Toponium formation and four-top production in present and future LHC data

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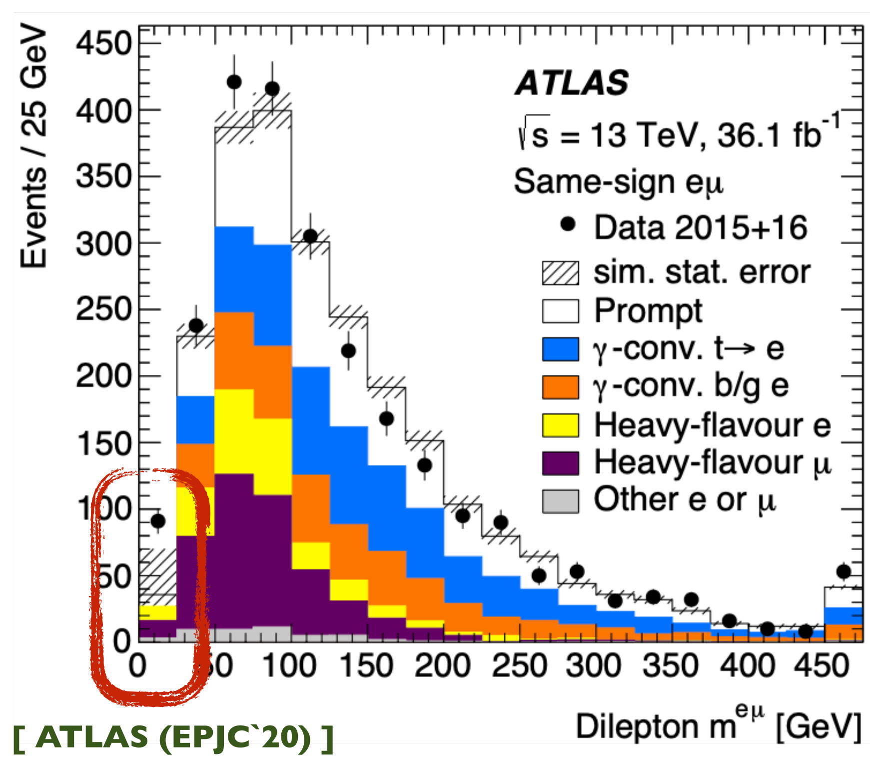
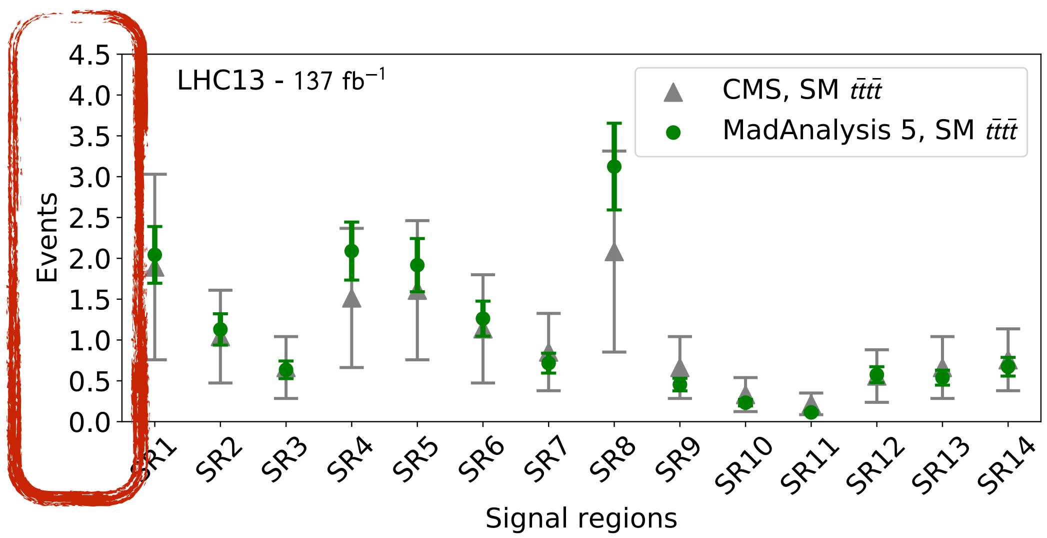
Rare effects in top physics at the LHC

- Copious top quark production at the LHC [σ(13 TeV) ~ 810 pb]
  - Detailed analysis of the top properties (mass, width, *etc.*)
  - Many differential distributions precisely measurable
  - Rare SM effects accessible: e.g. toponium formation
- Rare top production processes accessible
  - Run 3 (400/fb) and HL-LHC (3/ab): ample room for BSM studies
  - Example: four-top probes (≡ 1 event / 100,000 $t\bar{t}$ events)



[ATLAS (EPJC`20)]



[Darmé & BF (MPLA`21)]

Toponium @ LHC

[BF, Hagiwara, Ma & Zheng (PRD`21)]

Close to threshold

✦ Incorporating bound state effects in theory predictions

✤ Close to threshold, the non-relativistic approximation is valid ($\beta \ll 1$)

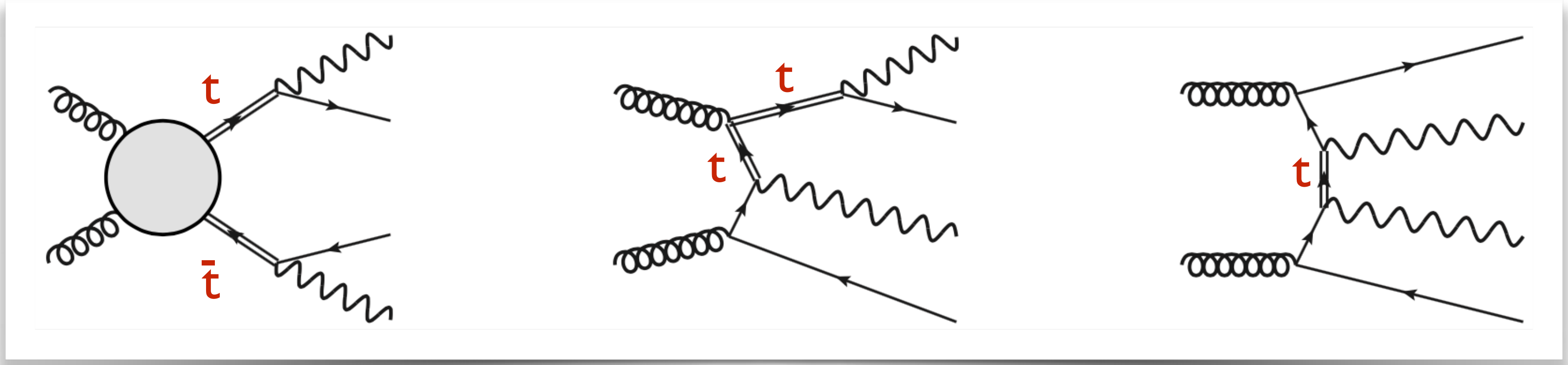
✤ Resummation of the Coulomb singularities $(\alpha_s/\beta)^n$

~ gluon exchanges between slowly-moving top quarks ≡ bound-state effects

✤ Predictions in the pNRQCD framework (Potential Non-Relativistic QCD)

✦ *Wb Wb* production in the threshold regime

✤ 3 classes of contributions with 0, 1 or 2 (possibly off-shell) tops



✤ Bound-state effects ~ first class of diagrams in the colour-singlet channel

★ Below or slightly above threshold

★ One off-shell top quark

★ Binding energy ⇔ Coulomb gluon exchanges

~ to be added to the perturbative treatment

~ better top pair-production modelling

Top pair production with toponium effects

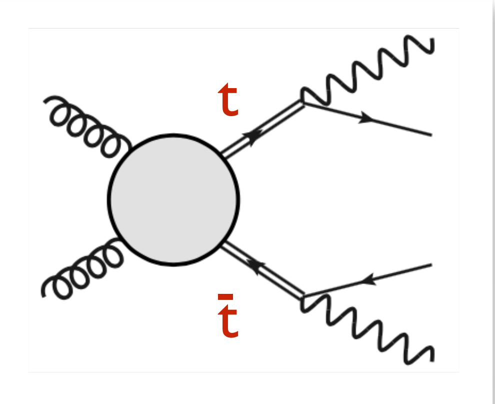
✦ The (tree-level) amplitude is enhanced close to threshold

✤ Involving non-relativistic Green's functions

$$i\mathcal{M}^{(c)} \to i\mathcal{M}^{(c)} \times \frac{G(E;p^*)}{G_0(E;p^*)}$$

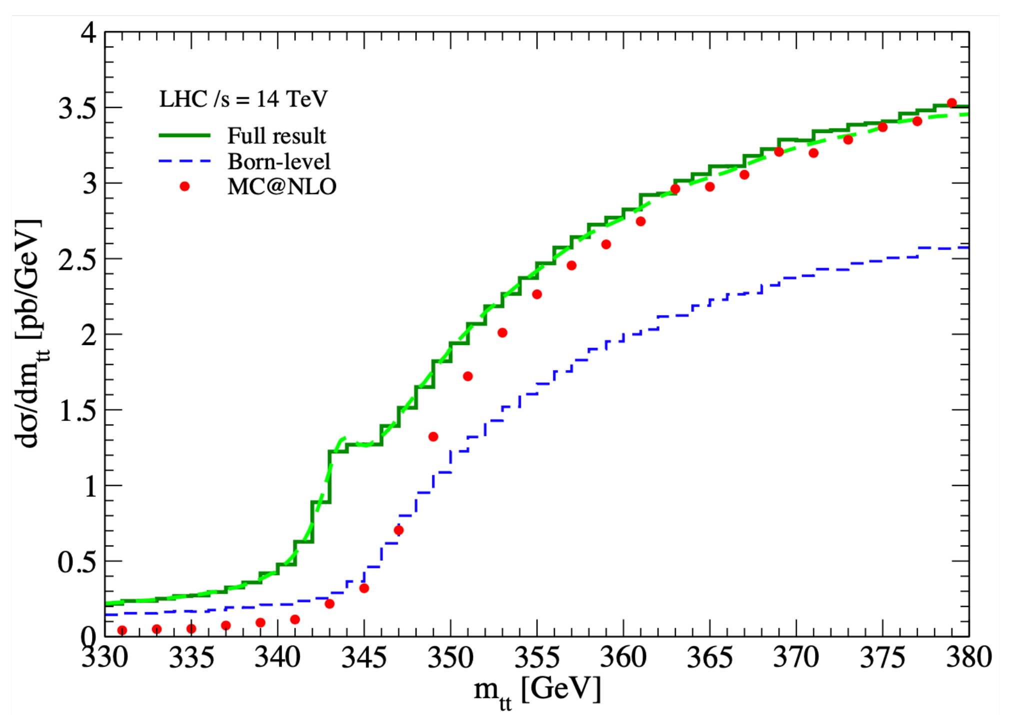
★ Ratio of Green's functions of the Hamiltonians with/without V_{QCD}

★ Different channels (*gg*/*qq*; ***1***/***8***)



[Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)]
[Jezabek, Kuhn & Teubner (Z.Phys.C`92)]

✦ Threshold enhancement



[Sumino & Yokoya (JHEP`10)]

✤ Full *WbWb* differential distribution (green)

★ Bound-state effects

★ Finite top-width effects

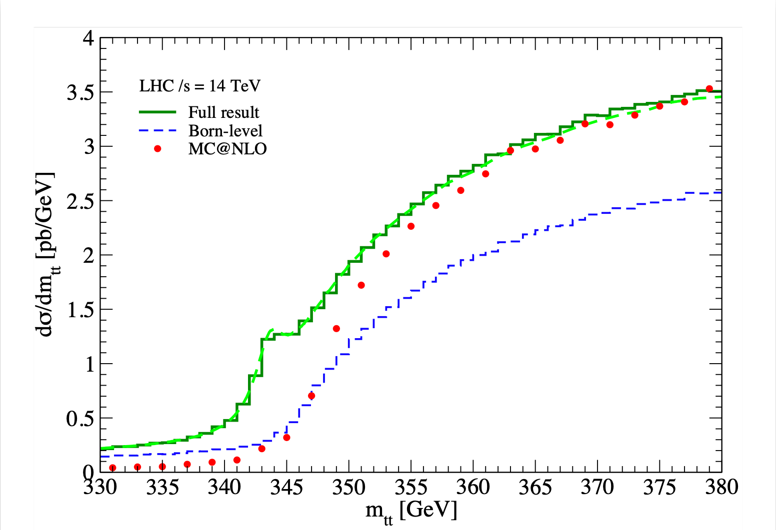
★ NLO effects: ISR, differential *K*-factors

✤ NLO *WbWb* differential distribution (red)

★ No bound-state effects

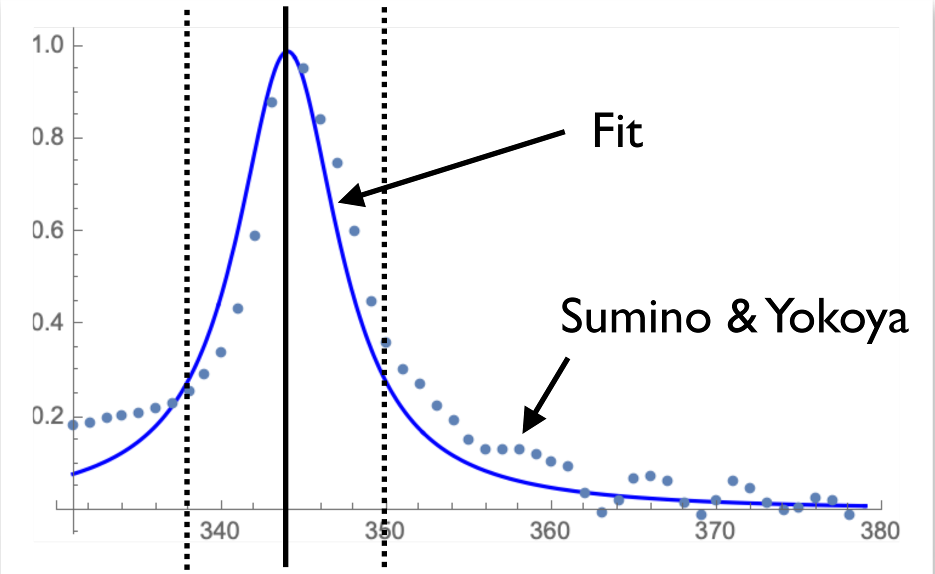
✤ Pure toponium contribution: "green - red"

✦ Breit-Wigner modelling: a resonance of 344 GeV with a 7 GeV width



[Sumino & Yokoya (JHEP`10)]

green - red ⇒



Toponium signal: $pp \to \eta_t \to t^{(*)}\bar{t}^{(*)} \to W^+ b W^- \bar{b}$

$m_{\eta_t} = 344$ GeV; $\Gamma_{\eta_t} \approx 7$ GeV

$\sigma(13 \text{ TeV}) \sim 6.5$ pb

✦ A simplified toponium toy model: SM + gauge-singlet pseudo-scalar

- ✤ Dominant production via gluon-fusion ⤳ coupling to gluons
- ✤ Connection with the top quark ⤳ coupling to top quarks

$$\mathcal{L}_{\eta_t} = \frac{1}{2}\partial_\mu \eta_t \partial^\mu \eta_t - \frac{1}{2} m_{\eta_t} \eta_t^2 - \frac{1}{4} g_{gg} \eta_t G^a_{\mu\nu} \tilde{G}^{a\mu\nu} - i g_{tt} \eta_t \bar{t} \gamma_5 t$$

3 fixed parameters
[$m/\Gamma/\sigma$ known]

Main toponium characteristics

✦ Verification: we assume a di-leptonic toponium decay

- Check of a few observables
- Expectation from spin density matrices

$$\sum_{\sigma,\bar\sigma,\sigma',\bar\sigma'} \rho^{\eta_t}_{\sigma\bar\sigma;\sigma'\bar\sigma'}\ \rho^{t\to b\bar\ell\nu_\ell}_{\sigma,\sigma'}\ \rho^{\bar t\to\bar b\ell'\bar\nu_{\ell'}}_{\bar\sigma,\bar\sigma'}$$

- Angular separation between the two leptons in the top/antitop rest frames

$$(1+\cos\bar\theta)(1+\cos\theta)+(1-\cos\bar\theta)(1-\cos\theta)+2\sin\bar\theta\sin\theta\cos(\bar\varphi-\varphi)$$

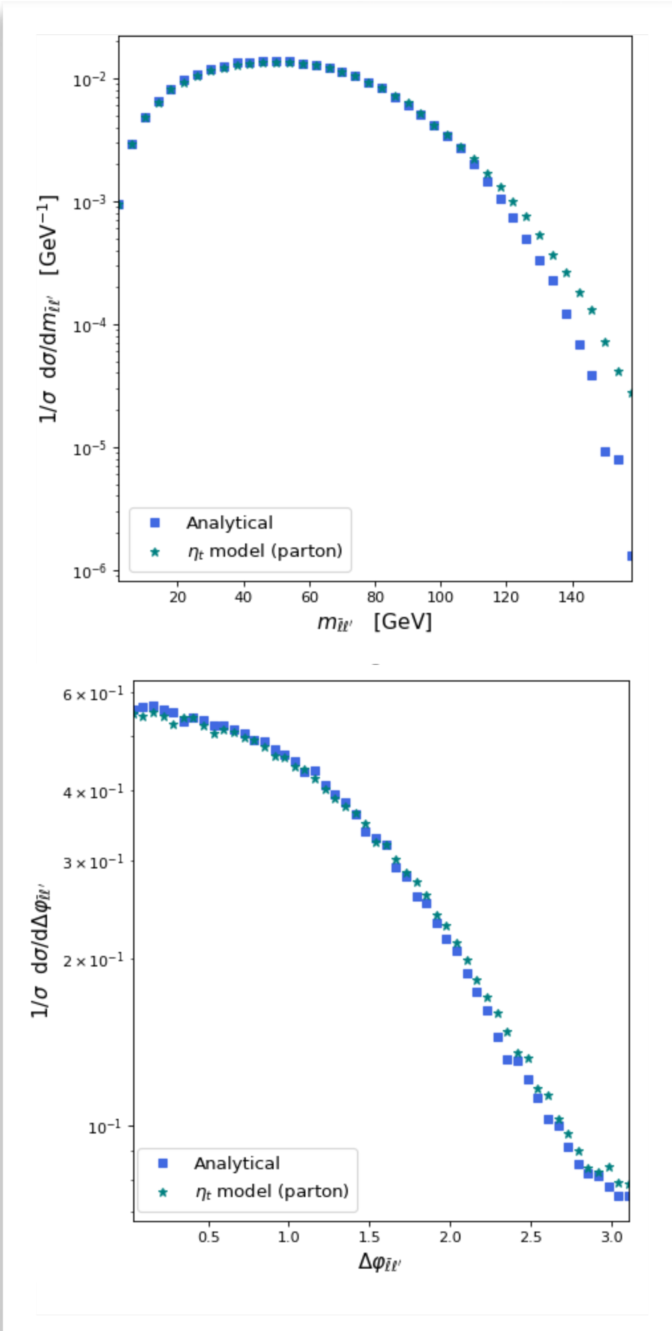
[Hagiwara, Yokoya & Zheng (JHEP'18)]

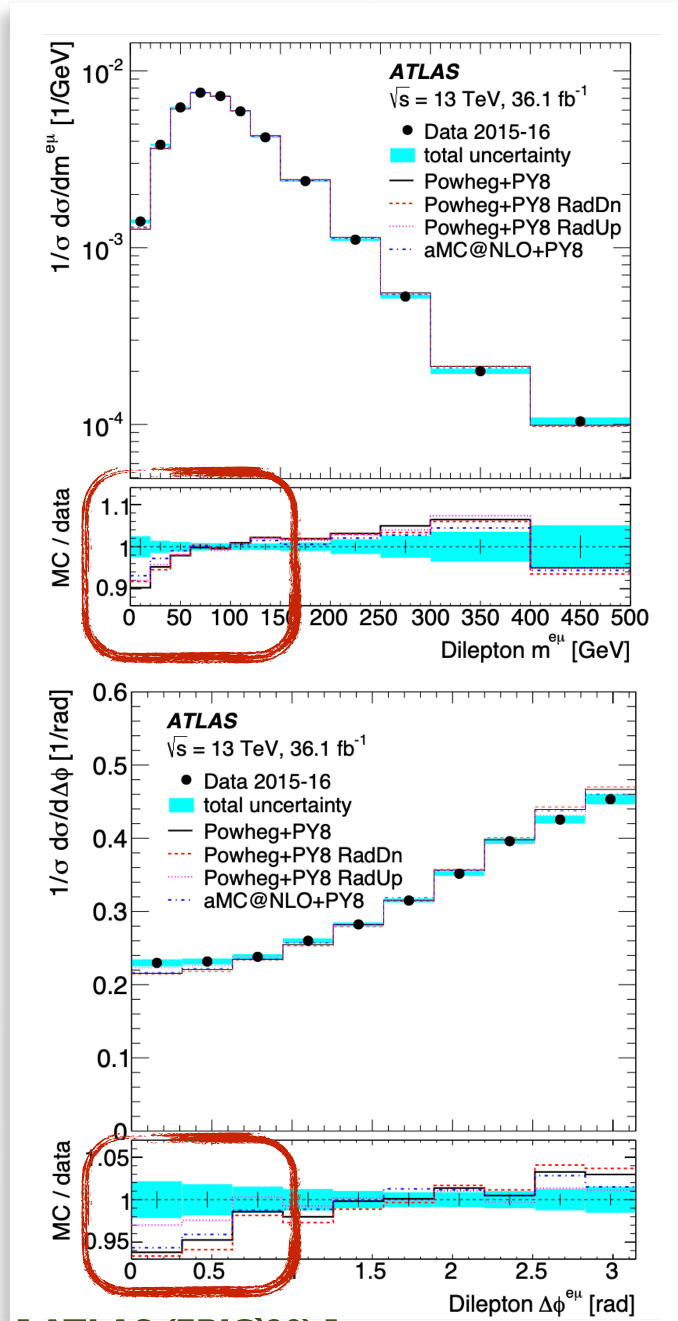
  - ~ small azimuthal angle separation (survives the lab frame boost)
  - ~ small di-lepton invariant mass (ignoring the binding energy):

$$m^2_{\bar\ell\ell'} = 2E_{\bar\ell}E_{\ell'}\Big(1-\sin\bar\theta\sin\theta\cos(\bar\varphi-\varphi)-\cos\bar\theta\cos\theta\Big)$$

- Toponium characteristic: small $m_{\ell\ell}$ and small $\Delta\varphi_{\ell\ell}$

Toponium decays in two leptons





[ATLAS (EPJC`20)]

✦ Signal definition

- ✤ *M(WbWb)* in [338, 350] GeV
- ✤ Re-weighting (→ pNRQCD)

$$|M|^2 \to |M|^2 \left|\frac{G(E;p^*)}{G_0(E;p^*)}\right|^2$$

✦ Modelling good enough

- ✤ Reproduction of the core toponium properties
- ✤ Toponium formation could be present in ATLAS data
  - ★ At small $m_{\ell\ell}$, small $\Delta\varphi_{\ell\ell}$

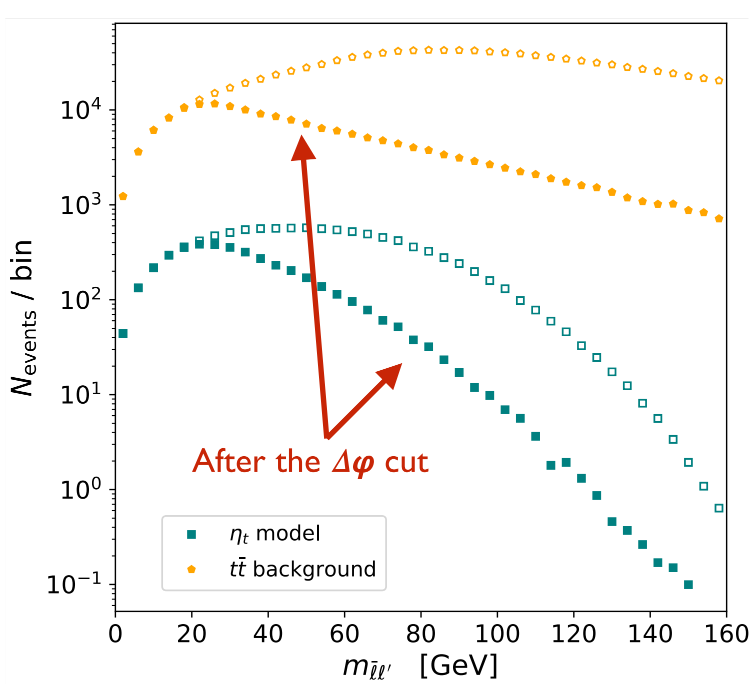
How to confirm it?

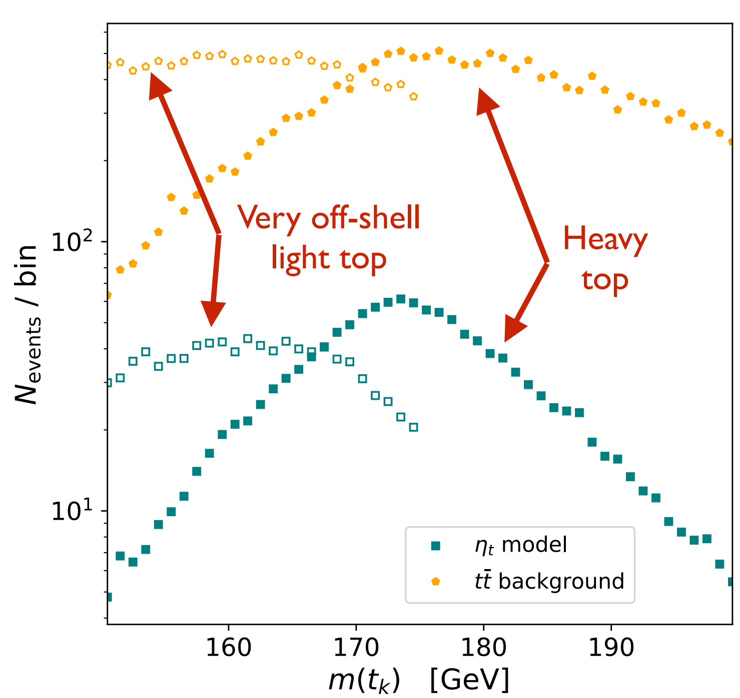
$\sigma(\eta_t)$ [pb]	$\sigma(t\bar{t})$ [pb]	Ratio
6.43	810	0.0079

⇝ Proper analysis

Towards toponium observation with di-leptons

- **Final-state composition**
  - Two isolated leptons + two isolated *b*-jets (p_T > 25 GeV; $|\eta|$ < 2.5; ΔR < 0.4)
- **ATLAS excess location ≡ bulk of the toponium events**
  - Small $\Delta\varphi_{\ell\ell}$ ($<\pi/5$), small $m_{\ell\ell}$ (< 40 GeV)
- **Constraining the transverse mass of the $\bar\ell\ell' b\bar b + \not{E}_T$ system (<320 GeV)**
- **Kinematical reconstruction of the toponium system (t_L/t_H)**
  - Assumption: $\vec p_T(t) = \vec p_T(\bar t)$
  - Definition of the leptons: ℓ_1 is the leading lepton, ℓ_2 the sub-leading one
  - Definition of the *b*-jets: $m(\ell_1, b_1) > m(\ell_1, b_2)$
  - Definition of the neutrinos: *W* reconstruction, '*top*' reconstruction

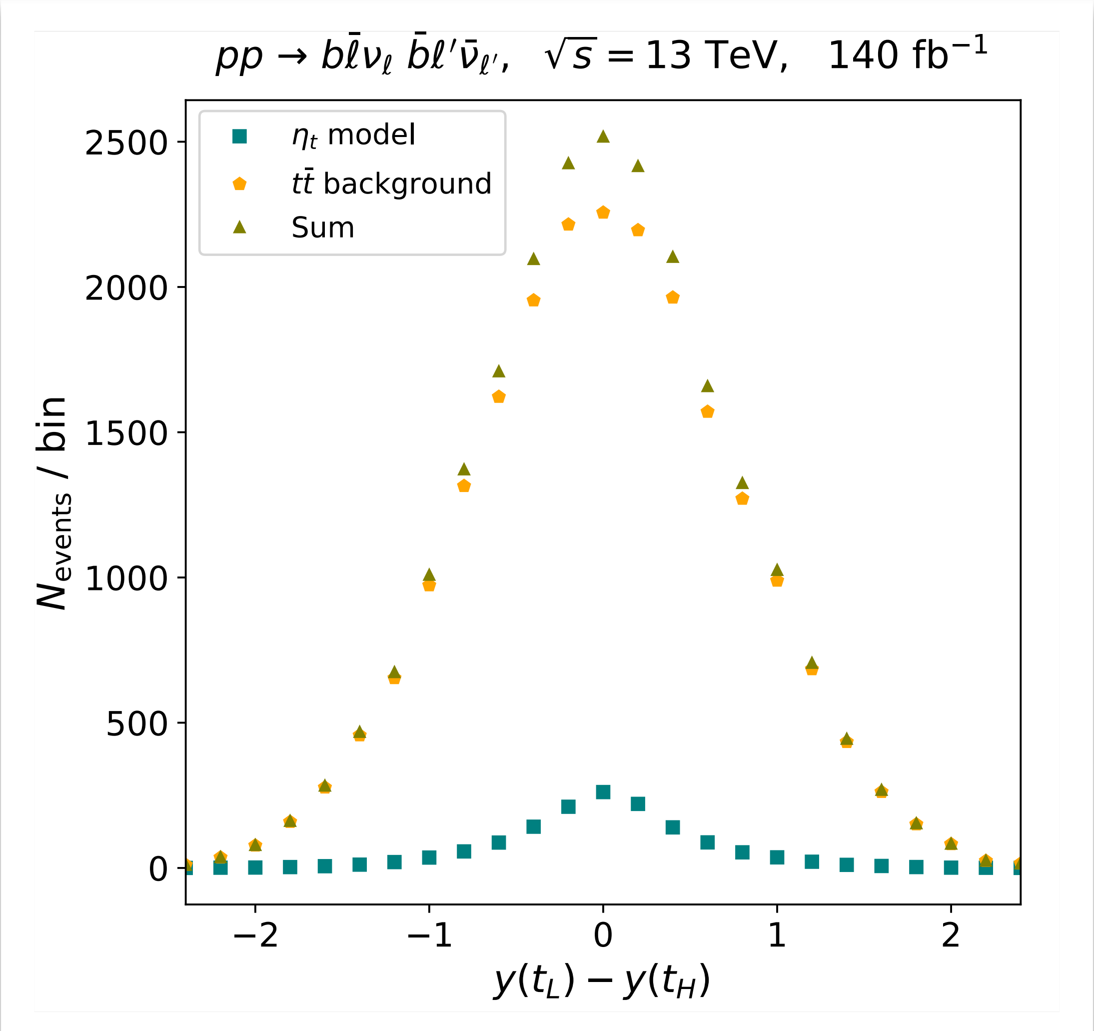




13 TeV, 140/fb

Cut	$t\bar t$	Toponium	Ratio
Initial	113,000,000	900,000	0.0079
Di-lepton	1,370,000	10,300	0.0076
$\Delta\varphi_{\bar\ell\ell'}$	178,000	4,060	0.023
$m_{\bar\ell\ell'}$	77,900	2,760	0.035
$m_T(\bar\ell\ell' b\bar b; \nu_\ell\bar\nu_{\ell'})$	40,800	2,460	0.060
$t\bar t$ kinematical fit	20,400	1,420	0.070

Key observable for a discovery



- **The rapidity difference distribution**
  - Peak at the origin
    - ~ smaller t_L/t_H momentum in the toponium rest frame
  - ★ t_L is the light reconstructed top
  - ★ t_H is the heavy reconstructed top

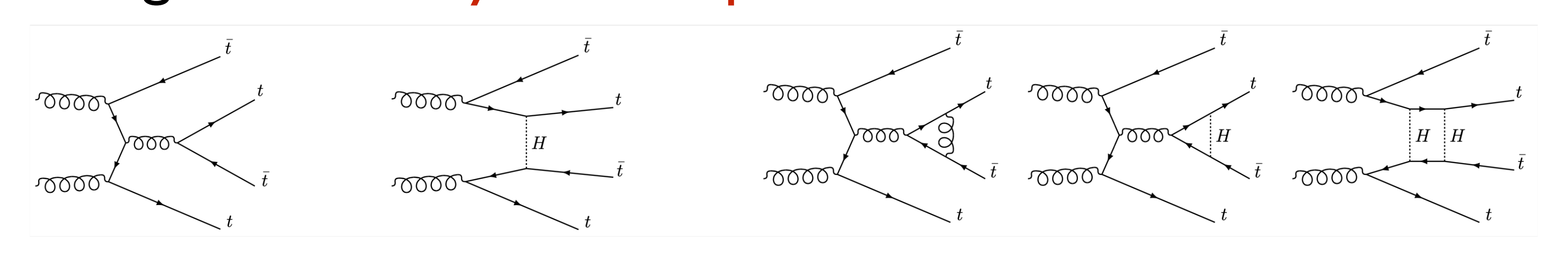
Potential for a S/B ratio of 10%

Four-top production as a probe for new physics

[Darmé, BF & Maltoni (to appear in JHEP)]

Four-top production & new physics

- Most precise theoretical predictions @ NLO (QCD+EW)
  - $\sigma_{4t}^{\rm SM} = 11.97^{+2.15}_{-2.51}$ fb [Frederix, Pagani & Zaro (JHEP`18)]
  - Large electroweak contributions canceling each other
- Current measurements leave room for top-philic BSM contributions
  - Investigated in many UV-complete frameworks and in the SMEFT



- New physics interpretation of four-top LHC results
  - Care must be taken with an EFT interpretation ➢ simplified models?
    - ★ Similar discussions within the DM@LHC working group
    - ★ Here: scalar, pseudo-scalar and vector top-philic states; colour singlets and octets
  - EFT description beyond the SMEFT @ dim-6

$$\mathcal{O}^1_{RR} = \bar t_R \gamma^\mu t_R\ \bar t_R \gamma_\mu t_R \qquad \mathcal{O}^1_{LL} = \bar t_L \gamma^\mu t_L\ \bar t_L \gamma_\mu t_L$$

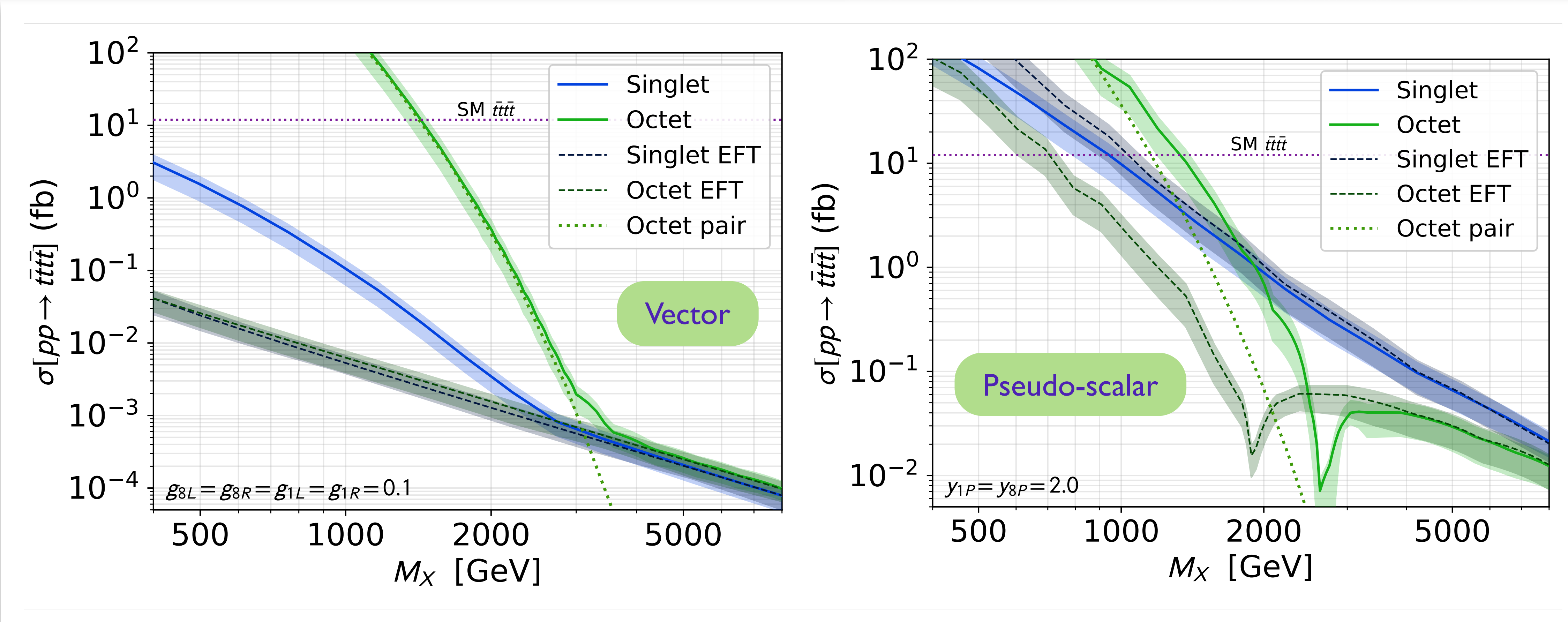
$$\mathcal{O}^1_{LR} = \bar t_L \gamma^\mu t_L\ \bar t_R \gamma_\mu t_R \qquad \mathcal{O}^8_{LR} = \bar t_L T^A \gamma^\mu t_L\ \bar t_R T^A \gamma_\mu t_R$$

$$\mathcal{O}^1_{S} = \bar t t\ \bar t t \qquad \mathcal{O}^8_{S} = \bar t T^A t\ \bar t T^A t \qquad \text{SU(2)}_L \text{ breaking}$$

$$\mathcal{O}^1_{PS} = \bar t t\ \bar t i\gamma^5 t \qquad \mathcal{O}^8_{PS} = \bar t T^A t\ \bar t T^A i\gamma^5 t \qquad \text{Parity breaking}$$

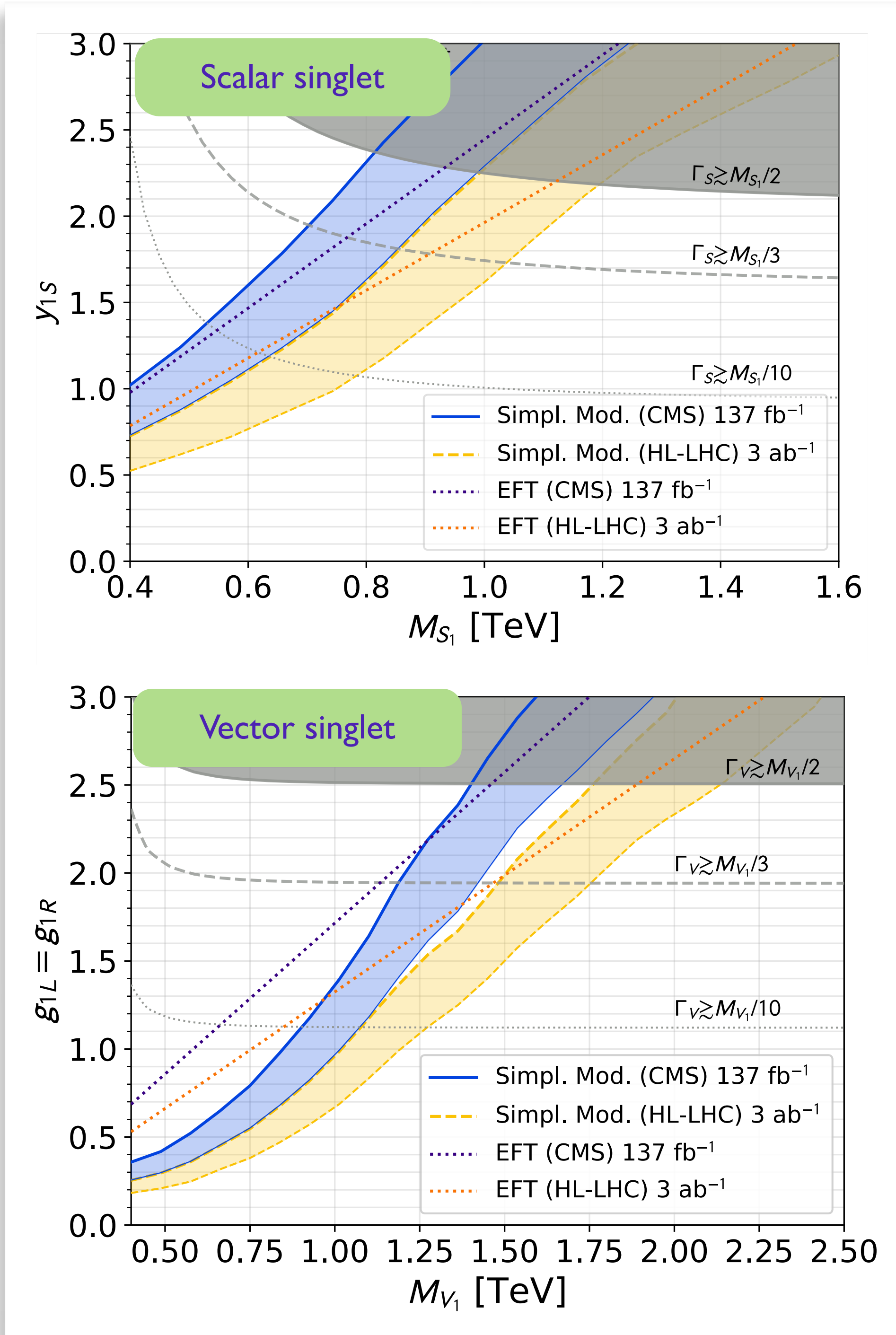
Simplified models *vs* EFT

- Total rates in the considered frameworks
  - Simplified models: on-shell production dominates (small masses and couplings)
    - Both double and single resonant channels
    - Good convergence to the EFT in the heavy and small coupling case
  - Large interference with the SM in the octet case → almost no impact @ LHC!
  - (Naive) EFT ≠ simplified models for masses reachable at the LHC
    - Beware of regimes where the EFT should not be used
    - Naive extraction of limits → does it make sense?



Probing new singlets with four tops @ LHC

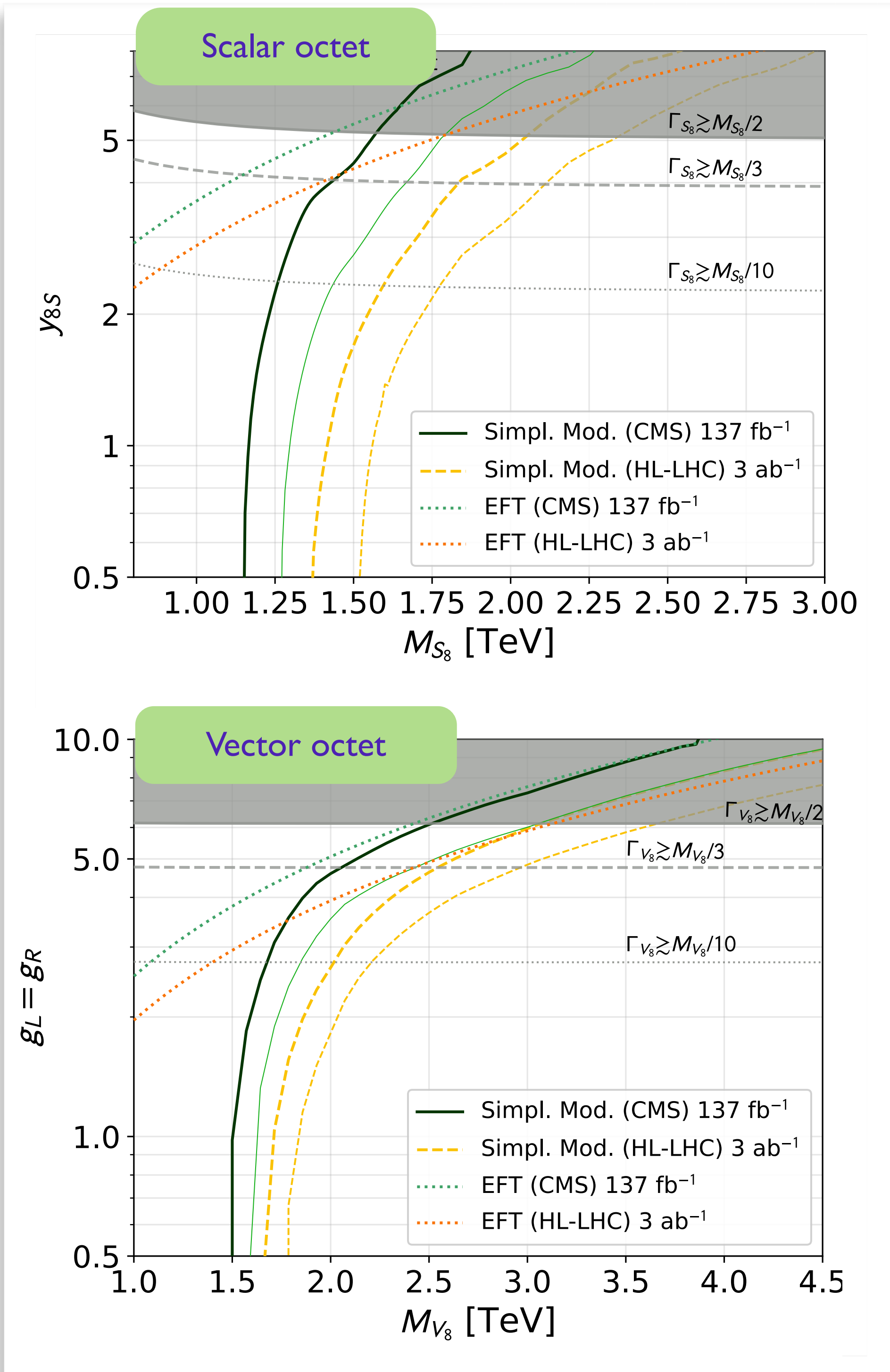
✦ The scalar and vector singlet cases



- ✤ Recasting the CMS-TOP-18-003 full run 2 study
  - ★ Including a new high-H_T signal region
  - ★ Dedicated to heavy new physics
- ✤ Simplified model bounds
  - ★ Limits include a K-factor of 1 − 2
    - ➡ Unknown impact of the EW corrections
  - ★ Gray area: not theoretical sound
    - ➡ Scalars: limits up to 0.8−1.2 TeV (LHC/HL-LHC)
    - ➡ Vectors: limits up to 1.2−1.7 TeV (LHC/HL-LHC)
  - ★ Excluded couplings moderate to large
- ✤ EFT bounds (translated in mass/couplings)
  - ★ Good naive agreement for scalars
    - ➡ Fortuitous, similar σ values
  - ★ Not applicable in viable parameter space regions (too small EFT scale)
    - ➡ Typical $\sqrt{s}$ too larger compared with Λ

Probing new octets with four tops @ LHC

✦ The scalar and vector octet case



- ✤ Recasting the CMS-TOP-18-003 study
  - ★ Including a new high-H_T signal region
- ✤ Stronger limits than in the singlet case
  - ★ Scalars: limits up to 1.5−2 TeV (LHC/HL-LHC)
  - ★ Vectors: limits up to 2.5−3 TeV (LHC/HL-LHC)
  - ★ Strong constraints for low masses
    - ➡ Even for small couplings (1.2 − 1.5 TeV)
- ✤ EFT bounds (translated in mass/couplings)
  - ★ Suitable only for the heavy vector case
    - ➡ The EFT limit sensible
  - ★ Not applicable otherwise
    - ➡ Typical $\sqrt{s}$ too larger compared with Λ
    - ➡ However, naively found overly conservative

Summary

Summary

✦ A wide range of opportunities for top physics at current and future LHC runs

- ✤ Rare effects could be observed in precise extractions of differential distributions
- ✤ Not necessarily visible at the total-rate level
- ✤ Example toponium bound state formation:
  - ★ 0.1% of the cross section
  - ★ 10% after a proper analysis in a small corner of the phase space
- ✤ Could already be there in current data

✦ ATLAS and CMS got the first four-top production measurements at run 2

- ✤ New physics contributions could play an important role
- ✤ Investigation of the EFT and simplified model interpretations
  - ★ Simplified models are relevant as long as on-shell new physics production open
  - ★ Care to be taken with EFT interpretations (naively incorrect, luckily conservative)
- ★ Importance of getting differential (our high-H_T bin)