Vector Boson Scattering

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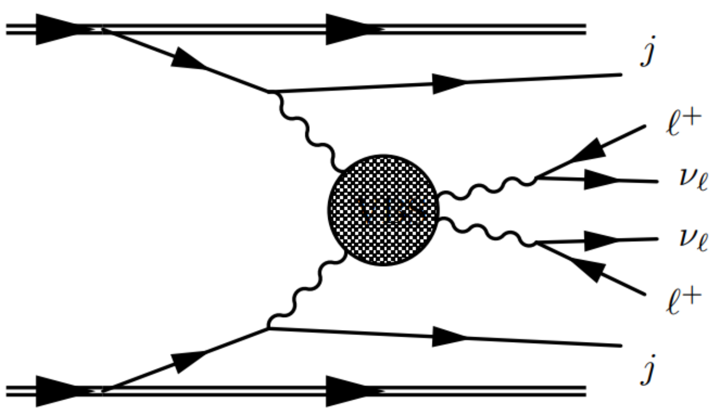
KIT Center Elementary Particle and Astroparticle Physics - KCETA

Introduction

Vector boson scattering (VBS)

- Basic process: VV→VV
- accompanied by 2 quark jets
  = tagging jets
- Identify weak bosons by decay leptons (or hadronic V decay)
- Important contributions from vector boson radiation off quark lines



Historical interest:

- vector boson fusion (VBF) of a (heavy) Higgs
- no-loose theorem for LHC/SSC

Today:

- Search for new resonances in the VV channels
- Effect of anomalous quartic gauge boson couplings (aQGC)
- Measurement of 125 GeV Higgs properties in VBF

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Comparative study of the benefits of forward jet tagging in heavy-Higgs-boson production at the Superconducting Super Collider

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The event rate for production of a Higgs boson of mass ~ 1 TeV with decay $H \to ZZ \to 4$ charged leptons is of order 25 events per year at standard Superconducting Super Collider luminosity and the QCD background is of comparable size. By tagging a *single* forward jet of energy $E_j > 1$ TeV and rapidity $2 < |\eta_j| < 5$ from the $qq \to qqZZ$ process, the QCD background can be essentially eliminated, with about 10 Higgs-boson signal events per year remaining, which amounts to 70% of the $qq \to qqZZ$ signal rate. The experimental separation of the vector-boson scattering subprocess is thereby possible.

Minijet veto: a tool for the heavy Higgs search at the LHC

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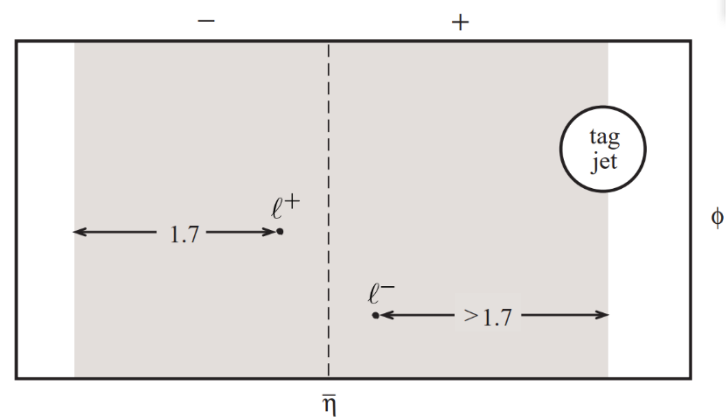
Abstract

The distinct color flow of the $qq \to qqH, H \to W^+W^-$ process leads to suppressed radiation of soft gluons in the central region, a feature which is not shared by major background processes like $t\bar{t}$ production or $q\bar{q} \to W^+W^-$. For the leptonic decay of a heavy Higgs boson, $H \to W^+W^- \to \ell^+\nu\ell^-\nu$, it is shown that these backgrounds are typically accompanied by minijet emission in the 20–40 GeV range. A central minijet veto thus constitutes a powerful background rejection tool. It may be regarded as a rapidity gap trigger at the semihard parton level which should work even at high luminosities.



Central ideas for Background rejection:

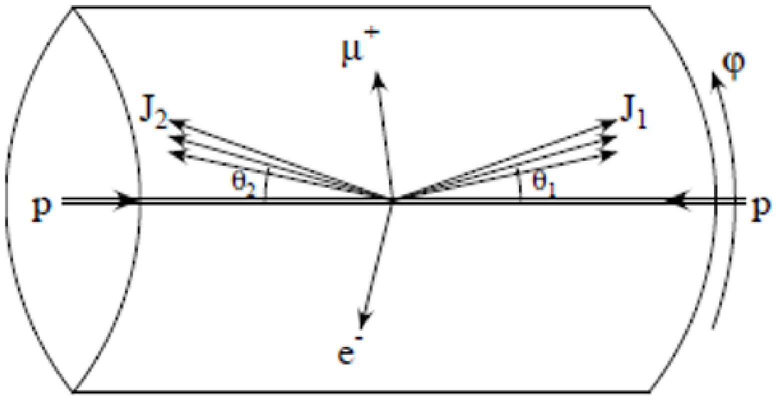
- Single forward tagging jet
- Veto additional central jets
- Require very hard central leptons

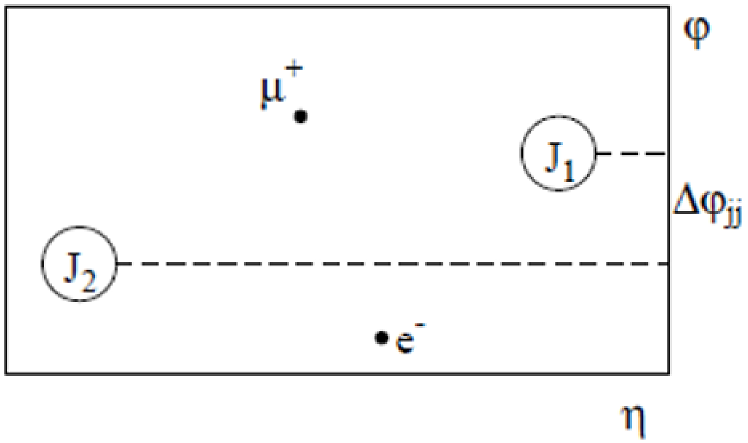
Drawback:

- Tagging jet confined to $\eta > 1.5$

Improvements (work with Kaoru, Dave Rainwater … on light Higgs)

- Double jet tagging
- Use rapidity differences: invariant under boost along beam axis





VBF/VBS characteristics:

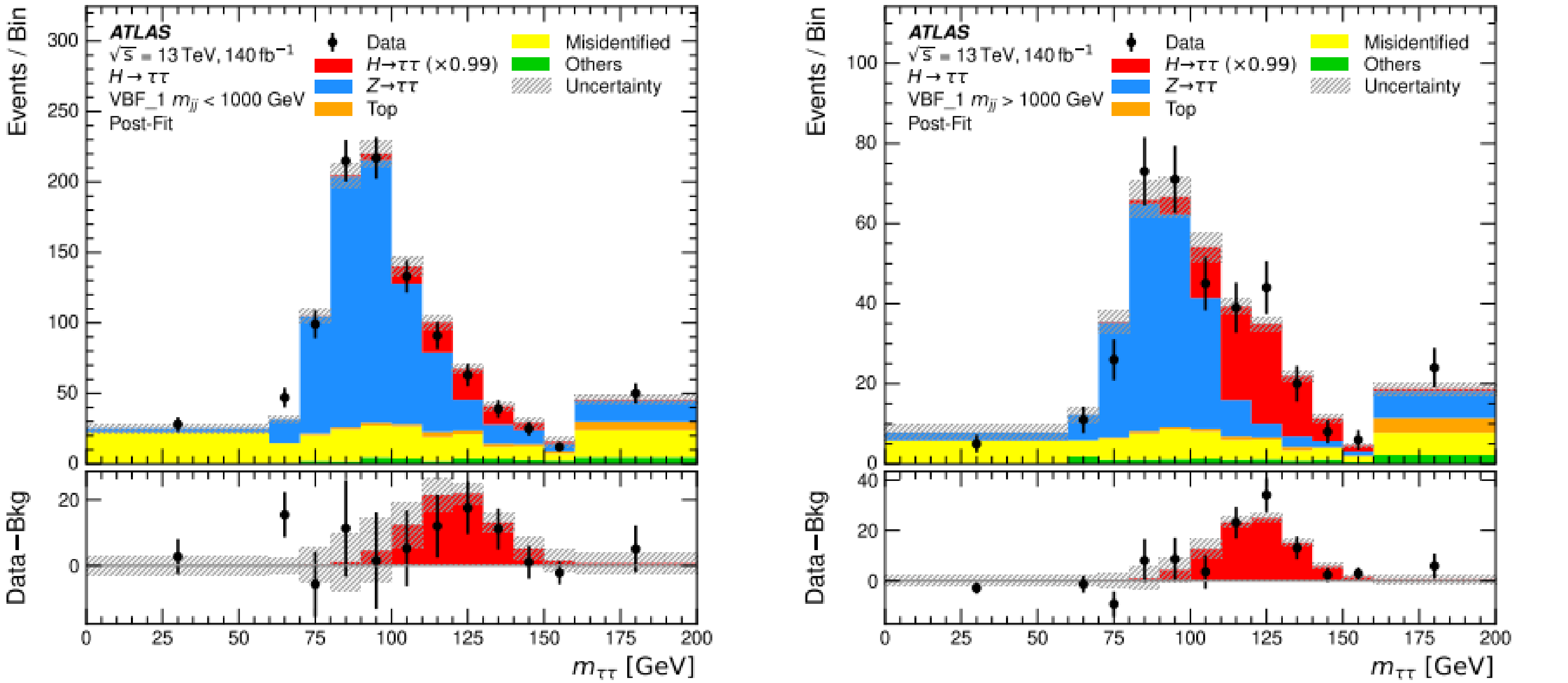
- energetic jets in the forward and backward directions ($p_T > 20$ GeV)
- large rapidity separation and large invariant mass of the two tagging jets
  $\Longrightarrow$ Enhance signal contributions by "VBF cuts", e.g.

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

- Higgs/V/VV decay products between tagging jets

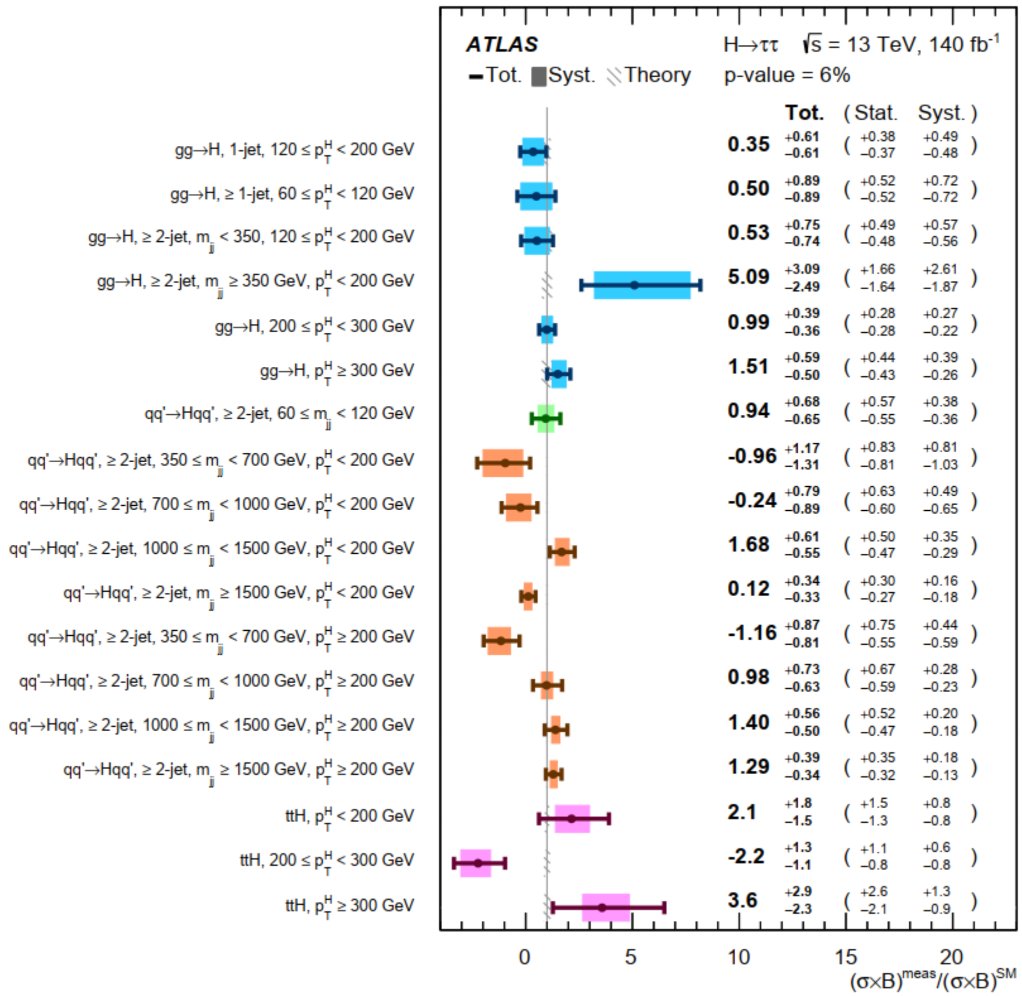
Ongoing measurements at LHC

- Example: H→tau tau in VBF



- Reconstructed tau pair invariant mass distribution clearly shows superposition of Z and Higgs peaks

Rates agree with SM expectations



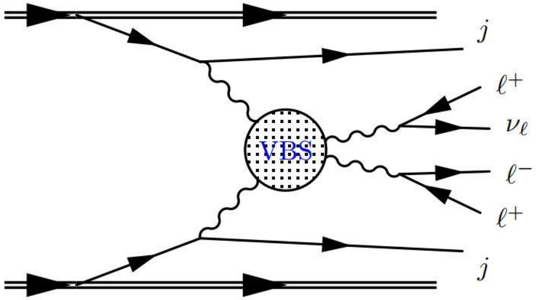
μ-values for H→tau tau for Higgs production by

gluon fusion

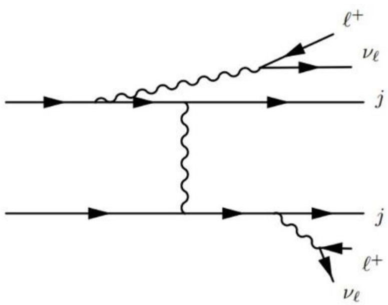
vector boson fusion

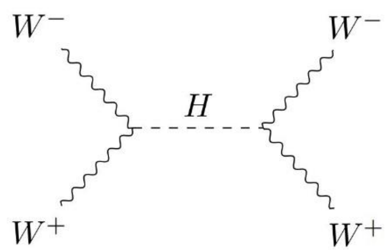
ttH production

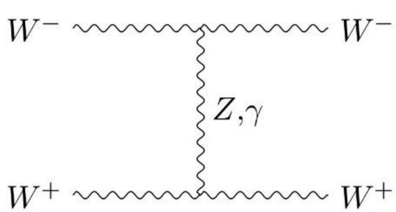
VBS and anomalous quartic gauge couplings (aQGC)

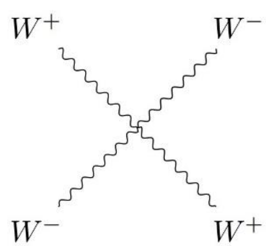


VBS provides rich source of information on dynamics of electroweak gauge bosons and EW symmetry breaking









Contributions from
- EW radiation
- Higgs exchange

- Triple gauge couplings
- Quartic gauge couplings

Use EFT to parameterize them

EFT operators for VBS

Karlsruher Institut für Technologie

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

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

$$+ \frac{f_{T_0}}{\Lambda^4} \mathrm{Tr}\left(\hat{W}^{\mu\nu} \hat{W}_{\mu\nu} \right) \mathrm{Tr}\left(\hat{W}^{\alpha\beta} \hat{W}_{\alpha\beta} \right) + \ldots \quad \text{(… = 7 more)}$$

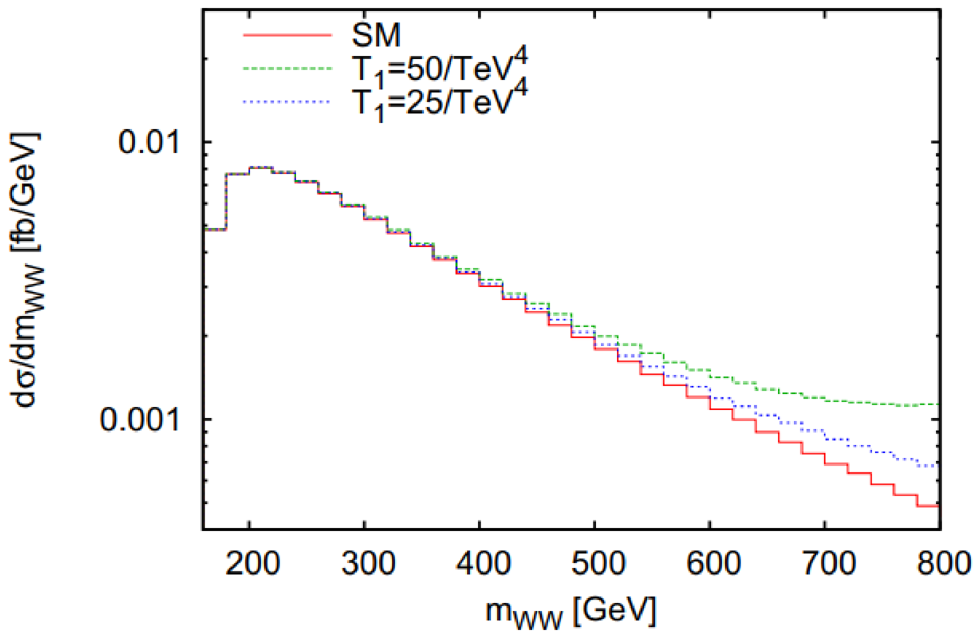
$$+ \frac{f_{M_0}}{\Lambda^4} \mathrm{Tr}\left[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] + \ldots \quad \text{(6 more)}$$

$$+ \frac{f_{S_0}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] + \ldots . \quad \text{(2 more)}$$

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

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

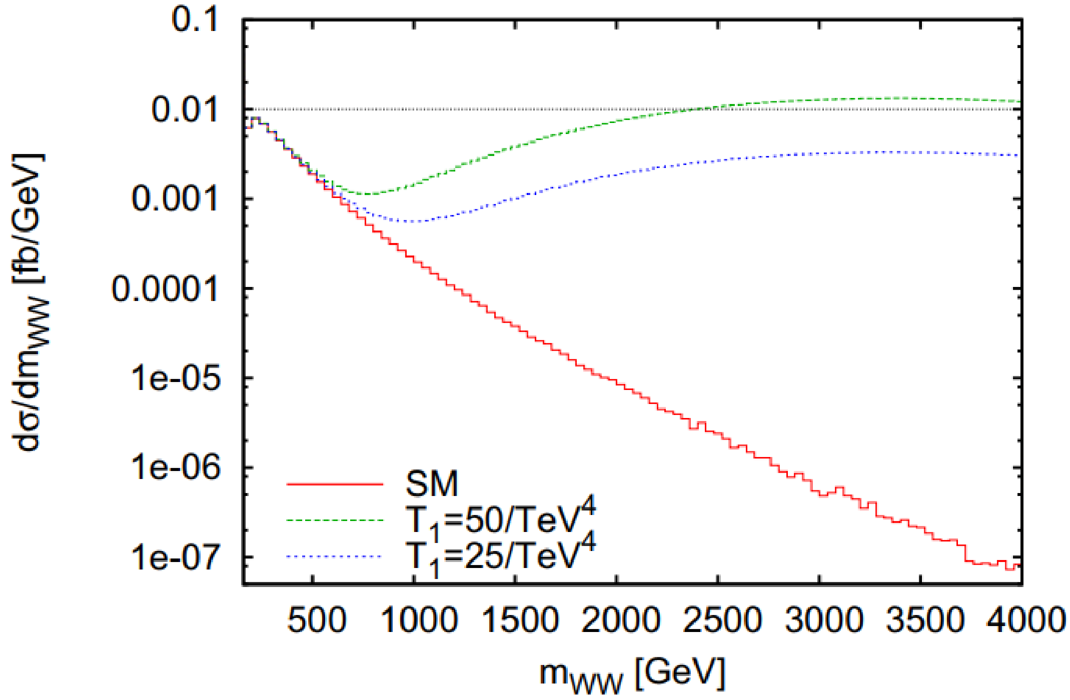
Effect of $\mathcal{L}_{eff} = \frac{f_{M,1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$
with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- 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

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

(Arzt, Einhorn, Wudka hep-ph/9405214)

- 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 $W^j_{\mu\nu} \sim f^{jkl} W^k_\mu W^l_\nu + \dots$ 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) (work with Lang, Liebler, Schäfer-Siebert)

- 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)

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

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

- 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

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

Full dim6+8 EFT considered

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

9 additional terms in EFT Lagrangian sufficient and necessary for low energy description

These operators affect:

- Dim-6

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

aTGC …

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

Propagator correction …

- Dim-8

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

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

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

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

aQGC …

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

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

aTGC …

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

Propagator correction …

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

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

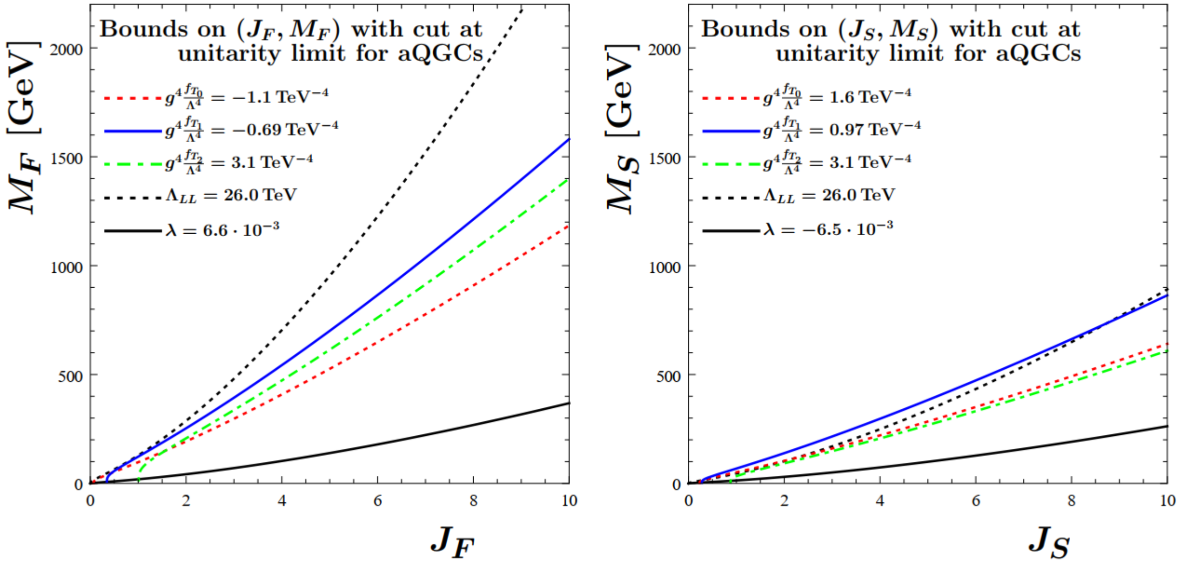
$$\frac{f_{T_1}}{\Lambda^4} = \sum_F n_F \frac{(-28C_{2,F}+13)\,T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(14C_{2,S}-5)\,T_S}{40320\pi^2 M_S^4},$$

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

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

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

Constraints from experiment (single multiplet case):

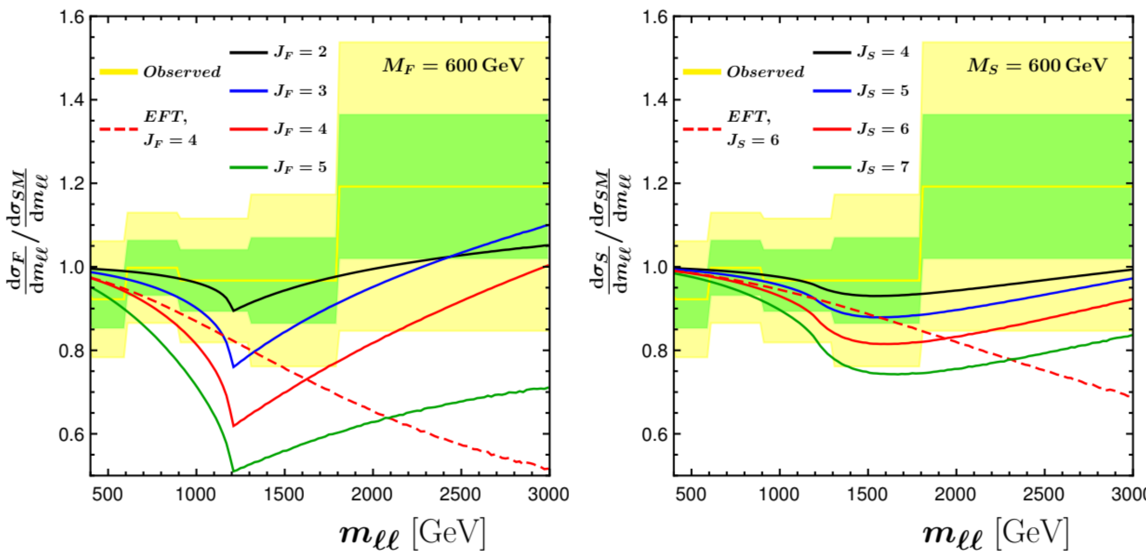


limits on individual Wilson coefficients:

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)

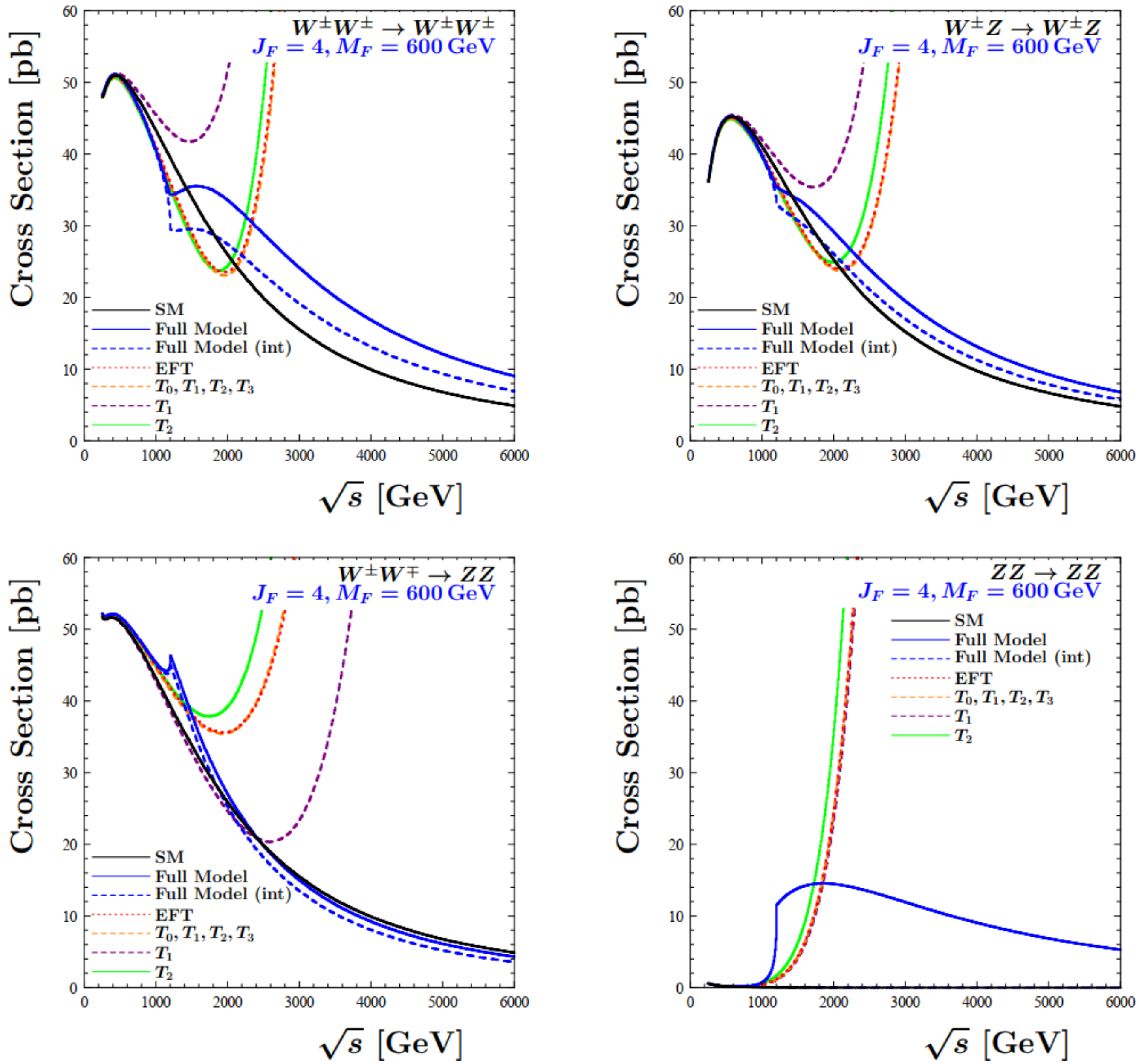


Parameter choices:

- 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:

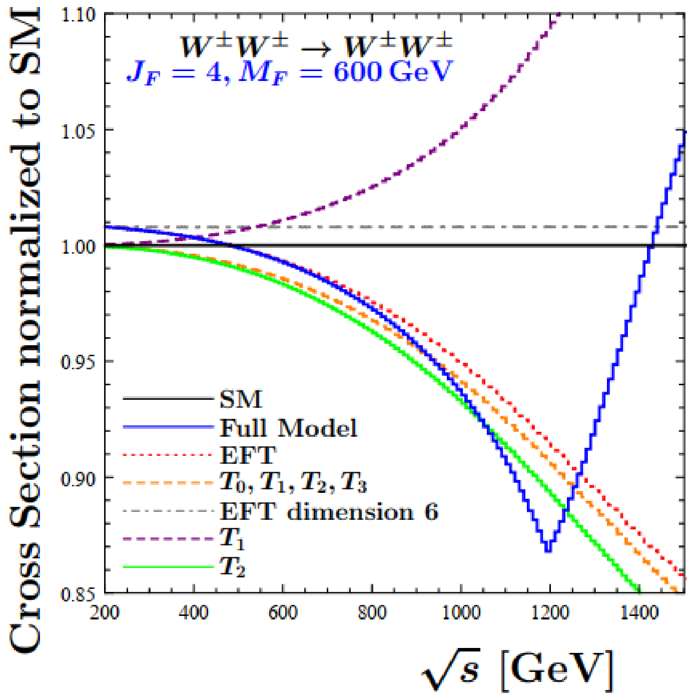
full model vs

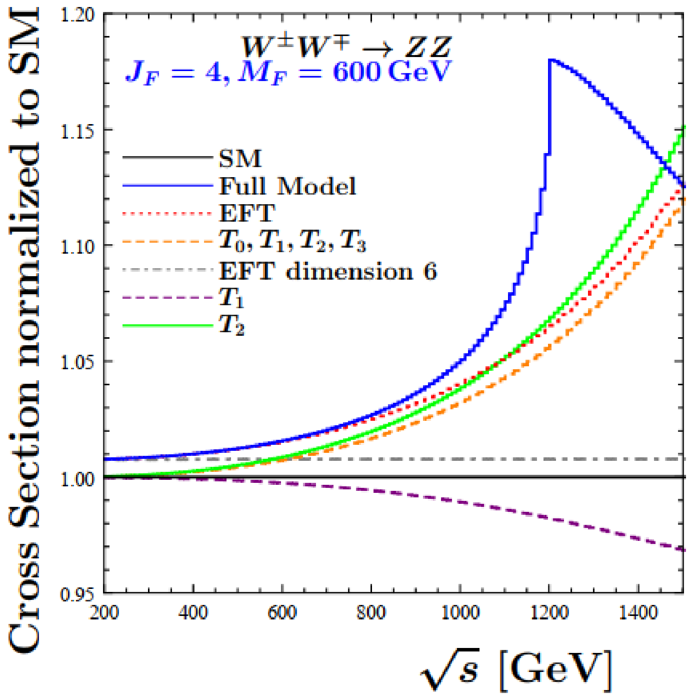
full model - no g^8 term

full EFT

individual dim 8 terms

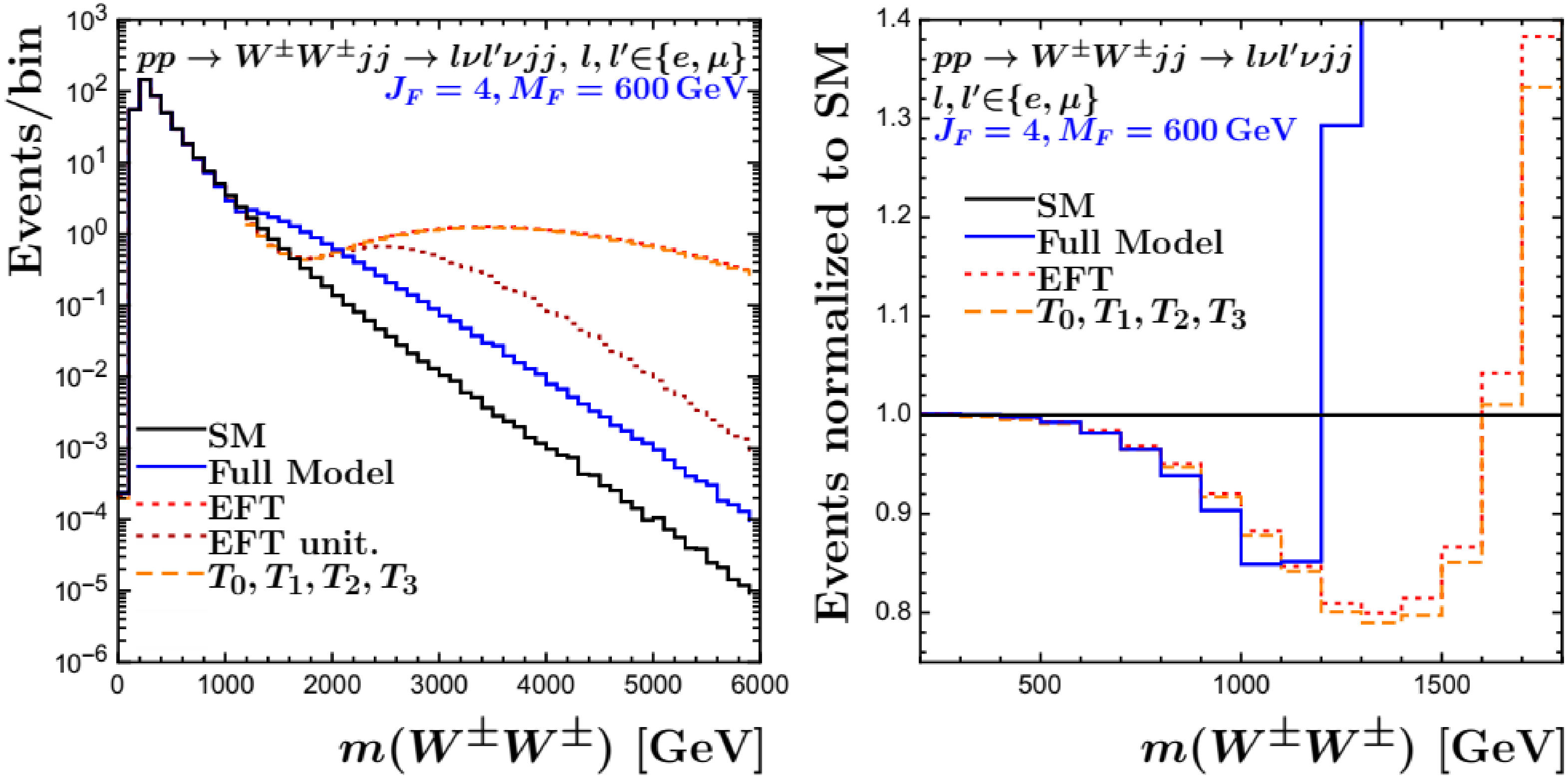
Onshell cross section in low energy region…





- 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

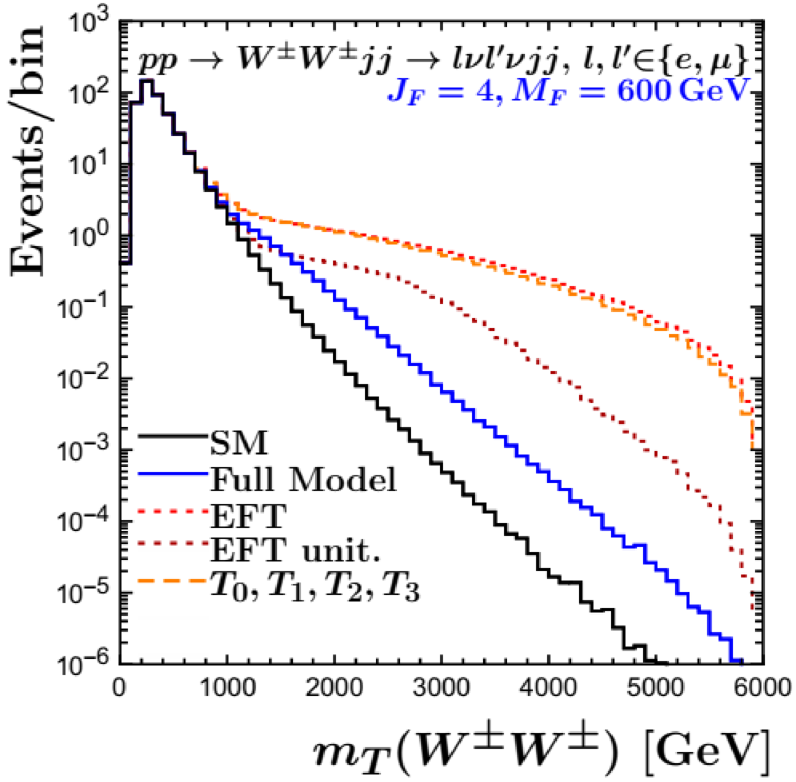
Full LHC cross sections simulations with VBFNLO

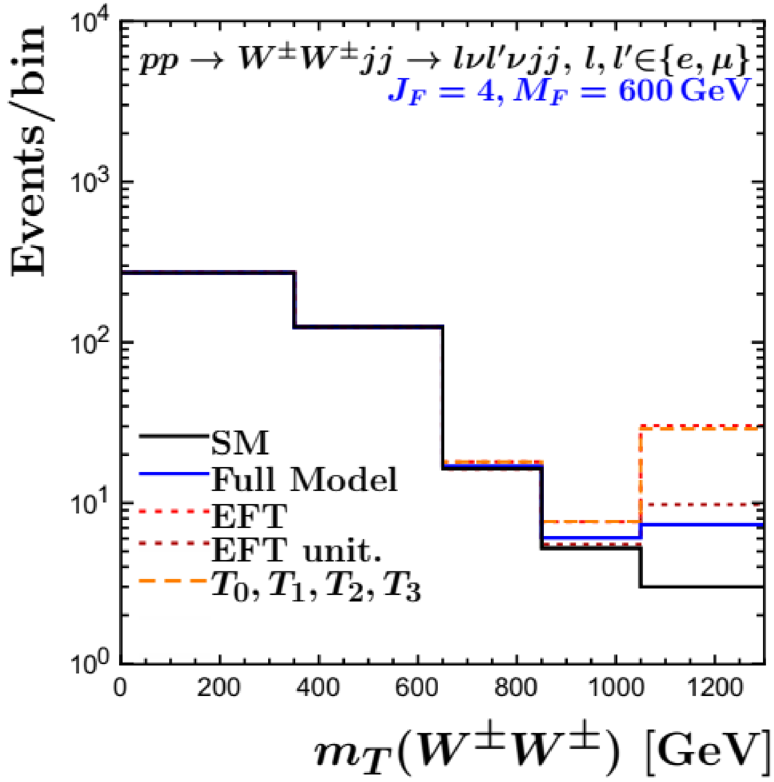


Sizable deviations from SM well above threshold, for high isospin fermions

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

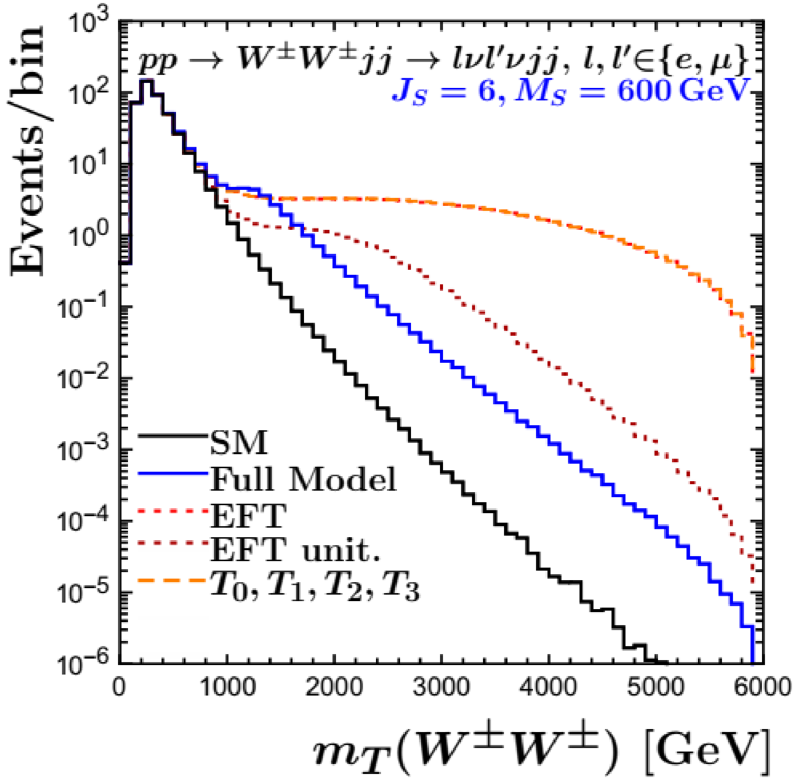
Transverse mass distribution of leptons + pTmiss

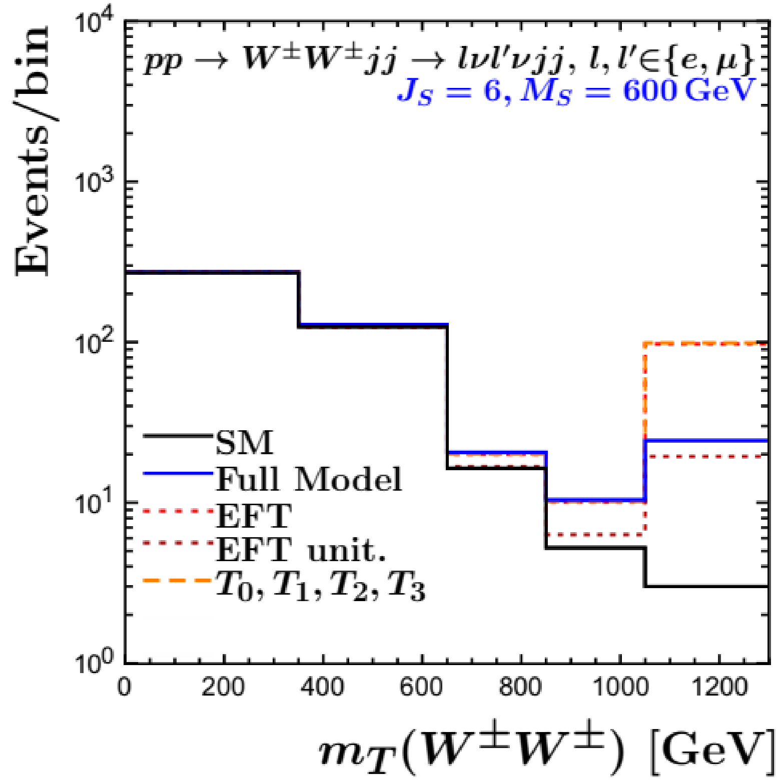




Only transverse mass can be reconstructed experimentally for same sign W pairs

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

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

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

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

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

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

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

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

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

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

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

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

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

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

- 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

… and consequences for VBS

- Observation of large loop-induced anomalous couplings (T- and also M-operators) at the LHC kills perturbative/weak coupling extrapolation of the SM well below the Planck scale with major consequences, e.g.
  1. Nearby Landau pole
  2. No GUT
  3. Lower Planck scale due to extra dimensions
- Alternatively: LHC observation of anomalies in transverse VBS is highly unlikely
  ➔ huge reduction of number of anomalous couplings which need to be considered in VBS analyses: S-operators are sufficient as long as experimental uncertainties are above a few percent

Conclusions

Karlsruher Institut für Technologie

- There are many formally 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

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 $\Phi = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} .$

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

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

Field strength ←→ transverse polarizations

Transverse operators

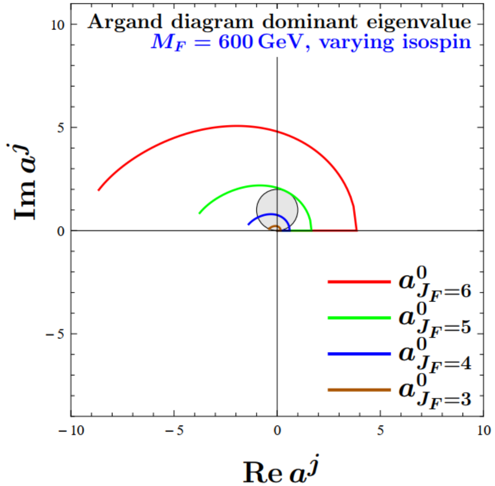
$$\mathcal{O}_{T_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$\mathcal{O}_{T_1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$\mathcal{O}_{T_2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right]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

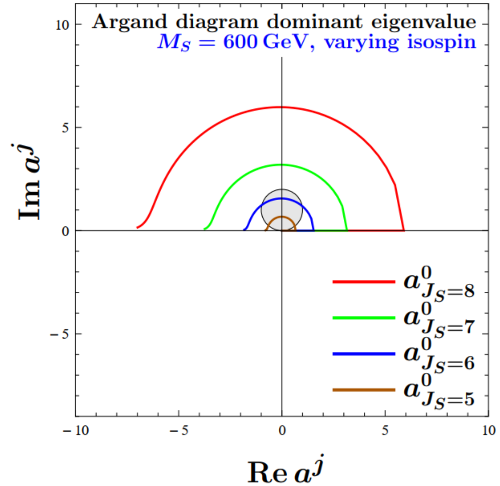
Mixed: transverse-longitudinal

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

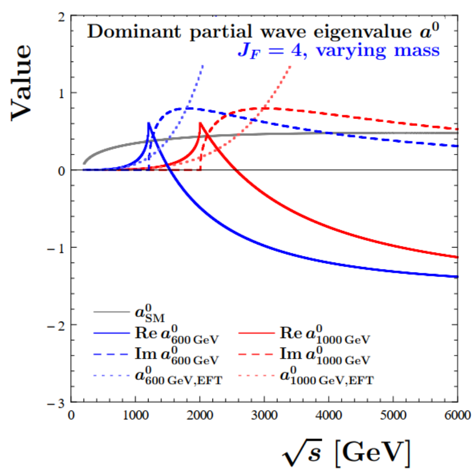
Unitarity considerations limit size of isospin representations

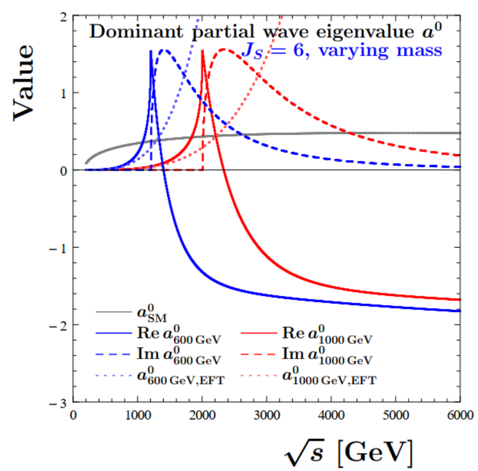
- Argand diagram for dominant VV→VV partial wave amplitude: At large J_R, model becomes non-perturbative





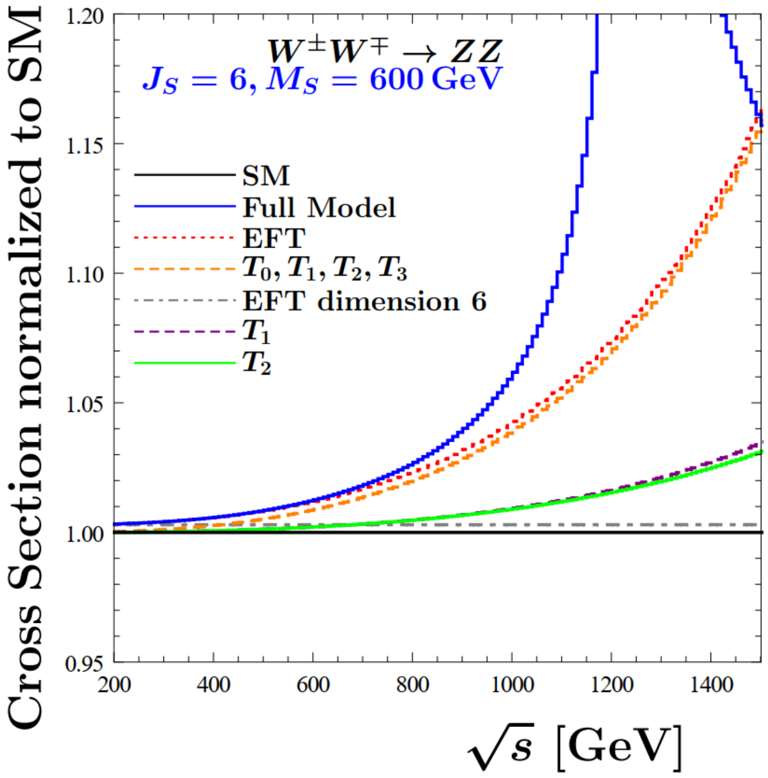
- Energy dependence of dominant partial wave amplitude

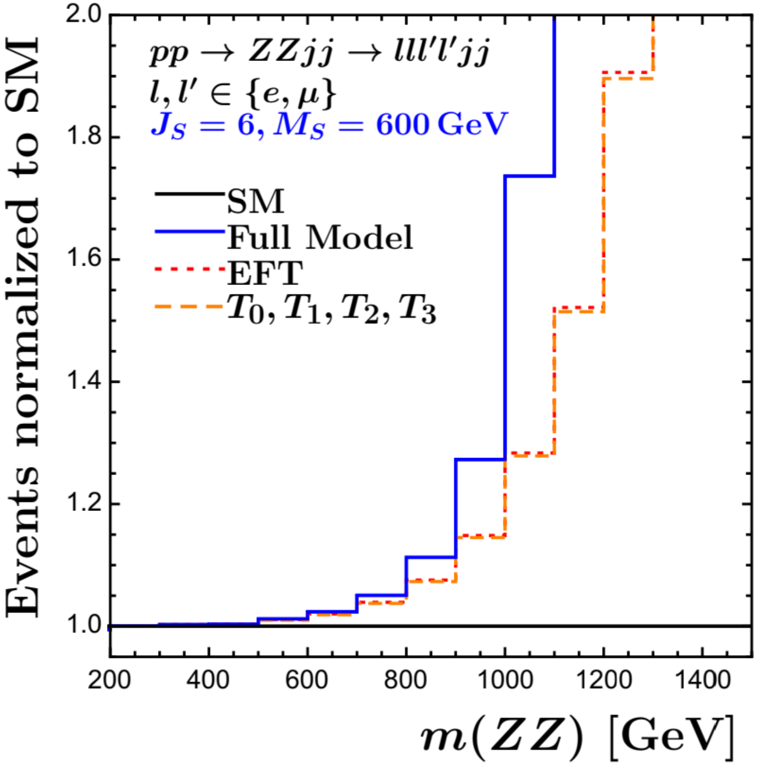




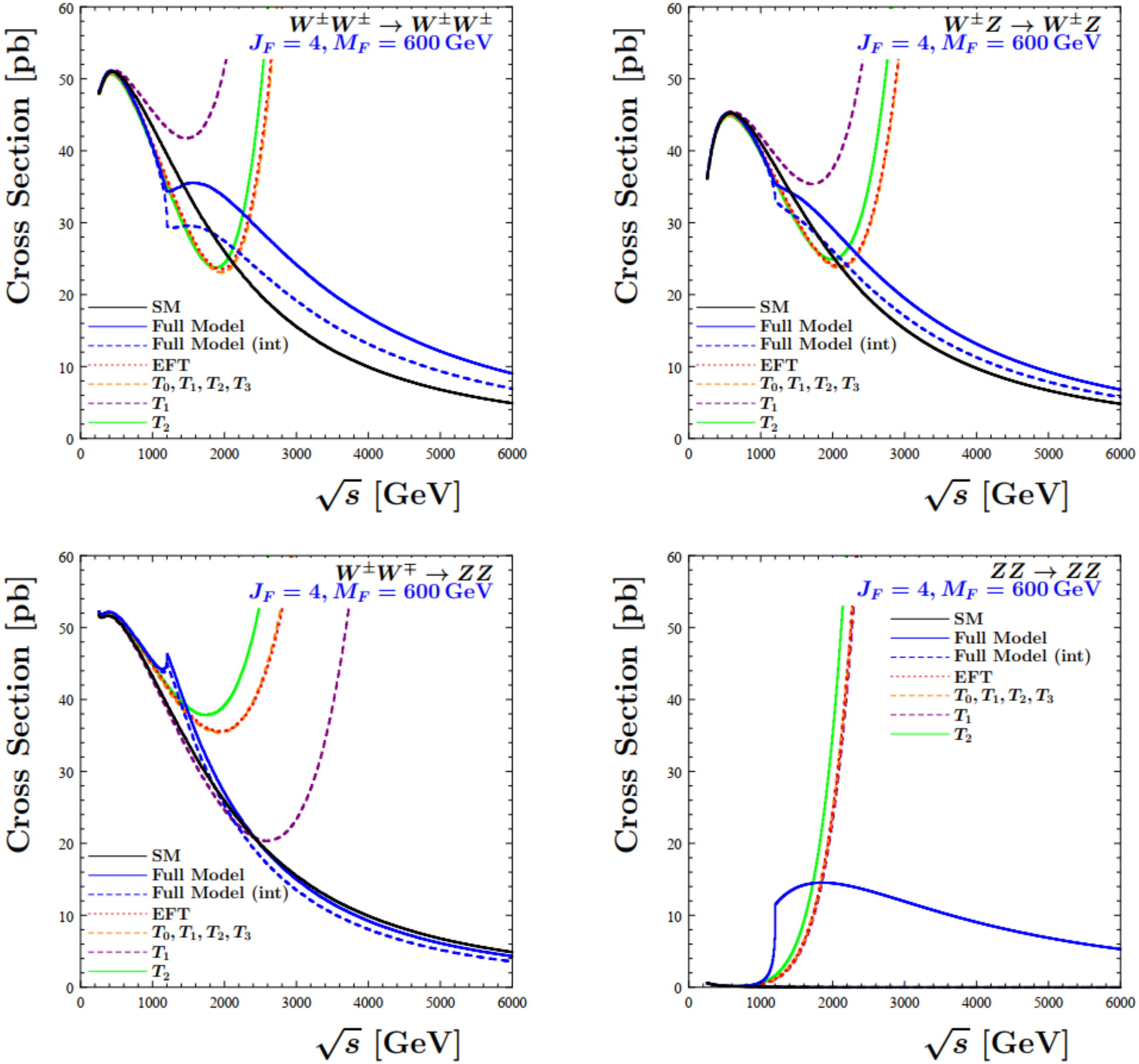
Consider $J_F \leq 4$ and $J_S \leq 6$ as range of perturbative domain

EFT validity range for ZZ production in VBS



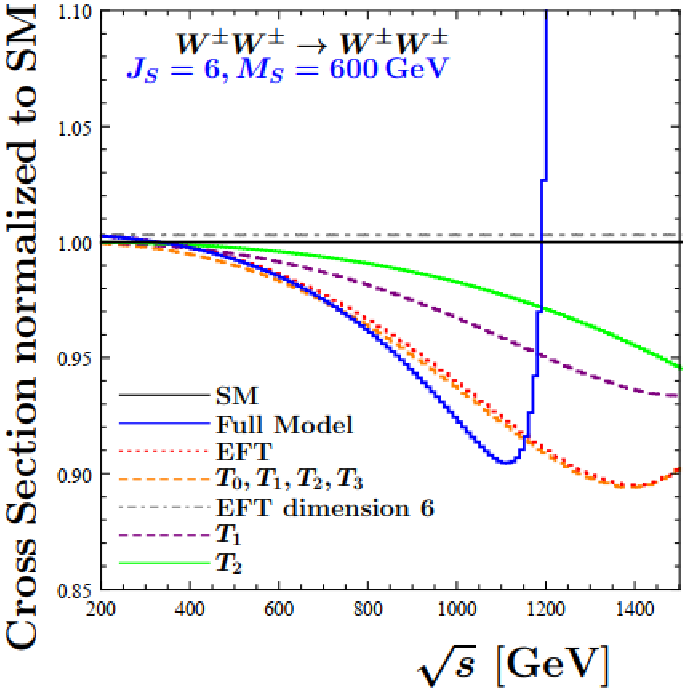


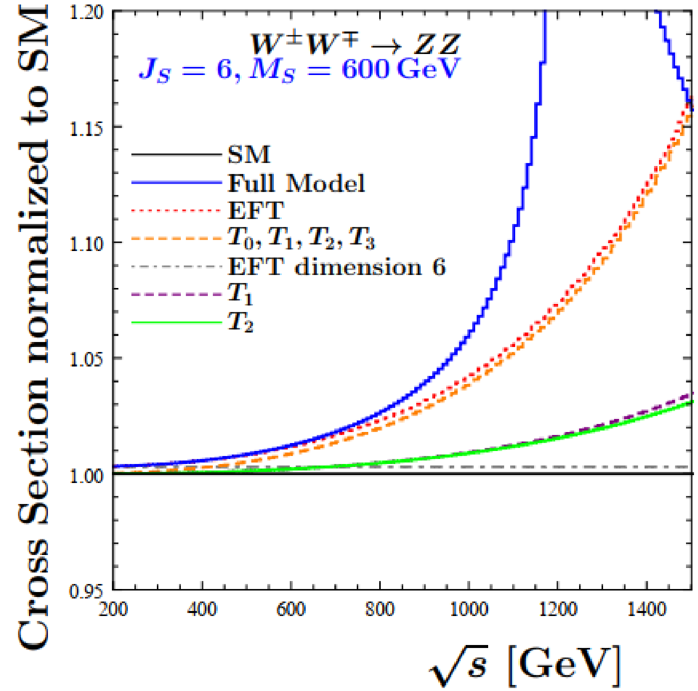
- EFT is valid only well below threshold at 2 M_S =1200 GeV (as expected)
- Deviations from SM barely reach 10% within EFT validity range, even for J_S= 6
- Because of J_R^5 vs J_R^3 growth, dim-8 terms are much more important than dim-6



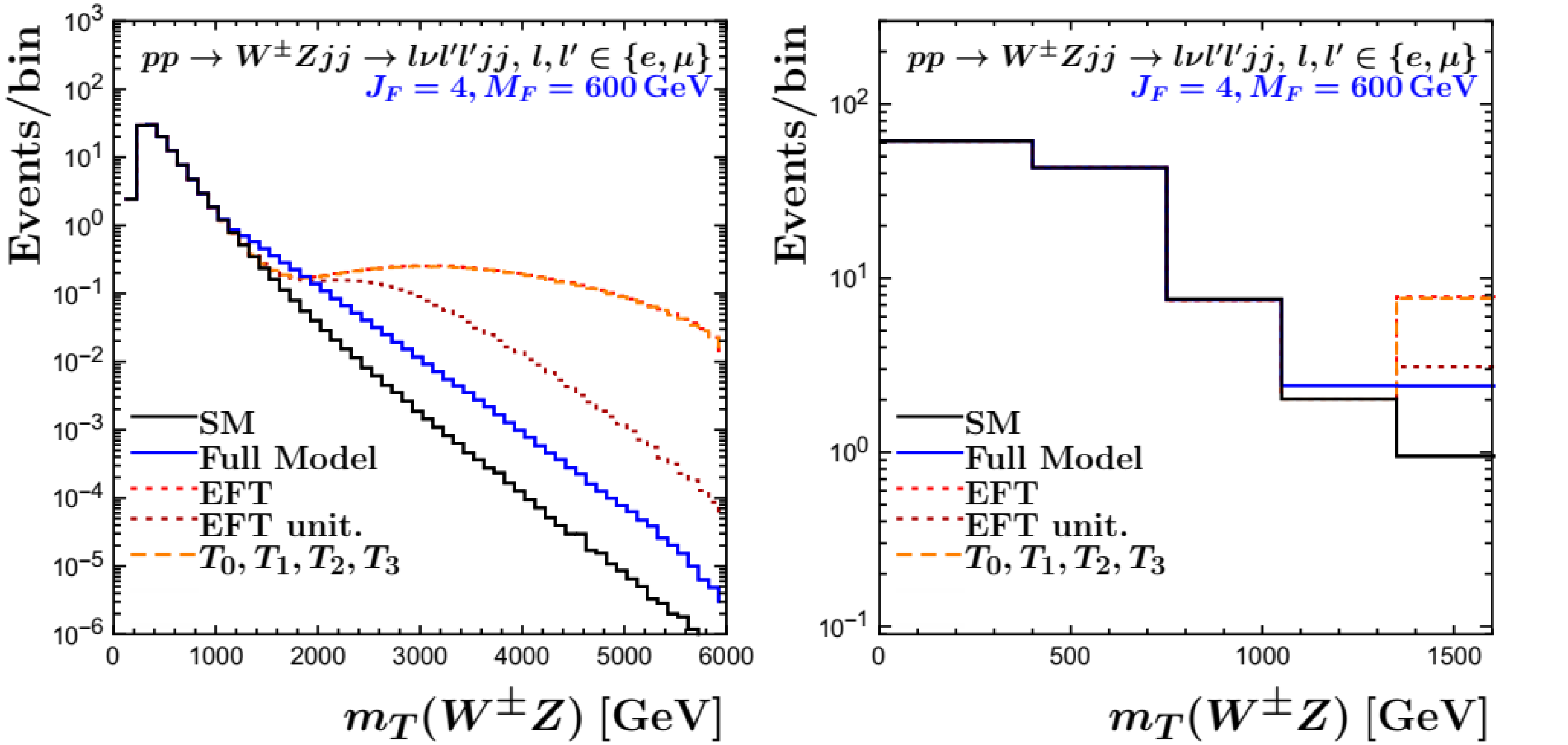
Onshell cross sections

…. 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



$pp \to W^{\pm}Zjj \to l\nu l'l'jj,\ l,l' \in \{e,\mu\}$
$J_F = 4, M_F = 600\,\mathrm{GeV}$
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]

Relative importance of terms (thesis Jannis Lang)

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

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.

Changing the mass of the heavy multiplets