

Vector-like quarks at the LHC

finite width, NLO and exotic decays

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Wallenbergs
Stiftelse*



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”?

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

SM Chiral fermions

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \quad j_R^\mu = 0$$
$$j^\mu = j_L^\mu + j_R^\mu = \bar{f} \gamma^\mu (1 - \gamma^5) f'$$

V-A structure

Vector-like fermions

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

V structure

Peculiar Properties

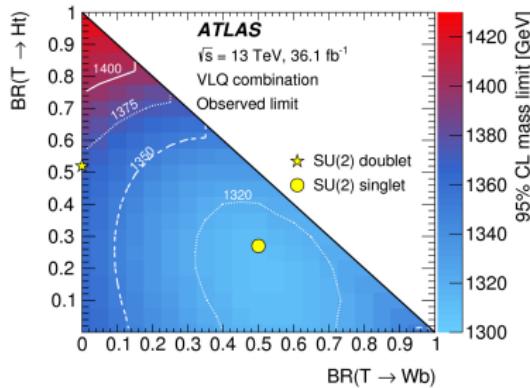
$$\mathcal{L}_M = -M \bar{\psi} \psi \quad \text{Gauge invariant mass term without the Higgs}$$

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

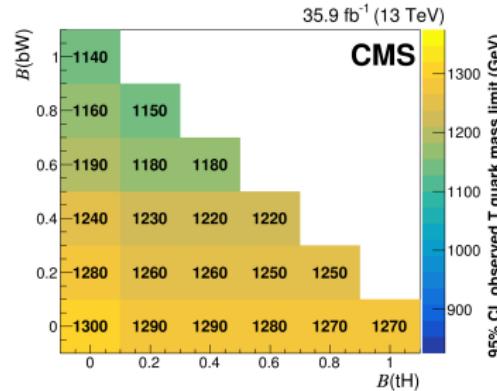
Vector-like quarks

an intense experimental effort

ATLAS 1808.02343



CMS 1805.04758



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

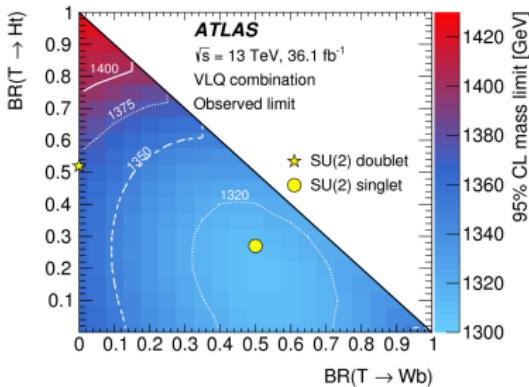
- SM extended with only **one representation** of VLQs
- Mixing only with **third generation** of SM quarks
- Pair production** or **Single production at LO**
- Narrow width** approximation
- Interacting only with **SM states**

More exploration is definitely needed!

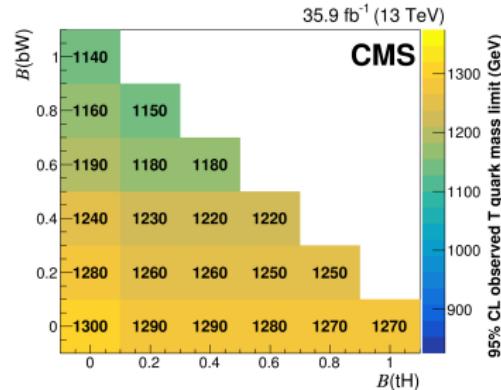
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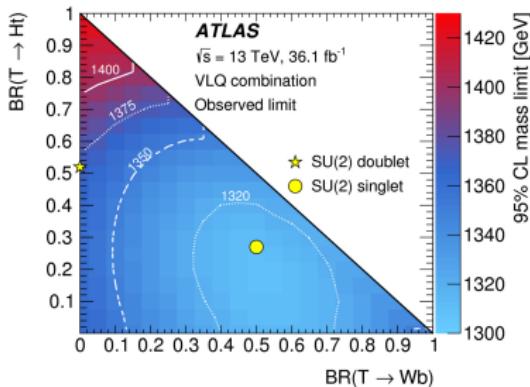
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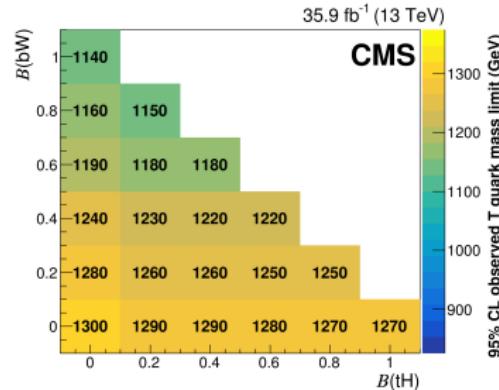
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- Narrow width approximation** Third part of the talk
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Single production of VLQs with finite width

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

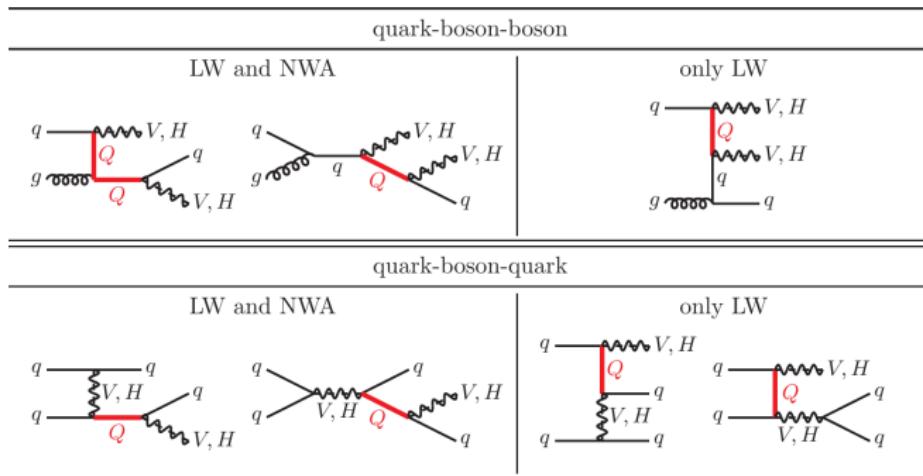
and

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 $\sqrt{s} = 13 \text{ TeV}$
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:

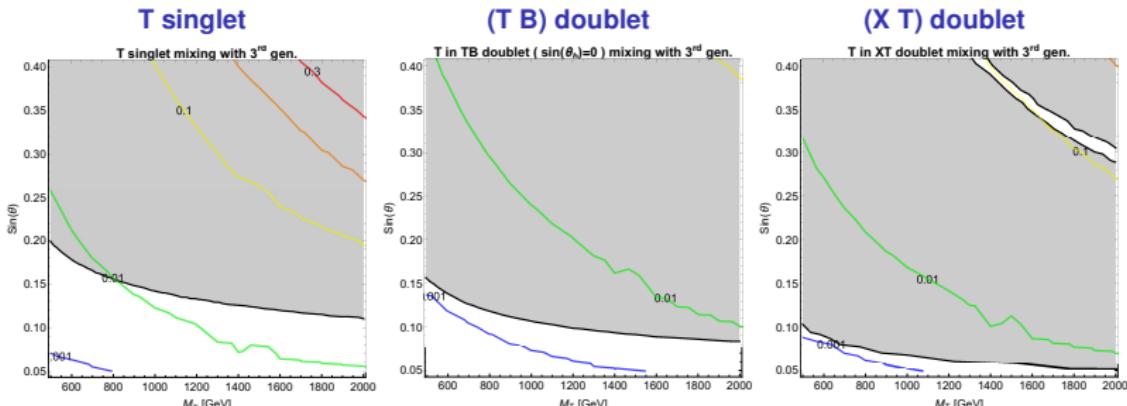
- **Off-shell effects** are not negligible anymore
- **Subdominant topologies** in the Narrow Width Approximation may become important
- Outside the NWA all topologies leading to the same final state must anyway be taken into account for **gauge invariance**
- Need to redefine the signal to take into 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

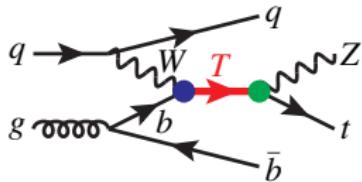
Simplified models with large couplings:



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

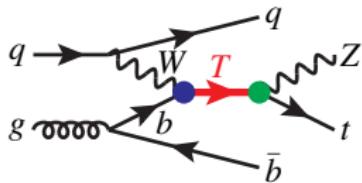
Parametrisation for large width regime



in the narrow-width approximation (NWA)

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

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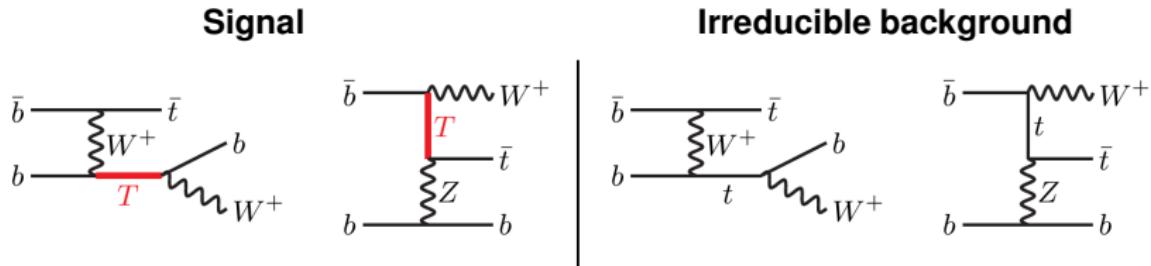
in the finite width regime (FW) and assuming negligible interference contributions

$$\sigma(C_1, C_2, m_Q, \Gamma_Q) = C_1^2 C_2^2 \hat{\sigma}(m_Q, \Gamma_Q)$$

- 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 with itself

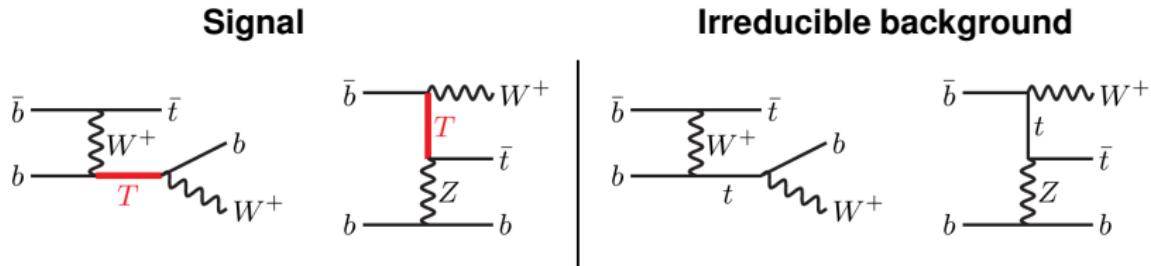
$$\sigma_S = C_2^2 \hat{\sigma}_S(C_1 \dots, M_Q, \Gamma_Q, \chi_Q)$$

χ_Q is the dominant chirality of the VLQ

signal with irreducible background

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

Interference



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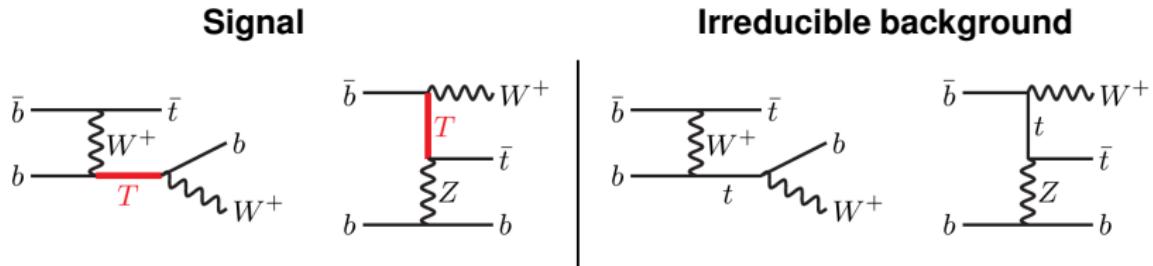
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Model-dependency is (almost) unavoidable

Interference



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Model-dependency is (almost) unavoidable

If signal topologies always involve the same two couplings

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

In general → fiducial cross-section

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

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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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 characterize the properties of the recently discovered Higgs boson, for each model:

- we include a brief description of the relevant signature;
- we indicate the FeynRules file and the aMC 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 files	UFO Libraries	Validation material
GMSF (more details)	C. Degrande	-	SM_Fr	SM_gmsf_UFO_1.f0p	-
Dark matter simplified models (more details)	K. Mawatari	[arXiv:1508.00354] [arXiv: 1508.01527]	-	DMsmp_UFO_2.f0p	-
Dark Matter Gauge Invariant simplified model (scalar s-channel mediator) (more details)	G. Bazzucchi	[arXiv:1612.03075] [arXiv: 1710.10764]	-	-	-
Effective LR symmetric model (more details)	K. Ratz	[arXiv:1512.01149]	effLRSM_fr	effLRSM_UFO	-
SM (more details)	A. Pilaftsis	[arXiv:1602.00957]	-	SM_NLO_UFO	-
Heavy Neutrino (more details)	B. Rutz	[arXiv:1311.1829] [arXiv: 1407.5089]	heavyNFr	HeavyN_UFO	-
Higgs characterization (more details)	K. Mawatari	[arXiv:1504.00013]	-	HC_NLO_UFO_UFO.f0p	-
Inclusive gluon pair production	B. Pukas	[arXiv:1412.5599]	sgluons_fr	sgluons_UFO.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Unstable particle $\rightarrow A(\bar{t}t) \rightarrow t\bar{t}$ bar (including interference) (more details)	D. Picozzi	[arXiv:1707.06769]	-	Atttbar_UFO_UFO	-
SprinT-2 (more details)	C. Degrande	[http://www.arXiv.org/abs/1605.09399]	SprinT2_fr	SPRINT2_UFO_UFO	SprinT2_validation.pdf ; SprinT2_validation_root.tgz
Stop pair $\rightarrow t\bar{t}$ bar + missing energy	B. Pukas	[arXiv:1412.5599]	stop_tbar_tlf_UFO	stop_tbar_tlf_UFO.tgz	stop_tbar_tlf_validation.pdf ; stop_tbar_tlf_validation_root.tgz
SUSY-QCD	B. Pukas	[arXiv:1510.00393]	-	susyqcd_UFO_UFO	All Figures available from the arxiv
Two-Higgs-Doublet Model (more details)	C. Degrande	[arXiv:1406.3030]	-	2HDM_NLO	-
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Vector like quarks	B. Pukas	[arXiv:1601.04932]	VlQ_v3.fr	UFO in the SPhN, UFO in the 4PNs, event generation scripts, coupling definitions in the LO conventions	All Figures available from the arxiv
W/Z2 model (more details)	Pukas	[arXiv:1701.05283]	vFermiNLO_fr	vFermiNLO_UFO	-
NTGC (more details)	C. Degrande	[JHEP-1402 (2014) 101]	NTGC_fr	NTGC_UFO at NLO	-
GGG_EFT_wt_to_4point_loops (more details) (requires $M_{H^\pm}, m_{H^\pm} > 0.2 -$)	V. Hirsch	[arXiv:1606.04996]	GGG_fr	GGG_EFT_wt_to_4point_loops_UFO	Analytic amplitude and cross-sections in the corresponding publication

Attachments (1)

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VLQ couplings have a dedicated coupling order “VLQ”

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

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Dark matter simplified models (more details)	K. Mawatari	[arXiv:1508.00354] [arXiv: 1508.01527]	-	DMSIMP_NLO_2.zip	-
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SprinT-2 (more details)	C. Degrande	[http://arxiv.org/abs/1605.09399]	SprinT2_SFR	SIMP_SprinT_UFO	SprinT2_interference.pdf ; SprinT2_validation.pdf
Stop pair $\rightarrow t\bar{t}$ bar + missing energy	B. Pukas	[arXiv:1412.3599]	stop_tbar_t_UFO.tgz	stop_tbar_t_UFO.tgz	stop_tbar_t_validation.pdf ; stop_tbar_t_validation.root.tgz
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Two-Higgs-Doublet Model (more details)	B. Pukas	[arXiv:1601.00001]	2HDMFR	2HDM_UFO	-
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GGG_EFT_wt_4point_loops (more details) (requires $M_{H^\pm}, m_{H^\pm} > 0.5 -$)	V. Hirsch	[arXiv:1606.04996]	GGGfr	GGG_EFT_wt_4point_loops_UFO	Analytic amplitude and cross-sections in the corresponding publication

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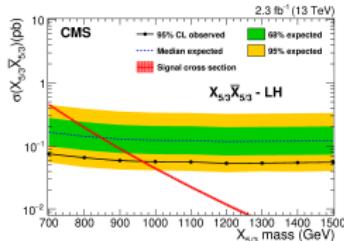
VLQ couplings have a dedicated **coupling order “VLQ”**

Single $T \rightarrow Wb$ 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)

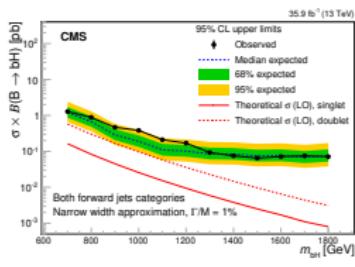
from NWA



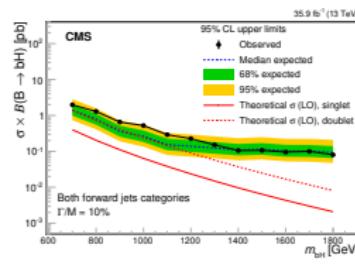
to Γ/M -dependent upper limits

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

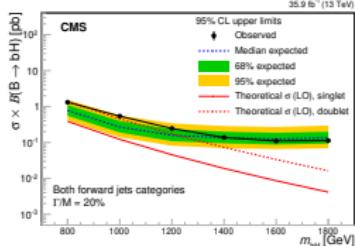
$$\frac{\Gamma}{M} = 1\% (\sim \text{NWA})$$



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



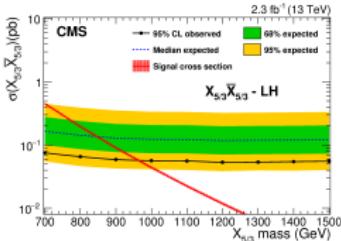
$$\frac{\Gamma}{M} = 20\%$$



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

Presentation of the results (2)

from NWA



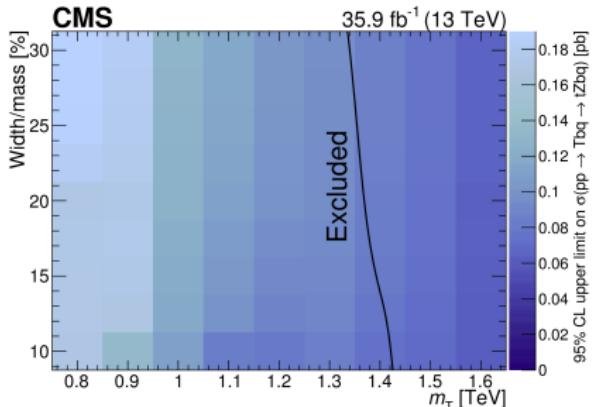
to Γ/M -dependent upper limits

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

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

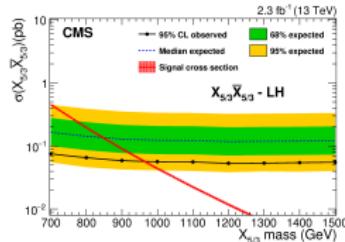
Mass [TeV]	$\hat{\sigma}_{FW} (\sigma)$ for $pp \rightarrow T\bar{b}q \rightarrow t\bar{Z}b\bar{q}$ [pb]			$\hat{\sigma}_{FW} (\sigma)$ for $pp \rightarrow T\bar{t}q \rightarrow t\bar{Z}t\bar{q}$ [pb]		
	10%	20%	30%	10%	20%	30%
0.8	226 (0.675)	108 (0.650)	70 (0.631)	19 (0.144)	9.3 (0.139)	6.0 (0.135)
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)

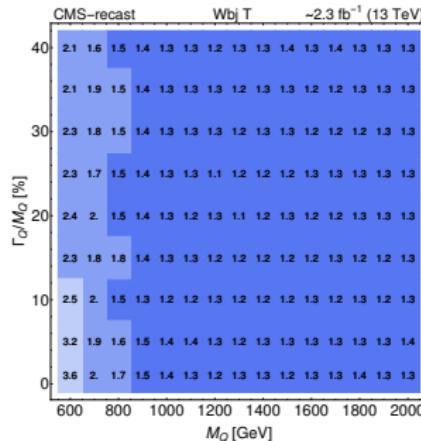
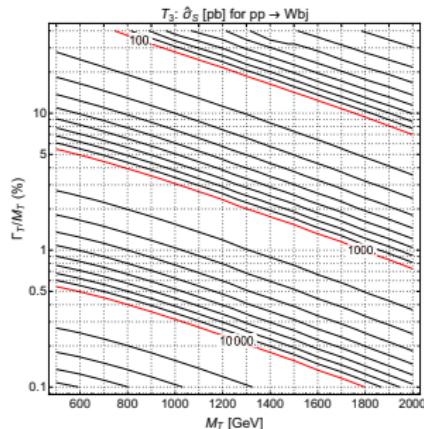
from NWA



to Γ/M -dependent upper limits

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

Reduced
cross-section
plot

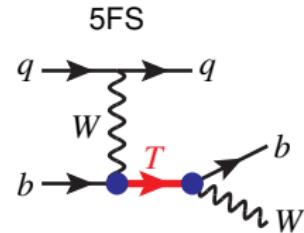
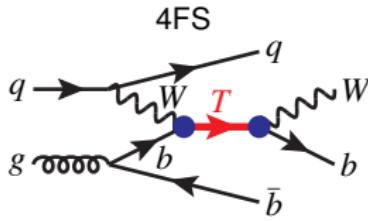


Upper
limits
grid

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

Finite width and kinematics

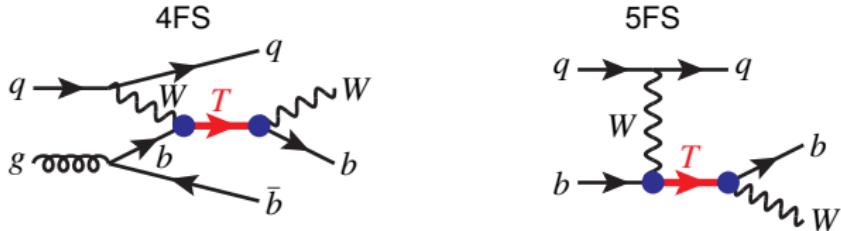
example for a specific channel



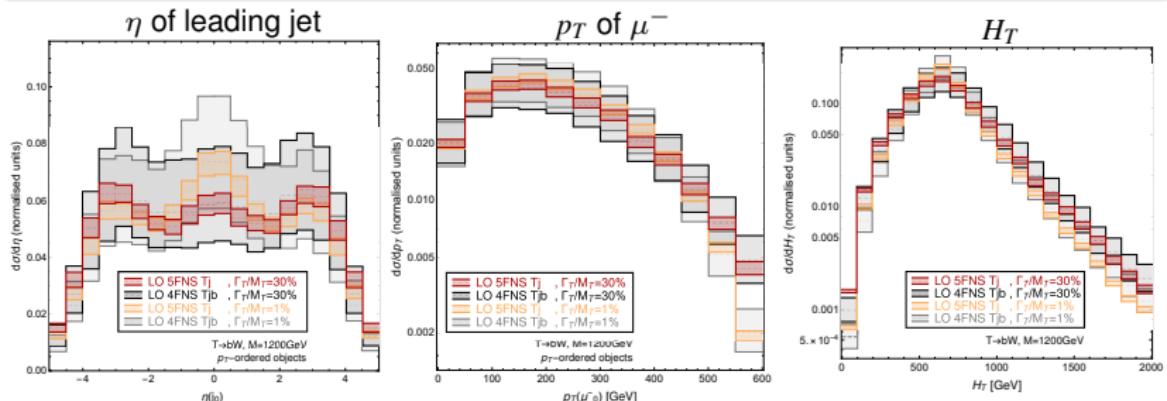
$M_T = 1200 \text{ GeV}$, $\Gamma_T/M_T = 1\%$ and 30% , and imposing muonic decay of W

Finite width and kinematics

example for a specific channel



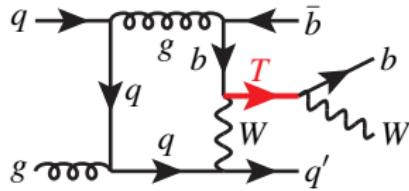
$M_T = 1200 \text{ GeV}$, $\Gamma_T/M_T = 1\%$ and 30% , and imposing muonic decay of W



Kinematical distributions can be sizably different in the finite width regime
what happens at NLO?

Single production of VLQs at NLO

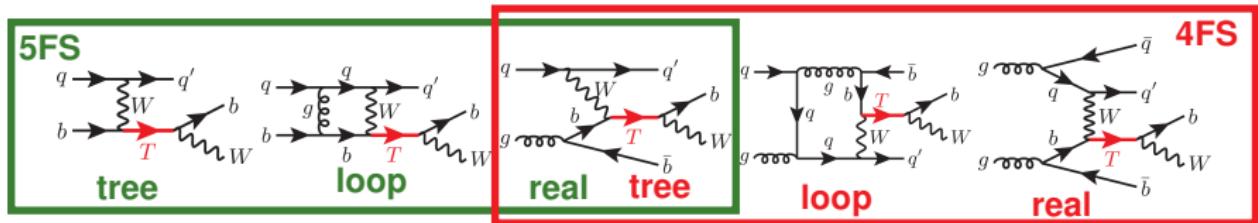
interacting only with SM states



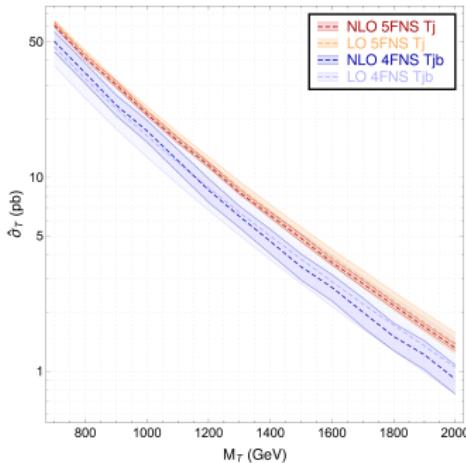
based on

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
arXiv:1811.05055, accepted by PLB

NLO predictions in the NWA

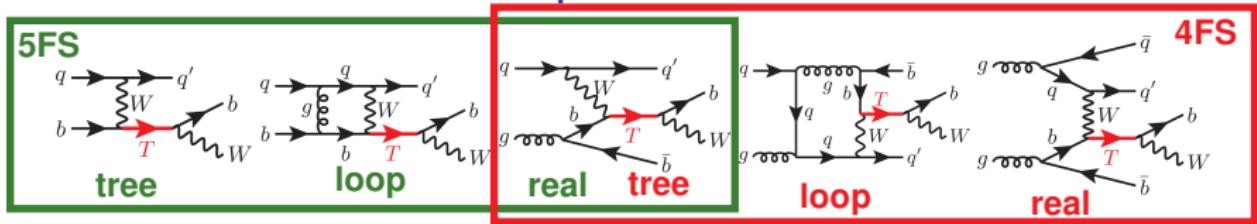


Total rates



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

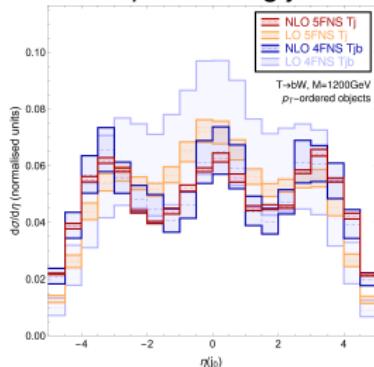
NLO predictions in the NWA



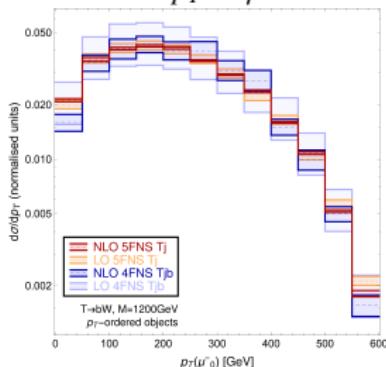
Distributions

$M_T = 1200$ GeV and imposing muonic decay of W

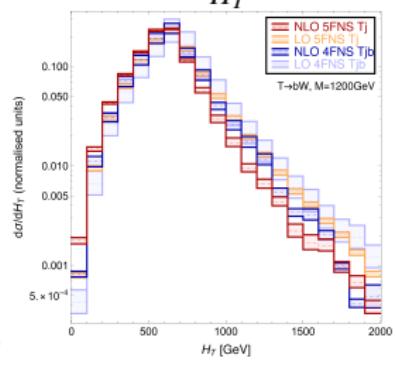
η of leading jet



p_T of μ^-

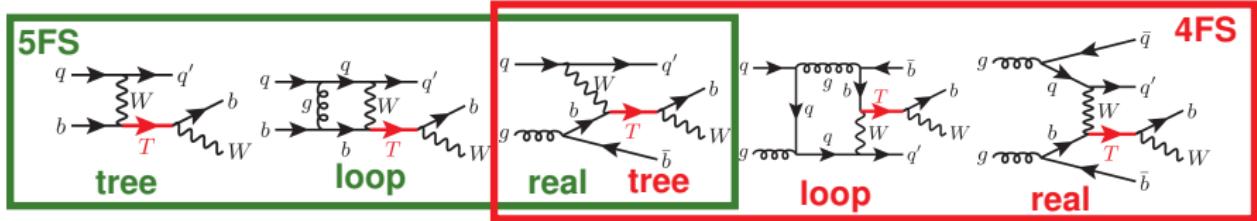


H_T



NLO corrections can significantly impact shapes

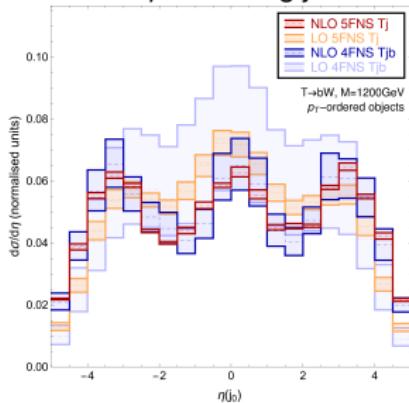
NLO predictions in the NWA



Distributions

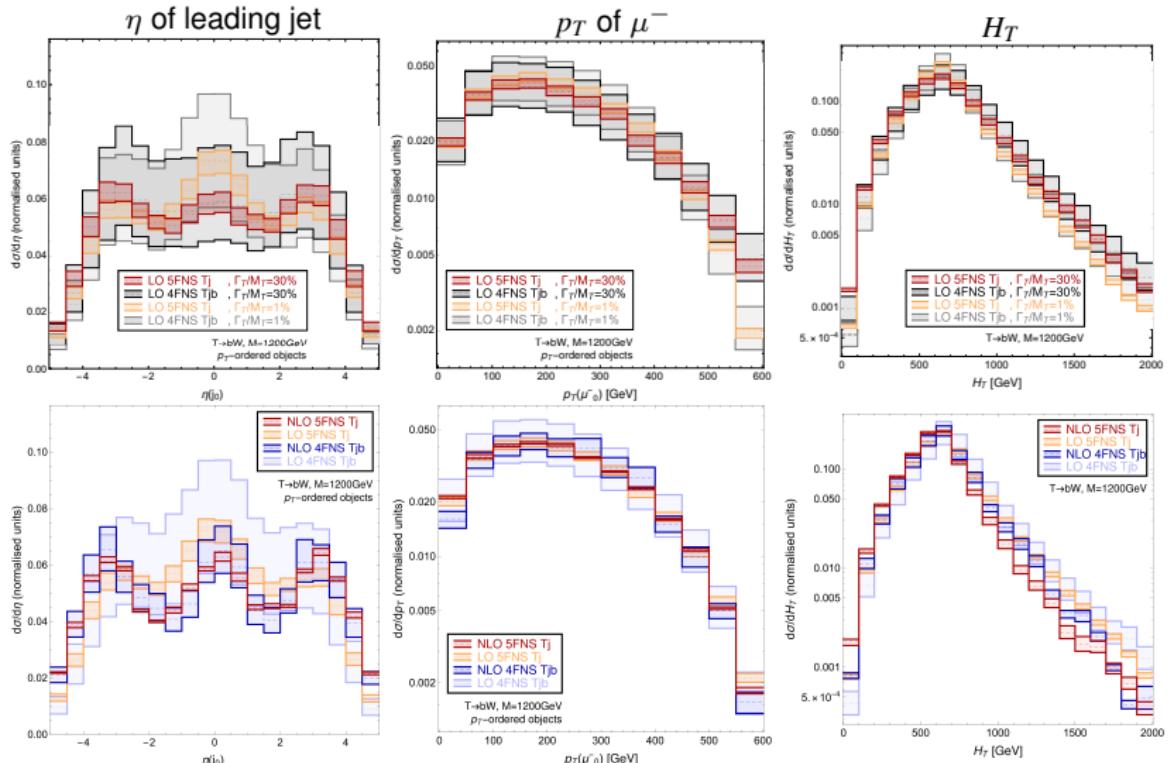
$M_T = 1200$ GeV and imposing muonic decay of W

η of leading jet



- 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

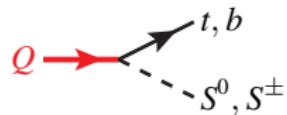
FW@LO vs NWA@NLO



What happens at NLO if the VLQ has large width?

Exotic decays of VLQs

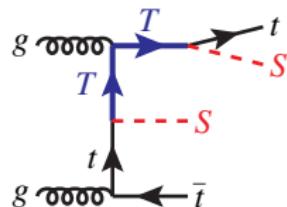
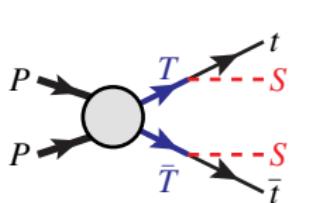
finite width effects



work in progress through

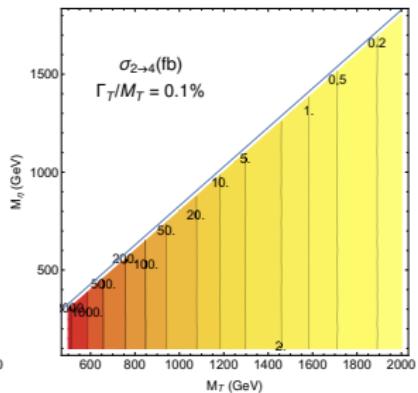
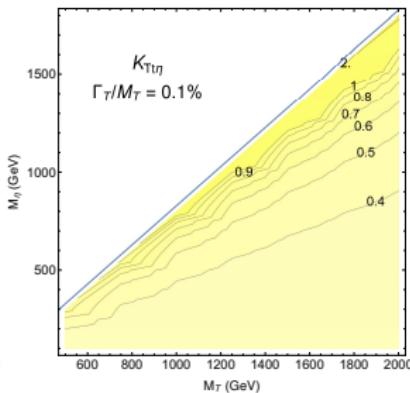
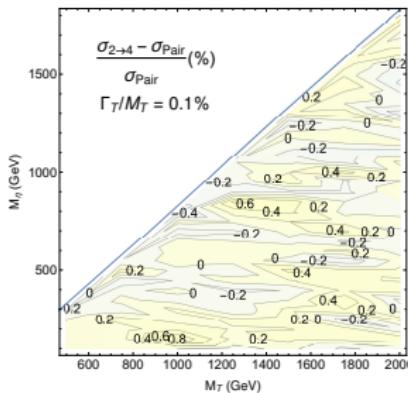


Mass of the scalar as new parameter

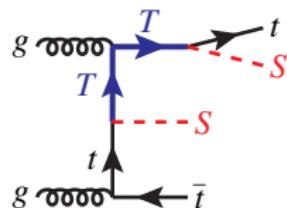
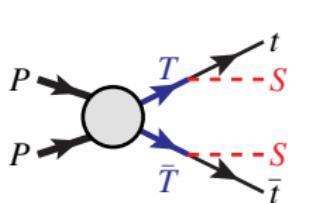


$$\sigma_{\bar{t}S\bar{S}}(C_{T\bar{S}}, M_T, m_S, \Gamma_T^{tot}(C_{decays}, M_T, m_{decays}),) = C_{T\bar{S}}^4 \hat{\sigma}_{\bar{t}S\bar{S}}(M_T, m_S, \Gamma_T^{tot}) \xrightarrow{\frac{\Gamma_T^{tot}}{M_T} \rightarrow 0} \sigma_{T\bar{T}}(M_T) BR(T \rightarrow tS)^2$$

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

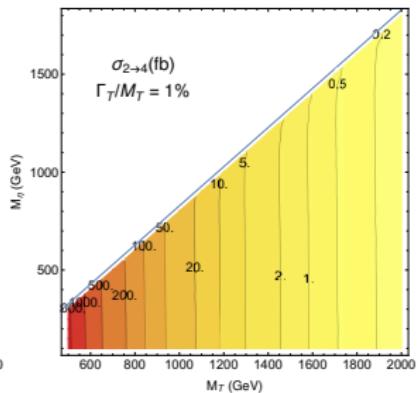
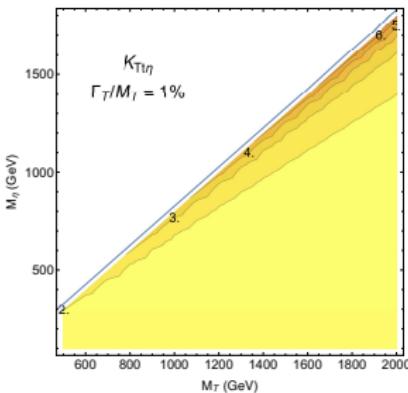
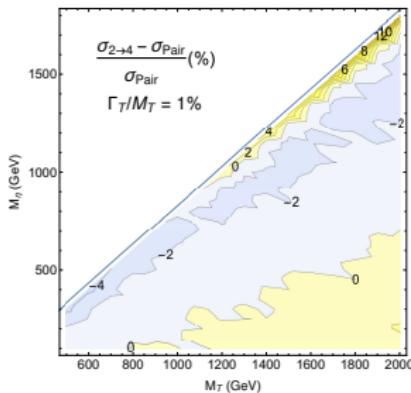


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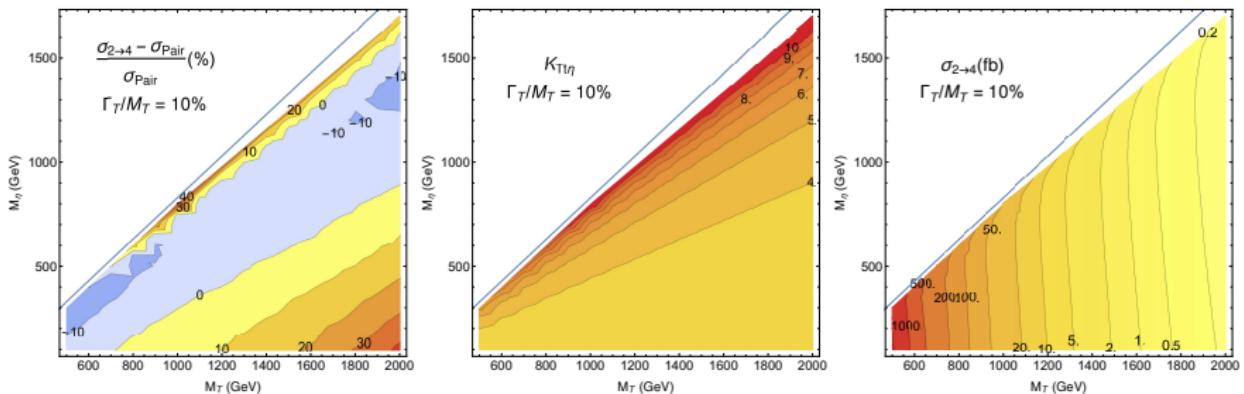


Mass of the scalar as new parameter



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

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

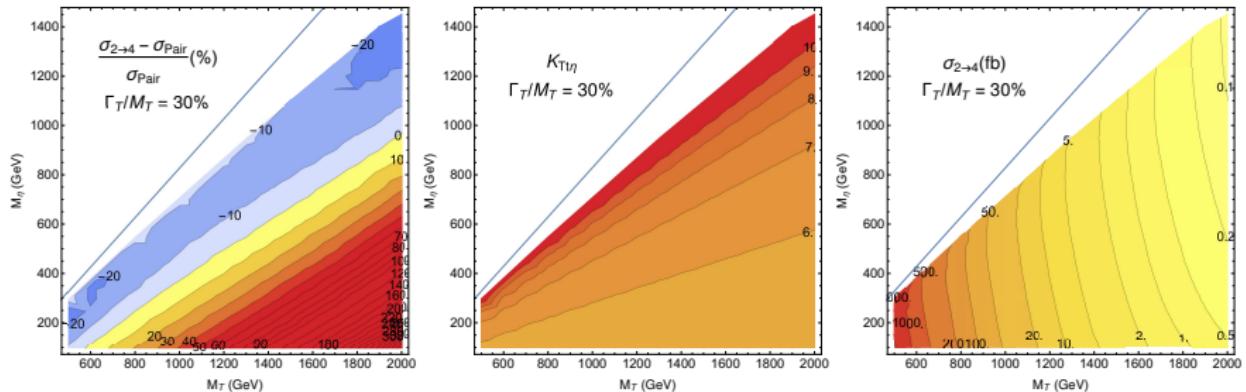


Mass of the scalar as new parameter

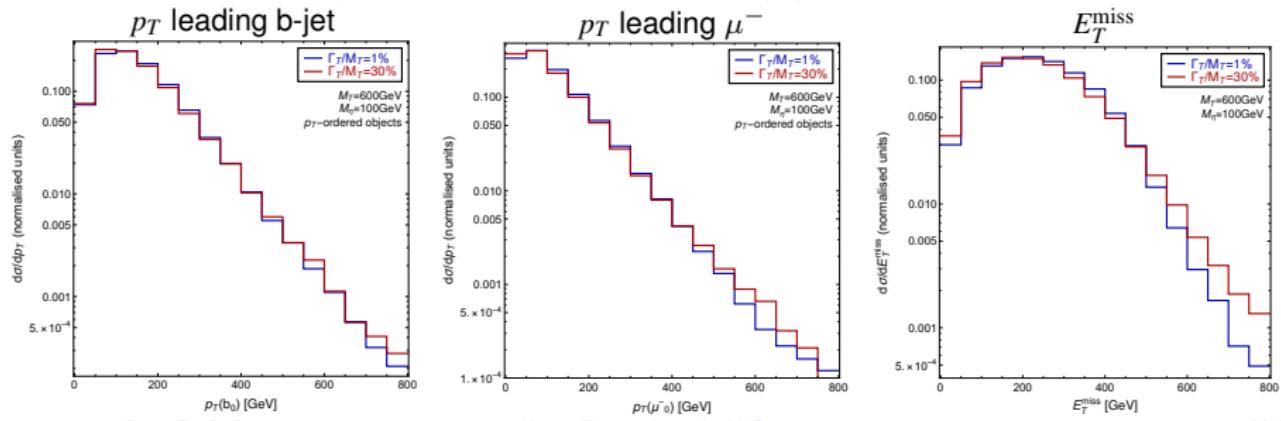
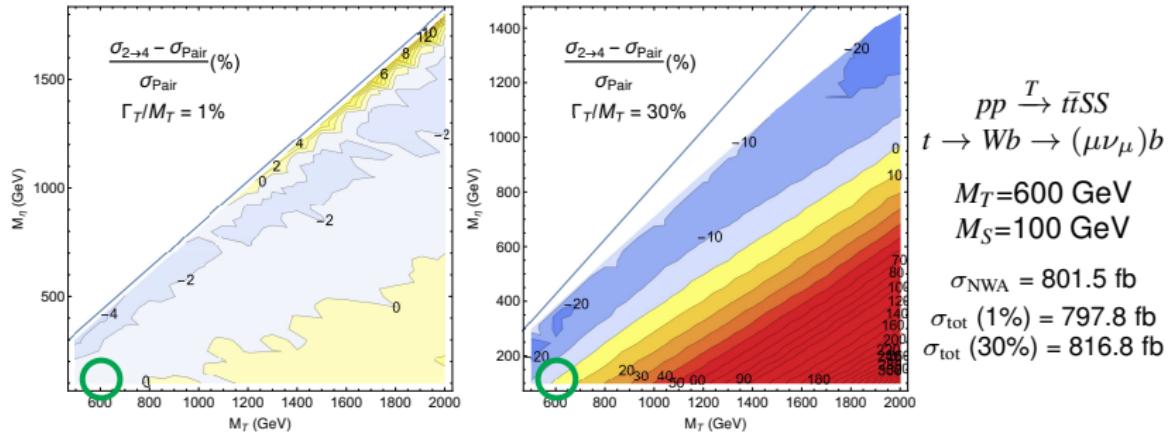


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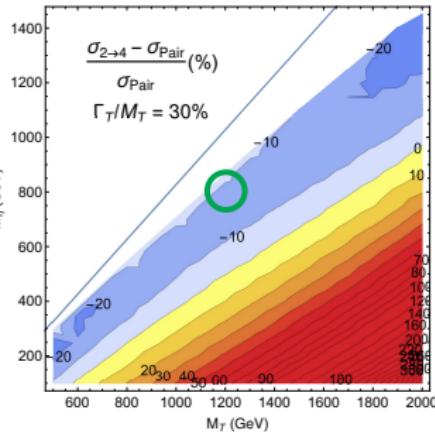
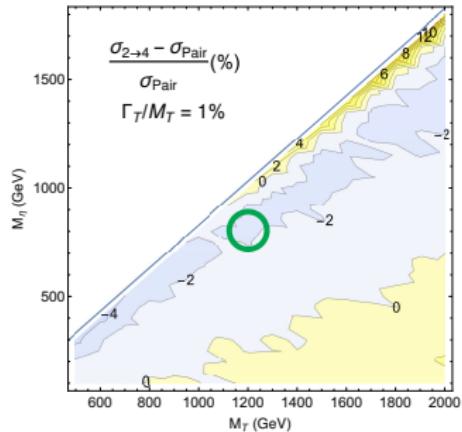
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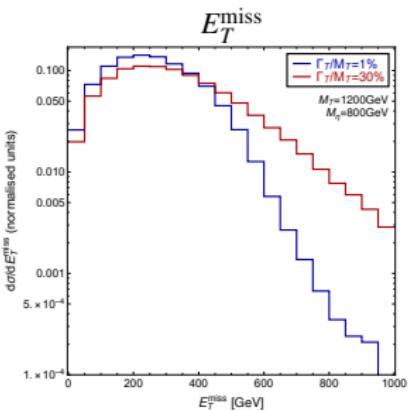
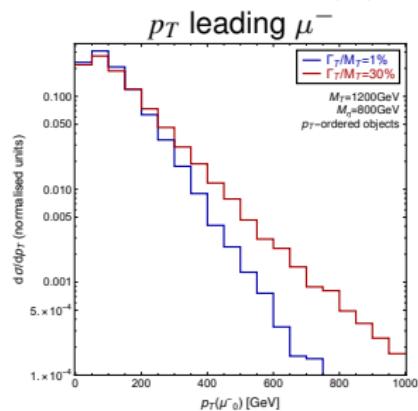
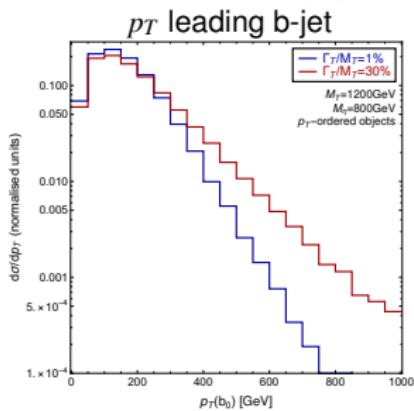
Kinematics in the finite width regime



Kinematics in the finite width regime



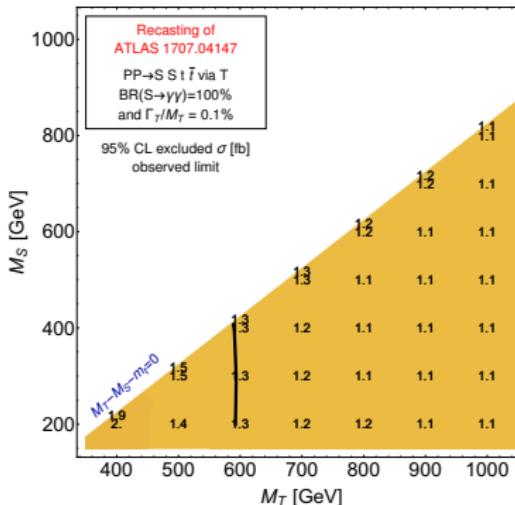
$pp \xrightarrow{T} t\bar{t}SS$
 $t \rightarrow Wb \rightarrow (\mu\nu_\mu)b$
 $M_T = 1200 \text{ GeV}$
 $M_S = 800 \text{ GeV}$
 $\sigma_{\text{NWA}} = 8.902 \text{ fb}$
 $\sigma_{\text{tot}} (1\%) = 8.716 \text{ fb}$
 $\sigma_{\text{tot}} (30\%) = 7.702 \text{ fb}$



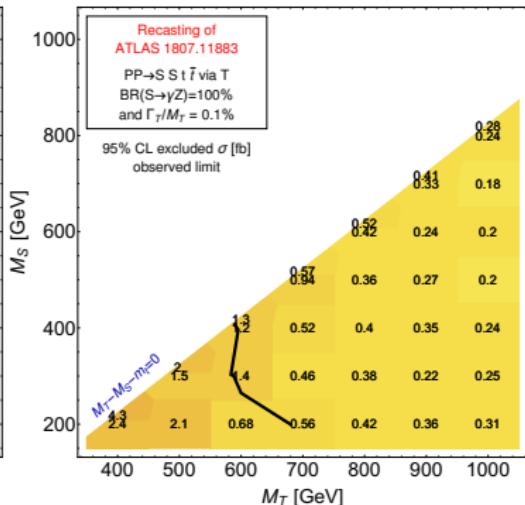
Presentation of the results

Recast of two ATLAS searches

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



Example with T and two S decays
 $\gamma\gamma, \gamma Z$



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

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 with finite width interacting also with exotic scalars

- Finite width effects can again be **sizable**
- Model-independent parametrisation in the **VLQ mass and scalar mass plane** for different **width-to-mass ratios** of the VLQ
- Ongoing study to assess the **limitations of a NWA analysis** or the possibility to develop **different strategies** for the finite width regime
- **UFO model validated** and soon publicly available

Backup



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.

Knut och Alice
Wallenbergs
Stiftelse

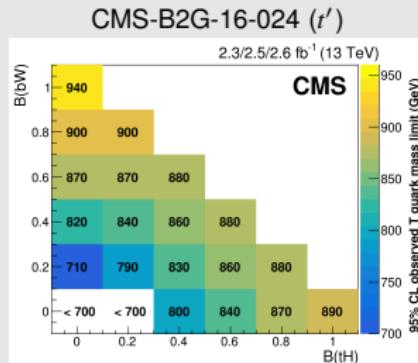


Vector-like quarks

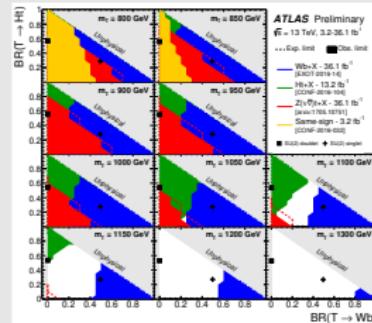
Vector-like quarks in many models of New Physics

- 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



ATLAS twiki: summary plots (t')



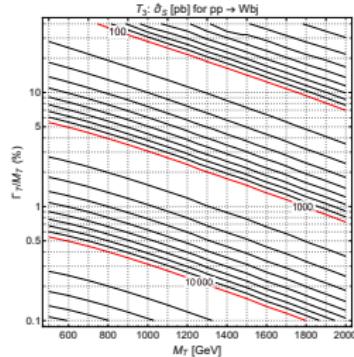
Characterising VLQ properties if a discovery is made would be essential for embedding them into some scenarios (and exclude others!)

Interference

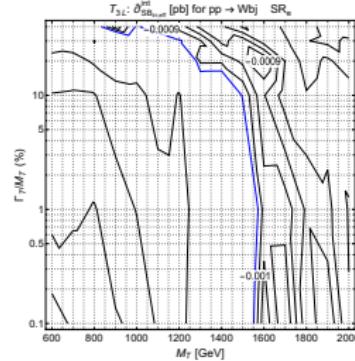
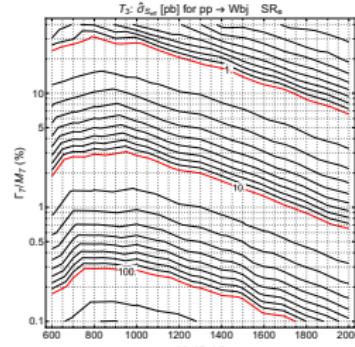
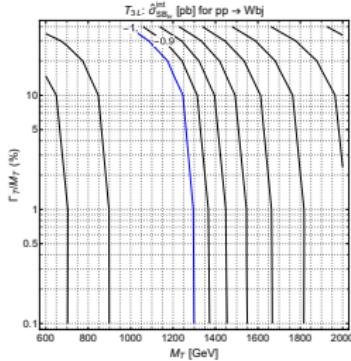
Recast of CMS-B2G-16-006

Folding search efficiencies into the reduced cross-section:

Signal



Interference
with SM



Mass of the scalar as new parameter



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

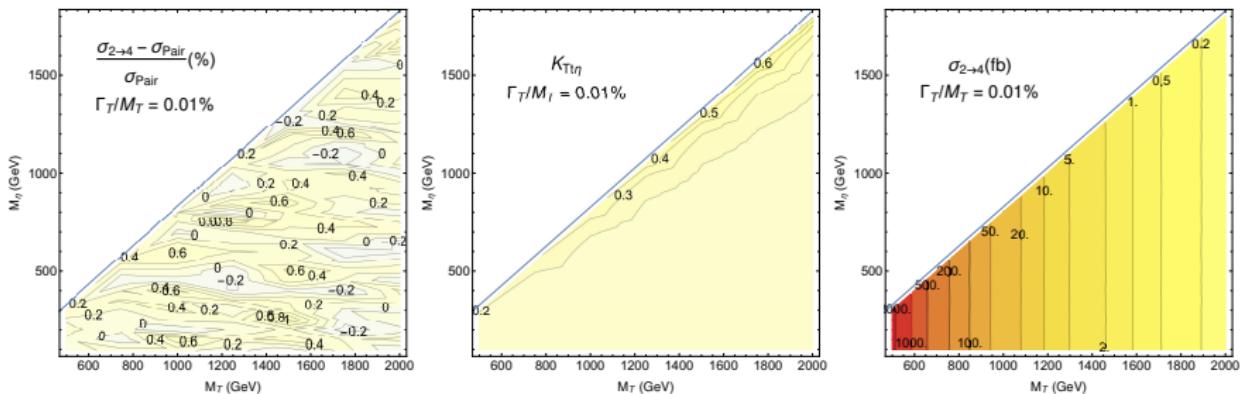
- **TtS coupling:** partial width and rescaling of cross-section
- **Masses and total widths:** kinematics

Mass of the scalar as new parameter



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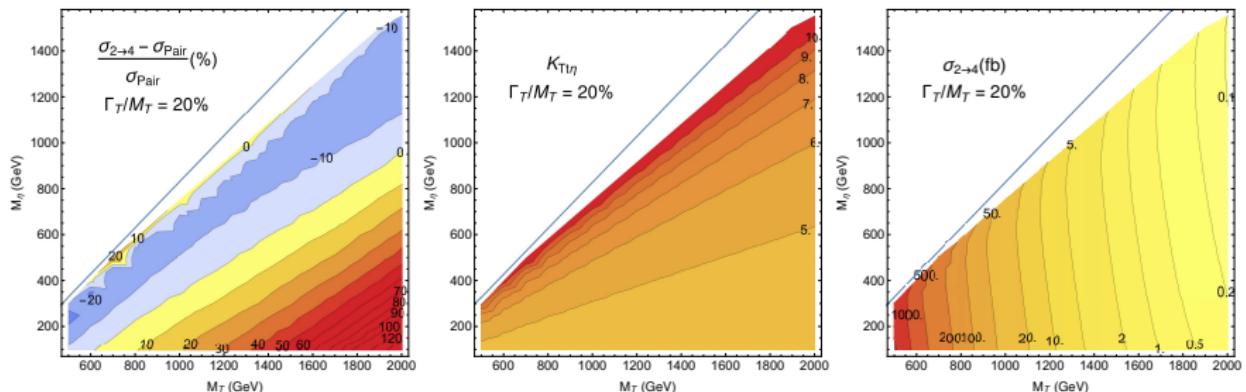


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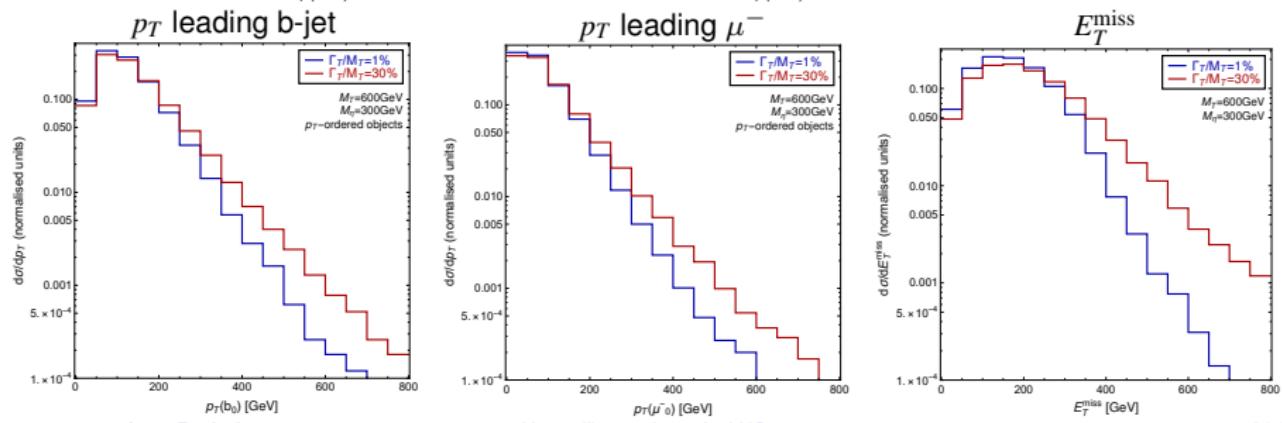
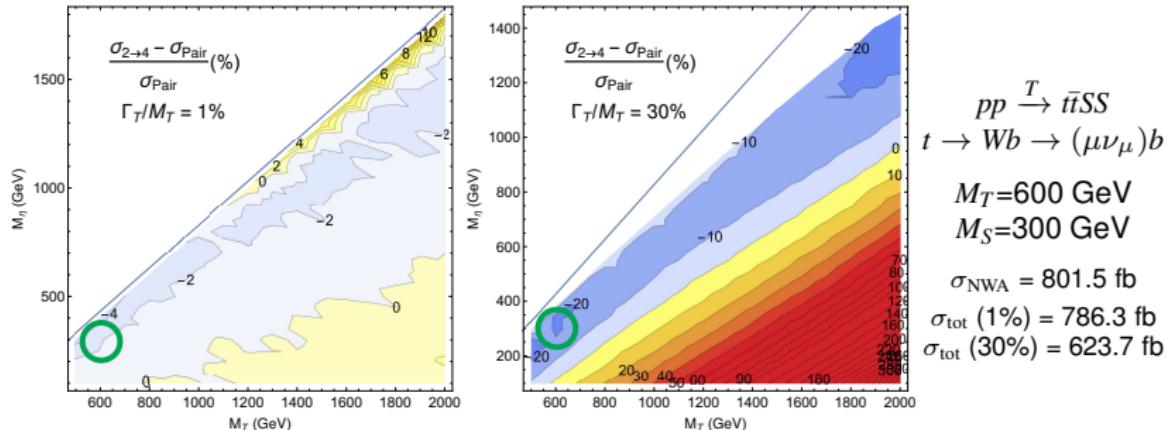


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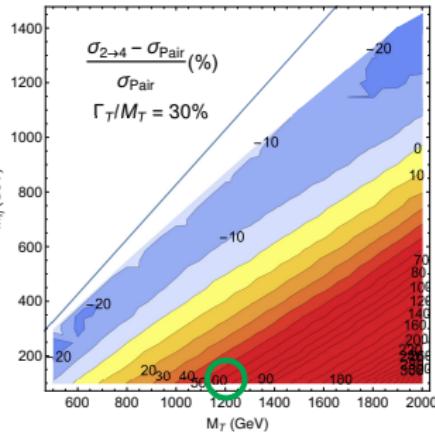
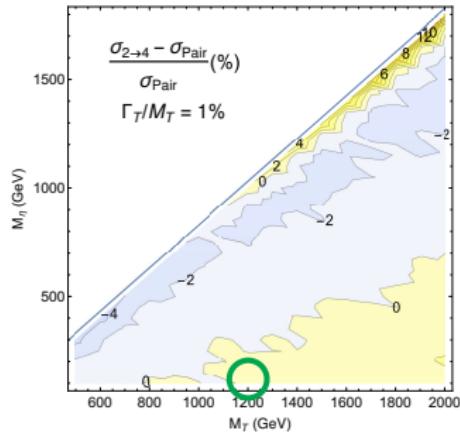
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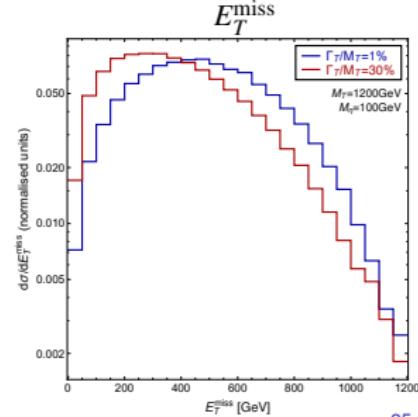
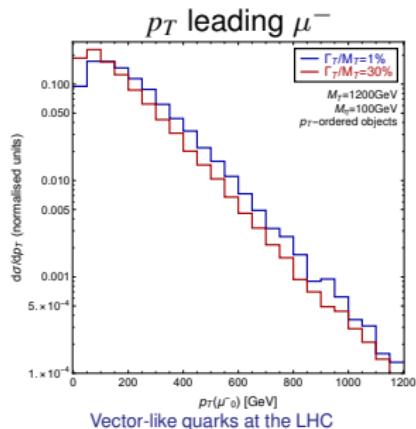
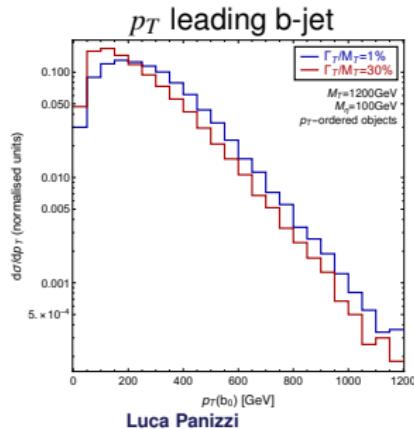
Kinematics in the finite width regime



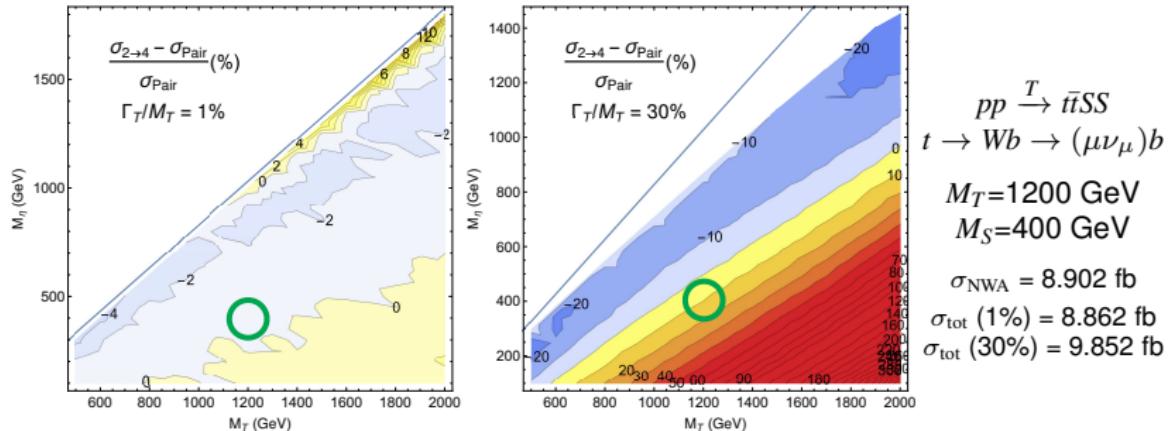
Kinematics in the finite width regime



$pp \xrightarrow{T} t\bar{t}SS$
 $t \rightarrow Wb \rightarrow (\mu\nu_\mu)b$
 $M_T = 1200$ GeV
 $M_S = 100$ GeV
 $\sigma_{\text{NWA}} = 8.902$ fb
 $\sigma_{\text{tot}} (1\%) = 8.944$ fb
 $\sigma_{\text{tot}} (30\%) = 14.75$ fb



Kinematics in the finite width regime



$pp \xrightarrow{T} t\bar{t}SS$
 $t \rightarrow Wb \rightarrow (\mu\nu_\mu)b$
 $M_T = 1200 \text{ GeV}$
 $M_S = 400 \text{ GeV}$
 $\sigma_{\text{NWA}} = 8.902 \text{ fb}$
 $\sigma_{\text{tot}} (1\%) = 8.862 \text{ fb}$
 $\sigma_{\text{tot}} (30\%) = 9.852 \text{ fb}$

