Vector-like quarks at the LHC

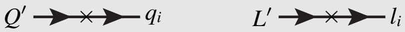
finite width, NLO and exotic decays

Luca Panizzi

Uppsala University

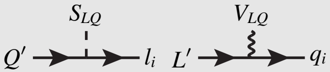
SM and new fermions

They can mix with SM fermions through Yukawa couplings



Dangerous FCNCs $\longrightarrow$ strong bounds on mixing parameters

They can couple without mixing



Non-minimal scenarios
e.g. with lepto-quarks

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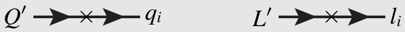

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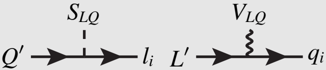

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A special case

They can mediate dark matter production

Only **SM partners** are allowed (up to 4-dim operators)
They must be odd under the Z_2 parity of DM $\longrightarrow$ they **cannot** mix with SM states

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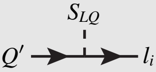

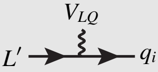

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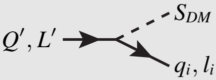

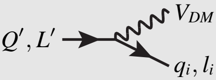

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If new fermions exist what can they be?

New fermions: the chiral hypothesis

aka adding a fourth chiral family to the SM

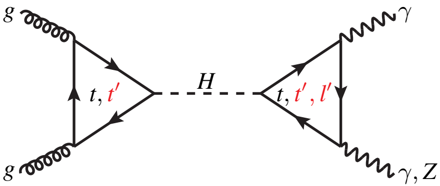
$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} t' \\ b' \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} \nu' \\ l' \end{pmatrix}$$

both quarks and leptons for anomaly cancellation

$$Tr[Q] = 3(\tfrac{2}{3} - \tfrac{1}{3}) + (0 - 1) = 0$$

Modifications to observed processes



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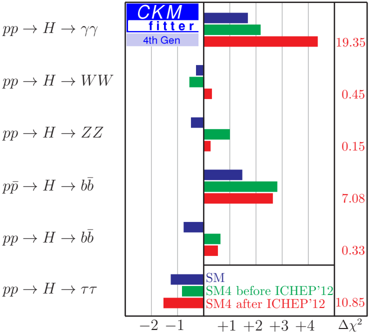

$(\mathcal{O}_{\text{exp}} - \mathcal{O}_{\text{fit}})/\Delta\mathcal{O}_{\text{exp}}$

O. Eberhardt, *et al.*
Impact of a Higgs boson at a mass of 126 GeV on the standard model with three and four fermion generations
Phys.Rev.Lett. 109 (2012) 241802, arXiv:1209.1101

400 GeV $< m_{t',b'} <$ 800 GeV
$m_{l'} >$ 100 GeV and $m_{\nu'} > M_Z/2$

A chiral 4th generation is excluded at 4.8σ
(or 5.3σ including $H \to b\bar{b}$ at Tevatron)
in the context of a simplified model where only the new family is added to the SM

Let's go for vector-like fermions

Vector-like fermions

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 $SU(2) \times U(1)_Y$

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Why "vector-like"?

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

SM Chiral fermions

$$j_L^\mu = \bar{f}_L \gamma^\mu f_L' \qquad j_R^\mu = 0$$

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

V-A structure

Vector-like fermions

$$j_L^\mu = \bar{f}_L \gamma^\mu f_L' \qquad j_R^\mu = \bar{f}_R \gamma^\mu f_R'$$

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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

Vector-like quarks

Vector-like quarks in many models of New Physics

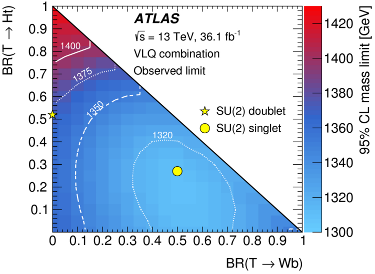
- Warped or universal **extra-dimensions**: KK excitations of bulk fields
- **Composite Higgs** models: excited resonances of the bound states which form SM particles
- **Little Higgs** models: partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
-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

Model independent approach

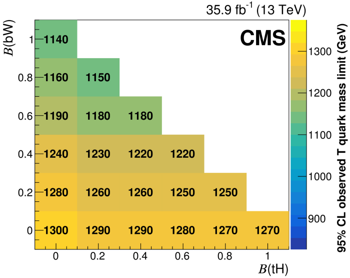
Vector-like quarks

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 at LO**
- **Narrow width** approximation
- Interacting only with **SM states**

More exploration is definitely needed!

Vector-like quarks

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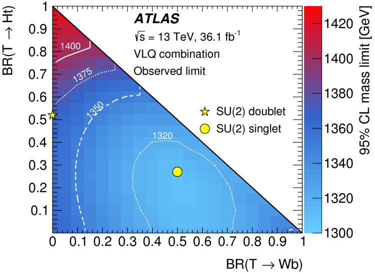

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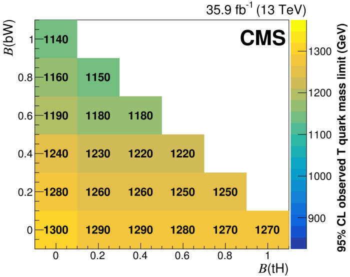

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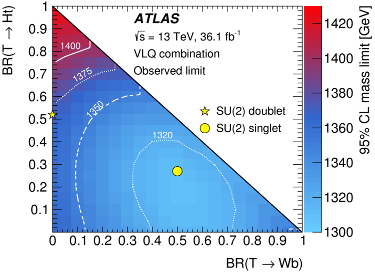

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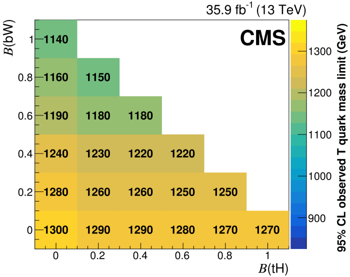

B(bW) \ B(tH)	0	0.2	0.4	0.6	0.8	1
1	1140					
0.8	1160	1150				
0.6	1190	1180	1180			
0.4	1240	1230	1220	1220		
0.2	1280	1260	1260	1250	1250	
0	1300	1290	1290	1280	1270	1270

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

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- **Narrow width** approximation
- Interacting only with **SM states** — **Third part of the talk**

More exploration is definitely needed!

Single production of VLQs with finite width

interacting only with SM states

based on

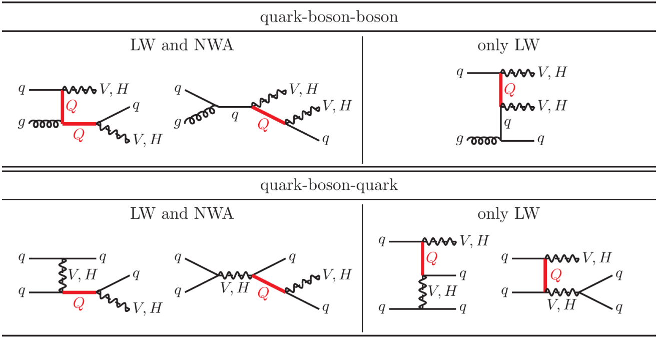
A. Carvalho, S. Moretti, D. O'Brien, **LP** and H. Prager
Single production of vectorlike quarks with large width at the Large Hadron Collider
Phys.Rev. D98 (2018) no.1, 015029

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**

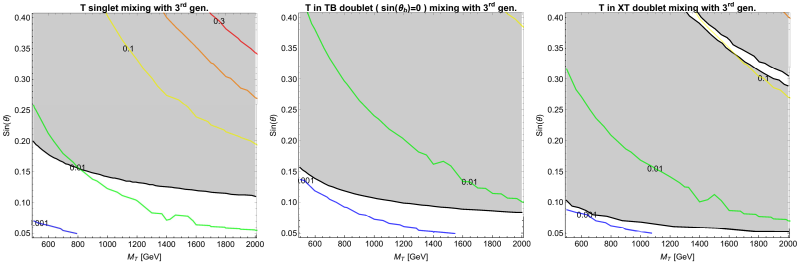
How large the width can be

To obtain a large width:

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

Simplified models with large couplings:

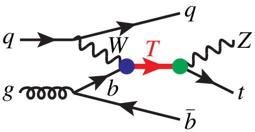
T singlet | **(T B) doublet** | **(X T) doublet**



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

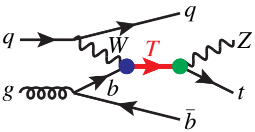
Parametrisation for large width regime



in the narrow-width approximation (NWA)

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

Parametrisation for large width regime



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

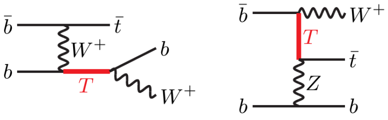
$$\sigma(C_1, C_2, m_{\mathrm{Q}}, \Gamma_Q) = C_1^2\, C_2^2\, \hat{\sigma}(m_{\mathrm{Q}}, \Gamma_Q)$$

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

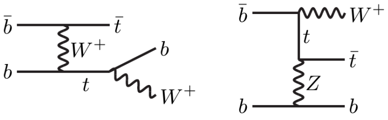
Consistency relation: $\Gamma_Q^{\text{partial}}(C_1) + \Gamma_Q^{\text{partial}}(C_2) \leq \Gamma_Q$

Interference

Signal



Irreducible background



signal with itself

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

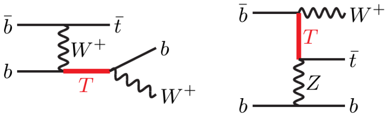
χ_Q is the dominant chirality of the VLQ

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



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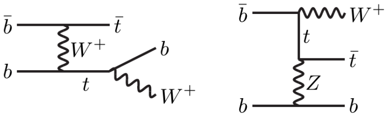

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Model-dependency is (almost) unavoidable

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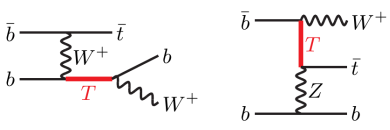

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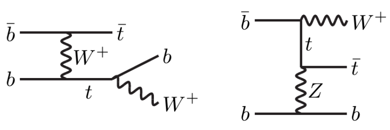

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$$\sigma_{SB_{\rm irr}}^{\rm int} = C_2\ \hat{\sigma}_{SB_{\rm irr}}^{\rm int}(C_1\ldots, M_Q, \Gamma_Q, \chi_Q)$$

Model-dependency is (almost) unavoidable

If signal topologies always involve the same two couplings

$$\sigma_{SB_{\rm irr}}^{\rm int} = C_1 C_2 \hat{\sigma}_{SB_{\rm irr}}^{\rm int}(M_Q, \Gamma_Q, \chi_Q) \quad \text{and same procedure as before}$$

In general $\rightarrow$ fiducial cross-section

$$S + B = L(\sigma_S \epsilon_S + \sigma_{SB_{\rm irr}}^{\rm int}\,\epsilon_{SB_{\rm irr}}^{\rm int}) + B_{\rm irr+red} \equiv L\sigma_{\rm eff} + B \quad \text{with} \quad \sigma_{\rm eff} = C_2^2\ \hat{\sigma}_S\ \epsilon_S + C_2\ \hat{\sigma}_{SB_{\rm irr}}^{\rm int}\ \epsilon_{SB_{\rm irr}}^{\rm int}$$

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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wiki: NLOModels — Start page | Index | History

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	-
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”

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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	-
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

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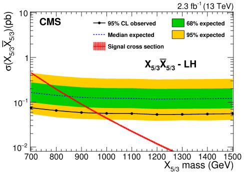
VLQ couplings have a dedicated **coupling order** “VLQ”

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)

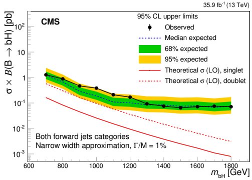
from NWA

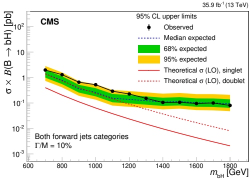


to Γ/M-dependent upper limits

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

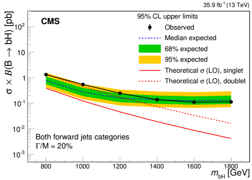
$\frac{\Gamma}{M}$ = 1% (∼ NWA)

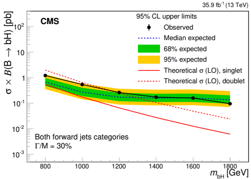




$\frac{\Gamma}{M}$ = 10%

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

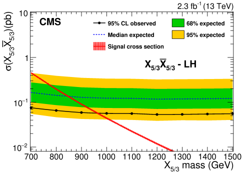




$\frac{\Gamma}{M}$ = 30%

Presentation of the results (2)

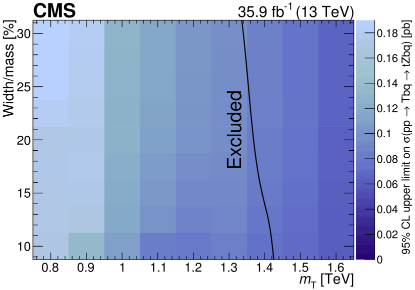
from NWA



to Γ/M-dependent upper limits

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

Upper limits colour code

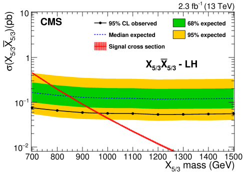


Reduced cross-section table ($\hat{\sigma}$)

Mass [TeV]	$\tilde{\sigma}_{FW}$ (σ) for pp → Tbq → tZbq [pb] 10%	20%	30%	$\tilde{\sigma}_{FW}$ (σ) for pp → Ttq → 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)

Presentation of the results (3)

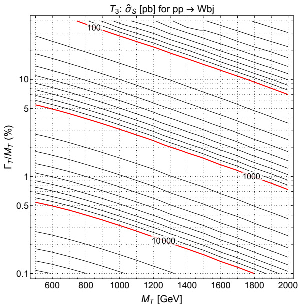
from NWA

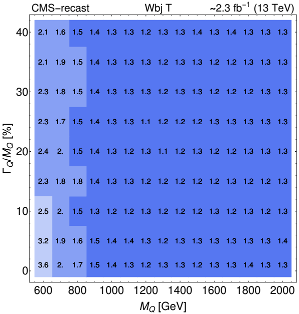


to Γ/M-dependent upper limits

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

Reduced cross-section plot





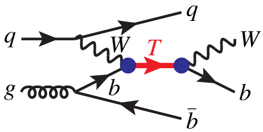
Upper limits grid

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

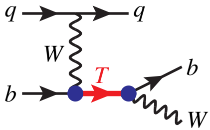
Finite width and kinematics

example for a specific channel

4FS



5FS

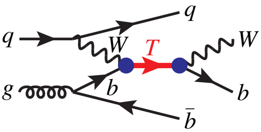


M_T = 1200 GeV, Γ_T/M_T = 1% and 30%, and imposing muonic decay of W

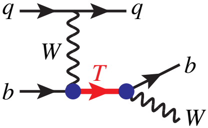
Finite width and kinematics

example for a specific channel

4FS

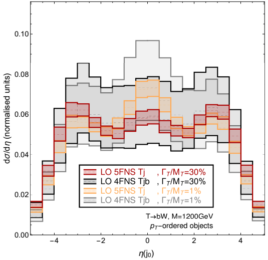


5FS

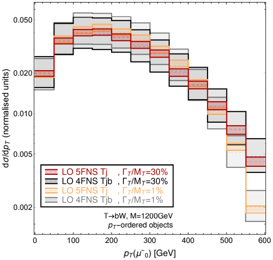


M_T = 1200 GeV, Γ_T/M_T = 1% and 30%, and imposing muonic decay of W

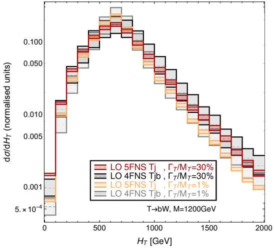
η of leading jet



p_T of μ^-



H_T

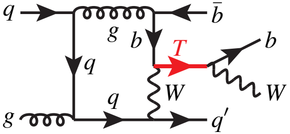


Kinematical distributions can be sizably different in the finite width regime

what happens at NLO?

Single production of VLQs at NLO

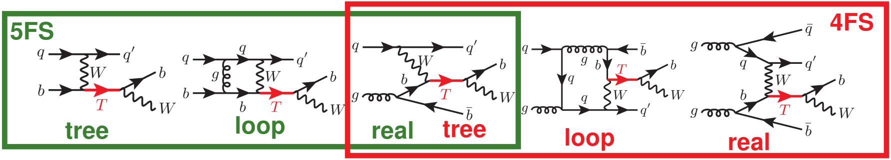
interacting only with SM states



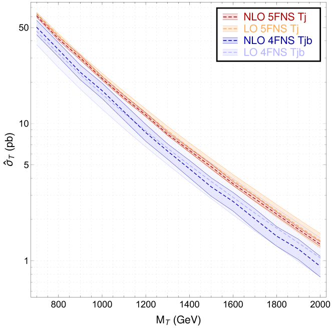
based on

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

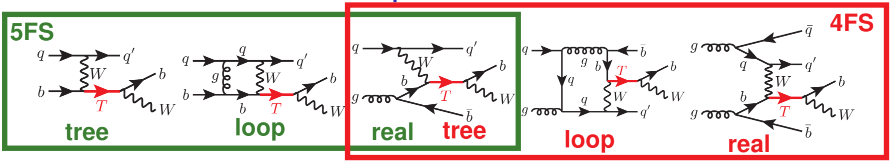


Total rates



- **Reduced uncertainties** for both 4FS and 5FS
- For **4FS** NLO $\sigma_{\rm NLO}$ is larger than $\sigma_{\rm LO}$ for $M_Q \lesssim$1 TeV, then opposite behaviour. K-factor from ∼0.9 to ∼1.1
  $\longrightarrow$ Impact of logarithms $\log Q^2/m_b^2$
- For **5FS** $\sigma_{\rm NLO}$ is always smaller than $\sigma_{\rm LO}$.
  $\longrightarrow$ 5FS features a more stable K-factor ∼0.9
- **Compatibility** between schemes **improved at NLO** at low masses.

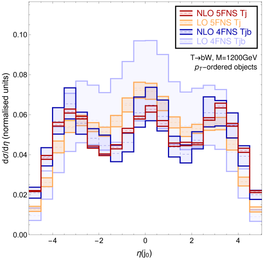
NLO predictions in the NWA



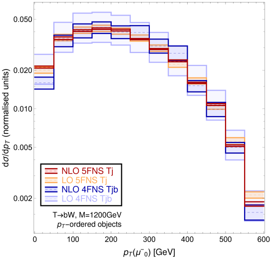
Distributions

M_T = 1200 GeV and imposing muonic decay of W

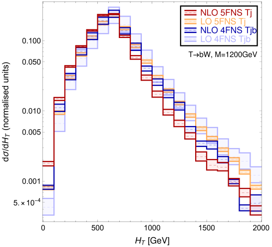
η of leading jet



p_T of μ^-

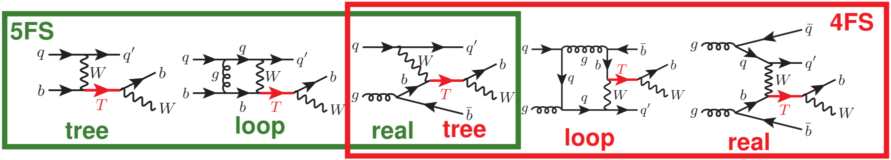


H_T



NLO corrections can significantly impact shapes

NLO predictions in the NWA



Distributions

M_T = 1200 GeV and imposing muonic decay of W

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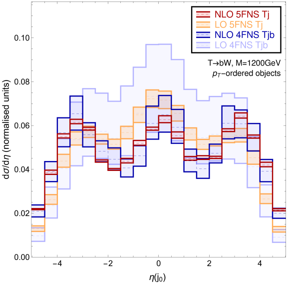
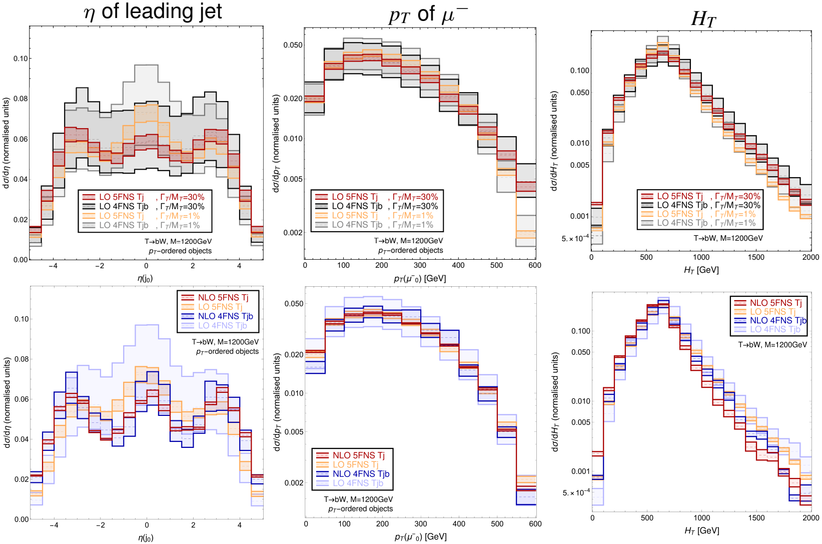


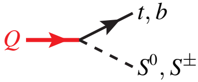
- The light jet is important for selection criteria
- The **differential K-factor** is not constant
- **Agreement** between 4FS and 5FS is **improved at NLO**
- The jet tends to be more **forward** at NLO

FW@LO vs NWA@NLO



What happens at NLO if the VLQ has large width?

Exotic decays of VLQs



work in progress through

SHIFt

Non-SM VLQ decays

Extension of the scalar sector of the SM is **theoretically justified**:

- Supersymmetry $\longrightarrow$ additional Higgs doublets
- Composite Higgs $\longrightarrow$ additional scalars (neutral and charged)
- ...

Different decay channels to explore

$$T \to S^0 t \qquad T \to S^+ b \qquad B \to S^0 b \qquad B \to S^- t$$
$$X_{5/3} \to S^+ t \qquad X_{5/3} \to S^{++} b \qquad Y_{-4/3} \to S^- b \qquad Y_{-4/3} \to S^{--} t$$

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Example with non-minimal Higgs sector: VLQ+2HDM extension of the SM

- 7 possible VLQ representations
  $\to$ 2 singlets: T and B
  $\to$ 3 doublets: $(X\ T)$, $(T\ B)$ and $(B\ Y)$
  $\to$ 2 triplets: $(X\ T\ B)$ and $(T\ B\ Y)$
- 2 Higgs doublets: 3 neutral states (h^0, H^0 and A^0) and 1 charged (h^+)

Non-SM VLQ decays

Extension of the scalar sector of the SM is **theoretically justified**:

- Supersymmetry $\longrightarrow$ additional Higgs doublets
- Composite Higgs $\longrightarrow$ additional scalars (neutral and charged)
- ...

Different decay channels to explore

$$T \to S^0 t \qquad T \to S^+ b \qquad B \to S^0 b \qquad B \to S^- t$$
$$X_{5/3} \to S^+ t \qquad X_{5/3} \to S^{++} b \qquad Y_{-4/3} \to S^- b \qquad Y_{-4/3} \to S^{--} t$$

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- 2 Higgs doublets: 3 neutral states (h^0, H^0 and A^0) and 1 charged (h^+)

Analysis from a **model-independent** perspective
couplings, masses and widths as **free parameters**

and subsequent reinterpretation in terms of specific models

A simplified model

$$\text{SM} + t' + S \quad \text{with} \quad t' \to St$$

- S can be either a **scalar** or a **pseudoscalar**
- Neglect (for the moment) other decays of the t'

A simplified model

SM $+ t' + S$ with $t' \to St$

- S can be either a **scalar** or a **pseudoscalar**
- Neglect (for the moment) other decays of the t'

The Lagrangian

$$\mathcal{L} = \left(\kappa_L^S \, \bar{t}'_R t_L S + \kappa_R^S \, \bar{t}'_L t_R S + \text{h.c.}\right) - \frac{S}{v} \sum_f m_f \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f\right)$$

$$+ \frac{S}{v} \left(2\lambda_W m_W^2 W_\mu^+ W^{-\mu} + \lambda_Z m_Z^2 Z_\mu Z^\mu\right) + \frac{S}{16\pi^2 v} \sum_V \left(\kappa_V g_V^2 \, V_{\mu\nu}^a V^{a\mu\nu} + \tilde{\kappa}_V g_V^2 \, V_{\mu\nu}^a \widetilde{V}^{a\mu\nu}\right)$$

A simplified model

SM $+ t' + S$ with $t' \to St$

- S can be either a **scalar** or a **pseudoscalar**
- Neglect (for the moment) other decays of the t'

The Lagrangian

interaction t'-S-t | **interaction S-SM fermions**

$$\mathcal{L} = \left(\kappa_L^S\, \bar{t}'_R t_L S + \kappa_R^S\, \bar{t}'_L t_R S + \text{h.c.}\right) - \frac{S}{v}\sum_f m_f\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right)$$

$$+ \frac{S}{v}\left(2\lambda_W m_W^2 W_\mu^+ W^{-\mu} + \lambda_Z m_Z^2 Z_\mu Z^\mu\right) + \frac{S}{16\pi^2 v}\sum_V\left(\kappa_V g_V^2\, V_{\mu\nu}^a V^{a\mu\nu} + \tilde{\kappa}_V g_V^2\, V_{\mu\nu}^a \widetilde{V}^{a\mu\nu}\right)$$

interaction S-SM gauge (tree level) (only for scalar S) | **interaction S-SM gauge (loop level)**

A simplified model

SM $+ t' + S$ with $t' \to St$

- S can be either a **scalar** or a **pseudoscalar**
- Neglect (for the moment) other decays of the t'

The Lagrangian

interaction t'-S-t

interaction S-SM fermions

$$\mathcal{L} = \left(\kappa_L^S\, \bar{t}'_R t_L S + \kappa_R^S\, \bar{t}'_L t_R S + \text{h.c.}\right) - \frac{S}{v}\sum_f m_f\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right)$$

$$+ \frac{S}{v}\left(2\lambda_W m_W^2 W_\mu^+ W^{-\mu} + \lambda_Z m_Z^2 Z_\mu Z^\mu\right) + \frac{S}{16\pi^2 v}\sum_V \left(\kappa_V g_V^2\, V_{\mu\nu}^a V^{a\mu\nu} + \tilde{\kappa}_V g_V^2\, V_{\mu\nu}^a \widetilde{V}^{a\mu\nu}\right)$$

interaction S-SM gauge (tree level) (only for scalar S)

interaction S-SM gauge (loop level)

Couplings can be switched on and off depending on the scenario under consideration

Numerical UFO model implemented and soon publicly available

Focus on S decaying with significant BR to either $\gamma\gamma$ or γZ (loop level interactions)

Bounds from LHC

Recast of LHC searches

$$pp \to t'\bar{t}' \to St\ S\bar{t}$$

Two S decays considered
$\{\gamma\gamma,\ \gamma Z\}$

- **Narrow width** approximation for both t' and S (width of t' set to 0.1% of its mass)
- The two channel are considered separately assuming **100% branching ratio** on each
- Masses of t' and S as **free parameters**
- Simulations at LO with MADGRAPH5_AMC@NLO associating NLO+NNLL pair production cross-sections computed with HATHOR

The searches

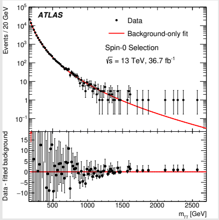
- ATLAS 1707.04147: "Search for new phenomena in **high-mass diphoton** final states using 37 fb^{-1} of proton–proton collisions collected at $\sqrt{s} = 13$ TeV with the ATLAS detector"
- ATLAS 1807.11883: "Search for new phenomena in events with **same-charge leptons** and b-jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"

Both searches implemented and validated in MADANALYSIS 5

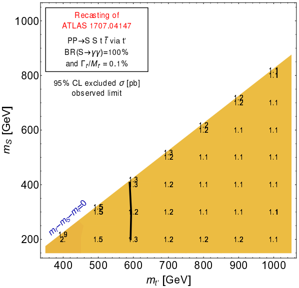
Recast of 1707.04147

The search

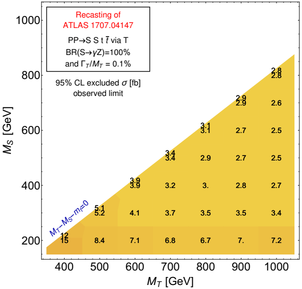
- diphoton with invariant mass from 170 GeV to 2600 GeV
- cuts on photon E_T: 40 GeV (30 GeV) for leading (subleading)
- cuts on photon $E_T/m_{\gamma\gamma}$: 0.4 (0.3) for leading (subleading)



$(\gamma\gamma\ t)(\gamma\gamma\ \bar{t})$



$(\gamma Z\ t)(\gamma Z\ \bar{t})$



More sensitive to final states where photons come from a resonance

Bound on m_t' above $\sim$ 600 GeV almost independent on m_S for $\gamma\gamma$ decay

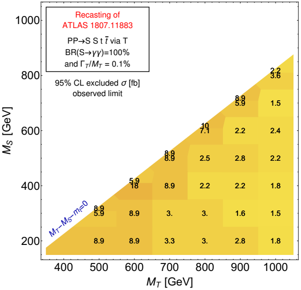
Recast of 1807.11883

The search

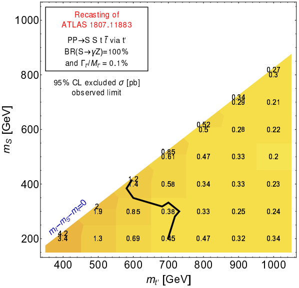
- 8 Signal regions
- 4 with SS leptons and 4 with three leptons
- 1 to multiple jets and 1 to 3 b-jets
- cuts on H_T and $\not{E}_T$

Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_\mathrm{T} < 2400$ GeV or $E_\mathrm{T}^\mathrm{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_\mathrm{T} > 1000$ GeV and $E_\mathrm{T}^\mathrm{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_\mathrm{T} > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_\mathrm{T} > 1200$ GeV and $E_\mathrm{T}^\mathrm{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$400 < H_\mathrm{T} < 1400$ GeV or $E_\mathrm{T}^\mathrm{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	++ or −−	$500 < H_\mathrm{T} < 1200$ GeV and $E_\mathrm{T}^\mathrm{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$H_\mathrm{T} > 1200$ GeV and $E_\mathrm{T}^\mathrm{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_\mathrm{T} < 2000$ GeV or $E_\mathrm{T}^\mathrm{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_\mathrm{T} > 1000$ GeV and $E_\mathrm{T}^\mathrm{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_\mathrm{T} < 2400$ GeV or $E_\mathrm{T}^\mathrm{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_\mathrm{T} > 1200$ GeV and $E_\mathrm{T}^\mathrm{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_\mathrm{T} > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_\mathrm{T} < 1000$ GeV and $E_\mathrm{T}^\mathrm{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_\mathrm{T} > 1000$ GeV and $E_\mathrm{T}^\mathrm{miss} > 40$ GeV

$(\gamma\gamma\, t)(\gamma\gamma\, \bar{t})$



$(\gamma Z\, t)(\gamma Z\, \bar{t})$



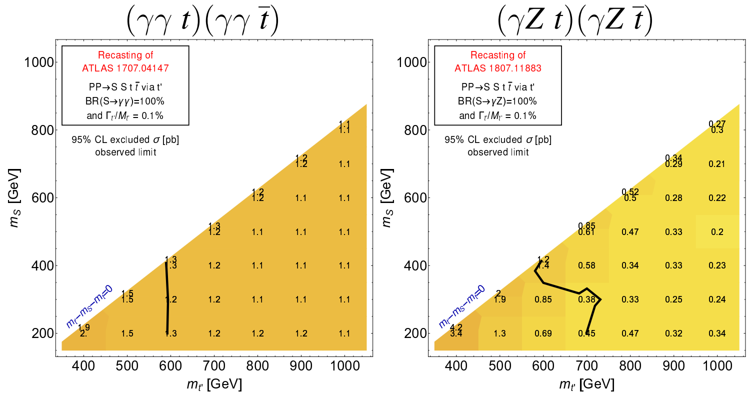
More sensitive to final states with enough number of leptons

Bounds complementary to the diphoton search

Bound around $m_t' \sim$ 600-700 GeV depending on m_S

Combined bounds

ATLAS 1707.04147 and 1807.11883



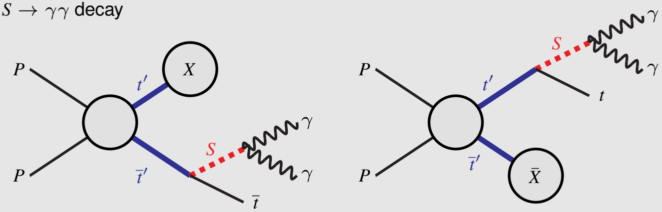
How to improve:

- OS dilepton searches
- diphoton at low invariant mass
- SUSY searches (?)

Analysis strategy

Force target decay on one branch, inclusive on the other

Example with $S \to \gamma\gamma$ decay



This allows to reconstruct less photons, otherwise bkg dominated mostly by (poorly controllable) fakes.

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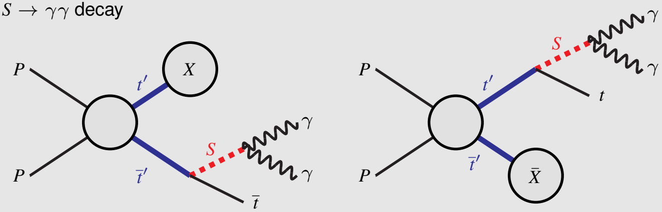

This allows to reconstruct less photons, otherwise bkg dominated mostly by (poorly controllable) fakes.

$\gamma\gamma$ signal region

1) $N_\gamma \geq 2$ with $p_T^{\gamma_{1,2}} > 30$ GeV and $|\eta^{\gamma_{1,2}}| < 2.37$
2) $N_j \geq 1$ with $p_T^{j_1} > 25$ GeV and $|\eta^{j_1}| < 2.47$
3) $N_b \geq 1$
4) $|m_{\gamma\gamma} - m_S| < 20$ GeV
5) $\Delta R_{\gamma\gamma} < 1.0\ (1.4)$ for $m_S = 100\ (\geq 200)$ GeV

Analysis strategy

Force target decay on one branch, inclusive on the other

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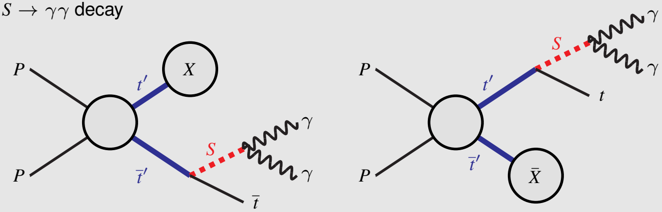

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5) $\Delta R_{\gamma\gamma} < 1.0\ (1.4)$ for $m_S = 100\ (\geq 200)$ GeV

γZ signal region

Z is reconstructed through leptonic decay

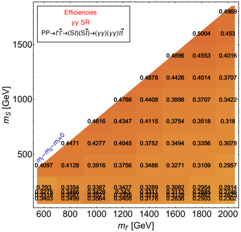
1) At least 1 reconstructed Z: $|m_{ll} - m_Z| < 10$ GeV
2) $N_\gamma \geq 1$ with $p_T^{\gamma_1} > 30$ GeV and $|\eta^{\gamma_1}| < 2.37$
3) $N_b \geq 1$
4) if $m_S < 200$ GeV: $p_T^\gamma + p_T^b + p_T^Z > 250$ GeV
4) if $m_S \geq 200$ GeV: $H_T + E_T^{\text{miss}} > 0.8 m_t'$
5) $|m_{\gamma Z} - m_S| < 15$ GeV

Efficiencies (preliminary results)

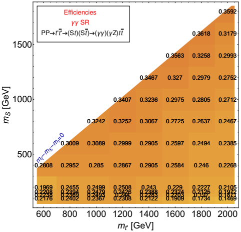
Example for $S \to \gamma\gamma$: $S = L\,\sigma(m_t')\left(\epsilon^{St,\gamma\gamma}_{St,\gamma\gamma} BR^2_{t'\to St}\, BR^2_{S\to\gamma\gamma} + \sum_{X\neq St,\gamma\gamma \text{ or } Y\neq St,\gamma\gamma} \epsilon^{Y}_{X} BR_{t'\to X} BR_{t'\to Y}\right)$

$\gamma\gamma$ SR (30-40%)

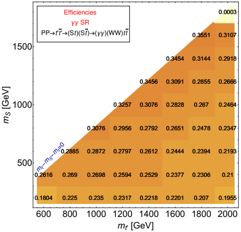
$(\gamma\gamma)(\gamma\gamma)$



$(\gamma\gamma)(\gamma Z)$

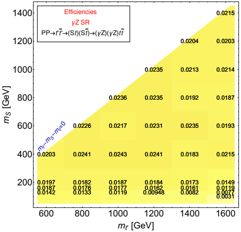


$(\gamma\gamma)(WW)$

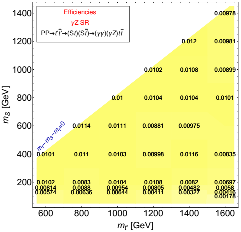


γZ SR (0.1-2%)

$(\gamma Z)(\gamma Z)$



$(\gamma\gamma)(\gamma Z)$



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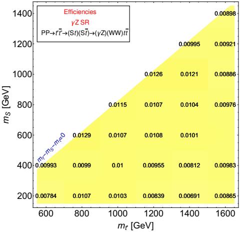
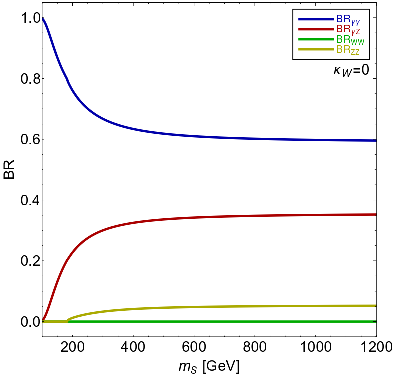
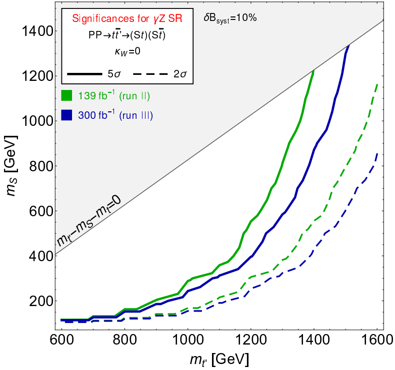


Expected reach (preliminary results)

Examples with the γZ SR

$$\text{Significance } Z = \sqrt{2\left[(s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right]}$$



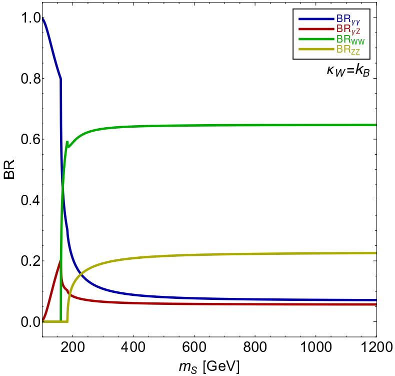


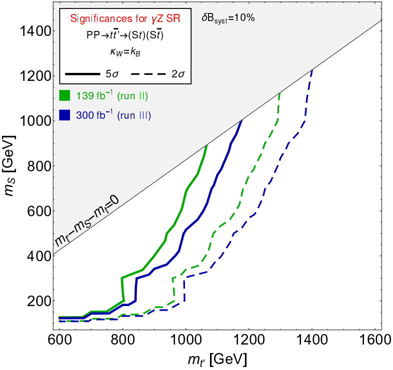
- Low m_S: suppression of γZ channel, discovery reach and bounds are weak
- High m_S: significant BRs in channels with photons and Z, discovery reach and bounds driven by the cross-section decrease

Expected reach (preliminary results)

Examples with the γZ SR

$$\text{Significance } Z = \sqrt{2\left[(s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right]}$$

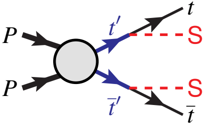


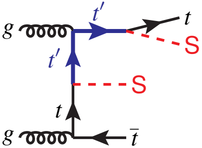


- Low m_S: suppression of γZ channel, discovery reach and bounds are weak
- High m_S: BRs in both γZ and $\gamma\gamma$ are low, discovery reach and bounds not as strong as in the previous case

Range of validity of the analysis

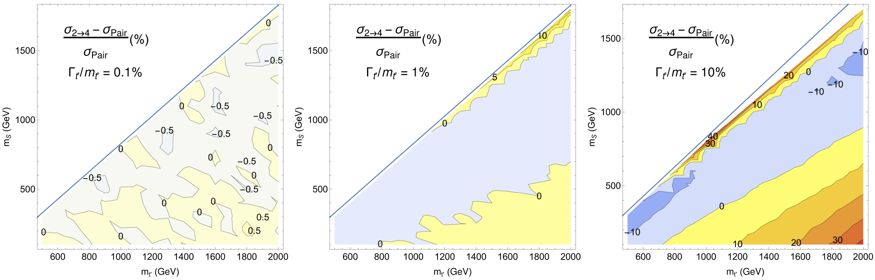
VLQ with finite width





$$\sigma_{t\bar{t}SS}(\kappa_{t'tS}, M_{t'}, m_S, \Gamma^{tot}_{t'}(C_{\text{decays}}, M_{t'}, m_{\text{decays}}),) = C^4_{t'tS}\,\hat{\sigma}_{t\bar{t}SS}(M_{t'}, m_S, \Gamma^{tot}_{t'}) \xrightarrow{\frac{\Gamma^{tot}_{t'}}{M_{t'}}\to 0} \sigma_{t'\bar{t}'}(M_{t'})BR(t' \to tS)^2$$

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

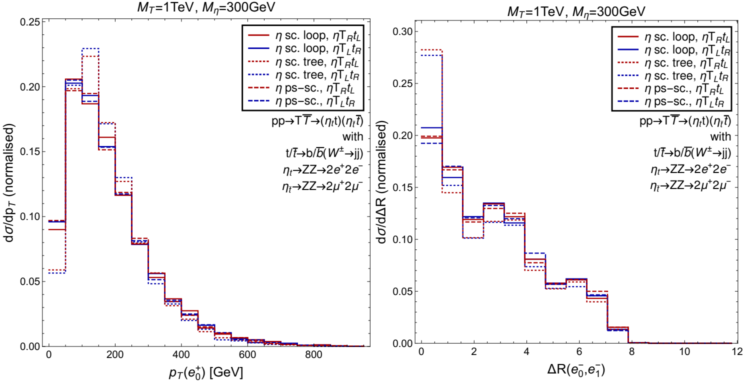


Range of validity of the analysis

Scalar vs Pseudoscalar (example with ZZ decay)

$$\mathcal{L}_S^{\rm loop} = \frac{S}{16\pi^2 v}\sum_V \kappa_V g_V^2\, V^a_{\mu\nu}V^{a\mu\nu} \qquad \mathcal{L}_S^{\rm tree} = \frac{S}{v}\lambda_Z m_Z^2 Z_\mu Z^\mu$$

$$\mathcal{L}_{PS} = \frac{S}{16\pi^2 v}\sum_V \tilde{\kappa}_V g_V^2\, V^a_{\mu\nu}\widetilde{V}^{a\mu\nu}$$



Small differences in a region which is likely cut away for these channels

Decays into charged scalars

$$X_{5/3} \to h^+ t$$

- No decays into the neutral scalar sector
- Only other possible decay to $W^+ t$, already searched by both ATLAS and CMS

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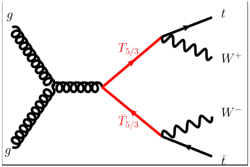
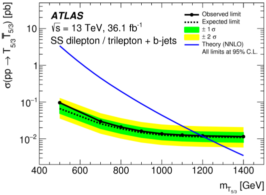
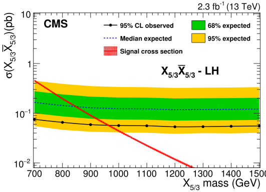
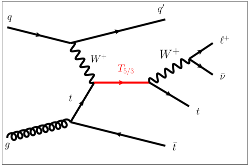
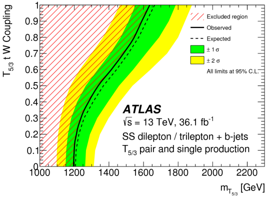










Recast of ATLAS 1807.11883

The search (a reminder)

- 8 Signal regions
- 4 with SS leptons and 4 with three leptons
- 1 to multiple jets and 1 to 3 b-jets
- cuts on H_T and $\not{E}_T$

Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	$++$ or $--$	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	$++$ or $--$	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	$++$ or $--$	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	$++$ or $--$	$H_T > 1200$ GeV and $E_T^{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	$++$ or $--$	$400 < H_T < 1400$ GeV or $E_T^{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	$++$ or $--$	$500 < H_T < 1200$ GeV and $E_T^{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	$++$ or $--$	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_T < 2000$ GeV or $E_T^{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_T < 1000$ GeV and $E_T^{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 40$ GeV

$$pp \to X_{5/3}\bar{X}_{5/3} \to (h^+ t)(h^- \bar{t})$$

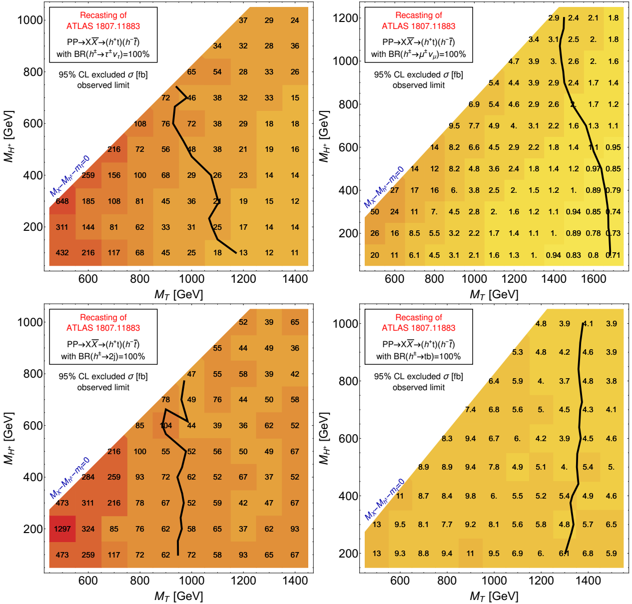
Four h^+ decays considered

$\tau^+\nu_\tau,\ \mu^+\nu_\mu$

$t\bar{b},\ jj(= ud + cs)$

- **Narrow width** approximation for both $X_{5/3}$ and h^+
- The four channel are considered separately assuming **100% branching ratio** on each
- Masses of $X_{5/3}$ and h^+ as **free parameters**

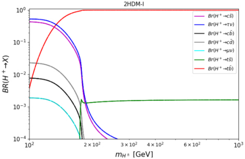
Recast of ATLAS 1807.11883



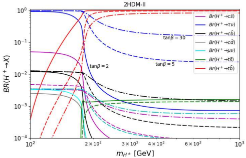
Benchmark examples

Decays of the charged Higgs

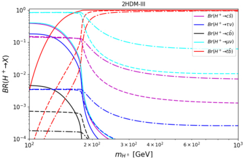
2HDM type I	2HDM type II	2HDM type III



- cs and $\tau\nu_\tau$ for low masses
- $t\bar{b}$ for high masses

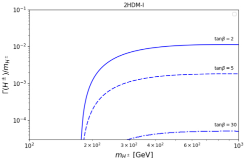


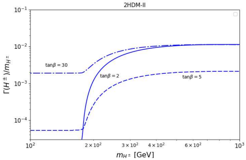
- $\tau\nu_\tau$ for low masses
- $t\bar{b}$ for high masses

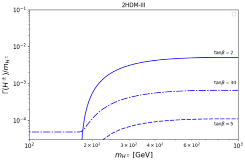


- $\mu\nu_\mu$ for low masses
- $t\bar{b}$ for high masses

Different dominant decay channels depending on assumptions on the interactions and on the m_{h^+}







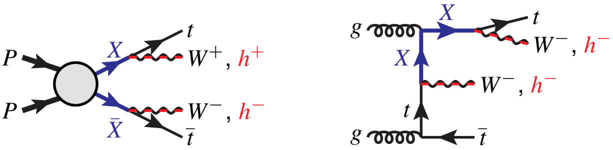
All scenarios correspond to a h^+ with narrow width

Benchmark examples

$M_X = 1000$ GeV $\sigma^{NNLO}_{\text{pair}} = 42.7$ fb

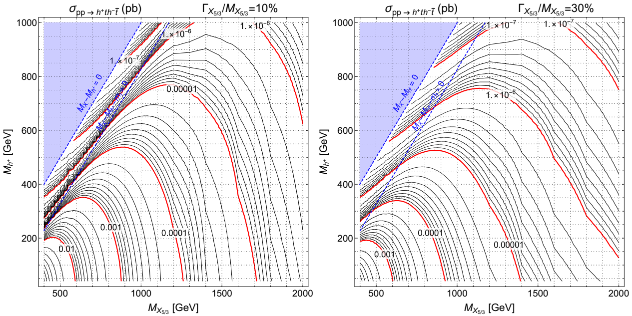
M_{h^+}	$\tau\nu_\tau$			$\mu\nu_\mu$			$t\bar{b}$			jj		
	BR	σ	σ_{excl}	BR	σ	σ_{excl}	BR	σ	σ_{excl}	BR	σ	σ_{excl}
2HDM-I with $\tan\beta$=10 and $\sin(\beta-\alpha)=1$												
100	0.67	19	25	$\sim$0	$\sim$0	2.1	-	-	-	0.295	3.7	72
200	$\sim$0	$\sim$0	31	$\sim$0	$\sim$0	2.2	0.998	42.5	8.1	$\sim$0	$\sim$0	58
500	$\sim$0	$\sim$0	48	$\sim$0	$\sim$0	4.8	0.998	42.5	7.8	$\sim$0	$\sim$0	52
2HDM-II with $\tan\beta$=10 and $\sin(\beta-\alpha)=1$												
100	0.975	40.6	25	$\sim$0	$\sim$0	2.1	-	-	-	$\sim$0	$\sim$0	72
200	0.46	9	31	$\sim$0	$\sim$0	2.2	0.53	12	8.1	$\sim$0	$\sim$0	58
500	0.105	0.47	48	$\sim$0	$\sim$0	4.8	0.892	34	7.8	$\sim$0	$\sim$0	52
2HDM-III with $\tan\beta$=3.5												
100	0.03	0.04	25	0.8	27	2.1	-	-	-	0.16	1	72
200	$\sim$0	$\sim$0	31	$\sim$0	$\sim$0	2.2	0.99	42	8.1	$\sim$0	$\sim$0	58
500	$\sim$0	$\sim$0	48	$\sim$0	$\sim$0	4.8	0.997	42	7.8	$\sim$0	$\sim$0	52

Increasing the width



Reduced cross-section:

$$\sigma_{h^+th^-\bar{t}}(M_{X_{5/3}}, \Gamma_{X_{5/3}}, m_{h^+}, y_{Xth^+}) = (y_{Xth^+})^4\ \hat{\sigma}_{h^+th^-\bar{t}}(M_{X_{5/3}}, \Gamma_{X_{5/3}}, m_{h^+})$$



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

Production of VLQs interacting also with exotic scalars

- New interesting channels for trying to **discover new physics** in extensions of the SM with **VLQs and new scalars**
- Ongoing study to assess the **sensitivity of experimental searches** and the possibility to develop **different strategies** for the finite width regime
- **UFO model validated** and soon publicly available

SHIFt

Solving the Higgs fine tuning with top partners
PI: Sara Strandberg (Stockholm University and ATLAS)

- 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.

Compositeness and VLQ branch

ATLAS: E. Bergeås Kuutmann, V. Ellajosyula, M. Isacson, T. Mathisen

Theory: R. Benbrik, D. Buarque Franzosi, R. Enberg, G. Ferretti, Y. B. Liu, T. Mandal, S. Moretti, **L. Panizzi**

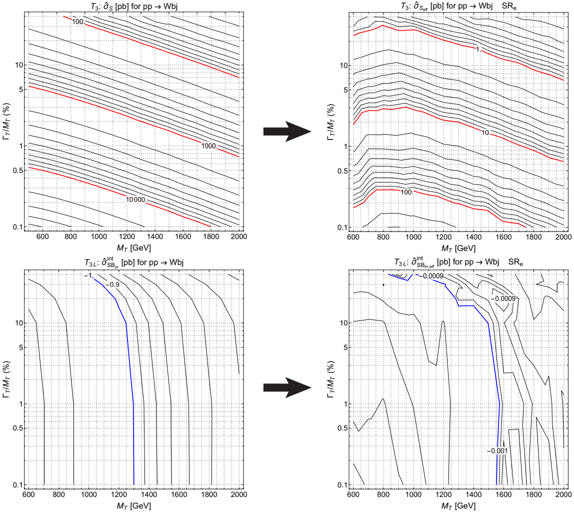
Knut och Alice Wallenbergs Stiftelse · CHALMERS UNIVERSITY OF TECHNOLOGY · UPPSALA UNIVERSITET · Stockholms universitet

Backup

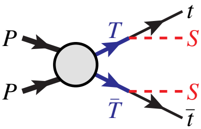
Folding search efficiencies into the reduced cross-section:

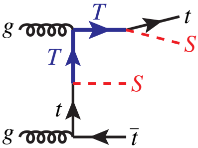
Signal

Interference with SM



Mass of the scalar as new parameter

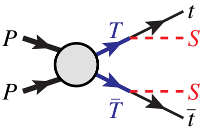


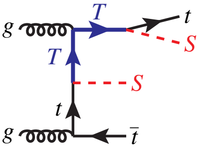


$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\, \hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T} \to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

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

Mass of the scalar as new parameter





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

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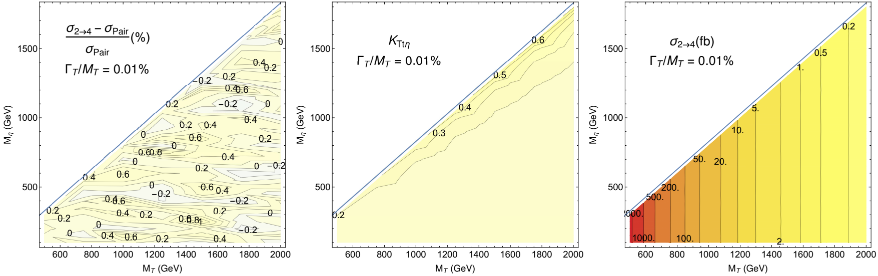
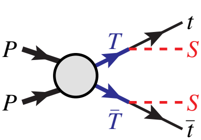
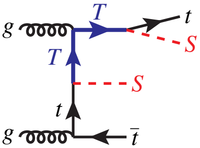


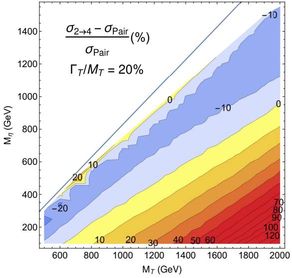
Mass of the scalar as new parameter

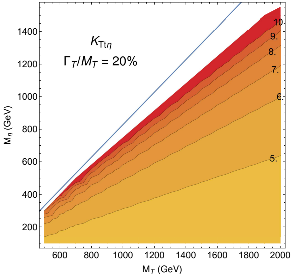


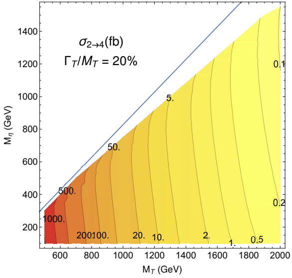


$$\sigma_{t\bar{t}SS}(C_{TtS}, M_T, m_S, \Gamma_T^{tot}(C_{\text{decays}}, M_T, m_{\text{decays}}),) = C_{TtS}^4\, \hat{\sigma}_{t\bar{t}SS}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T}\to 0} \sigma_{T\bar{T}}(M_T) BR(T \to tS)^2$$

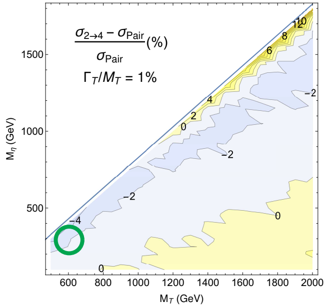
- **TtS coupling**: partial width and rescaling of cross-section
- **Masses and total widths**: kinematics

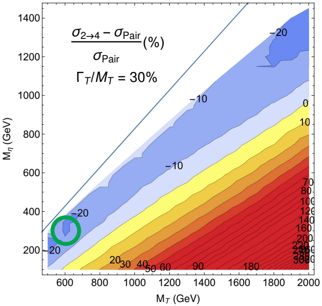






Kinematics in the finite width regime



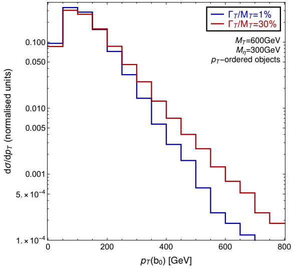


$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

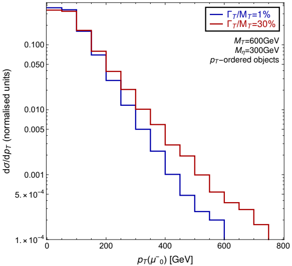
M_T=600 GeV
M_S=300 GeV

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

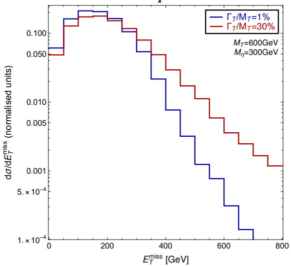
p_T leading b-jet



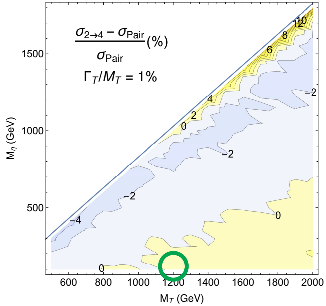
p_T leading μ^-

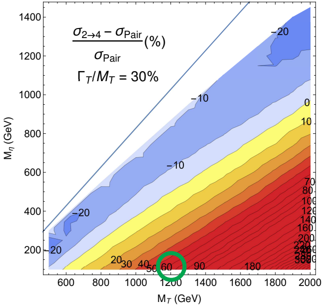


$E_T^{\rm miss}$



Kinematics in the finite width regime



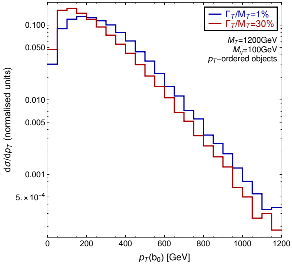


$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

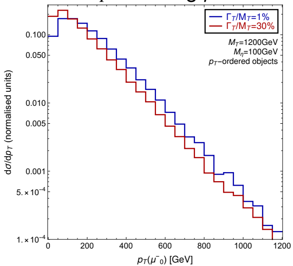
M_T=1200 GeV
M_S=100 GeV

$\sigma_{\rm NWA}$ = 8.902 fb
$\sigma_{\rm tot}$ (1%) = 8.944 fb
$\sigma_{\rm tot}$ (30%) = 14.75 fb

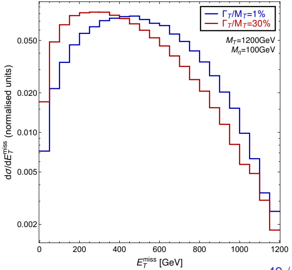
p_T leading b-jet



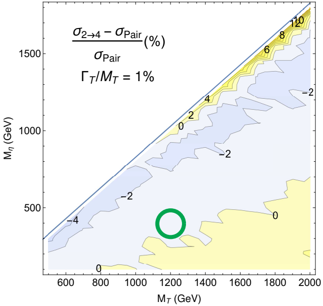
p_T leading μ^-

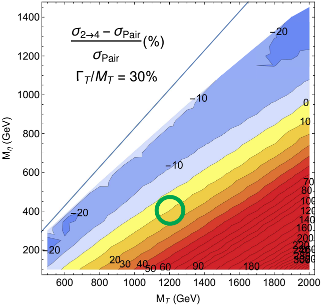


$E_T^{\rm miss}$



Kinematics in the finite width regime



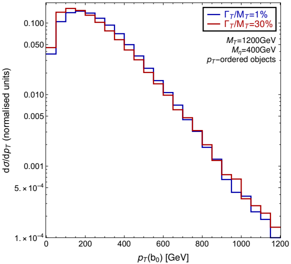


$$pp \xrightarrow{T} t\bar{t}SS$$
$$t \to Wb \to (\mu\nu_\mu)b$$

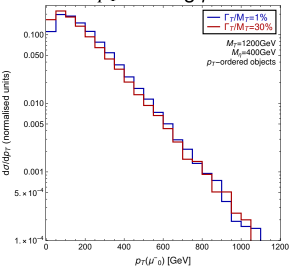
M_T=1200 GeV
M_S=400 GeV

$\sigma_{\rm NWA}$ = 8.902 fb
$\sigma_{\rm tot}$ (1%) = 8.862 fb
$\sigma_{\rm tot}$ (30%) = 9.852 fb

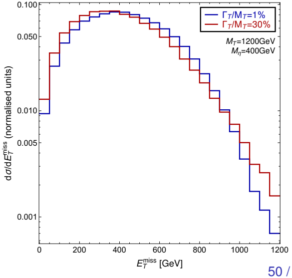
p_T leading b-jet



p_T leading μ^-



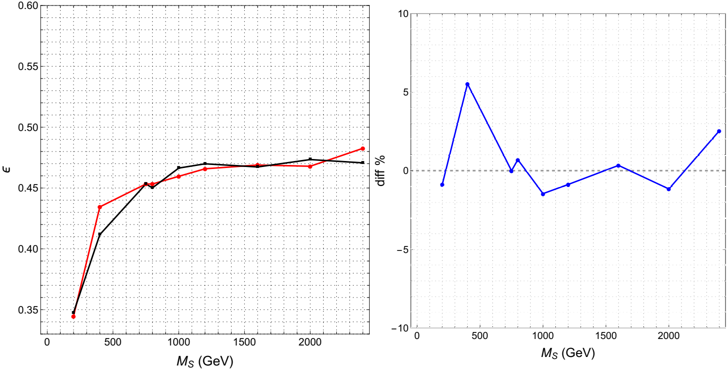
$E_T^{\rm miss}$



Recast of 1707.04147

Validation on $pp \to S \to \gamma\gamma$

Experimental acceptances (from HEPdata in black) vs simulation (in red), and relative difference



Validation at low m_{inv} achieved only by modifying the isolation parameters wrt to experimental value

Recast of 1807.11883

Validation on $pp \to X_{5/3}\bar{X}_{5/3} \to (W^+ t)(W^- \bar{t})$

Source	SR1b2ℓ	SR2b2ℓ	SR3b2ℓ_L	SR3b2ℓ
$t\bar{t}W$	$2.04 \pm 0.14 \pm 0.49$	$2.68 \pm 0.15 \pm 0.55$	$0.95 \pm 0.11 \pm 0.31$	$0.40 \pm 0.06 \pm 0.10$
$t\bar{t}Z$	$0.58 \pm 0.08 \pm 0.10$	$0.95 \pm 0.11 \pm 0.17$	$0.72 \pm 0.11 \pm 0.19$	$0.11 \pm 0.05 \ ^{+0.13}_{-0.10}$
Dibosons	$3.2 \pm 1.5 \pm 2.4$	< 0.5	$0.13 \pm 0.13 \ ^{+0.27}_{-0.00}$	< 0.5
$t\bar{t}H$	$0.56 \pm 0.07 \pm 0.07$	$0.57 \pm 0.10 \pm 0.09$	$0.91 \pm 0.11 \pm 0.22$	$0.19 \pm 0.05 \pm 0.07$
$t\bar{t}t\bar{t}$	$0.10 \pm 0.01 \pm 0.05$	$0.44 \pm 0.03 \pm 0.23$	$1.46 \pm 0.05 \pm 0.74$	$0.75 \pm 0.04 \pm 0.38$
Other bkg	$0.52 \pm 0.07 \pm 0.14$	$0.68 \pm 0.09 \pm 0.24$	$0.47 \pm 0.08 \pm 0.18$	$0.20 \pm 0.04 \pm 0.06$
Fake/non-prompt	$4.1 \ ^{+1.6}_{-1.4} \pm 2.4$	$2.5 \ ^{+1.0}_{-0.9} \pm 1.1$	$1.2 \ ^{+0.9}_{-0.7} \pm 0.6$	$0.20 \ ^{+0.46}_{-0.20} \pm 0.16$
Charge mis-ID	$1.17 \pm 0.10 \pm 0.27$	$1.29 \pm 0.10 \pm 0.28$	$0.32 \pm 0.04 \pm 0.09$	$0.21 \pm 0.04 \pm 0.04$
Total bkg	$12.3 \ ^{+2.2}_{-2.1} \pm 3.4$	$9.1 \ ^{+1.2}_{-1.1} \pm 1.2$	$6.2 \ ^{+1.0}_{-0.8} \pm 1.2$	$2.0 \ ^{+0.5}_{-0.2} \pm 0.3$
Data yield	14	10	12	4
BSM significance	0.31	0.25	1.7	1.1
SM $t\bar{t}t\bar{t}$ significance	0.33	0.38	2.1	1.6

Source	SR1b3ℓ	SR2b3ℓ	SR3b3ℓ_L	SR3b3ℓ
$t\bar{t}W$	$0.66 \pm 0.08 \pm 0.20$	$0.38 \pm 0.05 \pm 0.11$	$0.21 \pm 0.05 \pm 0.09$	$0.15 \pm 0.04 \pm 0.05$
$t\bar{t}Z$	$2.66 \pm 0.15 \pm 0.43$	$1.90 \pm 0.14 \pm 0.42$	$2.80 \pm 0.17 \pm 0.58$	$1.47 \pm 0.14 \pm 0.28$
Dibosons	$2.3 \pm 0.7 \pm 1.7$	$0.22 \pm 0.16 \pm 0.27$	< 0.5	< 0.5
$t\bar{t}H$	$0.30 \pm 0.04 \pm 0.04$	$0.28 \pm 0.05 \pm 0.05$	$0.38 \pm 0.06 \pm 0.07$	$0.10 \pm 0.03 \pm 0.02$
$t\bar{t}t\bar{t}$	$0.06 \pm 0.01 \pm 0.03$	$0.13 \pm 0.02 \pm 0.06$	$0.58 \pm 0.04 \pm 0.29$	$0.59 \pm 0.03 \pm 0.30$
Other bkg.	$1.37 \pm 0.13 \pm 0.45$	$0.65 \pm 0.10 \pm 0.27$	$0.17 \pm 0.09 \pm 0.10$	$0.31 \pm 0.07 \pm 0.11$
Fake/non-prompt	$1.0 \ ^{+0.6}_{-0.5} \pm 0.6$	$0.14 \ ^{+0.31}_{-0.12} \pm 0.09$	$0.00 \ ^{+0.38}_{-0.00} \ ^{+0.09}_{-0.00}$	$0.03 \ ^{+0.15}_{-0.02} \pm 0.00$
Total bkg	$8.3 \ ^{+0.9}_{-0.8} \pm 1.8$	$3.7 \ ^{+0.6}_{-0.3} \pm 0.4$	$4.2 \ ^{+0.4}_{-0.2} \pm 0.7$	$2.7 \pm 0.2 \pm 0.5$
Data yield	8	4	9	3
BSM significance	−0.09	0.14	1.8	0.19
SM $t\bar{t}t\bar{t}$ significance	−0.07	0.21	2.1	0.6