The 4-top-quark BSM potential: resonant and non-resonant opportunities

Luc Darmé

IP2I – CNRS

09/11/2022

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

Resonant vs non-resonant searches: EFT

Resonant vs non-resonant searches: Simplified models

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

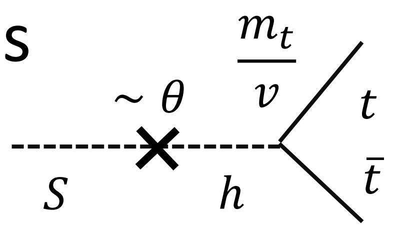
$$\mathcal{L}^{2\mathrm{HDM}}_{\mathrm{Yukawa}} = -\sum_{f=u,d,\ell} \boxed{\frac{m_f}{v}} \left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A \right)$$

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

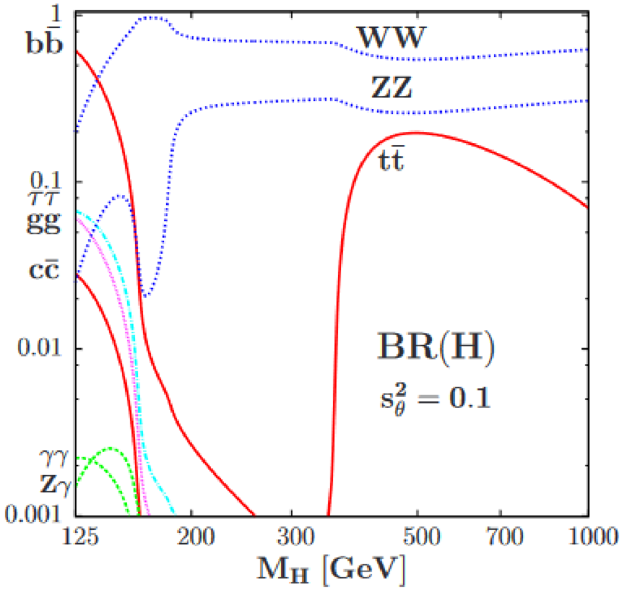
$$\tan\beta = \frac{v_2}{v_1} \qquad H^{\mathrm{SM}} = h\sin(\alpha-\beta) - H\cos(\alpha-\beta)$$

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



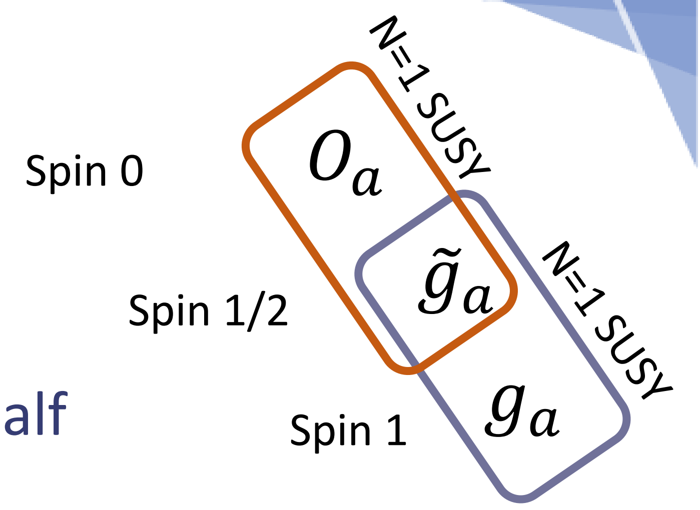
1903.03616



Corresponding simplified model

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

Supersymmetric constructions



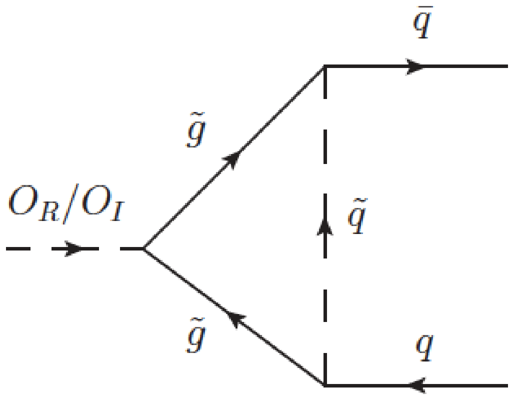
- Dirac Supersymmetric model

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

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

→ 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

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

Include direct QCD interactions

Composite constructions

- Partial compositeness scenarios

See e,g. 1507.02283, 1610.06591, etc…

→ While the Higgs boson is a composite state, the generation of Yukawa couplings is challenging

→ Many pNGB are generated, possibly colored (octet, sextet, etc…)

→ Also presence of vector "meson" composite states

The color representation of the pNGB depends on the details of the composite models …

- The top mass is obtained by mixing a fundamental quark field with new composite baryonic states, thus it inherits a preferential coupling to the pNGB

Corresponding simplified model

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

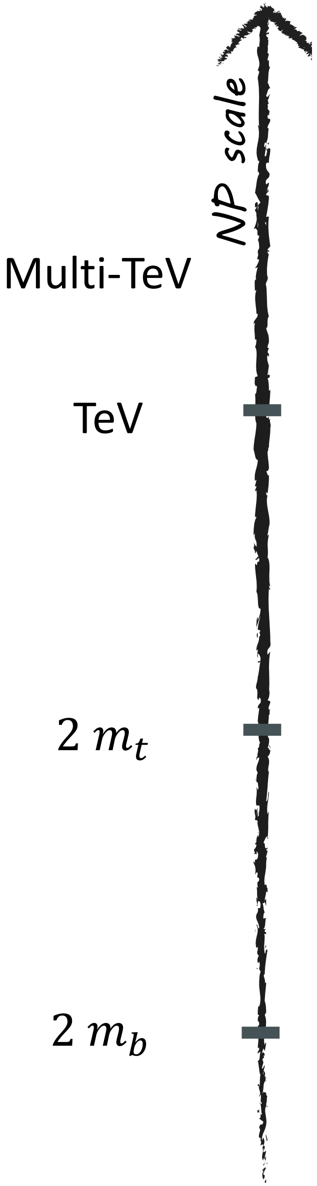
$$\mathcal{L}_{V_8} \supset -\frac{1}{4} V_8{}^{\mu\nu} V_{8\mu\nu} - \frac{1}{2} m_{V_8}^2 V_8{}^\mu V_{8\mu} + \bar{t}\gamma_\mu \left[g_{8L} P_L + g_{8R} P_R\right] V_8{}^\mu\, t$$

+ also sextet and singlet states …

Broad formalism, not very predictive from the top-down approach

Resonant vs non-resonant searches

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

- 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 …*

EFT and 4-top

- Top physics and EFT: building on the SMEFT approach to provide a complete picture

  → Include not only heavy quarks $\bar{t}t\bar{t}t$-like operator, but also heavy-light ($\bar{t}t\bar{q}q$) ones + mixed $t\bar{t}$ and bosonic ones

Banelli, Salvioni, Serra, Theil, Weiler 2010.05915

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

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

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

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

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

- The SM cross-section itself contribution is quite small ($\sim$ 12 fb) and close to where we can currently put limit

  → Not the "standard" case of "small effect over large SM signal", at currently accessible cross-sections, EFT NP^2 correction still dominates

  → We have to study both NP^2 and interference to get a proper result

$$\sigma_{4t} \sim \sigma_{4t}^{SM} + \sum_i \frac{C_i}{\Lambda} \sigma_{i,int} + \sum_{i,j} \frac{C_i C_j}{\Lambda^2} \sigma_{ij,NP^2}$$

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

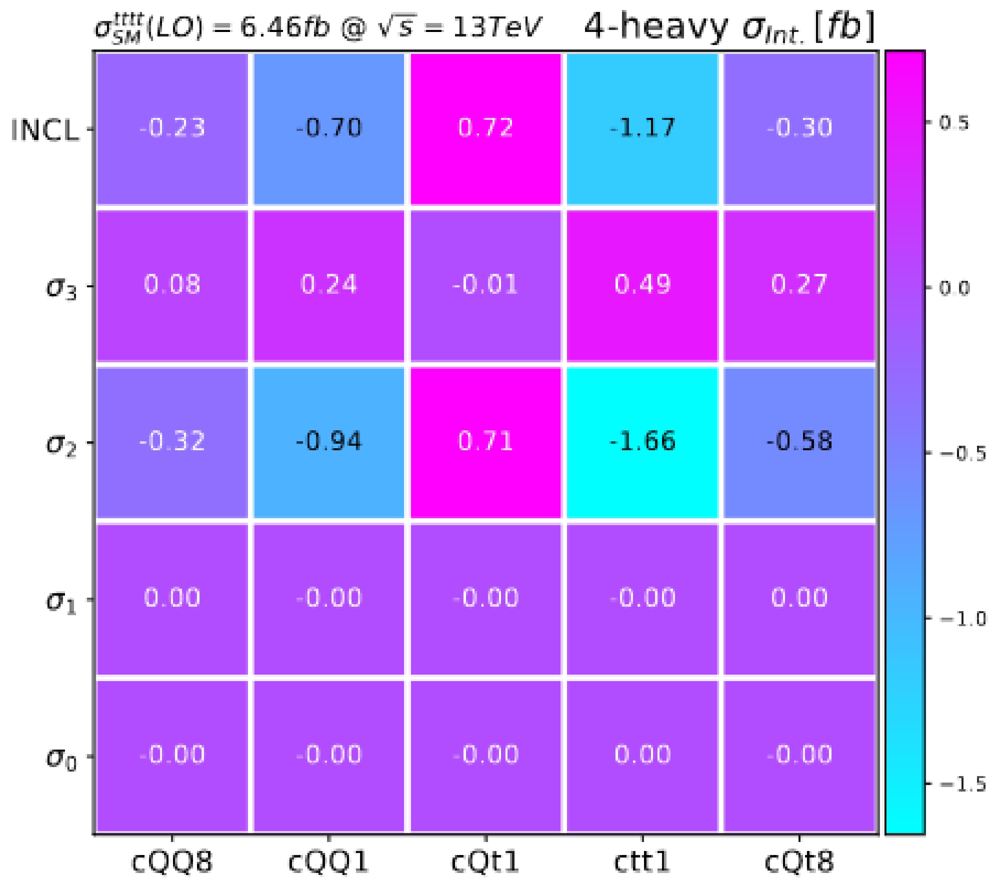
→ For the "heavy quark" operators, $\alpha_S^2\alpha_{EW}^1$ tend to dominate the interference contribution

$$\sigma_{incl}^{int} \sim \sigma_3 + \sigma_2 + \sigma_1 + \sigma_0$$

α_S^3 $\alpha_S^2\alpha_{EW}^1$ $\alpha_S^1\alpha_{EW}^2$ α_{EW}^3

For the $c/\Lambda \sim 1$, the NP^2 terms are of the same order as the interferences

Aoude et al. 2208.04962

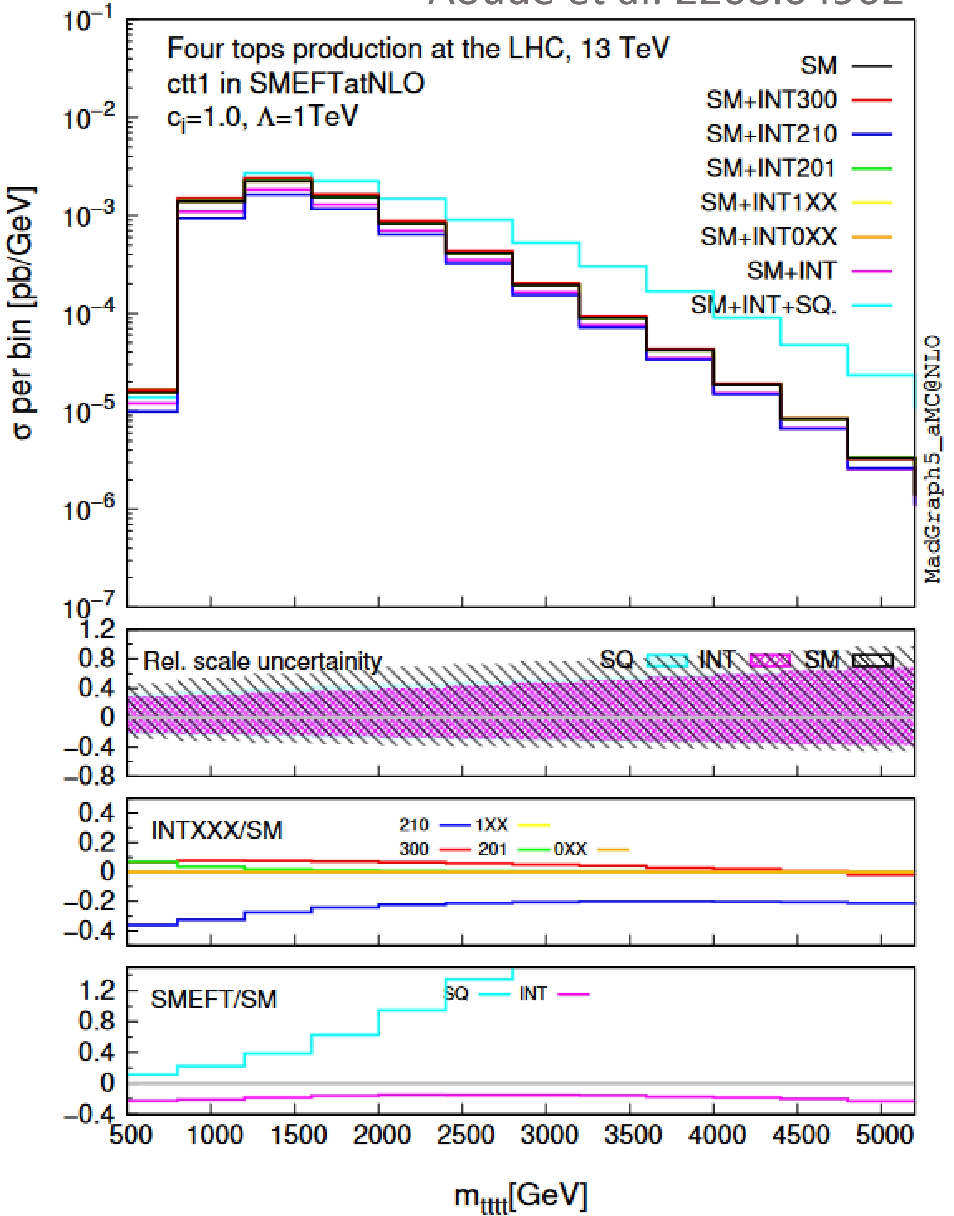


- Conclusion: always include EW interference in your simulations

See also Ježo and Kraus (2110.15159)

Differential measurements

Aoude et al. 2208.04962

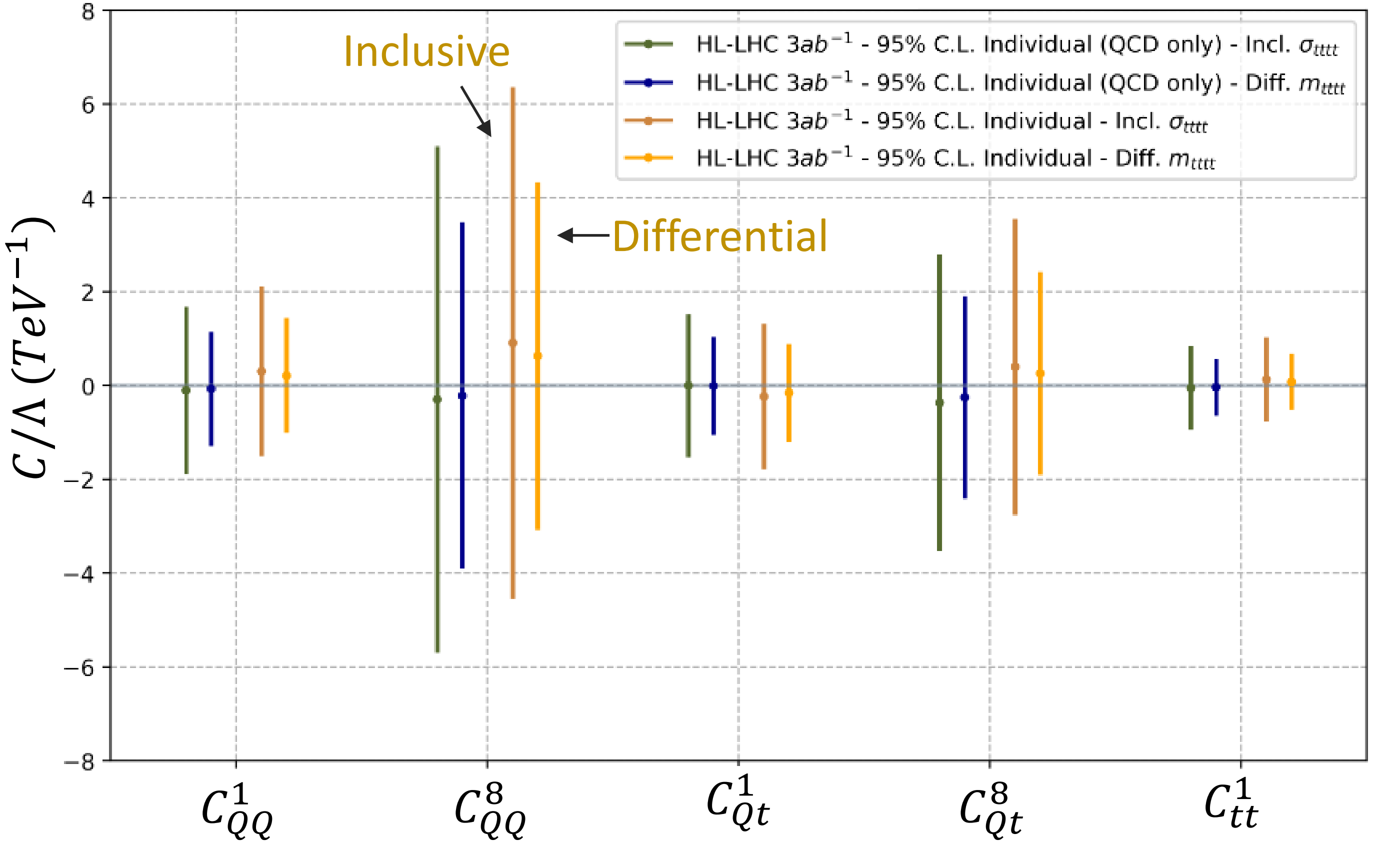


HL-LHC will give access to the differential informations

→ Allow for a « tail » strategy in searching for SMEFT effect

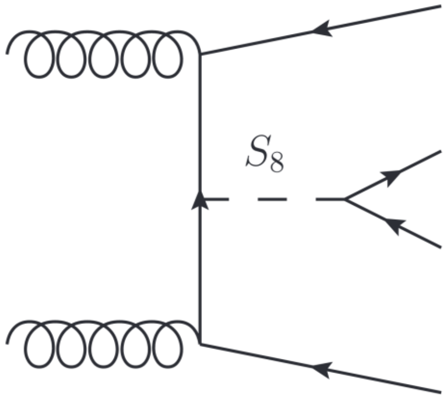
HL-LHC projected limit on EFT couplings

Aoude et al. 2208.04962

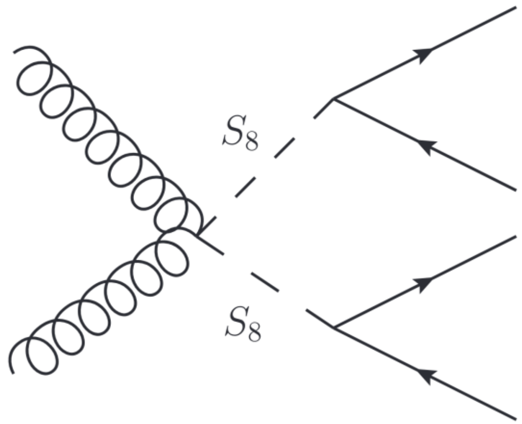


EFT viability

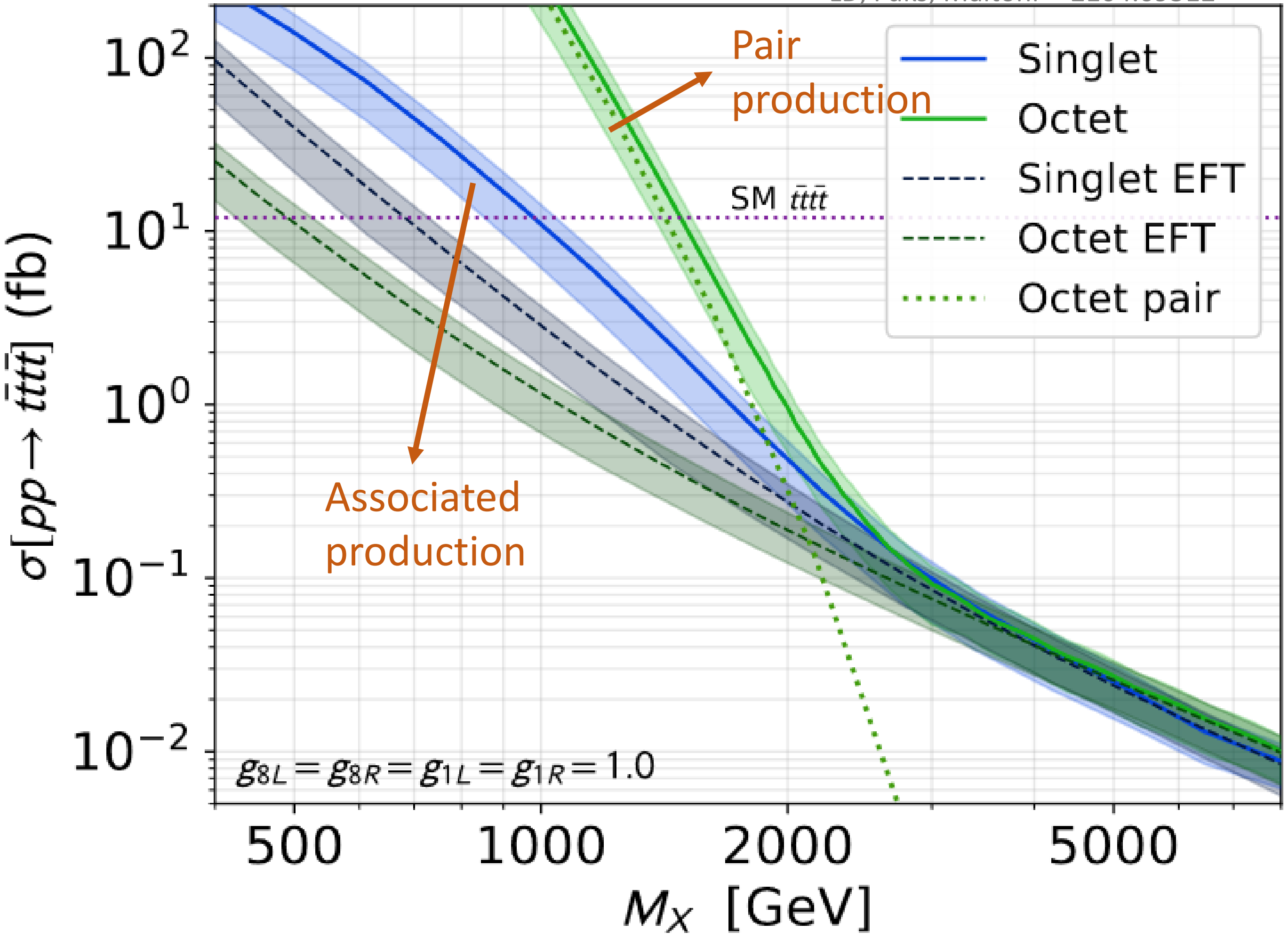
- The projected constraints, even at HL-LHC points to g/Λ at the TeV level
  - → In the low mass regime, on-shell production dominates
  - → Either in associated



  - → Or if available, by pair



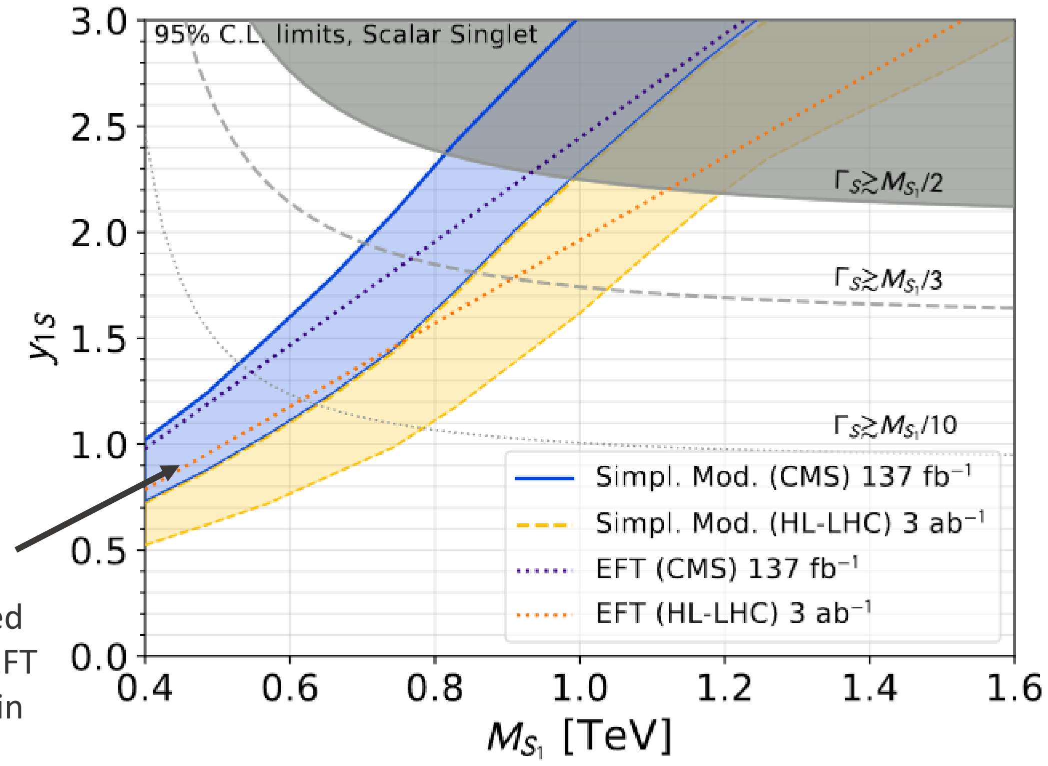
LD, Fuks, Maltoni -- 2104.09512



Results, singlet case

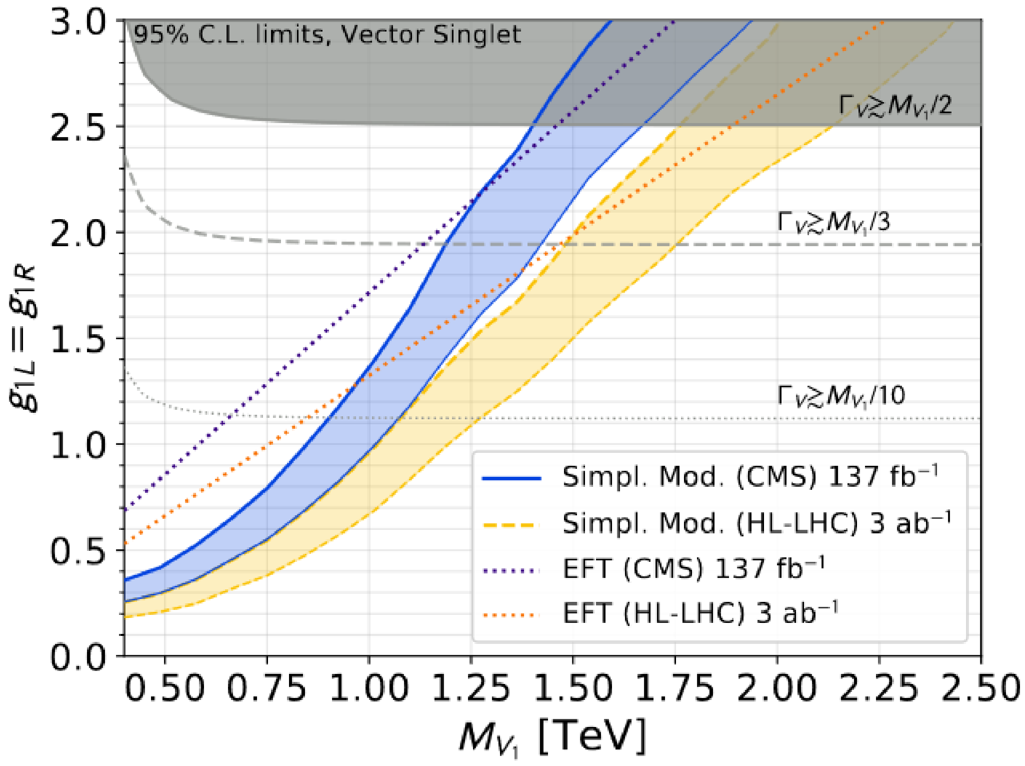
- Bands are from varying CS by factor of 2 (K factor 1 or 2)
- Note that the simplified approach quickly breaks down at large masses (width Γ_S too large)

LD, Fuks, Maltoni -- 2104.09512



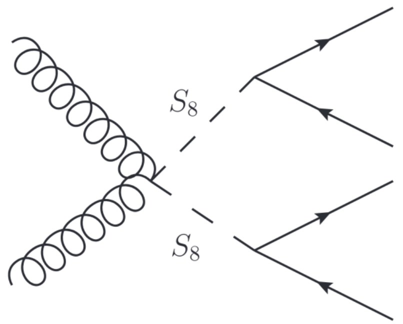
Fortuitious matching EFT/simplified model: the EFT is NOT valid in this range

LD, Fuks, Maltoni -- 2104.09512

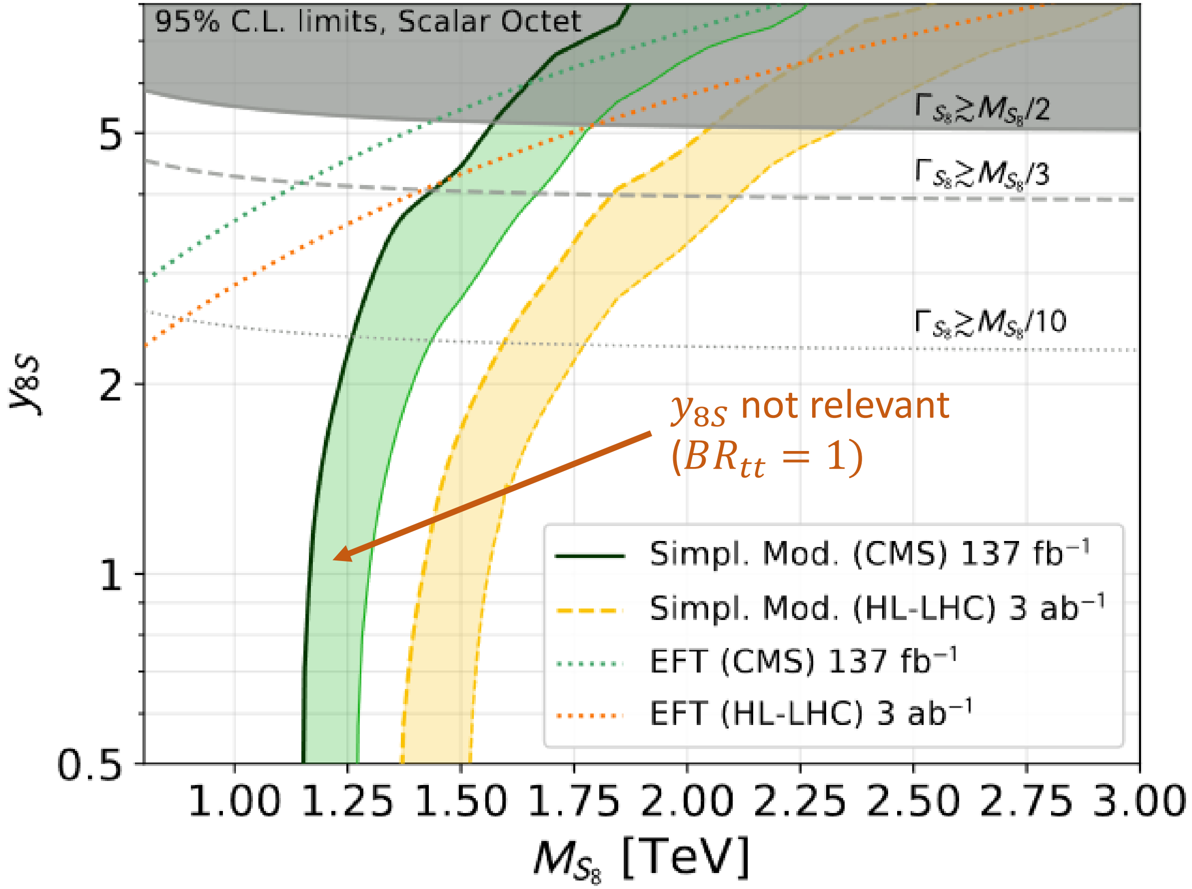


Results, octet case

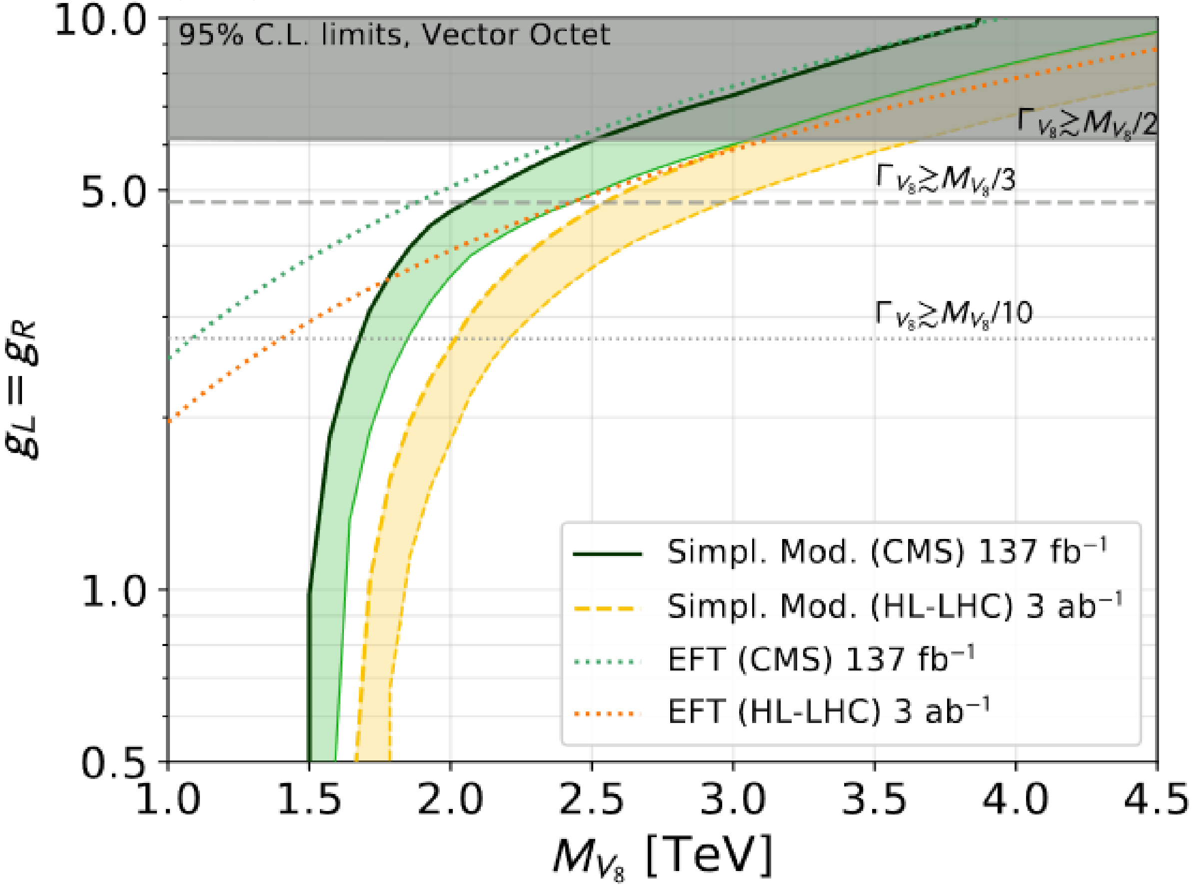
- Pair production dominates → A dedicated search strategy could deliver a massive improvement here
- Small region at large masses with good EFT/simplified match



LD, Fuks, Maltoni -- 2104.09512

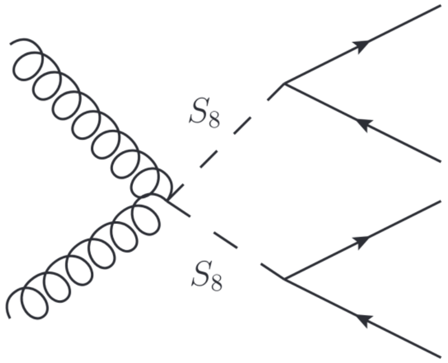


LD, Fuks, Maltoni -- 2104.09512



Going differential

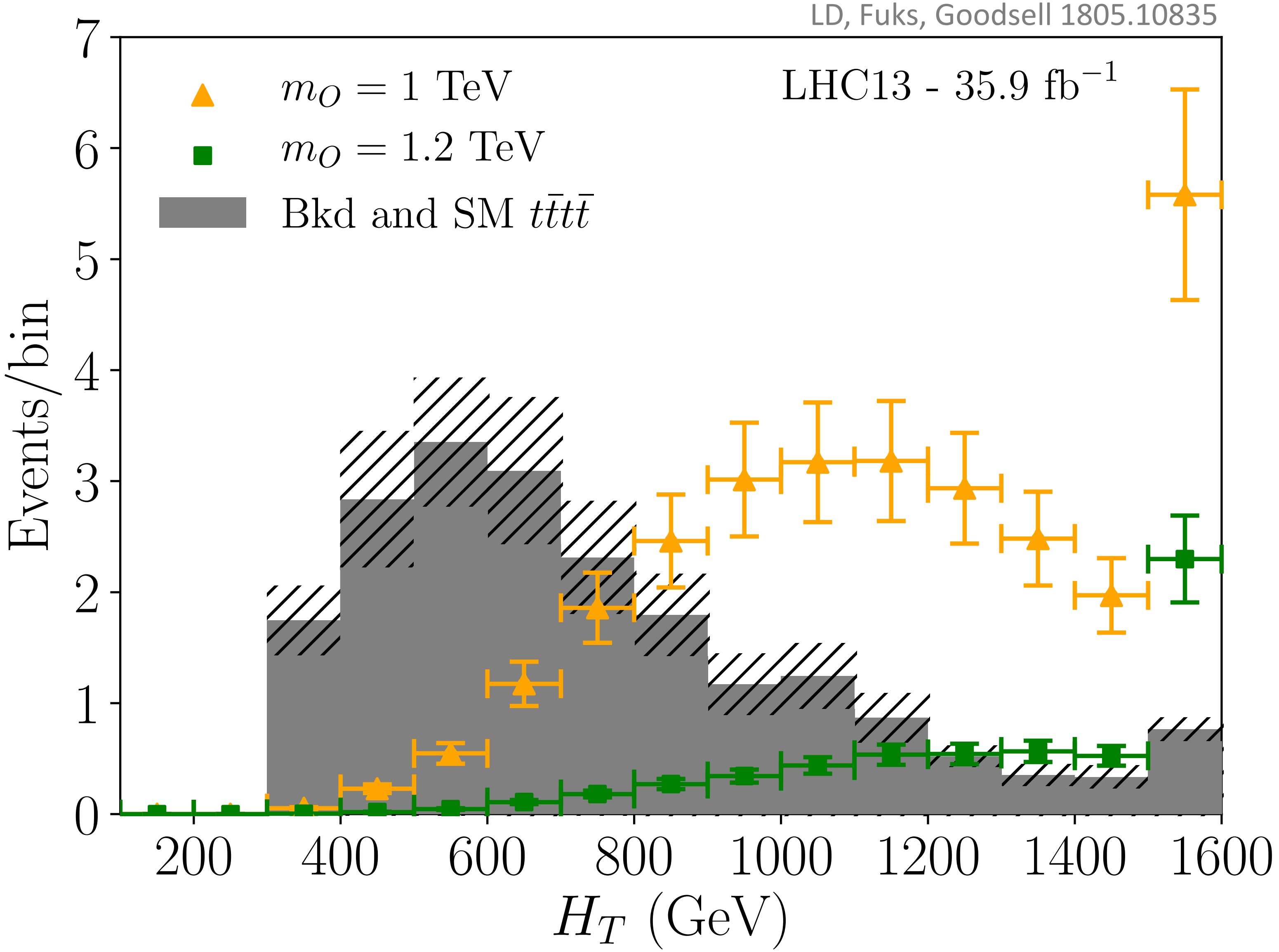
- Typical NP signal use on-shell production+ decay → again starkly different kinematics w.r.t the SM



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

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

LD, Fuks, Goodsell 1805.10835

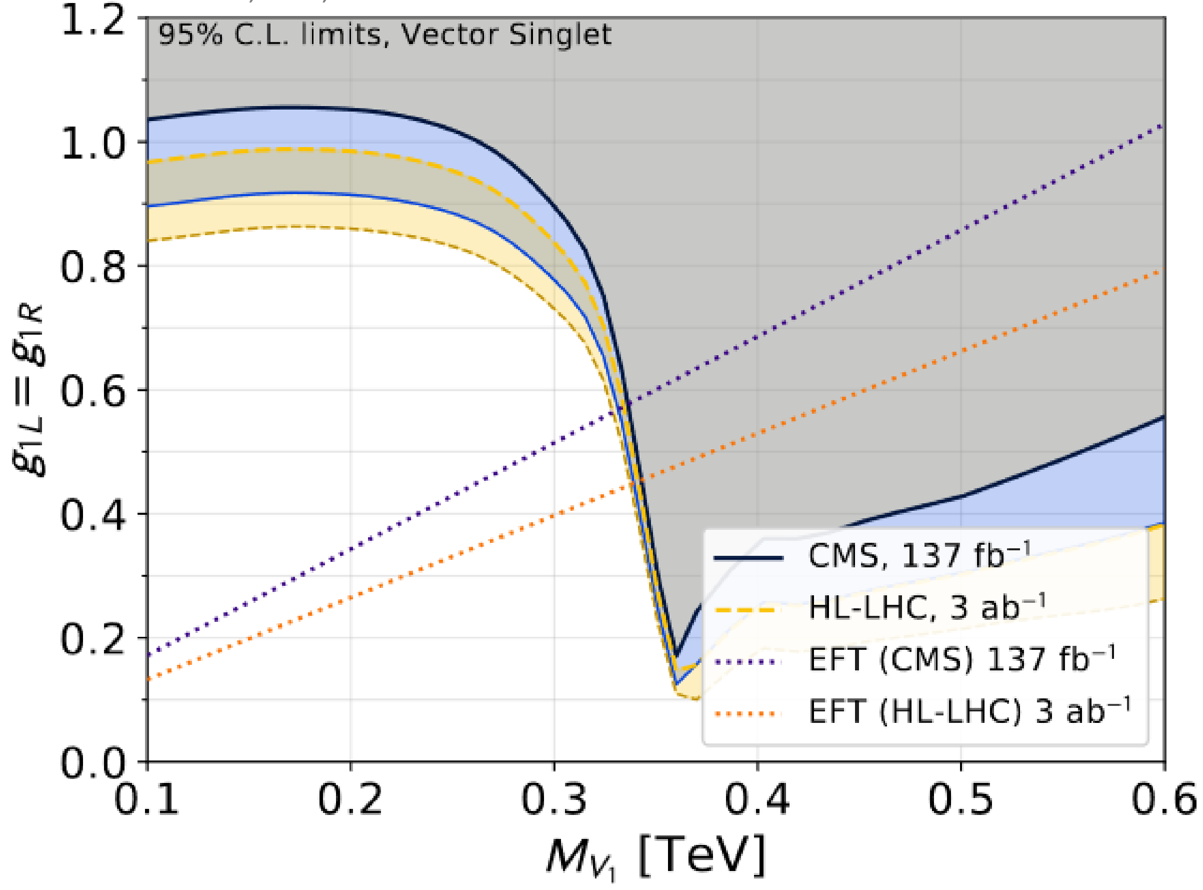


Comments on the "low masses" range

- 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)

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

LD, Fuks, Maltoni -- 2104.09512



- Use another decay channel in ttX configuration ?
  → With reconstruction of the $X \to bb, \mu\mu, \tau\tau$ etc…

Conclusion

Recent theory developments I did not give enough attention

- Study NP models, where $tttt$ plays an important role — Carpenter et al. 2107.13565, Alasfar et al. 2202.02333
- Investigating new idea to distinguish ttW from $tttt$ — Alvarez et al. 1911.09699, 2107.00668
  - → Demixer algorithm, Bayesian probabilistic modeling
- Measurement of CP property of the SM couplings — Cao et al. 1901.04567
- Toward better control of EW corrections — Jezo and Kraus 2110.15159 , Aoude et al. 2208.04962, Kulesza et al. 2022
- Better control over the EFT vs simplified model approach (using pdf) — Cohen, Doss, Lu 2111.09895
- Tying various anomalies together from tttt to ttW — Alvarez 2011.06514
- Updated EFT + simplified models limits — Banelli et al. 2010.05915 , Cao et al. 2105.03372, Aoude et al. 2208.04962, Blekman et al. 2208.04085

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