Vector-like quarks decaying to new scalars

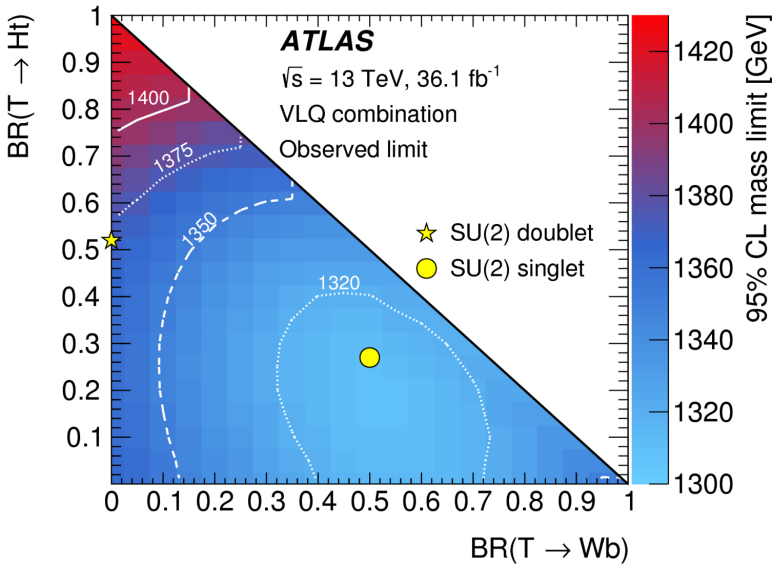
Luca Panizzi

Uppsala University

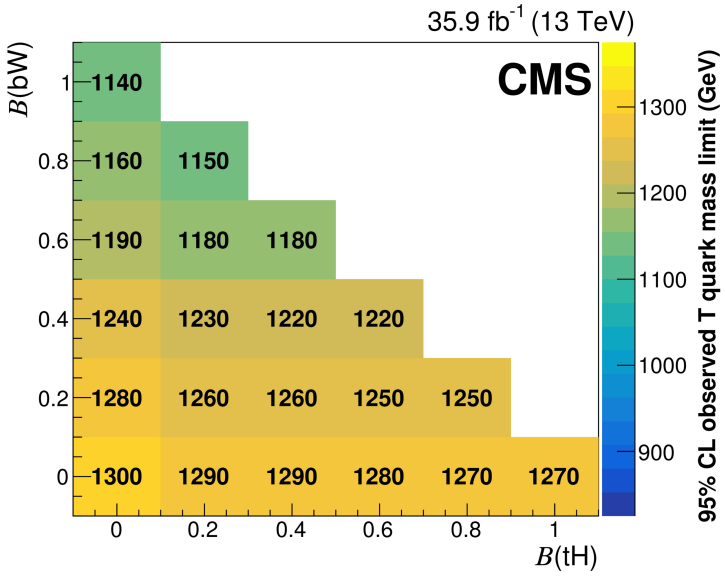
Vector-like quarks

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

an intense experimental effort

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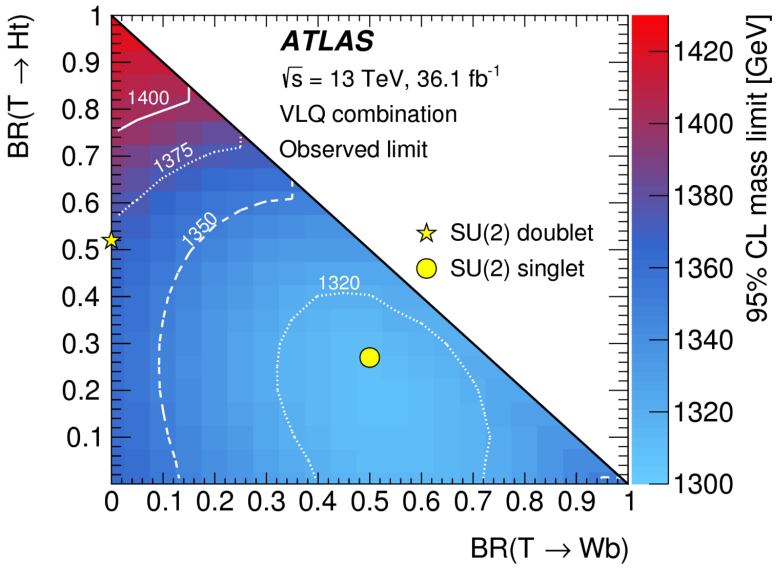

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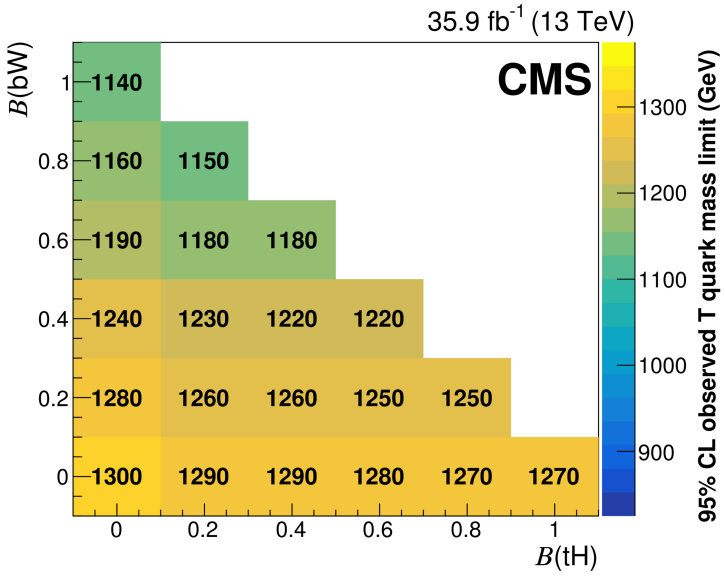

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Non-SM VLQ decays

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^+)

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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'

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The Lagrangian

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

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

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interaction t'-S-t — interaction S-SM fermions

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

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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

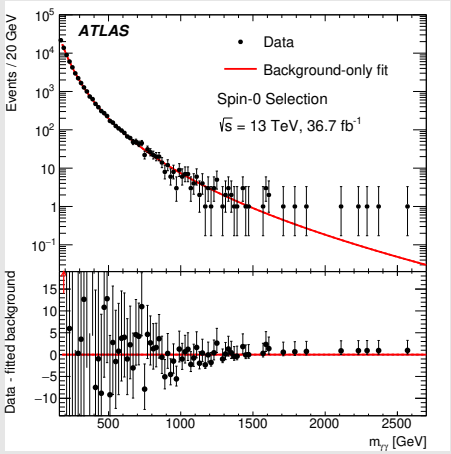
- ATLAS 1707.04147: "Search for new phenomena in **high-mass diphoton** final states using 37 fb^{-1} of proton–proton collisions collected at $\sqrt{s} = 13$ TeV with the ATLAS detector"
- ATLAS 1807.11883: "Search for new phenomena in events with **same-charge leptons** and b-jets in pp collisions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

Both searches implemented and validated in MADANALYSIS 5

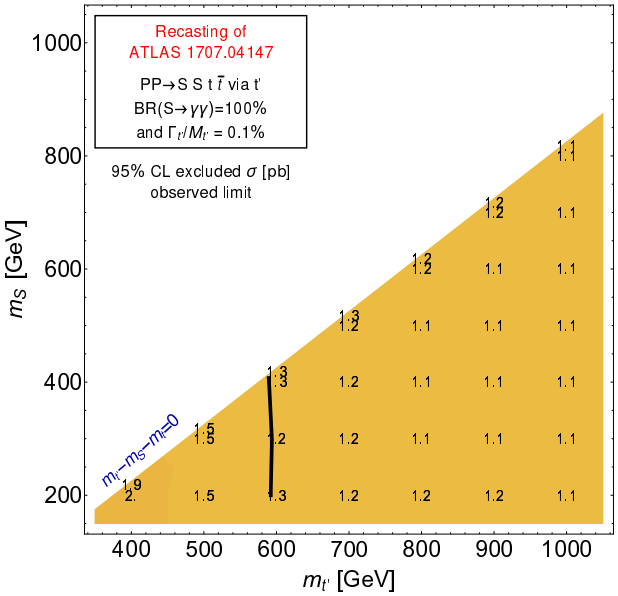
Recast of 1707.04147

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)



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



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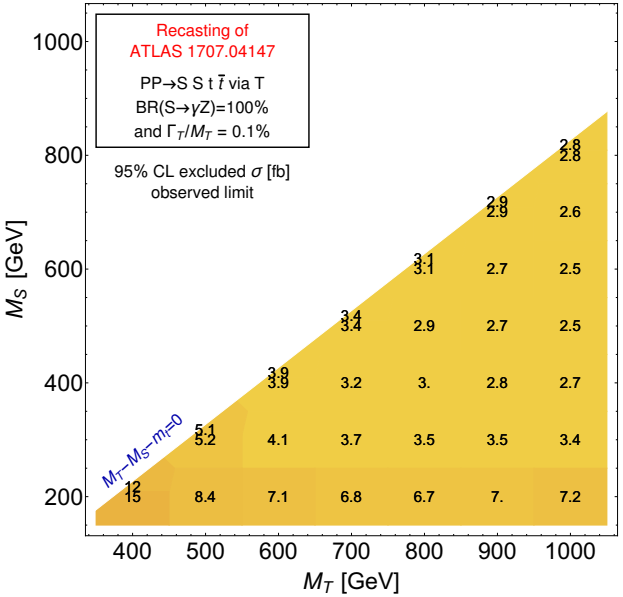


More sensitive to final states where photons come from a resonance

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

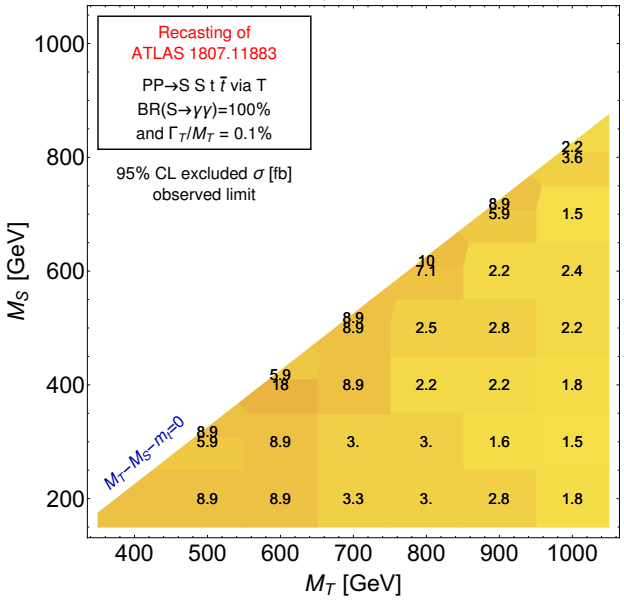
Recast of 1807.11883

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 −−	$400 < H_T < 2400$ 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

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



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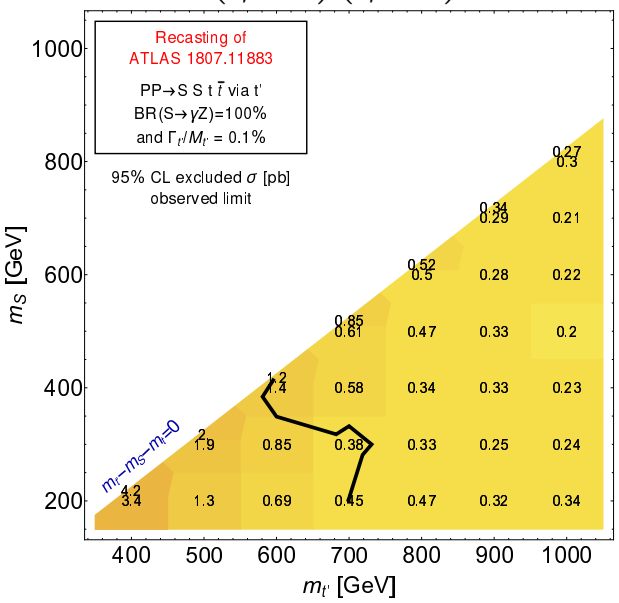


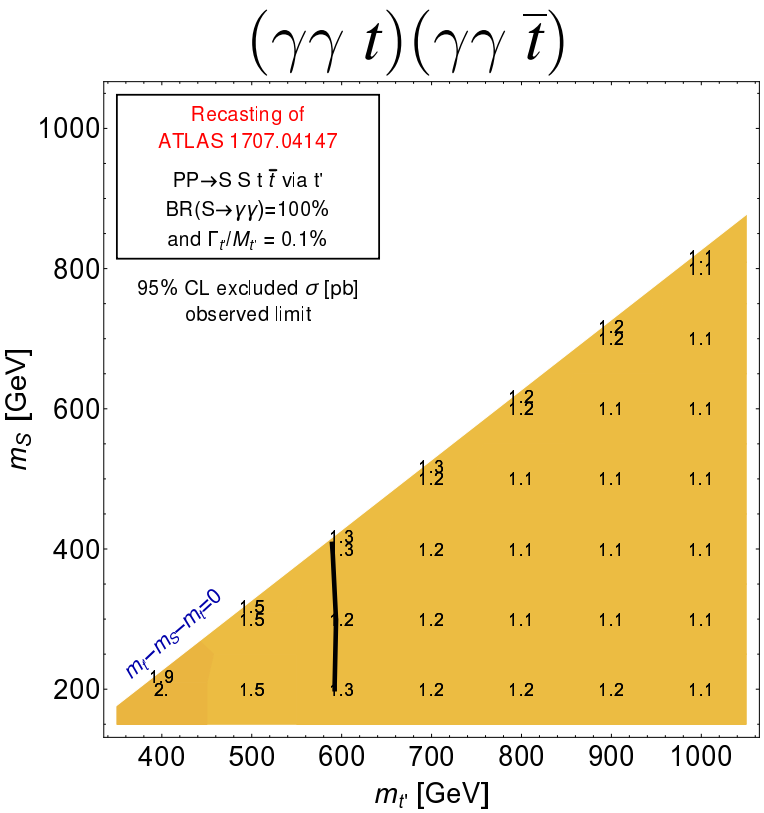
More sensitive to final states with enough number of leptons

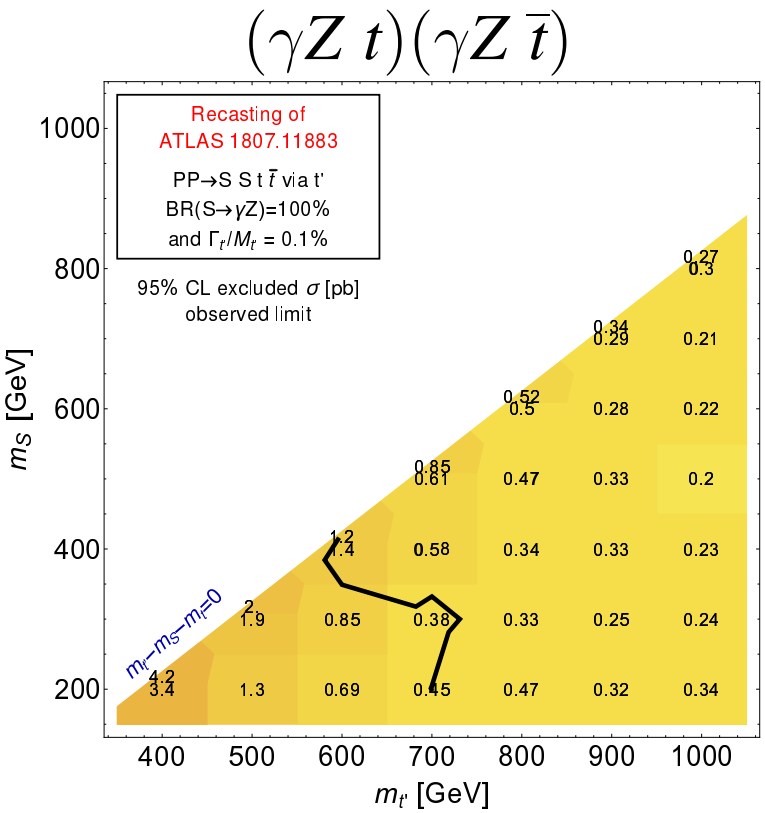
Bounds complementary to the diphoton search

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

Combined bounds

ATLAS 1707.04147 and 1807.11883





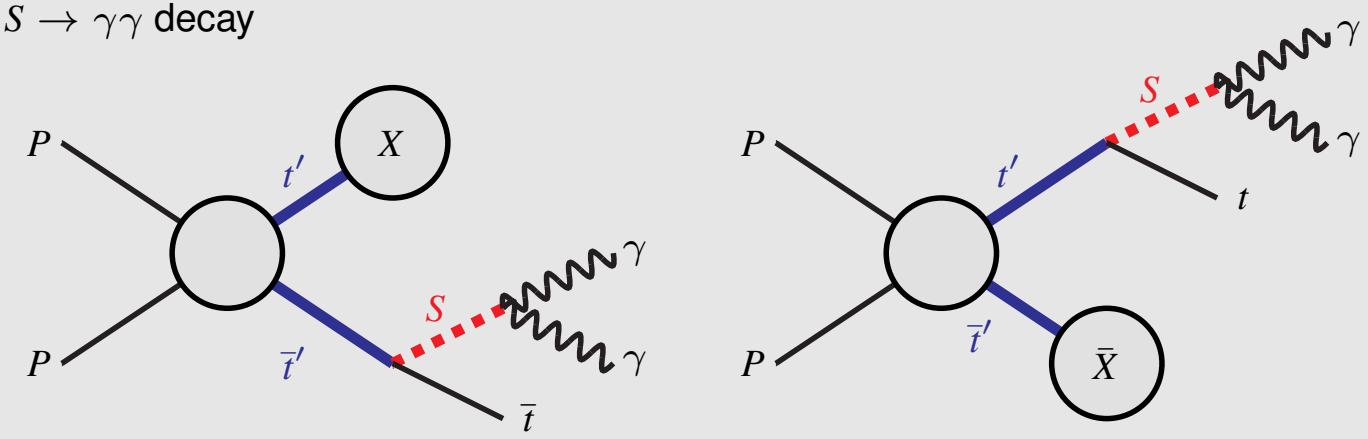
How to improve:

- 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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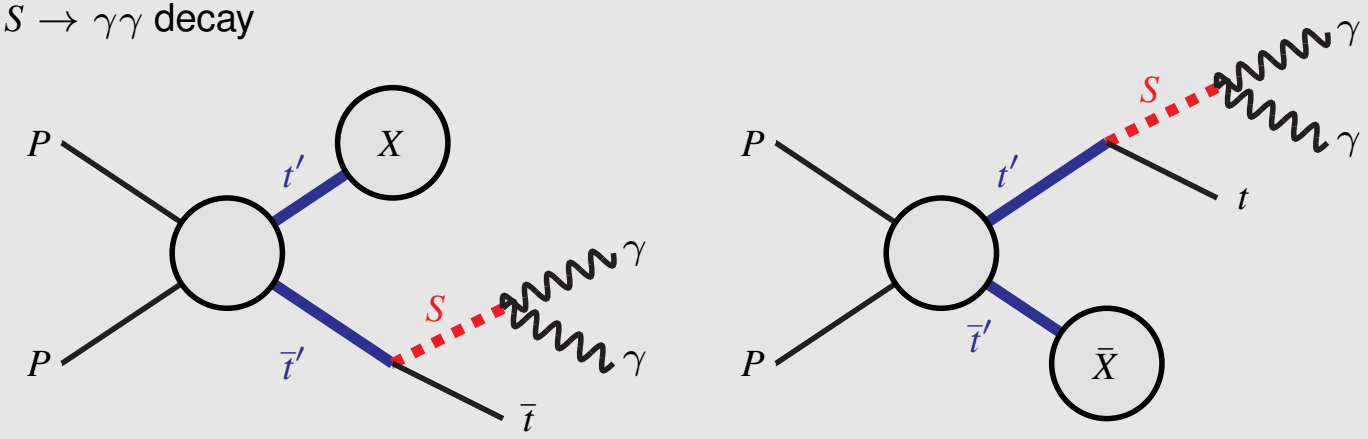

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$\gamma\gamma$ signal region

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

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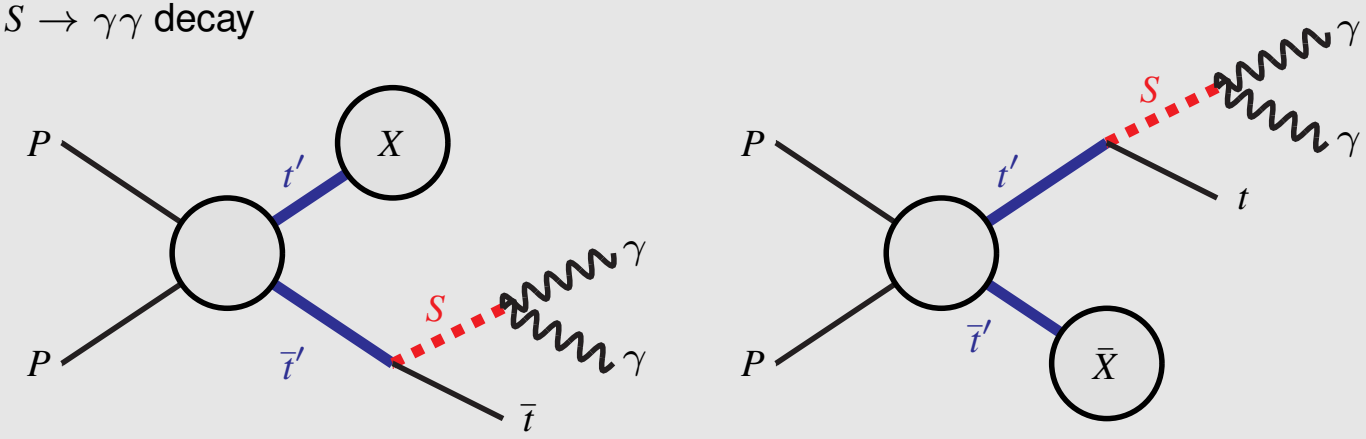

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γZ signal region

Z is reconstructed through leptonic decay

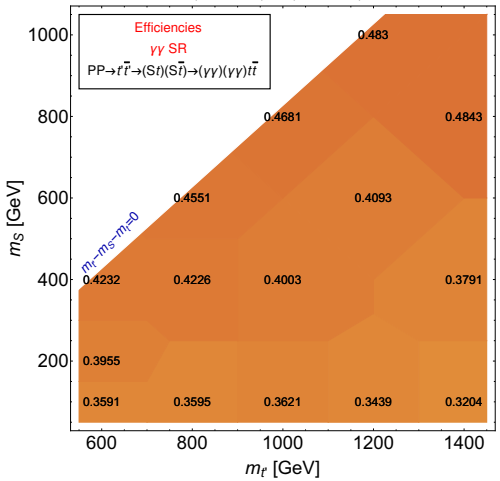
1) At least 1 reconstructed Z: $|m_{ll} - m_Z| < 10$ GeV
2) $N_\gamma \geq 1$ with $p_T^{\gamma_1} > 30$ GeV and $|\eta^{\gamma_1}| < 2.37$
3) $N_b \geq 1$
4) if $m_S < 200$ GeV: $p_T^\gamma + p_T^b + p_T^Z > 250$ GeV
4) if $m_S \geq 200$ GeV: $H_T + E_T^{\text{miss}} > 0.8 m_t'$
5) $|m_{\gamma Z} -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

Efficiencies (preliminary results)

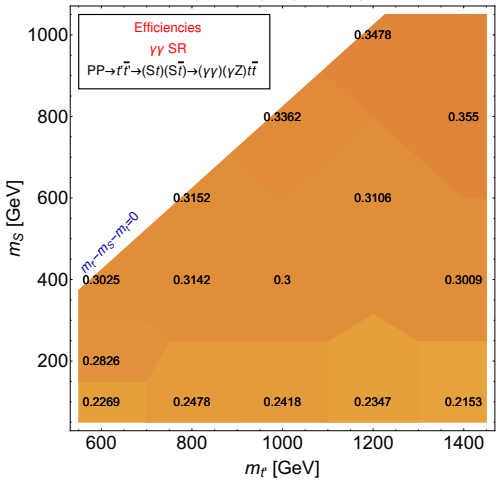
Example for $S \to \gamma\gamma$: $S = L\,\sigma(m_t')\,\left(\epsilon^{St,\gamma\gamma}_{St,\gamma\gamma} BR^2_{t'\to St}\, BR^2_{S\to\gamma\gamma} + \sum_{X\neq St,\gamma\gamma \text{ or } Y\neq St,\gamma\gamma} \epsilon^{Y}_{X} BR_{t'\to X} BR_{t'\to Y}\right)$

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

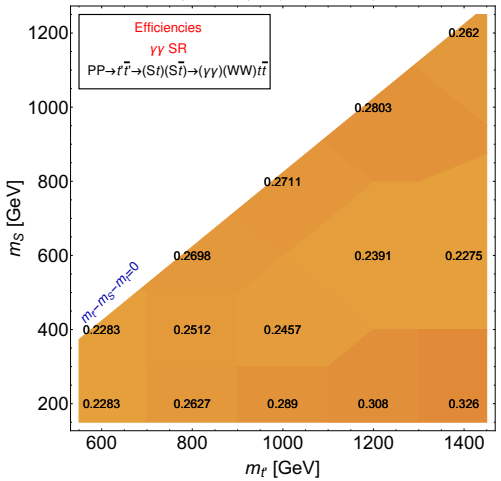
$(\gamma\gamma)(\gamma\gamma)$



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

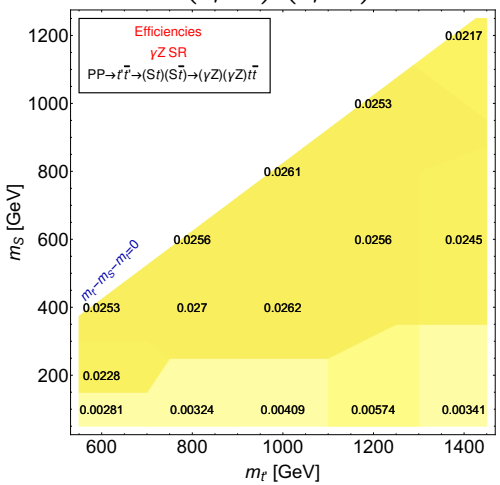


$(\gamma\gamma)(WW)$



γZ SR
(0.1-2%)

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



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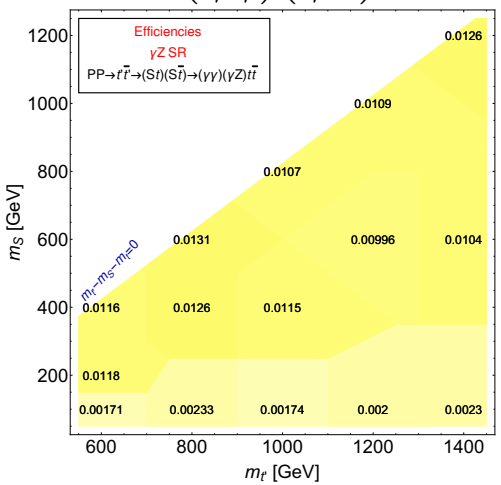

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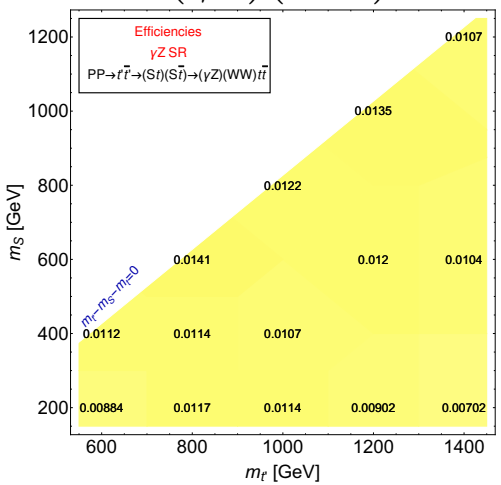
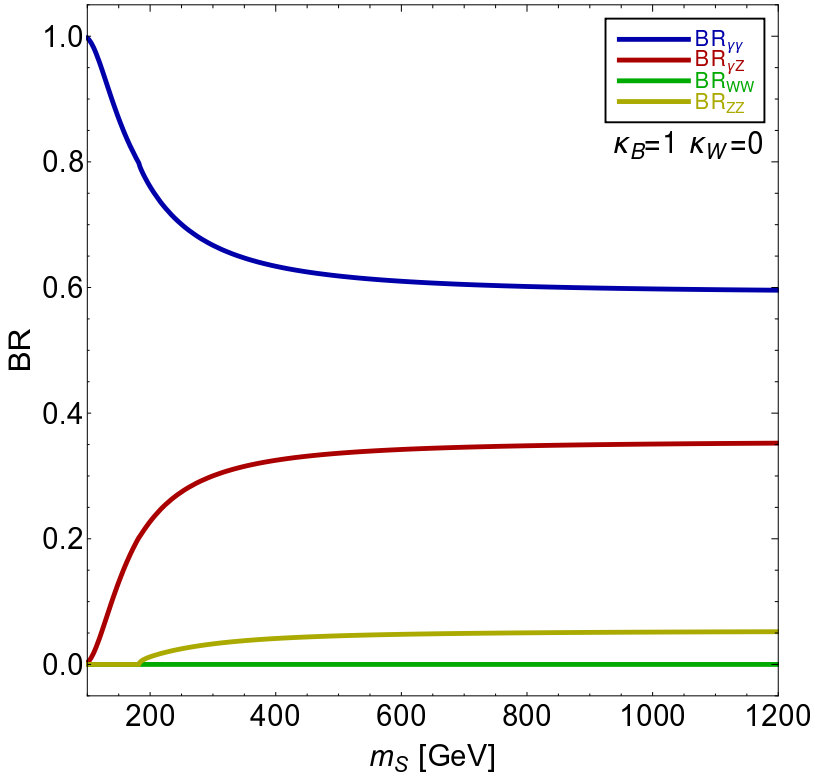
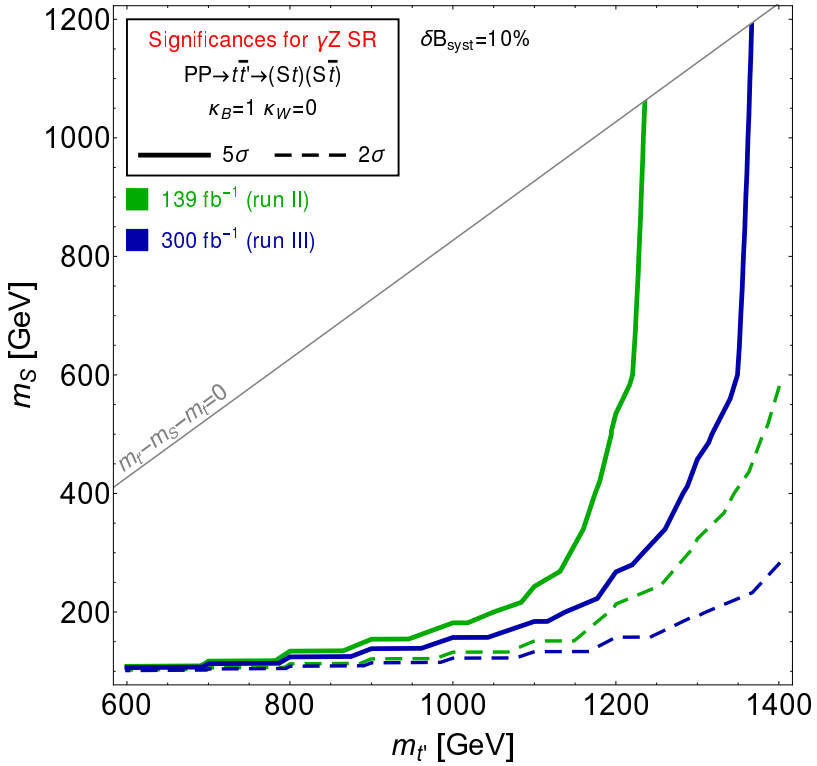


Expected reach (preliminary results)

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

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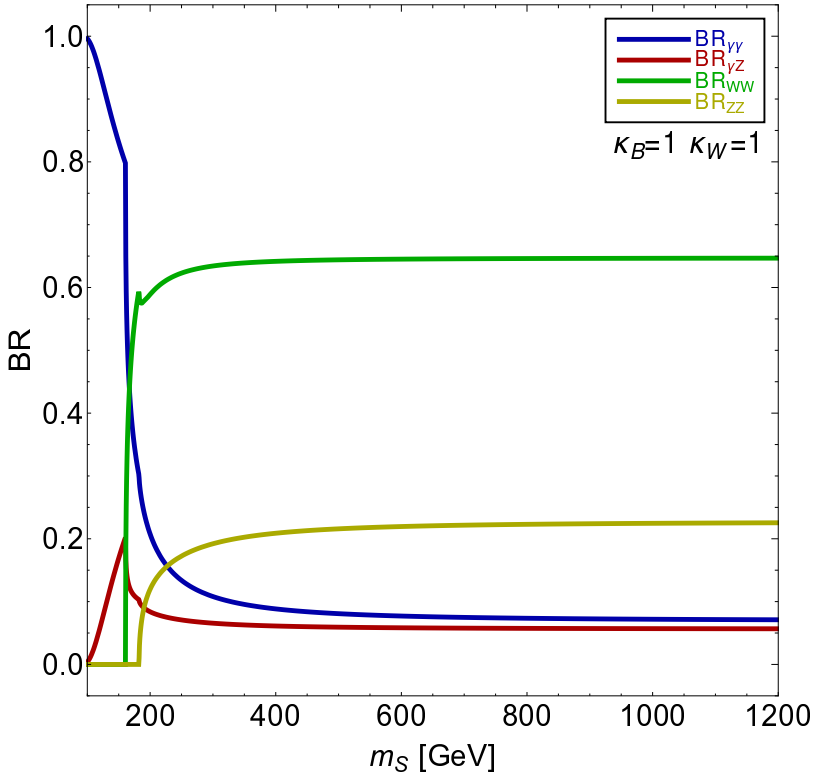
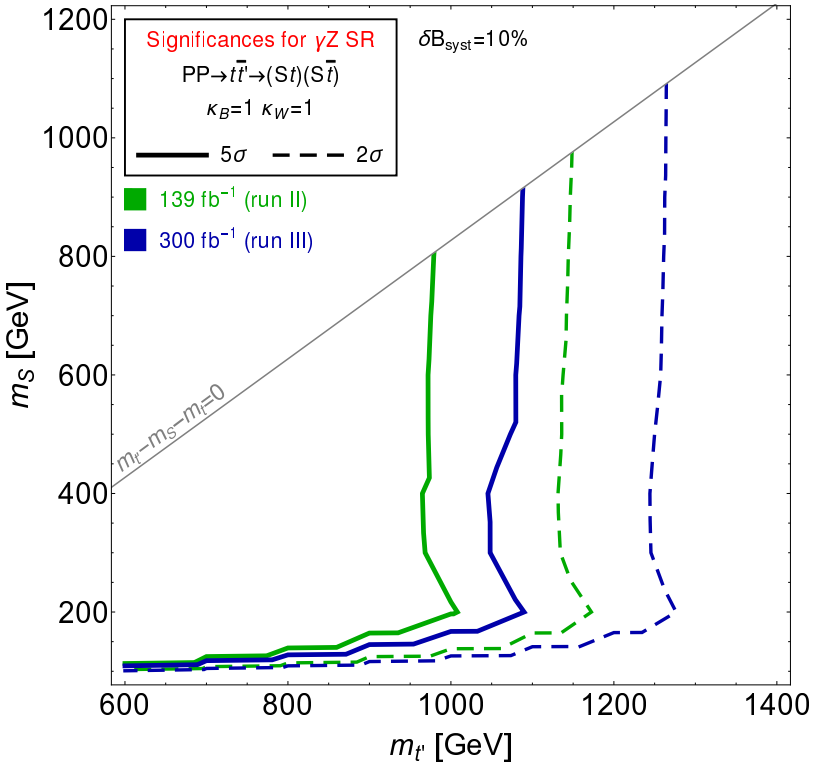
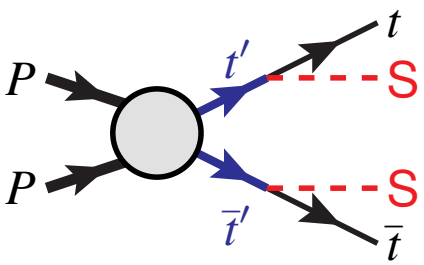


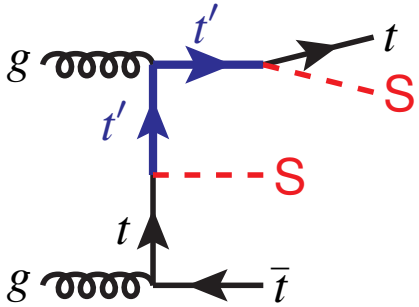


- Low m_S: suppression of γZ channel, discovery reach and bounds are weak
- High m_S: BRs in both γZ and $\gamma\gamma$ are low, discovery reach and bounds not as strong as in the previous case

Range of validity of the analysis

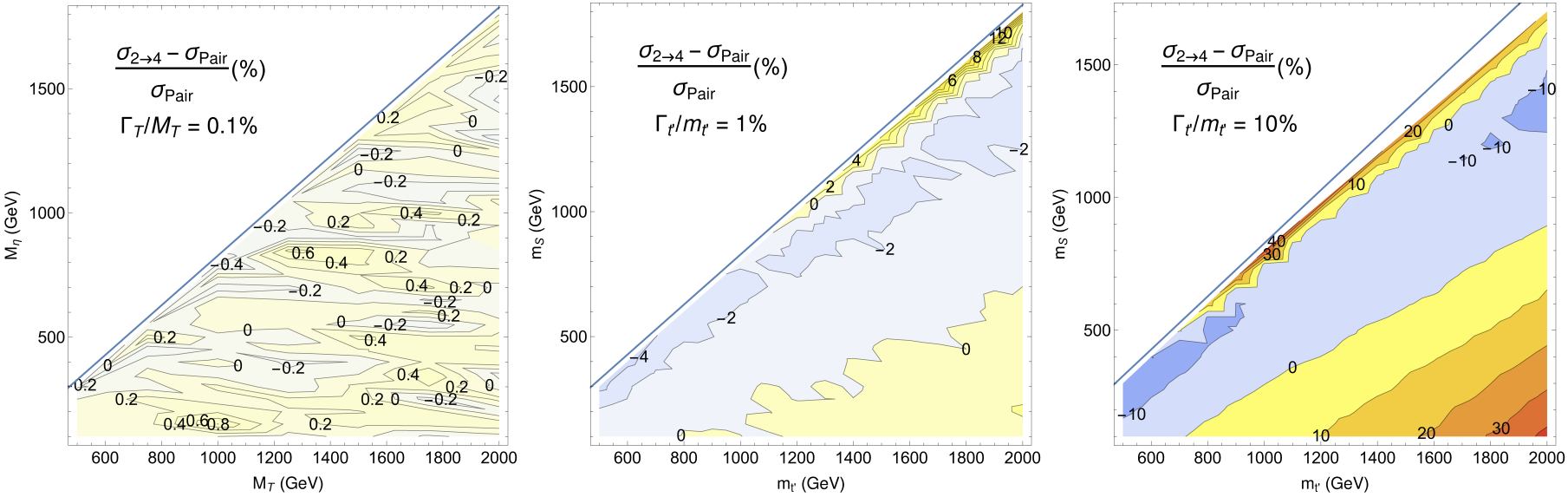
VLQ with finite width





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

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

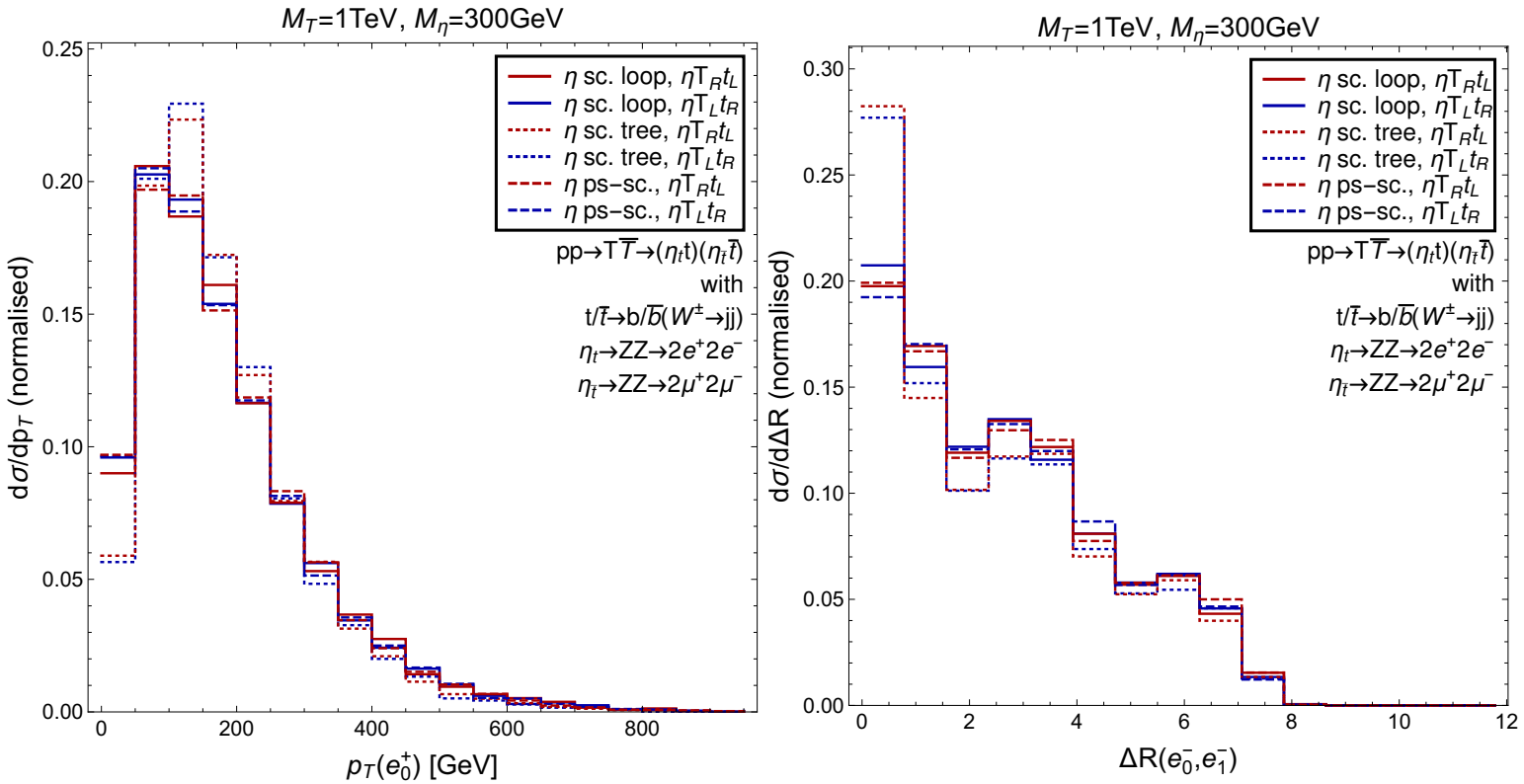


Range of validity of the analysis

Scalar vs Pseudoscalar (example with ZZ decay)

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

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



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

Conclusions

- New interesting channels for trying to **discover new physics** in extensions of the SM with **VLQs and new scalars**
- Exotic VLQ decays to neutral scalars are a promising channel which **should be experimentally tested**

Perspectives

- Determination of **discovery and exclusion reaches** at higher luminosities with current searches
- Development of **optimised search strategies**

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.

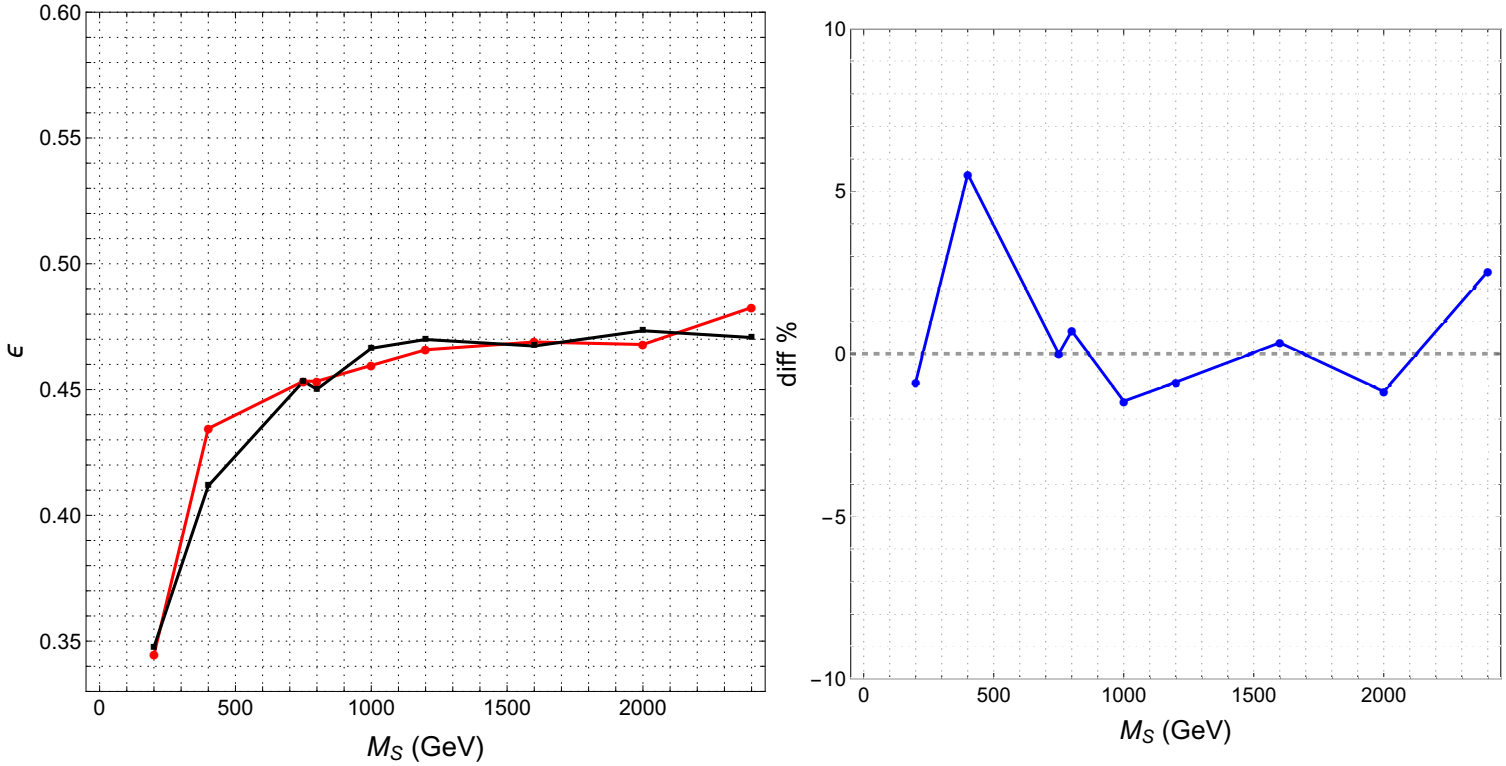
Compositeness and VLQ branch
ATLAS: E. Bergeås Kuutmann, V. Ellajosyula, M. Isacson, T. Mathisen
Theory: R. Benbrik, D. Buarque Franzosi, R. Enberg, G. Ferretti, Y. B. Liu, T. Mandal, S. Moretti, **L. Panizzi**

Backup

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