Constraining the top and Higgs sector with the search for four top quarks

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Higgs Couplings 2019 - Oxford

For the ATLAS and CMS Collaborations

FNAL LHC Physics Centre
distinguished Researcher 2020

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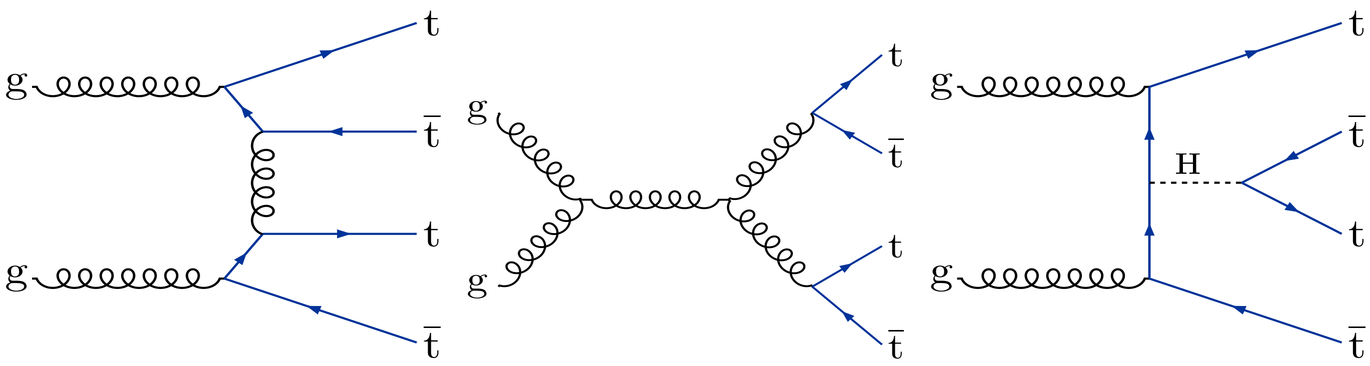
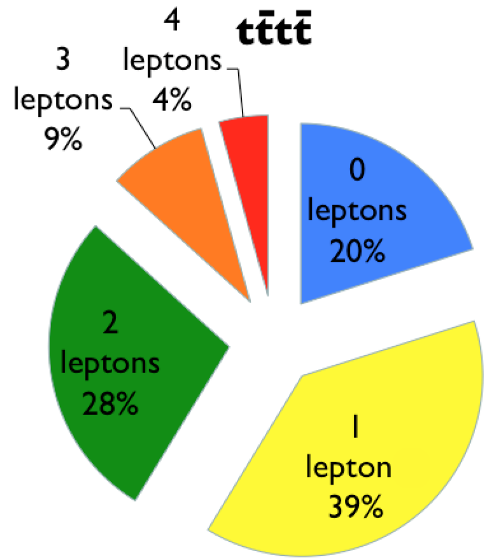
tttt: theory and strategy



Cross section ~1 order of magnitude smaller than ttH

Signatures: 4leptons4b - 3leptons4b2j – 2leptons4b4j -1lepton4b6j – 4b8j

Cross section at NLO QCD+EWK calculation available that gives ~12 fb
Frederix, Pagani, Zaro arXiv:1711.02116



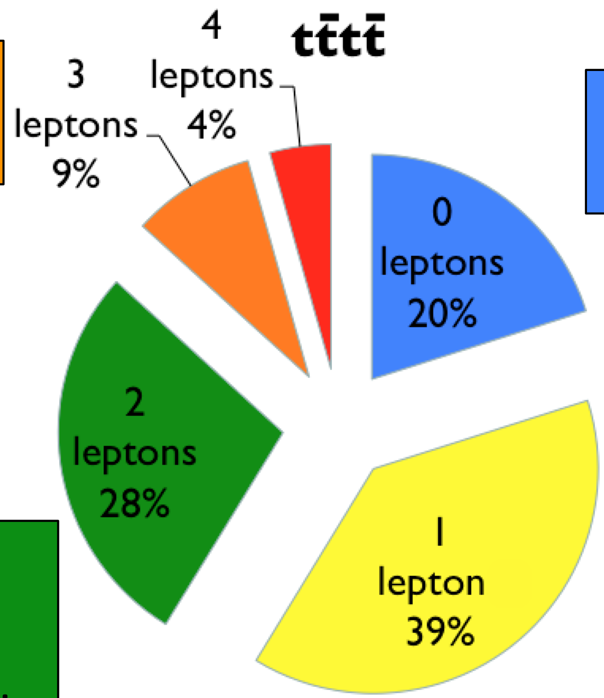
2016 data results use the previous NLO (QCD only) cross section at 9.2 fb

- easier to compare results. No influence on most limits/measurements

Analysis strategy

- Depends on final state
  - (remember ttH analysis: fewer leptons = more work)

Dominant background:
ttW/Z/H, dibosons, fakes



Dominant background:
multijet QCD

Refs SS dileptons/multileptons:
ATLAS arxiv 1807.11883 (36 fb^{-1})
CMS arxiv 1908.06463 (137 fb^{-1})

Dominant background:
OS dileptons: ttbar+HF
SS dileptons: ttW/Z/H, dibosons, fakes

Dominant background:
ttbar+HF

Refs l+jets, OS dileptons:
ATLAS arxiv 1811.02305 (36 fb^{-1})
CMS arxiv 1906.02805 (36 fb^{-1})

Different approaches to EFT

- ATLAS: BSM-like EFT looking for dramatic changes in shape at high scale
- CMS: SM-like EFT trying to constrain small changes cross section limit/uncertainties and mapping fit cross section limits to Wilson coefficients

- Both have pros and cons

EFT interpretation

- Like many rare processes involving loop diagrams, four-top production is extremely sensitive to new physics
- SM effective field theory at order 6

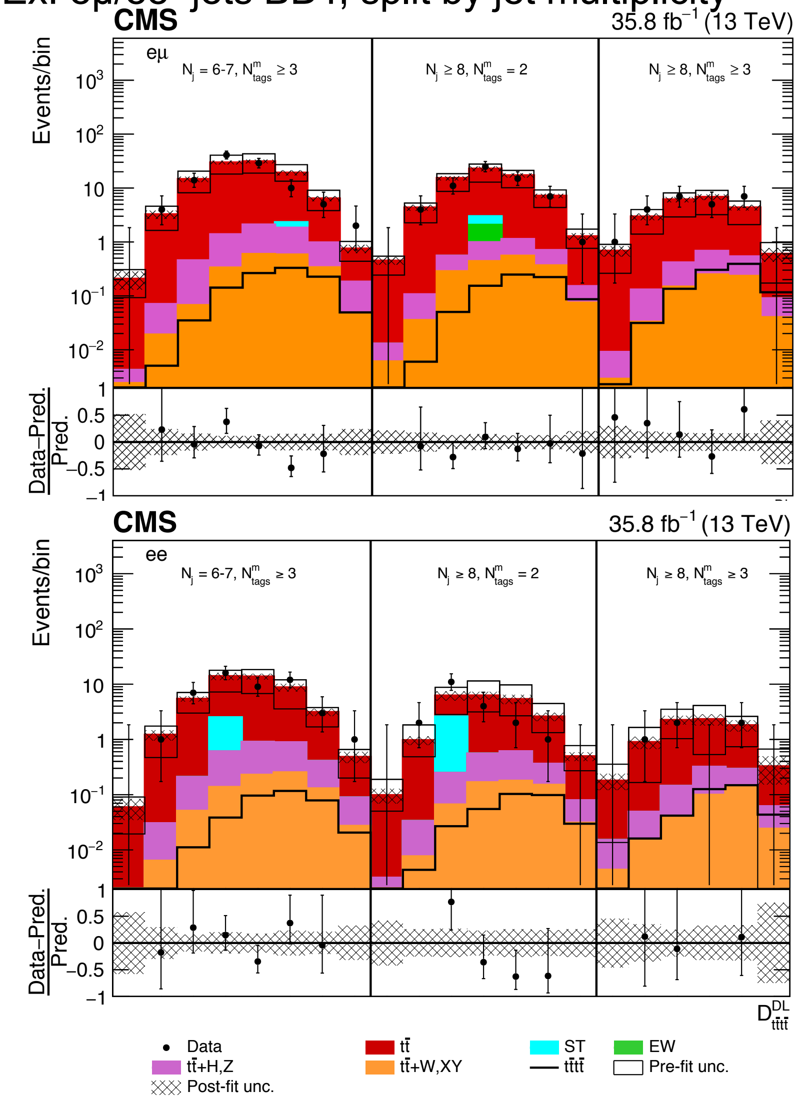
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + o\left(\frac{1}{\Lambda^2}\right)$$

- ATLAS: use $\mathcal{L}_{\text{EFT}}$ - $\mathcal{L}_{\text{SM}}^{(4)}$ as signal model, constrain Λ
- CMS: constrain $\mathcal{L}_{\text{EFT}}$ / $\mathcal{L}_{\text{SM}}^{(4)}$ with $\Delta\sigma_{tttt}/\sigma_{tttt}$, fix Λ, constrain C_k

CMS l+jets and OS dileptons: strategy

- MC based simultaneous fit of a boosted decision tree, using MC shapes including full theory uncertainties (source: Powheg)
  - BDT trained on kinematic, b-tagging and resolved top tagging information
  - Lower tag multiplicity and jet multiplicity 7-8 jets used to constrain (large) systematic uncertainties during simultaneous fit
  - Strategy similar to simultaneous fits used for ttbar cross section
- Weakness: many systematic uncertainties driven by theory uncertainties such as tt+HF via gluon splitting (largest), renormalization scale, etc
  - Conservative choice of systematic uncertainties creates weak limit when little statistics in control region part of fit
  - Plus: Method expected to gain precision with larger datasets when more statistics in control regions

Ex: eμ/ee+jets BDT, split by jet multiplicity



CMS arxiv 1906.02805 (36 fb^{-1})

CMS l+jets and OS dileptons: results

- OS dilepton analysis has lack of tttt candidate events creating 0 fb limit (single lepton has some sensitivity)
- Refitting improves also result 2016 same-charge and multilepton and gives CMS grand combination for tttt

cross section limits interpreted in EFT for separate Wilson parameters (also 2D) incl. marginalization over all other physical free parameter values
Using EFT basis recommended by TOP LHCWG arxiv:1802.07237

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

SM tttt limits	Expected (μ)	Observed (μ)	Expected (fb)	Observed (fb)	Signal strength (μ)	Signal strength (fb)
CMS 1L+OS2L 36 fb^{-1}	5.7	5.2	52 fb	48 fb	$0^{+2.2}$	0^{+20} fb
CMS 2016 combination 36 fb^{-1}	2.2	3.6	20 fb	33 fb	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9} fb

CMS arxiv 1906.02805 (36 fb^{-1})

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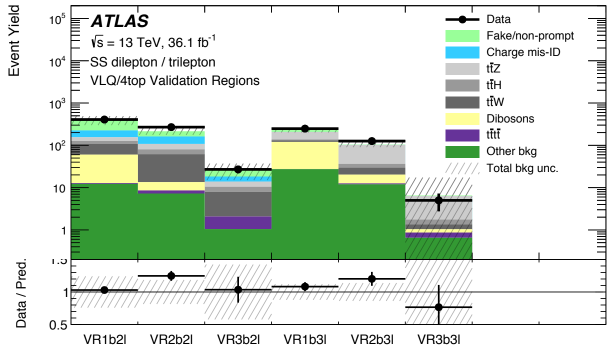
ATLAS SS/multi-leptons: method

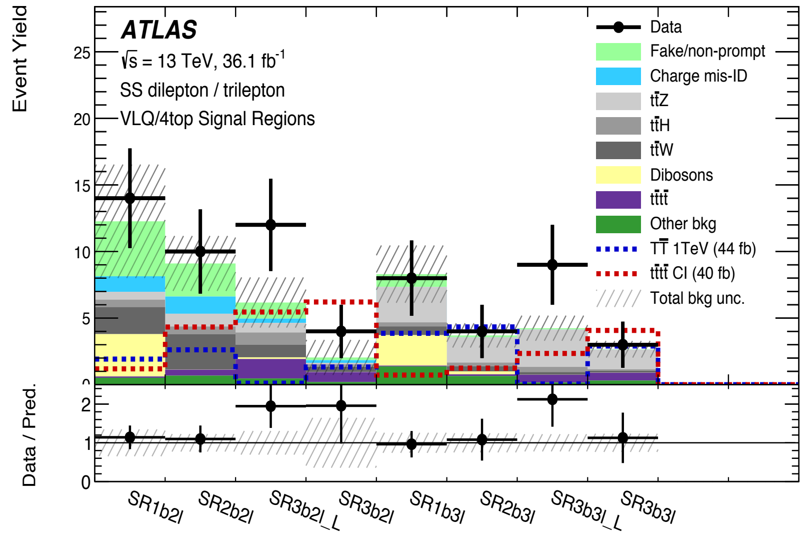
- BSM-oriented multi model search in same-sign and multi-leptons
  - Paper contains many searches where tttt can be background (incl tttt BSM-EFT, CP violating higgs, VLQ, etc)
  - Counting experiment in signal regions optimized for various BSM and tttt scenarios
    - For tttt that means many/SS leptons plus many b-jets

- Important for this kind of analysis:
  - Leptons have small probability to come from jets mimicking leptons ("fake leptons")
  - Probabilities derived from background and verified/corrected in control regions

Control regions



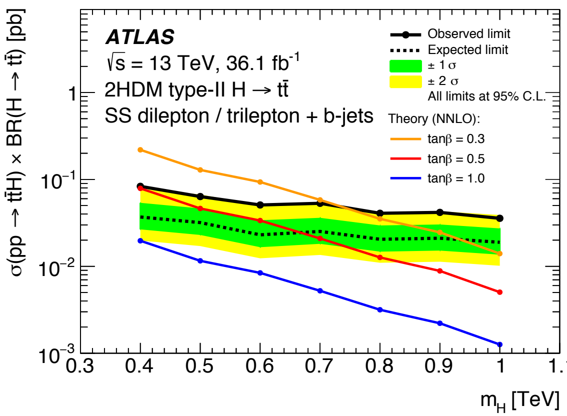
Signal regions

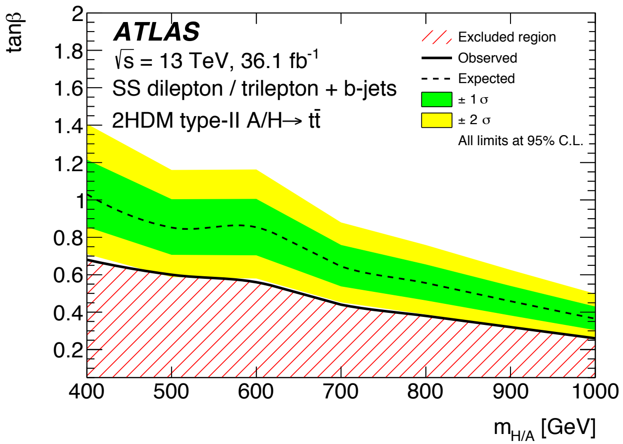


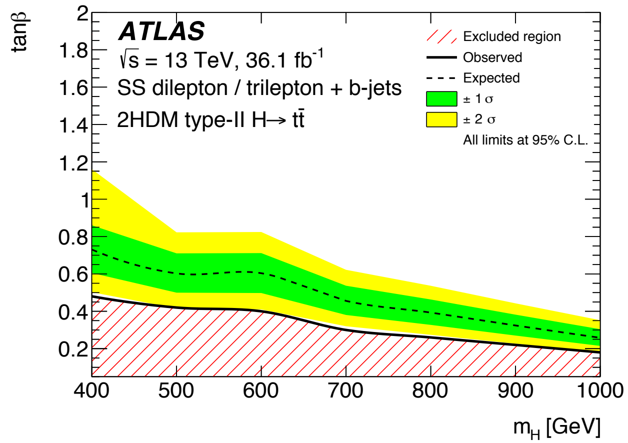
ATLAS arxiv 1807.11883 (36 fb^{-1})

ATLAS SS/multi-leptons: Results

- Four-top limits are also interpreted in:
  - 2HDM ttH, H->tt scenarios
    - Both for heavy Pseudo-scalar and scalar H
  - EFT scenarios with cross section constraint σ^{EFT}_{tttt} < 39 fb (21 fb expected)
  - EFT coupling constrained to $|C_{tttt}|/\Lambda^2$ < 2.6 TeV^{-2}







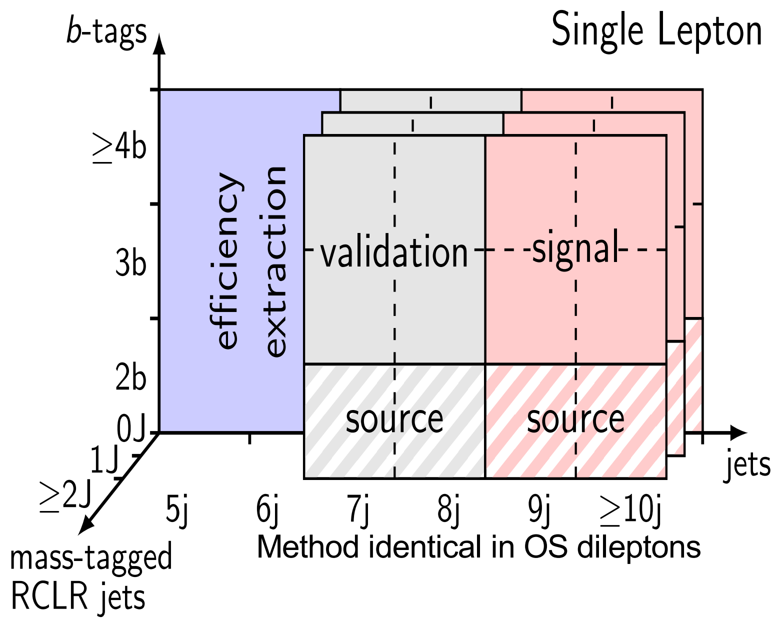
SM tttt limits (σ_{tttt} = 9.2 fb)	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
ATLAS >=3L-SS2L 36 fb^{-1}	3.2	7.5	29 fb	69 fb		

ATLAS arxiv 1807.11883 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: method

- Dominant background is ttbar+bbbar+jets
  - The additional jets are the main difference with ttH analysis strategies
  - ATLAS derives tagging efficiencies in ttbar+2 jet dominated region, verifies in ttbar+3-4 jet region
  - extrapolates from ttbar+no extra tags to ttbar+1/2 extra tags
  - Signal region in ttbar+5 or more jets plus 1 or 2 extra b tags
  - Includes category with top-tagged large cone jets
  - Misidentification leptons from QCD background is small and taken from data

Preselection requirements		
Requirement	Single-lepton	Dilepton
Trigger	Single-lepton triggers	
Leptons	1 isolated	2 isolated, opposite-sign
Jets	≥5 jets	≥4 jets
b-tagged jets	≥2 *b*-tagged jets	
Other	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV	$m_{\ell\ell} > 50$ GeV
	$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV	$\lvert m_{\ell\ell} - 91\ \mathrm{GeV}\rvert > 8$ GeV



Method identical in OS dileptons

ATLAS arxiv 1811.02305 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: method

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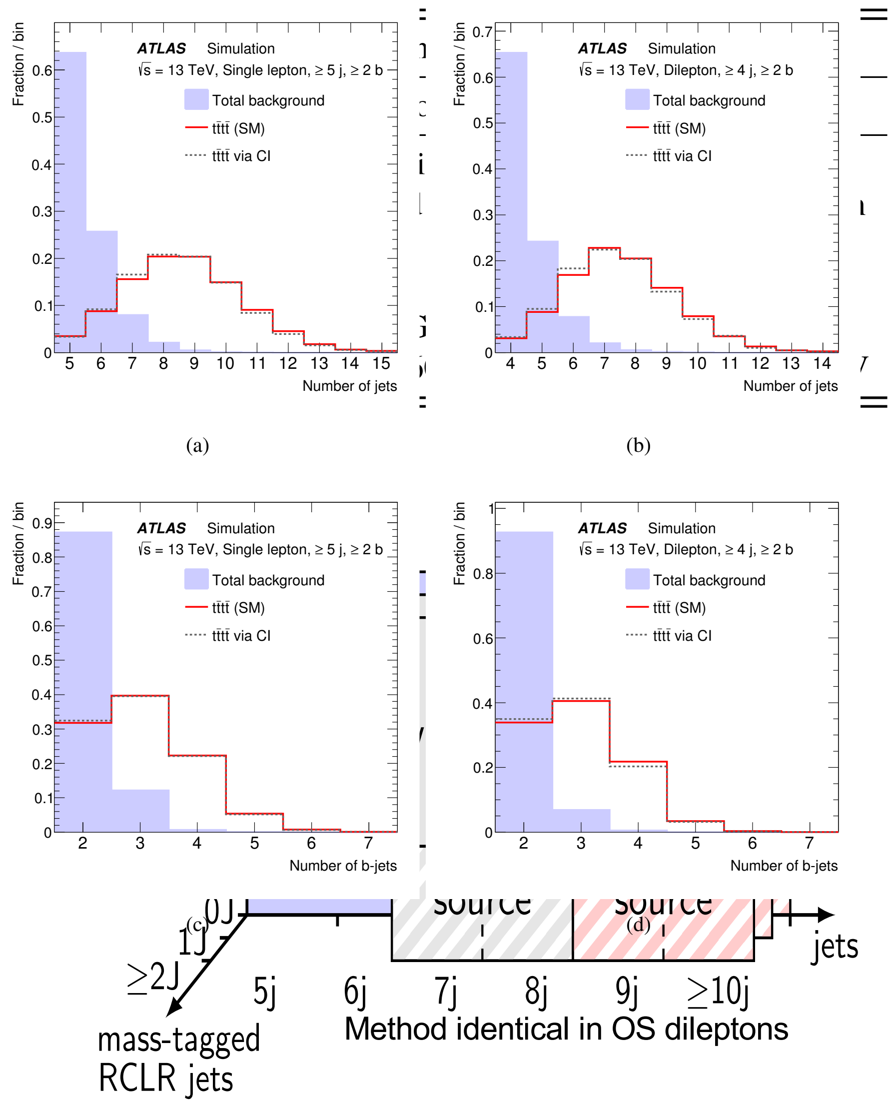
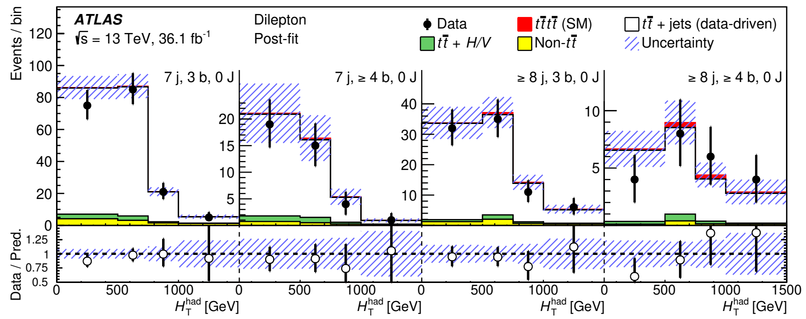


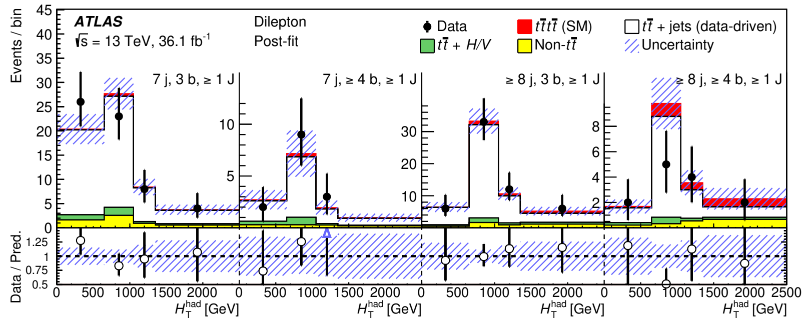
ATLAS arxiv 1811.02305 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: Results

- Data-driven backgrounds plus binned simultaneous fit to H_T
- Results are compared to NLO QCD $\sigma_{tttt} = 9.2\ ^{+2.9}_{-2.4}$ (scale) +/- 0.5 (pdf) fb
- EFT interpretation set uppper limits on scale of BSM $|C_{tttt}|/\Lambda^2 < 1.9\ \text{TeV}^{-2}$
- Combination with SS/multilepton result provided, lowers upper limit σ_{tttt} to 21 fb



(a)



Single lepton has analogue distributions

SM tttt limits (σ_{tttt} = 9.2 fb)	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
ATLAS 1L-OS2L 36 fb^{-1}	3.6	5.1	33 fb	47 fb	$1.7\ ^{+1.9}_{-1.7}$	$15.6^{+17.5}_{-15.6}$

ATLAS arxiv 1811.02305 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: Results

- Data-driven backgrounds plus binned simultaneous fit to H_T
- Results are compared to NLO QCD $\sigma_{tttt} = 9.2\ ^{+2.9}_{-2.4}$ (scale) +/- 0.5 (pdf) fb
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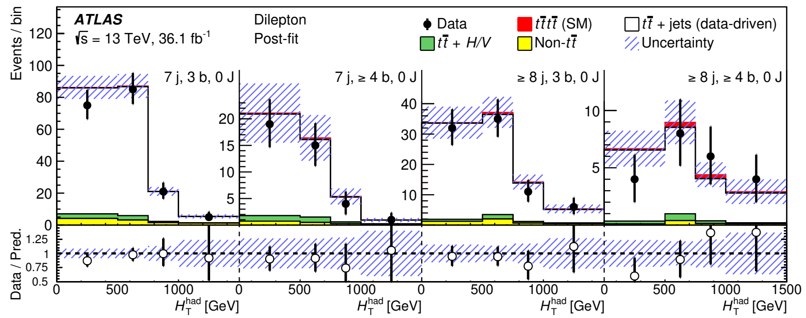

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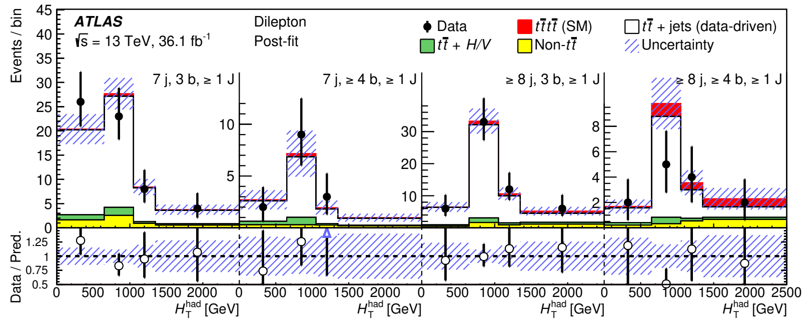

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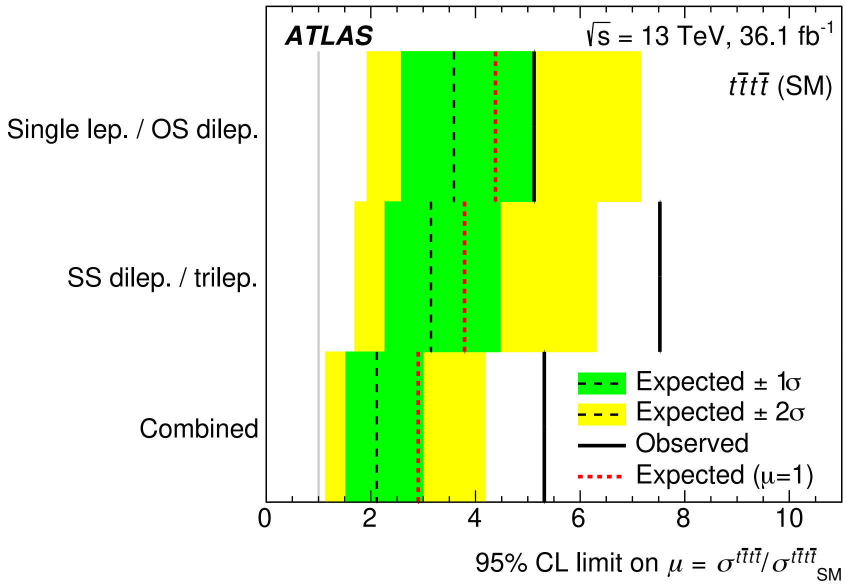
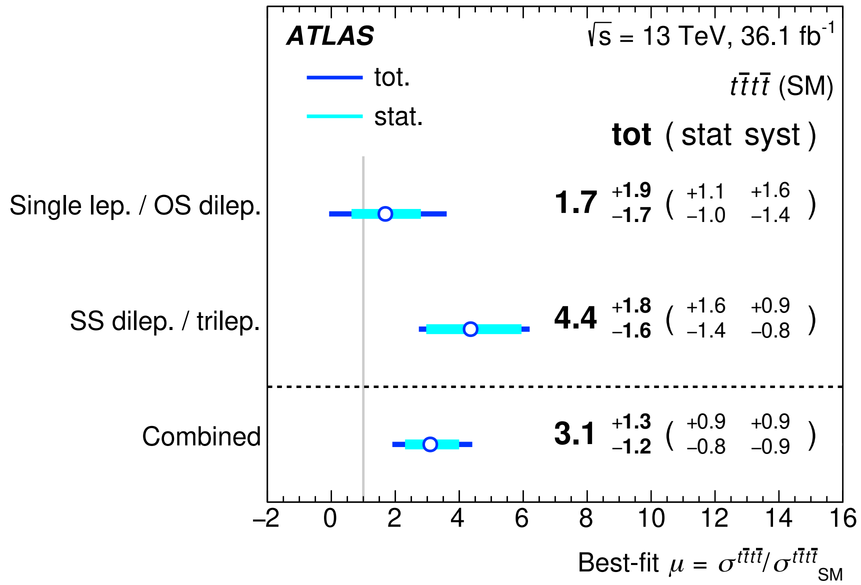
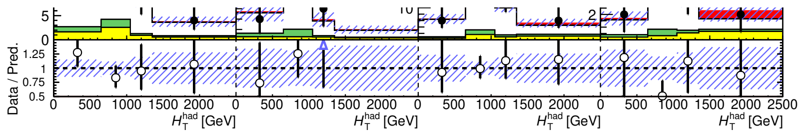
ATLAS, l+jets and OS dileptons: Results





- Combination with SS/multilepton result provided, lowers upper limit σ_{tttt} to 21 fb



Single lepton has analogue distributions

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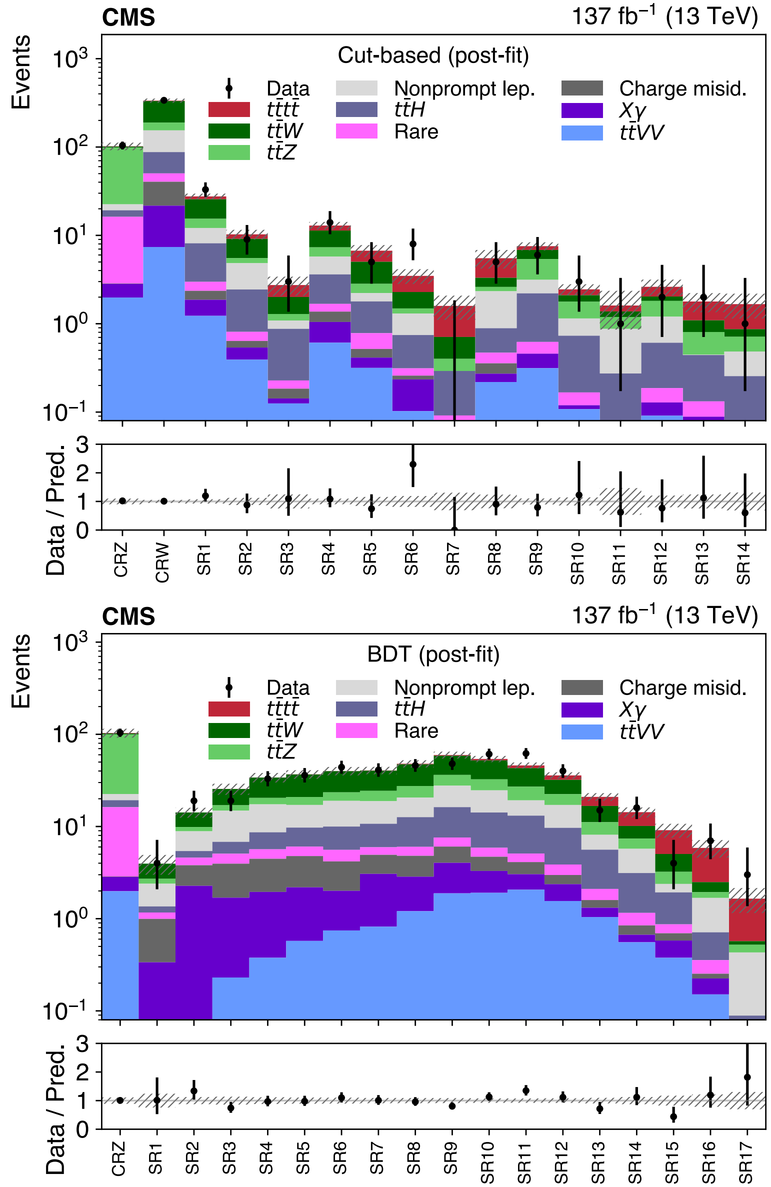
ATLAS arxiv 1811.02305 (36 fb^{-1})

CMS SS/multi-leptons: strategy

- Analysis in same-charge and multileptons
  - So dominated by ttH, ttZ/ttW and misidentification backgrounds
- Uses simultaneous fit in multiple lepton flavours and b-tag, jet categories
  - Dominant uncertainties:
    - modelling of SM backgrounds
    - Data-driven charge-misidentification estimates
    - knowledge heavy flavour tt+HF
- Boosted Decision tree to get optimal sensitivity
- Substantial improvement over cut-and-count approach but is available for recasting tools



CMS arxiv 1908.06463 (137 fb⁻¹)

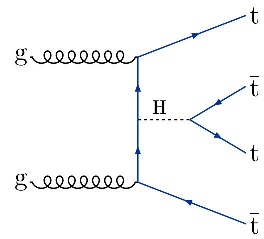
CMS SS/multi-leptons: results

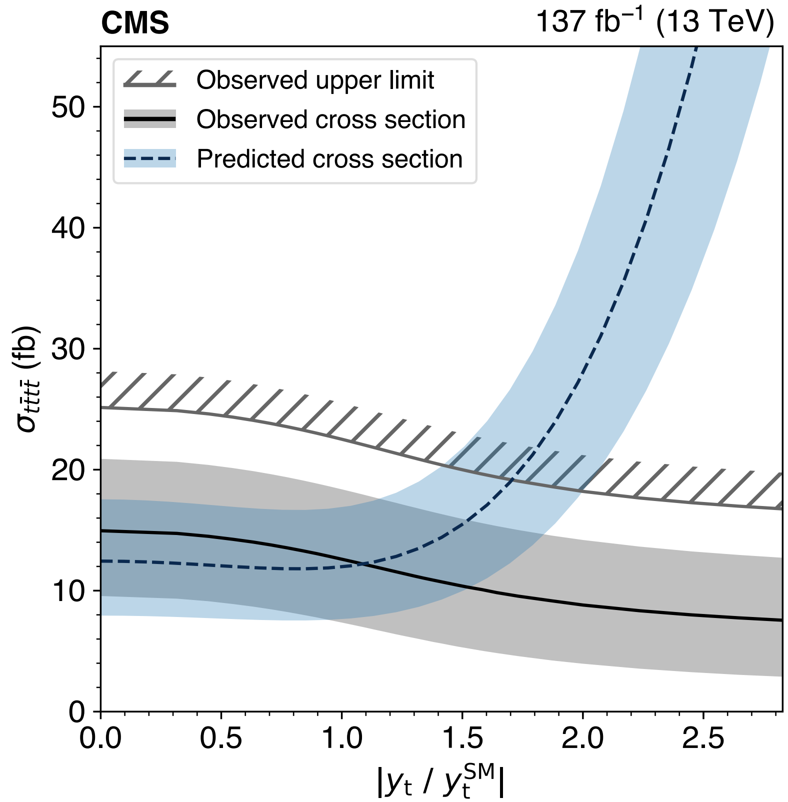
- Significance of BDT analysis has 2.6 standard deviations significance (2.7 expected) over background-only hypothesis!
  - Combination with other channels planned – stay tuned
  - Although not "officially" significant yet, main result is σ_{tttt} with about 45% uncertainty
  - Agrees well within uncertainties with NLO QCD+EWK value of $\sigma_{tttt}=12.0^{+2.2}_{-2.5}$ fb (Frederix et al arXiv:1711.02116)

SM tttt limits	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
CMS SS2L+>=3L 137 fb^{-1}				22.5 fb		$12.6\ ^{+5.8}_{-5.2}$ fb

CMS SS/multi-leptons: interpretation y_t

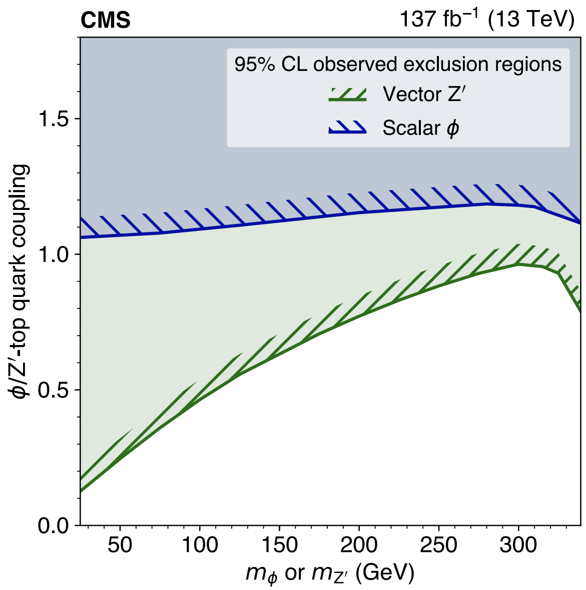
- About 20% of tttt production diagrams contain H, and y_t has substantial influence on value σ_{tttt}
- $\sigma_{tttt} = 12.6\ ^{+5.8}_{-5.2}$ fb measurement used according to Cao et al, arXiv:1602.01934
- ttH is included in background so scaling is not obvious
  - Most conservative scenario $|y_t/y_t^{SM}| < 1.7$ at 95% C.L.



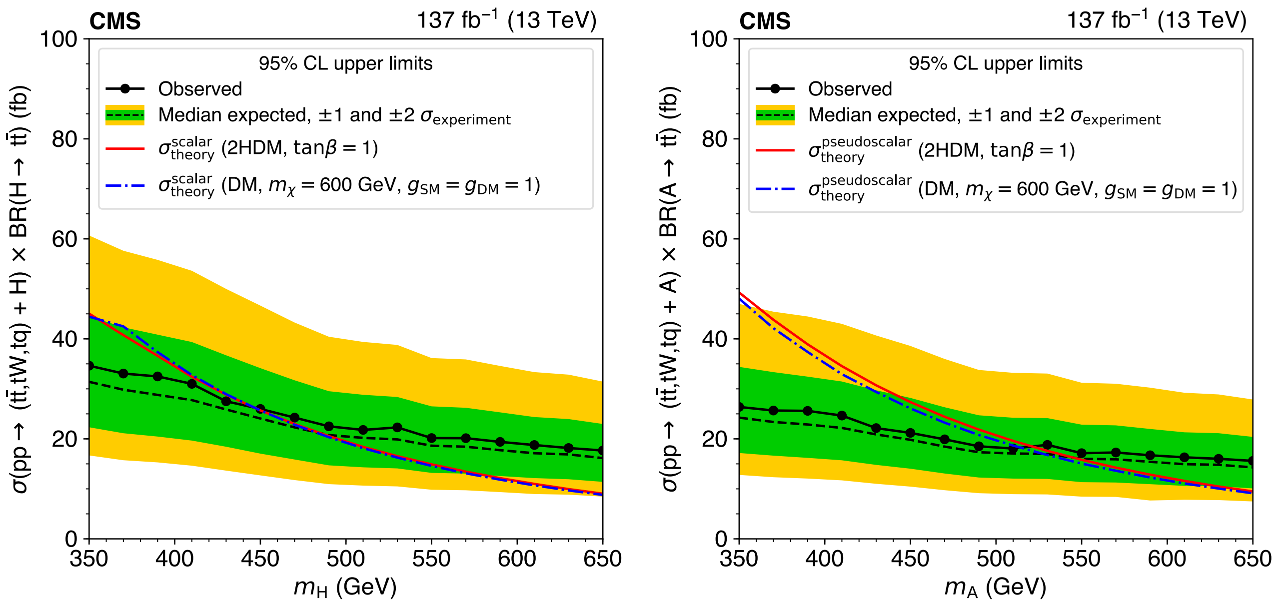


CMS arxiv 1908.06463 (137 fb^{-1})

CMS SS/multi-leptons: interpretation other BSM



- 2HDM (type II) limits on scalar and pseudoscalar



- Treat SM tttt as background see how BSM tttt Z' (or ϕ) enhances gives competitive limits at low masses
- Complementary to high mass ttbar resonance searches and competitive to direct searches sensitive to SM interference/spectrum modifications

CMS arxiv 1908.06463 (137 fb^{-1})

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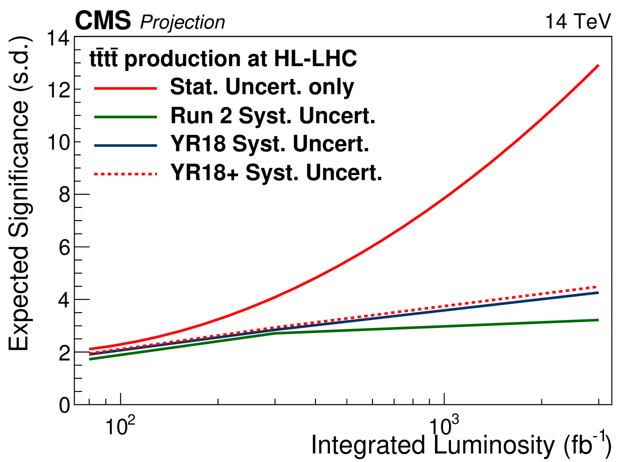
What about the future?

Int.Lumi at HL-LHC	ATLAS (shape analysis)	CMS (counting exp in categories)
300 fb^{-1}	5 s.d. signficance	Stat uncertainty 4 s.d. significance (deterioration with syst uncertainties)
3 ab^{-1}	Uncertainty xsec 11% (dominated by stat.uncertainty)	Uncertainty xsec 9% (stat only) to 28% (current syst.uncertainties)



Projections SS dileptons/multileptons:
ATLAS ATL-PHYS-PUB-2018-047
CMS PAS FTR-18-031
See also the HL-LHC/HE-LHC Yellow Reports

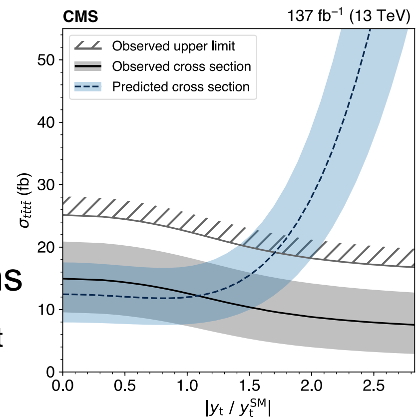
- ATLAS projection includes a full analysis for 3 ab^{-1} at HL-LHC (sqrt(s)=14 TeV) in SS dilepton/multileptons
  - Includes simultaneous fit in multiple tag/jet multiplicity categories, discriminating variable H_T
- CMS projection is scale-up of 2016 SS dilepton/multilepton counting experiment analysis for HL-LHC and HE-LHC
  - Includes EFT projections and various scenarios regarding systematic uncertainties also expected cross section uncertainties at HE-LHC
  - 1% exp. uncert. on xsec with full HE-LHC sample
- General conclusion: need about 300 fb^{-1} to get statistical significance up to 5 sigma depending complexity analysis
- Systematic uncertainties depend on experiment
  - ATLAS binned likelihood fit: not very important
  - CMS counting experiment: become important at large integrated luminosities

Summary

Production of four top quarks is being actively examined by ATLAS and CMS collaboration.
σ_{tttt} in SM (NLO QCD+EWK) 12 fb, and very sensitive to modifications from BSM

	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
ATLAS 1L-OS2L 36 fb^{-1}	3.6	5.1	33 fb	47 fb	$1.7^{+1.9}_{-1.7}$	$15.6^{+17.5}_{-15.6}$ fb
ATLAS >=3L-SS2L 36 fb^{-1}	3.2	7.5	29 fb	69 fb		
CMS 1L+OS2L 36 fb^{-1}	5.7	5.2	52 fb	48 fb	$0^{+2.2}$	0^{+20} fb
CMS 2016 combination 36 fb^{-1}	2.2	3.6	20 fb	33 fb	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9} fb
CMS >=3L-SS2L 137 fb^{-1}				22.5 fb		$12.6^{+5.8}_{-5.2}$fb

- With large LHC Run 2 dataset, CMS has 2.6 standard deviations excess, and measurement of $\Delta\sigma_{tttt}/\sigma_{tttt}\approx 45\%$ means CMS can constrain $|y_t/y_t^{SM}| < 1.7$ at 95% C.L.
- Collaborations are interpreting σ_{tttt} beyond just the SM value, in EFT and various BSM models
- HL-LHC: single channel observation possible at 5 standard deviations (in multilepton/SS dilepton channel) with 10%ish uncertainties on σ_{tttt}



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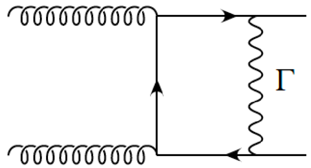
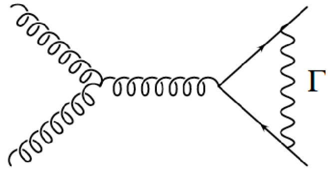
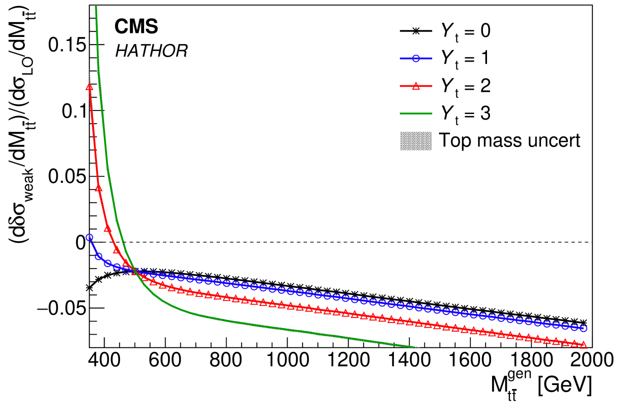
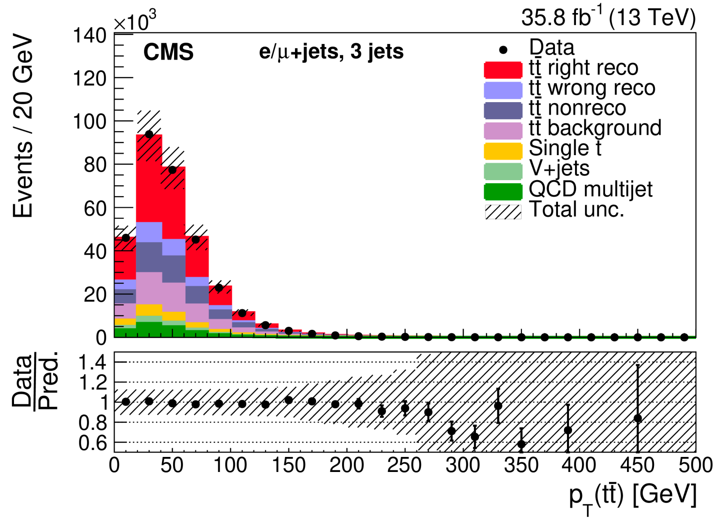
Other indirect y_t measurements: ttbar differential cross section

- Top quark pair production at threshold is sensitive to exchanges virtual particles including H
- Precision differential measurements can indirectly constrain top Yukawa this way
- CMS uses full reconstruction o top quark pair system and interprets kinematics (rapidity, pT, invariant mass, jet multiplicity) of top quark pairs in lepton+jets channel to compare to y_t
- Results:
  - $|y_t/y_t^{SM}|=1.07^{+0.34}_{-0.43}$
  - Upper limit $|y_t/y_t^{SM}| < 1.67$ (95% CL)









CMS arxiv 1907.01590 (36 fb^{-1})

EFT interpretations - results

Table 5: Expected and observed 95% CL intervals for selected coupling parameters. The intervals are extracted from upper limit on the $t\bar{t}t\bar{t}$ production cross section in the EFT model, where only one selected operator has a nonvanishing contribution.

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.8]	[−2.1, 2.0]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.8]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.3, 3.2]	[−3.5, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.3, 6.1]	[−7.9, 6.6]

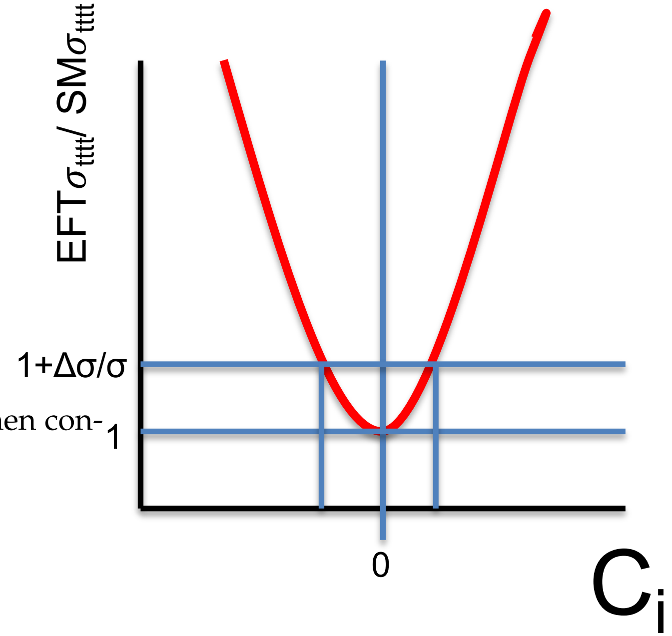


Table 6: Expected and observed 95% CL intervals for selected coupling parameters when contribution of other operators is marginalized.

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

Cross section luminosity scaling HL/HE-LHC

process	14 TeV/13 TeV	27 TeV/13 TeV
$t\bar{t}$ NLO	1.19	4.62
$t\bar{t}t\bar{t}$ NLO	1.33	12.79
$t\bar{t}H$ NLO	1.24	5.75
$t\bar{t}W$ NLO	1.16	3.68
$t\bar{t}Z$ NLO	1.21	5.62

▶ $t\bar{t}t\bar{t}$ in EFT approach

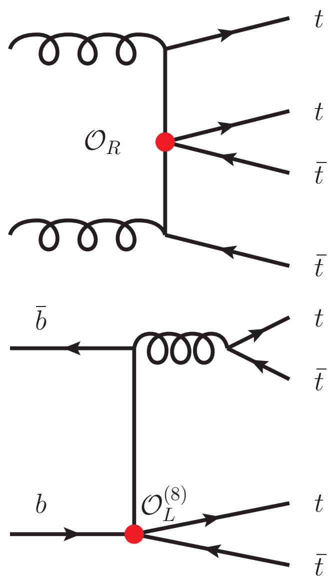
- SM Lagrangian is augmented by composite operators of the SM fields

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)}$$
$$\mathcal{L}^{(d)} = \frac{1}{\Lambda^{d-4}} \sum_i c_i \mathcal{O}_i$$

- Lowest dimension EFT operators contributing to $pp \to t\bar{t}t\bar{t}$ have d=6

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

- color singlet coupling RH tops: $\mathcal{O}_R = (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma_\mu t_R)$
- color singlet coupling LH tops and bottoms: $\mathcal{O}_L^{(1)} = (\bar{Q}_L \gamma_\mu Q_L)(\bar{Q}_L \gamma_\mu Q_L)$
- color octet coupling LH tops and bottoms: $\mathcal{O}_L^{(8)} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{Q}_L \gamma_\mu T^A Q_L)$
- color singlet coupling LH tops and bottoms and RH tops: $\mathcal{O}_B^{(1)} = (\bar{Q}_L \gamma_\mu Q_L)(\bar{t}_R \gamma_\mu t_R)$
- color octet coupling LH tops and bottoms and RH tops: $\mathcal{O}_B^{(8)} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{t}_R \gamma_\mu T^A t_R)$

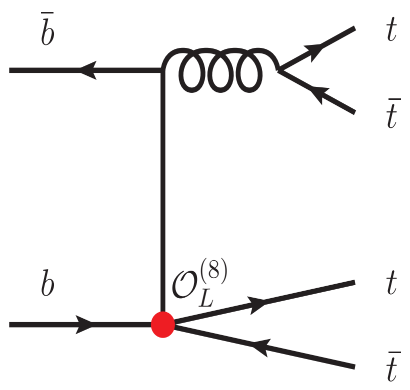


example 4-fermion EFT diagrams

▶ $\mathcal{O}_L^{(1)}$ and $\mathcal{O}_L^{(8)}$ correlation

Two operators have identical $t\bar{t}t\bar{t}$ terms:

- color singlet coupling LH tops and bottoms: $\mathcal{O}_L^{(1)} = \left(\bar{Q}_L\gamma_\mu Q_L\right)\left(\bar{Q}_L\gamma_\mu Q_L\right)$
- color octet coupling LH tops and bottoms: $\mathcal{O}_L^{(8)} = \left(\bar{Q}_L\gamma_\mu T^A Q_L\right)\left(\bar{Q}_L\gamma_\mu T^A Q_L\right)$



This type of diagram does not contribute at LO, when 4FS (standard) PDFs are used!

$$\mathcal{O}_L^{(1)} = \frac{1}{2}\left[\left(\bar{t}_L\gamma^\mu t_L\right)\left(\bar{t}_L\gamma_\mu t_L\right) + \left(\bar{b}_L\gamma^\mu b_L\right)\left(\bar{b}_L\gamma_\mu b_L\right)\right] + \left(\bar{t}_L\gamma^\mu t_L\right)\left(\bar{b}_L\gamma_\mu b_L\right)$$

$$\mathcal{O}_L^{(8)} = \frac{1}{6}\left[\left(\bar{t}_L\gamma^\mu t_L\right)\left(\bar{t}_L\gamma_\mu t_L\right) + \left(\bar{b}_L\gamma^\mu b_L\right)\left(\bar{b}_L\gamma_\mu b_L\right)\right] + \left(\bar{t}_L\gamma^\mu T^A t_L\right)\left(\bar{b}_L\gamma_\mu T^A b_l\right.$$

$\left(\bar{t}_L\gamma^\mu t_L\right)\left(\bar{b}_L\gamma_\mu b_L\right)$ and $\left(\bar{t}_L\gamma^\mu T^A t_L\right)\left(\bar{b}_L\gamma_\mu T^A b_L\right)$ contributions are suppressed by PDFs, therefore two operators have strong correlation.

Wilson coefficients, EFT basis

- Using EFT model that spans tttt production in 5 Wilson coefficients (from arxiv 1802.07237 for example) specifically designed for four-top production
- Caveat: this paper includes 5 coefficients but with the MC/pdf combo we use two LH top/bottom color couplings are ~ identical – so picked the singlet
- Same approach as suggested by LHC top physics working group

$$\mathcal{O}_R = (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$$
$$\mathcal{O}_L^{(1)} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma_\mu Q_L)$$
$$\mathcal{O}_B^{(1)} = (\bar{Q}_L \gamma_\mu Q_L)(\bar{t}_R \gamma_\mu t_R)$$
$$\mathcal{O}_B^{(8)} = \left(\bar{Q}_L \gamma_\mu T^A Q_L\right)\left(\bar{t}_R \gamma_\mu T^A t_R\right).$$

Signal region definitions and yields ATLAS SS/multileptons

Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$ GeV
VR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$400 < H_T < 1400$ GeV or $E_T^{miss} < 40$ GeV
SR3b2ℓ_L	≥ 7	≥ 3	2	++ or −−	$500 < H_T < 1200$ GeV and $E_T^{miss} > 40$ GeV
SR3b2ℓ	≥ 3	≥ 3	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR1b3ℓ	≥ 1	1	3	any	$400 < H_T < 2000$ GeV or $E_T^{miss} < 40$ GeV
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
VR2b3ℓ	≥ 2	2	3	any	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ GeV
VR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 400$ GeV
SR3b3ℓ_L	≥ 5	≥ 3	3	any	$500 < H_T < 1000$ GeV and $E_T^{miss} > 40$ GeV
SR3b3ℓ	≥ 3	≥ 3	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 40$ GeV

Source	SR1b2ℓ	SR2b2ℓ	SR3b2ℓ_L	SR3b2ℓ
$t\bar{t}W$	$2.04 \pm 0.14 \pm 0.49$	$2.68 \pm 0.15 \pm 0.55$	$0.95 \pm 0.11 \pm 0.31$	$0.40 \pm 0.06 \pm 0.10$
$t\bar{t}Z$	$0.58 \pm 0.08 \pm 0.10$	$0.95 \pm 0.11 \pm 0.17$	$0.72 \pm 0.11 \pm 0.19$	$0.11 \pm 0.05 \; {}^{+0.13}_{-0.10}$
Dibosons	$3.2 \pm 1.5 \pm 2.4$	< 0.5	$0.13 \pm 0.13 \; {}^{+0.27}_{-0.00}$	< 0.5
$t\bar{t}H$	$0.56 \pm 0.07 \pm 0.07$	$0.57 \pm 0.10 \pm 0.09$	$0.91 \pm 0.11 \pm 0.22$	$0.19 \pm 0.05 \pm 0.07$
$t\bar{t}t\bar{t}$	$0.10 \pm 0.01 \pm 0.05$	$0.44 \pm 0.03 \pm 0.23$	$1.46 \pm 0.05 \pm 0.74$	$0.75 \pm 0.04 \pm 0.38$
Other bkg	$0.52 \pm 0.07 \pm 0.14$	$0.68 \pm 0.09 \pm 0.24$	$0.47 \pm 0.08 \pm 0.18$	$0.20 \pm 0.04 \pm 0.06$
Fake/non-prompt	$4.1 \; {}^{+1.6}_{-1.4} \pm 2.4$	$2.5 \; {}^{+1.0}_{-0.9} \pm 1.1$	$1.2 \; {}^{+0.9}_{-0.7} \pm 0.6$	$0.20 \; {}^{+0.46}_{-0.20} \pm 0.16$
Charge mis-ID	$1.17 \pm 0.10 \pm 0.27$	$1.29 \pm 0.10 \pm 0.28$	$0.32 \pm 0.04 \pm 0.09$	$0.21 \pm 0.04 \pm 0.04$
Total bkg	$12.3 \; {}^{+2.2}_{-2.1} \pm 3.4$	$9.1 \; {}^{+1.2}_{-1.1} \pm 1.2$	$6.2 \; {}^{+1.0}_{-0.8} \pm 1.2$	$2.0 \; {}^{+0.5}_{-0.2} \pm 0.3$
Data yield	14	10	12	4
BSM significance	0.31	0.25	1.7	1.1
SM $t\bar{t}t\bar{t}$ significance	0.33	0.38	2.1	1.6

Source	SR1b3ℓ	SR2b3ℓ	SR3b3ℓ_L	SR3b3ℓ
$t\bar{t}W$	$0.66 \pm 0.08 \pm 0.20$	$0.38 \pm 0.05 \pm 0.11$	$0.21 \pm 0.05 \pm 0.09$	$0.15 \pm 0.04 \pm 0.05$
$t\bar{t}Z$	$2.66 \pm 0.15 \pm 0.43$	$1.90 \pm 0.14 \pm 0.42$	$2.80 \pm 0.17 \pm 0.58$	$1.47 \pm 0.14 \pm 0.28$
Dibosons	$2.3 \pm 0.7 \pm 1.7$	$0.22 \pm 0.16 \pm 0.27$	< 0.5	< 0.5
$t\bar{t}H$	$0.30 \pm 0.04 \pm 0.04$	$0.28 \pm 0.05 \pm 0.05$	$0.38 \pm 0.06 \pm 0.07$	$0.10 \pm 0.03 \pm 0.02$
$t\bar{t}t\bar{t}$	$0.06 \pm 0.01 \pm 0.03$	$0.13 \pm 0.02 \pm 0.06$	$0.58 \pm 0.04 \pm 0.29$	$0.59 \pm 0.03 \pm 0.30$
Other bkg.	$1.37 \pm 0.13 \pm 0.45$	$0.65 \pm 0.10 \pm 0.27$	$0.17 \pm 0.09 \pm 0.10$	$0.31 \pm 0.07 \pm 0.11$
Fake/non-prompt	$1.0 \; {}^{+0.6}_{-0.5} \pm 0.6$	$0.14 \; {}^{+0.31}_{-0.12} \pm 0.09$	$0.00 \; {}^{+0.38}_{-0.00} \; {}^{+0.09}_{-0.00}$	$0.03 \; {}^{+0.15}_{-0.02} \pm 0.00$
Total bkg	$8.3 \; {}^{+0.9}_{-0.8} \pm 1.8$	$3.7 \; {}^{+0.6}_{-0.3} \pm 0.4$	$4.2 \; {}^{+0.4}_{-0.2} \pm 0.7$	$2.7 \pm 0.2 \pm 0.5$
Data yield	8	4	9	3
BSM significance	−0.09	0.14	1.8	0.19
SM $t\bar{t}t\bar{t}$ significance	−0.07	0.21	2.1	0.6