

Vector-like quarks beyond minimality

large width, NLO and exotic decays

Luca Panizzi

Uppsala University

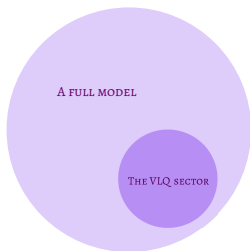


*Knut och Alice
Wallenbergs
Stiftelse*

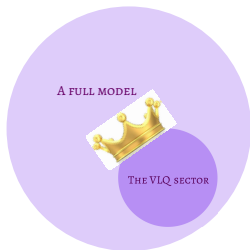


based (mostly) on **JHEP 08 (2021), 107** with
A. Deandrea, T. Flacke, B. Fuks and Hua-Sheng Shao

Common features and smoking guns

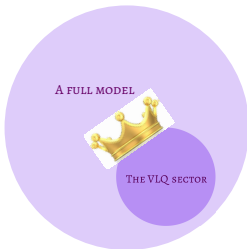


Common features and smoking guns



Hadron colliders

Common features and smoking guns



Hadron colliders*

*conditions apply

Conclusion



Summary

Thanks Manuel :)

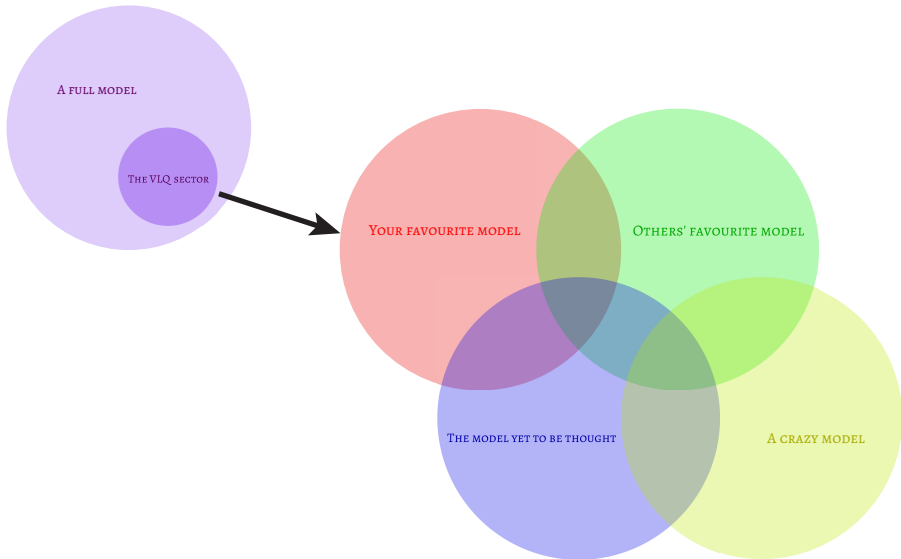
- Stochastic composite Higgs models are complicated
- Model M5, based on $SU(5) \times SU(6) \times U(1)/SO(5) \times Sp(6)$, has especially rich phenomenology
 - ▶ Color octet top partners excluded up to 2.7 TeV
 - ▶ Bounds from pair production of vector-like quarks are negligible since $m_{Q_6} \approx m_{Q_3}$

Future work

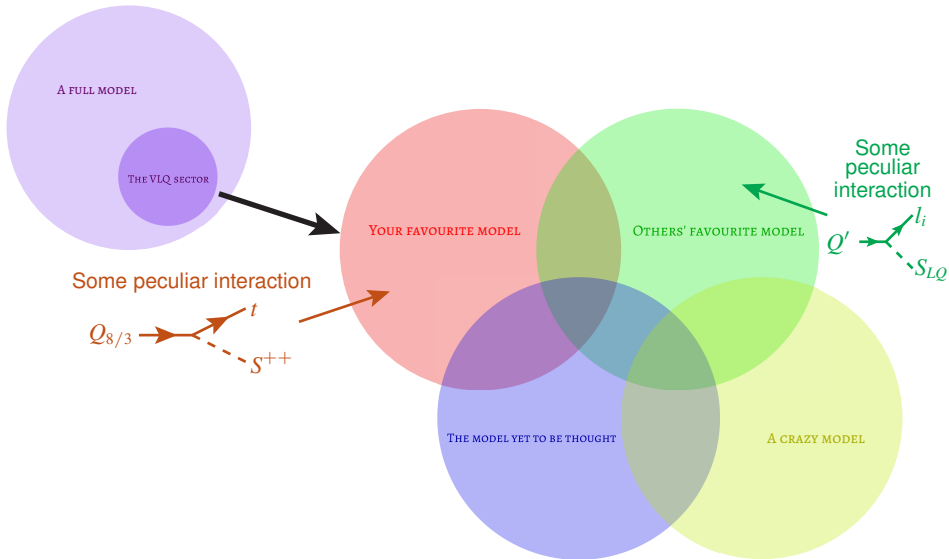
- ▶ Electroweak pNGBs in $SU(5)/SO(5)$
- ▶ Different mass hierarchy: $m_{\pi_3} < m_{\tilde{B}}$: lepton-number violating decays
 $\pi_3 \rightarrow b\tau^+, t\bar{\nu}_\tau$, neutrino masses via \tilde{B}
- ▶ Different top partner embedding: color sextet fermions, $Q_6 \rightarrow 5t + MET$

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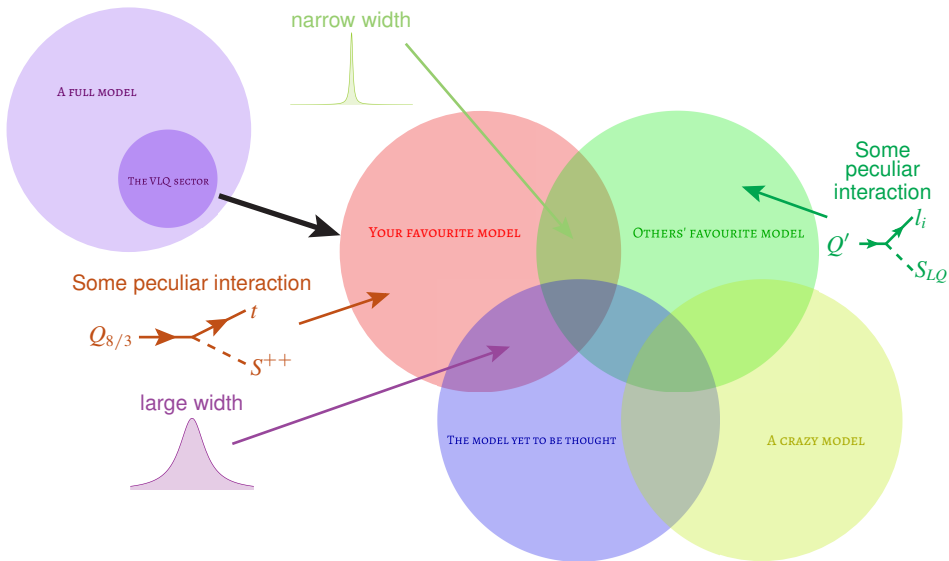
Common features and smoking guns



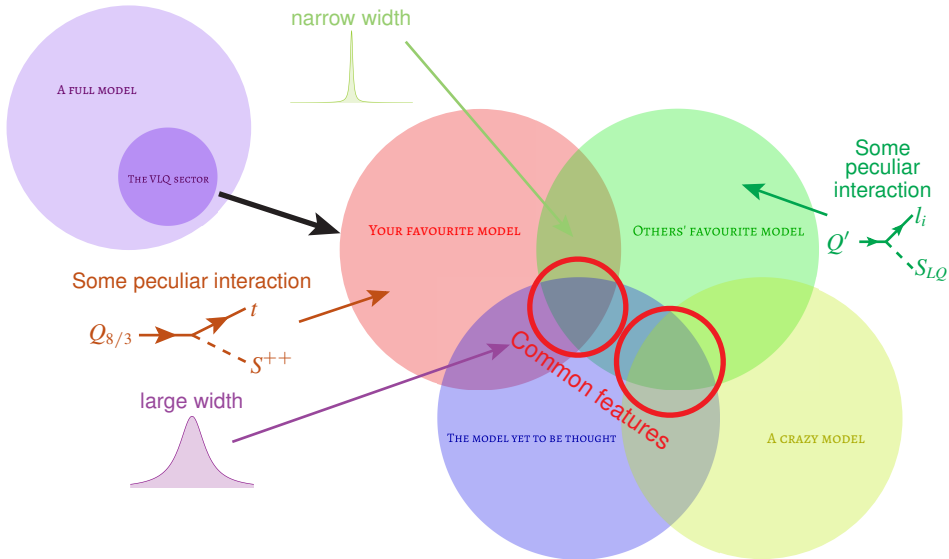
Common features and smoking guns



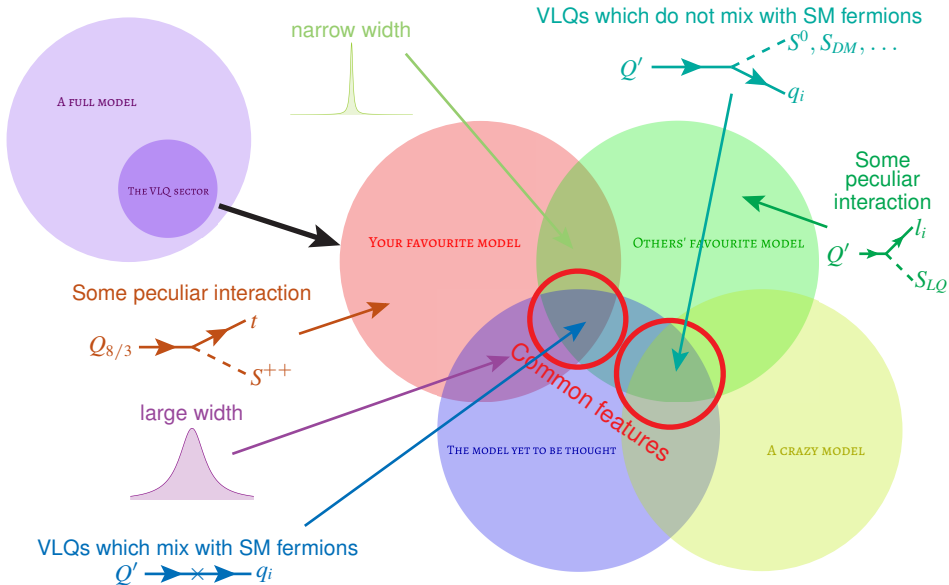
Common features and smoking guns



Common features and smoking guns



Common features and smoking guns



Outline

- 1 Where we are: experiment and tools
- 2 Single VLQ production with SM final states
 - Treating the large width
 - Including signal-background interference
 - Next-to-leading order results
- 3 Pair production with exotic final states
- 4 Where should we go? (*i.e.* setting priorities)

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Thanks Avik :)

Status of VLQ search @LHC

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2021

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Heavy quarks	VLO $TT \rightarrow Zt + X$	$2e/2\mu/3e, \mu \geq 1, b, \geq 1j$	-	139	T mass 1.4 TeV	SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi channel	-	36.1	B mass 1.34 TeV	SU(2) doublet
	VLO $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(S) \geq 3, e, \mu \geq 1, b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$2(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$
	VLO $T \rightarrow Ht/Zt$	$1, e, \mu \geq 1, b, \geq 3j$	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_2 = 0.5$
	VLO $Y \rightarrow b\bar{b}$	$1, e, \mu \geq 1, b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV	$2(Y \rightarrow Wb) = 1, c(YWb) = 1$
	VLO $B \rightarrow Hb$	$0, e, \mu \geq 2b, \geq 1j, \geq 1j$	-	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_{2b} = 0.3$

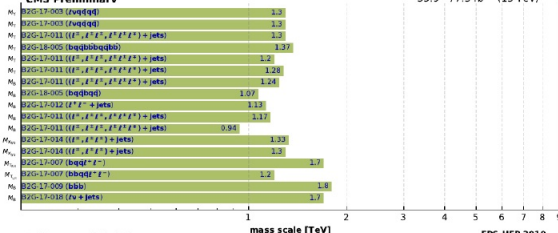
Overview of CMS B2G results

CMS Preliminary

$$35.9 - 77.3 \text{ fb}^{-1} (13 \text{ TeV})$$

Very Heavy Fermions

- YY → bbWW → ttqqqq, B(Y → tW) = 100%
- TT → bbWW → ttqqqq, B(T → tW) = 100%
- TT → tZt → (t⁺, t⁻, t⁰, t⁺ t⁻ t⁰) + jets, B(T → Z) = 100%
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- $X_{5/3} X_{5/3} \rightarrow tWt \rightarrow (t⁺, t⁻ t⁰) + jets, B(X_{5/3} → tW) = 100%$, NH
- $X_{5/3} X_{5/3} \rightarrow tWt \rightarrow (t⁺, t⁻ t⁰) + jets, B(X_{5/3} → tW) = 100%$, LH
- $T_{5/3} \rightarrow tZ \rightarrow b\bar{q}q t^+ t^-$, narrow T
- $B_T \rightarrow tZ \rightarrow b\bar{q}q t^+ t^-$, narrow T
- B → tW → bbb, narrow B
- B → tW → tt + jets, narrow B



Selection of observed exclusion limits at 95% CL (theory uncertainties are not included).

EPS-HEP 2019

Caveats:

- Simplified model framework (often with single VLQ)
- Interacting only with SM states (usually third generation)
- 100% BR to specific SM channels
 - Pair at NLO
 - Single at LO
- Until recently, usually narrow width approximation

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Thanks Avik :-)

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	VLO $BB \rightarrow Wt/Zb + X$	multi channel	-	36.1	B mass 1.34 TeV	SU(2) doublet 1907.11983
	VLO $T_{5/3} T_{5/3}/T_{5/3} \rightarrow Wt + X$	$2(SB)/2(3 e,\mu \geq 1 b, \geq 1j)$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$2(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} W) = 1$ ATLAS-COM-2021-040
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	VLO $B \rightarrow Hb$	$0 e,\mu \geq 2b, \geq 1j, \geq 1l$	-	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_{dB} = 0.3$

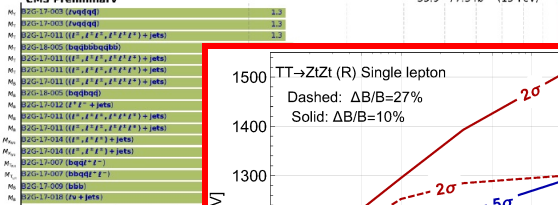
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- $T_{5/3} \rightarrow Z \rightarrow b\bar{q}q \ell^-, \text{ narrow T}$
- $B_{1/3} \rightarrow tZ \rightarrow b\bar{q}q \ell^-, \text{ narrow B}$
- B → H → bb̄b, narrow B
- B → W → ℓν + jets, narrow B



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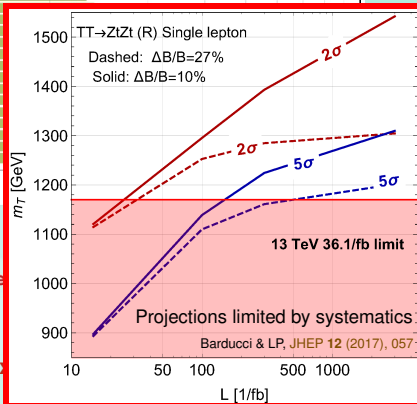
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M ₁	B2G-17-003 (vqqqq)	1.3
M ₂	B2G-17-003 (vqqqd)	1.3
M ₃	B2G-17-011 (($\ell^+, \ell^+ \ell^+, \ell^+ \ell^+ \ell^+$) + jets)	1.3
M ₄	B2G-18-005 (bqqbbqqbb)	
M ₅	B2G-17-011 (($\ell^+, \ell^+ \ell^+, \ell^+ \ell^+ \ell^+$) + jets)	
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M ₉	B2G-17-012 ($\ell^+ \ell^+ \ell^+$ + jets)	
M ₁₀	B2G-17-011 (($\ell^+, \ell^+ \ell^+, \ell^+ \ell^+ \ell^+$) + jets)	
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M ₁₂	B2G-17-014 (($\ell^+, \ell^+ \ell^+, \ell^+ \ell^+$) + jets)	
M ₁₃	B2G-17-014 (($\ell^+, \ell^+ \ell^+, \ell^+ \ell^+$) + jets)	
M ₁₄	B2G-17-007 (bbqq $\ell^+ \ell^-$)	
M ₁₅	B2G-17-007 (bbqq $\ell^+ \ell^-$)	
M ₁₆	B2G-17-009 (bbbb)	
M ₁₇	B2G-17-018 (rv + jets)	

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- B → bH → bb̄b, narrow B
- B → tW → tv + jets, narrow B



Need for non-minimality

Caveats:

- Simplified model framework (often)
- Interacting only with SM states
- 100% BR to specific SM channels
- Until recently, usually narrow width approx.

The numerical models

Interaction Lagrangian for T

$$\mathcal{L} = h\bar{T}(\hat{\kappa}_L P_L + \hat{\kappa}_R P_R)u_q + \frac{g}{2c_W}\bar{T}\tilde{Z}(\tilde{\kappa}_L P_L + \tilde{\kappa}_R P_R)u_q + \frac{g}{\sqrt{2}}\bar{T}\tilde{W}(\kappa_L P_L + \kappa_R P_R)d_q + \text{h.c.}$$

B. Fuks and H.-S. Shao, *Eur. Phys. J.C*77(2017), no. 2 135

- It also contains the Lagrangians for B , $X_{5/3}$ and $Y_{-4/3}$
- Suitable for NLO simulations

And the model has been recently extended
to include multiple non-SM decays of the VLQs and interactions between new states

$$T \rightarrow tS^0 \rightarrow tb\bar{b}, T \rightarrow bS^+ \rightarrow b\tau^+\nu_\tau, S^0 \rightarrow S^+W^- \dots$$

Banerjee et al., (LP), 2203.07270 (Snowmass 2021 contribution)

Both models are available on the **Feynrules** webpage

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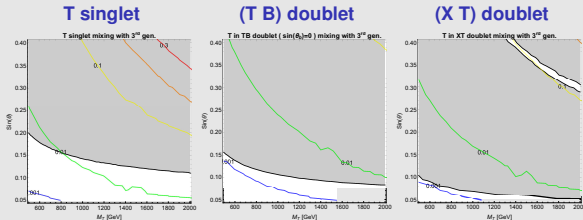
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How large can a large width be?

Two ways to obtain a large width

1 Increase couplings \rightarrow bounds from other observables (flavour, EWPT); perturbativity



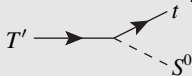
Minimal simplified models with large couplings already excluded by other observables

Moretti, O'Brien, LP and Prager, *Phys. Rev. D* **96** (2017) no.7, 075035
 using data from Chen, Dawson and Furlan, *Phys. Rev. D* **96** (2017) no.1, 015006

\rightarrow non-minimal extensions with multiple VLQs: escape bounds with large couplings

Cacciapaglia, Deandrea, Gaur, Harada, Okada and LP, *JHEP* **09** (2015), 012
 Cacciapaglia, Deandrea, Gaur, Harada, Okada and LP, *JHEP* **11** (2018), 055

2 Increase number of decay channels \rightarrow new physics, non-minimal extension

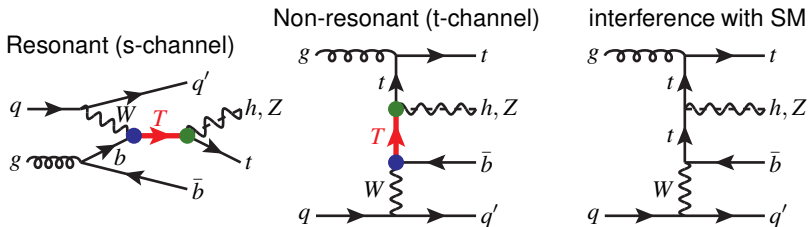


Aguilar-Saavedra, López-Fogliani and Muñoz, *JHEP* **06** (2017), 095
 Bizot, Cacciapaglia and Flacke, *JHEP* **06** (2018), 065
 Benbrik *et al.* (LP), *JHEP* **05** (2020), 028
 Banerjee, Franzosi and Ferretti, *JHEP* **03** (2022), 200

New physics has to be invoked

for the moment let's assume we are blind to it and focus on the SM channels

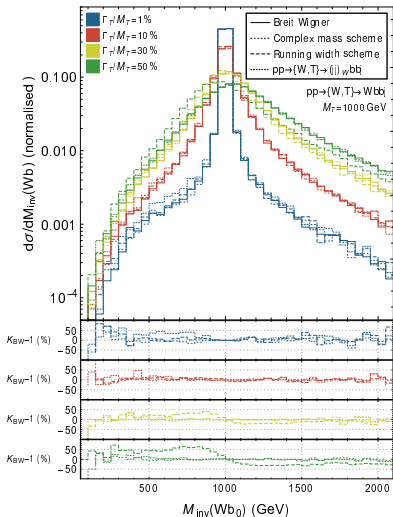
When the width is not narrow



If the width of the VLQ is large with respect to its mass:

- **Off-shell effects** are not negligible anymore
- **Subdominant topologies** in the Narrow Width Approximation may become important (t-channel)
- Outside the NWA all topologies leading to the same final state must anyway be taken into account for **gauge invariance**
- Need to take into account **interference effects**, both between signal topologies, and between signal and SM background

Width schemes



- Breit-Wigner $\frac{i(\not{p}+M_T)}{p^2-M_T^2+i\Gamma_T M_T}$
- **Complex mass scheme**
(only for the VLQ or for all particles)

$$M^2 \rightarrow \tilde{M}^2 = M^2 - iM\Gamma$$

consistent, gauge-invariant and applicable at NLO

A. Denner *et al.*, Nucl. Phys. B **560** (1999), 33-65
A. Denner *et al.*, Nucl. Phys. B **854** (2012), 504-507

- Running width

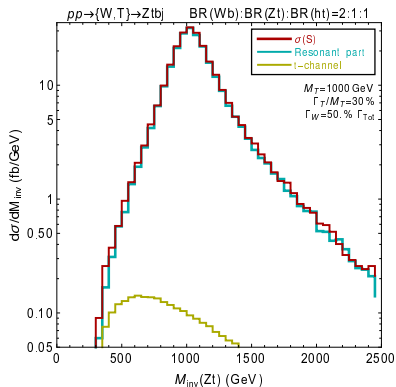
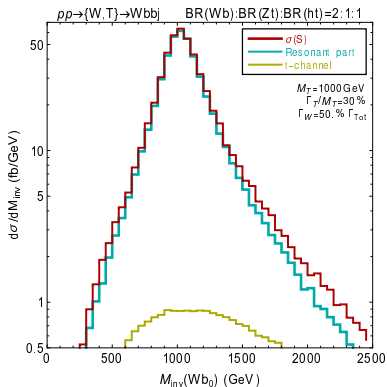
$$\frac{i(\not{p}+M_T)}{p^2-M_T^2+i\frac{p^2}{M^2}\Gamma_T M_T}$$

- Small differences in the M_{inv} shape
- In the RW the peak shifts to the left
cfr. D. Y. Bardin *et al.*, Phys. Lett. B **206** (1988), 539-542

It can be treated as a systematic uncertainty

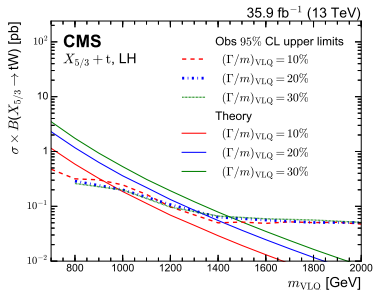
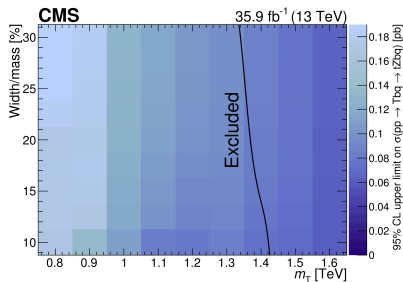
Final states with gauge bosons

W -mediated production: $Wbbj$ and $Ztbj$



**Small impact of t-channel (up to few %) at total and differential level
(mostly in the off-shell tails)**

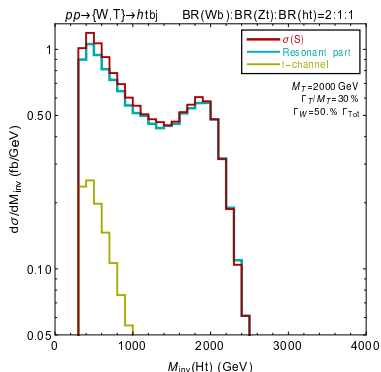
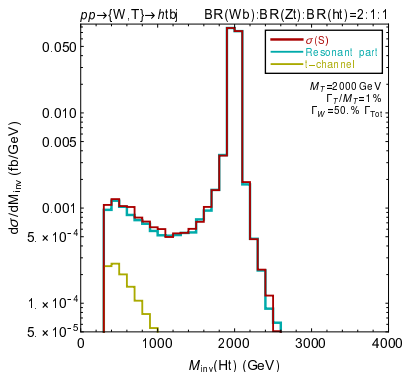
And indeed experimental results for VLQs with large width were appearing



but in 2019, people in ATLAS found something strange
(the discussions actually started here during a LIO workshop)

Final states with the Higgs

W -mediated production: $htbj$

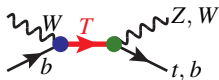


A double-peak structure emerges, even at small widths
and the peak at low invariant mass is still coming from the s-channel

What is that?

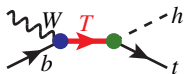
Analytical treatment

W boson approximation

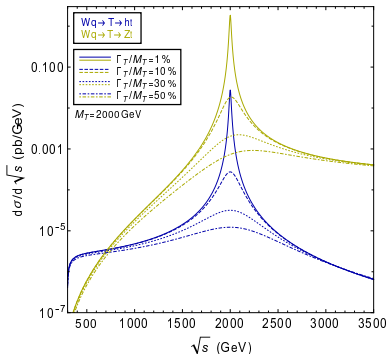


$$\sigma_{Wb} \sim \frac{\mathcal{N}_{Wb}(s)}{|s - \tilde{M}_T^2|^2}$$

$$\sigma_{Zt} \sim \frac{\mathcal{N}_{Zt}(s)}{|s - \tilde{M}_T^2|^2}$$



$$\sigma_{ht} \sim \frac{\mathcal{N}_{ht}(s)}{|s - \tilde{M}_T^2|^2} \frac{|\tilde{M}_T^2|}{s}$$



- The ht distribution shows a **plateau** for low \sqrt{s} , while the W and Z distributions fall down.
- Matrix element: the ht distribution flattens for larger widths
→ **higher relevance of the low \sqrt{s} region at large widths**
- PDFs enhancement at low Bjorken- x
→ **When convoluted with the PDFs the peak at low invariant mass emerges!**

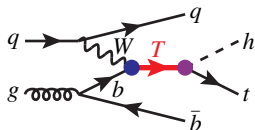
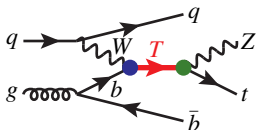
Important consequences: { **Interference with the SM background!**
Non-symmetric (non-BW-like) resonant shape!

Outline

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Parametrisation for large width regime

example for W -mediated production



In the narrow-width approximation - no interference with the SM background

$$\sigma(\kappa, \tilde{\kappa} \text{ OR } \hat{\kappa}, m_T, \Gamma_T) = \sigma_P(\kappa, m_T) BR_{T \rightarrow \text{decay channel}} = \kappa^2 \hat{\sigma}_{NWA}(m_T) BR_{T \rightarrow \text{decay channel}}$$

When the width is large (compared to the mass)

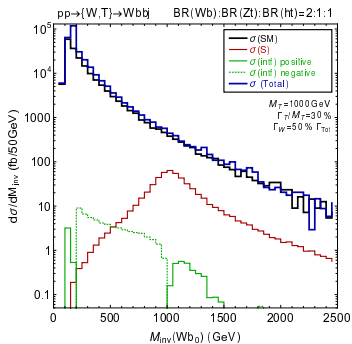
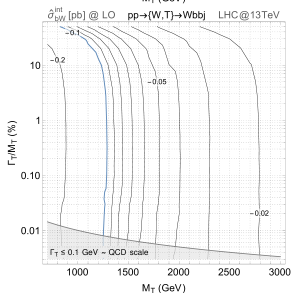
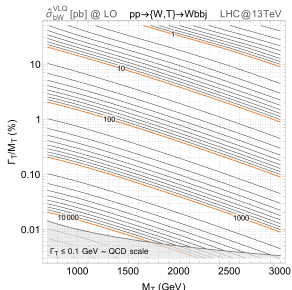
$$\begin{aligned} \sigma_{\text{tot}}(pp \rightarrow Wbbj) &= \sigma_{Wb}^{\text{SM}} + \kappa^4 \hat{\sigma}_{Wb}^{\text{VLQ}}(M_T, \Gamma_T) + \kappa^2 \hat{\sigma}_{Wb}^{\text{int}}(M_T, \Gamma_T), \\ \sigma_{\text{tot}}(pp \rightarrow Ztbj) &= \sigma_{Zt}^{\text{SM}} + \kappa^2 \tilde{\kappa}^2 \hat{\sigma}_{Zt}^{\text{VLQ}}(M_T, \Gamma_T) + \kappa \tilde{\kappa} \hat{\sigma}_{Zt}^{\text{int}}(M_T, \Gamma_T), \\ \sigma_{\text{tot}}(pp \rightarrow htbj) &= \sigma_{ht}^{\text{SM}} + \kappa^2 \hat{\kappa}^2 \hat{\sigma}_{ht}^{\text{VLQ}}(M_T, \Gamma_T) + \kappa \hat{\kappa} \hat{\sigma}_{ht}^{\text{int}}(M_T, \Gamma_T) \end{aligned}$$

- κ , $\tilde{\kappa}$ and $\hat{\kappa}$ couplings: partial widths and rescaling of cross-section
- Mass and total width: kinematics of the process

$$\text{Consistency relation: } \Gamma_T^{\text{partial}}(\kappa) + \Gamma_T^{\text{partial}}(\tilde{\kappa} \text{ or } \hat{\kappa}) \leq \Gamma_T$$

From $\hat{\sigma}$ to S and S+B

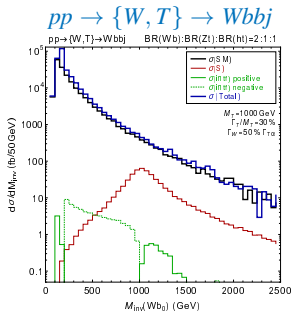
- Pick the values of $\hat{\sigma}$ corresponding to M_T and Γ_T
- Multiply by the appropriate values of the couplings



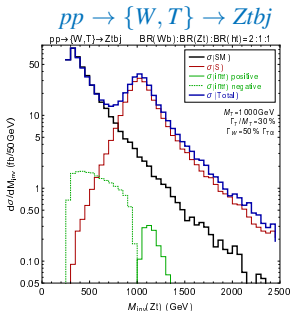
The same technique can be applied after experimental selections including the efficiencies for S and SB -interference

Numerical results

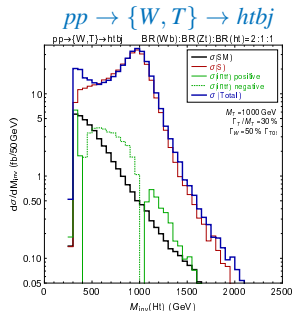
invariant masses



- large background due to $g \rightarrow b\bar{b}$
- interference cancels signal at low M_{inv}
- non-trivial S/B analysis



- no $g \rightarrow b\bar{b}$: large signal
- interference likely important only at low M_{inv}



- signal is huge
- interference competitive with signal at low M_{inv}

Assuming further decays into exotics would rescale all these contributions

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How to deal with NLO for large width

- NLO QCD corrections can have a **big impact** on total cross-sections (VLQs are coloured)
- **Distributions can be affected too!**
- Complex mass scheme required for gauge-invariance. . . **but not available at NLO!**

Approximate treatment

- 1) Generate events at LO with **large width** with the **complex mass scheme**
- 2) Generate events at **LO+PS** and **NLO+PS in the NWA**
- 3) For a given observable \mathcal{O} :

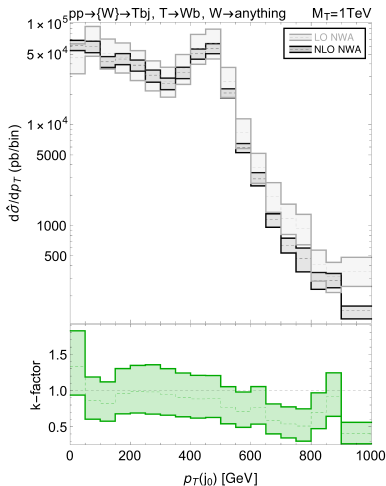
$$\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{NLO,LW}\}} \simeq \frac{\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{NLO,NWA}\}}}{\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{LO,NWA}\}}} \times \left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{LO,LW}\}} \equiv K_{\text{NWA}} \times \left(\frac{d\sigma}{d\mathcal{O}}\right)_{\{\text{LO,LW}\}}$$

Limitation: a differential K-factor **independent of the width/mass ratio** is applied

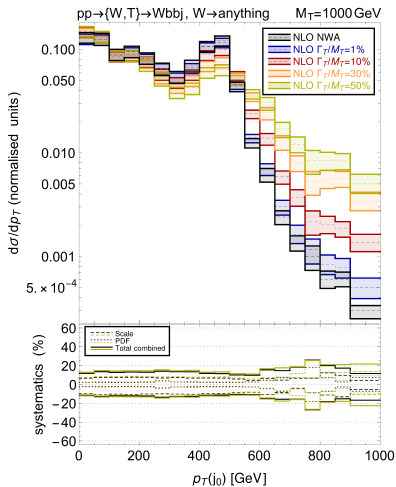
- s-channel must be dominant over t-channel (K-factor is evaluated in the NWA)
- interference must be negligible (simulations stop at the $2 \rightarrow 3$ processes)

Numerical results

example with $Wbbj$ and p_T of leading jet



- Reduction of theory uncertainties
- Peak at $M_T/2$ independent of Γ_T

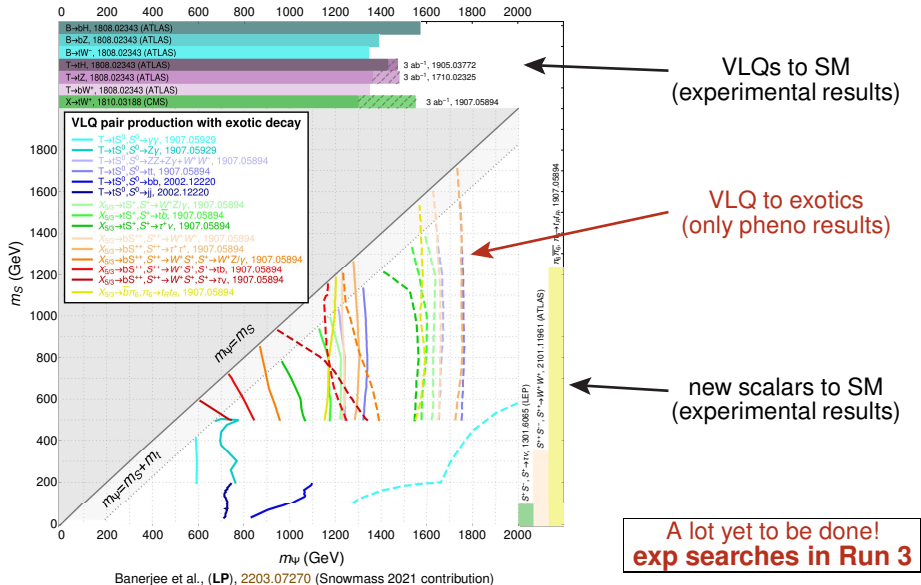


- No width dependence below M_T
- Large dependence above M_T (where the NLO corrections matter the most)

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A summary of the current status



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Intense study of **vector-like quarks interacting with SM particles**
from phenomenological and experimental sides

Still under way to complete the picture
(and hopefully see something, just bounds is a bit boring. . .)

To do (or in progress)

- projections for HL and HE** (pheno+experiments)
- large width and interference** (experiments)
- adding QCD NLO corrections for single production** (pheno+exp, if motivated)

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in full SM decays

Theoretical scenarios
are always **non minimal**

Exotic decays

A lot of pheno studies, but no experimental searches yet!

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Filling gaps: { **pair production with SM+exotic decays** (pheno+exp)
 { **single production via EW and decay to exotic** (pheno+exp)

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