A2b: Vector-Boson Scattering and Multi-Boson Production

Unitarization exemplified: A concrete model and its effective field theory

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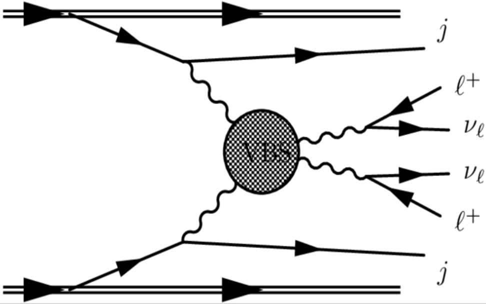


Outline

Goal

Description of BSM effects in Vector-Boson Scattering (VBS)

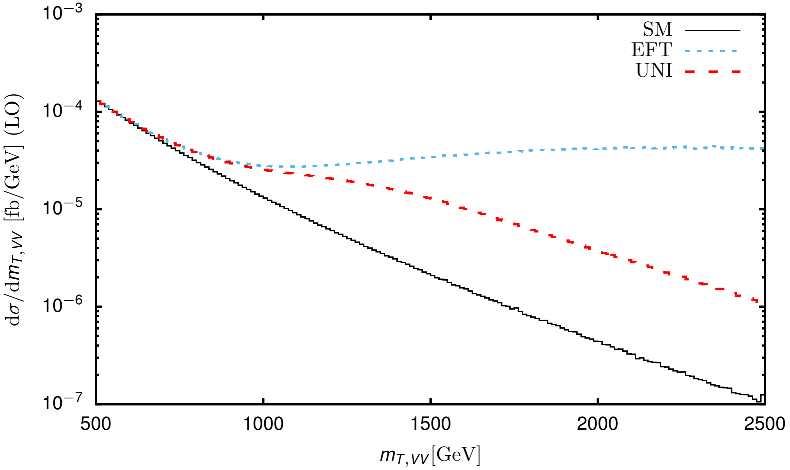
- UV complete model
- Bottom-up EFT

EFT

$$\mathcal{L}_{EFT} = \sum_{d=6}^{\infty} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} = \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} O_i^{(8)} + \dots$$
$$= \frac{f_{WWW}}{\Lambda^2} \mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu} \hat{W}^{\nu}{}_{\rho} \hat{W}^{\rho}{}_{\mu} \right) + \dots$$
$$+ \frac{f_{T_0}}{\Lambda^4} \mathrm{Tr}\left(\hat{W}^{\mu\nu} \hat{W}_{\mu\nu} \right) \mathrm{Tr}\left(\hat{W}^{\alpha\beta} \hat{W}_{\alpha\beta} \right) + \dots$$
$$+ \frac{f_{M_0}}{\Lambda^4} \mathrm{Tr}\left[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] + \dots$$
$$+ \frac{f_{S_0}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] + \dots . \quad (1)$$

- Deviations from the SM can rise with energy
- Finite range of validity

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



Goal

Description of BSM effects in Vector-Boson Scattering (VBS)

- UV complete model
- Unitarized bottom-up EFT
  - Cut-off, Clipping
  - Form-Factor
  - K-Matrix unitarization
  - T-Matrix projection (arxiv:1807.02512)
  - $\mathrm{T_u}$-model (arxiv:1807.02707)
  - ...

Which unitarization should one use?

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Which unitarization should one use?

- Any unitarization is better than no unitarization

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Which unitarization should one use?

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Limits

How well does the unitarized EFT describe features of the UV complete model?

- Small deviations
- Resonances
- Threshold behavior

Limits

How well does the unitarized EFT describe features of a UV complete model?

- Small deviations: quite well
- Resonances:
  - Transverse scattering: not at all (arxiv:1807.02512)
  - Longitudinal scattering: Ideas (e.g. Inverse Amplitude Method arxiv:1808.04413)
- Threshold behavior: ?

Toy Model

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Requirements

- Enhancement in transverse scattering
- Coupling only to vector bosons (and Higgs boson)
- Dimension-8 operators are dominant in the corresponding EFT (VBS is the most relevant channel)
- EFT is not ruled out (current limits on Wilson coefficients)

Toy Model

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Partice Contetn

- Massive fermionic and/or scalar $SU(2)_L$ multiplets
- $SU(2)_L$ representation R specified by isospin J_R
- coupling only to gauge bosons via $SU(2)_L$ gauge interaction
- Effects at one-loop level
- Charged loop particle lead to field strength tensors in EFT

Relevant Lagrangian in the $SU(2)_L$ limit

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

- Fermionic coupling is not chiral
- Model coincides with the class of minimal dark matter models (e.g. arxiv:0512090 [hep-ph])
- Give contributions to vector boson propagators, three vector boson vertices and four vector boson vertices at 1-loop level

Loop Calculation and Renormalization

- Rewrite loop contributions in terms of Passarino-Veltman integrals
- $\overline{MS}$ renormalization of the gauge boson fields and the coupling g, $\mu = M_F^2, M_S^2$

$$\delta_3 = -g^2\Delta_\epsilon\left(\sum_F n_F \frac{T_F}{12\pi^2} + \sum_S n_S \frac{T_S}{48\pi^2}\right) , \tag{3}$$

$$\delta_g = -\frac{1}{2}\delta_3 = \frac{g^2}{2}\Delta_\epsilon\left(\sum_F n_F \frac{T_F}{12\pi^2} + \sum_S n_S \frac{T_S}{48\pi^2}\right) , \tag{4}$$

$$\Delta_\epsilon = \frac{1}{\epsilon} - \gamma_E + \log(4\pi), \tag{5}$$

$$T_R = \frac{1}{3}\left[J_R(J_R+1)(2J_R+1)\right] , \quad C_{2,R} = J_R(J_R+1). \tag{6}$$

EFT

$$
\begin{aligned}
\mathcal{L}_{EFT} = {} & f_{WW} \mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right) + \frac{f_{DW}}{\Lambda^2}\mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}^\alpha, \hat{W}_{\mu\nu}]\right) \\
& + \frac{f_{WWW}}{\Lambda^2}\mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu}\hat{W}^{\nu}{}_{\rho}\hat{W}^{\rho}{}_{\mu}\right) + \frac{f_{D2W}}{\Lambda^4}\mathrm{Tr}\left([\hat{D}_\alpha, [\hat{D}^\alpha, \hat{W}^{\mu\nu}]][\hat{D}_\beta, [\hat{D}^\beta, \hat{W}_{\mu\nu}]]\right) \\
& + \frac{f_{DWWW_0}}{\Lambda^4}\mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu}{}_{\nu}][\hat{D}^\alpha, \hat{W}^{\nu}{}_{\rho}]\hat{W}^{\rho}{}_{\mu}\right) \\
& + \frac{f_{DWWW_1}}{\Lambda^4}\mathrm{Tr}\left([\hat{D}_\alpha, \hat{W}^{\mu\nu}][\hat{D}_\beta, \hat{W}^{\mu\nu}]\hat{W}^{\alpha\beta}\right) \\
& + \frac{f_{T_0}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\alpha\beta}\right) + \frac{f_{T_1}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}^{\alpha\beta}\hat{W}_{\mu\nu}\right) \\
& + \frac{f_{T_2}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu}{}_{\nu}\hat{W}^{\nu}{}_{\alpha}\right)\mathrm{Tr}\left(\hat{W}^{\alpha}{}_{\beta}\hat{W}^{\beta}{}_{\mu}\right) + \frac{f_{T_3}}{\Lambda^4}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}^{\alpha\beta}\right)\mathrm{Tr}\left(\hat{W}_{\nu\alpha}\hat{W}_{\beta\mu}\right) .
\end{aligned}
\tag{7}
$$

Matching

- Matching for $p_i \cdot p_j \ll M^2$
- Propagator corrections

$$f_{WW} = \sum_F n_F \frac{T_F}{24\pi^2}\left(\Delta_\epsilon + \log\left(\frac{\mu^2}{M_F^2}\right)\right) + \sum_S n_S \frac{T_S}{96\pi^2}\left(\Delta_\epsilon + \log\left(\frac{\mu^2}{M_S^2}\right)\right), \quad (8)$$

$$\frac{f_{DW}}{\Lambda^2} = \sum_F n_F \frac{T_F}{120\pi^2 M_F^2} + \sum_S n_S \frac{T_S}{960\pi^2 M_S^2}, \quad (9)$$

$$\frac{f_{D2W}}{\Lambda^4} = \sum_F n_F \frac{T_F}{1120\pi^2 M_F^4} + \sum_S n_S \frac{T_S}{13440\pi^2 M_S^4}. \quad (10)$$

Matching

- Three gauge boson vertex

$$\frac{f_{WWW}}{\Lambda^2} = \sum_F n_F \frac{13 T_F}{360\pi^2 M_F^2} + \sum_S n_S \frac{T_S}{360\pi^2 M_S^2} \,, \tag{11}$$

...

- Four gauge boson vertex

$$\frac{f_{T_0}}{\Lambda^4} = \sum_F n_F \frac{(-14 C_{2,F} + 1)\, T_F}{10080\pi^2 M_F^4} + \sum_S n_S \frac{(7 C_{2,S} - 2)\, T_S}{40320\pi^2 M_S^4} \,, \tag{12}$$

$$\frac{f_{T_2}}{\Lambda^4} = \sum_F n_F \frac{(196 C_{2,F} - 397)\, T_F}{25200\pi^2 M_F^4} + \sum_S n_S \frac{(14 C_{2,S} - 23)\, T_S}{50400\pi^2 M_S^4} . \tag{13}$$

...

Matching

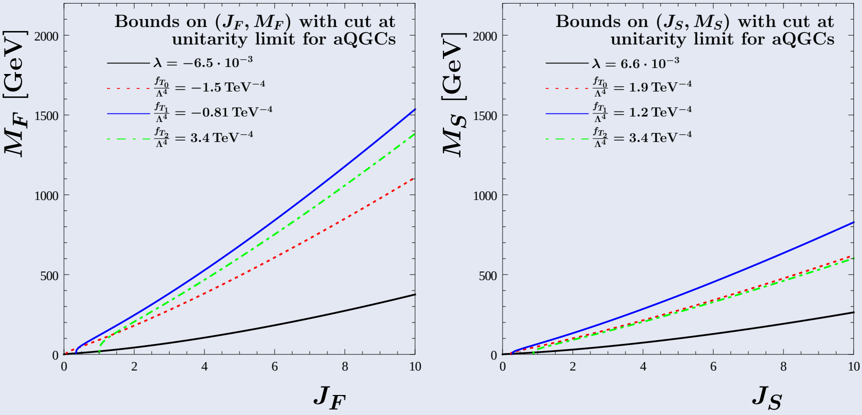
- Propagator and three gauge boson vertex corrections: J^3
- Four gauge boson vertex corrections: J^5
- Dimension-8 operators more dominant for larger J

Choice of M and J

Restrictions on J and M

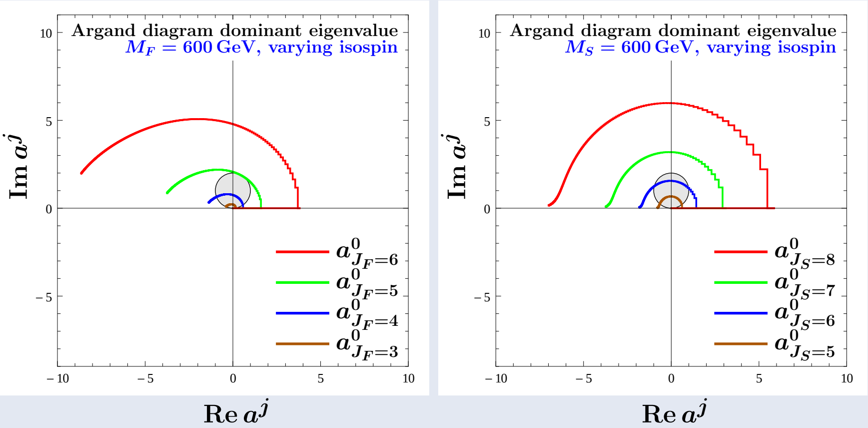
- Dim. 8 operators are dominant
- Perturbative unitarity
- Sizalbe but not yet excluded deviation from SM

Experimental Constraints

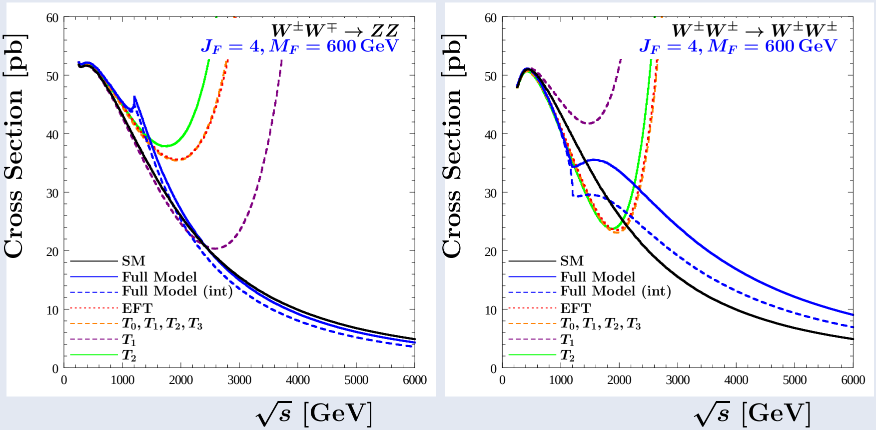


Value pairs below the curves would be disfavored by experimental analysis.

Perturbative Unitarity, Partial Wave Coefficients



On Shell Scattering



The cross sections are calculated with the total amplitude squared, only the Full Model (int) result (blue, dashed) is obtained using the typical NLO expansion of the cross section.

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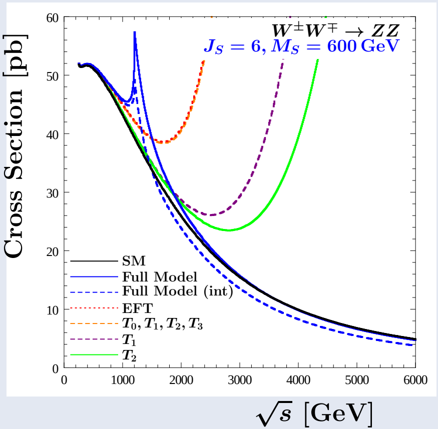

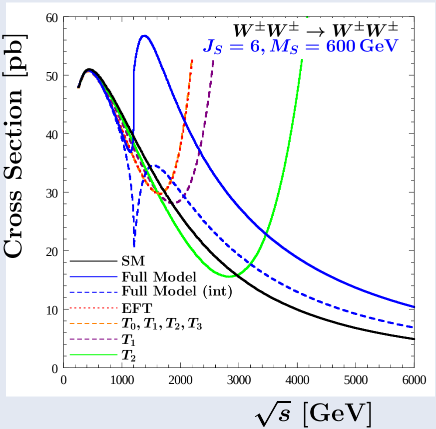

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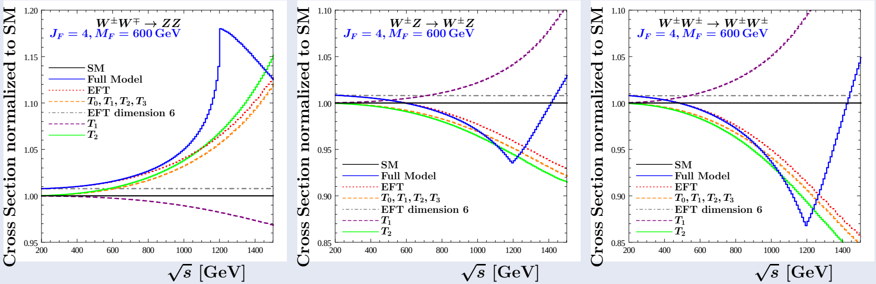
On Shell Scattering



Depending on the process:

- Constructive or destructive interference between different T-operators
- Constructive or destructive interference between the SM and the toy model

Good agreement between EFT and toy model up to $1\ \mathrm{TeV}$
Dim-6 operators are negligible

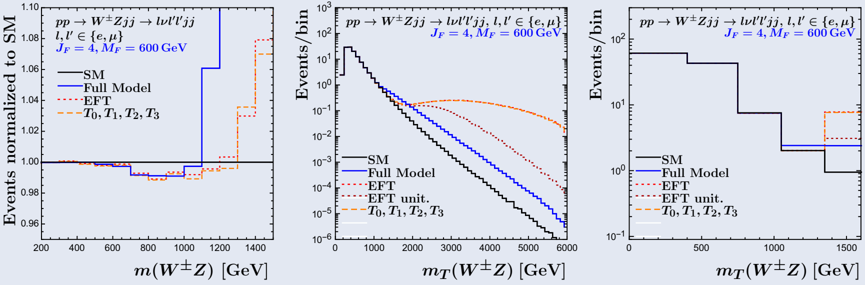
Full Analysis (VBFNLO)

Process:

$pp \to W^{\pm}Zjj \to l'^{\pm}\nu_{l'} l^{\pm} l^{\mp} jj$

Cuts:

$$
\begin{aligned}
p_T^{l'}, p_T^{l} &> 20\,\text{GeV}\,, & |\eta^{e}| &< 2.5\,, & |\eta^{\mu}| &< 2.4 \\
|m_{ll} - m_Z| &< 15\,\text{GeV}\,, & m_{3l} &> 100\,\text{GeV}\,, & p_T^{\text{miss}} &> 30\,\text{GeV} \\
|\eta^{j}| &< 4.7\,, & p_T^{j} &> 50\,\text{GeV}\,, & |\Delta R(j,l)| &> 0.4 \\
m_{jj} &> 500\,\text{GeV}\,, & |\Delta\eta_{jj}| &> 2.5\,, & \max(z_l^{*}) &< 1.0\,.
\end{aligned}
\tag{14}
$$



The number of events are shown for an integrated luminosity of 137 fb^{-1}.

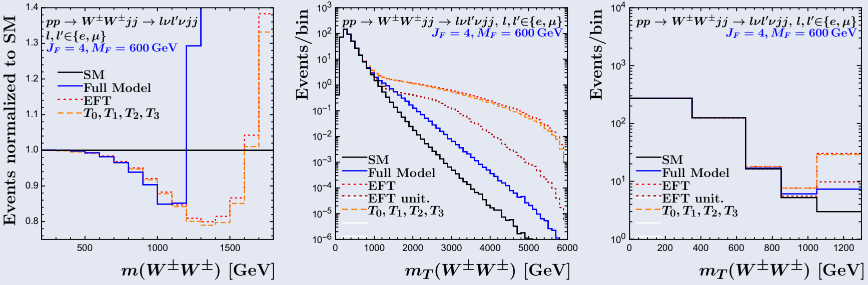
Full Analysis (VBFNLO)

Process:

$pp \to W^\pm W^\pm jj \to l^\pm \nu_l l'^\pm \nu_{l'}$

Cuts:

$$\begin{aligned} p_T^{l'}, p_T^{l} &> 20\,\text{GeV}\,, & |\eta^e| &< 2.5\,, & |\eta^\mu| &< 2.4 \\ |m_{ll} - m_Z| &< 15\,\text{GeV}\,, & m_{ll} &> 20\,\text{GeV}\,, & p_T^{\text{miss}} &> 30\,\text{GeV} \\ |\eta^j| &< 4.7\,, & p_T^j &> 50\,\text{GeV}\,, & |\Delta R(j,l)| &> 0.4 \\ m_{jj} &> 500\,\text{GeV}\,, & |\Delta\eta_{jj}| &> 2.5\,, & \max(z_l^*) &< 0.75\,. \end{aligned} \tag{15}$$



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Conclusion

Toy Model:

- Additional $SU(2)_L$ multiplets with large isospin J
- Coupling only to vector bosons (impact on VBS)
- Constructive (ZZ) and destructive (ssWW, WZ) interference with SM
- Destructive interference only visible in $m(VV)$ distribution, not in experimentally accessible $m_t(VV)$ distribution
- Even our exotic choice of $J_S = 6$ ($J_F = 4$) and $M = 600\ \mathrm{GeV}$ is compatible with SM

Conclusion

EFT:

- Dimension 8 operators can be important than dimension 6 operators (large J)
- Destructive interference between different $\mathcal{O}_T$ operators (single operator bounds overly constrain the model)
- Good agreement with Toy up to 1 TeV for $M = 600\ \mathrm{GeV} = \Lambda_{EFT}$
- Large deviations between EFT and the toy model at the pair production threshold (1.2 TeV)
- A unitarization improves the high energy behavior of the EFT but not in the threshold region

Backup

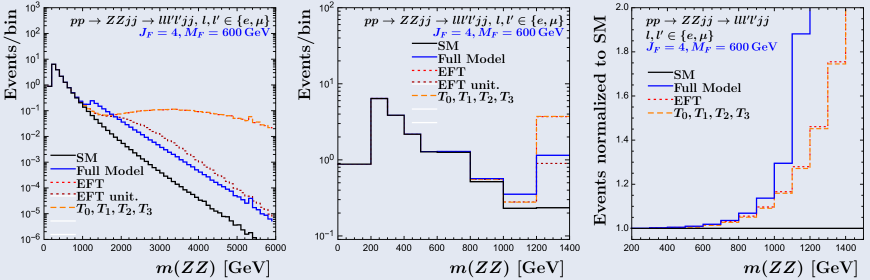
Full Analysis (VBFNLO)

Process:

$pp \to ZZjj \to l'^{\pm} l'^{\mp} l^{\pm} l^{\mp} jj$

Cuts:

$$\begin{aligned}
p_T^{l'}, p_T^{l} &> 20\,\text{GeV}\,, & |\eta^e| &< 2.5\,, & |\eta^\mu| &< 2.4 \\
|\eta^j| &< 4.7\,, & p_T^j &> 30\,\text{GeV} \\
|\Delta R(j,l)| &> 0.3\,, & m_{jj} &> 400\,\text{GeV}\,, & |\Delta\eta_{jj}| &> 2.4 \\
40\,\text{GeV} < m_{ll}, m_{l'l'} &< 120\,. & & & & \qquad (16)
\end{aligned}$$



The number of events are shown for an integrated luminosity of 137 fb^{-1}.

Drell-Yan

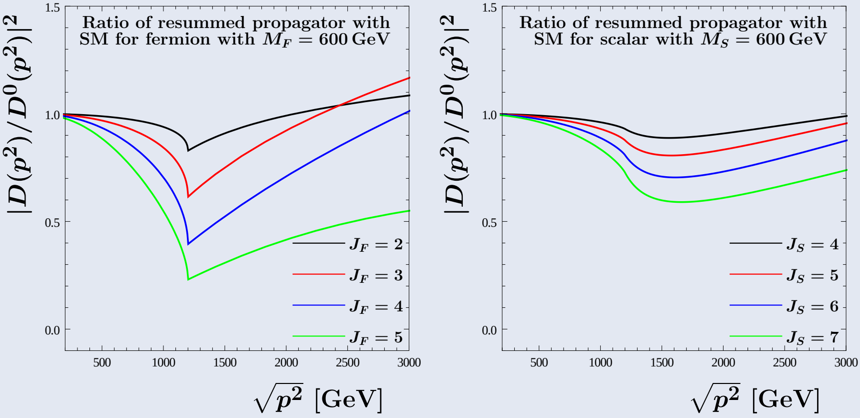


Figure: Estimation of the modification of Drell-Yan like four-fermion processes given by absolute square of the ratio of the one-loop resummed vector-boson propagator divided by the tree-level SM propagator.

$$\frac{f_{WWW}}{\Lambda^2} = \sum_F n_F \frac{13\,T_F}{360\pi^2 M_F^2} + \sum_S n_S \frac{T_S}{360\pi^2 M_S^2}\,, \tag{17}$$

$$\frac{f_{DWWW_0}}{\Lambda^4} = \sum_F n_F \frac{2\,T_F}{105\pi^2 M_F^4} + \sum_S n_S \frac{T_S}{1120\pi^2 M_S^4}\,, \tag{18}$$

$$\frac{f_{DWWW_1}}{\Lambda^4} = \sum_F n_F \frac{T_F}{630\pi^2 M_F^4} + \sum_S n_S \frac{T_S}{4032\pi^2 M_S^4}\,. \tag{19}$$

$$\frac{f_{T_0}}{\Lambda^4} = \sum_F n_F \frac{(-14 C_{2,F} + 1)\, T_F}{10080 \pi^2 M_F^4} + \sum_S n_S \frac{(7 C_{2,S} - 2)\, T_S}{40320 \pi^2 M_S^4}\,, \tag{20}$$

$$\frac{f_{T_1}}{\Lambda^4} = \sum_F n_F \frac{(-28 C_{2,F} + 13)\, T_F}{10080 \pi^2 M_F^4} + \sum_S n_S \frac{(14 C_{2,S} - 5)\, T_S}{40320 \pi^2 M_S^4}\,, \tag{21}$$

$$\frac{f_{T_2}}{\Lambda^4} = \sum_F n_F \frac{(196 C_{2,F} - 397)\, T_F}{25200 \pi^2 M_F^4} + \sum_S n_S \frac{(14 C_{2,S} - 23)\, T_S}{50400 \pi^2 M_S^4}\,, \tag{22}$$

$$\frac{f_{T_3}}{\Lambda^4} = \sum_F n_F \frac{(98 C_{2,F} + 299)\, T_F}{25200 \pi^2 M_F^4} + \sum_S n_S \frac{(7 C_{2,S} + 16)\, T_S}{50400 \pi^2 M_S^4}\,. \tag{23}$$