Four-tops: EFT and simplified models

Luc Darmé

IP2I – CNRS

17/05/2023

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

Top-philic NP particles: the origin

- Why would a New Physics (NP) boson 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

See Taylor's talk

Top-philic NP particles: the origin

- Why would a New Physics (NP) boson 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

See Taylor's talk

Because the top quark is made (partially) of NP

Partial top compositeness

See Giacomo's talk

Top-philic NP particles: the origin

- Why would a New Physics (NP) boson 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

See Taylor's talk

Because the top quark is made (partially) of NP

Partial top compositeness

See Giacomo's talk

Because the NP helps in generating the top quark mass

Extended Higgs sectors

Dark Higgs models (ie new singlet scalar)

Top-philic NP particles: the origin

- Why would a New Physics (NP) boson 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

See Taylor's talk

Because the top quark is made (partially) of NP

Partial top compositeness

See Giacomo's talk

Because it is a third generation quark

Flavour constructions

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

Because the NP helps in generating the top quark mass

Extended Higgs sectors

Dark Higgs models (ie new singlet scalar)

The top quark and LHC

- In this talk, we look at new physics which has dominant interaction of the form $X\bar{t}t$ (or leading to an EFT with $\bar{t}t\bar{t}t$).

  → Caution: this is different from a “top-partner”, no EW interaction expected

- LHC is a top-quark factory with expectedly a very rich top-quark program unfolding…

The top quark and LHC

- In this talk, we look at new physics which has dominant interaction of the form $X\bar{t}t$ (or leading to an EFT with $\bar{t}t\bar{t}t$).

→ Caution: this is different from a "top-partner", no EW interaction expected

- LHC is a top-quark factory with expectedly a very rich top-quark program unfolding…

- **The first observation of 4top**: of 4top reaches 6.1 (4.3) σ

→

SM is observed ! Now it's finally time to shine for NP searches ?

The top quark and LHC

- In this talk, we look at new physics which has dominant interaction of the form $X\bar{t}t$ (or leading to an EFT with $\bar{t}t\bar{t}t$).

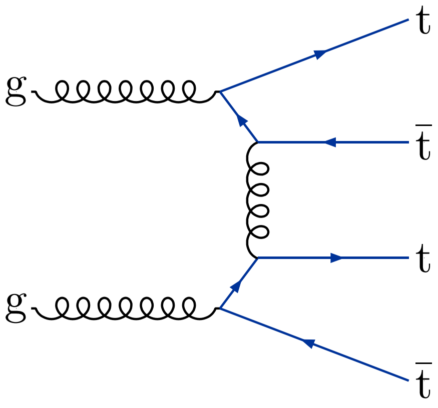
  → Caution: this is different from a “top-partner”, no EW interaction expected

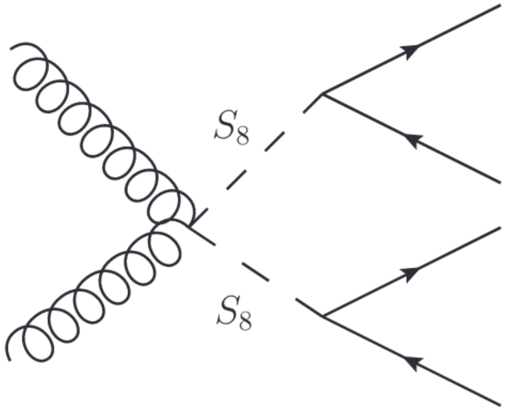
- LHC is a top-quark factory with expectedly a very rich top-quark program unfolding…

- **The first observation of 4top**: of 4top reaches 6.1 (4.3) σ

SM is observed ! Now it’s finally time to shine for NP searches ?

Therefore, we are currently probing tttt at the 10 fb level





The key point will be that NP topologie predicting four tops (or more…) are most of the time really different from the SM background

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 …

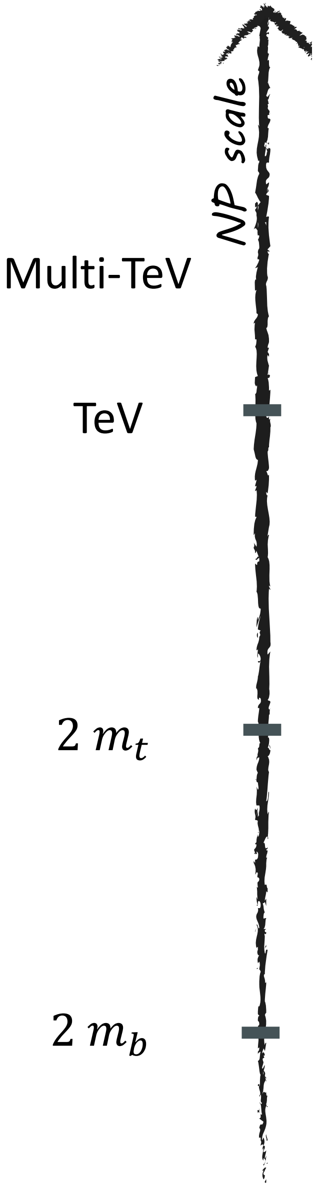
$$\mathcal{L}_{V_8} \supset -\frac{1}{4} V_8{}^{\mu\nu} V_{8\mu\nu} - \frac{1}{2} m_{V_8}^2 V_8{}^\mu V_{8\mu} + \bar{t}\gamma_\mu \left[g_{8L} P_L + g_{8R} P_R\right] V_8{}^\mu\, t$$

→ Composite models…

Include direct QCD interactions

EFT vs simplified models

From resonant searches to EFT



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

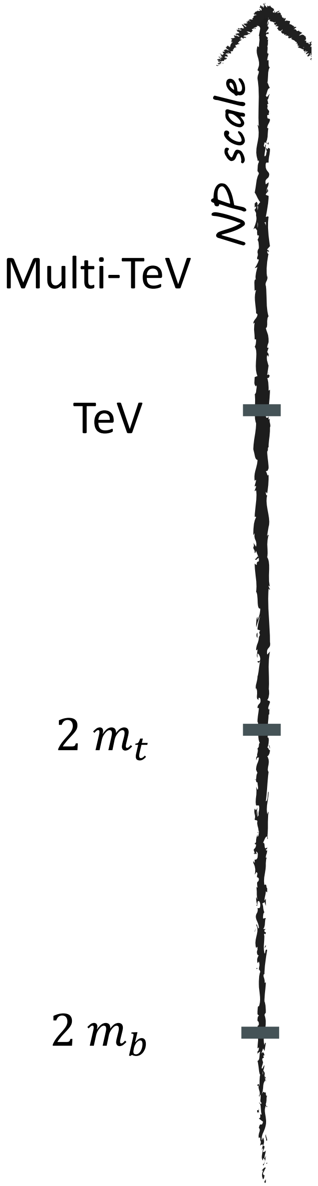
$$pp \to \bar{t}t\bar{t}t$$

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

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

When should we move from one description to the other ?

From resonant searches to EFT



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

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

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

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

When should we move from one description to the other ?

- 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 $\bar{t}t\,(\bar{b}b), \bar{t}t\,(\gamma\gamma)$, *etc …*

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

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

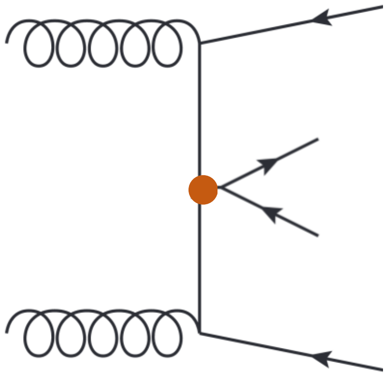
$$\sigma_{\bar{t}t\bar{t}t} \sim \sigma_{SM} + \frac{1}{\Lambda^2}\sigma_{\text{int}} + \frac{1}{\Lambda^4}\sigma^{NP^2}$$

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

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

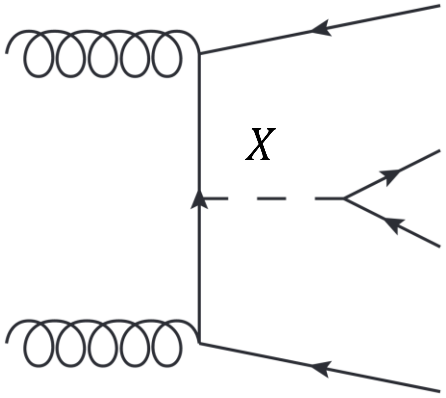
How to look for a heavy top-philic state ?

- The key requirement is that is decays mostly to tops, so we have the main requirements that couplings to g, q... are much smaller than $y_{X,t}$



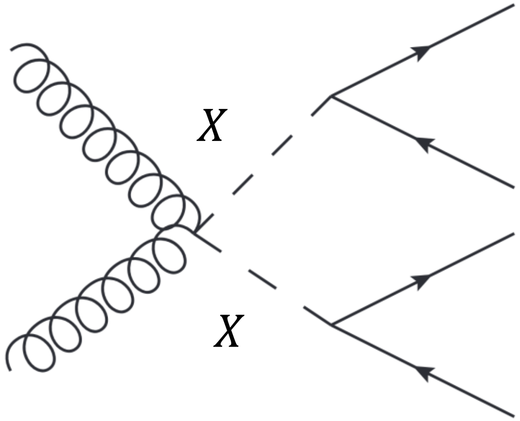
Final state: $tttt$

$$\sigma \propto \frac{s}{\Lambda^4}$$



Final state: $ttX, X \rightarrow tt$

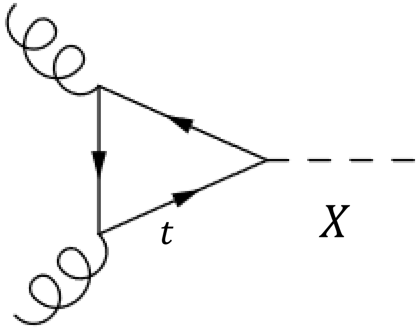
$$\sigma \propto y_{Xt}^2$$



Final state: $XX, X \rightarrow tt$

$$\sigma \propto g_s^4$$

Works only if the top-philic state is an octet



Final state: X

$$\sigma \propto \frac{g_s^4 y_{Xt}^2}{\pi^4}$$

Loop-induced, but no PDF suppression + only one X to produce

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

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…

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

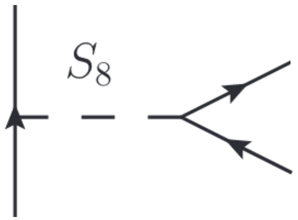
Four-top operators used in 2010.05915

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

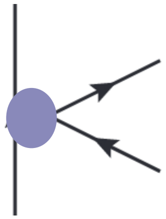
Simplified models matching (1.0.1)

- 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 …



$$\sim \frac{1}{p^2 - M_{S_8}^2} \rightarrow \frac{1}{\Lambda^2}$$



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	/	/	$-\frac{g_{1L}^2}{6M_{V_8}^2}$	$-\frac{g_{1R}^2}{6M_{V_8}^2}$	/	$-\frac{g_{8L}g_{8R}}{M_{V_8}^2}$

Importance of EW interference effect (LO)

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

Aoude et al. 2208.04962

→ 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

Aoude et al. 2208.04962

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

σ_3: α_S^3 ; σ_2: $\alpha_S^2 \alpha_{EW}^1$; σ_1: $\alpha_S^1 \alpha_{EW}^2$; σ_0: α_{EW}^3

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

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

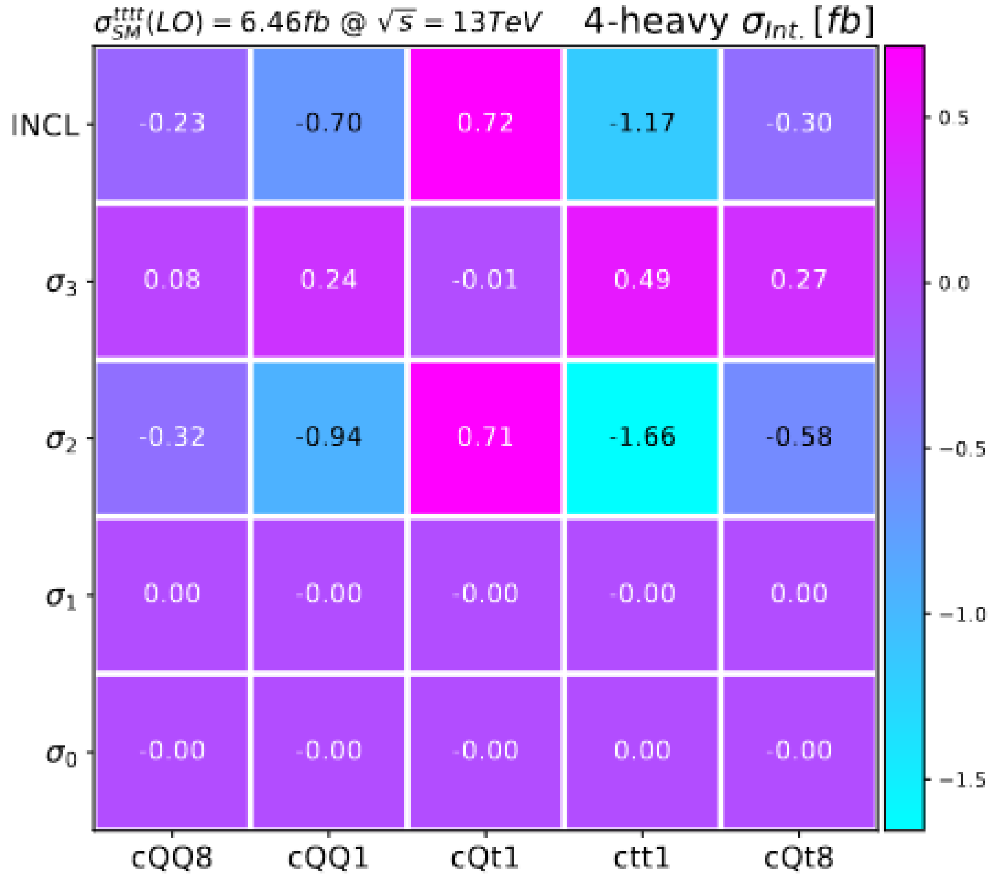
Aoude et al. 2208.04962

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

σ_3: α_S^3, σ_2: $\alpha_S^2\alpha_{EW}^1$, σ_1: $\alpha_S^1\alpha_{EW}^2$, σ_0: 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

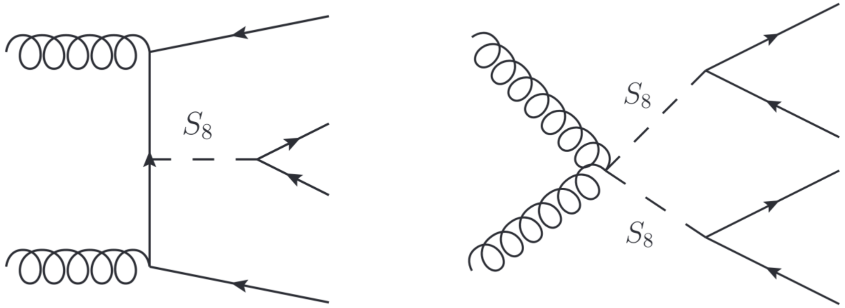


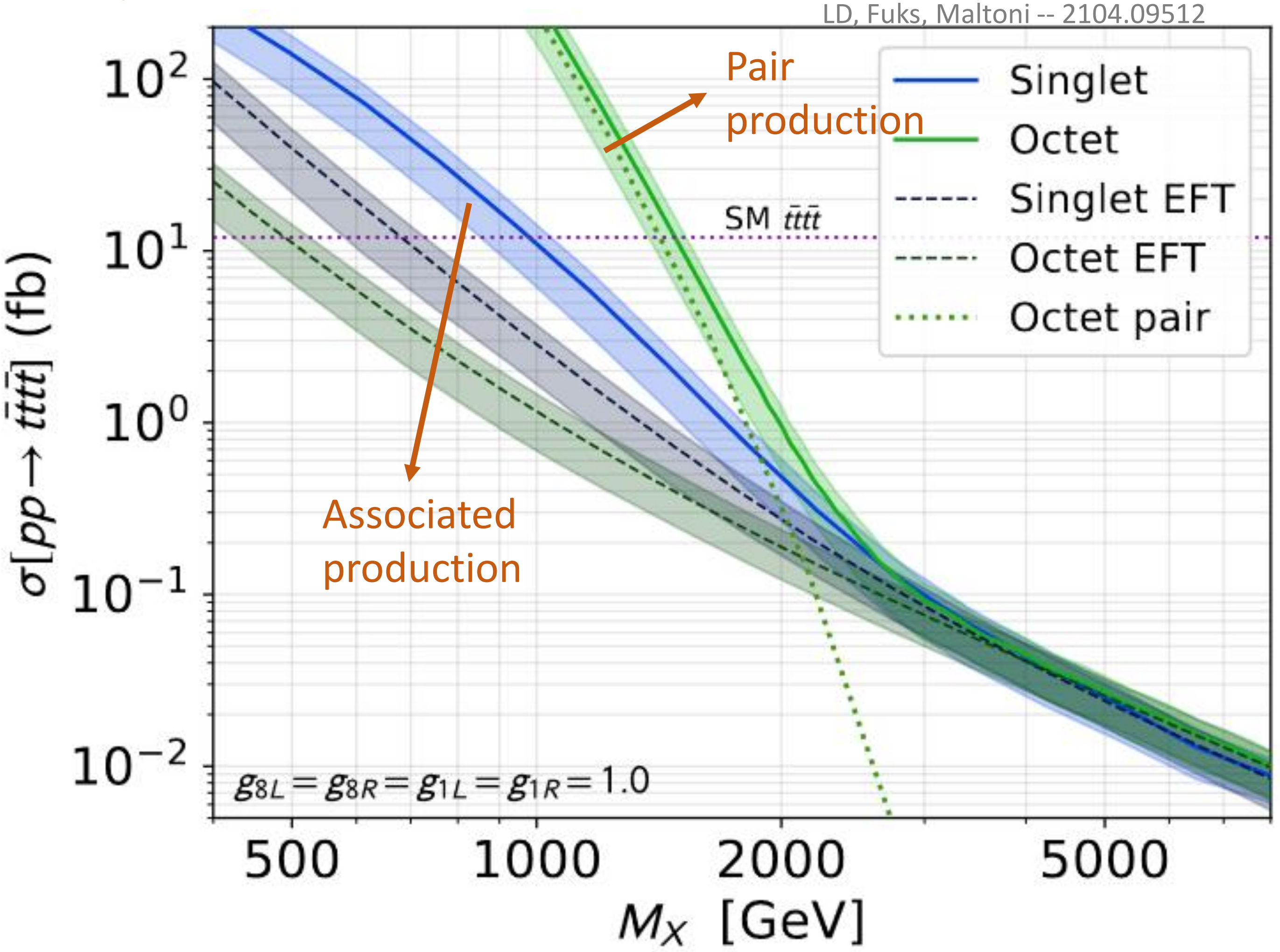
- Conclusion: always include EW interference in your simulations

See also Režo and Kraus (2110.15159)

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 single or pair production





- For perturbative values of the coupling, EFT approach is relevant only for X masses above 2 TeV (at the 0.1 fb level)

  → We need to find a way to beat the SM background to get there at HL-LHC

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

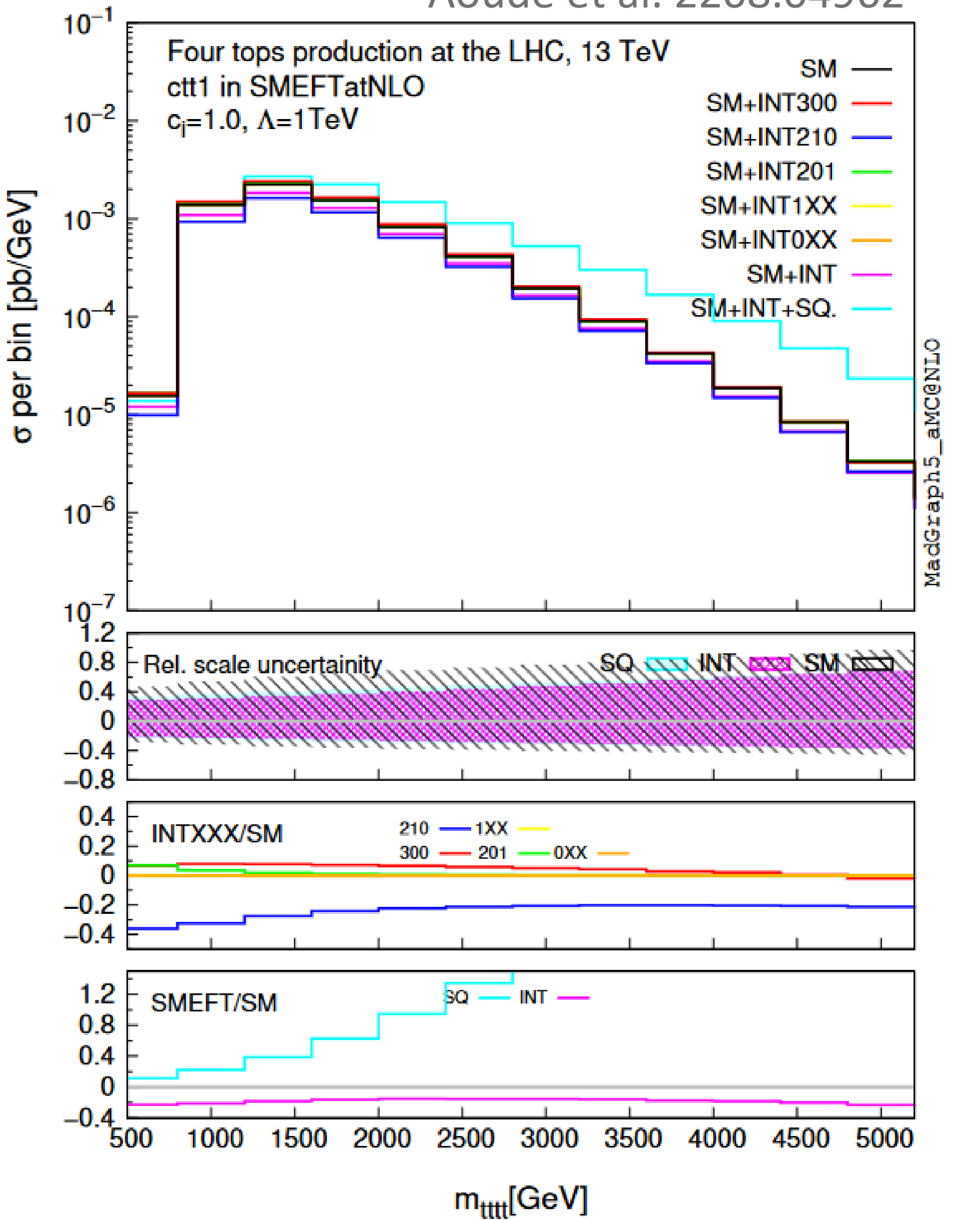
  → In $t\bar{t}X$-only process, $K_{QCD} \sim 1.5$ Cacciapaglia, LD, Darricau 23xx.xxxx

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

Limits and going differential

Differential measurements – EFT tails

Aoude et al. 2208.04962

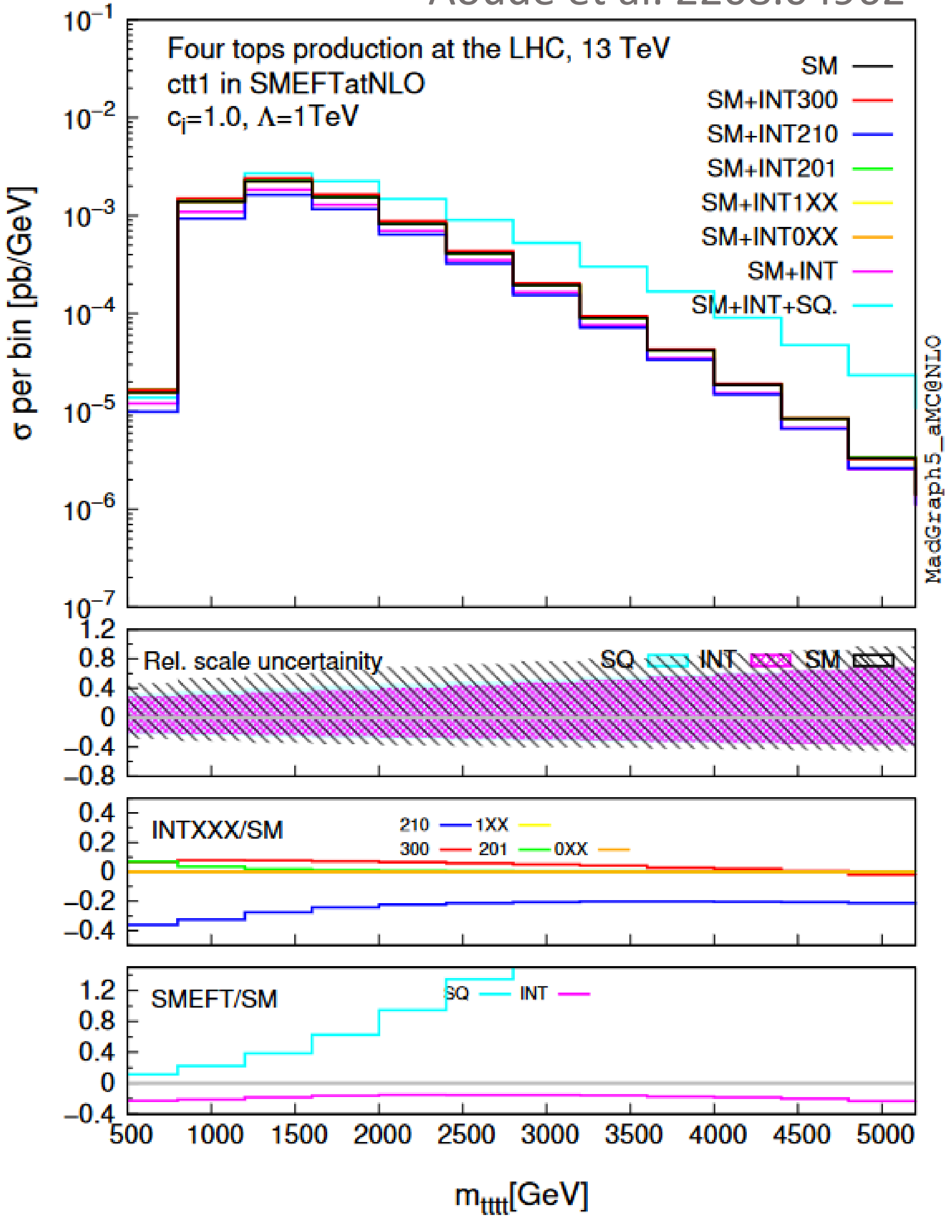


HL-LHC will give access to the differential informations

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

Differential measurements – EFT tails

Aoude et al. 2208.04962

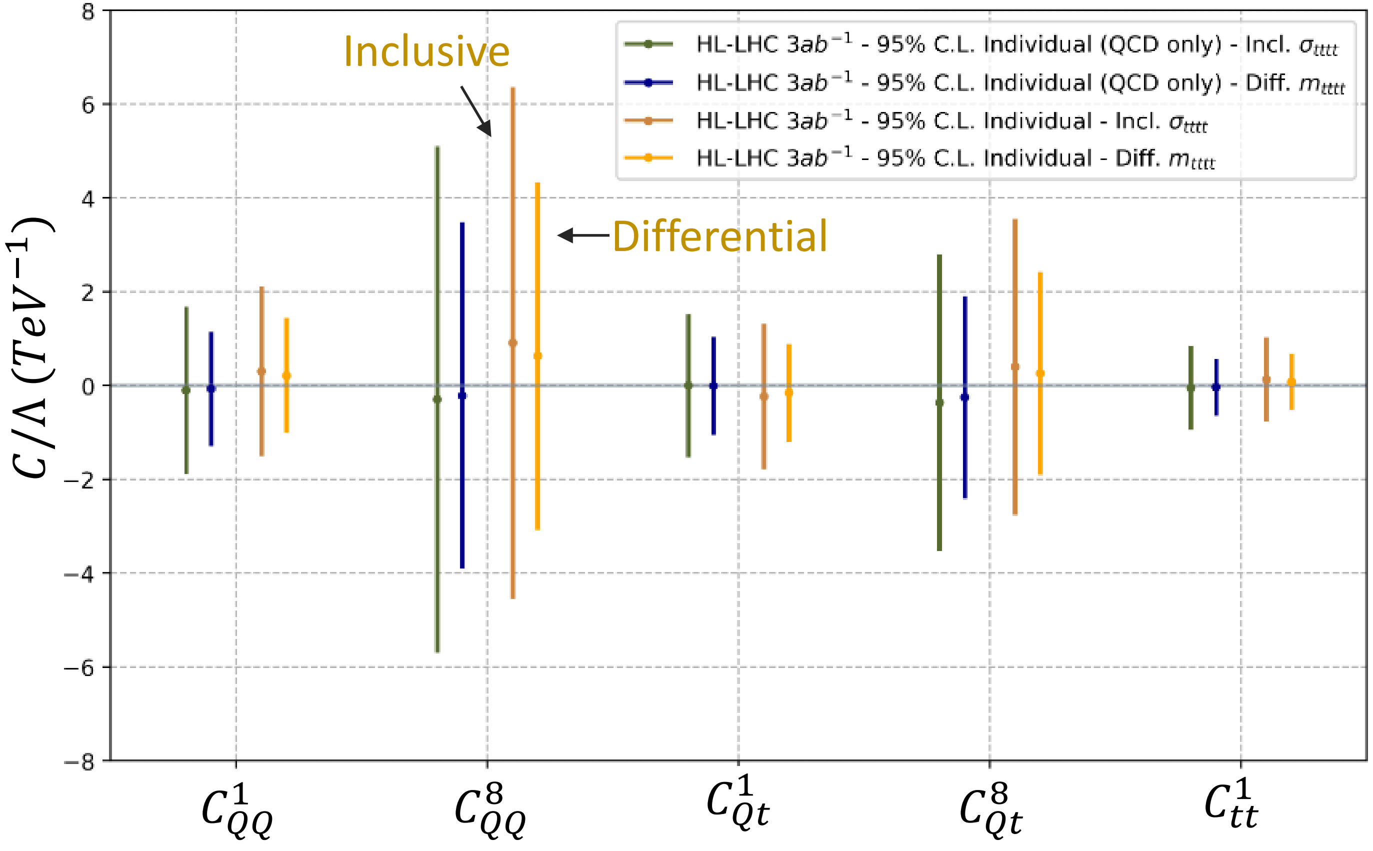


HL-LHC will give access to the differential informations

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

HL-LHC projected limit on EFT couplings

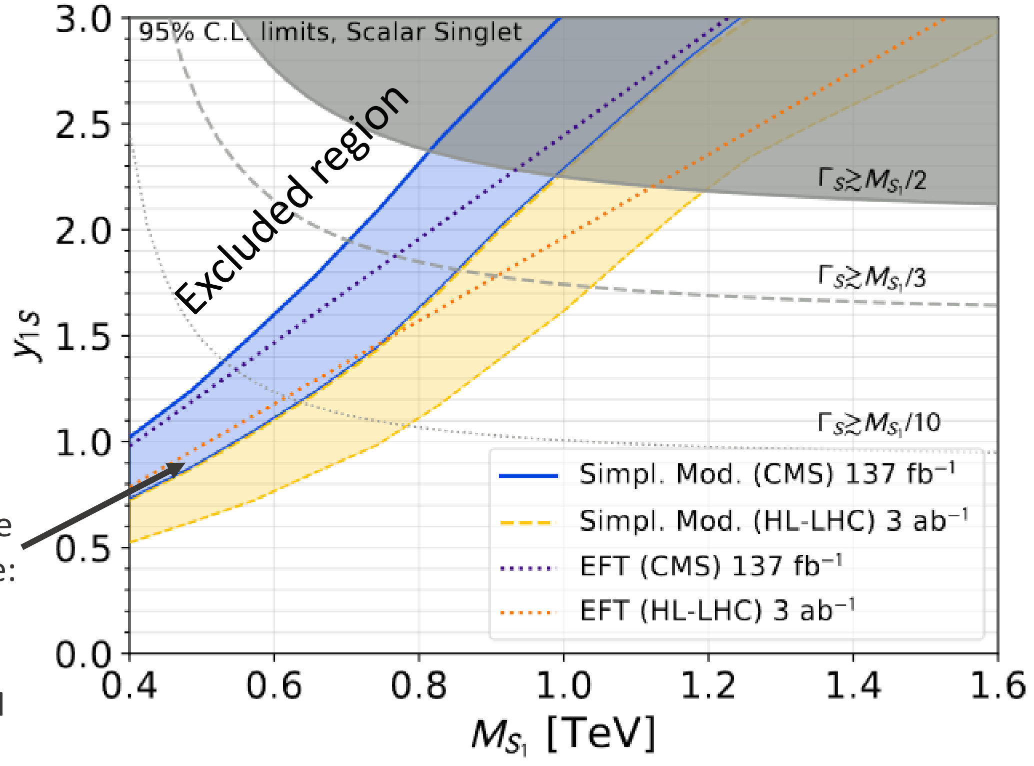
Aoude et al. 2208.04962



Colorful vs colorless

- Note that the simplified approach quickly breaks down at large masses
- Three main NP regimes to be tested: (1) Intermediate for color singlet < TeV, (2) EFT-like at large couplings above 2 TeV and (3) High-mass resonance > TeV

LD, Fuks, Maltoni -- 2104.09512

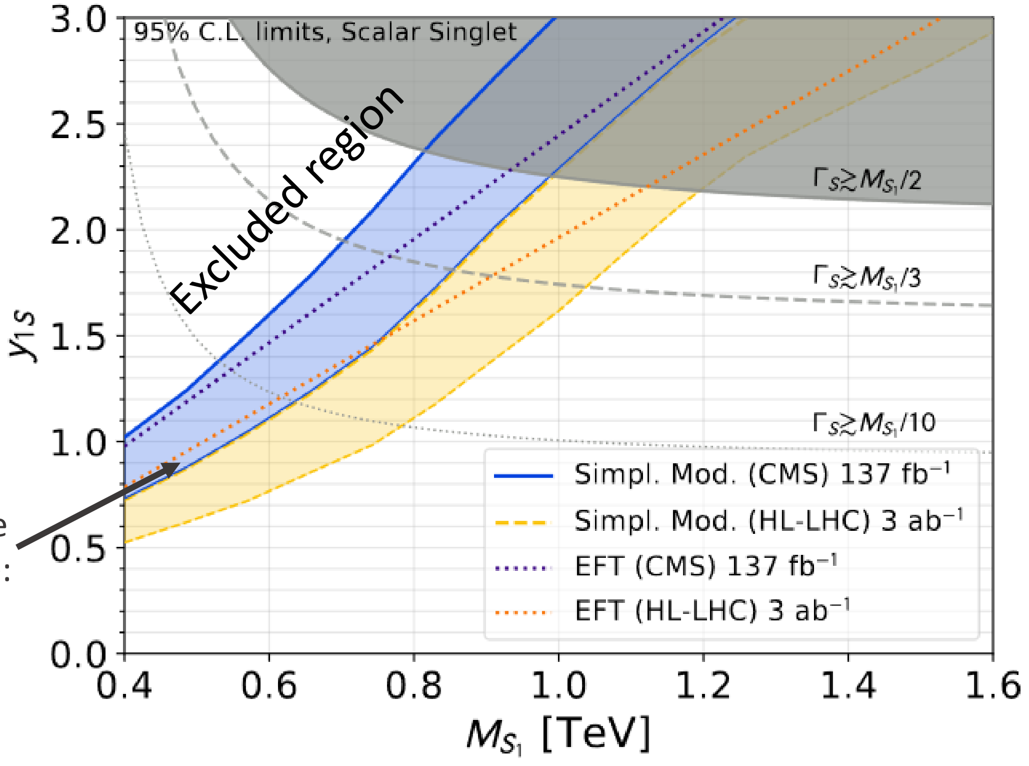


Intermediate mass regime: harder to distinguish from the SM

Colorful vs colorless

- Note that the simplified approach quickly breaks down at large masses
- Three main NP regimes to be tested: (1) Intermediate for color singlet < TeV, (2) EFT-like at large couplings above 2 TeV and (3) High-mass resonance > TeV

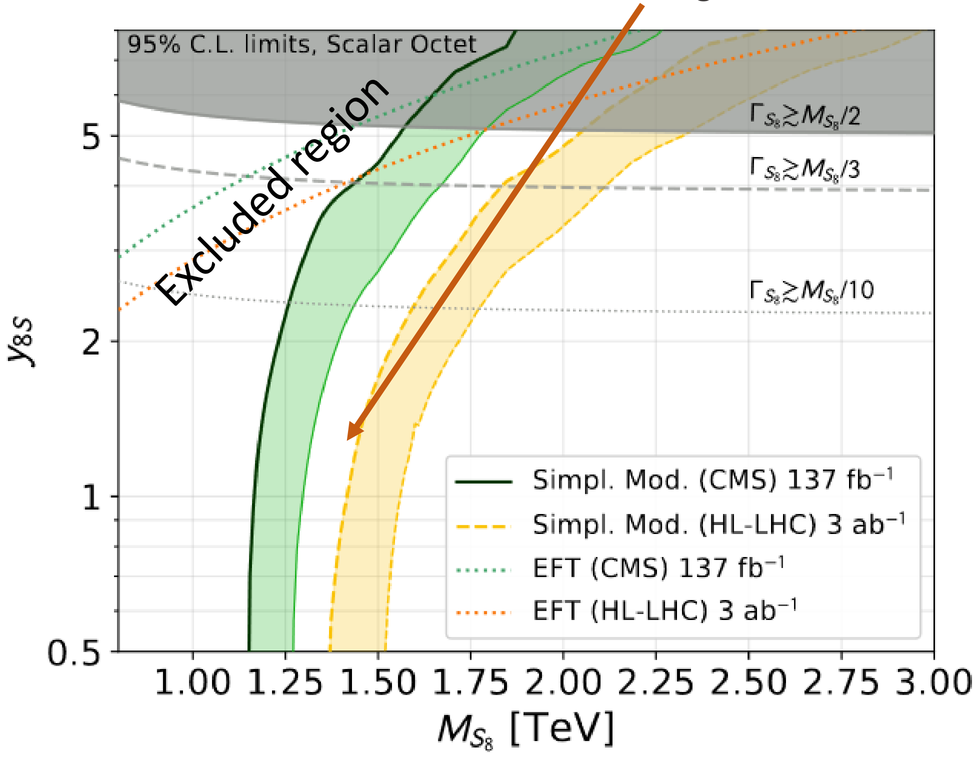
LD, Fuks, Maltoni -- 2104.09512



Intermediate mass regime: harder to distinguish from the SM

LD, Fuks, Maltoni -- 2104.09512

Large mass regime, resonance search should bypass most SM background



Above the di-top threshold: TeV-scale

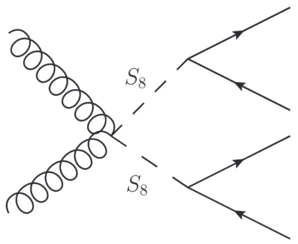
- In general, for TeV-scale new particles, we should be able to do much better by reconstructing the tops invariant mass and searching for the resonance

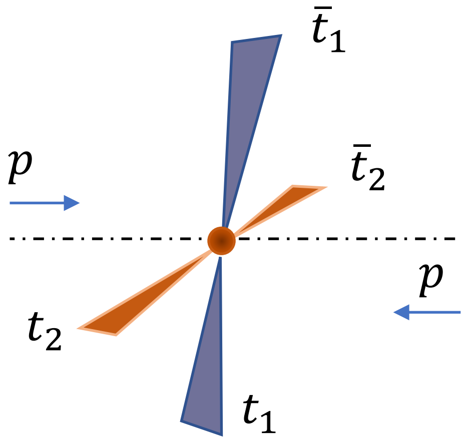
Work in progress with O. Mattelaer, and B. Fuks and collaborators

- Proposed strategy:

  → First reconstruct completely the four-top final states, either leptonic or hadronic (hhhh, hhhl and hhll)

  → Then determine the resonances from the tttt final states





Good preliminary results, the distinct topology of heavy resonance decay makes it relatively easy to identify the proper pairs of tops

Above the di-top threshold: TeV-scale

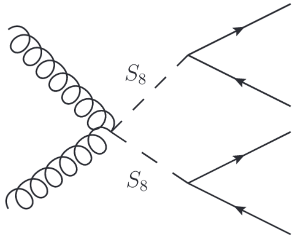
- In general, for TeV-scale new particles, we should be able to do much better by reconstructing the tops invariant mass and searching for the resonance

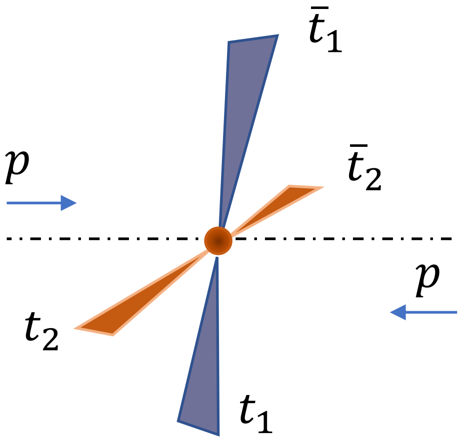
Work in progress with O. Mattelaer, and B. Fuks and collaborators

- Proposed strategy:

  → First reconstruct completely the four-top final states, either leptonic or hadronic (hhhh, hhhl and hhll)

  → Then determine the resonances from the tttt final states





Good preliminary results, the distinct topology of heavy resonance decay makes it relatively easy to identify the proper pairs of tops

- At intermediate masses, various machine learning techniques are being investigated by theory (and experimental?) groups

  Atkinson et al. 2302.08281

  → Reconstruct properly the tops from the final states particles via GNN

  → Distinguish ttW from $tttt$ (Demixer algorithm, Bayesian probabilistic modelling)

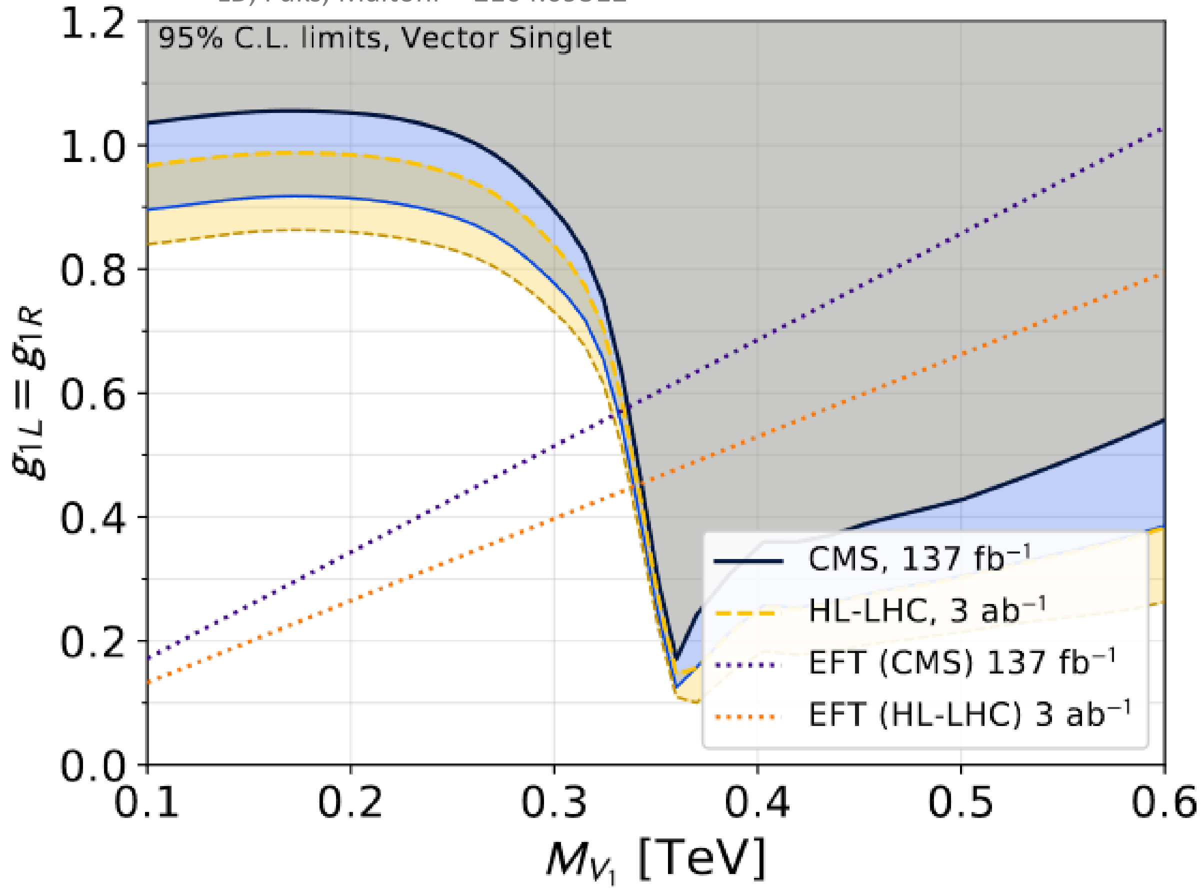
  Alvarez et al. 1911.09699, 2107.00668

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)

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

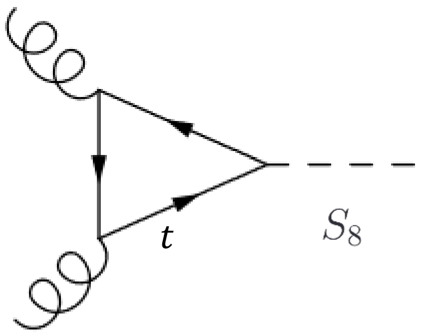
LD, Fuks, Maltoni -- 2104.09512



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

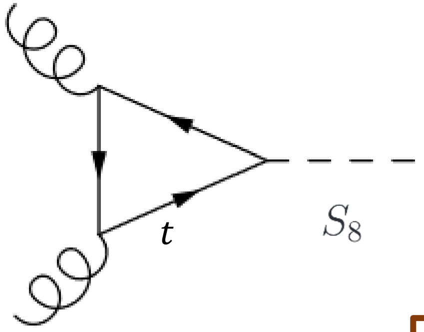
Loop processes at small masses

- With top-couplings only, loop-induced contribution can be important
  - → Similarly to the Higgs ggX and $\gamma\gamma X$ are loop-induced
  - → Running of α_S, y_{Sb} important



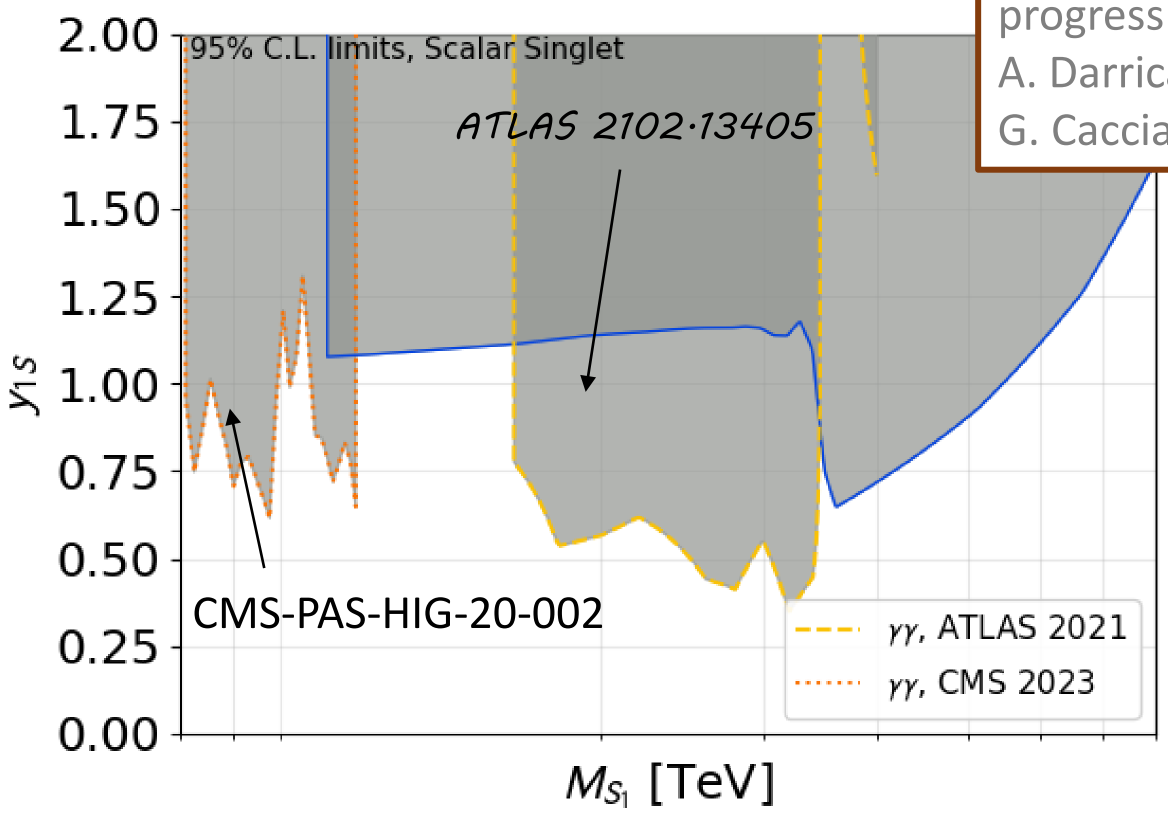
Loop processes at small masses

- With top-couplings only, loop-induced contribution can be important
  - → Similarly to the Higgs ggX and $\gamma\gamma X$ are loop-induced
  - → Running of α_S, y_{Sb} important



- In this regime, we can re-use a large range of Higgs-like NP searches

Work in progress with A. Darricau and G. Cacciapaglia



- Main open question: would a ttS final study be relevant in that case ?

Conclusion

Conclusion

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

  → Experiments are still statistically limited

- Dedicated NP searches are within reach: both on the "off-shell" EFT approach and on an "on-shell" NP production (resonant opportunities)

  → Illustrated by m_{tttt} tail for EFT

  → New dedicated analysis strategies probably required (top-tagging) to tame the SM background and explore the fb and sub-fb region at HL-LHC

- Still a pretty active field on the theory side !

  → New ideas tested to get the best out of the $t\bar{t}t\bar{t}$ states for NP-dedicated analysis