Theory of anomalous couplings using EFT

Celine Degrande
University of Illinois at Urbana-Champaign
Snowmass-electroweak @ Duke

Plan

- Introduction to EFT
- EFT for TGC
- EFT for QGC
- Concluding remarks

Effective Field Theory

- Assumption : new physics scale >> energy probed in experiments

Effective Field Theory

- Assumption : new physics scale >> energy probed in experiments

$\Updownarrow$

$\boxed{\text{EFT is an expansion}}$

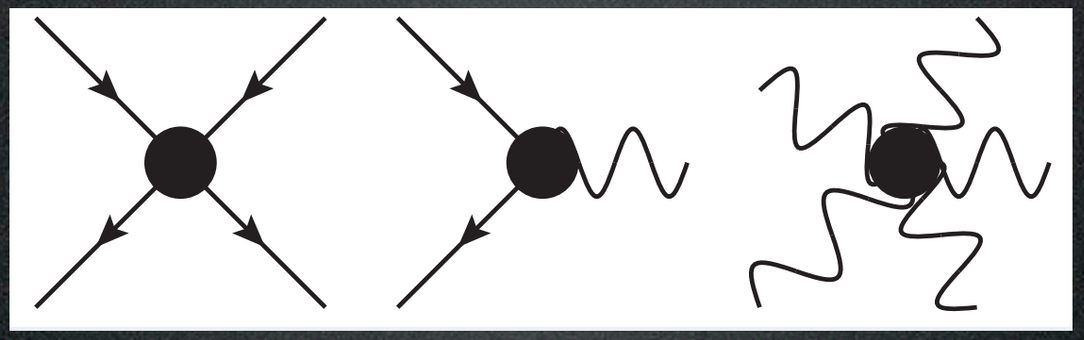
Effective Field Theory

- Assumption : new physics scale >> energy probed in experiments

$\Updownarrow$

EFT is an expansion

- NP appears as new interactions between the known particles



Effective Lagrangian

Effective Lagrangian

- From the SM fields only (Higgs boson included)

Effective Lagrangian

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

Effective Lagrangian

- From the SM fields only (Higgs boson included)
- Invariant under the SM symmetries
- Dimension d of the new operator is >4

Effective Lagrangian

- From the SM fields only (Higgs boson included)
- Invariant under the SM symmetries
- Dimension d of the new operator is >4
- New operators are suppressed by $1/\Lambda^{d-4}$

Effective Lagrangian

- From the SM fields only (Higgs boson included)
- Invariant under the SM symmetries
- Dimension d of the new operator is >4
- New operators are suppressed by $1/\Lambda^{d-4}$
- Keep only the first order (lowest dimension)

Effective Lagrangian

- From the SM fields only (Higgs boson included)
- Invariant under the SM symmetries
- Dimension d of the new operator is >4
- New operators are suppressed by $1/\Lambda^{d-4}$
- Keep only the first order (lowest dimension)

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

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

Effective Lagrangian

- From the SM fields only (Higgs boson included)
- Invariant under the SM symmetries
- Dimension d of the new operator is >4
- New operators are suppressed by $1/\Lambda^{d-4}$
- Keep only the first order (lowest dimension)

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

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

Effective Lagrangian

- From the SM fields only (Higgs boson included)
- Invariant under the SM symmetries
- Dimension d of the new operator is >4
- New operators are suppressed by $1/\Lambda^{d-4}$
- Keep only the first order (lowest dimension)

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

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

Th. error

Effective field theories

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

Effective field theories

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

- SM symmetries (B&L) : 59 dimension-six operators (one flavor)

C.D. et al, axXiv:1205.4231

Effective field theories

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

- SM symmetries (B&L) : 59 dimension-six operators (one flavor)
- Only few operators/process and different effects

C.D. et al, axXiv:1205.4231

Effective field theories

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

- SM symmetries (B&L) : 59 dimension-six operators (one flavor)
- Only few operators/process and different effects
- More predictive than anomalous couplings

C.D. et al, axXiv:1205.4231

Effective field theories

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

- SM symmetries (B&L) : 59 dimension-six operators (one flavor)
- Only few operators/process and different effects
- More predictive than anomalous couplings
- Unitarity is satisfied (no form factors)

C.D. et al, axXiv:1205.4231

Effective field theories

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

- SM symmetries (B&L) : 59 dimension-six operators (one flavor)
- Only few operators/process and different effects
- More predictive than anomalous couplings
- Unitarity is satisfied (no form factors)
- More than one vertex/operator (high multiplicities)

C.D. et al, axXiv:1205.4231

Effective field theories

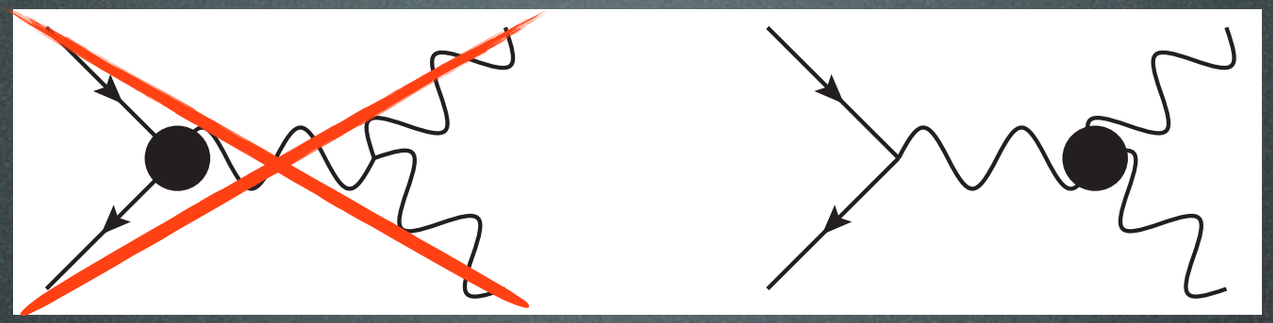
$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- SM symmetries (B&L) : 59 dimension-six operators (one flavor)
- Only few operators/process and different effects
- More predictive than anomalous couplings
- Unitarity is satisfied (no form factors)
- More than one vertex/operator (high multiplicities)
- Loop computation

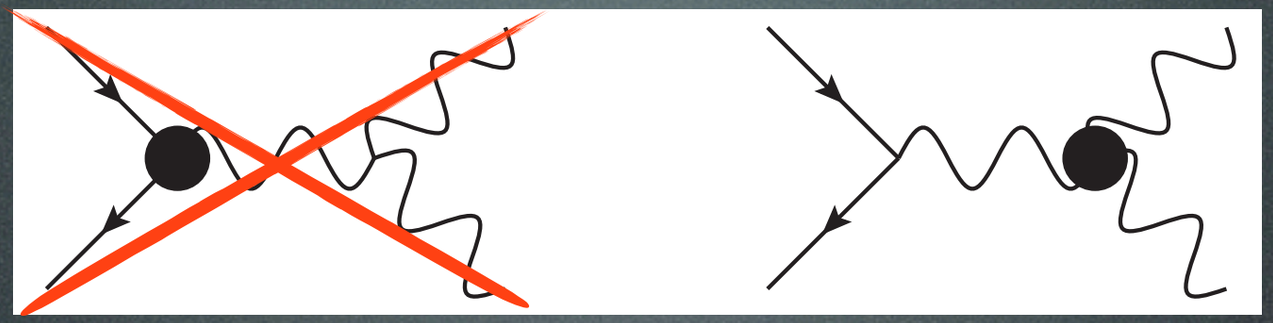
C.D. et al, axXiv:1205.4231

WW(WZ/WA) production

WW(WZ/WA) production



WW(WZ/WA) production



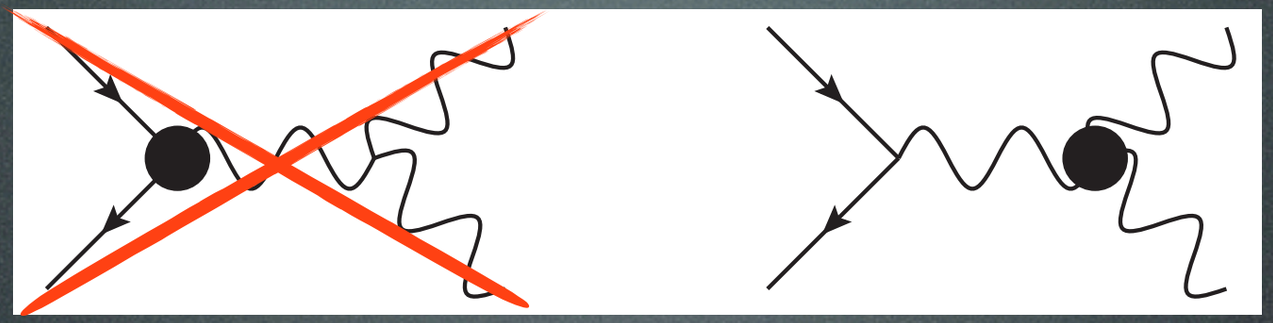
CP even operators

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

CP odd operators

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

WW(WZ/WA) production



CP even operators

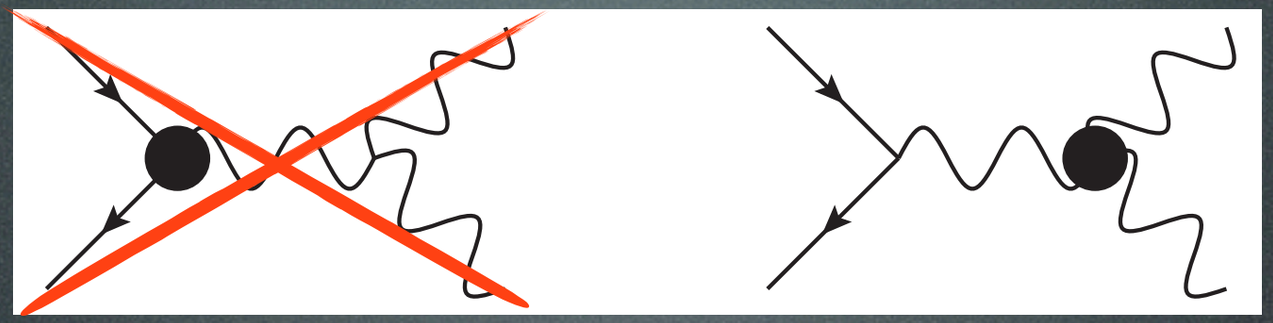
$$\begin{aligned}\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] \\ \mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\end{aligned}$$

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

CP odd operators

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

WW(WZ/WA) production



CP even operators

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

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

CP odd operators

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

Only 5 operators!

WW production

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

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

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

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

WW production

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

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

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

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

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

WW production

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

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

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

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

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

11(5+6) parameters

WW production

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

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

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

Why not adding derivatives

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

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

11(5+6) parameters

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

Dimension-six

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

Dimension-six

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

Dimension-six

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

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

Dimension-six

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

Form factors are higher dimension operators with arbitrarily fixed coefficients

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

Dimension-six

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

WW production

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

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

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

$$+\frac{g_2^V}{M_W^2}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})\partial_\rho\partial^\rho V^\nu$$

Dimension-six

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

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

EFT versus Anomalous Couplings

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

WW Production

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

WW Production

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

CP even Operators

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

CP odd operators

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

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

WW Production

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

CP even Operators

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

CP odd operators

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

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

constants

WW Production

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

CP even Operators

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

CP odd operators

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

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

$\Delta X = X - 1$

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

$$\kappa_Z = 1 + (c_W$$

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

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

$$\tilde{\kappa}_\gamma$$

$$\tilde{\kappa}_Z$$

$$0 = \tilde{\kappa}_Z + \tan^2\theta_W\tilde{\kappa}_\gamma$$

$$\tilde{\lambda}_\gamma = \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g}{2\Lambda^2}$$

PDG constraints

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

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

PDG constraints

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

At 68% C.L.

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

PDG constraints

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

At 68% C.L.

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

- Only LEP combination

PDG constraints

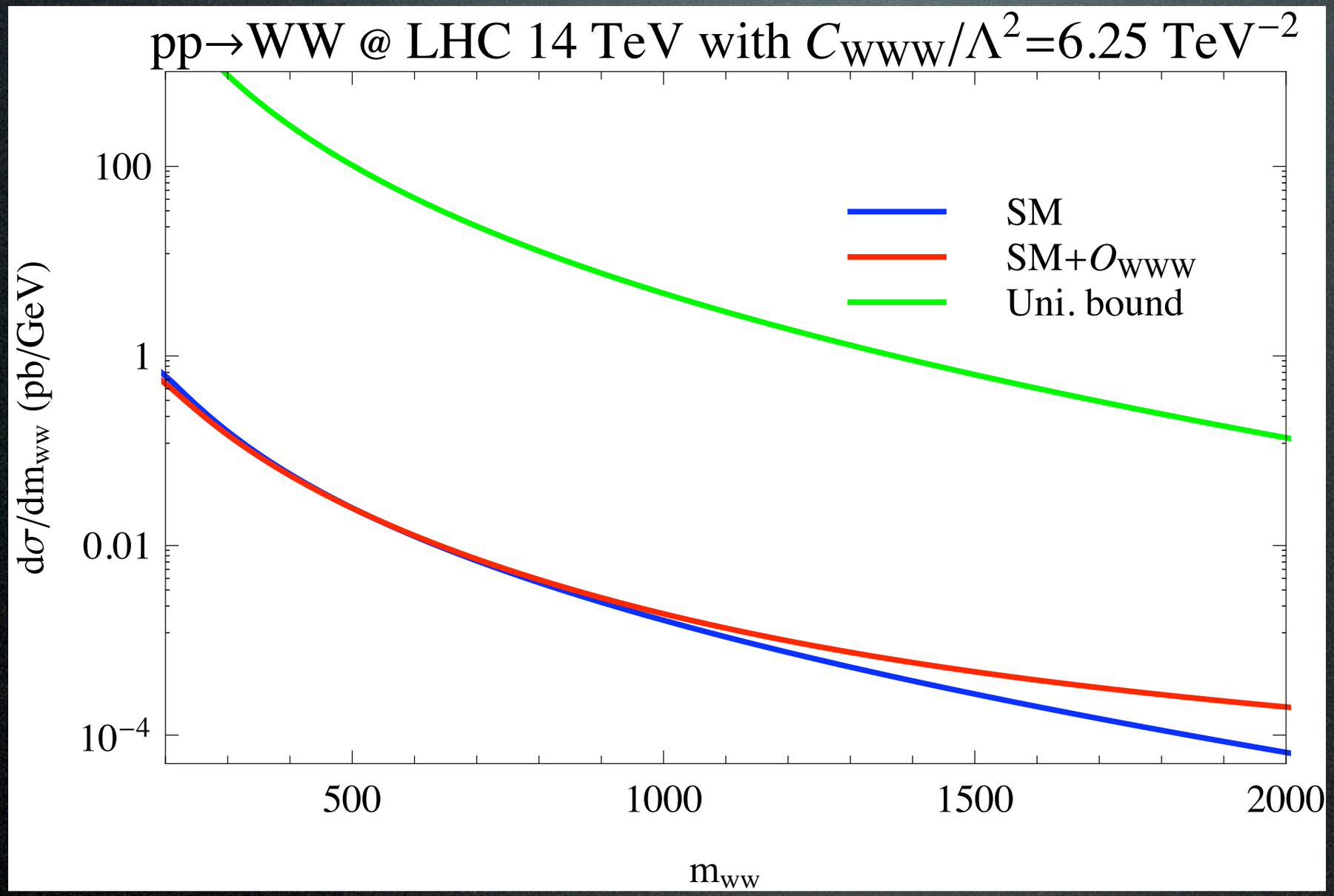
$$g_1^Z = 0.984^{+0.022}_{-0.019}$$
$$\kappa_\gamma = 0.979^{+0.044}_{-0.045}$$
$$\lambda_\gamma = -0.028^{+0.020}_{-0.021}$$
$$\tilde{\kappa}_Z = -0.12^{+0.06}_{-0.04}$$
$$\tilde{\lambda}_Z = -0.09 \pm 0.07$$

At 68% C.L.

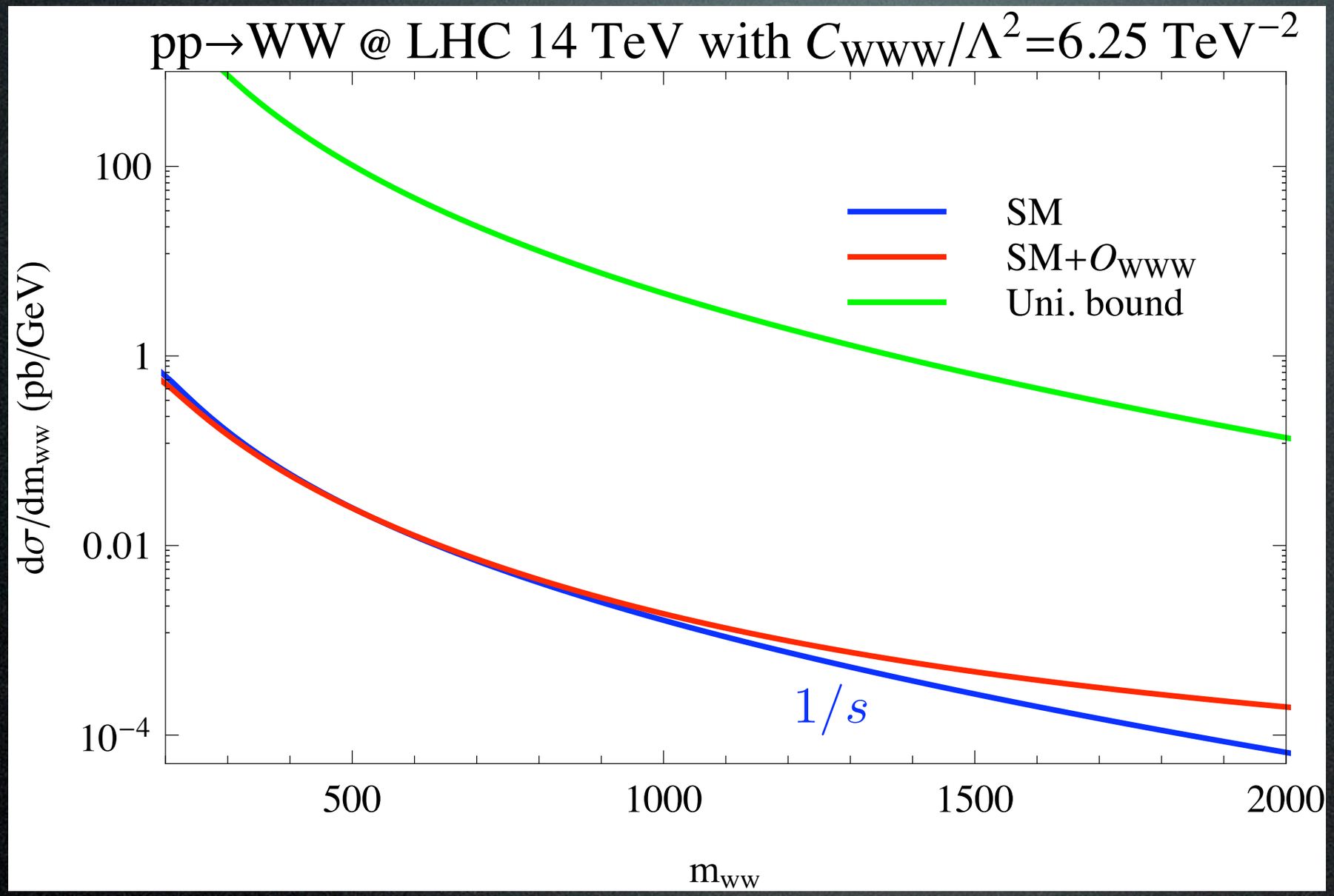
$$c_{WWW}/\Lambda^2 \in [-11.9, 1.94]\mathrm{TeV}^{-2}$$
$$c_W/\Lambda^2 \in [-8.42, 1.44]\mathrm{TeV}^{-2}$$
$$c_B/\Lambda^2 \in [-7.9, 14.9]\mathrm{TeV}^{-2}$$
$$c_{\tilde{W}WW}/\Lambda^2 \in [-185.3, -82.4]\mathrm{TeV}^{-2}$$
$$c_{\tilde{W}}/\Lambda^2 \in [-39.3, -4.9]\mathrm{TeV}^{-2}$$

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

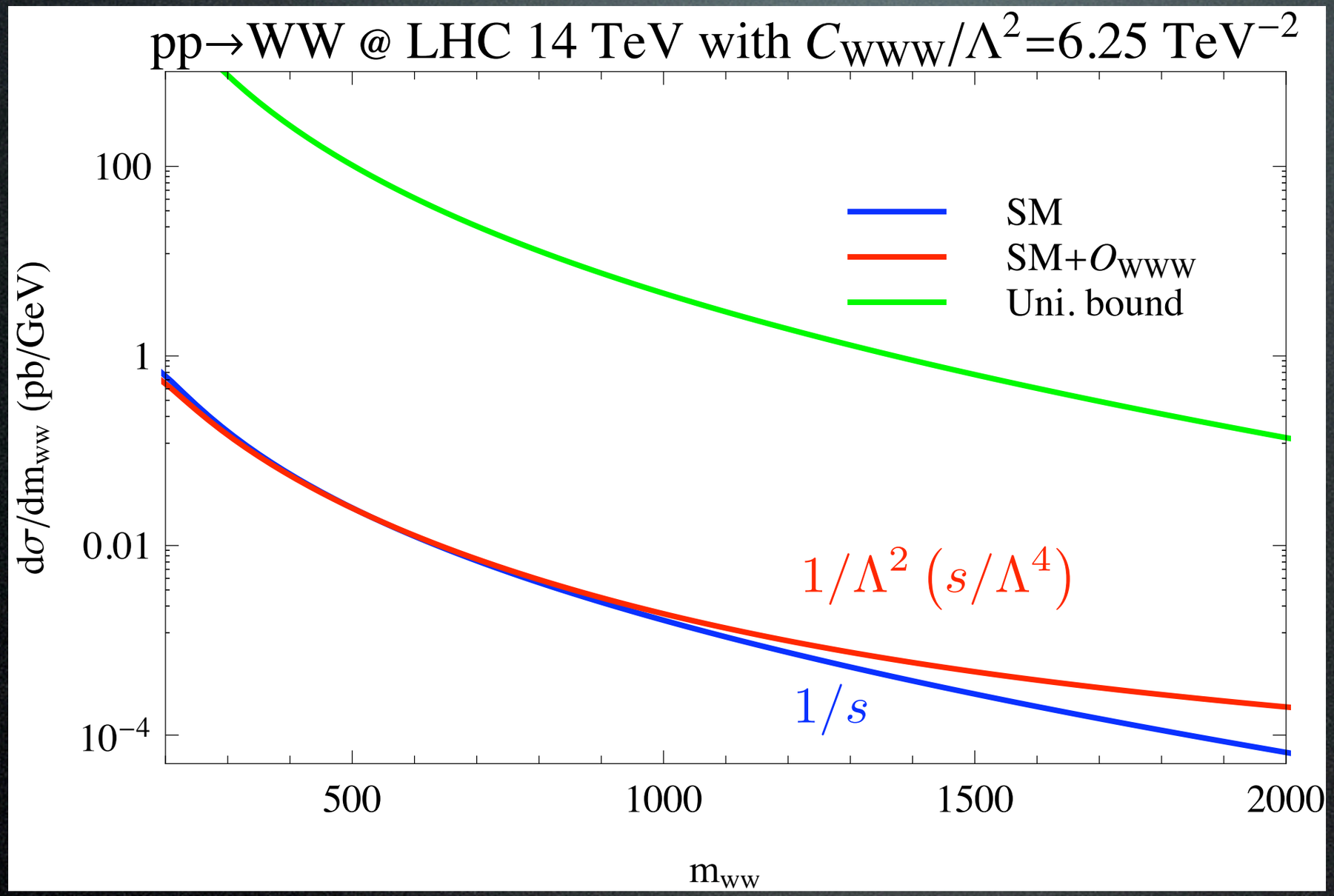
Unitarity bound



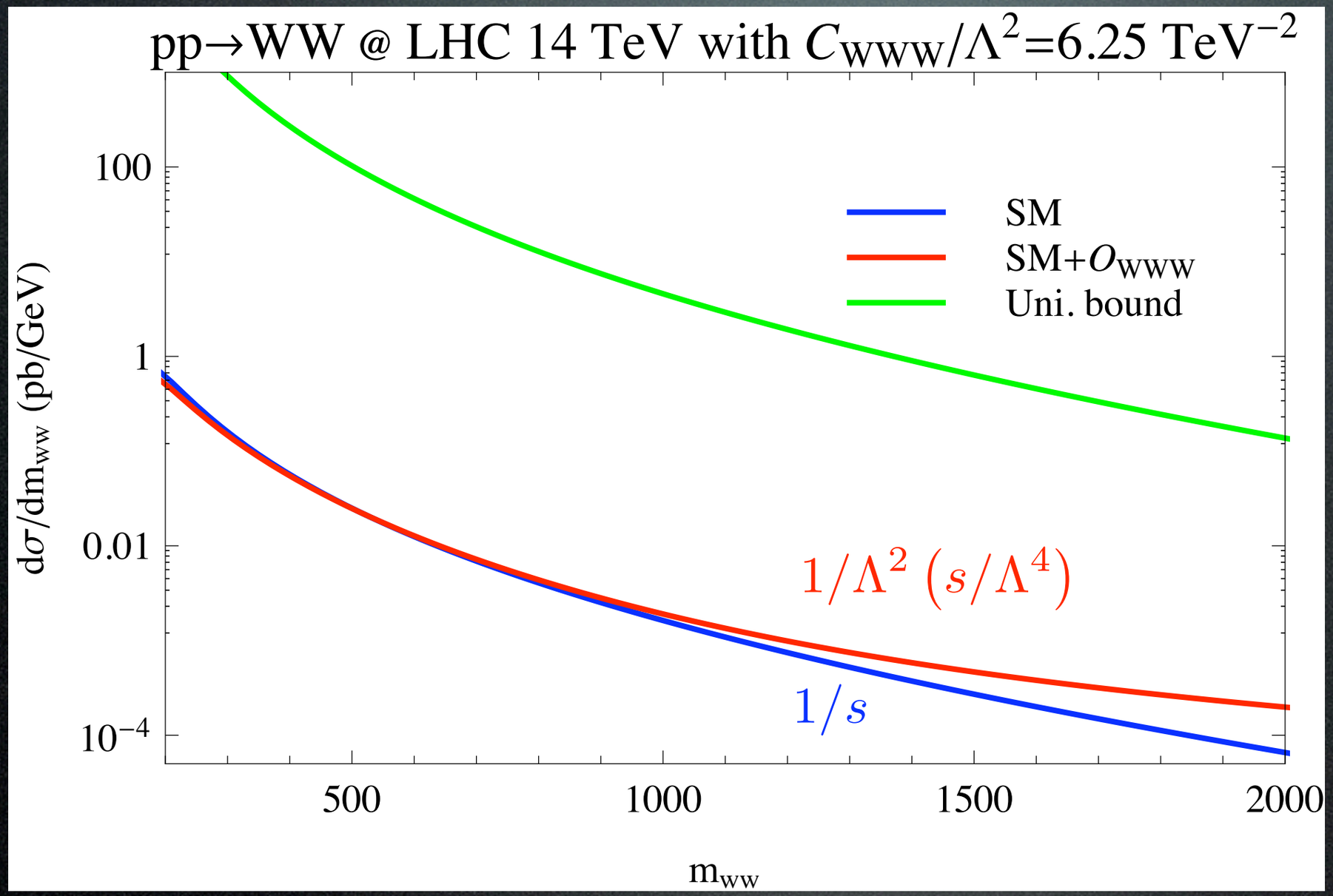
Unitarity bound



Unitarity bound

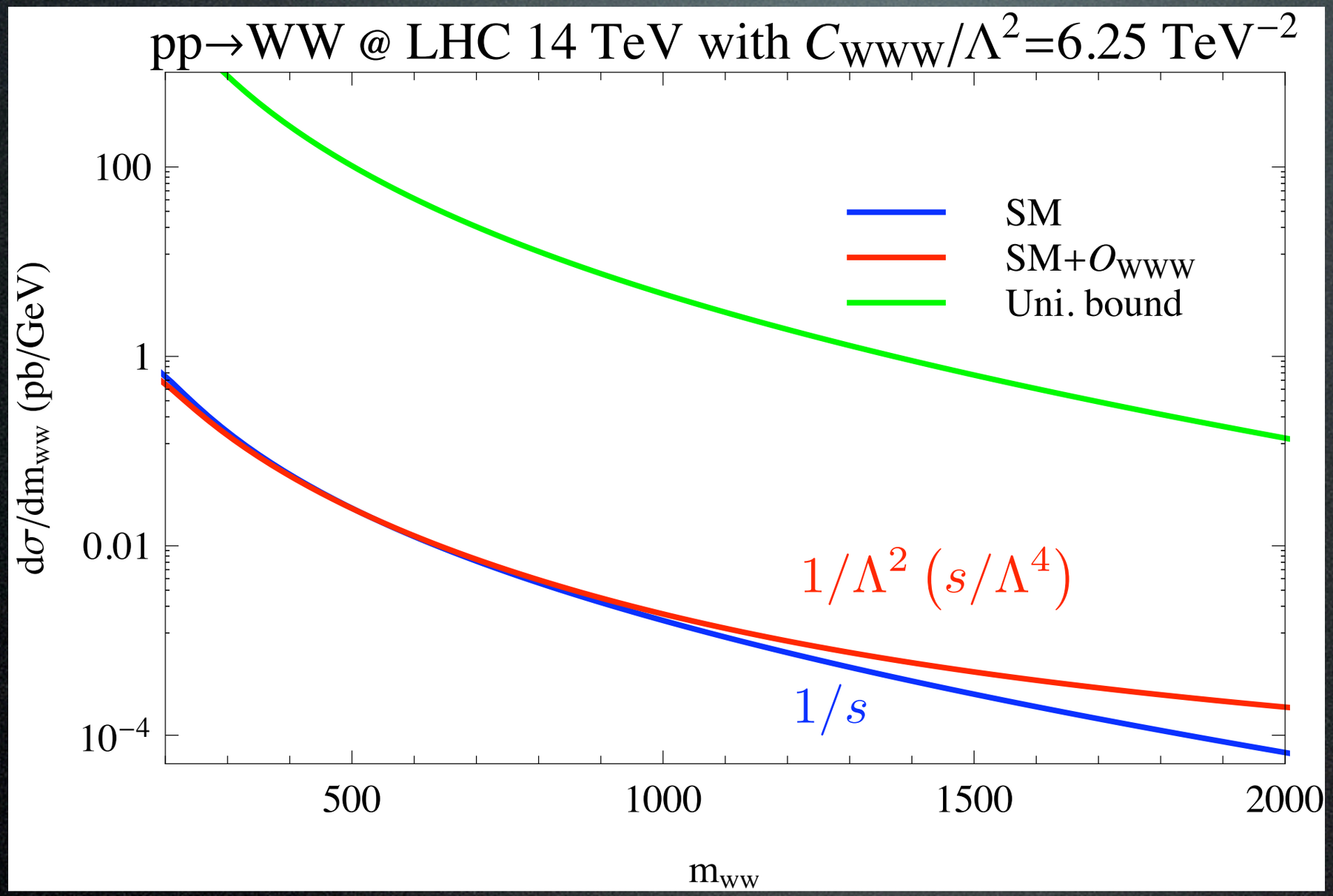


Unitarity bound



More than 2 orders of magnitude

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	$1/s\ (s)$	$1\ (s)$	$1\ (s)$	$1/s$

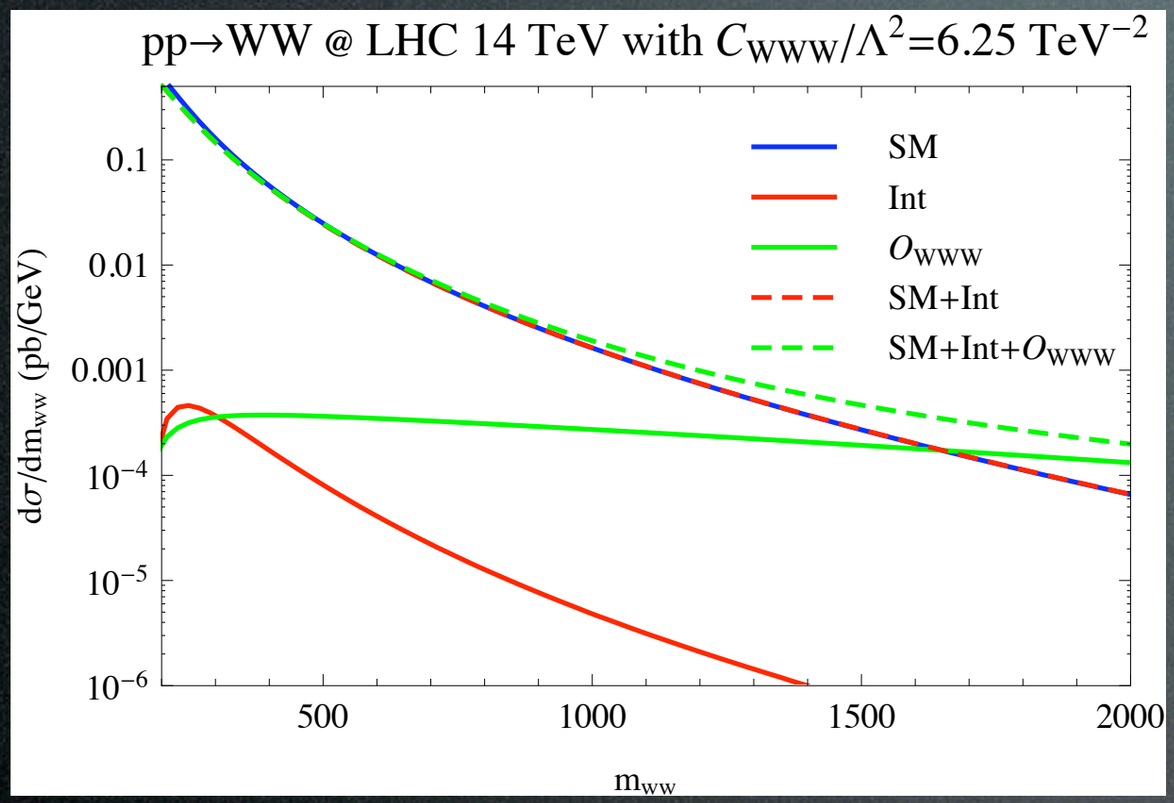
Invariant mass and polarisations

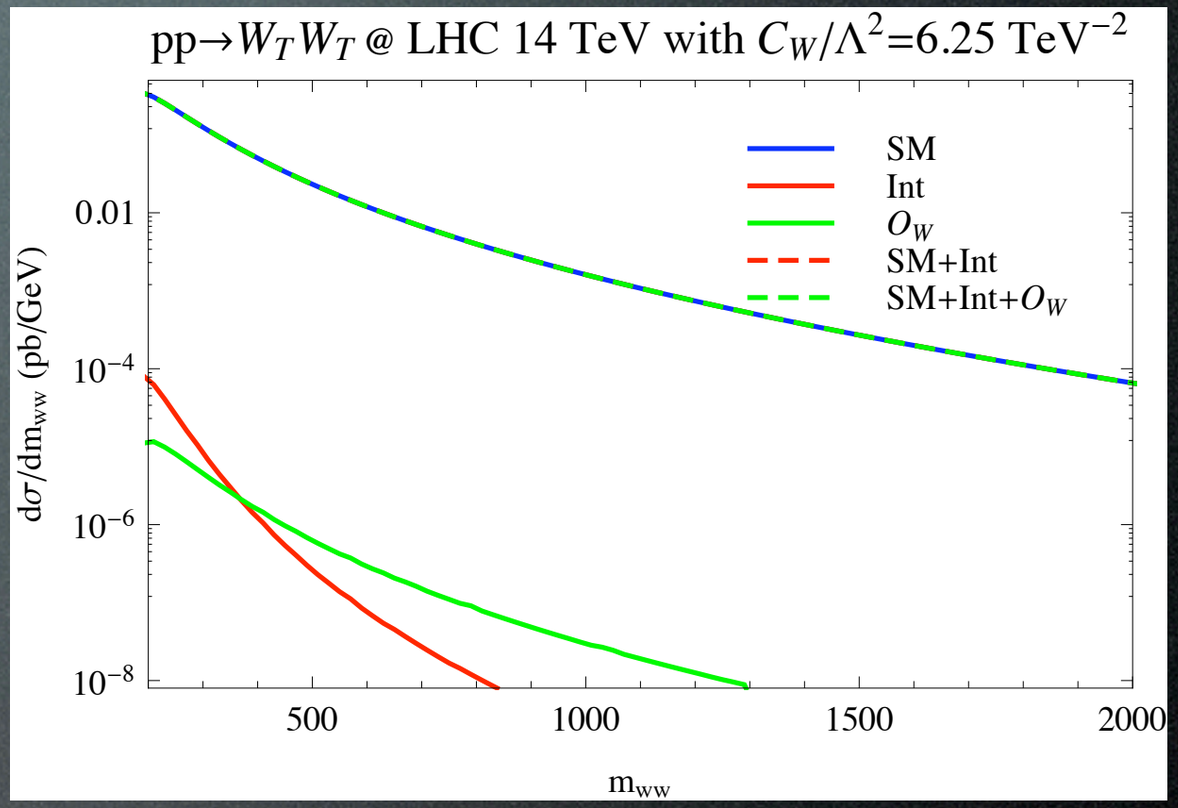
	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$	SM
LL	0	$1\ (s)$	$1\ (s)$	$1/s$
LT	$1/s\ (1)$	$1/s\ (1)$	$1/s\ (1)$	$1/s^2$
TT	$1/s\ (s)$	$1/s^2\ (1/s)$	0	$1/s$
Sum	$1/s\ (s)$	$1\ (s)$	$1\ (s)$	$1/s$

Invariant mass and polarisations

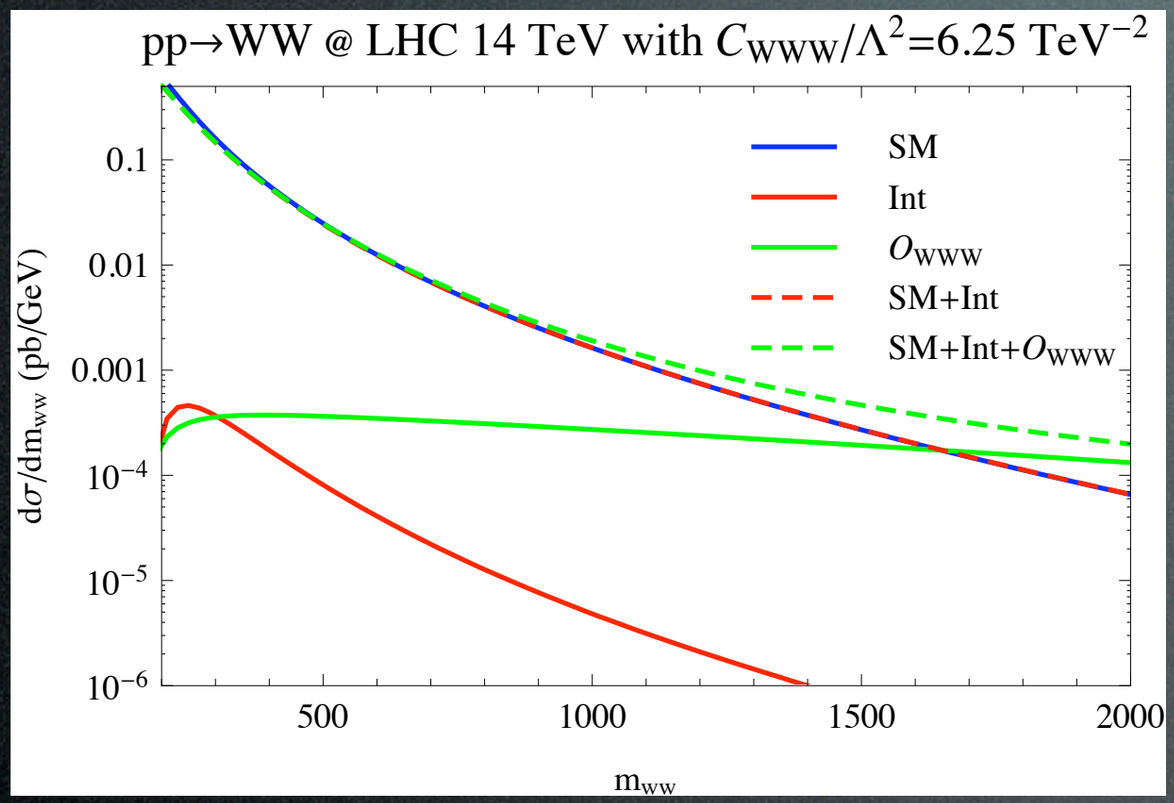
	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$	SM
LL	0	$1\ (s)$	$1\ (s)$	$1/s$
LT	$1/s\ (1)$	$1/s\ (1)$	$1/s\ (1)$	$1/s^2$
TT	$1/s\ (s)$	$1/s^2\ (1/s)$	0	$1/s$
Sum	$1/s\ (s)$	$1\ (s)$	$1\ (s)$	$1/s$

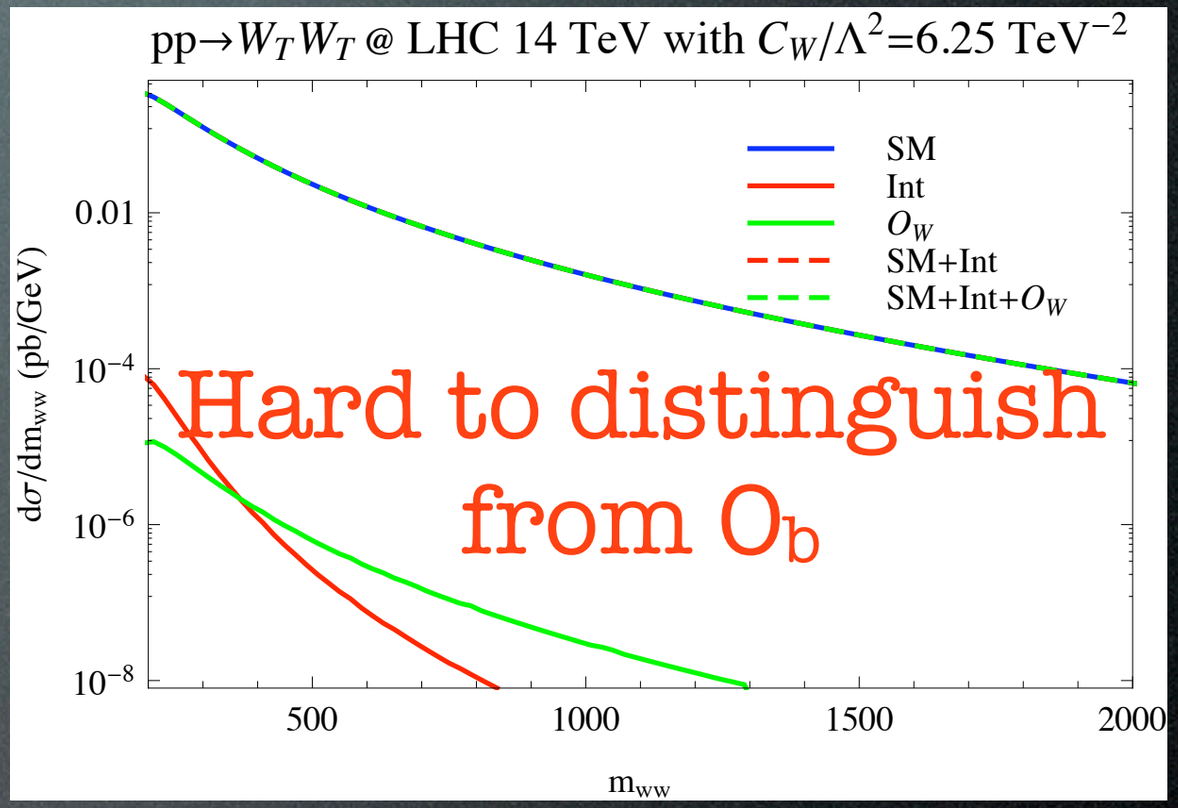
Tranverse polarizations





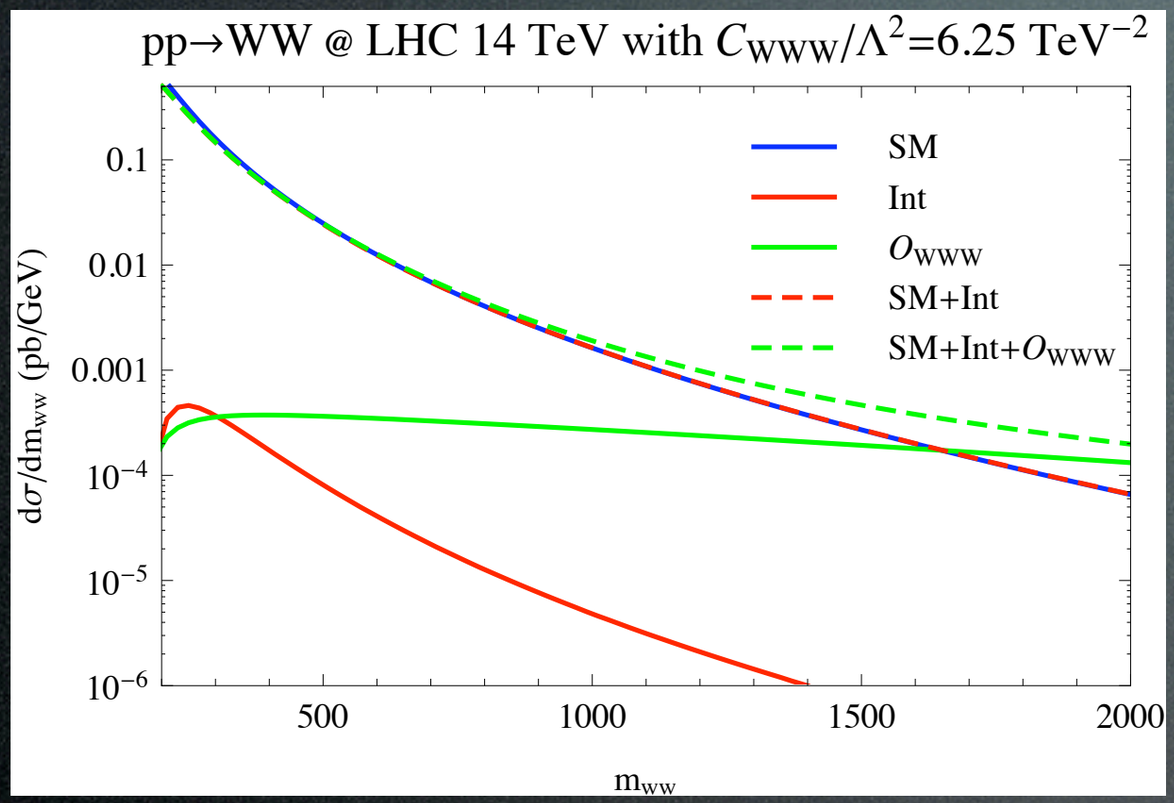
Tranverse polarizations

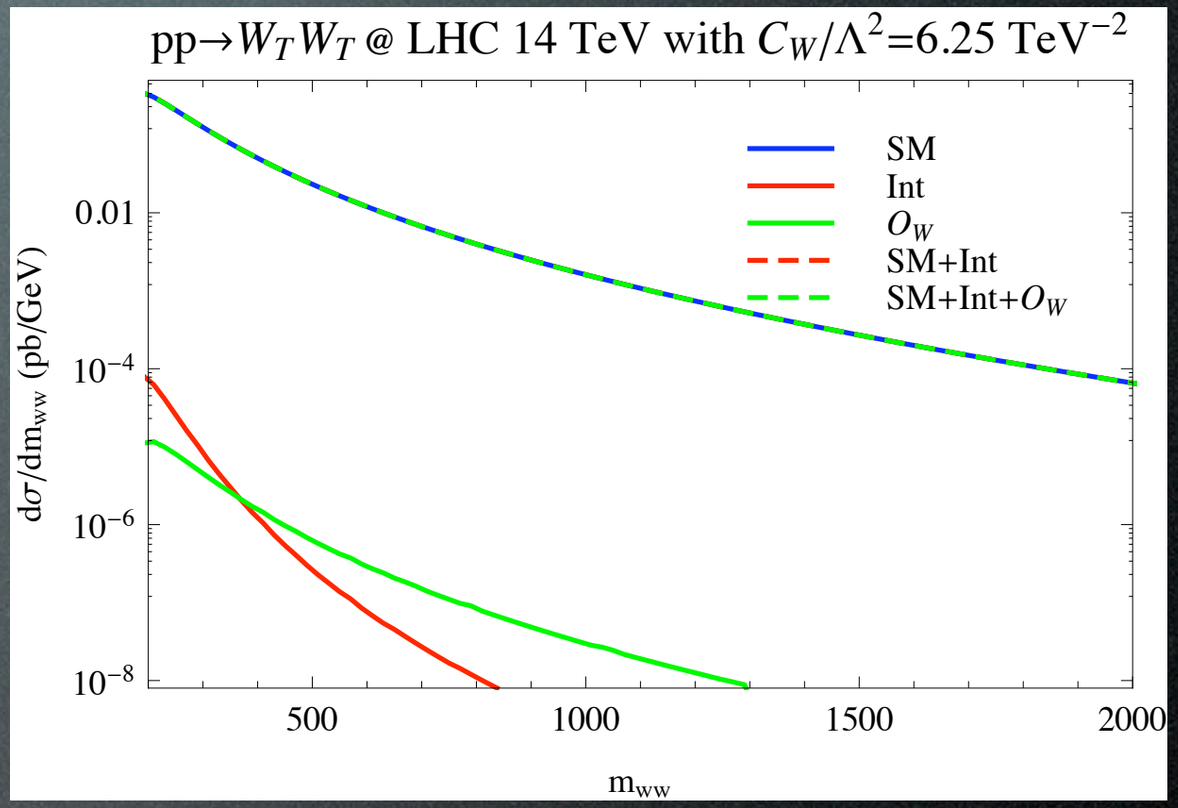




Hard to distinguish from O_b

Tranverse polarizations



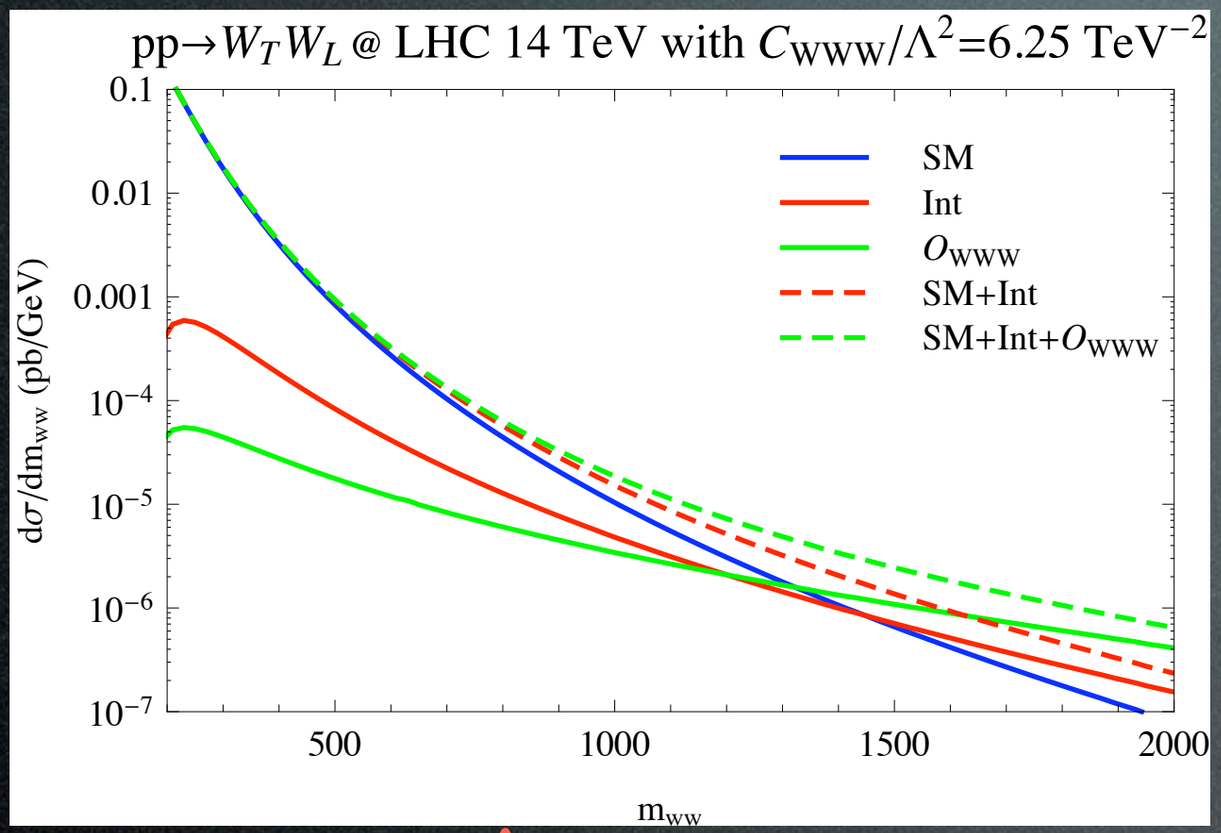


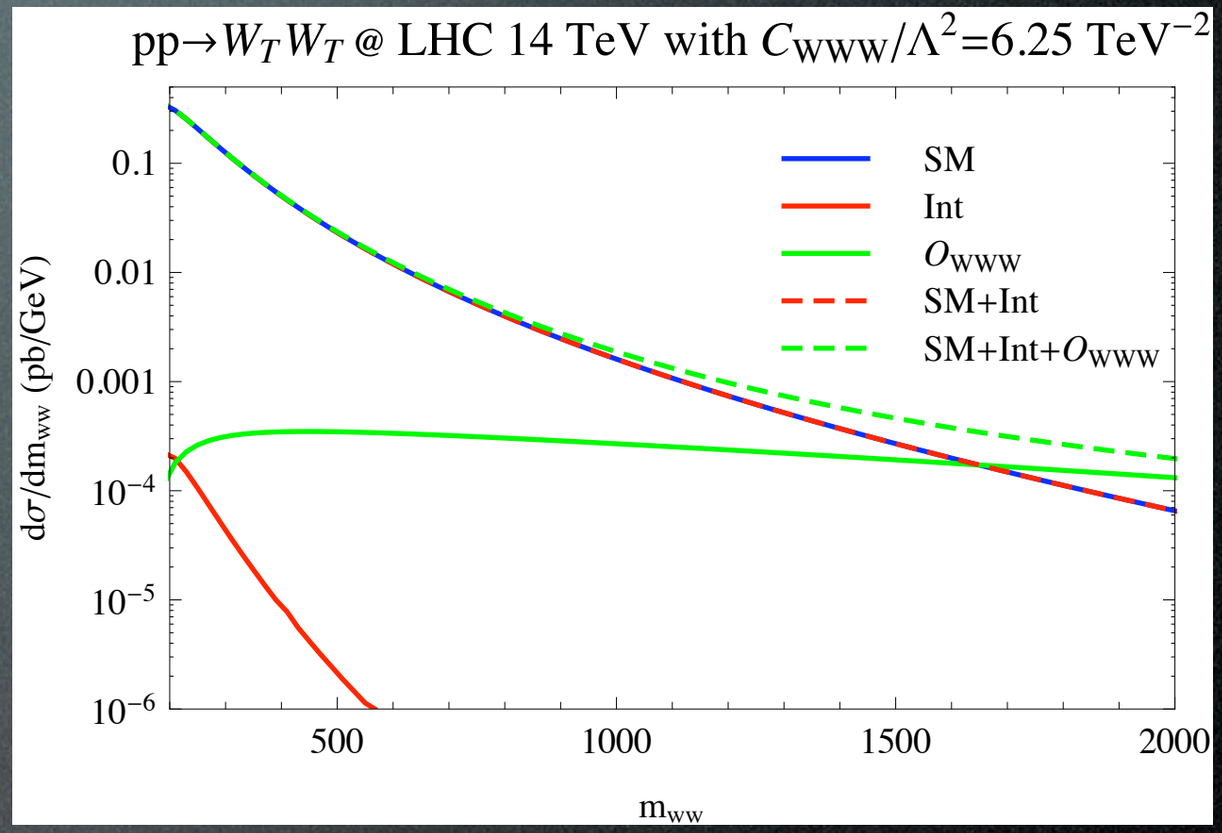
SM has a large contribution

Dim-6 operators have small contributions

→ Cut ?

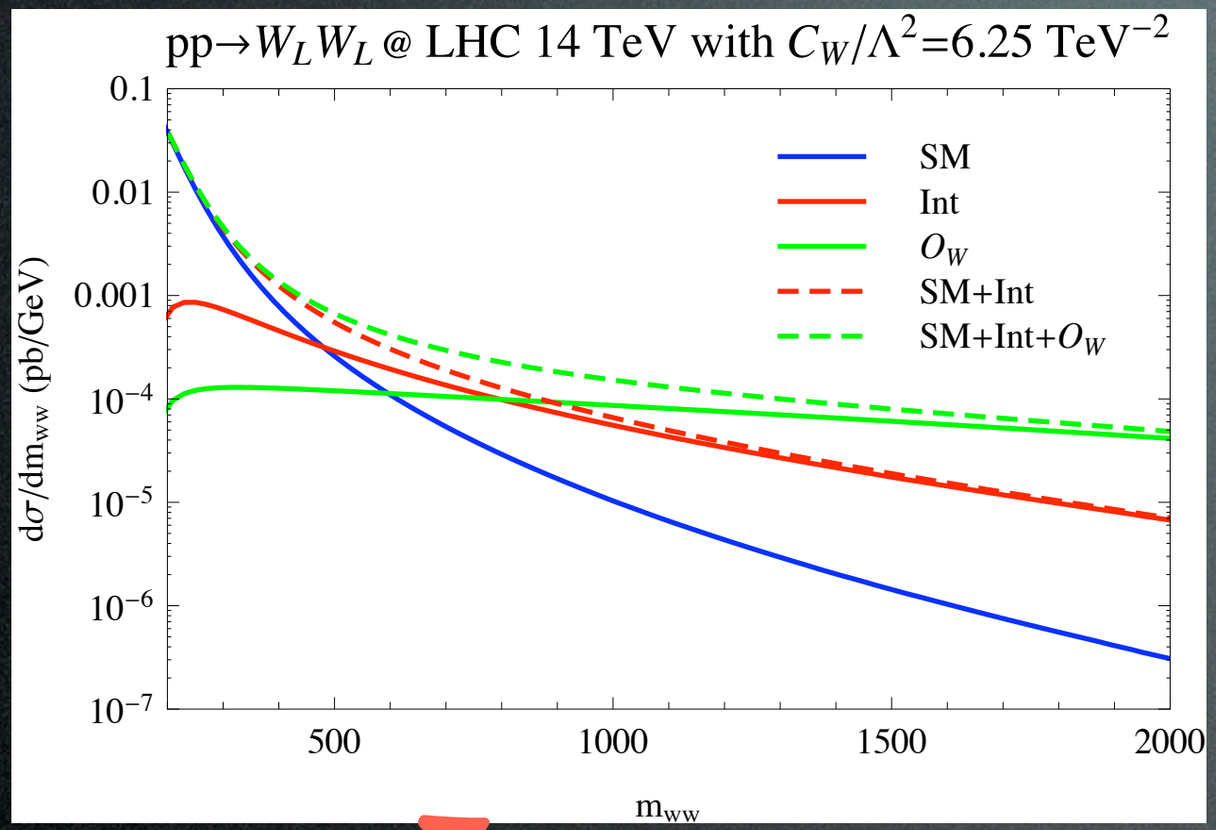
O_{WWW}

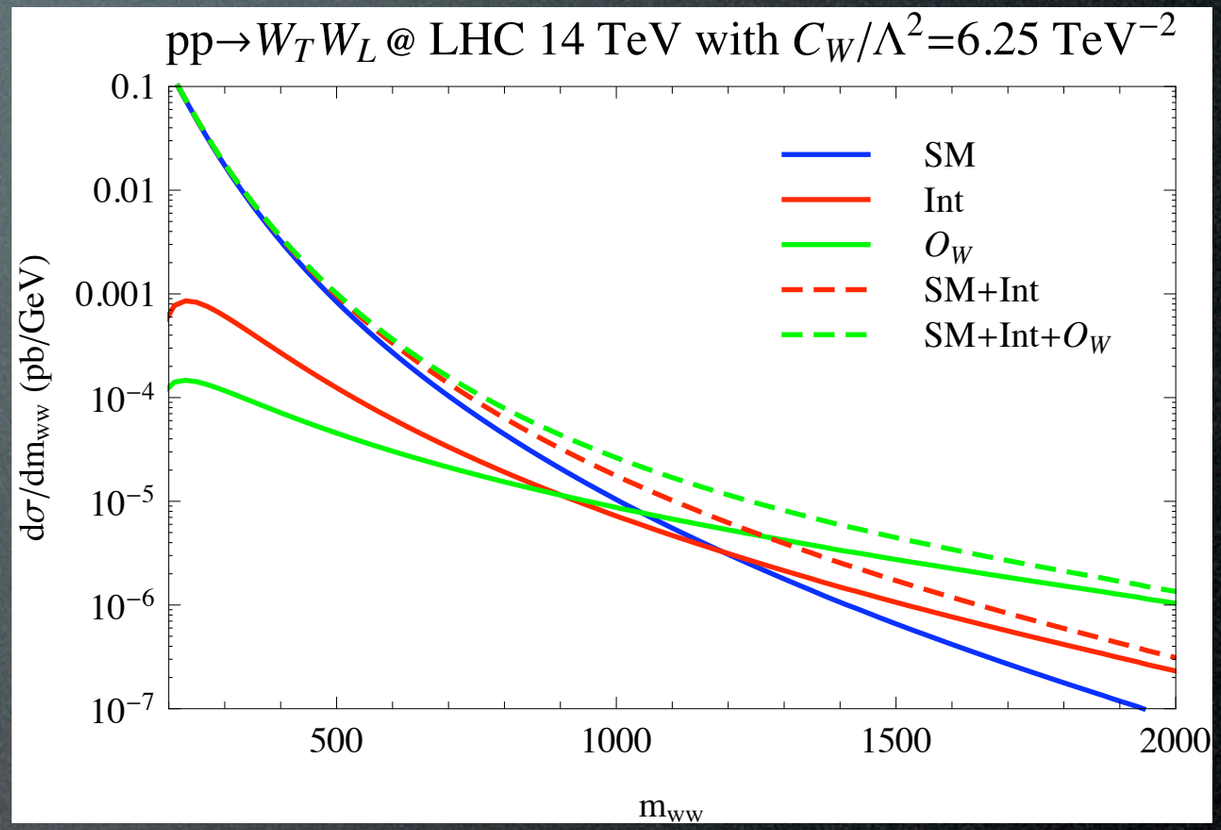


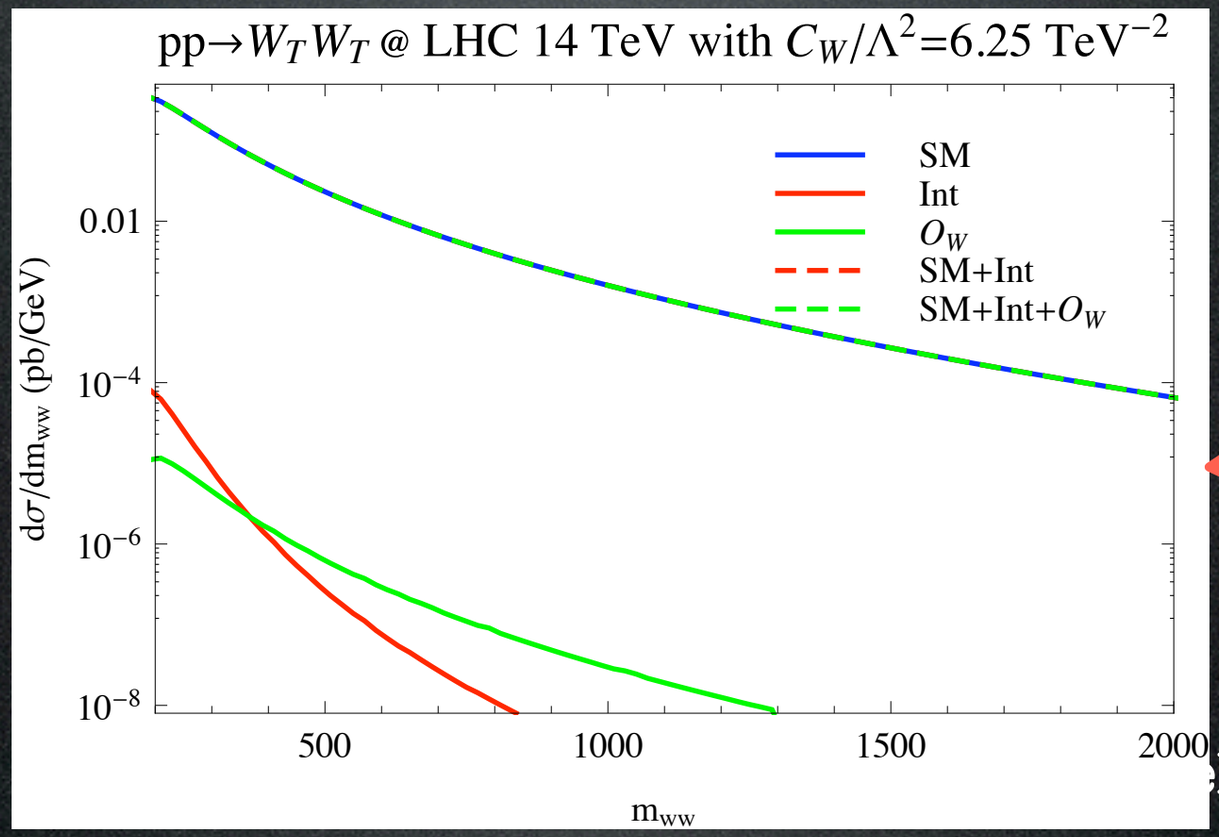


Largest for O_{WWW}

O_W



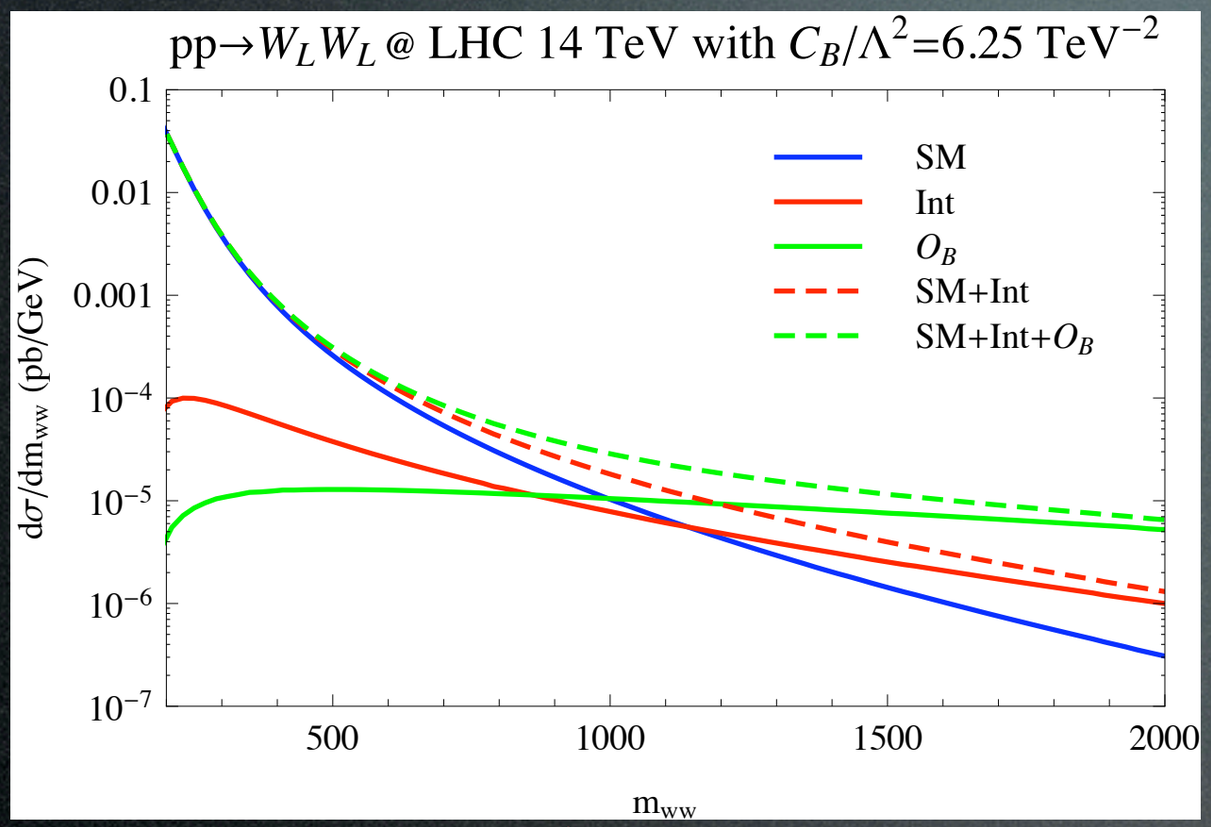


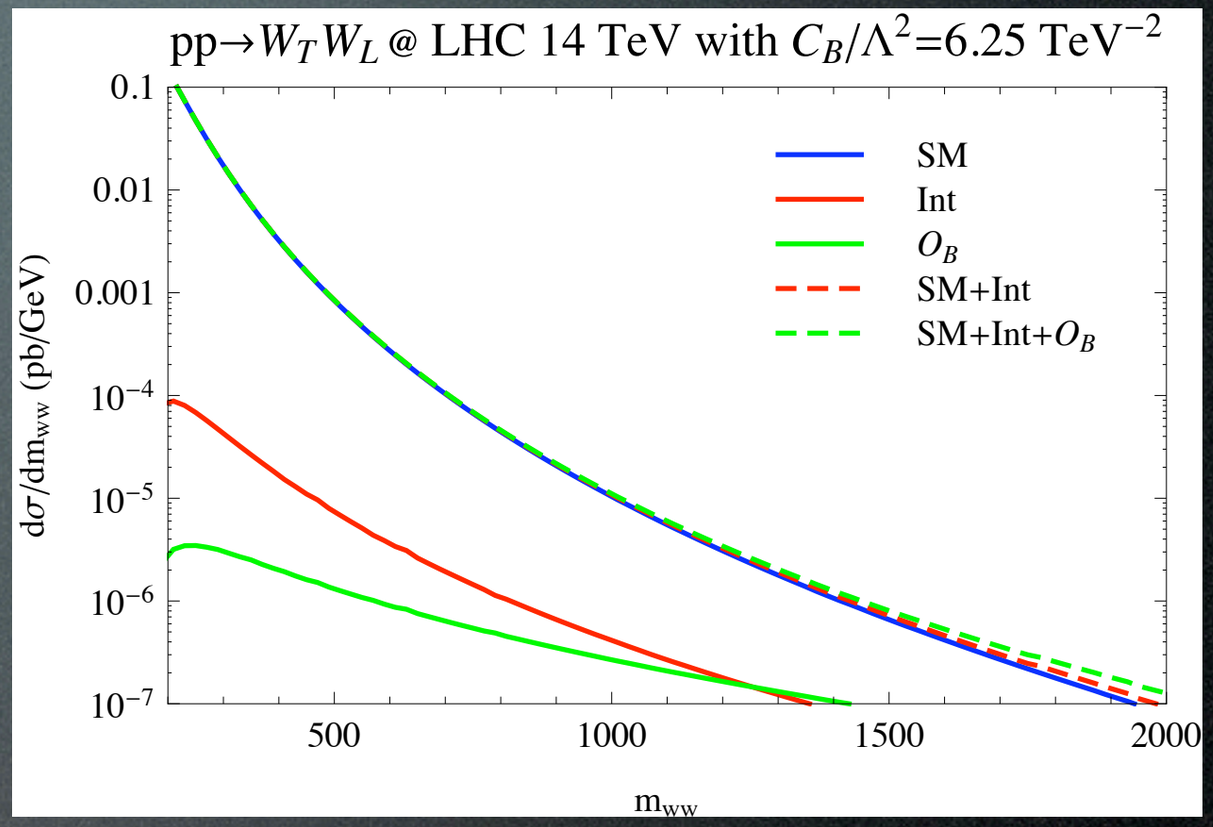


Largest for O_b
Smallest for SM

Smallest for O_b
Largest for SM

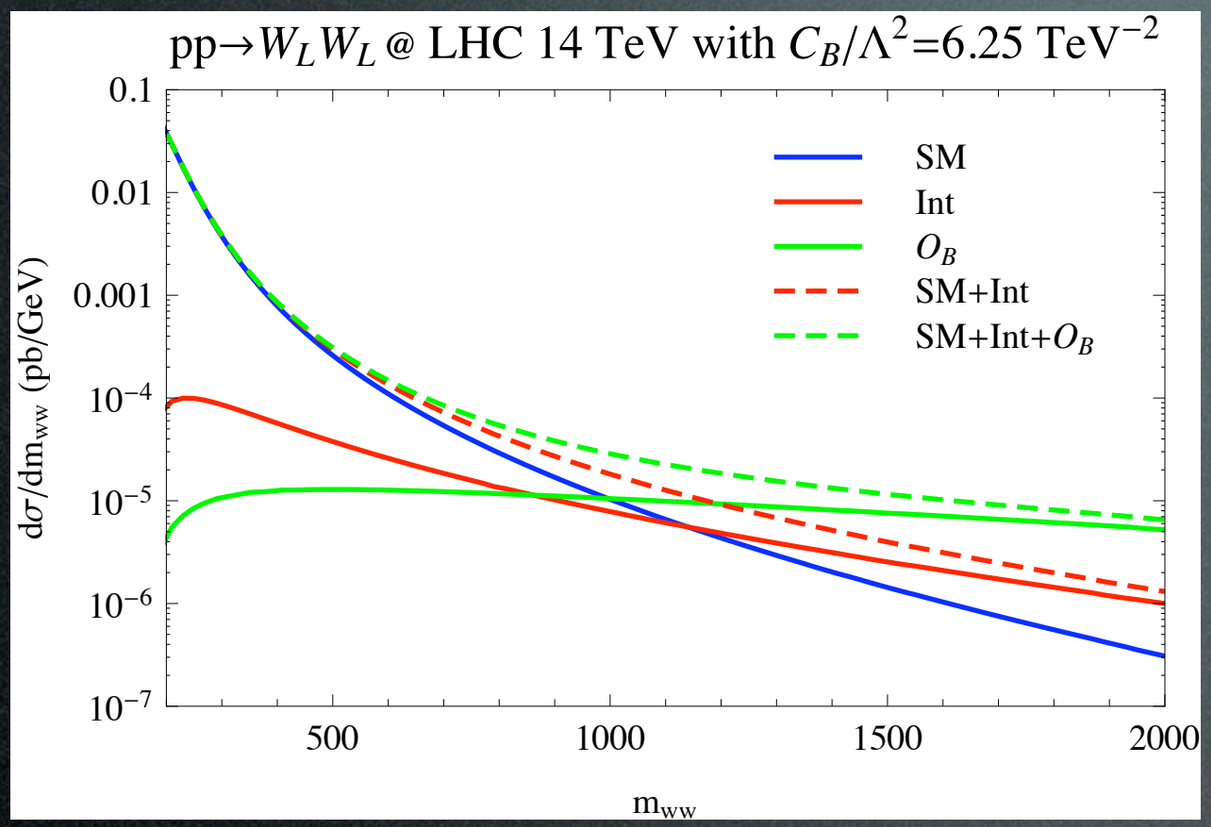
O_b

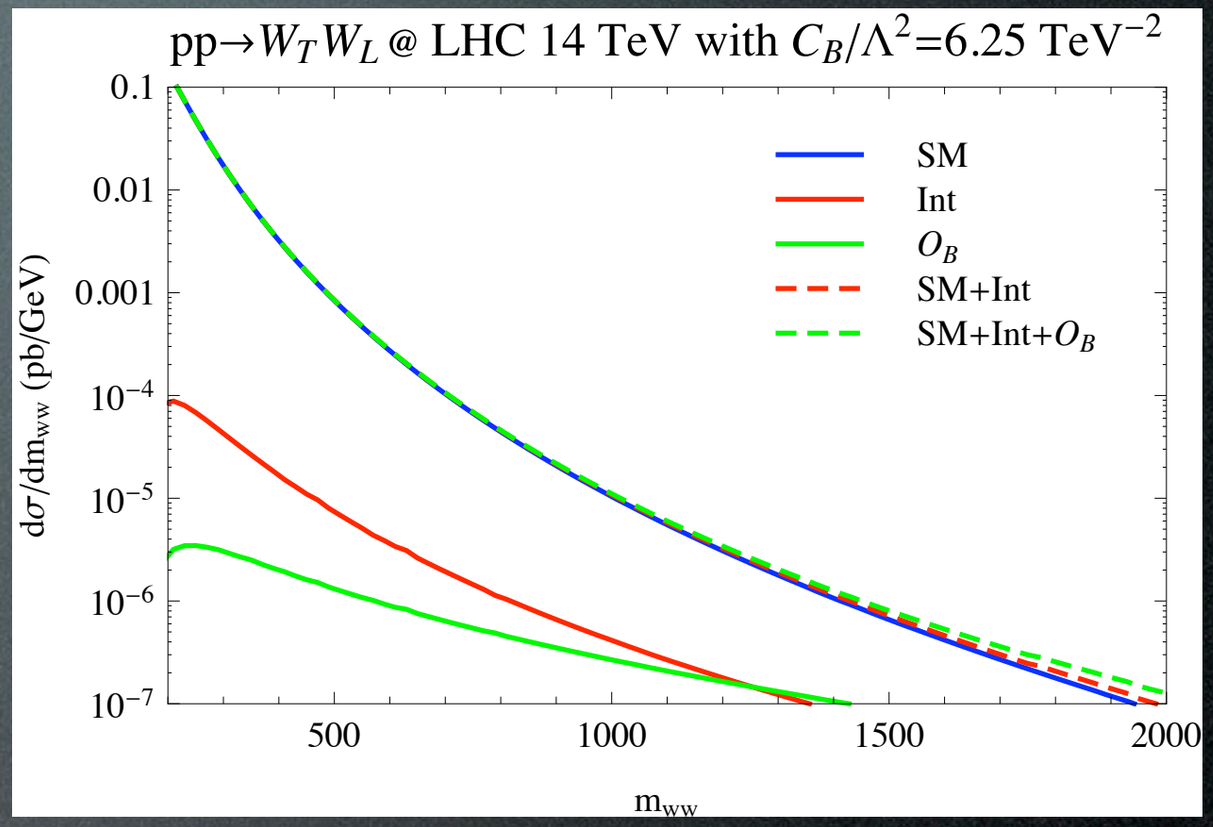




Largest for O_b
Smallest for SM

O_b





Largest for O_b
Smallest for SM

Similar to O_W with a smaller coefficient

EFT for QGC

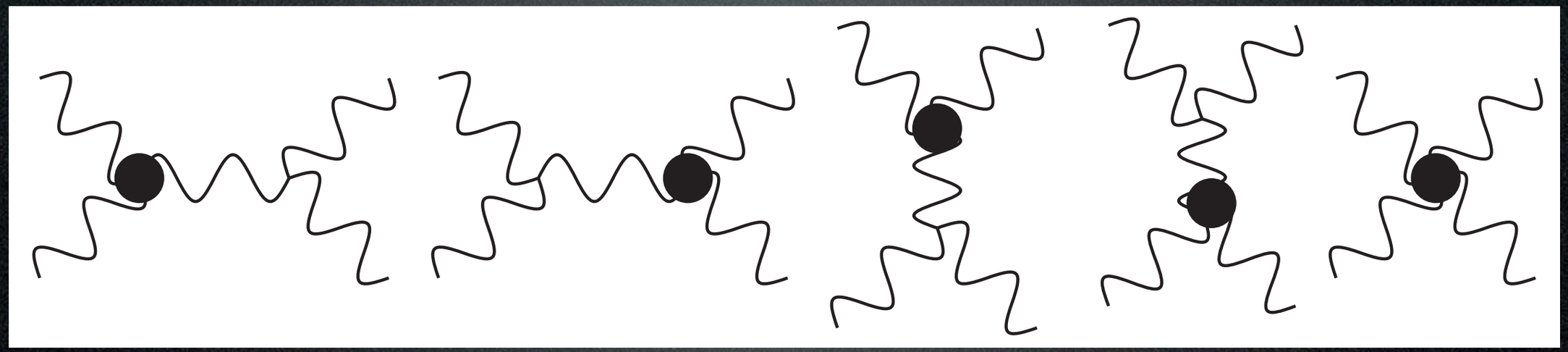
Celine Degrande (UIUC)

EFT for QGC

- Same operators than for TGC gives WWWW, WWZA, WWAA, WWZZ vertices

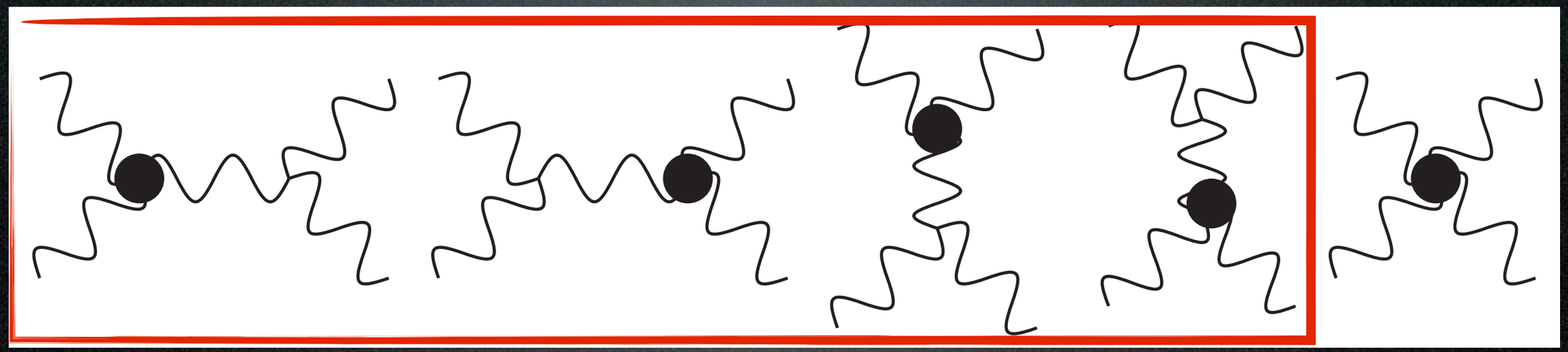
EFT for QGC

- Same operators than for TGC gives WWWW, WWZA, WWAA, WWZZ vertices
- gauge invariance requires 3 and 4 legs vertices to be related



EFT for QGC

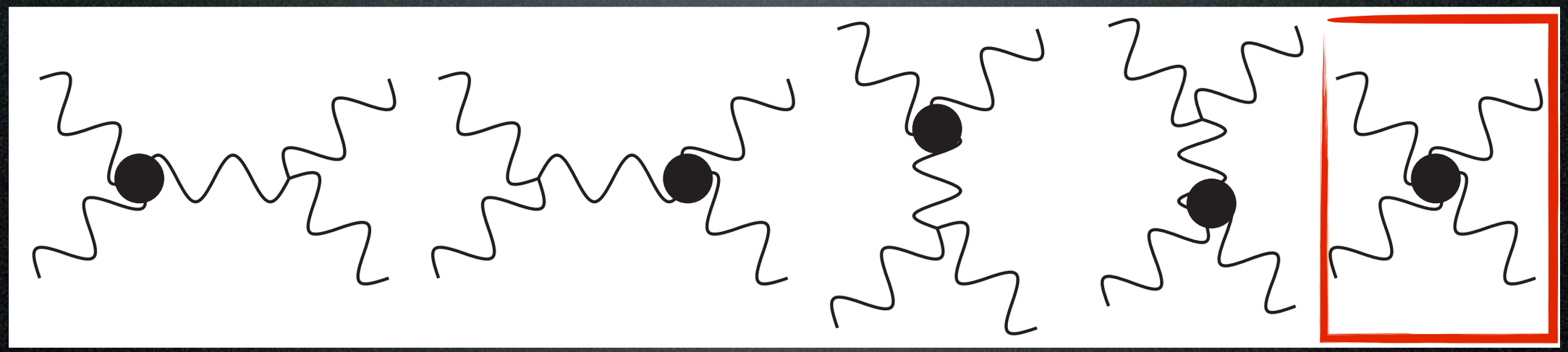
- Same operators than for TGC gives WWWW, WWZA, WWAA, WWZZ vertices
- gauge invariance requires 3 and 4 legs vertices to be related



TGC's alone are not gauge invariant

EFT for QGC

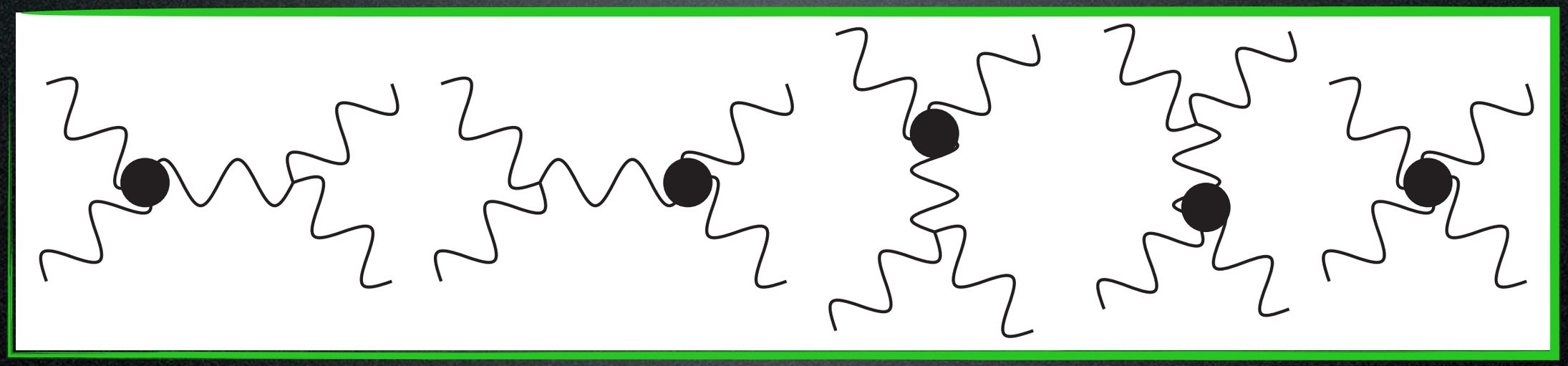
- Same operators than for TGC gives WWWW, WWZA, WWAA, WWZZ vertices
- gauge invariance requires 3 and 4 legs vertices to be related



QGC's alone are not gauge invariant

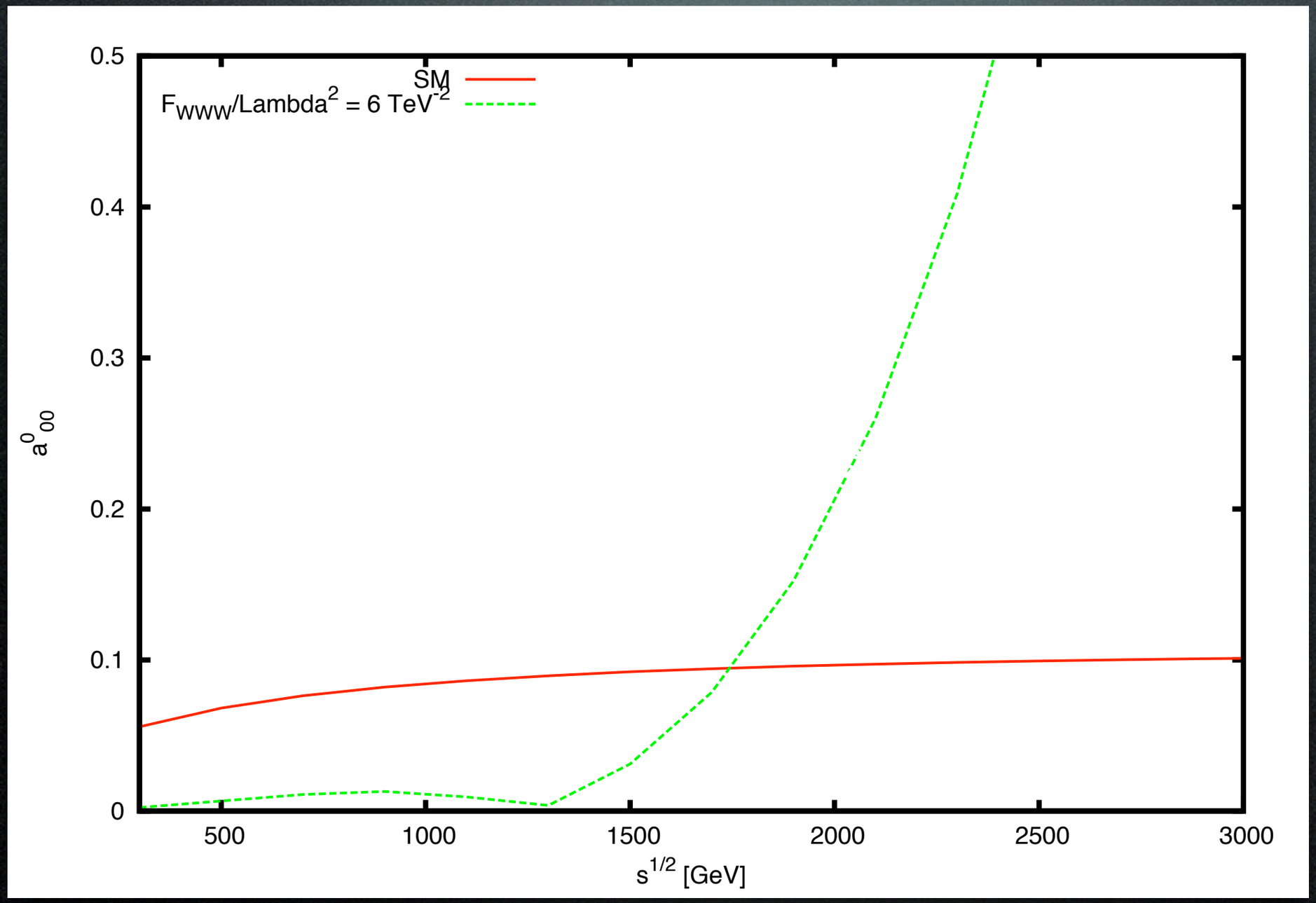
EFT for QGC

- Same operators than for TGC gives WWWW, WWZA, WWAA, WWZZ vertices
- gauge invariance requires 3 and 4 legs vertices to be related



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

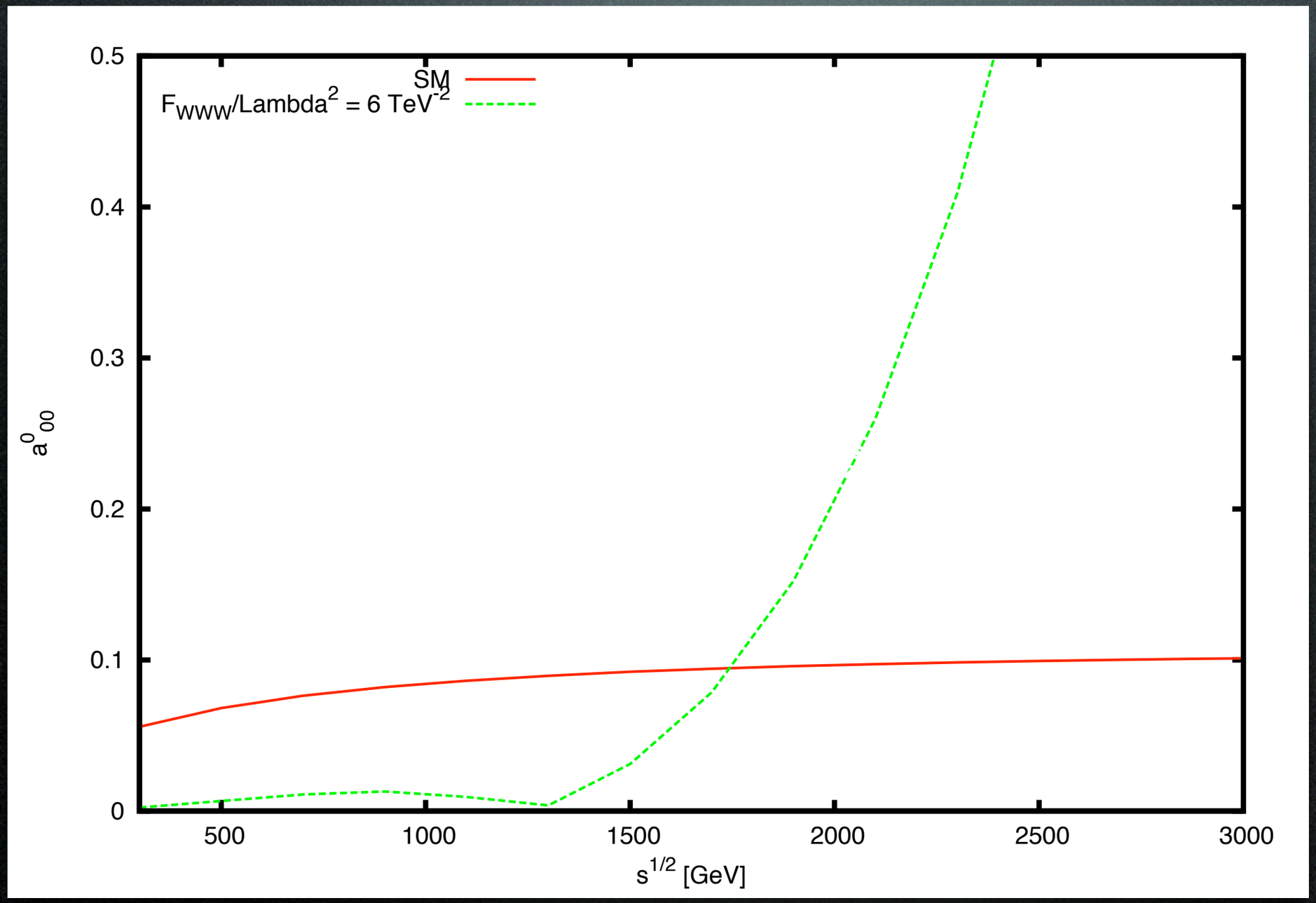
W scattering and unitarity



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

From M. Rauch

W scattering and unitarity



From M. Rauch

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

go by step

Concluding remarks

Concluding remarks

- EFT are a good way to search for heavy new physics

Concluding remarks

- EFT are a good way to search for heavy new physics
  - More predictive (same dim-6 op. for TGC and QGC, few (2?) dim-8 op for nTGC)

Concluding remarks

- EFT are a good way to search for heavy new physics
  - More predictive (same dim-6 op. for TGC and QGC, few (2?) dim-8 op for nTGC)
  - Satisfy unitarity

Concluding remarks

- EFT are a good way to search for heavy new physics
  - More predictive (same dim-6 op. for TGC and QGC, few (2?) dim-8 op for nTGC)
  - Satisfy unitarity
  - Take care of gauge invariance

Concluding remarks

- EFT are a good way to search for heavy new physics
  - More predictive (same dim-6 op. for TGC and QGC, few (2?) dim-8 op for nTGC)
  - Satisfy unitarity
  - Take care of gauge invariance
- 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%

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%
1	0%	10%	3%

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%
1	0%	10%	3%

- Extra assumptions if first order does not vanishes

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%
1	0%	10%	3%

- Extra assumptions if first order does not vanishes

- More parameters/less guidance

Dimension and errors

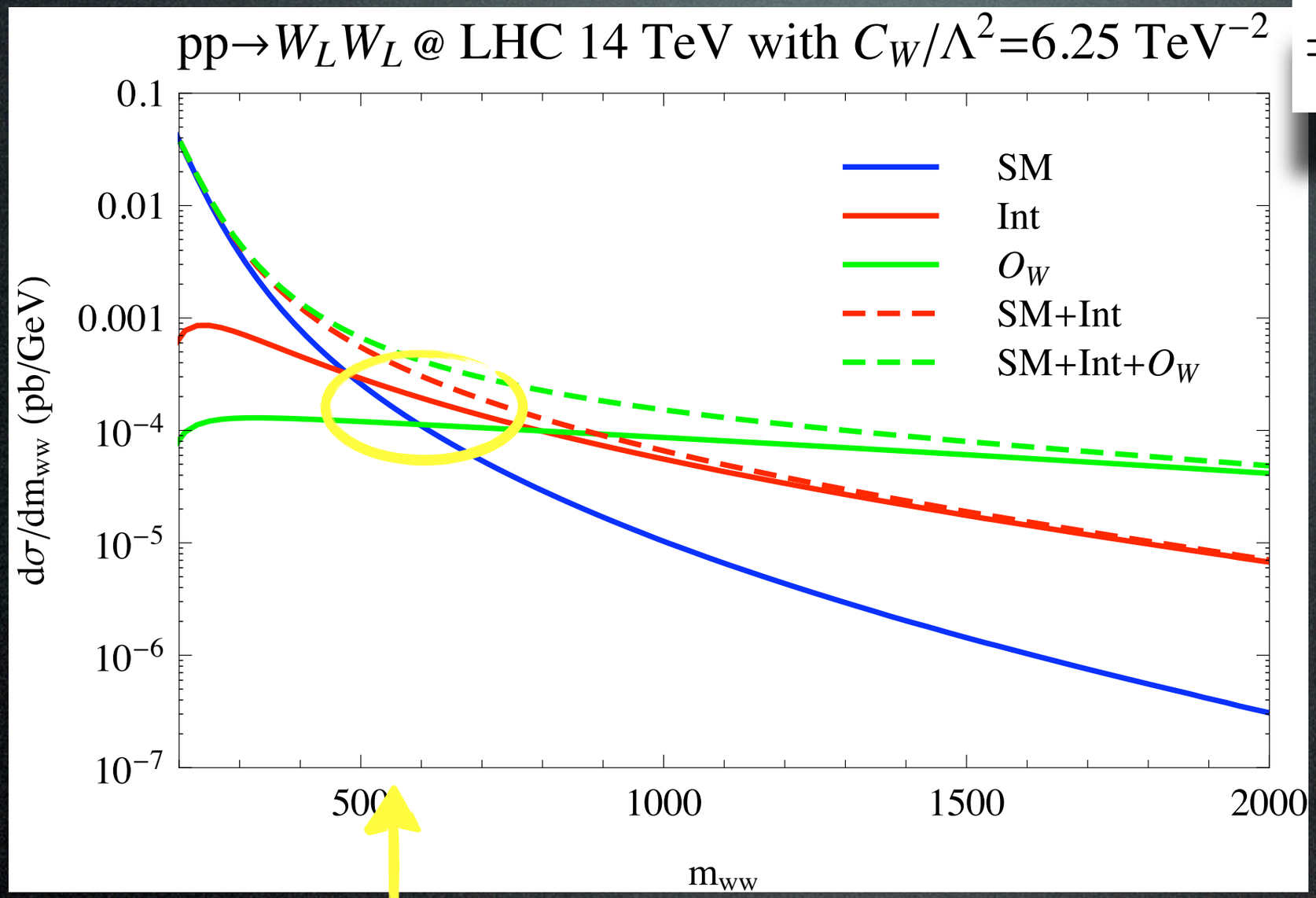
- Smaller effects or larger errors for higher dimension operators

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

1	10%	1%	0.1%
1	0%	10%	3%

- Extra assumptions if first order does not vanishes
- More parameters/less guidance
- Can affect a new observable

Expansion and error



$= 1/\,(400\mathrm{GeV})^2$

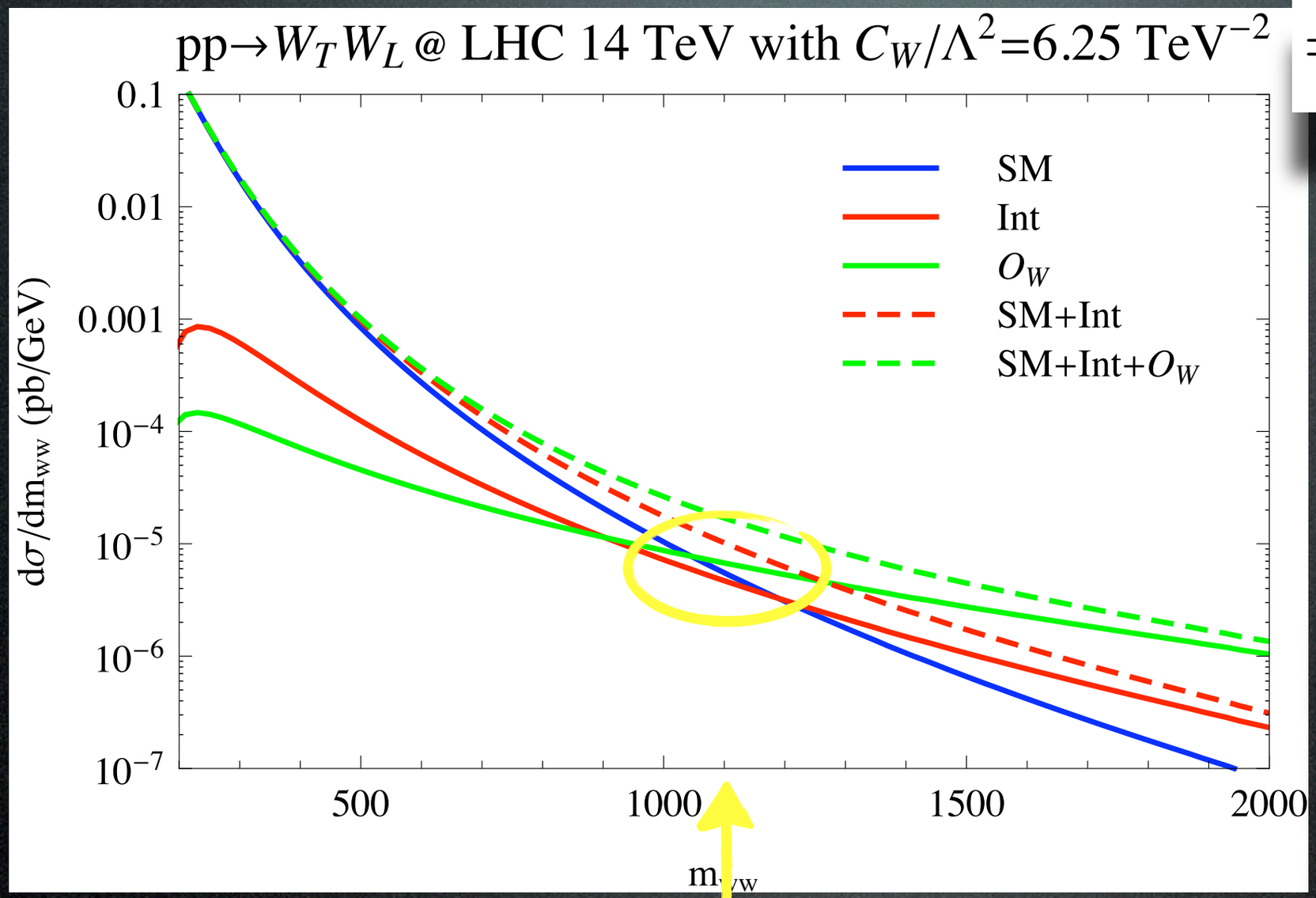
$1/\Lambda^4$

$1/\Lambda^2$

$1/\Lambda^0$

Expansion breaks

Expansion and error



$= 1/\,(400\mathrm{GeV})^2$

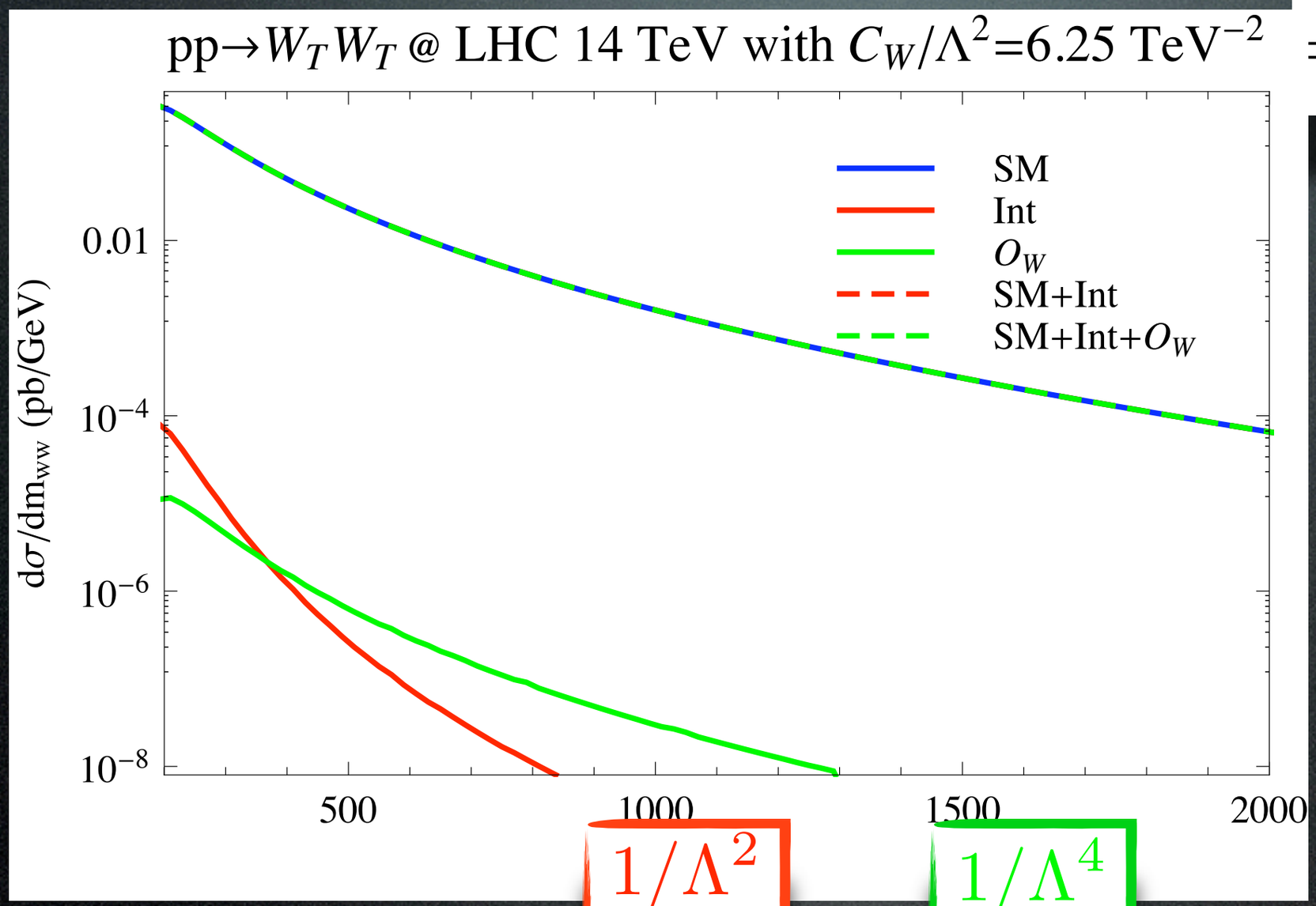
$1/\Lambda^4$

$1/\Lambda^2$

$1/\Lambda^0$

Expansion breaks

Expansion and error



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

$1/\Lambda^0$

$1/\Lambda^2$

$1/\Lambda^4$

NP is suppressed : Bad estimate of the scale