New insights on top-philic resonances with four top quarks

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Motivation

New window to New Physics offered by the observation of $t\bar{t}t\bar{t}$ in ATLAS and CMS with events containing 4 leptons, 3 leptons or 2 same-sign leptons. Experiments have already probed [1710.10614] [1807.1823] [1908.06463] [2305.13439]

- SM top Yukawa coupling and EFT,
  $gg \to t\bar{t}t\bar{t} \quad \& \quad gg \to t\bar{t}h,\ h \to t\bar{t}$
- (pseudo)scalars in 2HDM,
  $gg \to t\bar{t}H/A,\ H/A \to t\bar{t}$
- dark matter models.
  $gg \to t\bar{t}\phi/Z',\ \phi/Z' \to t\bar{t}$

Developments in jet top-taggers from Run 1 and 2 in CMS and ATLAS

[CMS-PAS-JME-13-007] [ATL-PHYS-PUB-2015-053] [ATL-PHYS-PUB-2022-039]

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Developments in jet top-taggers from Run 1 and 2 in CMS and ATLAS [CMS-PAS-JME-13-007] [ATL-PHYS-PUB-2015-053] [ATL-PHYS-PUB-2022-039]

Open questions :

1. Is it possible to investigate hadronic tops t_h in $t\bar{t}t\bar{t}$?
2. Is it possible to reconstruct the resonance ?
3. How do the limits of the parameter space improve ?

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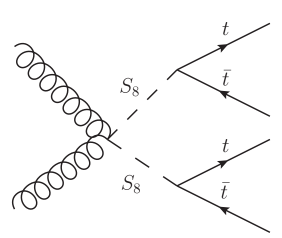
Theoretical framework

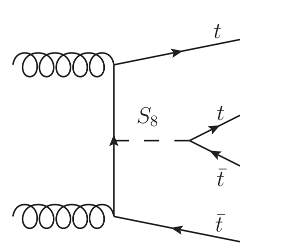
Extra scalars

Top-philic particles :

- octet scalar S_8

$$L_{S_8} = \frac{1}{2} D_\mu S_8^A D^\mu S_8^A - \frac{1}{2} m_{S_8}^2 S_8^A S_8^A + y_{8S} \bar{t} T^A S_8^A\, t$$





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- singlet scalar S_1

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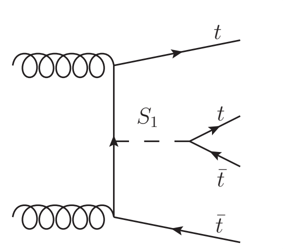

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Parameter space defined by two parameters : the mass of the scalar m_X and the coupling to top quarks y_X.

We illustrate our strategy with two benchmark points of the scalar octet:

- pure-pair dominated : $m_{S_8} = 1.3\,\text{TeV}$ with $y_{S_8} = 0.25$ (BP1),
- mixed production: $m_{S_8} = 2.0\,\text{TeV}$ with $y_{S_8} = 1.00$ (BP2).

Simulation samples

Backgrounds considered in this analysis :

- $t\bar{t}jj$
- $t\bar{t}Wj$
- $t\bar{t}Zj$
- $t\bar{t}t\bar{t}$

$\rightarrow$ $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}t$ have also been taken into account but are very small.

In practice, we have considered only the $t\bar{t}t\bar{t}$ at NLO while the signal and the other backgrounds are generated at LO.

Simulated samples are generated with MadGraph5_aMC@NLO, Pythia 8 and MadAnalysis 5 with FastJet.

Characterisation of the boosted four-top system

How well can we reconstruct the tops ?

First, we establish the building blocks to reconstruct the tops :

- Leptons : either isolated electrons or muons,
- Jets ($\equiv$ AK4 jets) : anti-k_t algorithm with p_T >20 GeV & $|\eta|$ <2.5,
- Large-R jets ($\equiv$ AK10 jets) : anti-k_t algorithm with p_T >350 GeV, m >40 GeV & $|\eta|$ <2.0.

Then, we tag the jets

- B-tagging of AK4 jets : Constant 77% efficiency, [ATL-PHYS-PUB-2016-012]
- Top-tagging of AK10 jets : [ATL-PHYS-PUB-2022-039]
  1. check if parton level top within cone of $\Delta R = 0.75$ of AK10 jet,
  2. check if b-hadron inside AK10 jet,
  3. consider a constant tagging rate of 80%,
  4. otherwise p_T-dependent false top-tagging rate of $\sim$ 5% (10%) in an optimistic (pessimistic) case.

Neutrinos and Leptonic Tops

For 1 top quark decaying leptonically t_l, we need to

1. reconstruct ν from $E_{miss,T}$ by assuming on-shell W boson,
2. solution p_ν^z giving a reconstructed top mass closest to pole mass is chosen,
3. have an isolated lepton,
4. find a b-tagged AK4 jet which does not overlap with an AK10 jet.

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For 2 top quarks decaying leptonically, we need to

1. minimize the maximum of the two transverse masses of the reconstructed W bosons (m_{T2} of the di-leptonic system),
2. smallest p_ν^z is chosen,
3. have two isolated leptons,
4. find two b-tagged AK4 jets which does not overlap with an AK10 jet,
5. pairing giving a reconstructed top mass closest to pole mass is chosen.

Signal Regions

We target the fully hadronic $t_h t_h t_h t_h$, the leptonic $t_h t_h t_h t_l$ and part of double leptonic $t_h t_h t_l t_l$ decay channels ($\approx 2/3$ of $t\bar{t}t\bar{t}$).

Signal Regions :

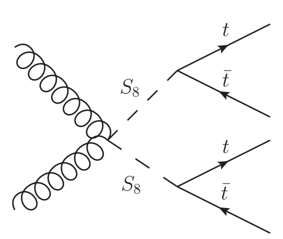
Decay Channels	$t_h t_h t_h t_h$	$t_h t_h t_h t_l$	$t_h t_h t_l t_l$
SR1	4/4	3/3	2/2
SR2	3/4	2/3	1/2
SSL	//	//	$\geq$1/2

Number of top-tagged AK10 jets/Number of AK10 jets in each signal regions of the decay channels.

Pairing Algorithm

Pairing Algorithm :

1. Compute $m_{\bar{t}t}$ from all possible pairs of tops,
2. Select the two pairs with smallest $m_{\bar{t}t}$ difference,
3. If difference is below a limit, keep the two pairs $\equiv pp \to XX$,



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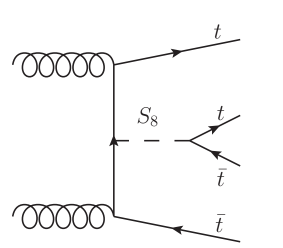
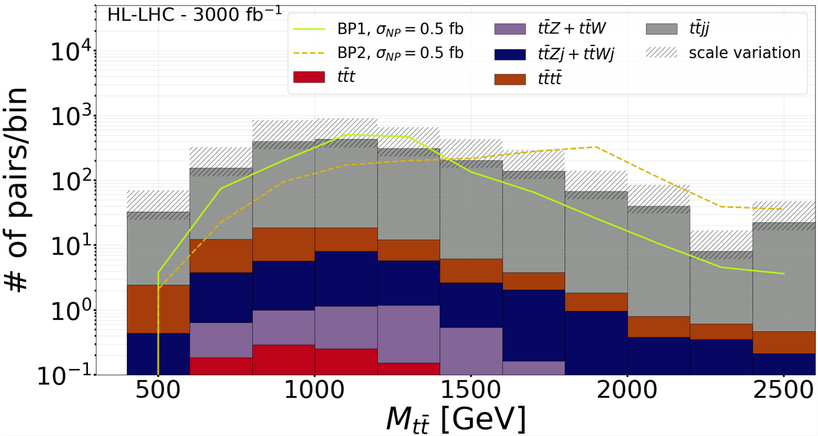
4. Otherwise, take the pair with largest opening angle $\equiv pp \rightarrow t_1 \bar{t}_2 X$.

$$\theta = \arccos\left(\frac{\vec{p}_1.\vec{p}_2}{\|\vec{p}_1\|\|\vec{p}_2\|}\right)$$



Invariant mass of top-pair

- pure-pair dominated : $m_{S_8} = 1.3\,\text{TeV}$ with $y_{S_8} = 0.25$ (BP1)
- mixed production: $m_{S_8} = 2.0\,\text{TeV}$ with $y_{S_8} = 1.00$ (BP2)



Results and Projections

Limits on Cross Section

Upper limits in fb on the BP1 and BP2 production cross sections for the decided signal regions, with optimistic and pessimistic top-tagging and for luminosities of 400 and 3000 fb^{-1}, obtained by pyhf.

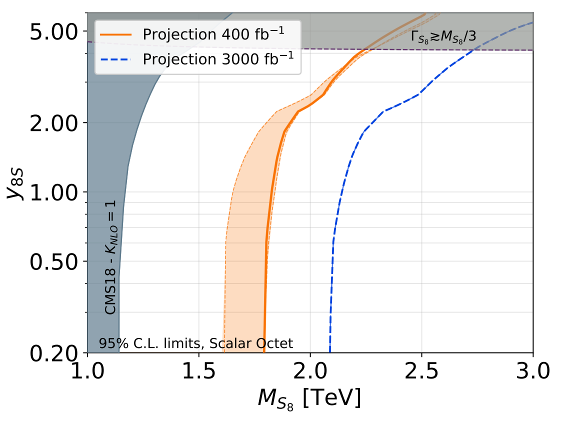
[10.5281/zenodo.1169739] [Journal of Open Source Software, 6(58), 2823]

	BP1				BP2			
Top-Tag	Optimistic		Pessimistic		Optimistic		Pessimistic	
$\mathcal{L}$ [fb^{-1}]	400	3000	400	3000	400	3000	400	3000
SR1	1.35	0.64	1.60	0.76	0.74	0.25	0.82	0.29
SR2	0.52	0.16	0.71	0.30	0.48	0.11	0.49	0.13
SSL	0.97	0.25	0.96	0.25	1.20	0.28	1.20	0.27

Limits on S_8 Parameter Space

We compare our preliminary limits for the octet scalar to the CMS analysis recasted in [2104.09512]:

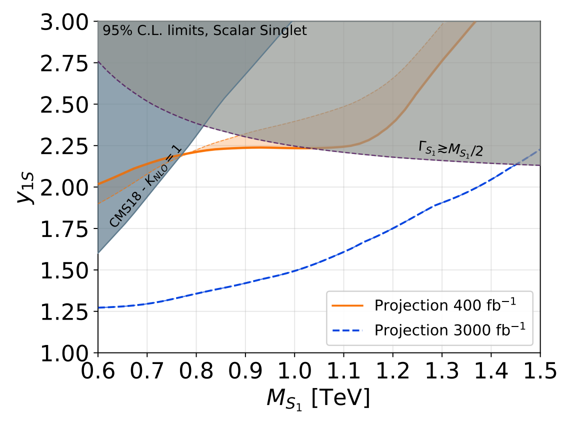
[2404.xxxxx]



Baseline is SR2 pessimistic, conservative is SSL pessimistic and best is SR2 optimistic.

Limits on S_1 Parameter Space

We compare our preliminary limits for the singlet scalar to the CMS analysis recasted in [2104.09512] (no SSL). [2404.xxxxx]



Conservative is SR2 pessimistic and best is SR2 optimistic.

Conclusion

Conclusion

1. Is it possible to investigate hadronic tops t_h ?
   Yes, jet top-taggers have improved a lot and are able to provide proxies for hadronically-decaying top quarks with AK10 jets.
2. Is it possible to reconstruct the resonance ?
   Yes, we look at the smallest difference in invariant masses for pair production and the largest opening angle for associated production.
3. How do the limits of the parameter space improve ?
   - In Run 3, limits on m_{S_8} are pushed to $\sim$1.6(1.8) TeV for a pessimistic(optimistic) mistagging rate. In HL-LHC, up to 2.4 TeV.
   - In Run 3, sensitivity across values of m_{S_1} and [2.00, 2.25] for y_{S_1} but limited by the width. Promising improvements at HL-LHC up to [1.25, 2.00].

Backgrounds

Process	σ(LO)	Scale	PDF	σ(NLO)	Scale	PDF
$t\bar{t}jj$	354.143	$^{+62.1\%}_{-35.6\%}$	$\pm$ 5.84%	352.7	$^{+3.7\%}_{-13.2\%}$	$\pm$ 2.6%
$t\bar{t}W$	0.3760	$^{+22.8\%}_{-17.2\%}$	$\pm$ 3.92%	0.5654	$^{+8.3\%}_{-8.3\%}$	$\pm$ 1.8%
$t\bar{t}Wj$	0.3290	$^{+39.3\%}_{-26.3\%}$	$\pm$ 2.1%	0.4515	$^{+8.1\%}_{-11.6\%}$	$\pm$ 1.2%
$t\bar{t}Z$	0.5631	$^{+31.4\%}_{-22.2\%}$	$\pm$ 4.84%	0.7562	$^{+9.2\%}_{-10.7\%}$	$\pm$ 2.1%
$t\bar{t}Zj$	0.6392	$^{+46.9\%}_{-29.8\%}$	$\pm$ 6.53%	0.6718	$^{+2.6\%}_{-9\%}$	$\pm$ 2.5%
$t\bar{t}t\bar{t}$	0.0061	$^{+65.1\%}_{-37.1\%}$	$\pm$ 13.4%	0.0092	$^{+27.7\%}_{-24.1\%}$	$\pm$ 6.0%
$t\bar{t}\overset{(-)}{t}$	0.0009	$^{+35.4\%}_{-25.3\%}$	$\pm$ 15.6%	Still	computing	...

Cross sections of the backgrounds considered in this analysis at LO and NLO in QCD. The center-of-mass energy is set at 13 TeV and we display the scale variations for the specific choice of the dynamical scheme relying on the variable $H_T/2$. The PDF set used is NNPDF2.3NLO. When a jet appears in the final state, a cut $p_T(j) > 20$ GeV is applied. Values are expressed in pb.

Isolated Leptons

Electrons :

- $p_T > 20$ GeV,
- $|\eta| < 2.74$,
- the ratio of the sum of the p_T of tracks within a cone of $\Delta R = \min(0.2, 10\ \mathrm{GeV}/p_T(e))$ excluding the p_T of the lepton should be smaller than 0.06.

Muons :

- $p_T > 20$ GeV,
- $|\eta| < 2.5$,
- the ratio of the sum of the p_T of tracks within a cone of $\Delta R = \min(0.3, 10\ \mathrm{GeV}/p_T(\mu))$ excluding the p_T of the lepton should be smaller than 0.04 for muons.

Elements removal

Trimming of the jets is performed with the Soft-Drop algorithm. [1402.2657]

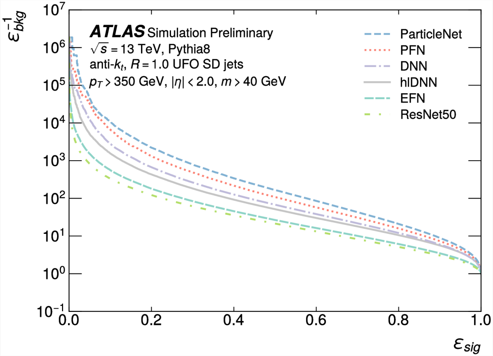
Procedure: [2007.14858]

1. Remove AK4 jets within $\Delta R = 0.2$ of an electron,
2. Remove electrons within $\Delta R = 0.4$ of an AK4 jet,
3. Remove AK4 jets within $\Delta R = 0.2$ of a muon if more than 3 tracks,
4. Remove muons within $\Delta R = 0.04 + 10/p_T(\mu)$ of an AK4 jet,
5. Remove electrons within $\Delta R = 0.1$ of a muon.

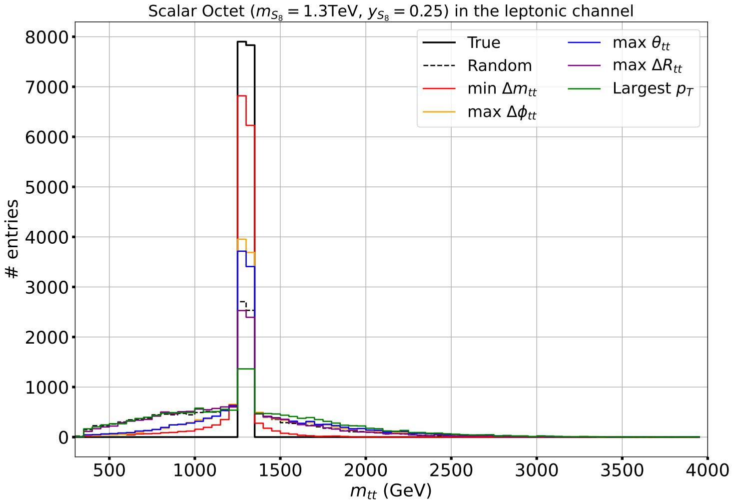
Tagging

For the b-tagging, we aim to replicate the efficiency of the MC2c10 multivariate algorithm giving p_T-dependent tagging and mis-tagging rates. We use the working point associated with a 77% tagging efficiency and the mis-tagging rate for c-jet, τ-jet and light jet are 16.7%, 4.5% and 0.75% respectively. [ATL-PHYS-PUB-2016-012]

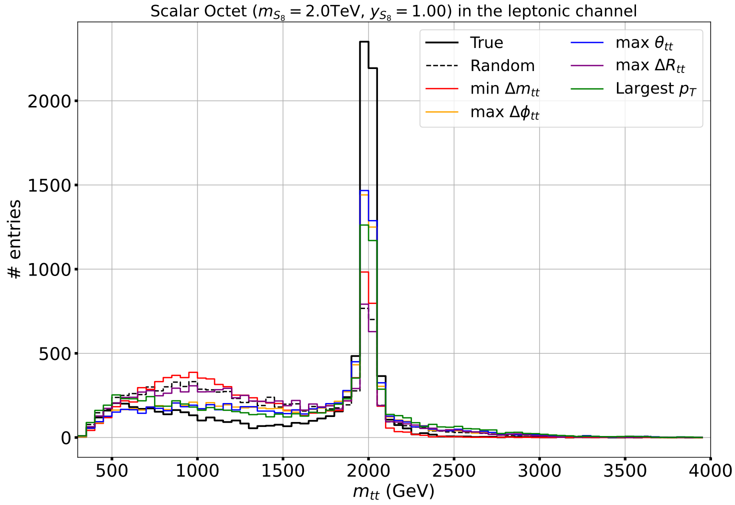
For top-tagging : Figure 7 in [ATL-PHYS-PUB-2022-039]



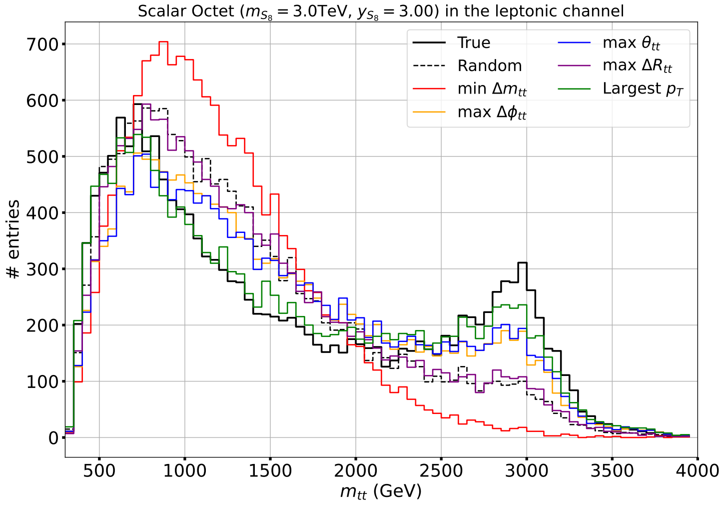
Pariring Observables : BP1



Pariring Observables : BP2



Pariring Observables : BP3



Pariring Observables : BP4