# Theory of anomalous gauge boson couplings

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# Plan

- Introduction
- aTGC : Anomalous couplings vs EFT
- Phenomenology (Unitarity)
- Other new interactions
- Concluding remarks

# Indirect detection of NP

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# Indirect detection of NP

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# Indirect detection of NP

E

Exp. range

NP scale

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# WWZ/A anomalous couplings

$$\mathcal{L} = ig_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho\right.$$

$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$

$$\left.-ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\right)$$

$$\boxed{g_{WW\gamma} = -e \qquad g_{WWZ} = -e\cot\theta_W}$$

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EM gauge invariance implies : $g_1^\gamma = 1 \qquad g_4^\gamma = g_5^\gamma = 0$

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$$\mathcal{L} = i g_{WWV} \Big( g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho$$

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**11(5+6) parameters**

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Why not adding derivatives

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Dimension-six

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Dimension-six

$$\sigma\left(pp \to WW\right) = \sigma_{SM} + g_1^V(1 + \frac{g_2^V}{g_1^V}\frac{s}{M_W^2})\sigma_1^V + \ldots$$

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Dimension-six

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Form factors are higher dimension operators with arbitrarily fixed coefficients

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Dimension-six

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$$\sigma\,(pp \to WV) = \sigma_{SM} + g_1^V(1 + \frac{g_2^V}{g_1^V}\frac{M_V^2}{M_W^2})\sigma_1^V + \ldots$$

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# Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d=6}^{\infty} \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- SM fields only (Higgs field included)
- Invariant under the SM symmetries

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu]$$

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Assumption : $\Lambda$>> $\mathrm{E}_{\mathrm{exp}}$

$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \mathscr{O}\left(\frac{1}{\Lambda^4}\right)$$

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Th. error

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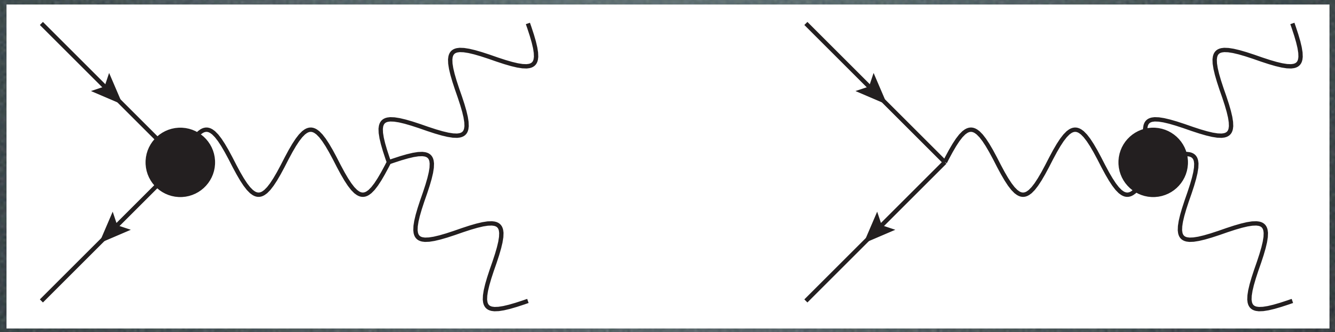
# WW(WZ/WA) production



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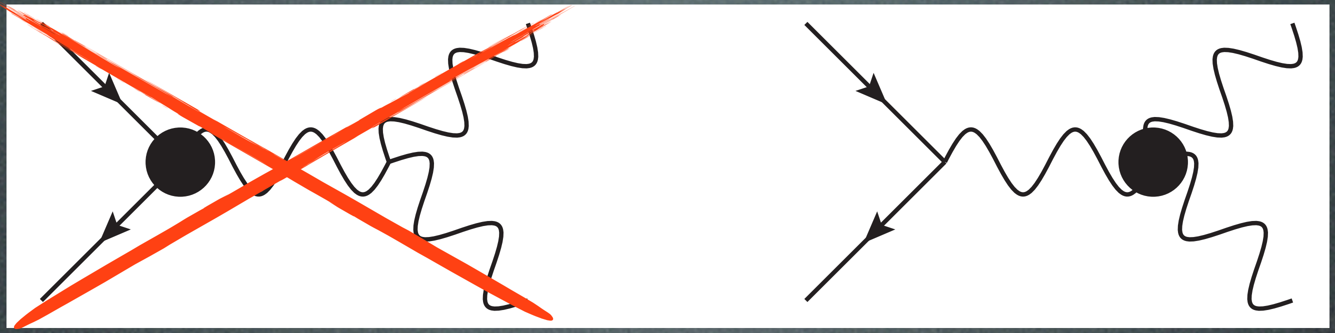

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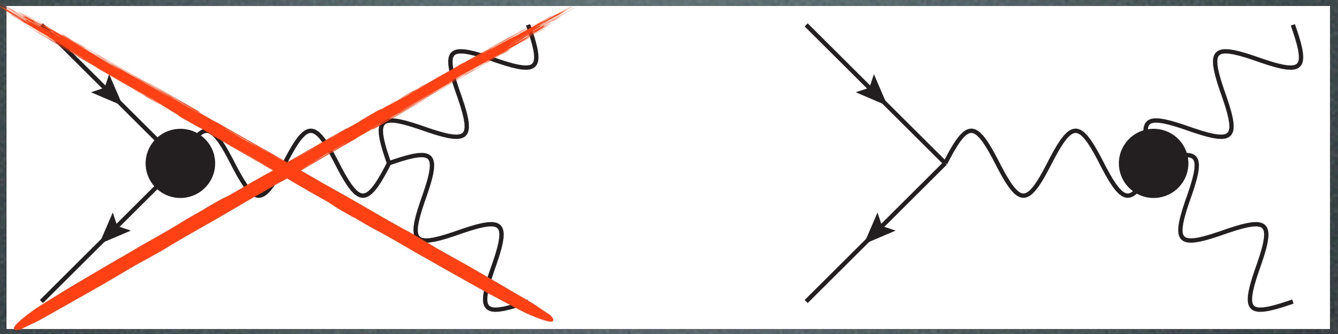

CP even operators

$$
\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)
\end{aligned}
$$

CP odd operators

$$
\begin{aligned}
\mathcal{O}_{\tilde{W}WW} &= \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\
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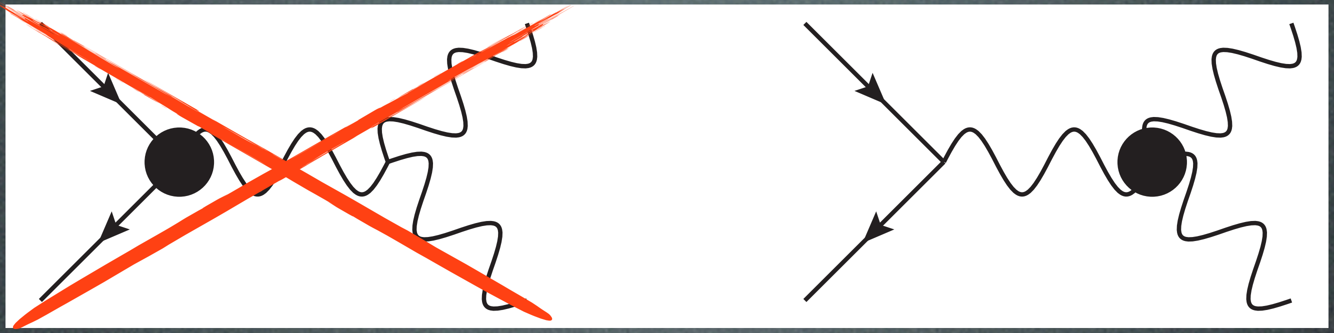

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TGC's and weak boson masses are affected by different operators at the tree-level in this basis

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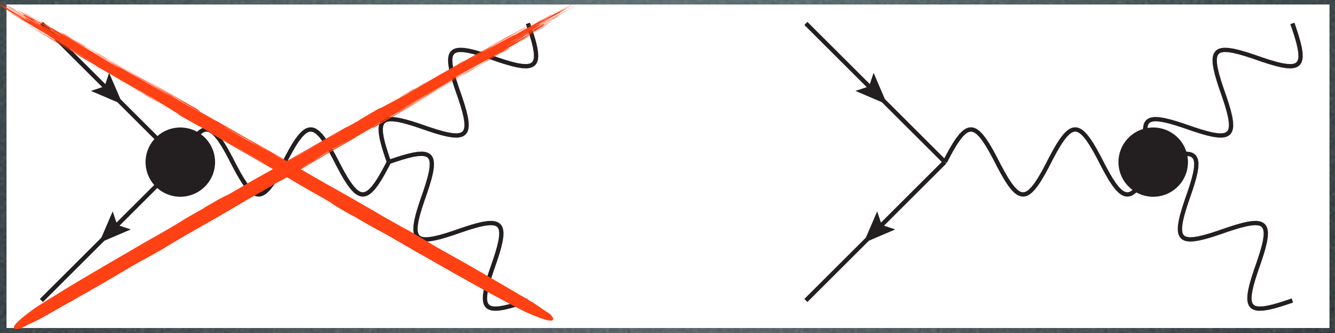

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Only 5 operators!

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# EFT versus Anomalous Couplings

| | EFT | AC |
|---|---|---|
| Lorentz | ✔ | ✔ |
| $SU(2)_L$ | ✔ | ✘ |
| $U(1)_{EM}$ | ✔ | (✔) |
| Scale suppression | ✔ | ✘ |
| # parameters | 5 | 11+ |

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# AC/EFT

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$$\left. - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\right)$$

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$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho] \\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

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$$\begin{aligned} g_1^Z &= 1 + c_W\frac{m_Z^2}{2\Lambda^2} \\ \kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\ \kappa_Z &= 1 + (c_W - c_B\tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\ \lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2} \\ g_4^V &= g_5^V = 0 \\ \tilde{\kappa}_\gamma &= c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2} \\ \tilde{\kappa}_Z &= -c_{\tilde{W}}\tan^2\theta_W\frac{m_W^2}{2\Lambda^2} \\ \tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2m_W^2}{2\Lambda^2} \end{aligned}$$

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constants

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# AC/EFT

$$\mathcal{L} = ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho + ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$
$$-ig_5^V\epsilon^{\mu\nu\rho\sigma}(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma + \tilde\kappa_V W^+_\mu W^-_\nu \tilde V^{\mu\nu} + \frac{\tilde\lambda_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde V^\mu_\rho\Big)$$

## CP even Operators

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho]$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

## CP odd operators

$$\mathcal{O}_{\tilde WWW} = \mathrm{Tr}[\tilde W_{\mu\nu}W^{\nu\rho}W^\mu_\rho]$$
$$\mathcal{O}_{\tilde W} = (D_\mu\Phi)^\dagger \tilde W^{\mu\nu}(D_\nu\Phi)$$

$\Delta X = X - 1$

$$g_1^Z = 1 + c_W\frac{m_Z^2}{2\Lambda^2}$$

$$\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W\Delta\kappa_\gamma$$

$$\lambda_\gamma = \lambda_Z = c_{WWW}\frac{3g^2m_W^2}{2\Lambda^2}$$

$$g_4^V = g_5^V = 0$$

$$0 = \tilde\kappa_Z + \tan^2\theta_W\tilde\kappa_\gamma$$

$$\tilde\lambda_\gamma = \tilde\lambda_Z = c_{\tilde WWW}\frac{3g^2m_W^2}{2\Lambda^2}$$

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# PDG constraints

$$g_1^Z = 0.984^{+0.022}_{-0.019}$$
$$\kappa_\gamma = 0.979^{+0.044}_{-0.045}$$
$$\lambda_\gamma = -0.028^{+0.020}_{-0.021}$$
$$\tilde{\kappa}_Z = -0.12^{+0.06}_{-0.04}$$
$$\tilde{\lambda}_Z = -0.09 \pm 0.07$$

$$c_{WWW}/\Lambda^2 \in [-11.9, 1.94]\mathrm{TeV}^{-2}$$
$$c_W/\Lambda^2 \in [-8.42, 1.44]\mathrm{TeV}^{-2}$$
$$c_B/\Lambda^2 \in [-7.9, 14.9]\mathrm{TeV}^{-2}$$
$$c_{\tilde{W}WW}/\Lambda^2 \in [-185.3, -82.4]\mathrm{TeV}^{-2}$$
$$c_{\tilde{W}}/\Lambda^2 \in [-39.3, -4.9]\mathrm{TeV}^{-2}$$

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At 68% C.L.

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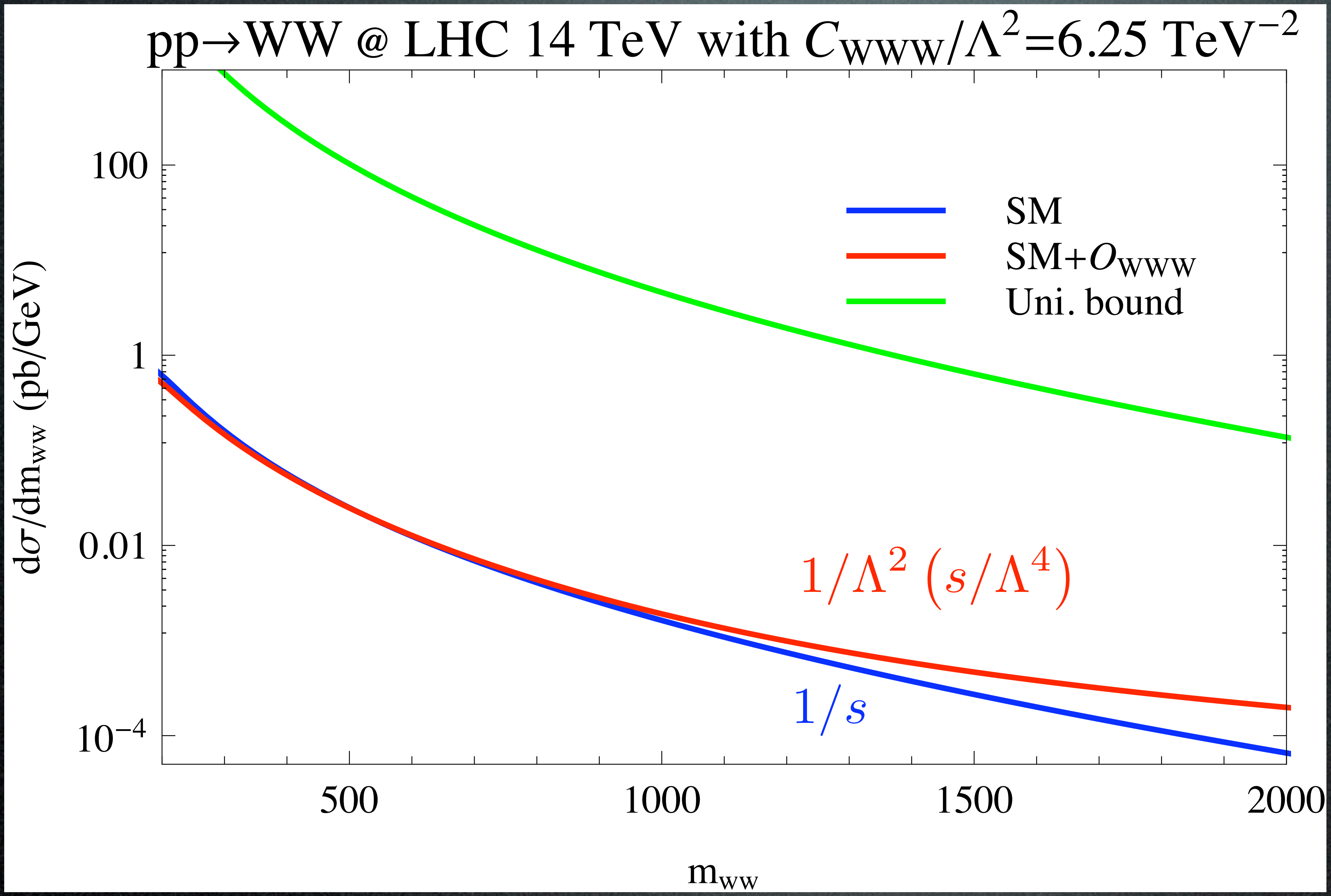
- Only LEP combination
- Tevratron measurements use form factors/other relations

# Unitarity bound

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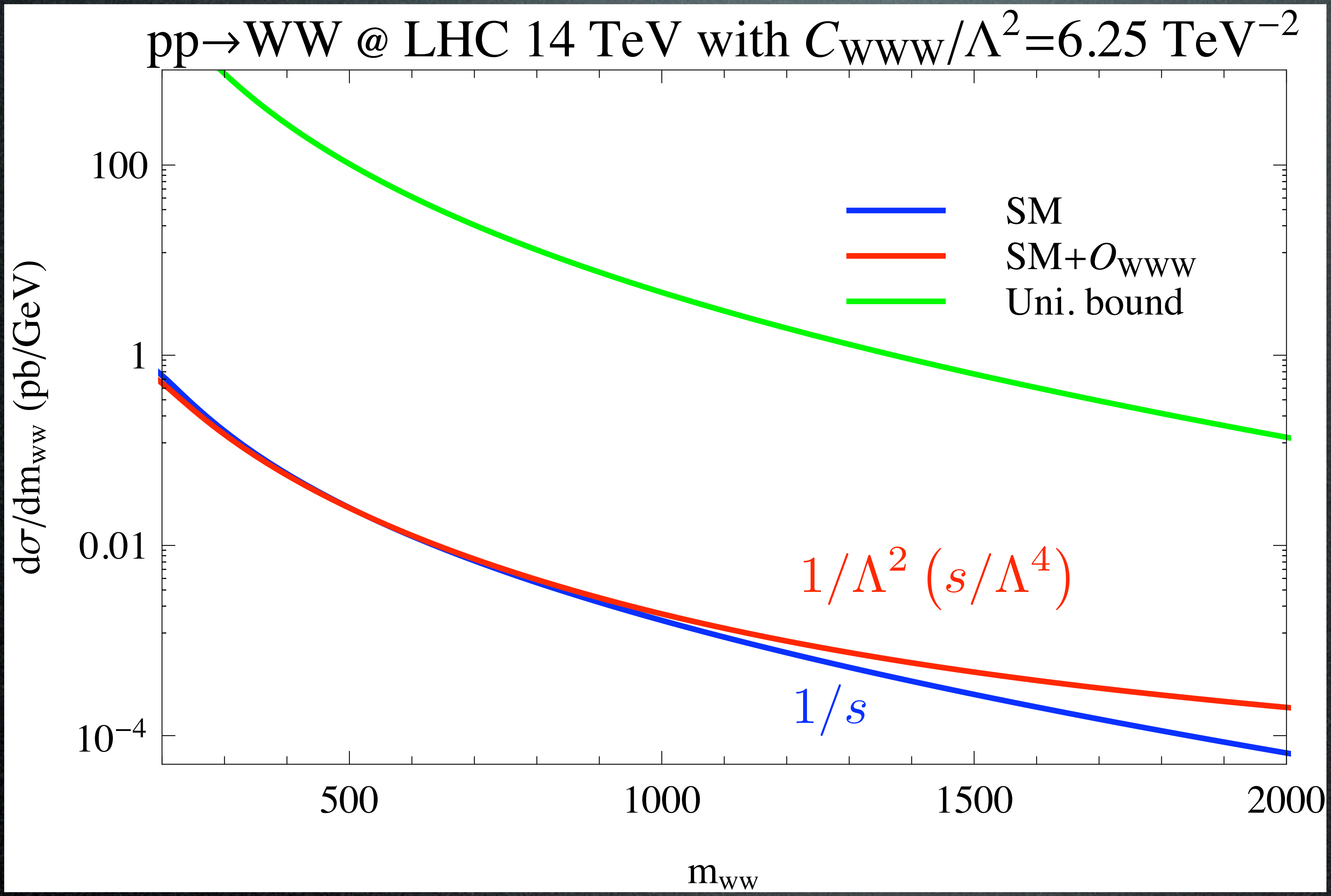
# Unitarity bound




More than 2 orders of magnitude

**Form factors are not needed!**

# Invariant mass and polarisations

| | $\mathcal{O}_{WWW}$ | $\mathcal{O}_W$ | $\mathcal{O}_B$ | SM |
|---|---|---|---|---|
| LL | 0 | $1\ (s)$ | $1\ (s)$ | $1/s$ |
| LT | $1/s\ (1)$ | $1/s\ (1)$ | $1/s\ (1)$ | $1/s^2$ |
| TT | $1/s\ (s)$ | $1/s^2\ (1/s)$ | 0 | $1/s$ |
| Sum | $1/s\ (s)$ | $1\ (s)$ | $1\ (s)$ | $1/s$ |

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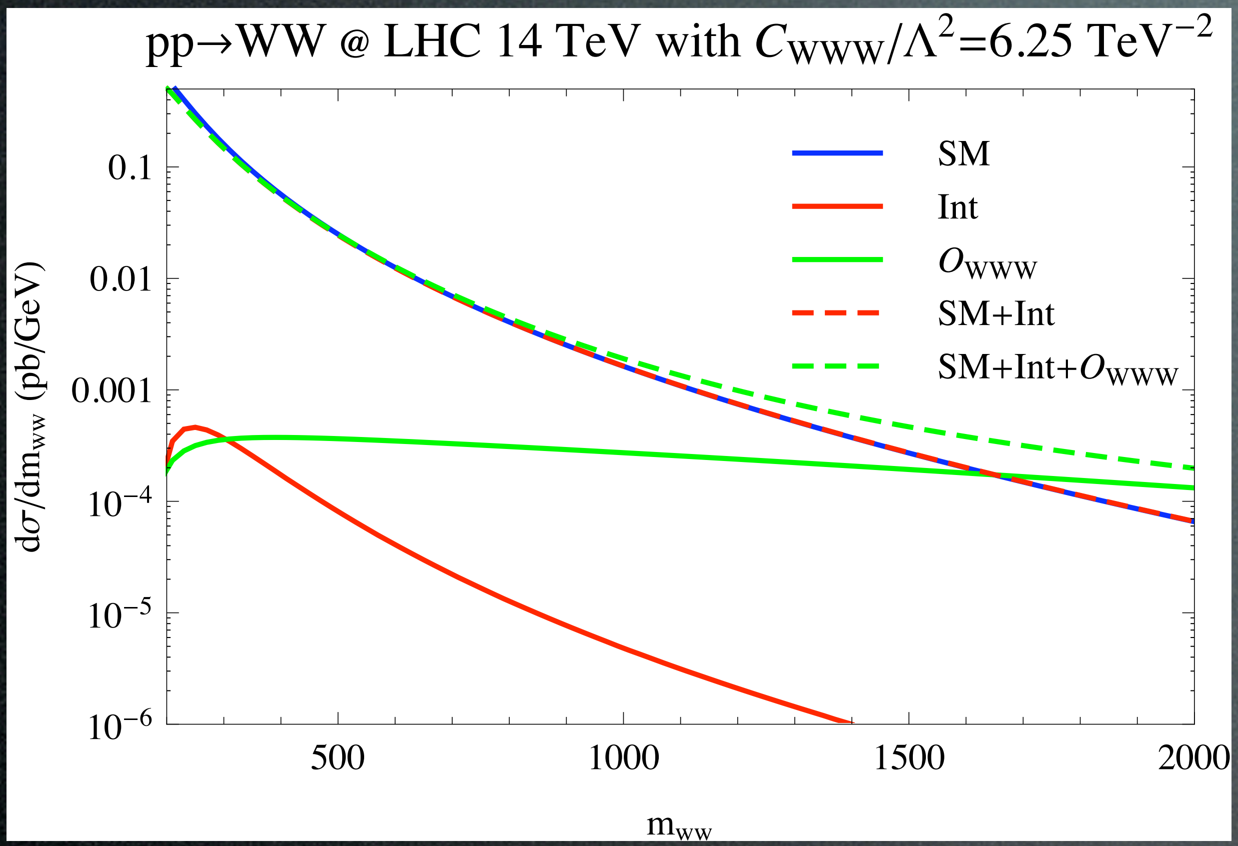
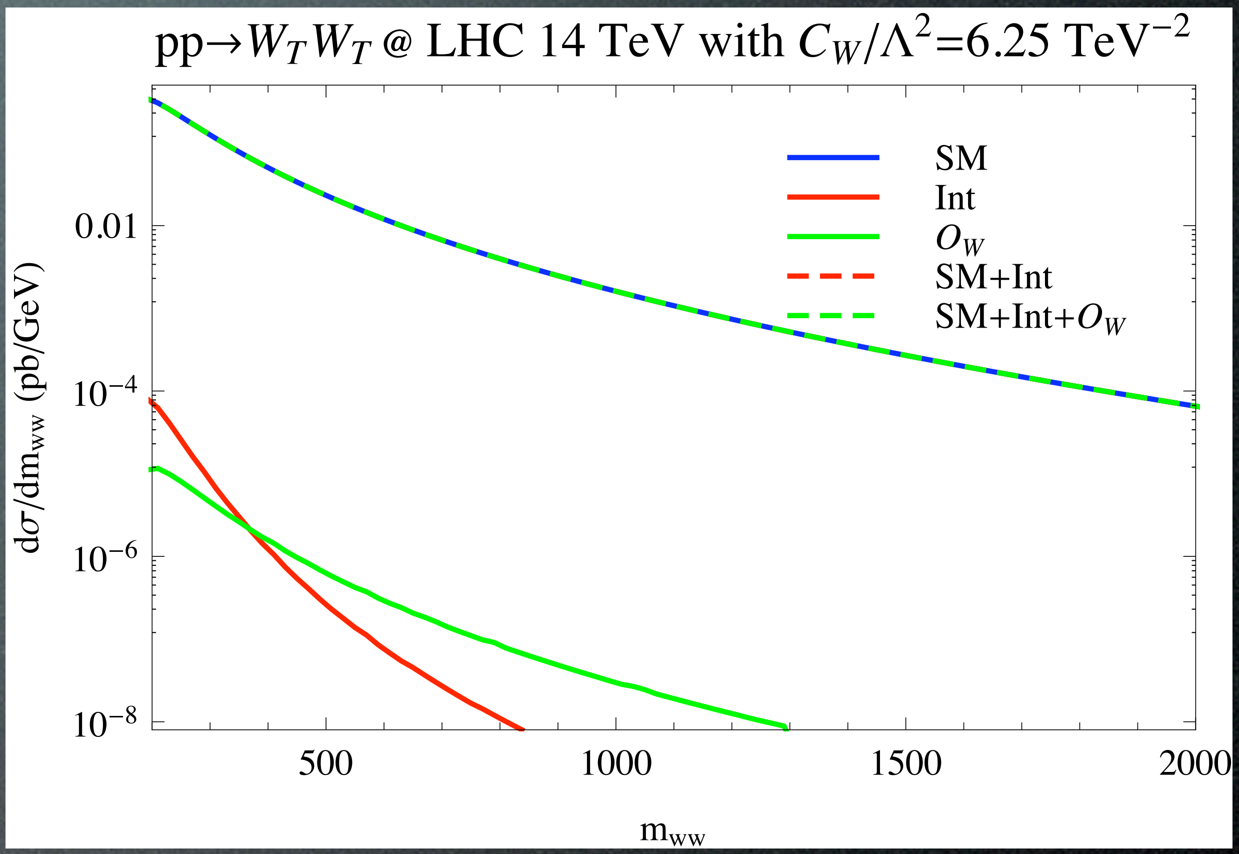
# Tranverse polarizations

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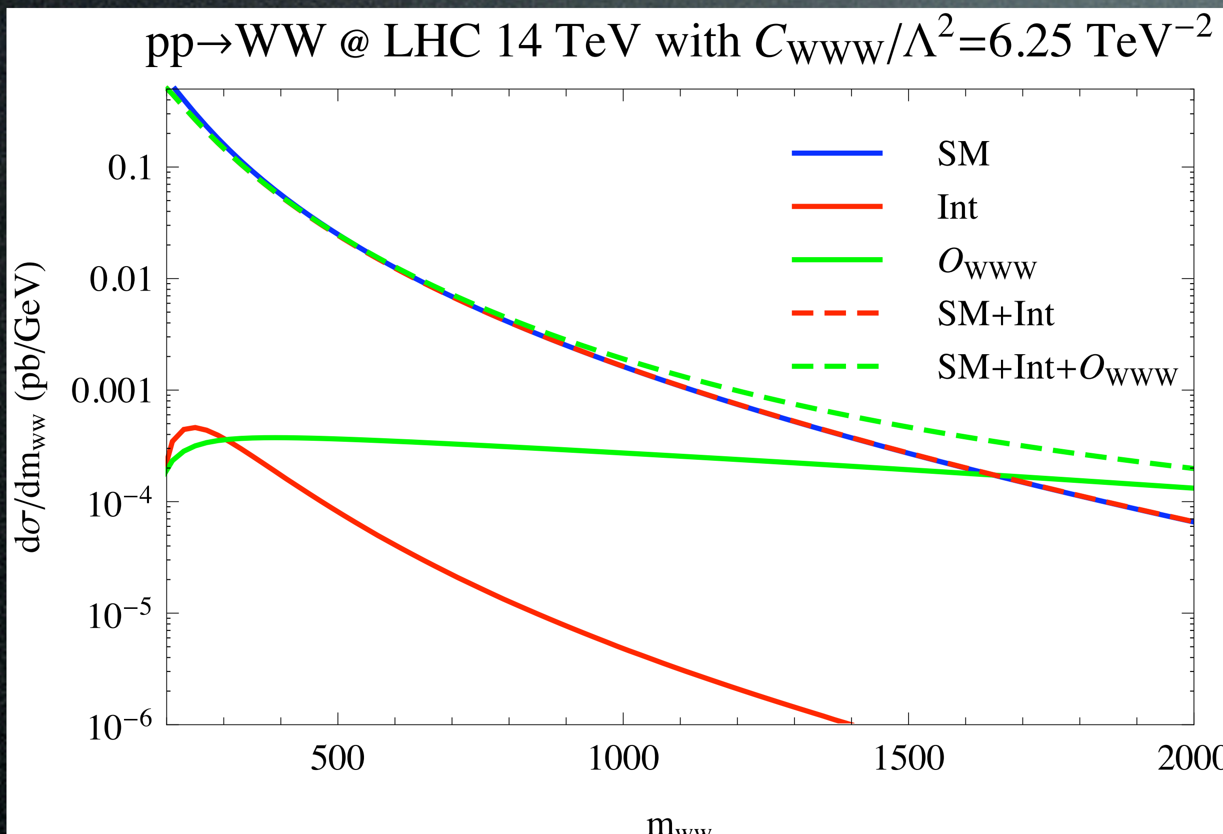
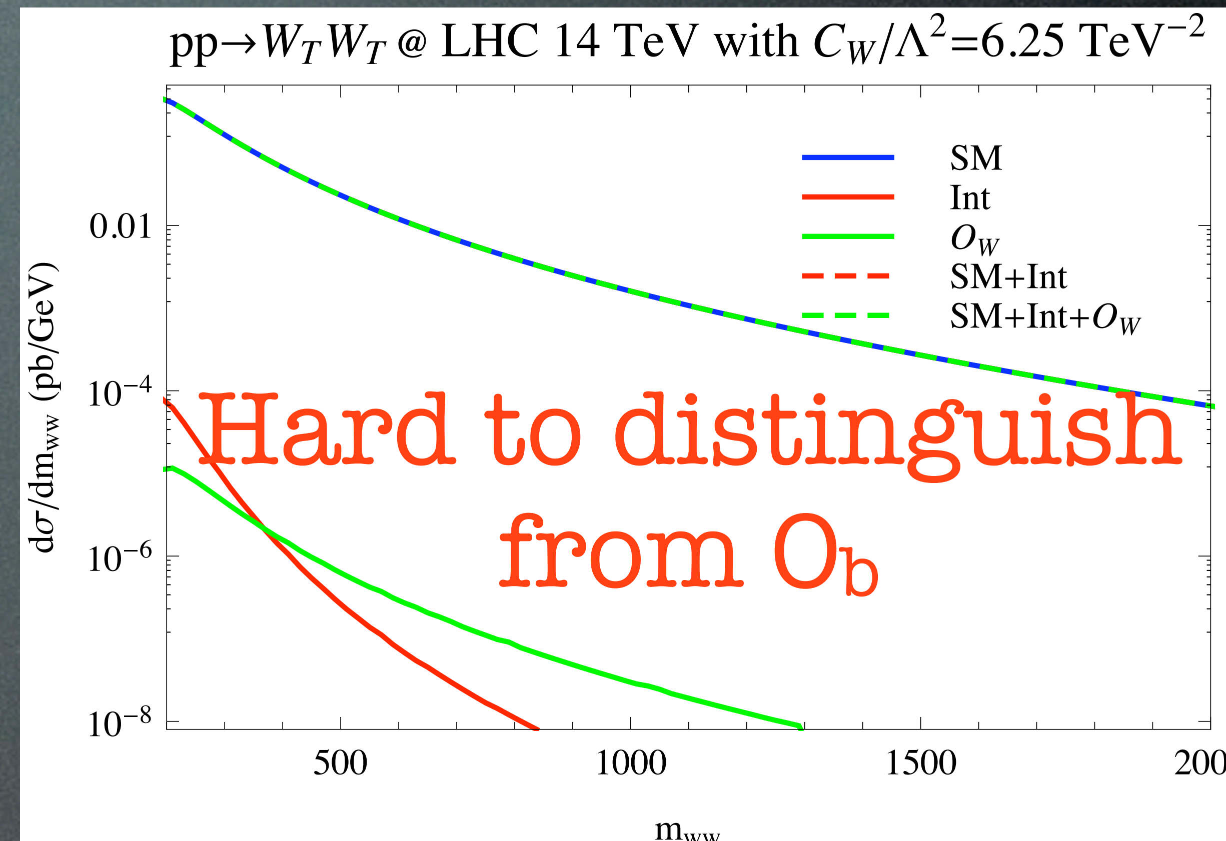
# Tranverse polarizations



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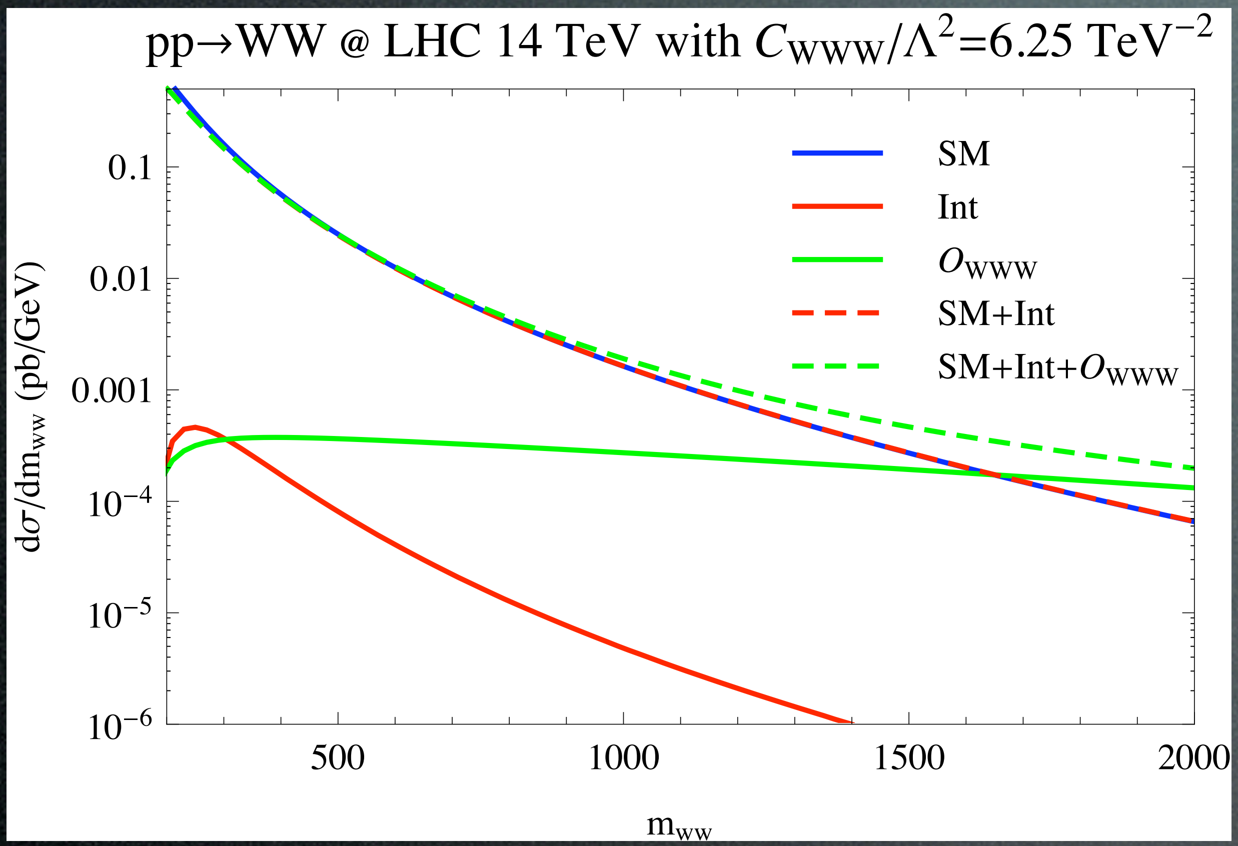


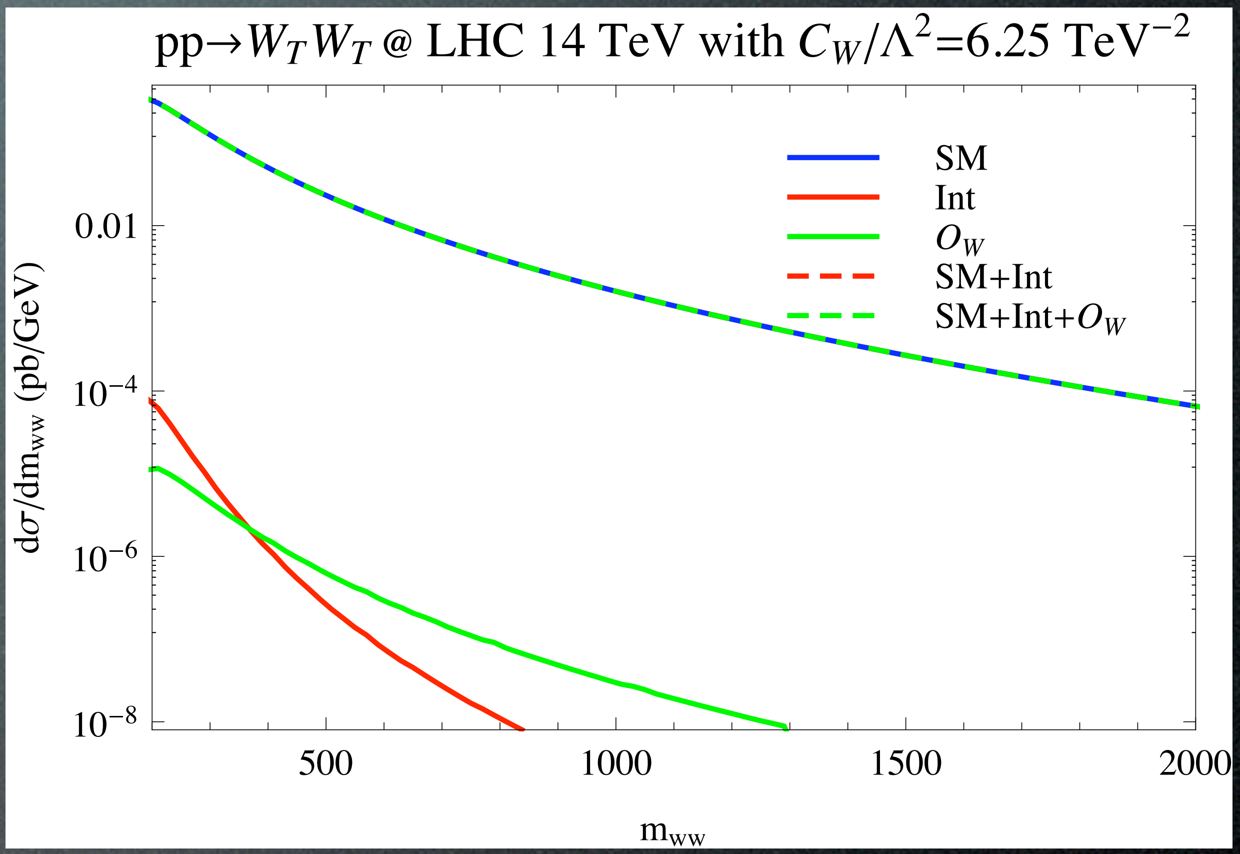


SM has a large contribution

Dim-6 operators have small contributions

Cut ?

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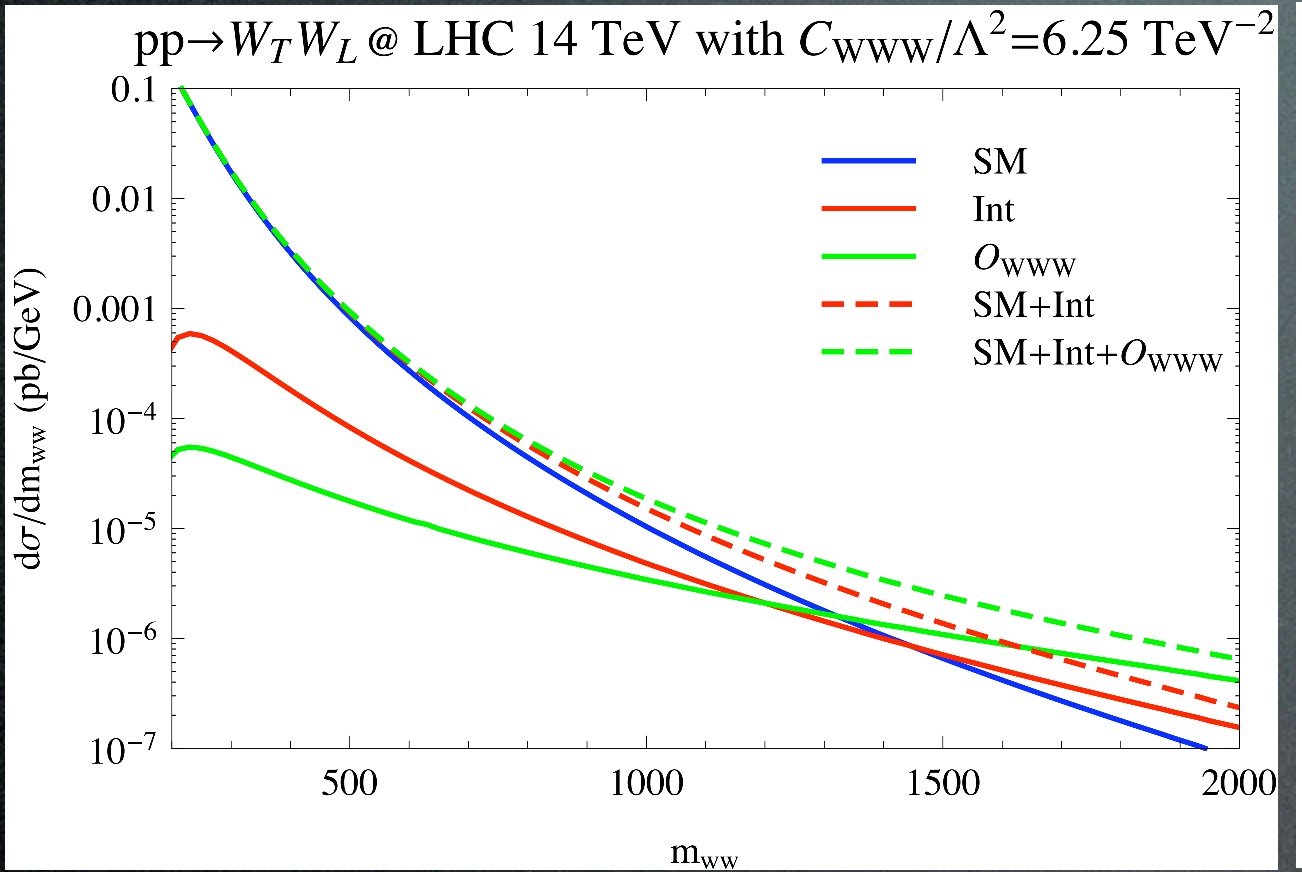
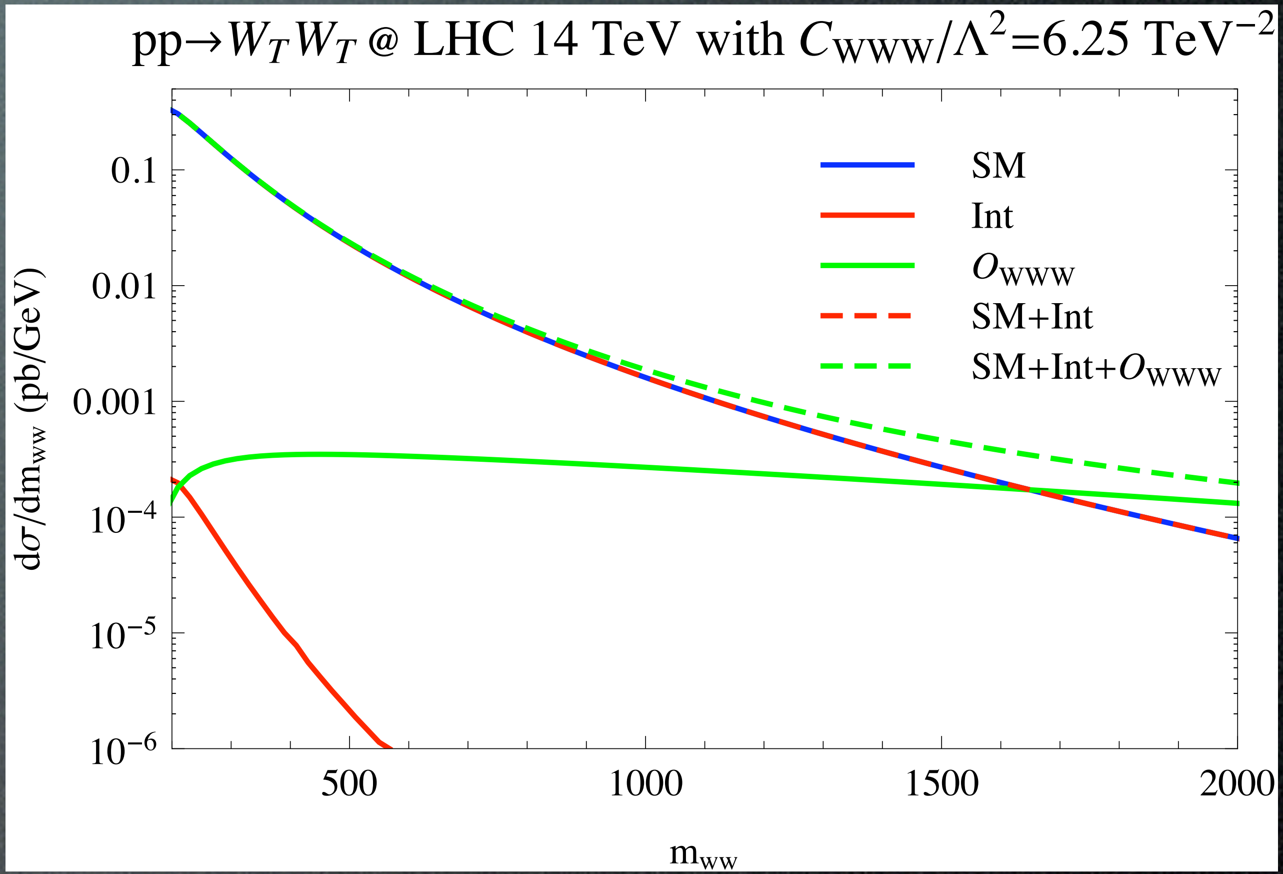
# $O_{WWW}$




Largest for $O_{WWW}$

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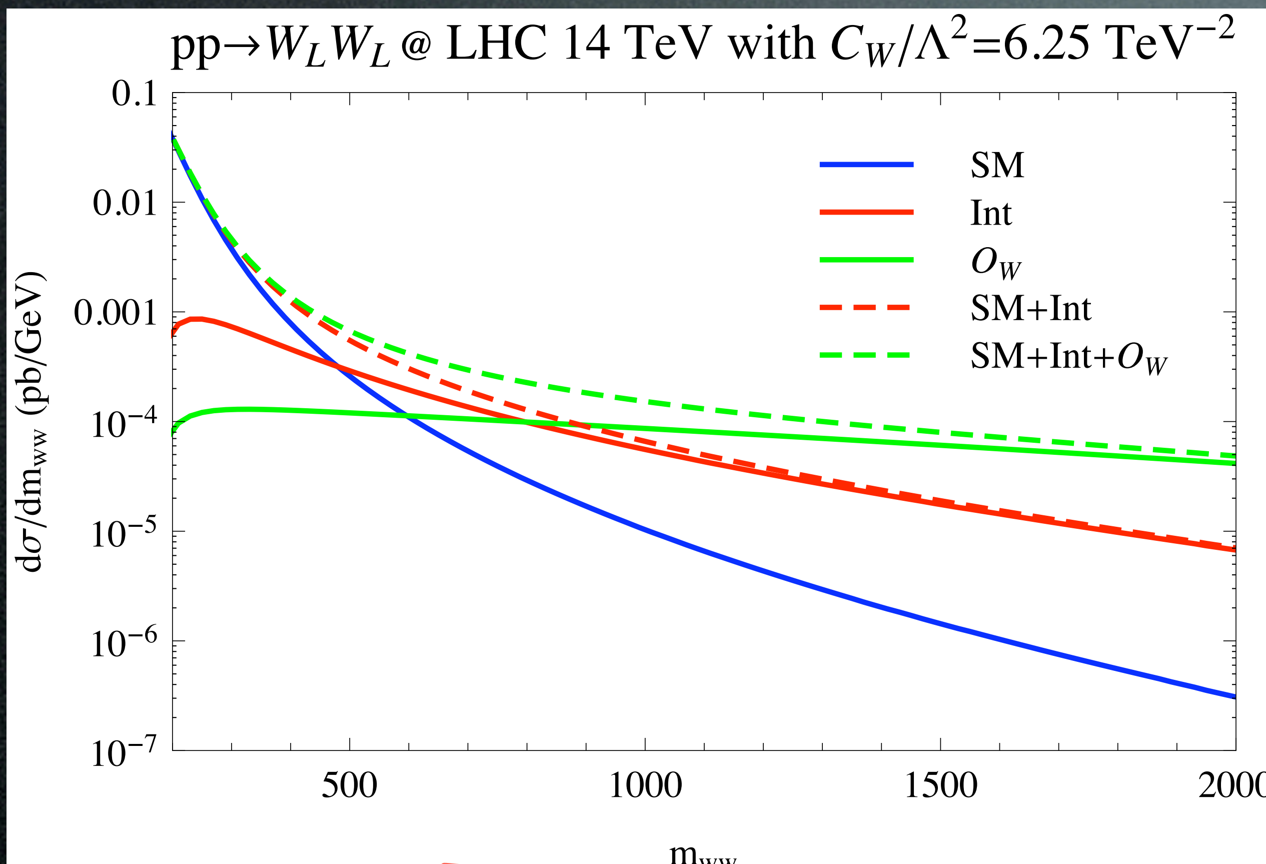
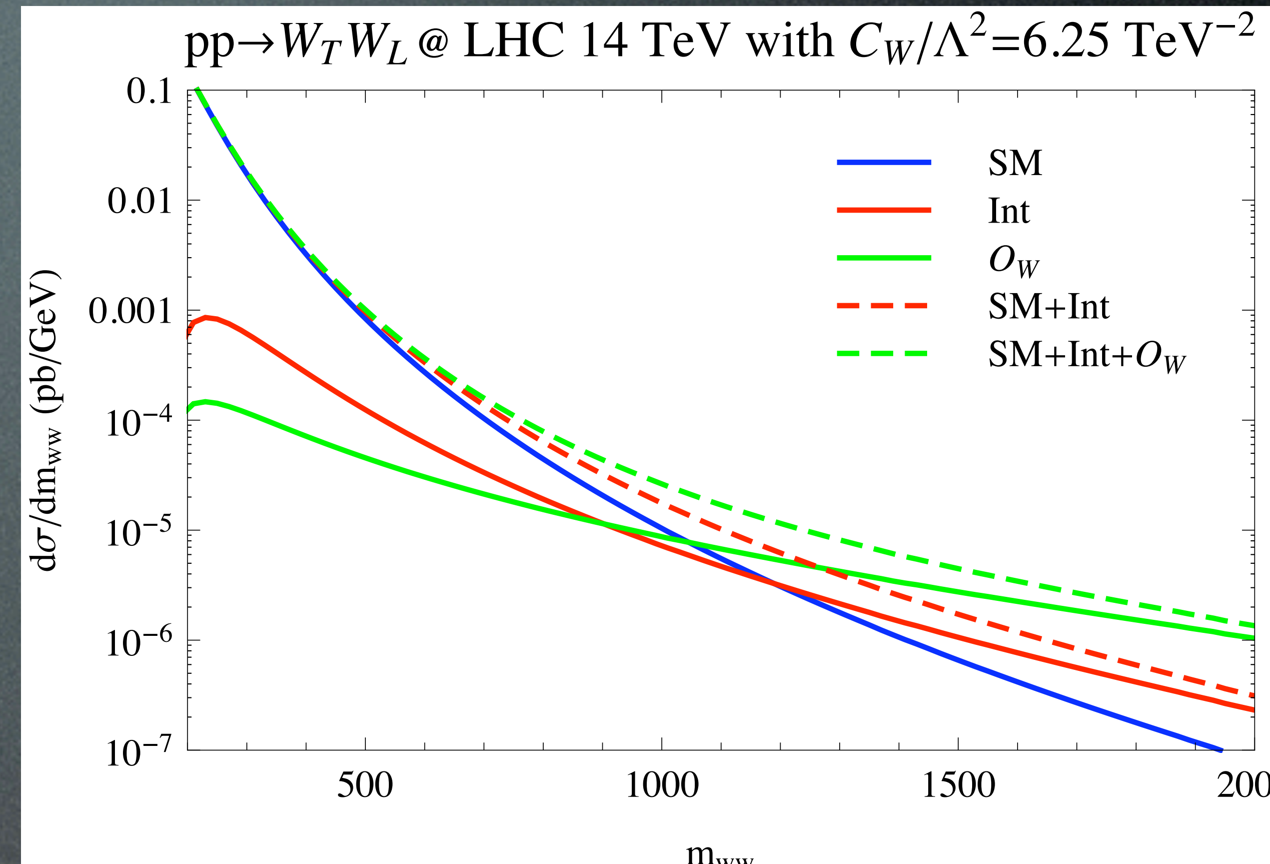
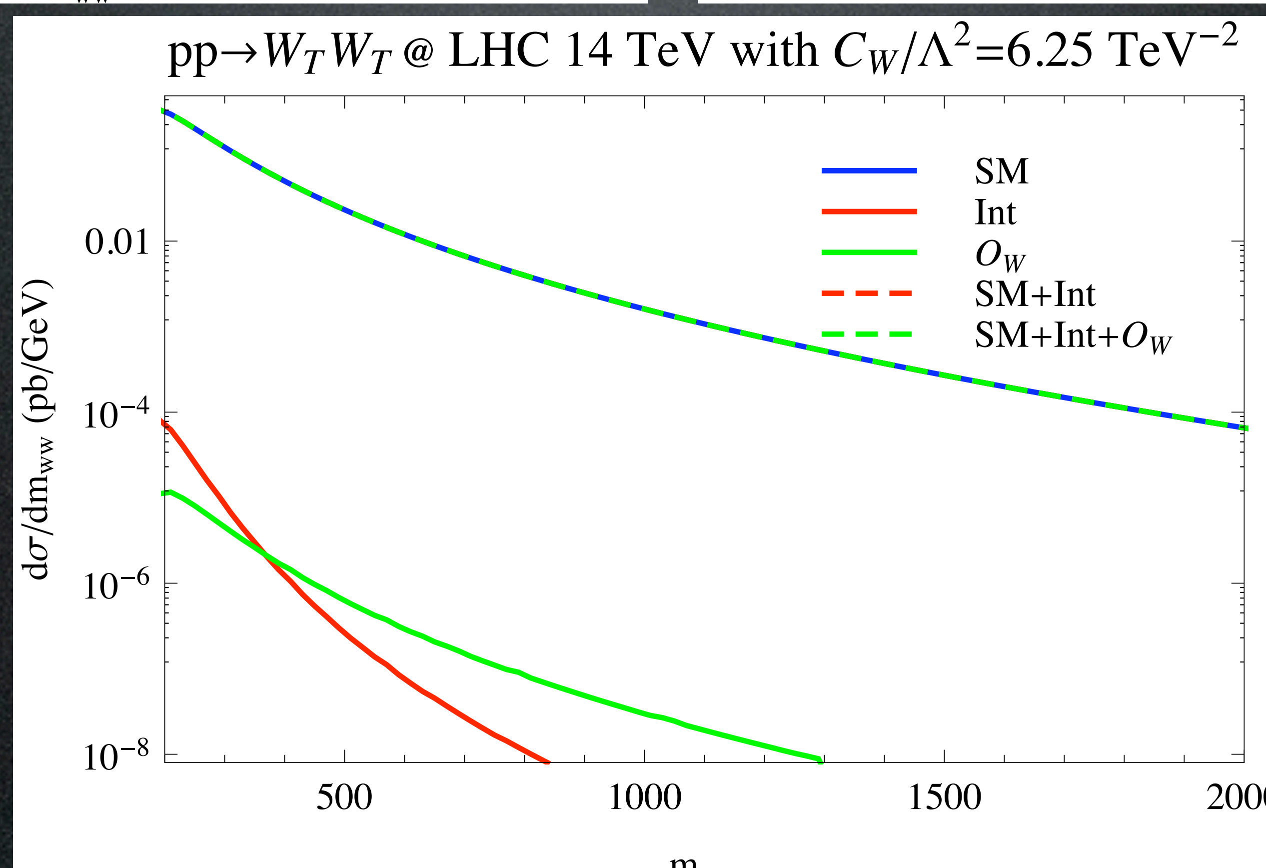
# $O_W$




Largest for $O_W$
Smallest for SM




Smallest for $O_W$
Largest for SM

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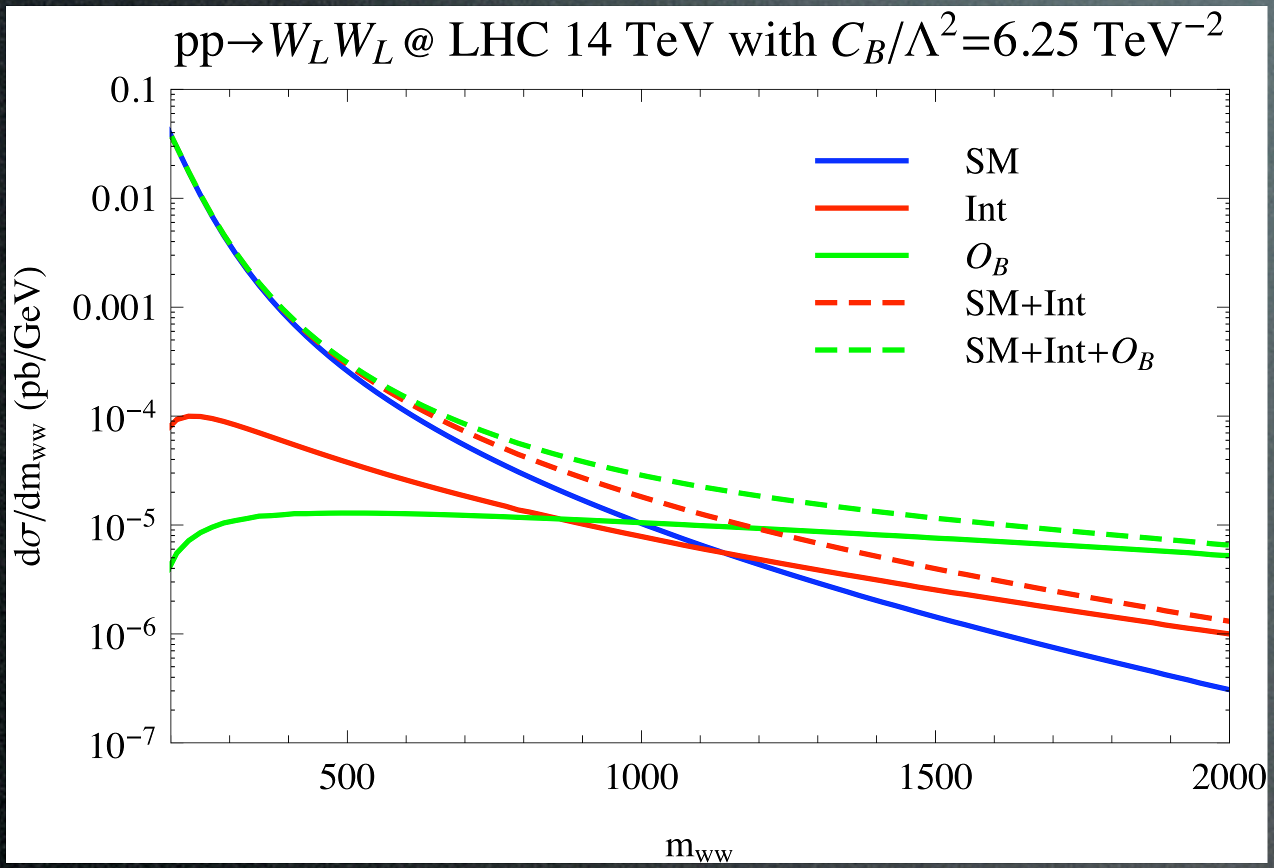
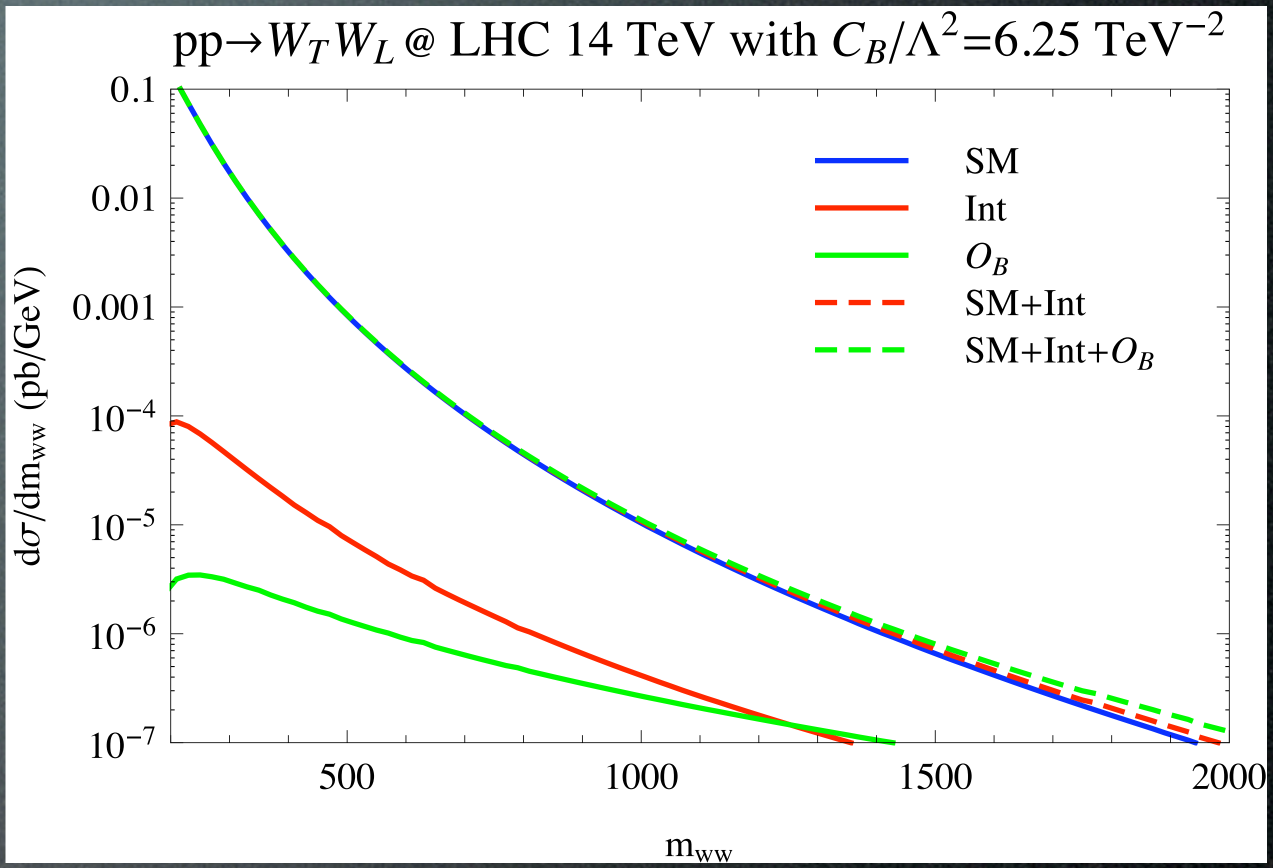
# $O_b$




$\boxed{\text{Largest for } O_b \text{ Smallest for SM}}$

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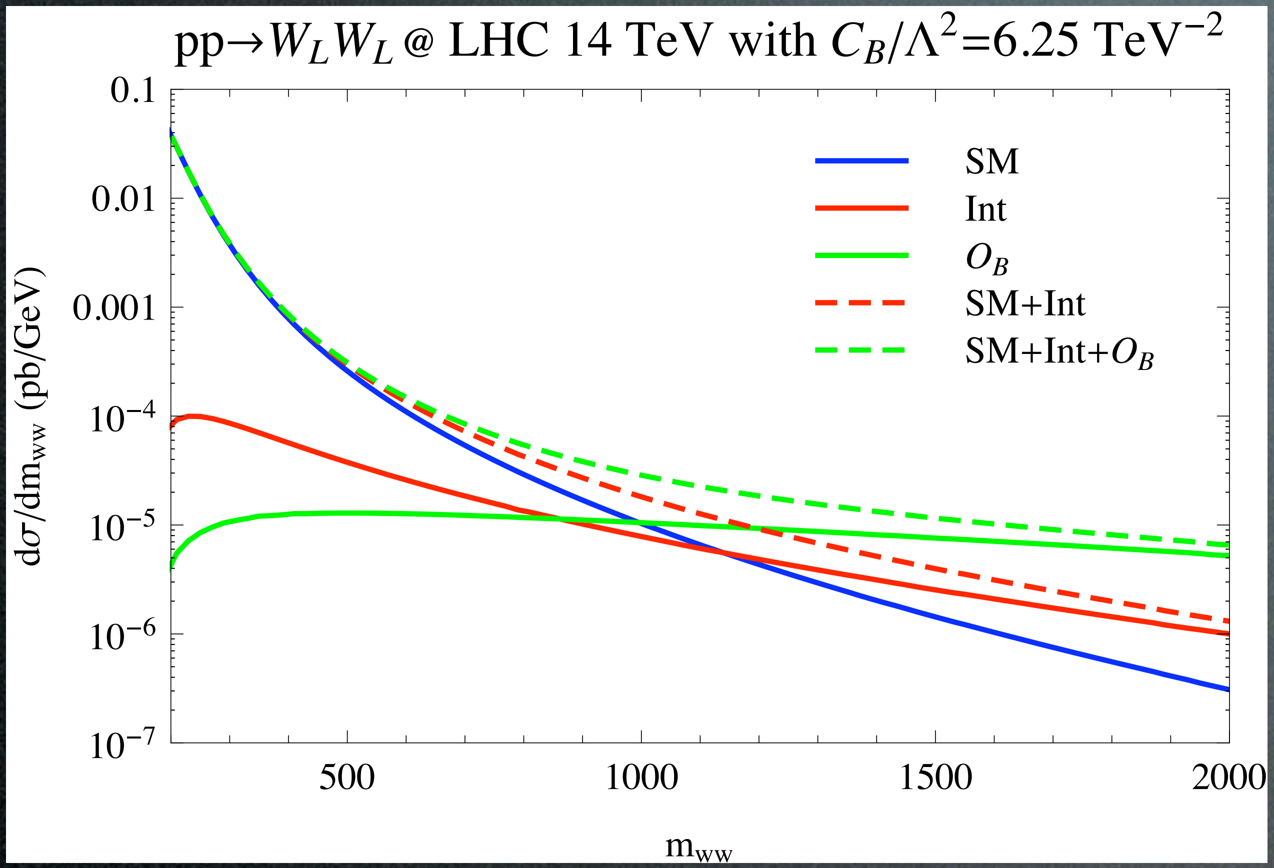
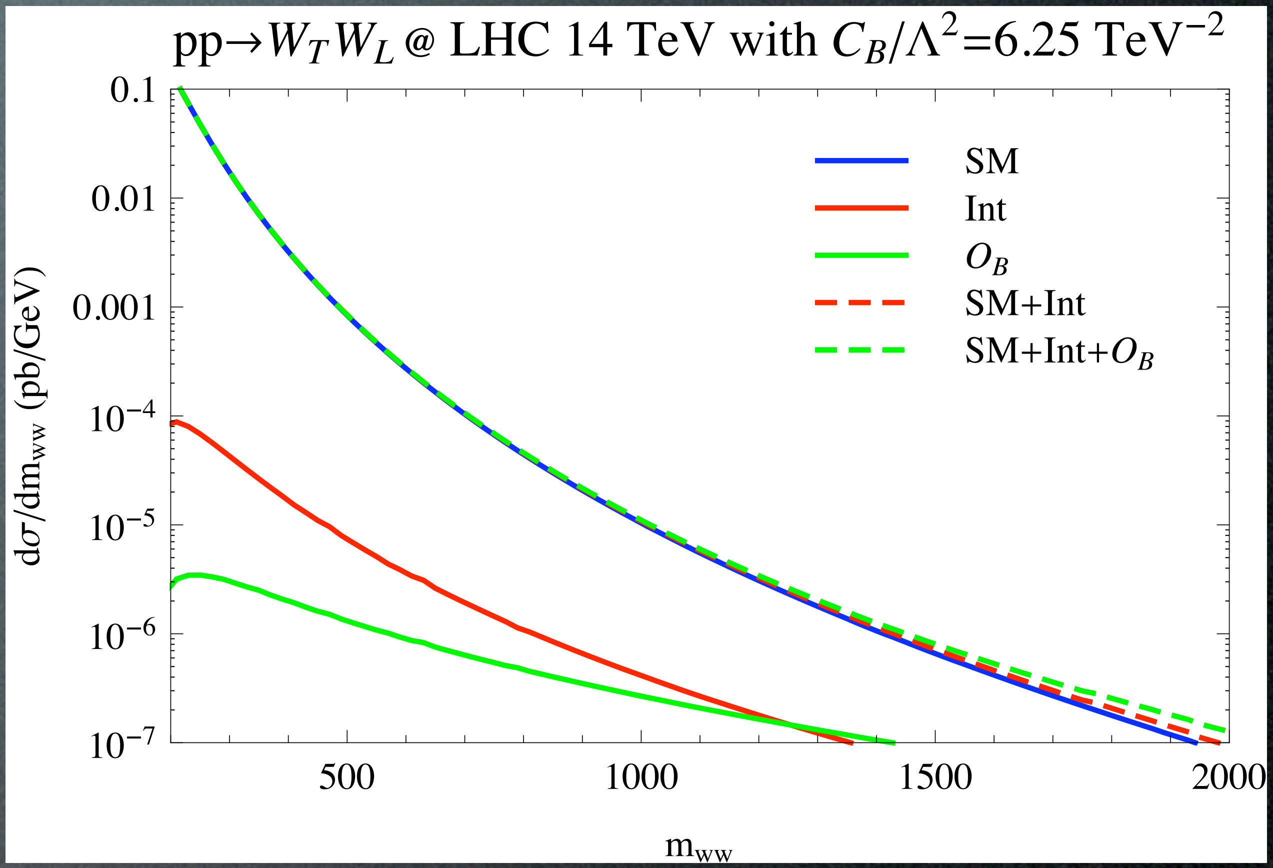
# $O_b$



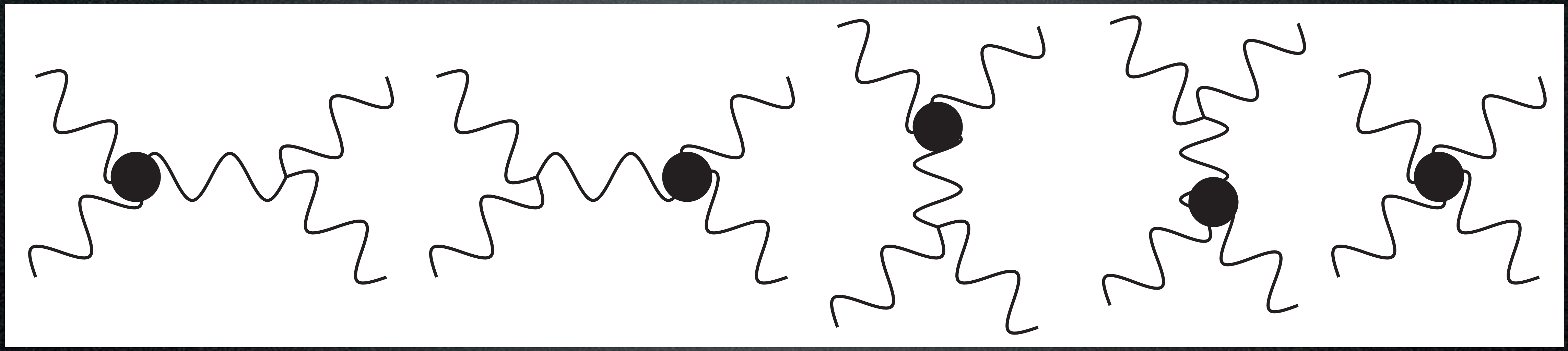




Largest for $O_b$ Smallest for SM

Similar to $O_W$ with a smaller coefficient

# EFT for QGC

- Same ($\cancel{O_B}$) operators than for TGC gives WWWW, WWZA, WWAA, WWZZ vertices
- gauge invariance requires 3 and 4 legs vertices to be related



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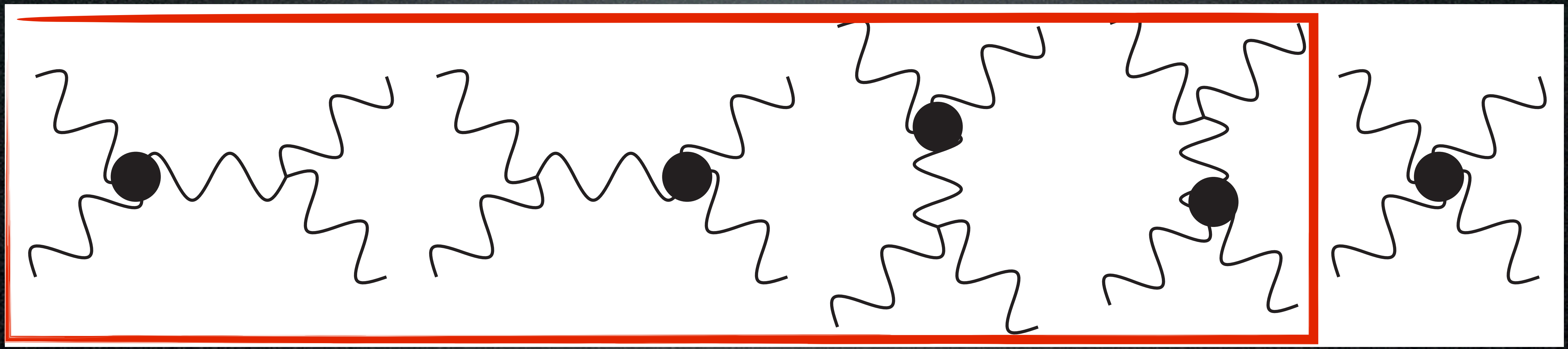

TGC's alone are not gauge invariant

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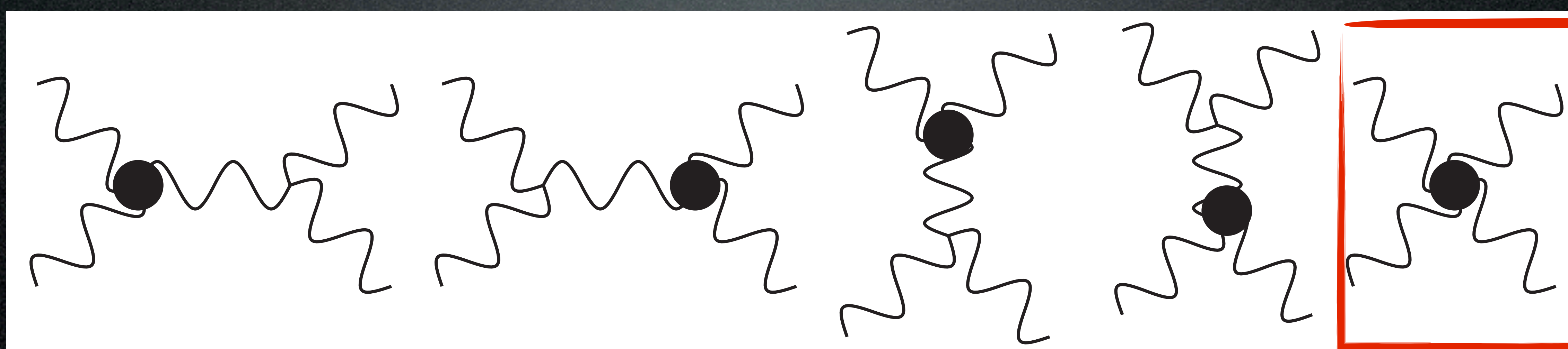

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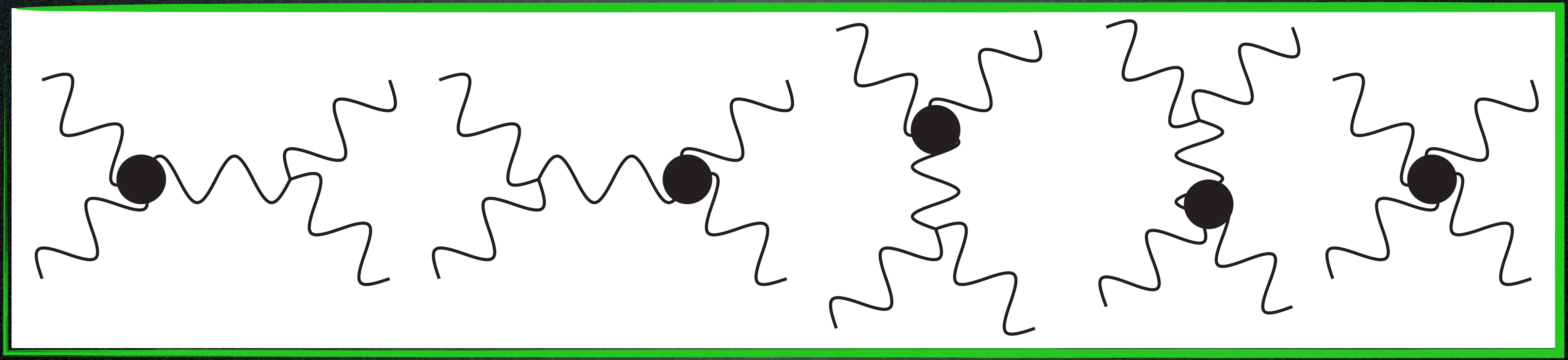

TGC's and QGC's from the dimension-six operators are gauge invariant

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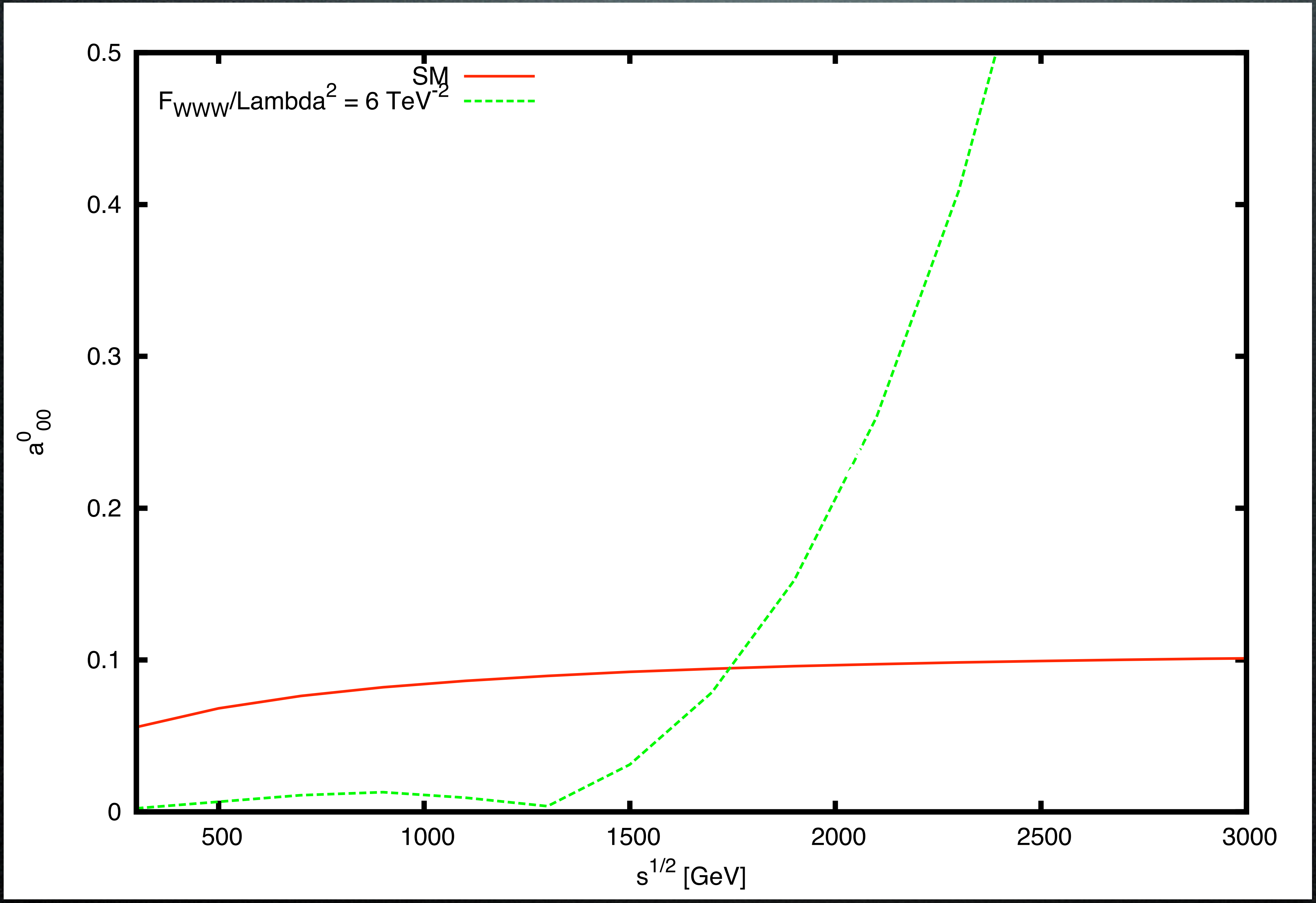
# W scattering and unitarity




How many events with an boson invariant mass above 2 TeV?

From M. Rauch

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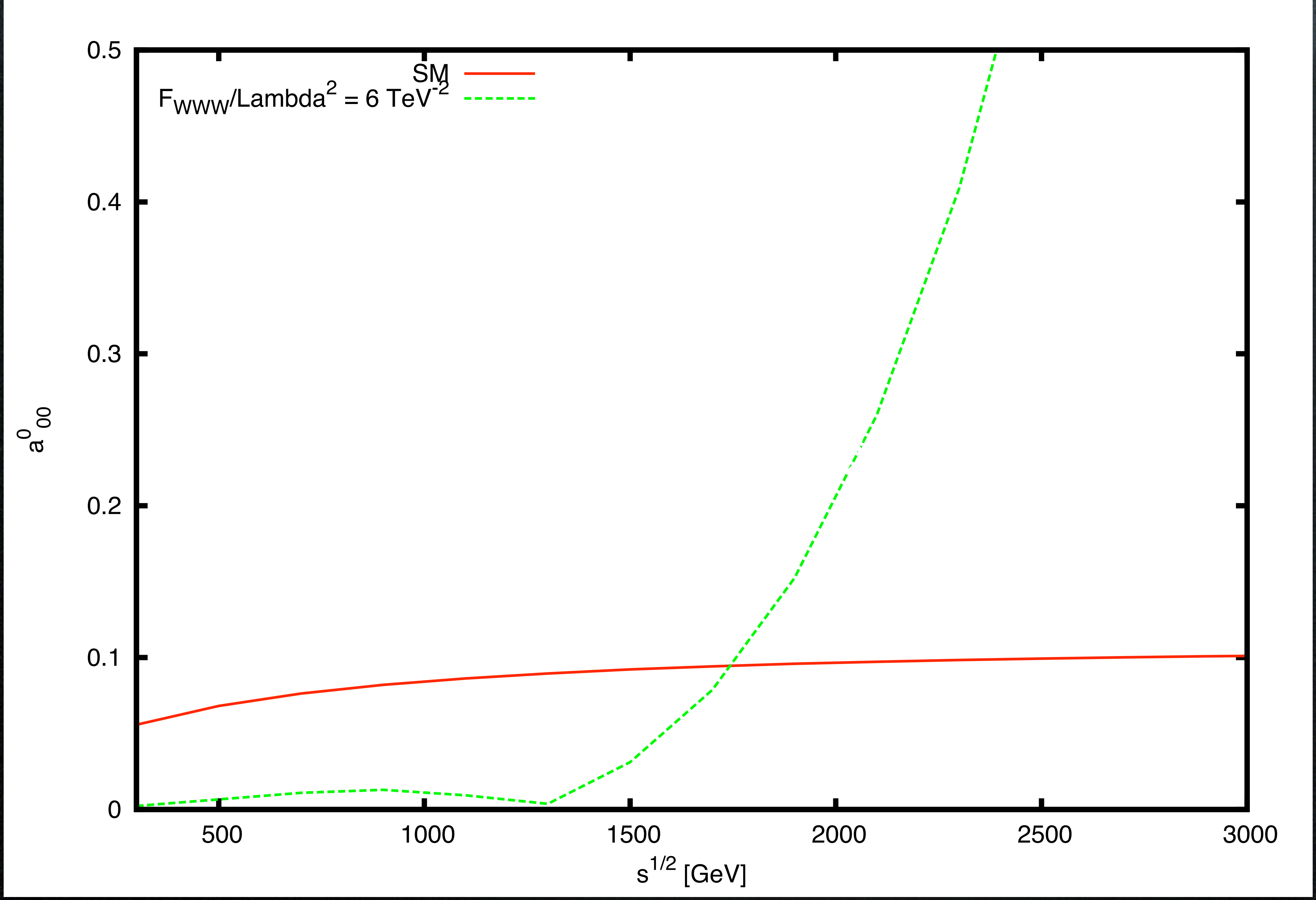
# W scattering and unitarity




How many events with an boson invariant mass above 2 TeV?

go by step

From M. Rauch

Celine Degrande (UIUC)

# nTGC

$$\mathcal{L}^{nTGC} = \mathcal{L}_{SM} + \boxed{0} + \sum_i \frac{C_i}{\Lambda^4} \mathcal{O}_i^8$$

No dim-6 operators

# nTGC

$$\mathcal{L}^{nTGC} = \mathcal{L}_{SM} + 0 + \sum_i \frac{C_i}{\boxed{\Lambda^4}} \mathcal{O}_i^8$$

Smaller effects

# nTGC

$$\mathcal{L}^{nTGC} = \mathcal{L}_{SM} + 0 + \sum_i \frac{C_i}{\Lambda^4}\mathcal{O}_i^8$$

1 CP-even operator

$$\mathcal{O}_{\widetilde{B}W} = i\,H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H$$

3 CP-odd operators

$$\begin{aligned}
\mathcal{O}_{BW} &= i\,H^\dagger B_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H \\
\mathcal{O}_{WW} &= i\,H^\dagger W_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H \\
\mathcal{O}_{BB} &= i\,H^\dagger B_{\mu\nu} B^{\mu\rho}\,\{D_\rho, D^\nu\}\,H
\end{aligned}$$

# nTGC

$$\mathcal{L}^{nTGC} = \mathcal{L}_{SM} + 0 + \sum_i \frac{C_i}{\Lambda^4}\mathcal{O}_i^8$$

1 CP-even operator

$$\mathcal{O}_{\widetilde{B}W} = i\,H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H$$

Only AZZ

3 CP-odd operators

$$\begin{aligned}
\mathcal{O}_{BW} &= i\,H^\dagger B_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H \\
\mathcal{O}_{WW} &= i\,H^\dagger W_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H \\
\mathcal{O}_{BB} &= i\,H^\dagger B_{\mu\nu} B^{\mu\rho}\,\{D_\rho, D^\nu\}\,H
\end{aligned}$$

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# Anomalous vertices

$$
\begin{aligned}
ie\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,q_3) &= \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left[f_4^V\left(q_3^\alpha g^{\mu\beta}+q_3^\beta g^{\mu\alpha}\right)-f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right]\\
ie\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,q_3) &= \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left\{h_1^V\left(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}\right)+\frac{h_2^V}{M_Z^2}q_3^\alpha\left[(q_3q_2)g^{\mu\beta}-q_2^\mu q_3^\beta\right]\right.\\
&\qquad \left.-h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho}-\frac{h_4^V}{M_Z^2}q_3^\alpha\epsilon^{\mu\beta\rho\sigma}q_{3\rho}q_{2\sigma}\right\}
\end{aligned}
$$

$$
\begin{aligned}
f_5^\gamma &= \frac{v^2M_Z^2}{4c_ws_w}\frac{C_{\widetilde{B}W}}{\Lambda^4}\\
h_3^Z &= \frac{v^2M_Z^2}{4c_ws_w}\frac{C_{\widetilde{B}W}}{\Lambda^4}
\end{aligned}
$$

$$
\begin{aligned}
f_5^Z &= 0\\
h_4^Z &= 0\\
h_3^\gamma &= 0\\
h_4^\gamma &= 0
\end{aligned}
$$

$$-47\ \mathrm{TeV}^{-4} < \frac{C_{\widetilde{B}W}}{\Lambda^4} < 47\ \mathrm{TeV}^{-4}$$

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# nTGC

$$|M|^2 = \underbrace{|M_{SM}|^2}_{\mathcal{O}(\Lambda^0)} + \underbrace{2\Re\left(M_{SM}M^*_{dim8}\right)}_{\mathcal{O}(\Lambda^{-4})} + \underbrace{\ldots}_{\mathcal{O}(\Lambda^{-6})} + \underbrace{|M_{dim8}|^2 + \ldots}_{\mathcal{O}(\Lambda^{-8})} + \mathcal{O}\left(\Lambda^{-10}\right)$$

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# nTGC

Not next to leading

$$|M|^2 = \underbrace{|M_{SM}|^2}_{\mathcal{O}(\Lambda^0)} + \underbrace{2\Re\left(M_{SM}M^*_{dim8}\right)}_{\mathcal{O}(\Lambda^{-4})} + \underbrace{\cdots}_{\mathcal{O}(\Lambda^{-6})} + \underbrace{|M_{dim8}|^2 + \cdots}_{\mathcal{O}(\Lambda^{-8})}$$

10)

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# nTGC

Not next to leading

$$|M|^2 = \underbrace{|M_{SM}|^2}_{\mathcal{O}(\Lambda^0)} + \underbrace{2\Re\left(M_{SM} M^*_{dim8}\right)}_{\mathcal{O}(\Lambda^{-4})} + \underbrace{\dots}_{\mathcal{O}(\Lambda^{-6})} + \underbrace{|M_{dim8}|^2 + \dots}_{\mathcal{O}(\Lambda^{-8})}$$

## 200 GeV e+e- collision (Λ>200 GeV)

$$\sigma(e\bar{e} \to A_T Z_L)/fb = 1364 + 0.383 C_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \dots + 2.11 \cdot 10^{-3} C^2_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \dots$$

$$\sigma(e\bar{e} \to A_T Z_T)/fb = 15620 + 7.96 \cdot 10^{-2} C_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \dots + 4.53 \cdot 10^{-4} C^2_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \dots$$

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# nTGC

Not next to leading

$$|M|^2 = \underbrace{|M_{SM}|^2}_{\mathcal{O}(\Lambda^0)} + \underbrace{2\Re\left(M_{SM}M^*_{dim8}\right)}_{\mathcal{O}(\Lambda^{-4})} + \underbrace{\dots}_{\mathcal{O}(\Lambda^{-6})} + \underbrace{|M_{dim8}|^2 + \dots}_{\mathcal{O}(\Lambda^{-8})} \quad 10)$$

## 200 GeV e$^+$e$^-$ collision ($\Lambda$>200 GeV)

$$\sigma(e\bar{e} \to A_T Z_L)/fb = 1364 + 0.383 C_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^4 + \dots + 2.11\cdot 10^{-3} C^2_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^8 + \dots$$

$$\sigma(e\bar{e} \to A_T Z_T)/fb = 15620 + 7.96\cdot 10^{-2} C_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^4 + \dots + 4.53\cdot 10^{-4} C^2_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^8 + \dots$$

## 1 TeV e$^+$e$^-$ collision ($\Lambda$>1 TeV)

$$\sigma(e\bar{e} \to A_T Z_L)/fb = 1.75 + 0.48 C_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^4 + \dots + 2.63 C^2_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^8 + \dots$$

$$\sigma(e\bar{e} \to A_T Z_T)/fb = 866 + 4.02\cdot 10^{-3} C_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^4 + \dots + 2.17\cdot 10^{-2} C^2_{\widetilde{B}W}\left(\frac{1\ \text{TeV}}{\Lambda}\right)^8 + \dots$$

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# nTGC

Not next to leading

$$|M|^2 = \underbrace{|M_{SM}|^2}_{\mathcal{O}(\Lambda^0)} + \underbrace{2\Re\left(M_{SM}M^*_{dim8}\right)}_{\mathcal{O}(\Lambda^{-4})} + \underbrace{\cdots}_{\mathcal{O}(\Lambda^{-6})} + \underbrace{|M_{dim8}|^2 + \cdots}_{\mathcal{O}(\Lambda^{-8})} \quad 10)$$

## 200 GeV e$^+$e$^-$ collision ($\Lambda$>200 GeV)

$$\sigma(e\bar{e} \to A_T Z_L)/fb = 1364 + 0.383 C_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \cdots + 2.11 \cdot 10^{-3} C^2_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \ldots$$

$$\sigma(e\bar{e} \to A_T Z_T)/fb = 15620 + 7.96 \cdot 10^{-2} C_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \cdots + 4.53 \cdot 10^{-4} C^2_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \ldots$$

## 1 TeV e$^+$e$^-$ collision ($\Lambda$>1 TeV)

$1/s^3$ $1/s$

$$\sigma(e\bar{e} \to A_T Z_L)/fb = 1.75 + 0.48 C_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \cdots + 2.63 C^2_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \ldots$$

$$\sigma(e\bar{e} \to A_T Z_T)/fb = 866 + 4.02 \cdot 10^{-3} C_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \cdots + 2.17 \cdot 10^{-2} C^2_{\widetilde{B}W}\left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \ldots$$

$1/s^2$ $1/s^2$

Celine Degrande (UIUC)

# nTGC

## 200 GeV $e^+e^-$ collision ($\Lambda$>200 GeV)

$$\sigma(e\bar{e} \to ZZ)/fb = 1252 - 3.2 \cdot 10^{-3} C_{\widetilde{B}W} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4 + \cdots + 1.4 \cdot 10^{-4} C_{\widetilde{B}W}^2 \left(\frac{1 \text{ TeV}}{\Lambda}\right)^8 + \ldots$$

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$$\sigma_{\theta cut}(e\bar{e} \to Z_T Z_L)/fb = 233 - 2.6 \cdot 10^{-2} C_{\widetilde{B}W} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4 + \cdots + 7.9 \cdot 10^{-5} C^2_{\widetilde{B}W} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^8 + \ldots$$

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## 1 TeV e⁺e⁻ collision (Λ>1 TeV)

1/s² 1/s

$$\sigma(e\bar{e} \to ZZ)/fb = 144 - 0.41 C_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \cdots + 7.1 C^2_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \ldots$$

$$\sigma_{\theta cut}(e\bar{e} \to Z_T Z_L)/fb = 0.59 - 0.44 C_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4 + \cdots + 6.9 C^2_{\widetilde{B}W} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^8 + \ldots$$

1/s³

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# Concluding remarks

- Search for new physics through new interactions between known particles
- EFT are a good way to search for heavy new physics
  - More predictive
  - Satisfy unitarity
  - Take care of gauge invariance
- s, θ and polarizations are affected by NP
- EFT (dim-6) for gauge bosons is available in MadGraph (https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Models/EWdim6)

# Back-up

# Dimension and errors

- Smaller effects or larger errors for higher dimension operators

$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum \frac{d_i}{\Lambda^4}\mathcal{O}_i^8 + \mathcal{O}\left(\Lambda^{-6}\right)$$

| | | | |
|---|---|---|---|
| 1 | 10% | 1% | 0.1% |

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- Can affect a new observable

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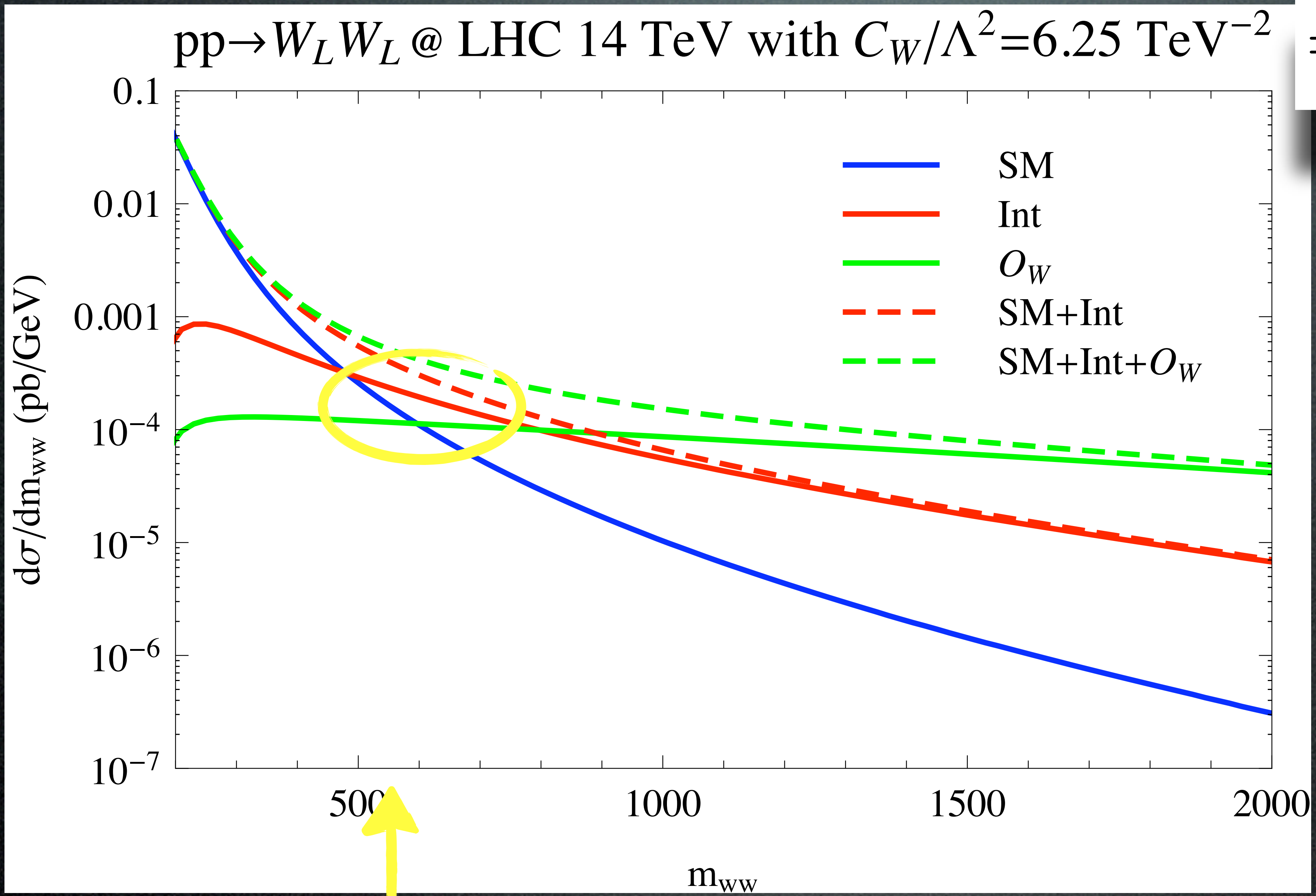
# Expansion and error




$= 1/\left(400\text{GeV}\right)^2$

$1/\Lambda^4$

$1/\Lambda^2$

$1/\Lambda^0$

Expansion breaks

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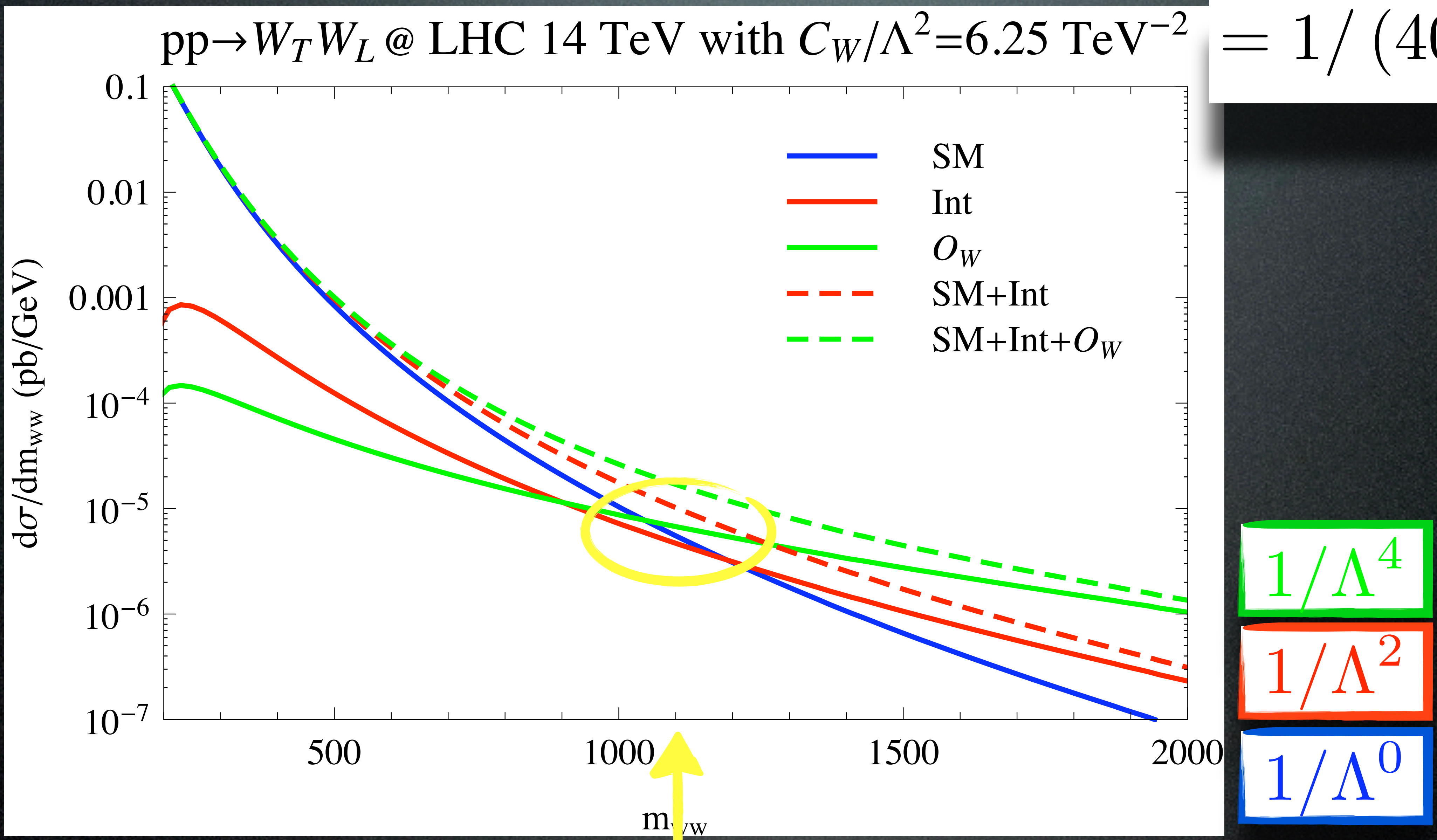


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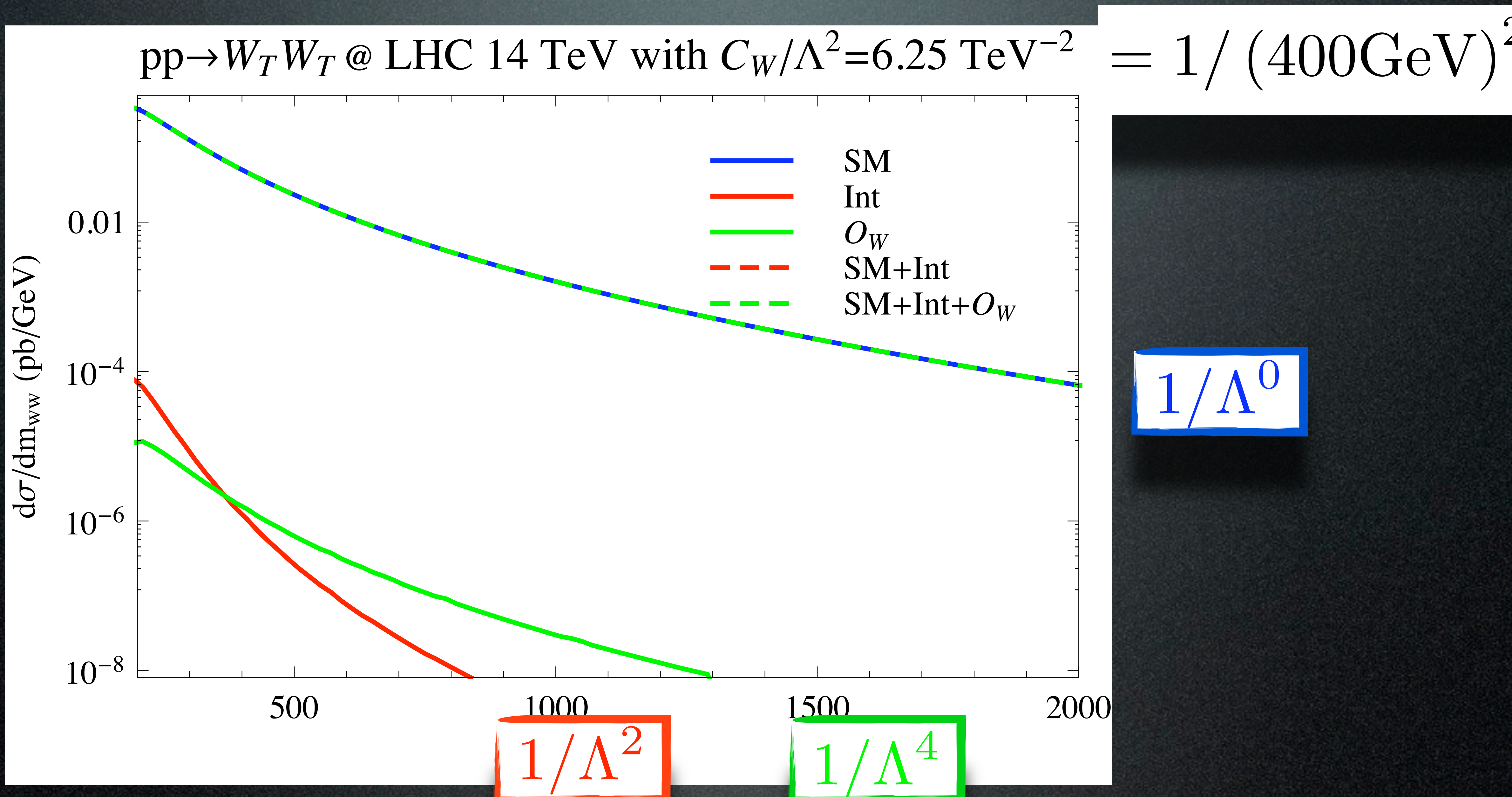


**NP is suppressed : Bad estimate of the scale**

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