Z’ and W’ gauge bosons in SU(2)xSU(2)xU(1) models : precision predictions for LHC

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Call for New Physics Beyond the SM

- **The most successful theory in the history of physics**:
    - Is a gauge theory: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
    - One massless (A) and three massive $(Z, W^{\pm})$ EW gauge bosons.
    - Higgs mechanism: Scalar $SU(2)_L$ doublet breaks G_{21} symmetry.

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  - Higgs mechanism: Scalar $SU(2)_L$ doublet breaks G_{21} symmetry.
- **The most successful theory in the history of physics also**:
  - 26 (unexplained) input parameters.
  - Not based on a simple gauge group
  - Far away from a theory of everything: No gravity.
  - Many problems: Dark matter/energy, BAU, neutrino masses etc.

Extended Gauge Group Models: G(221) Class

- The unification of the SM gauge group in a larger one (e.g E_6, SO(10)) is theoretically very attractive.
- Additional subgroups (e.g U(1), SU(2)) may appear at intermediate stage.
- A new U(1) group factor predicts one additional gauge boson (Z').
- A new SU(2) leads to three new gauge bosons (Z', W').
- $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X = G_{221}$.

$$\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_\mathrm{X}$$

BP – I

Identification: $\mathrm{SU}(2)_1 \equiv \mathrm{SU}(2)_\mathrm{L}$

Doublet: $\phi \sim (\mathbf{1}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$

Triplet: $\phi \sim (\mathbf{1}, \mathbf{3}, \mathbf{1})$

$\mathrm{SU}(2)_2 \times \mathrm{U}(1)_\mathrm{X}$

First Stage: $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ u_\mathrm{D} \end{pmatrix}$ (doublet), $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ u_\mathrm{T} & 0 \end{pmatrix}$ (triplet)

$\downarrow$

$\mathrm{U}(1)_\mathrm{Y}$

Second Stage: $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

$H \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{0})$, $\langle H\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} c_\beta & 0 \\ 0 & s_\beta \end{pmatrix}$

LR-D, LP-D, FP-D, HP-D

LR-T, LP-T, FP-T, HP-T

BP – II

Identification: $\mathrm{U}(1)_\mathrm{X} \equiv \mathrm{U}(1)_\mathrm{Y}$

Bi-doublet: $\phi \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{0})$

$\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2$

First Stage: $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}$

$\downarrow$

$\mathrm{SU}(2)_\mathrm{L}$

Second Stage: $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

$H \sim (\mathbf{1}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$, $\langle H\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

UU, NU

Both patterns

$\downarrow$

$\mathrm{U}(1)_\mathrm{e.m.}$

Charge Assignments

BP	Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
BP-I	Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
	Lepto-phobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $Y_{\rm SM}$ for leptons.
	Hadro-phobic (HP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$Y_{\rm SM}$ for quarks, $-\frac{1}{2}$ for leptons.
	Fermio-phobic (FP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$Y_{\rm SM}$for quarks, $Y_{\rm SM}$ for leptons.
BP-II	Un-unified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$Y_{\rm SM}$ for quarks. $Y_{\rm SM}$ for leptons.
	Non-universal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\rm rd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\rm rd}}$	$Y_{\rm SM}$ for quarks. $Y_{\rm SM}$ for leptons.

$SU(2)_l = SU(2)_L$ (BP-I)

$U(1)_x = U(1)_Y$ (BP-II)

- Note that these models do not contain any new fermionic fields except for a potential ν_R

Masses of the Physical Gauge Bosons (BP II)

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$$\mathscr{L}_{\phi} + \mathscr{L}_{H} \rightarrow \mathscr{L}_{\langle\phi\rangle} + \mathscr{L}_{\langle H\rangle} \equiv \mathscr{L}_{mass}$$

$\phi \sim (2,\bar{2},0)$ $\quad$ $H \sim (1,2,\frac{1}{2})$

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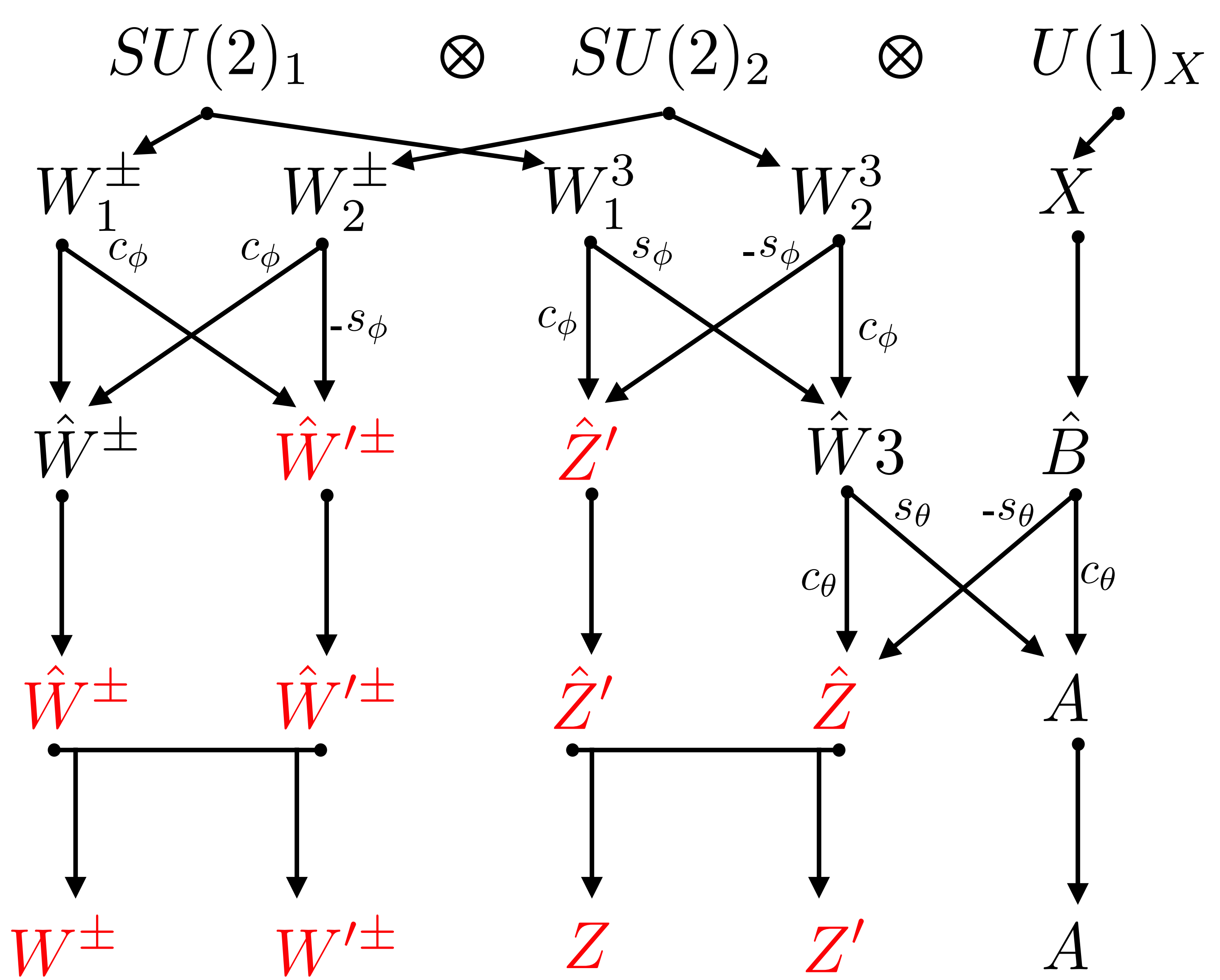
Mixing of the gauge bosons:



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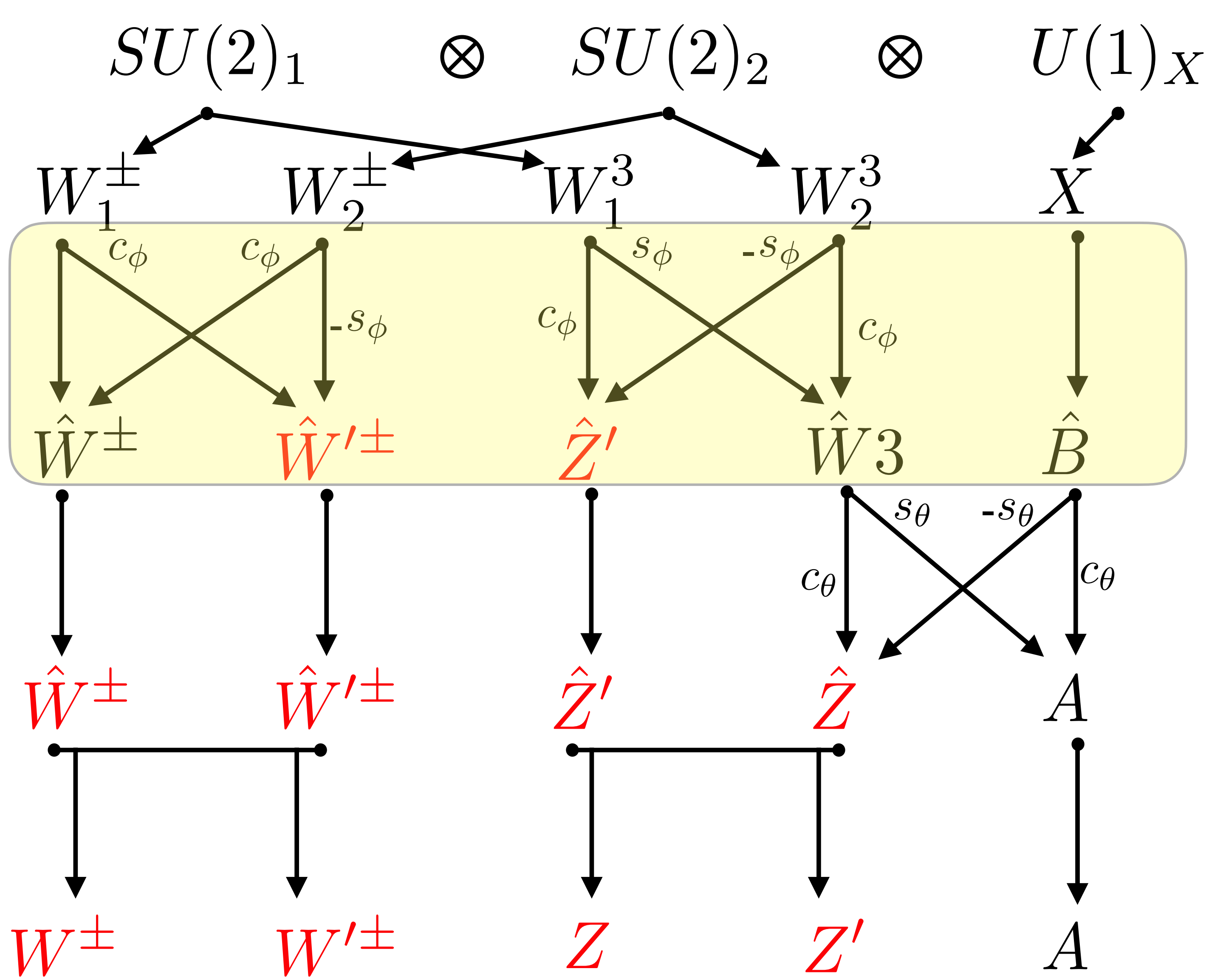

First Stage:

$$\mathscr{L}^1_{mass} = \frac{1}{2} M^2_{\hat{Z}'} \hat{Z}'_\mu \hat{Z}'^\mu + M^2_{\hat{W}'} \hat{W}'^+_\mu \hat{W}'^{-\mu}$$

Mixing angle: $t_\phi \equiv \frac{g_2}{g_1}$

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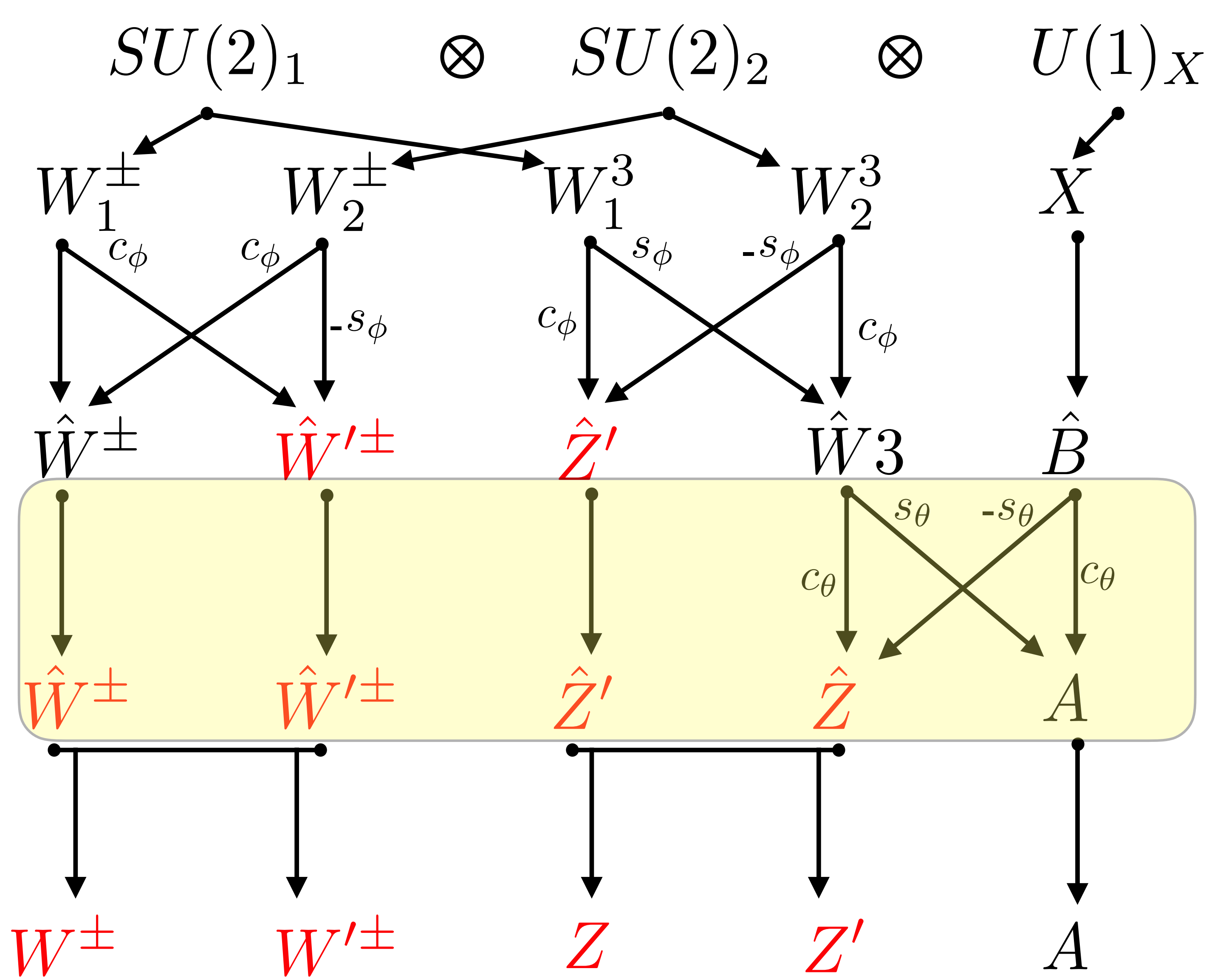

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Second Stage:

$$M_{\hat{Z}\hat{Z}'} = \begin{pmatrix} M^2_{\hat{Z}} & \delta M^2_{\hat{Z}} \\ \delta M^2_{\hat{Z}} & M^2_{\hat{Z}'} + \Delta M^2_{\hat{Z}'} \end{pmatrix}$$

Mixing angle: $t_\theta \equiv \dfrac{g_Y}{g_L}$

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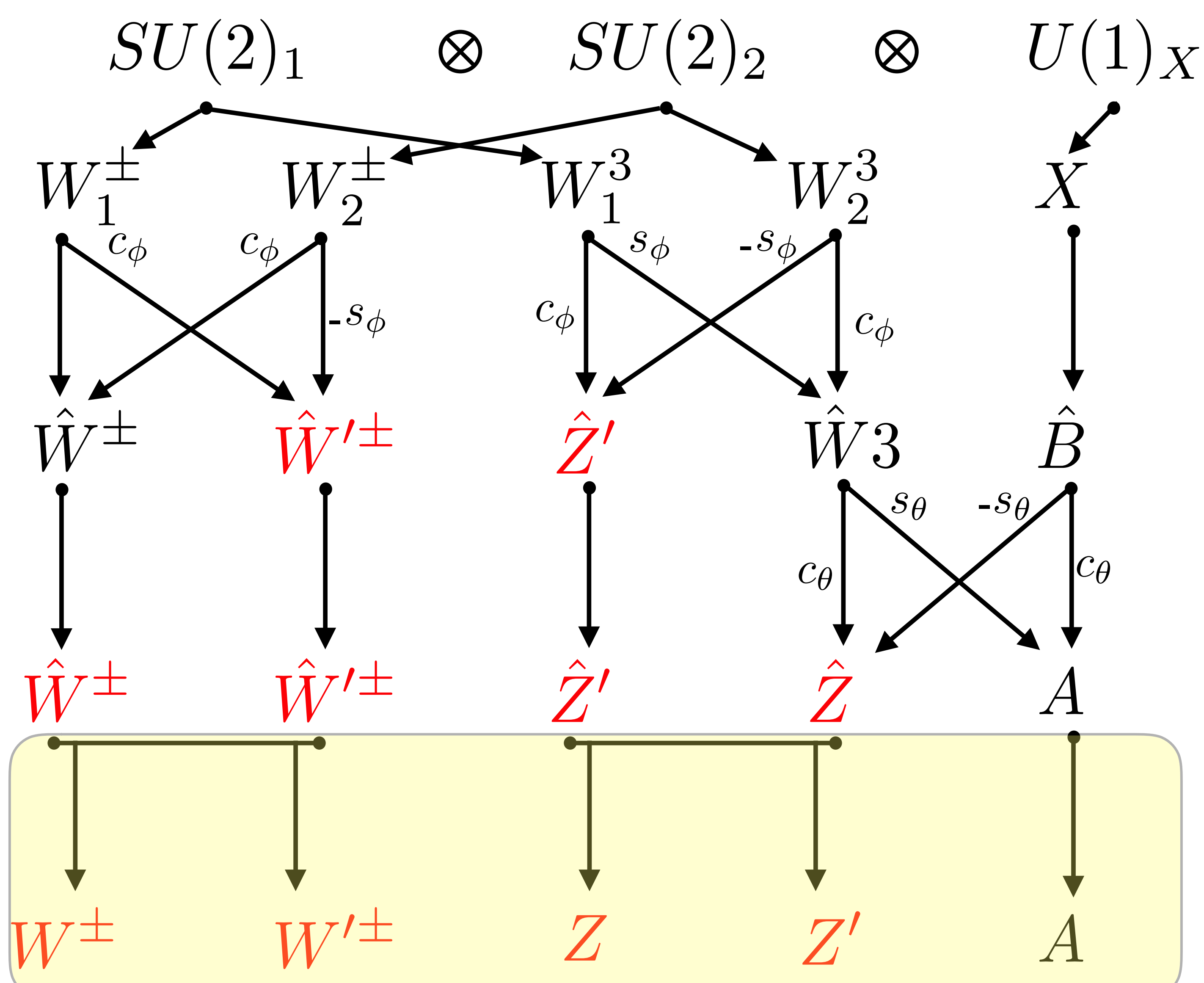

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Mixing angle: $t_\theta \equiv \frac{g_Y}{g_L}$

Masses:

$$M^2_Z = M^2_{\hat{Z}} - \frac{\delta M^4_{\hat{Z}}}{M^2_{\hat{Z}'} - M^2_{\hat{Z}} + \delta M^2_{\hat{Z}'}}$$

$$M^2_{Z'} = M^2_{\hat{Z}'} + \delta M^2_{\hat{Z}'} + \frac{\delta M^4_{\hat{Z}}}{M^2_{\hat{Z}'} - M^2_{\hat{Z}} + \delta M^2_{\hat{Z}'}}$$

Neutral and Charged Fermionic Currents

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$$\mathscr{L}_{int} = \bar{f}_i i\gamma_\mu D^\mu f_i = \hat{W}^+_\mu J^{+\mu} + \hat{W}^-_\mu J^{-\mu} + \hat{Z}_\mu J^{0\mu} + A_\mu J^\mu + \hat{W}'^+_\mu K^{+\mu} + \hat{W}'^-_\mu K^{-\mu} + \hat{Z}'_\mu K^{0\mu} .$$

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$$\begin{aligned}
\mathscr{L}_{int} = & W^+_\mu\left(J^{+\mu} - \frac{\delta M^2_{\hat{W}}}{M^2_{\hat{W}'}} K^{+\mu}\right) + (+\longleftrightarrow -) \\
& + W'^+_\mu\left(K^{+\mu} + \frac{\delta M^2_{\hat{W}}}{M^2_{\hat{W}'}} J^{+\mu}\right) + (+\longleftrightarrow -) \\
& + Z_\mu\left(J^{0\mu} - \frac{\delta M^2_{\hat{Z}}}{M^2_{\hat{Z}'}} K^{0\mu}\right) \\
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\end{aligned}$$

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Mass eigenstates:

$$Z \equiv \hat{Z} - \frac{\delta M^2_{\hat{Z}}}{M^2_{\hat{Z}'}}\hat{Z}', \quad Z' \equiv \frac{\delta M^2_{\hat{Z}}}{M^2_{\hat{Z}'}}\hat{Z} + \hat{Z}'$$

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$$\mathscr{L}_{int} = \bar{f}_i i\gamma_\mu D^\mu f_i = \hat{W}^+_\mu J^{+\mu} + \hat{W}^-_\mu J^{-\mu} + \hat{Z}_\mu J^{0\mu} + A_\mu J^\mu + \hat{W}'^+_\mu K^{+\mu} + \hat{W}'^-_\mu K^{-\mu} + \hat{Z}'_\mu K^{0\mu}\,.$$

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Model-independent effective Lagrangian

$$\mathcal{L}^{W'}_{\rm CC} = \frac{g_W}{\sqrt{2}}\left[\bar{u}_i\gamma^\mu\left(\left(C^{W'}_{q,L}\right)_{ij} P_L + \left(C^{W'}_{q,R}\right)_{ij} P_R\right) d_j + \bar{\nu}_i\gamma^\mu\left(\left(C^{W'}_{\ell,L}\right)_{ij} P_L + \left(C^{W'}_{\ell,R}\right)_{ij} P_R\right) e_j\right] W'_\mu + h.c.$$

$$\mathcal{L}^{Z'}_{\rm NC} = \frac{g_W}{c_{\theta_W}}\left[\sum_q \bar{q}_i\gamma^\mu\left(\left(C^{Z'}_{q,L}\right)_{ij} P_L + \left(C^{Z'}_{q,R}\right)_{ij} P_R\right) q_j + \sum_\ell \bar{\ell}_i\gamma^\mu\left(\left(C^{Z'}_{\ell,L}\right)_{ij} P_L + \left(C^{Z'}_{\ell,R}\right)_{ij} P_R\right) \ell_j\right] Z'_\mu + h.c.$$

- Couplings C given in the different G(221) models

Resummino

- Precision prediction for pp $\rightarrow$ W/W' $\rightarrow$ lν process in **RESUMMINO**.

Resummino

- **Public code RESUMMINO implements soft-gluon resummation for**:
  - Z', gaugino and slepton pair production.
  - Added the W' $\rightarrow l\nu$ process.
- Present QCD resummation predictions for:
  - $pp \rightarrow W/W' \rightarrow l\nu$ and $pp \rightarrow Z/Z' \rightarrow ll$.
  - Include the interferences.

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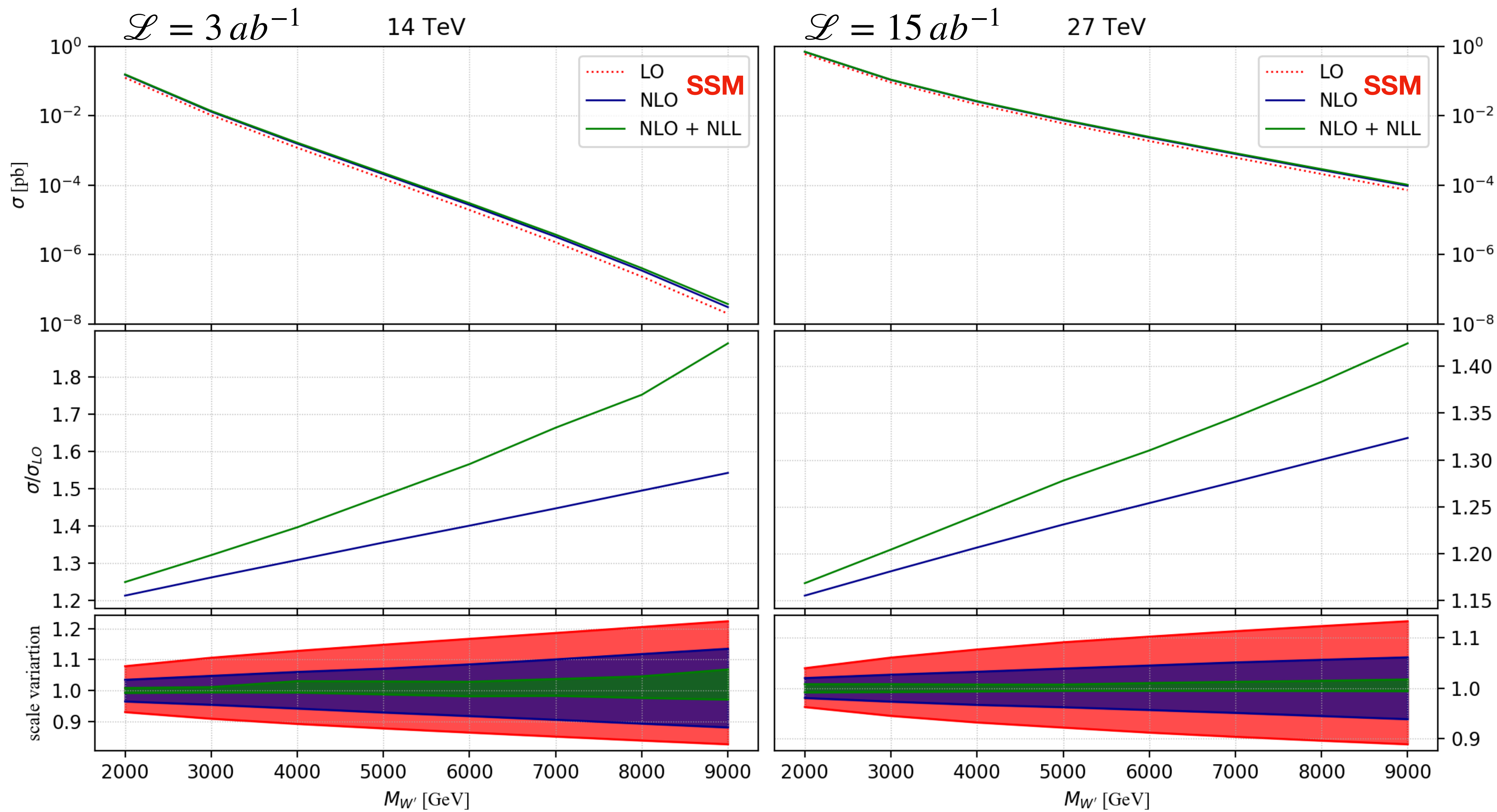
- Present QCD resummation predictions for:
  - pp → W/W' → lν and pp → Z/Z' → ll.
  - Include the interferences.
- **Input parameters**:
  - SSM : $M_{W'}$
  - G(221) models: Un-Unified (UU) and Generation Non-Universal (NU) : $M_{W'}, \tan\phi$
  - CT14 PDFs at NLO including error sets at 90% C.L.

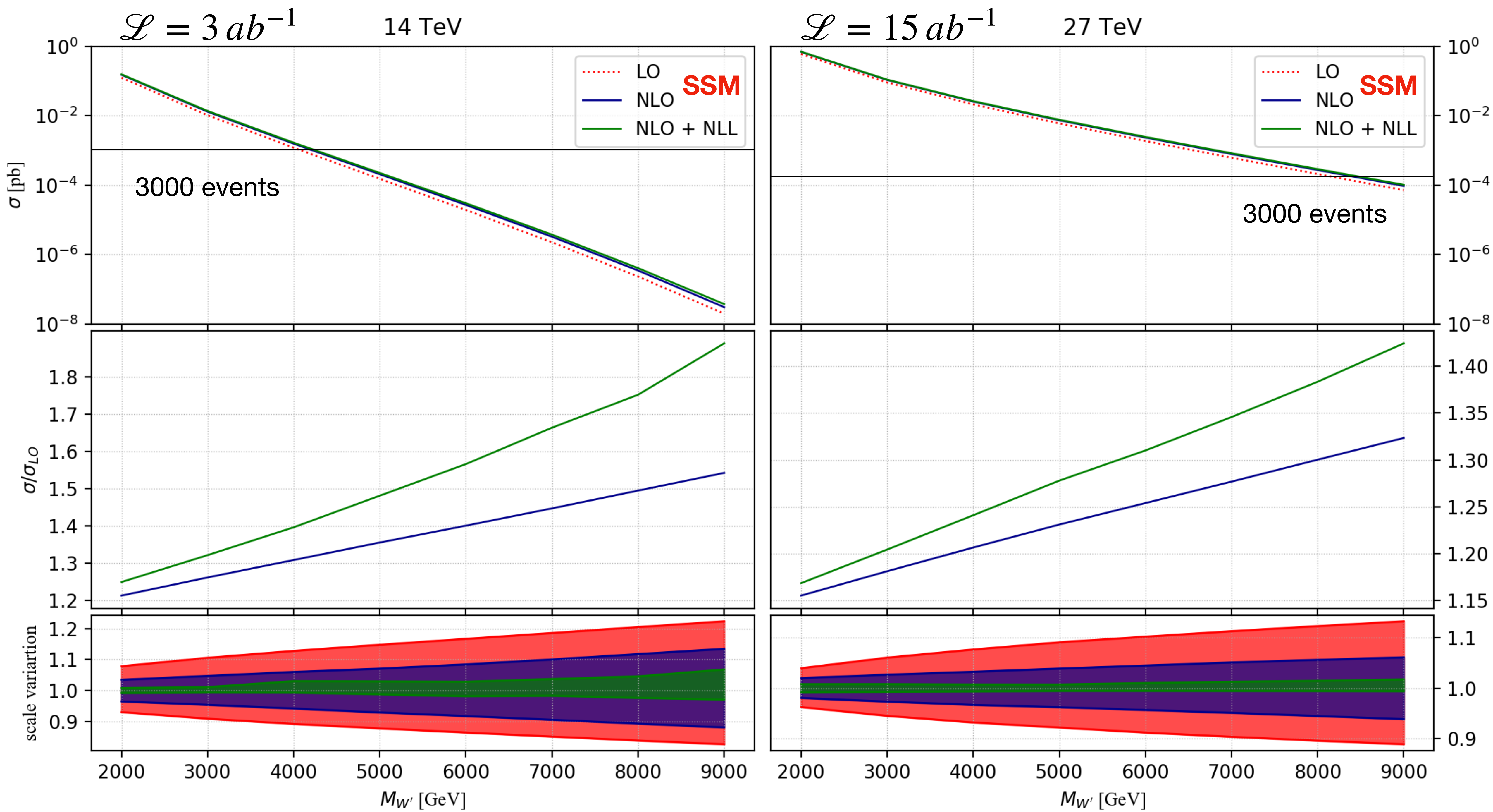
SSM:

Z' (W') have the same couplings to fermions as the Standard Model Z (W), width of the Z' (W') increases proportional to its mass.

Numerical Results



W' production cross sections at LHC14 and 27 at NLO+NLL in the SSM vs $M_{W'}$



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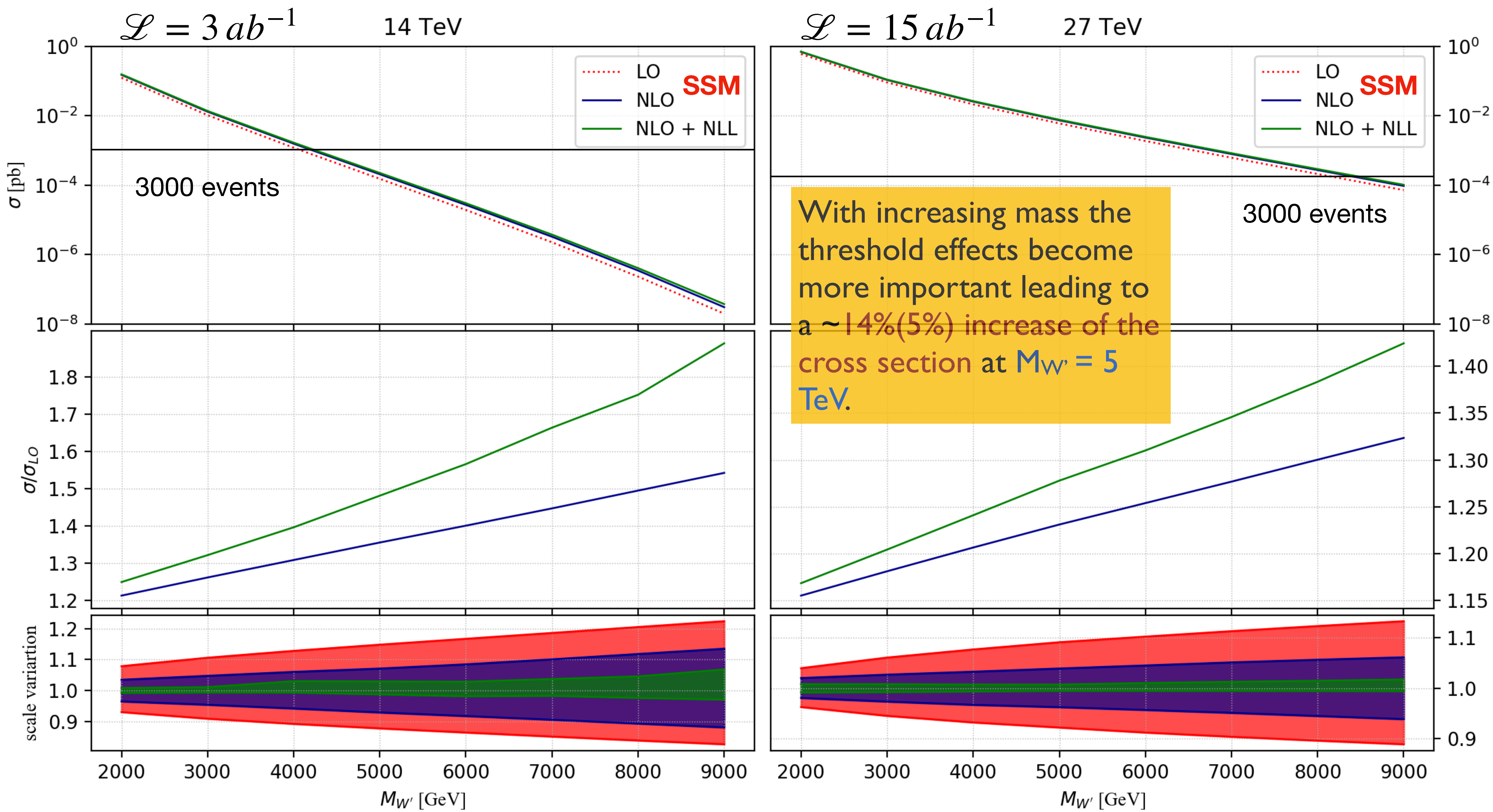


W' production cross sections at LHC14 and 27 at NLO+NLL in the SSM vs $M_{W'}$

PBZp

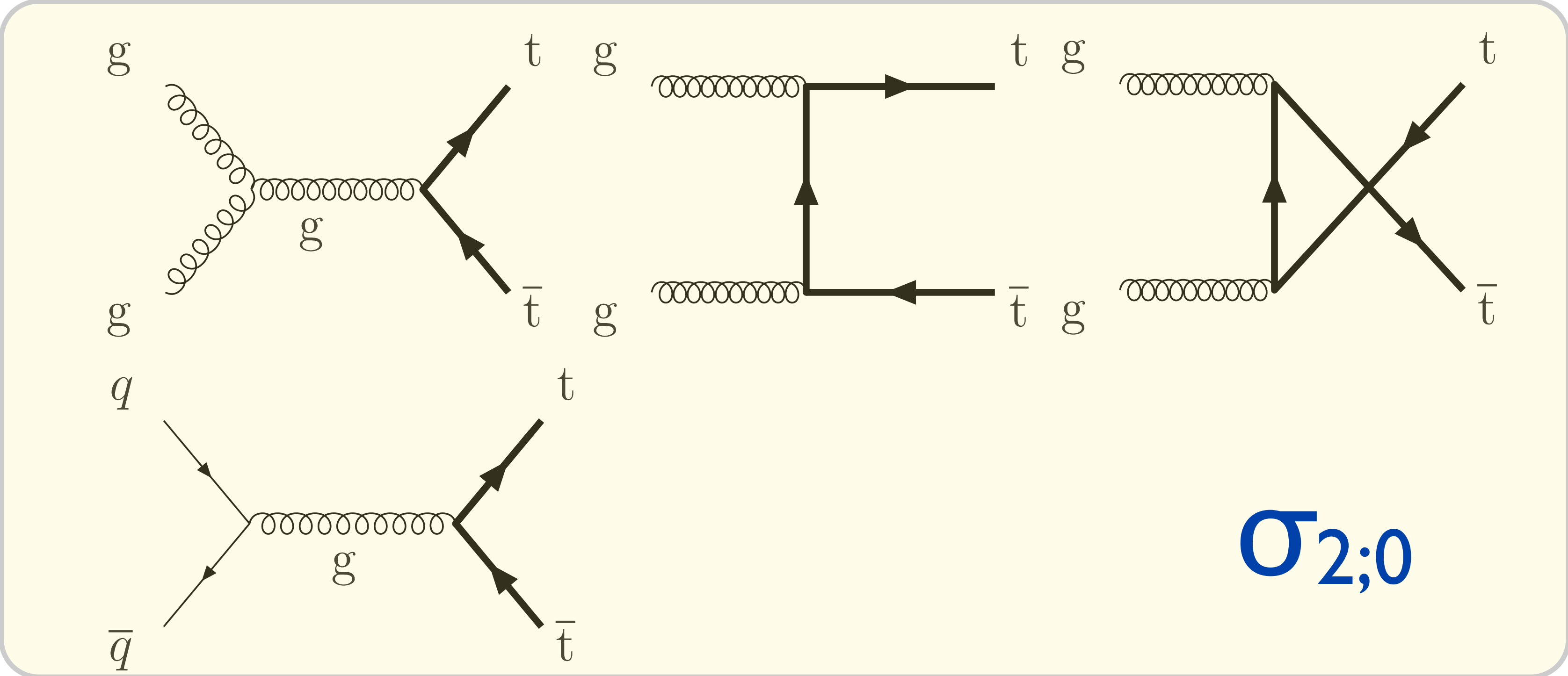
- EW top pair production at the LHC with Z' bosons including NLO QCD in **POWHEG**

PBZp

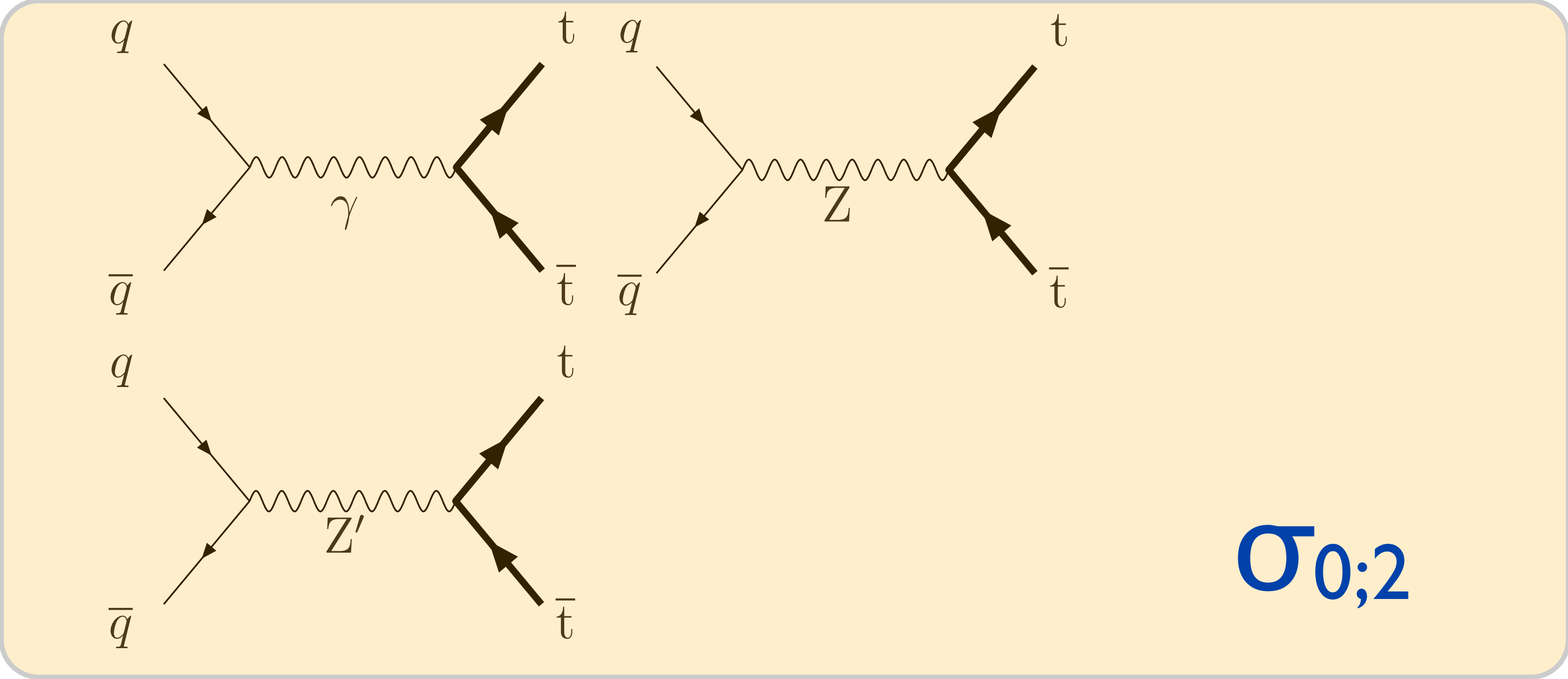
- Calculation of NLO QCD corrections to EW top-pair production at the LHC in the presence of a Z' boson. [arXiv:1511.08185]
  - Z' boson with general (flavour diagonal) couplings to SM fermions.
  - Results are implemented in the POWHEG BOX MC event generator: code named PBZp (POWHEG BOX Z').
  - Standard Model and new physics interference effects taken into account.
  - QED singularities consistently subtracted.

LO subprocesses

- $\hat{\sigma}^{\mathrm{LO}} = \hat{\sigma}_S^{\mathrm{LO}}(\alpha_S^2) + \hat{\sigma}_W^{\mathrm{LO}}(\alpha_W^2)$
- SM
  - gg, $\mathcal{O}(\alpha_S^2)$:
  - $q\overline{q}$, $\mathcal{O}(\alpha_S^2)$:

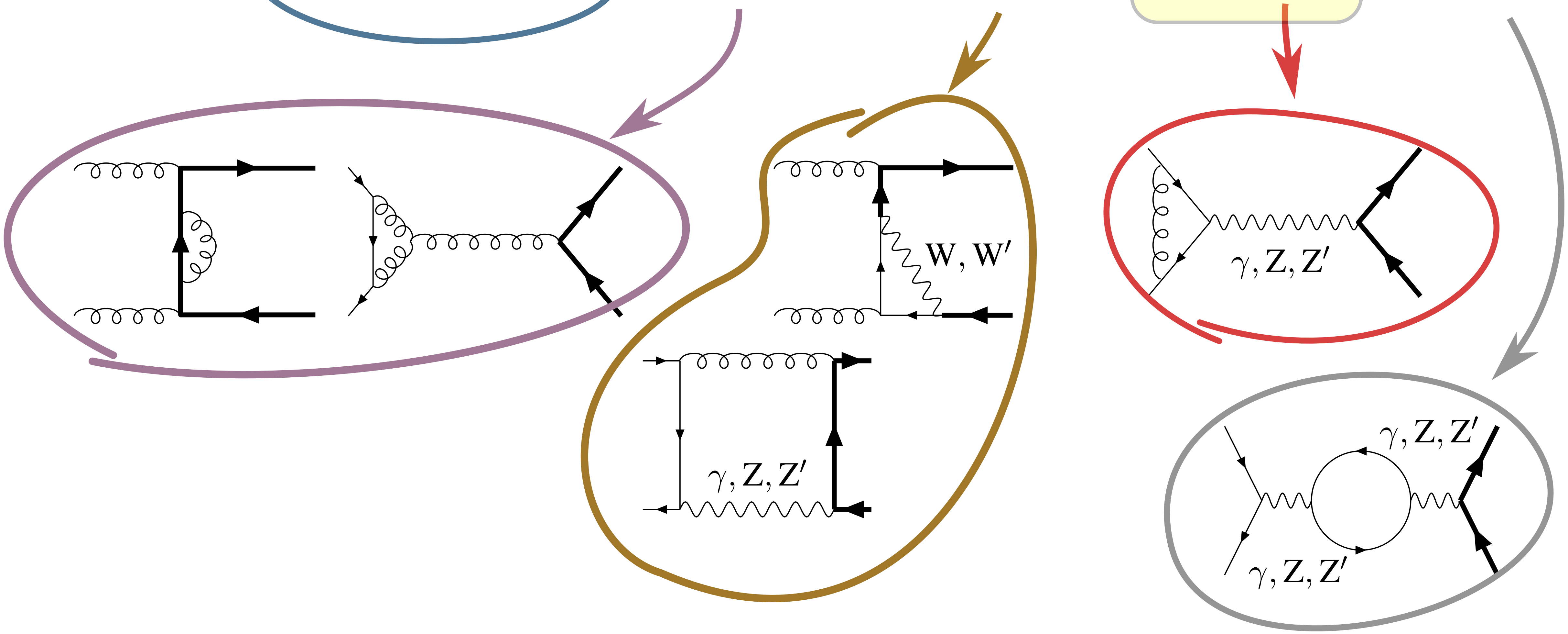


  - $q\overline{q}$, $\mathcal{O}(\alpha_W^2)$:
- beyond SM
  - $q\overline{q}$, $\mathcal{O}(\alpha_W^2)$:



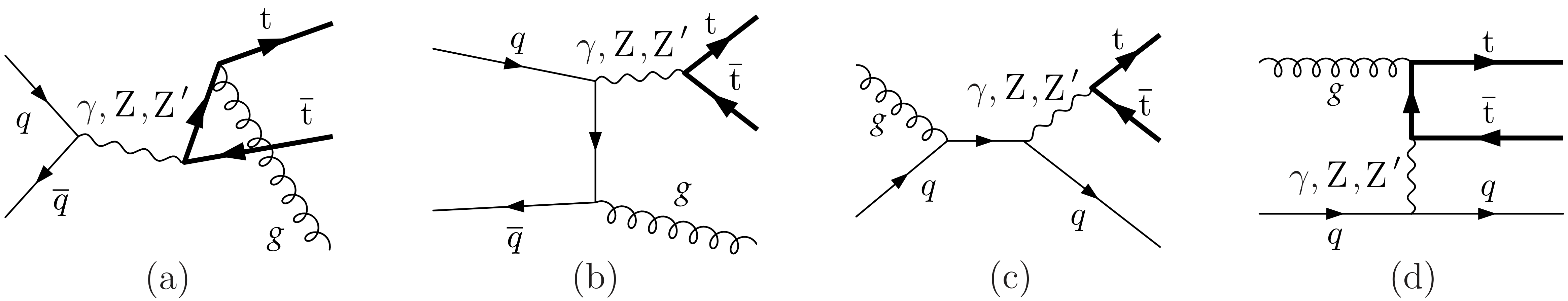
LO

- $\hat{\sigma}^{\text{NLO}} = \hat{\sigma}(\alpha_S^2) + \hat{\sigma}(\alpha_W^2) + \hat{\sigma}(\alpha_S^3) + \hat{\sigma}(\alpha_S^2\alpha_W) + \hat{\sigma}(\alpha_S\alpha_W^2) + \hat{\sigma}(\alpha_W^3)$



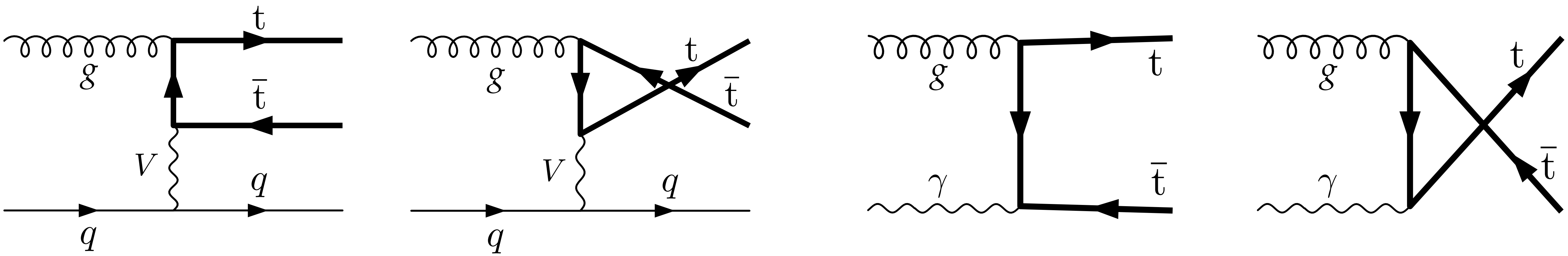
- $\mathcal{O}(\alpha_S^3)$ not affected by the presence of Z′
- we calculate $\mathcal{O}(\alpha_S\alpha_W^2)$

NLO real corrections



- interferences of real and real diagrams
- new channel as compared to tree-level and 1-loop diagrams
- no loops, no UV divergences
- IR divergences, after integration over 1 particle phase space
  - soft (S) divergences: radiation of a soft gluon (a), (b)
  - initial state collinear (ISC) divergences: (b), (d)
  - no final state collinear (FSC) divergences

QED contribution

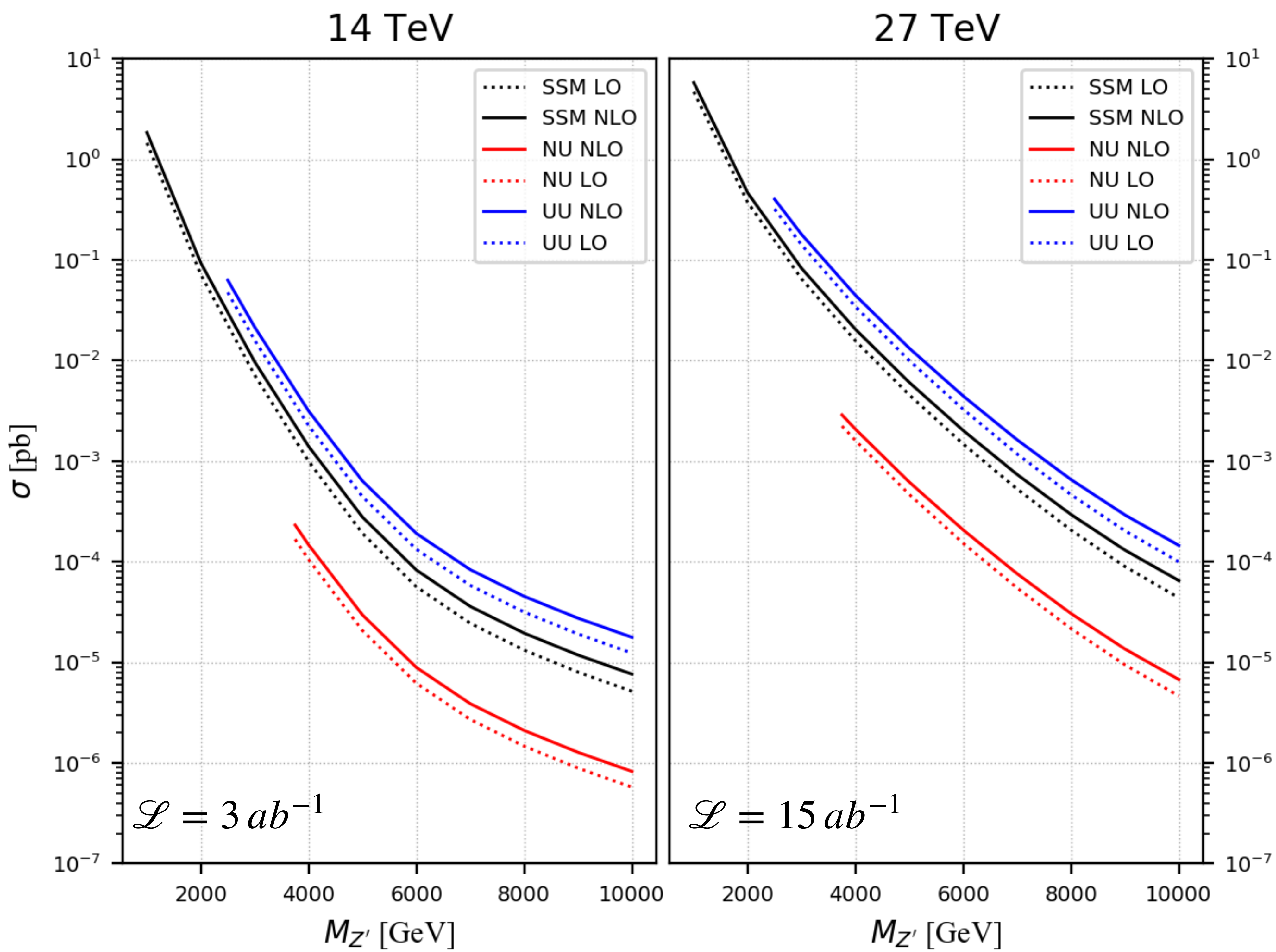


- The gq-channel has an initial state C-div. associated to a photon propagator

- For the mass factorization procedure need to introduce a photon PDF and have to include photon-initiated subprocesses

- This channel turns out to be numerically important

Numerical Results



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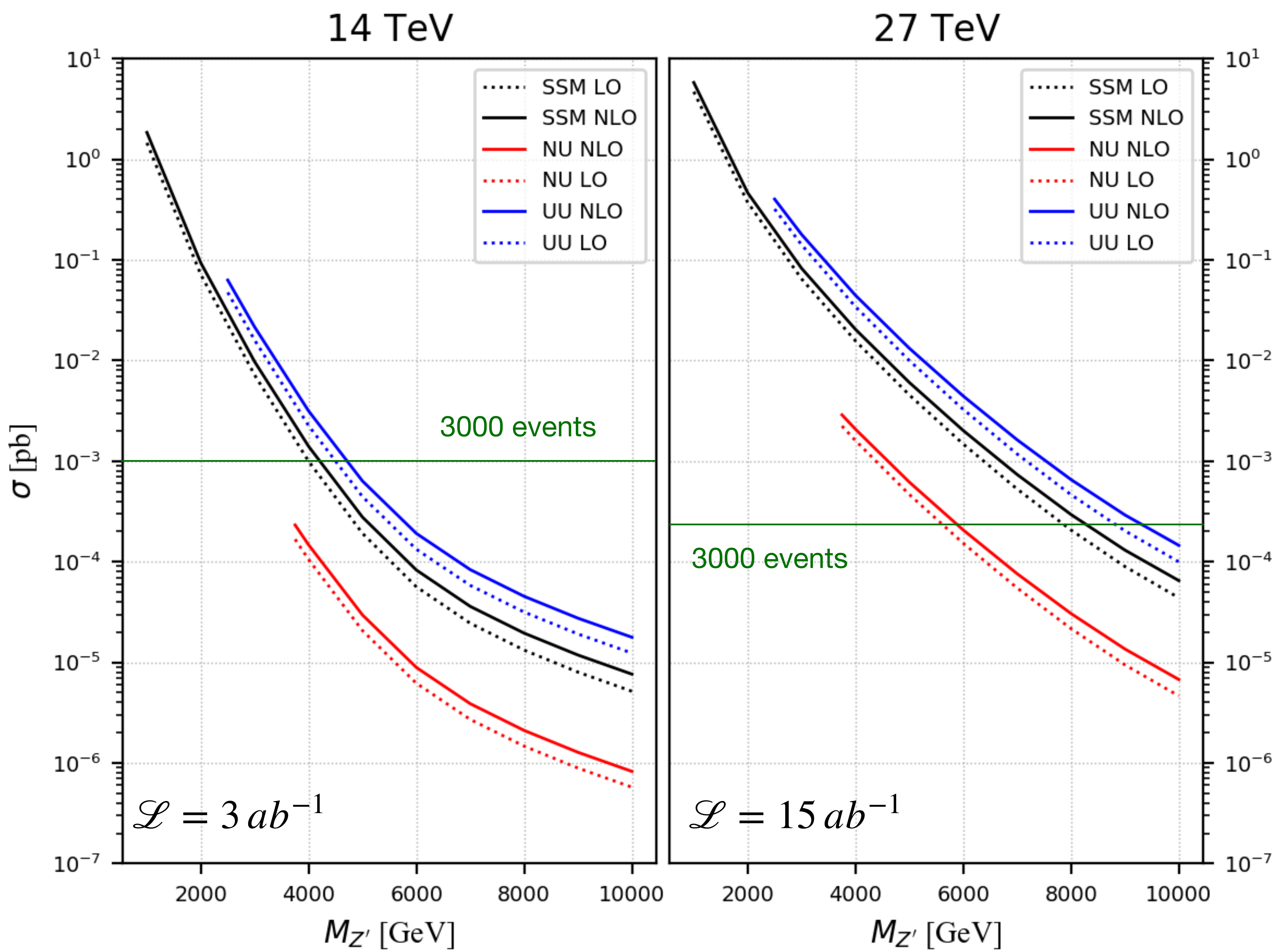

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PBZWp

Goal:

- Extend **PBZp** (→ **PBZWp**) to include the pp → W/W' → tb process including NLO QCD corrections.

- Include flavour non-diagonal Z' and W' couplings.

Recola

- **Recola**: **RE**cursive **C**omputation of **O**ne-**L**oop **A**mplitudes
- EW and QCD amplitudes in SM at NLO.
- Based on recursive method for the tensor coefficient.
- Based on Collier library for tensor integrals [Denner, Dittmaier, Hofer; 1604.06792].
- Publicly available at: https://recola.hepforge.org.
- Recola2 [Denner, Lang, Uccirati; 1705.06053] for BSM.

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  - Compare LO matrix elements between MF2 and MF3 in **MG5** sampling the full phase space.

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- **Perform phenomenological studies**.

Conclusions

- Studied G_{221} models.
- Calculated predictions for HL and HE LHC for new dilepton and top-pair resonances. [arXiv:1812.07831].
- Work on NLO QCD corrections to EW top-pair/top-bottom production with implementation in POWHEG BOX.

THANK YOU FOR YOUR ATTENTION