Four-top-quark signatures: from EFT to simplified models

Based on 1805.10835 with B. Fuks and M. Goodsell

And 2104.xxxx with B. Fuks and F. Maltoni

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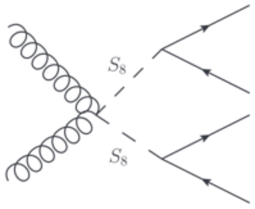
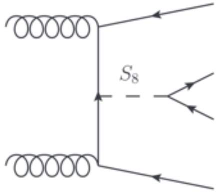
- LHC is a "top-quark factory", with the process pp $\rightarrow t\bar{t}t\bar{t}$ being particularly interesting:
  - Much rarer than top-pair production (CS in the SM $\sigma_{pp\rightarrow 4t} \sim 12$fb)
  - Important NP search channel → E.g. pair production of colored top-philic particle
- EFT for top-physics gathered a large interest → based on SMEFT approach
  - Important part of top WG "third generation operators"

- Simplified models often include EWSB

  → Using $SU(3)_c{\times}U(1)_{em}$ basis is important and leads to additional operators

- Typical SMEFT approach is redundant for top-only operators
- We perform the matching EFT/Simplified models





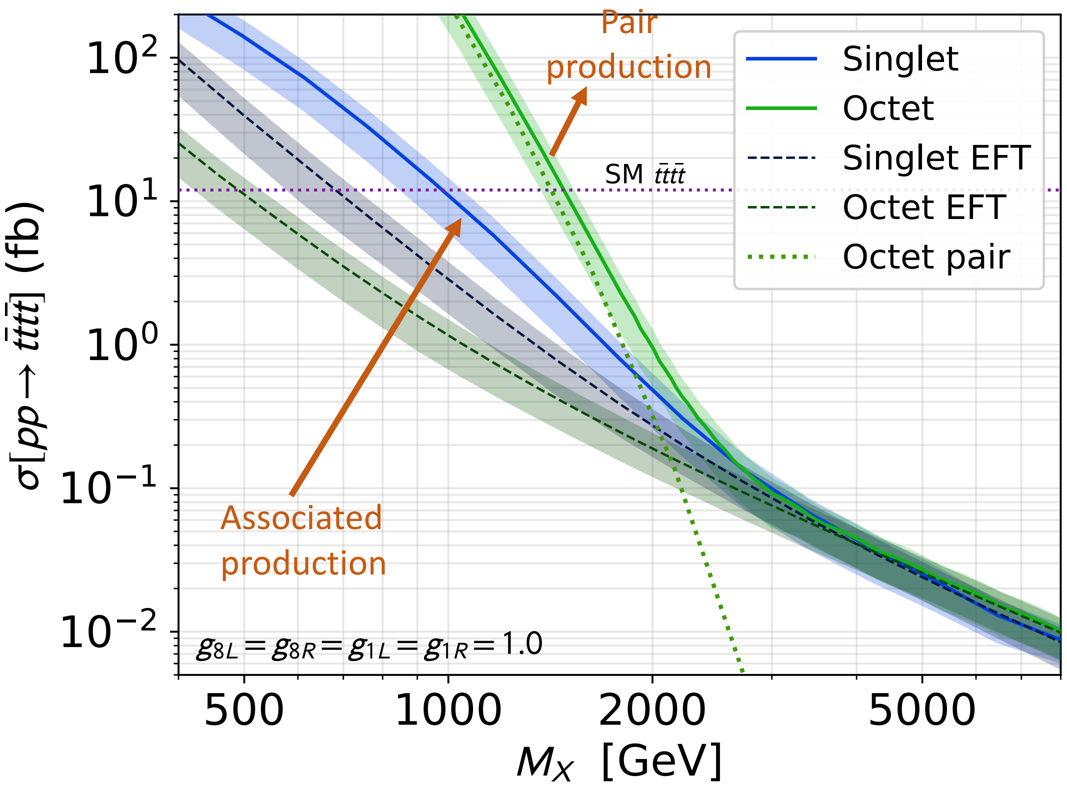
$$\mathcal{L}_{V_1} \supset -\frac{1}{4} V_1^{\mu\nu} V_{1\mu\nu} - \frac{1}{2} m_{V_1}^2 V_1^{\mu} V_{1\mu} + \bar{t}\gamma_\mu \left[g_{1L} P_L + g_{1R} P_R \right] V_1^{\mu}\, t \quad \longleftrightarrow$$

$$\begin{aligned}
\mathcal{O}_S^1 &= \bar{t}t\ \bar{t}t \\
\mathcal{O}_S^8 &= \bar{t}T^A t\ \bar{t}T_A t \\
\mathcal{O}_{RR}^1 &= \bar{t}_R\gamma^\mu t_R\ \bar{t}_R\gamma_\mu t_R \\
\mathcal{O}_{LL}^1 &= \bar{t}_L\gamma^\mu t_L\ \bar{t}_L\gamma_\mu t_L \\
\mathcal{O}_{LR}^1 &= \bar{t}_L\gamma^\mu t_L\ \bar{t}_R\gamma_\mu t_R \\
\mathcal{O}_{LR}^8 &= \bar{t}_L T^a\gamma^\mu t_L\ \bar{t}_R T_a\gamma_\mu t_R
\end{aligned}$$

1. EFT approach not accurate for models with heavy mediators

- In the HL-LHC accessible regime, on-shell production dominates

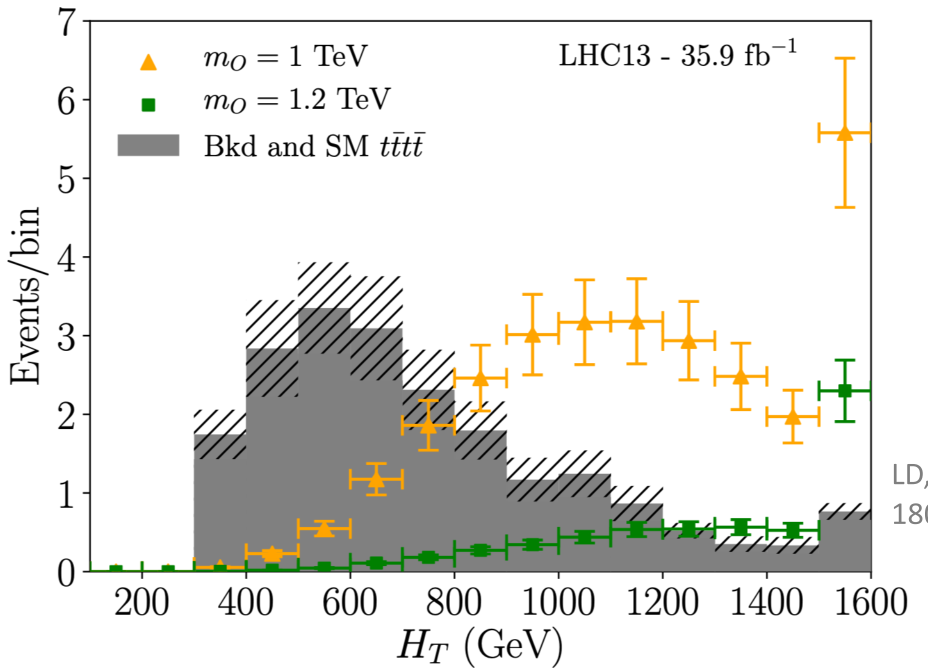
LD, Fuks, Maltoni -- 2104.xxxx preliminary results



2. Dedicated search strategies for resonances in tttt promising at HL-LHC

- The process generating $t\bar{t}t\bar{t}$ is completely different between SM and NP
  → We add a signal region with $H_T > 1.2$ TeV to CMS-TOP-18-003 search

$N_{\text{bkd+SM}} = 6.26 \pm 1.3 \qquad N_{\text{obs}} = 9$



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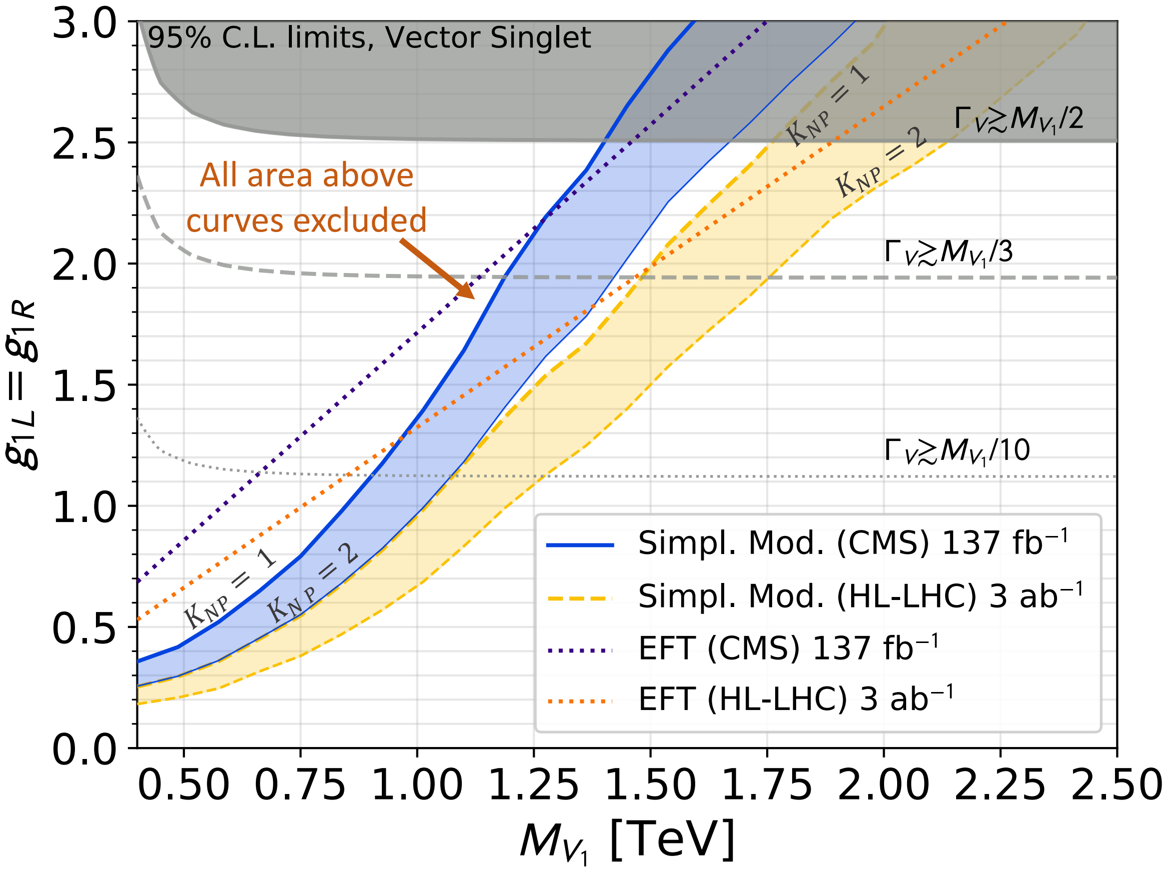
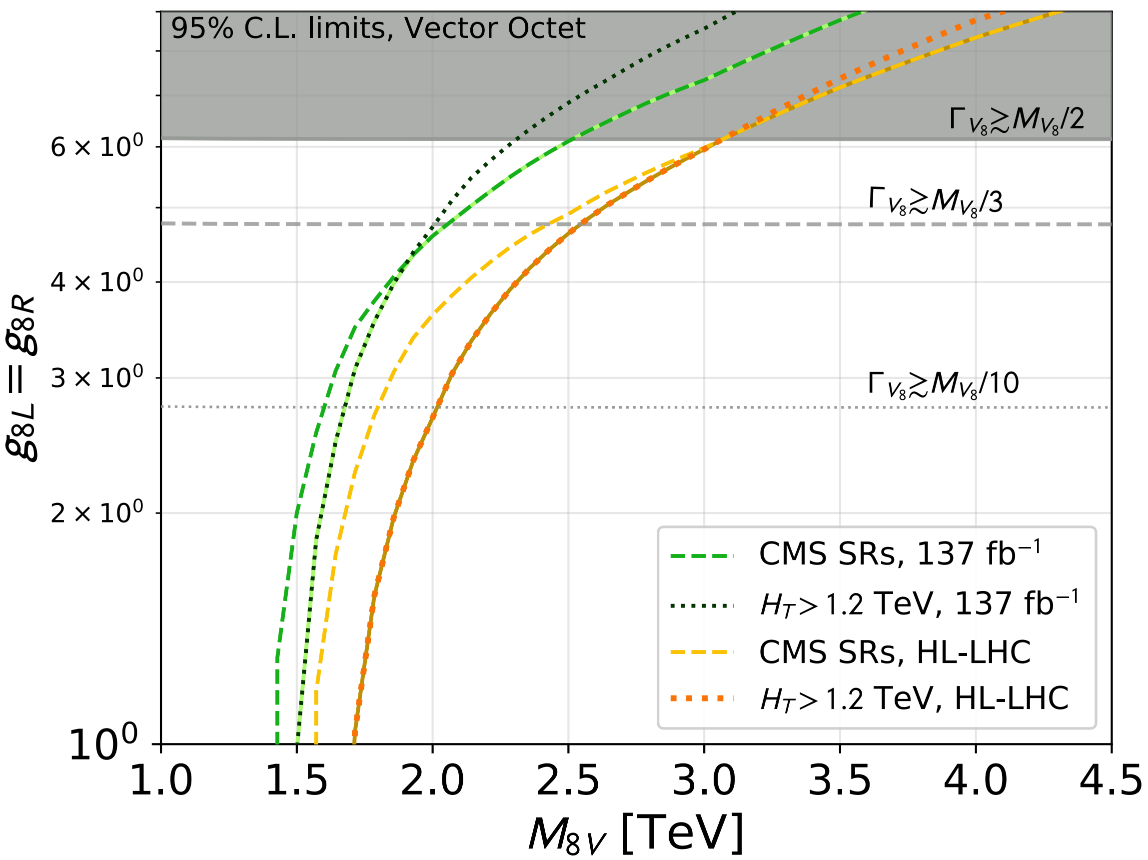
In more details …

- EFT approach tends to underestimate the limits
- Large uncertainty regarding size of NLO correction: we vary K-factor from 1 to 2



- High –Ht approach leads to a significant improvement in the 1 TeV to 2 TeV regime



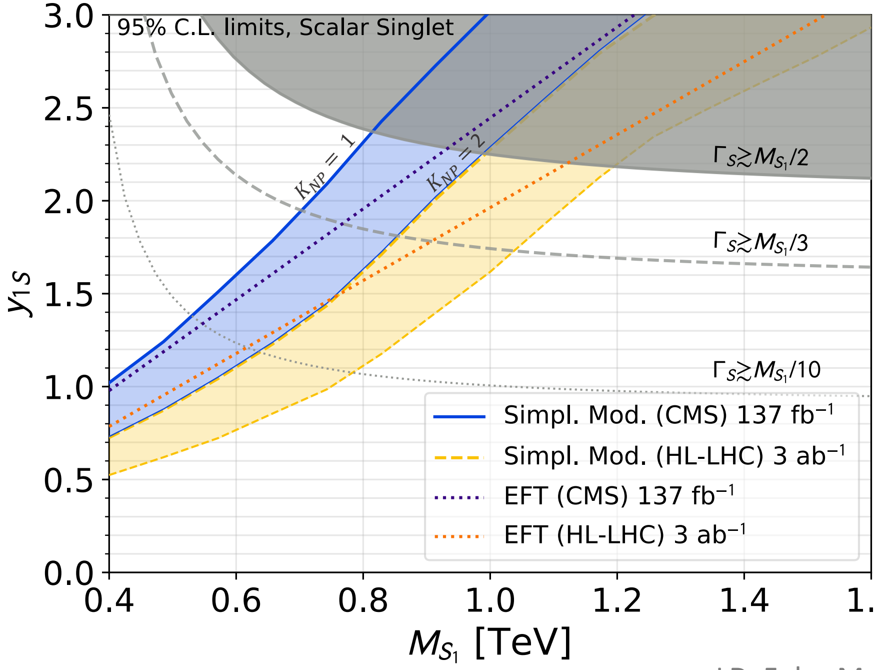
New simplified models limits

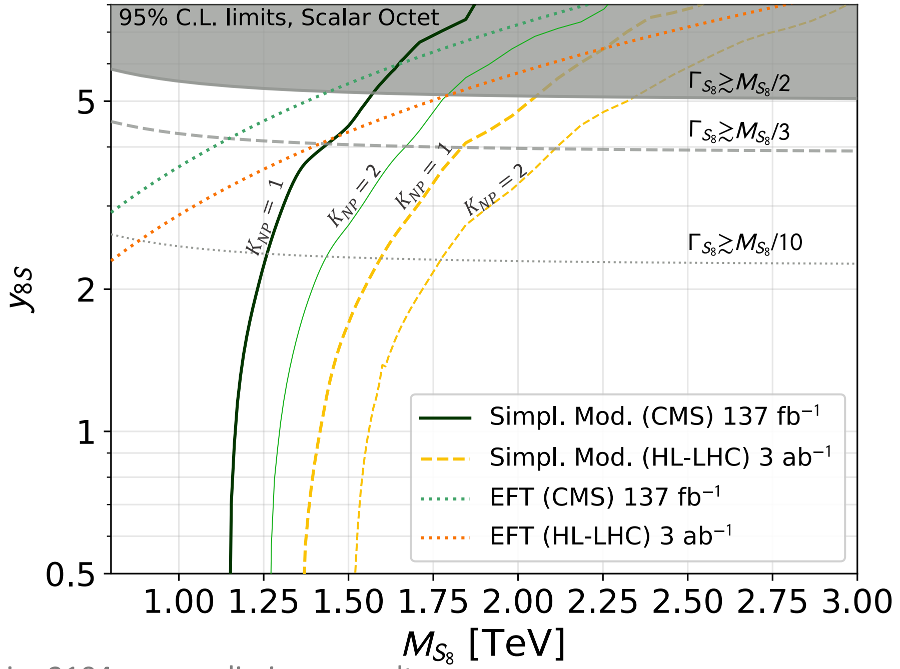
Updated limits for four simplified models:

- Vector Octet
- Scalar Octet
- Vector Singlet
- Scalar Singlet

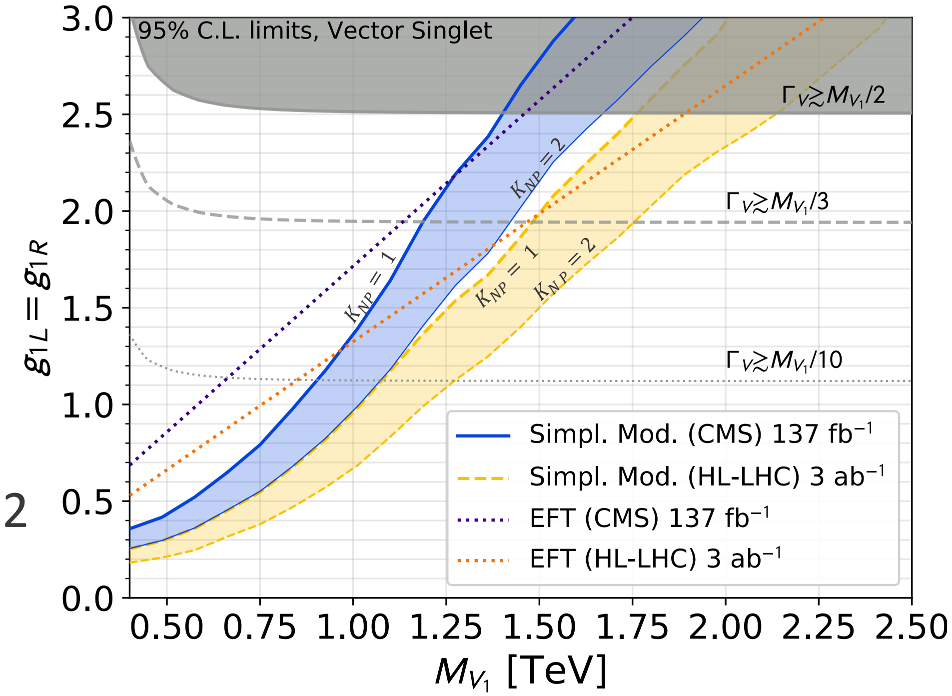
→ The EFT approach is adequate only for heaviest vector octets

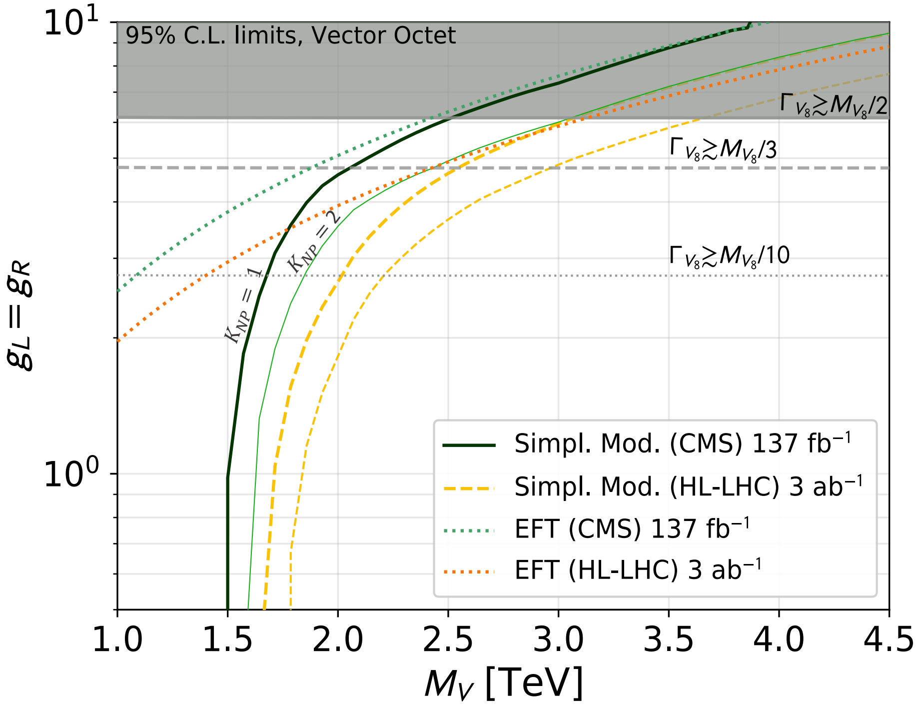
Limits are shown varying the K-factor K_{NP} between 1 and 2





LD, Fuks, Maltoni -- 2104.xxxx preliminary results





Conclusion

- Fast experimental progresses on $t\bar{t}t\bar{t}$ searches

  → Experiments are still statistically limited

- Simplified model with heavy top-philic mediators are reproduced by EFT only for high-masses, i.e. in regions with current low sensitivity

  → On-shell production dominates most of the time

- Detection strategy focusing on top-philic particles on-shell production are very promising
  - Illustrated by high-Ht analysis approach → dominates our recasted limit in the 1-2 TeV range
- We found that QED LO interference important + NLO QCD corrections large, but known only for QCD SM.

→ Complete-NLO corrections would be welcome (especially for composite models where EFT is relevant)…

Backup - EFT vs simplified models

Matching and comparing CS predictions

Simplified models

Include EWSB contributions

- We consider singlet top-philic particles…

$$\mathcal{L}_{S_1} \supset \frac{1}{2}\partial_\mu S_1 \partial^\mu S_1 - \frac{1}{2} m_{S_1}^2 S_1^2 + \bar{t}\left[y_{1S} + y_{1P} i\gamma^5\right] S_1\, t$$

→ contained for instance in 2HDM type-I or type-II

$$\mathcal{L}_{V_1} \supset -\frac{1}{4} V_1{}^{\mu\nu} V_{1\mu\nu} - \frac{1}{2} m_{V_1}^2 V_1{}^\mu V_{1\mu} + \bar{t}\gamma_\mu \left[g_{1L} P_L + g_{1R} P_R\right] V_1{}^\mu\, t$$

→ Via mixing with new VL quarks, etc…

- And color octets top-philic particles

$$\mathcal{L}_{S_8} \supset \boxed{\frac{1}{2} D_\mu S_8^a D^\mu S_{8a}} - \frac{1}{2} m_{S_8}^2 S_8^a S_{8a} + \bar{t}\left[y_{8S} + y_{8P} i\gamma^5\right] S_8\, t$$

→ Composite models, N=2 SUSY …

$$\mathcal{L}_{V_8} \supset \boxed{-\frac{1}{4} V_8{}^{\mu\nu} V_{8\mu\nu}} - \frac{1}{2} m_{V_8}^2 V_8{}^\mu V_{8\mu} + \bar{t}\gamma_\mu \left[g_{8L} P_L + g_{8R} P_R\right] V_8{}^\mu\, t$$

→ Composite models…

Include direct QCD interactions

Simplified models matching

- Integrating out the (assumed heavy) mediator leads to matching coefficients between the EFT and the simplified models
  - Notice that basis is compact enough that, e.g. pseudo-scalar top-philic particles does not need a dedicated operator

	$\mathcal{O}_S^1$	$\mathcal{O}_S^8$	$\mathcal{O}_{LL}^1$	$\mathcal{O}_{RR}^1$	$\mathcal{O}_{LR}^1$	$\mathcal{O}_{LR}^8$
S_1	$\frac{y_{1S}^2}{2M_{S_1}^2}$	/	/	/	/	/
$\tilde{S}_1$	$-\frac{y_{1P}^2}{2M_{\tilde{S}_1}^2}$	/	/	/	$-\frac{y_{1P}^2}{3M_{\tilde{S}_1}^2}$	$-2\frac{y_{1P}^2}{M_{\tilde{S}_1}^2}$
V_8	/	/	$-\frac{g_{1L}^2}{6M_{V_8}^2}$	$-\frac{g_{1R}^2}{6M_{V_8}^2}$	/	$-\frac{g_{8L}g_{8R}}{M_{V_8}^2}$

Backup - Detection strategy
EFT vs simplified models

Based on CMS-TO—18-003 analysis

The CMS 4t analysis

→ SM-like searches

- Large progresses in recent years!
- Both BDT and SR-based strategy based on number of jets/leptons …
- Backgrounds include $t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons etc …

N_ℓ	N_b	N_j	Region	$t\bar{t}t\bar{t}$ (SM - CMS)	$t\bar{t}t\bar{t}$ (Bkd - CMS)
2	3	6	SR5	1.61 ± 0.90	5.03 ± 0.77
2	≥ 4	≥ 5	SR8	2.08 ± 1.23	3.31 ± 0.95
≥ 3	≥ 3	4	SR12	0.56 ± 0.32	2.03 ± 0.48
≥ 3	≥ 3	5	SR13	0.66 ± 0.38	1.09 ± 0.28
≥ 3	≥ 3	≥ 6	SR14	0.76 ± 0.45	0.87 ± 0.30

CMS (17)

$\sigma_{4t}^{SM} = 16.9^{+13.8}_{-11.4}$ fb

35.9 fb^{-1}

(CMS 1710.10614)

CMS (19)

$\sigma_{4t}^{SM} = 12.6^{+5.8}_{-5.2}$ fb

137 fb^{-1}

(CMS 1908.06463)

- Since SM-driven, we need a full recast to get reliable NP bound

	SR5	SR8	Large H_T
$N_{\rm lim}$ (LHC)	5.3	6.6	10.1
$N_{\rm lim}$ (HL-LHC)	58	71	60

Recasting setup

- Simple recasting chain:
  - FEYNRULES

[Christensen & Duhr (CPC ’09); Alloul et al.(CPC’14) Degrande (CPC’16)]

  - MG5_aMC@NLO

Alwall et al. (JHEP’14)

  - PYTHIA 8

Sjostrand et al. (CPC’15)

  - MadAnalysis 5

[Conte et al.(CPC’12); Conte et al. (EPJC’14) Dumont et al. (EPJC ’15)]

Implement effective model with ,e.g:

$$\mathcal{L} \supset \frac{1}{2} D_\mu O^a D^\mu O_a - \frac{1}{2} m_O^2 O^a O_a + y_8 \bar{t} \gamma^5 t O$$

Generate $pp \rightarrow tttt$, including QED interferences

Decay tops inclusively t > w+ b, w+ > all al

The cross-section/signal shape depends only on the top-philic particle mass. → Scan over it

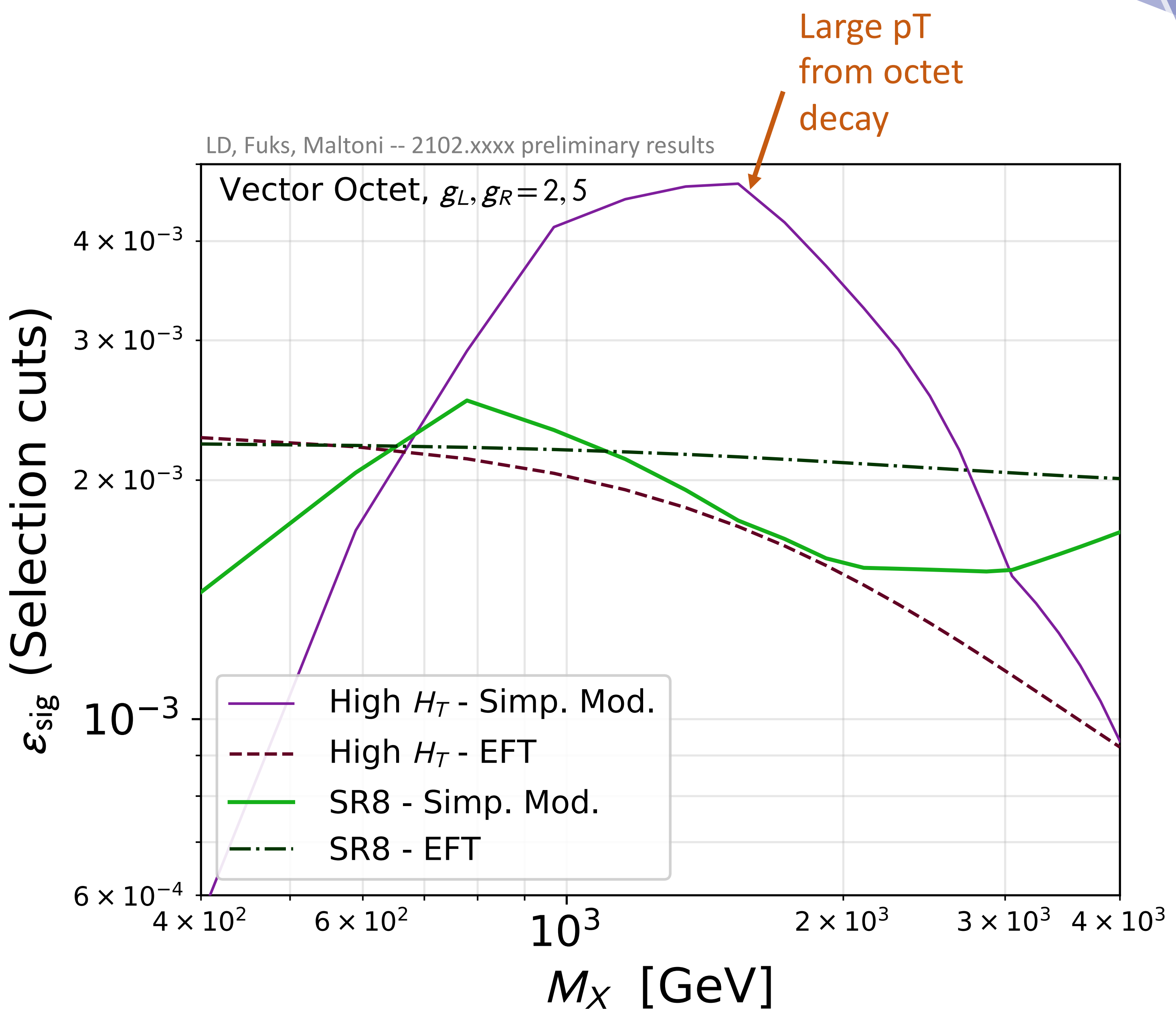
Efficiencies

- Comparing selection cut efficiencies for both approach

- “On-shell” effects important

--> Particularly for the High Ht analysis

- For large mass regime/EFT regime, signal is more mixed with the SM



Backup – EFT details

QED interferences and going NLO

- Only a partial knowledge of NLO effects …
  - In the SM, NLO-correction in QCD dominates → $K_{SM} \sim 2.3$
  - In the SMEFT, much smaller effects from → $K_{QCD} \lesssim 1$
  - In simplified model: case of pseudo-scalar octet led to $K_{QCD} \sim 2$
- Altogether, pretty uncertain situation: we will present limits varying the K-factor between 1 and 2

Frederix, Pagani, Zaro 1711.02116

Degrande et al. 2008.11743

LD, Fuks, Goodsell 1805.10835

- QED-interference terms are important!

(2008.11743 + Ken's talk)

	LO			NLO	
Op.	NP^2	Int. QCD only	Int. QED only	K_{NLO}^{QCD}	K_{SM}
$\mathcal{O}^1_{LL}/2$	$0.8^{+44\%}_{-28\%}$ fb	$0.20^{+47\%}_{-31\%}$ fb	$-0.80^{+41\%}_{-28\%}$ fb	~ 0.93	
$\mathcal{O}^8_{LR}$	$0.28^{+44\%}_{-29\%}$ fb	$0.22^{+52\%}_{-35\%}$ fb	$-0.49^{+42\%}_{-28\%}$ fb	~ 1.1	
SM	/	$4.7^{+66\%}_{-38\%}$ fb	$0.5^{+59\%}_{-35\%}$ fb	/	~ 2.3

For $\frac{c}{\Lambda^2} \sim 1\ \mathrm{TeV}^{-2}$

(1711.02116)

Matching EFT descriptions ...

tttt-related in SMEFT

$O_{tt} = (\bar{t}_R\gamma_\mu t_R)^2$
$O_{tq} = (\bar{t}_R\gamma_\mu t_R)(\bar{q}_L\gamma^\mu q_L)$
$O_{tq}^{(8)} = (\bar{t}_R\gamma_\mu t^A t_R)(\bar{q}_L\gamma^\mu t^A q_L)$
$O_{qq} = (\bar{q}_L\gamma_\mu q_L)^2$
$O_{qq}^{(8)} = (\bar{q}_L\gamma_\mu t^A q_L)^2$

Four-top operators used in 2010.05915

Pure tttt, SU(3)xU(1)

EW preserving

$$\mathcal{O}^1_{RR} = \bar{t}_R\gamma^\mu t_R\ \bar{t}_R\gamma_\mu t_R$$
$$\mathcal{O}^1_{LL} = \bar{t}_L\gamma^\mu t_L\ \bar{t}_L\gamma_\mu t_L$$
$$\mathcal{O}^1_{LR} = \bar{t}_L\gamma^\mu t_L\ \bar{t}_R\gamma_\mu t_R$$
$$\mathcal{O}^8_{LR} = \bar{t}_L T^A\gamma^\mu t_L\ \bar{t}_R T^A\gamma_\mu t_R$$

EW-breaking P-even

$$\mathcal{O}^1_{S} = \bar{t}t\ \bar{t}t$$
$$\mathcal{O}^8_{S} = \bar{t}T^A t\ \bar{t}T^A t\ .$$

EW-breaking P-odd

$$\mathcal{O}^1_{PS} = \bar{t}t\ \bar{t}(i\gamma^5)t$$
$$\mathcal{O}^8_{PS} = \bar{t}T^A t\ \bar{t}T^A(i\gamma^5)t$$

When the bottom-quark part is not included, this basis is redundant

$$\mathcal{O}^{\mathrm{WG},1}_{QQ} \equiv \frac{1}{2}\mathcal{Q}^{(1)}_{qq} \longrightarrow \frac{1}{2}\mathcal{O}^1_{LL}$$
$$\mathcal{O}^{\mathrm{WG},8}_{QQ} \equiv \frac{1}{8}\left(\mathcal{Q}^{(3)}_{qq} + \frac{1}{3}\mathcal{Q}^{(1)}_{qq}\right) \longrightarrow \frac{1}{6}\mathcal{O}^1_{LL}\ ,$$

EFT scales cut-off

- To make the EFT more robust, we can cut on an event-per-event basis

  → Partonic CoM smaller than the EFT scale

(Approach used in LHC –DM searches, before switching to simplified models)

- Effectively transform the LHC into a “lower energy” machine
- Typically “reduces” the EFT CS in a model-independent way