Exploring the Minimal Composite Higgs Model in the Higgs Sector at the LHC using the ttH and ttHH production channels.

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Different Scales of CH Models

Λ_{UV}

- Theory at high scale (a new strong force)
- $\Lambda_{UV} \gg \mathrm{TeV}$ (EW scale not sensitive to it)
- No fundamental Higgs

TeV

- Confinement
- Higgs is a bound state

Electroweak

- Standard Model (SM) is recovered

- Compositeness around the TeV scale:
  Hierarchy Problem solved (main motivation).
- Focus on models valid around the TeV scale, not beyond it.

MCHM5

- $f \sim 1\ \mathrm{TeV}$ scale: $SO(5) \to SO(4)$ breaking.
  - pNGB Higgs.
- Custodial Symmetry.
- Gauge sector is universal.
- Partial Compositeness hypothesis (Kaplan, Nucl. Phys., B365:259–278, 1991)
- Fermions depend on the representation of $SO(5)$ they belong to.
- Here I will focus on the **5** (MCHM_5):
  - Top partners transform as a fiveplet of SO(5).
    - Vector-like fermionic resonances

MCHM5

$$\Psi_5 = \frac{1}{\sqrt{2}}\{\underbrace{-i\,B + i\,X_{\frac{5}{3}}, -B - X_{\frac{5}{3}}, -i\,T - i\,X_{\frac{2}{3}}, T - X_{\frac{2}{3}}}_{\text{SO(4) fourplet } \Psi_4}, \underbrace{\sqrt{2}\,\tilde{T}}_{\text{SO(4) singlet } \Psi_1}\}$$

At scale f : → SO(4) fourplet Ψ_4 SO(4) singlet Ψ_1

Mass: → $\boxed{M_4 \sim \text{TeV}}$ $\boxed{M_1 \sim \text{TeV}}$

- Ψ_4 and Ψ_1 mix linearly with the top through couplings y_L, y_R

→ Masses get corrections from mixing and EW breaking $\sim \frac{y_{L,R}^2 f^2}{M_{1,4}^2}(1 \pm \frac{v_{EW}^2}{f^2})$

Going to the Experiment

- The model: MCHM5

$\Rightarrow$Modifications in the top and Higgs sector (next slide)

- Measurements at the LHC can:
  - Constrain the model
  - Disentangle the model from other models

- What new insights can HL-LHC and future colliders (HE-LHC, FCC) give us?

The ttH and ttHH Processes

- The tth production was measured by CMS $\mu_{tth} = 1.26^{+0.31}_{-0.26}$ (CMS Collaboration Phys.Rev. Lett. (2018) no.120, 231801), and ATLAS $\mu_{tth} = 1.32^{+0.28}_{-0.26}$ (ATLAS Collaboration CERN-EP-2018-138)
- In MCHMs, The tth coupling is modified in a way that depends on the partners representation (Liu et al. Phys.Rev. D96 (2017) no.3, 035013):

$$\boxed{\frac{y_{tth}^{MCHM}}{y_{tth}^{SM}} = 1 + \xi\, \Delta_{tth}}$$, with

MCHM$_5$: $\Delta_{tth} < 0$ **suppression**

MCHM$_{14}$: $\Delta_{tth} < 0$ **suppression**
$\Delta_{tth} > 0$ **enhancement**

$$\xi = \frac{v_{EW}^2}{f^2}$$

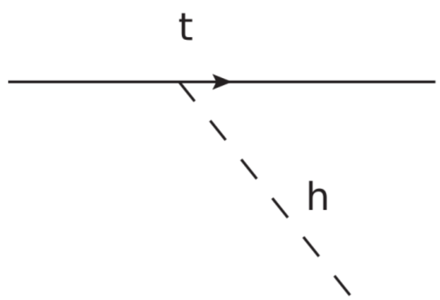
- Higgs sector non-linearities generate new vertices such as tthh

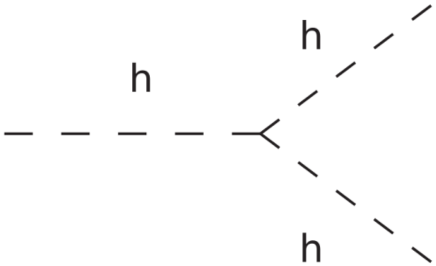
$$\boxed{y_{tthh}^{MCHM} = \xi\, \Delta_{tthh}}$$

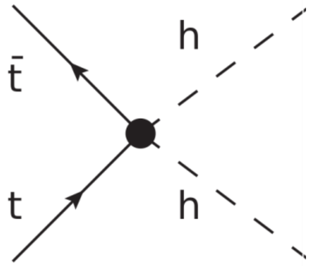
$\sigma_{tthh}^{MCHM} \sim$ **partner pair production**
+
non-resonant part

Correlation in tth vs NR-tthh

Three main effects contribute to tthh:







$$\frac{y_{tth}^{MCHM}}{y_{tth}^{SM}} \approx 1 - \frac{3}{2}\xi$$

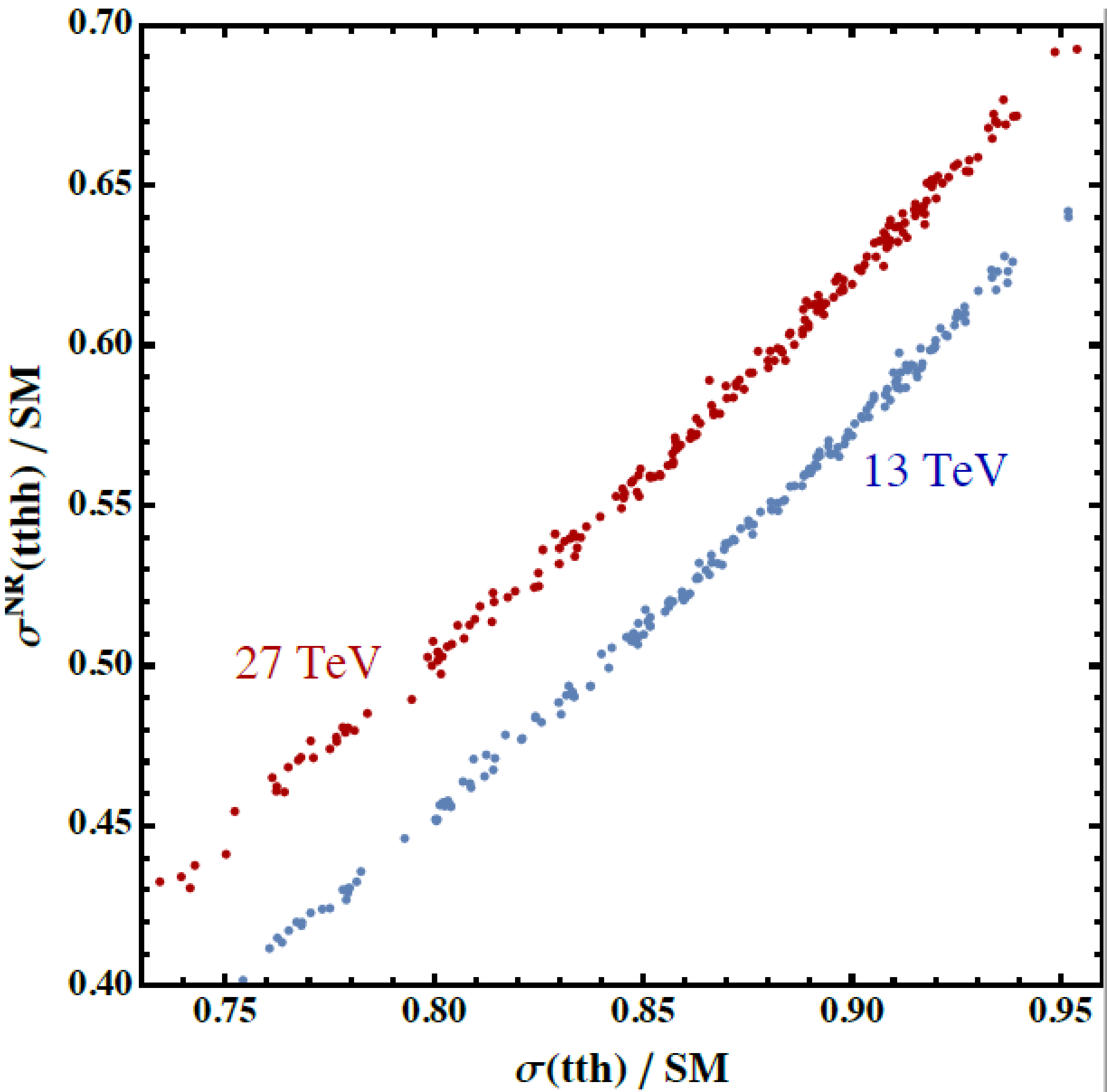
$$\frac{\lambda_{3h}^{MCHM}}{\lambda_{3h}^{SM}} \approx 1 - \frac{3}{2}\xi$$

$$y_{tthh}^{MCHM} \approx -2\,\xi$$

All set by $\xi = \frac{v_{EW}^2}{f^2}$

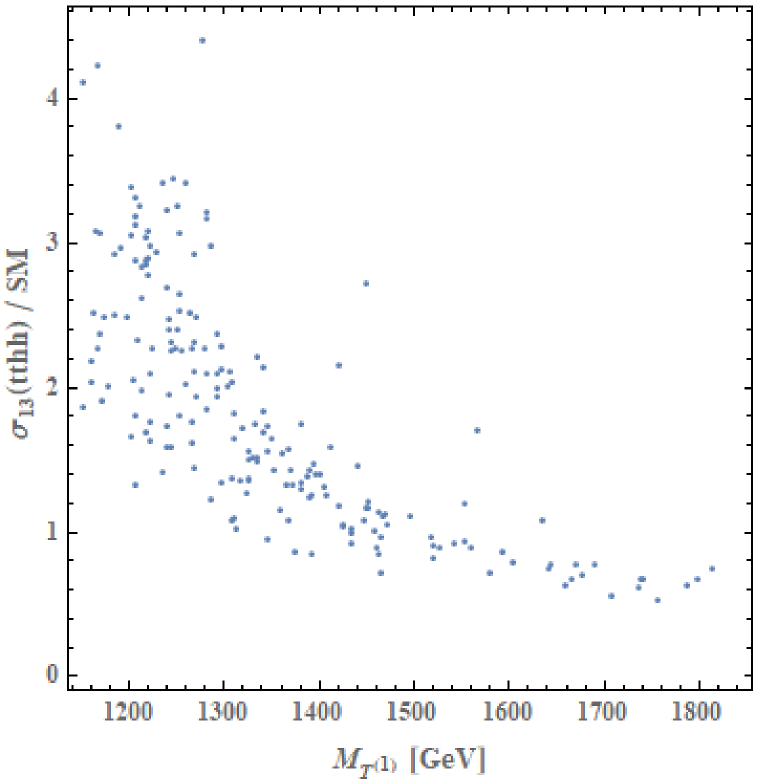
(+ subleading at high M)

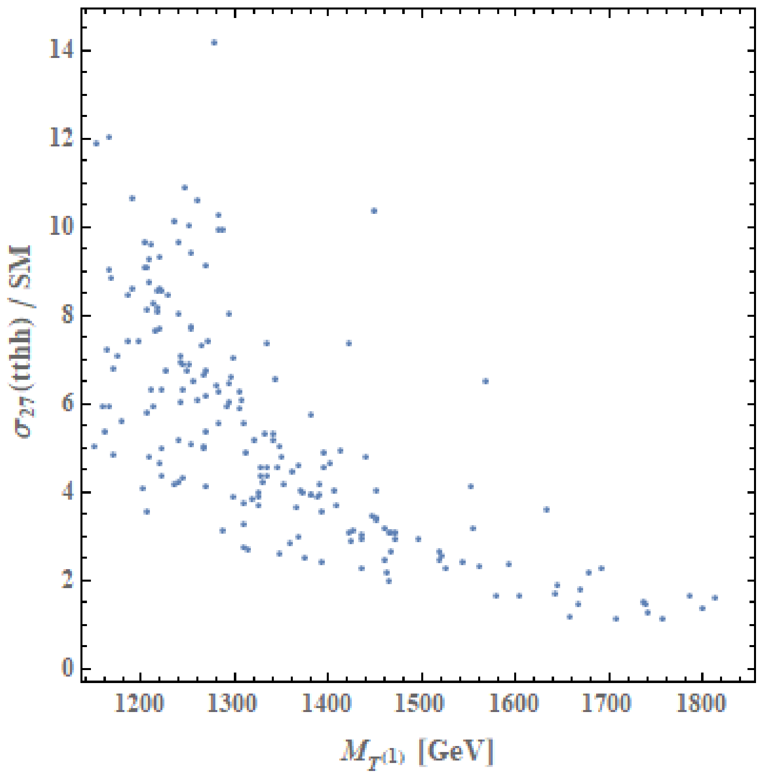
Non-resonant $\sigma(tthh)$ (normalized) vs $\sigma(tth)$ (normalized) at 13 TeV and 27 TeV.



- Clear correlation between NR- tthh and tth.
- Approx. slope for both energies is 1.2.
- Modification of y_t+ 20% of NR-tthh from other vertices.
- Since NR-tthh contains additional information about modified SM couplings, it is worth studying it in more detail.

$\sigma(tthh)$ normalized to SM vs $M_{T^{(1)}}$ at 13 TeV (left) and 27 TeV (right)



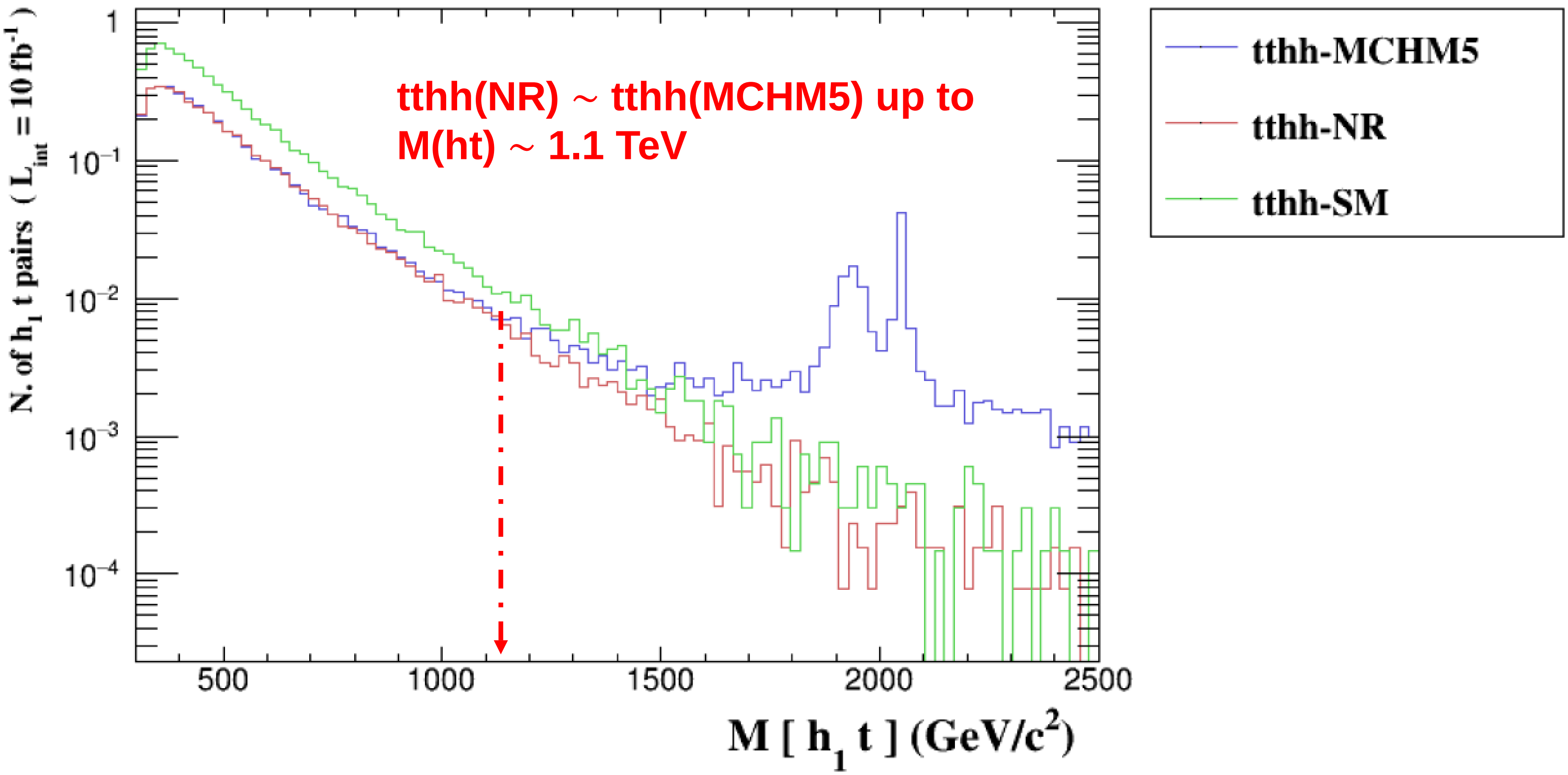


$\sigma^{NLO\ QCD}_{tthh,13\ TeV}$: 0.775 fb +1.5% -4.3% (QCD scale) ± 3.2% (PDF + α_s) (D. De Florian et al., LHC Higgs Cross Section Working Group, (CERN--2017--002-M),

$\sigma^{NLO\ QCD}_{tthh,27\ TeV}$: 5.2 fb (R. Frederix et al., *Higgs pair production at the LHC with NLO and parton-shower effects*, Phys.Lett. B732 (2014) 142-149)

- At 27 TeV, there can be a large increase, driven mainly by pair production, but there is also a contribution that is non-resonant, more important at larger $T^{(1)}$ mass (see later slides).

Sample Point at 13 TeV cm: Invariant Mass (ht)



- Non-resonant part (93% at 13 TeV). This is due to the larger resonance masses, 2 TeV and above.
- The non-resonant part contains important information about coupling modifications, and even this small relative effect may be seen at high luminosity.

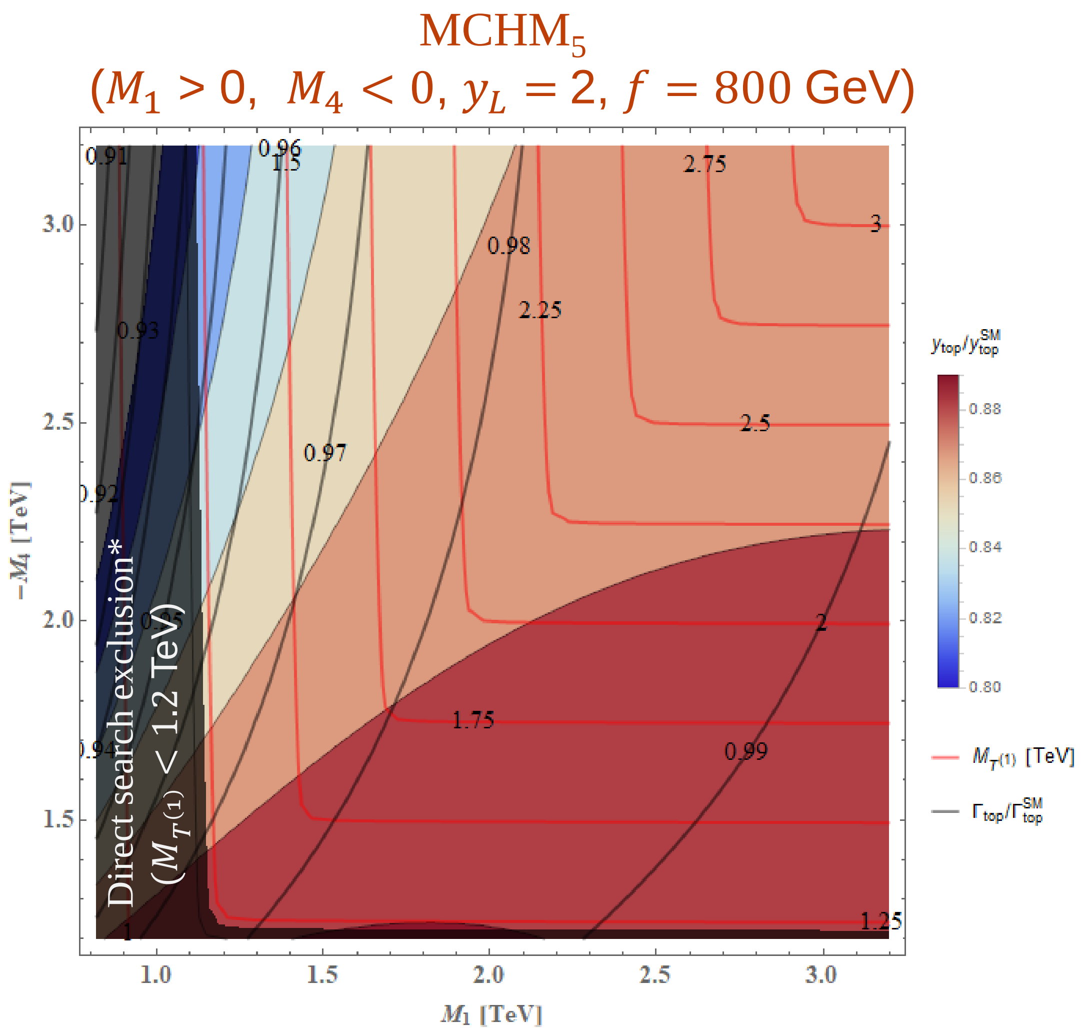
Conclusions

- The MCHM5 predicts deviations of observables with respect to the SM.
- ttH and NR-ttHH are correlated in the MCHM5.
- Discovery of MCHM5 means finding resonances (5 of them!) and observing NR contributions (form factors).
- If resonances are heavy we need high luminosity to see the NR part.
- If resonances are discovered, additional information can come from ttH and ttHH-NR.
  - ttH: y_t.
  - ttHH-NR: y_t+ 20% from other vertices.
- At HL-LHC and HE-LHC or FCC, it might be possible to better understand the MCHM and/or help in disentangling it from other theoretical interpretations (SUSY etc.)

Thank You

Additional Slides

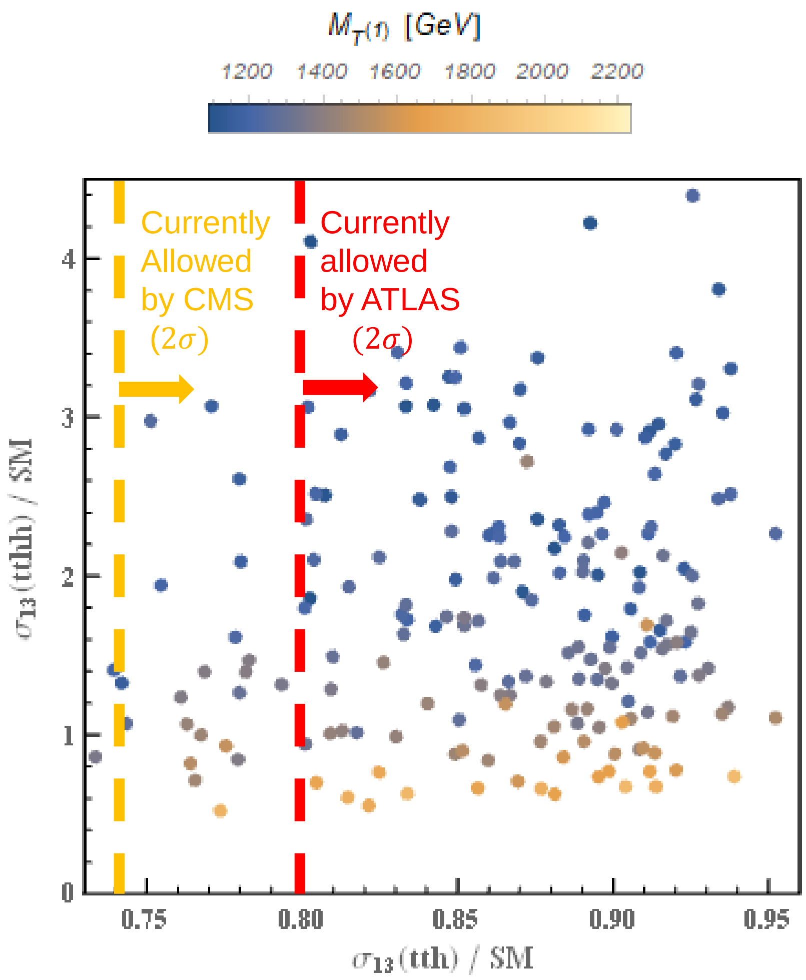
Contours for $T^{(1)}$ mass (red), normalized top yukawa (colors) and width (black)

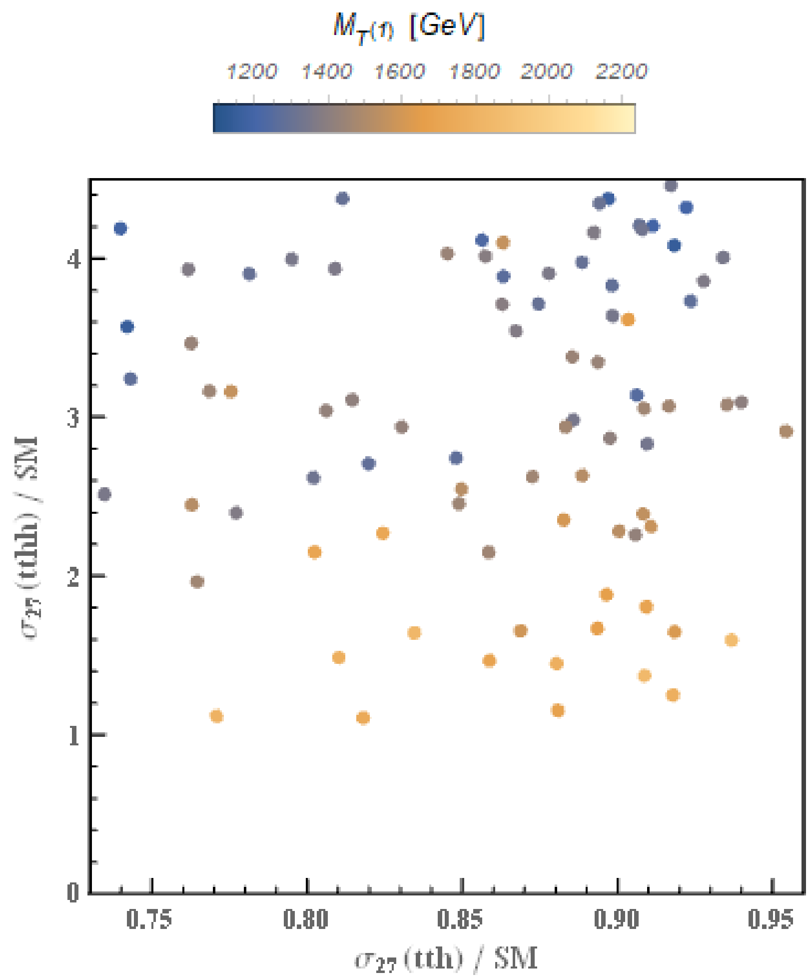


- Negative M_4 region. Supression for MCHM$_5$, varying from 80% to 87% times the SM value.
- The top width is very close to the SM value, since the partner masses are relatively high.
- Also shown is the 1.2 TeV exclusion limit, valid for BR$\left(T^{(1)} \to t\, h\right) \sim 50\,\%$.

(CMS: CMS-B2G-17-011, CERN-EP-2018-069; ATLAS: CERN-EP-2018-088, CERN-EP-2018-031, CERN-EP-2017-094, CERN-EP-2017-075)

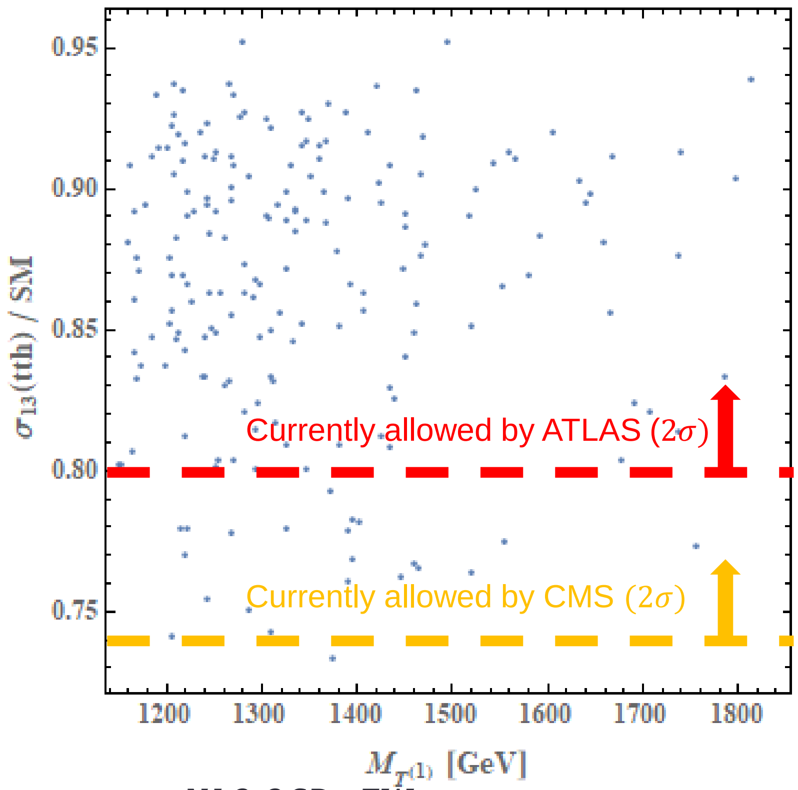
$\sigma(tthh)$ (normalized) vs $\sigma(tth)$ (normalized) at 13 TeV (left) and 27 TeV (right). Colors show $M_{T^{(1)}}$.

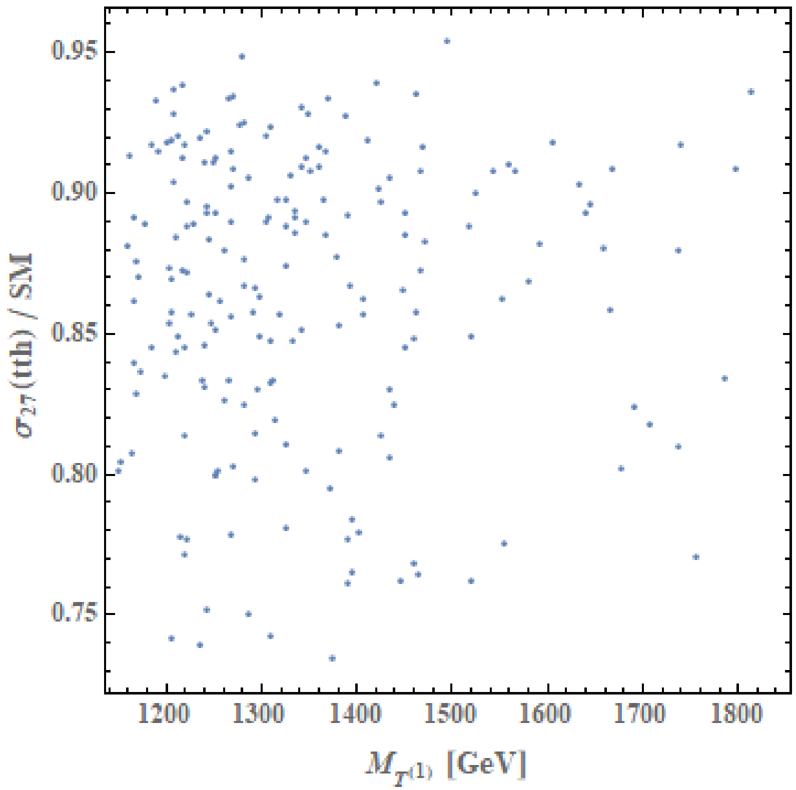




- While tth is insensitive to the $T^{(1)}$ mass, tthh is dominated at low masses by $T^{(1)}$ pair production.
- Also shown the 2σ limits for measured tth by ATLAS and CMS

$\sigma(tth)$ normalized to SM vs $M_{T^{(1)}}$ at 13 TeV (left) and 27 TeV (right)

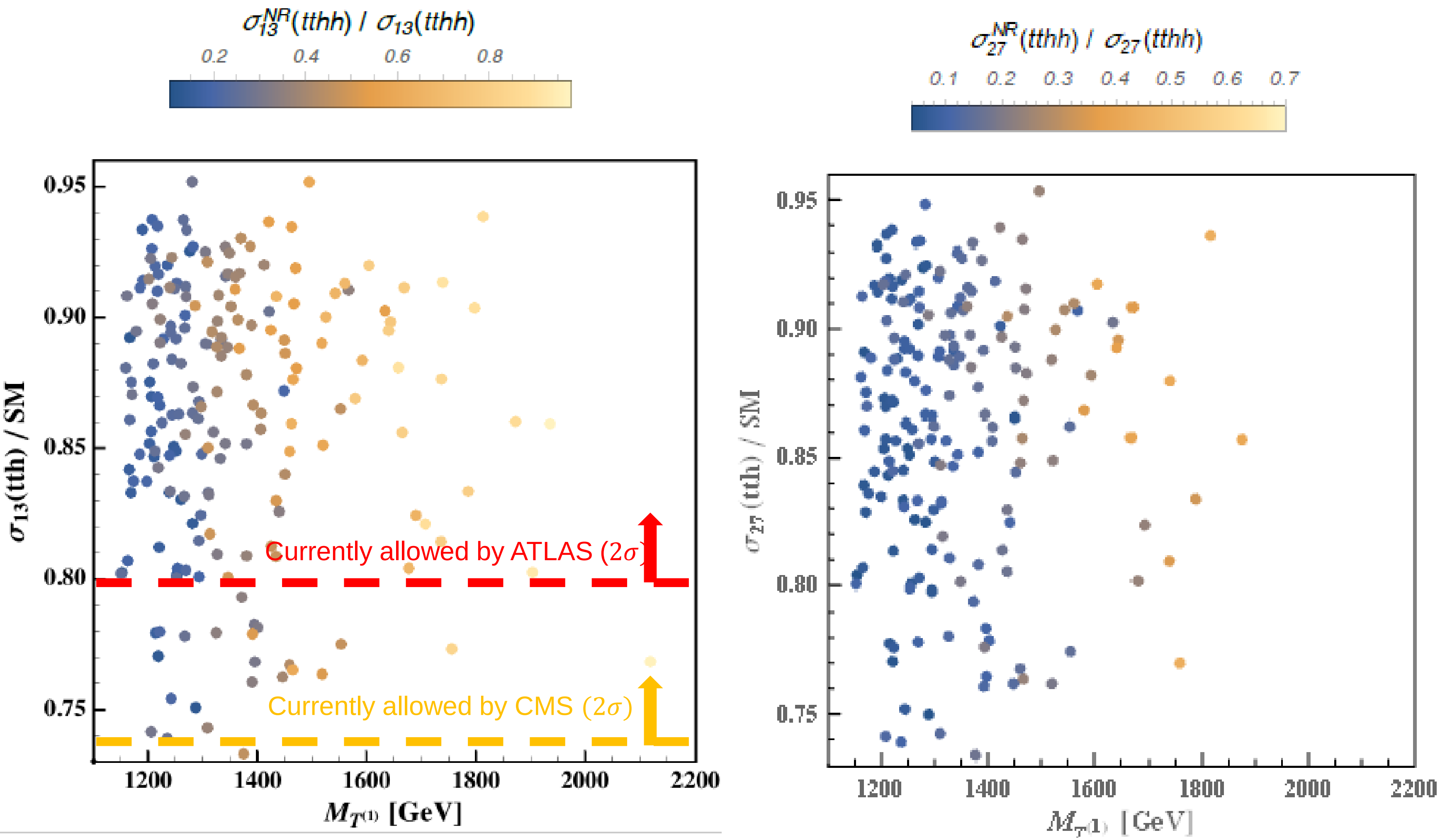




$\sigma^{NLO\ QCD+EW}_{tth,13\ TeV}$: 507.1 fb +5.8% -9.2% (QCD scale) ± 3.6% (PDF + α_s) (D. De Florian et al., LHC Higgs Cross Section Working Group, (CERN--2017--002-M), $\sigma^{NLO\ QCD}_{tth,27\ TeV}$: 2.8 pb (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy)

- The cross section is insensitive to the $T^{(1)}$ mass.
- Although there is an increase at 27 TeV, it mantains the ratio with respect to the SM.
- Also shown the 2σ limits for measured tth by ATLAS and CMS

$\sigma(tthh)$ (normalized) vs $\sigma(tth)$ (normalized) at 13 TeV (left) and 27 TeV (right). Colors show the ratio of resonant to non-resonant tthh cross section.



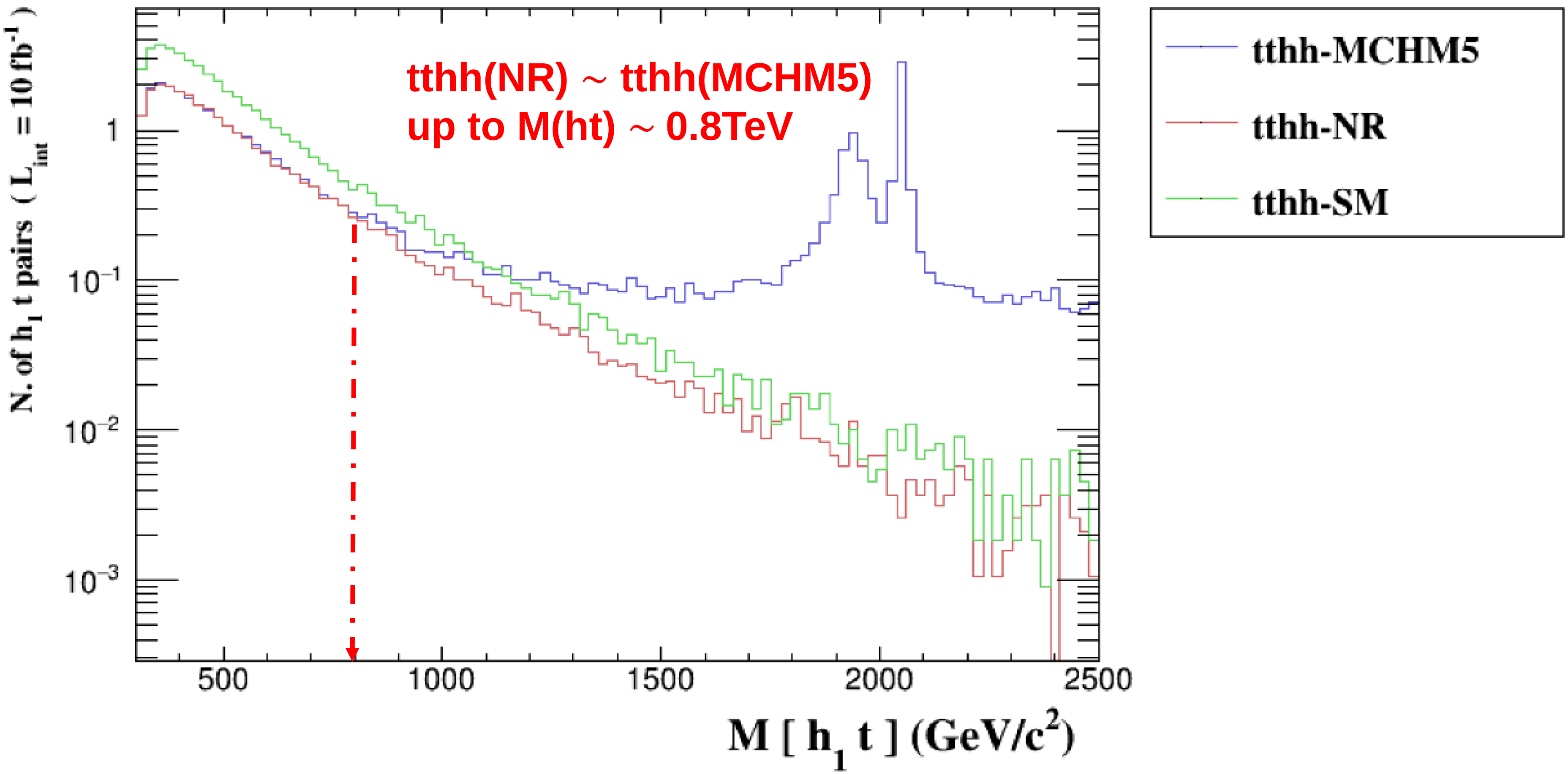
- At higher masses, the tthh cross section can be dominated by the non-resonant part.
- Also shown the 2σ limits for measured tth by ATLAS and CMS

Sample Points

		Point 1	Point 2	Point 3	Point 4	Point 5
Parameters	M_1 (GeV)	-808.6	-1317.3	-1830.7	-852.3	-3000
	M_4 (GeV)	1670.1	1579.8	2043.0	1409.1	3000
	f (GeV)	887	969	1084	1186	800
	y_L	0.74	1.66	1.98	0.88	1.00
	y_R	1.53	0.62	0.61	0.86	1.98
	$M_{T^{(1)}}$ (TeV)	1.49	1.44	1.94	1.28	3.00
	$M_{T^{(2)}}$ (TeV)	1.71	1.59	2.05	1.44	3.08
	$M_{T^{(3)}}$ (TeV)	1.86	2.25	2.96	1.76	3.41
	$M_{B^{(1)}}$ (TeV)	1.79	2.25	2.96	1.75	3.11
	$M_{X_{5/3}}$ (TeV)	1.67	1.58	2.04	1.41	3.00
	$BR(T^{(1)} \to t\,H)$	0.88	0.32	0.29	0.68	0.36
	$BR(T^{(1)} \to W^+\,b)$	0	0.46	0.48	0.11	0.02
	$BR(T^{(1)} \to t\,Z)$	0.05	0.23	0.24	0.21	0.24
		Cross Sections, normalized by the SM prediction				
	ttHH (13 TeV)	2.73	0.99	0.56	4.40	0.41
	ttHH (27 TeV)	10.38	2.95	0.92	14.19	0.54
	ttH (Both Energies)	0.87	0.83	0.86	0.93	0.73

Point 1 has $BR(T^{(1)} \to W^+ W^- t)=0.07$ and Point 5 has $BR(T^{(1)} \to W^+ W^- t)=0.35$

Sample Point at 27 TeV cm: Invariant Mass (ht)



- Even at 27 TeV, the non-resonant part is still 62%. If the mass bounds are pushed even further, it will become even more important. Furthermore, even in the case of discovery, it provides complementary information about the SM coupling modifications.