Four-top-quark signatures: simplified models and EFT

Luc Darmé
IP2I – CNRS
23/11/2022

Mostly based on 2104.09512 with B. Fuks and F. Maltoni

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101028626

Outline

Introduction: NP for top-philic particles

From simplified models to EFT: a cross-section study

Resonant vs non-resonant four-top search

Top-philic NP theories: the origin

- Why would New Physics (NP) prefers the top quarks over its lighter siblings ?

  → This question has of course everything to do with why does the top quark is actually the heaviest one …

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

N=2 SUSY constructions (sgluon)

Generic ALP models

Because the top quark is made (partially) of NP

Partial top compositeness

Because the NP helps in generating the top quark mass

Extended Higgs sectors

Dark Higgs models (ie new singlet scalar)

Because it is a third generation quark

Flavour constructions

(Can generate top-philic vectors, leptoquarks, etc…)

Extended Higgs sector

- The large top mass implies large Yukawa couplings
  - → Very important in extended Higgs sector searches, as the coupling to top quark can be expected to be sizeable
  - → In 2HDM, up to factors from the mixing, the couplings arise proportional to the quark masses

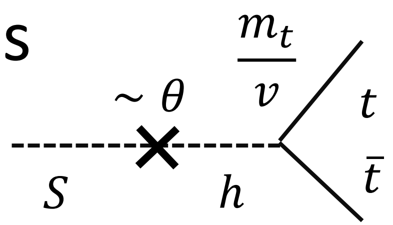
$$\mathcal{L}^{\rm 2HDM}_{\rm Yukawa} = -\sum_{f=u,d,\ell} \boxed{\frac{m_f}{v}} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i\xi_A^f \bar{f}\gamma_5 f A\right)$$

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

$$\tan\beta = \frac{v_2}{v_1} \qquad H^{\rm SM} = h\sin(\alpha-\beta) - H\cos(\alpha-\beta)$$

See, e.g. 2202.02333 for a recent work

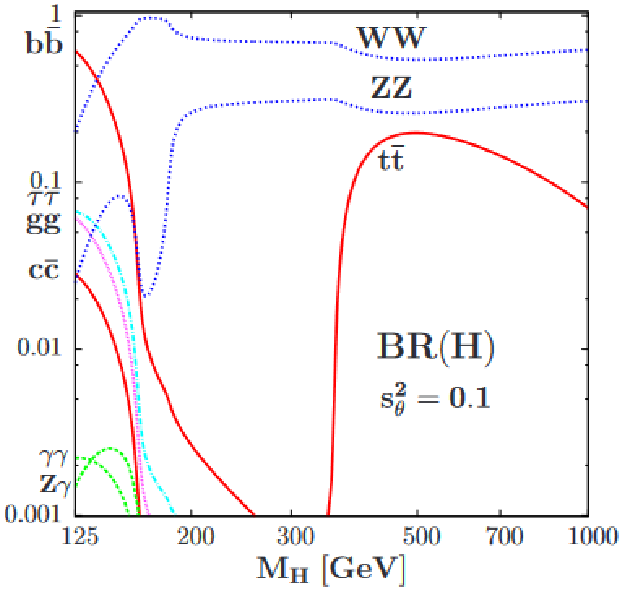
- In models with an inert scalar (e.g. Dark Higgs), the coupling arises from mixing, thus is dominantly with the top quark



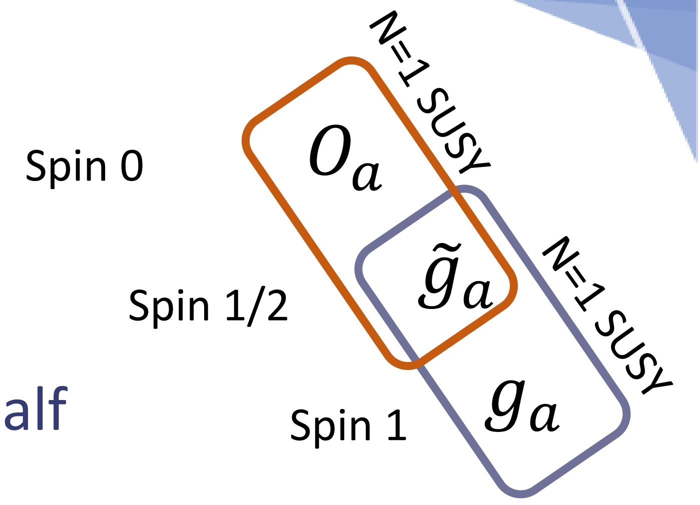
Corresponding simplified model

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

1903.03616



Supersymmetric constructions



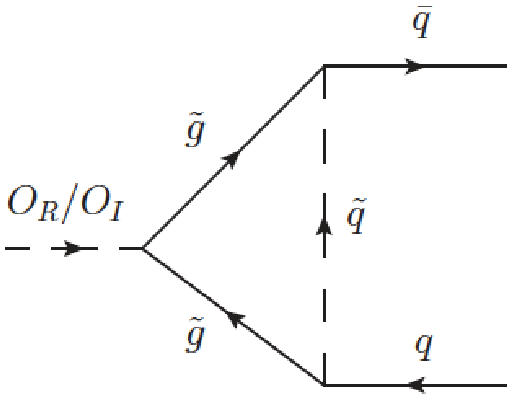
- Dirac Supersymmetric model

See, e.g. 2107.13565 for a recent work

→ makes gauginos Dirac fermions instead of Majorana (supersoftness + match with N=2 SUSY models). which contains half of the gluino degrees of freedom and a new, color octet complex scalar

$$O = \frac{O_R + \boxed{iO_I}}{\sqrt{2}} \longrightarrow$$

The pseudo-scalar octet O_I only couples to gluinos at tree-level



$g_{Oqq} \propto m_q$

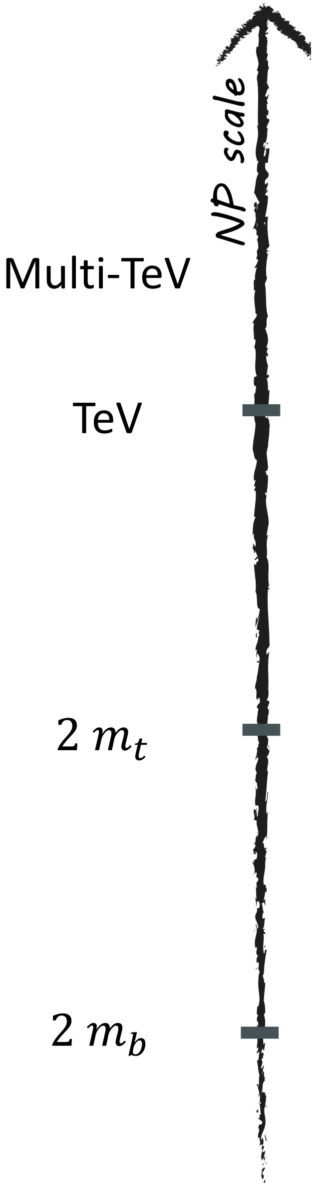
required by chirality flip + the fact that all couplings in the loop are in g_s)

Corresponding simplified model

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

→ Include direct QCD interactions

From resonant searches to EFT



- The NP is completely decoupled, the SMEFT approach is relevant

$$pp \to \bar{t}t\bar{t}t$$

Four non-redundant 4t operators + many other involving Z,W,H or light quarks

Where should we make the transition?

- The “high-pT” region, one or two NP particles produced on-shell

$$pp \to \bar{t}tX, XX\,, \qquad X \to t\bar{t}$$

Top quarks with very large pT, correct reconstruction possible ?

- Resonance easily produced, but decay with little pT

$$pp \to \bar{t}tX, XX\,, \qquad X \to t\bar{t}$$

Large signal rate / Large background region

- Resonance easily produced, but decay cannot proceed in tops

$$pp \to \bar{t}tX^* \to \bar{t}t\bar{t}t$$

But also $\bar{t}t\,(\bar{b}b), \bar{t}t\,(\bar{\tau}\tau)$, *etc …*

Resonant vs non-resonant searches: Cross-section study

Simplified models

- We consider singlet top-philic particles…

Include EWSB contributions

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

→ 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

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

→ Composite models, N=2 SUSY …

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

→ Composite models…

Include direct QCD interactions

A minimal EFT basis

- 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

  → No need to keep track of b-quark

$$O_{tt} = (\bar{t}_R \gamma_\mu t_R)^2$$

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

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

$$O_{qq} = (\bar{q}_L \gamma_\mu q_L)^2$$

$$O_{qq}^{(8)} = \left(\bar{q}_L \gamma_\mu t^A q_L\right)^2$$

Four-top operators used in 2010.05915

$$O_{qq}^{(8)} \sim O_{qq}/3$$

EW-breaking part (P-conserving)

$$\mathcal{O}_S^1 = \bar{t}t\ \bar{t}t$$

$$\mathcal{O}_S^8 = \bar{t}T^A t\ \bar{t}T_A t$$

EW-preserving part

$$\mathcal{O}_{RR}^1 = \bar{t}_R \gamma^\mu t_R\ \bar{t}_R \gamma_\mu t_R$$

$$\mathcal{O}_{LL}^1 = \bar{t}_L \gamma^\mu t_L\ \bar{t}_L \gamma_\mu t_L$$

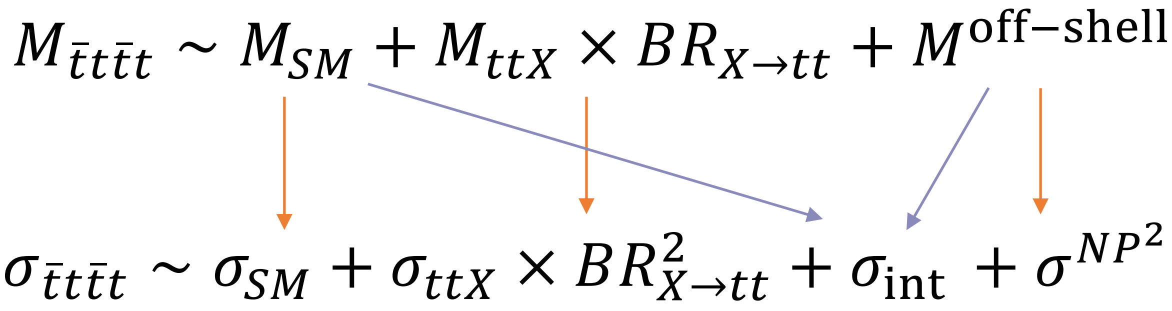
$$\mathcal{O}_{LR}^1 = \bar{t}_L \gamma^\mu t_L\ \bar{t}_R \gamma_\mu t_R$$

$$\mathcal{O}_{LR}^8 = \bar{t}_L T^a \gamma^\mu t_L\ \bar{t}_R T_a \gamma_\mu t_R$$

Also two further P-breaking operators…

Cross-section estimates

- The amplitude for the $pp \to \bar t t\, \bar t t$ with a NP simplified model can be (artificially) decomposed in 3 main pieces

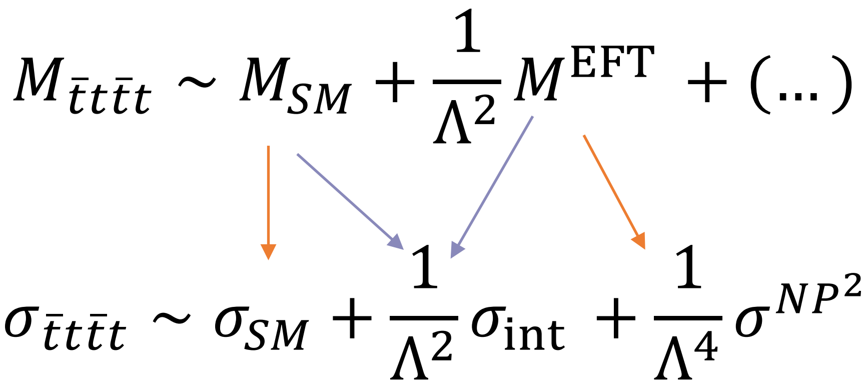


$$M_{\bar t t \bar t t} \sim M_{SM} + M_{ttX} \times BR_{X\to tt} + M^{\text{off}-\text{shell}}$$

$$\sigma_{\bar t t \bar t t} \sim \sigma_{SM} + \sigma_{ttX} \times BR^2_{X\to tt} + \sigma_{\text{int}} + \sigma^{NP^2}$$

Contrary to the "usual" case, we just started to measure σ_{SM}…

- For the EFT, the on-shell piece is assumed to be subdominant



$$M_{\bar t t \bar t t} \sim M_{SM} + \frac{1}{\Lambda^2} M^{\text{EFT}} + (\ldots)$$

$$\sigma_{\bar t t \bar t t} \sim \sigma_{SM} + \frac{1}{\Lambda^2}\sigma_{\text{int}} + \frac{1}{\Lambda^4}\sigma^{NP^2}$$

Given the current sensitivity, LHC (and HL-LHC) are in a regime with:

$$\sigma_{SM} \sim \frac{1}{\Lambda^4}\sigma^{NP^2} \gtrsim \frac{1}{\Lambda^2}\sigma_{\text{int}}$$

Importance of EW interference effect (LO)

- Interferences become important for CS around the fb, and EW-contributions are dominant!

→ Similar to the full SM result where $\alpha_S^2\alpha_{EW}^2$ terms were found much larger than expected

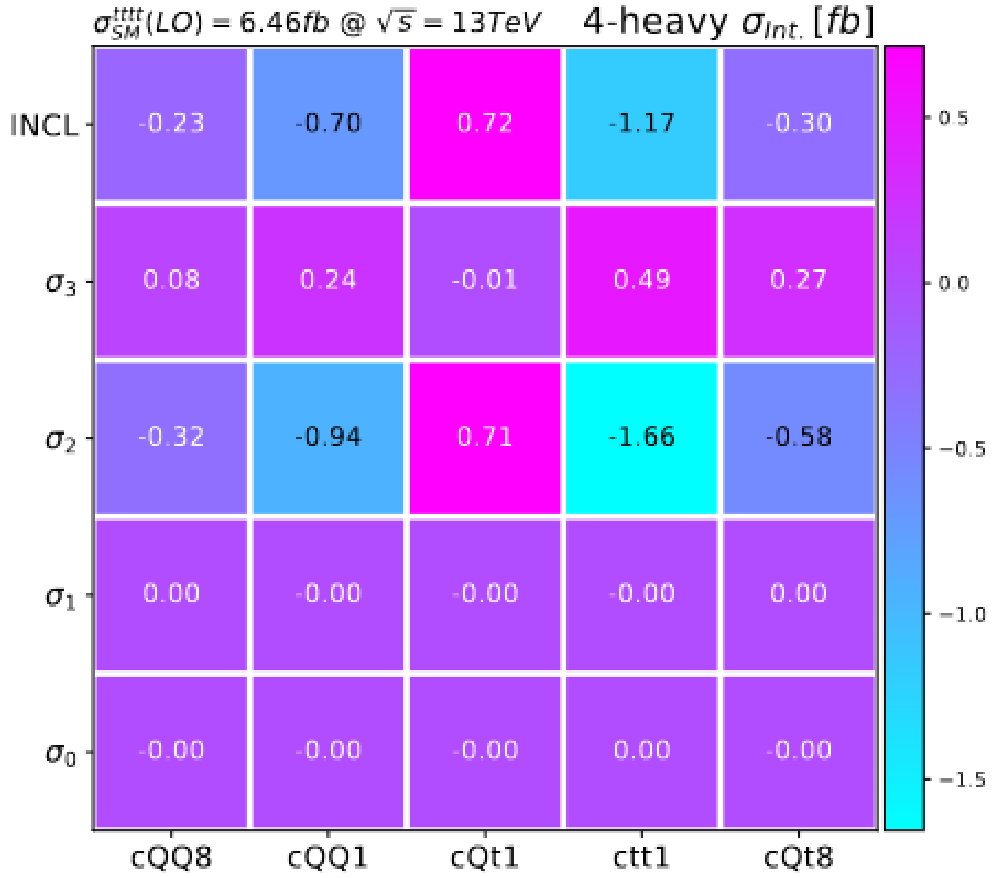
Frederix, Pagani, Zaro 1711.02116

→ For the "heavy quark" operators, $\alpha_S^2\alpha_{EW}^1$ tend to dominate the interference contribution

$$\sigma_{incl}^{int} \sim \underset{\alpha_S^3}{\sigma_3} + \underset{\alpha_S^2\alpha_{EW}^1}{\sigma_2} + \underset{\alpha_S^1\alpha_{EW}^2}{\sigma_1} + \underset{\alpha_{EW}^3}{\sigma_0}$$

For the $c/\Lambda \sim 1$, the NP² terms are of the same order as the interferences

Aoude et al. 2208.04962


$\sigma_{SM}^{tttt}(LO) = 6.46fb$ @ $\sqrt{s} = 13TeV$ 4-heavy $\sigma_{Int.}$ [fb]

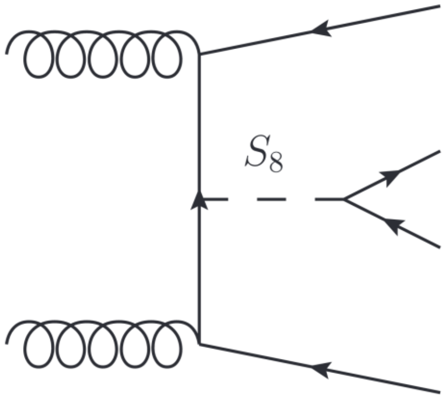
	cQQ8	cQQ1	cQt1	ctt1	cQt8
INCL	-0.23	-0.70	0.72	-1.17	-0.30
σ_3	0.08	0.24	-0.01	0.49	0.27
σ_2	-0.32	-0.94	0.71	-1.66	-0.58
σ_1	0.00	-0.00	-0.00	-0.00	0.00
σ_0	-0.00	-0.00	-0.00	0.00	-0.00

- Conclusion: always include EW interference in your simulations

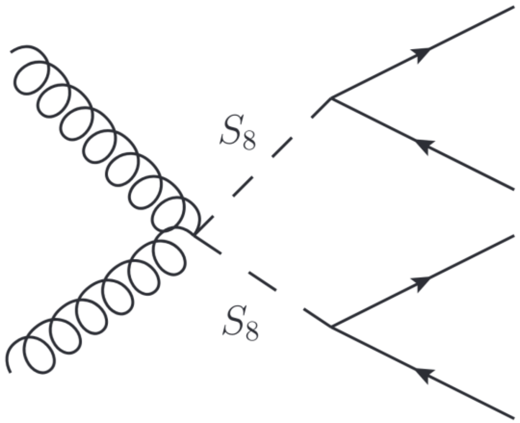
See also Ježo and Kraus (2110.15159)

EFT vs simplified model

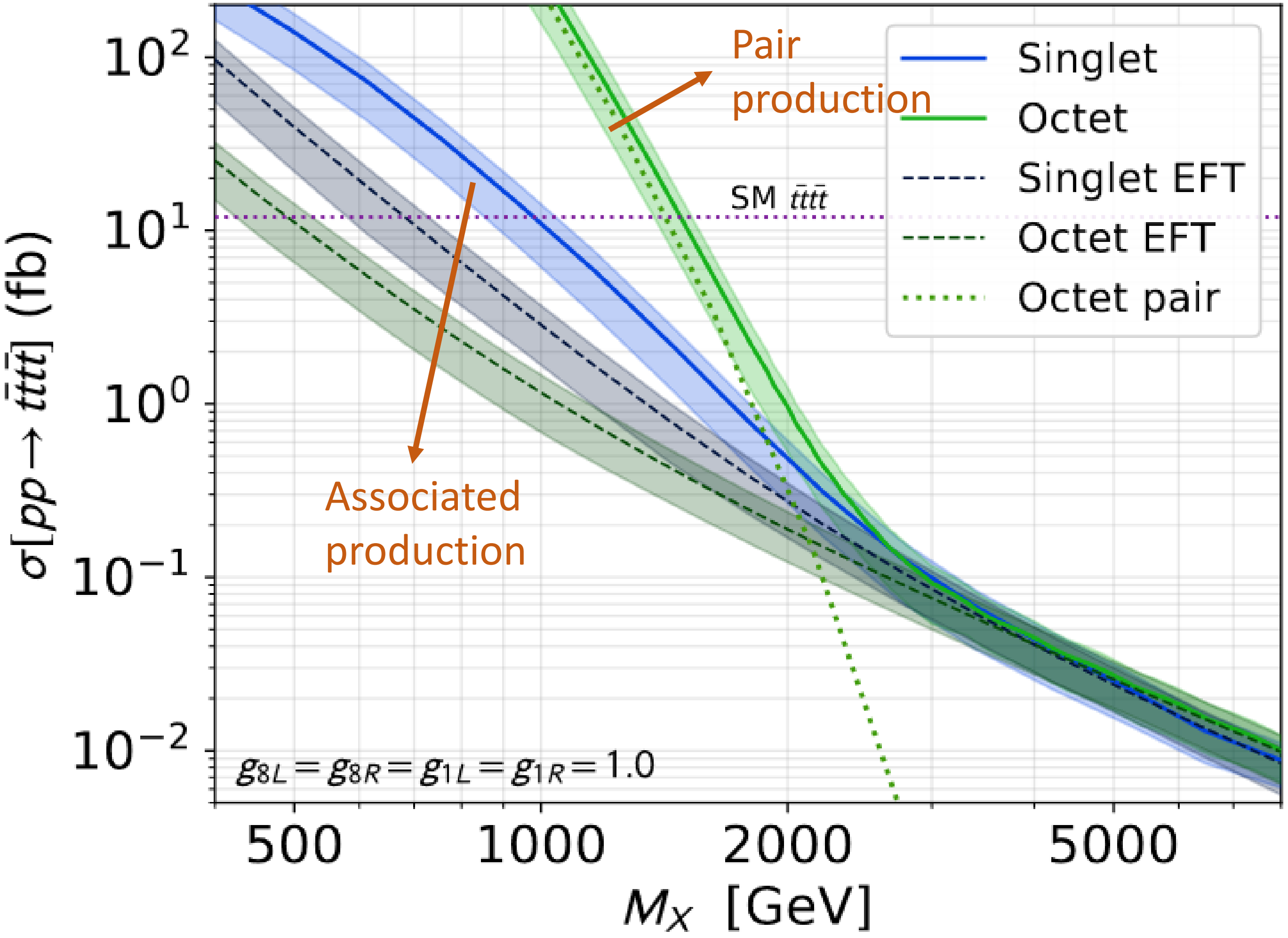
- The projected EFT constraints, even at HL-LHC points to g/Λ at the TeV level
  - → In the low mass regime, on-shell production dominates
  - → Either in associated



  - → Or if available, by pair



LD, Fuks, Maltoni -- 2104.09512



Going NLO

- We define the K-factor as the ratio between LO and NLO cross-section

  →Can we estimate the size of NLO corrections from the SM estimate?

$$\tilde{\sigma}_{\rm NP}^{\rm C-NLO} = \sigma_{\rm SM}^{\rm C-NLO} \times \left(\frac{\sigma_{\rm NP}^{\rm LO}}{\sigma_{\rm SM}^{\rm LO}}\right) \equiv K_{\rm SM}\, \sigma_{\rm NP}^{\rm LO}$$

- No…only a partial knowledge of NLO effects …

  → In the SM, NLO-correction in QCD dominates → $K_{SM} \sim 2.3$ Frederix, Pagani, Zaro 1711.02116

  → In the SMEFT, much smaller effects,
  Depends on the operator, typically $K_{QCD} \gtrsim 1$ Degrande et al. 2008.11743

  → In simplified model: case of pseudo-scalar octet led to $K_{QCD} \sim 2$ LD, Fuks, Goodsell 1805.10835

- Altogether, pretty uncertain situation: we will present limits varying the K-factor between 1 and 2

Resonant vs non-resonant searches: Limits

Recasting setup

- Simple recasting chain:
  - FeynRules

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

    Implement EFT and simplified models Lagrangians, e.g.

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

  - MG5_aMC@NLO

    Alwall et al. (JHEP'14)

    Load UFO, generate $pp \rightarrow tttt$, including EW interferences

  - PYTHIA 8

    Sjostrand et al. (CPC'15)

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

  - MadAnalysis 5

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

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

The CMS 4t analysis

- The most recent search are focusing on SM-like signals

  → 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)

CMS (19) + CMS (22)

$\sigma_{4t}^{SM} = 17^{+5}_{-5}$ fb

138 fb^{-1}

(CMS-PAS-TOP-21-005)
All hadronic final states

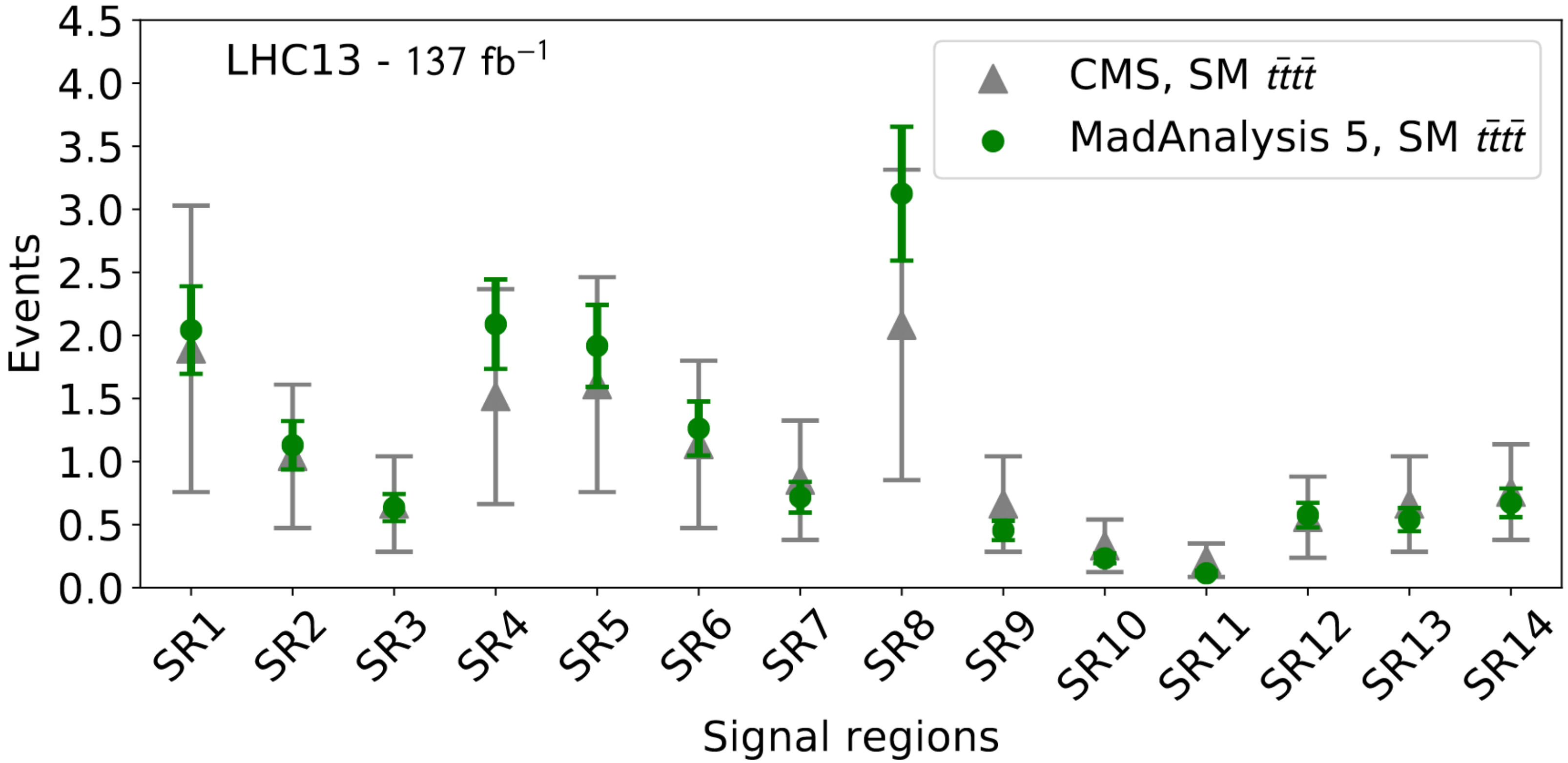
- Since SM-driven, we need a full recast to get reliable NP bound

MadAnalysis 5 implementation

- Challenging analysis to reproduce
  - → High-multiplicity final states: isolation criteria (defined back in CMS’ 1605.0317)
  - → Relatively strong cuts (sizeable MC dataset required), signal efficiency < 0.002

- Signal regions depend crucially on number of b-tagged jets;

→ Reproduce the efficiency of DeepCSV algorithm, medium working point in Delphes (MA5 tune)



Ht data from CMS

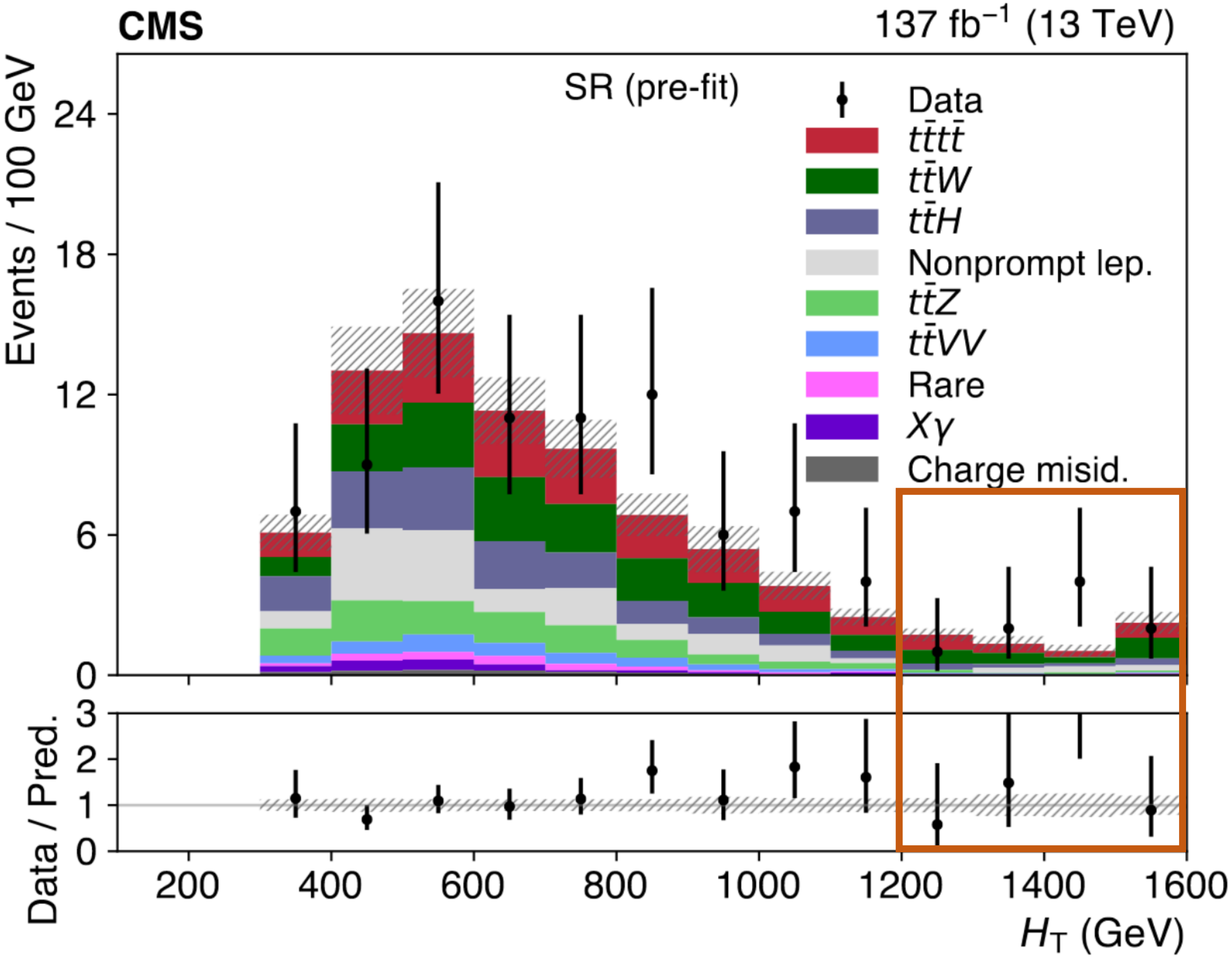
- We add a signal region with $H_T > 1.2$ TeV to the CMS search

$$N_{\rm bkd+SM} = 6.26 \pm 1.3$$

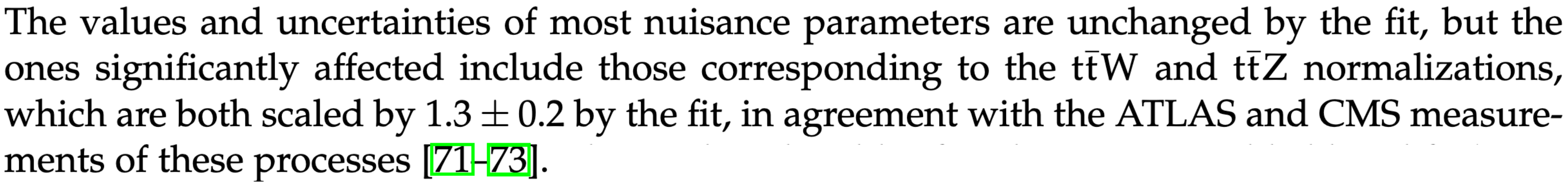
$$N_{\rm obs} = 9$$

- Actually the tail of the distribution is in excess

→ Possible link with the issues plaguing ttW and ttZ + multijets ?



CMS, 1908.06463


The values and uncertainties of most nuisance parameters are unchanged by the fit, but the ones significantly affected include those corresponding to the $t\bar{t}W$ and $t\bar{t}Z$ normalizations, which are both scaled by 1.3 ± 0.2 by the fit, in agreement with the ATLAS and CMS measurements of these processes [71–73].

Signal efficiencies

- EFT efficiencies close to simplified models ones for CMS analysis
  - → This is because on-shell effects are not really leveraged/used here
- With a high-Ht cut, the “on-shell” effects becomes more important
  - → High Ht analysis has a very good signal efficiency in the 1-3 TeV mass window
  - → The EFT of course cannot capture this effect

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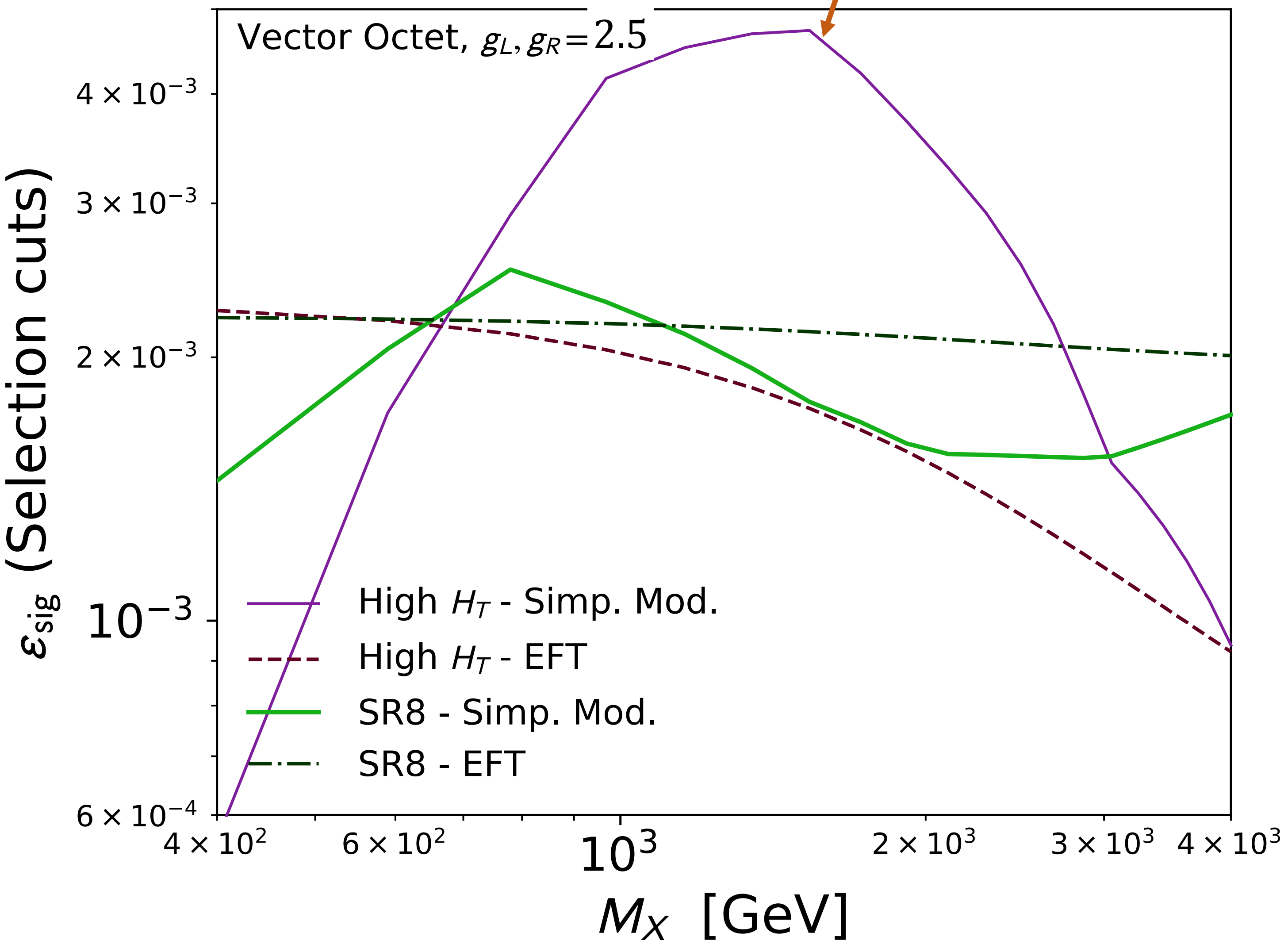
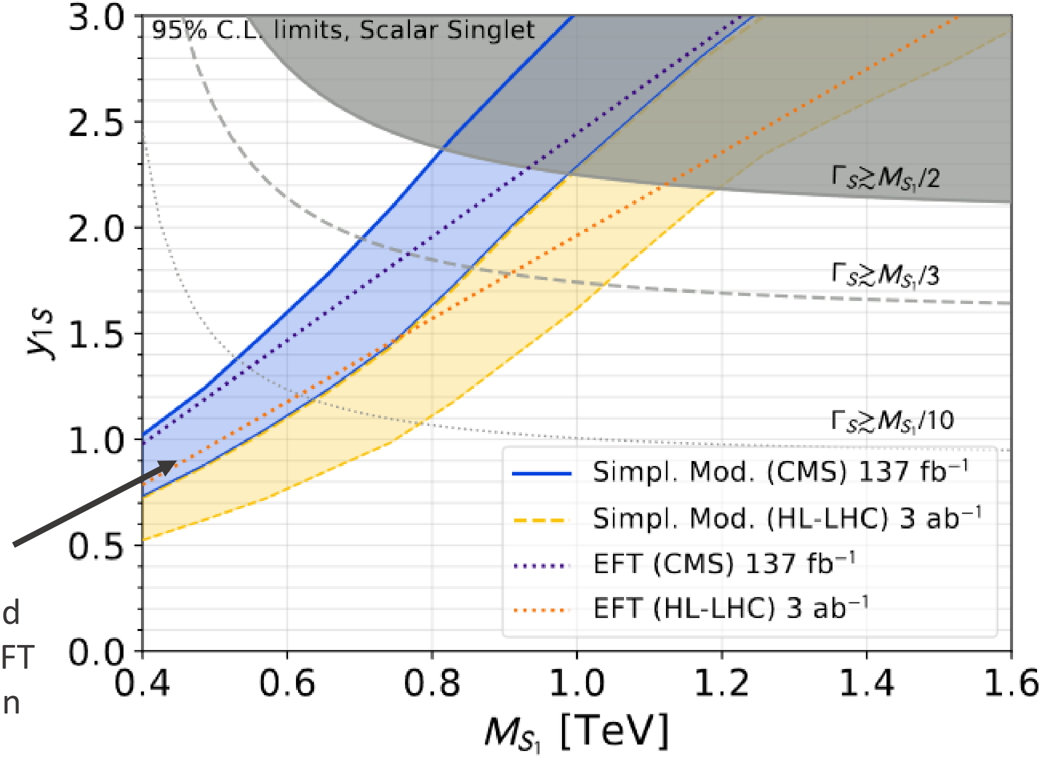
Large pT from octet decay



Results, singlet case

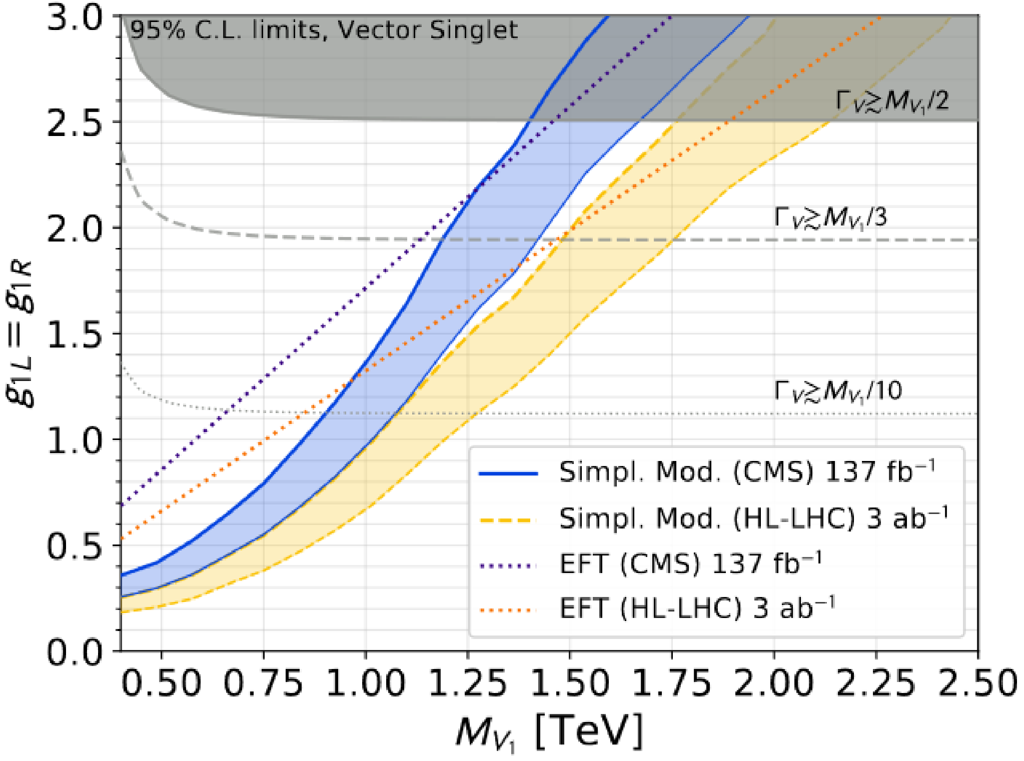
- Bands are from varying CS by factor of 2 (K factor 1 or 2)
- Note that the simplified approach quickly breaks down at large masses (width Γ_S too large)

LD, Fuks, Maltoni -- 2104.09512



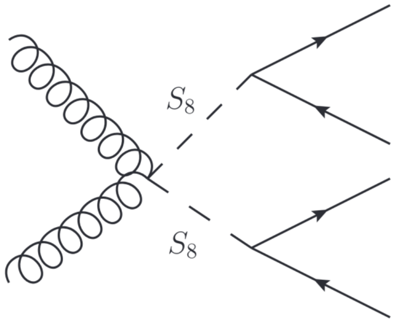
Fortuitious matching EFT/simplified model: the EFT is NOT valid in this range

LD, Fuks, Maltoni -- 2104.09512



Results, octet case

- Pair production dominates → A dedicated search strategy could deliver a massive improvement here
- Small region at large masses with good EFT/simplified match



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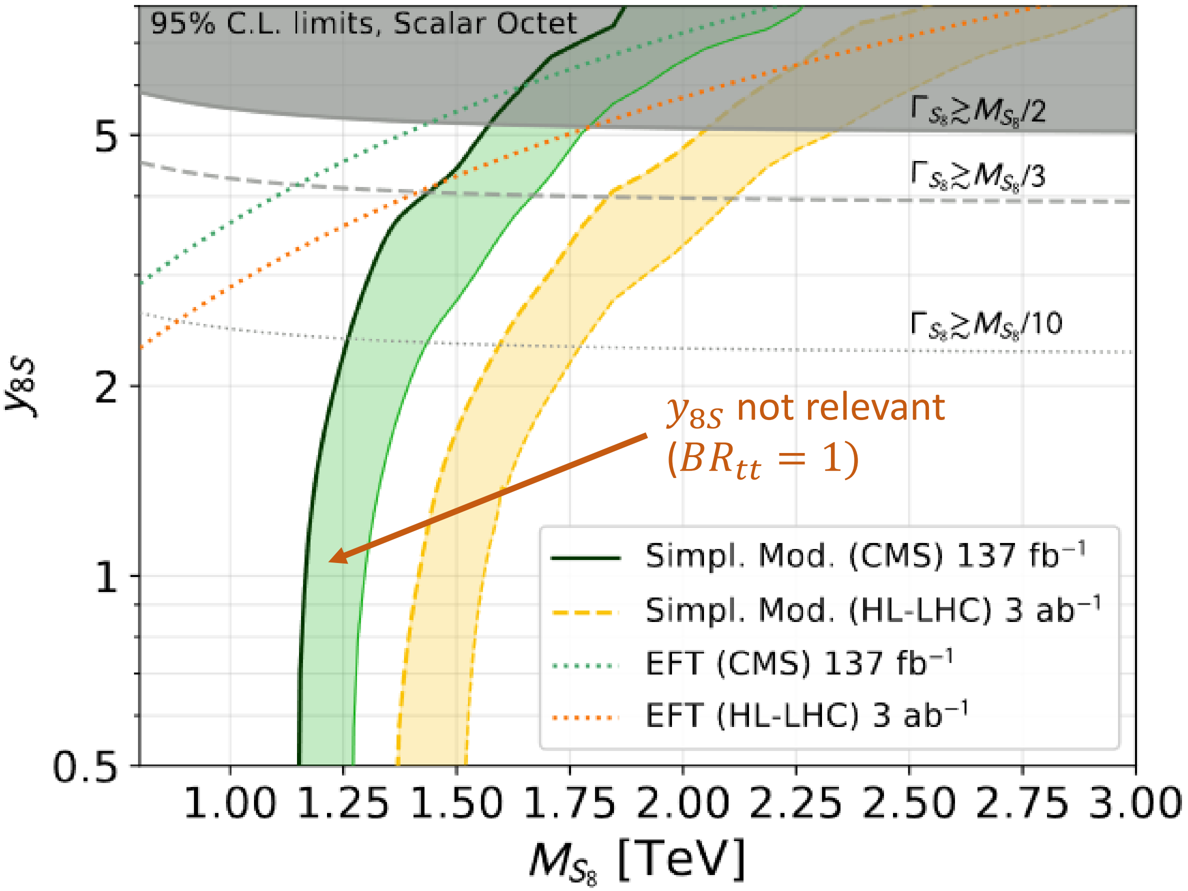
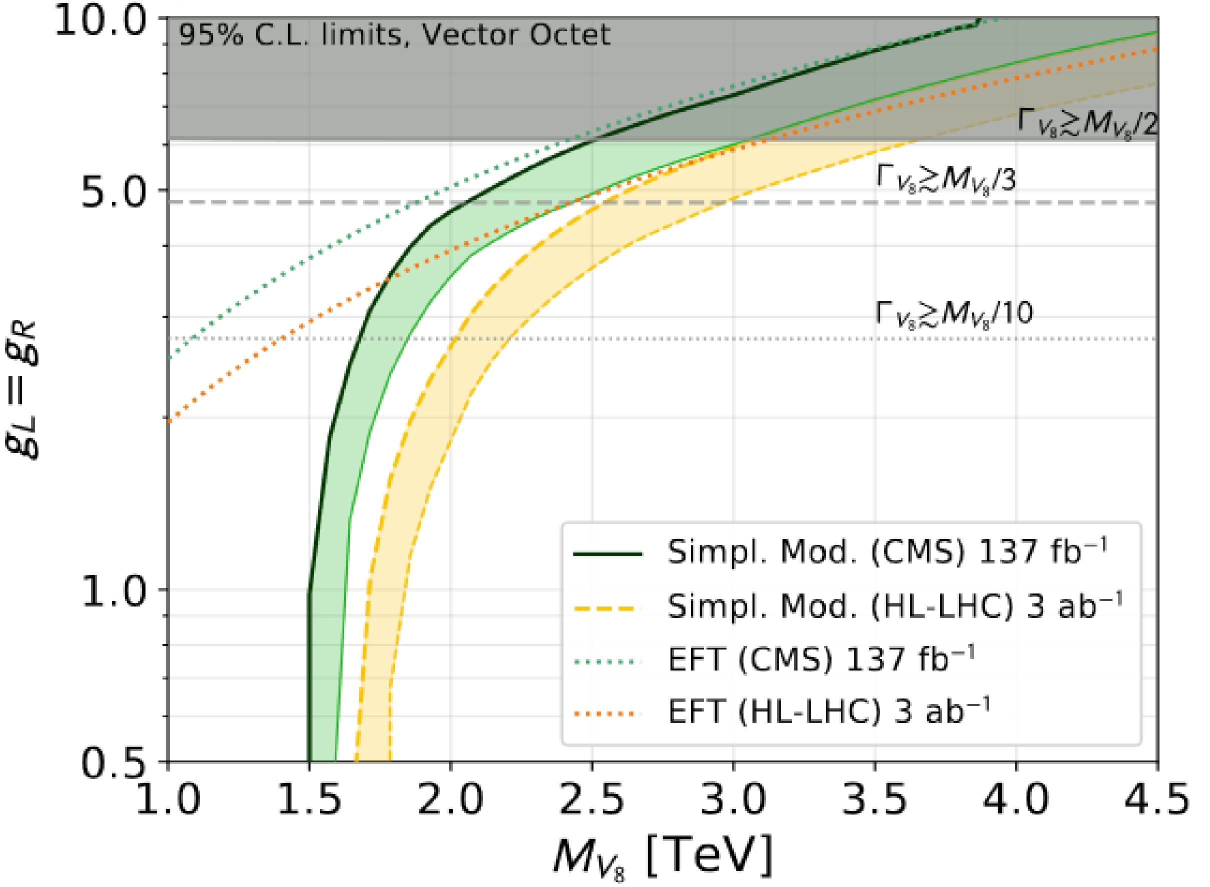


y_{8S} not relevant ($BR_{tt} = 1$)

LD, Fuks, Maltoni -- 2104.09512

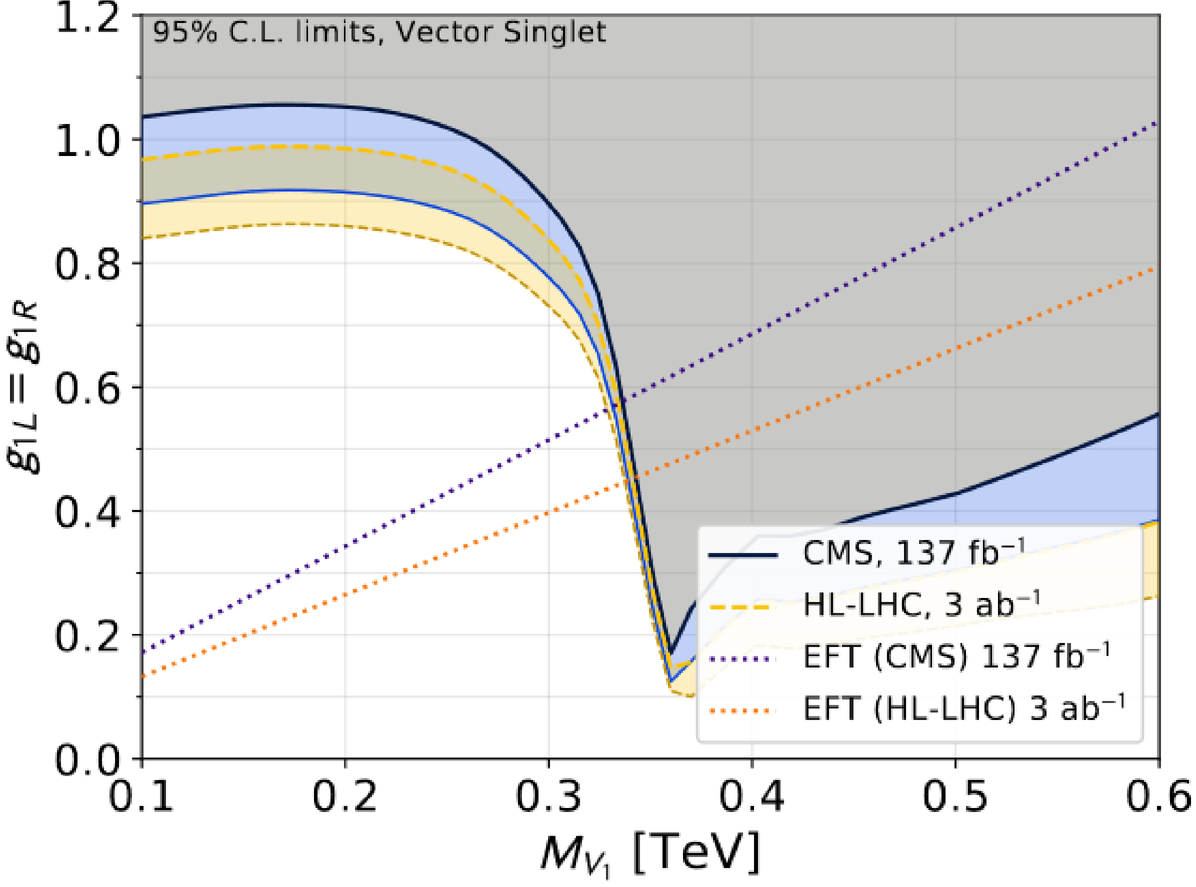


Comments on the "low masses" range

- When the top-philic particle is lighter than two top masses: no on-shell decay (to tops) available
- Situation closely mimics the existing SM processes
  - → Interference plays an important role
  - → Measurement gets close to the SM precision prediction (NP will become "systematics"-dominated at HL-LHC if no advance on theory side)

$$\sigma_{4t}^{\mathrm{SM}} = 11.97^{+2.15}_{-2.51}\ \mathrm{fb}$$

LD, Fuks, Maltoni -- 2104.09512



- Use another decay channel in ttX configuration, or compare with gluon fusion ?

  → With reconstruction of the $X \rightarrow bb, \mu\mu, \tau\tau, \gamma\gamma$ etc…

Conclusion

Conclusion

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

  → Experiments are still statistically limited

- Still a pretty active field on the theory side !

  → We are getting a better control over the SMEFT predictions for this process and its range of validity (NLO estimates are going to be long run effort)

- A focus on "on-shell" NP production (resonant opportunities) is critical to properly leverage the capability of both LHC and HL-LHC

  → Illustrated by high-Ht analysis approach, m_{tttt} tail, etc …

  → New dedicated analysis strategies probably required