UNIVERSITÉ Grenoble Alpes

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

ICHEP 2020

NLO QCD corrections to the electroweak top-pair production beyond the Standard Model

Mohammad Mahdi ALTAKACH

In collaboration with T. Jezo, M. Klasen, J.-N. Lang, and I. Schienbein for the calculation
and also with J. Butterworth for an upcoming phenomenological study

31 Jul 2020

MCnet

Introduction

- New heavy resonances are predicted in a variety of models with extra U(1) or SU(2)

- In many cases, the resonance can decay leptonically and the strongest constraints come from searches with leptonic final states

- Nevertheless, **final states with top quarks** are very interesting:

- The heavy top quark may play a special role w.r.t. to EWSB and BSM physics which couples preferentially to the third generation or not to leptons

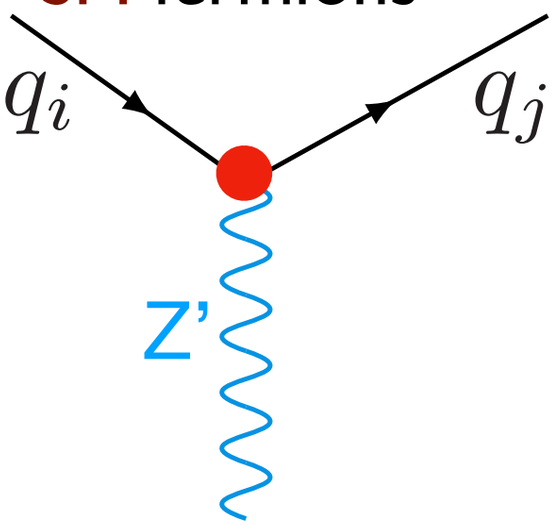
- Even for models with couplings to leptons, the addition of top quark observables is important to distinguish between different BSM scenarios

EW top pair production at the LHC with Z' bosons to NLO QCD in POWHEG

R. Bonciani, T. Jezo, M. Klasen, F. Lyonnet, I. Schienbein, JHEP(2016), arXiv:1511.08185

Introduction

- In 2015 **T. Jezo et al.** performed a 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 generation non-universal and flavour diagonal couplings to SM fermions



$$\begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{pmatrix}$$

- Standard Model (γ, Z) and new physics (Z') interference effects taken into account
- Results are implemented in the POWHEG BOX framework
- Initial state QED singularities are consistently treated

The Calculation

The Calculation

The partonic top-quark pair production cross section at NLO:

$$\sigma_{ab}(\mu_r) = \sigma_{2;0}(\alpha_S^2) + \sigma_{0;2}(\alpha^2) + \sigma_{3;0}(\alpha_S^3) + \sigma_{2;1}(\alpha_S^2\alpha) + \sigma_{1;2}(\alpha_S\alpha^2) + \sigma_{0;3}(\alpha^3)$$

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- $\sigma_{2;1}$: EW corrections to the SM QCD

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Our Calculation

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Subprocesses (5 FNS)

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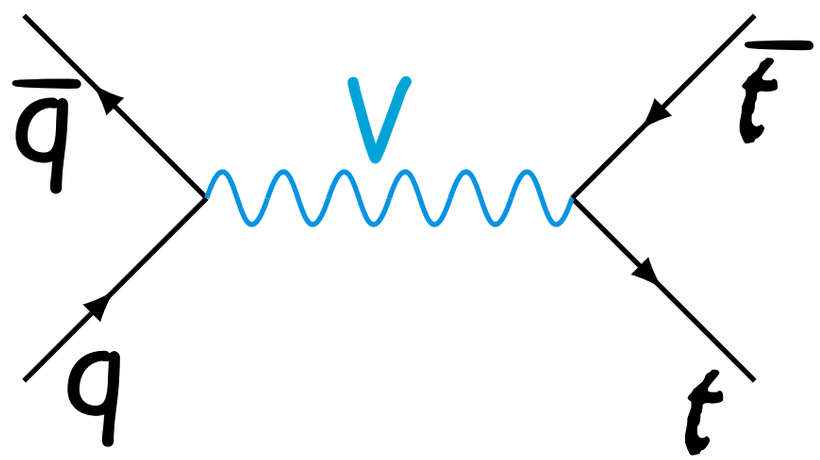
Born



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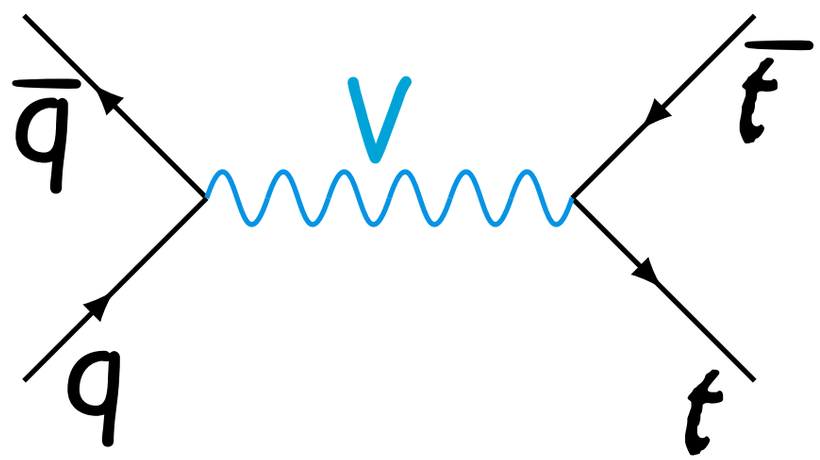
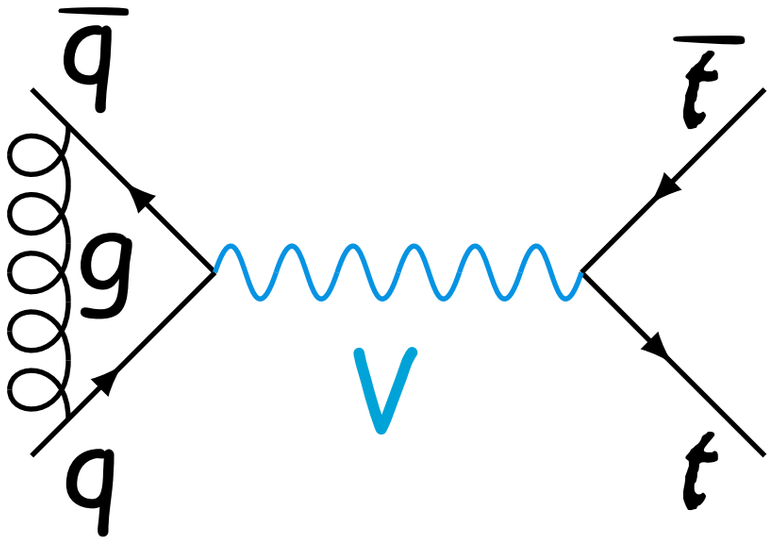
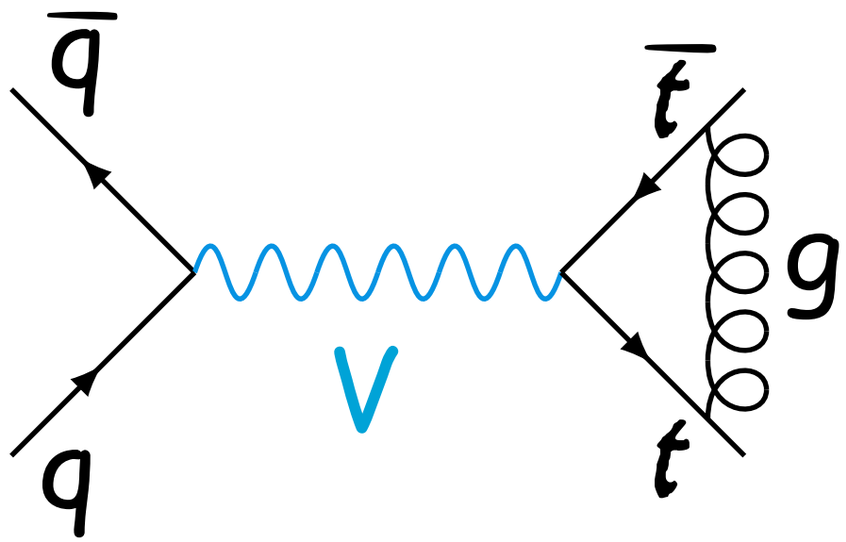


Virtual

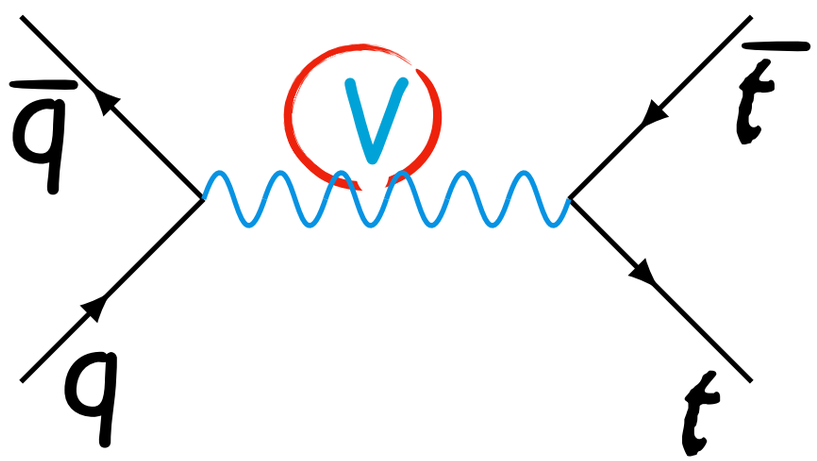




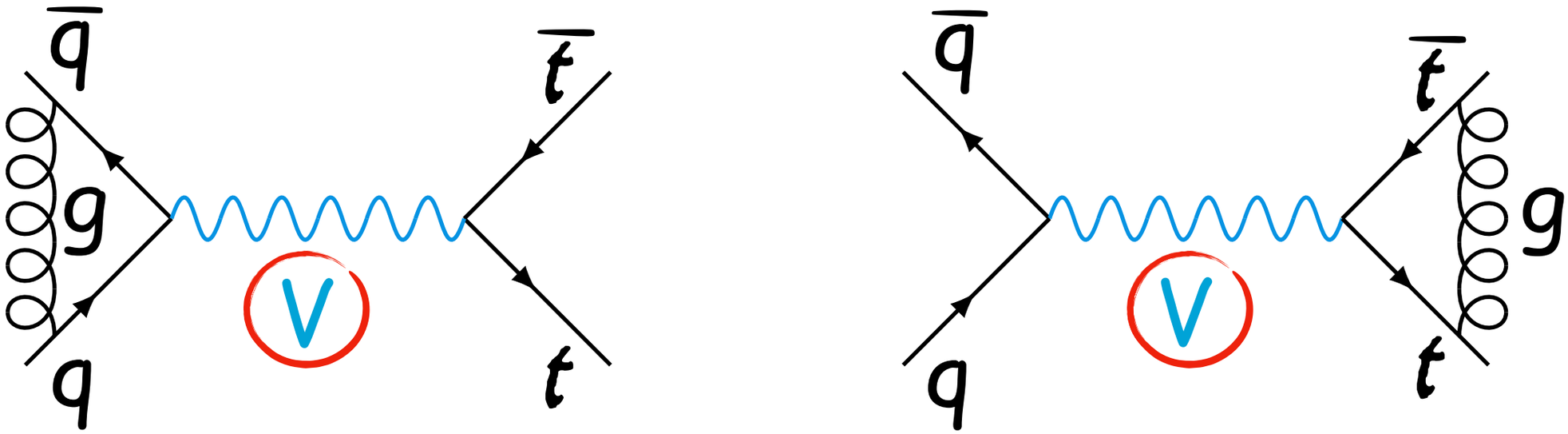
Subprocesses (5 FNS)

γ, Z, Z'

Born

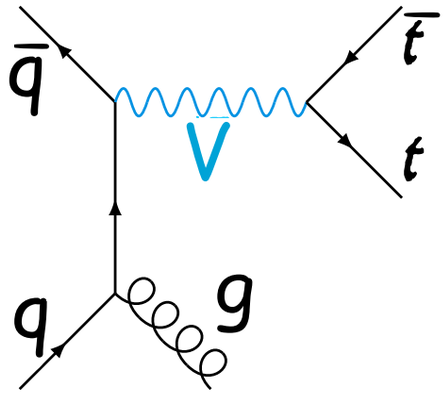


Virtual



Subprocesses (5 FNS)

Real



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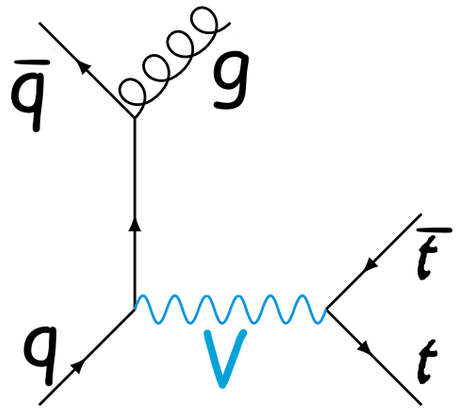
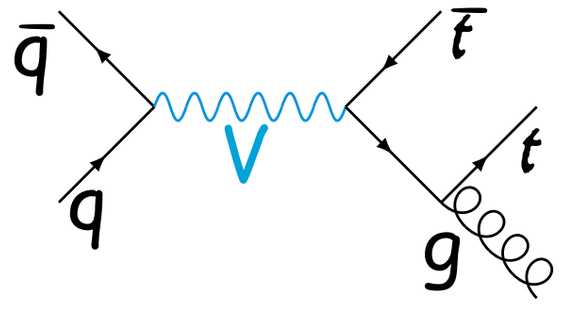
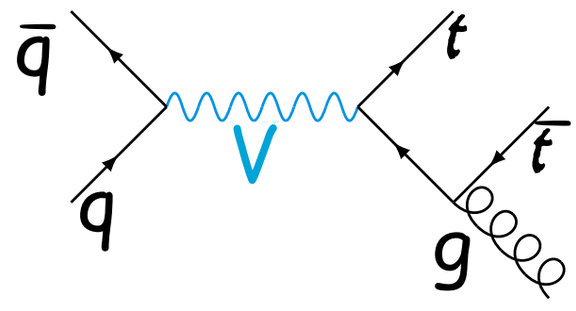


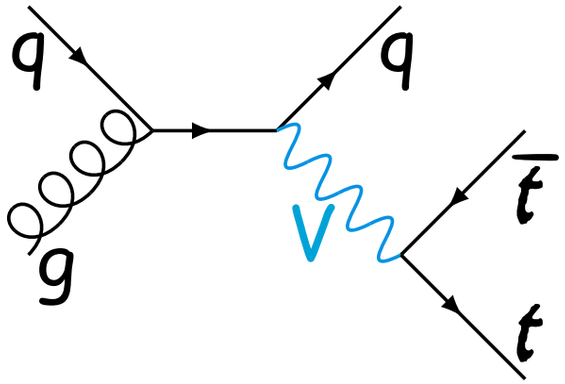
(b)



(c)



(d)



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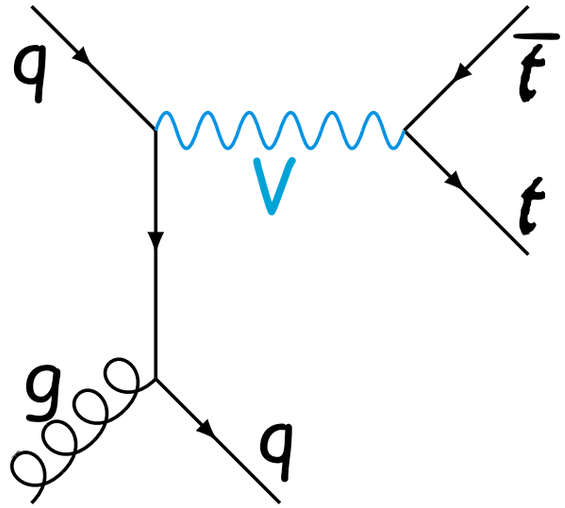

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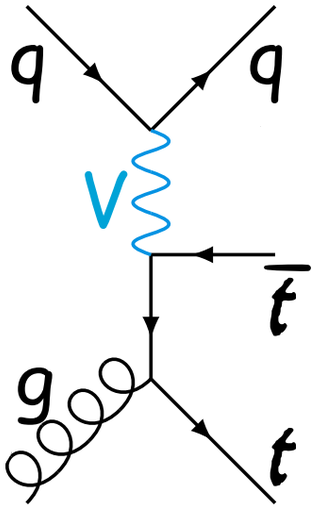
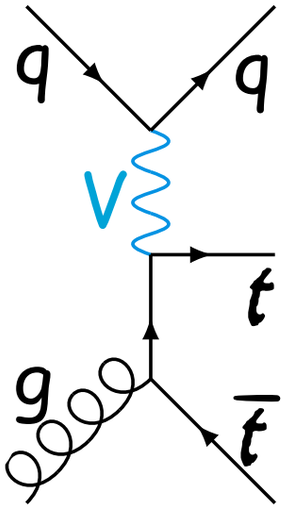


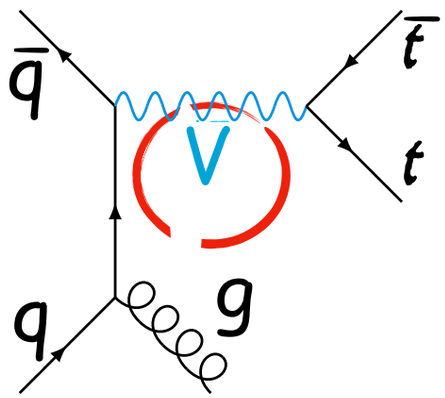
(g)



(h)

Subprocesses (5 FNS)

Real



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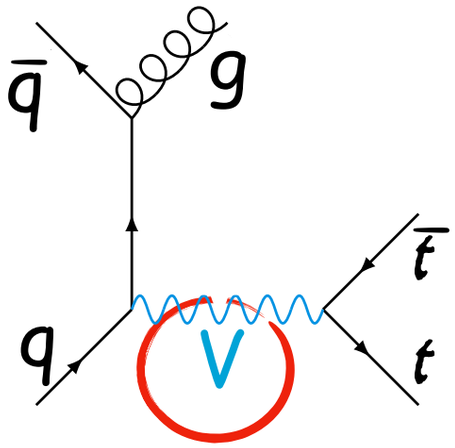

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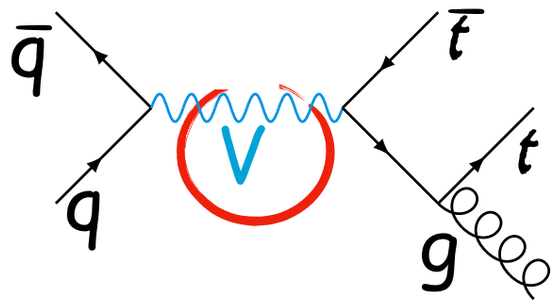

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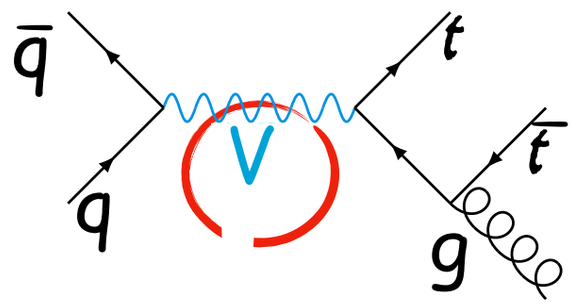

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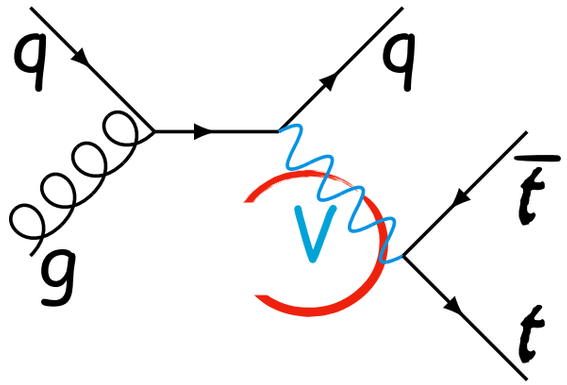
γ, Z, Z'



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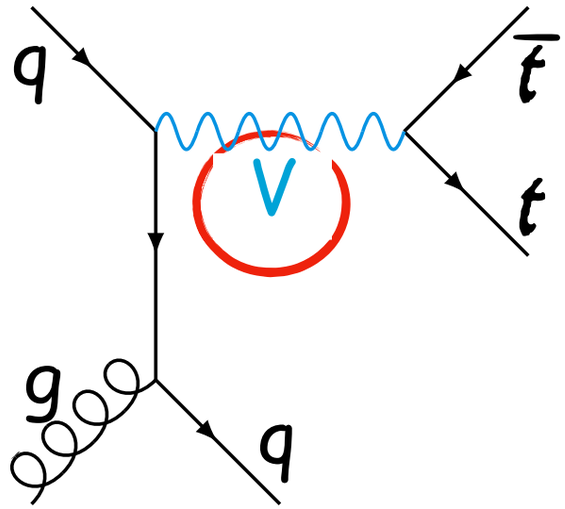

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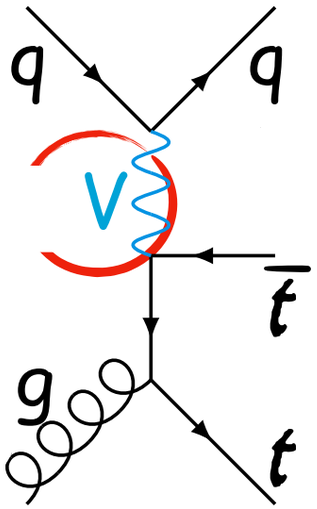

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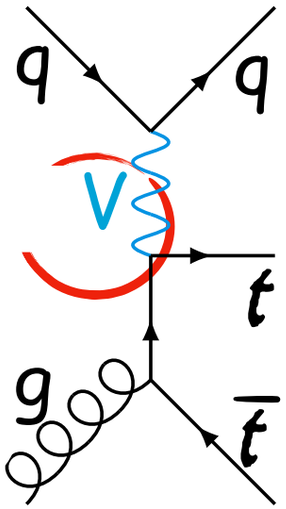


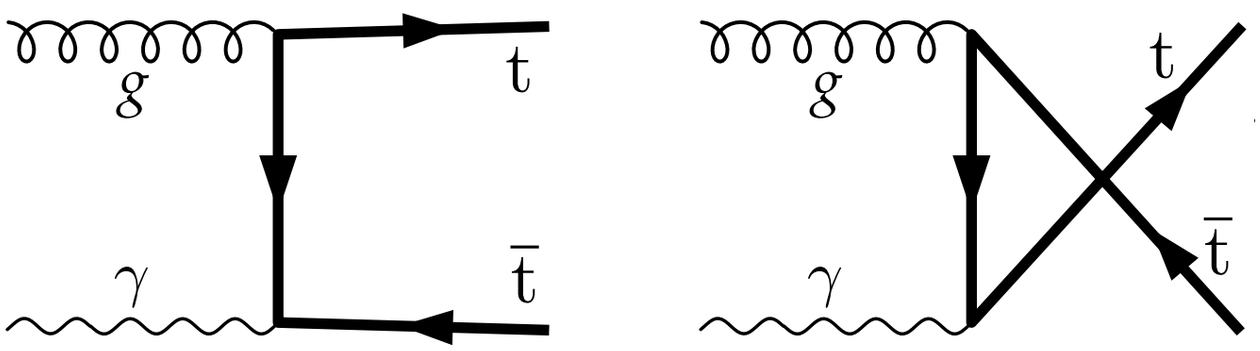
(h)

Subprocesses

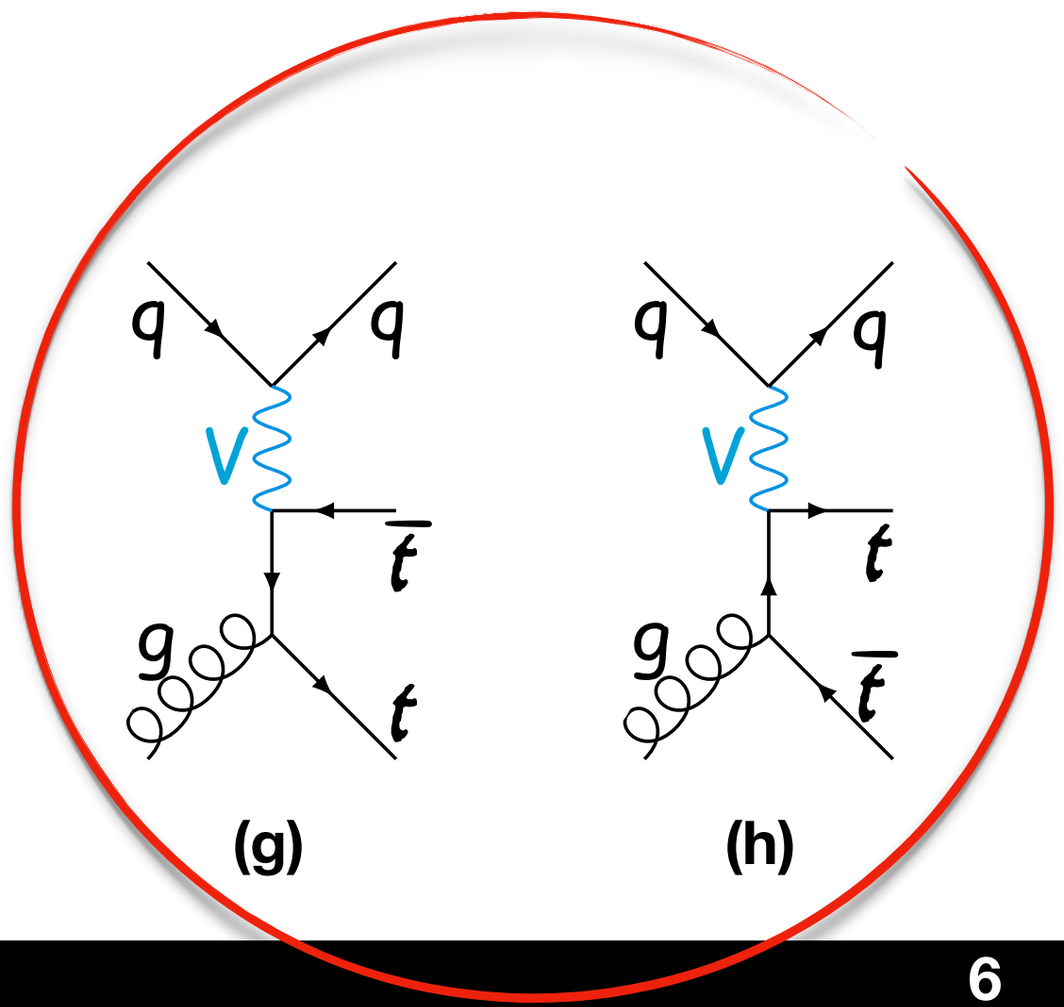
QED contribution

- The fact that (g) & (h) have an initial state C-div. associated to a photon propagator has two consequences:

  - We have to introduce a photon PDF inside the proton
  - The corresponding underlying Born process must be included in the calculation



- This channel turns out to be numerically important



Summary

- The first calculation of NLO QCD corrections to EW top-pair production in the SM

- It was matched to PS (NLO+PS accuracy) within the POWHEG BOX framework: code named **PBZp** (**P**OWHEG **B**OX **Z'**)

However this calculation lacks some features:

- Does not contain the contribution of the t-channel W nor W'

- Cannot deal with a Z' with flavour non-diagonal couplings

EW top pair production in the presence of heavy Z' and W' bosons at NLO QCD in POWHEG

M. M. AlTakach, T. Jezo, M. Klasen, J.-N. Lang, I. Schienbein, arXiv:xxxx.xxxxx

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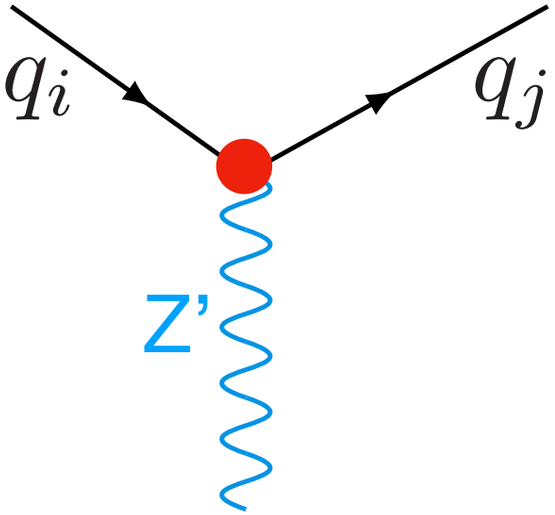
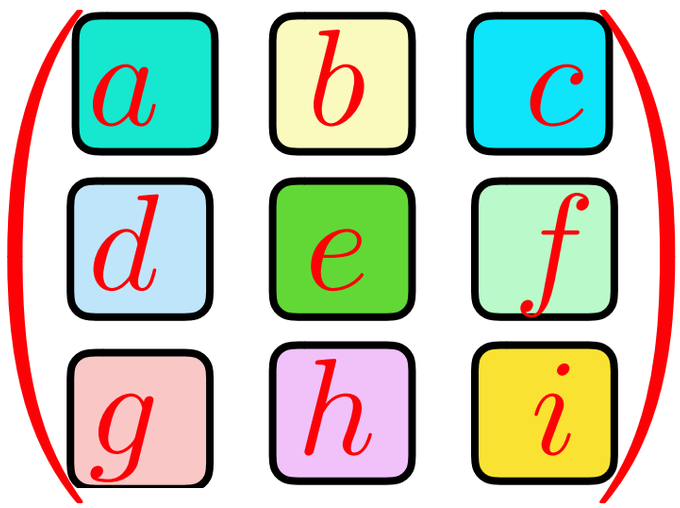
Introduction

- We performed a complete re-calculation of the processes implemented in the **PBZp** including a number of improvements:
  - The amplitudes have been calculated using the Recola2 package:
    - Recola2 (**RE**cursive **C**omputation of **O**ne-**L**oop **A**mplitudes)
    - Publicly available at: https://recola.hepforge.org
    - EW and QCD amplitudes for BSM models at NLO [Denner, Lang, Uccirati; 1705.06053]
- The amplitudes were implemented in Monte Carlo event generators (within the POWHEG BOX framework)
- First use case of Recola2 BSM amplitudes in NLO+PS matched calculation
- The calculation now includes t-channel W and W' contributions

Introduction

- We performed a complete re-calculation of the processes implemented in the **PBZp** including a number of improvements:
  - The new code can deal with general couplings for both Z' and W'





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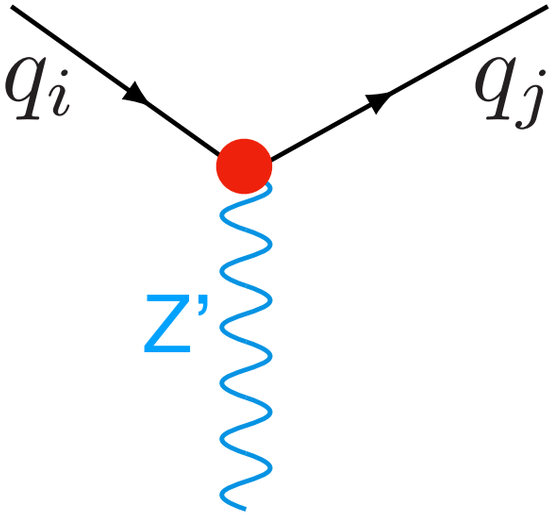

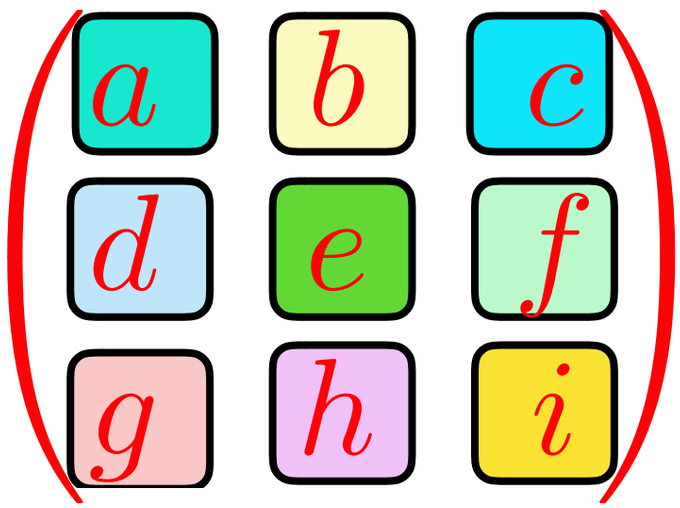

  - Standard Model (γ, Z, W) and new physics (Z',W') interference effects taken into account

The new calculation was validated against the old-PBZp finding

Full agreement

Subprocesses (5 FNS)

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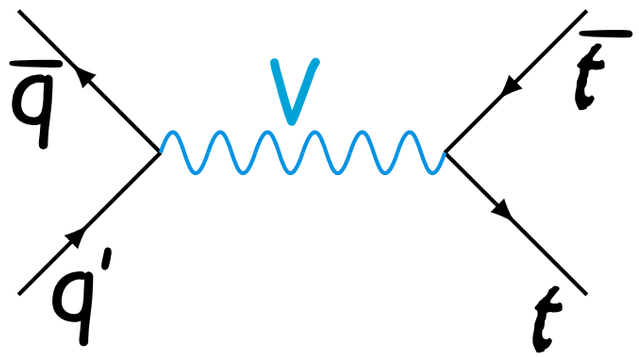
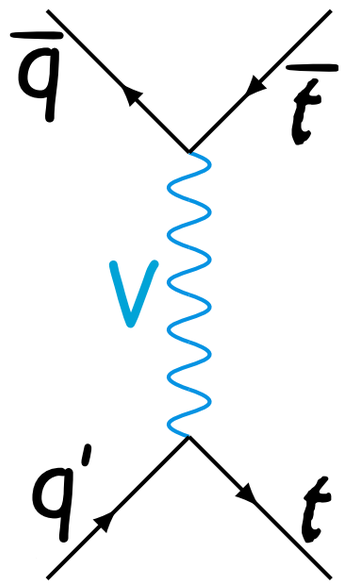
Born



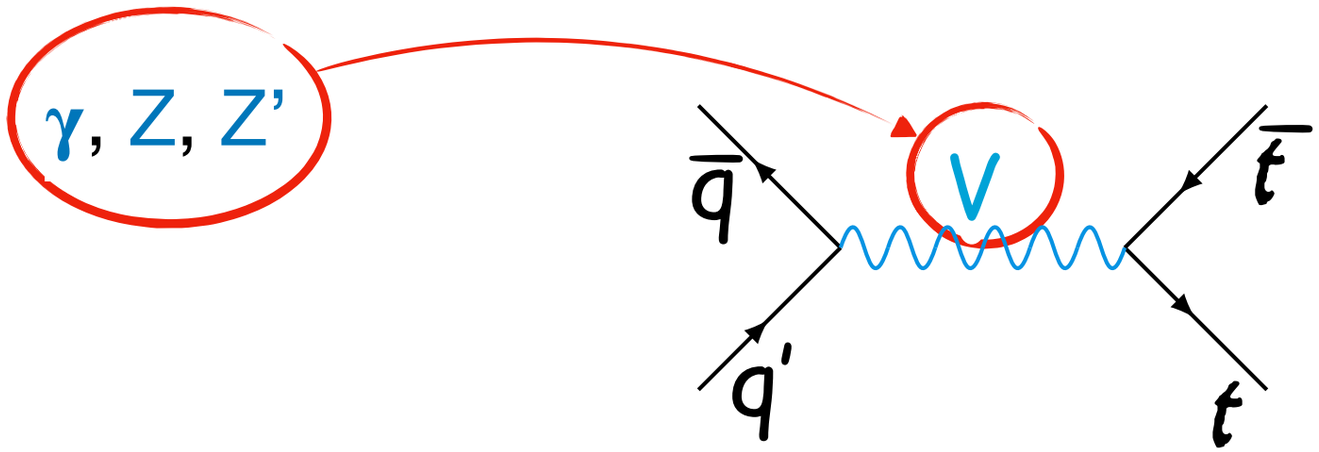
(a)



(b)

Subprocesses (5 FNS)

Born



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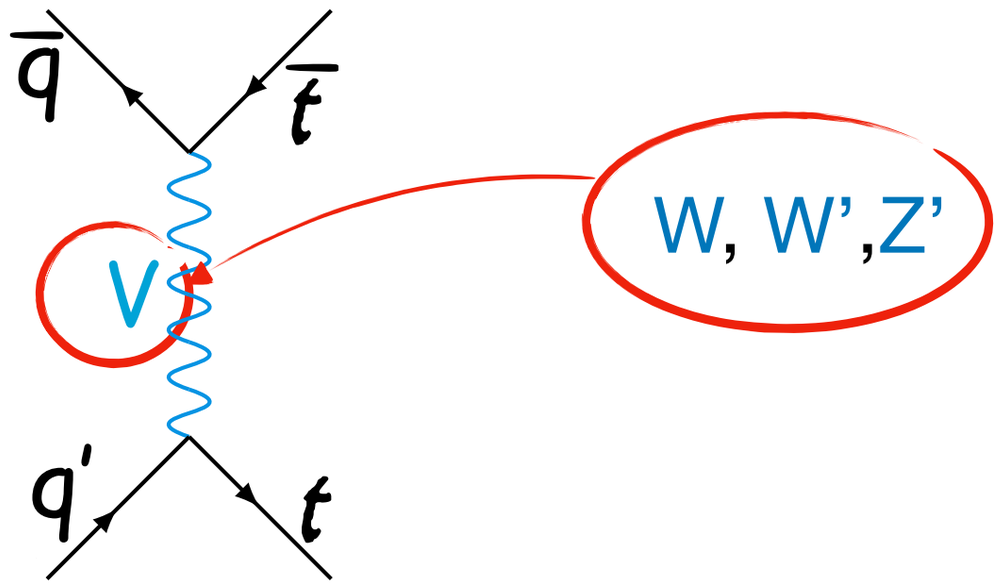

(b)

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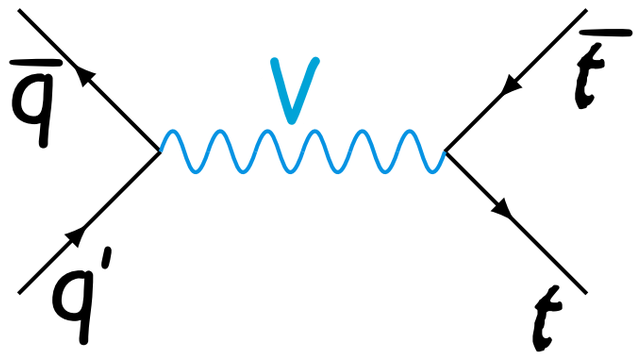
Born



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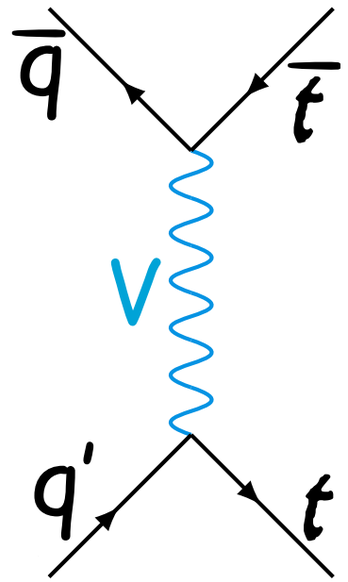
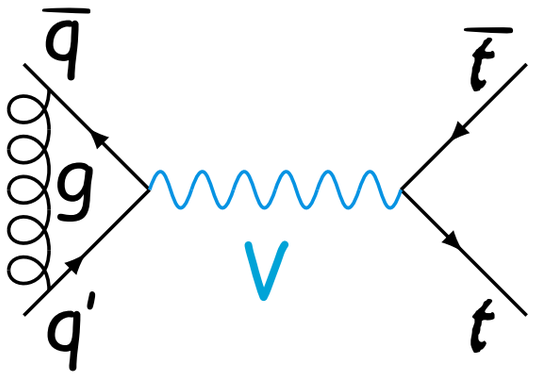


(b)

Virtual



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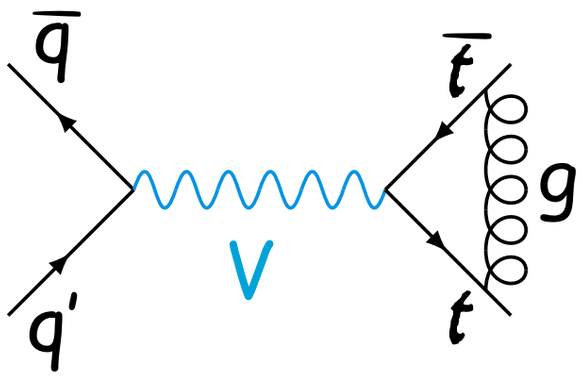

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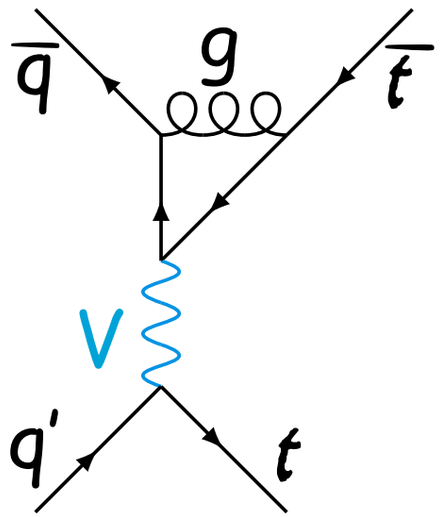

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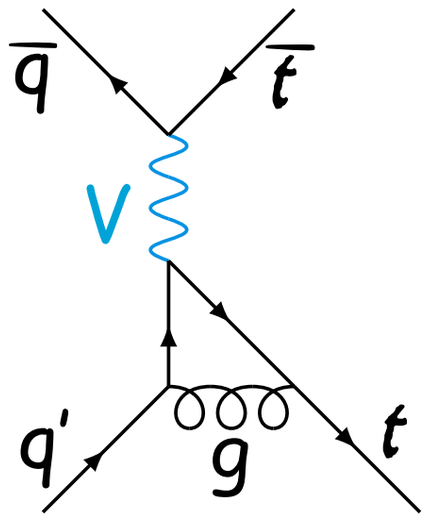
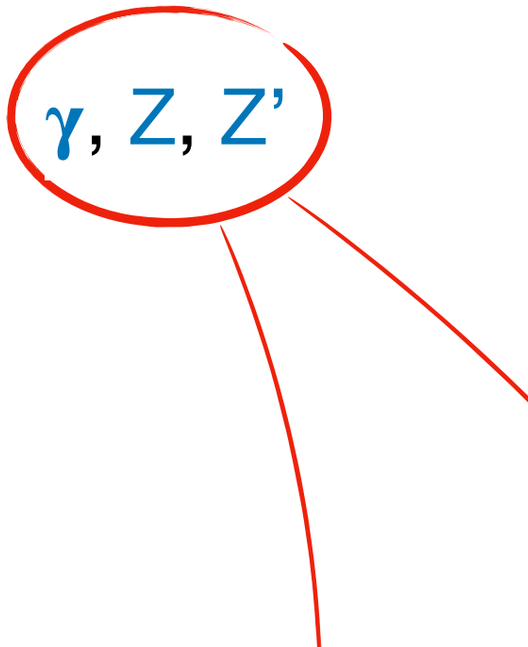
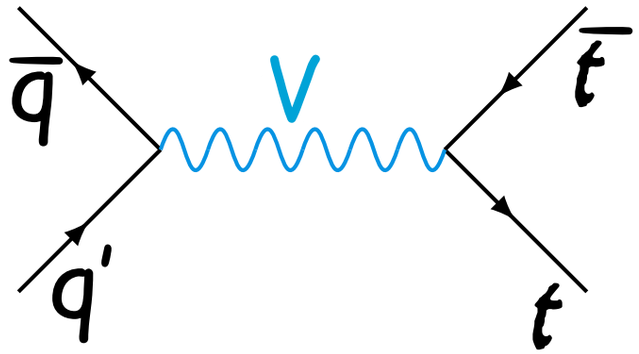


(d)

Subprocesses (5 FNS)

Born





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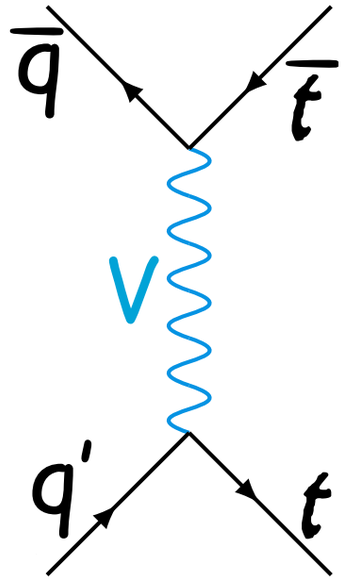

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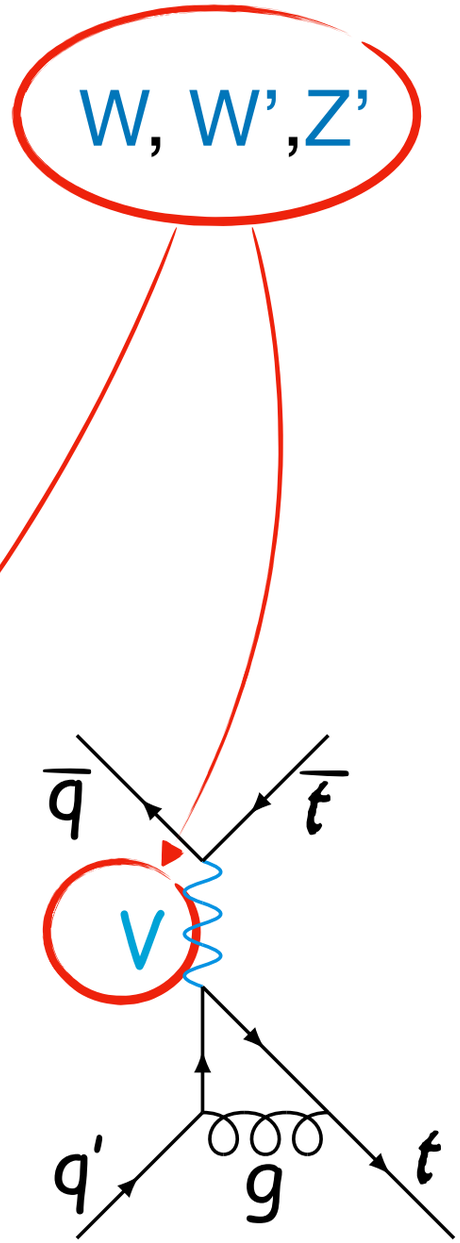
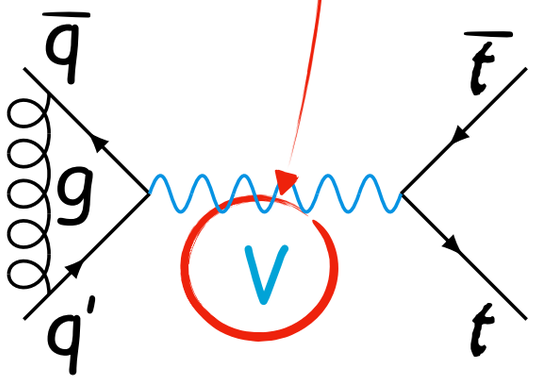
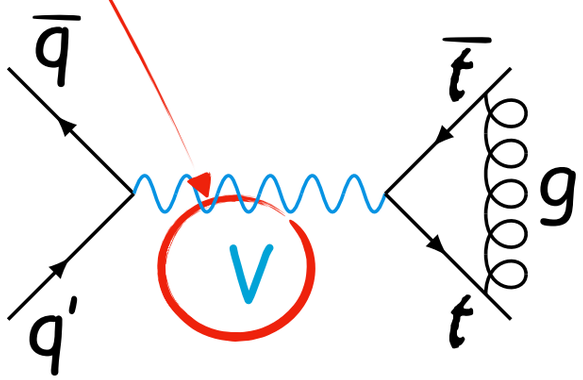


Virtual



(a)



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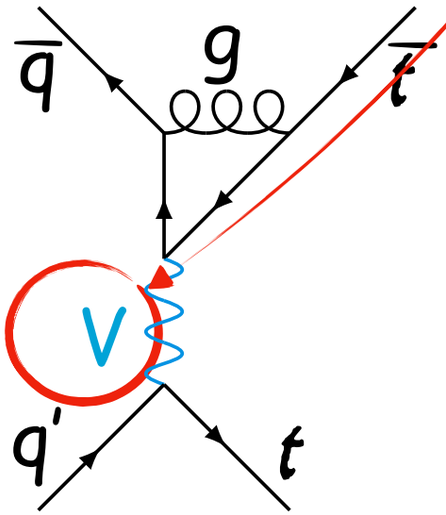
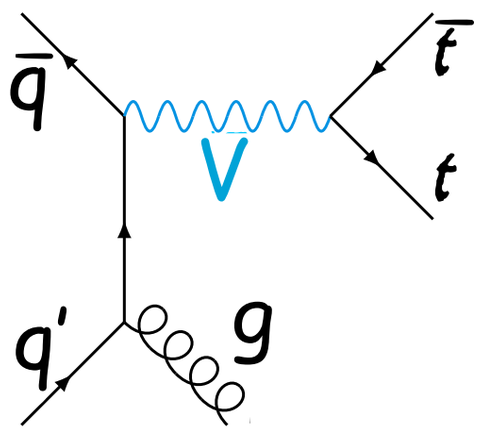


(c)

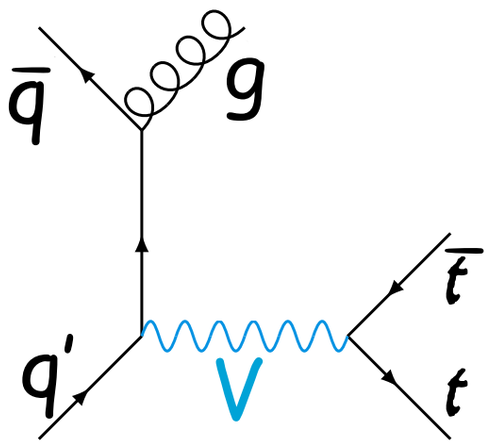
(d)

Subprocesses (5 FNS)

Real ($q' + \bar{q} \to t + \bar{t} + g$**)**



(a)



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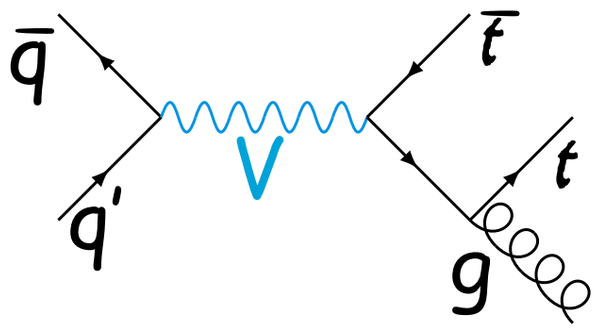

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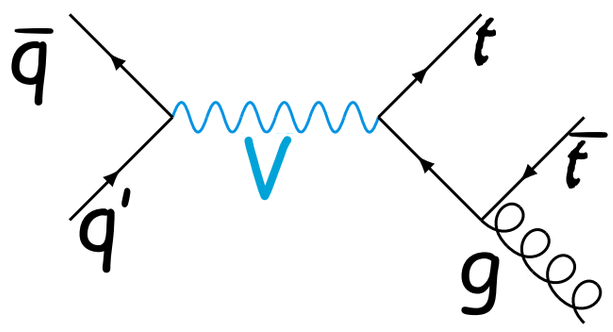
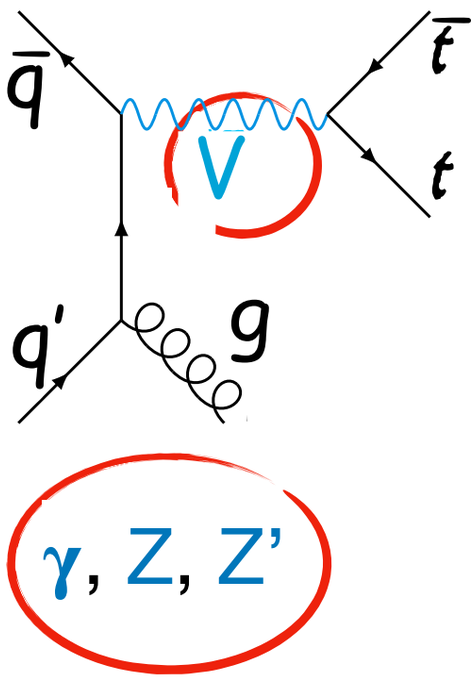


(d)

Subprocesses (5 FNS)

Real ($q' + \bar{q} \to t + \bar{t} + g$)



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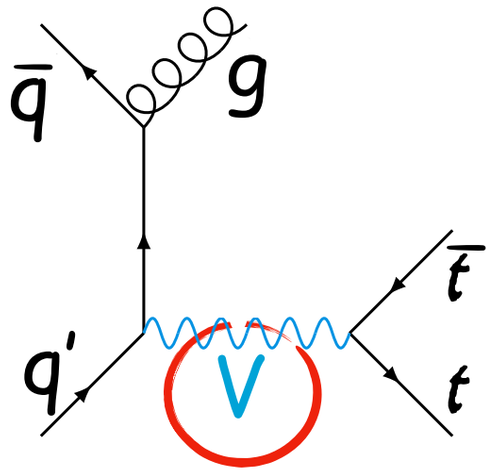

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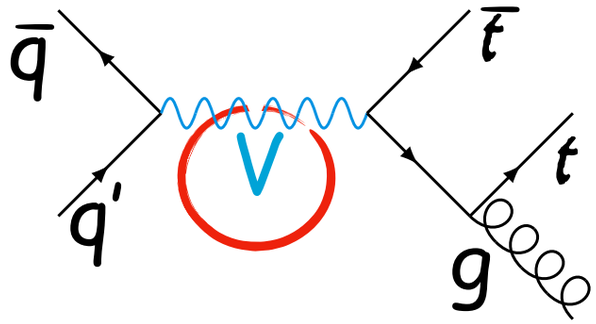

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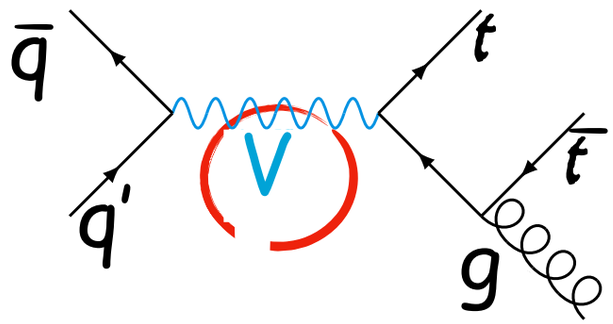
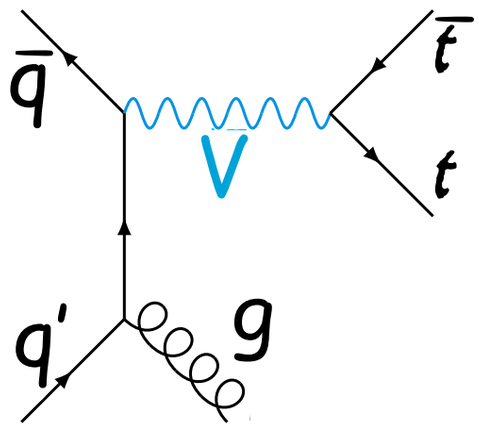
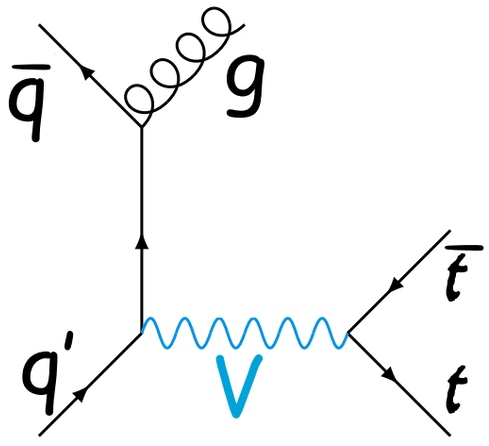


Subprocesses (5 FNS)

Real ($q' + \bar{q} \to t + \bar{t} + g$)



(a)



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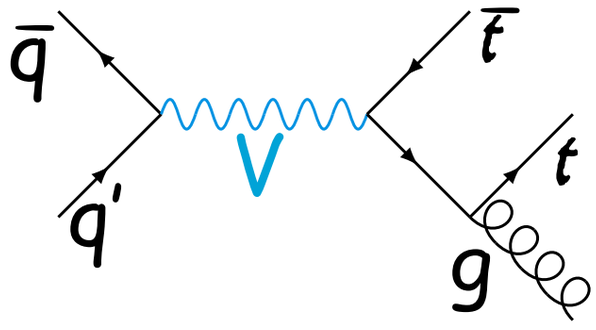

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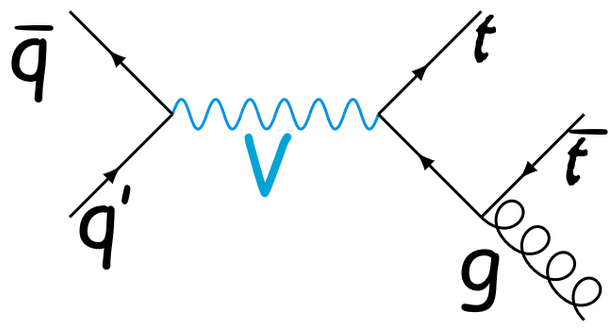

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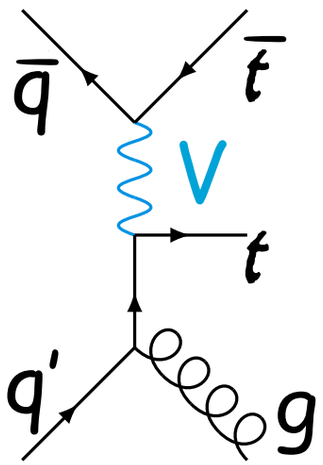

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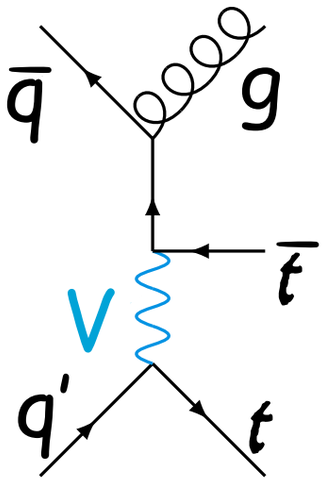

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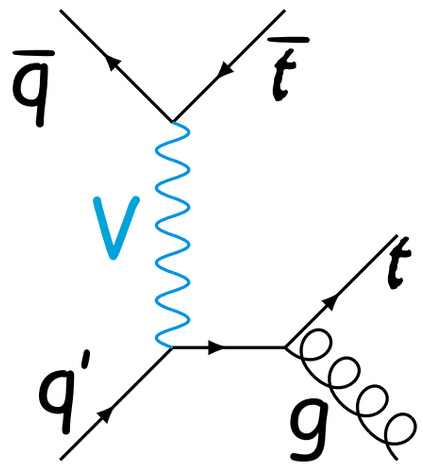
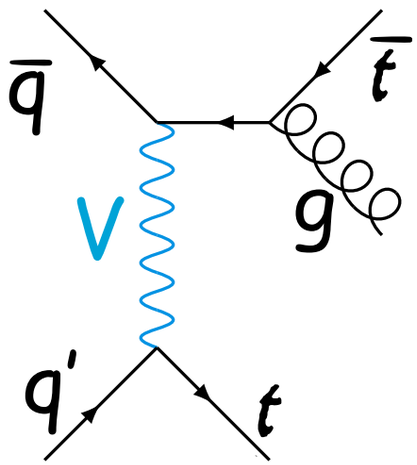


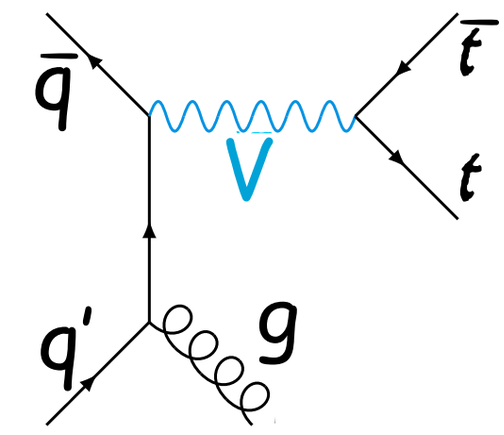
(g)

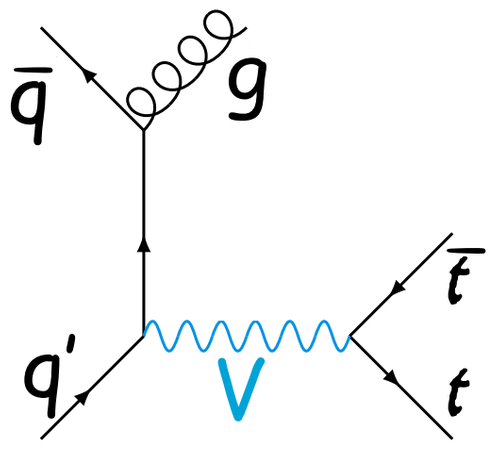


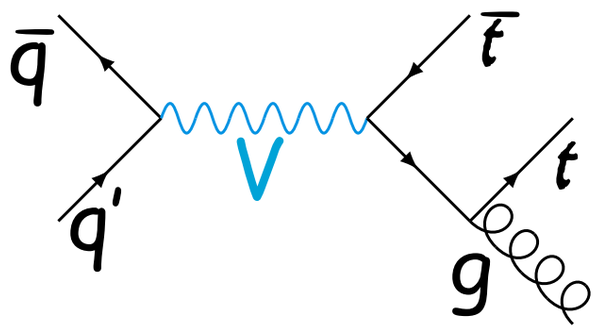
(h)

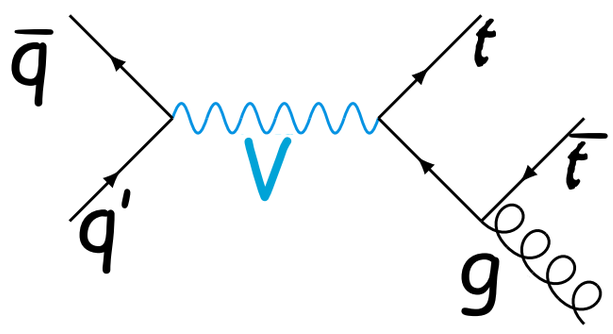
Subprocesses (5 FNS)

Real ($q' + \bar{q} \to t + \bar{t} + g$**)**







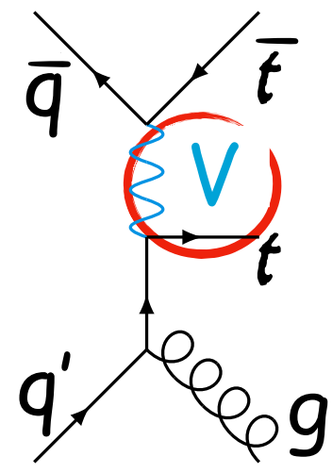


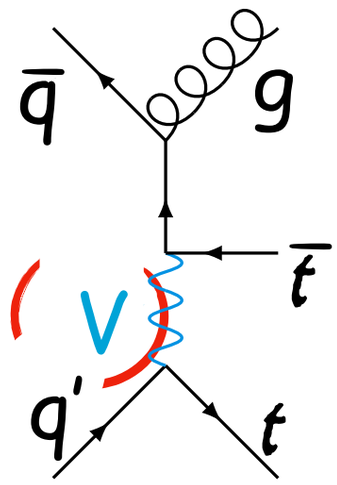
W, W',Z'

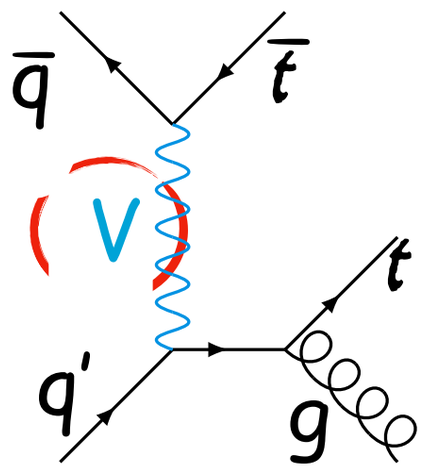
(b)

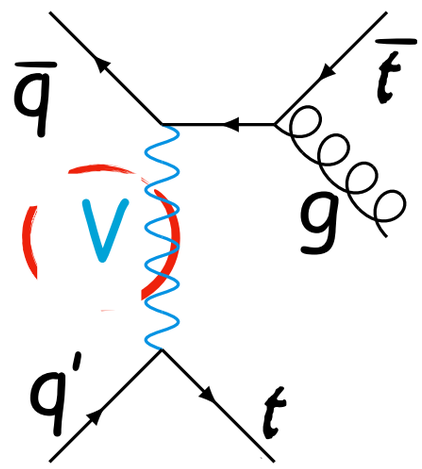
(c)

(d)









(e)

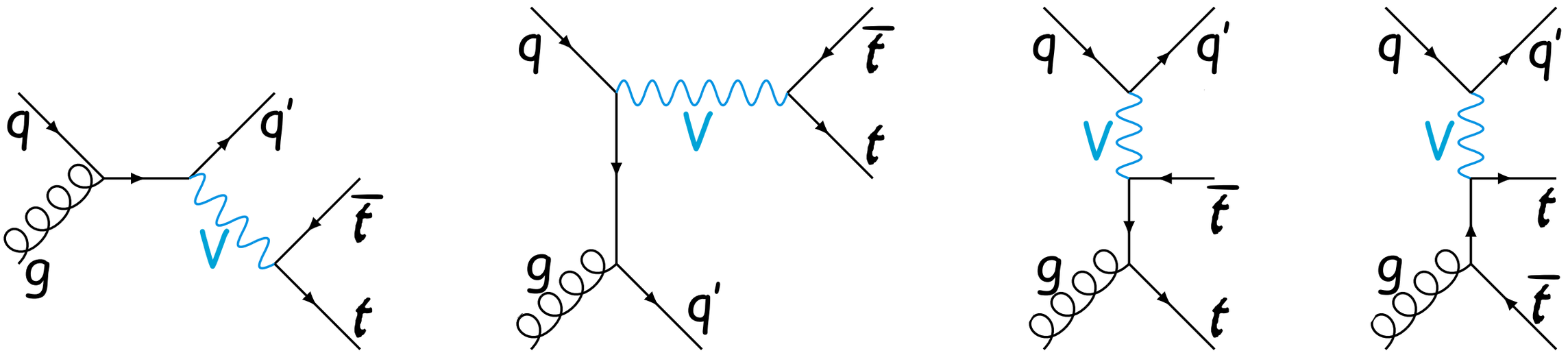
(f)

(g)

(h)

Subprocesses (5 FNS)

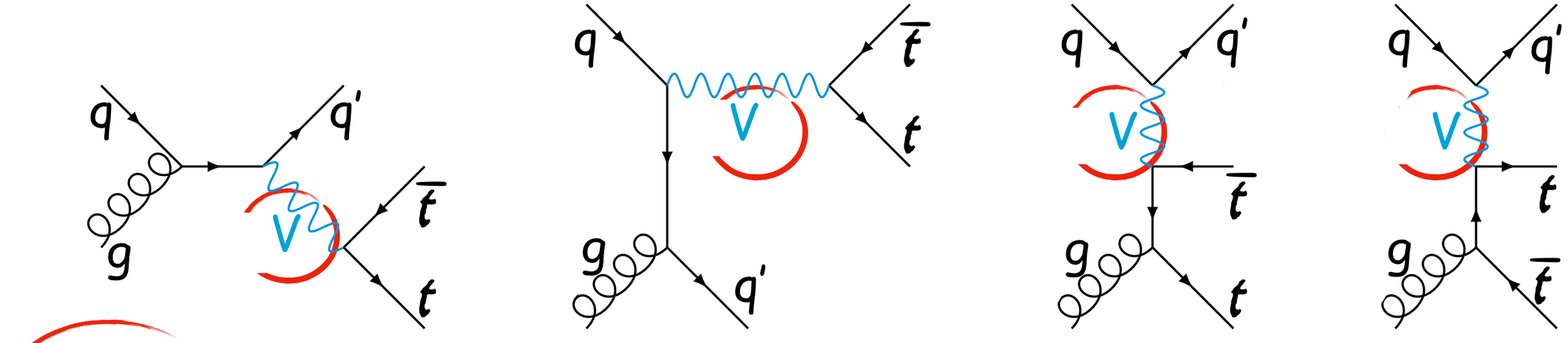
Real ($g + q \to t + \bar{t} + q'$ **)**



(a) **(b)** **(c)** **(d)**

Subprocesses (5 FNS)

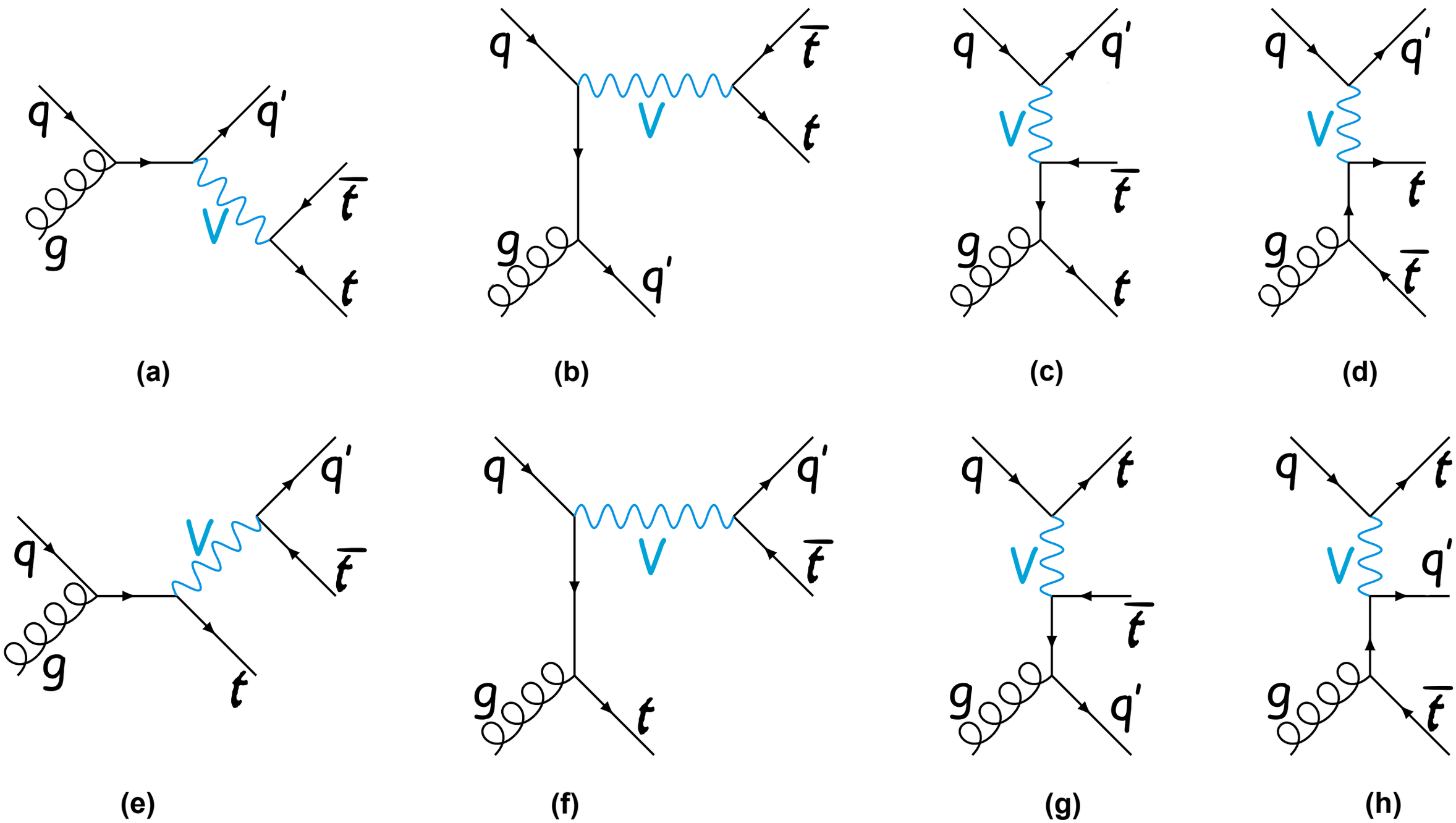
Real ($g + q \to t + \bar{t} + q'$ **)**



γ, Z, Z’ a) (b) (c) (d)

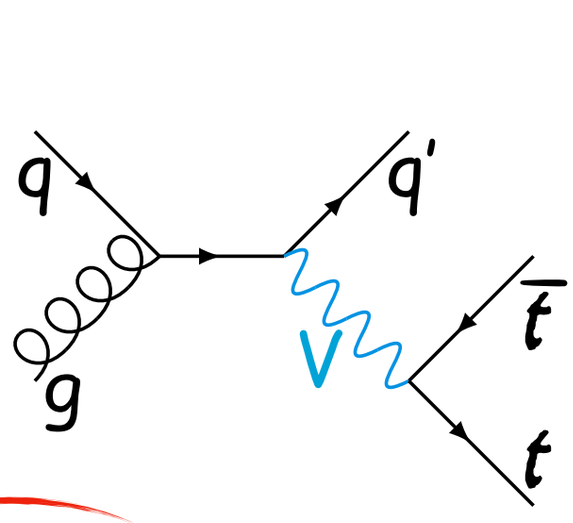
Subprocesses (5 FNS)

Real ($g + q \to t + \bar{t} + q'$ **)**

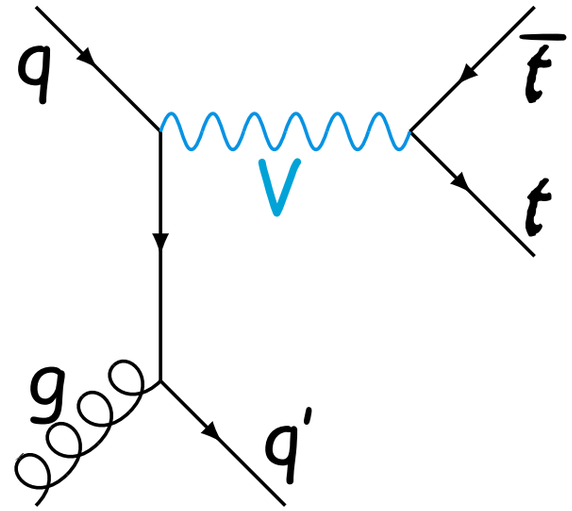


Subprocesses (5 FNS)

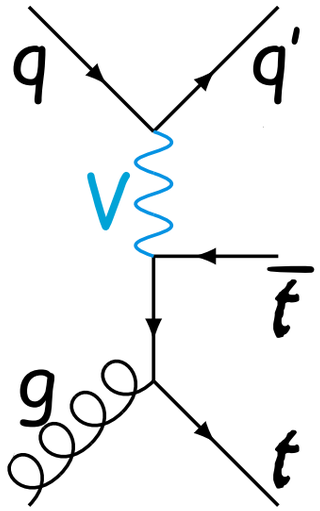
Real ($g + q \to t + \bar{t} + q'$)



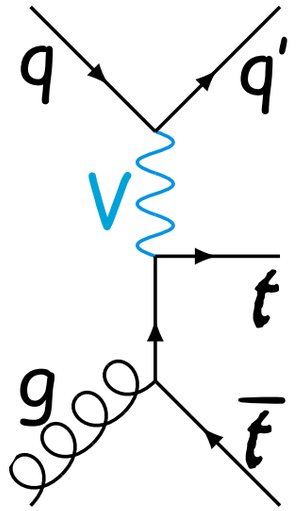
(a)



(b)

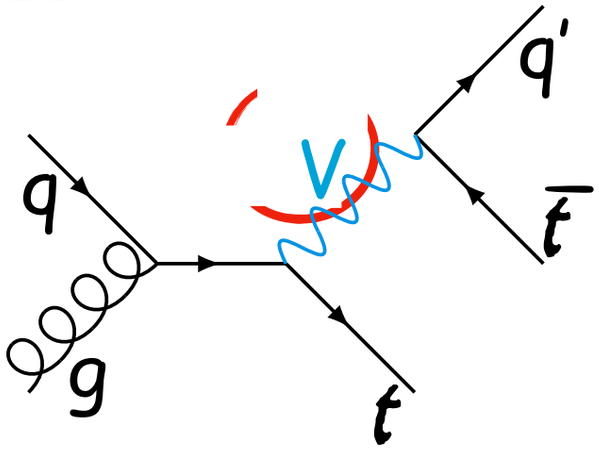


(c)

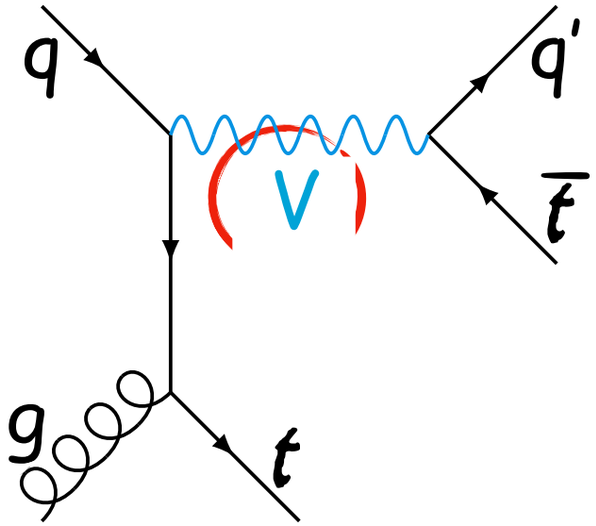


(d)

W, W',Z'



(e)



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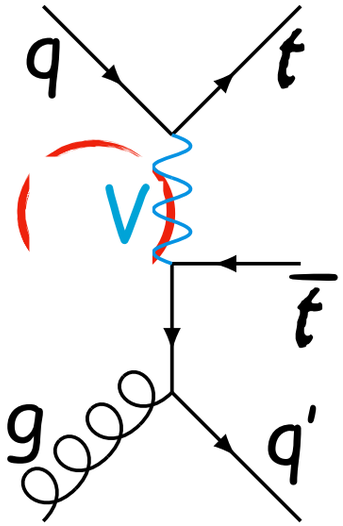
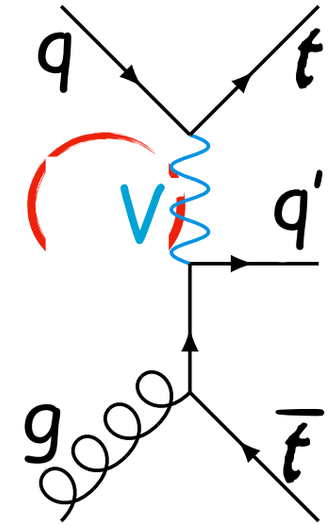


(g)



(h)

Investigation of the potential impact of the new features

Models

Sequential SM (**SSM**):

- A toy model where Z' (W') have the same couplings to fermions as the SM Z (W)
- The width of Z' (W') increases proportionally to its mass
- It is a widely used benchmark model in which LHC data are analysed

- Most stringent limits:
  - Leptonic final states:
    - $M_{Z'} \geq 5.15$ TeV assuming $\Gamma/M_{Z'} = 3\%$ [CMS-PAS-EXO-19-019]
  - Hadronic final states:
    - $M_{Z'} \geq 2.7$ TeV assuming $\Gamma/M_{Z'} = 3\%$ [arXiv:1910.08447]

- Input parameter: $M_{Z'}$ ($M_{W'}$)

Models

Leptophobic Topcolor model (**TC**) [arXiv:1112.4928]:

- New strong dynamics with $SU(3)_2$ symmetry coupling preferentially to the third generation while the original $SU(3)_1$ gauge group couples only to the 1st and 2nd generation; breaking $SU(3)_1 x SU(3)_2 \rightarrow SU(3)_C$

- To block the formation of a bottom quark condensate an additional $U(1)_2$ symmetry with associated Z' is introduced; $U(1)_1 x U(1)_2 \rightarrow U(1)_Y$

- Z' couples only to 1st and 3rd generation

- The **TC** model is frequently studied in ATLAS & CMS searches

Models

Leptophobic Topcolor model (**TC**) [arXiv:1112.4928]:

- Most stringent limits:
  - $M_{Z'} \geq 6.65$ TeV (5.25 TeV, 3.8 TeV) for $\Gamma/M_{Z'} = 30\%$ (10%, 1%) [arXiv:1810.05905v2]

- Input parameters:
  - $M_{Z'}$
  - The Ratio of the two U(1) coupling constants: $\cot \Theta_H$

Models

Third Family Hypercharge model (**TFHMeg**) [arXiv:1809.01158]:

- A minimal extension of the SM by an anomaly-free, spontaneously-broken $U(1)_F$ gauge symmetry
- Explains the neutral current B anomaly measurements and the heaviness of the third family fermions
- Z' with generation non-universal/ flavour non-diagonal couplings

- Most stringent limits:
  - $M_{Z'} \geq 1.2$ TeV* [arXiv:1904.10954]

- Input parameters:
  - $M_{Z'}$
  - The $U(1)_F$ gauge coupling: g_F
  - The mixing angle between second and third generation: θ_{sb}

* a portion of the parameter space is ruled out for $M_{Z'} < 1.5$ TeV

Numerical Results

Setup and Input

- Events in LHE format using new-**PBZp** with stable on-shell top quark

- Generation cut on the top pair invariant mass:
  - $M_{t\bar{t}} \geq 0.75 M_{Z'}$
  - Applied at the Born phase space level
  - More statistics in the interesting regions

- PYTHIA 8.2 to decay the top quark leptonically and to shower the events

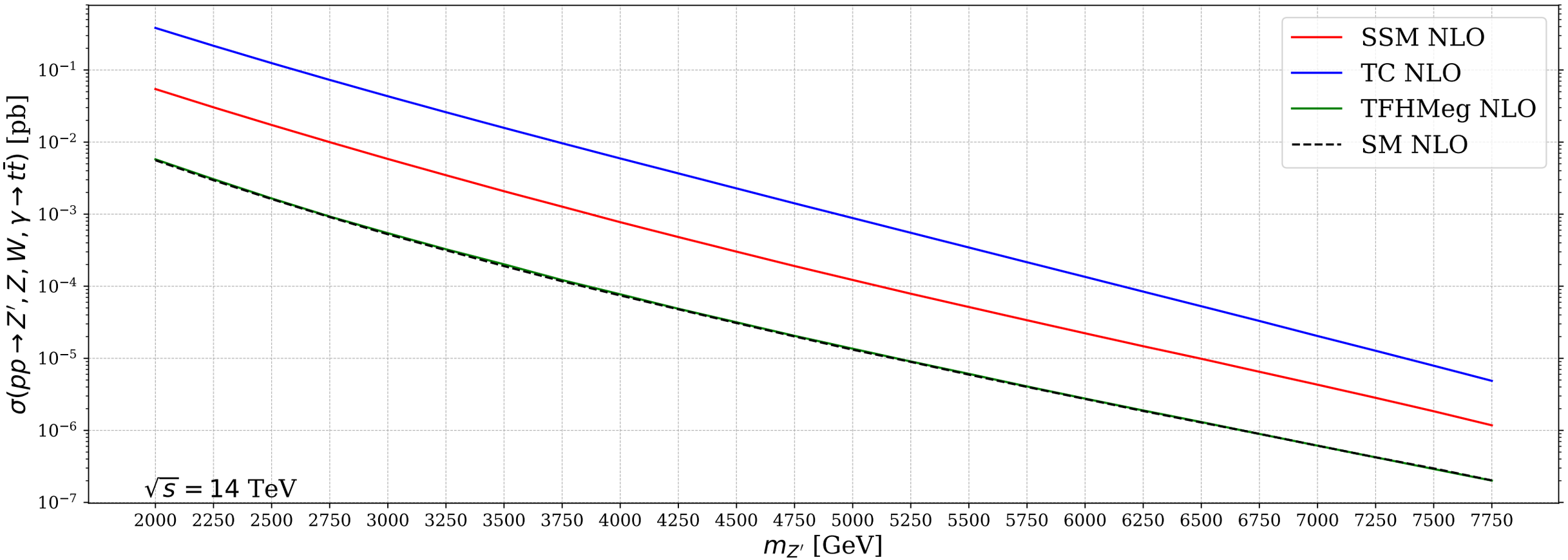
- Rivet to impose the following acceptance cuts:
  - R = 0.5 (anti-k_T), $p_T > 25$ GeV, $|\eta| < 2.5$ GeV

Setup and Input

- $\sqrt{s}$ = {14 TeV, 27 TeV, 50 TeV, 100 TeV}
- $M_{Z'}$ = {2000 GeV, …, 7750 GeV}
- M_{top} = 173.2 GeV
- **PDF** choice: NNPDF31_nlo_as_0118_luxqed
- $\mu_R^2 = \mu_F^2$ = shat

Results for Integrated Cross Sections

EW Top-quark pair production cross section at NLO at LHC14 in the SM, SSM, TC, and TFHMeg vs $M_{Z'}$



Results for Integrated Cross Sections

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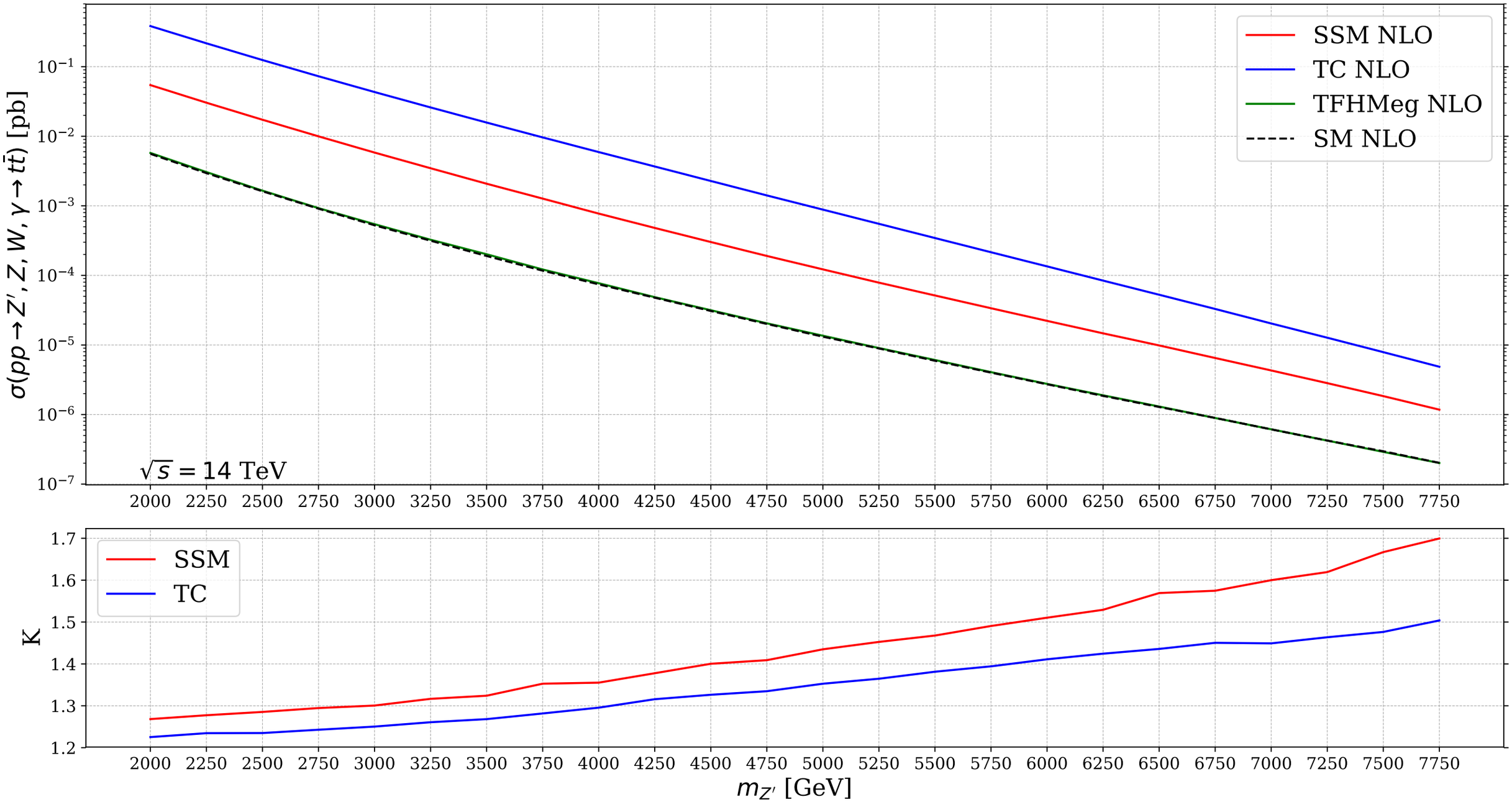

Results for Integrated Cross Sections

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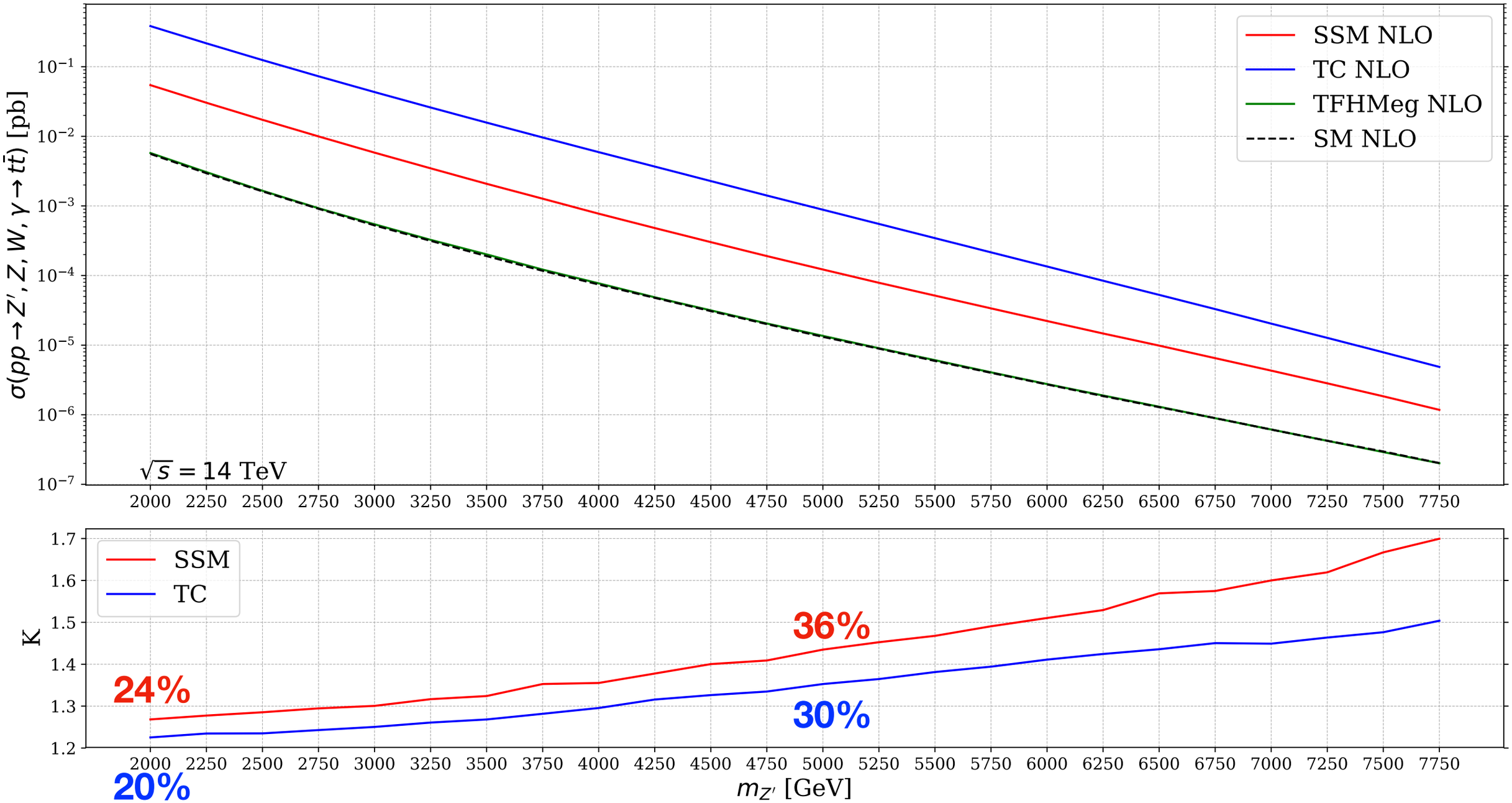
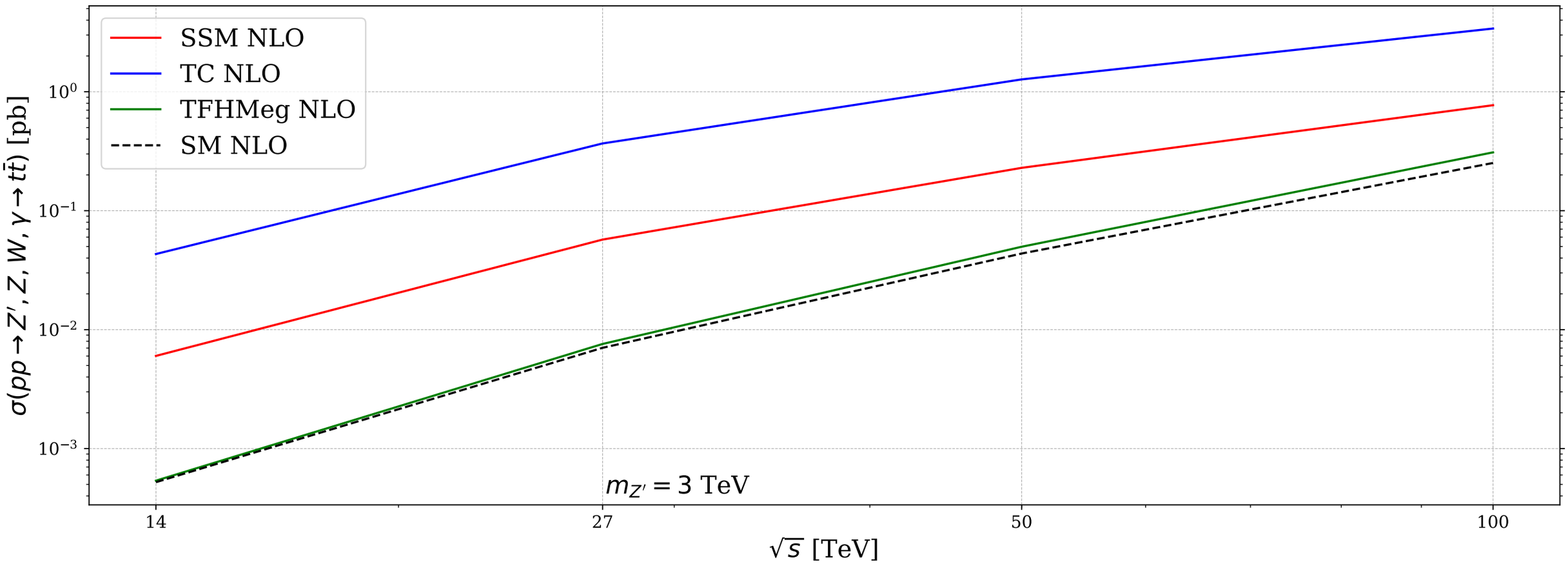


Results for Integrated Cross Sections

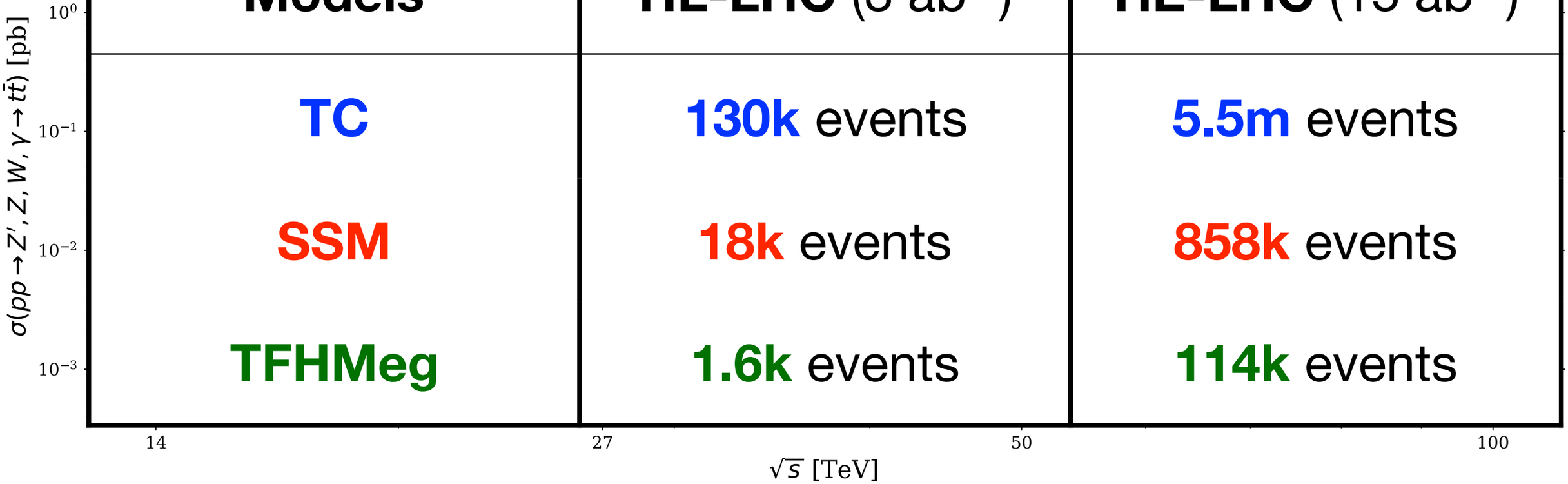
EW Top-quark pair production cross section at NLO in the SM, SSM, TC, and TFHMeg vs √s



Results for Integrated Cross Sections

EW Top-quark pair production cross section at NLO in the SM, SSM, TC, and TFHMeg vs √s

Models	HL-LHC (3 ab^{-1})	HE-LHC (15 ab^{-1})
TC	**130k** events	**5.5m** events
SSM	**18k** events	**858k** events
TFHMeg	**1.6k** events	**114k** events



Results for Integrated Cross Sections

EW Top-quark pair production cross section at NLO in the SM, SSM, TC, and TFHMeg vs √s

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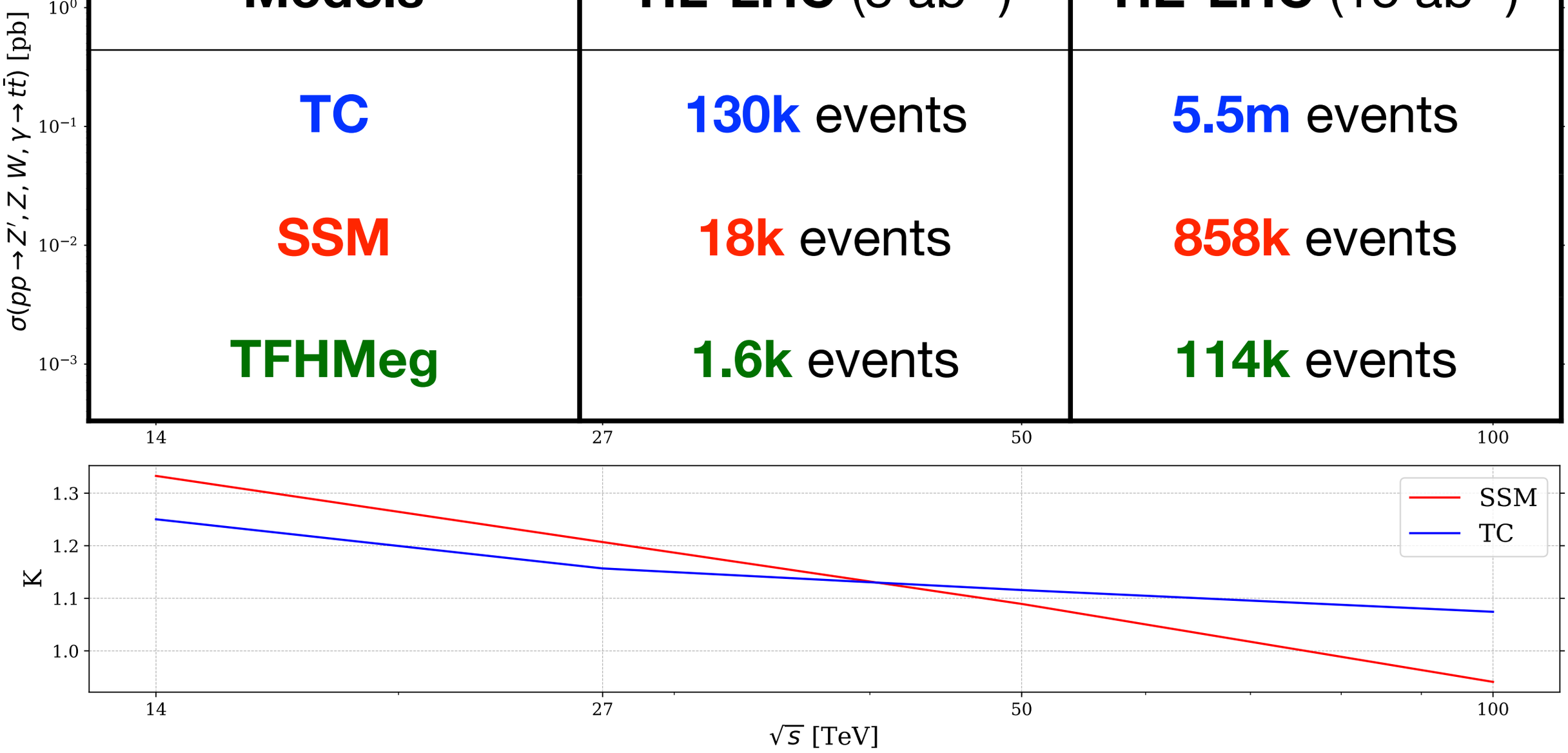
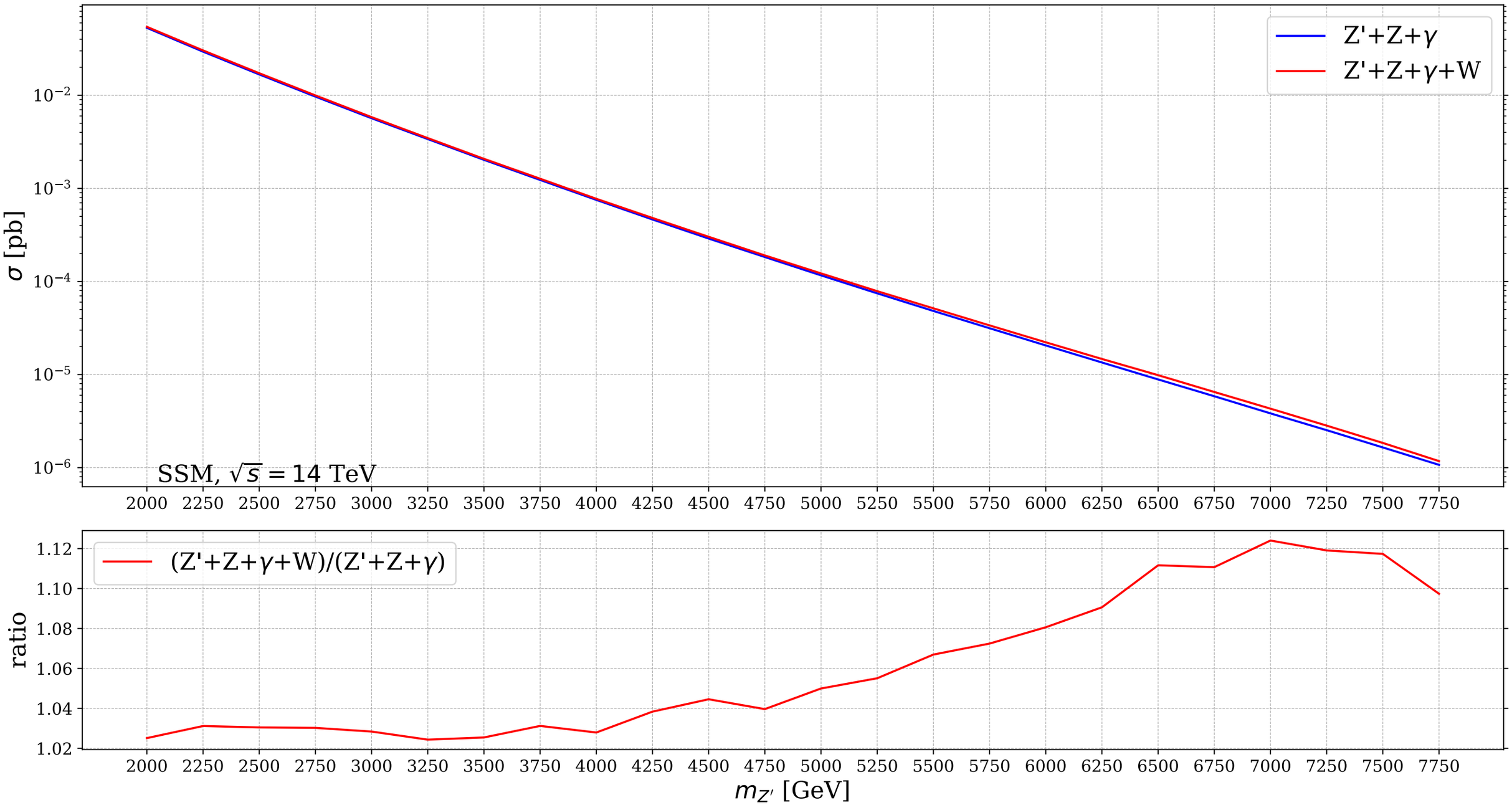


Importance of W contributions

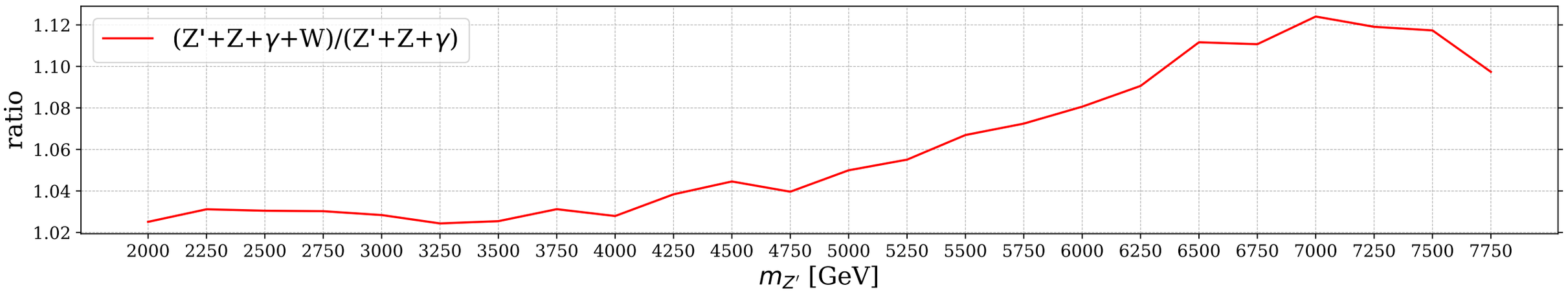
EW Top-quark pair production cross section at NLO at LHC14 in the SSM, w/o t-channel W vs $M_{Z'}$



Importance of W contributions

EW Top-quark pair production cross section at NLO at LHC14 in the SSM, w/o t-channel W vs $M_{Z'}$

$M_{Z'}$ = 5.5 TeV $\sqrt{s}$ = 14 TeV	Z' + Z + γ + W		Z' + Z + γ
No cuts	5.8 pb	60%	3.1 pb
Generation cut	10^{-4} pb	42%	6.5×10^{-5} pb
Fiducial cuts	5.1×10^{-5} pb	7%	4.8×10^{-5} pb



Summary

- Presented a complete re-calculation of NLO QCD corrections to EW top-pair production using Recola2 in the presence of Z' and W' bosons:
  - Z' and W' with general couplings
  - t-channel W contributions are included
  - Standard Model and new physics interference effects taken into account.
  - Matched to PS (NLO+PS accuracy) within the POWHEG BOX framework

- Showed numerical results for **SSM**, **TC**, and **TFHMeg** to illustrate the new features of the code

- Paper in preparation