Probing Top-Philic Particles with Boosted Four Top Searches

李浩林
中山大学物理学院

重味物理与量子色动力学研讨会
南京 2025.04.21

Based on 2404.14482 with Luc Darme, Benjamin Fuks, Matteo Maltoni, Olivier Mattelaer, Julien Toucheque

- 2013-2018 Ph.D. University of Massachusetts Amherst
- 2018-2021 Postdoc, Institute of Theoretical Physics, CAS
- 2021-2024 Postdoc, University of Louvain, Center of Cosmology and Particle Physics Phenomenology (CP3)
- 2025-present Assistant Professor, Sen Yat-Sen University
- Developing the Young Tensor Method for EFT operator basis construction

  One of authors of package ABC4EFT

  (with Jiang-Hao Yu and Ming-Lei Xiao)

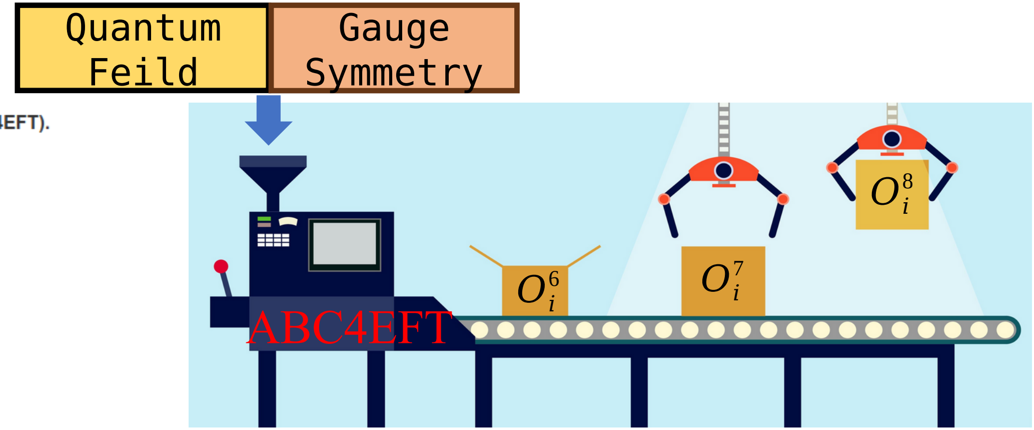
Welcome to the HEPForge Project: ABC4EFT

This is the website for the Mathematica package: Amplitude Basis Construction for Effective Field Theories (ABC4EFT).

Package

This package has the following features:

- It provides a general procedure to construct the independent and complete operator bases for generic Lorentz invariant effective field theory, given any kind of gauge symmetry and field content, up to any mass dimension.
- Various operator bases have been systematically constructed to emphasize different aspects: operator independence (y-basis), flavor relation (p-basis) and conserved quantum number (j-basis).
- It provides a systematic way to convert any operator into our on-shell amplitude basis and the basis conversion can be easily done.



[https://abc4eft.hepforge.org/]

New physics and top quark

- Largest couplings to Higgs

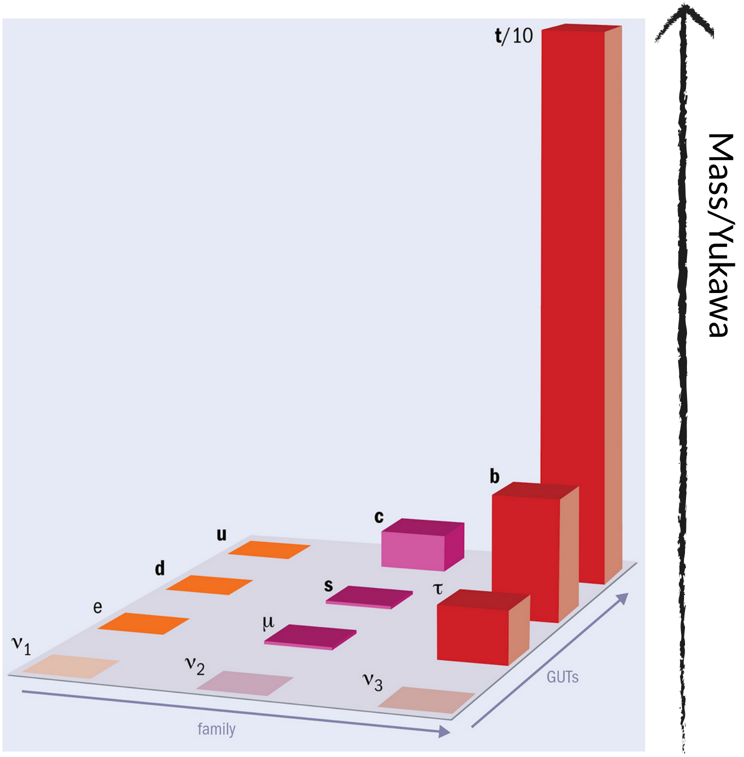
  – Sensitive to Models that modify the EWSB or solving the Hierarchy Problem e.g. Composite Higgs Model, SUSY, Extra Dimension…

  – Radiative correction to Higgs potential
  thus sensitive to vacuum stability

  – Top-philic Models – New particle preferentially couple to Top

- LHC is essentially a top factory

  Top copiously produced, enabling precision study.



Top-philic NP theories: the origin

- In this talk, Top-philic scalar particle X, $SU(3)$ octet and singlet $y_s \bar{t} t S$
  - Which decays mostly into a pair of top quarks $y_s \bar{t} T^a t S_8^a$
  - Production cannot rely on EW gauge boson or quarks in proton

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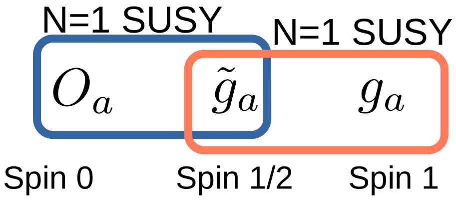
- Why would a New Physics (NP) boson prefers the top quarks

Because the quark mass enters into the coupling (e.g. SU(2) breaking required)

Extended SUSY (sgluon)

e.g. 2107.13565



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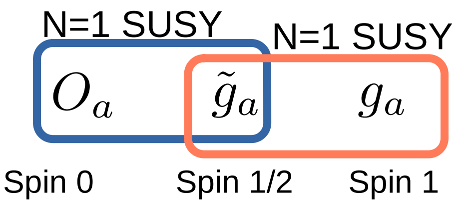
Because the top quark is made (partially) of NP

Partial top compositeness

e,g. 1507.02283, 1610.06591



Color coset	$SU(3)_c \times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{8}_0 + \mathbf{6}_{(-2/3 \text{ or } 4/3)} + \bar{\mathbf{6}}_{(2/3 \text{ or } -4/3)}$
$SU(6)/Sp(6)$	$\mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3}$
$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{8}_0$

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N=1 SUSY N=1 SUSY

O_a $\tilde{g}_a$ g_a

Spin 0 Spin 1/2 Spin 1

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$SU(3) \times SU(3)'/SU(3)_D$	$\mathbf{8}_0$

Because the NP helps in generating the top quark mass

Extended Higgs sectors

e.g. 2202.02333

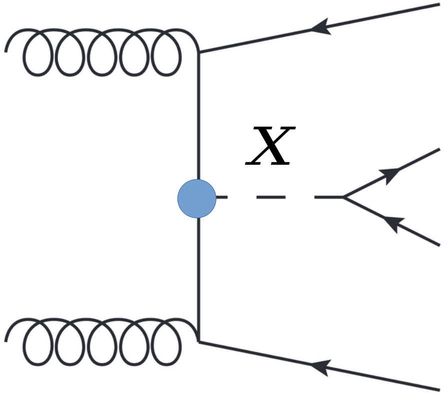
$$\mathcal{L}^{\rm 2HDM}_{\rm Yukawa} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A\right)$$

	Type I	Type II	Lepton-specific
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$

Heavy top-philic NP Production @LHC

Final state: 4 tops

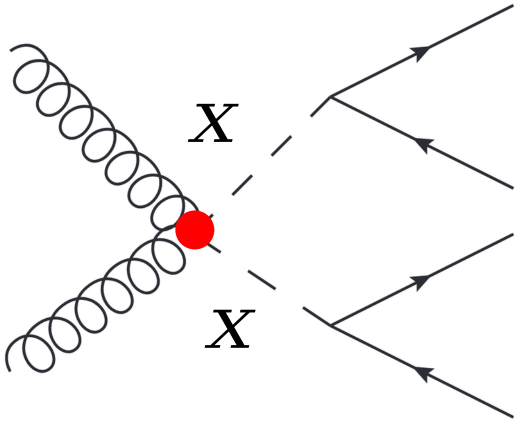
Associate production



$$\sigma \propto y_s^2$$

Need energetic gluons
Depend on ys

pair production

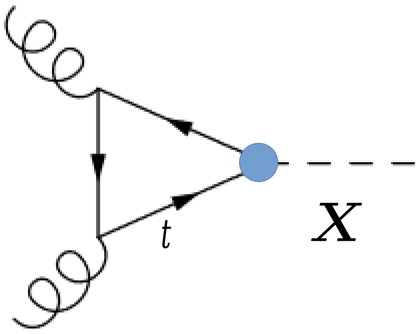


$$\sigma \propto \alpha_s^2$$

Need energetic gluons and
only works for octet

Final state: di-top

single production



$$\sigma \propto \frac{1}{(4\pi)^4} y_s^2$$

Loop-induced,
Good for ligther resonance,
May suffer large background

Four top theory prediction summary

- SM NLO (QCD+EW) predictions (MadGraph):
  Full NLO correction up to order $\mathcal{O}(\alpha_s^i \alpha^j)$ with $i+j = 4,5$. Treating top quark as stable particle, i.e. without decay.
  Frederix, Pagani, Zaro 1711.02116

- SM NLO QCD matched to parton shower (POWHEG-BOX):
  NLO QCD + LO EW, LO top quark spin correlation effect are included in the decay.
  Ježo, Kraus 2110.15159

- SM NLO (QCD+EW) + NLL' :
  NLL threshold resummation, without top decay.
  Beekveld, Kulesza, Valero 2212.03259

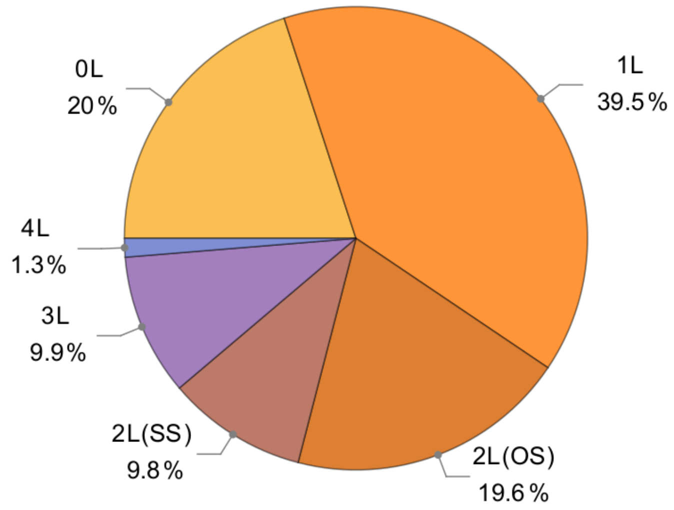
- SM NLO QCD with 3/4 leptonic decay channel:
  Higher order QCD effect in the decay are included.
  Dimitrakopoulos, Wore 2410.05960 2401.10678

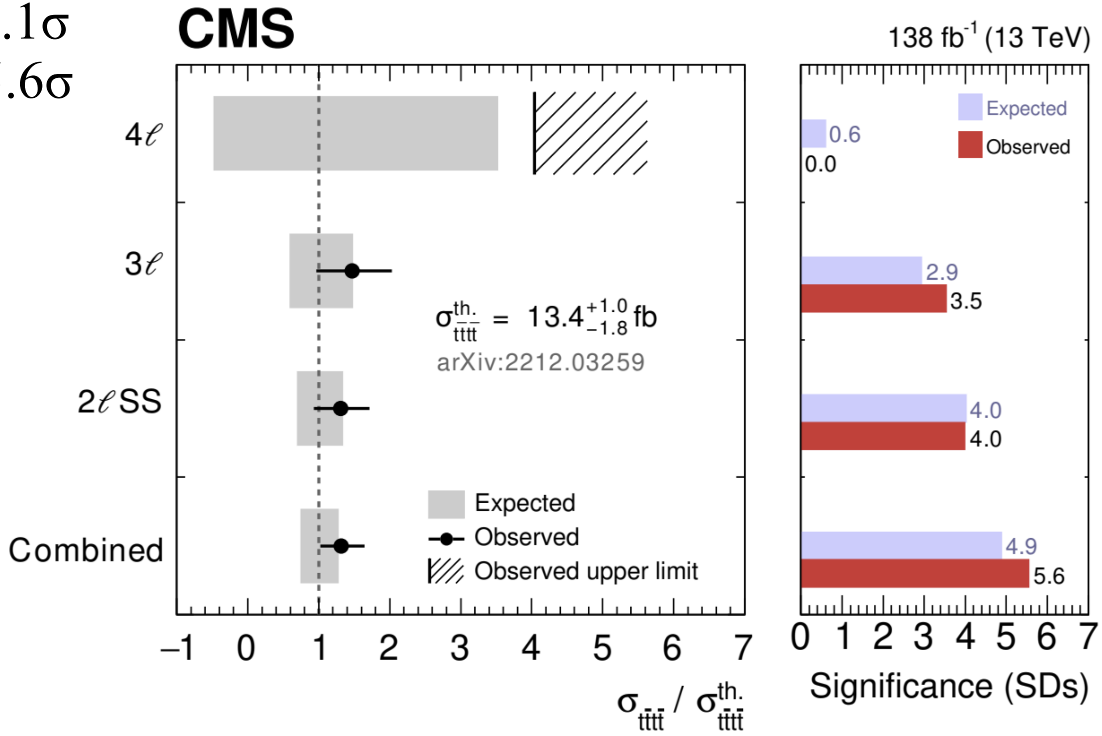
- SMEFT correction at LO and NLO QCD up to dim-6:
  Aoude et.al, 2208.04962; Degrande, Rosenfeld, Vasquez 2402.06528

SM four top measurements @ LHC

For SM most signal are produced at threshold very hard to reconstruct tops
Searches from ATLAS and CMS mostly foucs on the multilepton final states:

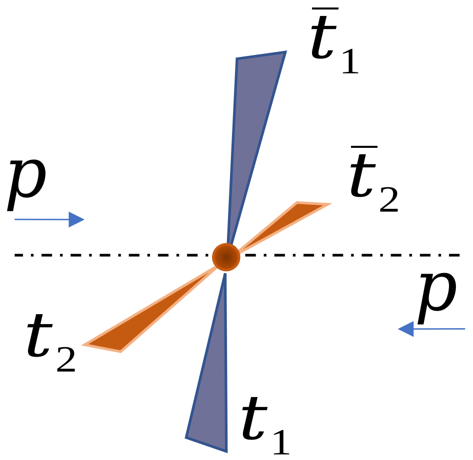
ATLAS[2303.15061] 2LSS and 3L – 6.1σ
CMS[2305.13439] 4L 3L and 2LSS – 5.6σ

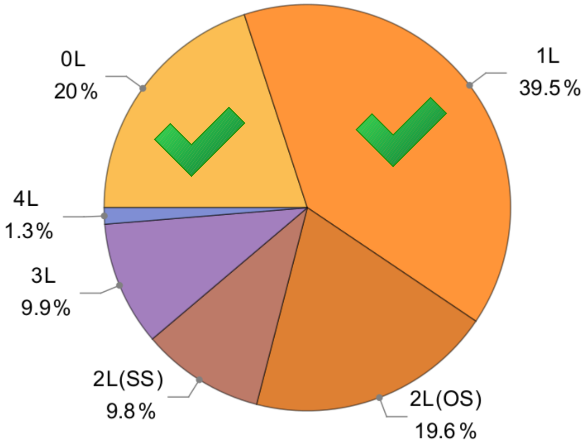


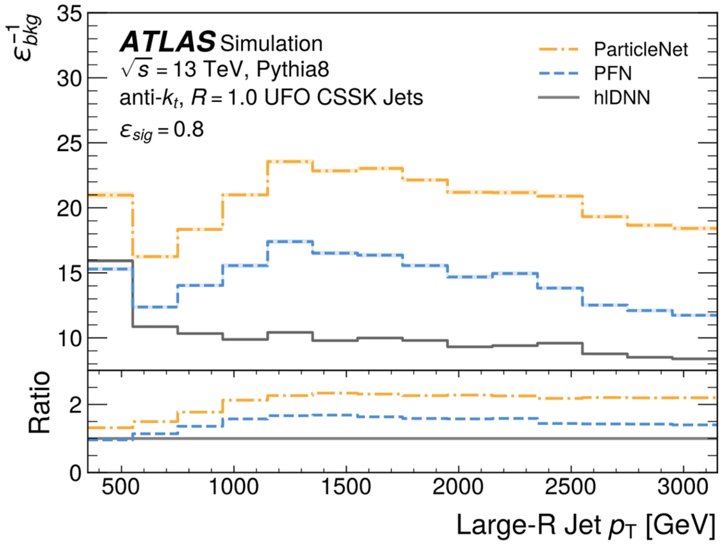


Boosted 4-top searches for NP

If the Top-philic particle are heavy (>1 TeV) then the four top produced are highly boosted, one can leverage the boosted top tagging developed in recent years to search for signal.
Aim for: four reconstructed tops in fully hadronic decay and 1L channel (~60% BR)







Top tag mis-tagging rate

Simulation and Event selection

FeynRules UFO model → **MadGraph@NLO** → **Pythia8** → **MadAnalysis5**

Reconstruction:

– AK10-jets: pT>350 GeV and |η|<2, top-tag with 80% efficiency if dR(jet, top)<=0.75

– AK4-jets: with pT>30 GeV |η|<2.5 b-tag with MV2c10 77% WP

– Isolated lepton, remove AK10-jet if dR(*l*, AK10-jet)<1.0

– Remove b-tagged jets if dR(bjet, AK10-jet)<1.0

Fully hadronic decay:
– 4 top tagged AK10-jets
– 0 isolated lepton

One Leptonic decay:
– 3 top tagged AK10-jets,
– 1 isolated lepton,
– 1 b-tagged jets
Neutrino pz are determined assuming W is on-shell

$$\frac{M_{tt}^1 - M_{tt}^2}{M_{tt}^1} < 30\%$$

Pair production restore two Mtt

Associated Production restore largest Mtt

Background study

Process	σ (LO)	Scale	PDF	σ (NLO)	Scale	PDF
$t\bar{t}jj$	354	$^{+62\%}_{-35\%}$	$\pm5.8\%$	352	$^{+3.7\%}_{-13\%}$	$\pm2.6\%$
$t\bar{t}W$	0.376	$^{+23\%}_{-17\%}$	$\pm3.9\%$	0.565	$^{+8.3\%}_{-8.3\%}$	$\pm1.8\%$
$t\bar{t}Wj$	0.329	$^{+39\%}_{-26\%}$	$\pm2.1\%$	0.452	$^{+8.1\%}_{-12\%}$	$\pm1.2\%$
$t\bar{t}Z$	0.563	$^{+31\%}_{-22\%}$	$\pm4.8\%$	0.756	$^{+9.2\%}_{-11\%}$	$\pm2.1\%$
$t\bar{t}Zj$	0.639	$^{+47\%}_{-30\%}$	$\pm6.5\%$	0.672	$^{+2.6\%}_{-9\%}$	$\pm2.5\%$
$t\bar{t}t\bar{t}$	0.00612	$^{+65\%}_{-37\%}$	$\pm13\%$	0.00920	$^{+28\%}_{-24\%}$	$\pm6.0\%$
$t\bar{t}t + t\bar{t}\bar{t}$	0.00155	$^{+22\%}_{-17\%}$	$\pm13\%$	0.00201	$^{+20\%}_{-19\%}$	$\pm7.5\%$

Backgrounds are simulated at leading order and rescaled to NLO cross-section

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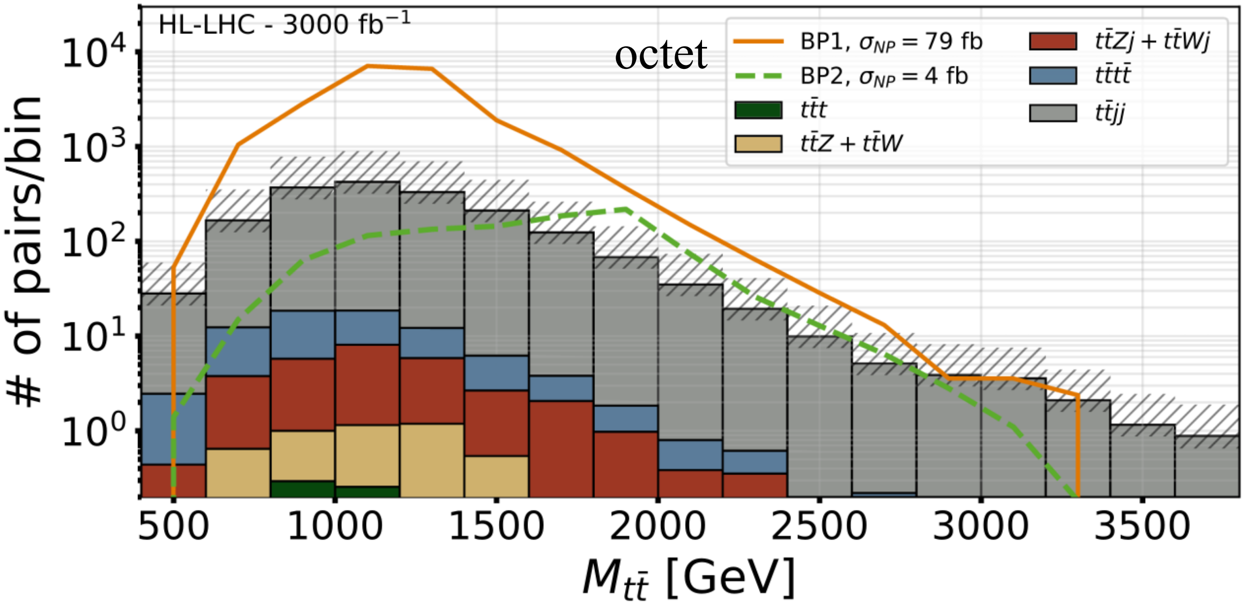
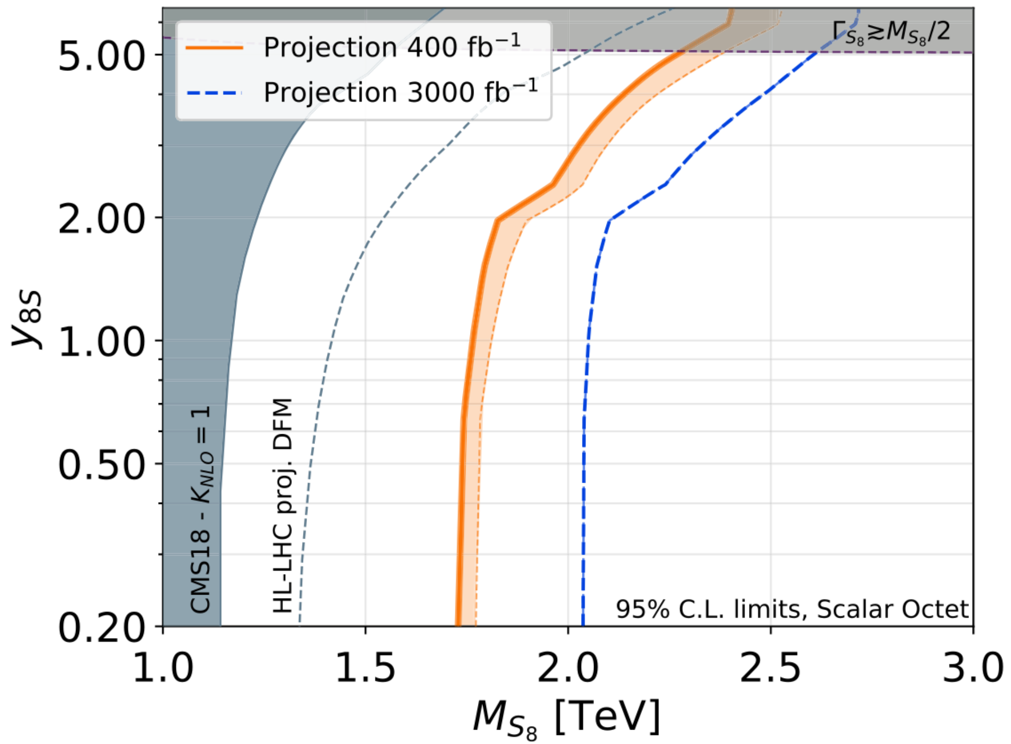
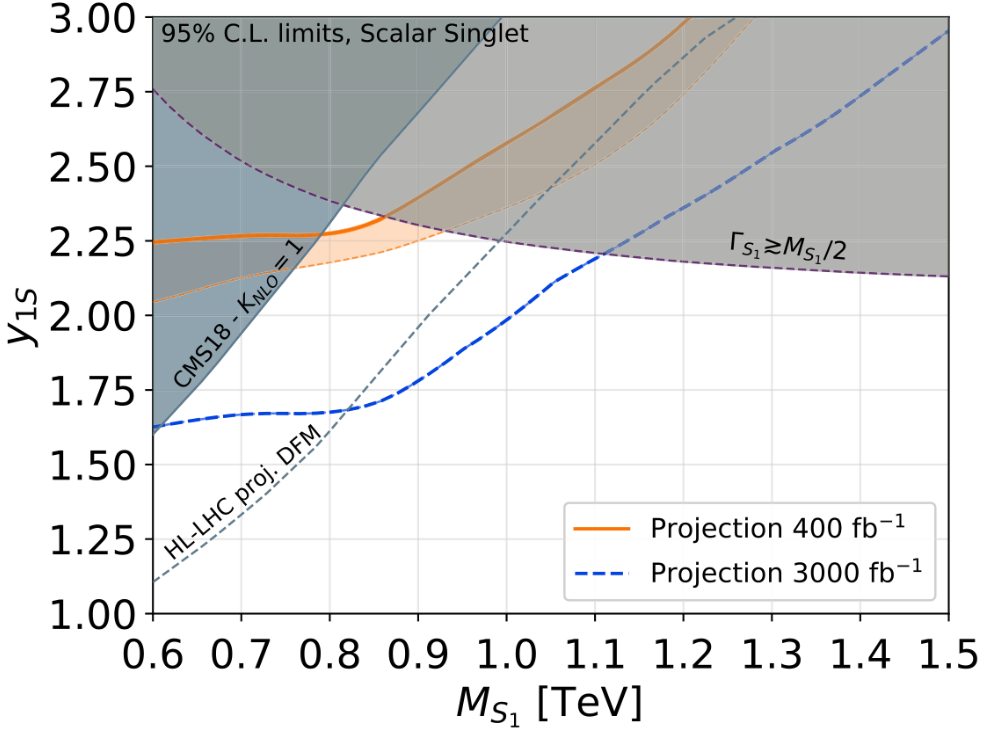
After all the selection cuts the dominant background is ttjj with like jet false tagged



BP1: M=1.3TeV, ys=0.25, Γ=1.45 GeV pair dominant
BP2: M=2TeV, ys=1.0, Γ=38.04 GeV mixed production

Result





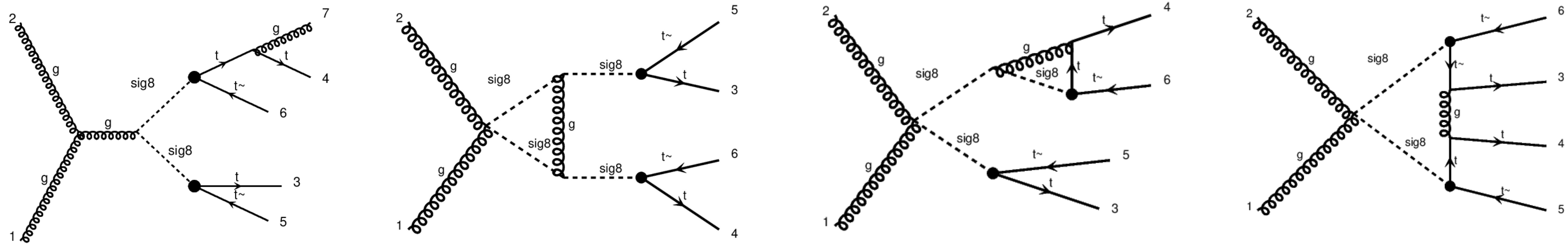
Octet exclude M<2.1TeV for L = 3000 fb^{-1} due to superior pair production efficiency.

For singlet it outperform conventional search at larger mass

NLO signal computation (preliminary)

- We generate NLO UFO model with **`FeynRules`** + **`NLOCT`** including UV and R2 counter-terms
- Compute Full NLO QCD correction to LO NP four tops production match to parton shower:

$$\mathcal{O}(\alpha_s y_S^2) \to \mathcal{O}(\alpha_s^2 y_S^2)$$



Include corrections to both production and decay

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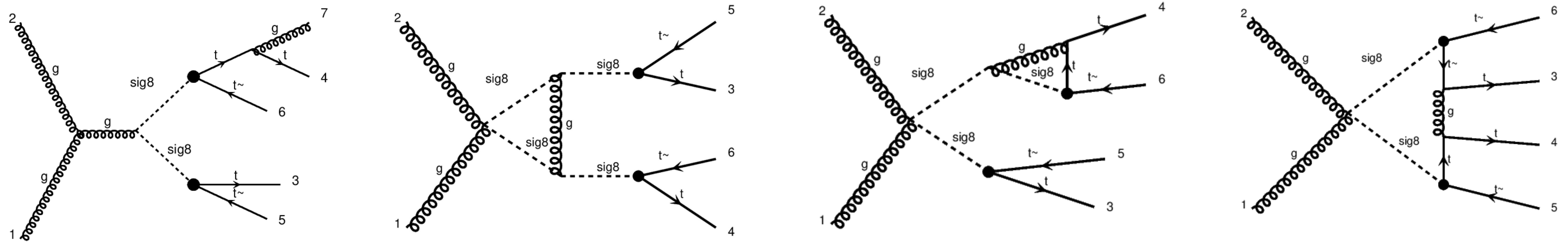

Include corrections to both production and decay

	Octet M=1TeV, y=1	Octet M=2TeV, y=1	Singlet M=1.5 TeV, y=1
$\sigma_{4t,NLO}$	$54.27^{+9.4\%\ +9\%}_{-13.1\%\ -9\%}$	$0.2199^{+15.9\%\ +16.9\%}_{-16.7\%\ -16.9\%}$	$0.4512^{+19.9\%\ +11\%}_{-17.9\%\ -11\%}$
K_{4t}	1.74	1.69	1.87
$\sigma_{OO/ttS,NLO}$	$45.37^{+17.5\%\ +9\%}_{-17.1\%\ -9\%}$	$0.06859^{+19.3\%\ +27\%}_{-18.2\%\ -27\%}$	$0.3909^{+19.5\%\ +12.1\%}_{-18.7\%\ -12.1\%}$
$K_{OO/ttS}$	1.63	1.56	1.86

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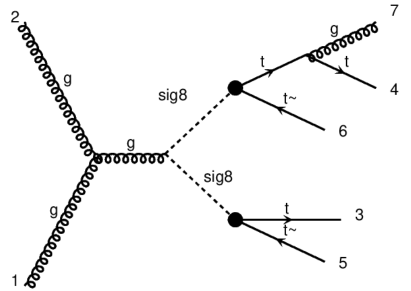
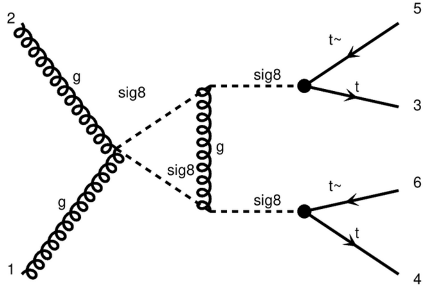
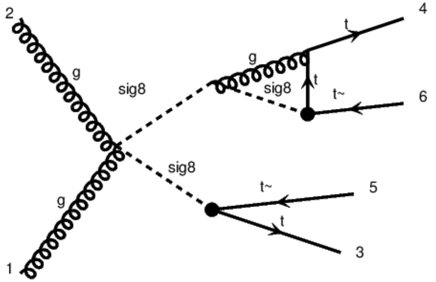
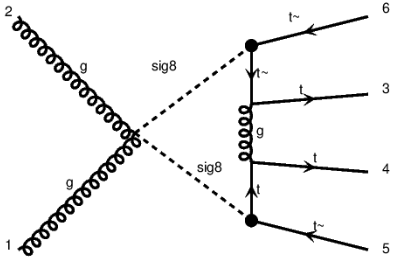


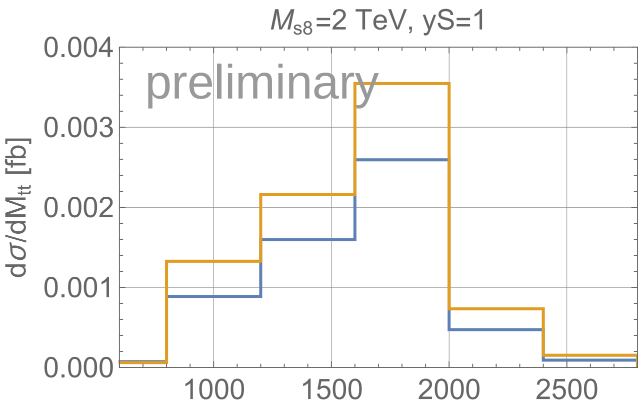


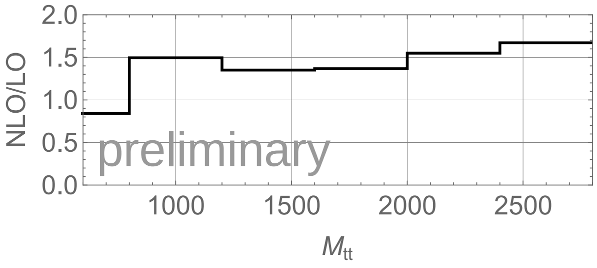




Include corrections to both production and decay

Distribution of reconstructed M_{tt} for the full Hadronic decay channel, passing all the cuts while allowing one AK10-jet not top tagged.





Summary

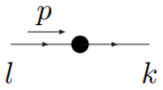
- Top-philic particle present in different types of UV theory.
- Color octet can be pair produced at LO and without suppression from the scalar couplings
- Fully hadronic decay and 1 leptonic decay channels are good for searching top-philic particle in the mass range 1-3 TeV
- The NLO QCD correction to the top-philic particle production is significant for both pair and associative production.

Rational term in 1-loop reduction in MadGraph (OPP)

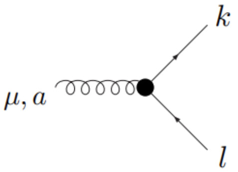
$$\mathcal{M}^{1\text{loop}} = \sum_{i_0,i_1,i_2,i_3} d_{i_0 i_1 i_2 i_3} \bar{\mathcal{D}}_{i_0 i_1 i_2 i_3} + \sum_{i_0,i_1,i_2} c_{i_0 i_1 i_2} \bar{\mathcal{C}}_{i_0 i_1 i_2} + \sum_{i_0,i_1} b_{i_0 i_1} \bar{\mathcal{B}}_{i_0 i_1} + \sum_{i_0} a_{i_0} \bar{\mathcal{A}}_{i_0} + \mathcal{O}(\varepsilon)$$

$$\mathcal{M}^{1\text{loop}} = \sum_{i_0,i_1,i_2,i_3} d_{i_0 i_1 i_2 i_3} \mathcal{D}_{i_0 i_1 i_2 i_3} + \sum_{i_0,i_1,i_2} c_{i_0 i_1 i_2} \mathcal{C}_{i_0 i_1 i_2} + \sum_{i_0,i_1} b_{i_0 i_1} \mathcal{B}_{i_0 i_1} + \sum_{i_0} a_{i_0} \mathcal{A}_{i_0} + R + \mathcal{O}(\varepsilon)$$

R2: ε-dimenson from the numerator
need to treat model by model



$$= \frac{ig^2}{16\pi^2} \frac{N_{col}^2 - 1}{2N_{col}} \delta_{kl}(-\not{p} + 2m_q)\,\lambda_{HV}$$



$$= \frac{ig^3}{16\pi^2} \frac{N_{col}^2 - 1}{2N_{col}} t^a_{kl}\gamma_\mu\,(1 + \lambda_{HV})$$

Draggiotis, Garzelli, Papadopoulos, Pittau, arXiv:0903.0356

R1: ε-dimenson from the denominator
Universital

$$\frac{1}{\bar{D}_i} = \frac{1}{D_i}\left(1 - \frac{\tilde{l}^2}{\bar{D}_i}\right)$$

Motivation for Extended SUSY model

MSSM
strong Constraint
from LHC

Little Hierarchy problem

Continous R-symmetry (soft breaking)

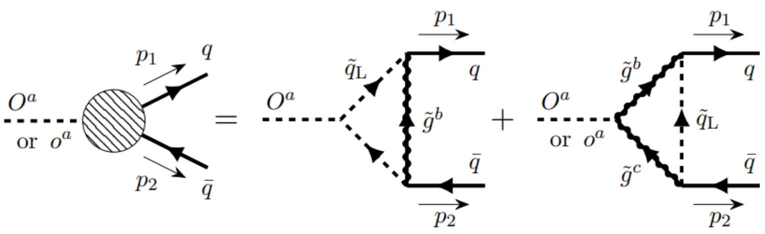
Forbidde Gaugino mass

Add new chiral superfield of adjoint representation and make gaugino Dirac. this also introduce new adjoint scalar

$$\mathcal{L} \supset \sum_{k=1}^{3} \int \mathrm{d}^2\theta \, \frac{\kappa_k}{\Lambda} \, \mathcal{W}'^{\alpha} \mathcal{W}^a_{k\alpha} \mathcal{A}^a_k + \text{H.c.},$$

$$\mathcal{L} \supset \int \mathrm{d}^2\theta \, \mathrm{d}^2\theta^\dagger \left[\mathcal{Q}^{\dagger i} \exp\left\{ 2g_3 [t^c_3 \mathcal{V}^c_3]_i{}^j \right\} \mathcal{Q}_j + \mathcal{A}^{\dagger a}_3 \exp\left\{ 2g_3 [t^c_3 \mathcal{V}^c_3]_a{}^b \right\} \mathcal{A}_{3b} \right]$$

	Superfield	R	Boson	R	Fermion	R
Gluon	$\mathcal{W}_3$	+1	g	0	λ_3	+1
Left-chiral quark	$\mathcal{Q}$	+1	$\tilde{q}_{\mathrm{L}}$	+1	q_{L}	0
Right-chiral quark	$\overline{\mathcal{U}}^\dagger, \overline{\mathcal{D}}^\dagger$	0	$\tilde{u}_{\mathrm{R}}, \tilde{d}_{\mathrm{R}}$	0	$u_{\mathrm{R}}, d_{\mathrm{R}}$	+1
Higgs	$\mathcal{H}_{\mathrm{u}}, \mathcal{H}_{\mathrm{d}}$	+1	$H_{\mathrm{u}}, H_{\mathrm{d}}$	+1	$\tilde{H}_{\mathrm{u}}, \tilde{H}_{\mathrm{d}}$	0
$\mathrm{SU(3)_c}$ adjoint	$\mathcal{A}_3$	0	φ_3	0	ψ_3	−1



$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) $\times$ SU(6)/SO(6)				
$SO(N_{\rm HC})$	$5\times\mathbf{S}_2$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 55$	$\frac{5(N_{\rm HC}+2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$N_{\rm HC}\geq 15$	$\frac{5(N_{\rm HC}-2)}{6}$	1/3	/	
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=7,9$	$\frac{5}{6}$, $\frac{5}{12}$	1/3	$N_{\rm HC}=7,9$	M1, M2
$SO(N_{\rm HC})$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=7,9$	$\frac{5}{6}$, $\frac{5}{3}$	2/3	$N_{\rm HC}=7,9$	M3, M4

Electro-weak coset	$SU(2)_L\times U(1)_Y$
$SU(5)/SO(5)$	$\mathbf{3}_{\pm1}+\mathbf{3}_0+\mathbf{2}_{\pm1/2}+\mathbf{1}_0$
$SU(4)/Sp(4)$	$\mathbf{2}_{\pm1/2}+\mathbf{1}_0$
$SU(4)\times SU(4)'/SU(4)_D$	$\mathbf{3}_0+\mathbf{2}_{\pm1/2}+\mathbf{2'}_{\pm1/2}+\mathbf{1}_{\pm1}+\mathbf{1}_0+\mathbf{1'}_0$

Color coset	$SU(3)_c\times U(1)_Y$
$SU(6)/SO(6)$	$\mathbf{8}_0+\mathbf{6}_{(-2/3\text{ or }4/3)}+\bar{\mathbf{6}}_{(2/3\text{ or }-4/3)}$
$SU(6)/Sp(6)$	$\mathbf{8}_0+\mathbf{3}_{2/3}+\bar{\mathbf{3}}_{-2/3}$
$SU(3)\times SU(3)'/SU(3)_D$	$\mathbf{8}_0$

$$\Sigma_r = e^{i2\sqrt{2}c_5\pi_r^a T_r^a/f_r}\cdot\Sigma_{0,r}\,,\qquad \Phi_r = e^{ic_5 a_r/f_{a_r}}$$

$$m_t\bar{t}_L(\Sigma_\chi)^{n_\chi/2}t_R + h.c. \sim m_t\bar{t}t + i\frac{n_\chi}{\sqrt{2}}c_5\frac{m_t}{f_\chi}\,\pi_8^a\,\bar{t}\gamma^5\lambda^a t + \ldots$$

	FullNP_gg	SmintNP_gg	qq4tNP	qq4tSMint
Msig8=1TeV y=1	0.04406 +- 0.0001438	7.206e-05 +- 1.49e-06	0.008611 +- 1.487e-05	4.439e-07 +- 6.706e-08
Msig8=2TeV y=1	0.000241 +- 6.113e-07	1.859e-05 +- 2.699e-07	1.183e-05 +- 1.442e-08	3.439e-08 +- 7.566e-09
Msig8=3TeV y=1	9.917e-06 +- 2.703e-08	8.323e-06 +- 9.265e-08	1.053e-07 +- 2.718e-10	1.833e-08 +- 3.664e-09
Msig8=1TeV y=2	0.04697 +- 0.0001081	0.0002819 +- 5.179e-06	0.003085 +- 7.715e-06	1.222e-06 +- 2.565e-07
Msig8=2TeV y=2	0.000552 +- 1.416e-06	7.576e-05 +- 1.052e-06	1.381e-05 +- 3.831e-08	9.743e-08 +- 4.138e-08
Msig8=3TeV y=2	4.233e-05 +- 1.498e-07	3.387e-05 +- 3.958e-07	3.267e-07 +- 9.956e-10	7.956e-08 +- 1.466e-08

	double only gg	single only gg	t only gg
Msig8=1TeV y=1	0.03322 +- 6.773e-05	0.007346 +- 1.242e-05	2.252e-05 +- 8.959e-08
Msig8=2TeV y=1	5.82e-05 +- 1.227e-07	0.0001617 +- 3.479e-07	3.066e-06 +- 1.151e-08
Msig8=3TeV y=1	1.873e-07 +- 3.784e-10	8.113e-06 +- 1.991e-08	7.735e-07 +- 2.557e-09
Msig8=1TeV y=2	0.0306 +- 7.811e-05	0.02854 +- 6.694e-05	0.0003607 +- 1.383e-06
Msig8=2TeV y=2	6.025e-05 +- 1.436e-07	0.0007248 +- 2.257e-06	4.858e-05 +- 1.842e-07
Msig8=3TeV y=2	3.151e-07 +- 6.268e-10	5.183e-05 +- 1.712e-07	1.236e-05 +- 3.037e-08

Top tag.	BP1				BP2			
	Optimistic		Conservative		Optimistic		Conservative	
$\mathcal{L}$ [fb^{-1}]	400	3000	400	3000	400	3000	400	3000
SR1	1.35	0.52	1.69	0.64	0.68	0.24	0.82	0.30
SR2	0.64	0.26	0.75	0.36	0.51	0.14	0.61	0.20
SSL	0.97	0.27	0.97	0.27	1.13	0.29	1.12	0.28