UNIVERSITÉ Grenoble Alpes

WWU MÜNSTER

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Moriond 2021

Constraining models with extra heavy gauge bosons using LHC measurements

Mohammad Mahdi ALTAKACH

In collaboration with J.M. Butterworth, T. Jezo, M. Klasen, J.-N. Lang, and I. Schienbein

30 Mar 2021

MCnet

DAAD

EW top pair hadroproduction 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:2012.14855]

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

The calculation

- We performed a **complete new calculation** of **EW** **top** pair production at the **LHC** including a **number of 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** (**MCEG**) (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

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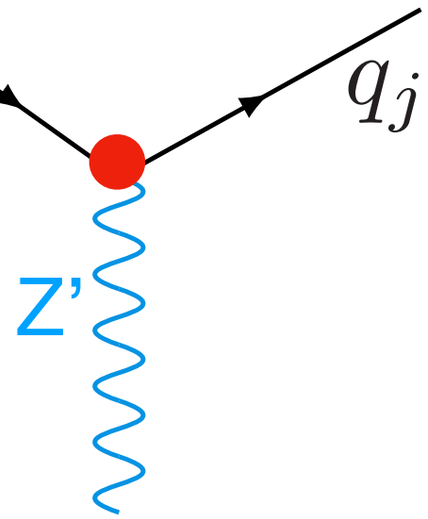
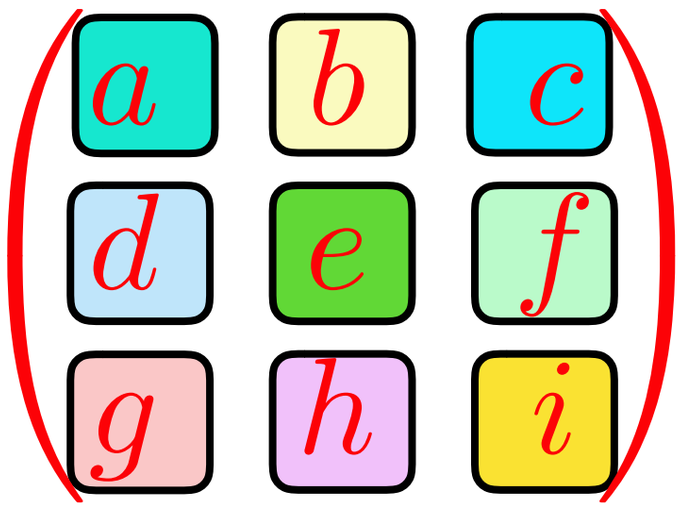
- We performed a **complete new calculation** of **EW** **top** pair production at the **LHC** including a **number of improvements** with respect to a previous one done in [arXiv:1511.08185]:
  - The new code can deal with **general couplings** for both **Z'** & **W'**





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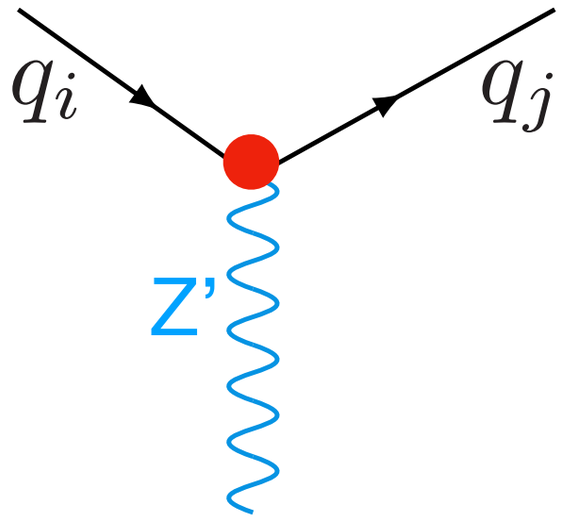

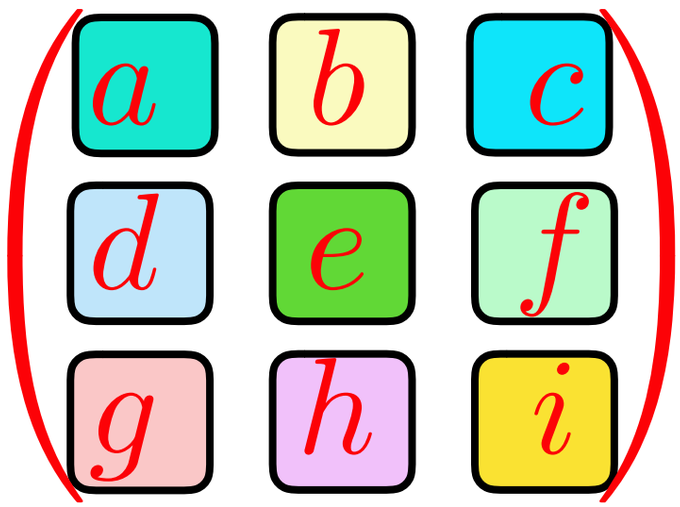

  - **Standard Model** (γ, **Z**, **W**) and **new physics** (**Z'**,**W'**) **interference effects** taken into account

The new calculation was validated against the old one finding

Full agreement

Top-pair hadroproduction

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

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

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Our Calculation

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- $\sigma_{0;3}$: **EW** corrections to **EW** **top-quark** pair production

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

A. Buckley et al. [arXiv:2102.04377]

Contur

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

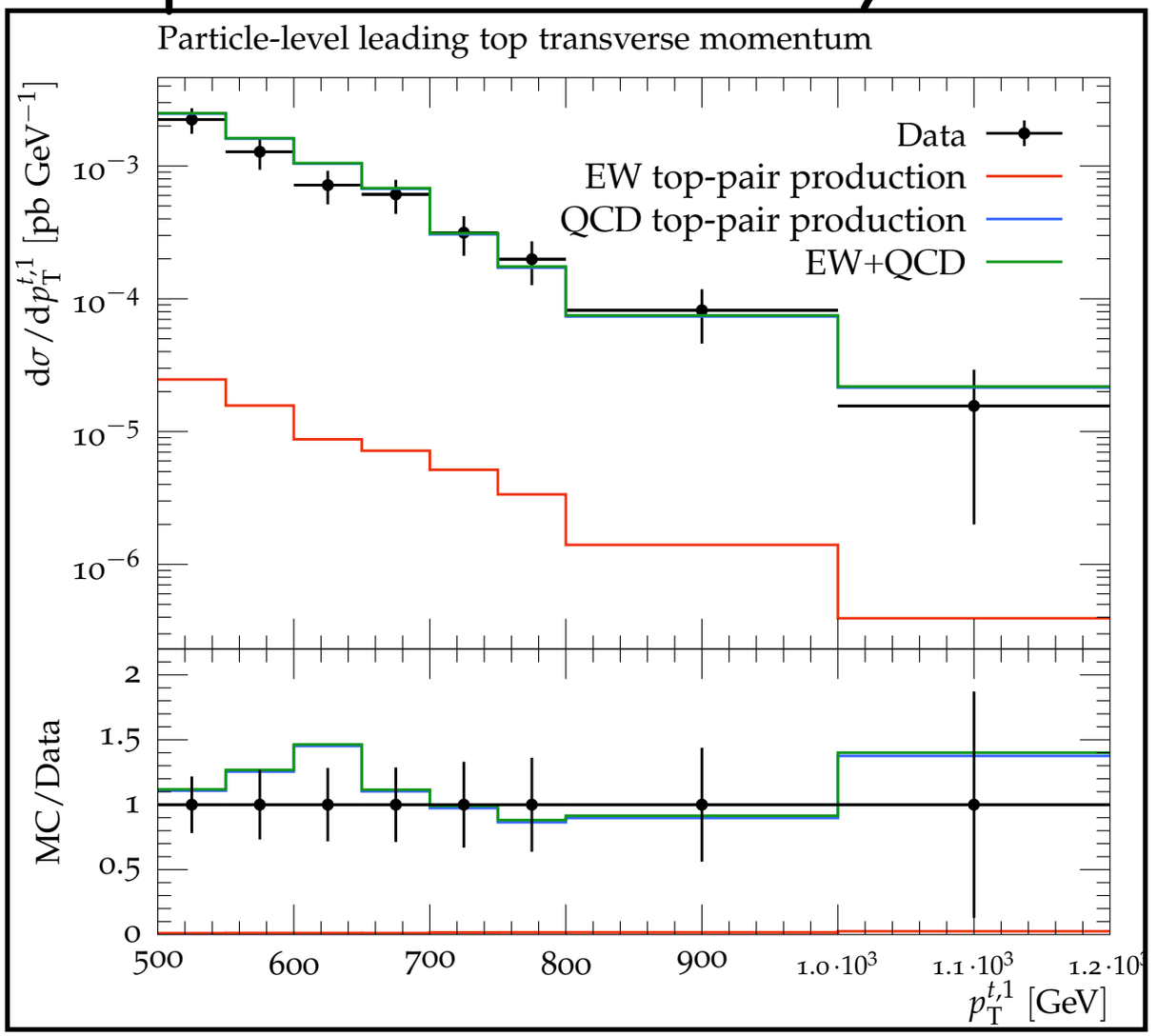
- **C**onstraints **O**n **N**ew **T**heories **U**sing **R**ivet

- 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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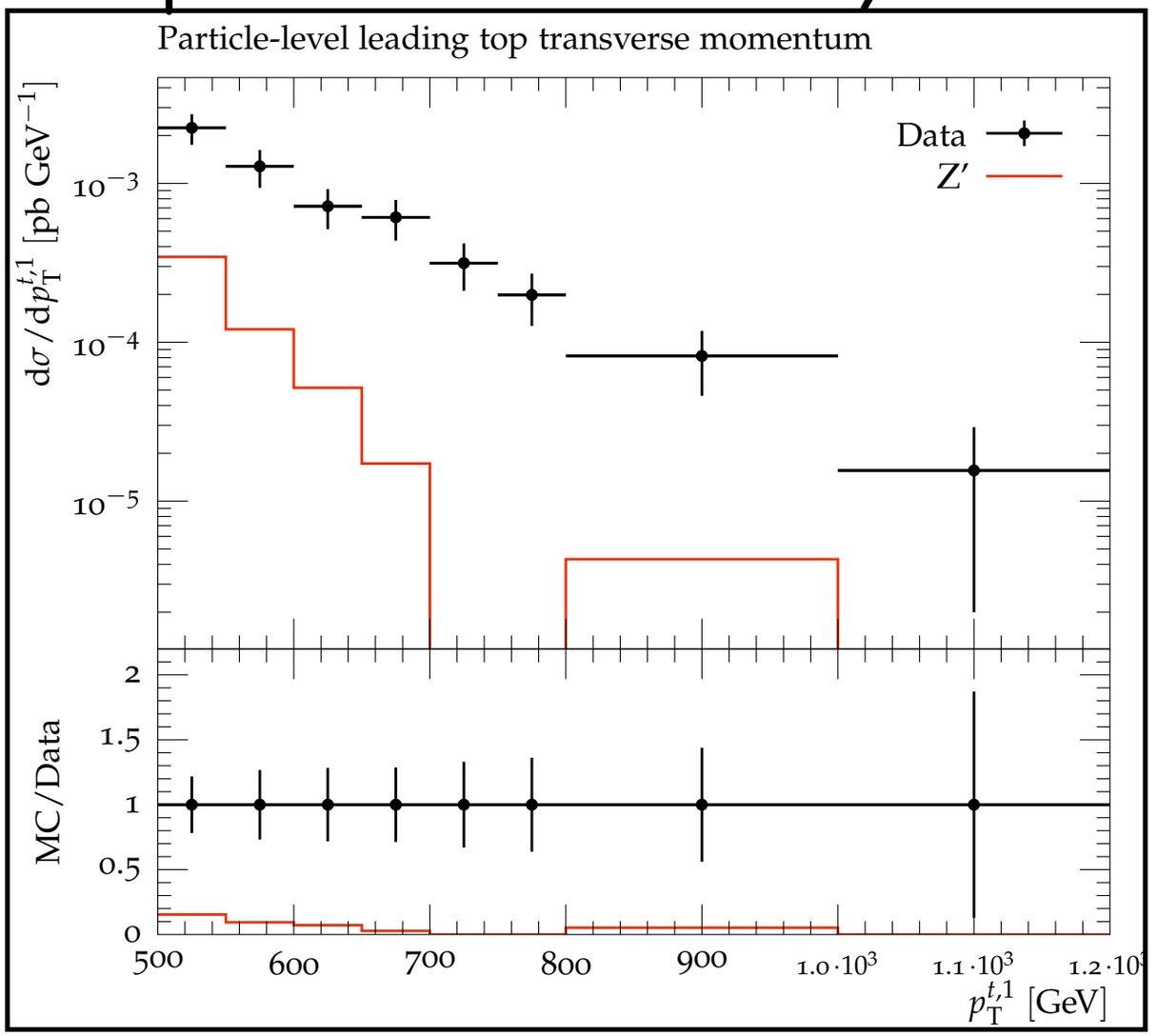

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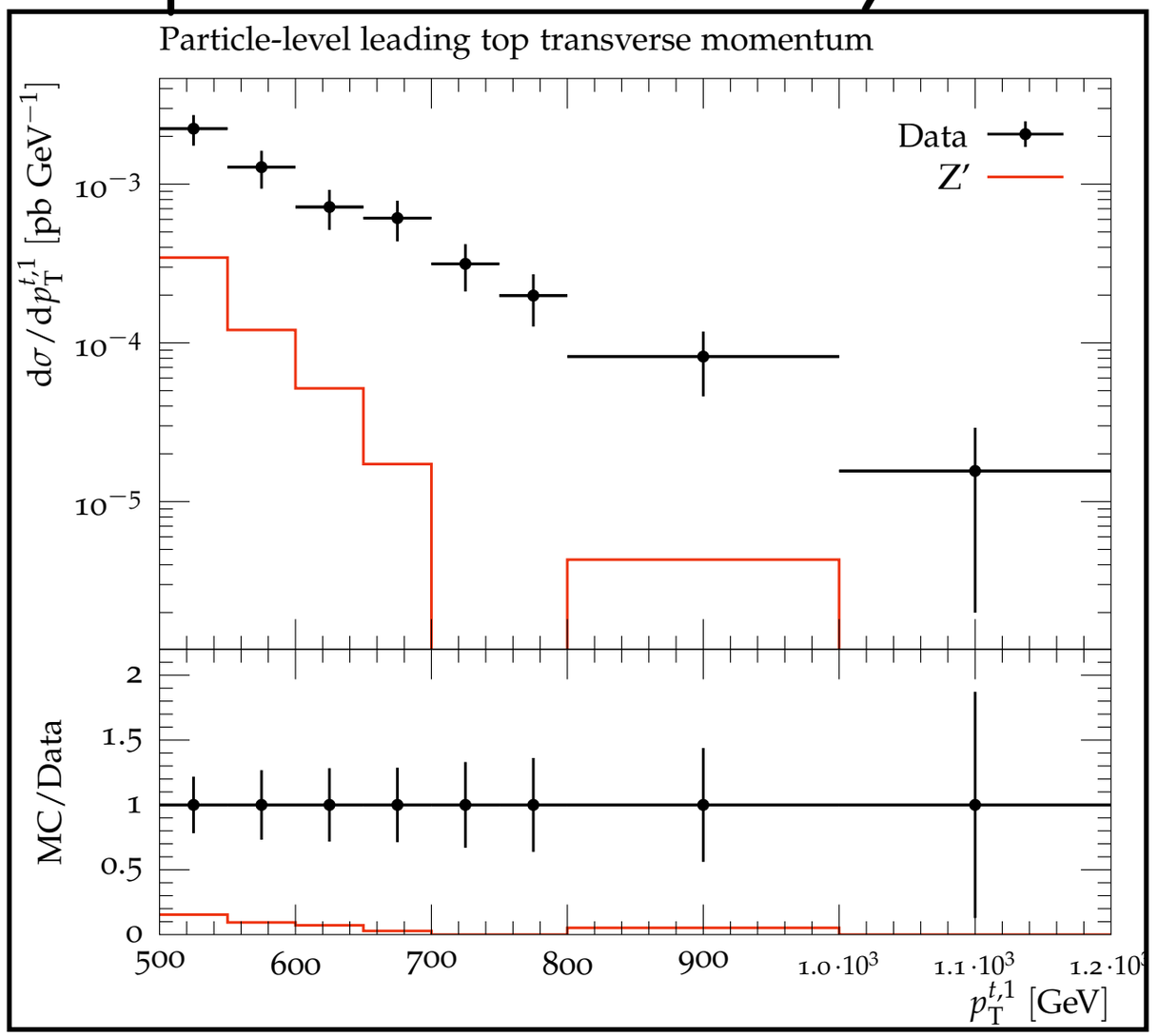
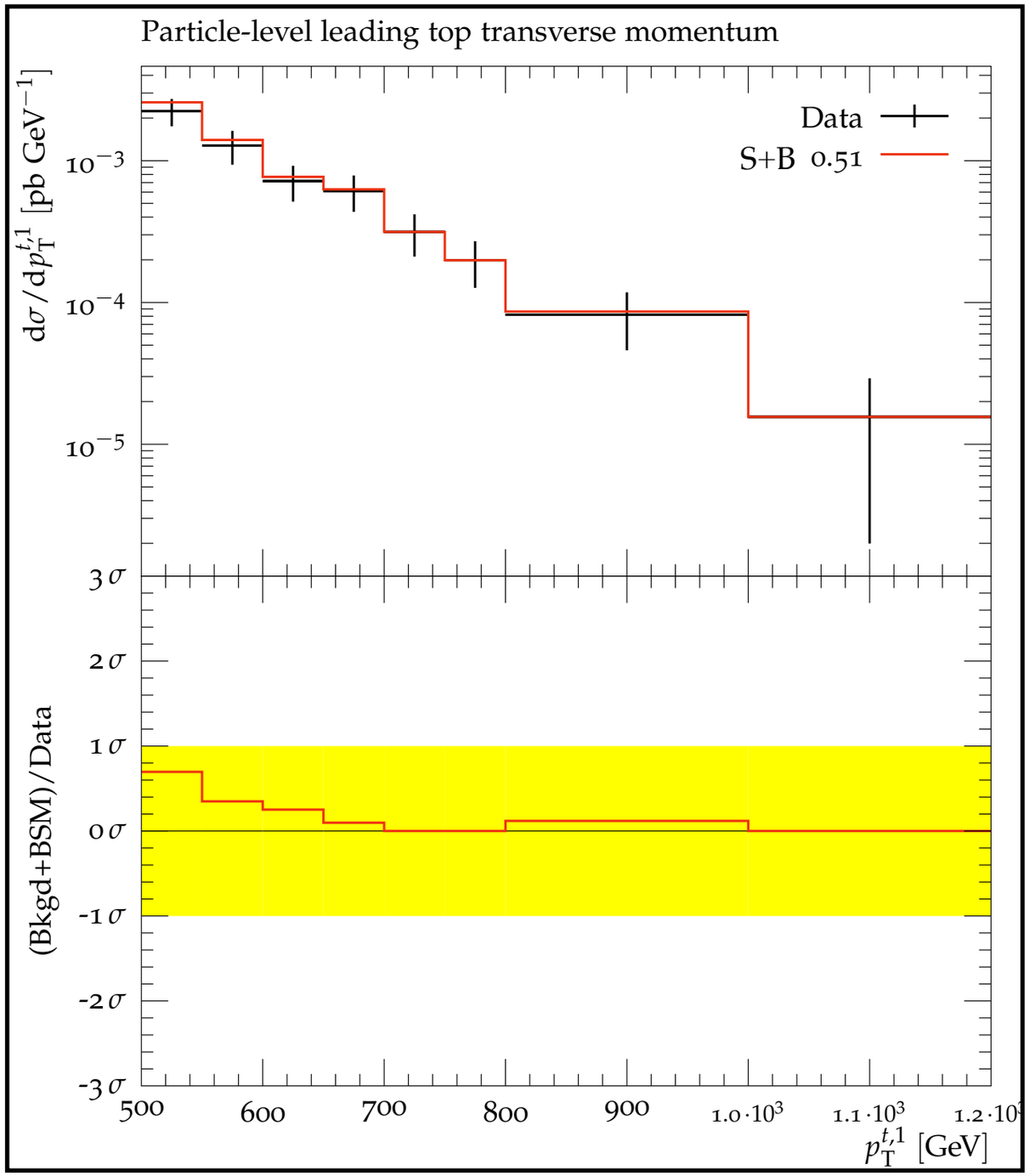


Contur uses bank of **LHC** results preserved in **Rivet** to rapidly check if new models are already ruled out

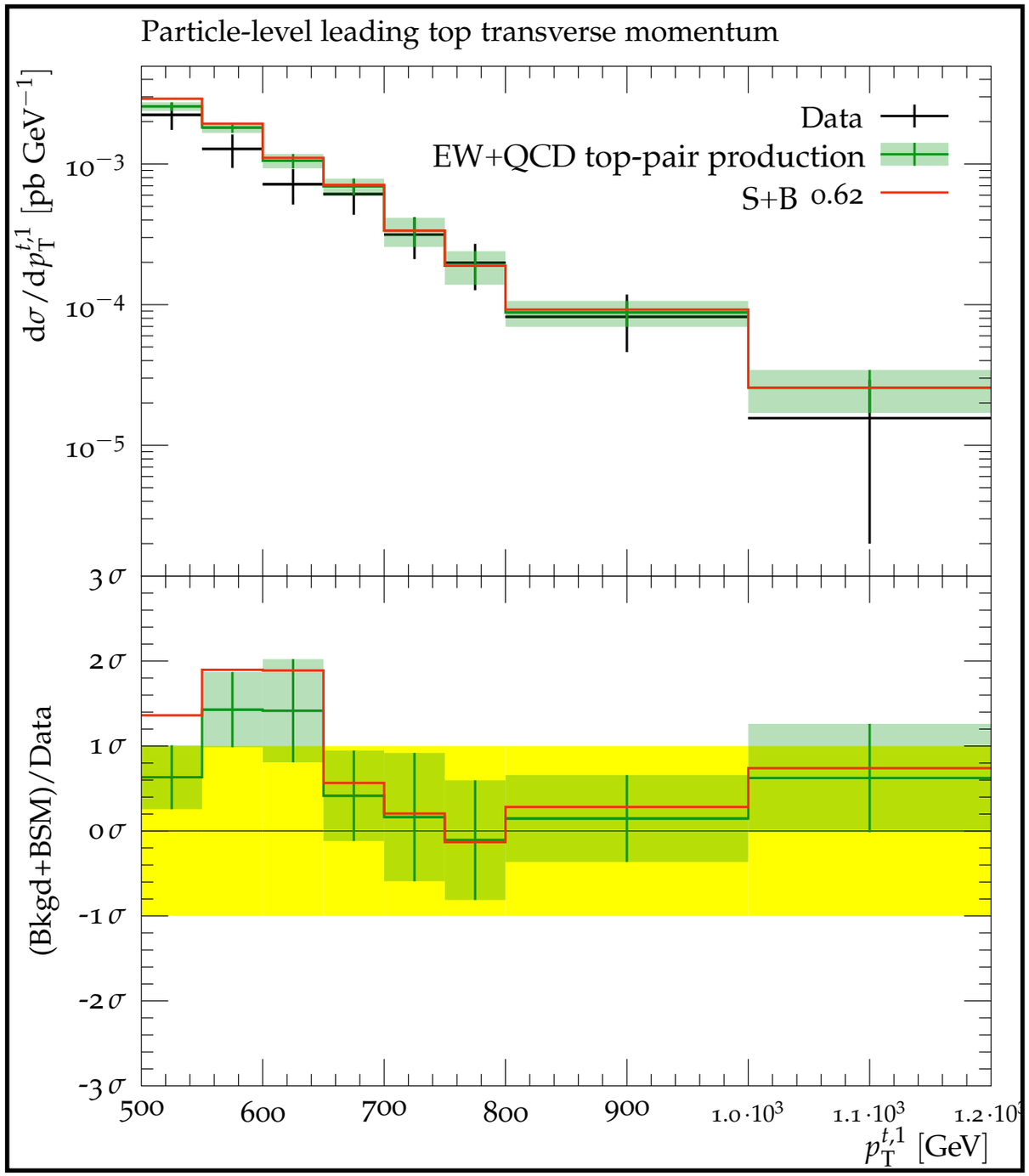
The Contur method

- **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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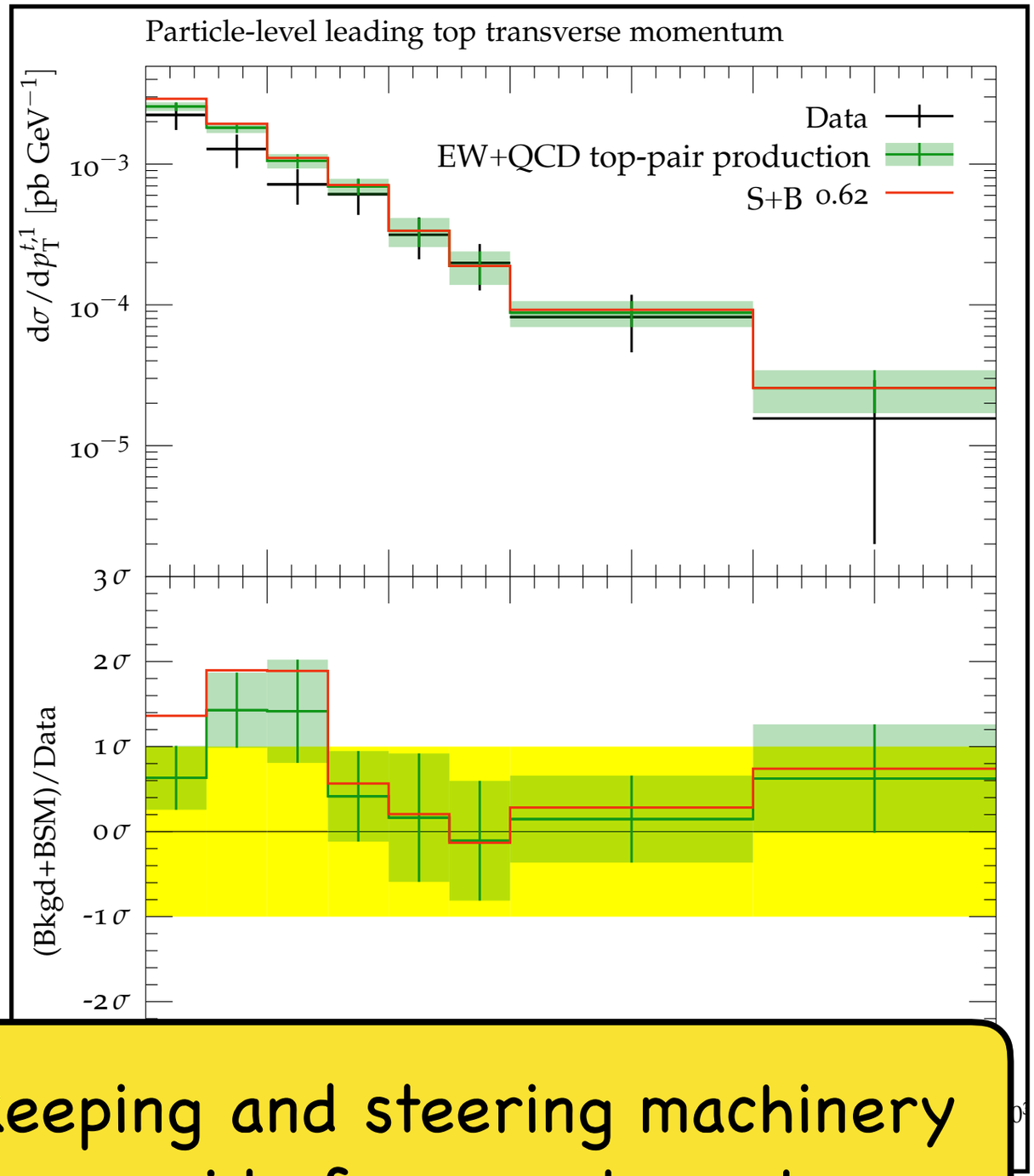

Contur provides the book-keeping and steering machinery to repeat this process over a grid of parameter values

Constraints on theories with extra Z' boson in the top pair final state using Contur

M. M. AlTakach, J.M. Butterworth, T. Jezo, M. Klasen, I. Schienbein [arXiv:21xx.xxxx]

The tool-chain

- The exclusion limits on **BSM** models with extra **Z'** bosons in the **top** pair final state are obtained as follows:

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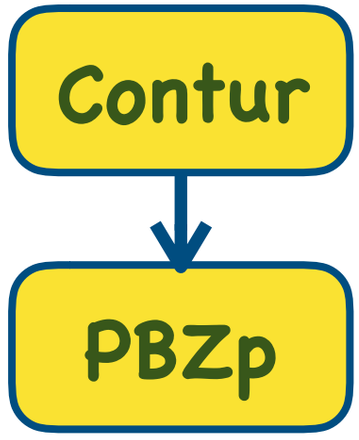

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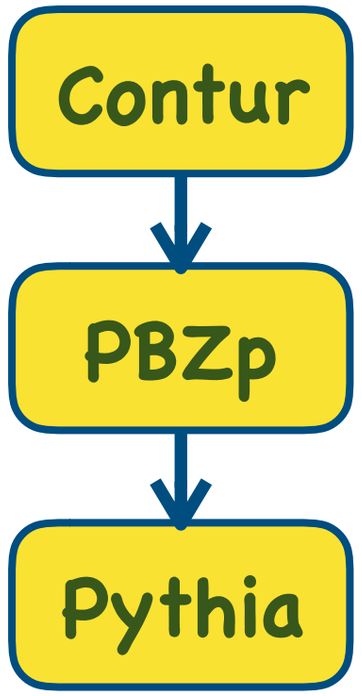

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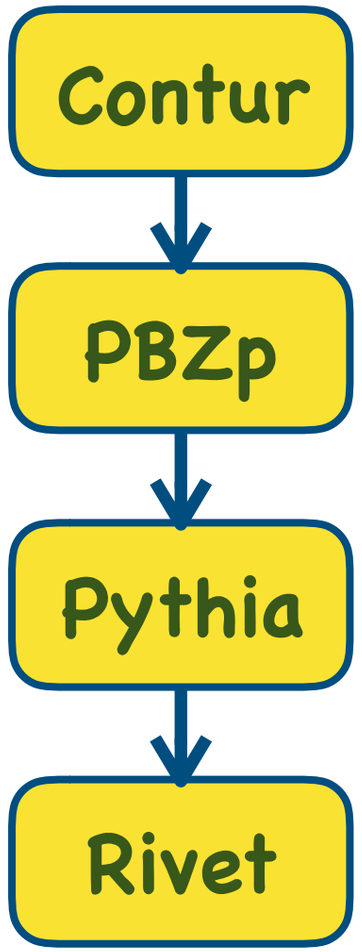

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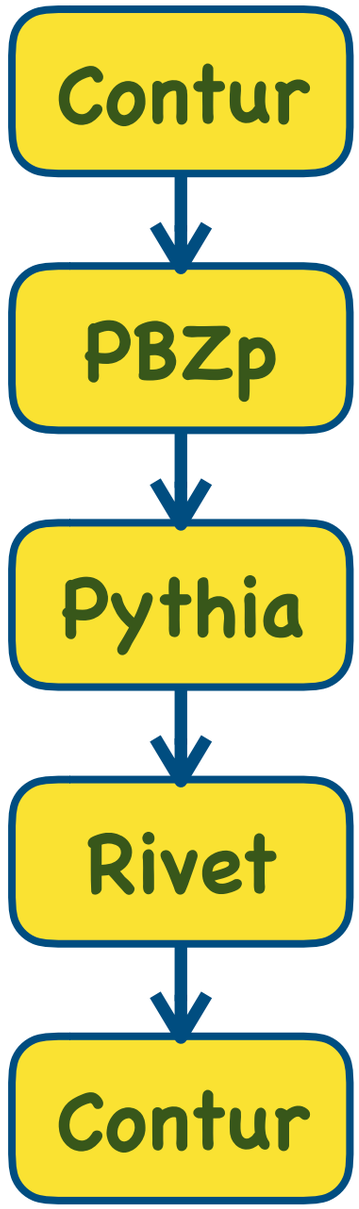
  - **Contur**: Compares the size of any deviation to the background for each set of parameters and gives an exclusion limit. Combines the limits of all the sets into one map



An illustrative example

Leptophobic Topcolour 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

- 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 $\Gamma_{Z'}/M_{Z'} = 30\%$ (10%, 1%) [arXiv: 1810.05905v2]

An illustrative example

Leptophobic Topcolour model (TC) [arXiv:1112.4928]:

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

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

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

An illustrative example

Leptophobic Topcolour model (TC) [arXiv:1112.4928]:

- Input parameters:
  - $M_{Z'}$ = {1000 GeV, ..., 5000 GeV}
  - $\Gamma_{Z'}/M_{Z'}$ = {1%, ..., 30%}

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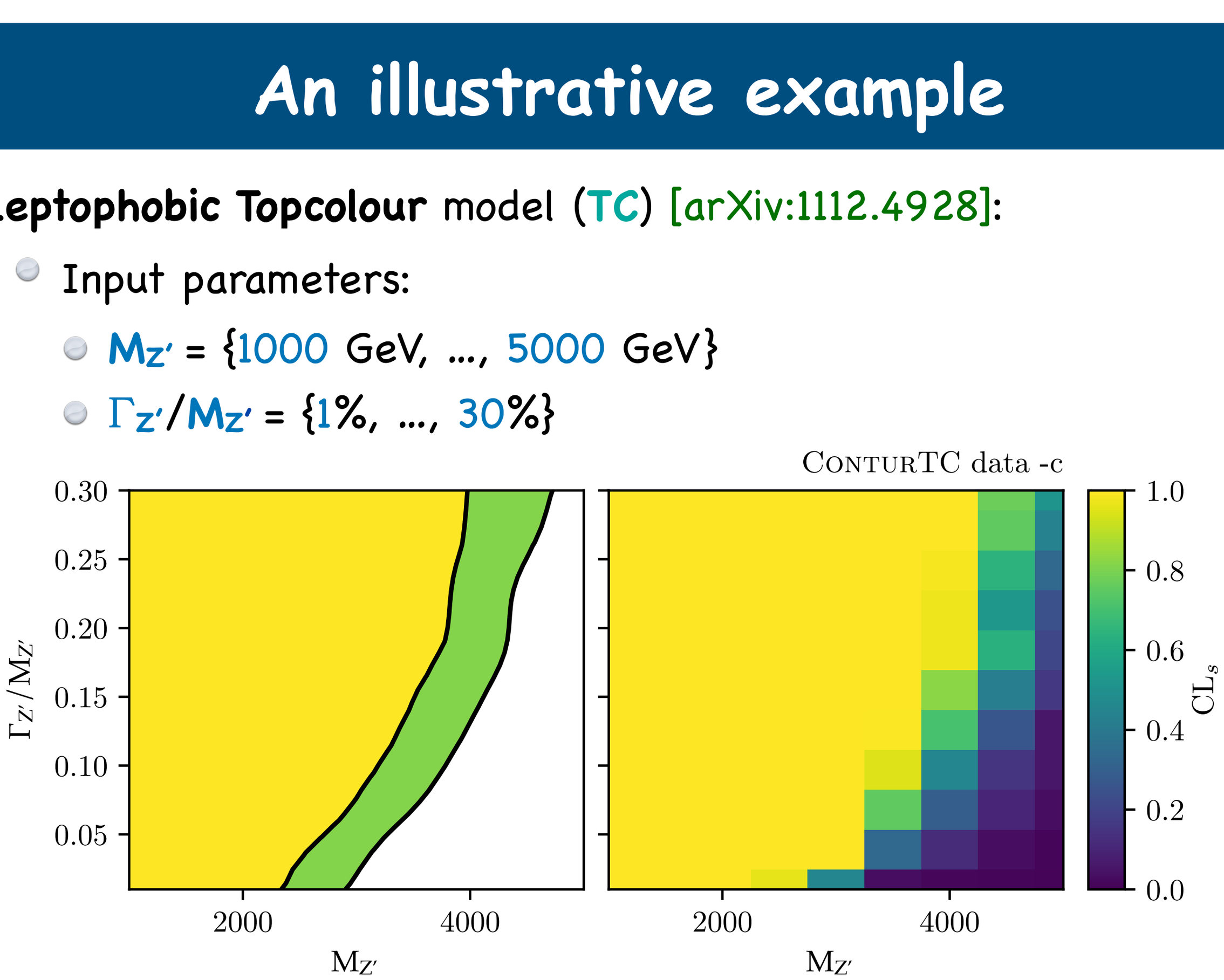

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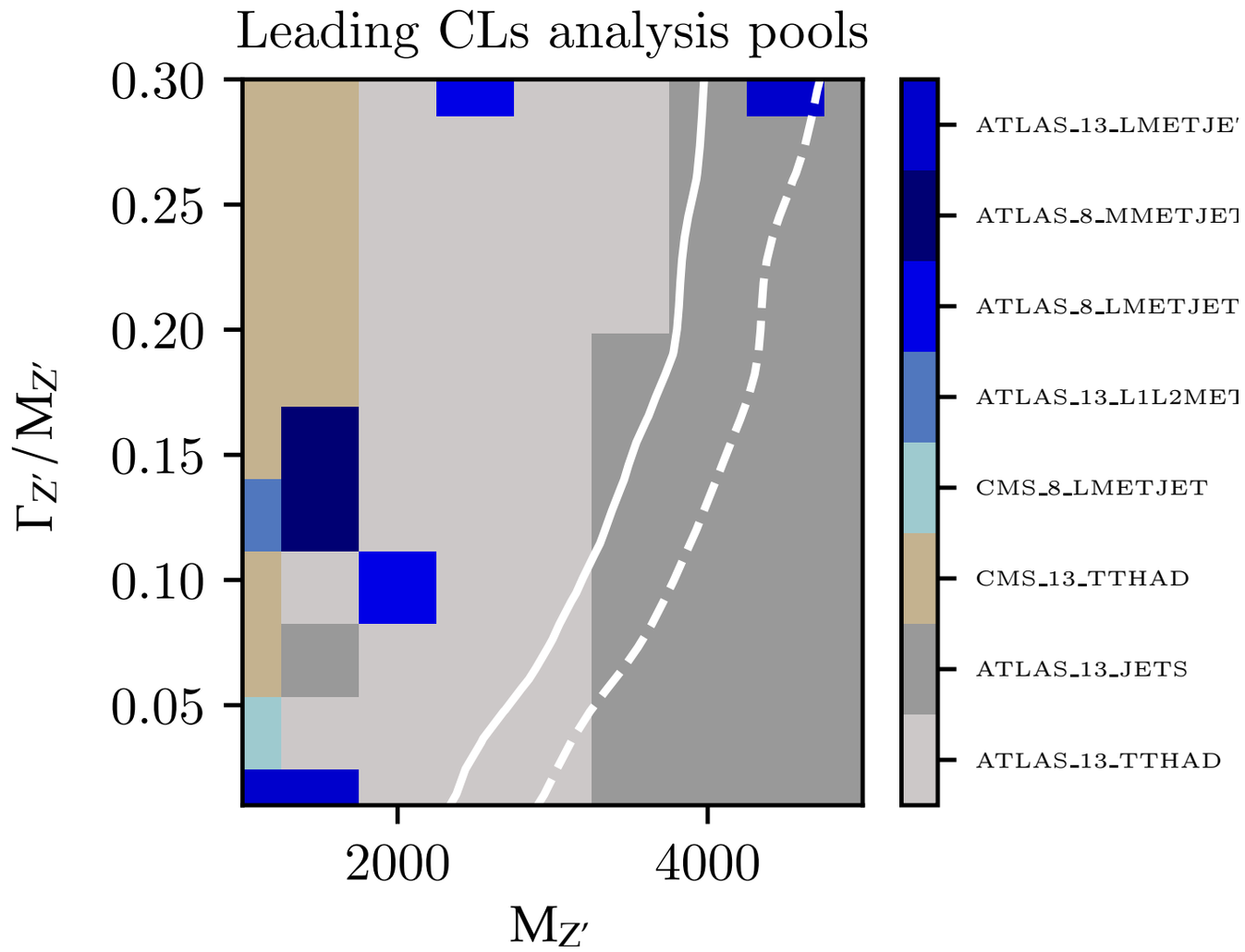
Colours indicate dominant pool of LHC analyses in each point of param space



Summary

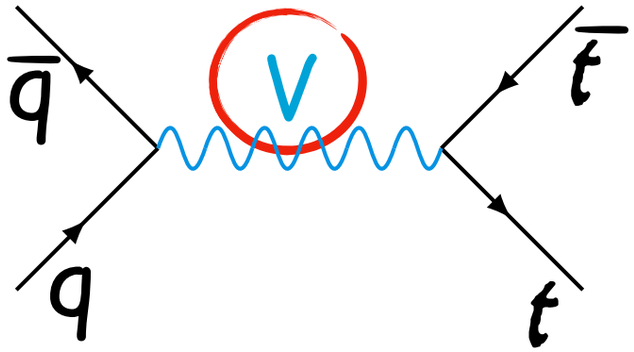
- Presented a complete re-calculation of **NLO QCD** corrections to **EW top** pair production using **Recola2** in the presence of **Z'** and **W'** bosons:
  - **Z'** and **W'** with **general couplings**
  - **t-channel W** contributions are included
  - **Standard Model** and **new physics interference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

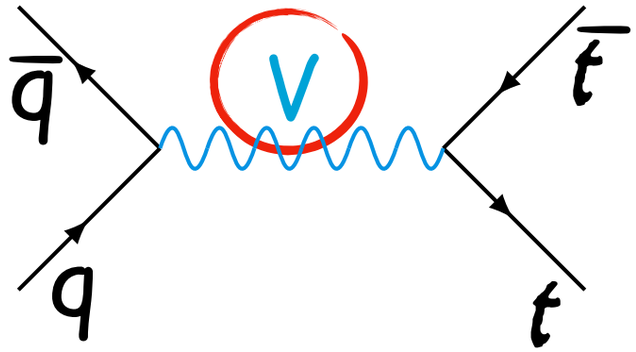
- Presented a **complete chain** of **tools** that allows us to obtain **exclusion limits** for **BSM** models with an extra **Z'** boson in the **top** pair channel

Backup slides

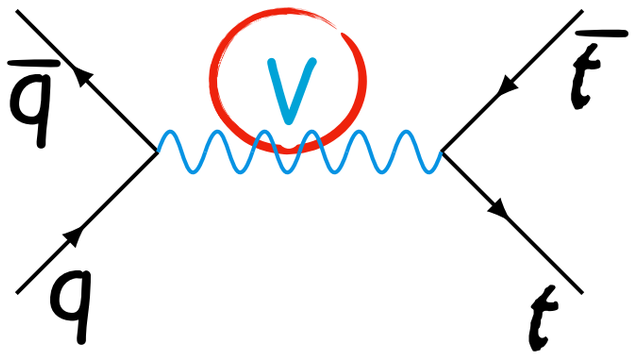
Subprocesses (5 FNS)

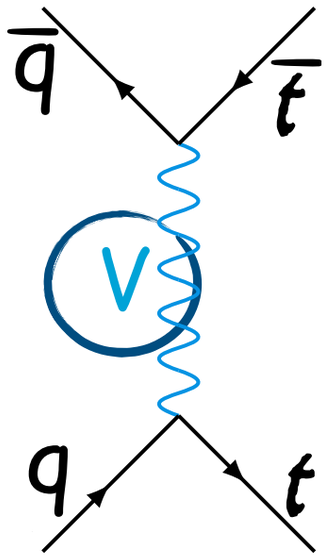
Born (0QCD4EW0BSM)





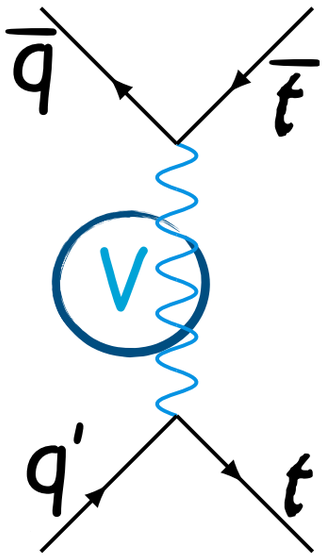
γ, Z

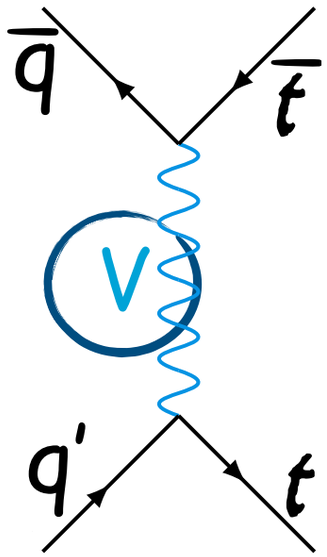




γ, Z

W



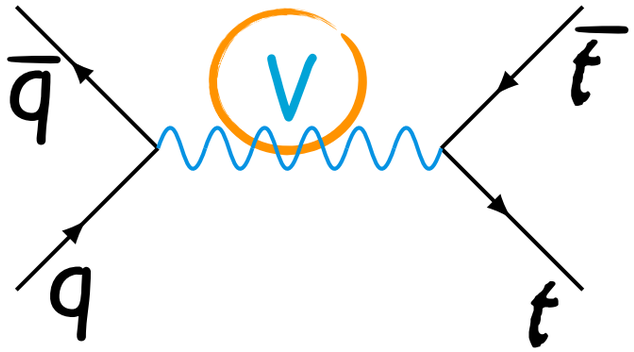


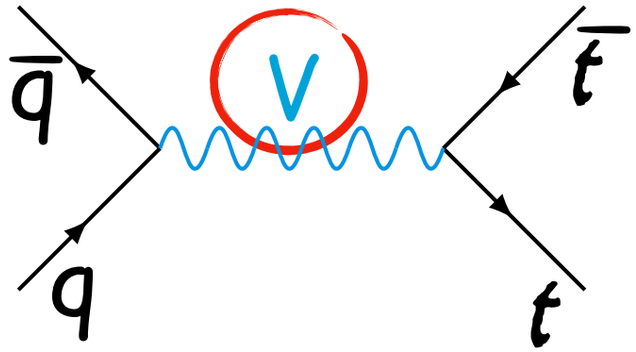
W

Subprocesses (5 FNS)

Born (0QCD4EW2BSM)

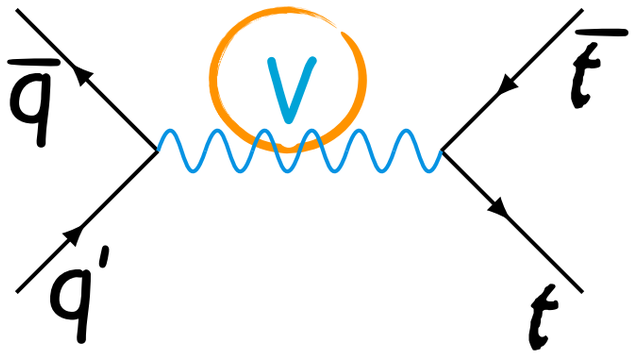
Z′

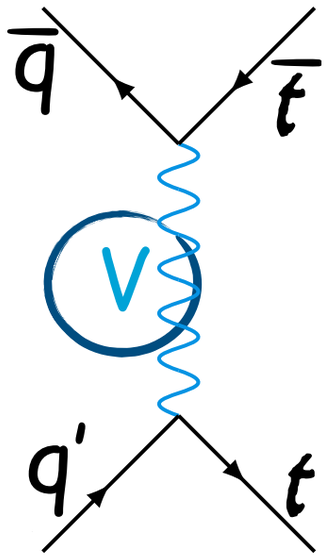




γ, Z

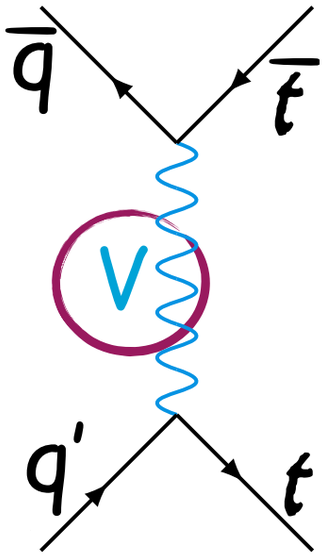
Z′

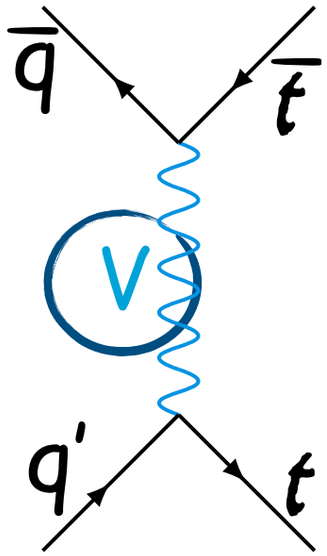




W

W′



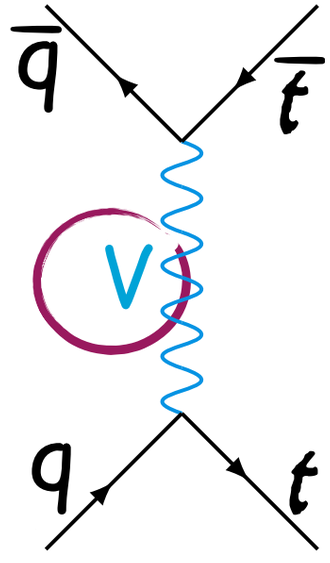


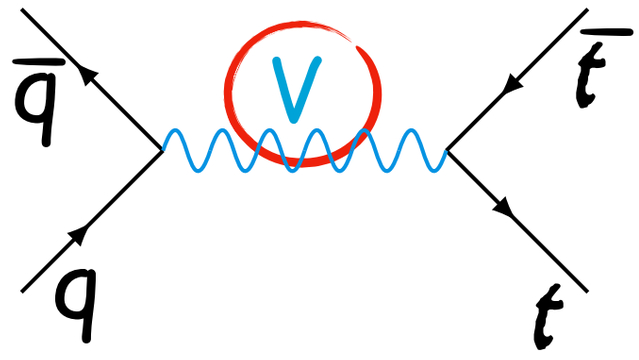
W

Subprocesses (5 FNS)

Born (0QCD4EW2BSM)

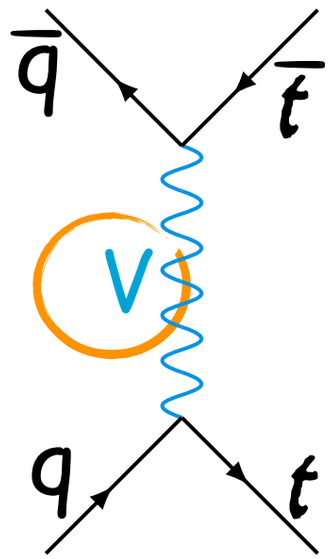
W′

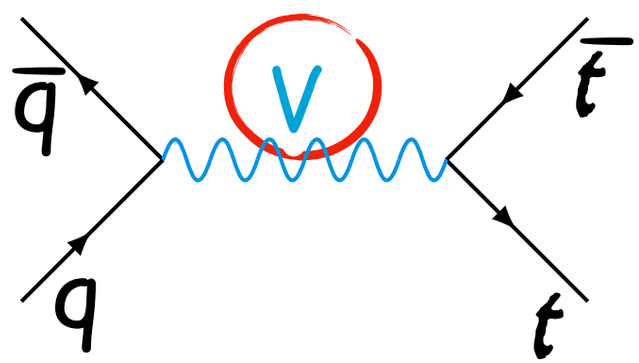




γ, Z

Z′



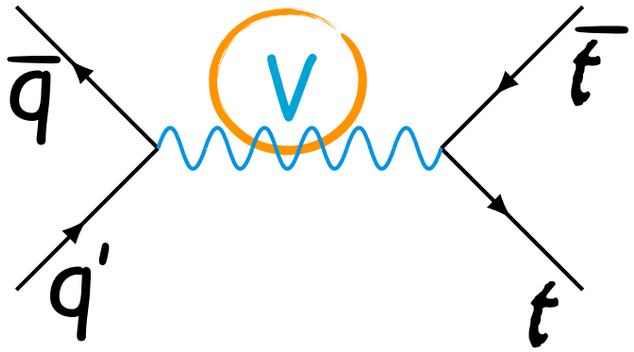


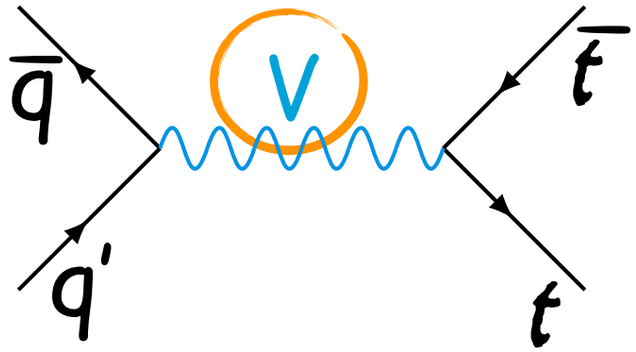
γ, Z

Subprocesses (5 FNS)

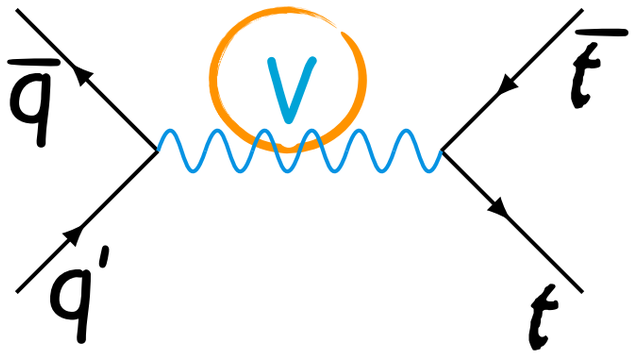
Born (0QCD4EW4BSM)

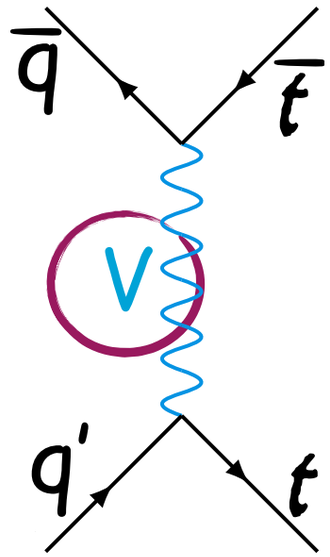
Z′



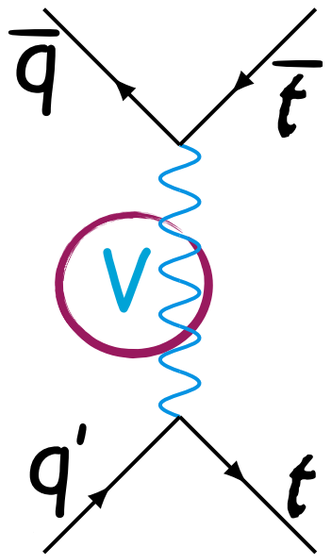


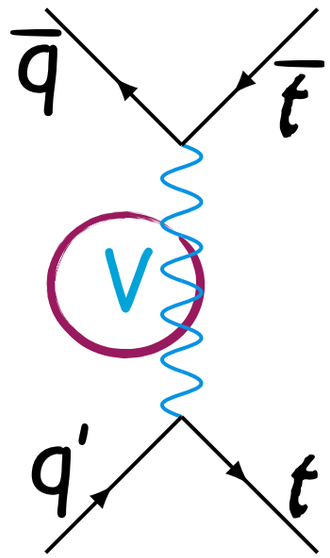
Z′





W′

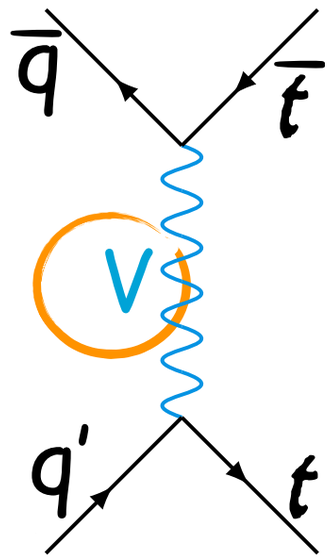


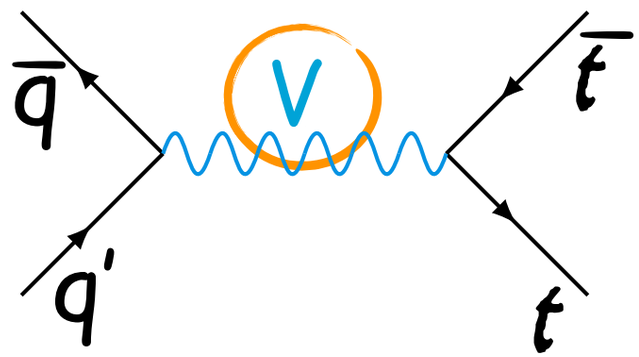


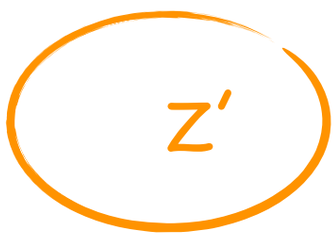
W′

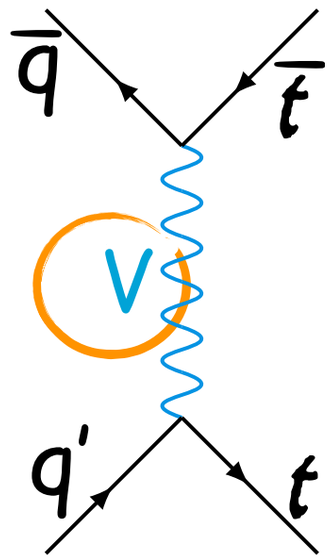
Subprocesses (5 FNS)

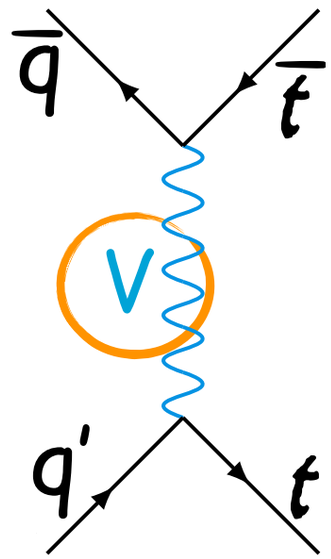
Born (0QCD4EW4BSM)











Subprocesses (5 FNS)

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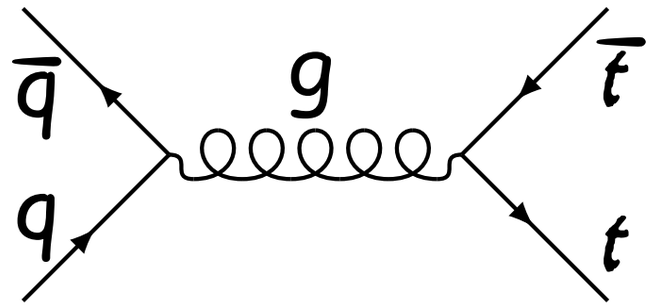

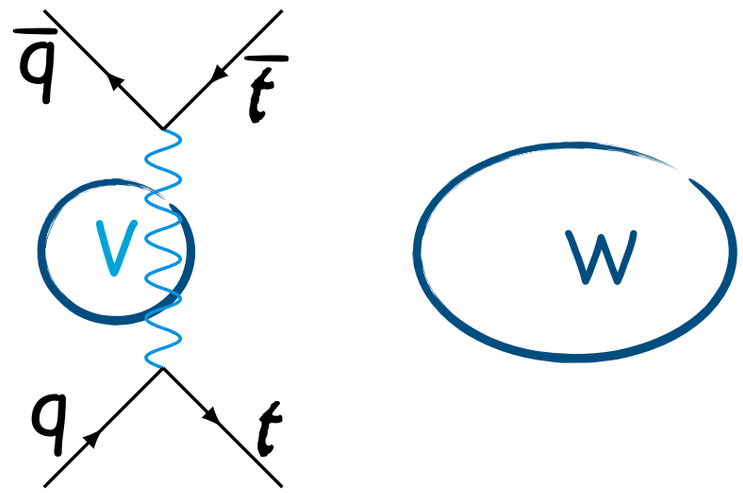

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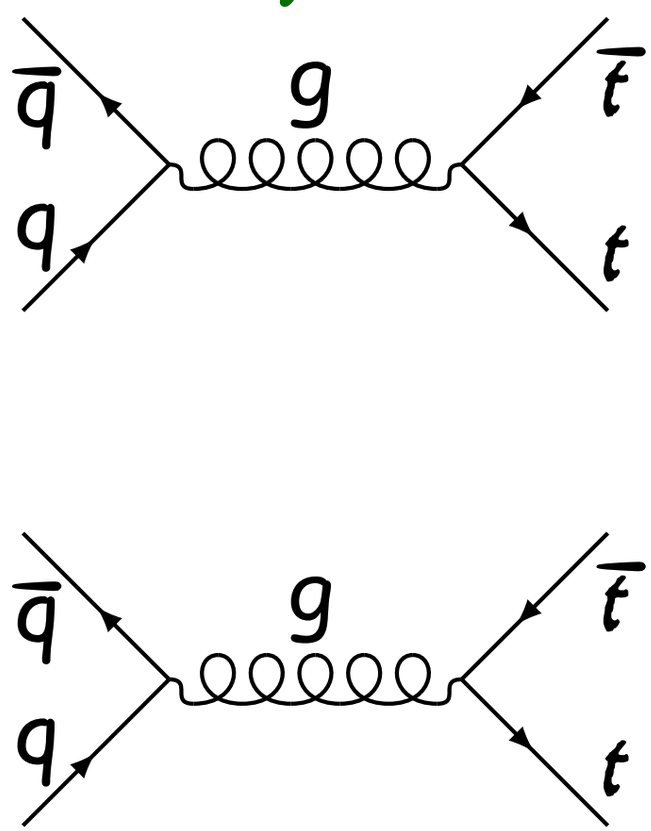
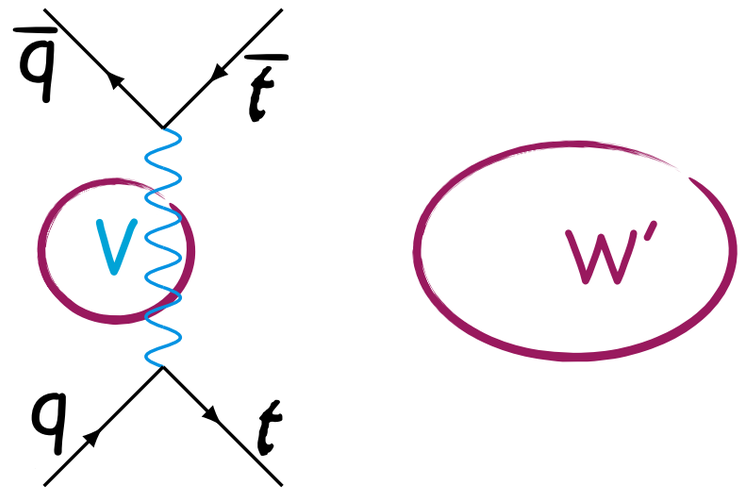
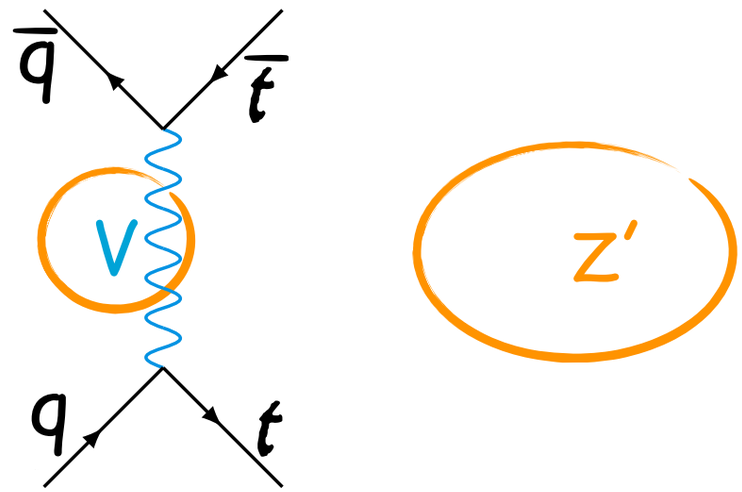
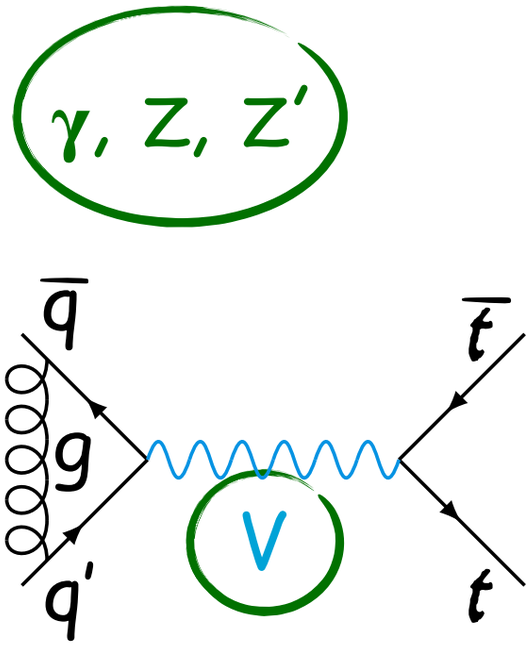




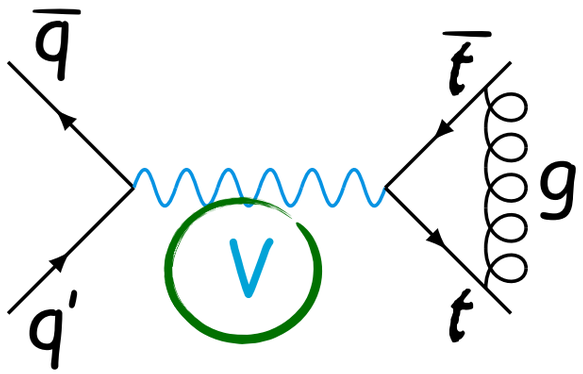


Subprocesses (5 FNS)

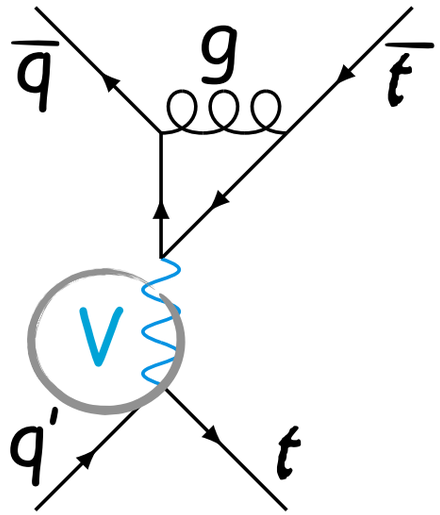
Virtual



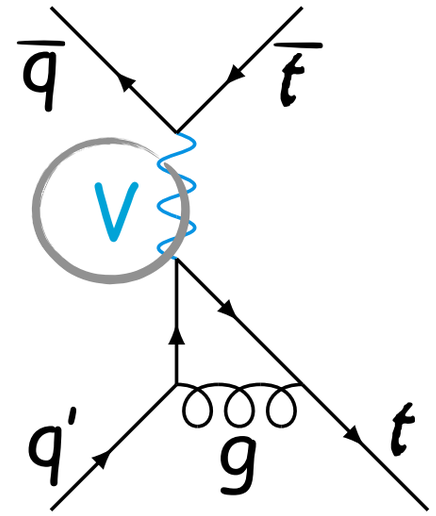
(a)



(b)



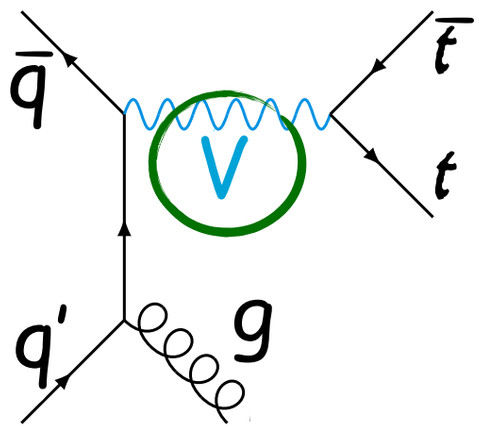
(c)



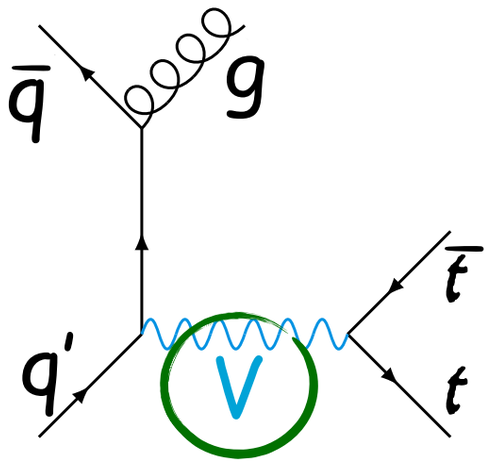
(d)

Subprocesses (5 FNS)

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



(a)



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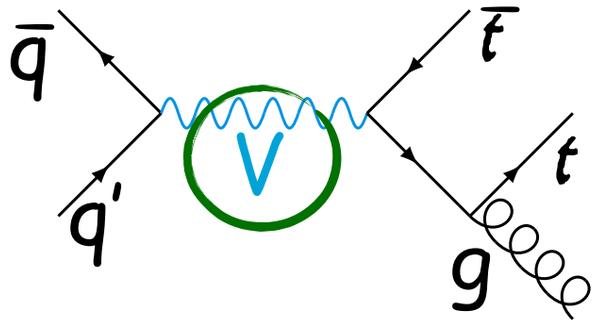
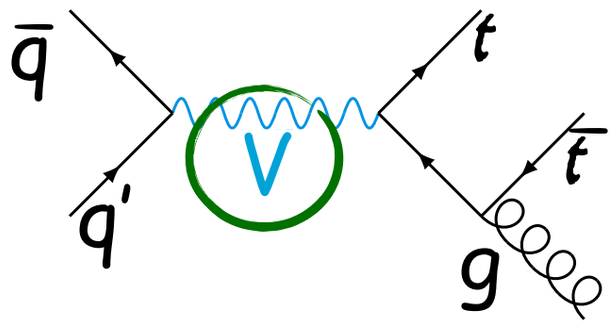


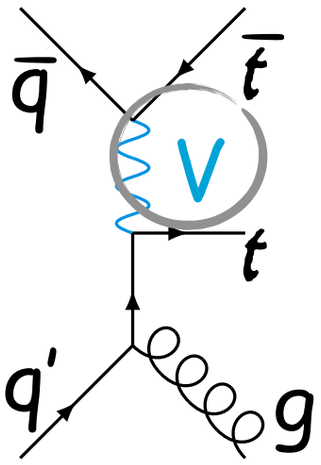
(c)



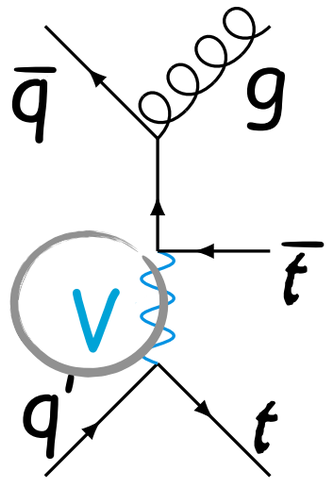
(d)

γ, Z, Z'

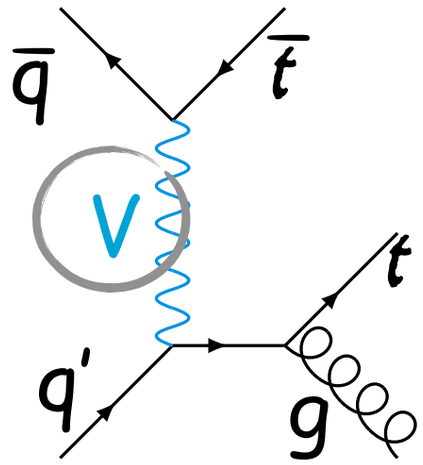
W, W',Z'



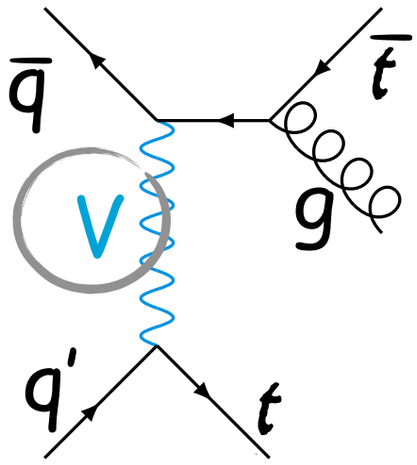
(e)



(f)



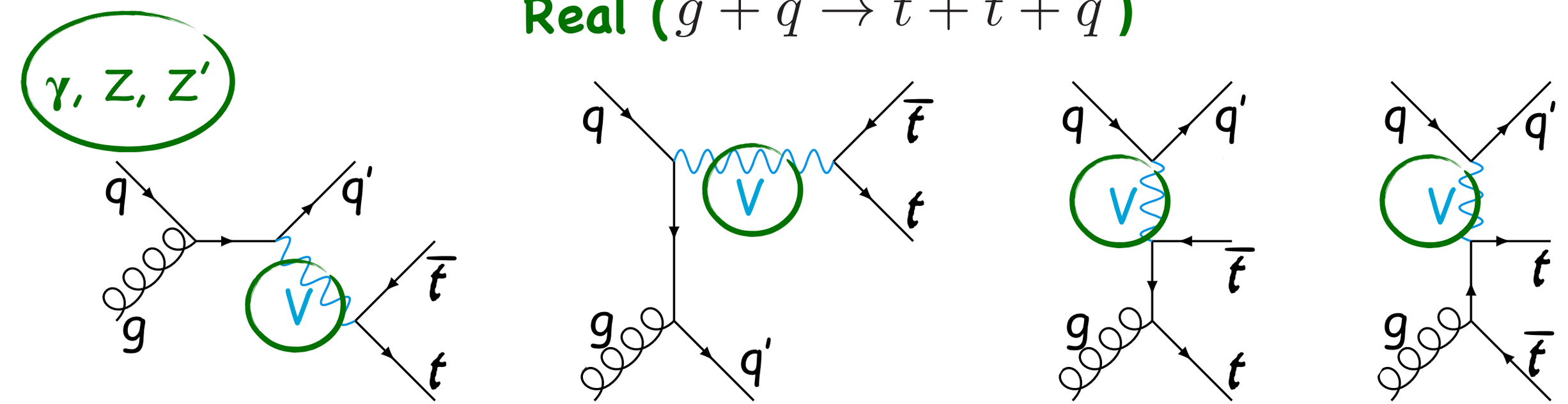
(g)



(h)

Subprocesses (5 FNS)

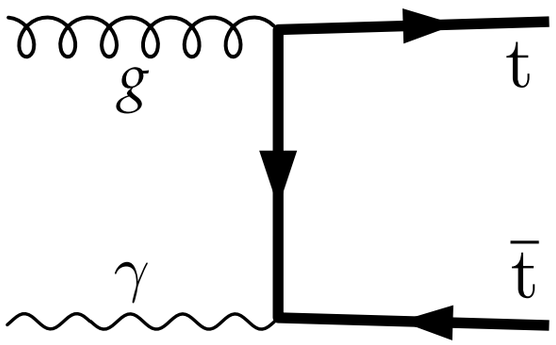
Real ($g + q \to t + \bar{t} + q'$)

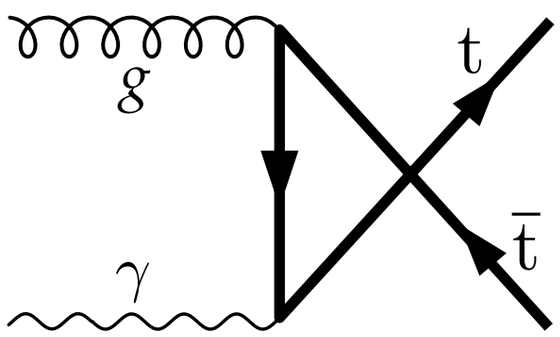


Subprocesses (5 FNS)

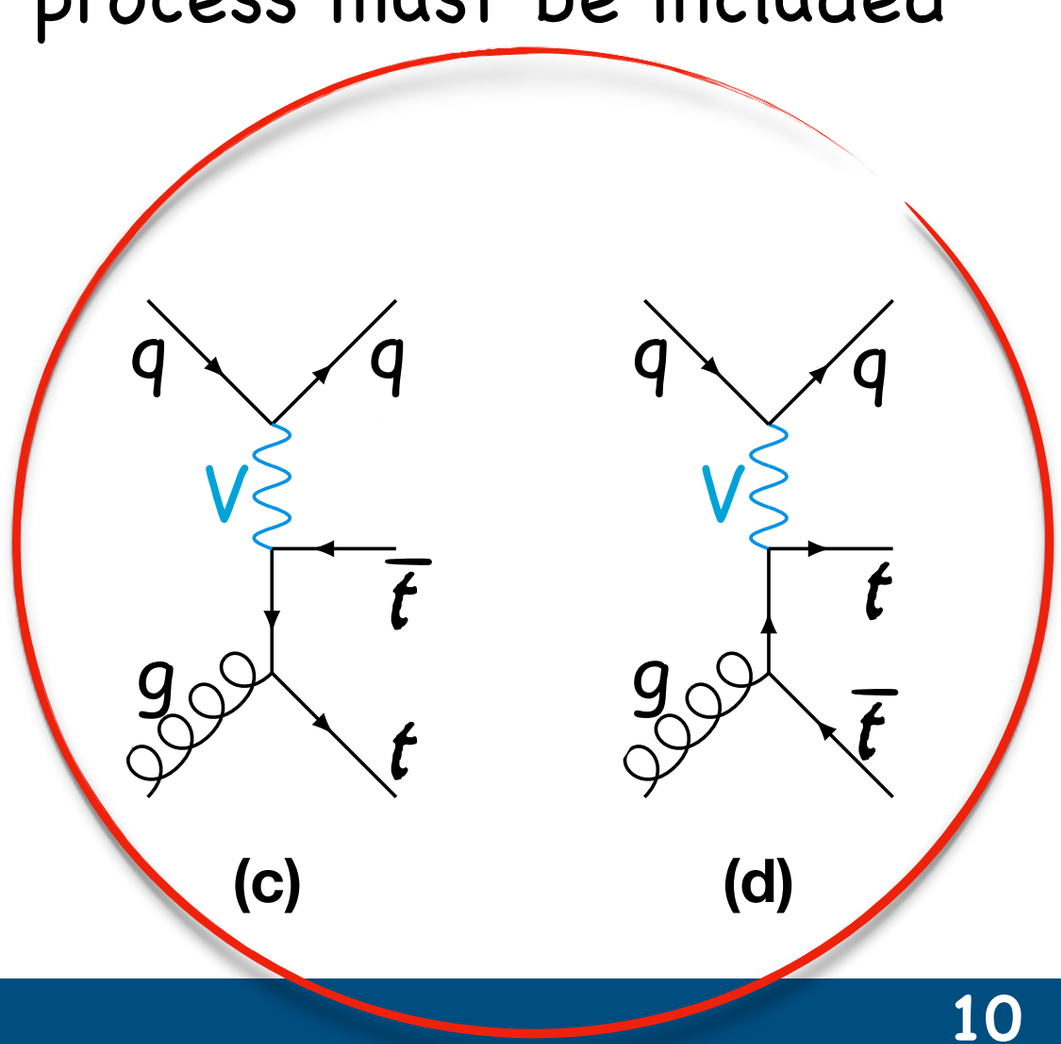
QED contribution

- 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**



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

Setup & 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

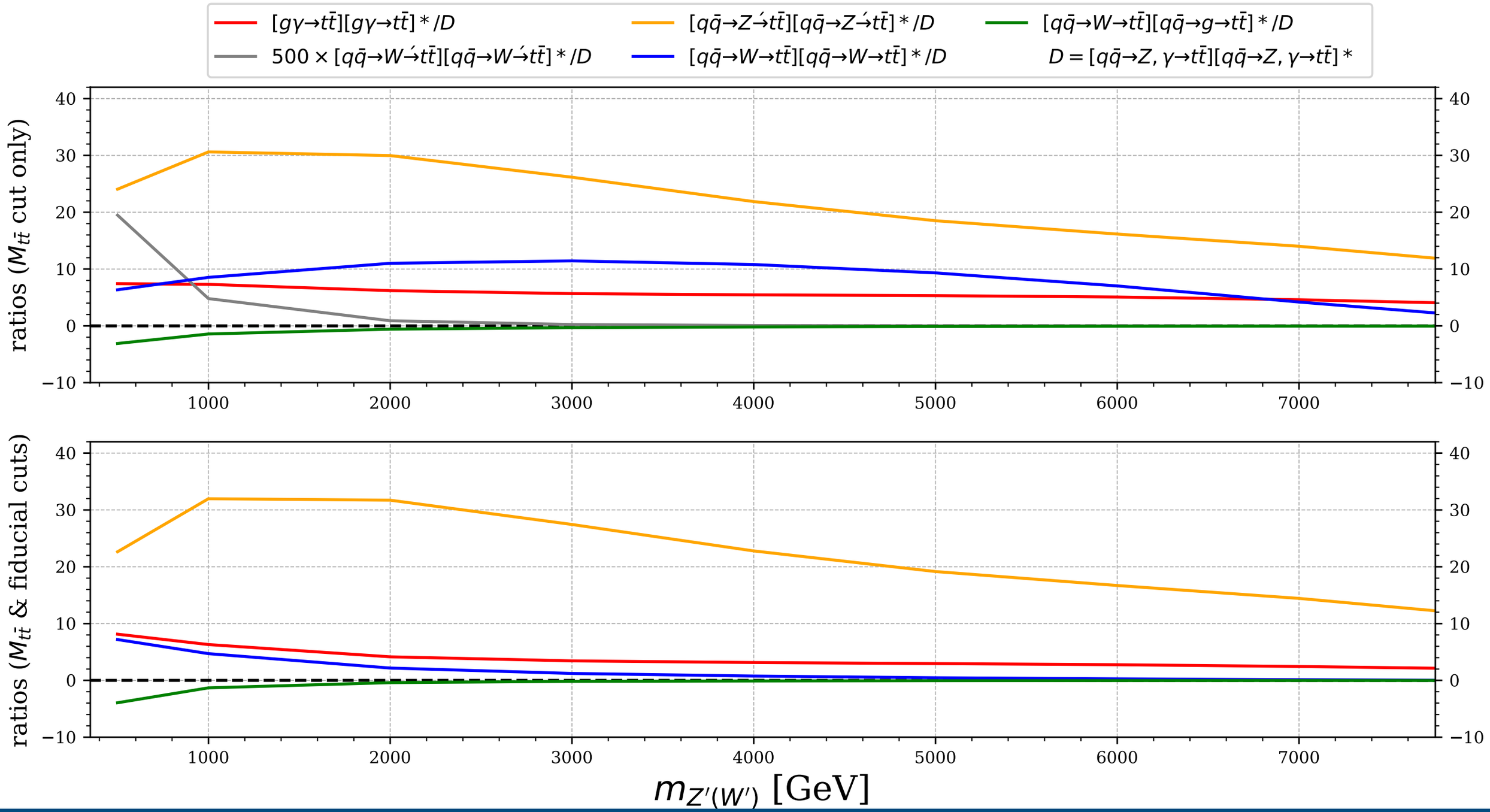
- **Rivet** to impose the following **acceptance** cuts:
  - **R** = 0.5 (**anti-k_T**), **p_T** > 25 GeV, **$|\eta|$** < 2.5

Setup & input

- $\sqrt{s}$ = {14 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

Results for Integrated Cross Sections

Contributions to EW Top-quark pair production cross section at LO at LHC14 vs $M_{Z'}$



TC model

Leptophobic Topcolour model (TC) [arXiv:1112.4928]:

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

- Total decay-width:

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