Vector-like quarks beyond minimality

large width, NLO and exotic decays

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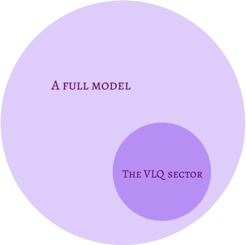
SHIFt

based (mostly) on JHEP **08** (2021), 107 with

A. Deandrea, T. Flacke, B. Fuks and Hua-Sheng Shao

Common features and smoking guns



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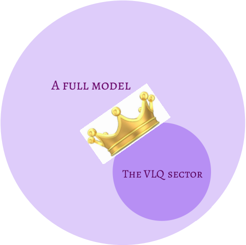
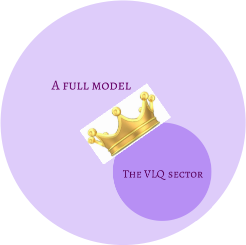


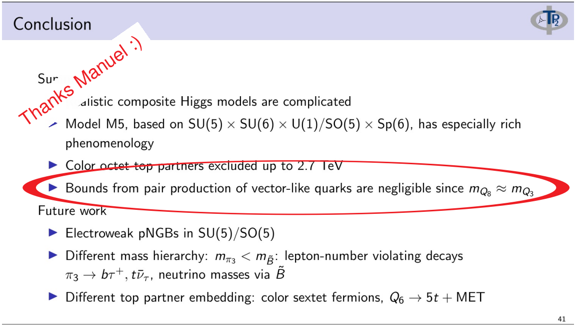
Hadron colliders

Common features and smoking guns



Hadron colliders*

*conditions apply



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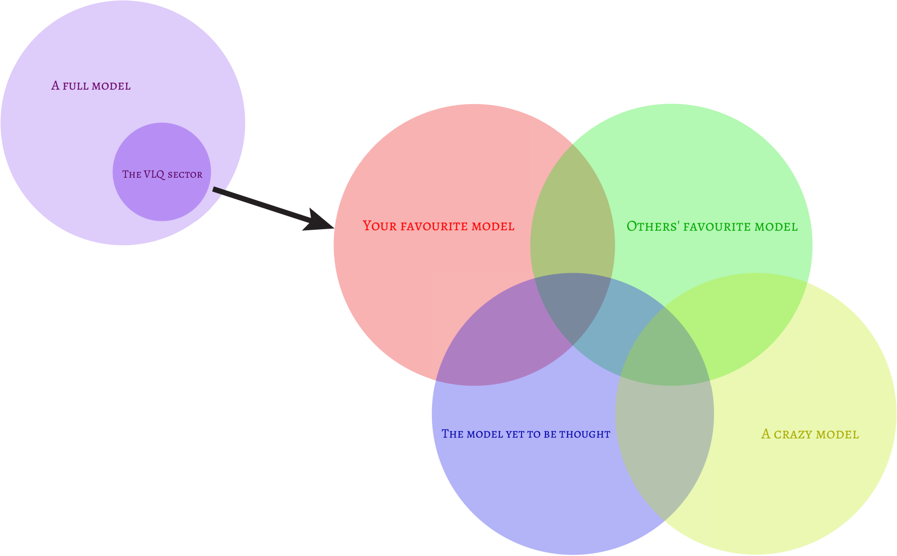

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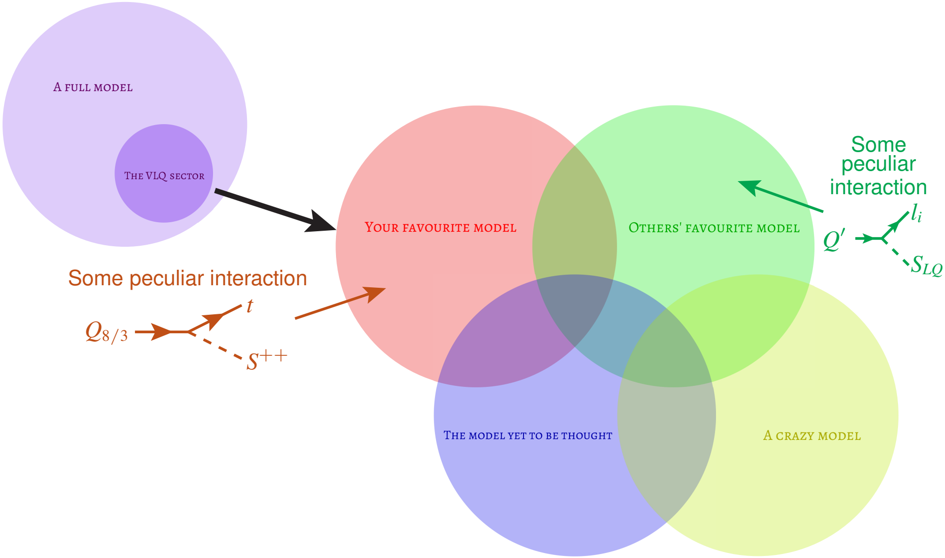

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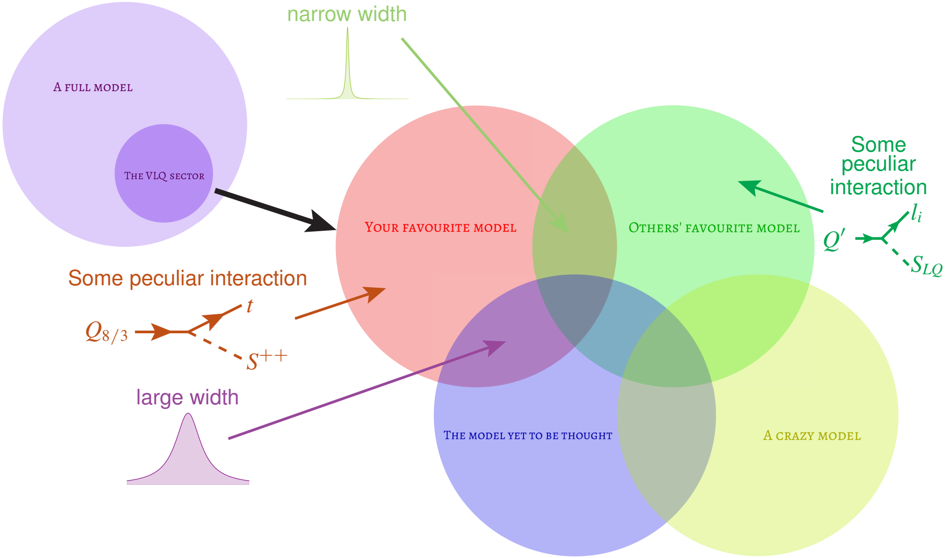

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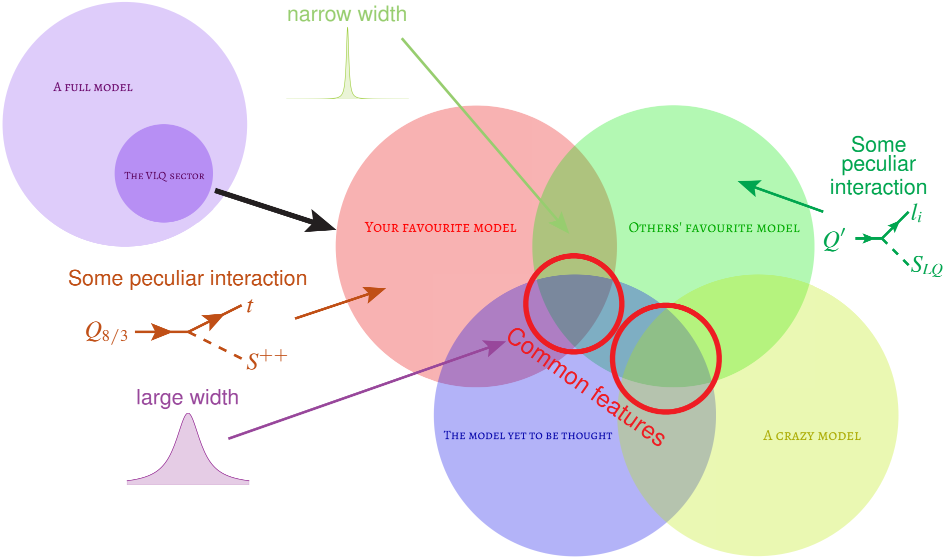

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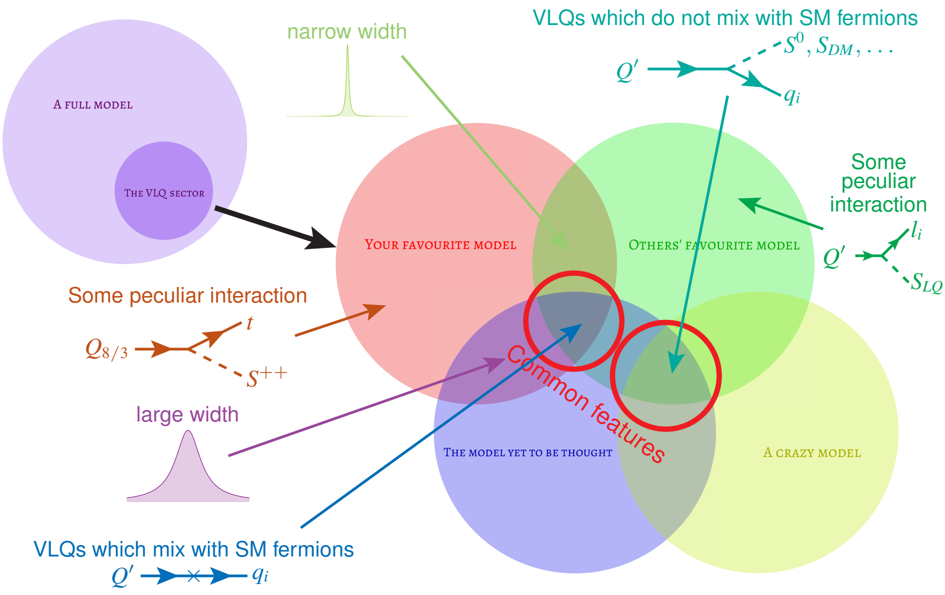

Outline

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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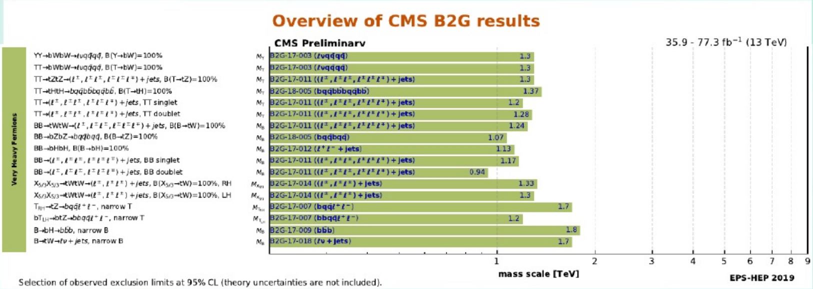
Thanks Avik :)

Status of VLQ search @LHC



Caveats:

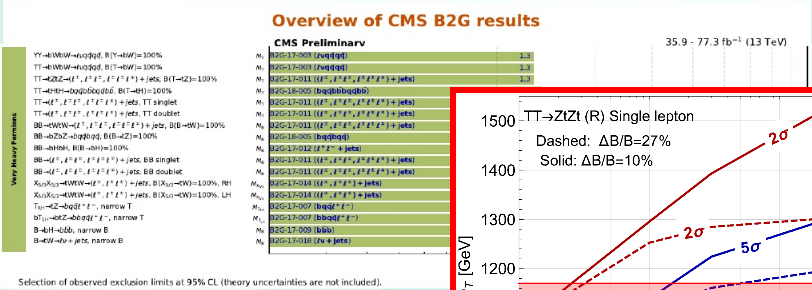
- Simplified model framework (often with single VLQ)
- Interacting only with SM states (usually third generation)
- 100% BR to specific SM channels
- Until recently, usually narrow width approximation

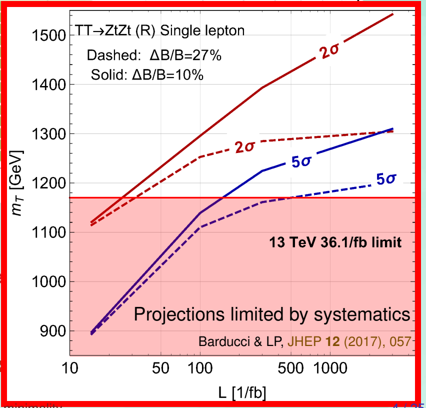
- Pair at NLO
- Single at LO

18

Thanks Avik :)

Status of VLQ search @LHC





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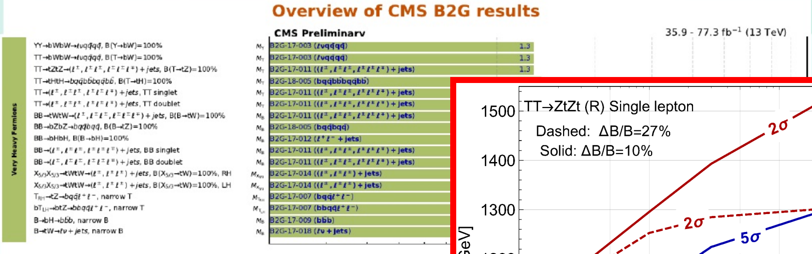
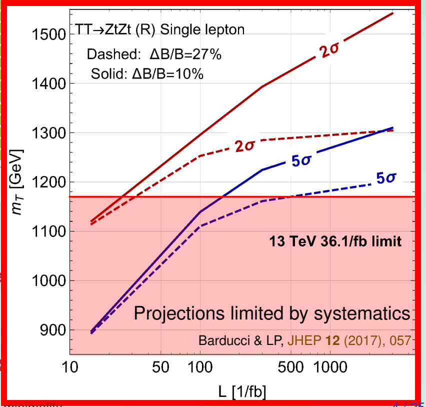


Need for non-minimality



Caveats:

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- **Until recently, usually narrow width approx**

The numerical models

Interaction Lagrangian for T

$$\mathcal{L} = h\bar{T}\big(\hat{\kappa}_L P_L + \hat{\kappa}_R P_R\big)u_q + \frac{g}{2c_W}\bar{T}\not{Z}\big(\tilde{\kappa}_L P_L + \tilde{\kappa}_R P_R\big)u_q + \frac{g}{\sqrt{2}}\bar{T}\not{W}\big(\kappa_L P_L + \kappa_R P_R\big)d_q + \text{h.c.}$$

B. Fuks and H.-S. Shao, Eur. Phys. J.C77(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

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

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

Both models are available on the Feynrules webpage

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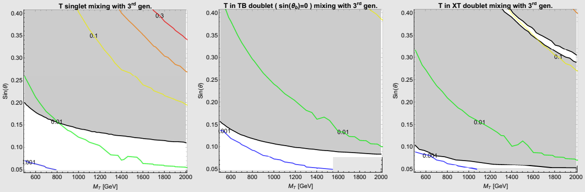
How large can a large width be?

Two ways to obtain a large width

1. **Increase couplings** ⟶ bounds from other observables (flavour, EWPT); perturbativity

T singlet **(T B) doublet** **(X T) doublet**



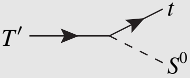
Minimal simplified models with large couplings already excluded by other observables

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

⟶ 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

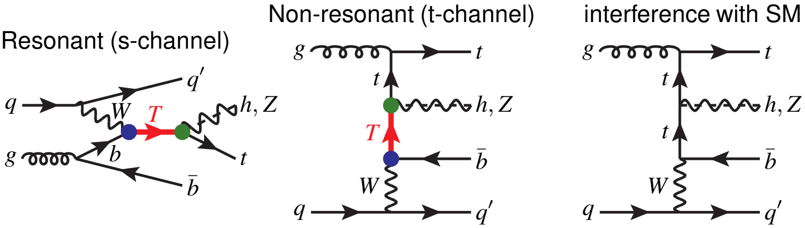
2. **Increase number of decay channels** ⟶ new physics, non-minimal extension



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

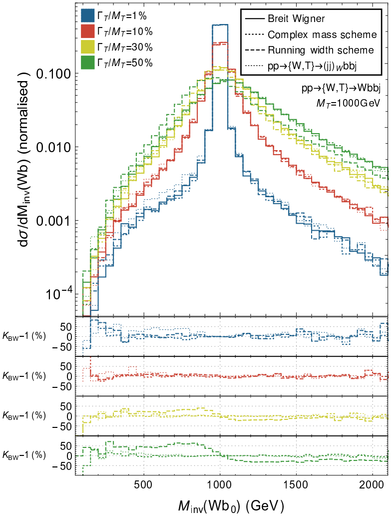
When the width is not narrow



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)

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

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

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

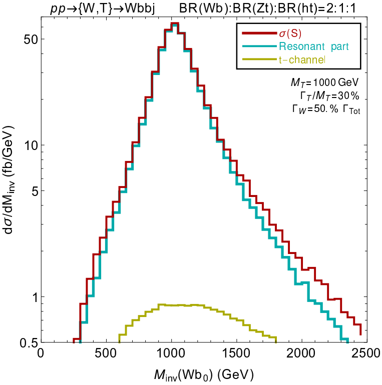
- Small differences in the $M_{\rm inv}$ shape
- In the RW the peak shifts to the left

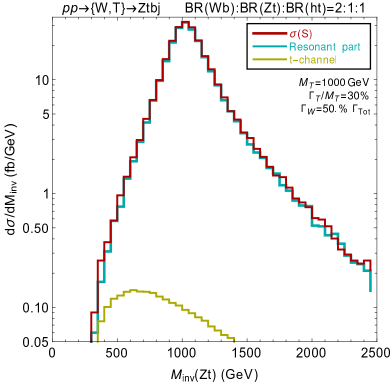
cfr. D. Y. Bardin *et al.*, Phys. Lett. B **206** (1988), 539-542

It can be treated as a systematic uncertainty

Final states with gauge bosons

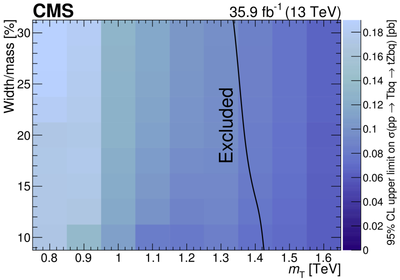
W-mediated production: $Wbbj$ and $Ztbj$

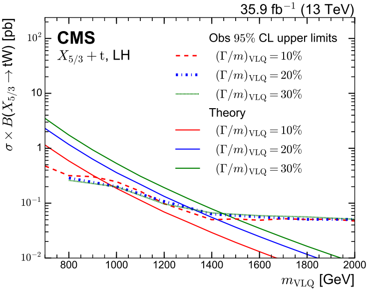




Small impact of t-channel (up to few %) at total and differential level
(mostly in the off-shell tails)

And indeed experimental results for VLQs with large width were appearing

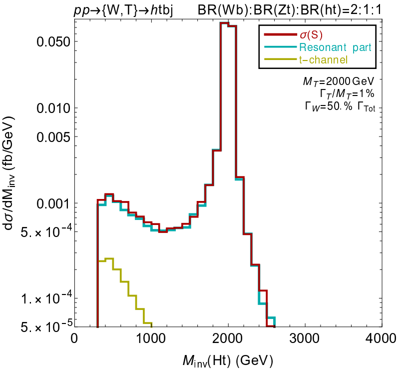


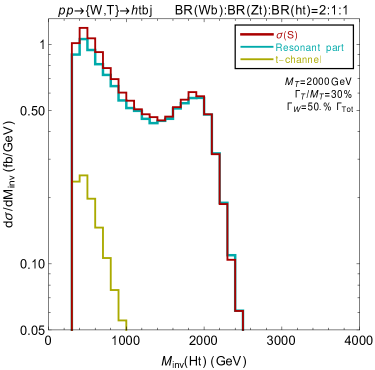


but in 2019, people in ATLAS found something strange
(the discussions actually started here during a LIO workshop)

Final states with the Higgs

W-mediated production: $htbj$





A double-peak structure emerges, even at small widths

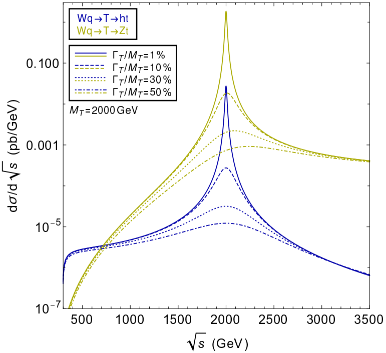
and the peak at low invariant mass is still coming from the s-channel

What is that?

Analytical treatment

W boson approximation

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



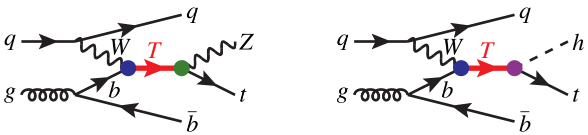
- The ht distribution shows a **plateau** for low $\sqrt{s}$, while the W and Z distributions fall down.
- Matrix element: the ht distribution flattens for larger widths $\rightarrow$ **higher relevance of the low $\sqrt{s}$ region at large widths**
- PDFs enhancement at low Bjorken-x $\rightarrow$ **When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

Parametrisation for large width regime

example for W-mediated production



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

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

When the width is large (compared to the mass)

$$\sigma_{\text{tot}}(pp \to Wbbj) = \sigma^{\text{SM}}_{Wb} + \kappa^4\, \hat{\sigma}^{\text{VLQ}}_{Wb}(M_T, \Gamma_T) + \kappa^2\, \hat{\sigma}^{\text{int}}_{Wb}(M_T, \Gamma_T)\,,$$

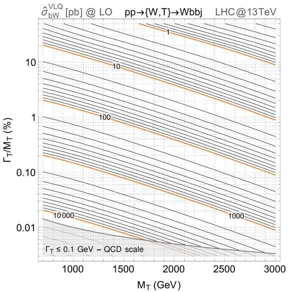
$$\sigma_{\text{tot}}(pp \to Ztbj) = \sigma^{\text{SM}}_{Zt} + \kappa^2\tilde{\kappa}^2\, \hat{\sigma}^{\text{VLQ}}_{Zt}(M_T, \Gamma_T) + \kappa\tilde{\kappa}\, \hat{\sigma}^{\text{int}}_{Zt}(M_T, \Gamma_T)\,,$$

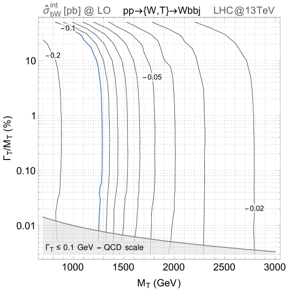
$$\sigma_{\text{tot}}(pp \to htbj) = \sigma^{\text{SM}}_{ht} + \kappa^2\hat{\kappa}^2\, \hat{\sigma}^{\text{VLQ}}_{ht}(M_T, \Gamma_T) + \kappa\hat{\kappa}\, \hat{\sigma}^{\text{int}}_{ht}(M_T, \Gamma_T)$$

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

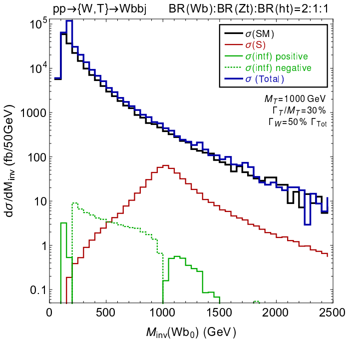
Consistency relation: $\Gamma^{\text{partial}}_T(\kappa) + \Gamma^{\text{partial}}_T(\tilde{\kappa} \text{ or } \hat{\kappa}) \leq \Gamma_T$

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

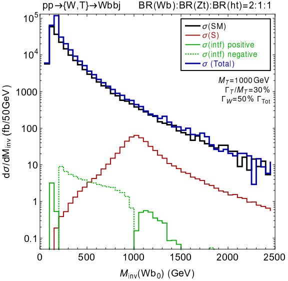


The same technique can be applied after experimental selections including the efficiencies for S and SB-interference

Numerical results

invariant masses

$pp \to \{W, T\} \to Wbbj$



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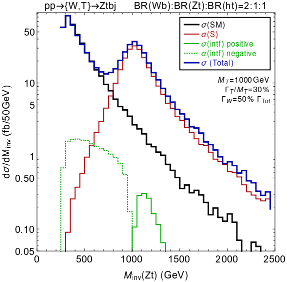
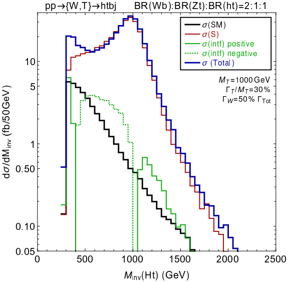


$pp \to \{W, T\} \to htbj$



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

- no $g \to b\bar{b}$: **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 $\mathcal{O}$:

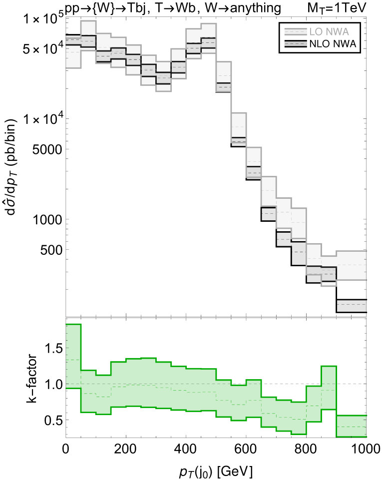
$$\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\text{\{NLO,LW\}}} \simeq \frac{\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\text{\{NLO,NWA\}}}}{\left(\frac{d\sigma}{d\mathcal{O}}\right)_{\text{\{LO,NWA\}}}} \times \left(\frac{d\sigma}{d\mathcal{O}}\right)_{\text{\{LO,LW\}}} \equiv K_{\text{NWA}} \times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

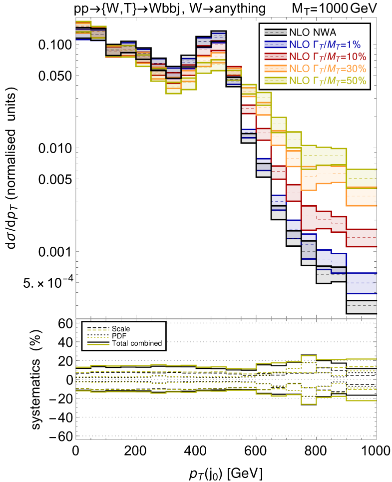
Limitation: a differential K-factor **independent of the width/mass ratio** is applied

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

Numerical results

example with $Wbbj$ and p_T of leading jet



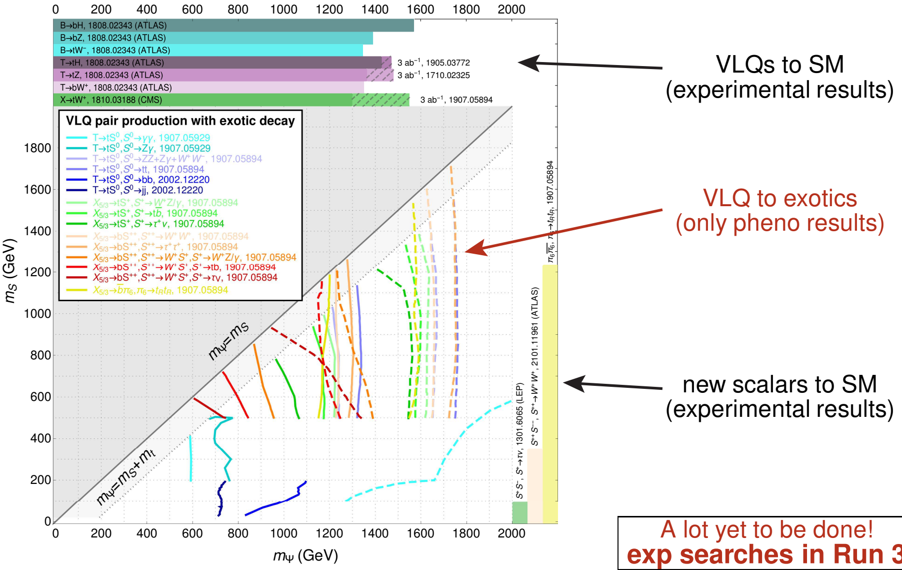


- Reduction of theory uncertainties
- Peak at $M_T/2$ independent of Γ_T

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

Outline

A summary of the current status



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

A lot yet to be done!
exp searches in Run 3

Outline

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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No signs of new physics
in full SM decays

Theoretical scenarios
are always **non minimal**

↘ ↙

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

To do (or in progress)

- **completing the exotic spectrum of decays** (pheno+experiment)
- **finding reasonable smoking guns** (theory + pheno $\rightarrow$ experiment)

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Filling gaps:
- **pair production with SM+exotic decays**
- **single production via EW and decay to exotic**

(pheno+exp)

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