Visible Decays of a Single Vector-like Top

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Introduction

- **Vector-like quarks (VLQs)** are predicted in many BSM theories like the little Higgs models, extra dimensions, composite Higgs models, non-minimal SUSY extensions.

Introduction

- **Vector-like quarks (VLQs)** are predicted in many BSM theories like the little Higgs models, extra dimensions, composite Higgs models, non-minimal SUSY extensions.
- **Goal:** To **determine the importance of off-shell contributions and interference effects for the pair production of VLQs** at the LHC, allowing for higher accuracy when interpreting experimental results.

Chirality and Gauge

- For a particle in **spinor representation** ϕ, the left and right handed components are given by :

$$\phi = \phi_R + \phi_L = \mathcal{P}_R\phi + \mathcal{P}_L\phi.$$

Where the **projection operators** are defined as:

$$\mathcal{P}_R = \frac{1+\gamma^5}{2} \quad \text{and} \quad \mathcal{P}_L = \frac{1-\gamma^5}{2}.$$

- A fermion is defined **vector-like (VL)** under a specific group $\mathcal{G}$ if its **left and right-handed projections belong to the same representation** of such a gauge group. For the SM :

$$\mathcal{G} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

.

Charge Current Example

- Examining the **charge current Lagrangian** $\mathcal{L} = \frac{g}{\sqrt{2}}(\mathcal{J}^{\mu+} W_{\mu}^{+} + \mathcal{J}^{\mu-} W_{\mu}^{-})$, **SM fermions** are in agreement with empirically observed $(V - A)$ structure of the weak interaction if they **only have left-handed charge currents:**

$$\mathcal{J}^{\mu+} = \mathcal{J}_L^{\mu+} = \bar{t}_L \gamma^{\mu} b_L = \bar{t}\gamma^{\mu} \frac{(1-\gamma^5)}{2} b.$$

- **Whereas a VLQ has both left-handed and right-handed projections transform identically** under the SM $SU(2)$ gauge groups **resulting in the charge currents having only a vector component** (V):

$$\mathcal{J}^{\mu+} = \mathcal{J}_L^{\mu+} + \mathcal{J}_R^{\mu+} = \bar{T}\gamma^{\mu} \frac{(1-\gamma^5)}{2} B + \bar{T}\gamma^{\mu} \frac{(1+\gamma^5)}{2} b = \bar{T}\gamma^{\mu} B.$$

Symmetry

- For the SM the left-handed component is a doublet and the right-handed component is a singlet of $SU(2)_L$
- With the **addition of a single VLQ Q to the model, which is coupled to the SM quarks q through a Yukawa coupling** y, the scalar Lagrangian can be defined as:

$$\mathcal{L}_Y = -y\bar{q}HQ + h.c.$$

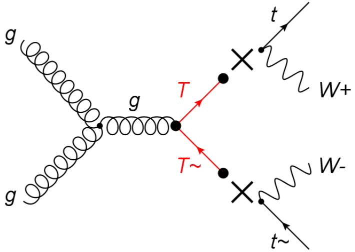
- This can be represented in terms of $SU(2)_L$ by

$$\bar{q}_R \otimes H \otimes Q = 1 \otimes 2 \otimes n = 1 \oplus ... \quad n = 2, \text{ which is a doublet}$$

$$\bar{q}_L \otimes H \otimes Q = 2 \otimes 2 \otimes n = 1 \oplus ... \quad n = 1 \; or \; 3, \text{ singlet or triplet}$$

Processes: NWA, σ_X

In the **Narrow Width Approximation (NWA)** the production and decay of the heavy quarks can be separated and factorised.



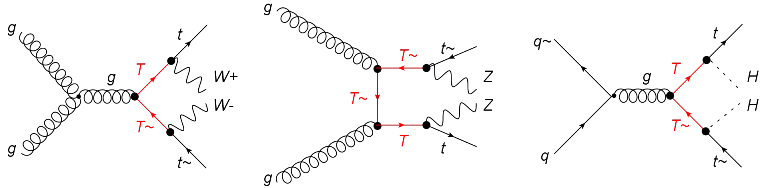
- This allows us to simplify the computation of complex processes.
- Cross-section for this process involving pair-production of VLQs:

$$\boxed{\sigma_X \equiv \sigma_{2\to 2} BR(Q) BR(\bar{Q})}$$

- Where $\sigma_{2\to 2}$ only considers the QCD topologies.

Processes: Pair Production σ_P

QCD pair production and decay of VLQs, but without imposing the on-shell condition, provides a better description in large width regions.

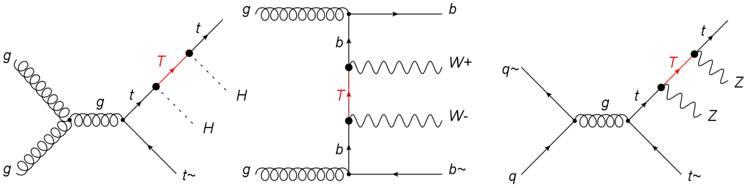


- The cross-section for this process, labeled σ_P, **is equivalent to** σ_X **in the NWA region.**
- Production and decays are not factorised.
- Includes spin correlation between $q, \bar{q}$ branches unlike σ_X.

Processes: Full Signal σ_S

Full signal cross-section σ_S,

- All topologies with **at least one VLQ propagator** are considered in the full signal including pair production topologies.



- So these diagrams also contribute to the cross-section σ_S, which again **in the NWA region has the same value as σ_X.**
- This is the **only truly physical processes, unlike the last processes mentioned** which are used as benchmarks of what experimentalists use in MCs.

Processes: Background and Total Signal, σ_B and σ_T

SM irreducible background σ_B,

- This process includes all $2 \rightarrow 4$ **topologies which do not include any VLQ propagators.**

Total process cross-section σ_T,

- This process accounts for the **full signal, SM background and interference terms.**

$$\sigma_T = \sigma_S + \sigma_B + \sigma_{\textbf{interference}}$$

Observables

Observables considered to determine the large width effects on the cross-section:

- $\frac{\sigma_P - \sigma_X}{\sigma_X}$ Quantifies the pure **off-shell contributions** to the **pair production** and decay of VLQs.
- $\frac{\sigma_S - \sigma_X}{\sigma_X}$ Measuring both the **off-shell and sub-leading contributions** from topologies with **at least one VLQ propagator.**
- $\frac{\sigma_T - (\sigma_X + \sigma_B)}{\sigma_X + \sigma_B}$ **Correction factor** to apply to obtain full cross-section with pair production in the NWA and SM background considered independently.
- $\frac{\sigma_T - (\sigma_S + \sigma_B)}{\sigma_S + \sigma_B}$ Measuring the size of the **interference effects** between signal and SM background.

Channels

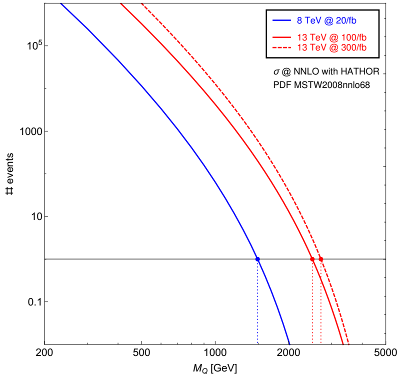
All channels in which the VL-Top and its anti-particle $T, \bar{T}$ can decay is shown by the following matrix:

$WdW\bar{d}$	$WdZ\bar{u}$	$WdH\bar{u}$	$WdW\bar{s}$	$WdZ\bar{c}$	$WdH\bar{c}$	$WdW\bar{b}$	$WdZ\bar{t}$	$WdH\bar{t}$
$ZuW\bar{d}$	$ZuZ\bar{u}$	$ZuH\bar{u}$	$ZuW\bar{s}$	$ZuZ\bar{c}$	$WdH\bar{c}$	$ZuW\bar{b}$	$ZuZ\bar{t}$	$ZuH\bar{t}$
$HuW\bar{d}$	$HuZ\bar{u}$	$HuH\bar{u}$	$HuW\bar{s}$	$HuZ\bar{c}$	$WdH\bar{c}$	$HuW\bar{b}$	$HuZ\bar{t}$	$HuH\bar{t}$
$WsW\bar{d}$	$WsZ\bar{u}$	$WsH\bar{u}$	$WsW\bar{s}$	$WsZ\bar{c}$	$WdH\bar{c}$	$WsW\bar{b}$	$WsZ\bar{t}$	$WsH\bar{t}$
$ZcW\bar{d}$	$ZcZ\bar{u}$	$ZcH\bar{u}$	$ZcW\bar{s}$	$ZcZ\bar{c}$	$WdH\bar{c}$	$ZcW\bar{b}$	$ZcZ\bar{t}$	$ZcH\bar{t}$
$HcW\bar{d}$	$HcZ\bar{u}$	$HcH\bar{u}$	$HcW\bar{s}$	$HcZ\bar{c}$	$WdH\bar{c}$	$HcW\bar{b}$	$HcZ\bar{t}$	$HcH\bar{t}$
$WbW\bar{d}$	$WbZ\bar{u}$	$WbH\bar{u}$	$WbW\bar{s}$	$WbZ\bar{c}$	$WdH\bar{c}$	$WbW\bar{b}$	$WbZ\bar{t}$	$WbH\bar{t}$
$ZtW\bar{d}$	$ZtZ\bar{u}$	$ZtH\bar{u}$	$ZtW\bar{s}$	$ZtZ\bar{c}$	$WdH\bar{c}$	$ZtW\bar{b}$	$ZtZ\bar{t}$	$ZtH\bar{t}$
$HtW\bar{d}$	$HtZ\bar{u}$	$HtH\bar{u}$	$HtW\bar{s}$	$HtZ\bar{c}$	$WdH\bar{c}$	$HtW\bar{b}$	$HtZ\bar{t}$	$HtH\bar{t}$

In our research we have considered the top left and bottom right quadrants of this matrix, which correspond to T quark only interacting with the first or third generation.

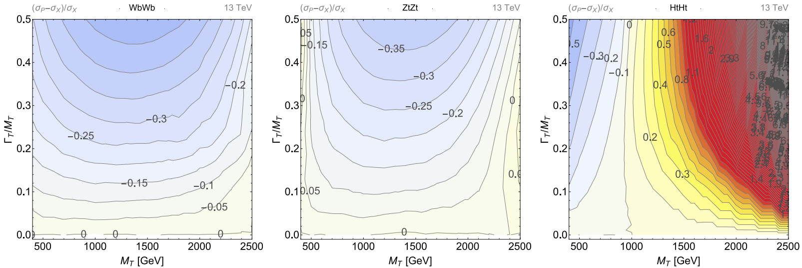
Number of events

This analysis is only of interest for a VLQ mass range when the predicted number of events is larger than 1. In reality 10 or more would be ideal.

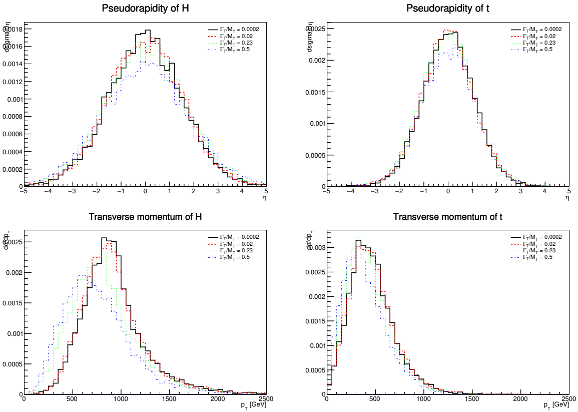


QCD pair production and decay of VLQs, $\frac{\sigma_P - \sigma_X}{\sigma_X}$

- As expected for a **small width the off-shell contributions are negligible**, becoming more significant with a larger width of T.
- The cancellation for *HtHt* is due to the different structure of the coupling (proportional to M_T) compared to *WbWb* and *ZtZt* which share the same behaviour.



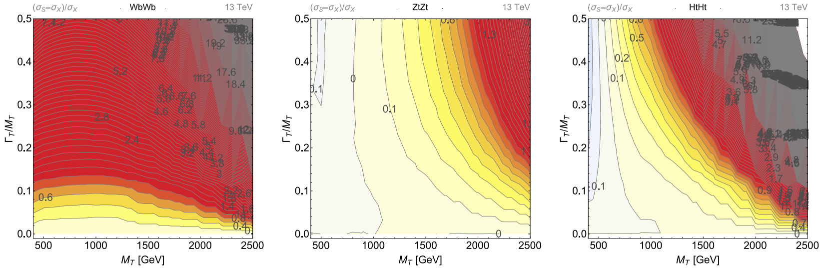
Partonic level differential cross-sections for the *HtHt* channel.



- T mass of 1000 GeV, for which $\sigma_P \sim \sigma_X$ independent of the T width.
- **Area beneath the curve is the same**, giving the same cross-sections leading to the cancellation, **yet tails have different behaviours.**

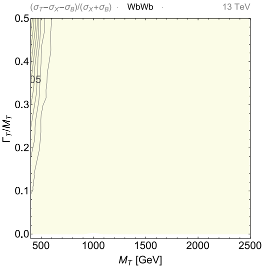
Full signal, $\frac{\sigma_S - \sigma_X}{\sigma_X}$

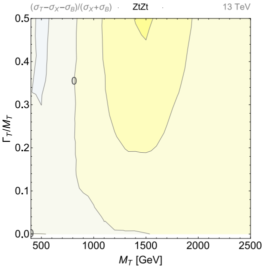
- The **NWA is still a good approximation for QCD pair production yet** the effects of **sub-leading topologies become important.**
- A crucial study is to investigate how kinematical cuts can be applied to reduce the relevance of the topologies with single resonance.

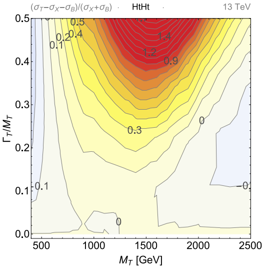


Correction Factor, $\frac{\sigma_T-(\sigma_X+\sigma_B)}{\sigma_X+\sigma_B}$

- The **observable** considered **depends strongly on** the importance of the **SM background** in determining the total cross-section compared to the NWA pair production.
- For *ZtZt* and *HtHt* the **SM background is negligible compared to the signal contribution**, such that the width and mass dependence is more pronounced.

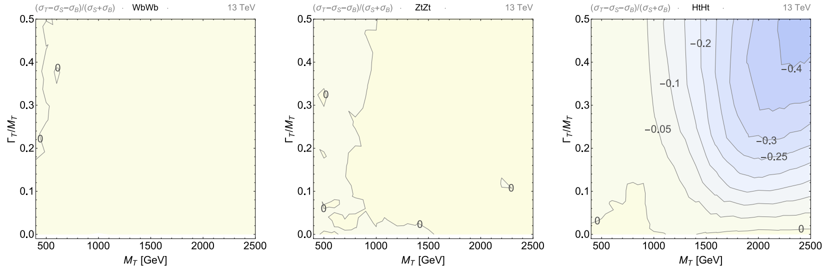






Interference Effects $\frac{\sigma_T-(\sigma_S+\sigma_B)}{\sigma_S+\sigma_B}$

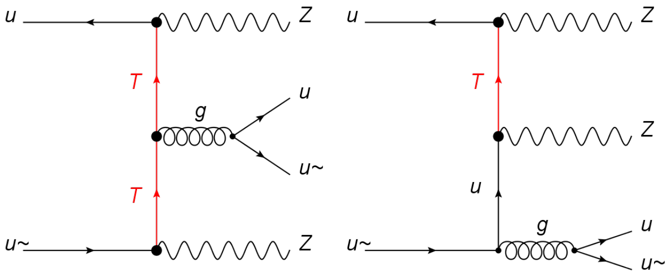
- The relevance of **interference is always negligible** when considerably **with the inclusion of single-resonance effects** from the full signal.
- This is expected as the kinematic properties of the signal and the background are usually different.



1. Vector-like Quarks
   - Introduction
   - Phenomenology of VLQs
2. Results
   - Phenomenological Relevance
   - Third Generation
   - First Generation with Cuts
3. Conclusion

Collinear Divergences

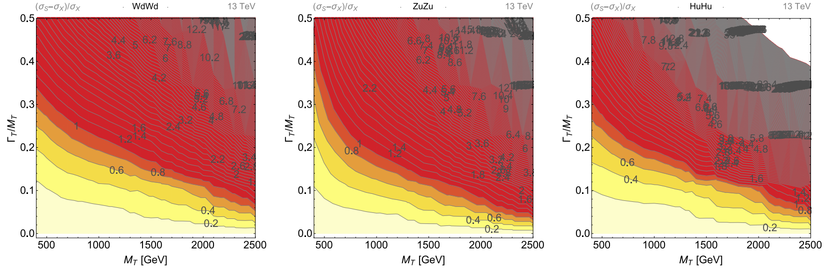
When the T quark couples to first generation quarks, the $2 \to 4$ process contains **topologies which are absent in the case of third generation:**



- **These topologies** indeed **contribute to the signal and cannot be removed.**
- **They contain collinear divergences due to the gluon splitting,** which must be cured by applying the kinematical cuts imposed on the jets in the final state.

Full Signal, $\frac{\sigma_S - \sigma_X}{\sigma_X}$

- **Applying cuts** with $\eta_j < 1$ instead of the default 5, **some of the divergence can be removed** but not all.
- We are still investigating the role the cuts play in removing the divergences arising from the gluon splitting.



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Conclusion

- Studied the importance of the off-shell contributions and interference effects of VLQs decaying into SM particles in a model independent way.
- Looked at the effects of applying cuts when the VLQ couplings to the first generation are present.
- Concluded that a more in depth, detector level study on applying cuts needs to be done for the lighter generation of quarks.

Thank you for your attention.

- The $\mathcal{L}$agrangian used in our model is given by:

$$\mathcal{L}_{T_{single}} = \kappa_W V^{4i}_{L/R} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^{/mu} d^i_{L/R}] + \kappa_Z V^{4i}_{L/R} \frac{g}{2c_W} [\bar{T}_{L/R} Z_\mu \gamma^{/mu} u^i_{L/R}]$$
$$- \kappa_H V^{4i}_{L/R} \frac{M}{v} [\bar{T}_{R/L} H u^i_{L/R}] + h.c.$$

- Where M is the mass of the VLQ, $V^{4i}_{L/R}$ represents the mixing matrices between the VLQ and the three SM generations labelled by i, and the parameters κ_V $(V = W, Z, H)$ encodes the couplings to the three bosons.

$$\Gamma(T' \rightarrow Wb, Zt, Ht) = \kappa^2_{W,Z,H} |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\Pi m_W^2} \quad \times \Gamma_{W,Z,H}(M_{T'}, m_{W,Z,H}, m_{b,t,t})$$

For a mass M of the VLQs and mixing matrices between VLQs and SM quarks is $|V^{4i}_{L/R}|$ with the kinematic relations are given by:

$$\Gamma_{W,Z} = \frac{1}{2}\lambda^{\frac{1}{2}}\left(1, \frac{m_q^2}{M_{T'}^2}, \frac{m_{W,Z}^2}{M_{T'}^2}\right)\left[\left(1 - \frac{m_q^2}{M_{T'}^2}\right)^2 + \frac{m_{W,Z}^2}{M_{T'}^2} \times -2\frac{m_{W,Z}^4}{M_{T'}^4} + \frac{m_q^2 m_{W,Z}^2}{M_{T'}^4}\right]$$

and

$$\Gamma_H = \frac{1}{2}\lambda^{\frac{1}{2}}\left(1, \frac{m_q^2}{M_{T'}^2}, \frac{m_H^2}{M_{T'}^2}\right)\left[1 + \frac{m_q^2}{M_{T'}^2} - \frac{m_H^2}{M_{T'}^2}\right]$$

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Quantum Numbers

	SM quarks	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	$(T)\,(B)$	$\begin{pmatrix} X \\ T \end{pmatrix} \begin{pmatrix} T \\ B \end{pmatrix} \begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix} \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
$SU(2)_L$	$q_L = 2$ $q_R = 1$	1	2	3
Y	$Y_{q_L} = 1/6$ $Y_{u_R} = 2/3$ $Y_{d_R} = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
$\mathcal{L}_m$	forbidden[1]	$-M\bar{\phi}\phi$	$-M\bar{\phi}\phi$	$-M\bar{\phi}\phi$

[1] The Higgs mechanism is needed.

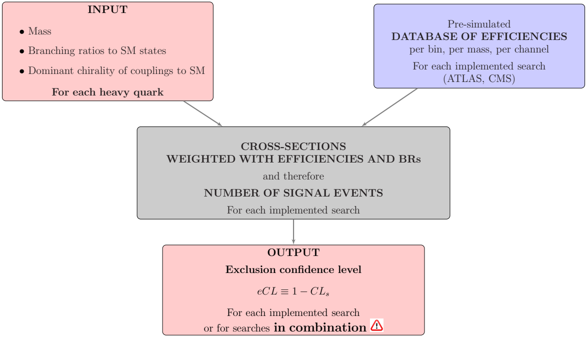
Actual project

XQCAT in a nutshell

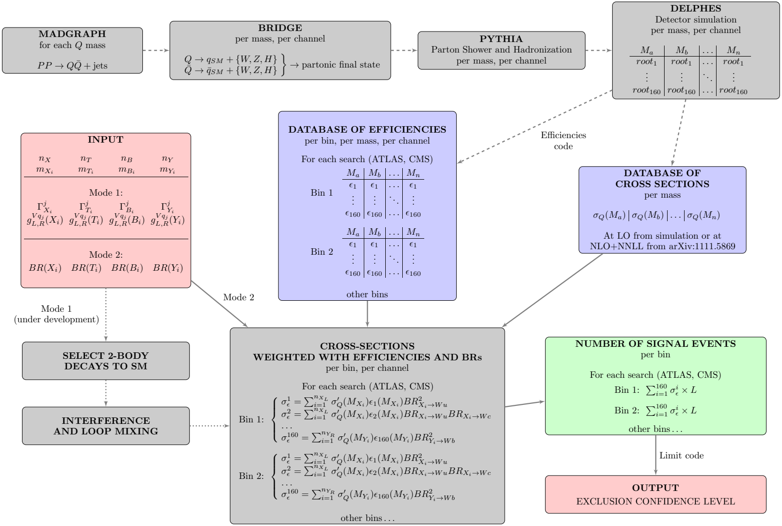
XQCAT = eXtra Quark Combined Analysis Tool
https://launchpad.net/xqcat

1) D. Barducci, A. Belyaev, M. Buchkremer, G. Cacciapaglia, A. Deandrea, S. De Curtis, J. Marrouche S. Moretti and **LP**, *Model Independent Framework for Analysis of Scenarios with Multiple Heavy Extra Quarks*, **arXiv:1405.0737 [hep-ph]** (submitted to JHEP)

2) D. Barducci, A. Belyaev, M. Buchkremer, J. Marrouche, S. Moretti and **LP**, *XQCAT: eXtra Quark Combined Analysis Tool*, **arXiv:1409.3116 [hep-ph]** (to be submitted to CPC)

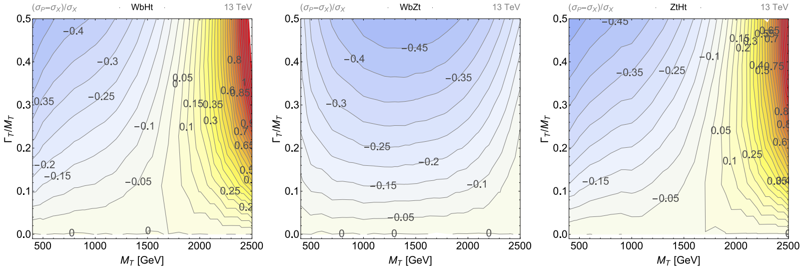


Global project

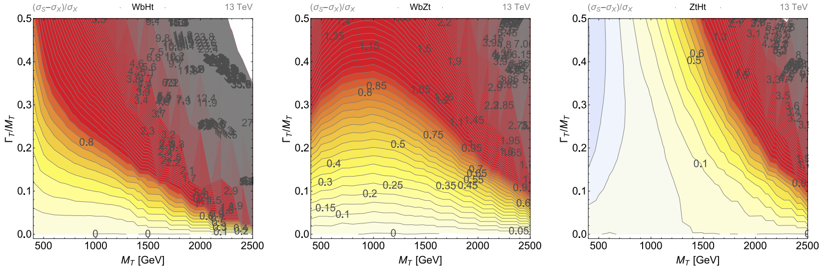


Ratio $\frac{\sigma_P - \sigma_X}{\sigma_X}$

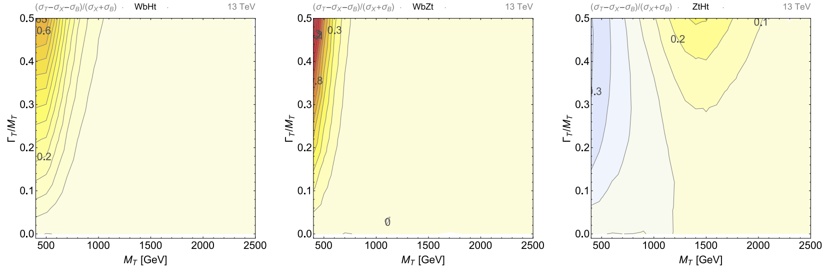
- The off-diagonal component can be seen to produce the same general behaviour as the diagonal plots, just with a shifted value of the cancellation.



Ratio $\frac{\sigma_S - \sigma_X}{\sigma_X}$



Ratio $\frac{\sigma_T-(\sigma_X+\sigma_B)}{\sigma_X+\sigma_B}$



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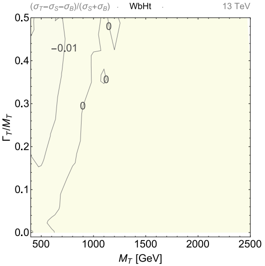
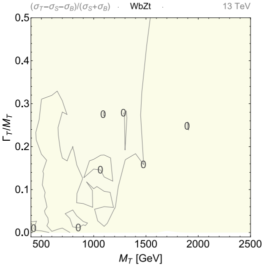
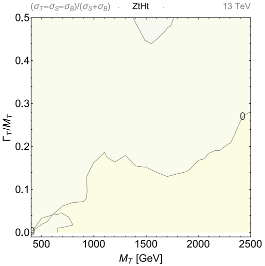
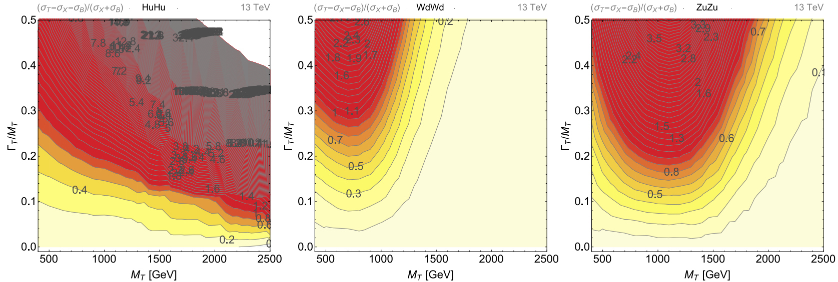
Ratio $\frac{\sigma_T-(\sigma_S+\sigma_B)}{\sigma_S+\sigma_B}$







Ratio $\frac{\sigma_T-(\sigma_X+\sigma_B)}{\sigma_X+\sigma_B}$



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