Electroweak top-pair production in the presence of Z' and W' bosons at NLO QCD+PS

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based on:
R. Bonciani, T. Jezo, M. Klasen, D. Lamprea, F. Lyonnet, IS, arXiv: 1511.08185
M. Altakach, T. Jezo. M. Klasen. J.-N. Lang, IS, arXiv: 2012.14855

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LPSC
Laboratoire de Physique Subatomique et de Cosmologie

Introduction and Overview

Motivation

- New heavy spin-1 resonances (Z',W') are predicted in a variety of models, in particular in models with an extended gauge symmetry

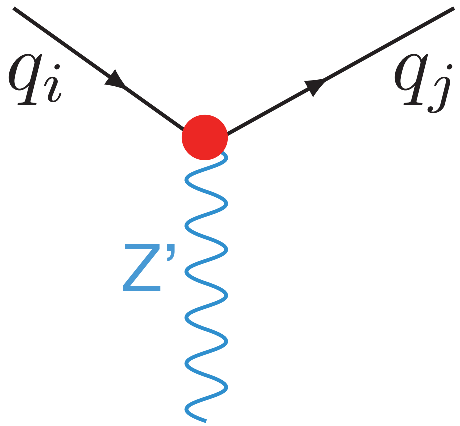
- In many cases, the Z' can decay leptonically and the strongest constraints come from searches with leptonic final states

- 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 [PRD86(2012)035005]

PBZp calculation

- In 2015 we 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 general, flavour diagonal couplings to SM fermions



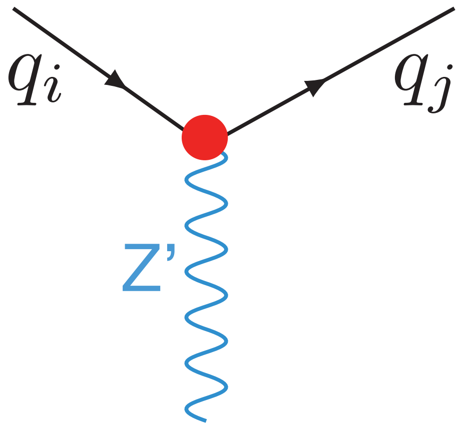
  - Results implemented in the POWHEG BOX framework

  - SM (γ,Z) and new physics (Z') interference effects taken into account

  - QED singularities consistently treated

New PBZp calculation

- We have performed a complete re-calculation [arXiv:2012.14855]
- Amplitudes generated using the Recola2 package [arXiv:1705.06053]
- New code can deal with general Z' and W' couplings to SM fermions



- The calculation now includes t-channel W and W' contributions
- As before, POWHEG implementation: **NLO+PS** matched calculation
- As before, all interference terms included; QED singularities treated

New PBZp calculation

- New calculation much more involved
- Many more diagrams
- Different amplitude generation
- Different technical details (e.g., γ_5 treatment)
- **Full agreement** with old PBZp if reduced to old setup

Top-pair hadroproduction

Top-quark pair production

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

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

- $\sigma_{2;0}$: SM QCD background
- $\sigma_{3;0}$: NLO QCD corrections to the SM background

• NLO known since the late 80ths	Nason, Dawson, Ellis ’88/’89 Beenakker, Kuif, van Neerven, Smith ’89 Bojak, Stratmann ’03: polarized case
• NLO predictions for heavy quark correlations	Mangano, Nason, Ridolfi ’92
• Spin correlations between t and tbar	Bernreuther, Brandenburg, Si, Uwer, ’01/’04
• NNLO calculation completed	Czakon, Mitov ’13: σ_{tot} Czakon, Mitov ’14: distributions

Top-quark pair production

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

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

- $\sigma_{2;0}$: SM QCD background
- $\sigma_{3;0}$: NLO QCD corrections to the SM background
- $\sigma_{2;1}$: EW corrections to the QCD background

- Gauge invariant subset, no QCDxEW interferences from box diagrams — Beenakker,Denner,Hollik,Mertig,Sack,Wackeroth '94; Kao,Wackeroth '00: 2HDM
- Rest of EW corrections including Z-gluon interferences and corrections from real and virtual photons — Kühn,Scharf,Uwer, '06; Moretti,Nolten,Ross '06; Bernreuther,Fuecker,Si '06; Hollik,Kollar '08

Top-quark pair production

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

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

Existing calculations including a Z' boson:

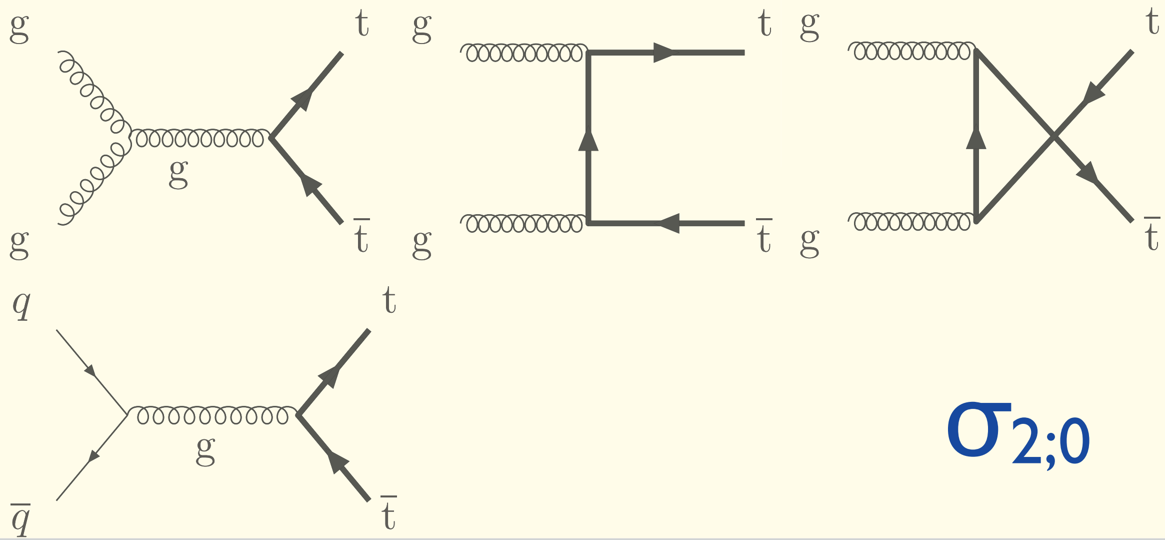
- Factorized approach (no SMxZ', no qg-channel with Z'), purely vector or axial vector or left or right couplings — Gao, C.S. Li, B.H. Li, Yuan, Zhu '10
- no SMxZ', includes: qg-channel, top-decay in NWA with spin correlations, Z' contribution to $\sigma_{2;1}$ (broad resonances) — Caola, Melnikov, Schulze '13

- **Our calculation**: includes: SMxZ' interferences, general couplings, QED contribution, POWHEG implementation, top-decay, no Z' contribution to $\sigma_{2;1}$
  - $\sigma_{0;2}$: EW top-quark pair production — arXiv:1511.08185, arXiv:2012.14855
  - $\sigma_{1;2}$: NLO QCD corrections to EW top-quark pair production
- $\sigma_{0;3}$: neglected

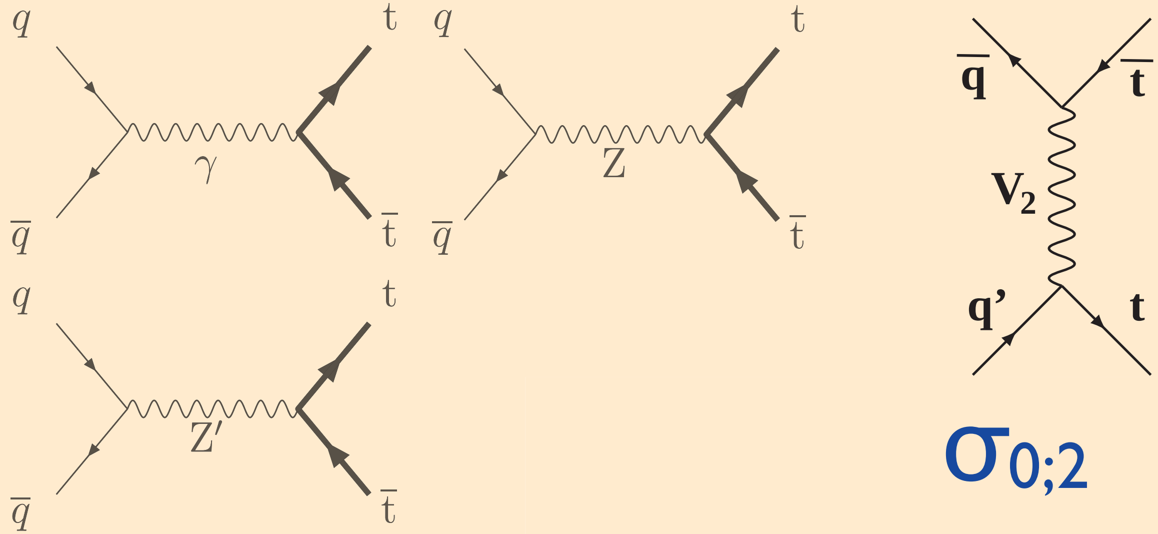
LO subprocesses: $\sigma_{2;0}$ and $\sigma_{0;2}$

- $\hat{\sigma}^{\mathrm{LO}} = \hat{\sigma}_S^{\mathrm{LO}}(\alpha_S^2) + \hat{\sigma}_W^{\mathrm{LO}}(\alpha_W^2)$

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



$\sigma_{2;0}$

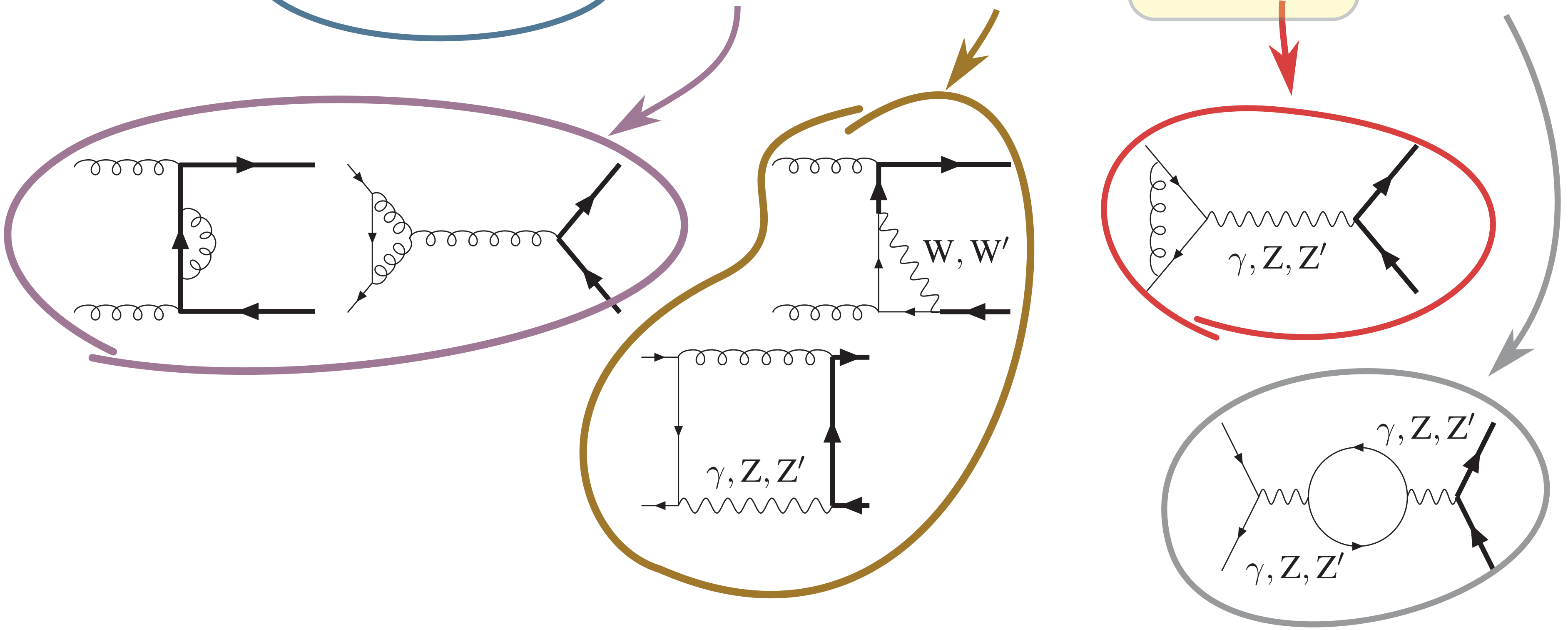


$\sigma_{0;2}$

NLO virtual

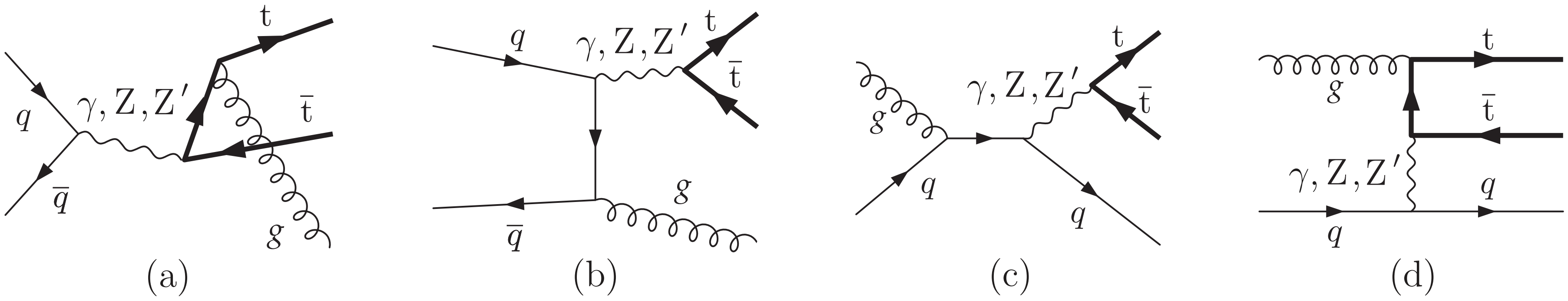
LO

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



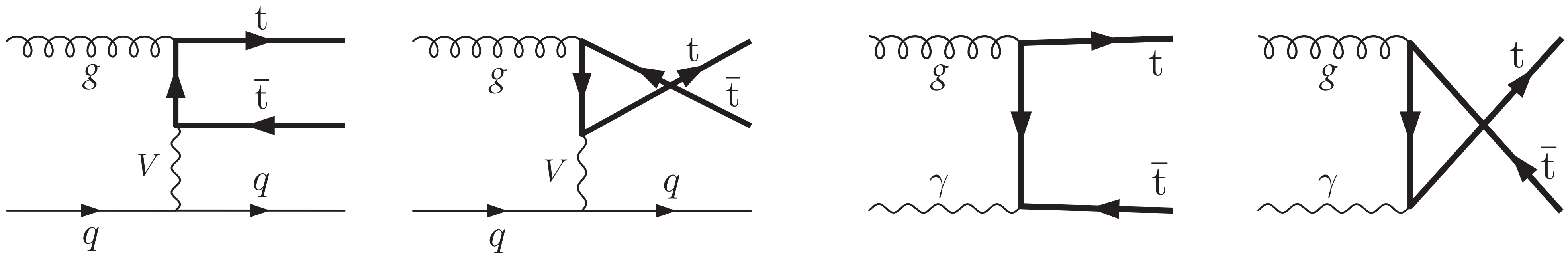
- $\mathcal{O}(\alpha_S^3)$ not affected by the presence of Z′
- we calculate $\mathcal{O}(\alpha_S\alpha_W^2)$

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

- Counting the photon PDF as $O(\alpha)$ the LO gγ-channel contributes to $\sigma_{1;2}(\alpha_s\alpha^2)$

- This channel turns out to be numerically important

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: $M_{Z'}$ ($M_{W'}$)

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 $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$

- Formation of top quark condensate generates large top mass

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

- Z' couples only to 1st and 3rd generation; no significant coupling to leptons

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

- 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]

Leptophobic Topcolor model

- Three parameters (in addition to $M_{Z'}$):
  - Ratio of the two U(1) coupling constants: $\cot \Theta_H$
  - f_1: relative strength of the Z'-coupling to right-handed up-type quarks w.r.t. to the left-handed up-type quarks
  - f_2: same for down-type quarks

- $\cot \Theta_H$ should be large to enhance the condensation of top quarks but no bottom quarks

- The LO cross sections are usually computed using
  - a fixed small Z' width (which fixes $\cot \Theta_H$): $\Gamma_{Z'} = 1.2\% \, M_{Z'}$
  - $f_1=1, f_2=0$ (maximes the fraction of Z' bosons decaying into top pairs)

Third Family Hypercharge Model [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 flavour non-diagonal couplings; now possible in PBZp
- 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}

Numerical Results

- 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:

  - >=2 charged leptons, >= 2 neutrinos, >= 2 b-jets
  - $R = 0.5$ (anti-k_T), $p_T > 25$ GeV, $|\eta| < 2.5$

Setup and Input

- $\sqrt{s}$ = {14 TeV, 27 TeV, 50 TeV, 100 TeV}
- $M_{Z'}$ = {2000 GeV, …, 8000 GeV}
- M_{top} = 172.5 GeV
- **PDF** choice: NNPDF31_nlo_as_0118_luxqed
- $\mu_R^2 = \mu_F^2$ = shat

Effect of cuts

Table 1: Total cross sections in LO for top-pair production at $\mathcal{O}(\alpha_s\alpha)$ and $\mathcal{O}(\alpha^2)$ in the SM and SSM at $\sqrt{S} = 14$ TeV. The Z'-boson mass is set to 5 TeV. For all the predictions in this table we use NLO α_S and NLO PDFs.

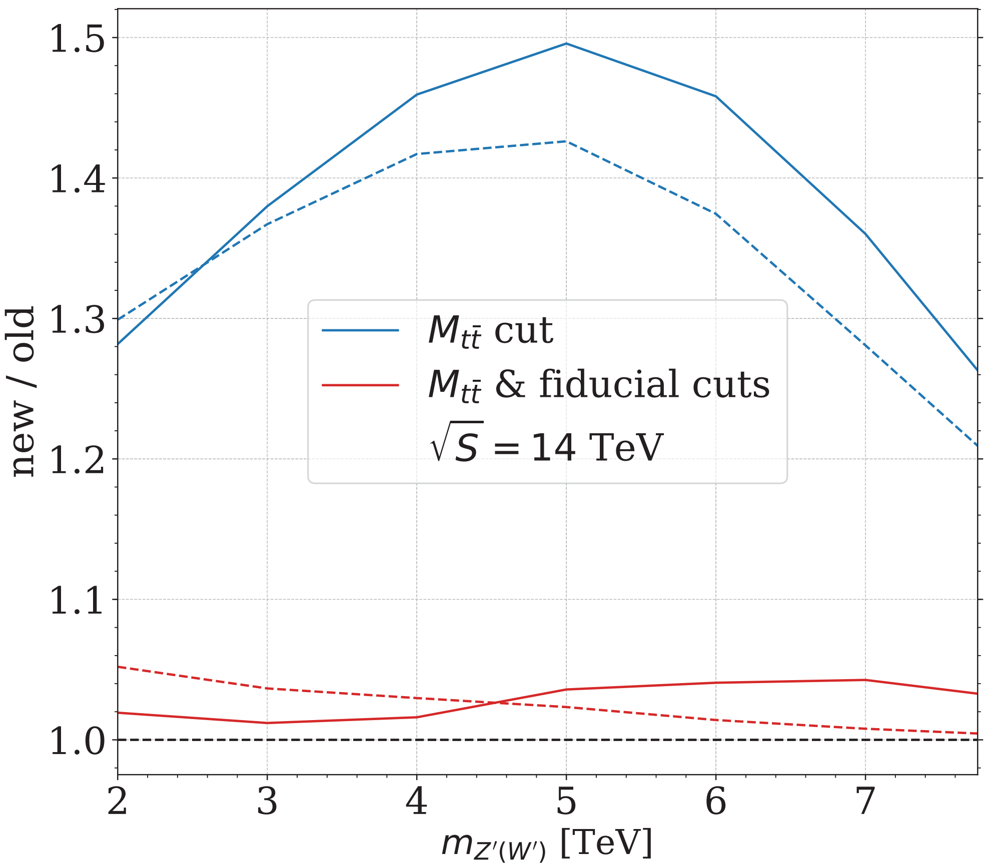
SM

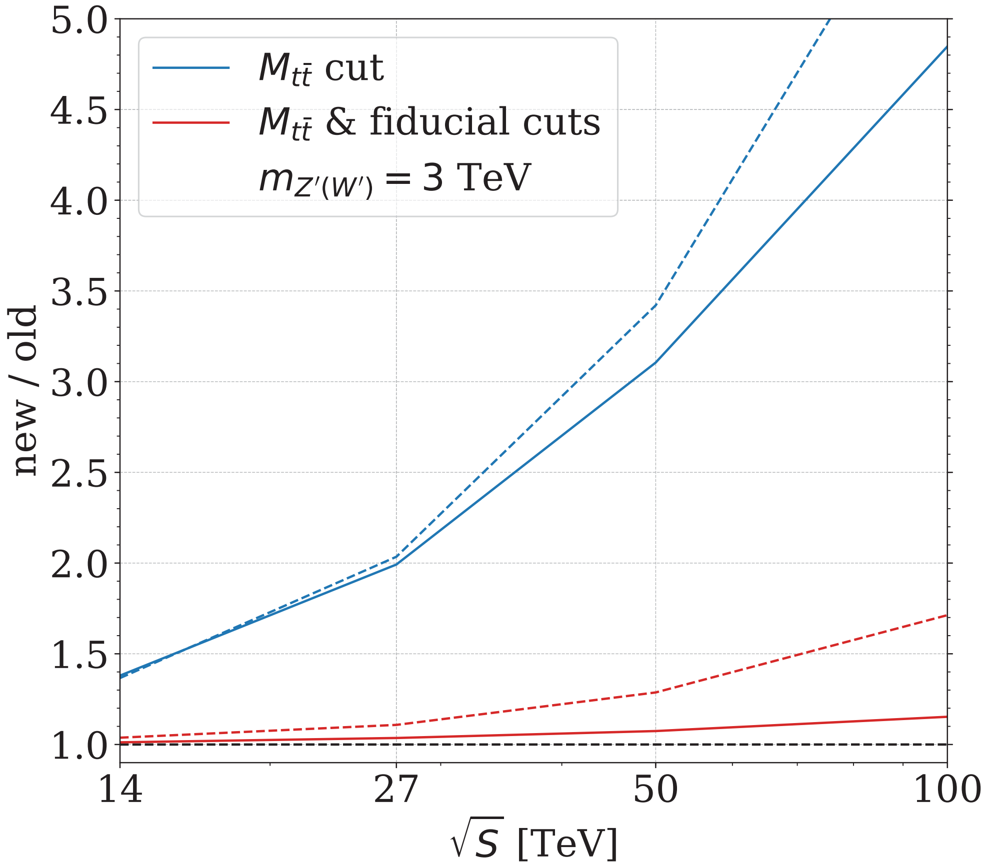
Further reduction in %

Contribution	no cuts [fb]	$m_{t\bar{t}}$ cut [fb]	$m_{t\bar{t}}$ & fiducial cuts [%]
$\gamma g + g\gamma \to t\bar{t},\ \mathcal{O}(\alpha\alpha_s)$	3700	0.0327	41.6
$q\bar{q}' \to W \to t\bar{t},\ \mathcal{O}(\alpha^2)$ + interf.	3220	0.0573	3.7
$q\bar{q} \to g/W \to t\bar{t},\ \mathcal{O}(\alpha\alpha_s)$	-1680	0.000703	37.4
$q\bar{q} \to \gamma/Z \to t\bar{t},\ \mathcal{O}(\alpha^2)$	510	0.00614	74.9
$q\bar{q} \to Z' \to t\bar{t},\ \mathcal{O}(\alpha^2)$	0.210	0.114	77.4
$q\bar{q}' \to W' \to t\bar{t},\ \mathcal{O}(\alpha^2)$ + interf.	0.0025	–	–

Signal

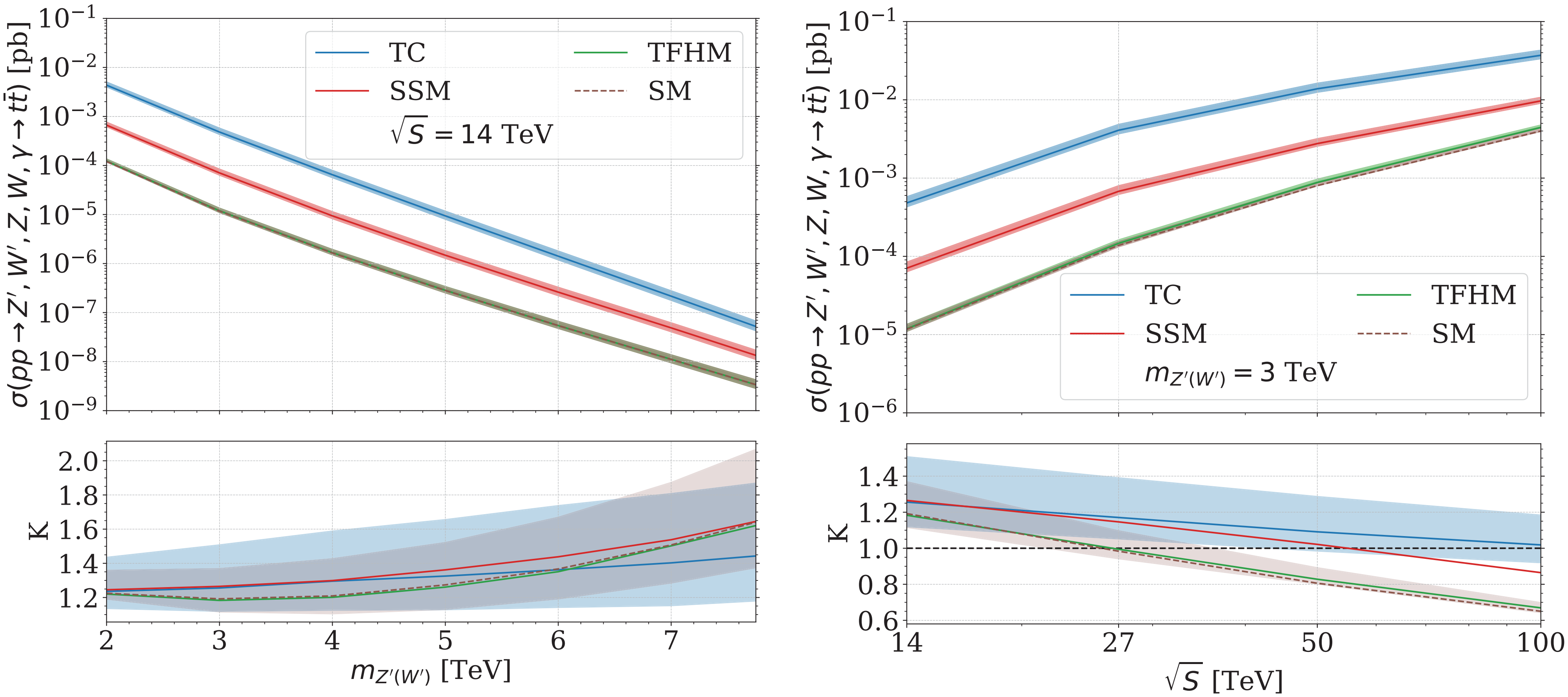
New PBZp vs Old PBZp





- **Dashed: LO+PS ; Solid: NLO+PS**
- **Fiducial cuts important to effectively suppress new contributions**
- **At 100 TeV, the ratio still exceeds 1.5 at LO+PS**

Fiducial cross sections for EW Top pair production at NLO+PS



- **At LHC14: K-factor increases with Z'-mass; whereas cross section drops**
- **As function of energy: K-factor drops; cross section increases**
- **Predictions for TFHM can barely be distinguished from SM; At 100 TeV, K=1.13**

Conclusions

- **New PBZp code available: NLO+PS**
- **New t-channel** contributions in PBZp small **after** fiducial cuts
- **K-factors and cross sections can be calculated with PBZp depending on the model, chosen parameters and cuts.**
- **TFHM not accessible in top-pair production at LHC14 Accessible at FCC100? Requires more detailed study**
- **More dedicated studies for FCC-hh possible** for models with extra gauge bosons: integrated cross sections, invariant mass distributions, transverse momentum and rapidity distributions
- **New PBZp has been implemented in CONTUR in collaboration with Jon Butterworth (ATLAS)**

Backup slides

Total cross sections for $M_{Z'}$ = 3 TeV

For LO uses the NNPDF23_lo_as0119_qed PDF set

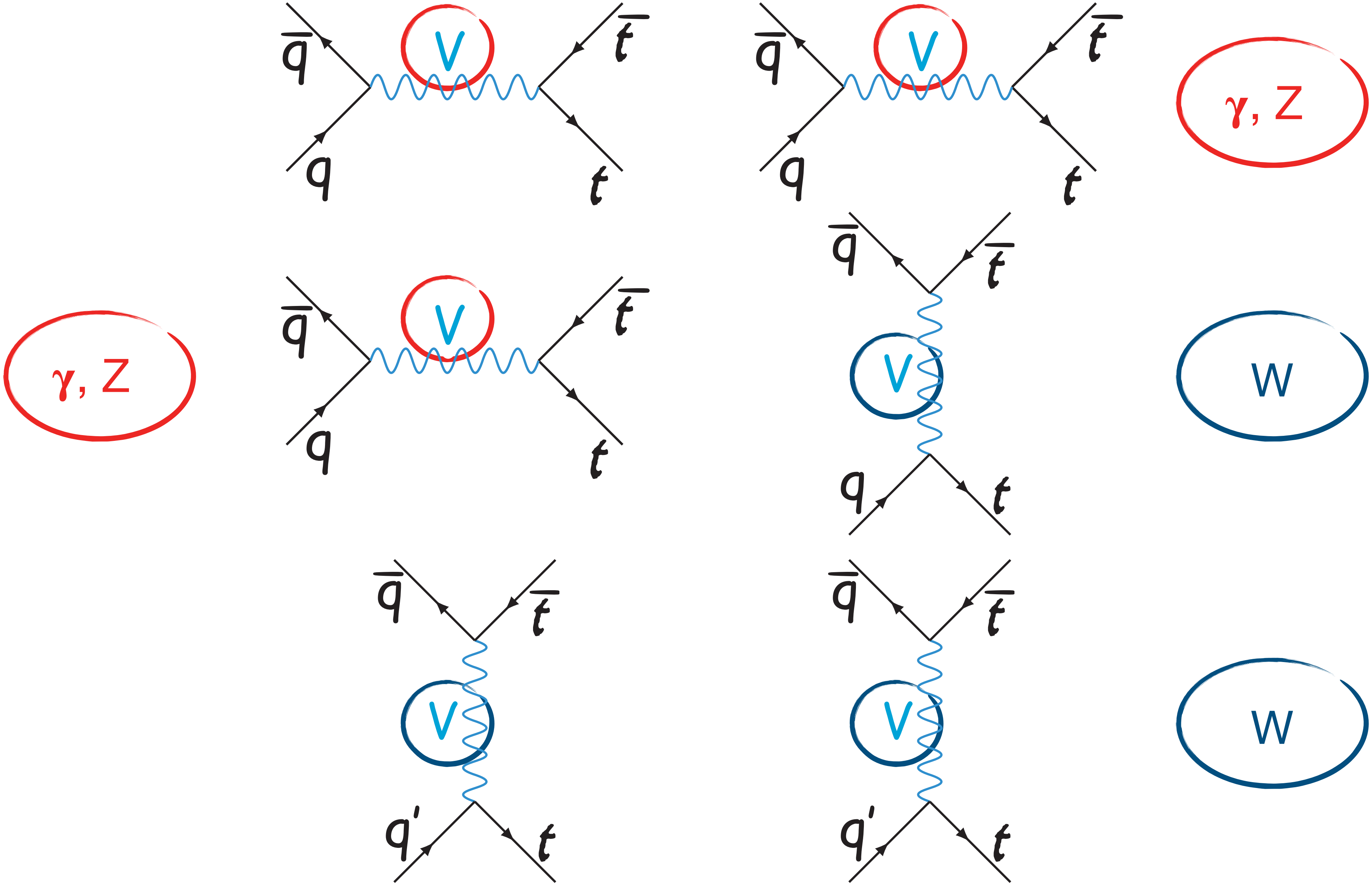
cut reduces bgd by more than three orders of mag.

cut reduces signal by only about 10%;
still signal only 3% to 8% of QCD background
→ additional cuts needed

Order	Processes	Model	σ [pb]	σ [pb] $(m_{t\bar{t}} > \frac{3}{4} m_{Z'})$
	… $gg \to t\bar{t}$		473.93(7)	0.15202(2)
	… $gg + qg \to t\bar{t} + q$		1261.0(2)	0.45255(7)
LO	$\gamma g + g\gamma \to t\bar{t}$		4.8701(8)	0.0049727(6)
LO	$\gamma g + g\gamma \to t\bar{t}$ (NLO α_s and PDFs)		5.1891(8)	0.004661(6)
LO	$q\bar{q} \to \gamma/Z \to t\bar{t}$	SM	0.36620(7)	0.00017135(3)
	… $\to \gamma/Z \to t\bar{t}$	SM	0.5794(1)	0.00017174(5)
	… $+ qg \to \gamma/Z + q \to t\bar{t} + q$	SM	4.176(2)	0.001250(6)
	… $\to Z' \to t\bar{t}$	SSM	0.0050385(8)	0.0044848(7)
	… $\to \gamma/Z/Z' \to t\bar{t}$	SSM	0.35892(7)	0.0043464(7)
	… $\to \gamma/Z/Z' \to t\bar{t}$	SSM	0.5676(1)	0.005155(3)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	SSM	4.172(2)	0.007456(9)
LO	$q\bar{q} \to Z' \to t\bar{t}$	TC	0.012175(2)	0.011647(2)
LO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.38647(7)	0.011984(2)
NLO	$q\bar{q} \to \gamma/Z/Z' \to t\bar{t}$	TC	0.6081(2)	0.01468(1)
NLO	$q\bar{q} + qg \to \gamma/Z/Z' + q \to t\bar{t} + q$	TC	4.202(2)	0.01002(1)

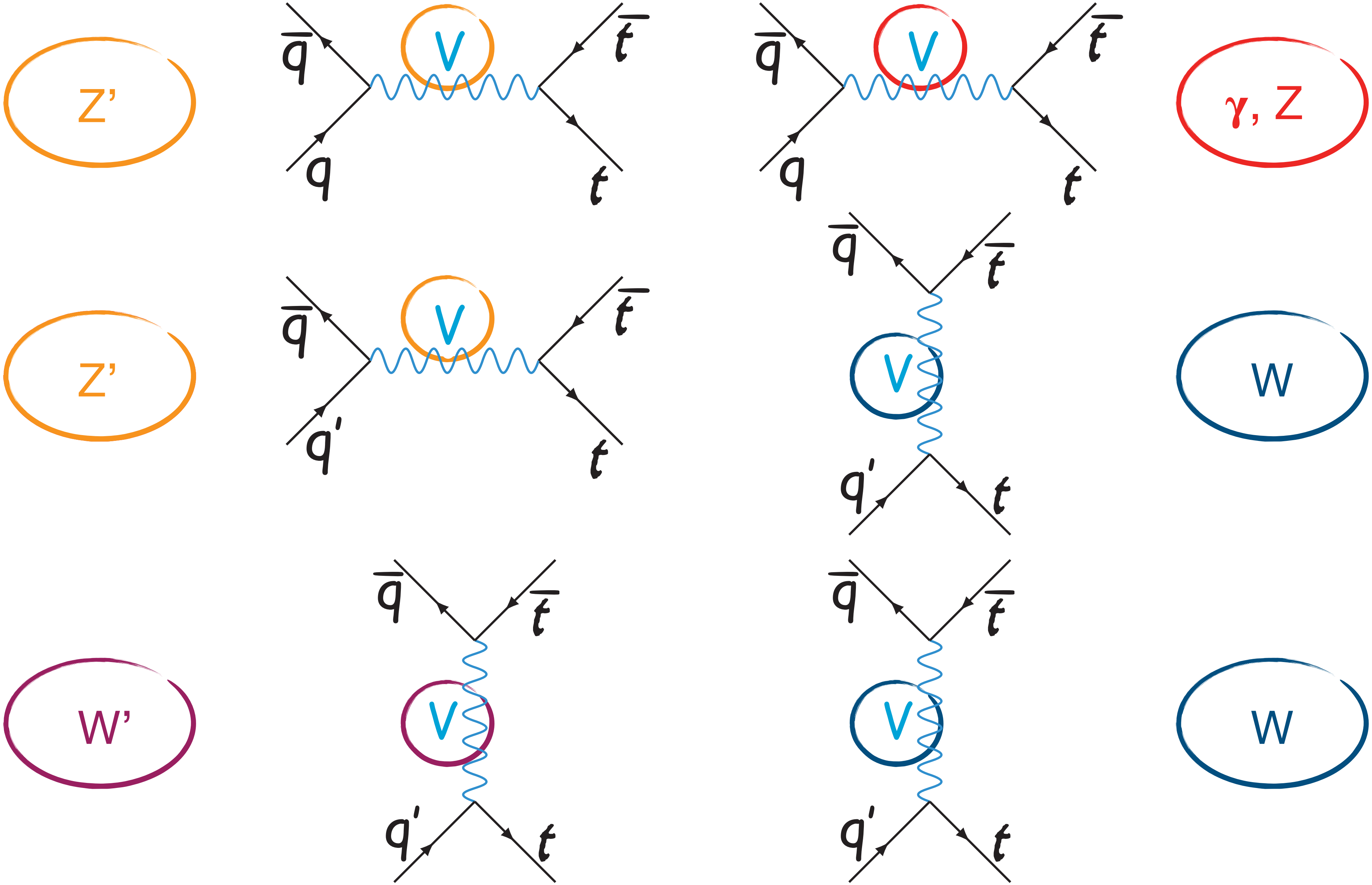
Subprocesses (5 FNS)

Born (0QCD4EW0BSM)



Subprocesses (5 FNS)

Born (0QCD4EW2BSM)



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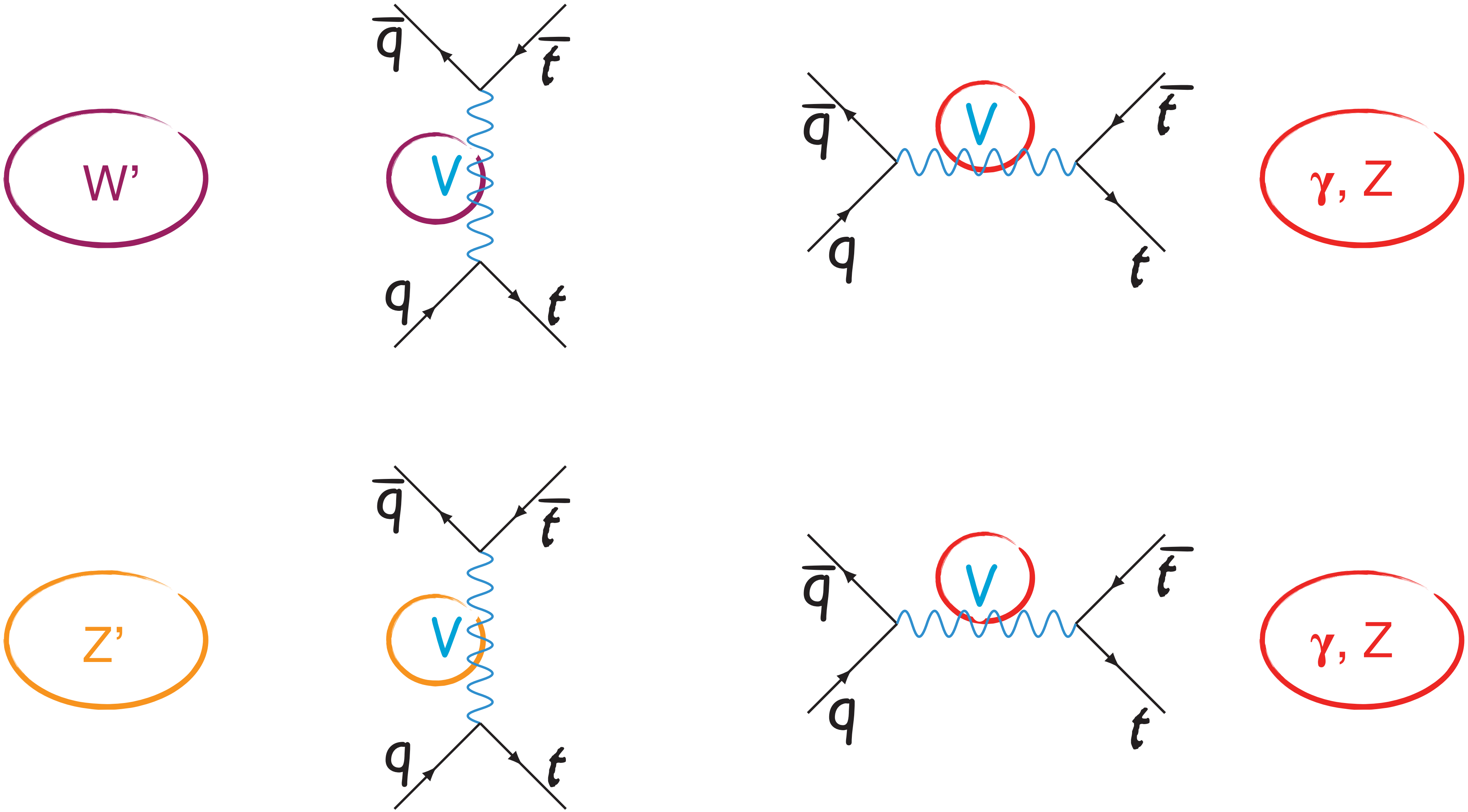

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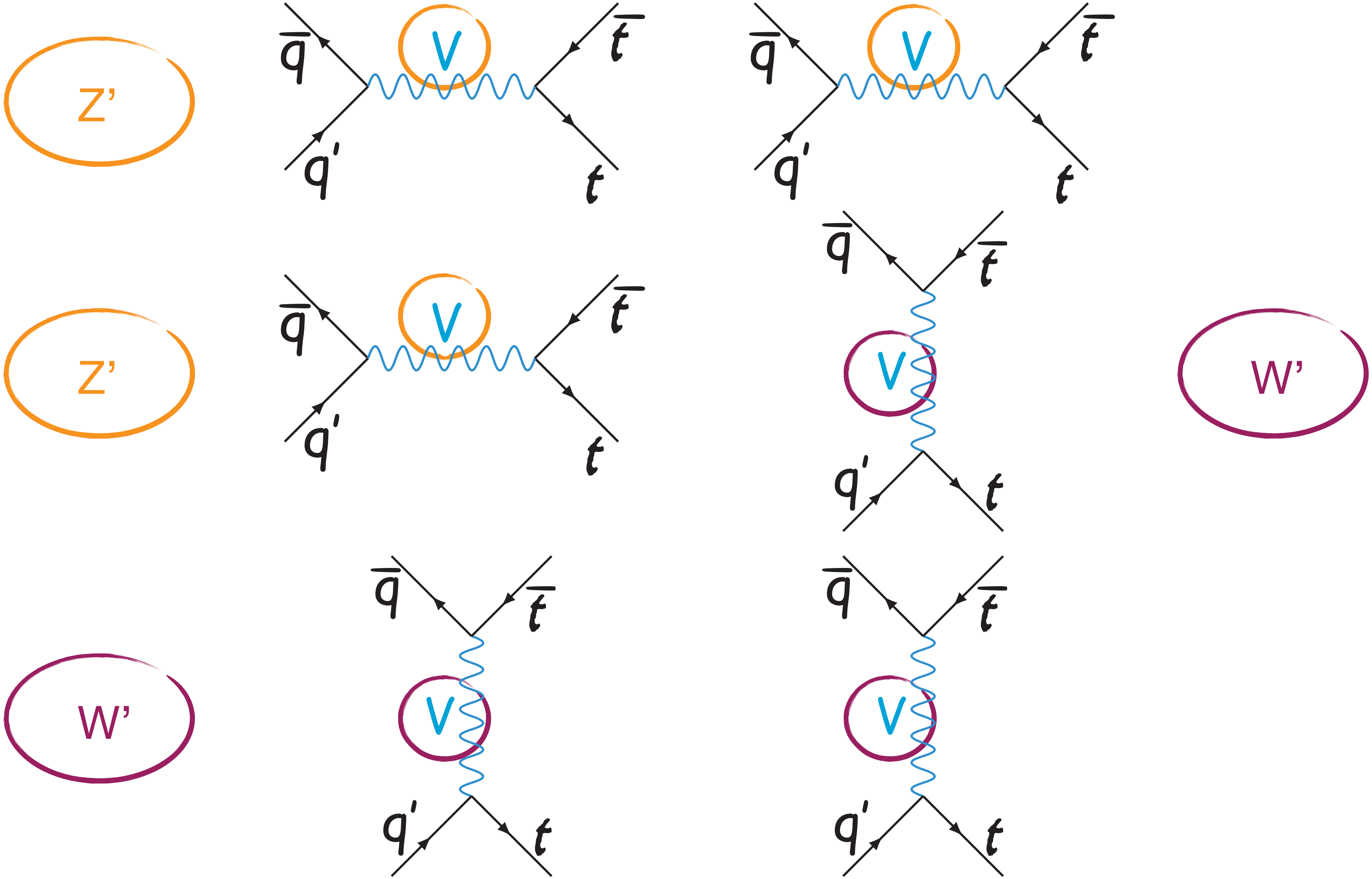

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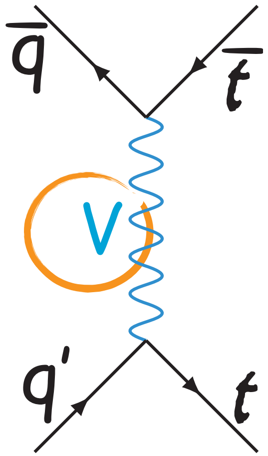
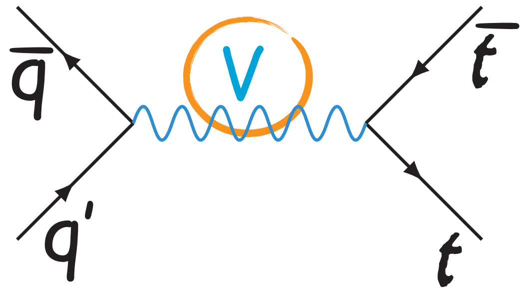
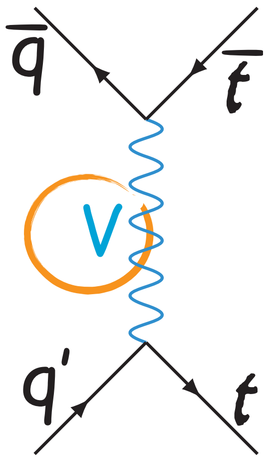
Born (0QCD4EW4BSM)

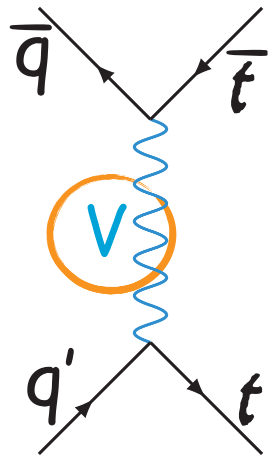
Z'





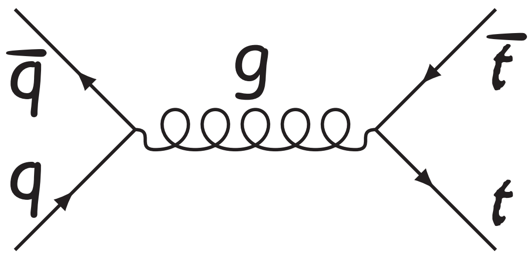
Z'

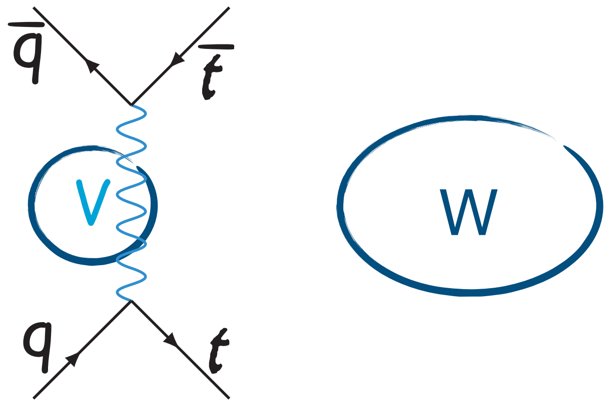




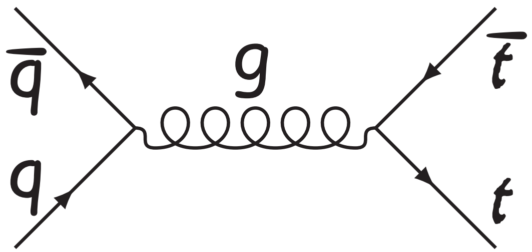
Subprocesses (5 FNS)

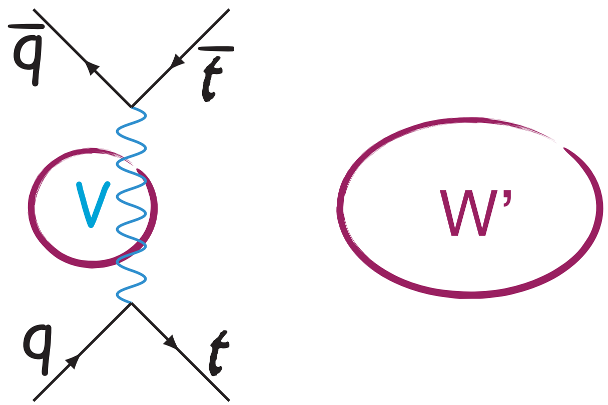
Born (2QCD2EW0BSM):

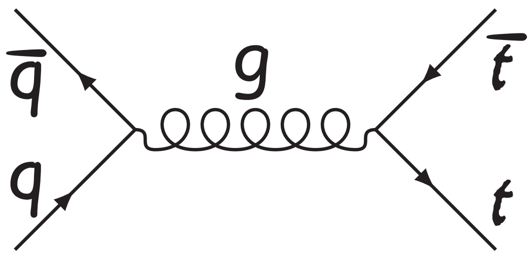


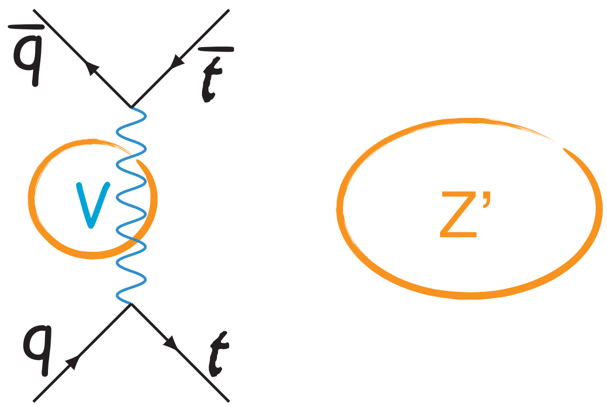


Born (2QCD2EW2BSM):



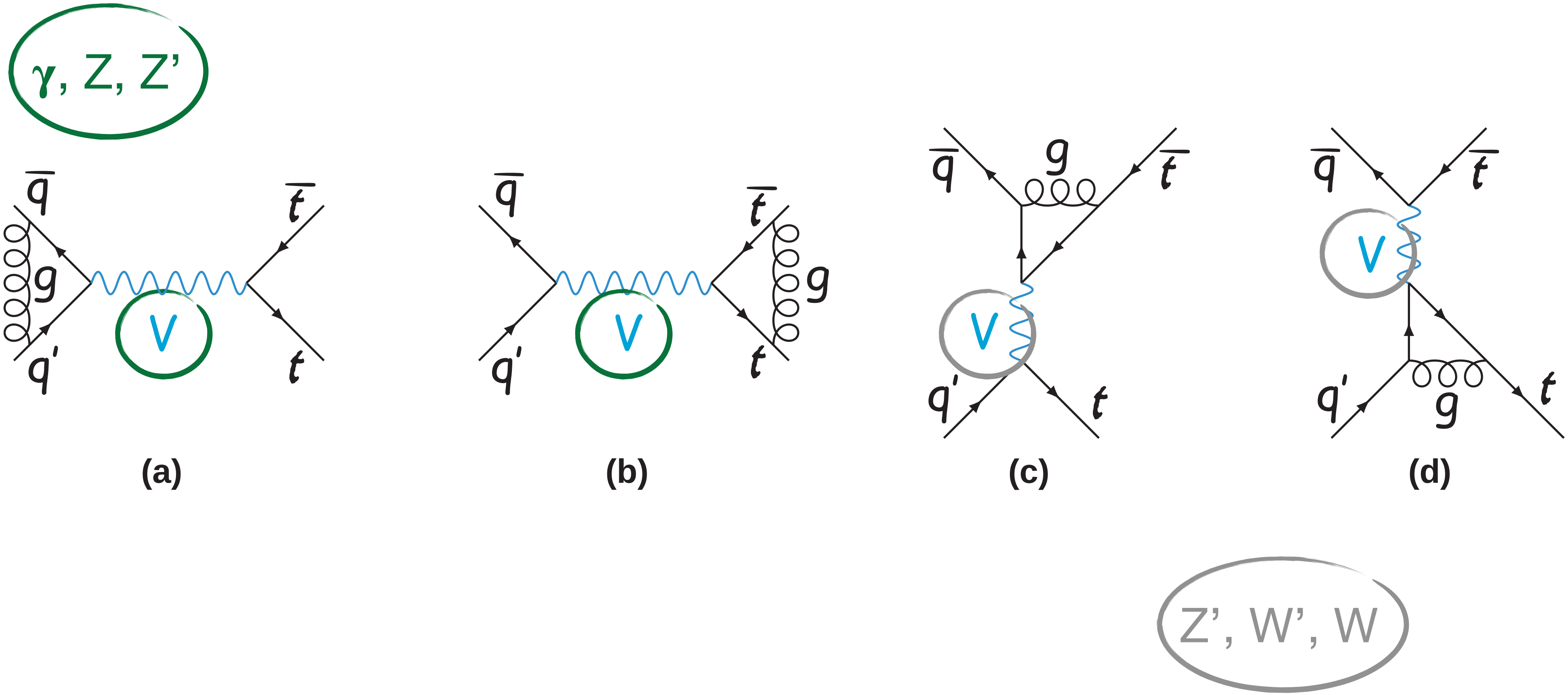






Subprocesses (5 FNS)

Virtual



Subprocesses (5 FNS)

$$q' + \bar{q} \to t + \bar{t} + g$$

Subprocesses (5 FNS)

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