Composite Higgs and non-standard top partner decays

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Non Minimal Higgs
European Commission

The problem

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

What is this?

There's a mass scale μ^2 in the Higgs sector, it's the only mass in the SM, and moreover

$$\mu^2 \ll m_{\rm Pl}^2$$

Why is $-\mu^2 < 0$?

- Because then EW symmetry is broken

Why is EW symmetry broken?

- Because $-\mu^2 < 0$.

Composite Higgs: dynamical mechanism for EWSB

[See talk by Stefania De Curtis for details!]

Strongly interacting sector; broken global symmetry
$G \rightarrow H$ where H contains the SM symmetry G_{SM}

- No fundamental scalars needed
- The low Higgs mass is naturally explained: pseudo-Nambu-Goldstone boson (pNGB) of broken symmetry
- New sectors of composite particles
  - ✓ Higgs and other scalars: **pNGBs**
  - ✓ Partners of SM fermions: **vectorlike quarks (VLQs)**
  - ✓ Vectors, scalar resonances …

Additional scalars

When the new symmetry is broken, **G → H**, there are Nambu-Goldstone bosons: one per broken generator

No. of pNGBs = dim of coset manifold **G/H**

When (subgroup of) **H** is gauged, turn into ***pseudo***-NGB

We want **H** to contain $SU(2)_L \times SU(2)_R \sim SO(4)$ **[custodial]**

Examples:

- **Minimal Composite Higgs**: SO(5) / SO(4): 10−6 = 4
  4 goldstones = components of SM Higgs doublet
- **Composite 2HDM**: SO(6) / [SO(4)×SO(2)]: 15−7 = 8
  8 goldstones = two Higgs doublets

Top partners

- In particular the top has vectorlike top partners T
- Partial compositeness:
  - ✓ Top partners mix with the top quark
  - ✓ Top quark gets mass from mixing
- After mixing, there are additional heavy top quarks
- Couplings are model-dependent
- Generically, can also have bottom partners B and "exotic VLQs" X,Y,S,…, charges +5/3, −4/3, +8/3,…
- LHC top partner bounds so far only considering SM decays $T \rightarrow tZ, bW^+, th_{SM}$

Simplified model

We consider a simplified model that can encompass various interesting models, for example:

- **SU(4)/Sp(4) model with partial compositeness**
  E.g. Gripaios et al, Barnard et al, Ferretti et al, Cacciapaglia et al, Bizot et al. [Talk by T. Flacke]
- **The composite 2HDM**
  Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer; De Curtis, Delle Rose, Moretti, Yagyu [Talk by S. De Curtis]
- **2HDM with VLQs**
  Aguilar-Saavedra, Benbrik, Heinemeyer, Pérez-Victoria; Arhrib, Benbrik, King, Manaut, Moretti, Un [Talk by J. Song]

Simplified model Lagrangian

Scalar ϕ or pseudoscalar η interactions with gauge bosons and SM fermions, schematically

$$\mathcal{L}_S = \eta \sum_V \frac{\kappa_V^\eta}{v} V_{\mu\nu}^a \widetilde{V}^{a\mu\nu} + \phi \sum_V \left(\kappa_V^\phi v V_\mu^a V^{a\mu} + \frac{\kappa_{V_2}^\phi}{v} V_{\mu\nu}^a V^{a\mu\nu} \right)$$

$$+ \sum_f m_f \left(\kappa_f^\phi \, \bar{\psi}\psi \, \phi + i\kappa_f^\eta \, \bar{\psi}\gamma_5\psi \, \eta \right)$$

Interactions with VLQs given by Yukawa couplings with $t_{1L}, t_{1R}, t_{2L}, t_{2R}$

This Lagrangian can encompass the models mentioned

SU(4)/Sp(4) = SO(6)/SO(5)

Symmetry breaking: SU(4)~SO(6) → Sp(4)~SO(5)

5 pNGBs: fit in *bidoublet* and *singlet* of $SU(2)_L \times SU(2)_R$ (custodial symmetry) in a **5** rep of Sp(4):

$$\mathcal{H} \oplus \eta \equiv \begin{pmatrix} H^{0*} & H^{+} \\ -H^{+*} & H^{0} \end{pmatrix} \oplus \eta \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) = \mathbf{5}$$

There are also **5 VLQs**: three top partners, one bottom partner and one exotic X with charge 5/3:

$$\Psi \equiv \begin{pmatrix} T & X \\ B & T' \end{pmatrix} \oplus \tilde{T} \in (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) = \mathbf{5}$$

Lightest VLQ, degenerate with X

SU(4)/Sp(4)

No diagonal couplings of the scalars to the VLQs:

$$\mathcal{L}_{t_2 S} = \kappa_S^L\ \bar{t}_{2L} t_{1R} \phi + \kappa_S^R\ \bar{t}_{1L} t_{2R} \phi + \kappa_S^L\ \bar{t}_{2L} t_{1R} \eta + \kappa_S^R\ \bar{t}_{1L} t_{2R} \eta + \text{h.c.}$$

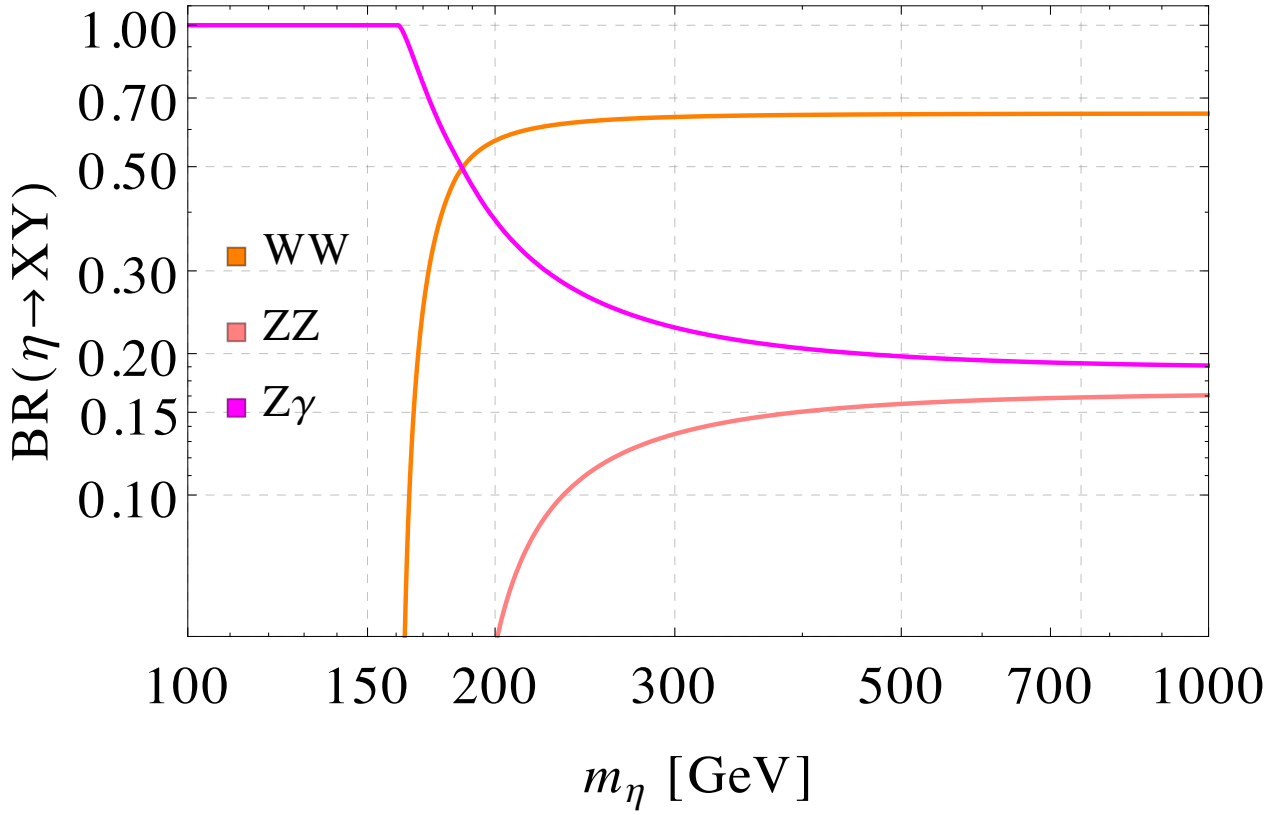
Couplings of η to gauge bosons from dim-5 operators from the anomaly have no γγ or gg couplings:

$$\mathcal{L}_{\eta VV} = \frac{A \cos\theta}{16\pi^2 f}\, \eta \left(\frac{g^2 - g'^2}{2} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + g g' F_{\mu\nu} \tilde{Z}^{\mu\nu} + g^2 W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right)$$

→ No γγ or gg decay/production from dim-5 or loops

SU(4)/Sp(4)

BR(η) where η = singlet pseudoscalar



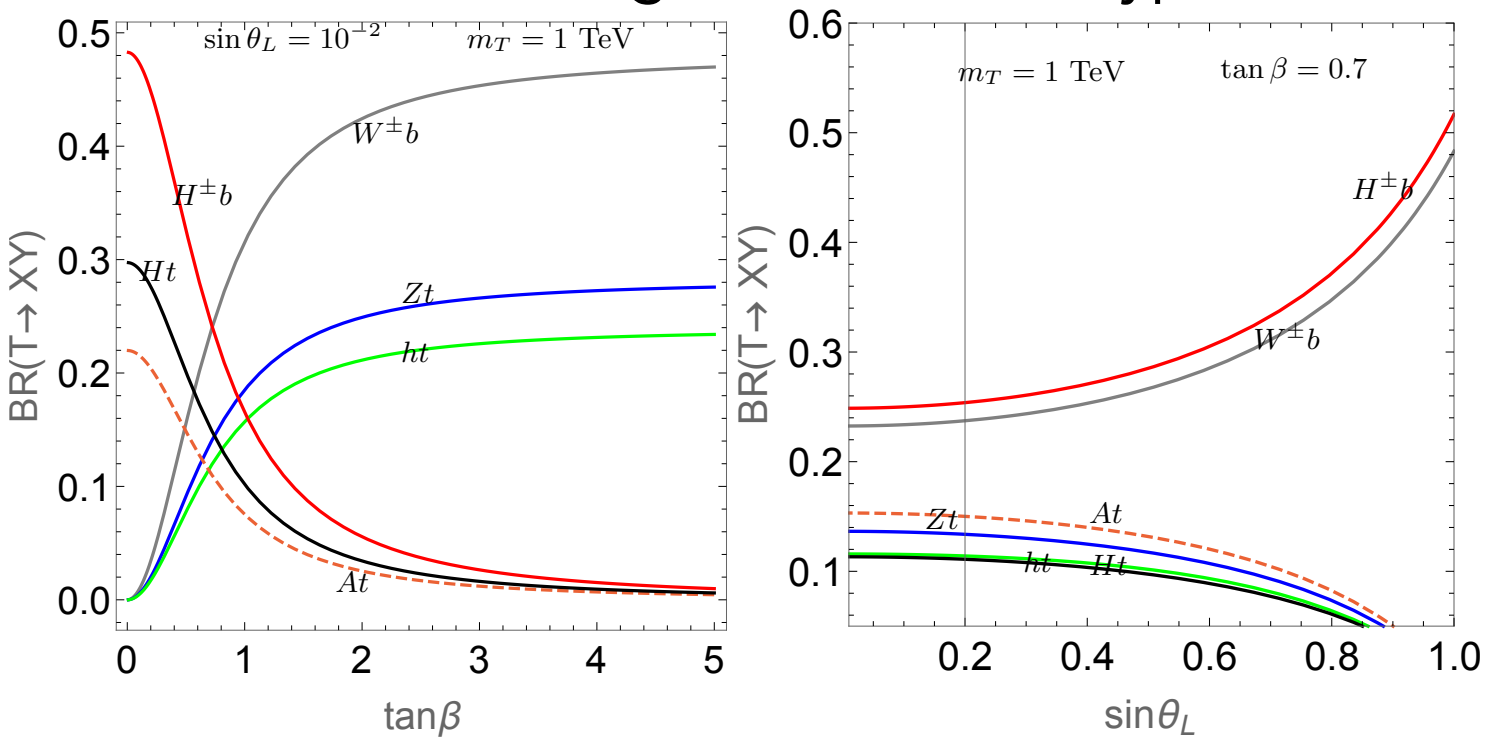
Plot from Bizot, Cacciapaglia, Flacke, 1803.00021

2HDM + VLQ

Minimal fundamental Higgs model with these decays: **T → tA, tH**

Arhrib et al, 1607.08517, add a singlet T to 2HDM type II

Example BR:



We are investigating singlet, doublet, triplet VLQs in 2HDM, [Arhrib, Benbrik, RE, Manaut, Moretti, Panizzi, Rouchad, Taj]

ATLAS studies

Non-standard decays of VLQ; pair production

$$pp \to T\bar{T}$$

where T is the lightest top partner and we consider scalars or pseudoscalars S of the model

Assume $T \to tS \quad \text{with} \quad S = \eta \text{ or } \phi$

and scalar decays $S \to \gamma\gamma,\ \gamma Z,\ W^+W^-$

Simulate everything using MG5, Pythia, Delphes (developed Delphes card to mimic ATLAS conditions)

Bounds on T

Current LHC bounds only consider SM decay channels:
We need to establish bounds from existing data on our decay channels: do a ***recasting*** of published analyses

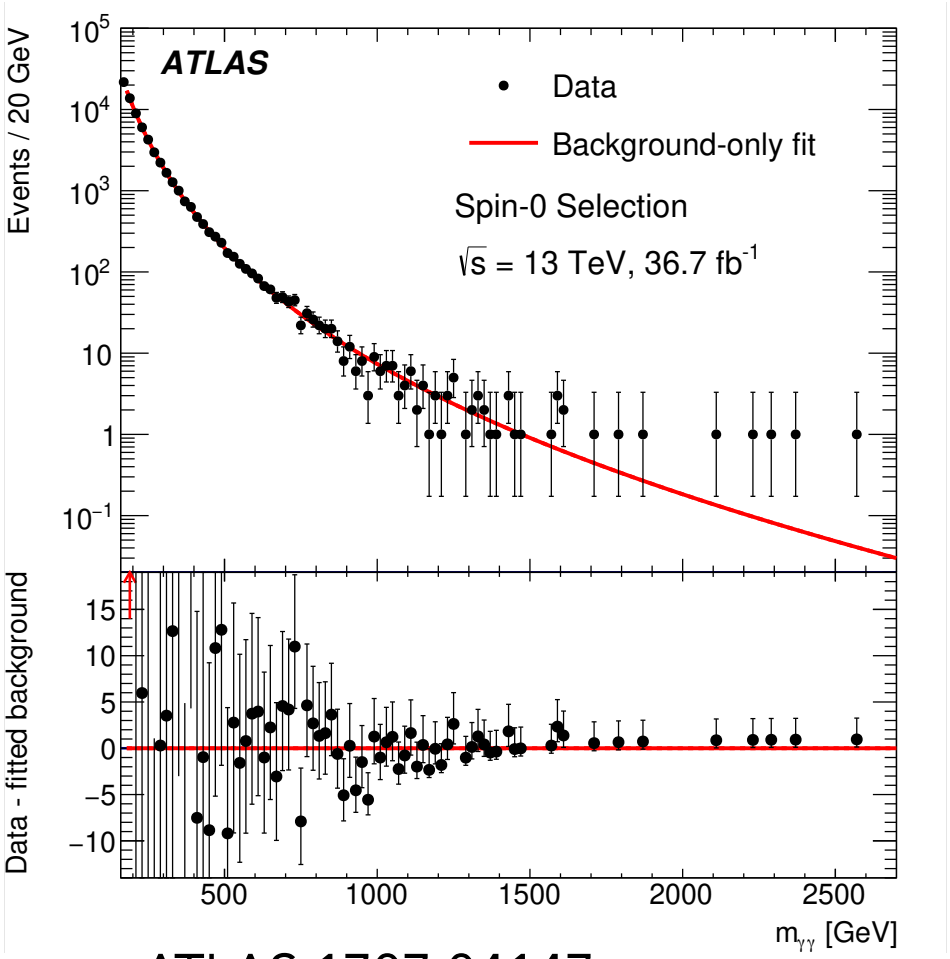
For example: We recast the following ATLAS searches:

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"

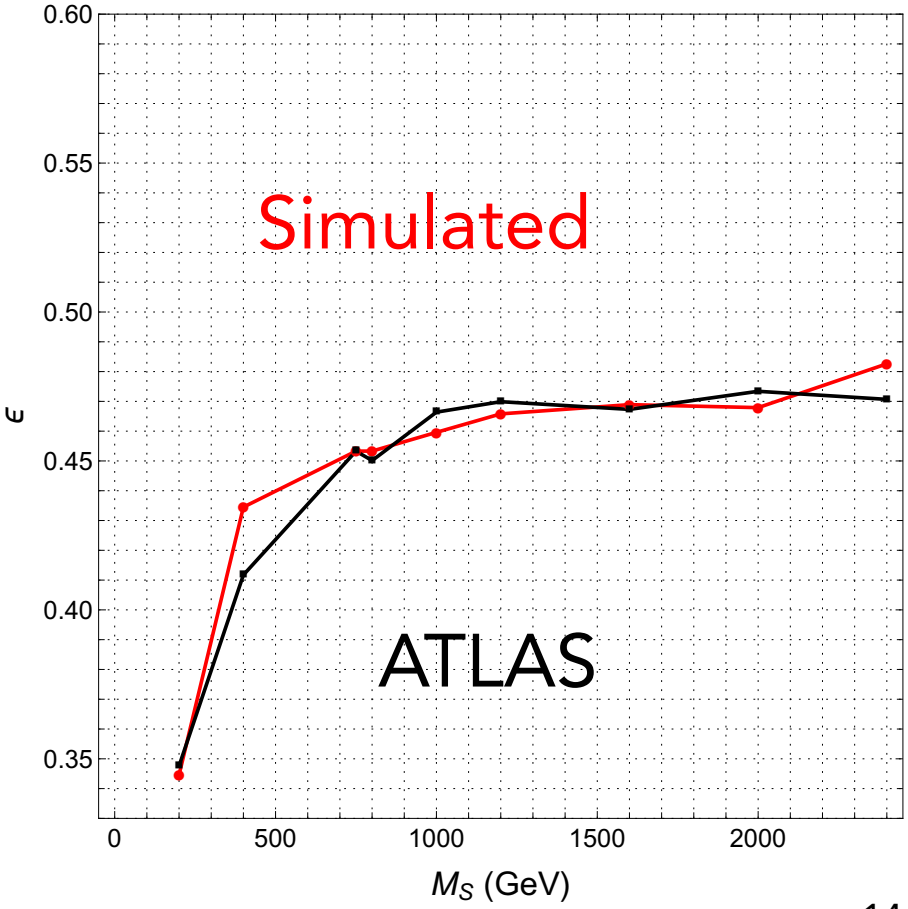
ATLAS 1807.11883: "Search for new phenomena in events with **same-charge leptons and b-jets** in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector"

Recasting

Simulate using Delphes, mimic ATLAS conditions.
E.g.: the γγ analysis. Right plot: validate expt acceptance



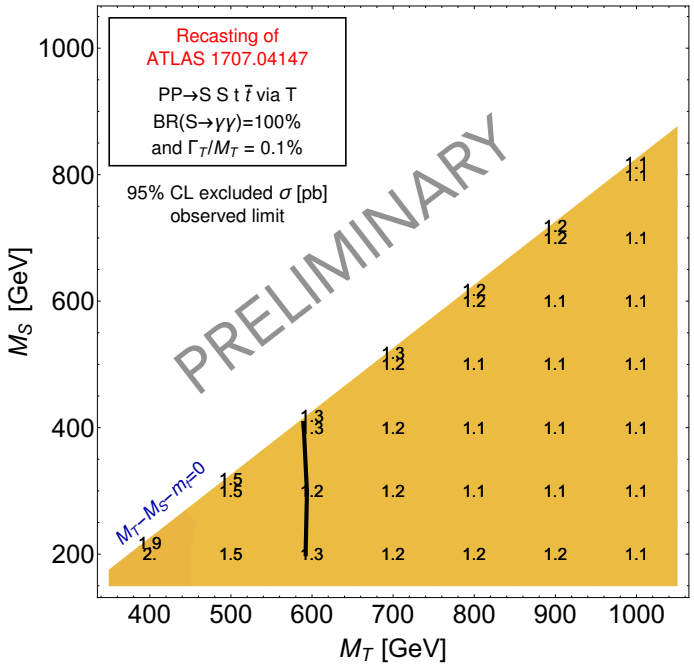
ATLAS 1707.04147



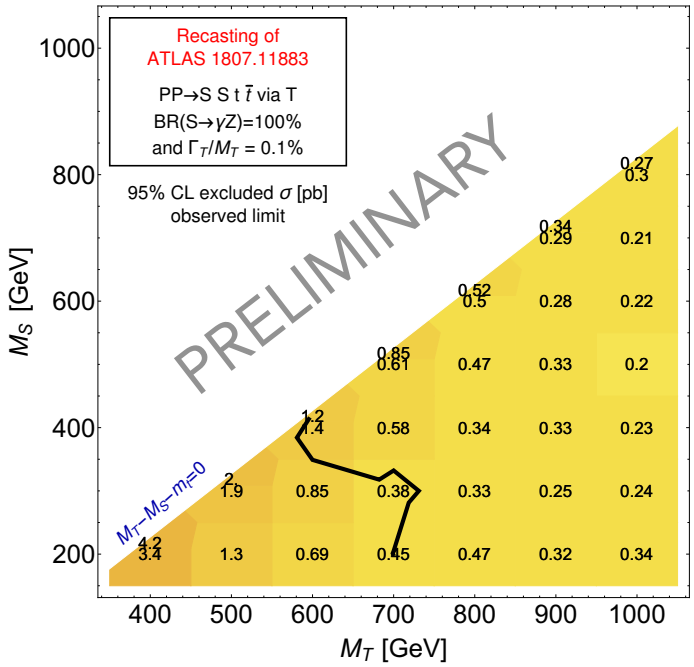
Combined bounds

$$pp \to T\bar{T} \text{ with } T \to tS$$

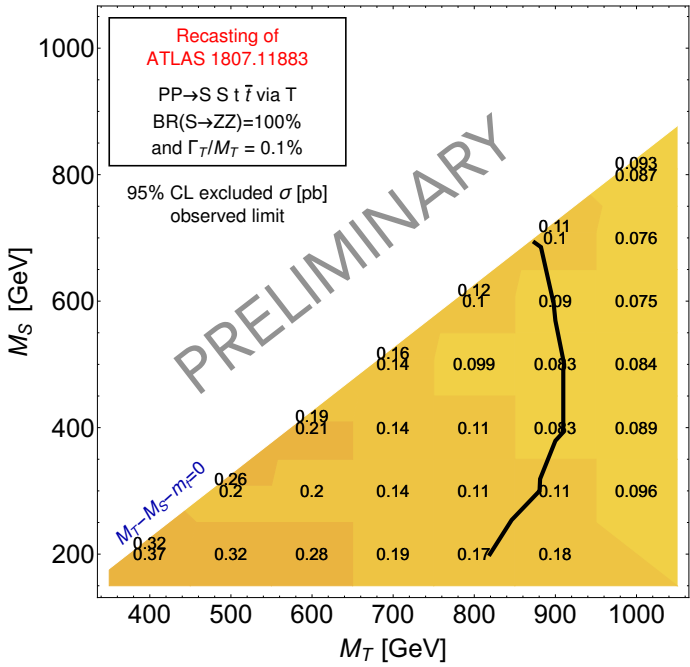
$S \to \gamma\gamma$



$S \to Z\gamma$



$S \to ZZ$



$M_T > 600$ GeV

$M_T > 600$-700 GeV

$M_T > 800$-900 GeV

Also using HiggsBounds to check bounds on scalars from Higgs searches

Can we test scalar/pseudoscalar?

$$pp \to T\bar{T} \to tS\bar{t}S$$

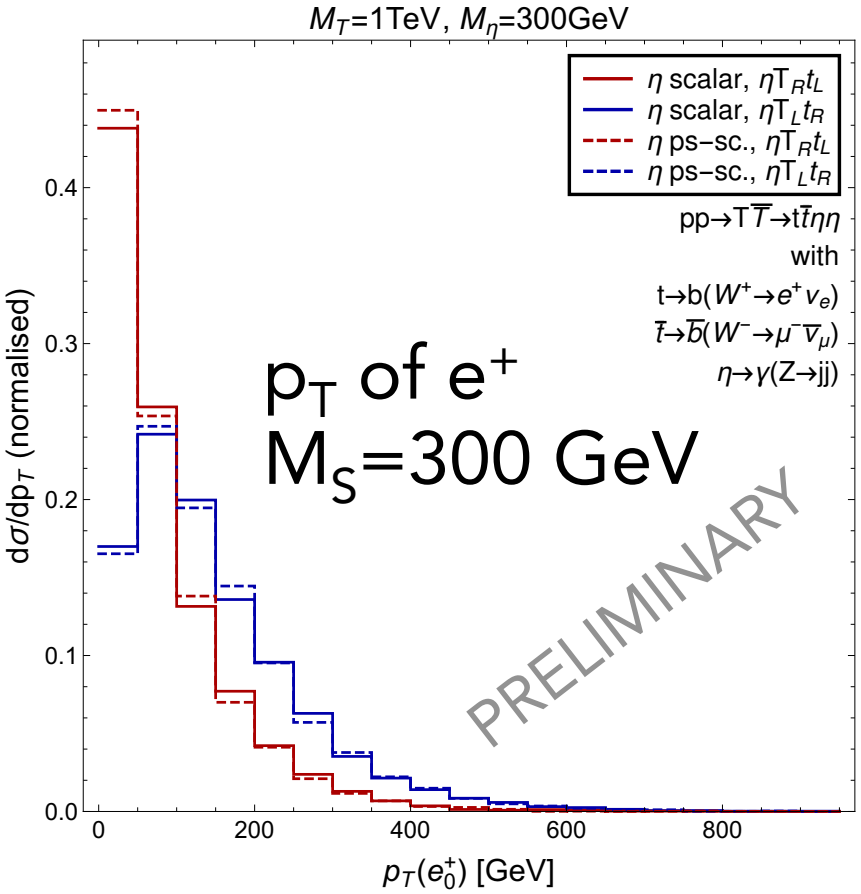
$$S = \eta \text{ or } \phi$$

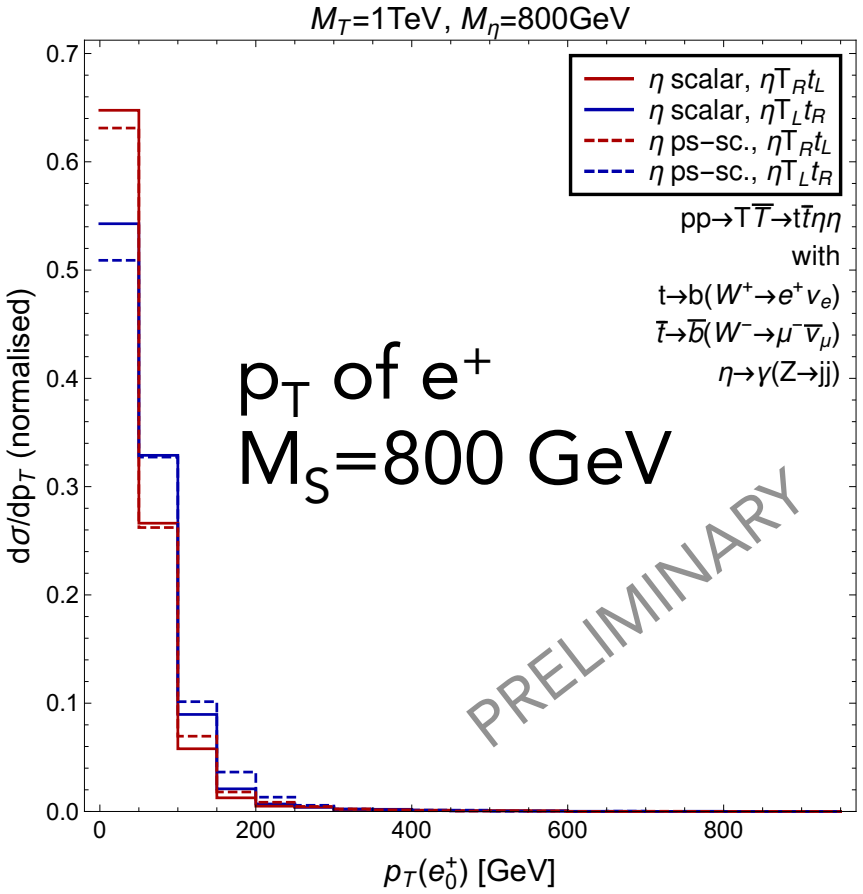
with

$$t \to W^+ b \to e^+ \nu b$$

$$\bar{t} \to W^- \bar{b} \to \mu^- \bar{\nu} \bar{b}$$

$$S \to \gamma Z \to \gamma jj$$





(Distributions in η and ΔR do not show any difference)

LHC searches

Theory study of the sensitivity of LHC experiments to searches with pair production and T decay as above and

$$S \to \gamma\gamma \text{ or } Z\gamma$$

Diphoton + jets in first case
Photon(s) + dileptons + jets in second case

- Phenomenology paper on these searches
  [Will be arXiv:190x.yyyyy]

Summary

- Top quark important to understand for Higgs physics
- Models for composite Higgs with dynamical EWSB typically have vectorlike top partners
- Existing bounds only consider SM decays (minimal)
- We are considering non-minimal models with decays to new scalars and LHC phenomenology
- Results to appear very soon