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3rd FCC-France / Higgs & ElectroWeak Factory Workshop

Testing new-physics models with global comparisons to collider measurements

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In collaboration with: J. Butterworth, Tomáš Ježo, M. Klasen, J.-N. Lang, and Ingo Schienbein

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Plan of the presentation

- **Introduction**
- **New heavy resonances in the top-pair final state**
  - The calculation
  - Top-pair hadroproduction
  - Numerical results
- **Comparison with LHC measurements**
  - Contur
  - Rivet
  - The Contur method
  - The tool-chain
  - Results
- **Conclusions**

Part I

Introduction

Introduction

- **Theoretical** World:
  - Large number of theoretical models

- **Experimental** World:
  - Hundreds of measurement

No clear signals of new physics (**NP**) in the first two runs of the **LHC**

- **Goal**:
  - Test new theory ideas against the bank of LHC measurements in a model independent way

- **NP idea**:
  - Models with extra **U(1)** or **SU(2)** ⇔ (**Z′**) or (**Z′**, **W′**)

Introduction

- 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

Part II

New heavy resonances in the top-pair channel

M. M. AlTakach, T. Jezo, M. Klasen, J.-N. Lang, I. Schienbein [arXiv:2012.14855]

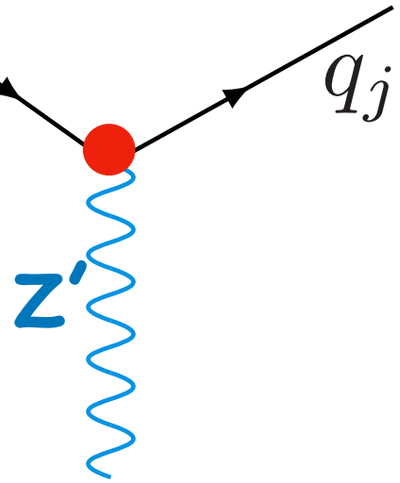
EW top pair hadroproduction in the presence of heavy Z' and W' bosons at NLO QCD in POWHEG

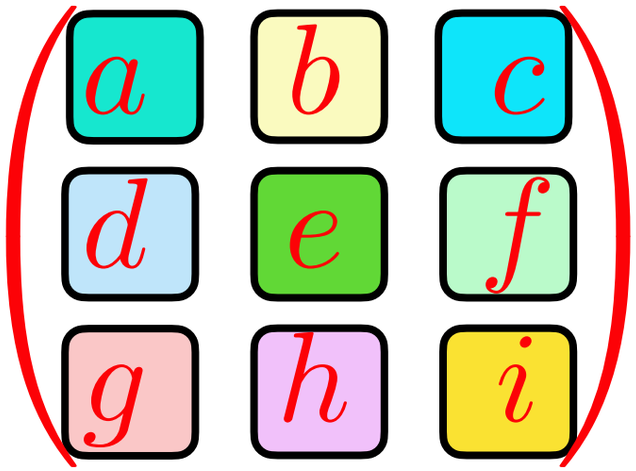
The calculation

- We performed a **new calculation** of **EW** **top** pair production at the **LHC** including a **number of major improvements** with respect to a previous one done in [arXiv:1511.08185]:
  - 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

The calculation

- We performed a **new calculation** of **EW** **top** pair production at the **LHC** including a **number of major improvements** with respect to a previous one done in [arXiv:1511.08185]:
  - The new code can deal with **general couplings** for both **Z'** & **W'**





- **Standard Model** (γ, **Z**, **W**) and **new physics** (**Z'**,**W'**) **interference effects** taken into account
- Initial state **QED** **singularities** are consistently treated
- The code is dubbed **PBZpWp**

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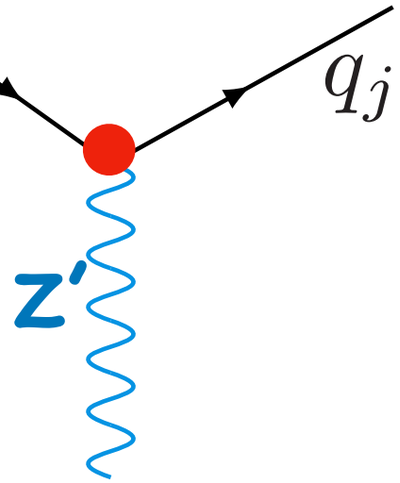

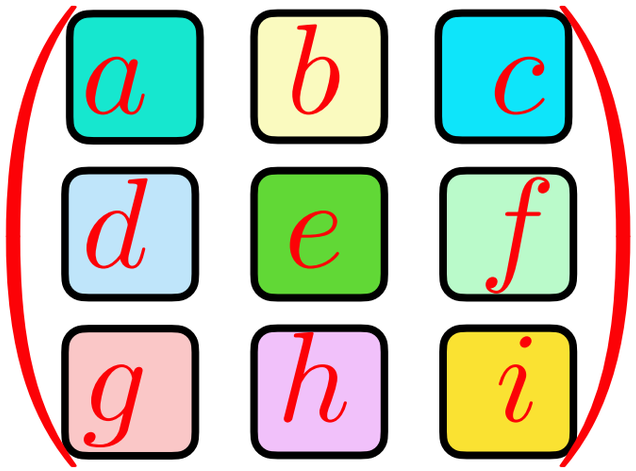

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The new calculation was validated against the old one finding **Full agreement**

Top-pair hadroproduction

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

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

- $\sigma_{2;0}$: **SM QCD**
- $\sigma_{3;0}$: **NLO QCD** corrections to the **SM QCD**
- $\sigma_{2;1}$: **EW** corrections to the **SM QCD**
- $\sigma_{1;1}$: Interference between **QCD** & **EW** **top** quark pair production
- $\sigma_{0;2}$: **EW** **top** quark pair production
- $\sigma_{1;2}$: **NLO QCD** corrections to **EW** **top** quark pair production
- $\sigma_{0;3}$: **EW** corrections to **EW** **top** quark pair production

Our Calculation

Numerical results: models

The 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

- Input parameters:
  - The mass of the resonances: $m_{Z'}$, $m_{W'}$

Numerical results: models

The Leptophobic Top-colour 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 $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$

- 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

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

Numerical results: models

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

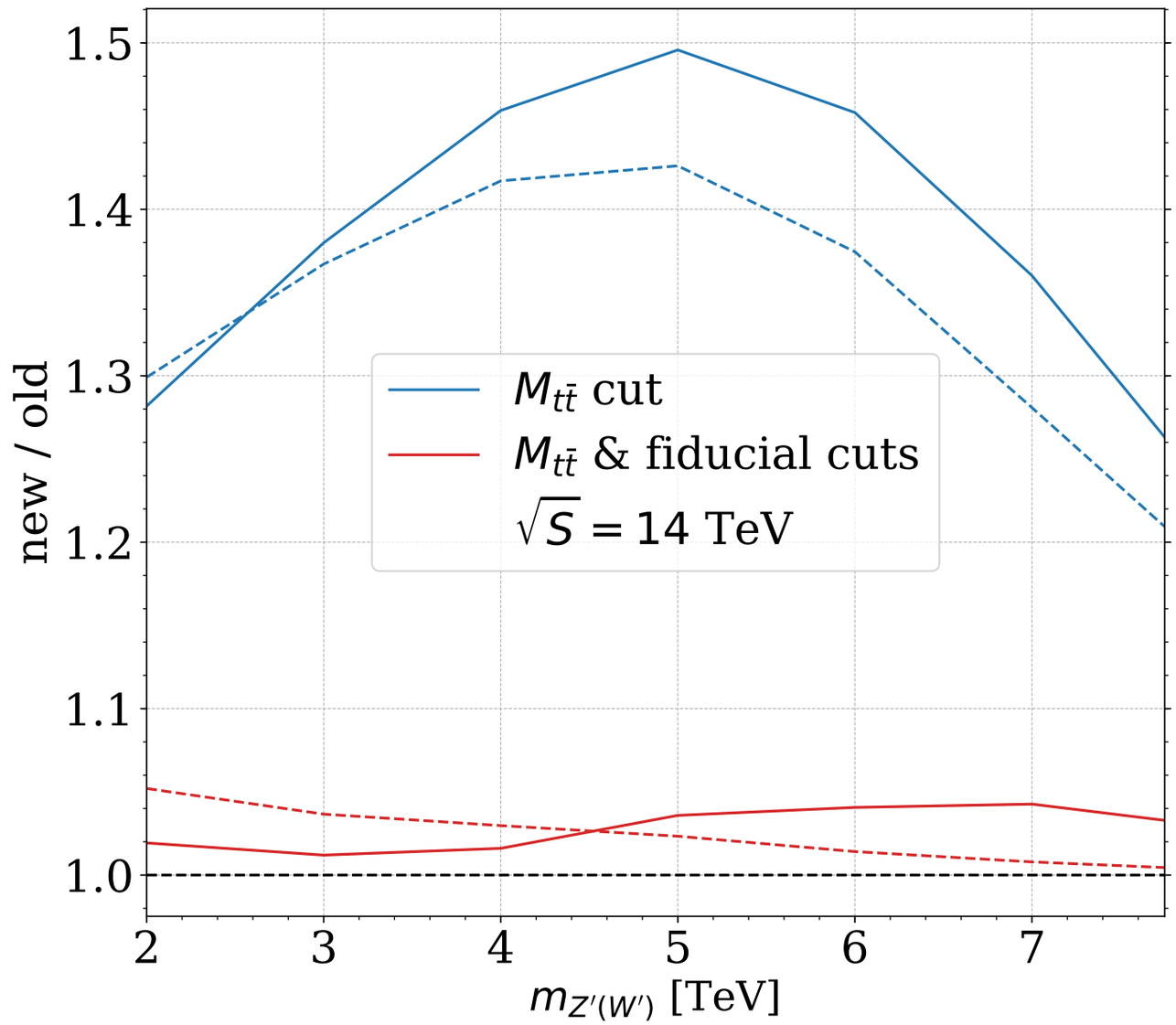
- A minimal extension of the SM by an extra $U(1)_F$ gauge symmetry
- Explains the neutral current B anomalies and the heaviness of the third family fermions
- Z' with generation non-universal/ flavour non-diagonal couplings
- Input parameters:
  - The mass of Z': $m_{Z'}$
  - The $U(1)_F$ gauge coupling: g_F
  - The mixing angle between second and third generation: θ_{sb}

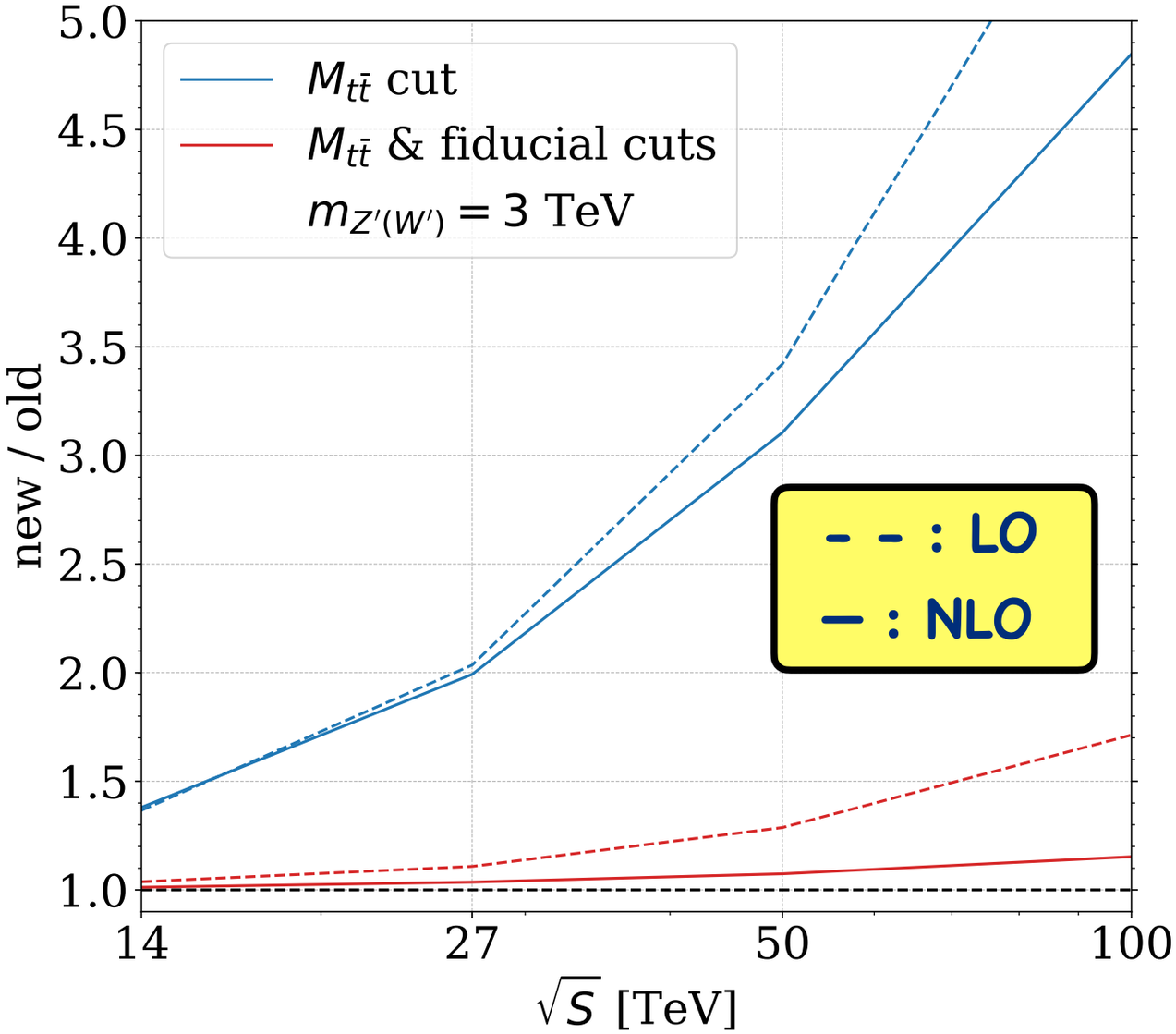
Numerical results: setup & input

- Events in **LHE** format using **PBZpWp** with stable on-shell **top** quark
- **Generation** cut on the **top** pair invariant mass:
  - $M_{tt} \geq 0.75\ m_{Z'}$
  - 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, $|\eta| < 2.5$

Numerical results: non-resonant contributions

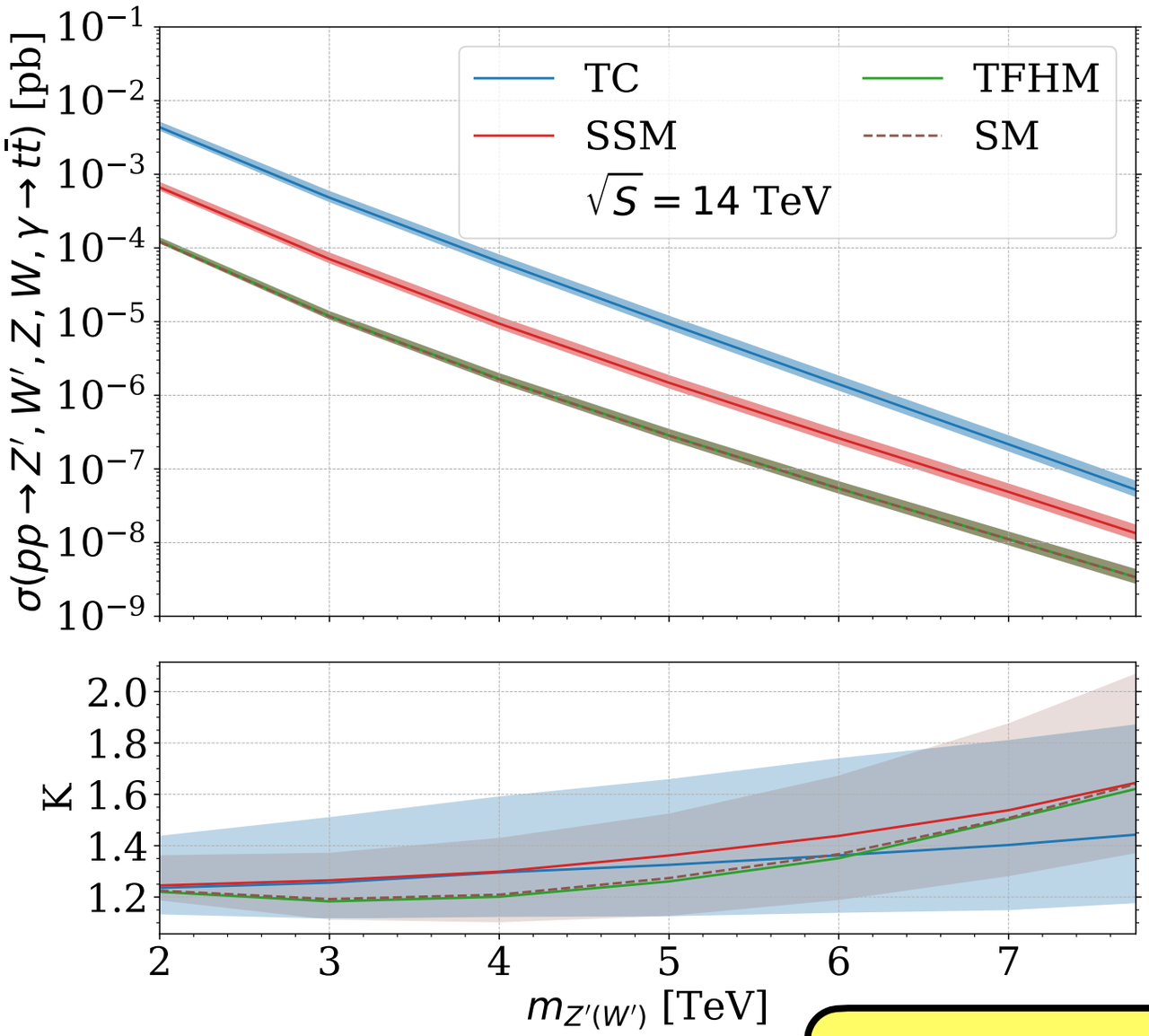
EW top quark pair production cross section at NLO in the SSM vs $m_{Z'(W')}$ (left) & $\sqrt{S}$ (right)

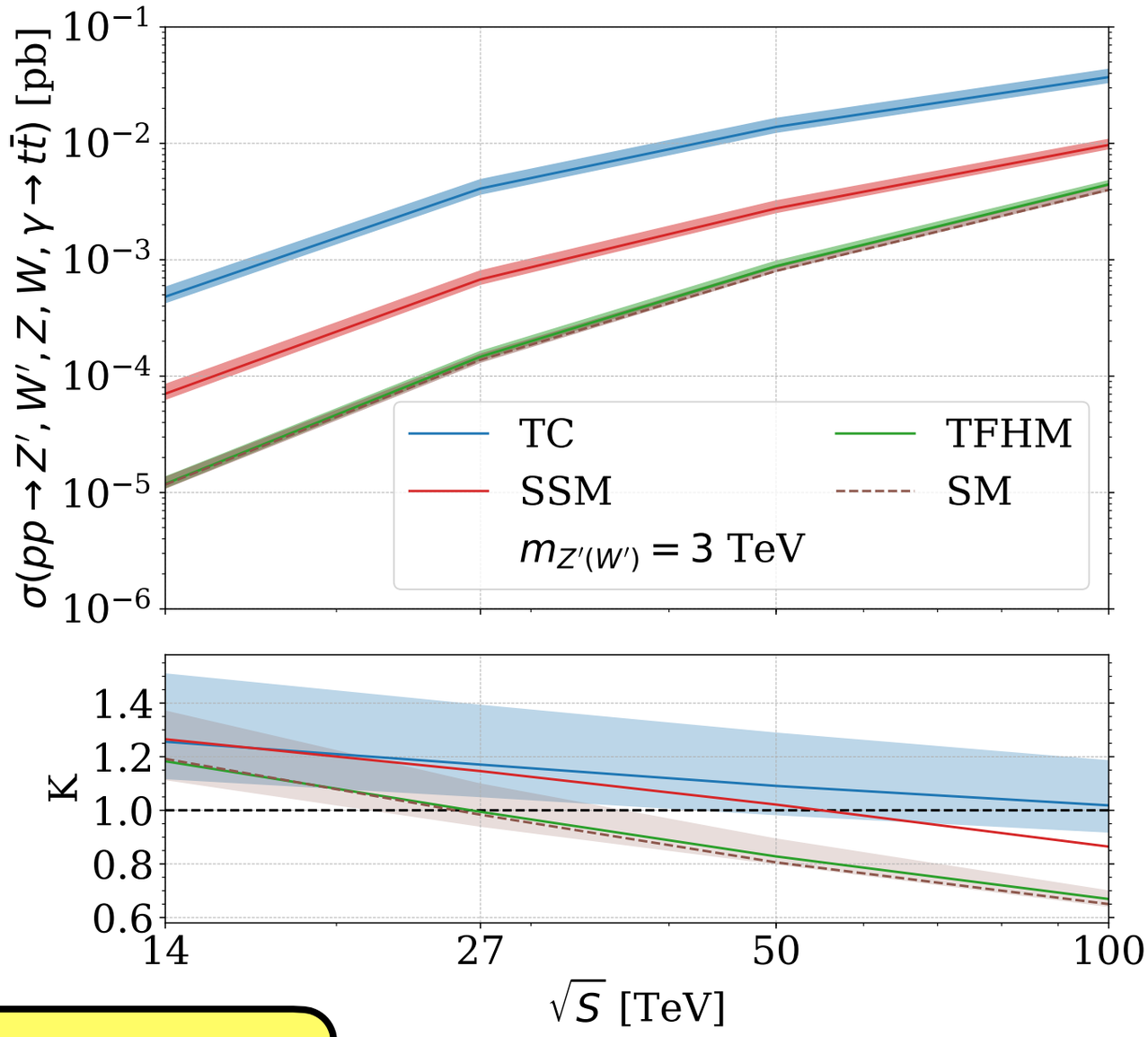




Numerical results: integrated cross sections

EW top quark pair production cross section at NLO in the SM, SSM, TC, and TFHMeg vs $m_{Z'(W')}$ (left) & $\sqrt{S}$ (right)





K-factor = NLO/LO

Part III

Comparison with LHC measurements

A. Buckley et al. [arXiv:2102.04377]

Testing new-physics models with global comparisons to collider measurements: the Contur toolkit

M.M AlTakach, J.M Butterworth, T. Jezo, M. Klasen, J.-N. Lang, I. Schienbein [arXiv:2111.15406]

Probing a leptophobic top-colour model with cross section measurements and precise signal and background predictions: a case study

Contur

- Question for any given **BSM** proposal:
  "at what significance do existing measurements already exclude this?"

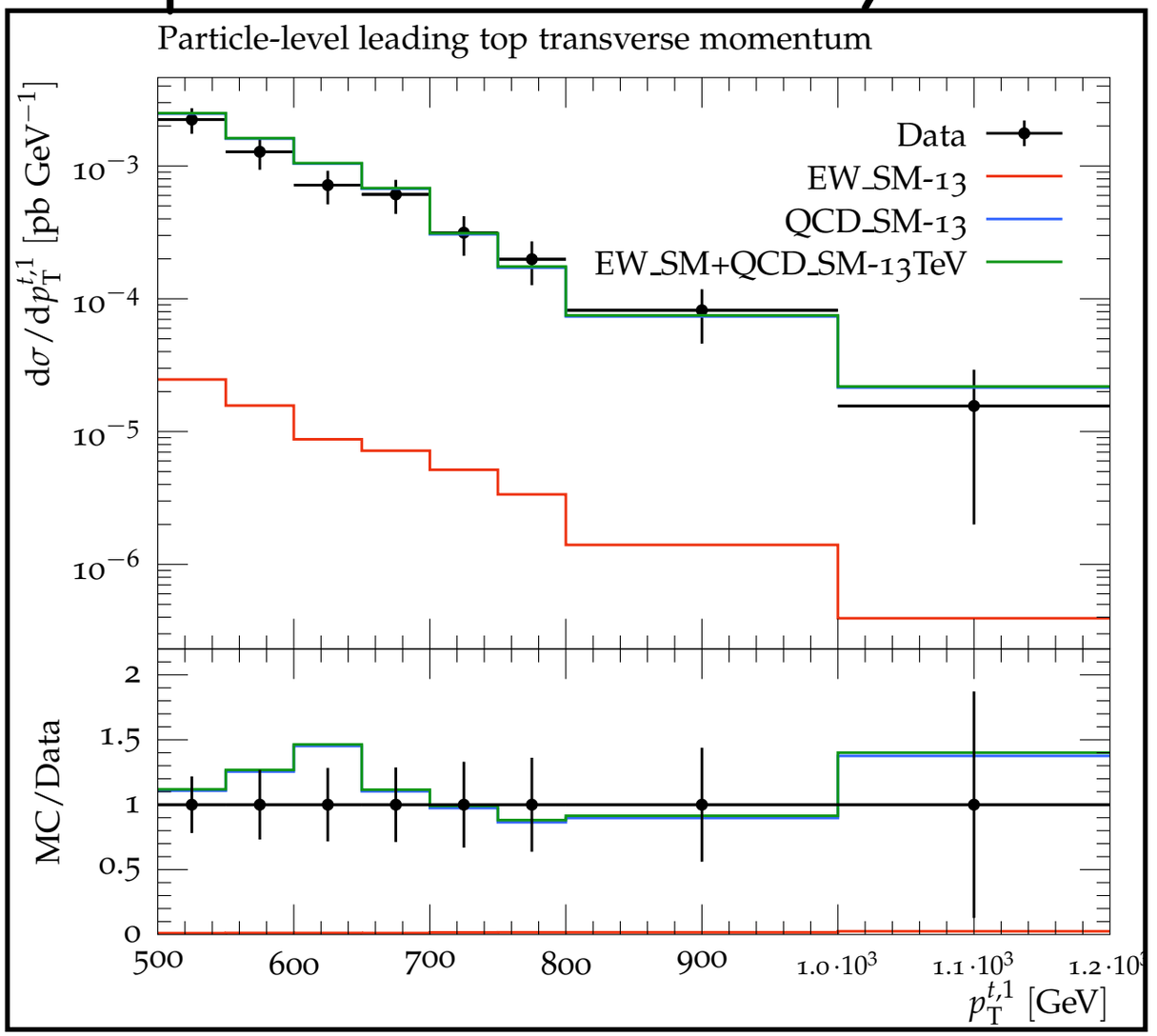
- **C**onstraints **O**n **N**ew **T**heories **U**sing **R**ivet

- Exploits the fact that **particle-level** differential measurements made in fiducial regions of phase space have a high degree of model independence

- These measurements can therefore be compared to **BSM** physics implemented in **MC** generators in a very generic way

Rivet

- **R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory
  - Preservation of particle-collider analyses logic
  - Tuning of non perturbative parameters
  - Validation and improvement of **MCEG** codes
  - Analysis reinterpretation via **MC** simulations



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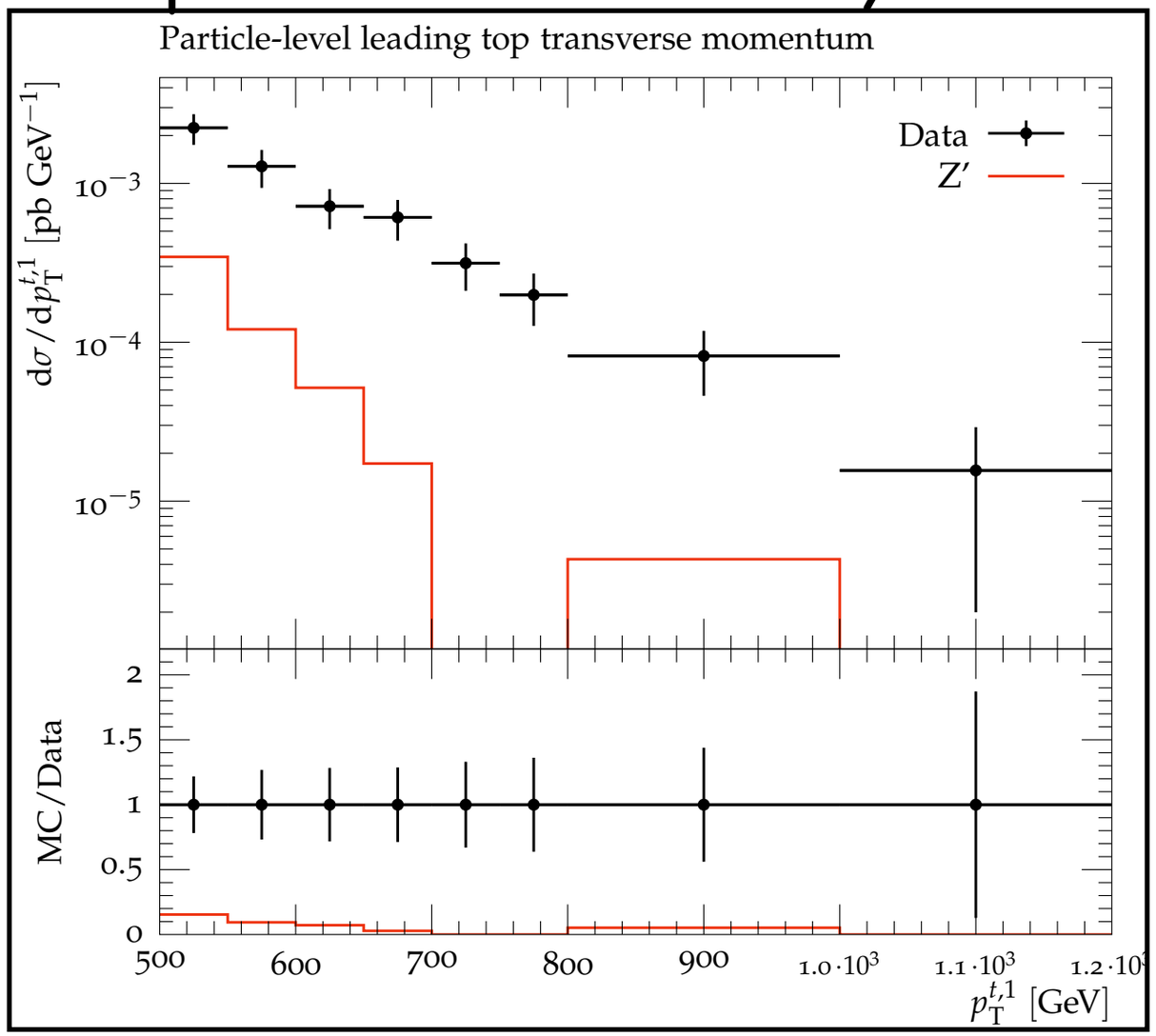

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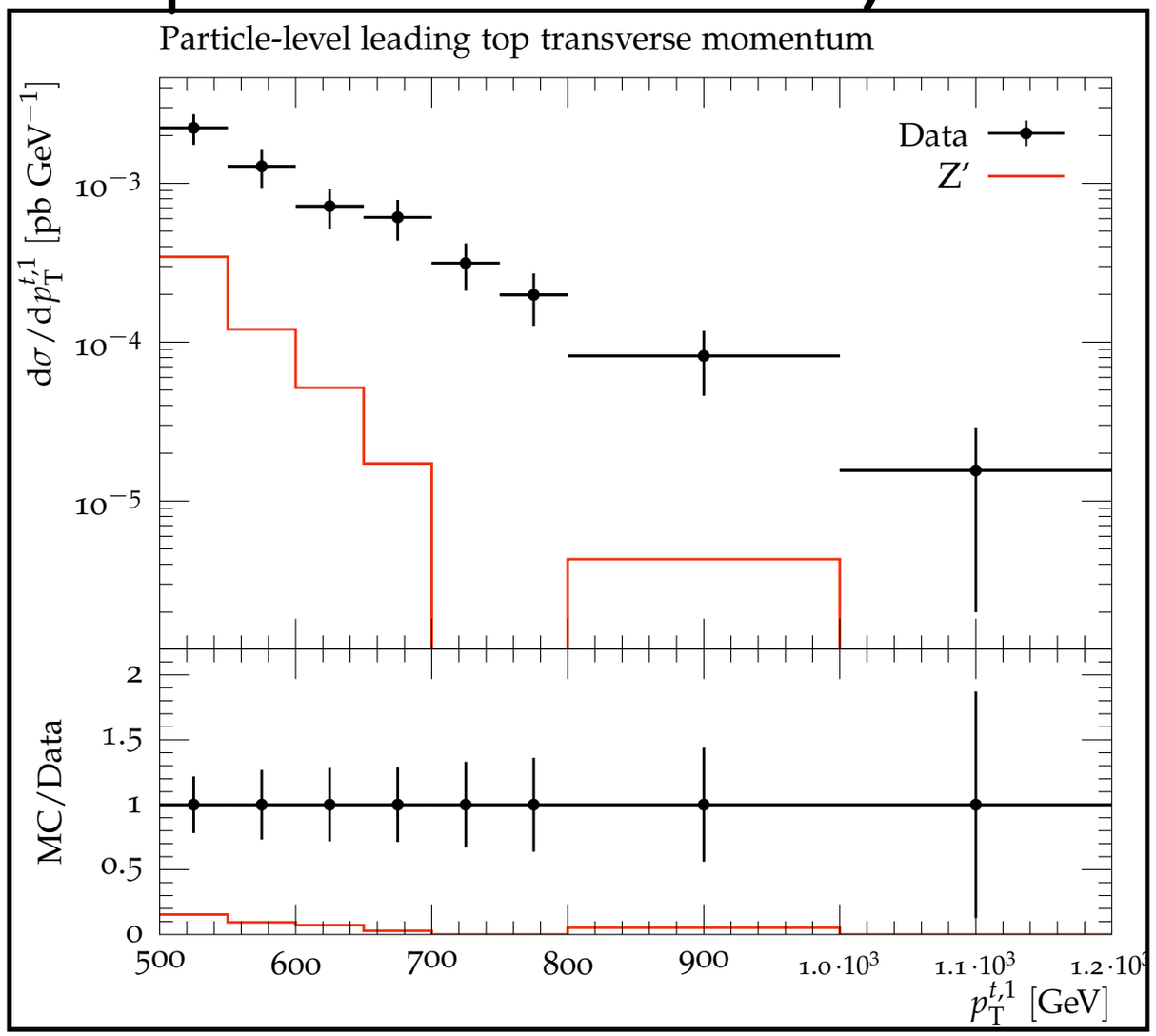
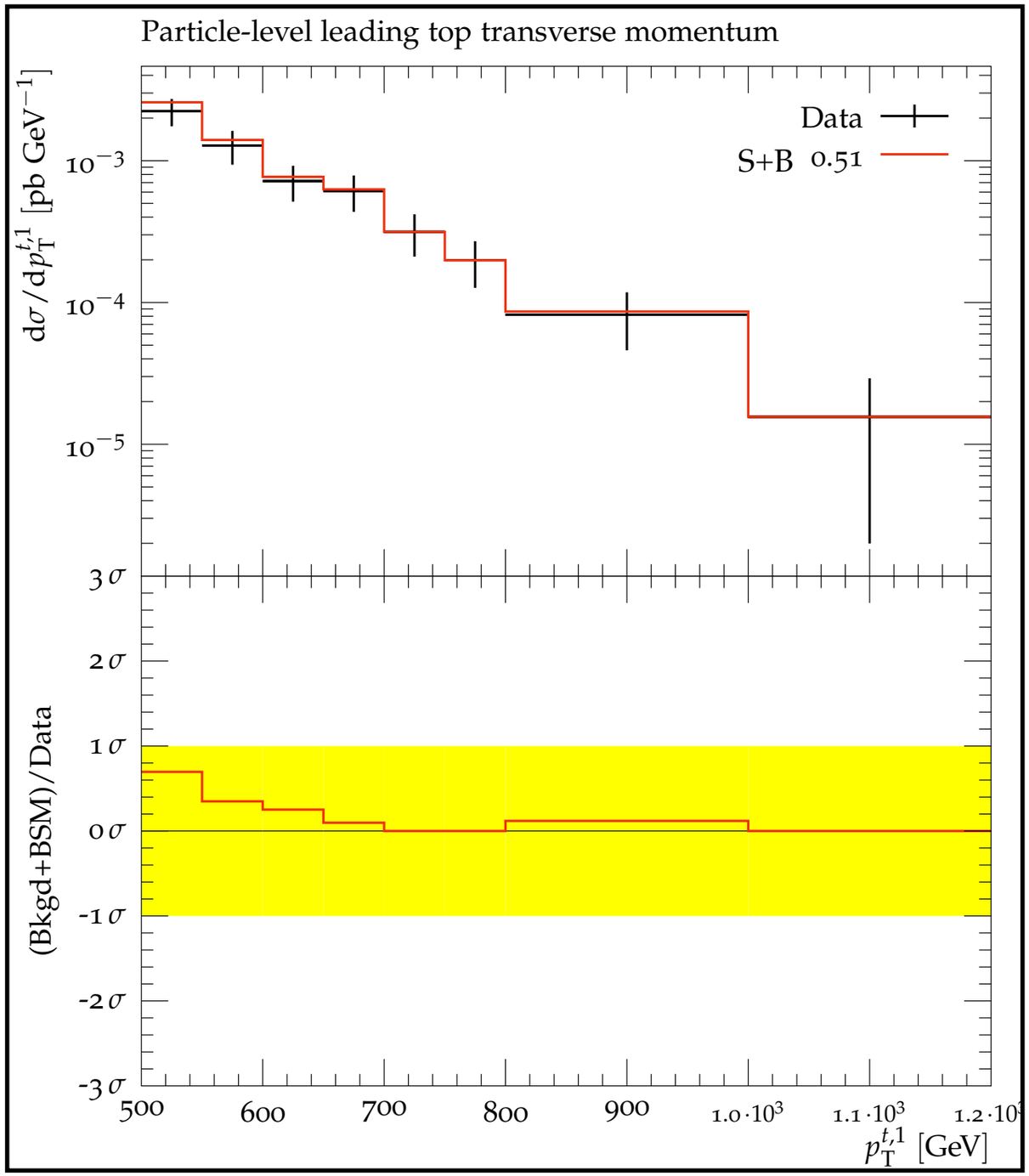


Contur uses bank of **LHC** results preserved in **Rivet** to rapidly check if new models are already ruled out

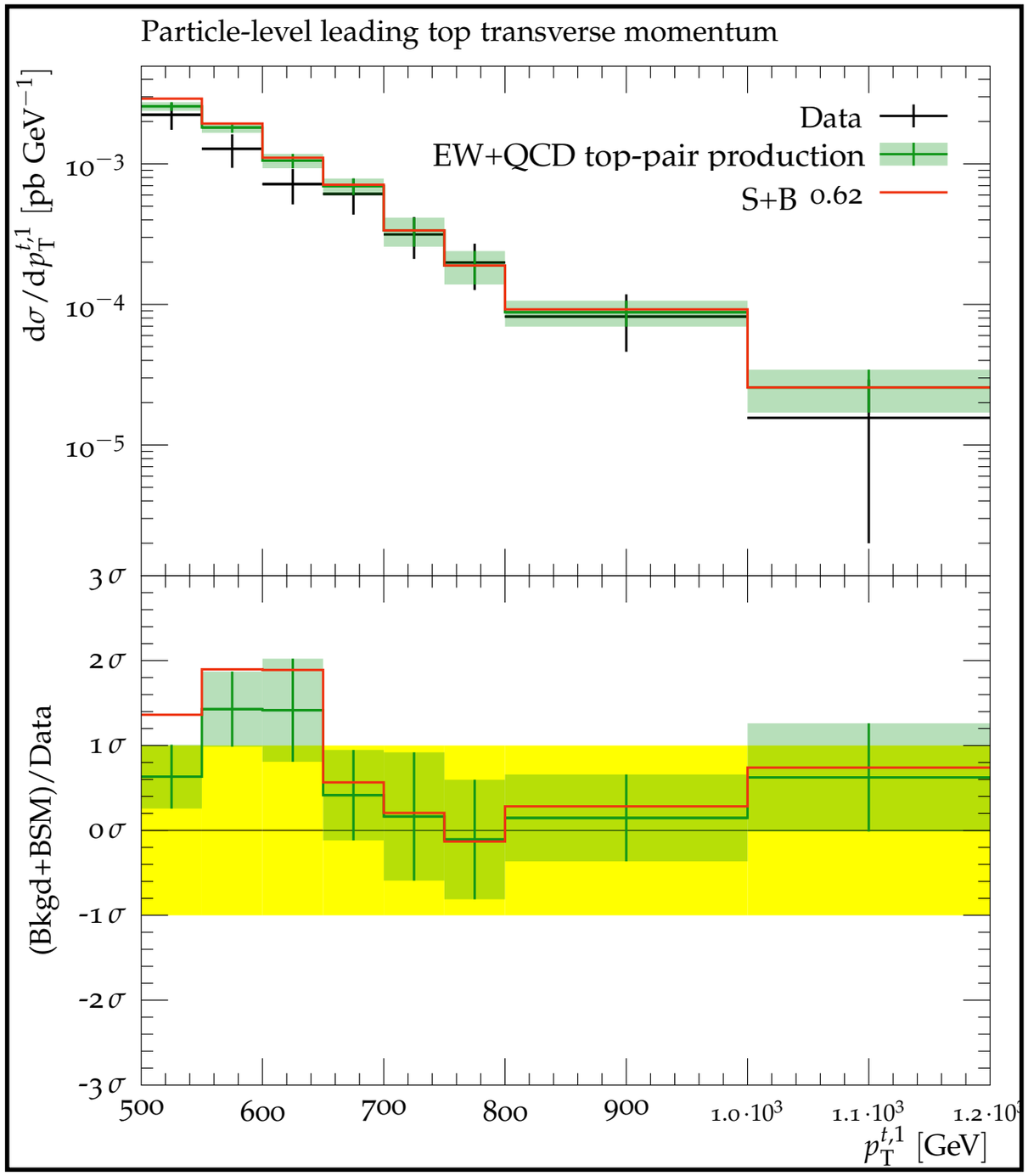
The Contur method

- 1st Approach:
  - Striking signals
  - Data which agree with SM calculation
  - Data = SM
  - Uncertainties on the data define the room left for BSM signatures



The Contur method

- **2nd Approach:**
  - Precision **SM** calculations with their associated uncertainties define the background
  - Superimpose the putative signal
  - Check for consistency with the data within uncertainties



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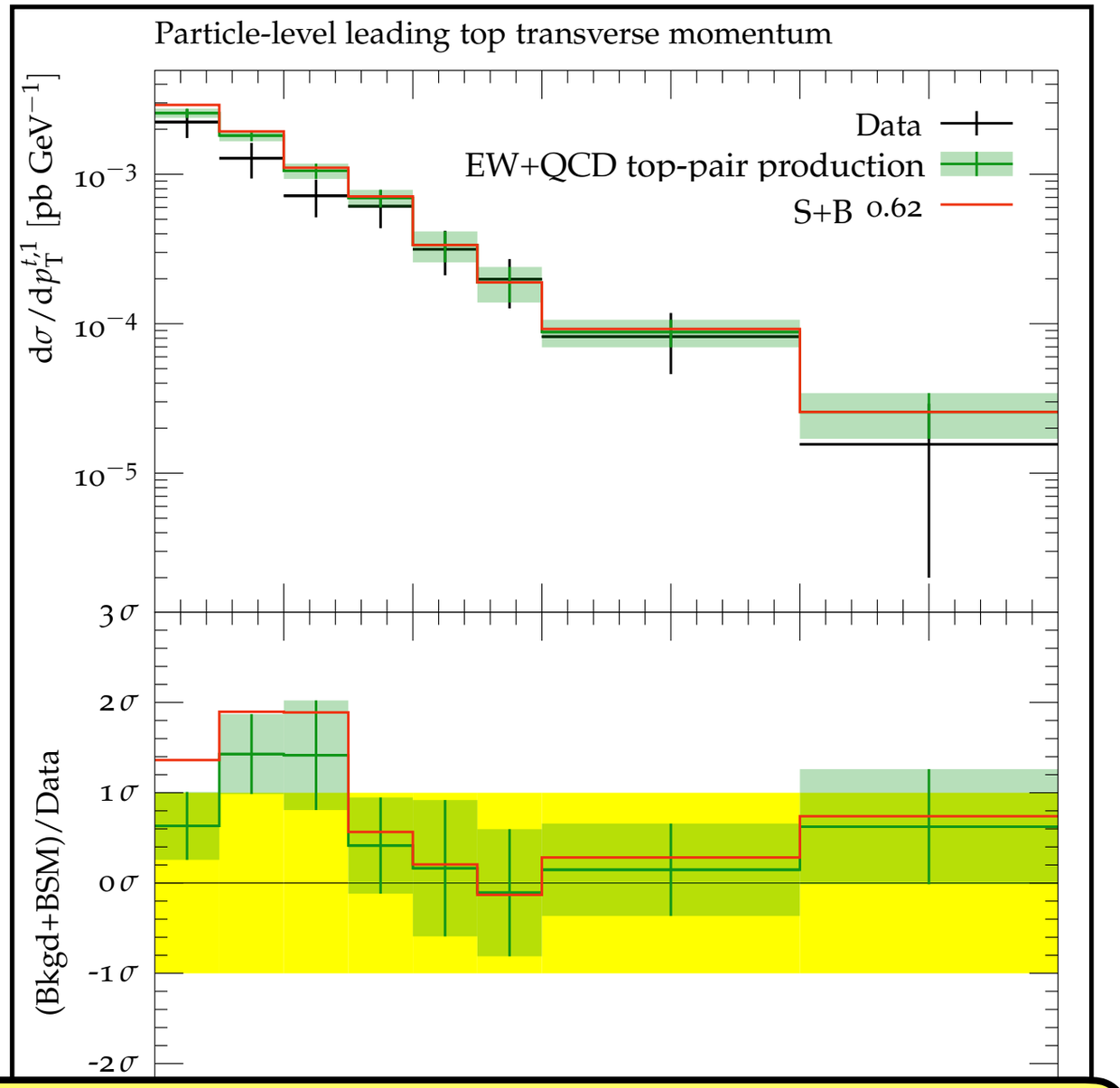
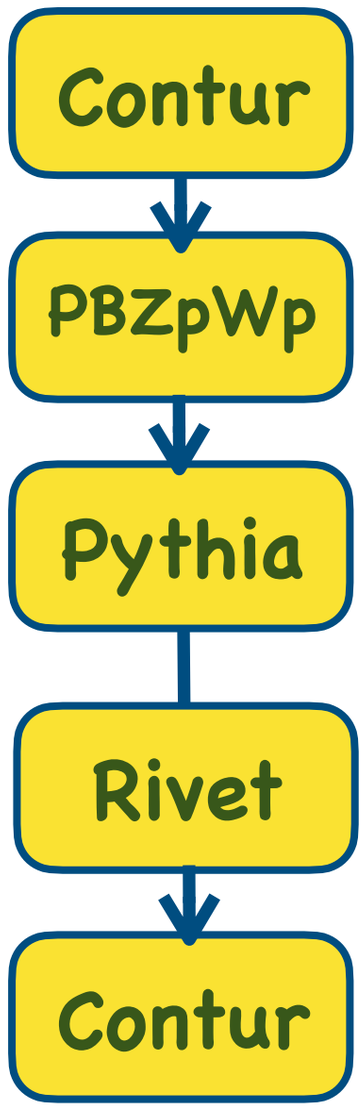


Contur provides the book-keeping and steering machinery to repeat this process over a grid of parameter values

The tool-chain

- The exclusion limits on **BSM** models with extra **Z′** bosons in the **top** pair final state are obtained as follows:
  - **Contur**: specifies the range for each input parameter
  - **PBZpWp**: generates **LH** events for processes Involving **Z′** boson for a given set of parameter values
  - **Pythia**: showers the **LH** events to obtain **particle-level** events in the **HepMC** format
  - **Rivet**: imposes fiducial cuts on the produced events
  - **Contur**: Compares the size of any deviation to the background for each set of parameters and gives an exclusion limit. Combines the limits of all the sets into one map



Results

Leptophobic Top-colour model (**TC**):

- Input parameters:
  - The mass of **Z′**: $m_{Z'}$
  - The Ratio of the two **U(1)** coupling constants: **cot** θ_H

Results

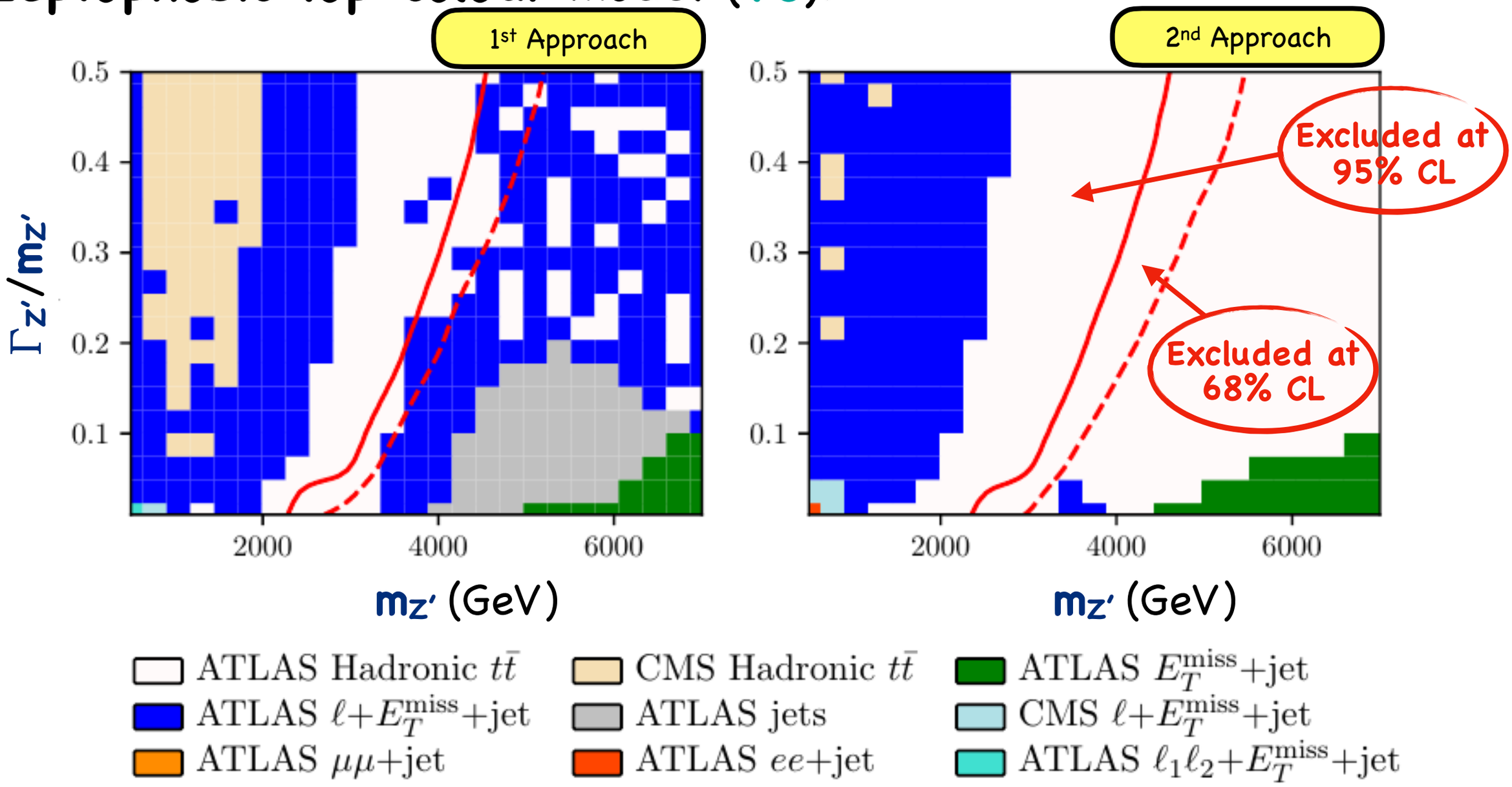
Leptophobic Top-colour model (**TC**):

- Input parameters ($m_{Z'}$, **cot** θ_H) ↔ ($m_{Z'}$, $\Gamma_{Z'}/m_{Z'}$):
  - The mass of **Z'**: $m_{Z'}$
  - The Ratio of the two **U(1)** coupling constants: **cot** θ_H
  - The total decay width of **Z'**: $\Gamma_{Z'}$

$$\Gamma_{Z'} = \frac{\alpha \cot^2 \theta_H m_{Z'}}{8 \cos^2 \theta_W} \left[\sqrt{1 - \frac{4m_t^2}{m_{Z'}^2}} \left(2 + \frac{4m_t^2}{m_{Z'}^2} \right) + 4 \right]$$

Results

Leptophobic Top-colour model (TC):



Conclusions

$\Gamma_{Z'}/m_{Z'}$ [%]	1st Approach	2nd Approach	CMS [1810.05905]
1	2.29 TeV	2.35 TeV	3.80 TeV
10	3.17 TeV	3.22 TeV	5.25 TeV
30	4.01 TeV	4.04 TeV	6.65 TeV
50	4.54 TeV	4.61 TeV	-

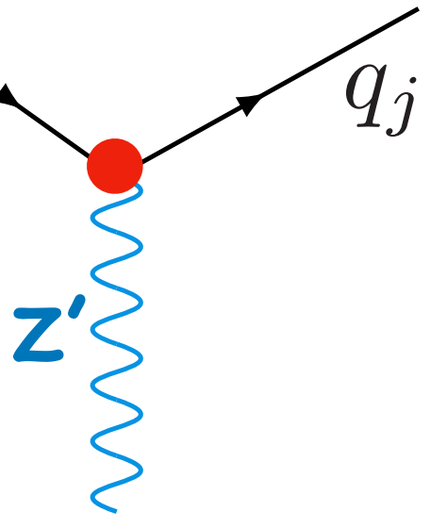
Our limits are weaker than the direct searches

- Reasons:
  - No measurements with full Run 2 Luminosity in **Rivet**
  - Binning in **measurements** vs binning in **searches**

Backup slides

The old calculation (old-PBZp)

- 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

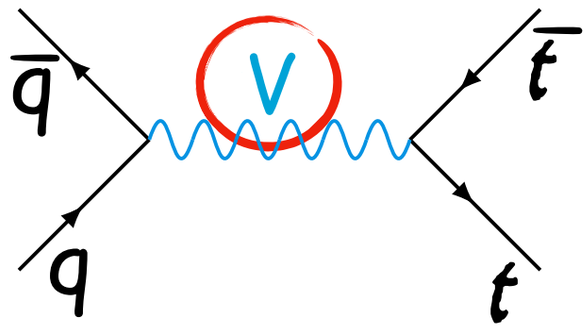


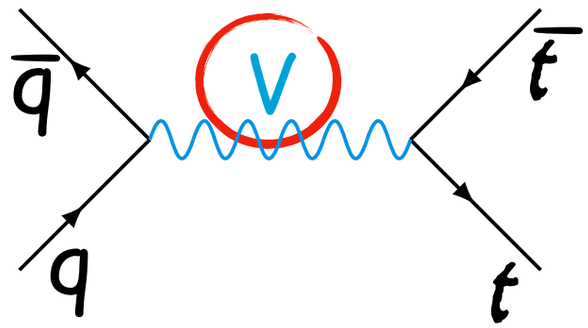
$$\begin{pmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{pmatrix}$$

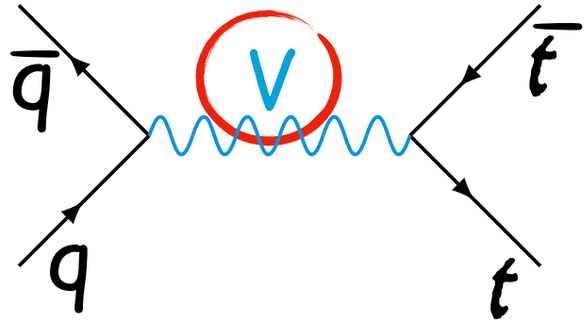
- Standard Model (γ, **Z**) and new physics (**Z'**) interference effects taken into account
- Results are implemented in the **POWHEG BOX** framework
- Initial state **QED** singularities are consistently treated

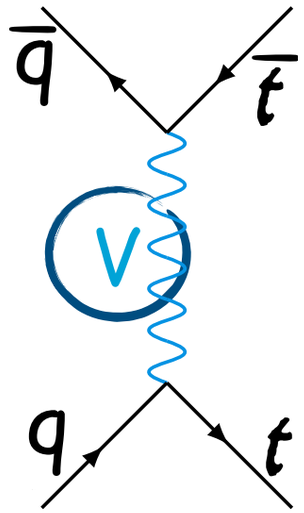
Parton-level processes (5 FNS)

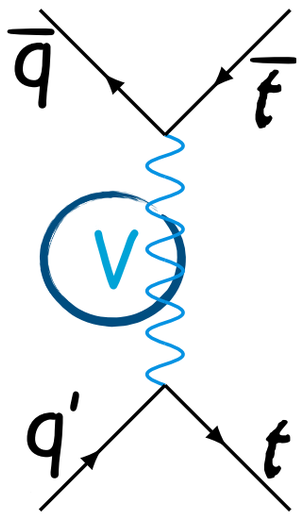
Born (0:QCD; 4:EW; 0:BSM)

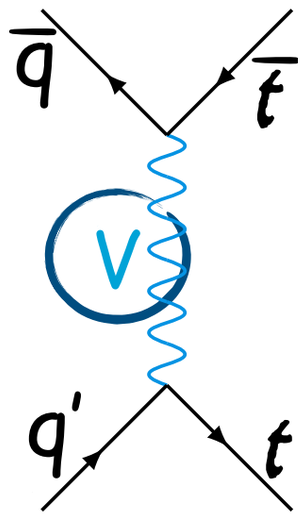












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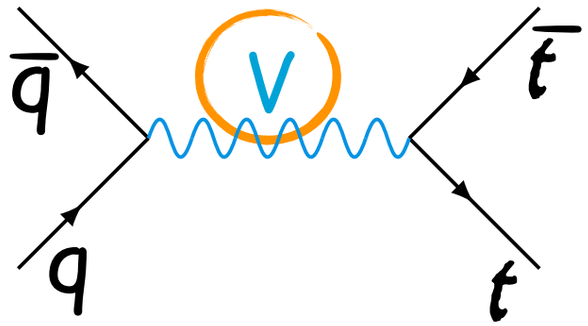
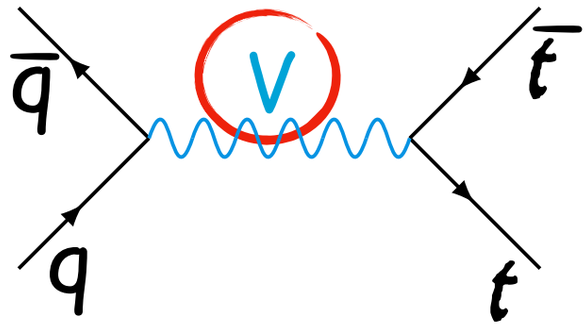
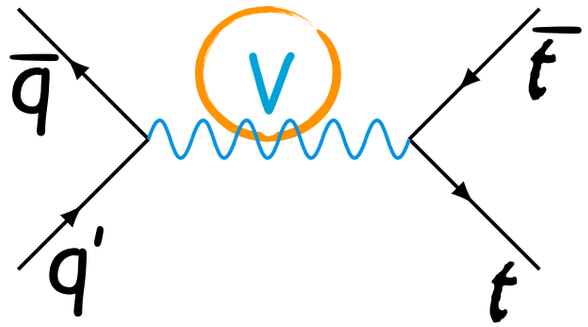
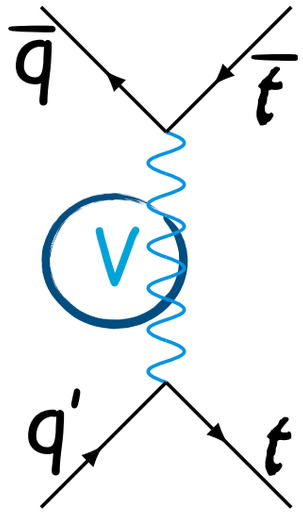




γ, Z

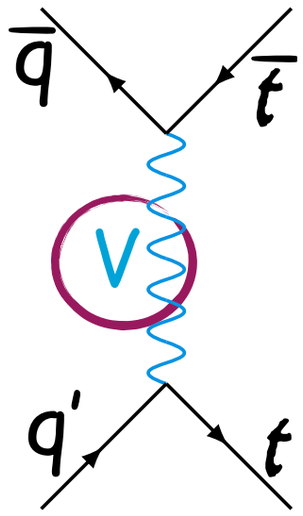
Z′

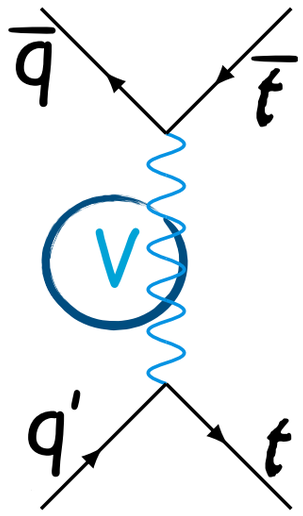




W

W′





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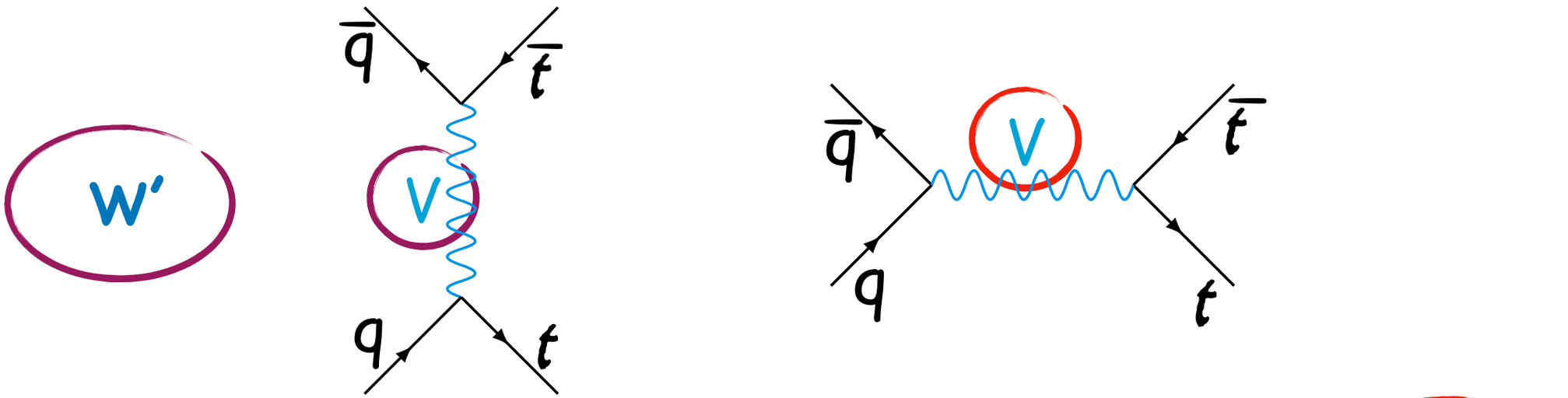

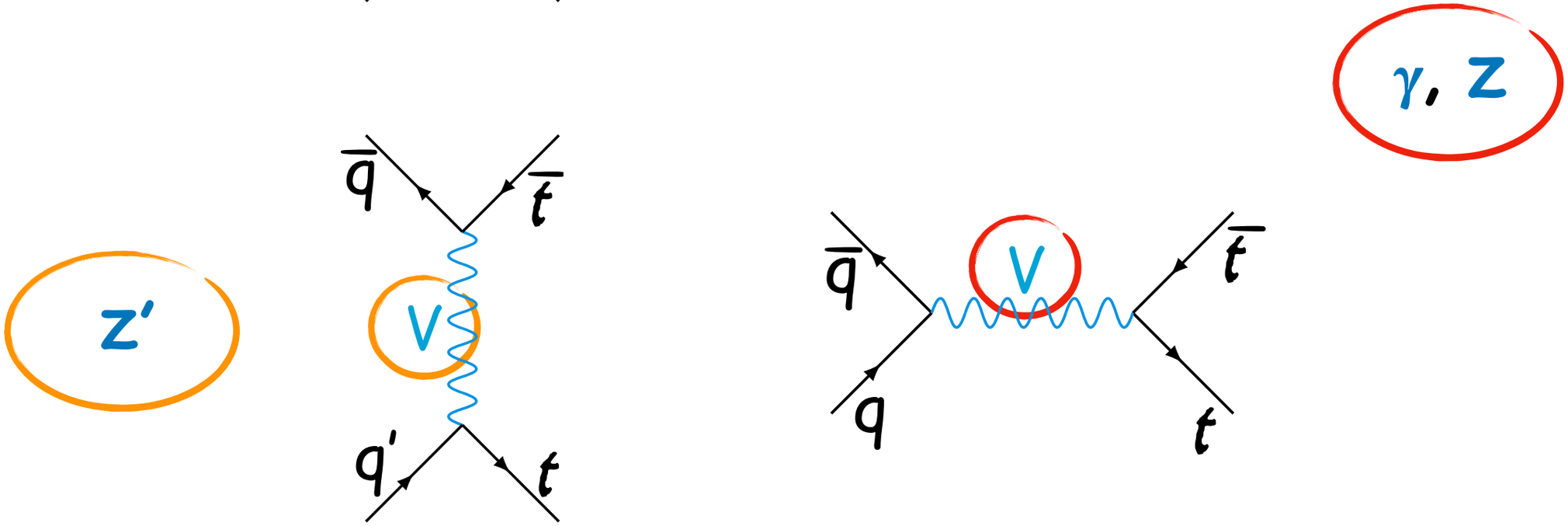

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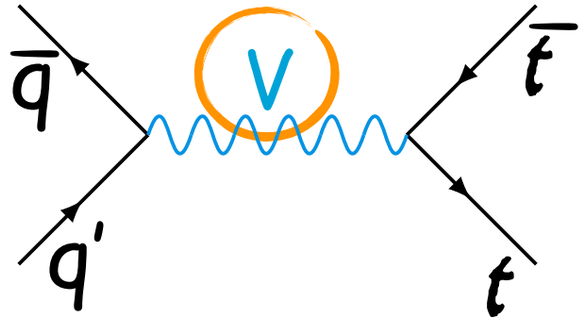
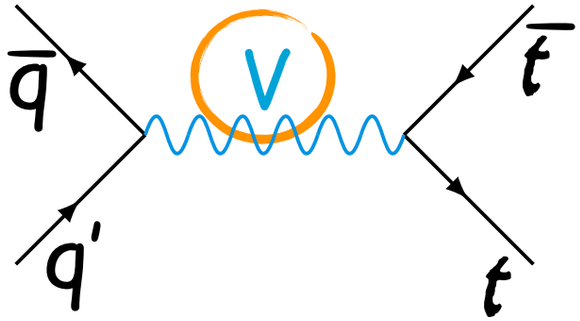
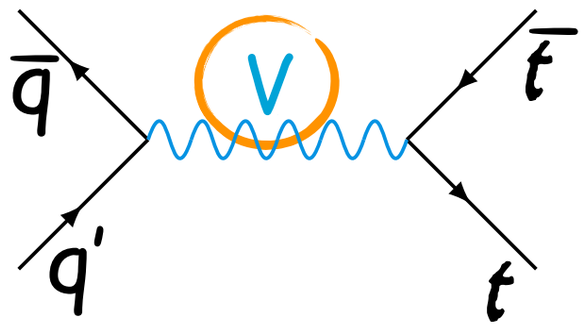
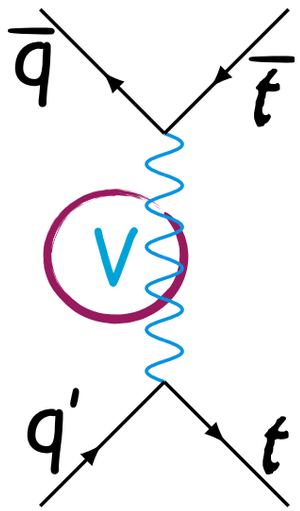
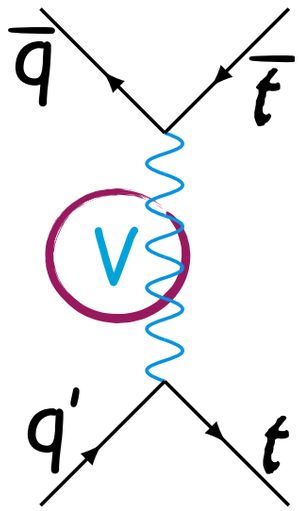


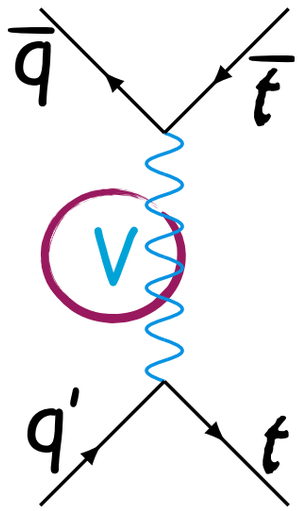


Z′





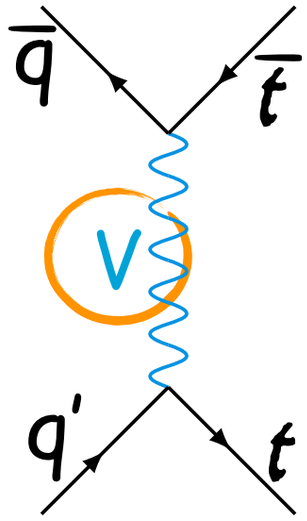


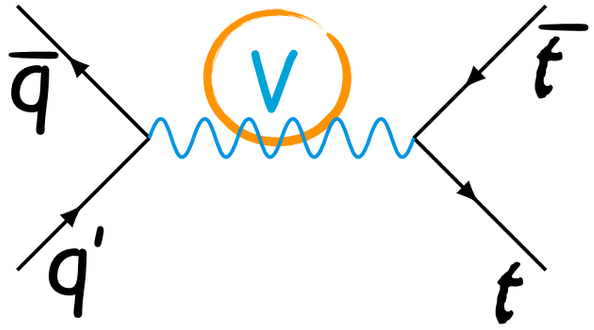


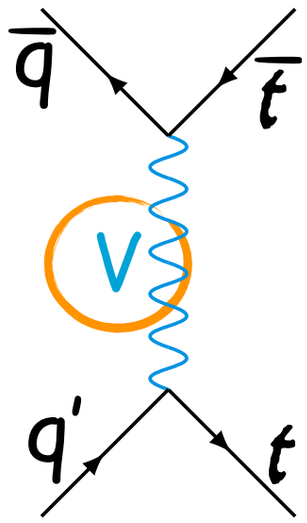
W′

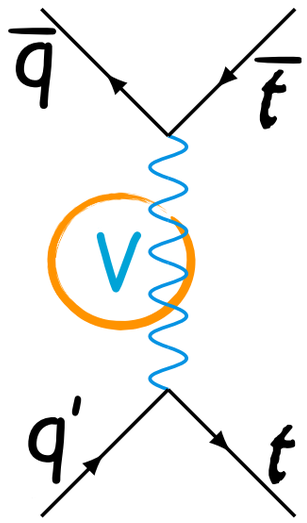
Parton-level processes (5 FNS)

Born (0:QCD; 4:EW; 4:BSM)



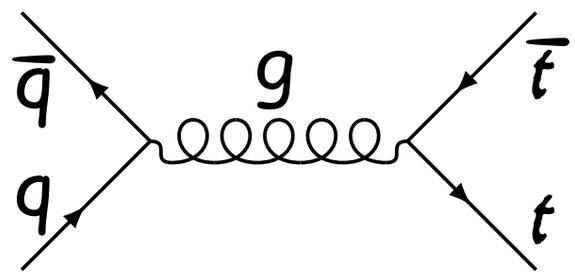


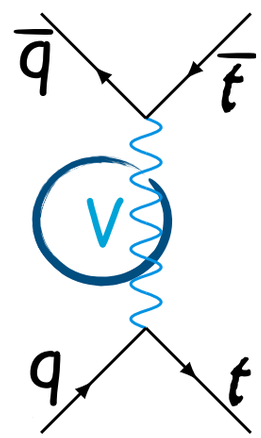




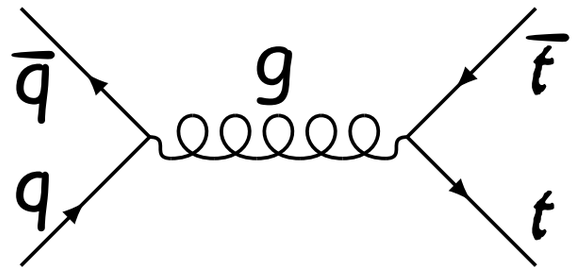
Parton-level processes (5 FNS)

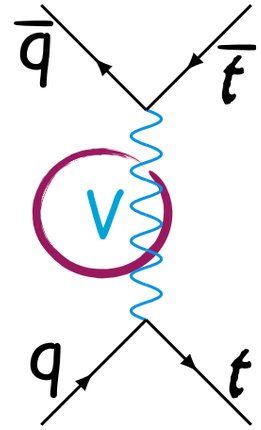
Born (2:QCD; 2:EW; 0:BSM)

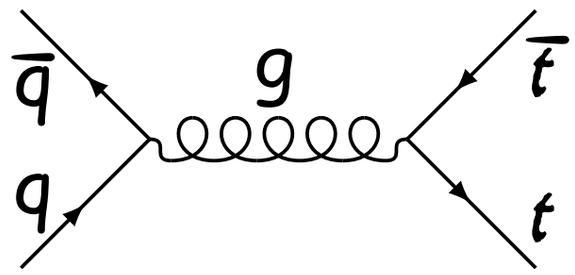


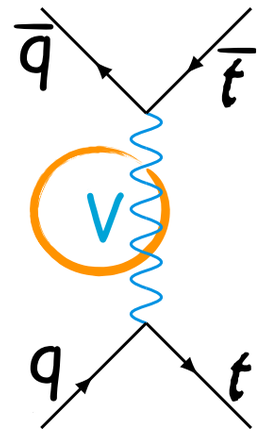


Born (2:QCD; 2:EW; 2:BSM)





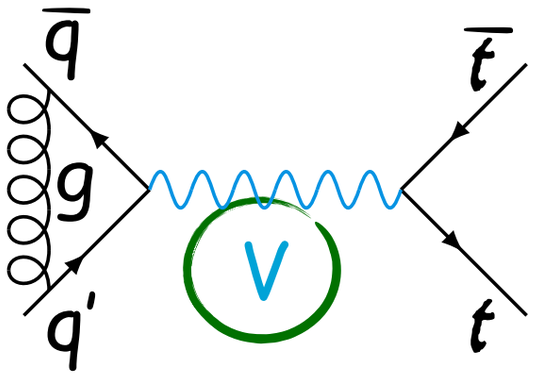




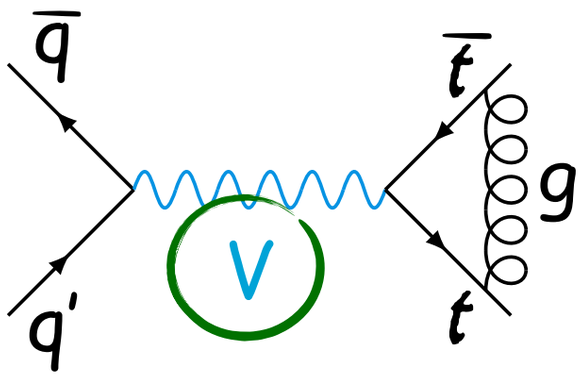
Parton-level processes (5 FNS)

Virtual

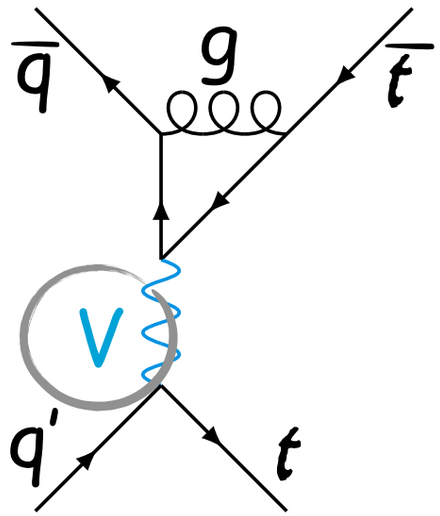
γ, Z, Z'



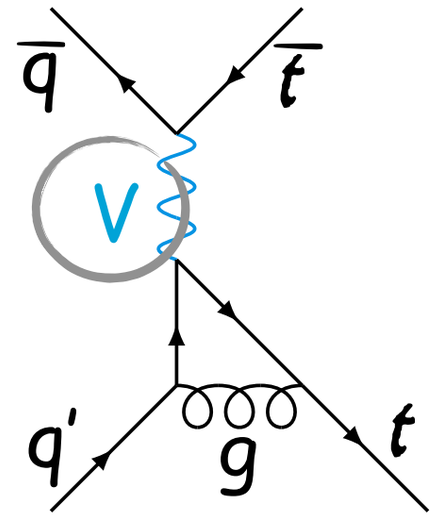
(a)



(b)



(c)

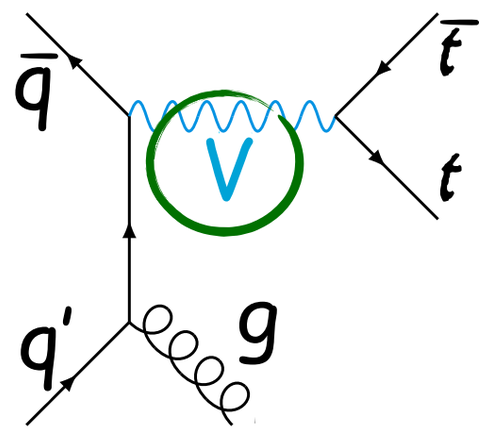


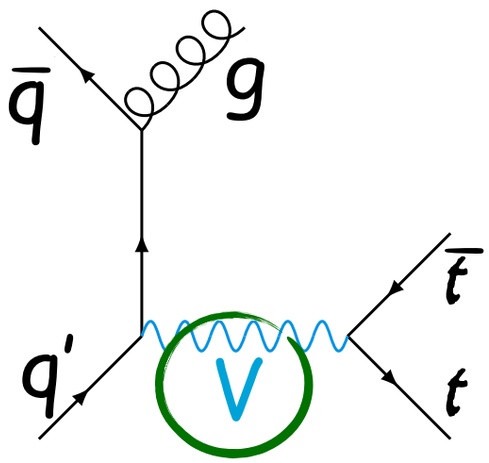
(d)

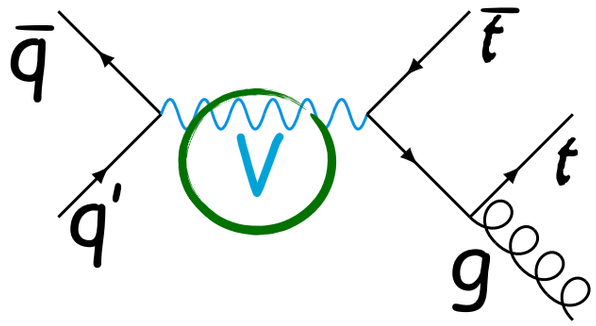
Z', W', W

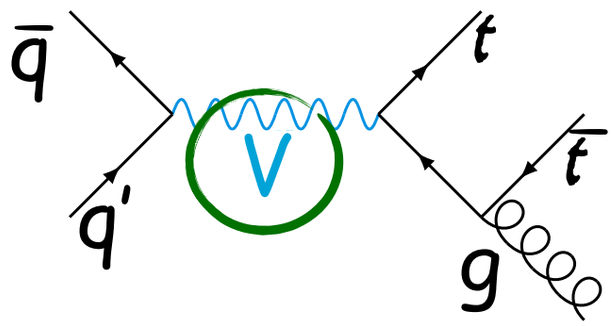
Parton-level processes (5 FNS)

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

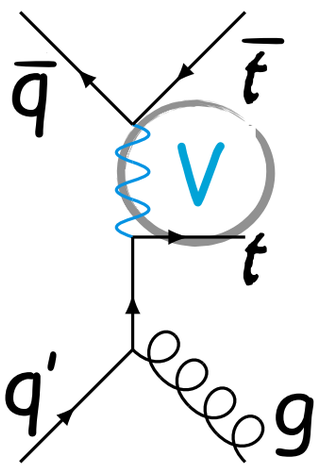




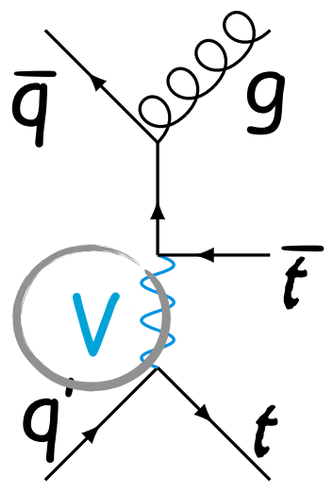




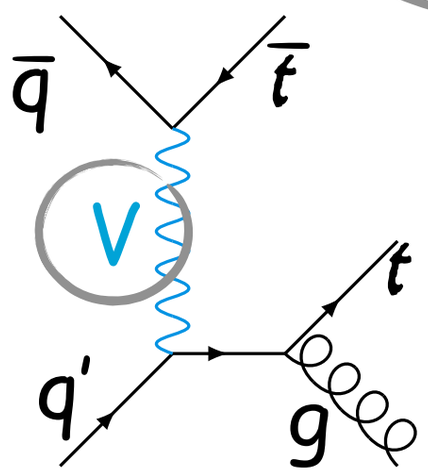
(a)



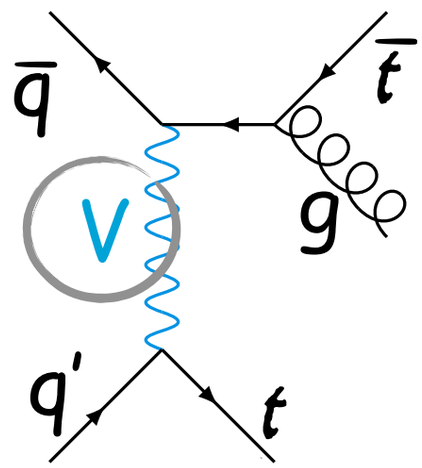
(b)



(c)



(d)



(e)

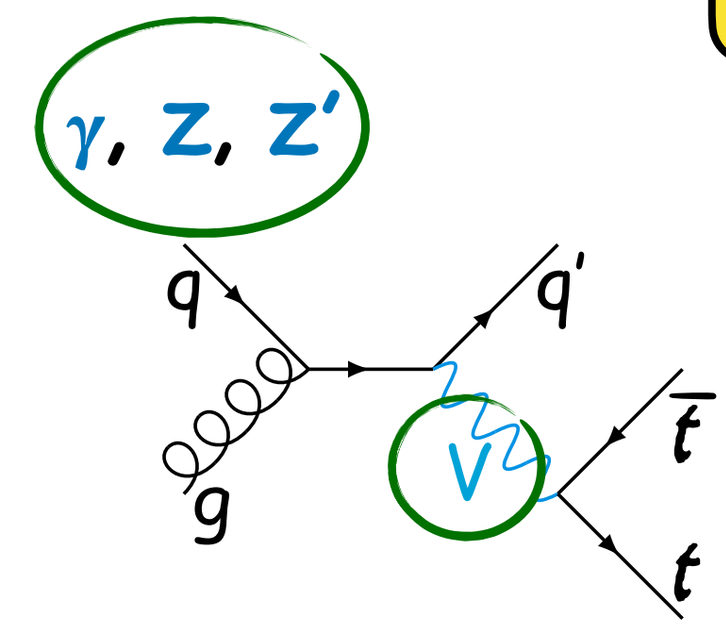
(f)

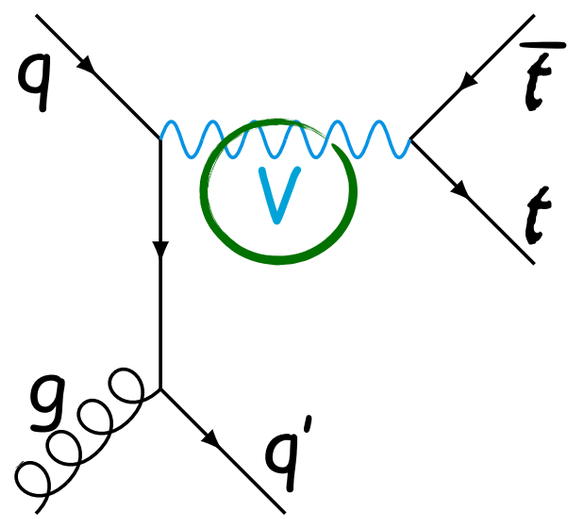
(g)

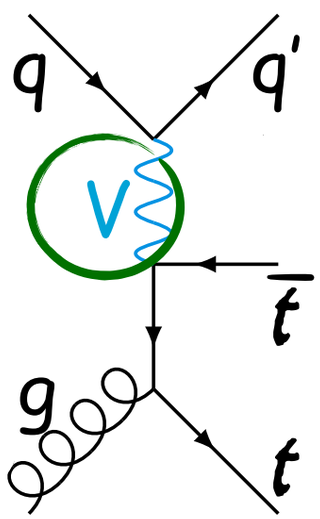
(h)

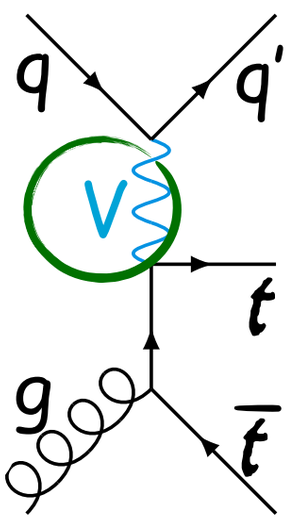
Parton-level processes (5 FNS)

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

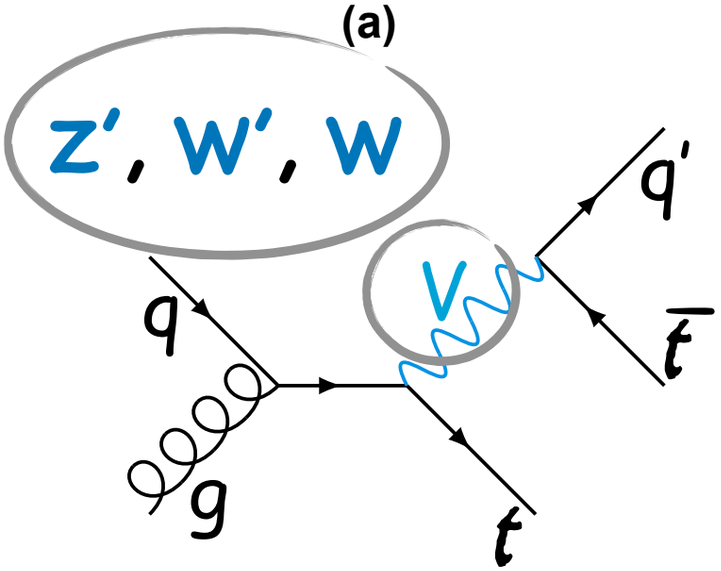








(a)



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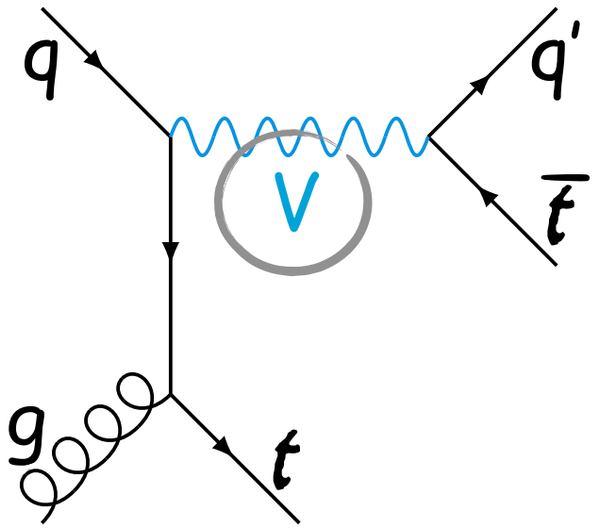
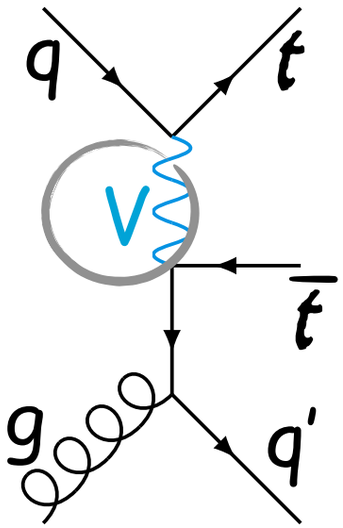
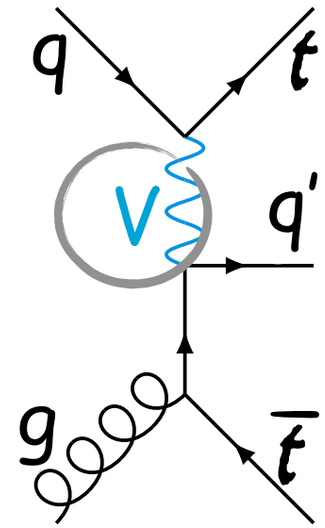


(c)



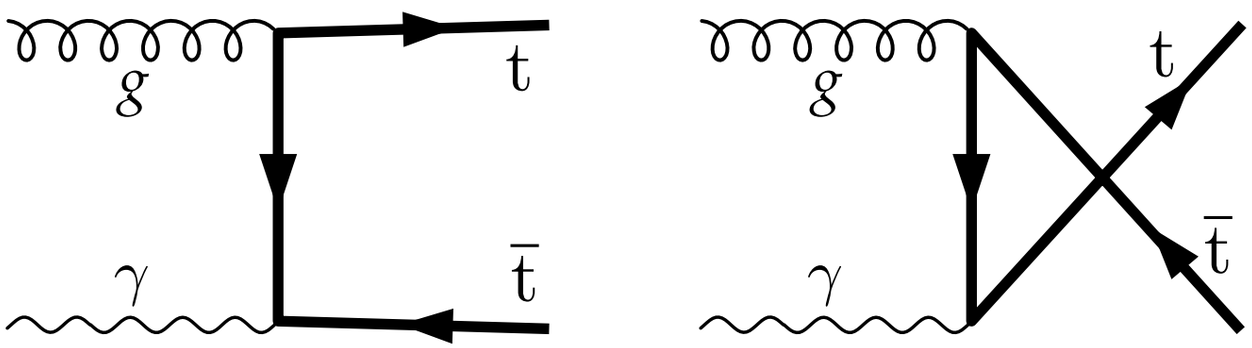
(d)



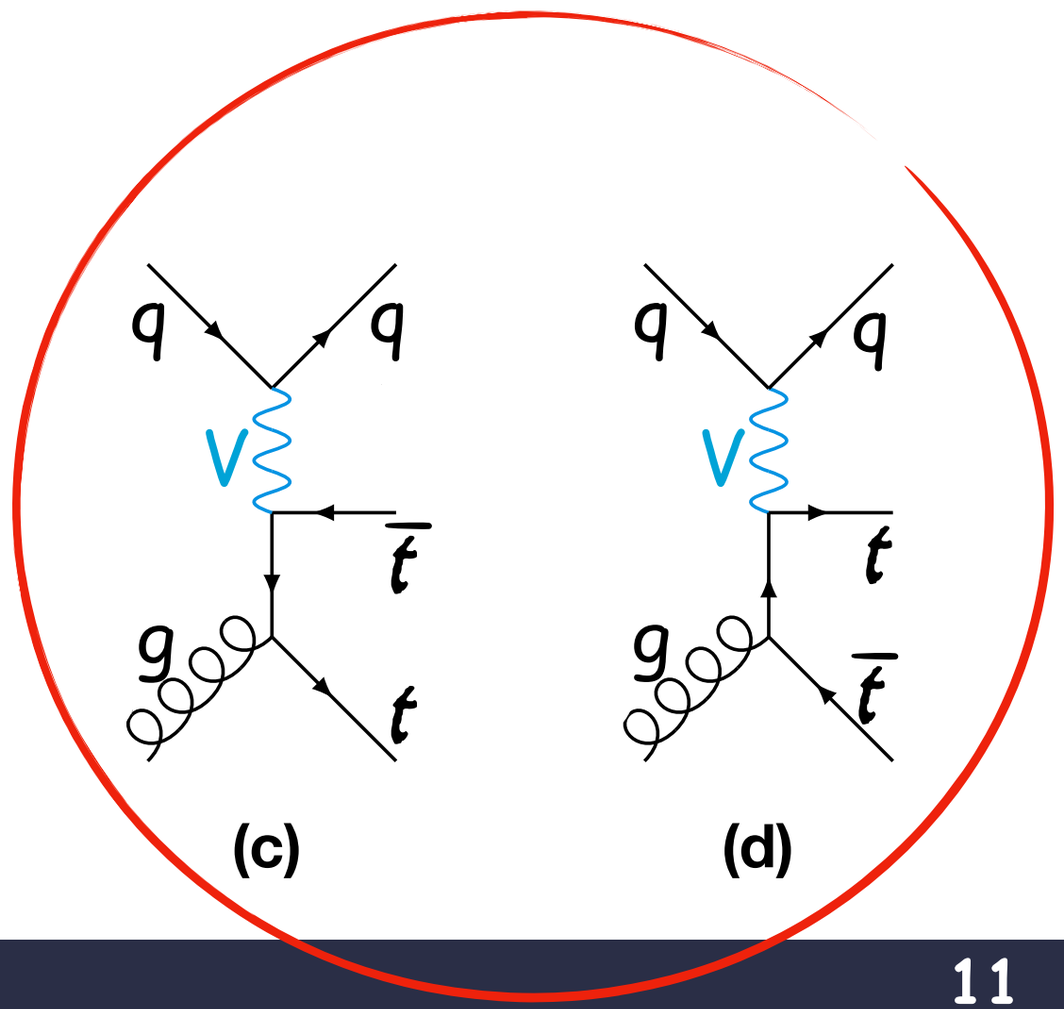
(e) (f) (g) (h)

Divergences

- The fact that **(c)** & **(d)** 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**



Numerical results: setup & input

- $\sqrt{s}$ = {14 TeV, 27 TeV, 50 TeV, 100 TeV}
- $m_{Z'(W')}$ = {2000 GeV, ..., 8000 GeV}
- m_t = 172.5 GeV
- **PDF** choice: NNPDF31_nlo_as_0118_luxqed
- $\mu_R^2 = \mu_F^2$ = shat
- **SSM**:
  - $\Gamma_{Z'}/m_{Z'}$ = 3%, $\Gamma_{W'}/m_{W'}$ = 3.3%
- **TC**:
  - $\Gamma_{Z'}/m_{Z'}$ = {3.1%, ..., 3.2%}
- **TFHMeg**:
  - $g_F/m_{Z'}$ = 0.265, θ_{sb} = 0.095, $\Gamma_{Z'} = \frac{5 g_F^2 M_{Z'}}{36\pi}$

Measurements vs Searches

Contur Category	$\mathcal{L}$ [fb^{-1}]	Rivet/Inspire ID	Highest SM Order	Rivet description
ATLAS 8 LMETJET	20.3	ATLAS_2015_I1397637 [44]	NLO	Boosted $t\bar{t}$ differential cross-section
ATLAS 8 LMETJET	20.3	ATLAS_2015_I1404878 [45]	NLO	$t\bar{t}$ (to l+jets) differential cross sections at 8 TeV
CMS 8 LMETJET	19.7	CMS_2017_I1518399 [46]	NLO	Differential $t\bar{t}$ cross-section as a function of the leading jet mass for boosted top quarks at 8 TeV
ATLAS 13 LMETJET	3.2	ATLAS_2017_I1614149 [50]	NNLO	Resolved and boosted $t\bar{t}$ l+jets cross sections at 13 TeV
ATLAS 13 LMETJET	3.2	ATLAS_2018_I1656578 [51]	NNLO	Differential $t\bar{t}$ l+jets cross-sections at 13 TeV
ATLAS 13 LMETJET	36	ATLAS_2019_I1750330 [49]	NNLO	Semileptonic $t\bar{t}$ at 13 TeV
CMS 13 LMETJET	2.3	CMS_2016_I1491950 [54]	NNLO	Differential $t\bar{t}$ cross sections using the lepton+jets final state in pp collisions at 13 TeV
CMS 13 LMETJET	35.9	CMS_2018_I1662081 [52]	NNLO	Differential $t\bar{t}$ cross sections as a function of kinematic event variables in pp collisions at 13 TeV
CMS 13 LMETJET	35.8	CMS_2018_I1663958 [43]	NNLO	$t\bar{t}$ lepton+jets 13 TeV
ATLAS 13 L1L2METJET	36.1	ATLAS_2019_I1759875 [48]	NNLO	Dileptonic $t\bar{t}$ at 13 TeV
ATLAS 13 TTHAD	36.1	ATLAS_2018_I1646686 [53]	NNLO	All-hadronic boosted $t\bar{t}$ at 13 TeV
CMS 13 TTHAD	35.9	CMS_2019_I1764472 [47]	NNLO	Differential $t\bar{t}$ cross section as a function of the jet mass and top quark mass in boosted hadronic top quark decays
ATLAS 13 JETS	3.2	ATLAS_2018_I1634970 [55]	NLO	ATLAS inclusive jet and dijet cross section measurement at 13 TeV

Category	$\mathcal{L}$ [fb^{-1}]	decay channels
CMS 13	35.9	Leptonic and hadronic decays of the top
ATLAS 13	139	Fully hadronic decay channel only
ATLAS 13	36.1	Fully hadronic decay mode
ATLAS 13	36.1	Semileptonic decay mode