Vector-like quarks with large width at the LHC

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SHIFt

Vector-like fermions

defining features

A fermion is **vector-like** under a gauge group
if its left-handed and right-handed chiralities transform in the **same way**

e.g. SM quarks are vector-like under $SU(3)_c$ but are chiral under $SU(2) \times U(1)_Y$

Why "vector-like"?

$\mathcal{L}_W = g/\sqrt{2}\, j^{\mu\pm} W^{\pm}_{\mu}$ Charged current Lagrangian

SM Chiral fermions

$$j^{\mu}_L = \bar{f}_L \gamma^{\mu} f'_L \qquad j^{\mu}_R = 0$$

$$j^{\mu} = j^{\mu}_L + j^{\mu}_R = \bar{f}\gamma^{\mu}(1-\gamma^5)f'$$

V-A structure

Vector-like fermions

$$j^{\mu}_L = \bar{f}_L \gamma^{\mu} f'_L \qquad j^{\mu}_R = \bar{f}_R \gamma^{\mu} f'_R$$

$$j^{\mu} = j^{\mu}_L + j^{\mu}_R = \bar{f}\gamma^{\mu} f'$$

V structure

Peculiar Properties

$\mathcal{L}_M = -M\bar{\psi}\psi$ Gauge invariant mass term without the Higgs

No need to add both quarks and leptons: axial anomalies are automatically absent

VLQ representations

Minimal SM extensions with one VLQ representation interacting through Yukawa terms

	SM	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(t')	(b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \end{pmatrix}$	$\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c t'_R$ $-\lambda_d^i \bar{q}_L^i H b'_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	

Larger representations are allowed if multiple VLQs or extended Higgs sector

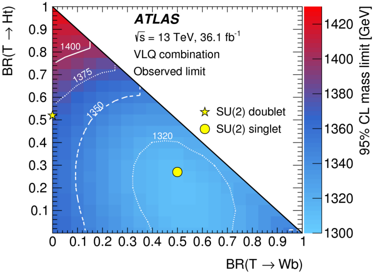
Vector-like quarks in many models of New Physics

- Warped or universal **extra-dimensions**: KK excitations of bulk fields
- **Composite Higgs** models: excited resonances of the bound states which form SM particles
- **Little Higgs** models: partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- Non-minimal **SUSY extensions**: increase corrections to Higgs mass without affecting EWPT

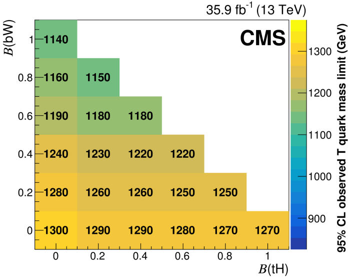
Vector-like quarks

an intense experimental effort

ATLAS 1808.02343



CMS 1805.04758



Bounds above the TeV, but usually under specific **assumptions**:

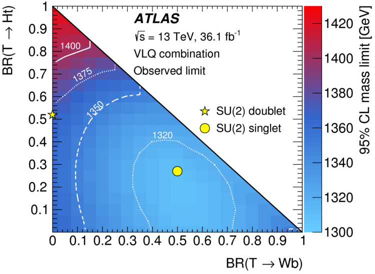
- SM extended with only **one representation** of VLQs
- Mixing only with **third generation** of SM quarks
- **Pair production** or **Single production@LO**
- **Narrow width** approximation
- Interacting only with **SM states**

More exploration is definitely needed!

Vector-like quarks

an intense experimental effort

ATLAS 1808.02343



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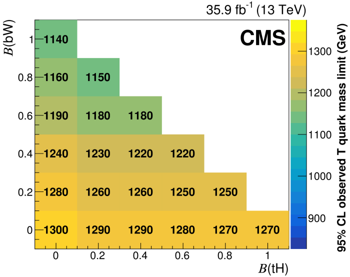

Bounds above the TeV, but usually under specific **assumptions**:

- SM extended with only **one representation** of VLQs
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Single production of VLQs with finite width

interacting only with SM states

based on

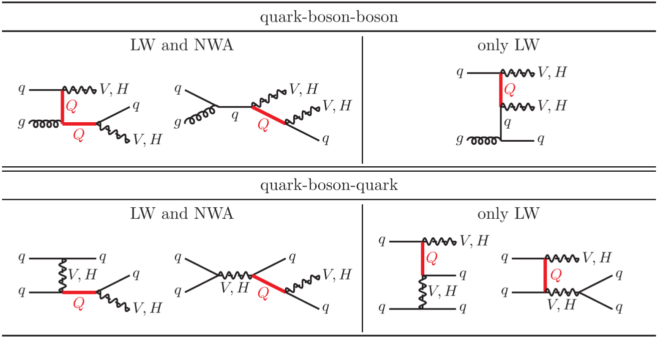
A. Carvalho, S. Moretti, D. O'Brien, **LP** and H. Prager
Single production of vectorlike quarks with large width at the Large Hadron Collider
Phys.Rev. D98 (2018) no.1, 015029

and

CMS Collaboration
Search for single production of a vector-like T quark decaying to a Z boson and a top quark in proton-proton collisions at $\sqrt{s}$ = 13 TeV
Phys.Lett. B781 (2018) 574-600

Search for single production of vector-like quarks decaying to a b quark and a Higgs boson
JHEP 1806 (2018) 031

Including more topologies



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
- Outside the NWA all topologies leading to the same final state must anyway be taken into account for **gauge invariance**
- Need to redefine the signal to take into account **interference effects**

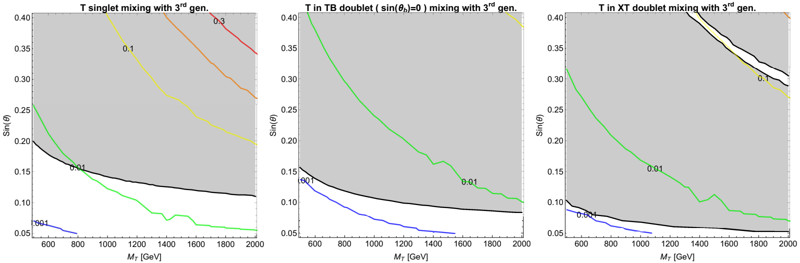
How large the width can be

To obtain a large width:

- **Increase couplings**
  - ⟶ bounds from other observables (flavour, EWPT); perturbativity
  - ⟶ non-minimal extensions which allow to escape bounds while enlarging couplings
- **Increase number of decay channels** ⟶ new physics, non-minimal extension

Simplified models with large couplings:

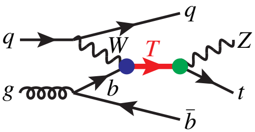
T singlet **(T B) doublet** **(X T) doublet**



Bounds from C.-Y. Chen, S. Dawson, and E. Furlan, *Vector-like Fermions and Higgs Effective Field Theory Revisited*, Phys. Rev. D **96** (2017) no.1, 015006.

Simplified models with large couplings already excluded by other observables
New physics has to be invoked

Parametrisation for large width regime



in the narrow-width approximation (NWA)

$$\sigma(C_1, C_2, m_Q, \Gamma_Q) = \sigma_P(C_1, m_Q) BR_{Q\to\text{decay channel}} = C_1^2 \hat{\sigma}_{NWA}(m_Q) BR_{Q\to\text{decay channel}}$$

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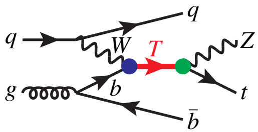


in the narrow-width approximation (NWA)

$$\sigma(C_1, C_2, m_\mathrm{Q}, \Gamma_Q) = \sigma_P(C_1, m_\mathrm{Q}) BR_{Q\to\text{decay channel}} = C_1^2 \hat{\sigma}_{NWA}(m_\mathrm{Q}) BR_{Q\to\text{decay channel}}$$

in the finite width regime (FW) and assuming negligible interference contributions

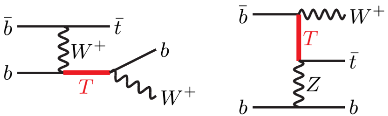
$$\sigma(C_1, C_2, m_\mathrm{Q}, \Gamma_Q) = C_1^2\ C_2^2\ \hat{\sigma}(m_\mathrm{Q}, \Gamma_Q)$$

- C_1 **and** C_2 **couplings**: partial widths and rescaling of cross-section
- **Mass and total width**: kinematics of the process

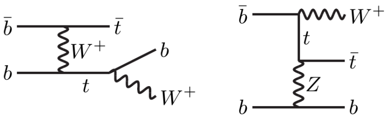
Consistency relation: $\Gamma_Q^{\text{partial}}(C_1) + \Gamma_Q^{\text{partial}}(C_2) \leq \Gamma_Q$

Interference

Signal



Irreducible background



signal with itself

$$\sigma_S = C_2^2 \, \hat{\sigma}_S(C_1 \ldots, M_Q, \Gamma_Q, \chi_Q)$$

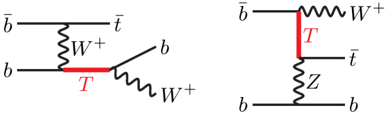
χ_Q is the dominant chirality of the VLQ

signal with irreducible background

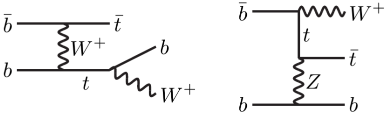
$$\sigma^{\text{int}}_{SB_{\text{irr}}} = C_2 \, \hat{\sigma}^{\text{int}}_{SB_{\text{irr}}}(C_1 \ldots, M_Q, \Gamma_Q, \chi_Q)$$

Interference

Signal



Irreducible background



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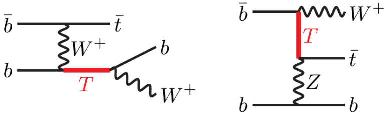
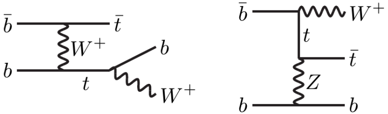
Model-dependency is (almost) unavoidable

Interference

Signal



Irreducible background



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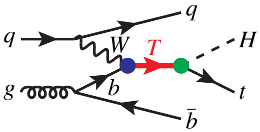
Model-dependency is (almost) unavoidable

If signal topologies always involve the same two couplings

$$\sigma_{S+B_{\text{irr}}} = \sigma(B_{irr}) + C_1^2 \; C_2^2 \; \hat{\sigma}(m_Q, \Gamma_Q) + C_1 \; C_2 \; \hat{\sigma}^{\text{int}}_{SB_{\text{irr}}}(m_Q, \Gamma_Q, \chi_Q)$$

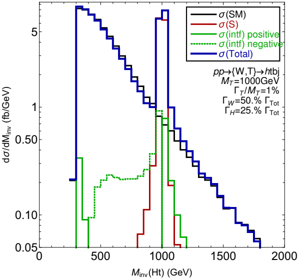
The relative role of interference depends also on the couplings

Role of interference

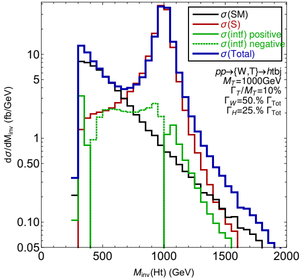


$$\Gamma_{Wb} = 50\%\Gamma_{tot} \text{ and } \Gamma_{Ht} = \Gamma_{Zt} = 25\%\Gamma_{tot}$$
(singlet-like)

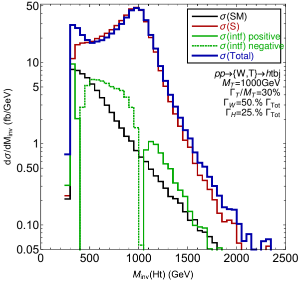
$\Gamma_{tot}/M = 1\%$



$\Gamma_{tot}/M = 10\%$



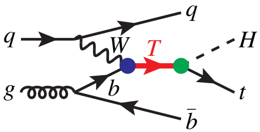
$\Gamma_{tot}/M = 30\%$



M=1000 GeV

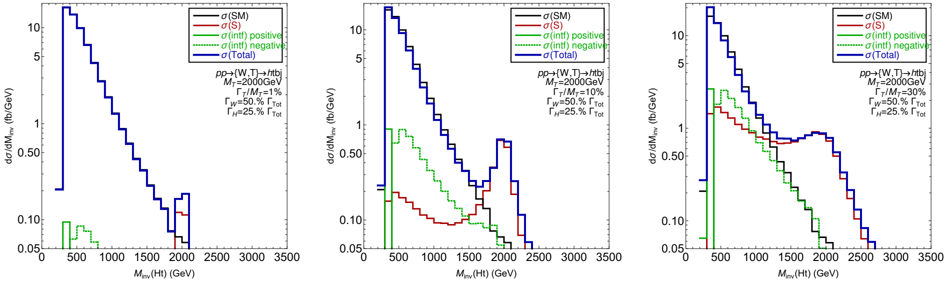
- To get a large width **the couplings become large** and the signal dominates over background
- **Enhancement** of the total distribution at low invariant mass due to **positive interference**

Role of interference



$$\Gamma_{Wb} = 50\%\Gamma_{tot} \text{ and } \Gamma_{Ht} = \Gamma_{Zt} = 25\%\Gamma_{tot}$$
(singlet-like)

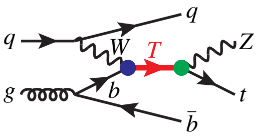
$\Gamma_{tot}/M = 1\%$ $\Gamma_{tot}/M = 10\%$ $\Gamma_{tot}/M = 30\%$



M=2000 GeV

- **The signal is cancelled by negative interference** to the left of the peak in the large width regime, except near the threshold of production, where interference becomes positive

Role of interference



$\Gamma_{Wb} = 50\%\Gamma_{tot}$ and $\Gamma_{Ht} = \Gamma_{Zt} = 25\%\Gamma_{tot}$
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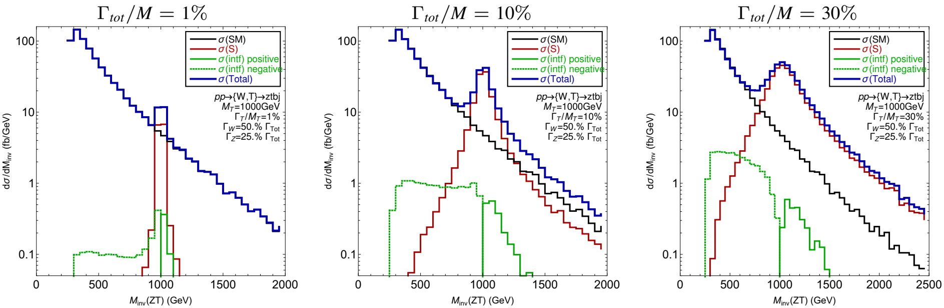
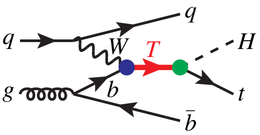


M=1000 GeV

- The role of **negative interference** is relevant only at small invariant mass where the background dominates

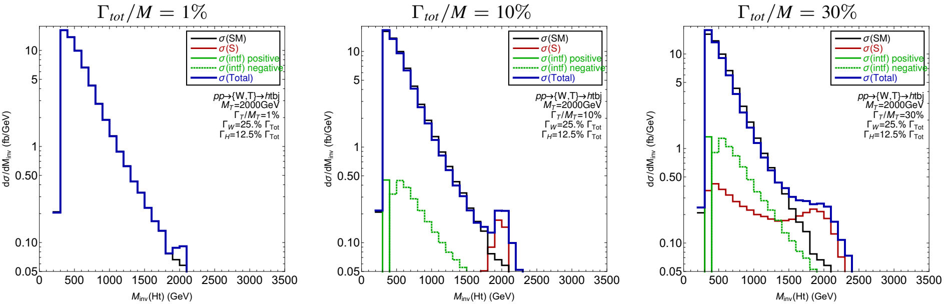
Analogous results for M=2000 GeV

Role of interference



$\Gamma_{Wb} : \Gamma_{Ht} : \Gamma_{Zt} = 2 : 1 : 1$ (singlet-like)

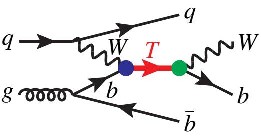
but $\Gamma_{Wb} + \Gamma_{Ht} + \Gamma_{Zt} = 50\%\Gamma_{tot}$
(there are other decay channels)



M=2000 GeV

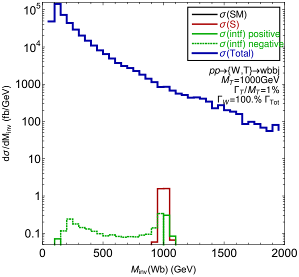
- **The couplings are small** even for large width and the signal dominates over background only at large invariant mass
- The **interference is dominant** with respect to the signal to the left of the peak

Role of interference



$$\Gamma_{Wb} = 100\% \Gamma_{tot}$$

$\Gamma_{tot}/M = 1\%$



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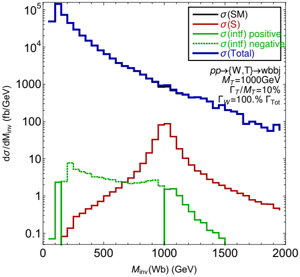
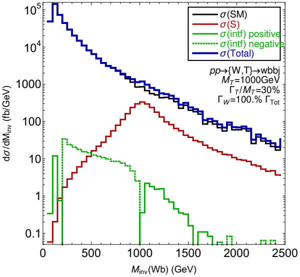


$\Gamma_{tot}/M = 30\%$



M=1000 GeV

- **The couplings remain small** also for large width and the background dominates over signal
- The role of **negative interference** is relevant only at small invariant mass where the background dominates

Strategy to generate the signal

1) Fix M_Q and Γ_Q/M_Q (with small enough Q couplings for consistency)

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FeynRules models to be used for NLO calculations with aMC@NLO

This page contains a collection of models that have been implemented in FeynRules in the context of NLO calculations in the framework of aMC@NLO. It contains up to now simplified models inspired by the current searches undertaken by ATLAS and CMS, as well as a model developed to characterise the properties of the recently discovered Higgs boson. For each model:

- we include a brief description of the relevant signature,
- we provide the FeynRules model files as well as the UFO library to be used with MadGraph5_aMC@NLO,
- we indicate reference paper with the documentation on the model, together with the name of the contact person,
- validation figures generated in the framework of each model are provided, so that any user could try to reproduce them to verify their setup.

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
SM 5F (more details)	C. Degrande	-	SM.fr	SM5F_NLO.tar.gz	-
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
Dark Matter Gauge invariant simplified model (scalar s-channel mediator) (more details)	G. Busoni	arXiv:1612.03475 , arXiv: 1710.10764 ,	-	-	-
Effective LR symmetric model (more details)	R. Ruiz	arXiv:1610.08985	effLRSM.fr	EffLRSM UFO	-
GM (more details)	A. Peterson	arXiv:1512.01243	-	GM_NLO UFO	-
Heavy Neutrino (more details)	R. Ruiz	arXiv:1602.06957	heavyN.fr	HeavyN NLO UFO	-
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Lineshape of pp -> A(H) -> t tbar (including interference) (more details)	D.B. Franzosi	http://arxiv.org/abs/1707.06760	-	AHttbar NLO UFO	-
Spin-2 (more details)	C. Degrande	http://arxiv.org/abs/1605.09359	dm_s_spin2.fr	SMspin2 NLO UFO	-
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
SUSY-QCD	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vector like quarks	B. Fuks	arXiv:1610.04622	VLQ_v3.fr	UFO in the 5FNS, UFO in the 4FNS, event generation scripts, coupling calculator in the LO conventions	All figures available from the arxiv
W'/Z' model (more details)	[illegible] Fuks	arXiv:1701.05263	vPrimeNLO.fr	vPrimeNLO UFO	-
NTGC (more details)	C. Degrande	JHEP 1402 (2014) 101	NTGC.fr	NTGC UFO at NLO	
GGG_EFT_up_to_4point_loops (more details) (requires MG5_aMC v2.6.3+)	V. Hirschi	arXiv:1806.04696	GGG.fr	GGG_EFT_up_to_4point_loops UFO	Analytic amplitude and cross-sections in the corresponding publication

-

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VLQ couplings have a dedicated **coupling order** "VLQ"

Single T→Wb final state with propagation of T: "generate p p > j b w+ / bp x y VLQ==2"

Strategy to generate the signal

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Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
SUSY-QCD	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-
Top FCNC Model (more details)	C. Zhang	[illegible]	[illegible]	[illegible]	
Vector like quarks	B. Fuks	arXiv:1610.04622	VLQ_v3.fr	UFO in the 5FNS, UFO in the 4FNS, event generation scripts, coupling calculator in the LO conventions	All figures available from the arxiv
W'/Z' model (more details)	[illegible] Fuks	arXiv:1701.05263	vPrimeNLO.fr	vPrimeNLO UFO	-
NTGC (more details)	C. Degrande	JHEP 1402 (2014) 101	NTGC.fr	NTGC UFO at NLO	
GGG_EFT_up_to_4point_loops (more details) (requires MG5_aMC v2.6.3+)	V. Hirschi	arXiv:1806.04696	GGG.fr	GGG_EFT_up_to_4point_loops UFO	Analytic amplitude and cross-sections in the corresponding publication

-

▸ Attachments (16) — *Last modified 7 weeks ago*

Download in other formats:

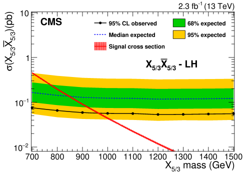
VLQ couplings have a dedicated **coupling order** “VLQ”

Single T$\rightarrow$Wb final state with propagation of T: “generate p p > j b w+ / bp x y VLQ==2”

3) Scan over M_Q and Γ_Q/M_Q to obtain the signal **kinematics** and experimental **efficiencies** and obtain the **upper limits** on the cross-section

Presentation of the results (1)

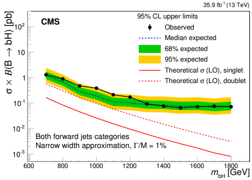
from NWA

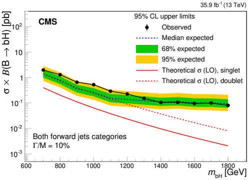


to Γ/M-dependent upper limits

CMS single-B search (JHEP 1806 (2018) 031)

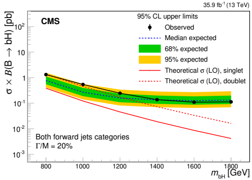
$\frac{\Gamma}{M}$ = 1% (~ NWA)

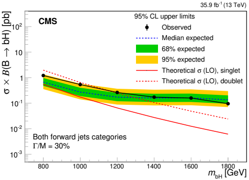




$\frac{\Gamma}{M}$ = 10%

$\frac{\Gamma}{M}$ = 20%

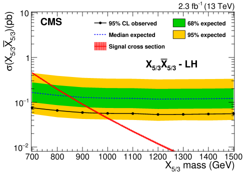




$\frac{\Gamma}{M}$ = 30%

Presentation of the results (2)

from NWA



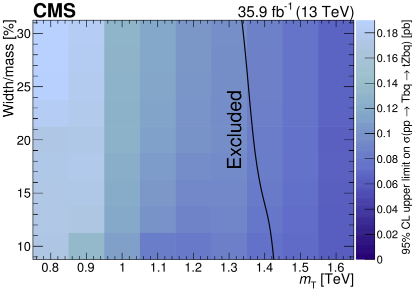
to Γ/M-dependent upper limits

CMS single-T search (Phys.Lett. B781 (2018) 574-600)

Reduced cross-section table ($\hat{\sigma}$)

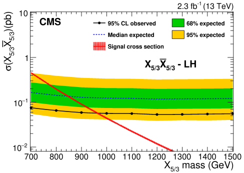
Mass [TeV]	$\tilde{\sigma}_{FW}$ (σ) for pp $\to$ Tbq $\to$ tZbq [pb] 10%	20%	30%	$\tilde{\sigma}_{FW}$ (σ) for pp $\to$ Ttq $\to$ tZtq [pb] 10%	20%	30%
0.8	226 (0.675)	108 (0.650)	70 (0.631)	19 (0.144)	9.3 (0.139)	6.0 (0.135)
1.0	183 (0.314)	87 (0.299)	55 (0.284)	17 (0.075)	7.9 (0.072)	5.0 (0.069)
1.2	145 (0.158)	68 (0.149)	43 (0.141)	14 (0.042)	6.4 (0.039)	4.1 (0.037)
1.4	112 (0.084)	52 (0.079)	33 (0.074)	11 (0.024)	5.0 (0.022)	3.2 (0.021)
1.6	85 (0.047)	39 (0.043)	29 (0.041)	8.2 (0.014)	3.8 (0.013)	2.4 (0.012)

Upper limits colour code



Presentation of the results (3)

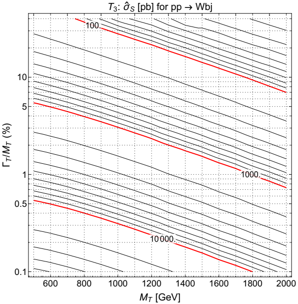
from NWA

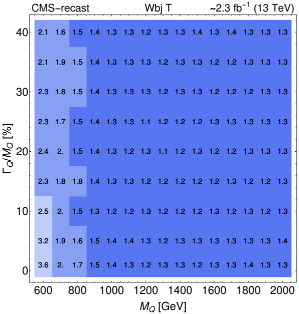


to Γ/M-dependent upper limits

Recast (Phys.Rev. D98 (2018) no.1, 015029)

Reduced cross-section plot





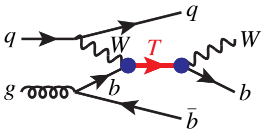
Upper limits grid

Providing limits in the M vs Γ/M plane allows for reinterpretation in a wide range of scenarios

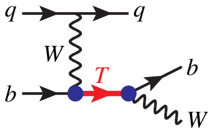
Finite width and kinematics

ignoring interference

4FS



5FS

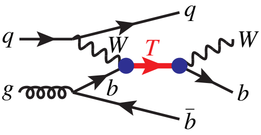


M_T = 1200 GeV, Γ_T/M_T = 1% and 30%, and imposing muonic decay of W

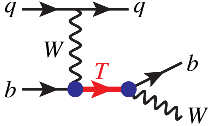
Finite width and kinematics

ignoring interference

4FS

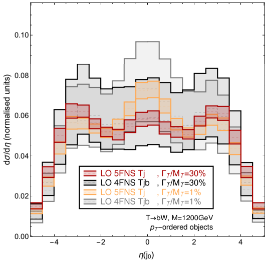


5FS

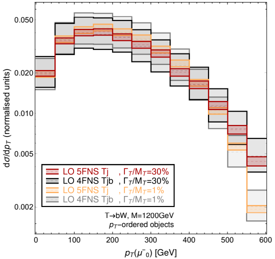


M_T = 1200 GeV, Γ_T/M_T = 1% and 30%, and imposing muonic decay of W

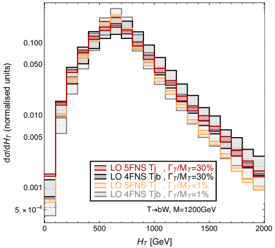
η of leading jet



p_T of μ^-



H_T

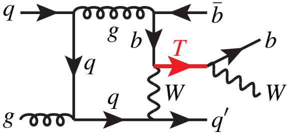


Kinematical distributions can be sizably different in the finite width regime

what happens at NLO?

Single production of VLQs at NLO

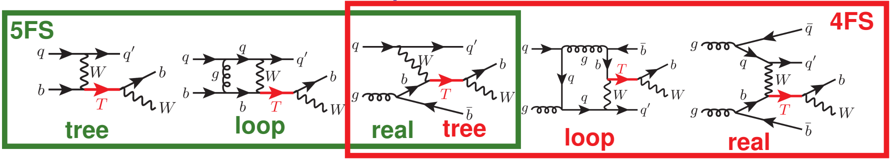
interacting only with SM states



based on

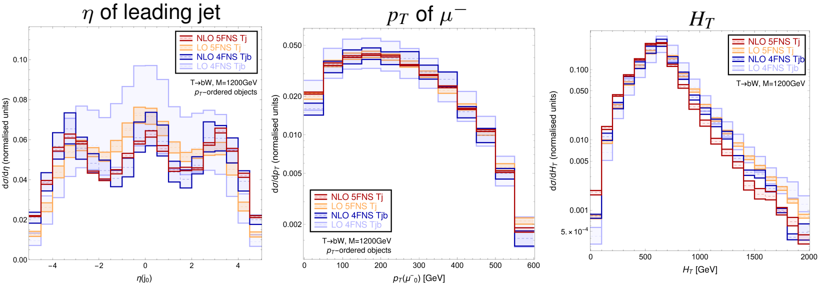
G. Cacciapaglia, A. Carvalho, A. Deandrea, T. Flacke, B. Fuks, D. Majumder, **LP** and and H.S. Shao
Next-to-leading-order predictions for single vector-like quark production at the LHC
Phys. Lett. B **793** (2019) 206

NLO predictions in the NWA



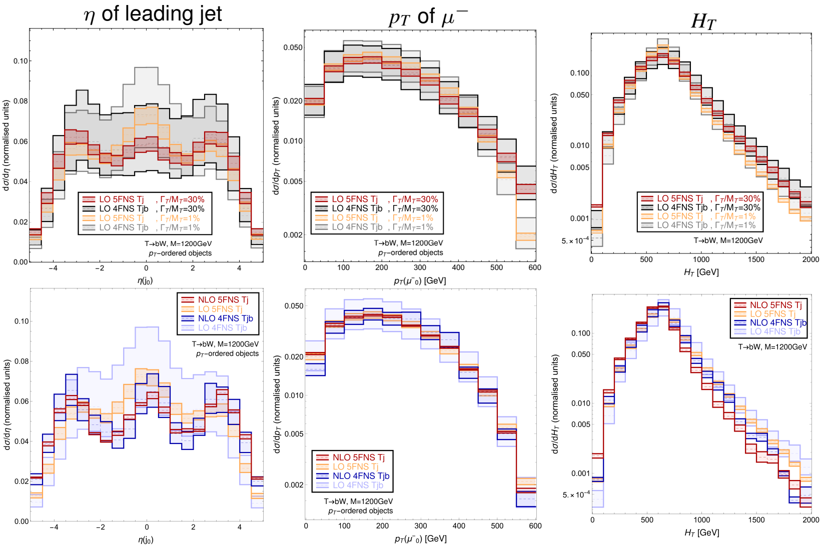
Distributions

M_T = 1200 GeV and imposing muonic decay of W



NLO corrections can significantly impact shapes

FW@LO vs NWA@NLO



What happens at NLO if the VLQ has large width?

Simulations for large width

- Simulations for large width should be done in the **complex mass scheme**, where masses are “complex quantities, defined as the location of the poles in the complex k^2 plane of the corresponding propagator with momentum k”.

  $\mu = M(1 - i\frac{\Gamma}{M})$ for every unstable particle

  A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. B **560** (1999) 33
  A. Denner, S. Dittmaier, M. Roth and L. H. Wieders, Nucl. Phys. B **724** (2005) 247
  A. Denner and S. Dittmaier, Nucl. Phys. Proc. Suppl. **160** (2006) 22

- **Consistent and gauge invariant**

The complex mass scheme can be set at LO in MadGraph but not at NLO yet for the VLQ UFO model

NLO Single production of VLQs with large width

Work in progress with B. Fuks and H.S. Shao

1) Generate events at LO with the **running width** (sample 1)

- $P(p) = [p^2 - M^2 + ip^2(\Gamma/M)\theta(p^2)]^{-1}$

  A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. B **560** (1999) 33

- $P(p) = [p^2 - M^2 + i\left(\sqrt{p^2}/M\right)^{\alpha} M\Gamma]^{-1}$ with $\alpha = 0, 2, 4\ldots$ (with $\alpha = 2$ the expressions are equivalent)

NLO Single production of VLQs with large width

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2) Generate events at **LO+PS** (sample 2) and **NLO+PS** (sample 3) in the NWA

NLO Single production of VLQs with large width

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     A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. B **560** (1999) 33
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2) Generate events at **LO+PS** (sample 2) and **NLO+PS** (sample 3) in the NWA
3) For a given observable $\mathcal{O}$: $\frac{d\sigma}{d\mathcal{O}} \equiv \frac{\frac{d\sigma^{(3)}}{d\mathcal{O}}}{\frac{d\sigma^{(2)}}{d\mathcal{O}}} \times \frac{d\sigma^{(1)}}{d\mathcal{O}}$

   differential k-factor

NLO Single production of VLQs with large width

Work in progress with B. Fuks and H.S. Shao

1) Generate events at LO with the **running width** (sample 1)

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A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. B **560** (1999) 33

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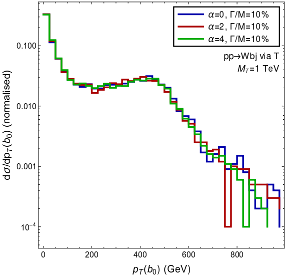
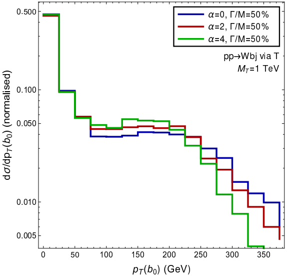
differential k-factor

Preliminary results





Conclusions

Single production of VLQs with finite width interacting with the SM

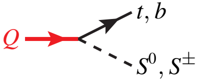
- **Finite width** effects can be **sizable**
- **Model-independent** parametrisation in terms of **mass** and **width-to-mass ratio**
- **UFO model available** for generation of signal and interference studies in the finite width regime and for NLO studies in the NWA

Ongoing studies for analysis of NLO effects in the finite width regime

Backup

Exotic decays of VLQs

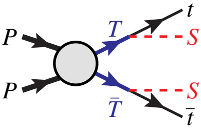
finite width effects

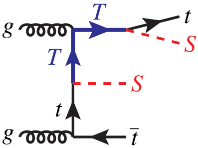


based on

R. Benbrik, E. B. Kuutmann, D. B. Franzosi, V. Ellajosyula, R. Enberg, G. Ferretti
M. Isacson, Yao-Bei L., T. Mandal, T. Mathisen, S. Moretti and **LP**
"Signatures of vector-like top partners decaying into new neutral scalar or pseudoscalar bosons"
arXiv:1907.05929 [hep-ph]

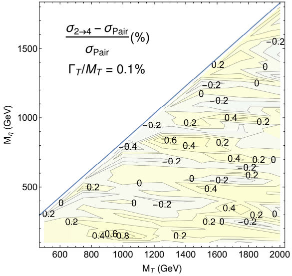
Mass of the scalar as new parameter

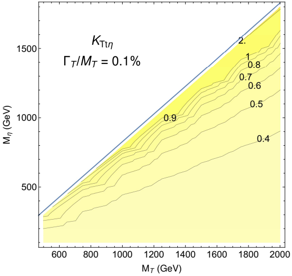


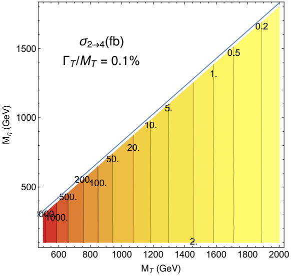


$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\, \hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T} \to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

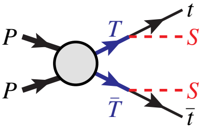
- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics

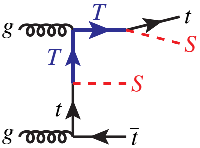






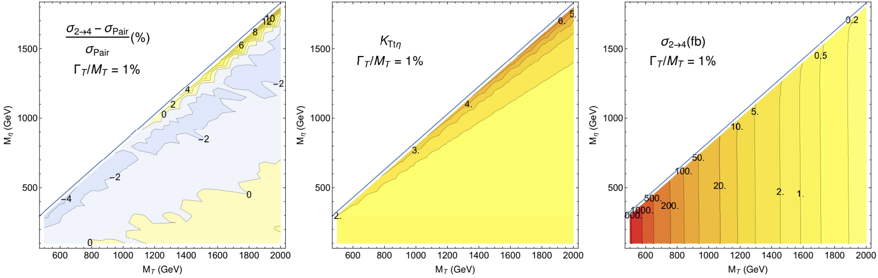
Mass of the scalar as new parameter



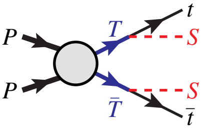


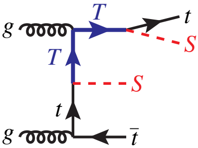
$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\, \hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T} \to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics



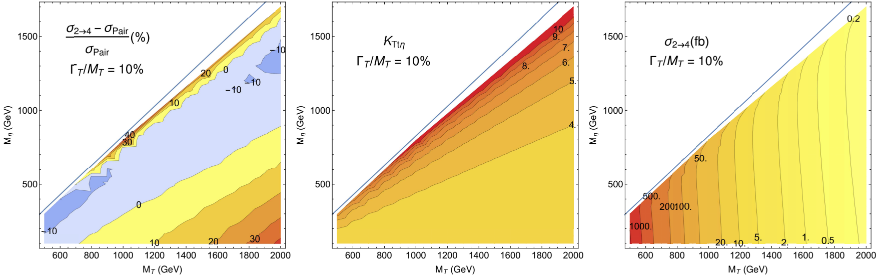
Mass of the scalar as new parameter



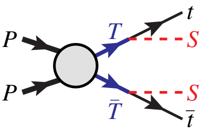


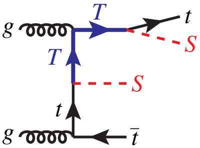
$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C^4_{TtS}\,\hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T} \to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics



Mass of the scalar as new parameter





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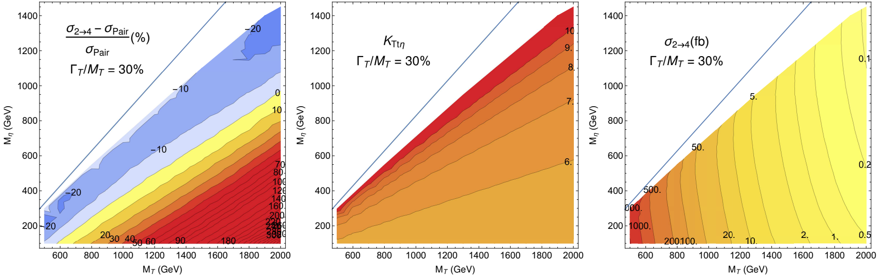
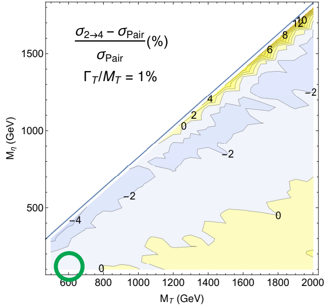
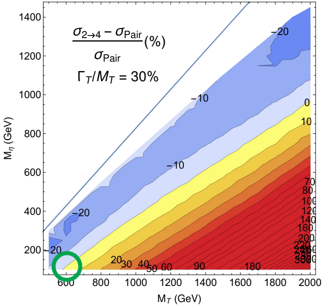
- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics



Kinematics in the finite width regime





$$pp \xrightarrow{T} t\bar{t}SS$$

$$t \to Wb \to (\mu\nu_\mu)b$$

M_T=600 GeV

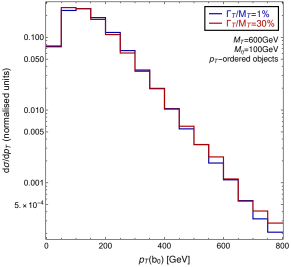
M_S=100 GeV

σ_{NWA} = 801.5 fb

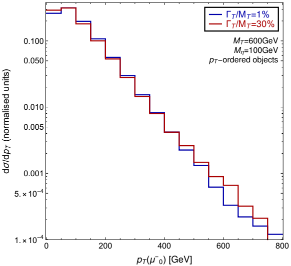
σ_{tot} (1%) = 797.8 fb

σ_{tot} (30%) = 816.8 fb

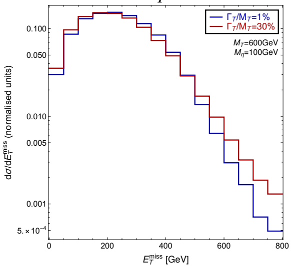
p_T leading b-jet



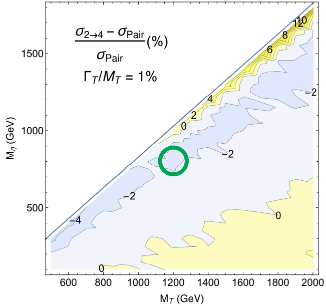
p_T leading μ^-

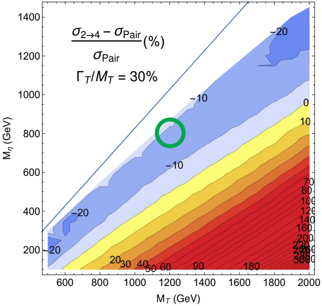


E_T^{miss}



Kinematics in the finite width regime



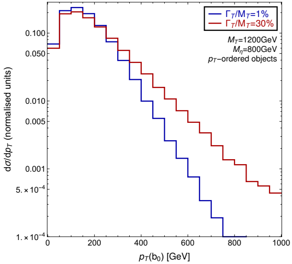


$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

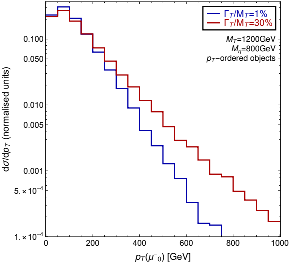
M_T=1200 GeV
M_S=800 GeV

σ_{NWA} = 8.902 fb
σ_{tot} (1%) = 8.716 fb
σ_{tot} (30%) = 7.702 fb

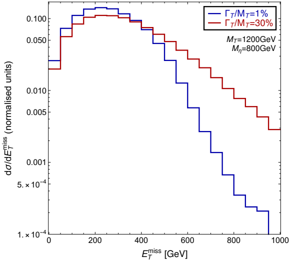
p_T leading b-jet



p_T leading μ^-



E_T^{miss}



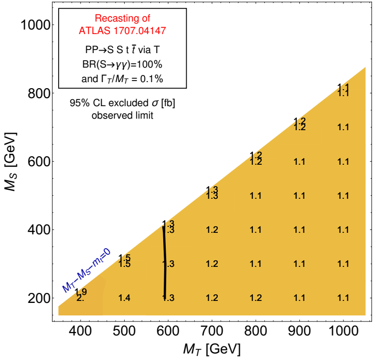
Presentation of the results

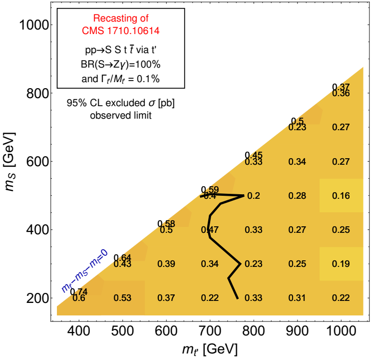
Recast of two ATLAS searches

$pp \to T\bar{T} \to (St)(S\bar{t})$

Example with T and two S decays

$\gamma\gamma$, γZ





If the T has a finite width, analogous plots for different Γ/M values

SHIFt

Solving the Higgs fine tuning with top partners

PI: Sara Strandberg (Stockholm University and ATLAS)
ATLAS members in Uppsala: Elin Bergeås Kuutmann, Venugopal Ellajosyula, Thomas Mathisen
Theory members in Uppsala: Rikard Enberg, Tanumoy Mandal, Luca Panizzi

- Aim: widen the searches for physics beyond the SM that solves the Higgs fine-tuning problem
- Three different and complementary tracks:
  1) Direct searches for the scalar top squarks in SUSY
  2) Direct searches for the vector-like top quarks in compositeness models
  3) Indirect searches for top partners which are not kinematically accessible at the LHC energies
- Strengthen collaboration between experimental and theoretical particle physicists in Sweden
- Construct non-minimal simplified:
  - SUSY models for direct searches for stops
  - compositeness models for direct searches for vector-like quarks
- Quantify ATLAS' current sensitivity to these models and if still viable, search for them with Run 2 and early Run 3 data
- Construct optimal observables for indirect searches of top partners and use them in analyses of Run 2 and early Run 3 data.

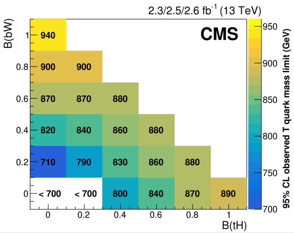
Vector-like quarks

Vector-like quarks in many models of New Physics

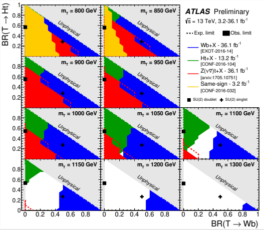
- Warped or universal **extra-dimensions**: KK excitations of bulk fields
- **Composite Higgs** models: excited resonances of the bound states which form SM particles
- **Little Higgs** models: partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- Non-minimal **SUSY extensions**: increase corrections to Higgs mass without affecting EWPT

Intense experimental effort

CMS-B2G-16-024 (t')



ATLAS twiki: summary plots (t')



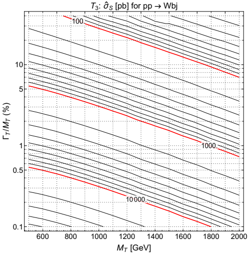
Characterising VLQ properties if a discovery is made would be essential for embedding them into some scenarios (and exclude others!)

Interference

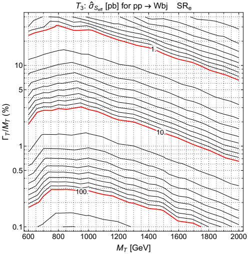
Recast of CMS-B2G-16-006

Folding search efficiencies into the reduced cross-section:

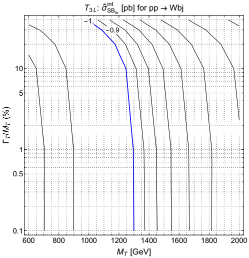
Signal



→



Interference with SM



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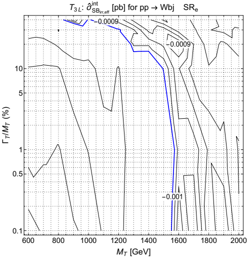
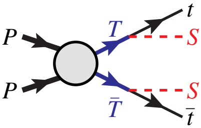
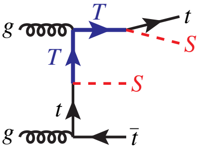


Mass of the scalar as new parameter

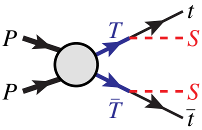


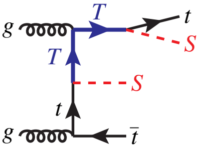


$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\, \hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T} \to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics

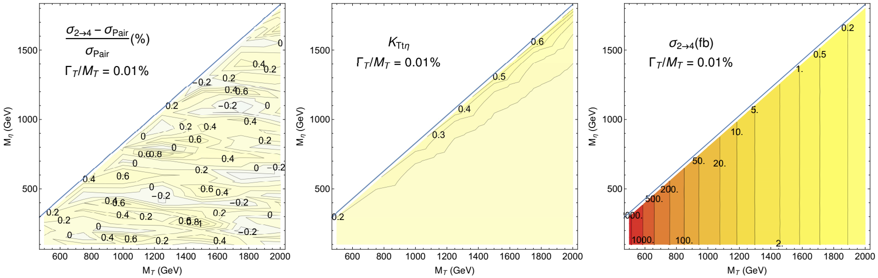
Mass of the scalar as new parameter



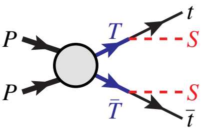


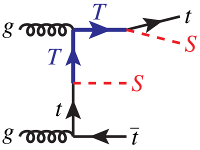
$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\,\hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T}\to 0} \sigma_{T\bar{T}}(M_T) BR(T\to tS)^2$$

- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics



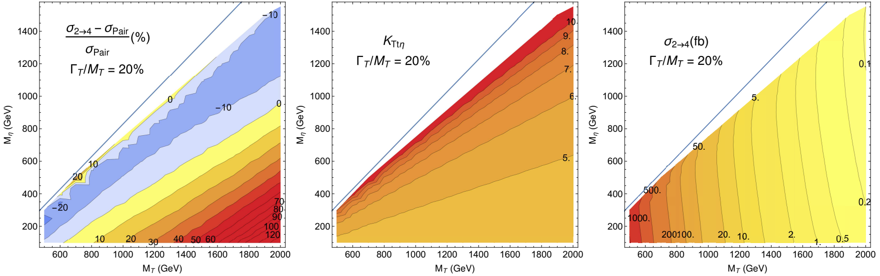
Mass of the scalar as new parameter



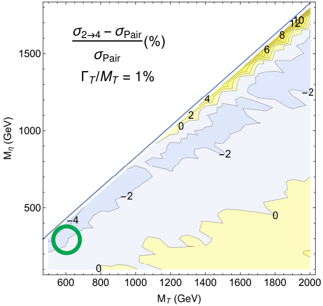


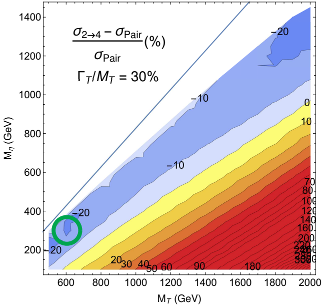
$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\, \hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T}\to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics



Kinematics in the finite width regime



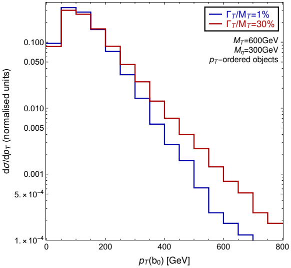


$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

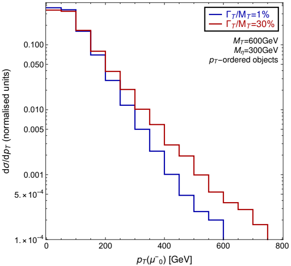
M_T=600 GeV
M_S=300 GeV

$\sigma_{\rm NWA}$ = 801.5 fb
$\sigma_{\rm tot}$ (1%) = 786.3 fb
$\sigma_{\rm tot}$ (30%) = 623.7 fb

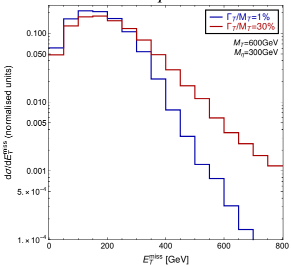
p_T leading b-jet



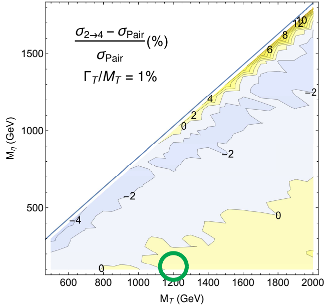
p_T leading μ^-

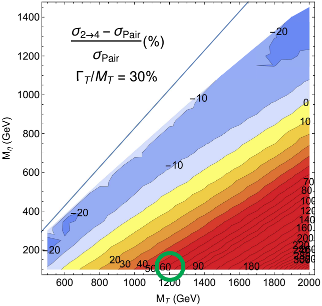


$E_T^{\rm miss}$



Kinematics in the finite width regime



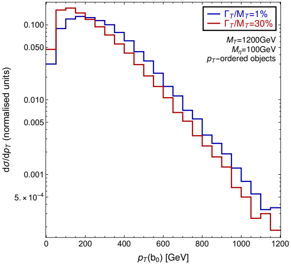


$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

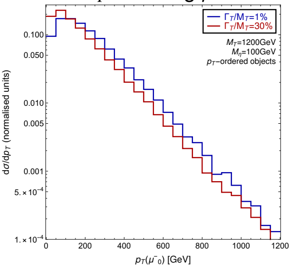
M_T=1200 GeV
M_S=100 GeV

σ_{NWA} = 8.902 fb
σ_{tot} (1%) = 8.944 fb
σ_{tot} (30%) = 14.75 fb

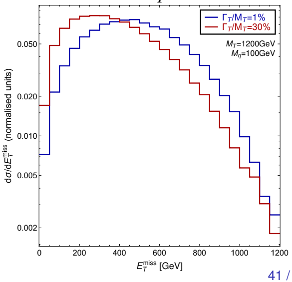
p_T leading b-jet



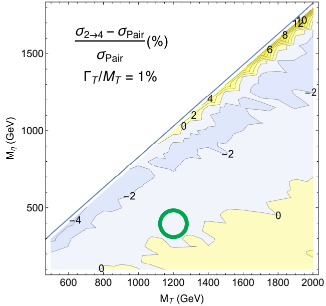
p_T leading μ^-

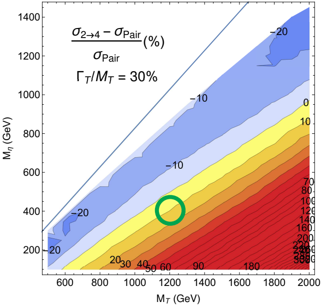


E_T^{miss}



Kinematics in the finite width regime





$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

M_T=1200 GeV

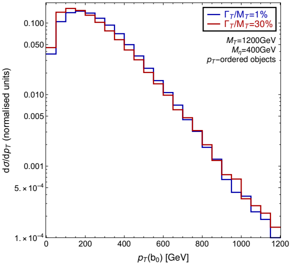
M_S=400 GeV

$\sigma_{\rm NWA}$ = 8.902 fb

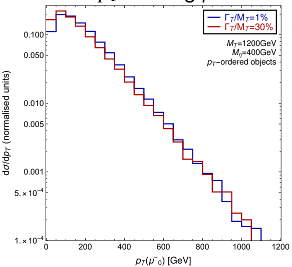
$\sigma_{\rm tot}$ (1%) = 8.862 fb

$\sigma_{\rm tot}$ (30%) = 9.852 fb

p_T leading b-jet



p_T leading μ^-



$E_T^{\rm miss}$