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

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05/05/2021

Based on 1805.10835 with B. Fuks and M. Goodsell
And 2104.09512 with B. Fuks and F. Maltoni

Outline

Introduction: 4-top and new physics

EFT vs simplified models: matching and CS analysis

Re-interpretation and experimental efficiencies

Updated limits and projections at HL-LHC

Four top signatures and New Physics

- LHC is a top-quark factory

  → expectedly a very rich top-quark program

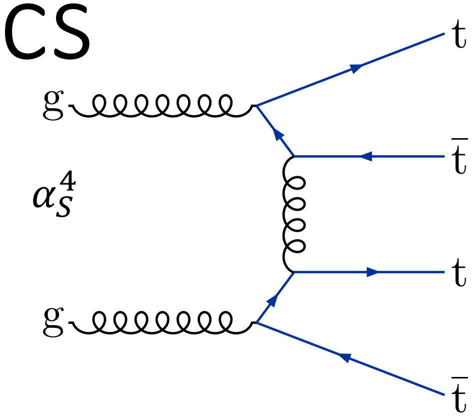
- The process pp → $t\bar{t}t\bar{t}$ is particularly interesting:

  → One of the heaviest SM final states accessible

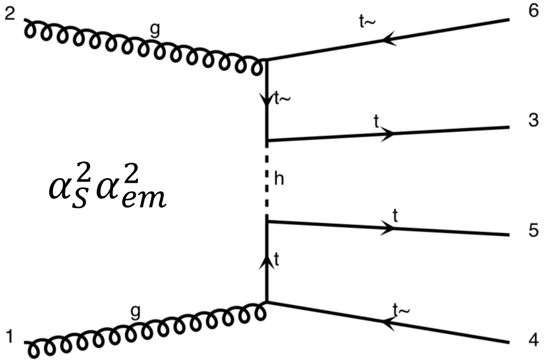
  → Much rarer than top-pair production

  (in the SM $\sigma_{pp\to 4t}^{13\ \mathrm{TeV}} \sim 12$ fb)

  → Sensitive the Higgs-induced processes



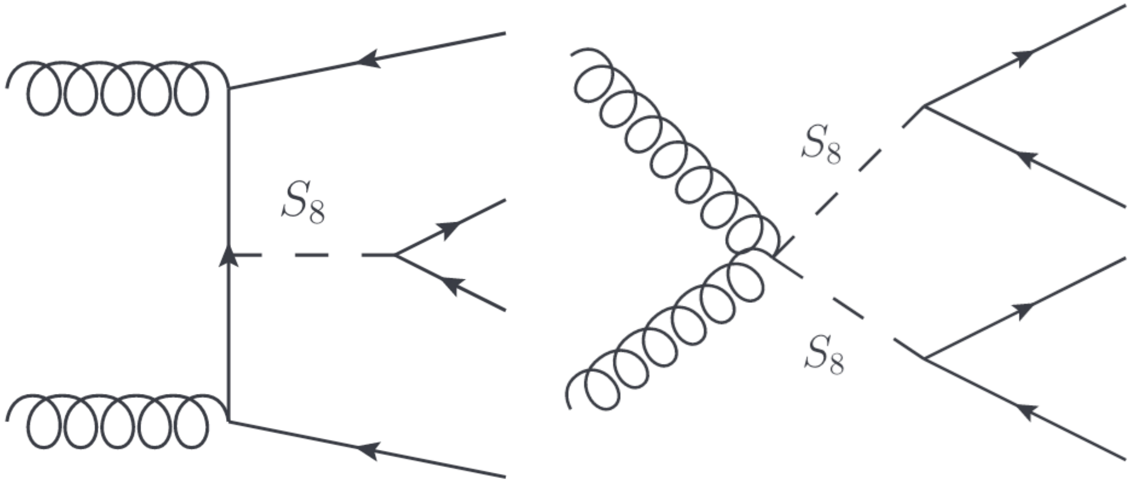
Dominant QCD-induced production



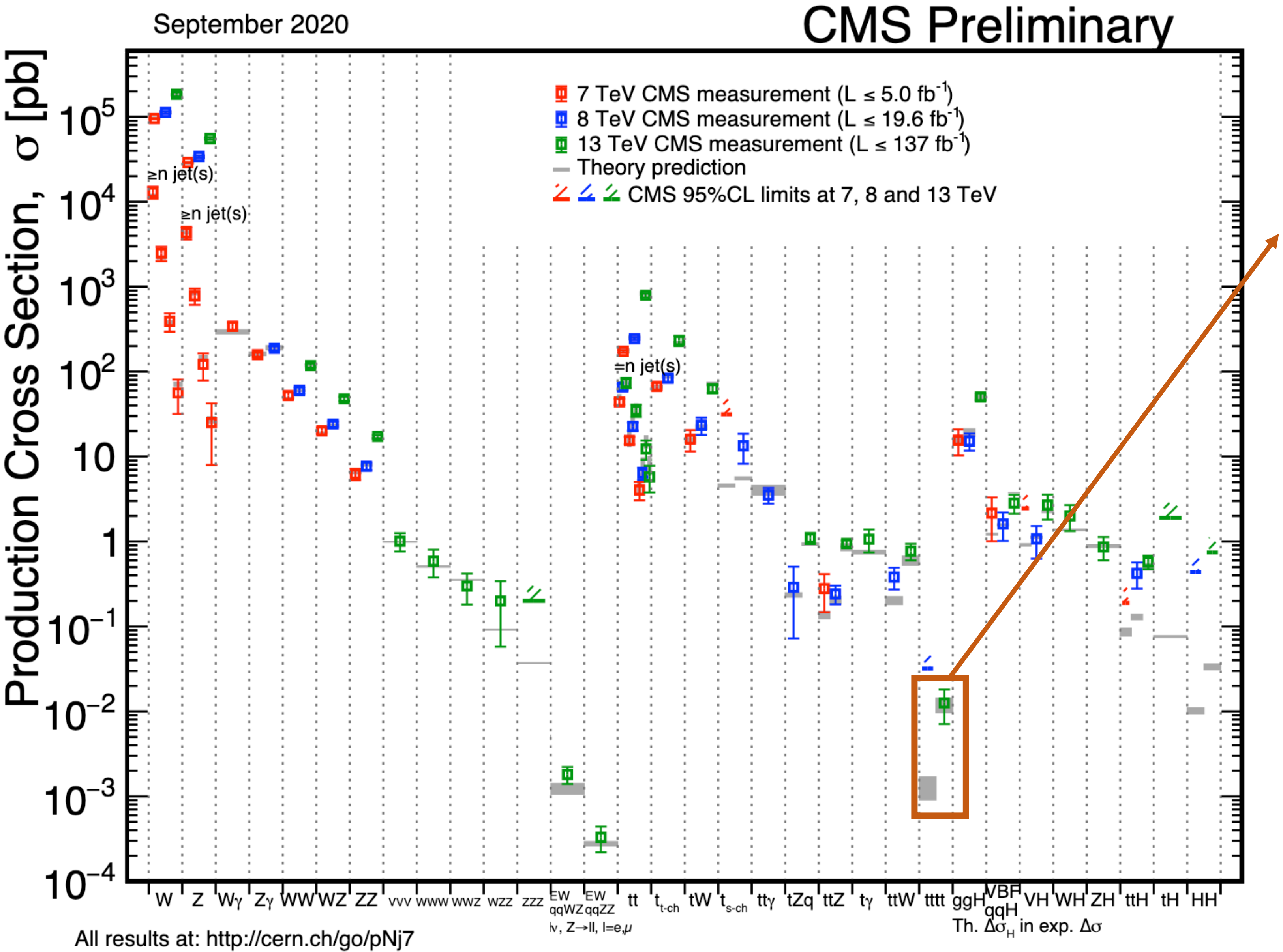
Example of EW-induced production

- Important NP search channel

  → E.g. pair production of colored top-philic particle



LHC processes, by cross-sections



At 8 TeV, SM cross-section
 ~ fb

$O(10)$ events

Run 1: ~20 fb-1

At 13 TeV, SM cross-section
~10 fb

$\sim$1400 events

Run 2: ~140 fb-1

$\sim$3000 events

Run 3: ~300 fb-1

$\sim 3 \cdot 10^4$ events

HL-LHC: ~3000 fb-1

Back in time: DM@LHC in the 2010s

- The original idea (~2010): describe missing energy searches at LHC using a effective opertors such as

$$\mathcal{L}_{\mathrm{EFT}} = \frac{1}{\Lambda^2}\left(\bar{q}q\right)\left(\bar{\chi}\chi\right)$$

- It was quickly realized that the EFT paradigm of "integrating out" heavy fields was simply not consistent at the LHC energies

$$\frac{1}{Q_{\mathrm{tr}}^2 - M^2} = -\frac{1}{M^2}\left(1 + \frac{Q_{\mathrm{tr}}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\mathrm{tr}}^4}{M^4}\right)\right)$$

Quantitative approach in e.g. 1307.2253, 1308.6799, 1607.02475 and many others

→ In the accessible parameter space, the EFT was often not relevant as the heavy mediator was produced on-shell

- This triggered lengthy discussions in dozens of paper on the best way of treating this, before focusing on simplified models

→ Note that a part of those works would then prove to be really useful for light dark matter model!

EFT and 4-top

- Top physics and EFT: building on the SMEFT approach

  LHC TOP Working Group 1802.07237

  → Important part of top WG "third generation operators"

  → Significant progresses in recent year in e.g. global fits, NLO corrections, etc…

- Relevant for new physics scenarios with composite UV (and large couplings) and heavy new top-philic fields…

Banelli, Salvioni, Serra, Theil, Weiler 2010.05915

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

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

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

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

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

- 4-top processes have small CS

  → Learning from DM@LHC, there is a good chance that an EFT approach will be relevant only for strongly-coupled model

- In this talk: we compare EFT with Simplified models, their CS predictions and in their experimental efficiencies

EFT vs simplified models

Matching and comparing CS predictions

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

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

→ 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

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

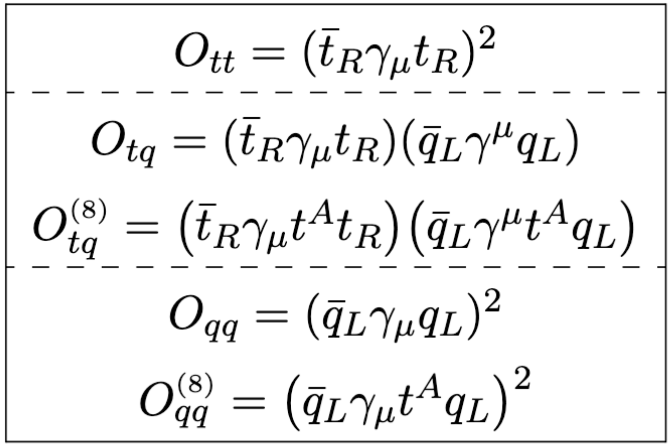
EW-breaking part (P-conserving)

$$\mathcal{O}^1_S = \bar{t}t\ \bar{t}t$$
$$\mathcal{O}^8_S = \bar{t}T^A t\ \bar{t}T_A t$$

EW-preserving part

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

Also two further P-breaking operators…



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

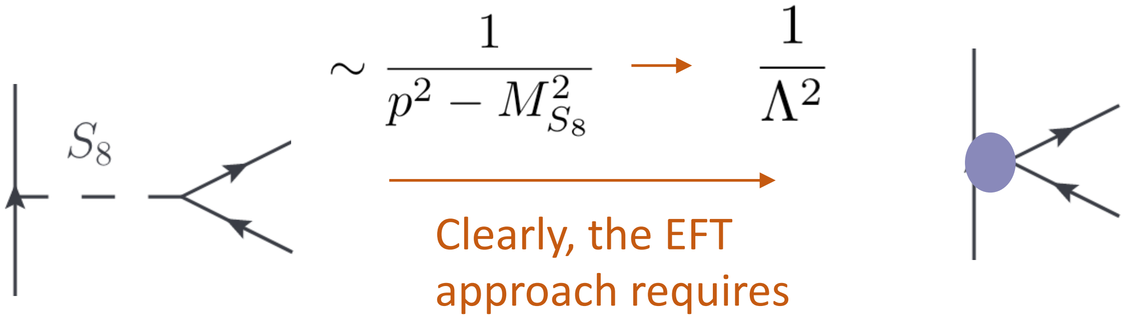
Four-top operators used in 2010.05915

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

Simplified models matching (1.0.1)

- Integrating out the to match EFT and simplified models (particularly easy in this case)

  → Followed by Fierz transformations to fall back to our minimal basis …



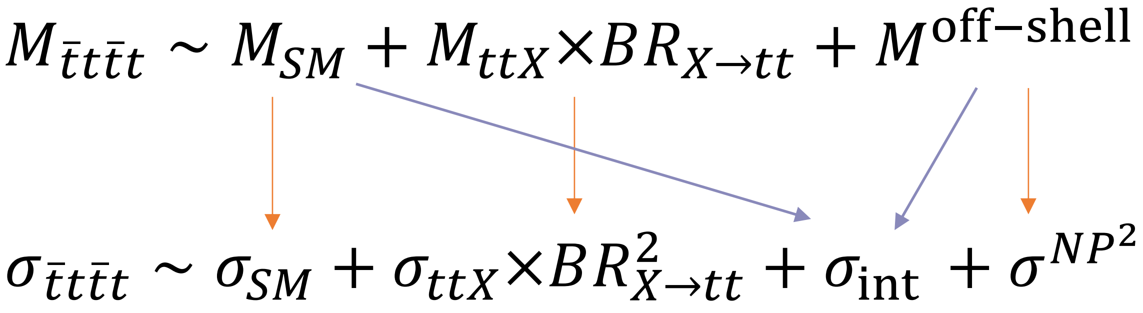
Clearly, the EFT approach requires heavy top-philic mediator

- The EFT basis is compact enough that, e.g. pseudo-scalar top-philic particles do 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	/	/	$-\frac{g_{1L}^2}{6M_{V_8}^2}$	$-\frac{g_{1R}^2}{6M_{V_8}^2}$	/	$-\frac{g_{8L}g_{8R}}{M_{V_8}^2}$

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

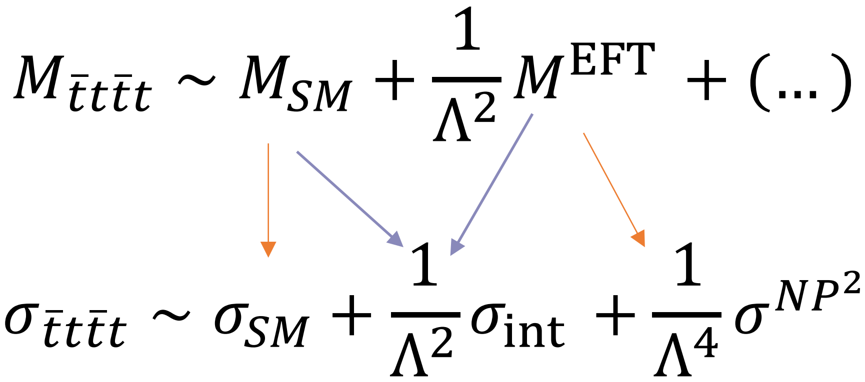


$$M_{\bar{t}t\bar{t}t} \sim M_{SM} + M_{ttX} \times BR_{X\to tt} + M^{\text{off-shell}}$$

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

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

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



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

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

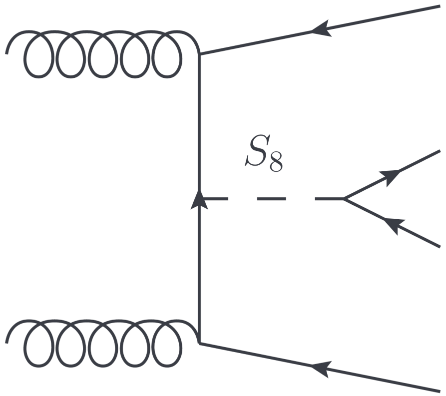
Given the current sensitivity, LHC (and HL-LHC) are in a regime with:

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

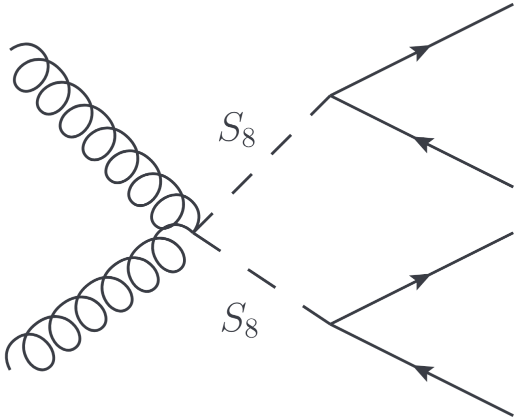
Numerical estimate: vector states

- We run Madgraph on the various simplified models + EFT
- In the low mass regime, on-shell production dominates

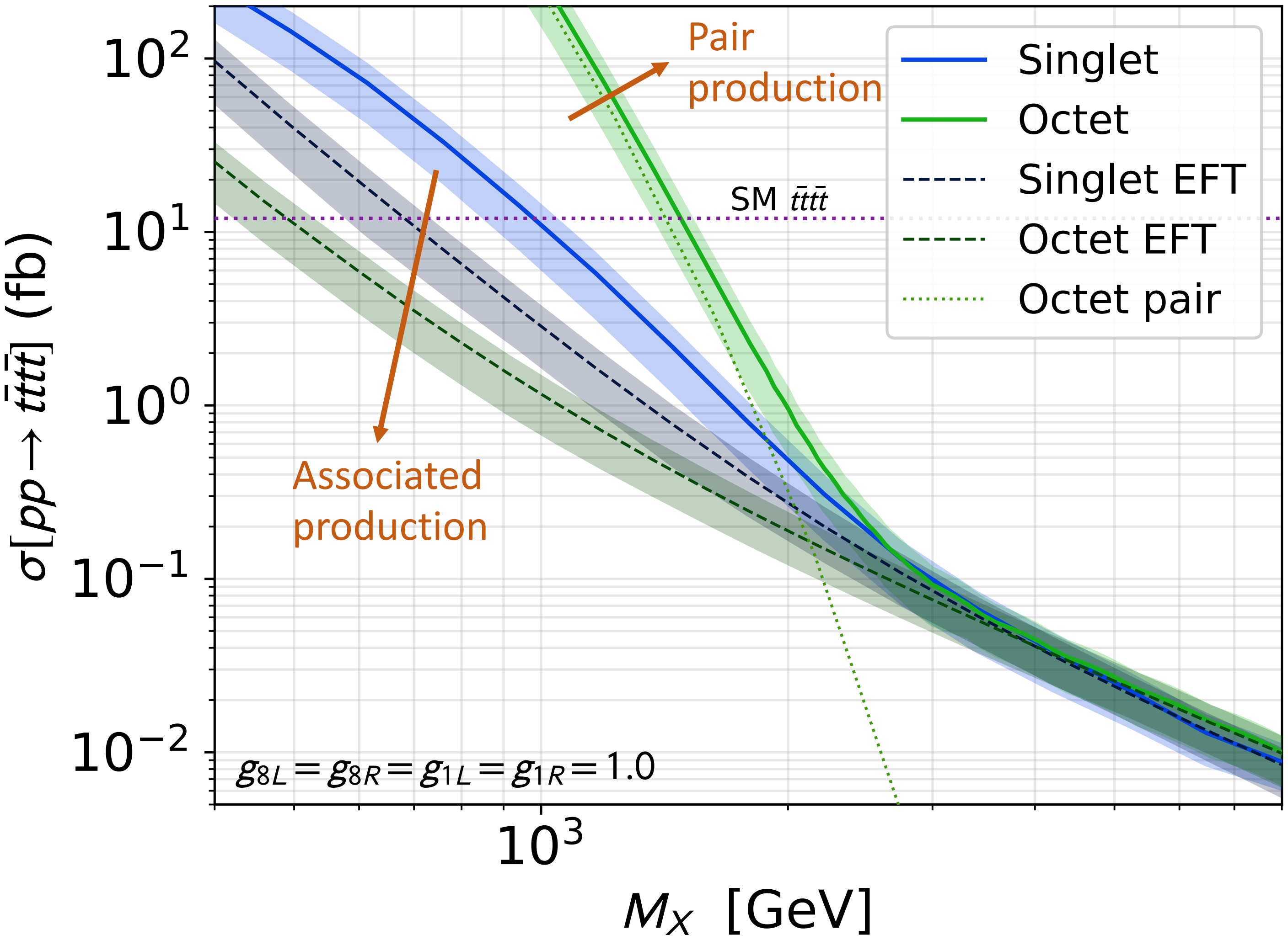
→ Either in associated



→ Or if available, by pair



LD, Fuks, Maltoni -- 2104.09512



Pair production

Associated production

CS matching, top-philic scalars

- Clearly large couplings are needed when no pair-production available …

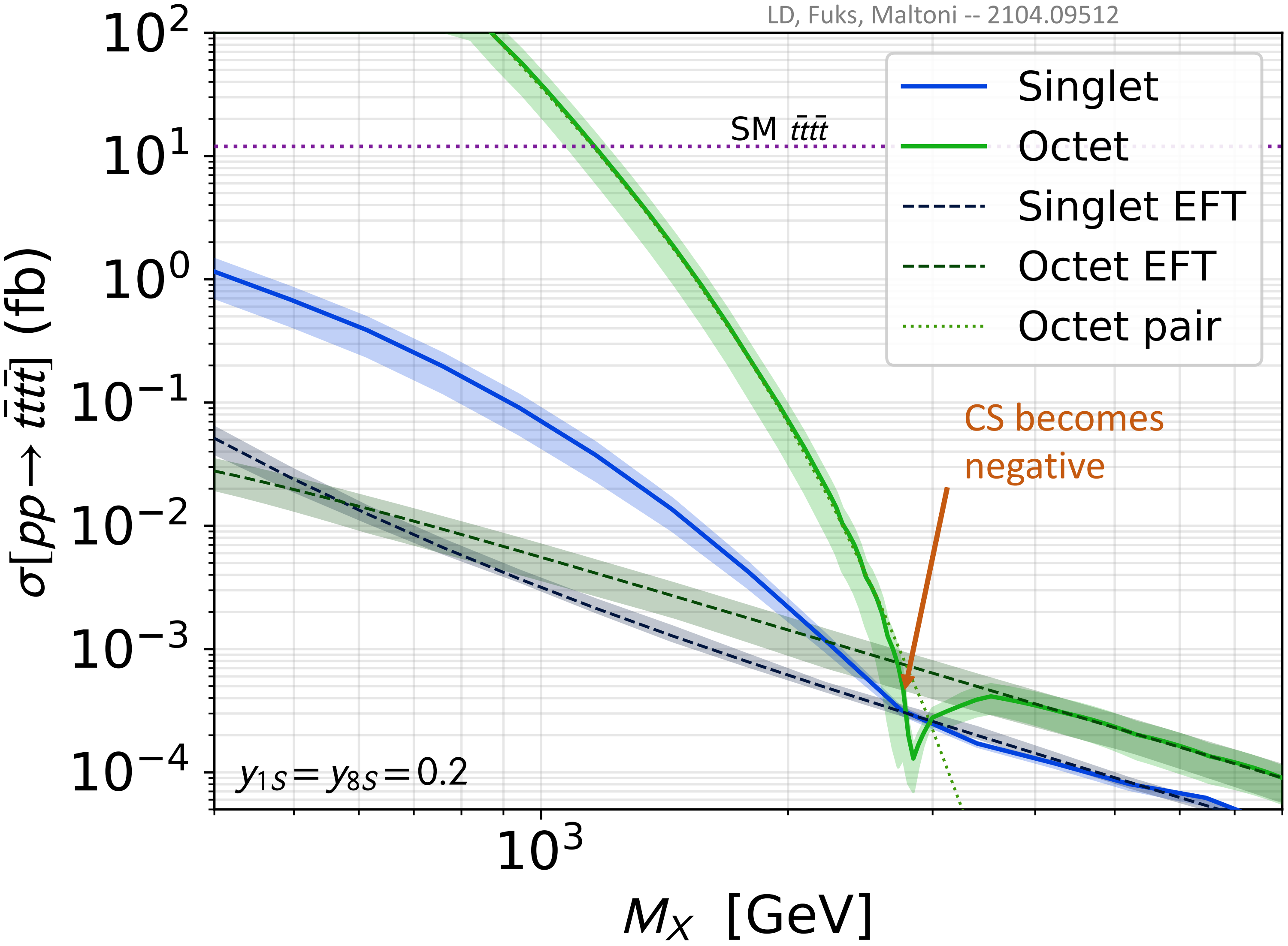
  → A word of caution: large width limit

$$\Gamma_{S_1} \sim \frac{3\ M_{S_1}\ y_{1S}^2}{8\pi}$$

  We have $\Gamma_{S_1} \sim M_{S_1}/2$ already at $y_{1s} \sim 2$

- Negative interference term for scalar octet

  → NP contribution to the $t\bar{t}t\bar{t}$ CS vanishes (then becomes negative)



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

Importance of QED interference effect (LO)

- EFT approach includes interference with SM, but this SM contribution is quite small ($\sim$ 0.01 pb)

→ Not the ”standard” case of “small effect over large SM signal”, at currently accessible CS, EFT NP^2 correction still dominates

- 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

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

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

Summary so far …

- For CS of the order of 10 fb, relevant for current LHC searches: on-shell top-philic particle production dominates for non-perturbative coupling

  →One should rely on simplified model

- For CS of the order of few fb, relevant for future HL-LHC searches

  → Less clear-cut situation

  → EFT prediction are challenging, in particular at NLO

Now we will try to be more concrete and focus on studying both the EFT and simplified models in the latest CMS analysis on 4-top signatures

Detection strategy
EFT vs simplified models

Based on CMS analysis

CMS-TOP-18-003

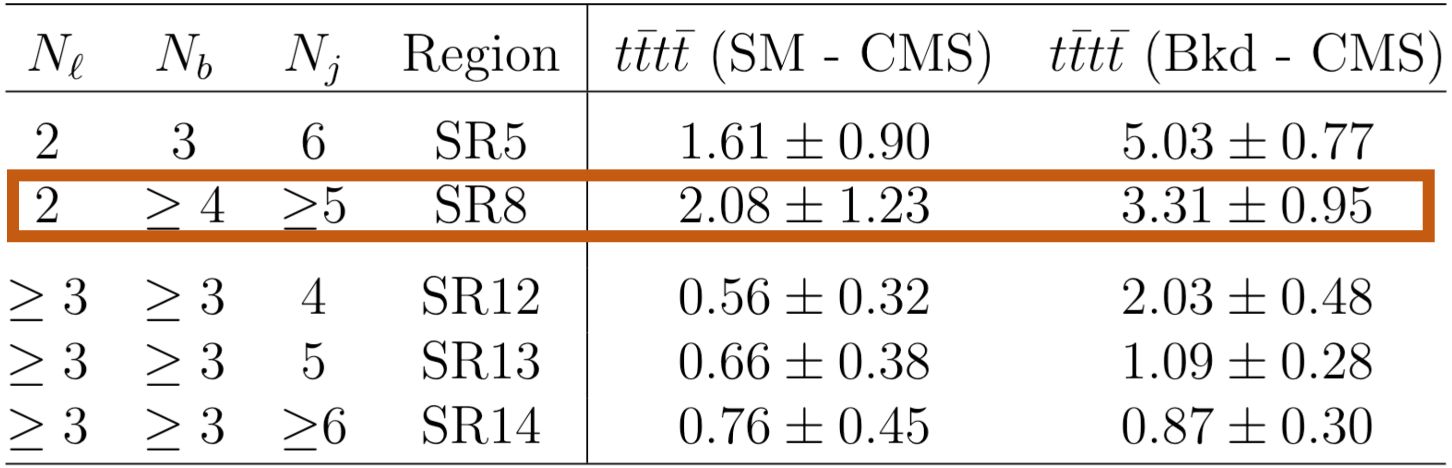
The CMS 4t analysis

- 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}

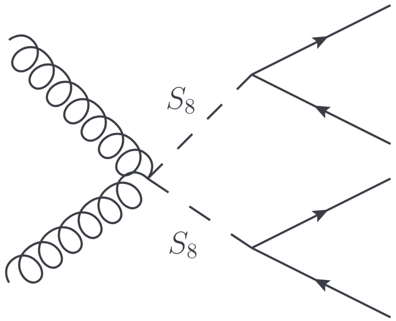
(CMS 1908.06463)

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

SM vs NP signals

- Typical NP signal use on-shell production+ decay

  → starkly different kinematics w.r.t the SM

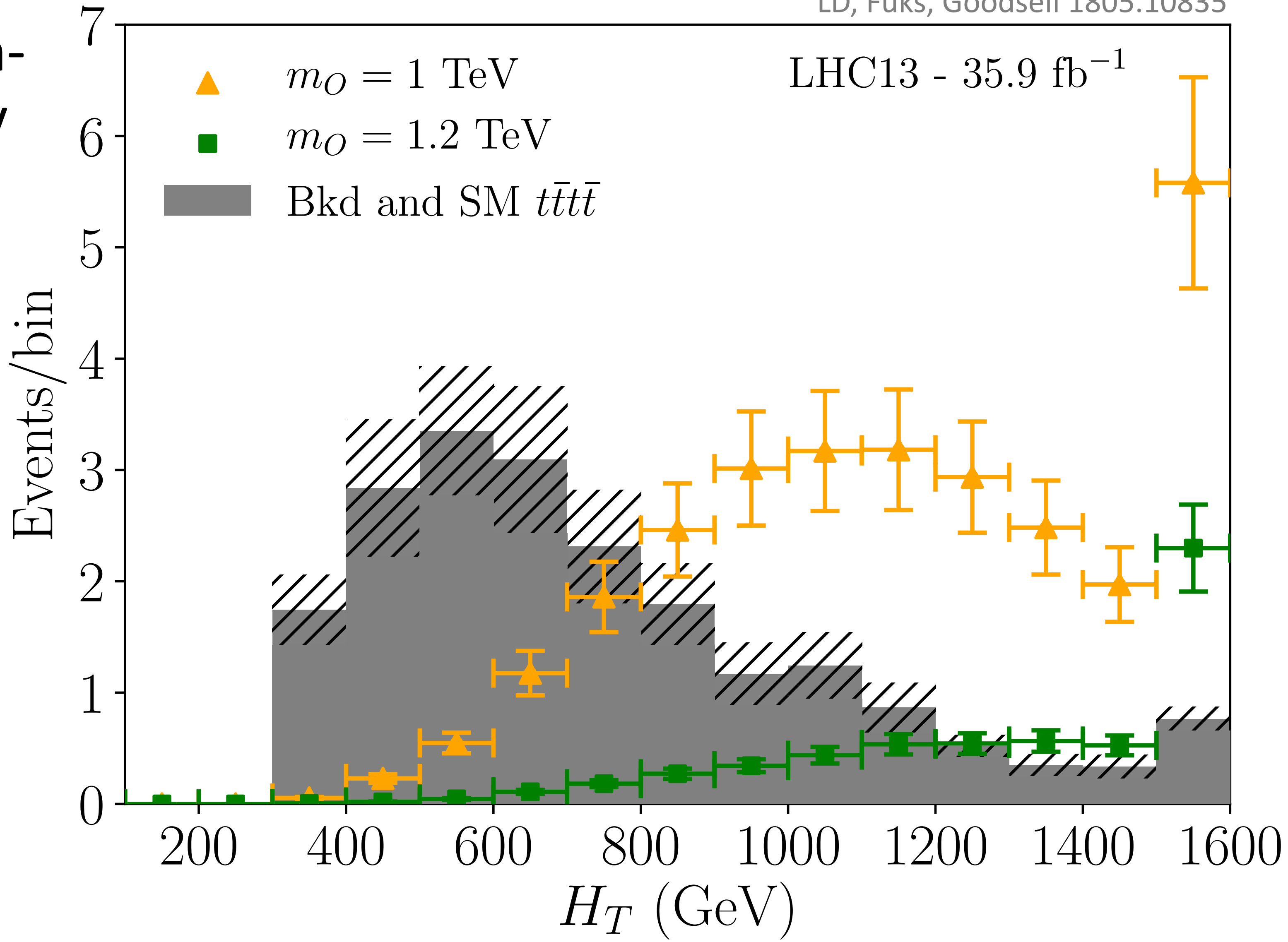


- We add a signal region with $H_T > 1.2$ TeV to the CMS search

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

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

LD, Fuks, Goodsell 1805.10835



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)]

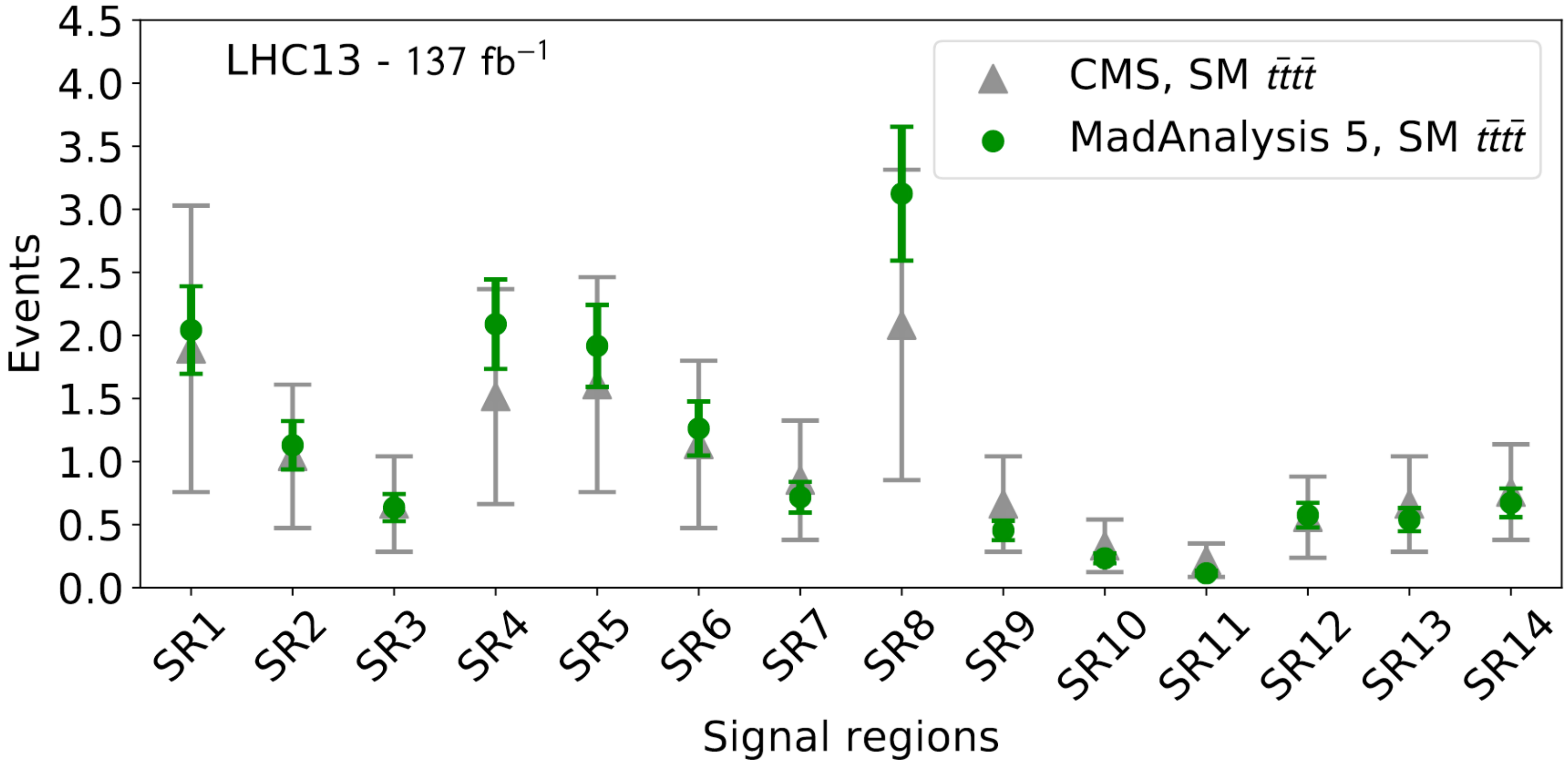
The cross-section/signal shape depends only on the top-philic particle mass. → Scan over it

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)



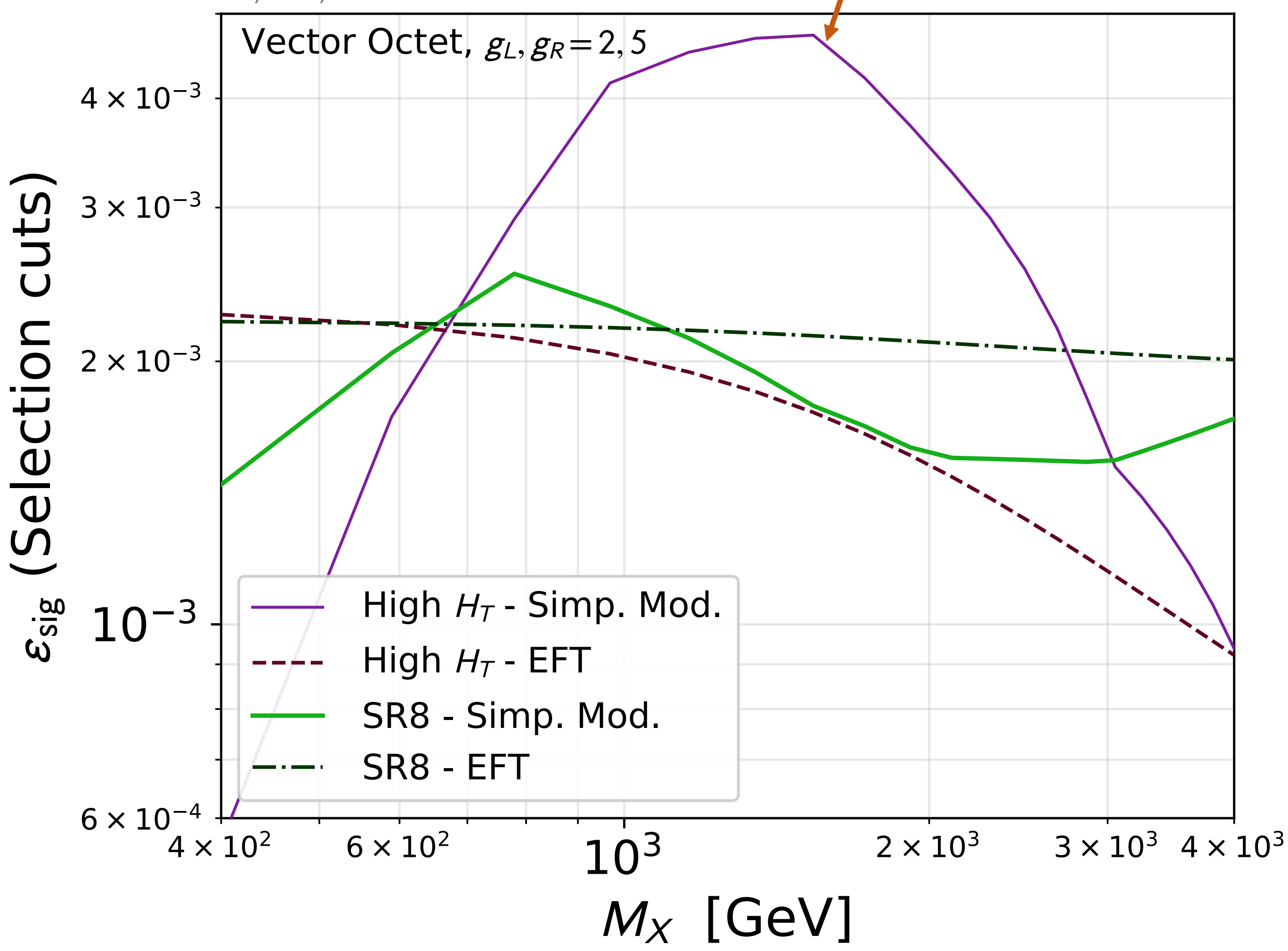
Signal efficiencies

- Comparing selection cut efficiencies for both approaches

  → EFT efficiencies close to simplified models ones for CMS analysis

- "On-shell" effects important

  → High Ht analysis has a very good signal efficiency in the 1-3 TeV mass window



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Large pT from octet decay

Summary so far …

- “Naive” recasting of and EFT analysis in term of simplified model possible
  - → Signal efficiency similar for CMS searches
  - → Compensating for the CS difference will lead to consistent limits

This also indicates that the CMS search strategy is not adapted to on-shell production in 4-top final states

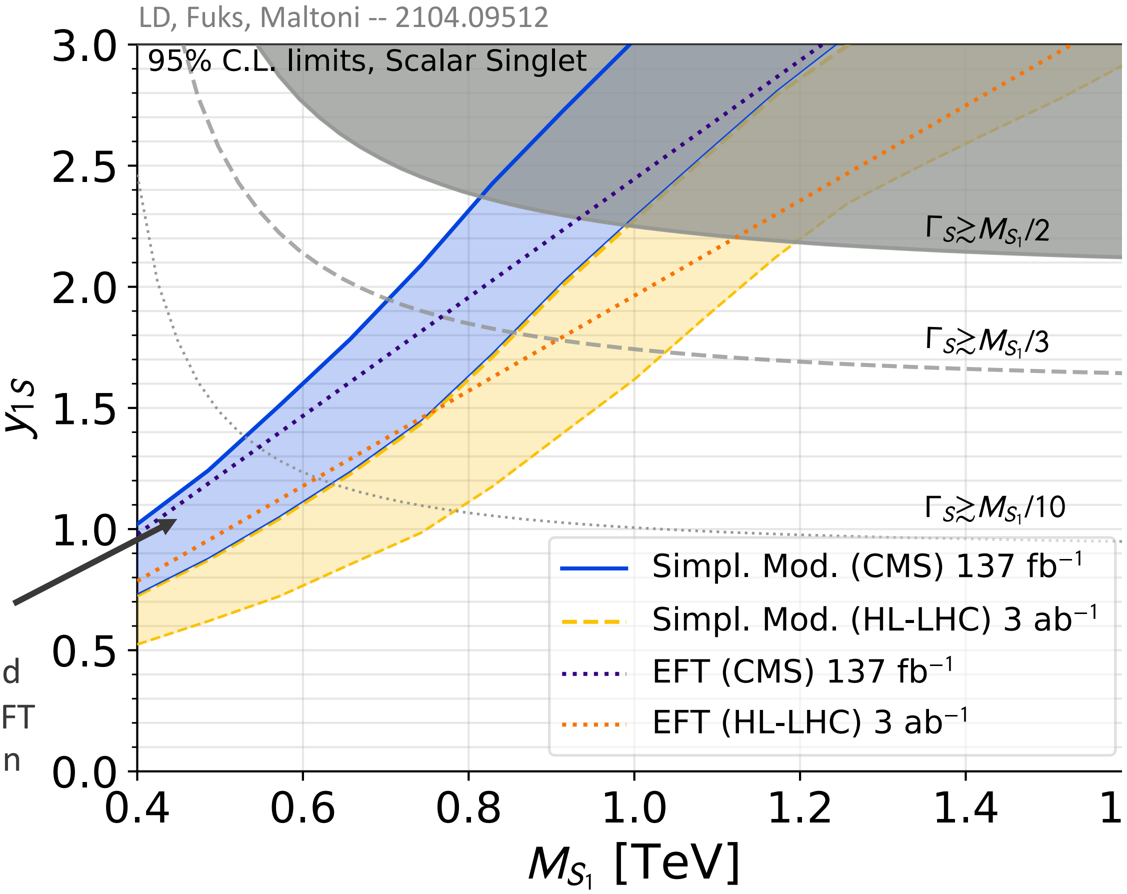
→ Even the simple “high Ht” signal region has a significantly large signal efficiencies than the full analysis

Updated limits and projections

Putting both approaches to work

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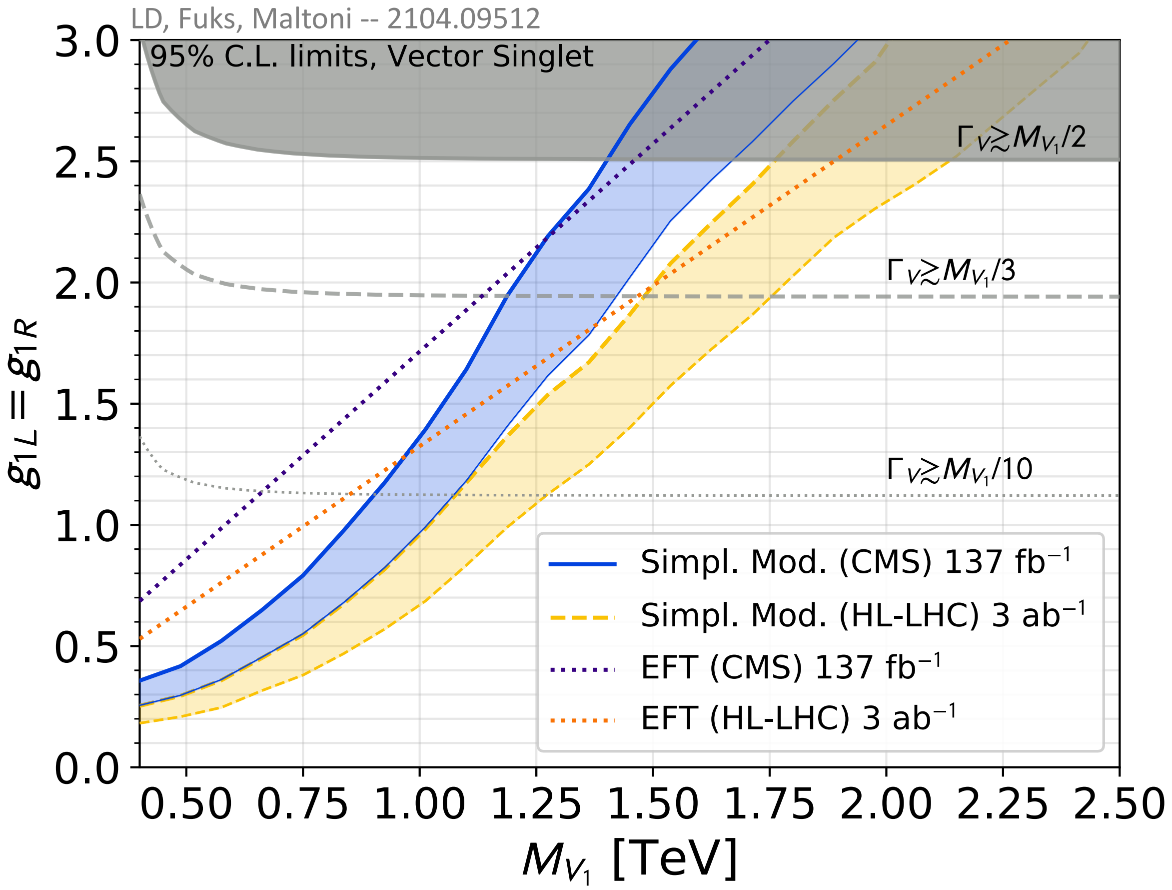
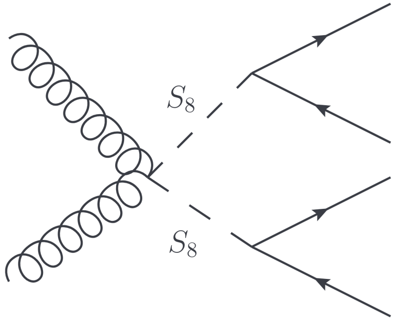
Fortuitious matching EFT/simplified model: the EFT is NOT valid in this range


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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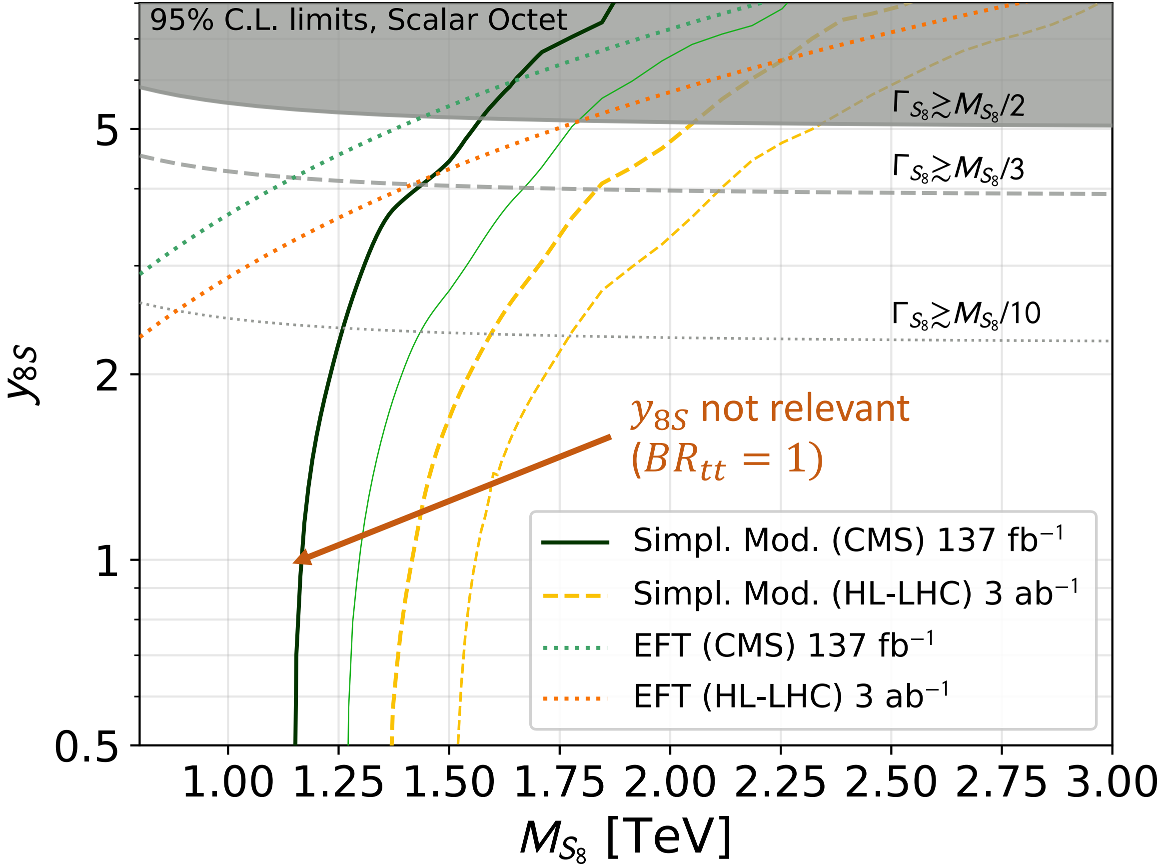

y_{8S} not relevant
$(BR_{tt} = 1)$

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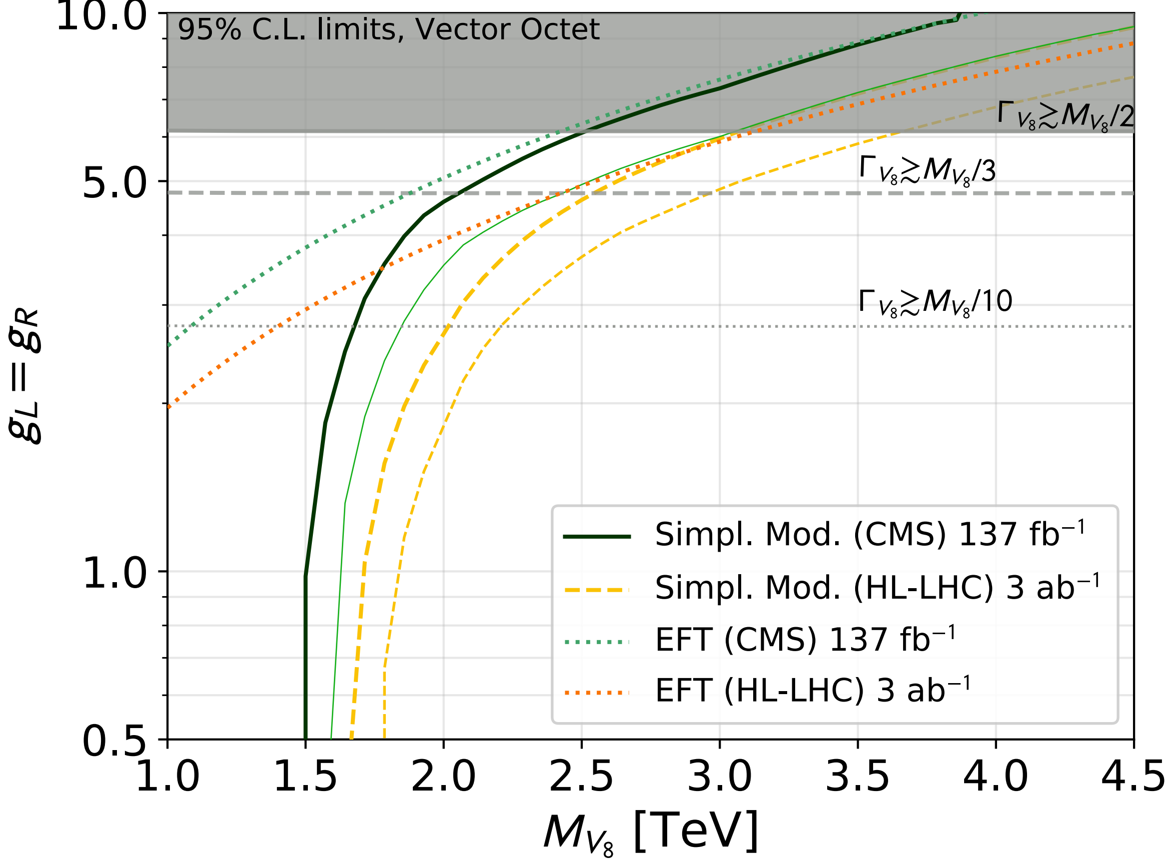

Comparison of search strategies

- Comparing both analysis (Dashed: CMS SRs vs Dotted: High Ht)

→ The latter typically dominate in the 1-3 TeV range, especially at HL-LHC

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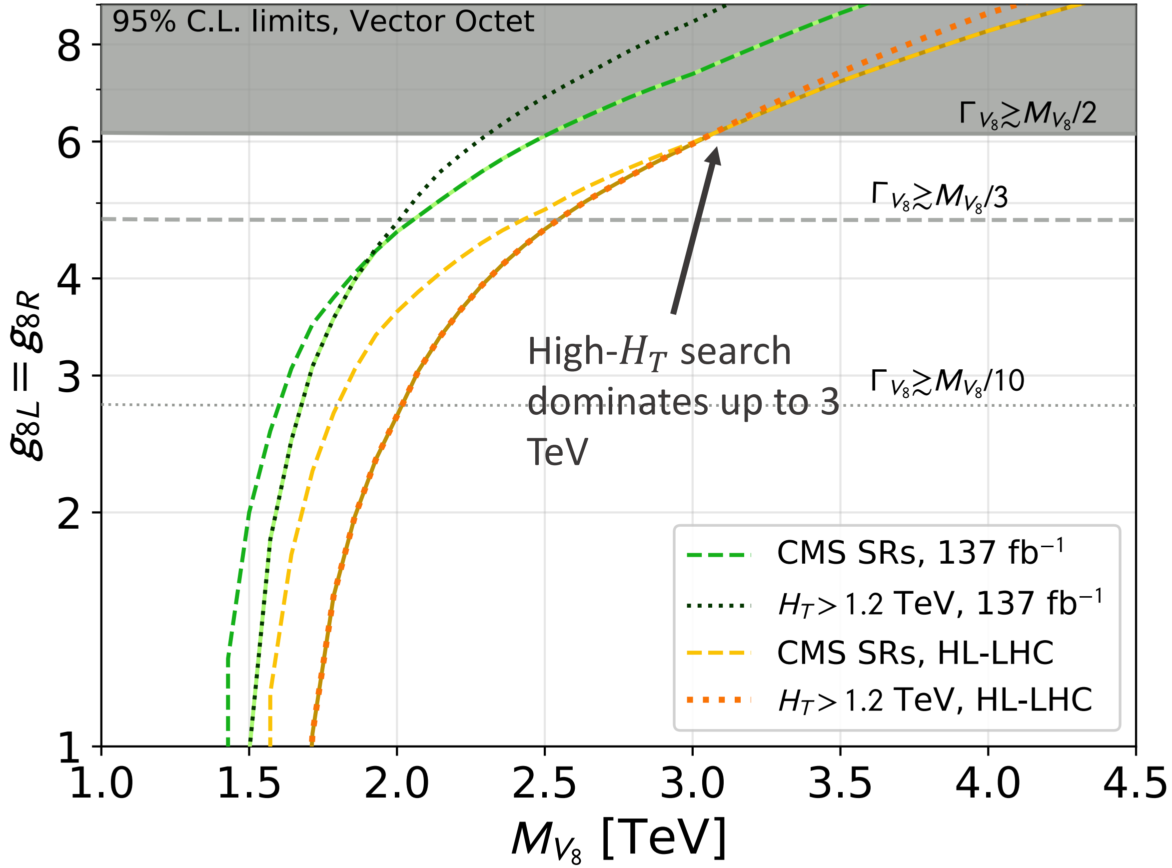

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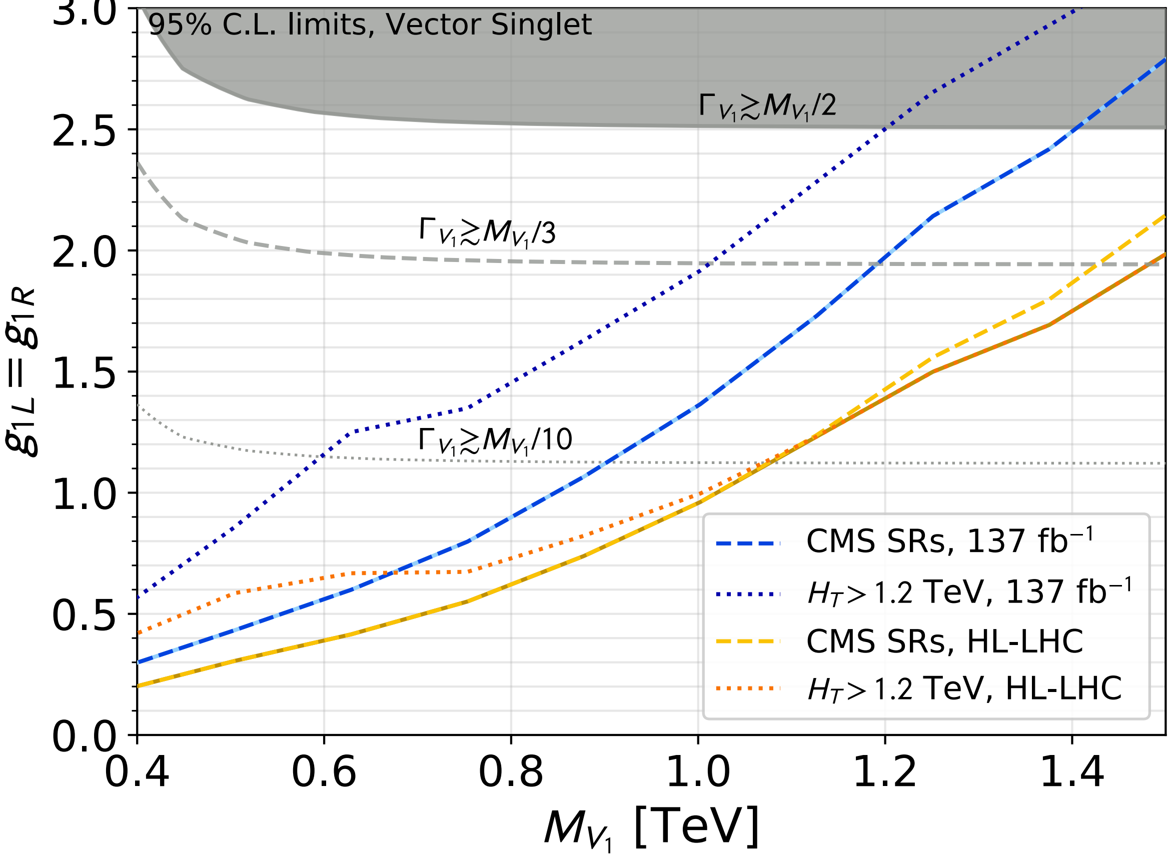


Comment on the “low masses” range

- When the top-philic particle is lighter than two top masses: no on-shell decay available
- Situation closely mimics the existing SM processes

→ Interference plays an important role

→ Use of full SM analysis from the collaborations possible (Boosted Decision Tree analysis)

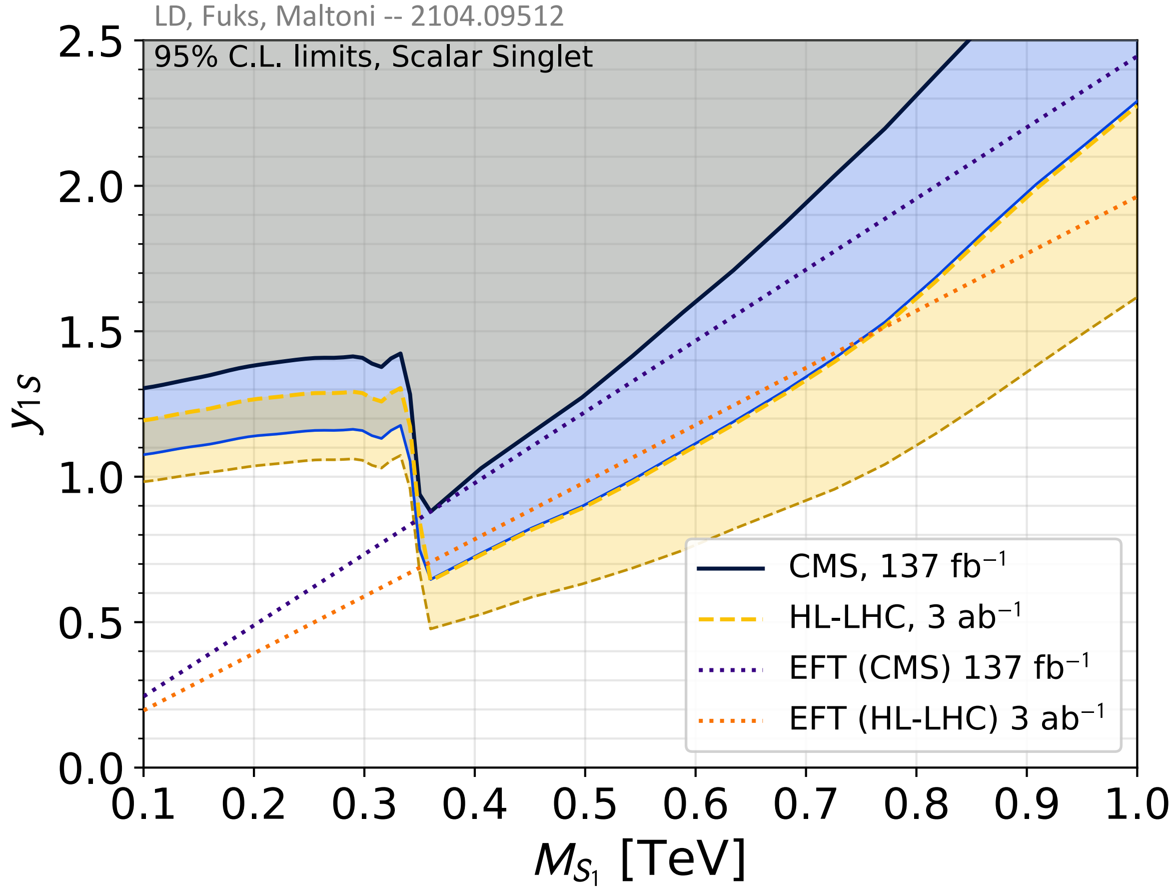
$$\sigma_{4t}^{\mathrm{NP+SM}} = 12.6^{+5.8}_{-5.4}\ \mathrm{fb}\ .$$

- Measurement gets close to the SM precision prediction

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

→ The limit on NP will become “systematics”-dominated at HL-LHC, if no additional theoretical advances on the SM cross-section

Results: low mass regime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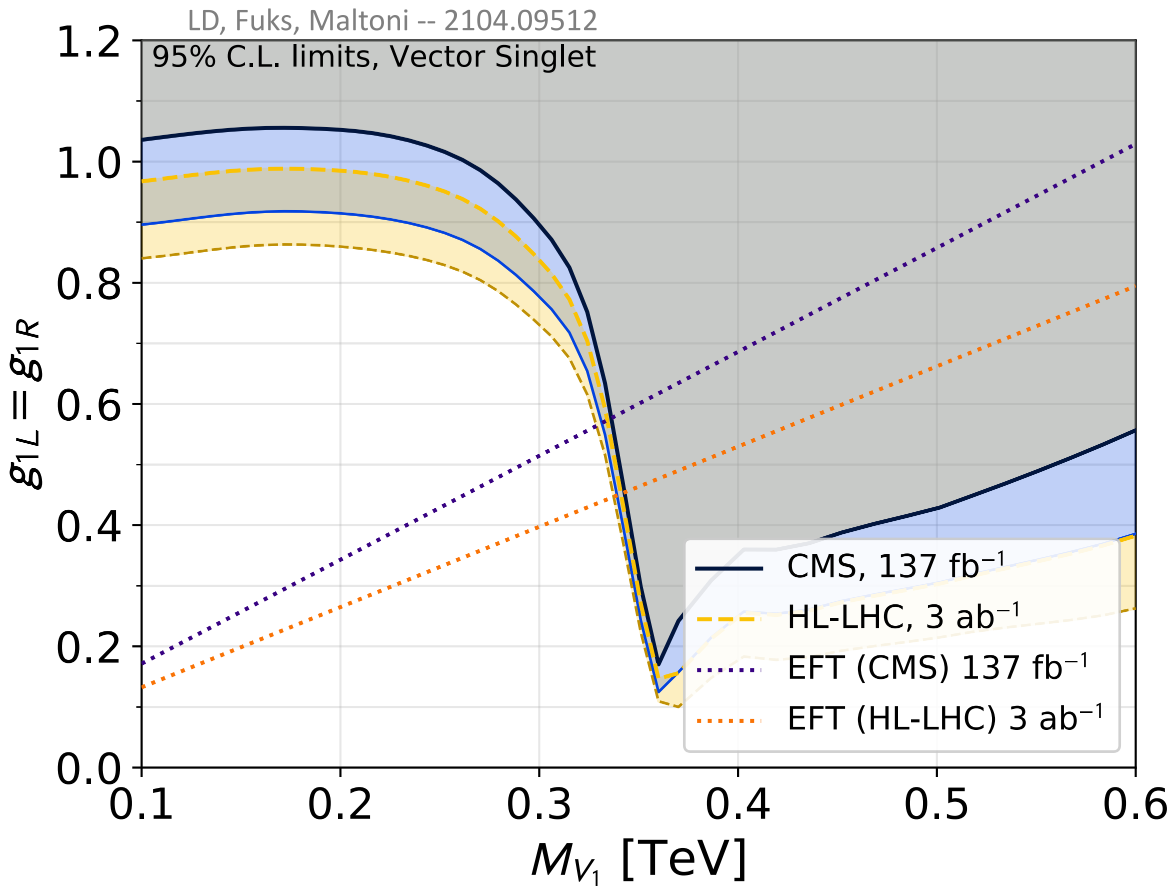
95% C.L. limits, Scalar Singlet


LD, Fuks, Maltoni -- 2104.09512

95% C.L. limits, Vector Singlet

- We use a pure vector interaction → no large CS increase at small masses
- Assumes that the signal fakes a SM topology and uses BDT results directly

Conclusion

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

- New theoretical insights needed for:

  → NLO estimates for the EFT cross-sections

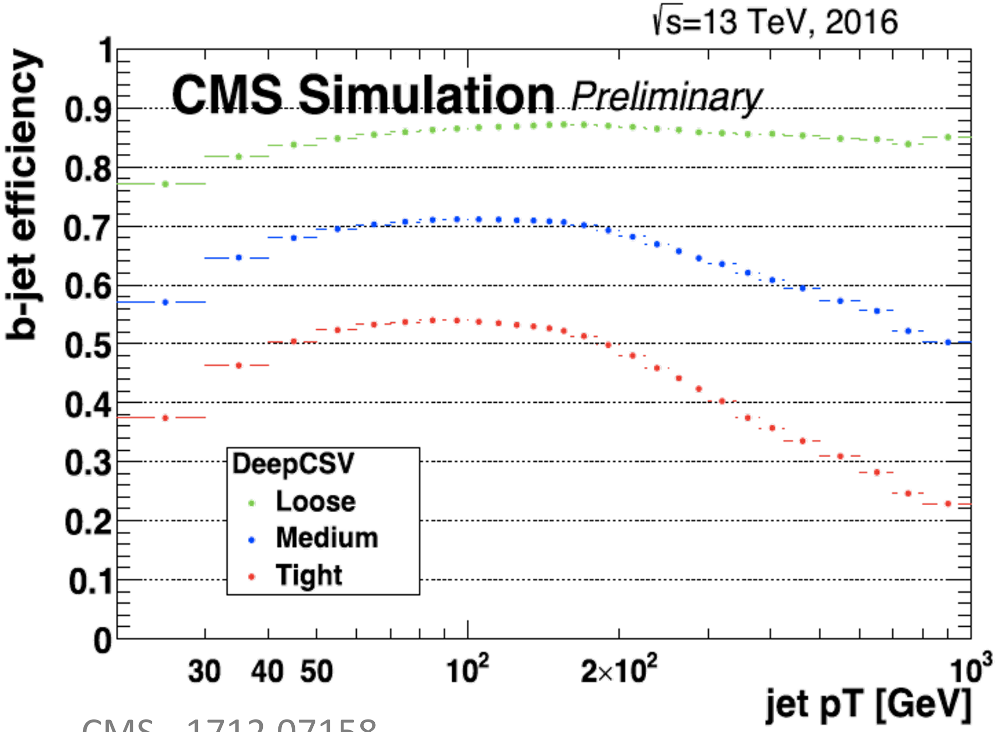
  → Higher precision for the pure SM contribution (NNLO ?)

Backup slides

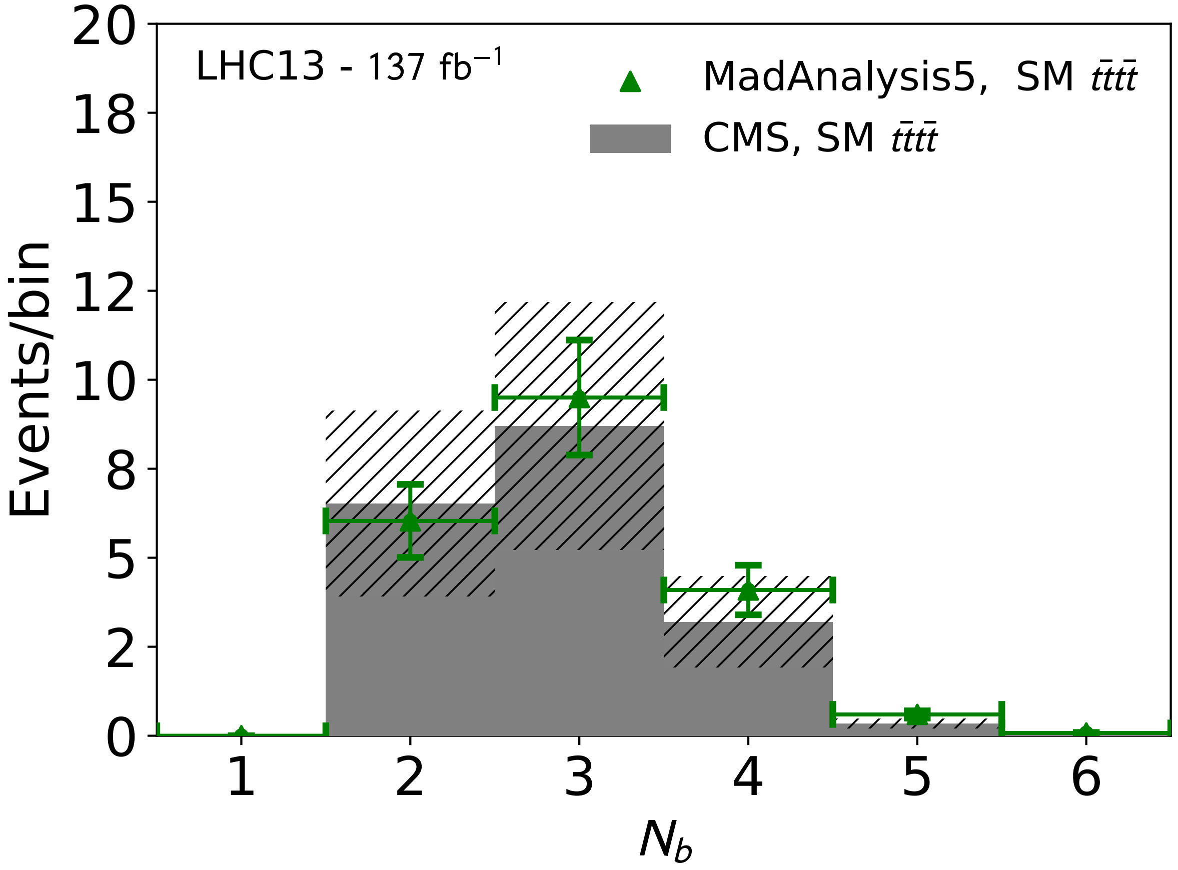
B-tagging implementation

- Signal regions depend crucially on number of b-tagged jets
    - Most simplified models have (with all 4 jets b-tagged)

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

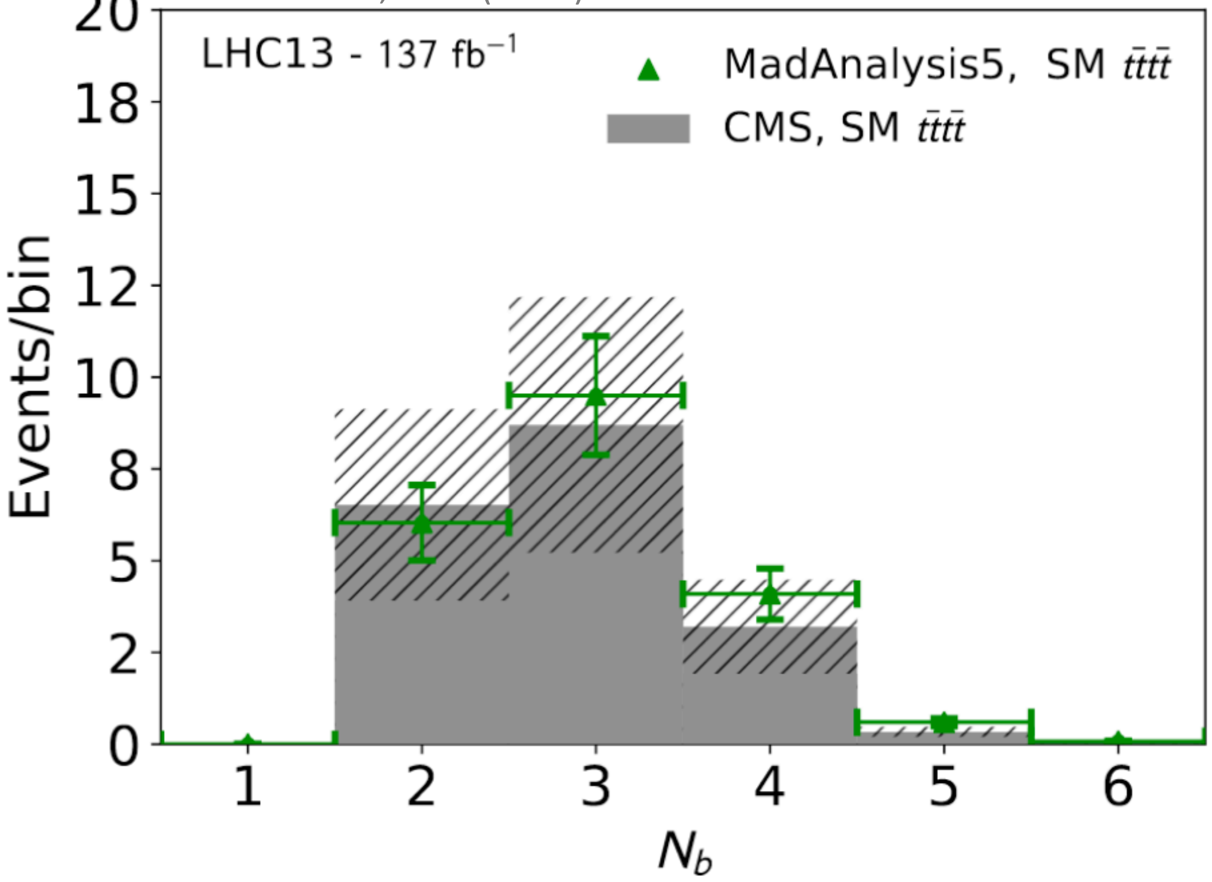


CMS - 1712.07158

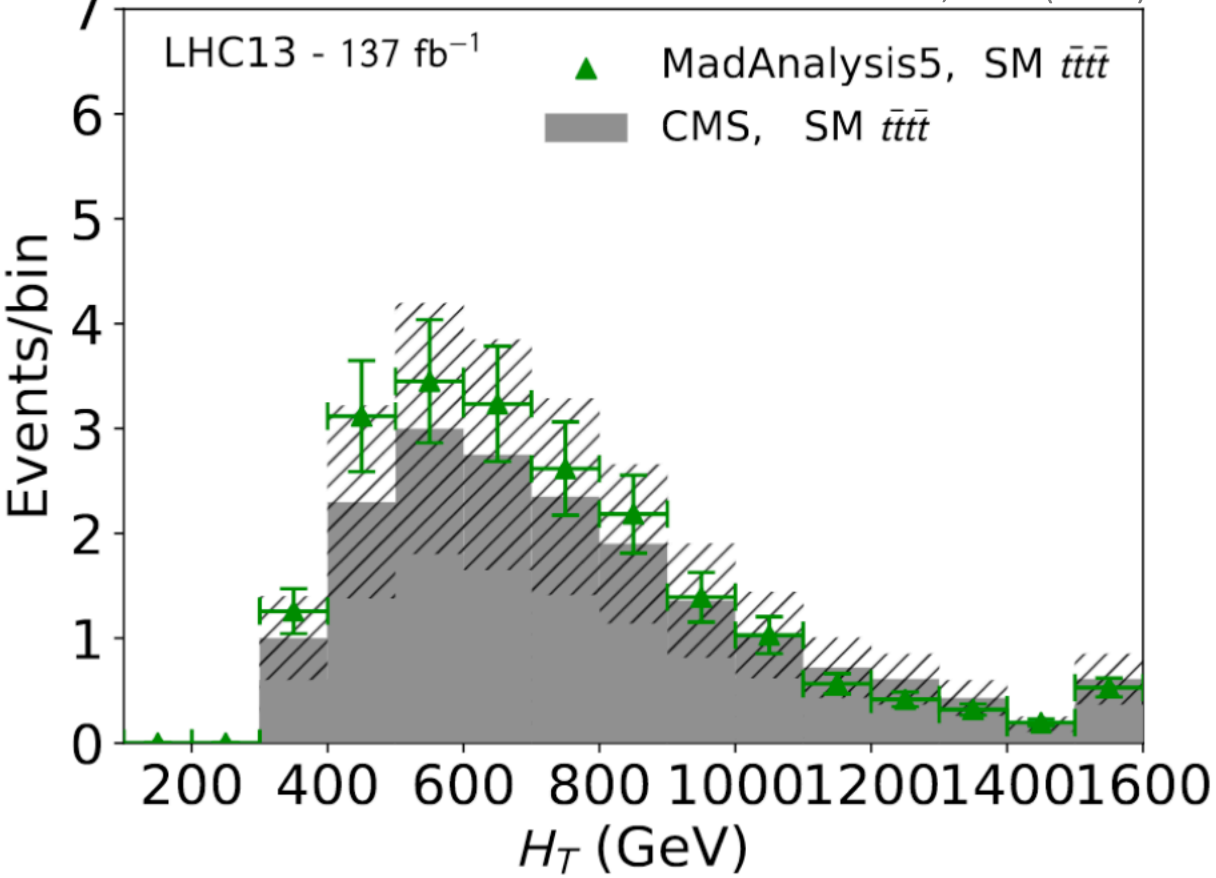


Validation – SM modeling

LD, Fuks (2020)



LD, Fuks (2020)



High Ht --CMS

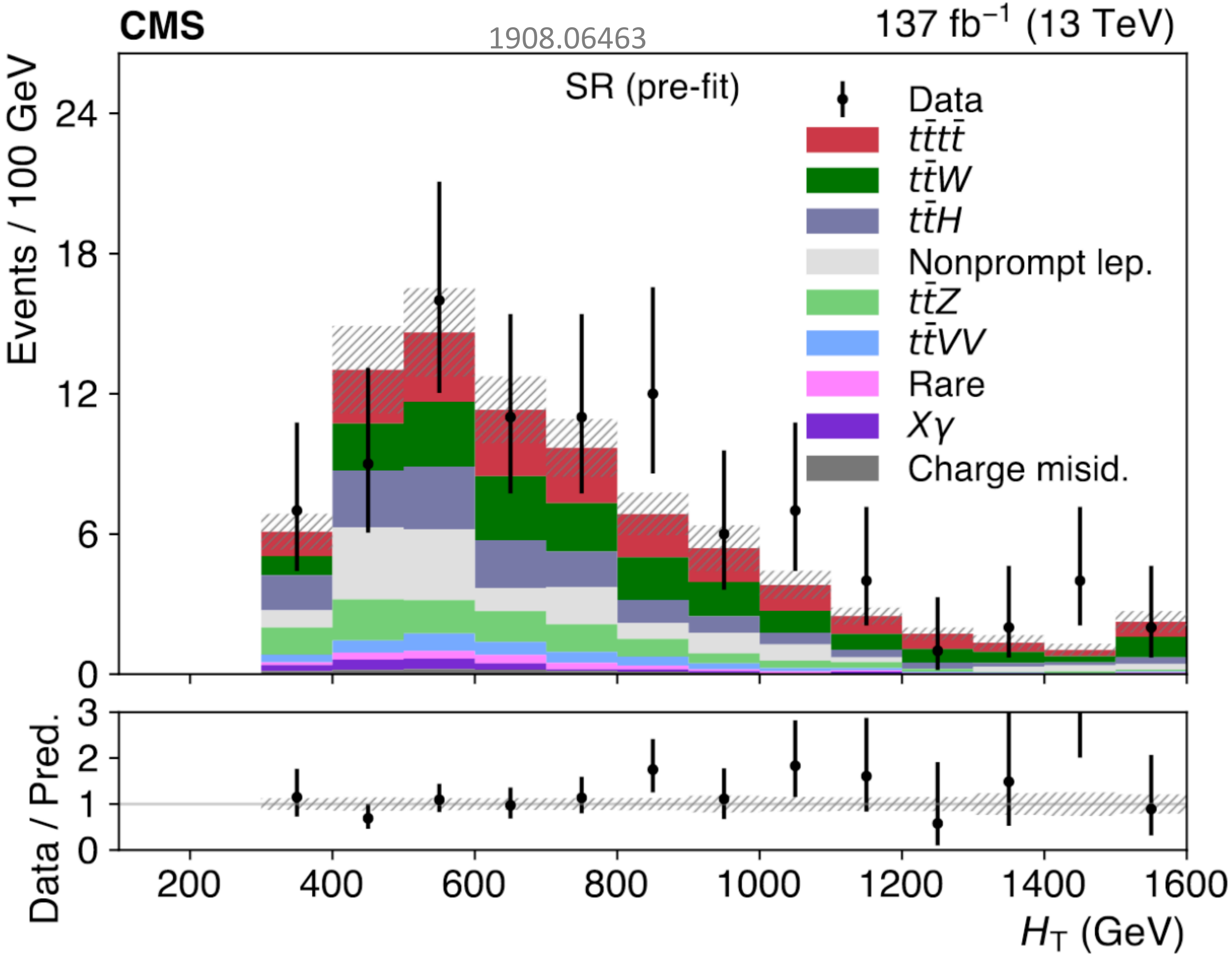
- Use the last bins
- Assume maximally correlated background (worse case scenario)

→ Very conservative limits

- Tiny excess further restricting the limits

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

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



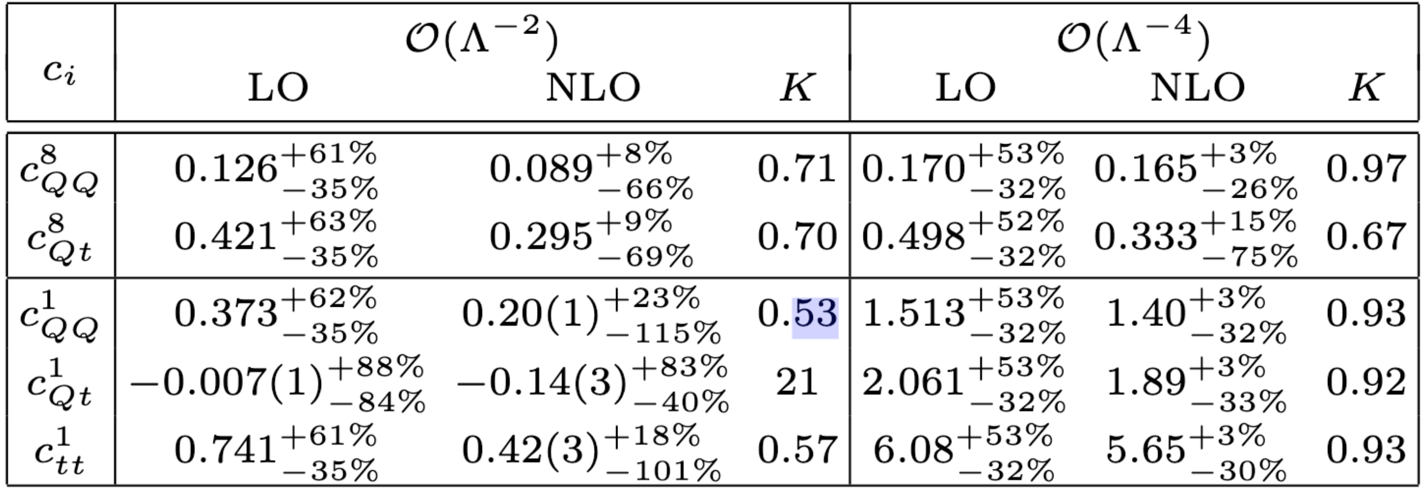
K factors

- 2008.11743 uses a relatively low renormalisation scale: 2mt to allow for comparison with pair top production
- We use:

$$\mu \in [\sqrt{s}/4, \sqrt{s}] \ ,$$

→ Typically larger, explain the difference with our LO estimate

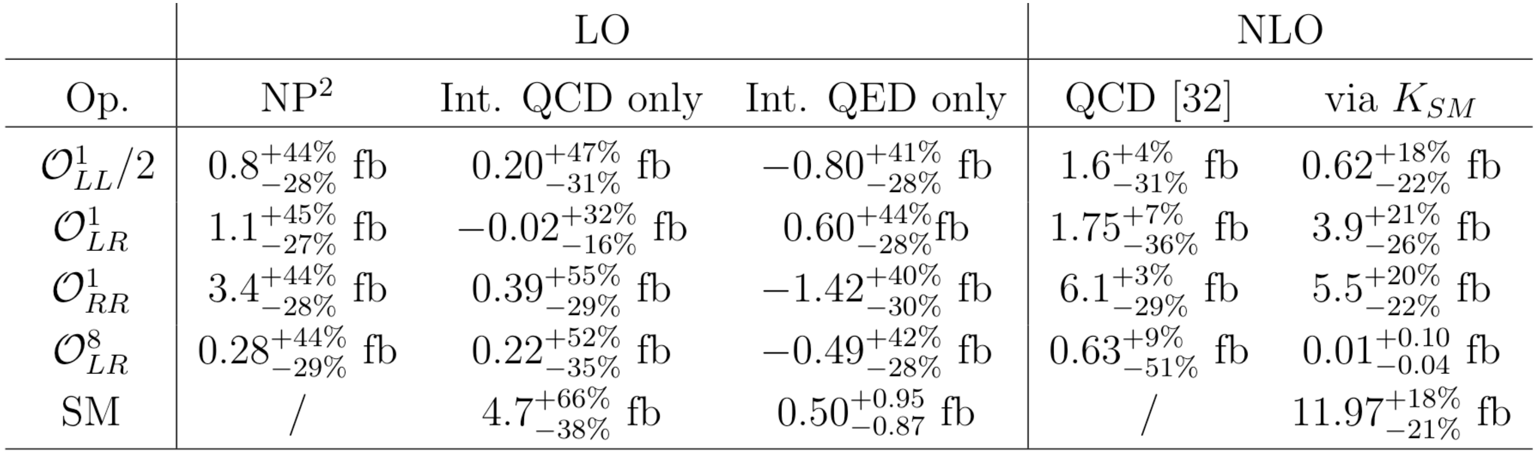
2008.11743



c_i	$\mathcal{O}(\Lambda^{-2})$ LO	NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	NLO	K
c^8_{QQ}	$0.126^{+61\%}_{-35\%}$	$0.089^{+8\%}_{-66\%}$	0.71	$0.170^{+53\%}_{-32\%}$	$0.165^{+3\%}_{-26\%}$	0.97
c^8_{Qt}	$0.421^{+63\%}_{-35\%}$	$0.295^{+9\%}_{-69\%}$	0.70	$0.498^{+52\%}_{-32\%}$	$0.333^{+15\%}_{-75\%}$	0.67
c^1_{QQ}	$0.373^{+62\%}_{-35\%}$	$0.20(1)^{+23\%}_{-115\%}$	0.53	$1.513^{+53\%}_{-32\%}$	$1.40^{+3\%}_{-32\%}$	0.93
c^1_{Qt}	$-0.007(1)^{+88\%}_{-84\%}$	$-0.14(3)^{+83\%}_{-40\%}$	21	$2.061^{+53\%}_{-32\%}$	$1.89^{+3\%}_{-33\%}$	0.92
c^1_{tt}	$0.741^{+61\%}_{-35\%}$	$0.42(3)^{+18\%}_{-101\%}$	0.57	$6.08^{+53\%}_{-32\%}$	$5.65^{+3\%}_{-30\%}$	0.93

TABLE II. Third-generation four-fermion operator contributions [fb] to $t\bar{t}t\bar{t}$ production at the LHC $\sqrt{s} = 13\,\text{TeV}$, with K-factors ($\equiv \sigma_{\text{NLO}}/\sigma_{\text{LO}}$). The SM NLO QCD cross-section is $13.9^{+10\%}_{-20\%}$ fb ($K = 1.37$).

LD, Fuks, Maltoni, 2102.xxxx

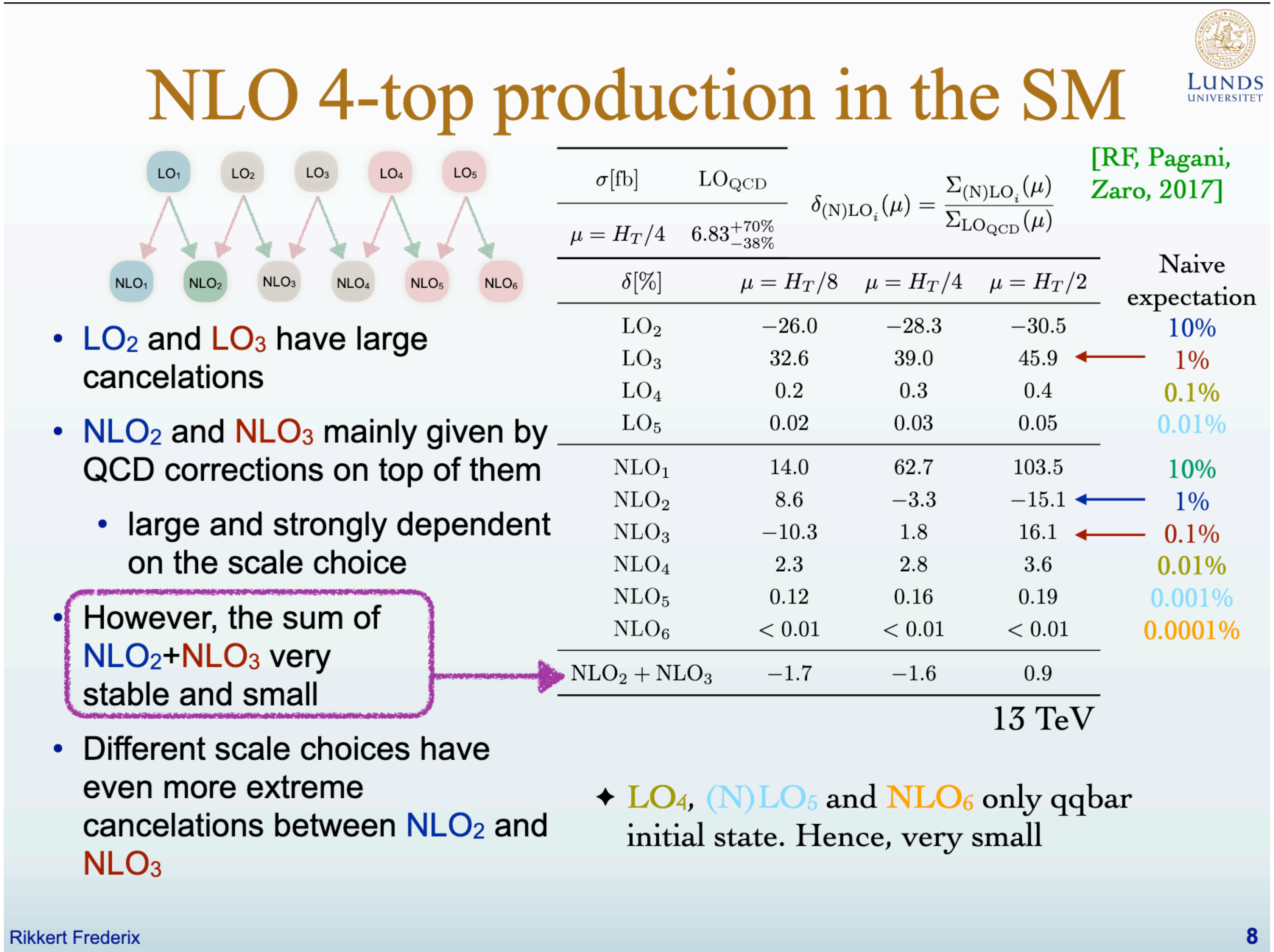


	LO			NLO	
Op.	NP^2	Int. QCD only	Int. QED only	QCD [32]	via K_{SM}
$\mathcal{O}^1_{LL}/2$	$0.8^{+44\%}_{-28\%}$ fb	$0.20^{+47\%}_{-31\%}$ fb	$-0.80^{+41\%}_{-28\%}$ fb	$1.6^{+4\%}_{-31\%}$ fb	$0.62^{+18\%}_{-22\%}$ fb
$\mathcal{O}^1_{LR}$	$1.1^{+45\%}_{-27\%}$ fb	$-0.02^{+32\%}_{-16\%}$ fb	$0.60^{+44\%}_{-28\%}$fb	$1.75^{+7\%}_{-36\%}$ fb	$3.9^{+21\%}_{-26\%}$ fb
$\mathcal{O}^1_{RR}$	$3.4^{+44\%}_{-28\%}$ fb	$0.39^{+55\%}_{-29\%}$ fb	$-1.42^{+40\%}_{-30\%}$ fb	$6.1^{+3\%}_{-29\%}$ fb	$5.5^{+20\%}_{-22\%}$ fb
$\mathcal{O}^8_{LR}$	$0.28^{+44\%}_{-29\%}$ fb	$0.22^{+52\%}_{-35\%}$ fb	$-0.49^{+42\%}_{-28\%}$ fb	$0.63^{+9\%}_{-51\%}$ fb	$0.01^{+0.10}_{-0.04}$ fb
SM	/	$4.7^{+66\%}_{-38\%}$ fb	$0.50^{+0.95}_{-0.87}$ fb	/	$11.97^{+18\%}_{-21\%}$ fb

SM estimate

From R. Frederix, 2021, indico.cern.ch/event/1004023/

- LO2 are QED-QCD interferences terms in $\alpha_s^3\alpha_{em}$
- LO3 are QED-squared diagrams in $\alpha_s^2\alpha_{em}^2$



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NLO 4-top production in the SM

σ[fb]	LO$_{\rm QCD}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$

$$\delta_{\rm (N)LO_i}(\mu) = \frac{\Sigma_{\rm (N)LO_i}(\mu)}{\Sigma_{\rm LO_{QCD}}(\mu)}$$

[RF, Pagani, Zaro, 2017]

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$	Naive expectation
LO$_2$	-26.0	-28.3	-30.5	10%
LO$_3$	32.6	39.0	45.9	1%
LO$_4$	0.2	0.3	0.4	0.1%
LO$_5$	0.02	0.03	0.05	0.01%
NLO$_1$	14.0	62.7	103.5	10%
NLO$_2$	8.6	-3.3	-15.1	1%
NLO$_3$	-10.3	1.8	16.1	0.1%
NLO$_4$	2.3	2.8	3.6	0.01%
NLO$_5$	0.12	0.16	0.19	0.001%
NLO$_6$	< 0.01	< 0.01	< 0.01	0.0001%
NLO$_2$ + NLO$_3$	-1.7	-1.6	0.9	

13 TeV

- LO$_2$ and LO$_3$ have large cancelations
- NLO$_2$ and NLO$_3$ mainly given by QCD corrections on top of them
  - large and strongly dependent on the scale choice
- However, the sum of NLO$_2$+NLO$_3$ very stable and small
- Different scale choices have even more extreme cancelations between NLO$_2$ and NLO$_3$

✦ LO$_4$, (N)LO$_5$ and NLO$_6$ only qqbar initial state. Hence, very small

Rikkert Frederix

Matching EFT descriptions ...

tttt-related in SMEFT

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

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

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

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

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

Four-top operators used in 2010.05915

Pure tttt, SU(3)xU(1)

EW preserving

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

EW-breaking P-even

$$\left\{\begin{aligned} \mathcal{O}_S^1 &= \bar{t}t\ \bar{t}t \\ \mathcal{O}_S^8 &= \bar{t}T^A t\ \bar{t}T^A t\ . \end{aligned}\right.$$

EW-breaking P-odd

$$\left\{\begin{aligned} \mathcal{O}_{PS}^1 &= \bar{t}t\ \bar{t}(i\gamma^5)t \\ \mathcal{O}_{PS}^8 &= \bar{t}T^A t\ \bar{t}T^A(i\gamma^5)t \end{aligned}\right.$$

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

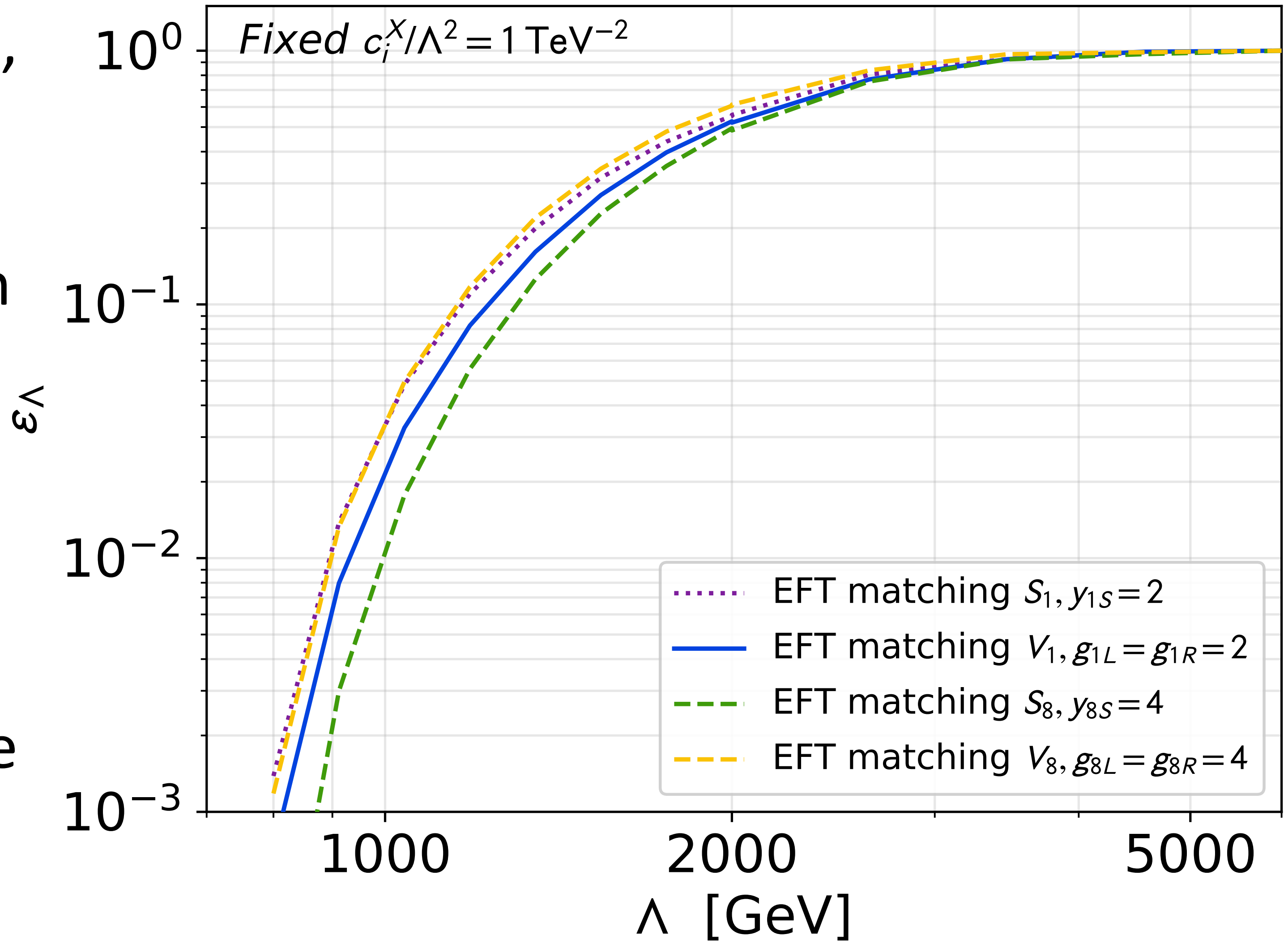
$$\begin{aligned} \mathcal{O}_{QQ}^{\mathrm{WG},1} &\equiv \frac{1}{2}\mathcal{Q}_{qq}^{(1)} & \longrightarrow \quad & \frac{1}{2}\mathcal{O}_{LL}^1 \\ \mathcal{O}_{QQ}^{\mathrm{WG},8} &\equiv \frac{1}{8}\left(\mathcal{Q}_{qq}^{(3)} + \frac{1}{3}\mathcal{Q}_{qq}^{(1)}\right) & \longrightarrow \quad &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

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

Ht data from CMS

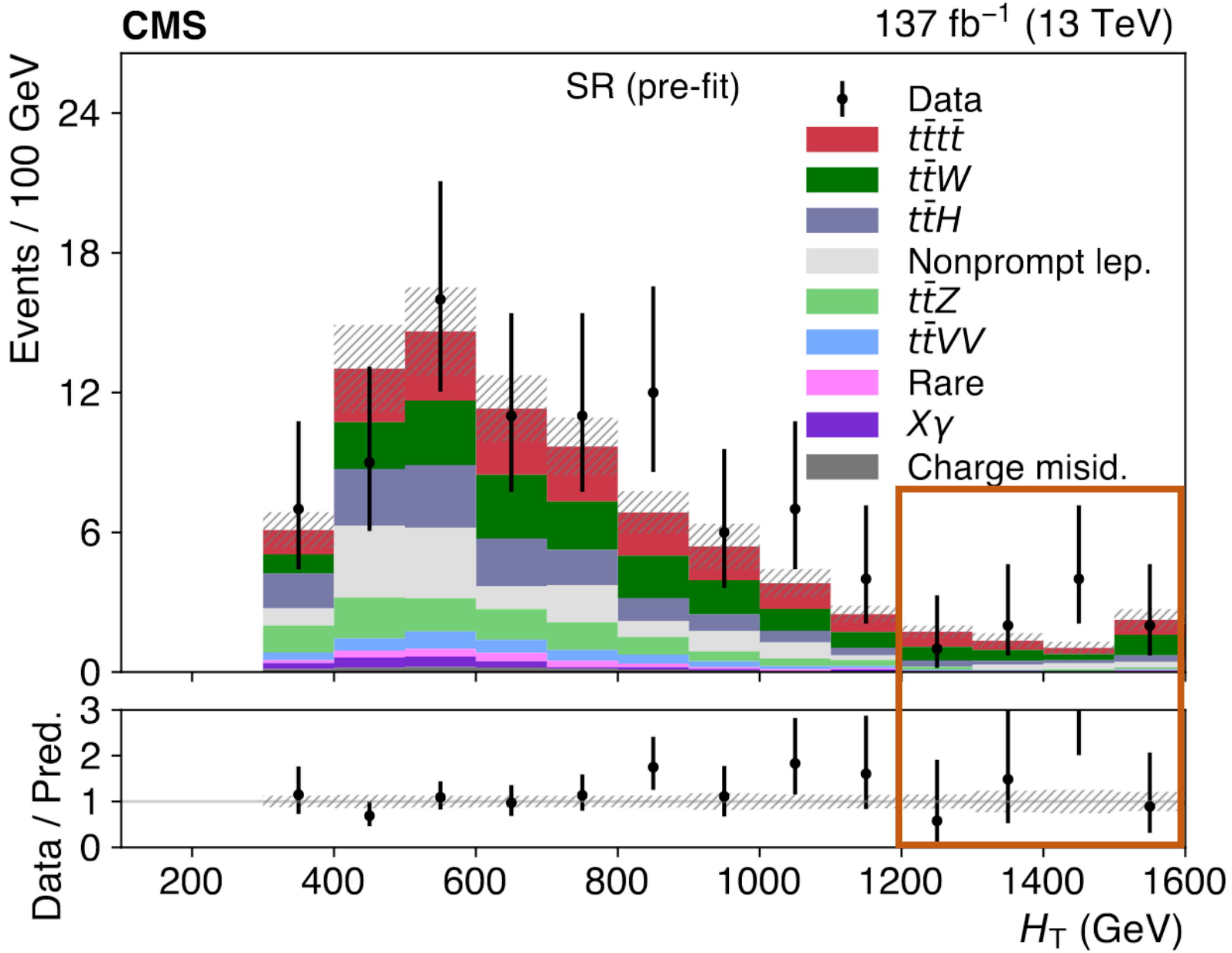
- We add a signal region with $H_T > 1.2$ TeV to the CMS search

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

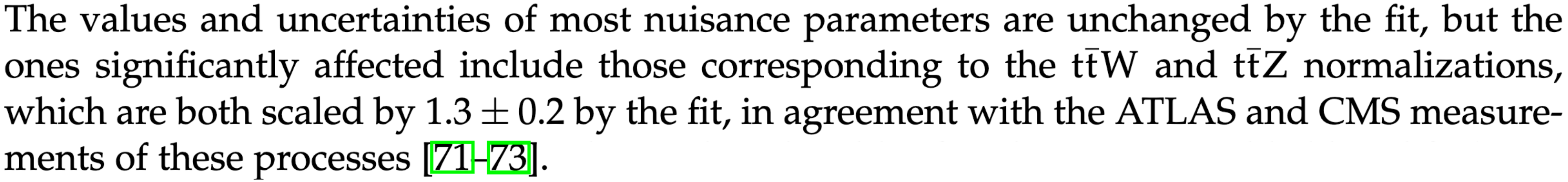
$$N_{\text{obs}} = 9$$

- Actually the tail of the distribution is in excess

→ Any link with the issues plaguing ttW and ttZ ?



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].