Anomalous Gauge Couplings using Effective Theories

Celine Degrande
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Snowmass-electroweak

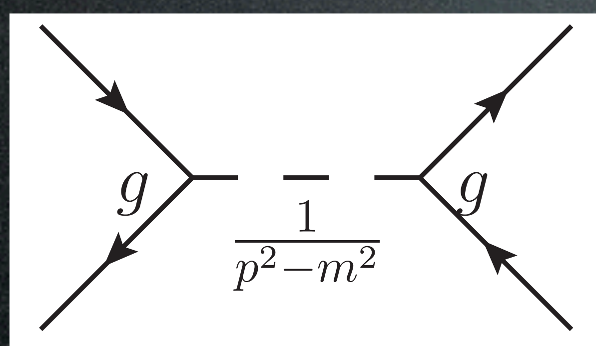
Plan

- Introduction to EFT
- EFT for pp(ee)>WW
- The constraints
- The effects
- EFT for pp>WWW, pp>WWjj
- Concluding remarks

Model Independent searches

Resonances

Assumption : One particle exchanged

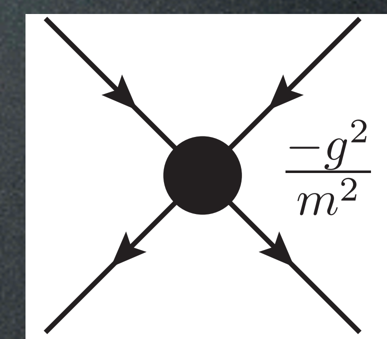


Example : Z'

Effects : Peak in the invariant mass distribution

Effective theory

Assumption : The new physics is heavy



Example : Fermi th.

Effects :
Normalisation : m^2/Λ^2
Shape : s/Λ^2

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Model Independent searches

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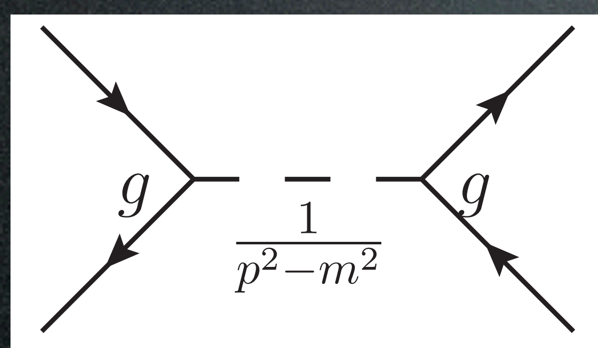

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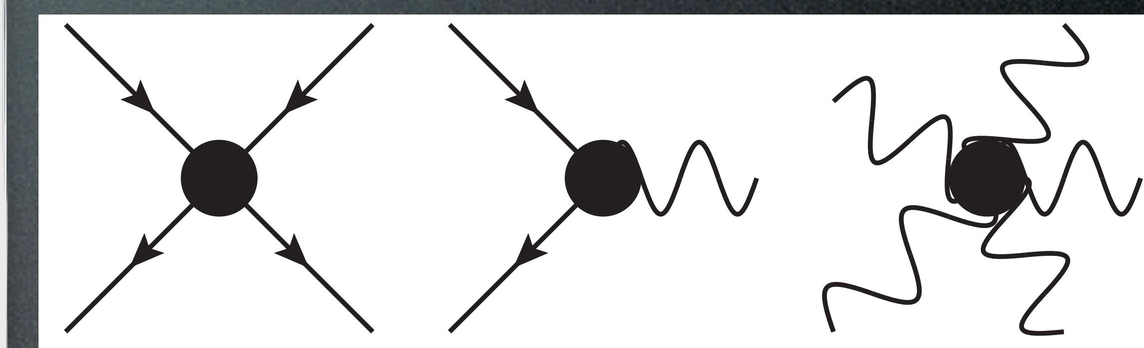

Example : Fermi th.

Effects :

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Effective Lagrangian

- From the SM fields only
- 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)

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

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

Th. error

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Effective field theories

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

- 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

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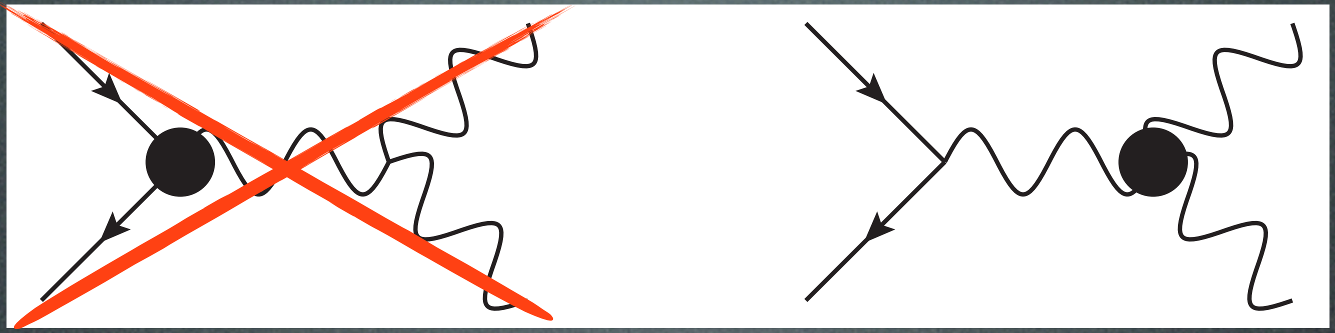
WW(WZ/WA) production



CP even operators

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

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

CP odd operators

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

Only 5 operators!

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WW production

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

$$+ i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu)$$

$$- i g_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Big)$$

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

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

11(5+6) parameters

WW production

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

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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

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

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

CP even Operators

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

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

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

constants

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WW Production

$$\mathcal{L} = i g_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho + i g_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$

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CP odd operators

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

$\Delta X = X - 1$

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

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

$$\kappa_Z = 1 + (c_W \ldots$$

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

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

$$\tilde\kappa_\gamma \ldots$$

$$\tilde\kappa_Z = \ldots$$

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

$$\tilde\lambda_\gamma = \tilde\lambda_Z = c_{\tilde WWW}\frac{\ldots}{2\Lambda^2}$$

constants

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PDG constraints

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

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 are more precise but use form factors/other relations

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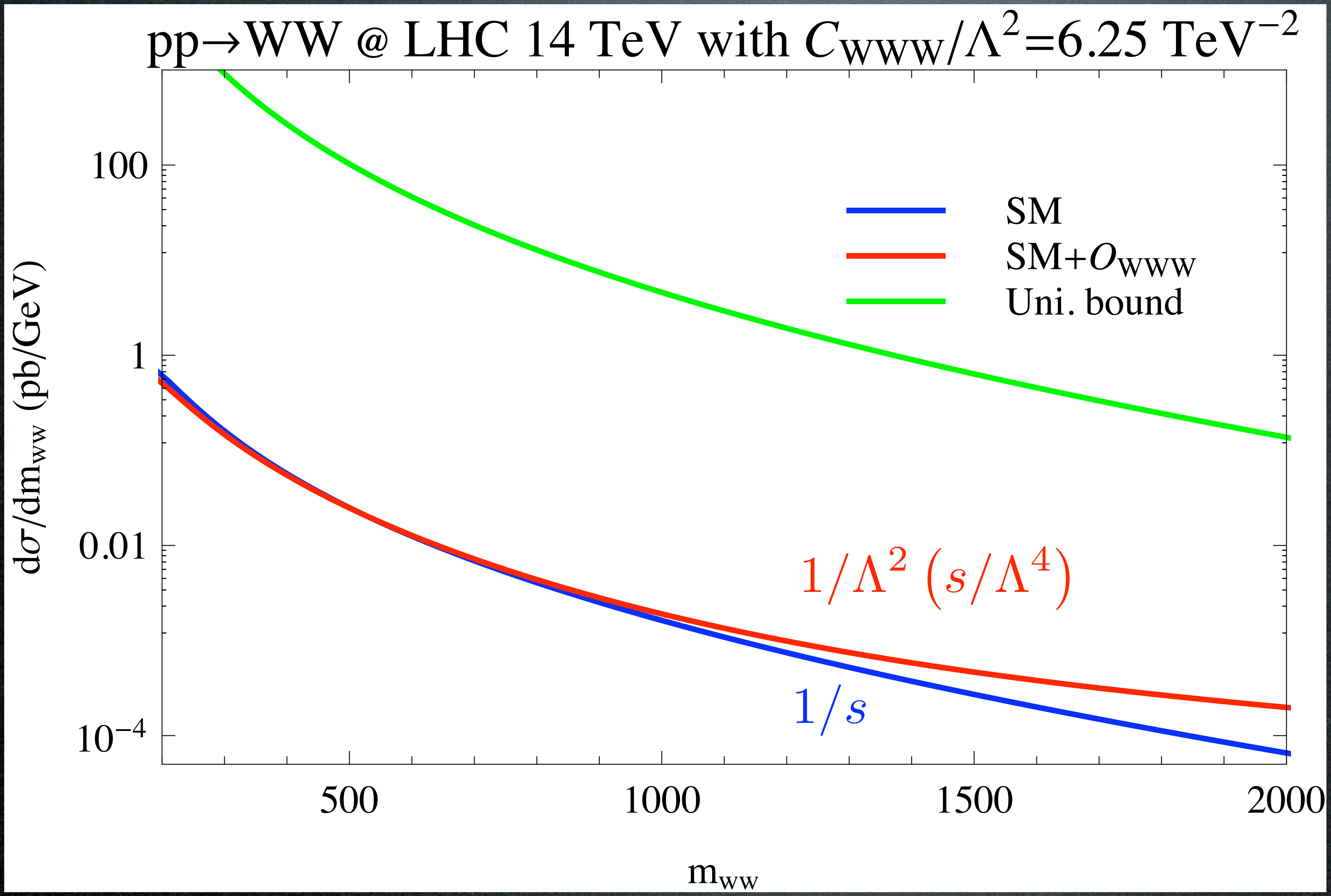
Unitarity bound



More than 2 orders of magnitude

Form factors are not needed!

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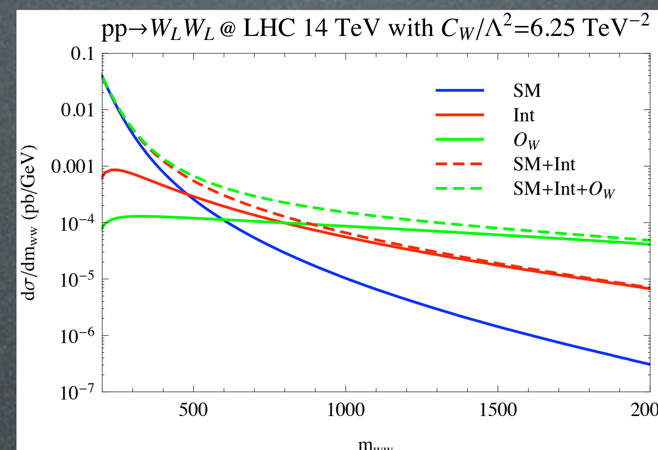
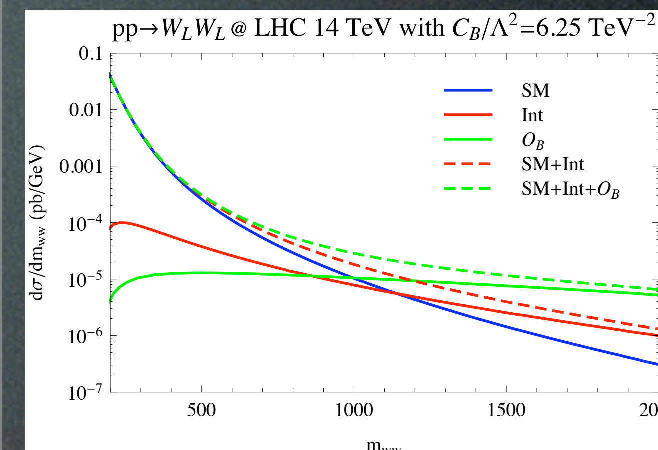
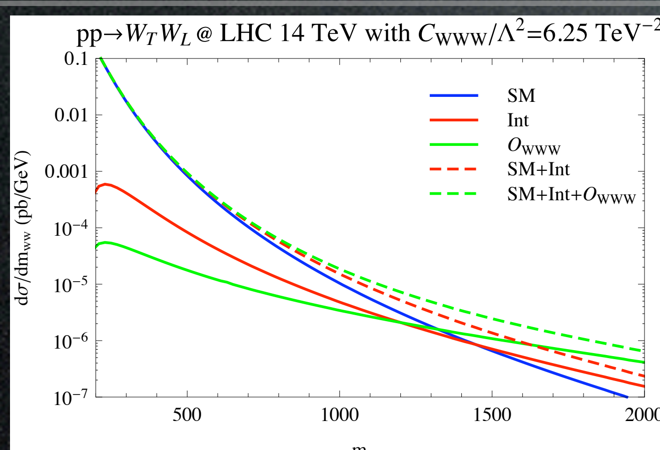
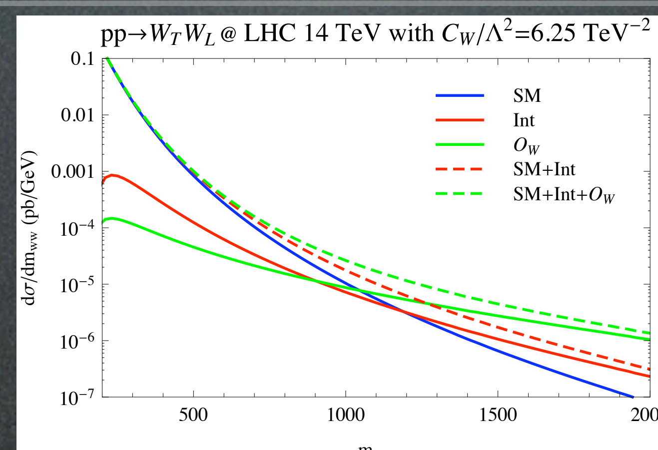
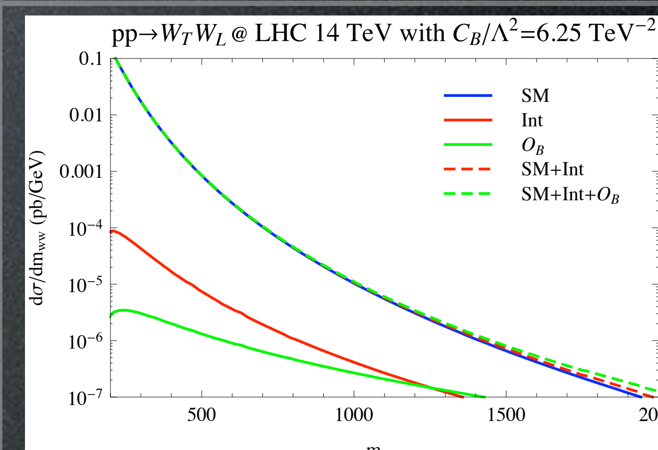
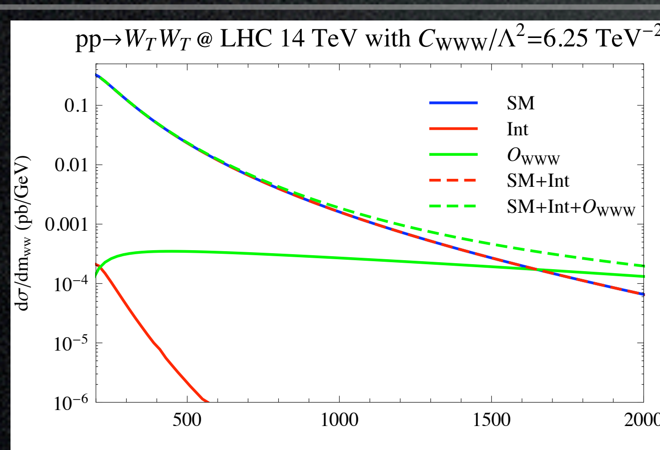
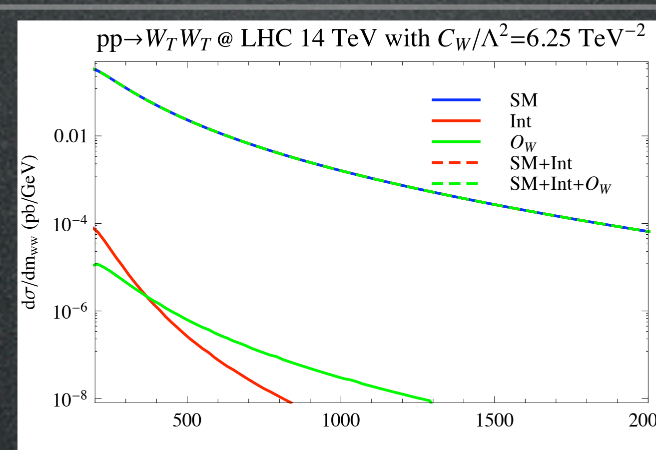
Invariant mass and polarisations

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$
LL	0		
LT			
TT			0

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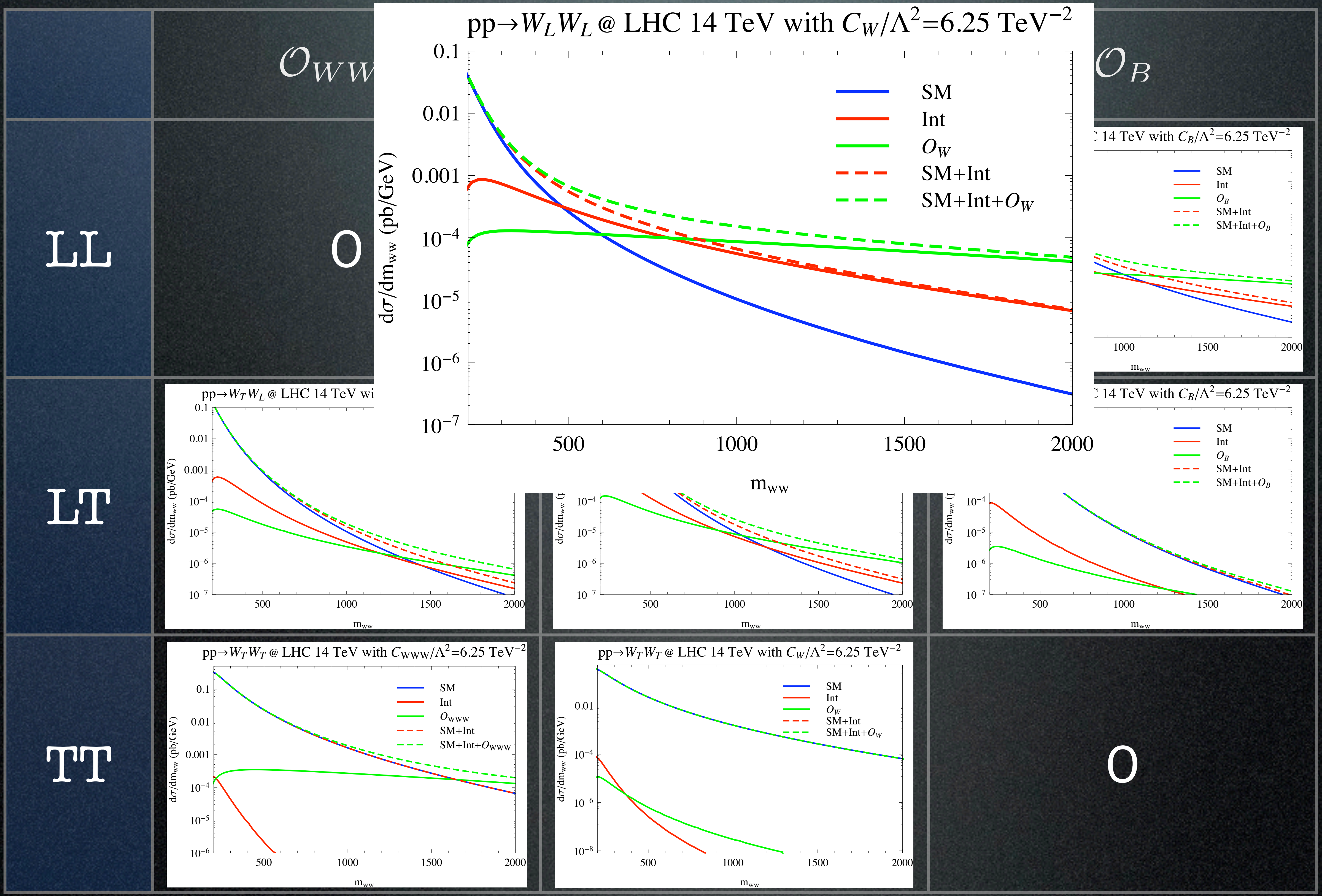

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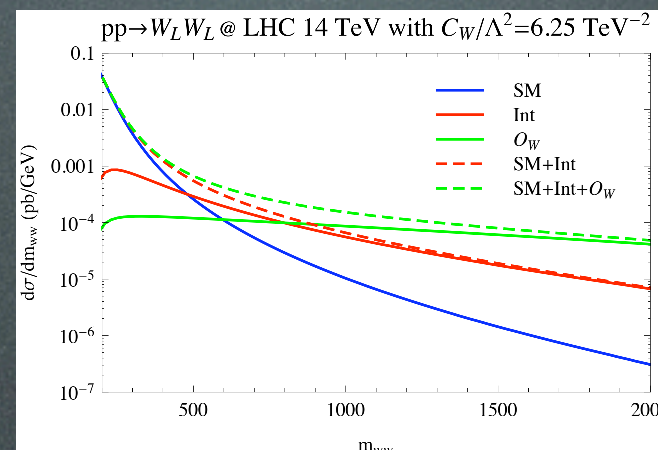
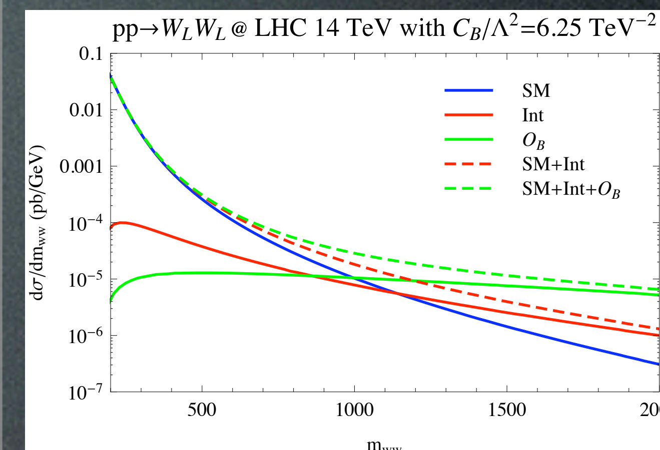
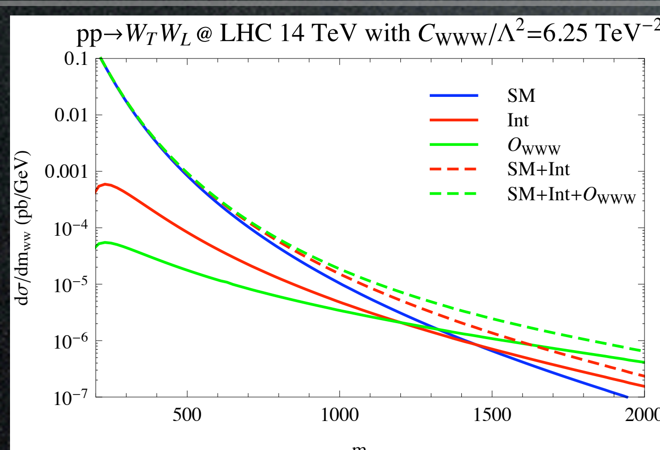
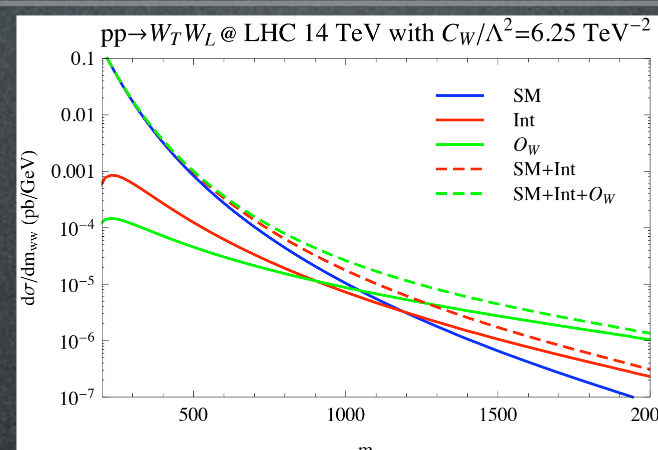
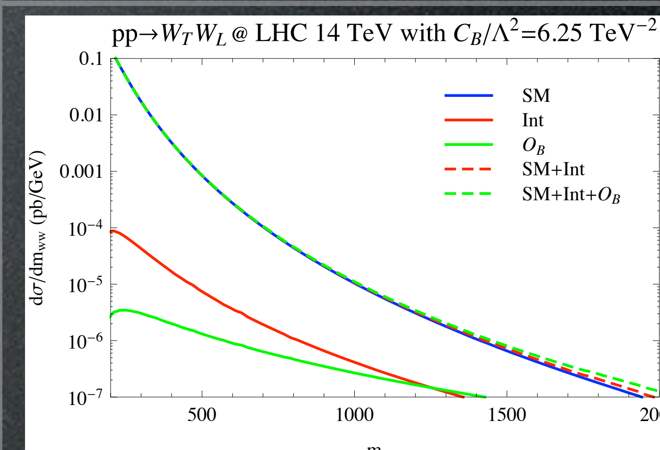
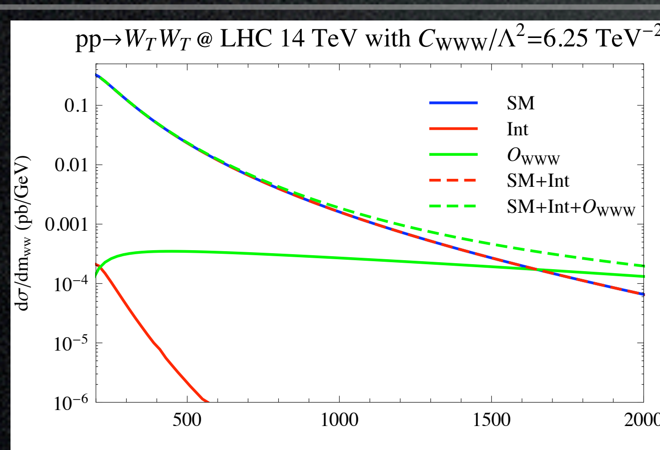
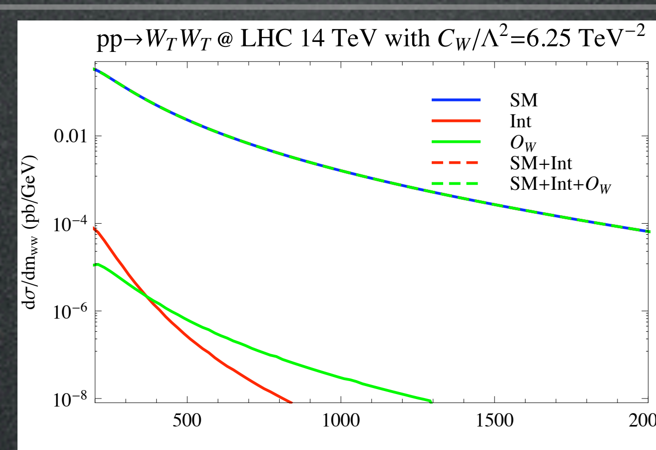
LL	0		
LT			
TT			0

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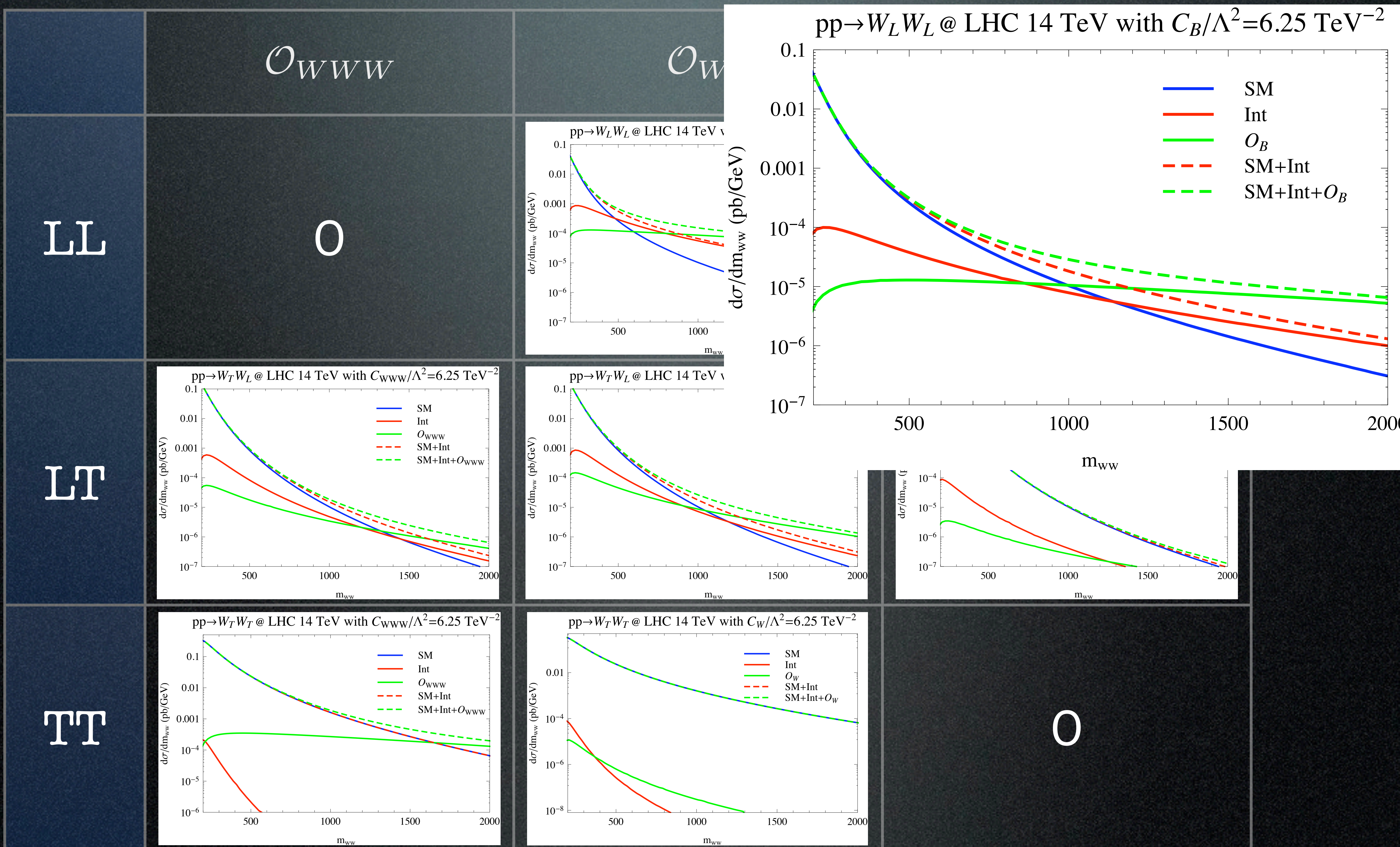

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Invariant mass and polarisations

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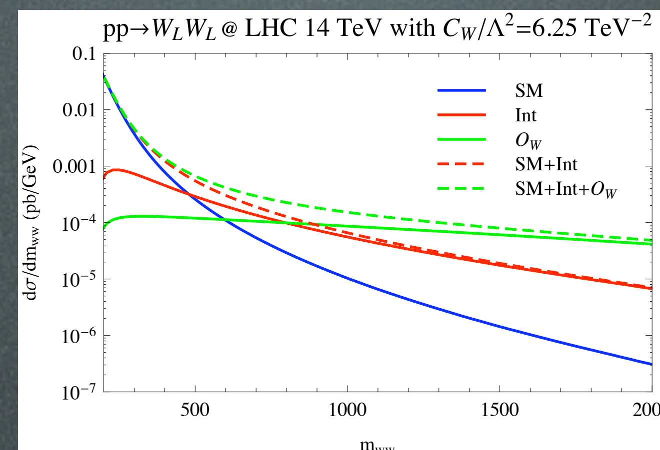
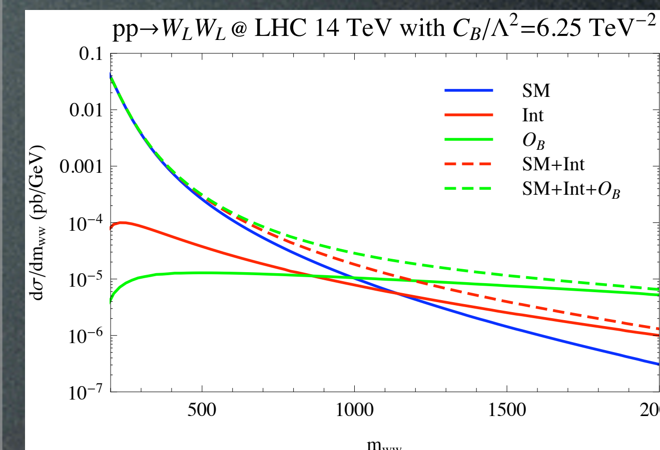
<tr><td>LL</td><td>0</td><td>
</td><td>
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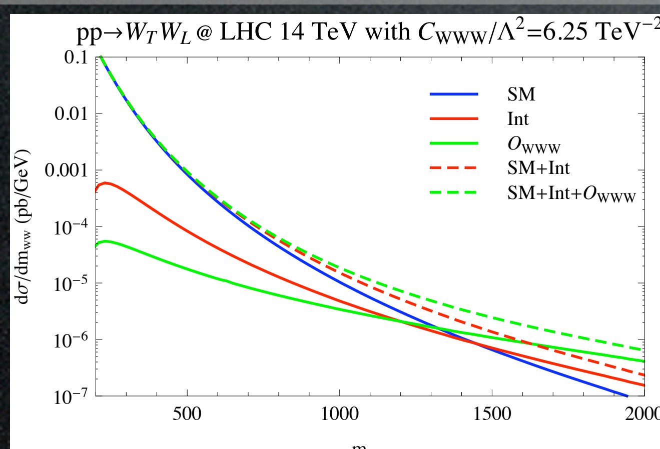
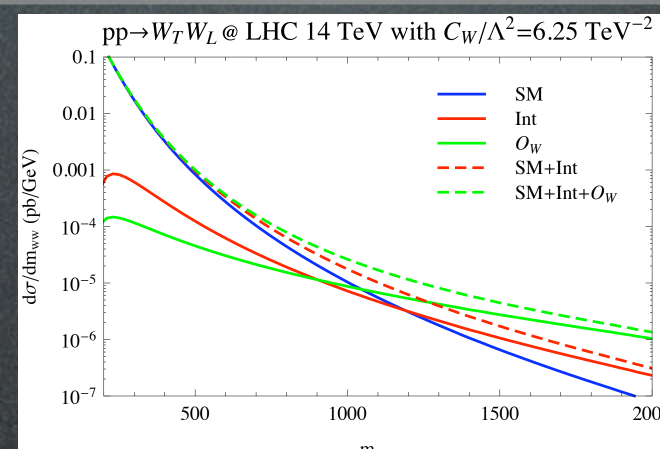
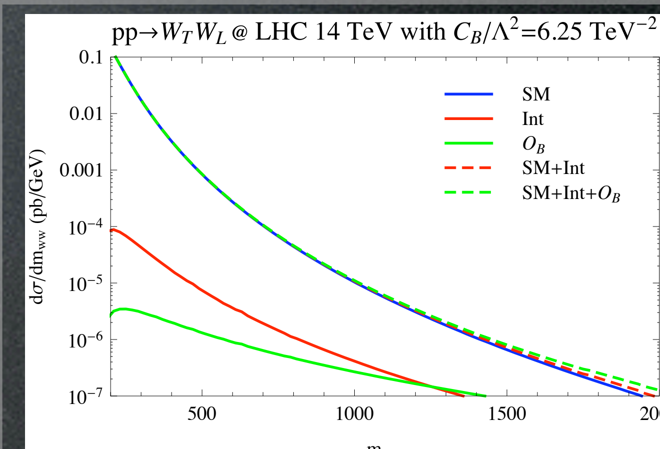
<tr><td>LT</td><td>
</td><td>
</td><td>
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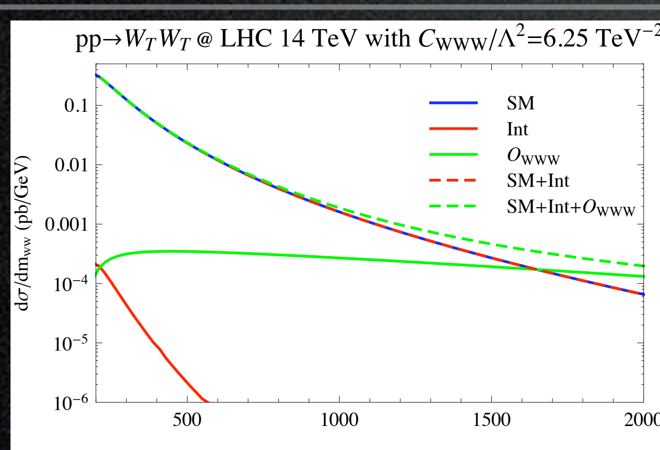
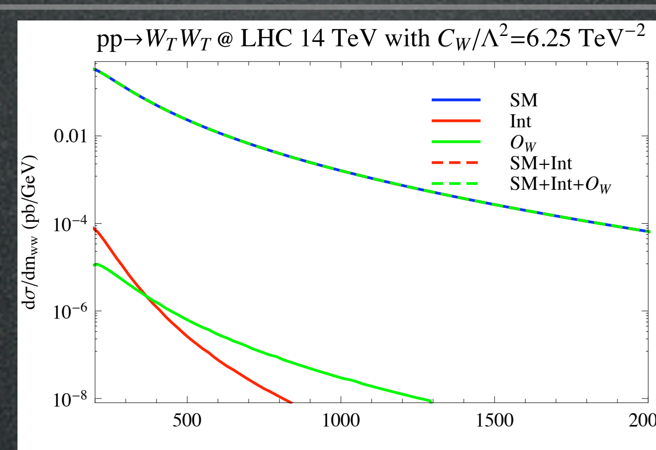
<tr><td>TT</td><td>
</td><td>
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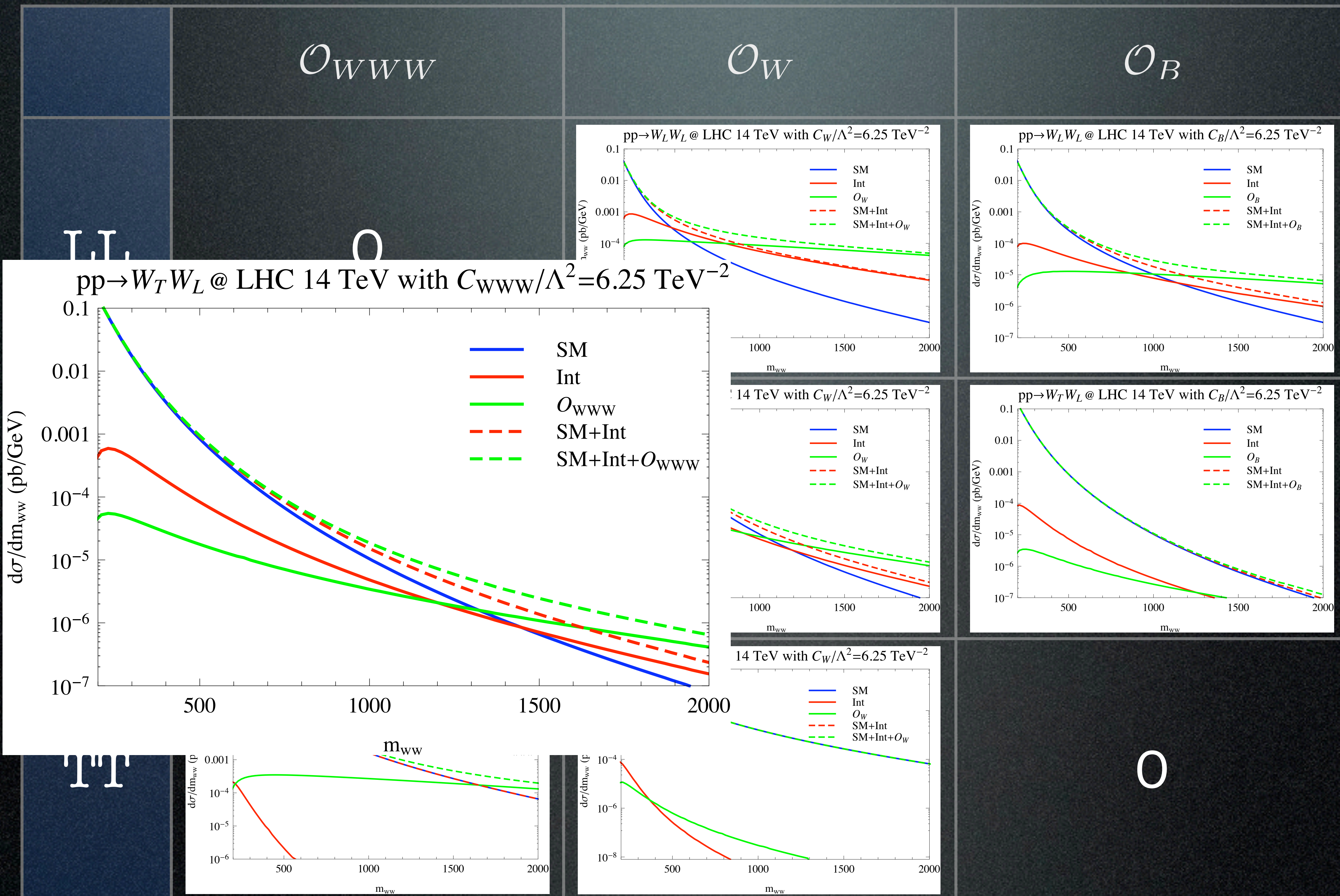
Invariant mass and polarisations



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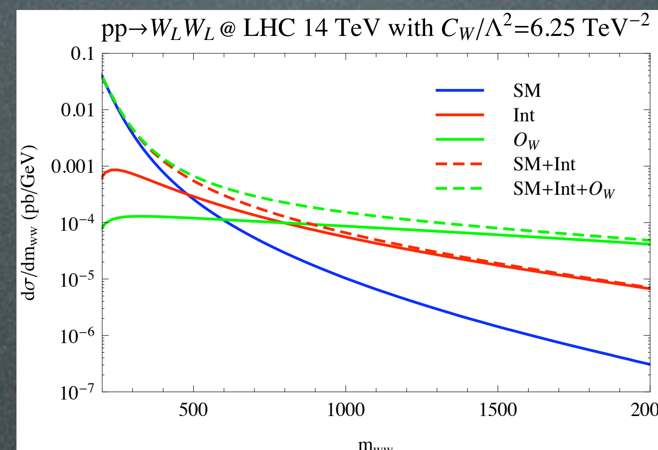
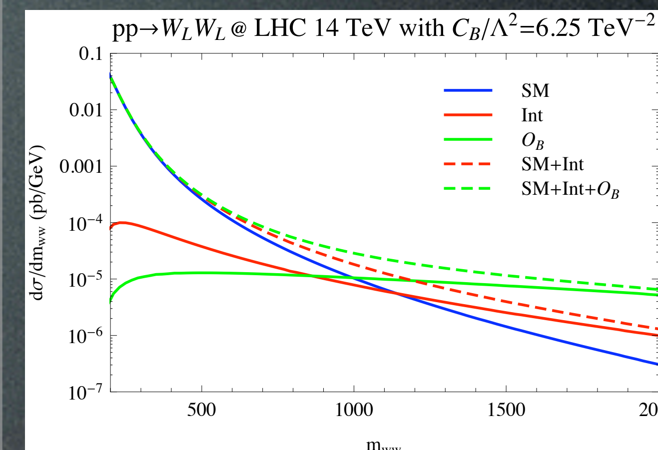
<tr><td>LL</td><td>0</td><td>
</td><td>
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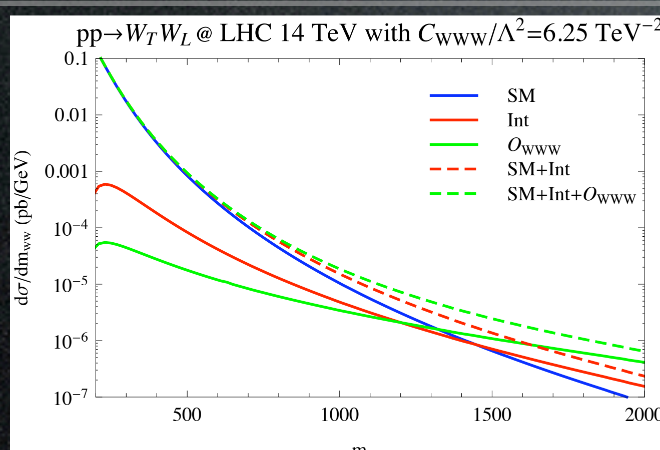
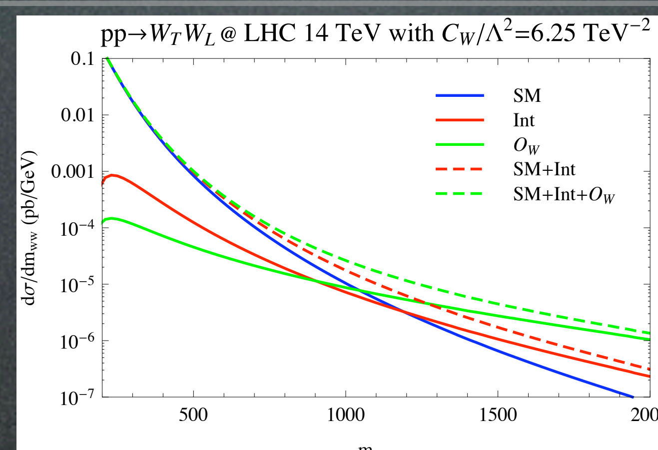
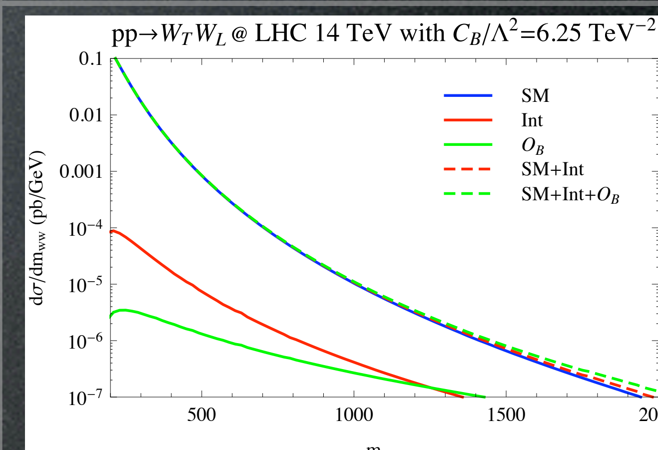
<tr><td>LT</td><td>
</td><td>
</td><td>
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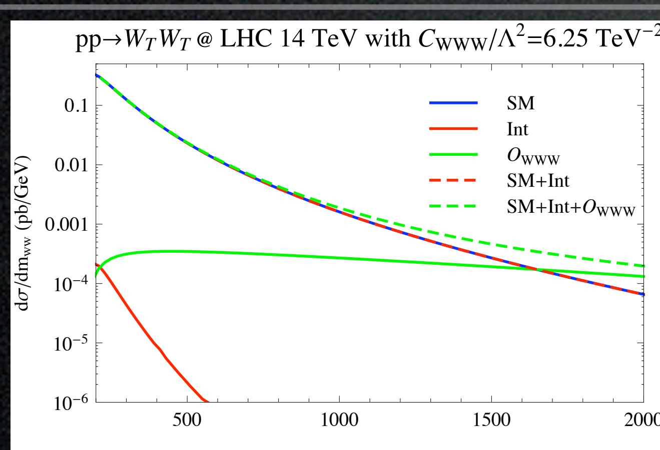
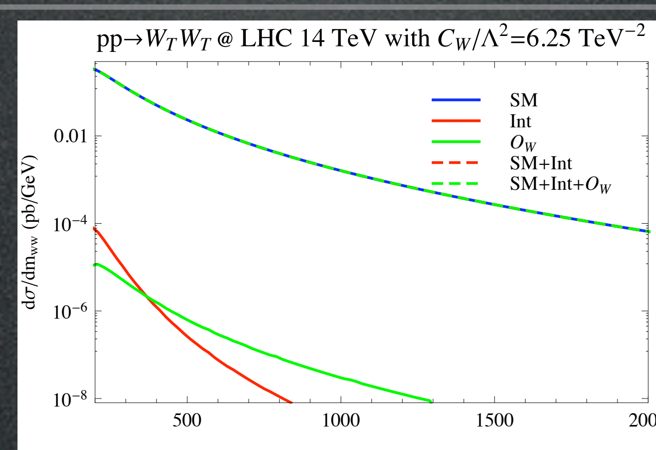
<tr><td>TT</td><td>
</td><td>
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Invariant mass and polarisations

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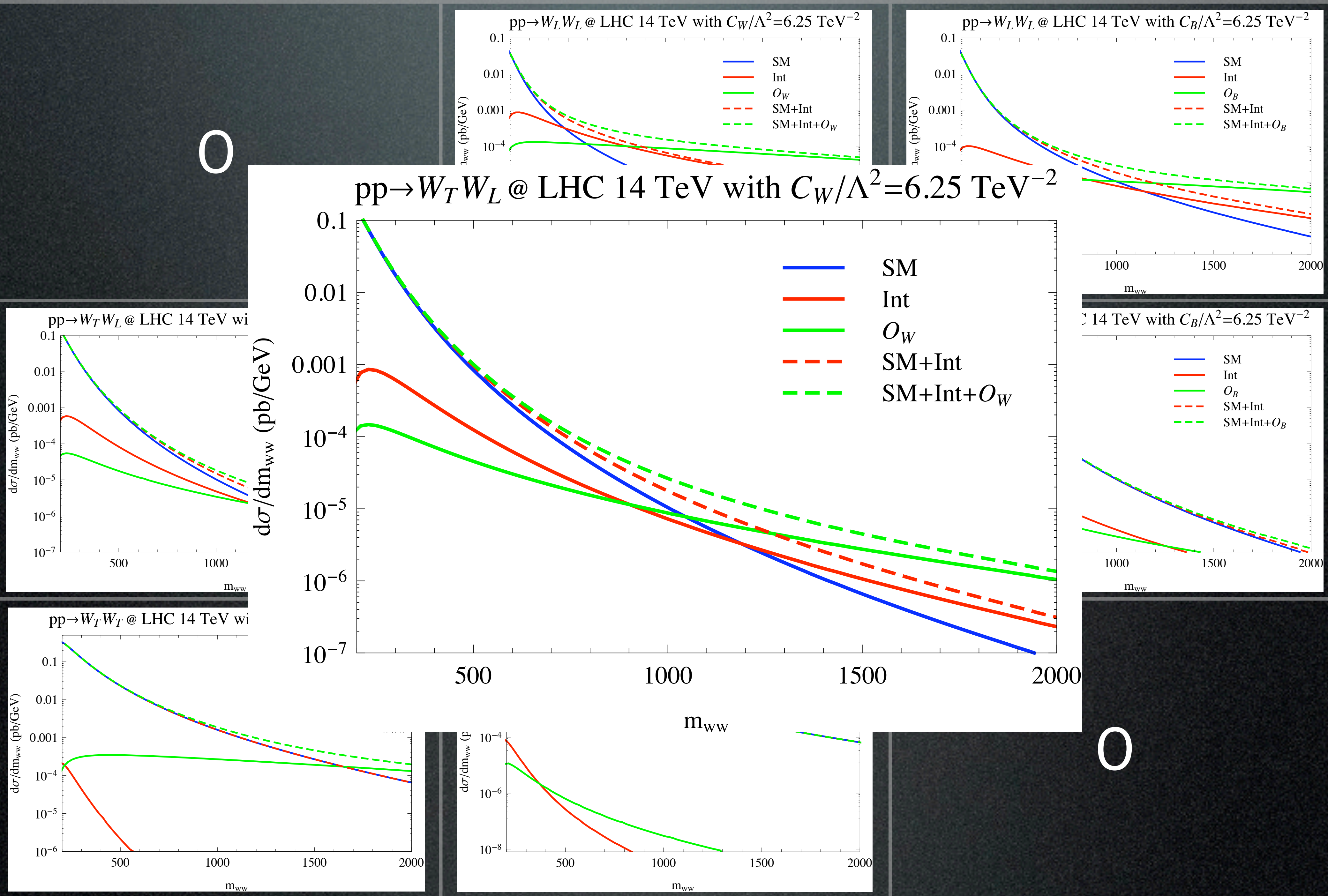

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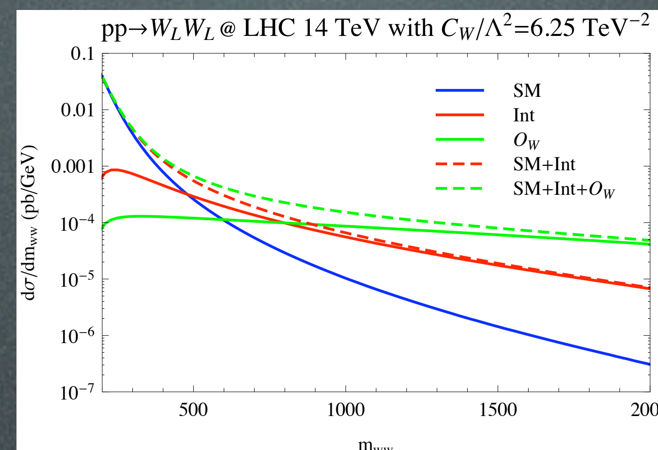
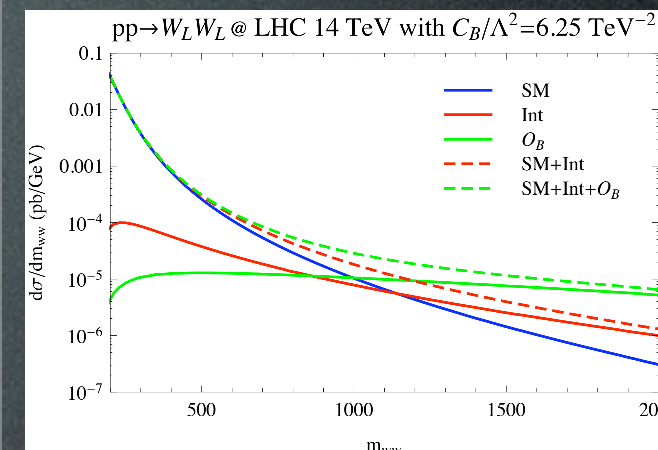
<tr><td>LL</td><td>0</td><td>
</td><td>
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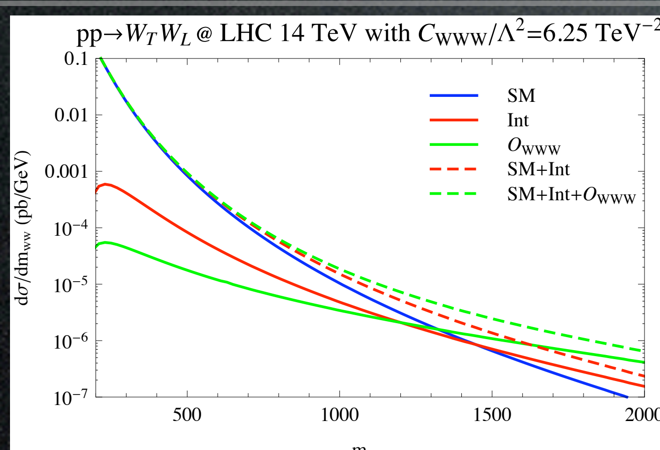
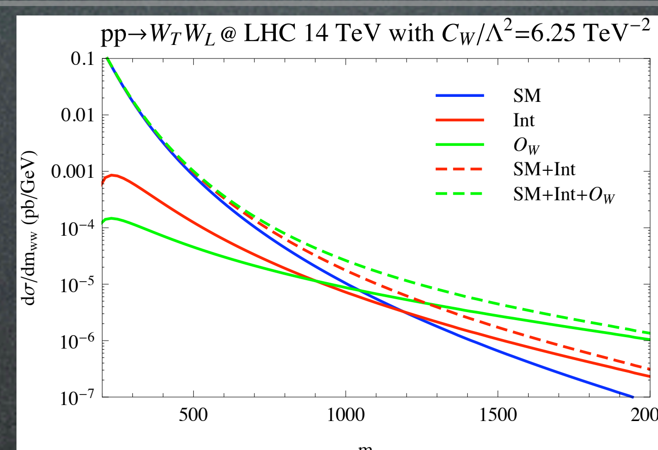
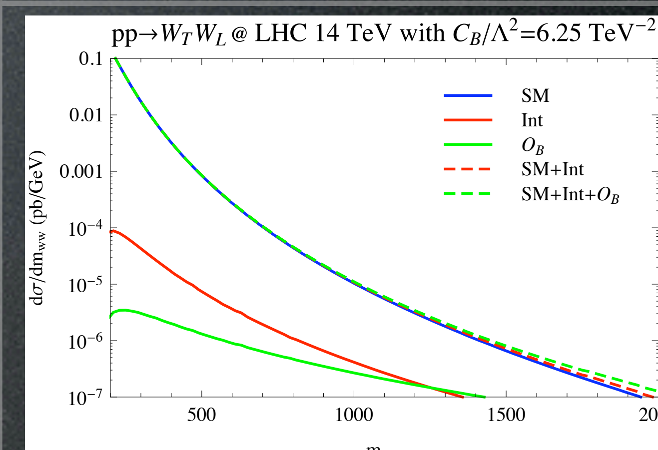
<tr><td>LT</td><td>
</td><td>
</td><td>
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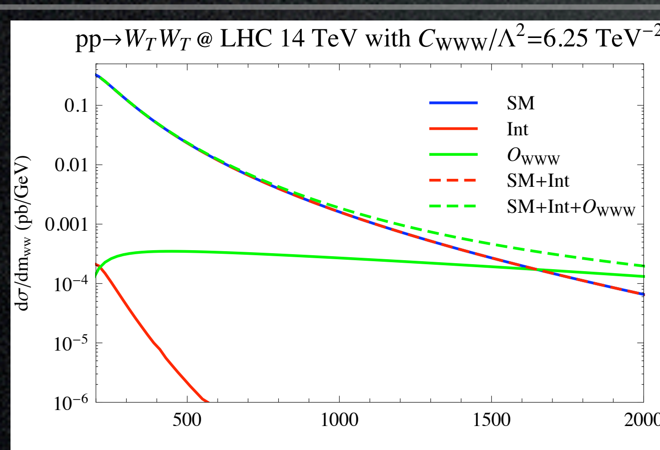
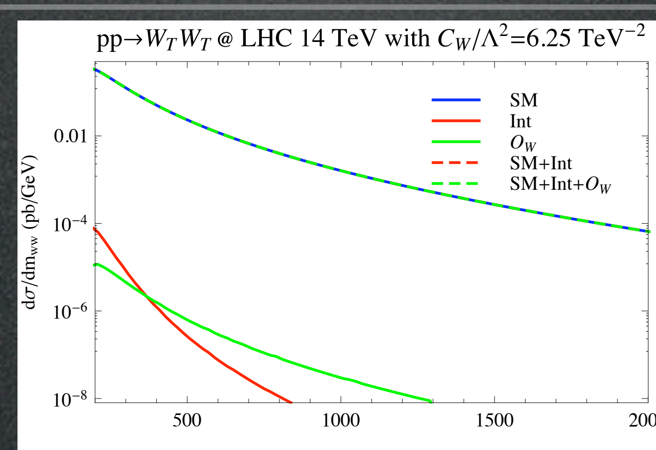
<tr><td>TT</td><td>
</td><td>
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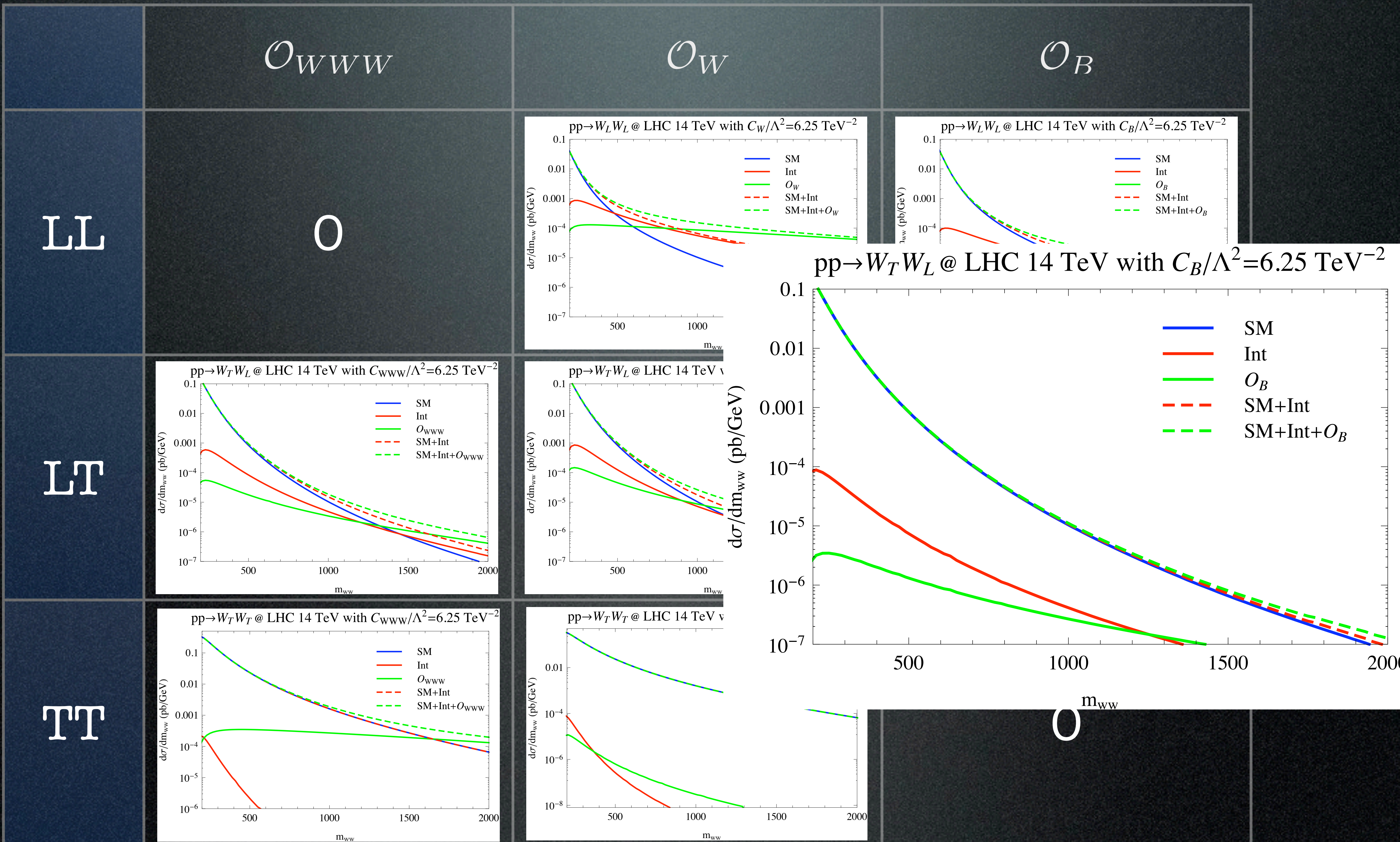
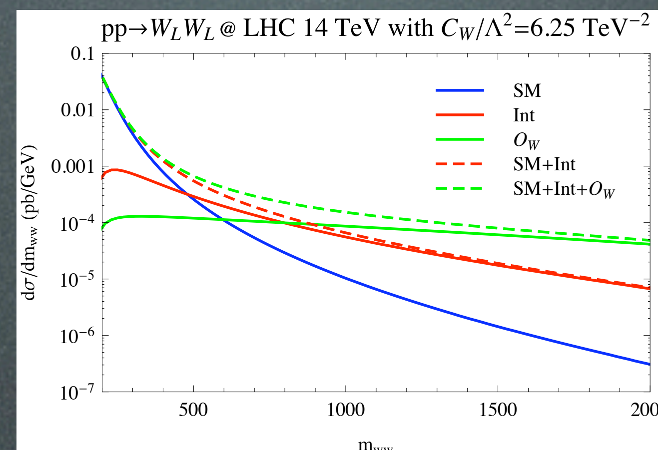
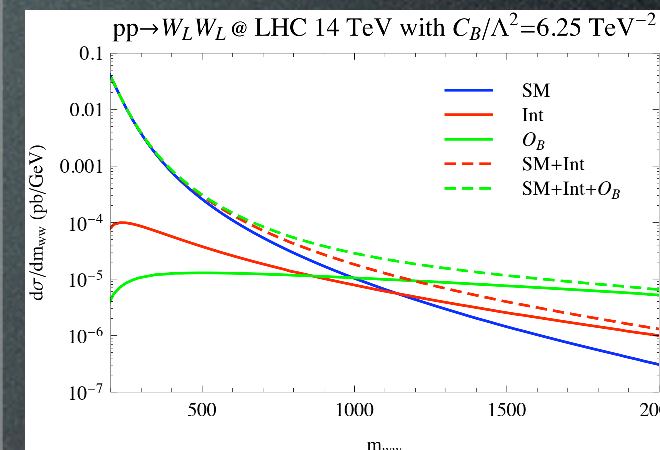
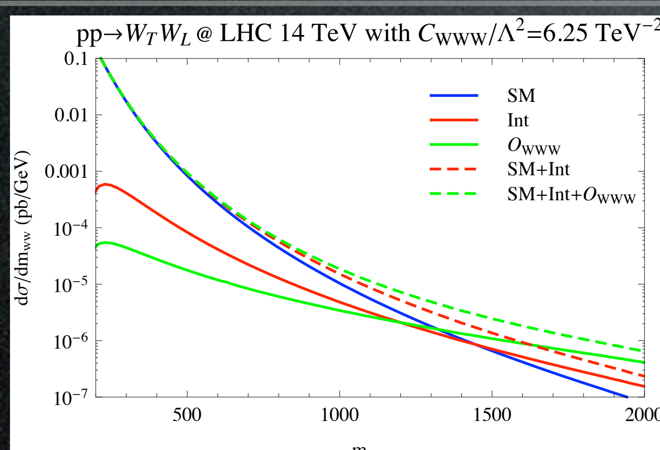
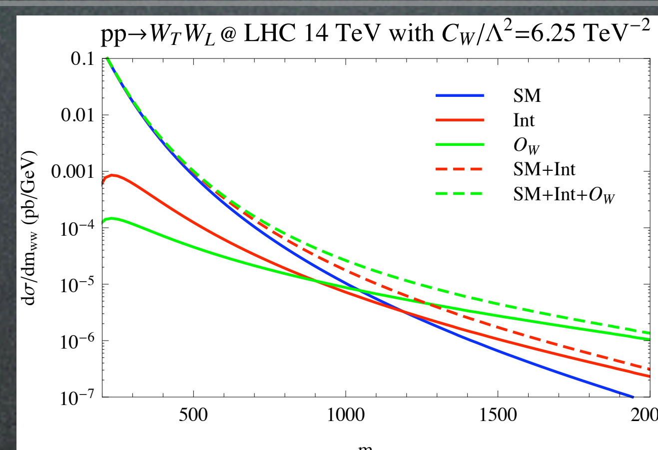
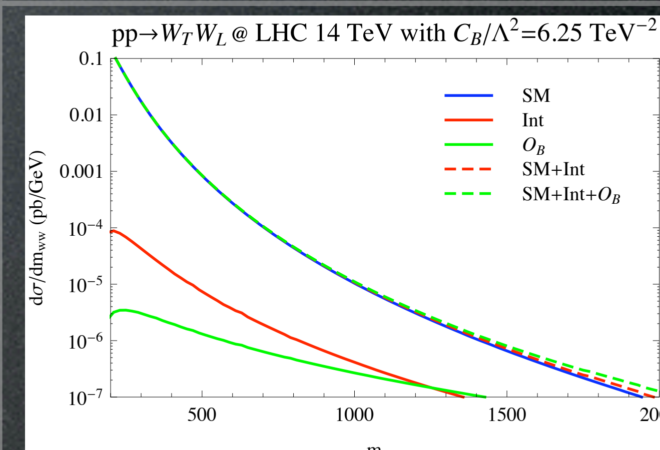
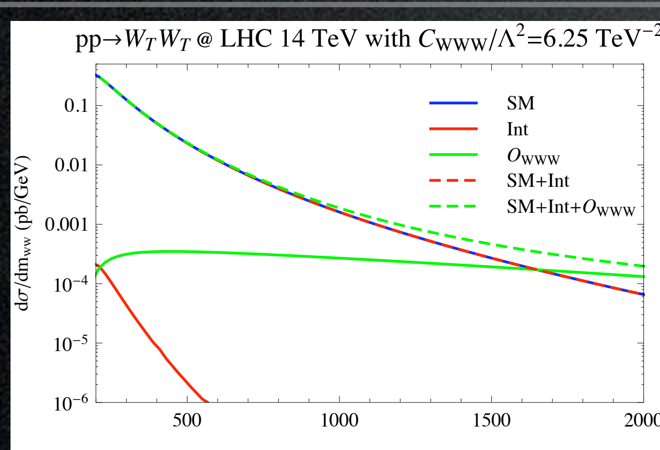
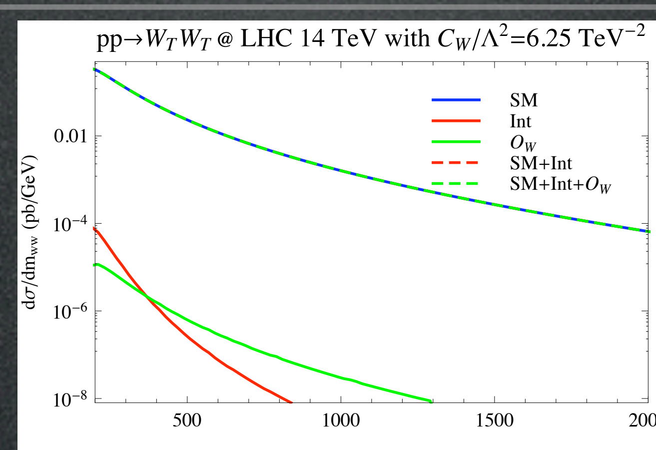
Celine Degrande (UIUC)

Invariant mass and polarisations

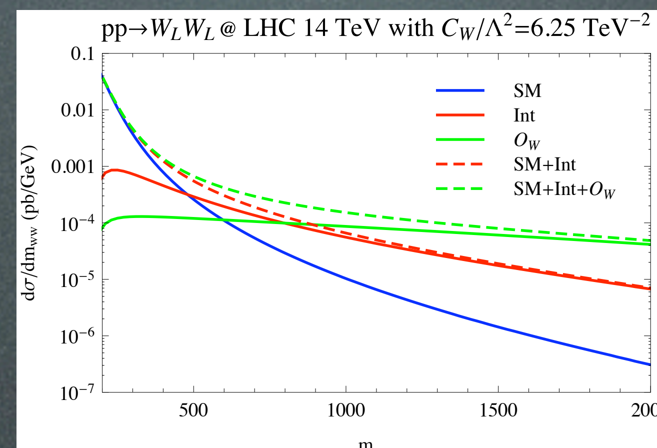
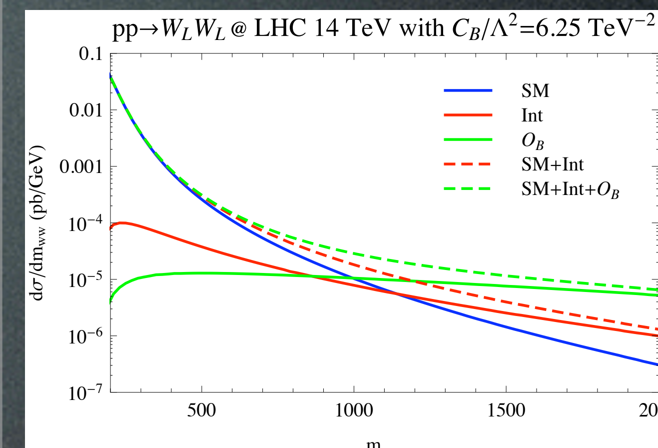
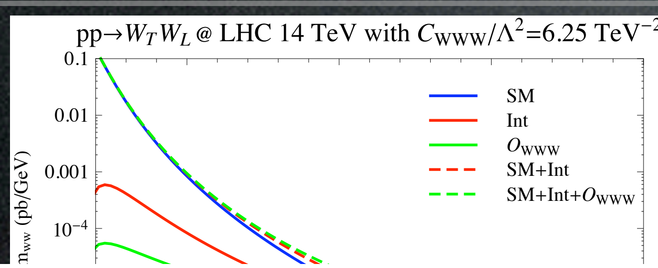
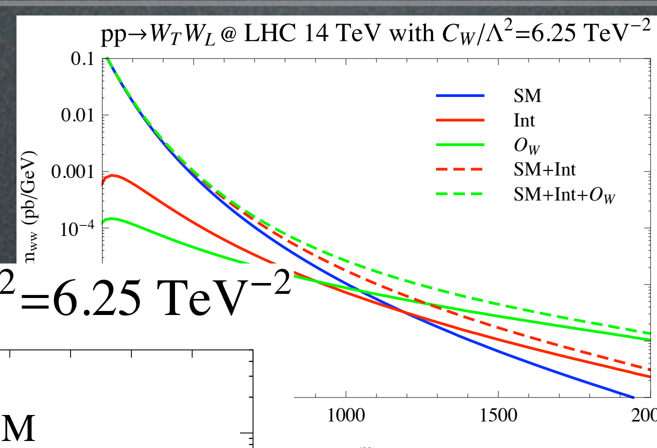
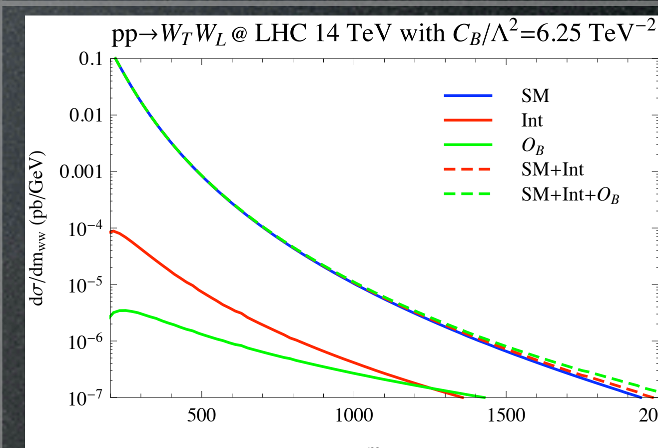
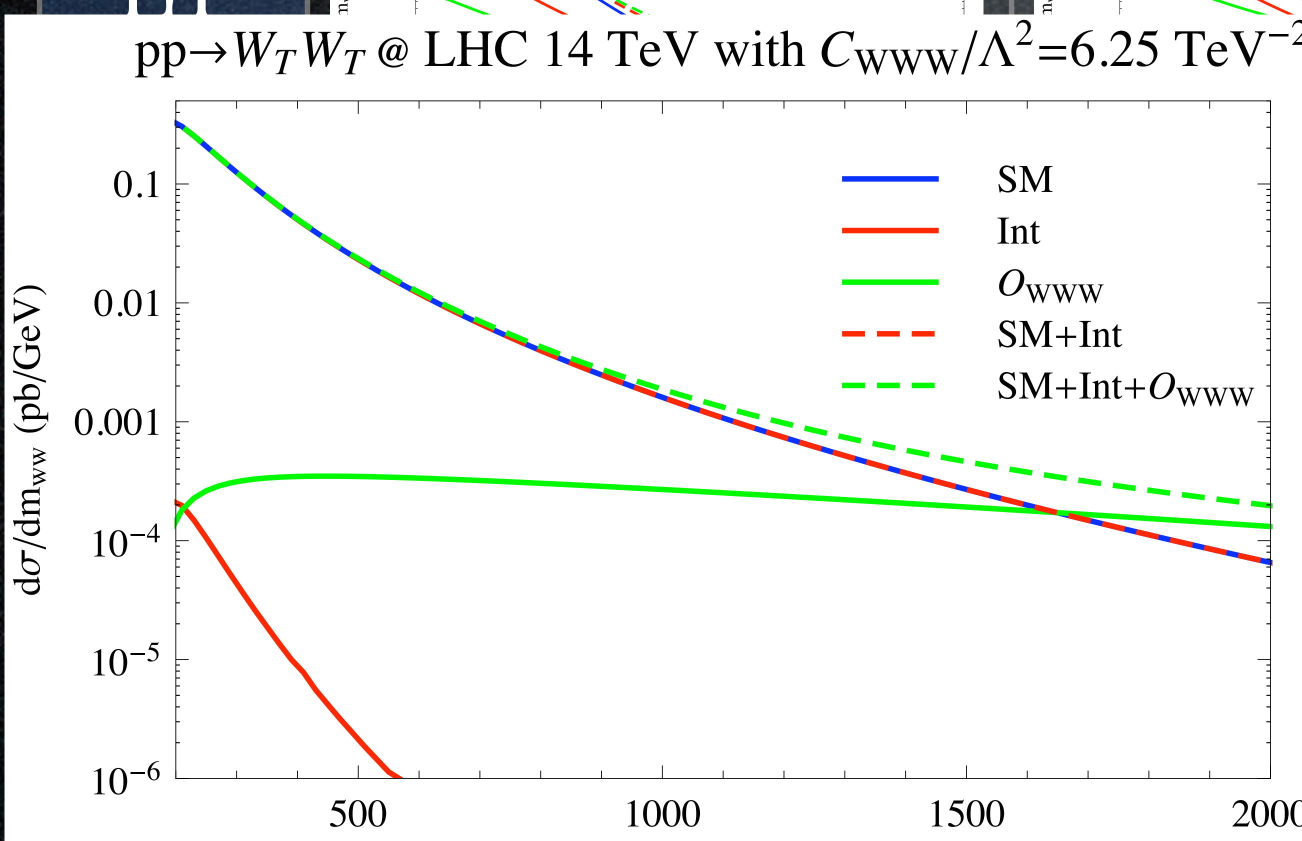
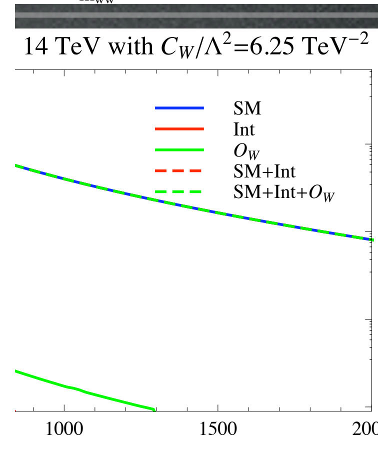


Celine Degrande (UIUC)

Invariant mass and polarisations

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$
LL	0		
LT			
TT			0

Invariant mass and polarisations

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$
LL	0		
LT			
TT			0

Celine Degrande (UIUC)

Invariant mass and polarisations

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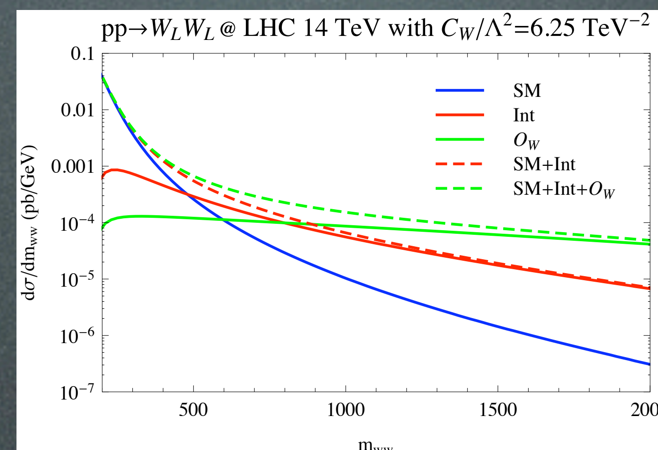
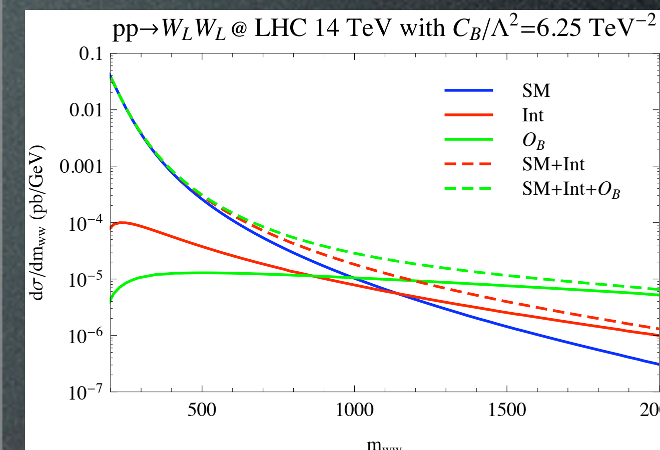
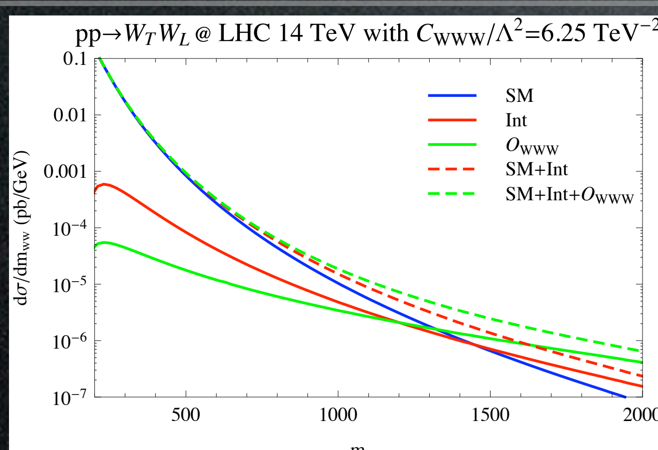
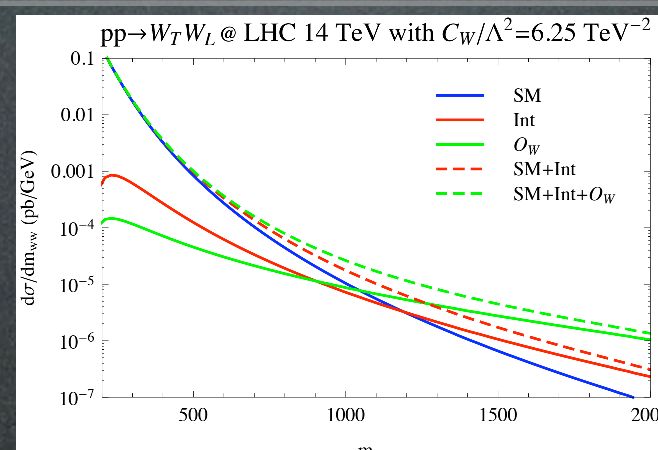
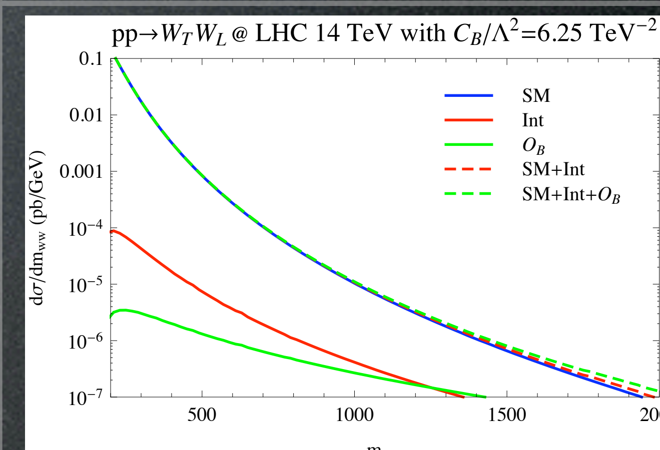
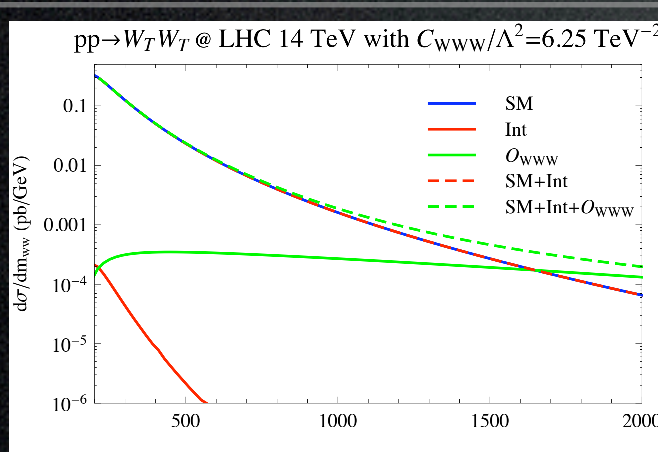
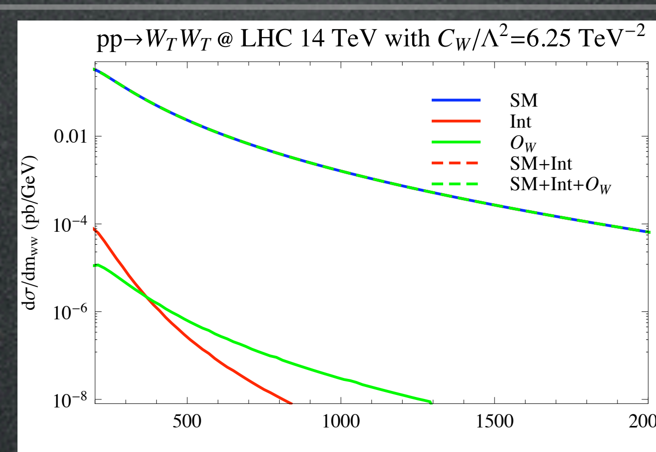
<tr><th></th><th>$\mathcal{O}_{WWW}$</th><th>$\mathcal{O}_W$</th><th>$\mathcal{O}_B$</th></tr>
<tr><td>LL</td><td>0</td><td></td><td></td></tr>
<tr><td>LT</td><td></td><td></td><td></td></tr>
<tr><td>TT</td><td></td><td></td><td>0</td></tr>
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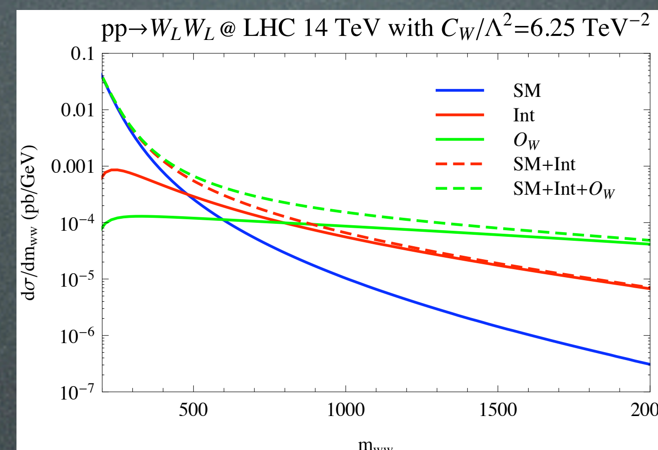
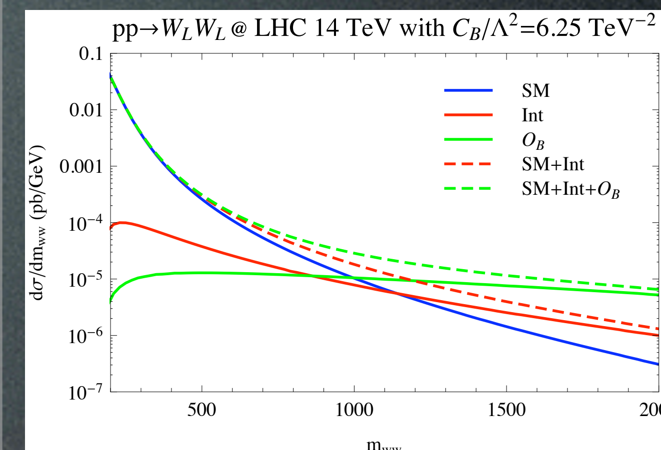
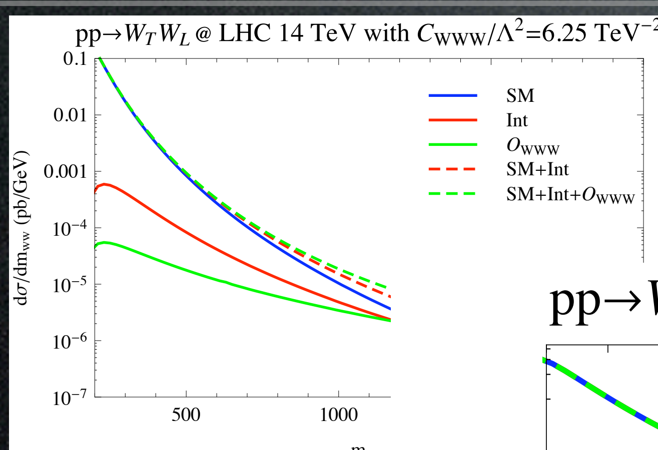
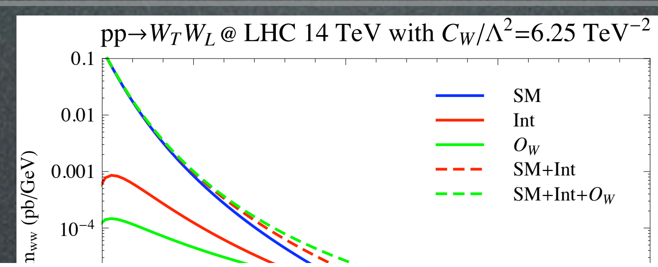
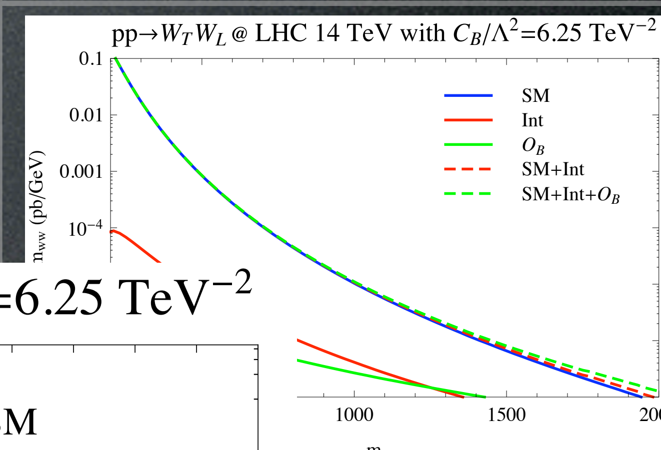
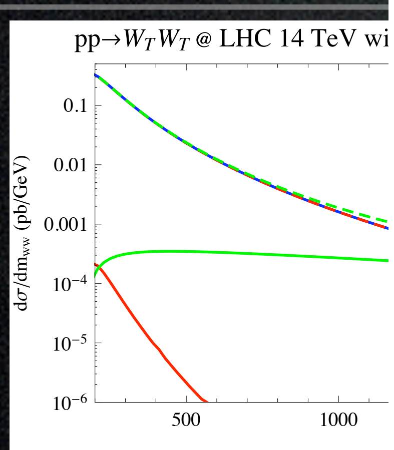
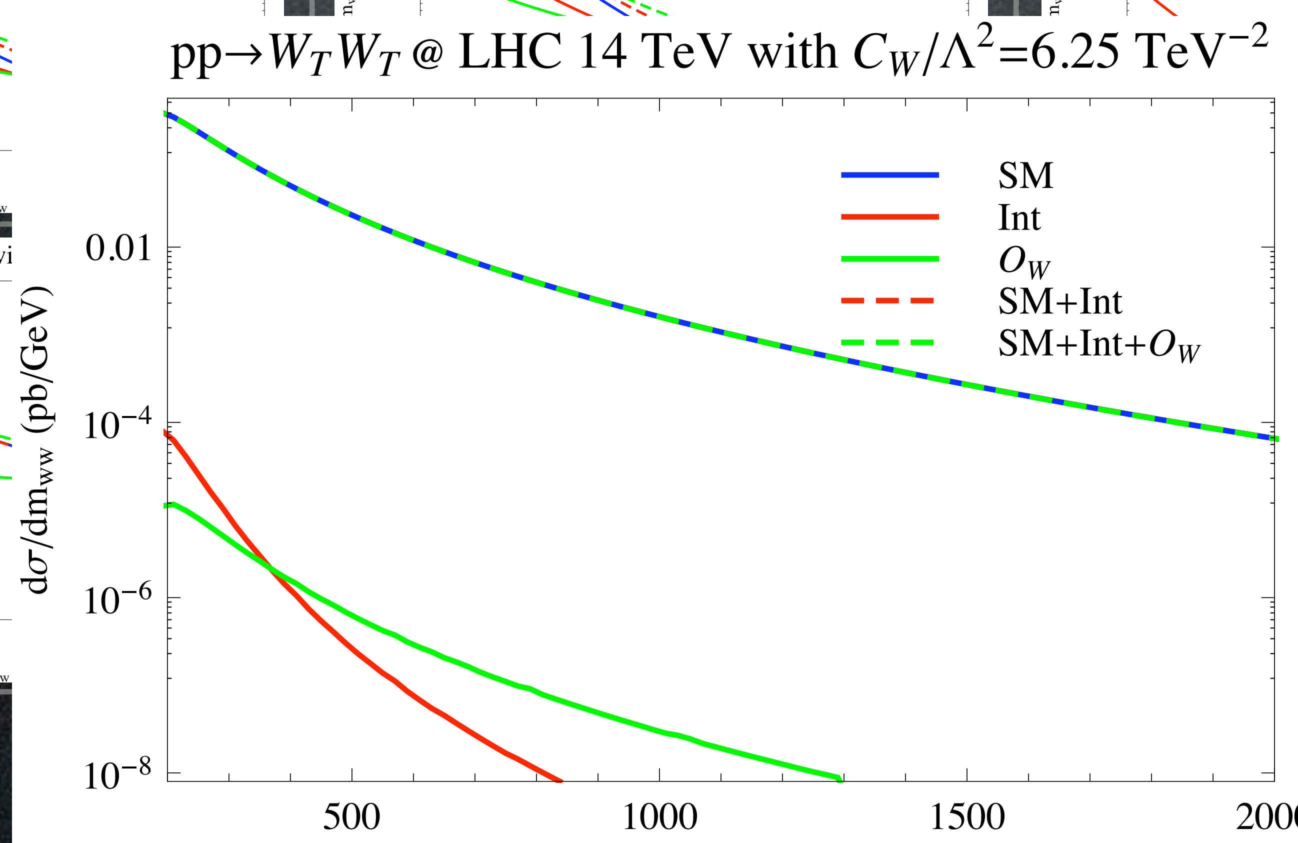
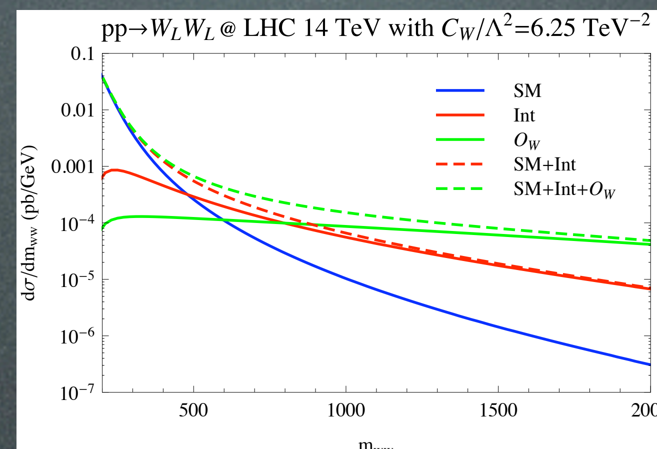
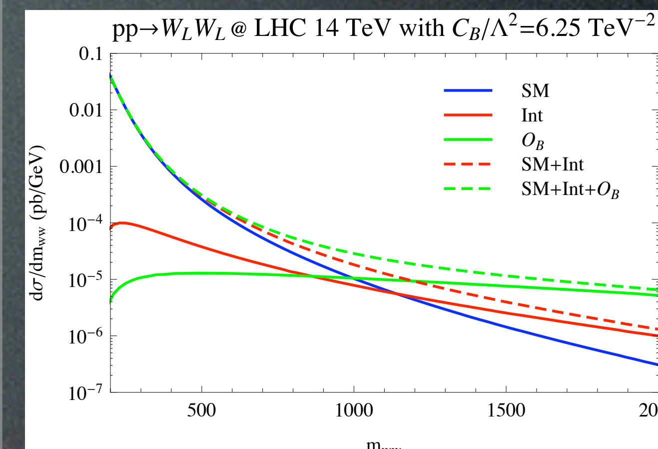
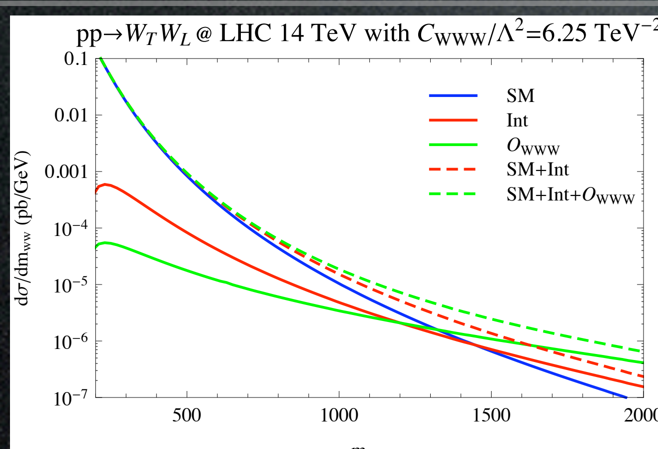
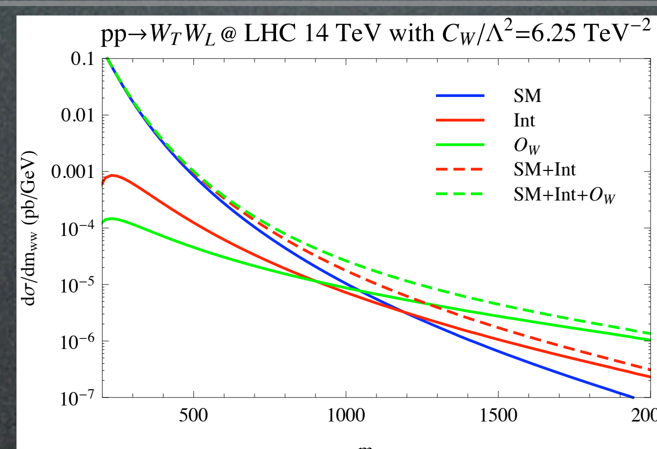
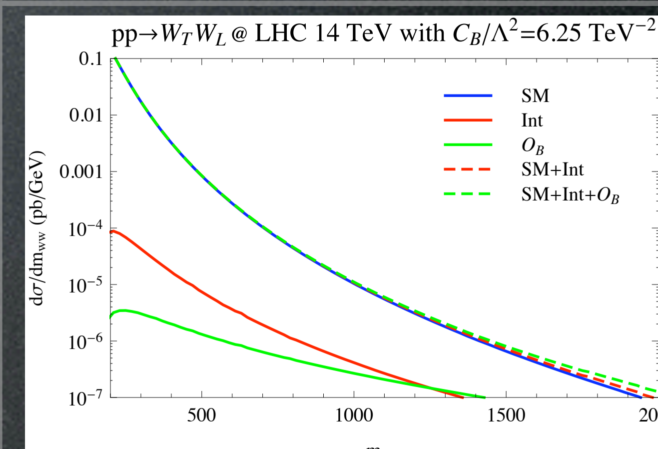
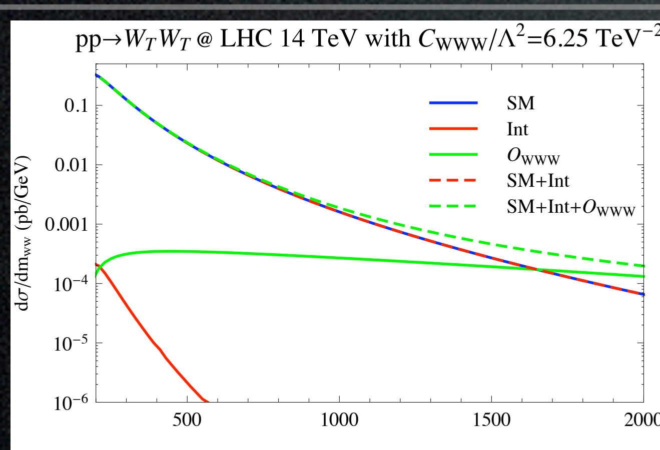
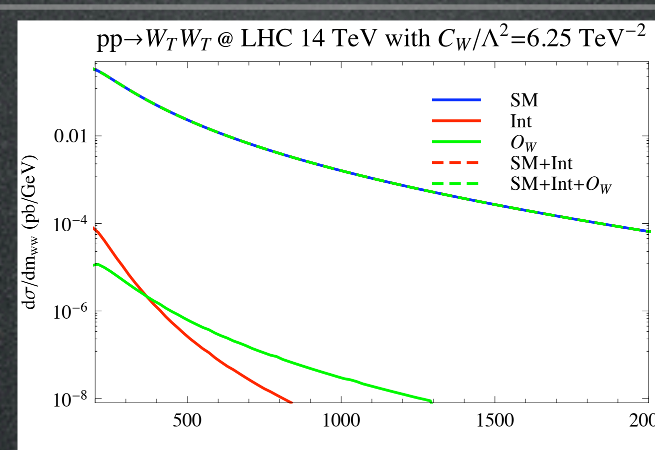
Celine Degrande (UIUC)

Invariant mass and polarisations

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$
LL	0		
LT			
TT			0



Invariant mass and polarisations

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$
LL	0		
LT			
TT			0

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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	$1/s$

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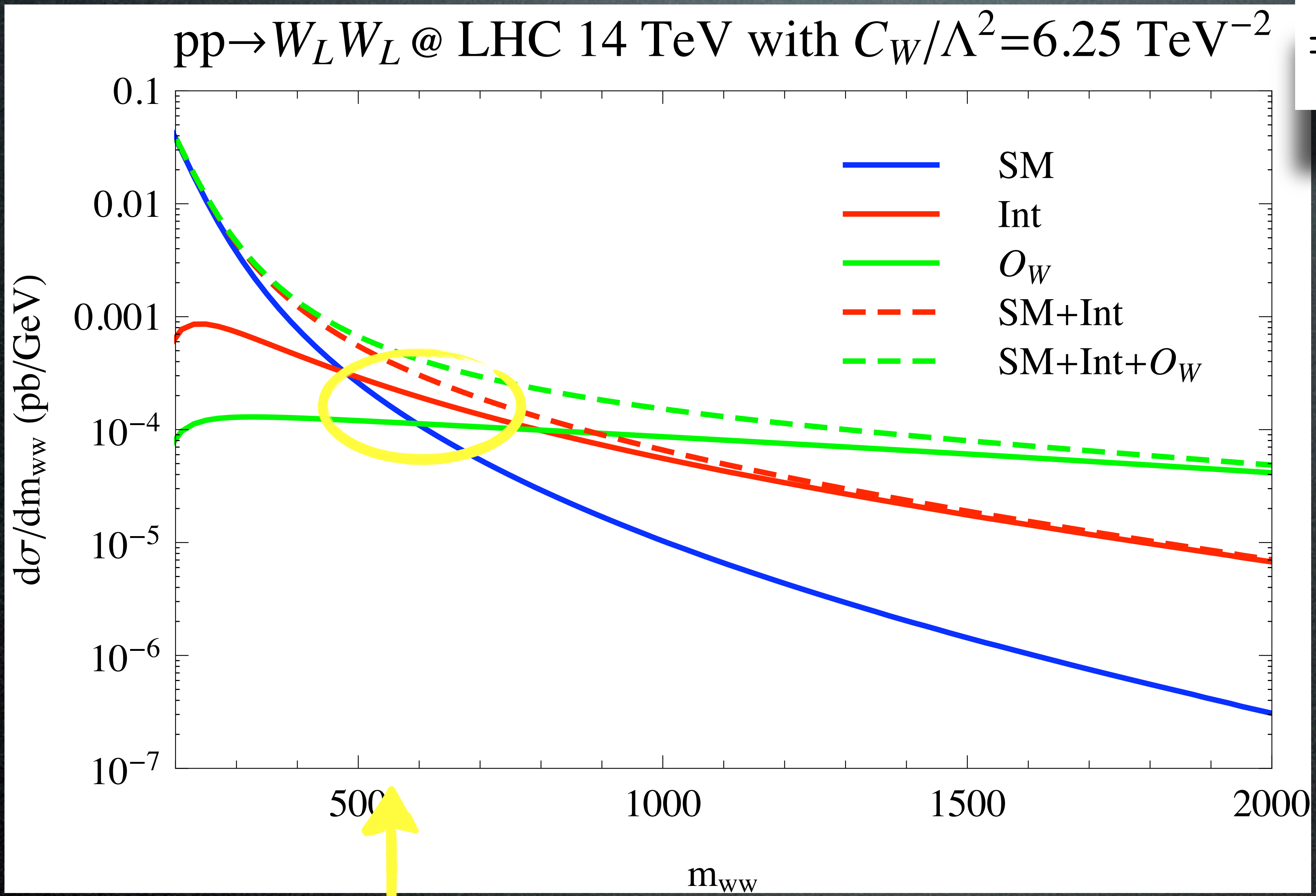
Expansion and error



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

$1/\Lambda^4$

$1/\Lambda^2$

$1/\Lambda^0$

Expansion breaks

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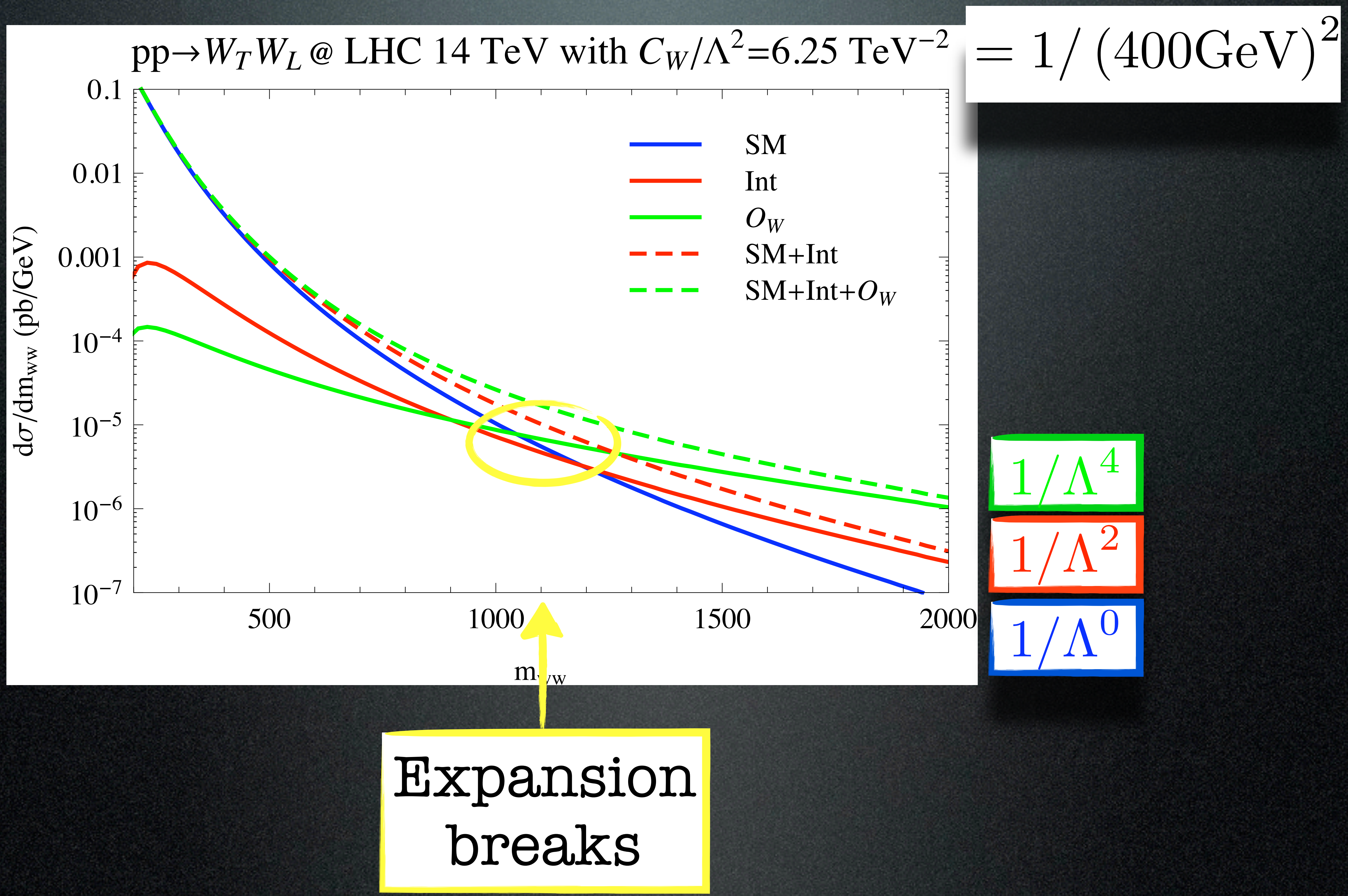
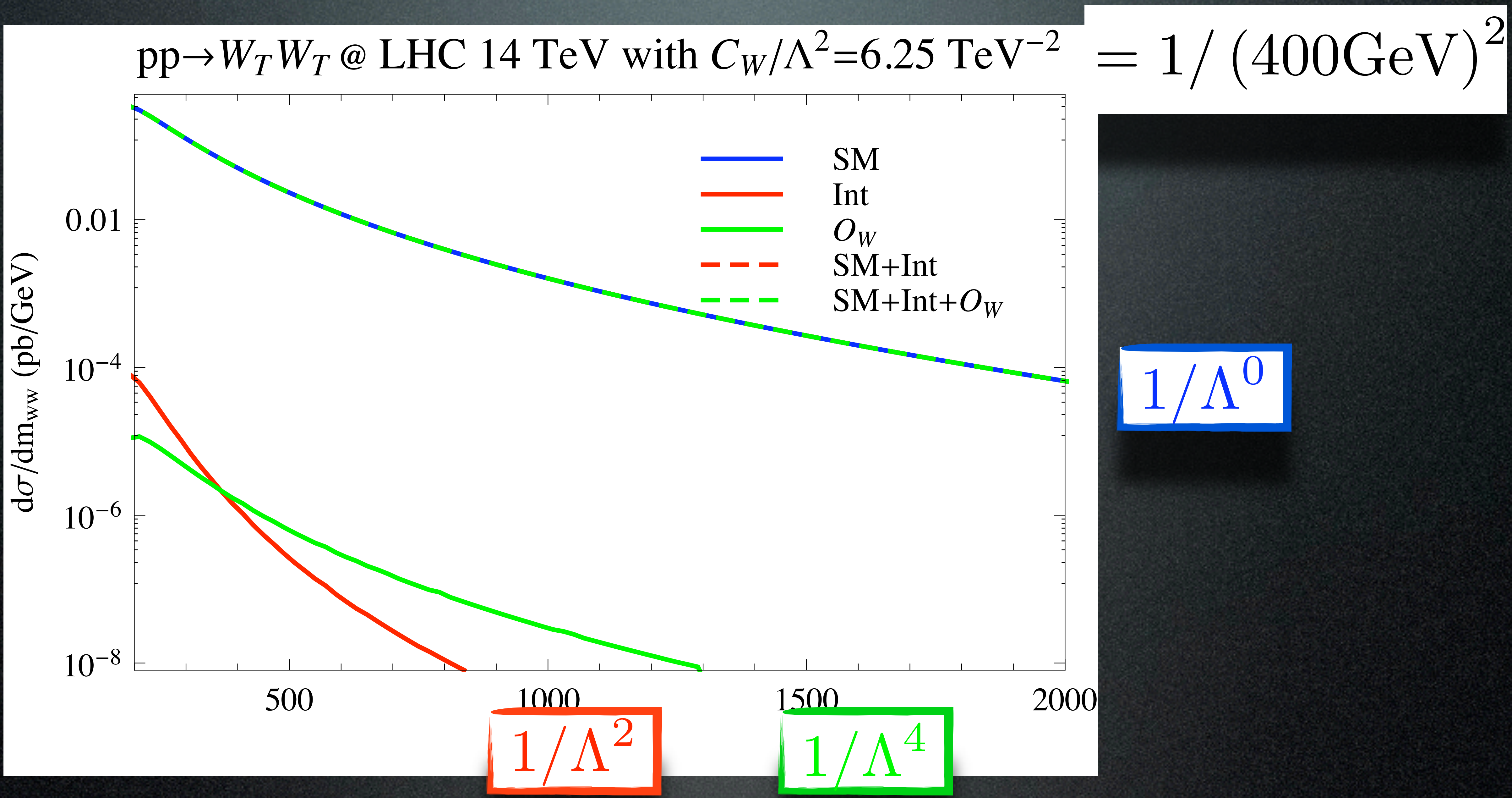
Expansion and error



Celine Degrande (UIUC)

Expansion and error



NP is suppressed : Bad estimate of the scale

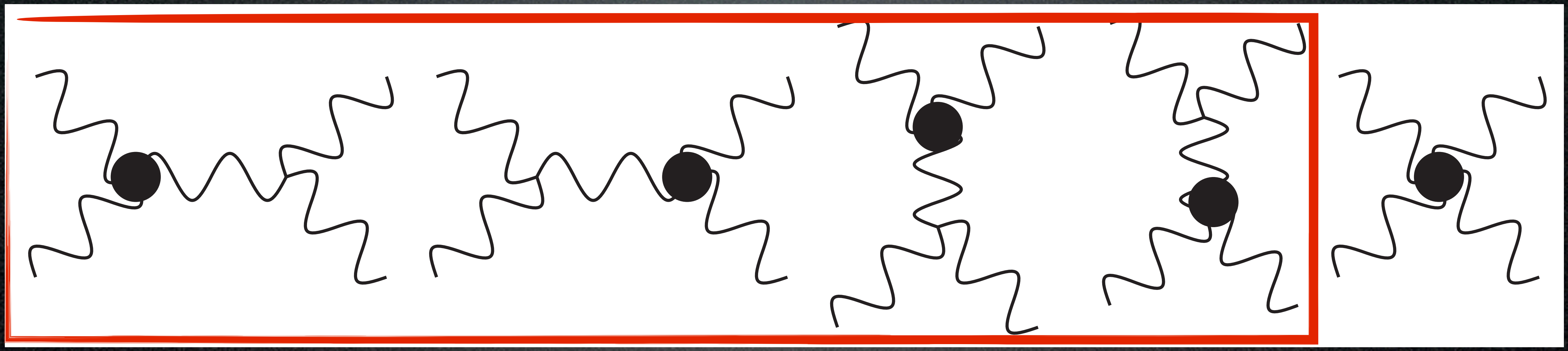
Celine Degrande (UIUC)

Plan

- Introduction to EFT
- EFT for pp(ee)>WW
- The constraints
- The effects
- EFT for pp>WWW, pp>WWjj
- Concluding remarks

pp>WWW or pp>WWjj

- Same operators for 4W amplitudes
- gauge invariance requires 3 and 4 legs vertices to be related

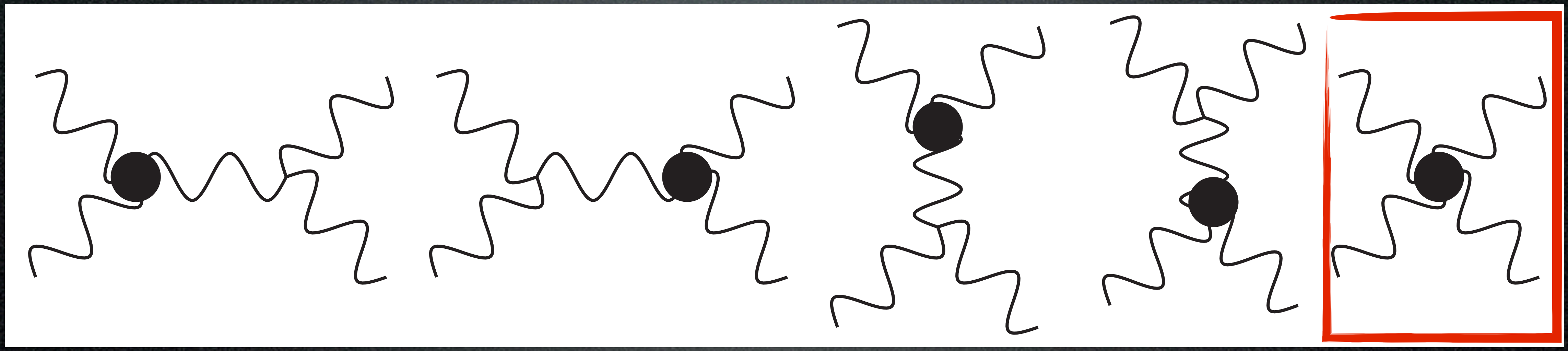


TGC's alone are not gauge invariant

Celine Degrande (UIUC)

pp>WWW or pp>WWjj

- Same operators for 4W amplitudes
- gauge invariance requires 3 and 4 legs vertices to be related

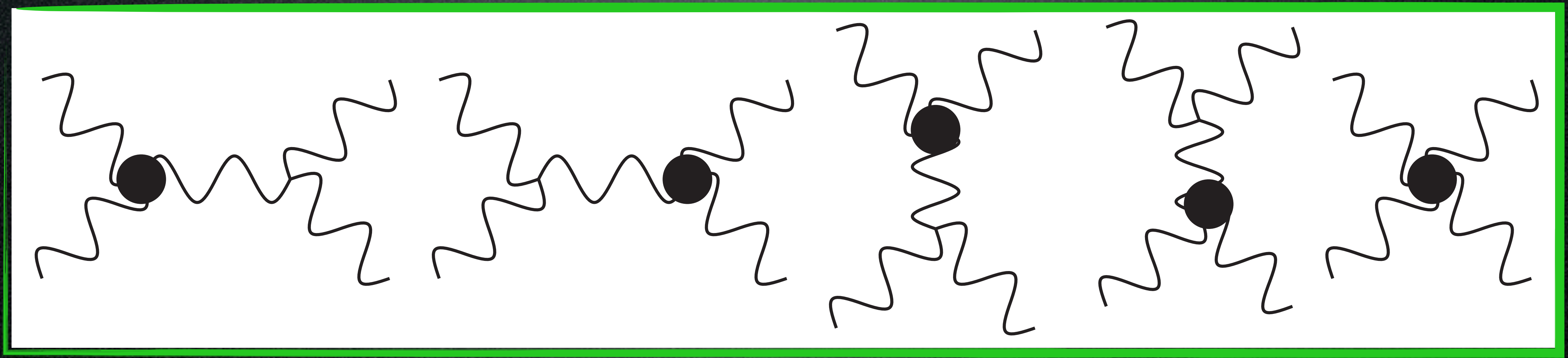


QGC's alone are not gauge invariant

Celine Degrande (UIUC)

pp>WWW or pp>WWjj

- Same operators for 4W amplitudes
- gauge invariance requires 3 and 4 legs vertices to be related



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

Celine Degrande (UIUC)

Plan

- Introduction to EFT
- EFT for pp(ee)>WW
- The constraints
- The effects
- EFT for pp>WWW, pp>WWjj
- Concluding remarks

Concluding remarks

- EFT are a good way to search for heavy new physics
  - More predictive (guidance)
  - Satisfy unitarity
  - Take care of gauge invariance for any process
  - Allow loop computation
- EFT are available in MadGraph (https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Models/EWdim6)

Back-up

Dim-6 versus dim-8

- Smaller effects or larger errors

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

1 10% 1% 0.1%

Dim-6 versus dim-8

- Smaller effects or larger errors

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

1	10%	1%	0.1%
1	0%	10%	0.3%

Celine Degrande (UIUC)

Dim-6 versus dim-8

- Smaller effects or larger errors

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

1	10%	1%	0.1%
1	0%	10%	0.3%

- Extra assumptions

Dim-6 versus dim-8

- Smaller effects or larger errors

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

1	10%	1%	0.1%
1	0%	10%	0.3%

- Extra assumptions
- More parameters/less guidance

Celine Degrande (UIUC)

Dim-6 versus dim-8

- Smaller effects or larger errors

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

1	10%	1%	0.1%
1	0%	10%	0.3%

- Extra assumptions
- More parameters/less guidance
- Can affect a new observable

Celine Degrande (UIUC)