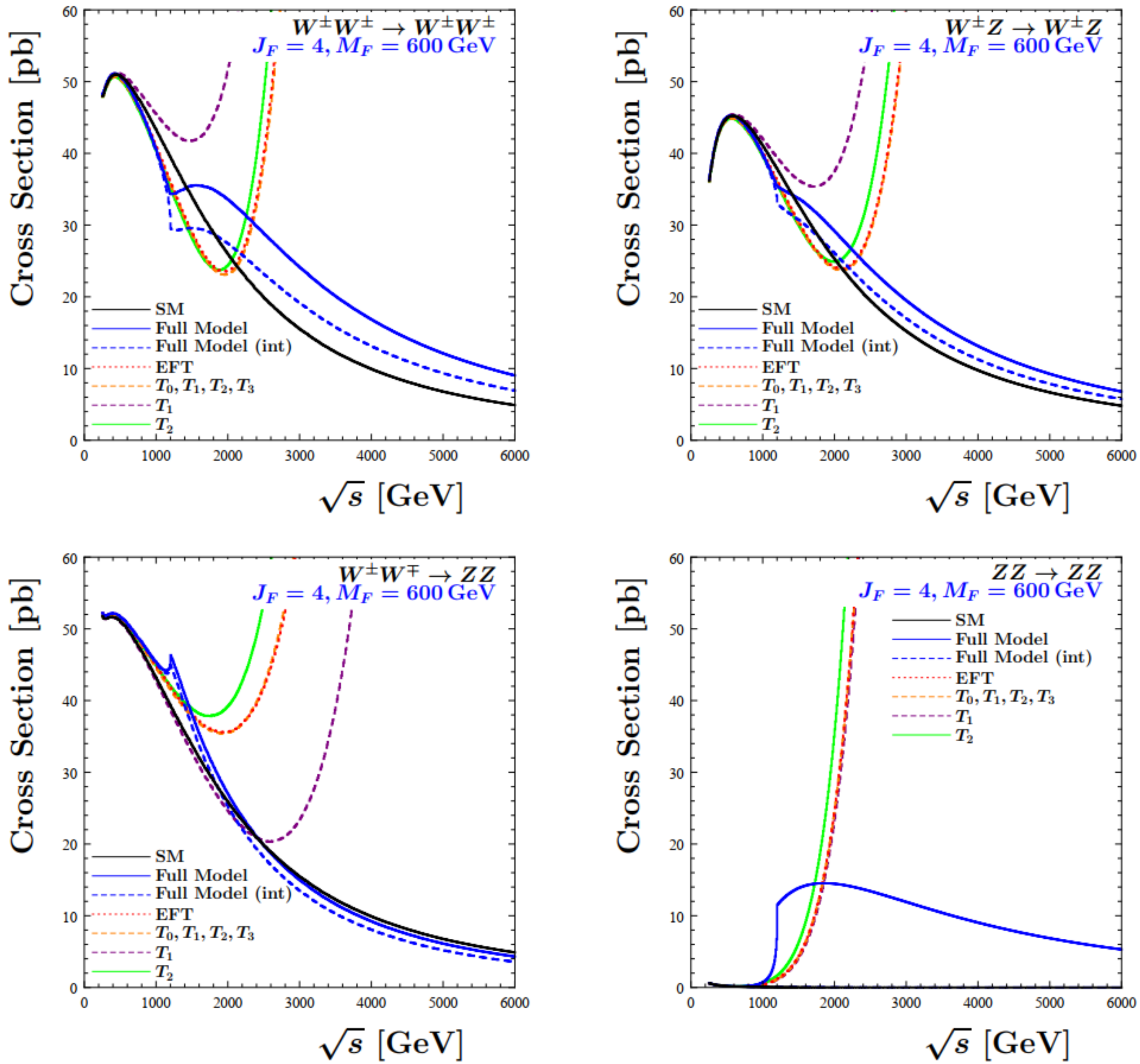


EFT validity range for ZZ production in VBS



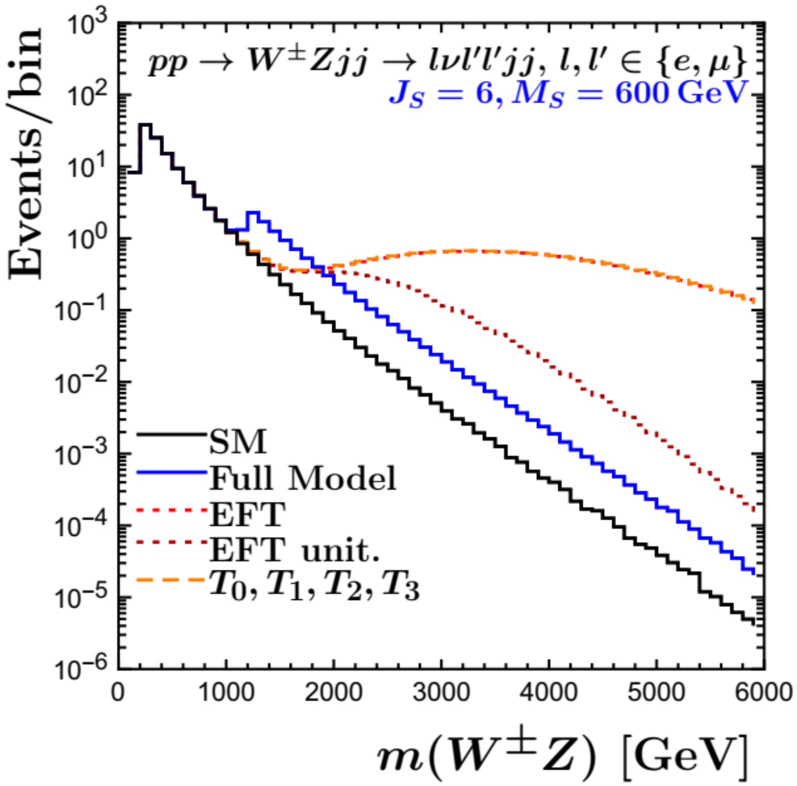


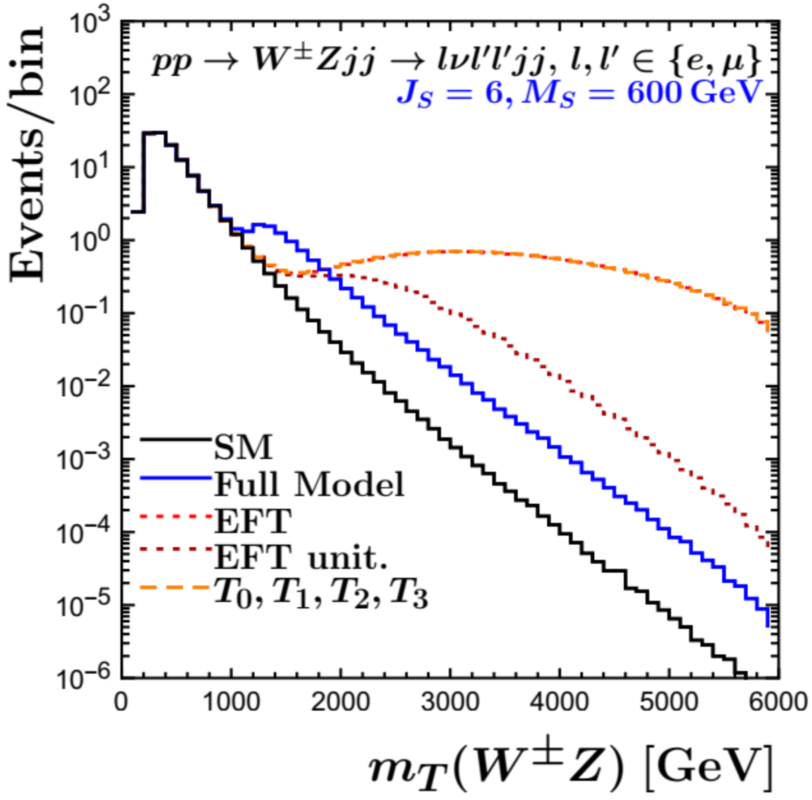
- EFT is valid only well below threshold at 2 M_S =1200 GeV (as expected)
- Deviations from SM barely reach 10% within EFT validity range, even for J_S= 6
- Because of J_R^5 vs J_R^3 growth, dim-8 terms are much more important than dim-6



Onshell cross sections

Diboson mass vs transverse mass





Dependence on multiplet mass