Vector-like quark production at the LHC, beyond the Narrow Width Approximation

NExT Meeting at Sussex

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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 with the irreducible background for the pair production of VLQs**.

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

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 Yukawa Lagrangian can be defined as:

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

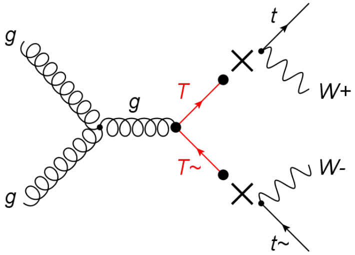
- This can be represented in terms of $SU(2)_L$ by

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

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

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:

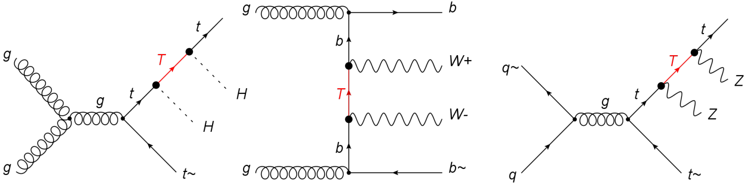
$$\sigma_X \equiv \sigma_{2\to 2} BR(Q) BR(\bar{Q})$$

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

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 we expect **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:

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

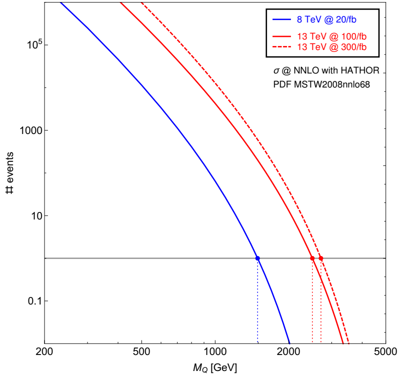
All channels in which the VL-Top and its anti-particle T, $\bar{T}$ can decay is shown by the following matrix:

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

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 the number of events must be large enough with respect to the background to have enough significance.



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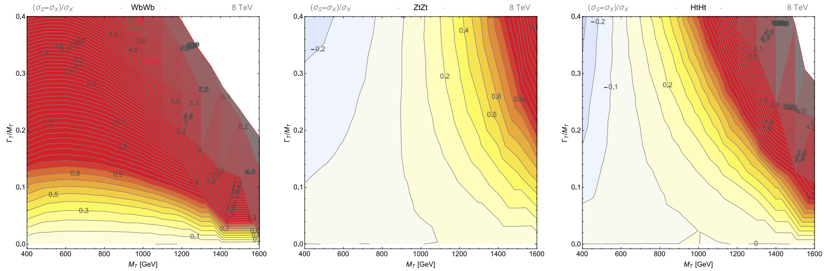
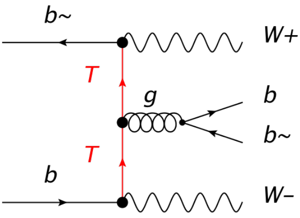
Full Signal, $\frac{\sigma_S - \sigma_X}{\sigma_X}$

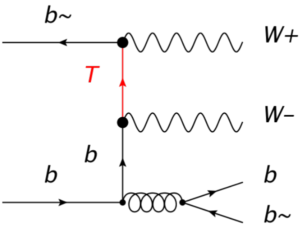
- The **NWA is still a good approximation for QCD pair production yet** off-shell effects and that of **sub-leading topologies become important.**
- **Large difference between the NWA and the full signal** can be seen **for WbWb due to collinear divergences** present in certain diagrams. These topologies are shown on the following slide.



Full Signal, Subdominant Topologies contain Collinear Divergences

The WbWb channel has divergent topologies which contribute to the full signal. The ZtZt and HtHt channels however do not contain this collinear divergence due to the final state containing a massive top.

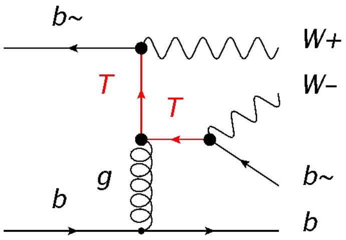




The **collinear divergence arises due to the gluon splitting,** which must be cured by applying the kinematical cuts imposed on the b-jets in the final state. The soft divergence is controlled by applying cuts on the p_{Tj}^{min}, collinear divergences are removed by the cuts on $|\eta_j|^{\text{max}}$ and $\Delta R_{jj}^{\text{min}}$.

Additional Topologies with Large Contributions to the Full Signal

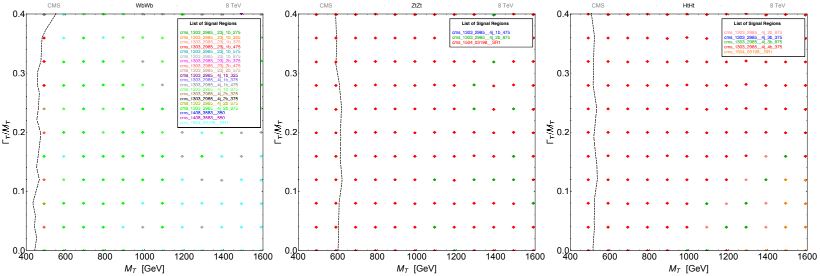
There are additional **topologies which contribute to the signal, which also have to be removed by applying a kinematical cuts .**



The contribution of the **diagram on the left can be removed by applying cuts on ΔR_{jj}.**

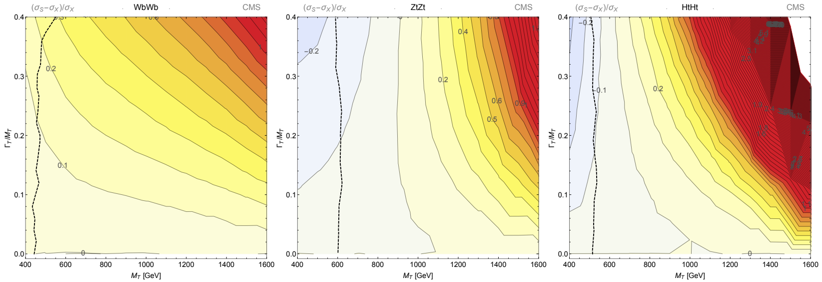
Detector Level, CMS Analyses, 3rd Generation Mixing

- The **width effects on the exclusion limit have been simulated using MadGraph then re-casted using CheckMate2** (CM2), at 8 TeV.



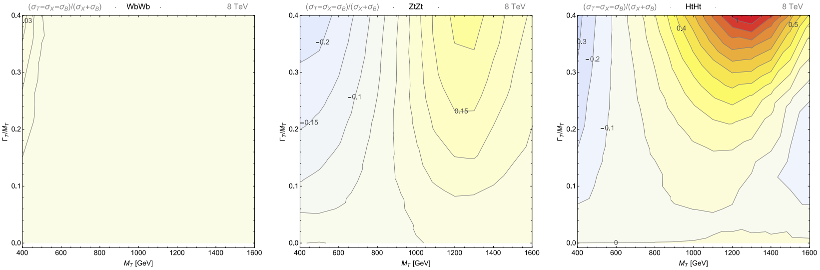
Detector Level Exclusion-CMS-Third Generation Mixing

- The **exclusion line** for detector level analysis at 8 TeV **shows no widths dependence** though, so the full signal has the same mass bound as the NWA.
- The **divergence from subdominant diagrams in the WbWb channel has been mostly removed at event generation level by applying cuts** on the b-jet in the final state, cuts applied by **the analyses also remove these contributions at detector level**.



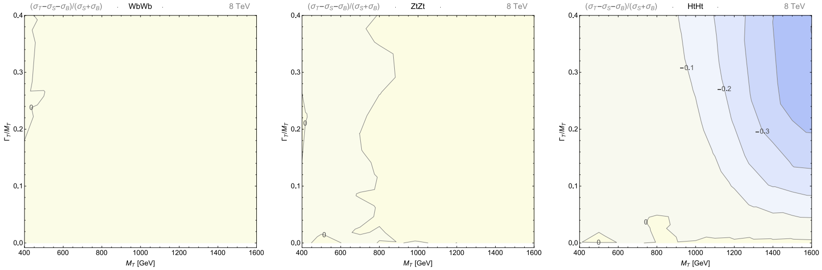
Correction Factor, $\frac{\sigma_T-(\sigma_X+\sigma_B)}{\sigma_X+\sigma_B}$

- 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.



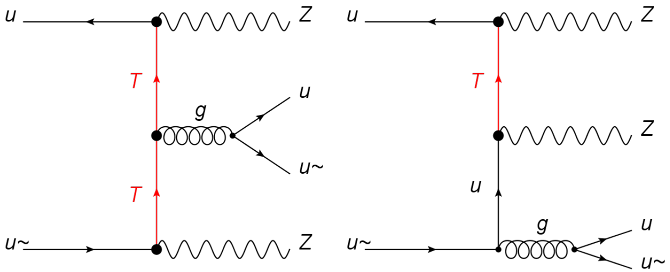
Interference Effects $\frac{\sigma_T-(\sigma_S+\sigma_B)}{\sigma_S+\sigma_B}$

- The relevance of **interference is mostly negligible with the inclusion of single-resonance effects** from the full signal, except for HtHt at large values of the VLQ mass M_T and the width Γ_T.
- This is expected as the kinematic properties of the signal and the background are usually different.



Collinear Divergences for First Generation Mixing

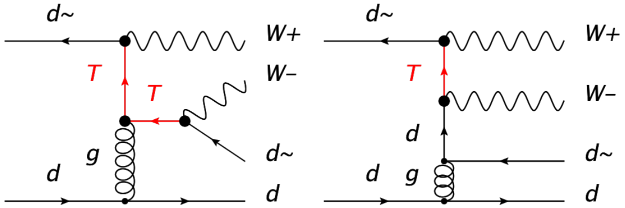
When the T quark couples to first generation quarks, the $2 \rightarrow 4$ process contains **certain topologies which are negligible in the case of third generation due to a massive top being in the final state, become important:**



- **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, Subdominant Topologies contain Collinear Divergences

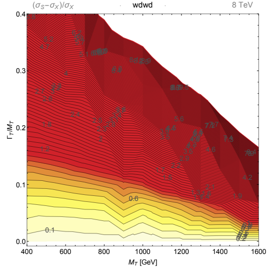
After applying cuts the kinematical cuts $p_{Tj}^{\text{min}} = 100$ GeV, $|\eta_j|^{\text{max}} = 1$ and $\Delta R_{jj}^{\text{min}} = 1$ **on the quarks in the final state** (like was done for the 3rd generation). It can be seen on the following slide that **most of these large contributions cannot be removed at event generation level.**

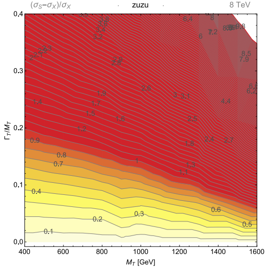


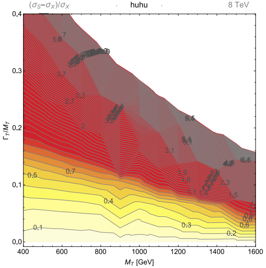
- This is again **due to the light masses of the the 1st generation quarks**, and the **PDFs having a different effect since you have "more" up and down quarks in the proton**, so the contributions are larger.

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

- By **applying stronger cuts** on η_j (max rapidity of the jets), **some of the divergences can be removed from the gluon splitting, but only a small proportion**, most of the contributions of the topologies previously mentioned remain.
- **At detector level these divergences will also remain causing a width dependence.**

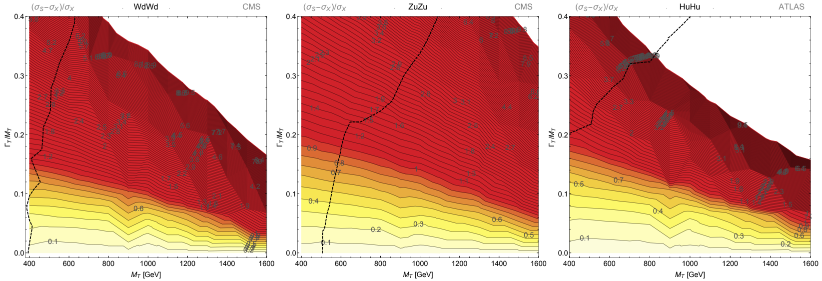






Detector Level Exclusion-CMS-First Generation Mixing

- The **exclusion line** for detector level analysis at 8 TeV **shows widths dependence.**
- **This implies** that the set of searches used in all **the combined analysis from CM2 could also not control the large contributions arising from having light quarks in the final state**.
- This means the **Full Signal better describes the physics then the NWA**, **giving a higher bound on the mass of the VLQ**.



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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 width effects on the exclusion line at detector level for first and third generation mixing at 8TeV.
- Future studies on $2 \rightarrow 3$ processes for single production of a VLQ.

Thank you for your attention.

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

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

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.

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

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

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

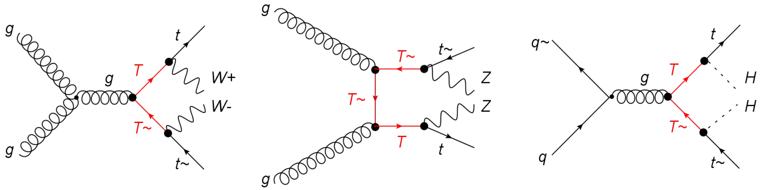
Quantum Numbers

	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.

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.

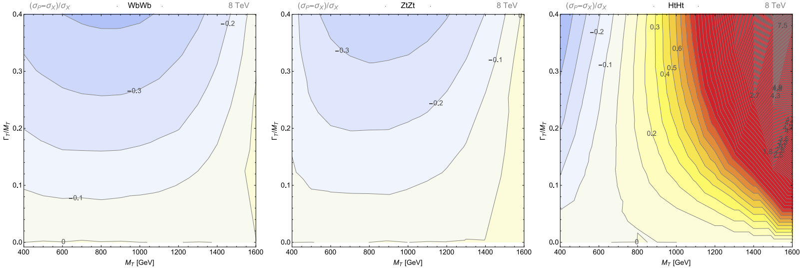


- The cross-section for this process, labeled σ_P, **should be equivalent to σ_X in the NWA region.**
- Production and decays are not factorised.
- Includes spin correlation between $q, \bar{q}$ branches unlike σ_X.

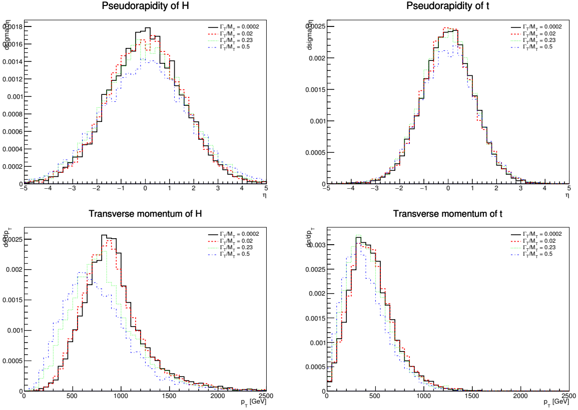
- Two types of infrared singularities, soft and collinear.
- Soft divergences are associated with low energy photons.
- Collinear divergences occur in high energy theories

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 physical** and is due to the different **structure of the coupling (proportional to M_T)** compared to *WbWb* and *ZtZt* which share the same behaviour.

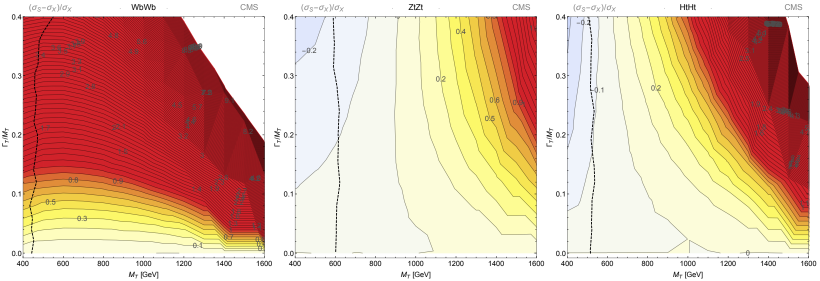


Partonic level differential cross-sections for the *HtHt* channel.



- 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, **since the tails fall in different fashions compensating for the differences in the peak heights and positions.**

Detector Level Analyses-CMS-Third Generation Mixing



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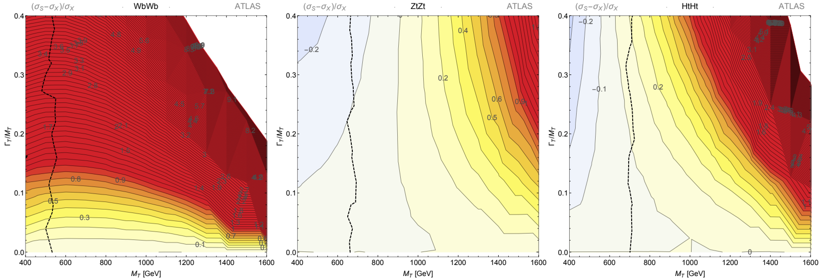
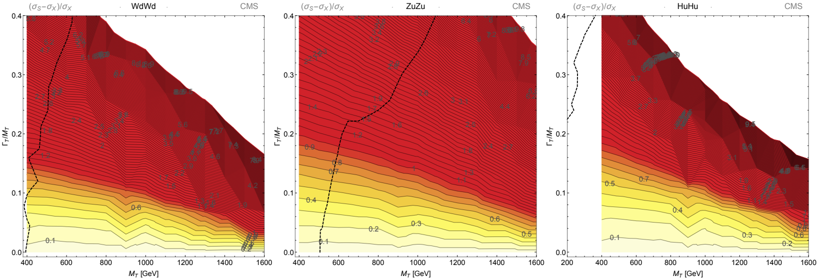
Detector Level Analyses-ATLAS-Third Generation Mixing



Detector Level Analyses-CMS-First Generation Mixing



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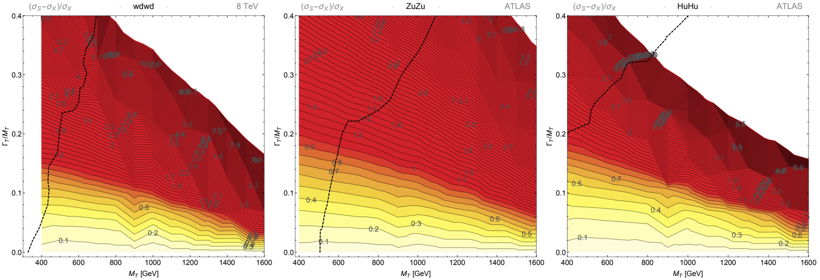
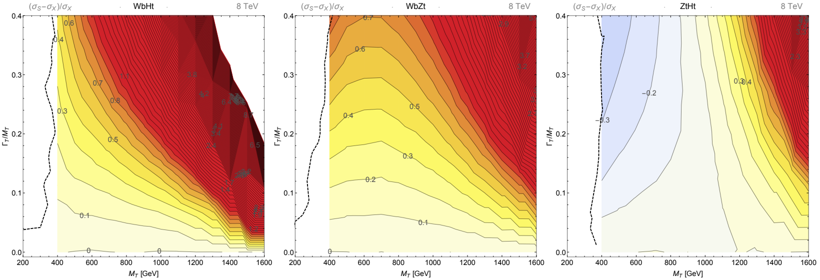
Detector Level Analyses-ATLAS-First Generation Mixing



Detector Level Analyses-CMS-Third Generation Mixing



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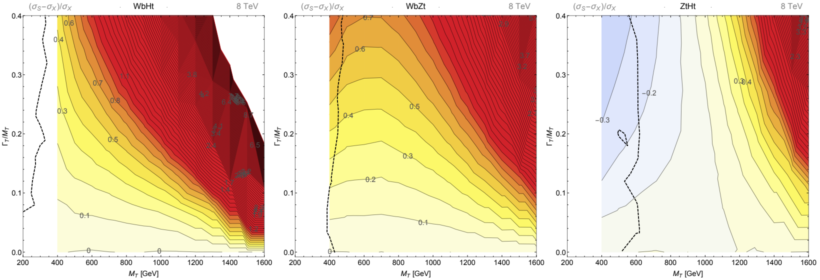

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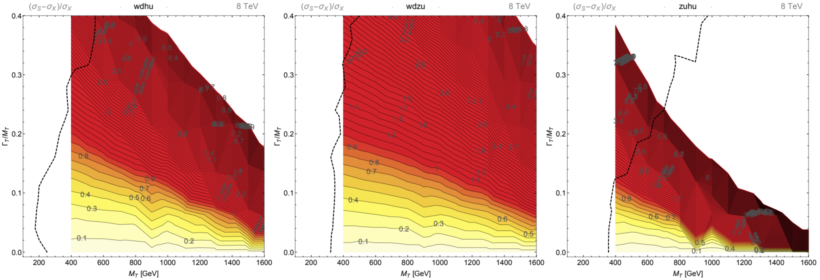

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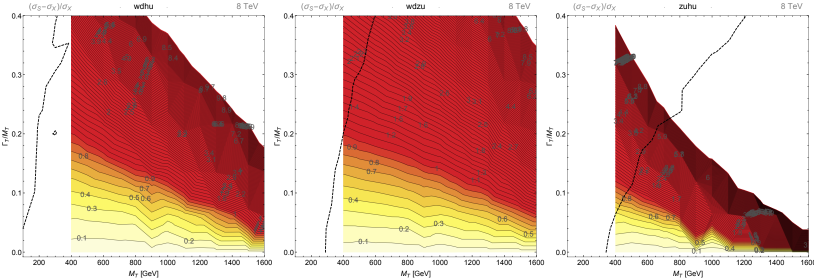
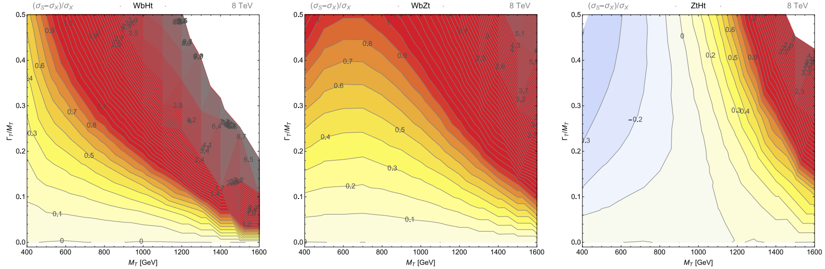
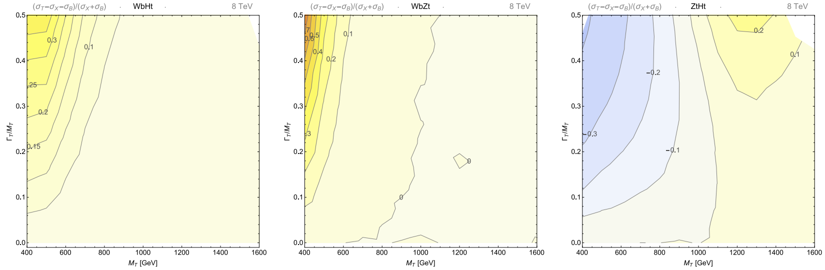


Ratio $\frac{\sigma_S - \sigma_X}{\sigma_X}$



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



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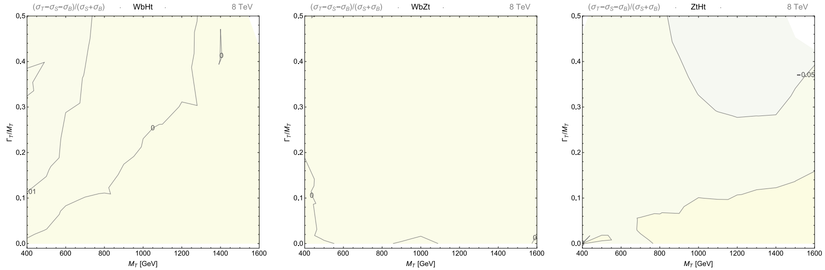
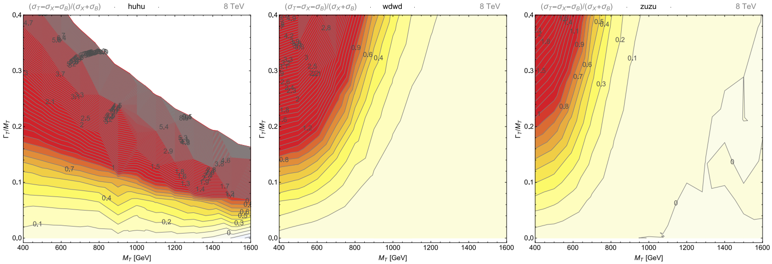
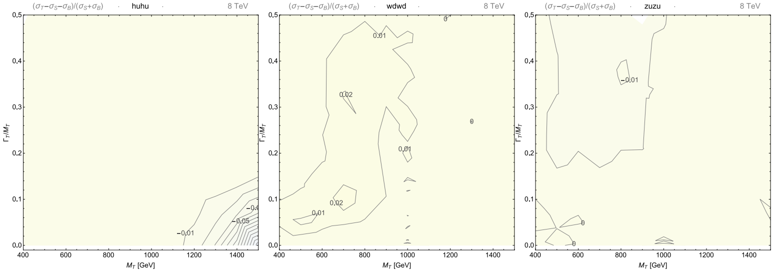
Ratio $\frac{\sigma_T-(\sigma_S+\sigma_B)}{\sigma_S+\sigma_B}$



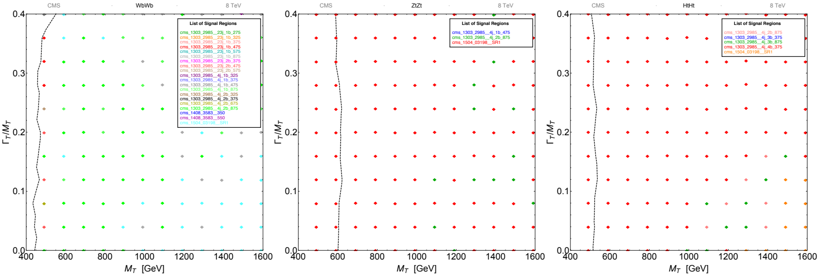
Ratio $\frac{\sigma_T-(\sigma_X+\sigma_B)}{\sigma_X+\sigma_B}$



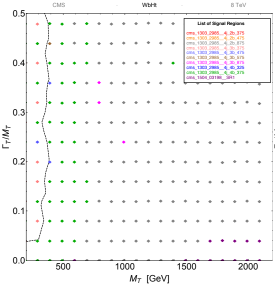
Ratio $\frac{\sigma_T - (\sigma_S + \sigma_B)}{\sigma_S + \sigma_B}$

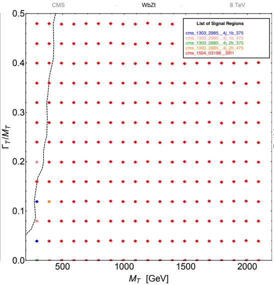


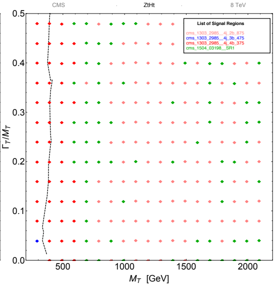
Detector Level, CMS Analyses, 3rd Generation Mixing



Detector Level, CMS Analyses, 3rd Generation Mixing







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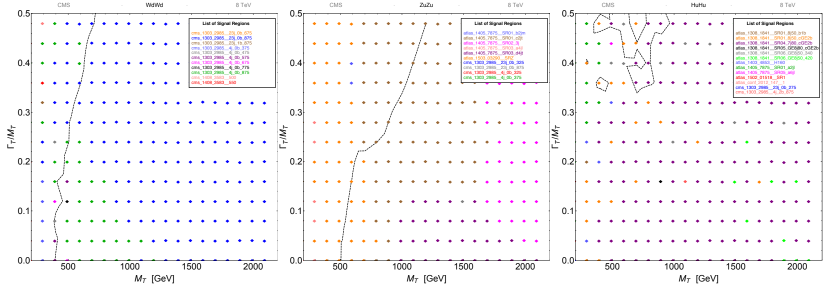
Detector Level, CMS Analyses, 1st Generation Mixing



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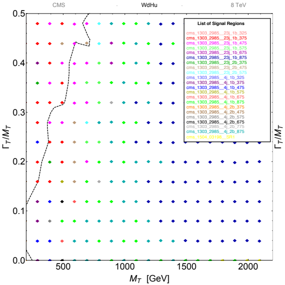
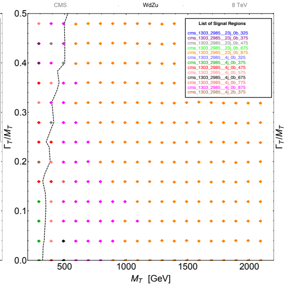
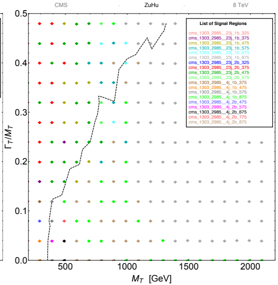
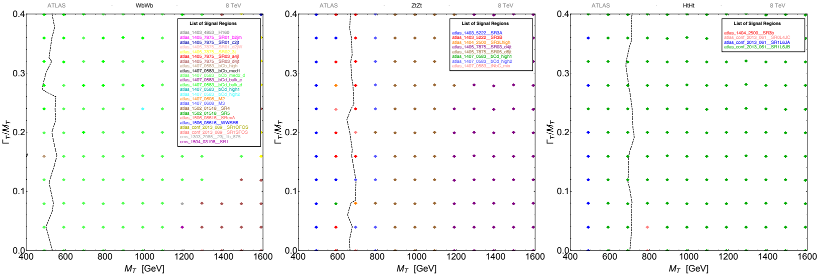
Detector Level, CMS Analyses, 1st Generation Mixing



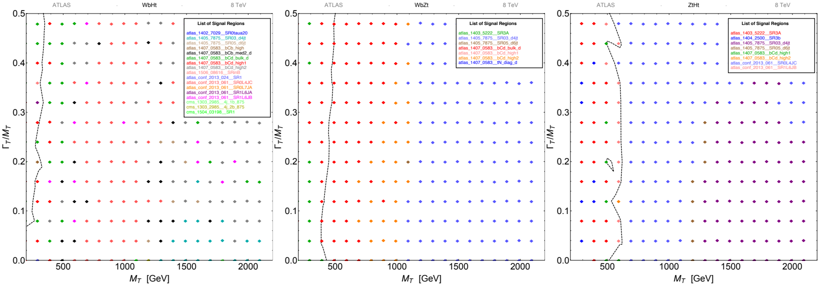




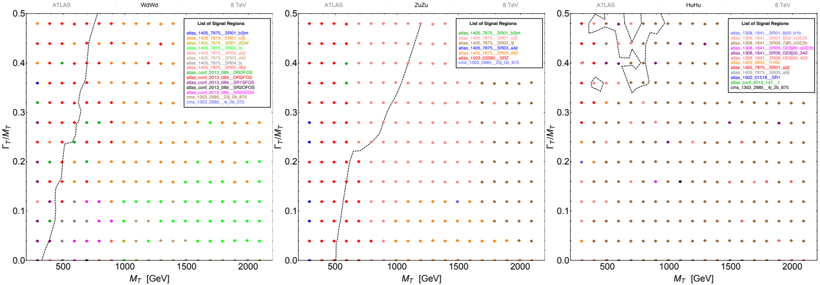
Detector Level, ATLAS Analyses, 3rd Generation Mixing



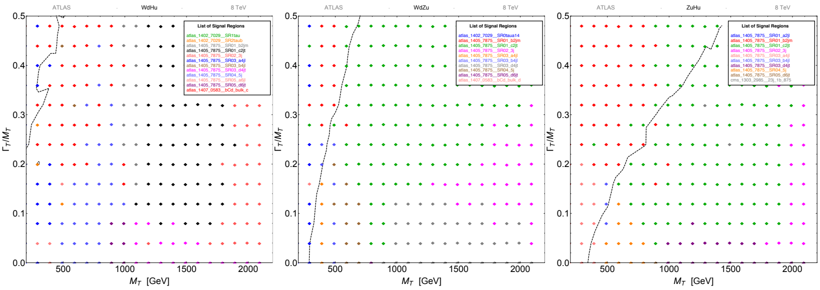
Detector Level, ATLAS Analyses, 3rd Generation Mixing



Detector Level, ATLAS Analyses, 1st Generation Mixing



Detector Level, ATLAS Analyses, 1st Generation Mixing



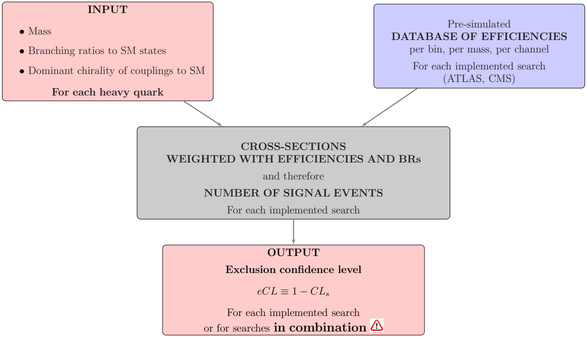
Actual project

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