Highlights from $t\bar{t}$+X at ATLAS and CMS

Rencontres de Blois

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What is ‘$t\bar{t}$+X’?

- For the purposes of this talk, $t\bar{t}$ produced in association with visible (or visibly-decaying) particles
  - Don’t have time to talk about the many $t\bar{t}+p_T^{miss}$ (invisible) searches
  - Includes Standard Model production: $t\bar{t}$+W/Z/γ, as well as $t\bar{t}+t\bar{t}$
  - $t\bar{t}$+H also very important, but covered in two separate talks [1,2]
  - Measure SM top quark couplings, probe effective couplings
  - Events with many objects (leptons, jets, p_T^{miss}), challenging analyses
- In beyond-SM production, top+X pairs typically produced from decays of heavier new physics particles
  - Very high energy / mass scales, boosted tops and bosons

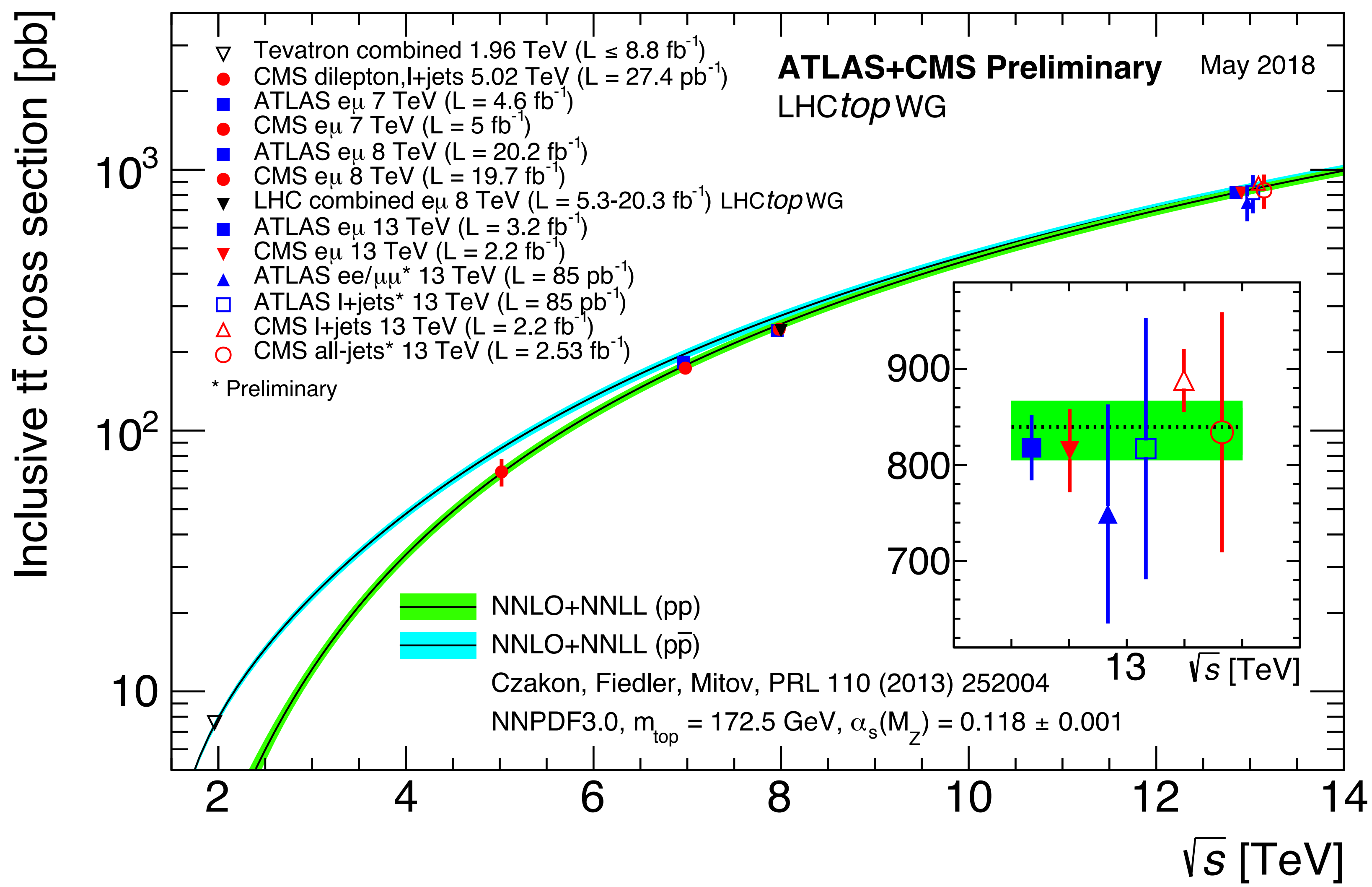
[1] Roberto Di Nardo, ATLAS : https://indico.cern.ch/event/677667/contributions/3011173/
[2] Daniel Salerno, CMS : https://indico.cern.ch/event/677667/contributions/2996225/

$t\bar{t}$ cross sections at 13 TeV

ATLAS eμ: 1606.02699
CMS eμ: 1611.04040
CMS ℓν+jj: 1701.06228

- ATLAS and CMS made precise measurements of the inclusive $t\bar{t}$ cross sections at 13 TeV in 2015 data (2.2 - 3.2 fb^{-1})
- Statistical uncertainties negligible, no need to add 2016 dataset, which contained 10 - 15 times more data (36 fb^{-1})
- General agreement with theoretical predictions, and between channels

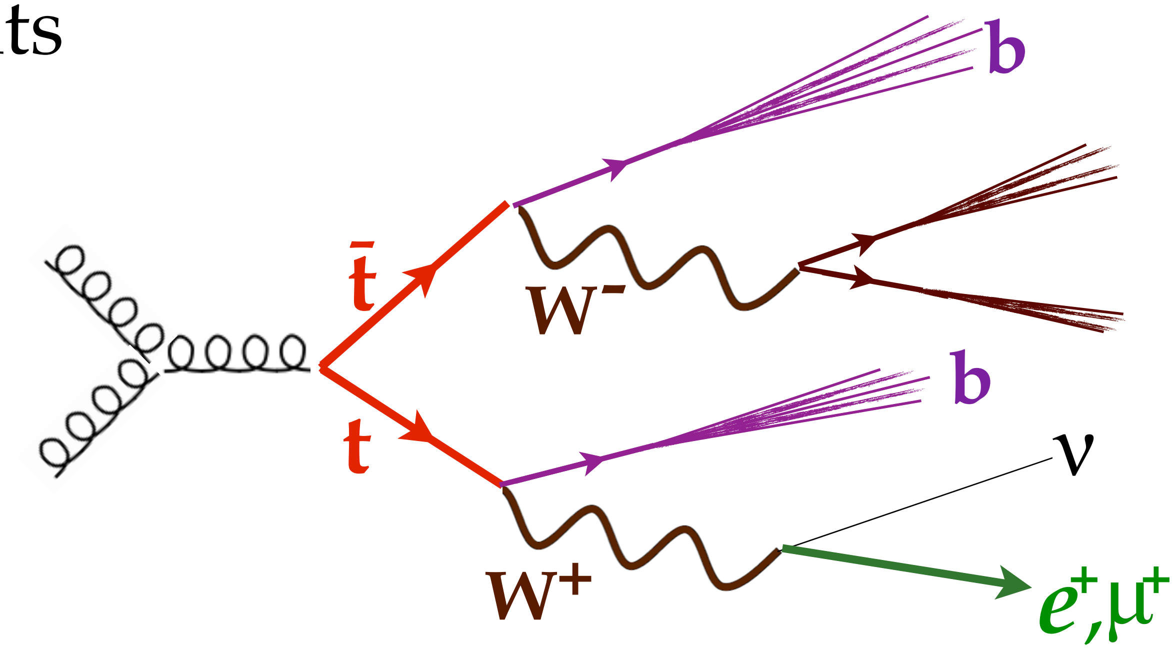
$\sigma(t\bar{t})$ at 13 TeV, m_t = 172.5 GeV	
NNLL pred	832 $^{+20}_{-29}$ (scale) ± 35 (PDF + α_s) pb
ATLAS eμ	818 ± 9 (stat) ± 27 (syst) ± 19 (lumi) ± 12 (beam)
CMS eμ	815 ± 9 (stat) ± 38 (syst) ± 19 (lumi) pb
CMS ℓν+jj	888 ± 2 (stat) ± 27 (syst) ± 20 (lumi) pb

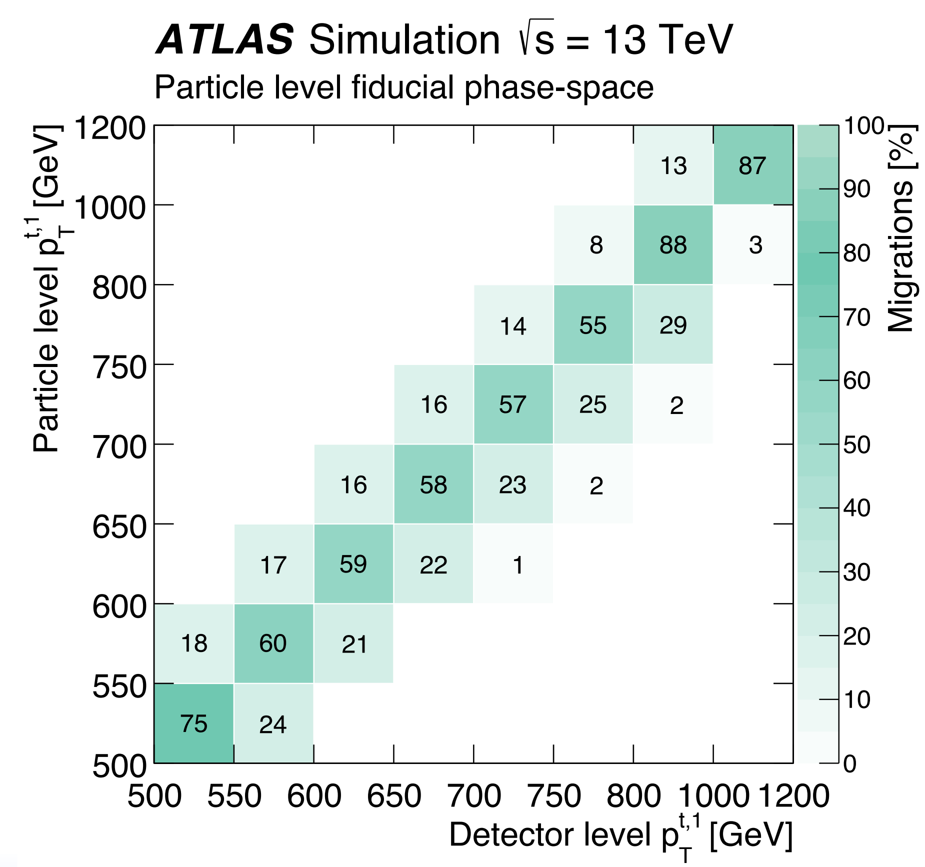


Differential $t\bar{t}$ cross sections

[ATLAS eμ: 1612.05220](#)
[ATLAS ℓν+jj: 1708.00727](#)
[CMS ℓν+jj: 1803.03991](#)

- Differential cross-section measurements are interesting and challenging - and can always benefit from more stats
- Probe hidden new physics scenarios (e.g. very high mass scale) using very precise measurements of $t\bar{t}$ system kinematics and correlations
    - Also validate and tune / correct MC simulation - important!
- Use tools which are fundamental to other $t\bar{t}$+X searches and measurements, e.g. kinematic reconstruction of $t\bar{t}$ system from its decay products

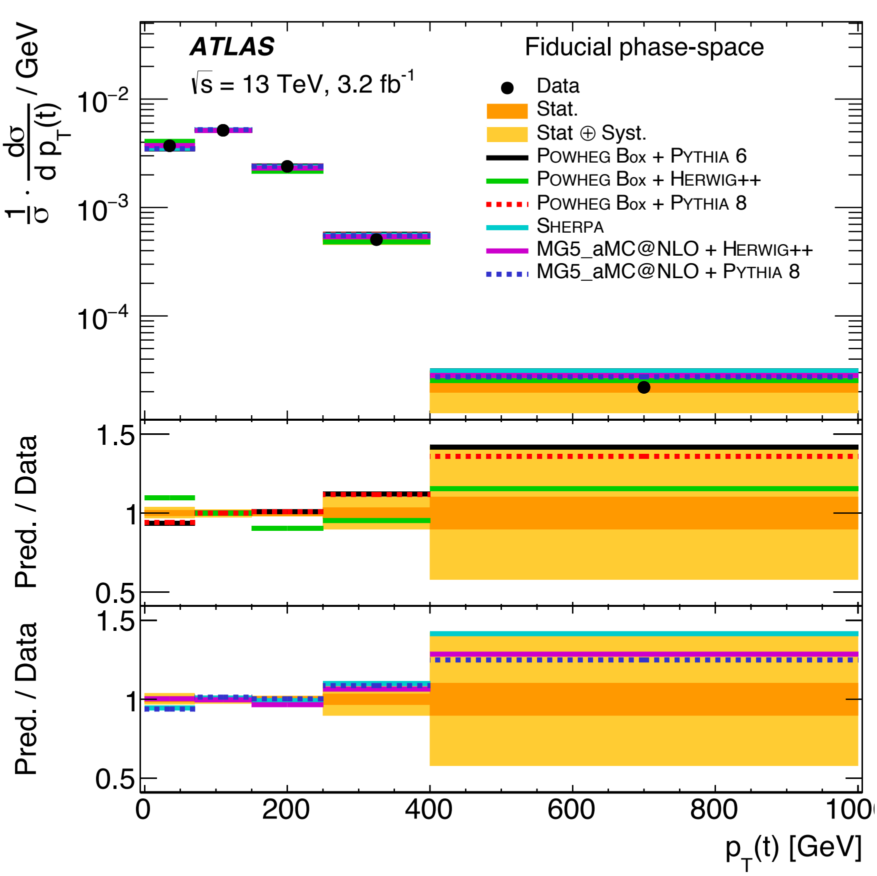


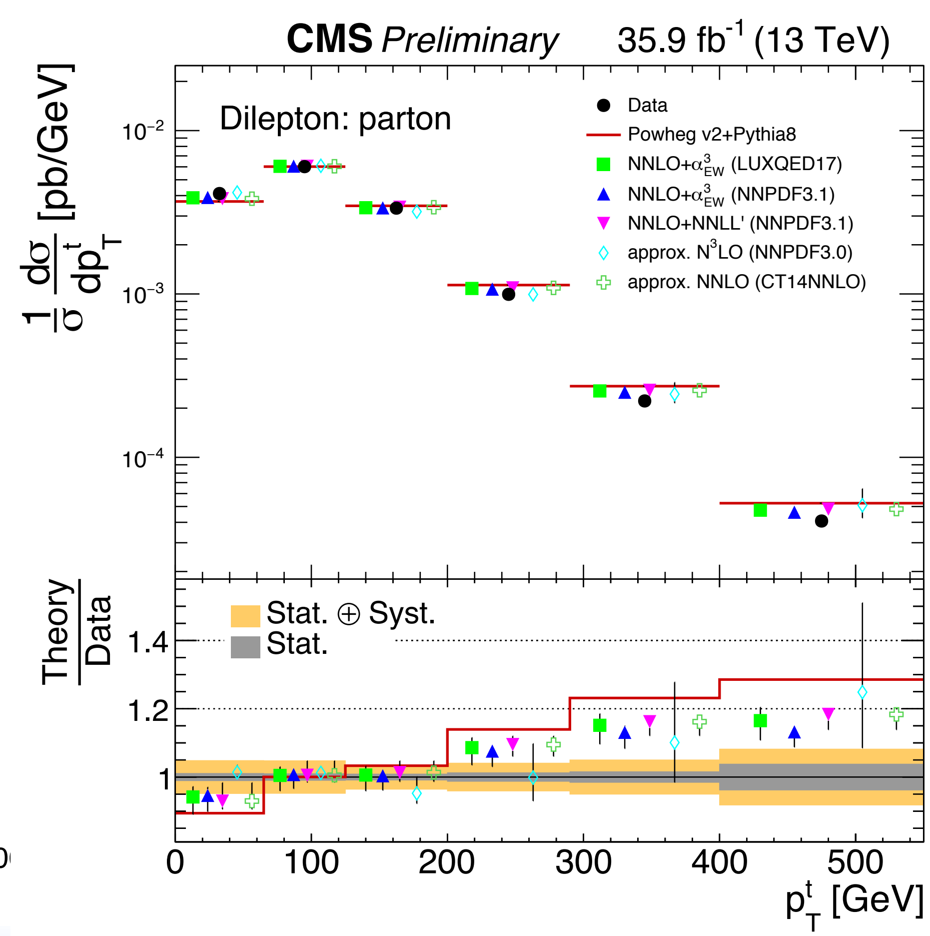


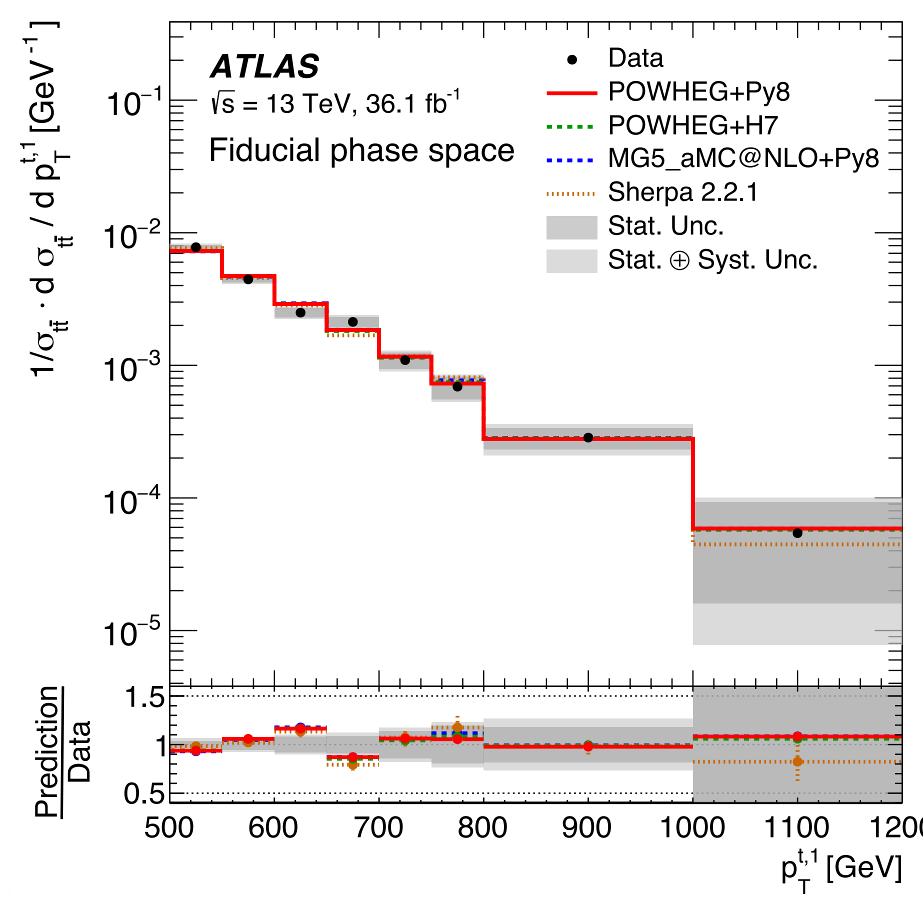
Differential $t\bar{t}$ cross sections

ATLAS boosted: 1612.05220
CMS eμ: TOP-17-014

- Primarily use $b\ell\nu$ + bjj and $b\ell\nu$ + $b\ell\nu$ decay modes at 13 TeV
  - Probe many observables (p_T, y, etc.) of top and its decay products
  - Also use boosted bjj + bjj measurement to reach higher in p_T
- Both CMS and ATLAS see softer p_T (top) than pred. by MC / theory







$t\bar{t}$+X analyses

Final state	ATLAS			CMS		
	Dataset	ID	Link	Dataset	ID	Link
$t\bar{t}+\gamma$	20 fb^{-1}, 8 TeV	JHEP 11	1706.03046	20 fb^{-1}, 8 TeV	JHEP 10	1706.08128
$t\bar{t}$+W	3.2 fb^{-1}, 13 TeV	EPJC 77	1609.01599	**36 fb^{-1}, 13 TeV**	TOP-17-005*	1711.02547
$t\bar{t}$+Z						
$t\bar{t}$H (bb)	**36 fb^{-1}, 13 TeV**	PRD 97	1712.08895	**5+20+36 fb^{-1}, 7+8+13 TeV**	HIG-17-035*	1804.02610
$t\bar{t}$H (W/Z/τ)	**36 fb^{-1}, 13 TeV**	PRD 97	1712.08891			
$t\bar{t}$H ($\gamma\gamma$)	**36 fb^{-1}, 13 TeV**	HIGG-16-21*	1802.04146			
$t\bar{t}+t\bar{t}$	**36 fb^{-1}, 13 TeV**	EXOT-16-13*	1803.09678	**36 fb^{-1}, 13 TeV**	EPJC 78	1710.10614
$t\bar{t}$+HH/ZZ				**36 fb^{-1}, 13 TeV**	B2G-17-011*	1805.04758
$t\bar{t}+\tau\tau$	- - - - -	- - - - -	- - - - -	**36 fb^{-1}, 13 TeV**	B2G-16-028*	1803.02864
$t\bar{t}+gg$	- - - - -	- - - - -	- - - - -	**36 fb^{-1}, 13 TeV**	PLB 778	1711.10949

- Most final states covered by both ATLAS and CMS with full 2016 dataset

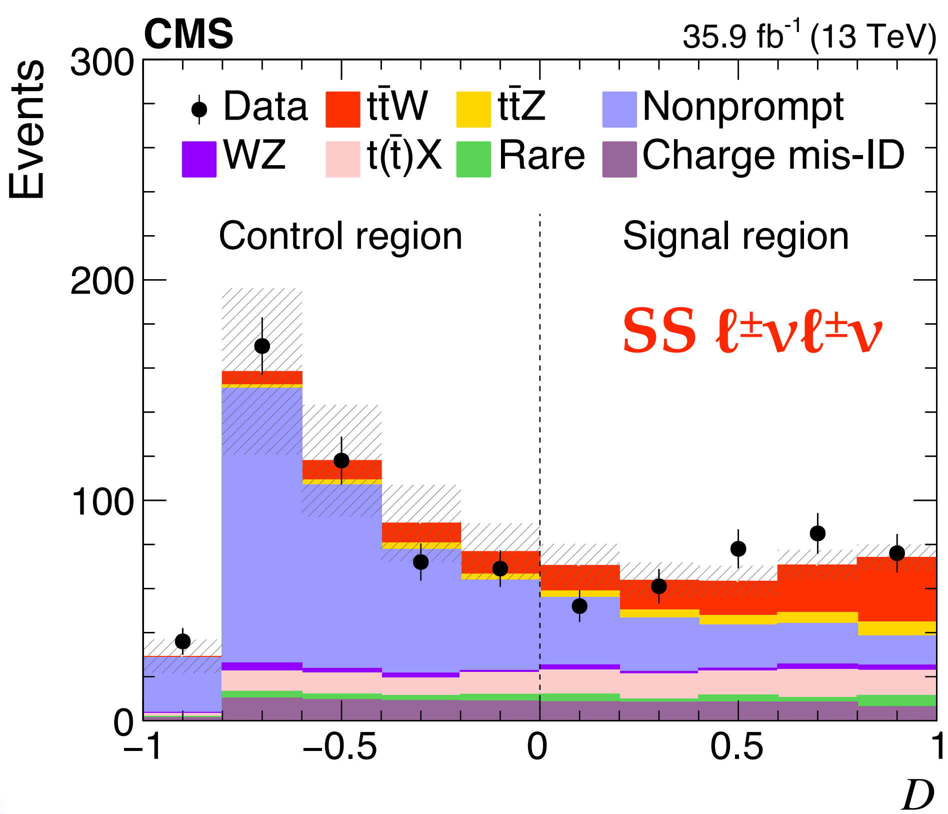
*** Submitted for publication**

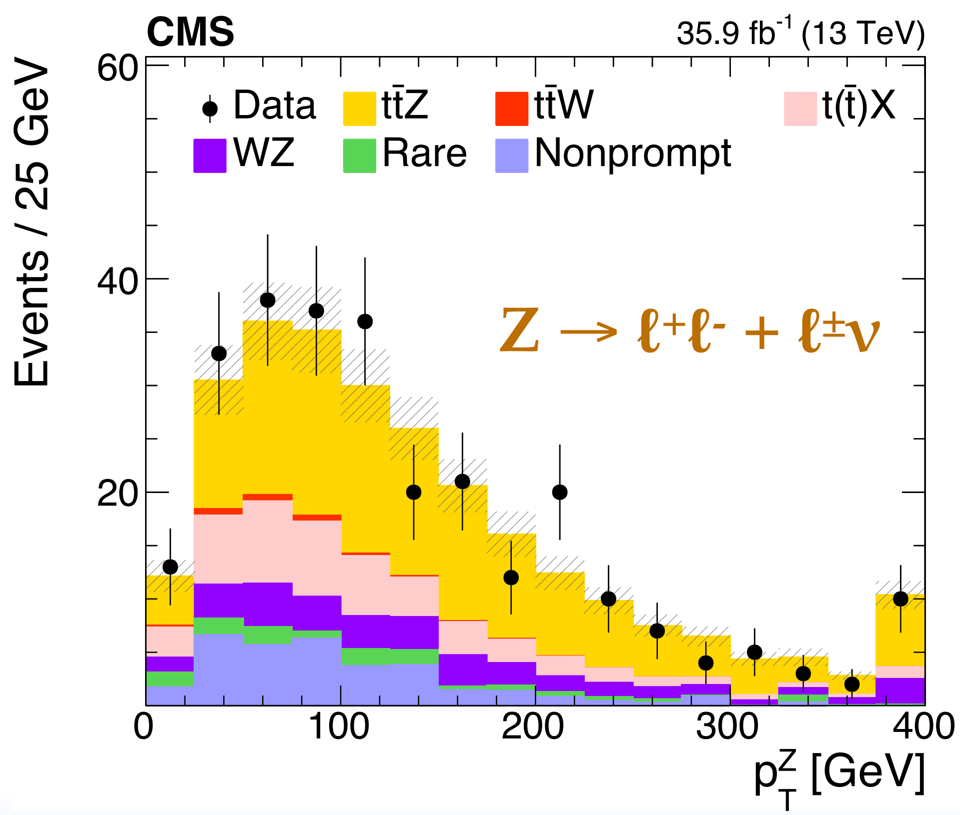
ATLAS: 1609.01599
CMS: 1711.02547

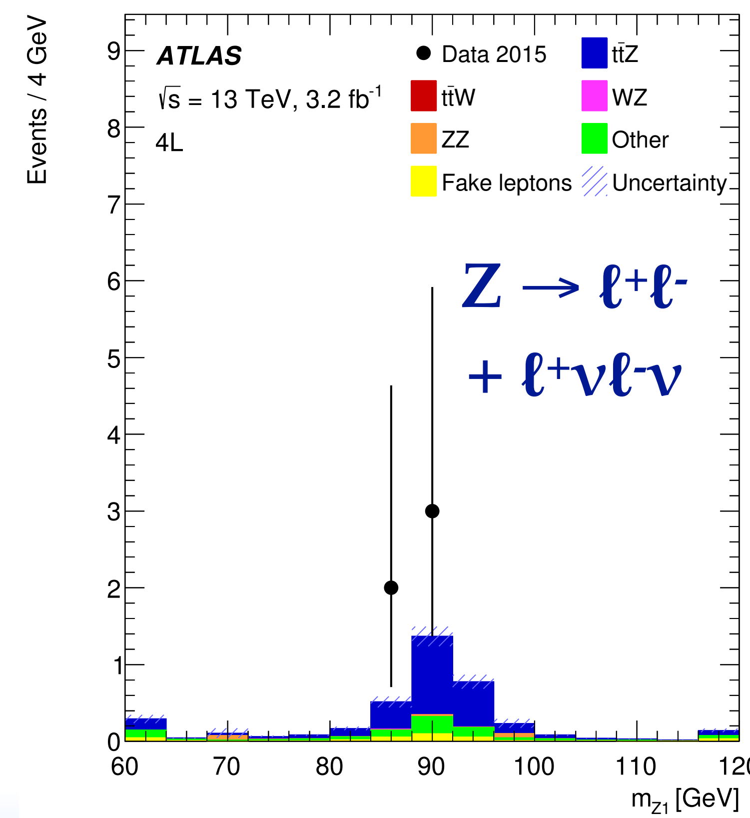
$t\bar{t}$+W and $t\bar{t}$+Z

- CMS and ATLAS measure $t\bar{t}$W and $t\bar{t}$Z at 13 TeV in three channels : same-sign 2ℓ, 3ℓ, and 4ℓ (ℓ = *e* or μ)
  - $t\bar{t}$Z probes top-Z coupling, both sensitive to new physics
- CMS uses BDT in SS 2ℓ to distinguish $t\bar{t}$W from $t\bar{t}$ with non-prompt lepton *and* from other t($\bar{t}$)+X
- Other channels in CMS and ATLAS categorize on number of leptons, jets, b-tagged jets, and Z-mass $\ell^+\ell^-$

$t\bar{t}$ decay modes	
0 ℓν + 4 j + 2 b	55.6%
1 ℓν + 2 j + 2 b	37.9%
2 ℓν + 0 j + 2 b	6.5%
W → $\ell^\pm\nu$	25.4%
Z → $\ell^+\ell^-$	6.8%





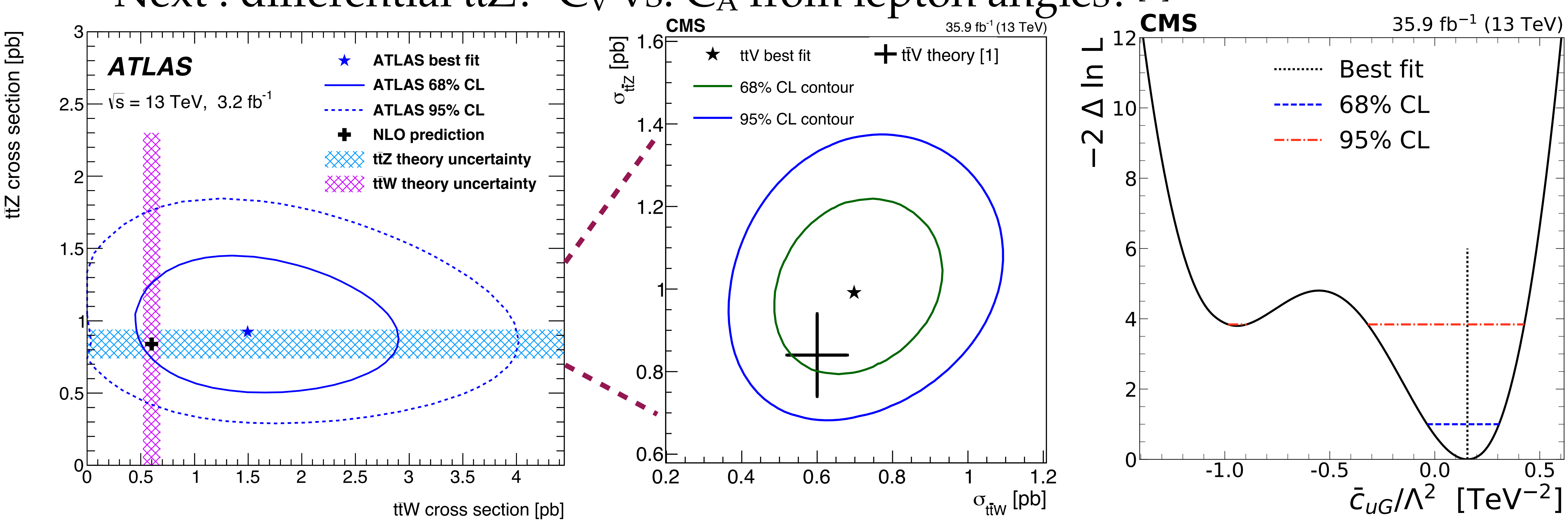


ATLAS: 1609.01599
CMS: 1711.02547

$t\bar{t}$+W and $t\bar{t}$+Z

- With ~10x more events in 2016 than 2015, CMS can measure $t\bar{t}W$ cross-section within 22%, $t\bar{t}Z$ within 14%
  - ATLAS uncertainties mostly statistical, expect update soon
  - CMS many small uncertainties, statistical ≈ systematic
- CMS uses 2D $t\bar{t}Z$ vs. $t\bar{t}W$ to set limits on 6-dimension EFT operators, constrain new physics (stay tuned! [1])
  - Next : differential $t\bar{t}Z$? C_V vs. C_A from lepton angles? [2]

SM σ($t\bar{t}W$)	628 ± 82 fb
ATLAS	1500 ± 790 fb
CMS	770 ± 170 fb
SM σ($t\bar{t}Z$)	839 ± 101 fb
ATLAS	920 ± 290 fb
CMS	990 ± 140 fb



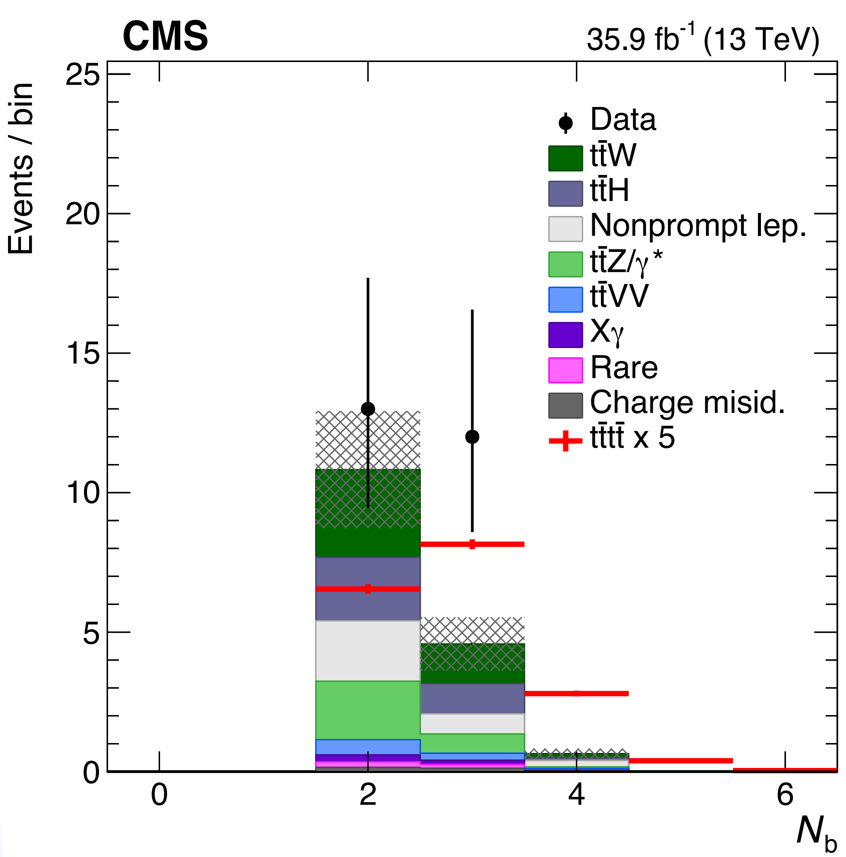
[1] See https://indico.cern.ch/event/677667/contributions/2996198/ [2] Röntsch and Schulze : arxiv.org/abs/1501.05939

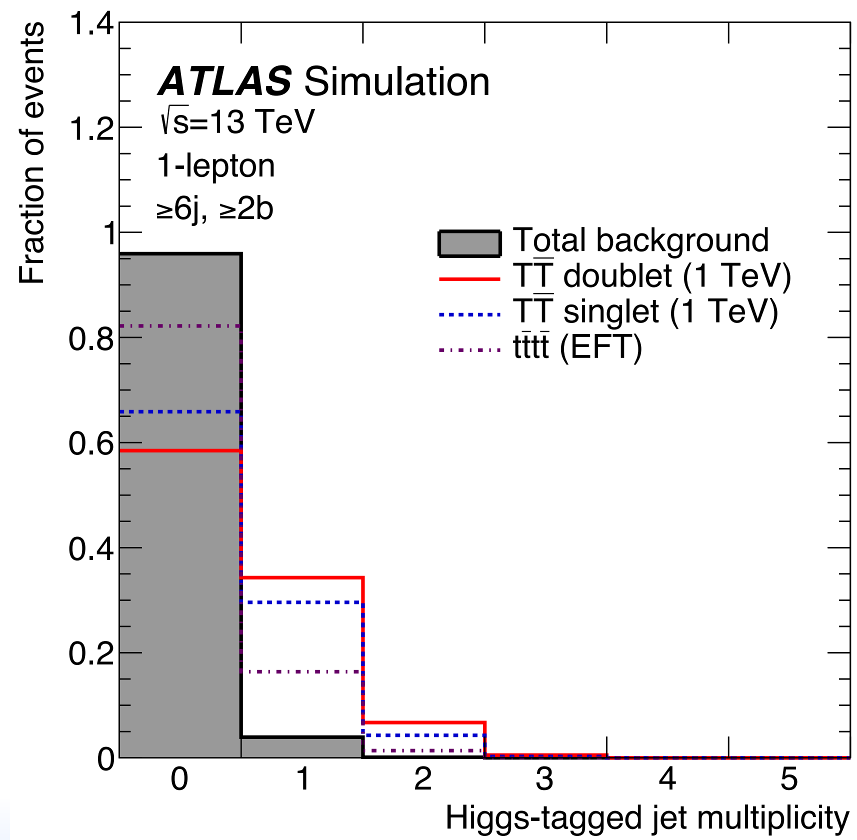
$t\bar{t}+t\bar{t}$ (4-top)

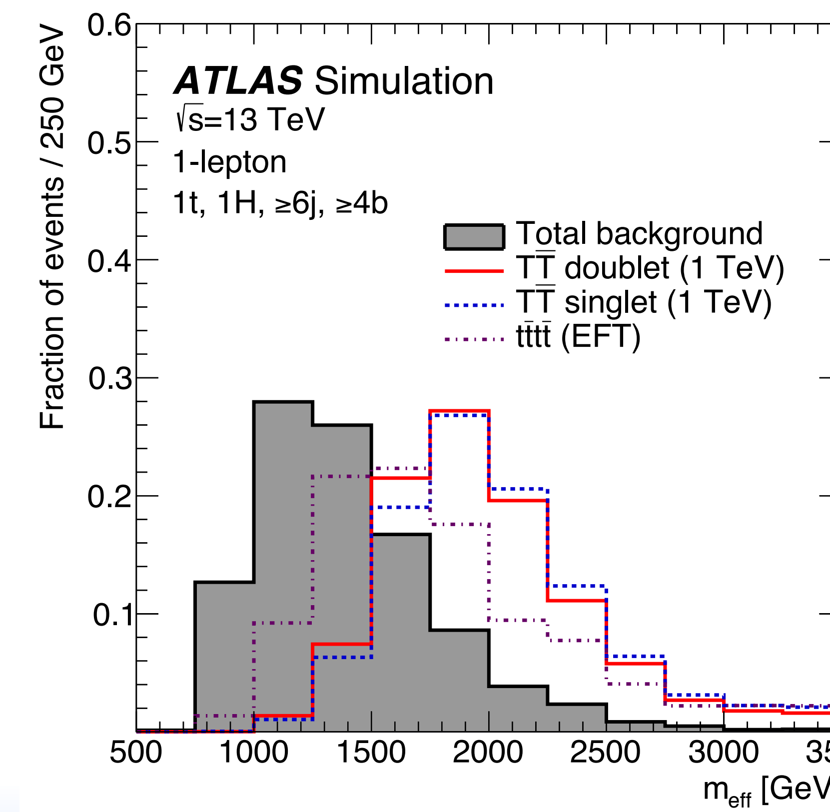
- 4-top production the highest-mass, highest-multiplicity SM process probed at the LHC
  - Very low SM cross-section (~10 fb), stats limited
- Different approaches from CMS and ATLAS
  - High-purity vs. high-stats + complex kinematics
  - CMS does SM search, ATLAS constrains EFT 4-top

$t\bar{t}+t\bar{t}$ decay modes	
0 ℓν + 8 j + 4 b	31.0%
1 ℓν + 6 j + 4 b	42.2%
2 OS ℓν + 4 j + 4 b	14.4%
2 SS ℓν + 4 j + 4 b	7.2%
3 ℓν + 2 j + 4 b	4.9%
4 ℓν + 0 j + 4 b	0.4%

ATLAS: 1 ℓν and 2 OS ℓν rows
CMS: 2 SS ℓν and 3 ℓν rows







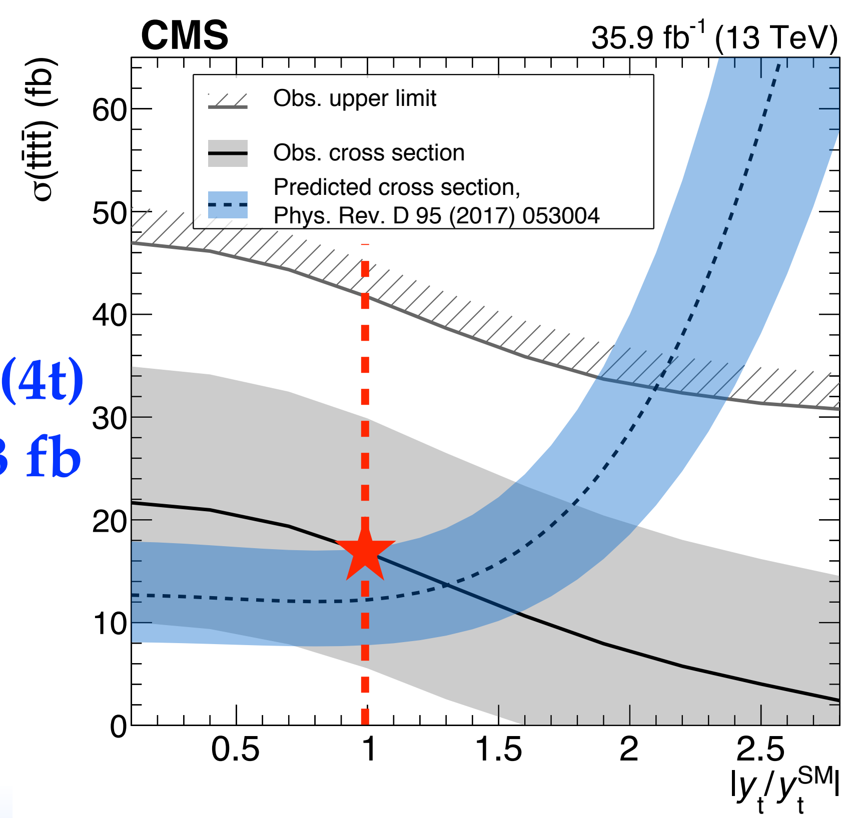
[ATLAS: 1803.09678](https://arxiv.org/abs/1803.09678)
[CMS: 1710.10614](https://arxiv.org/abs/1710.10614)

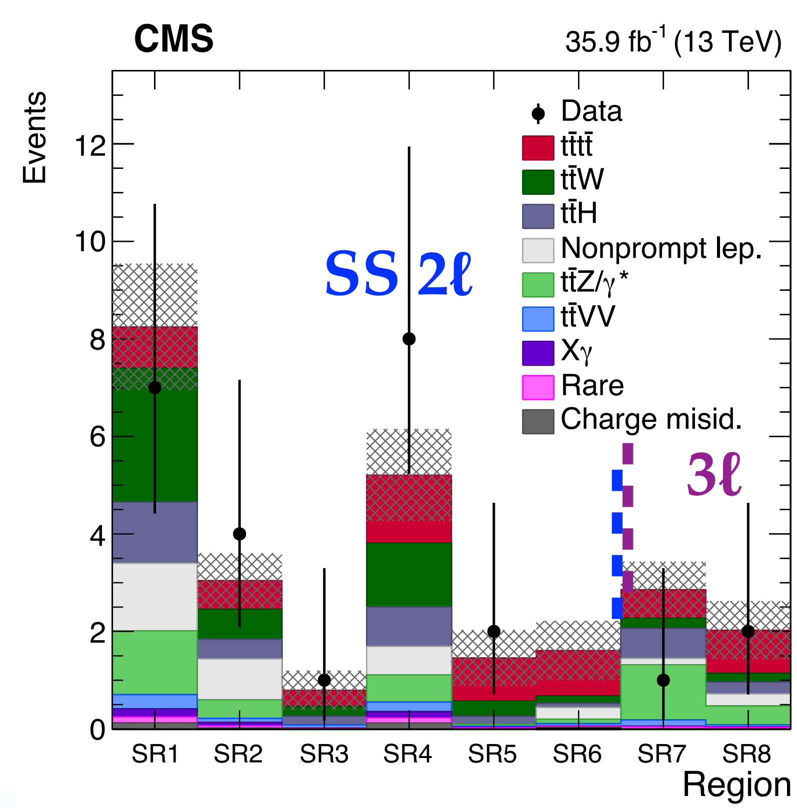
$t\bar{t}+t\bar{t}$ (4-top)

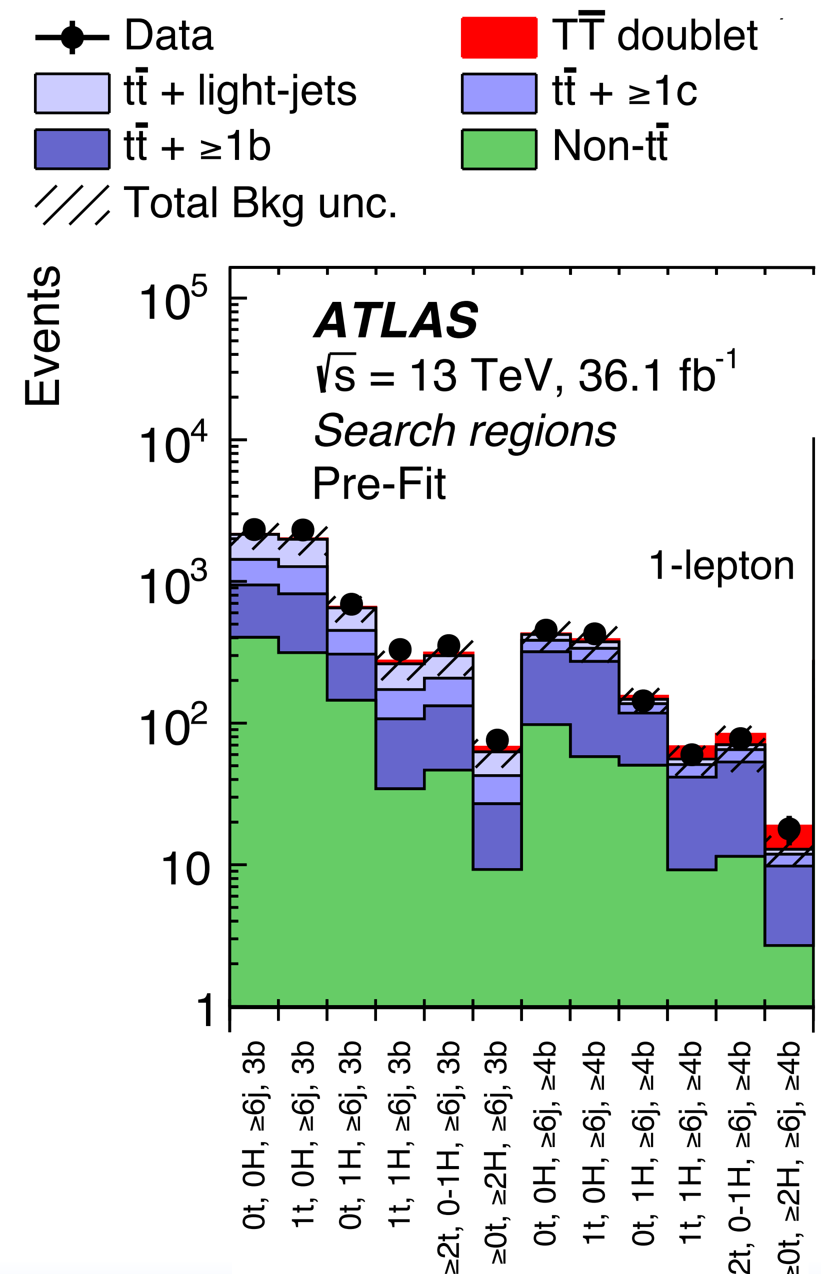
- For more boosted EFT signature, ATLAS uses large, high-pT jets to tag Higgs → bb and top → bjj decays
  - Categorize on # of jets, b-jets, H-tags, and top-tags
  - Sensitive region : ≥ 4 b's + ≥ 6 j's + ≥ 2 H+top-tags
- CMS categorizes on # of leptons, jets, and b-jets
  - Sensitive regions : ≥ 3 b's, SS 2ℓ + ≥ 5 j's, 3ℓ+ ≥ 4 j's

ATLAS : σ(EFT 4t)
< 16 fb (obs.)
< 32 fb (exp.)

CMS : σ(4t)
= 17 ± 13 fb



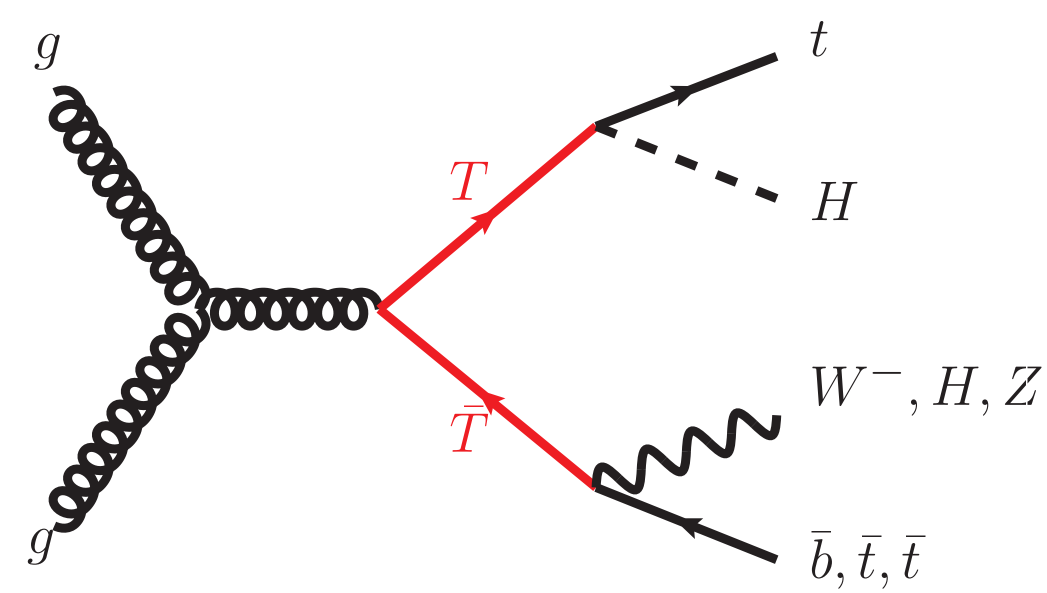


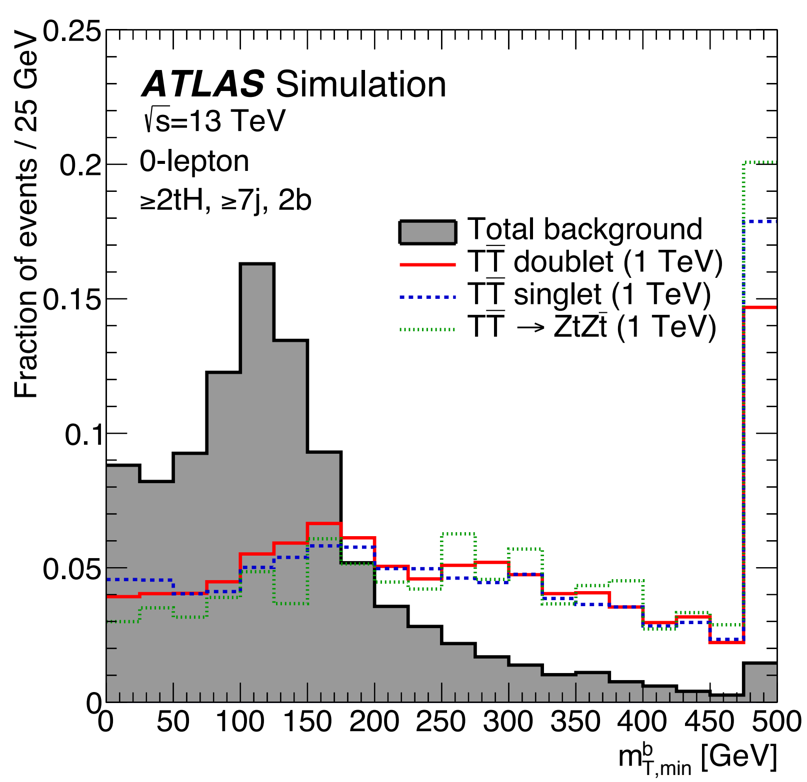


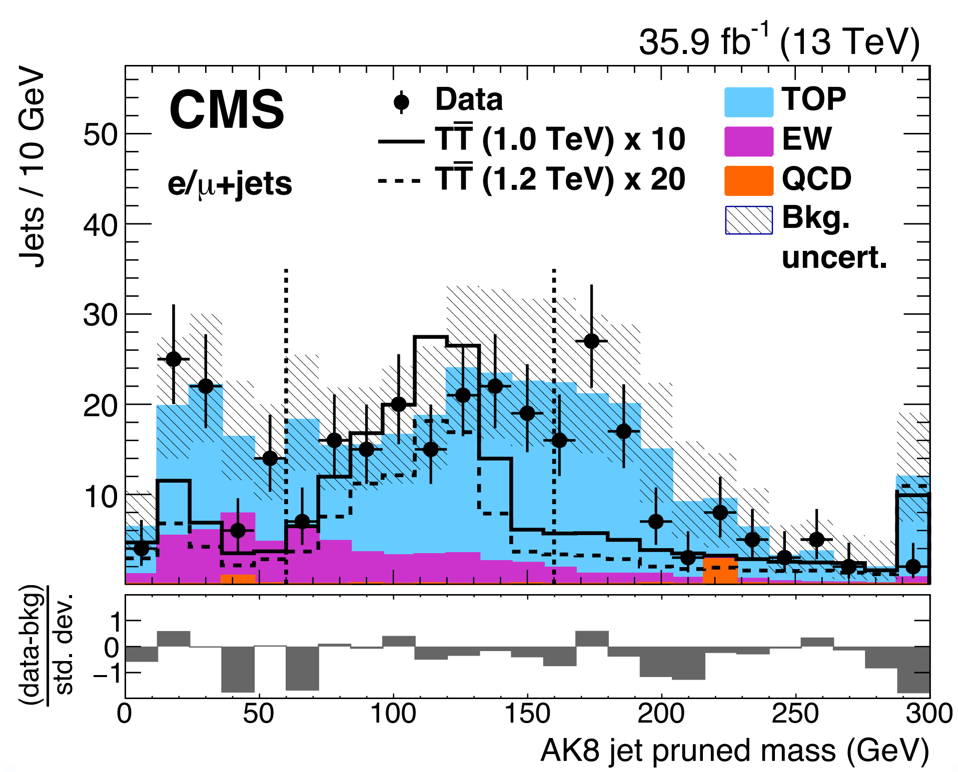
Vector quarks : $t\bar{t}$ + multi-Z/H

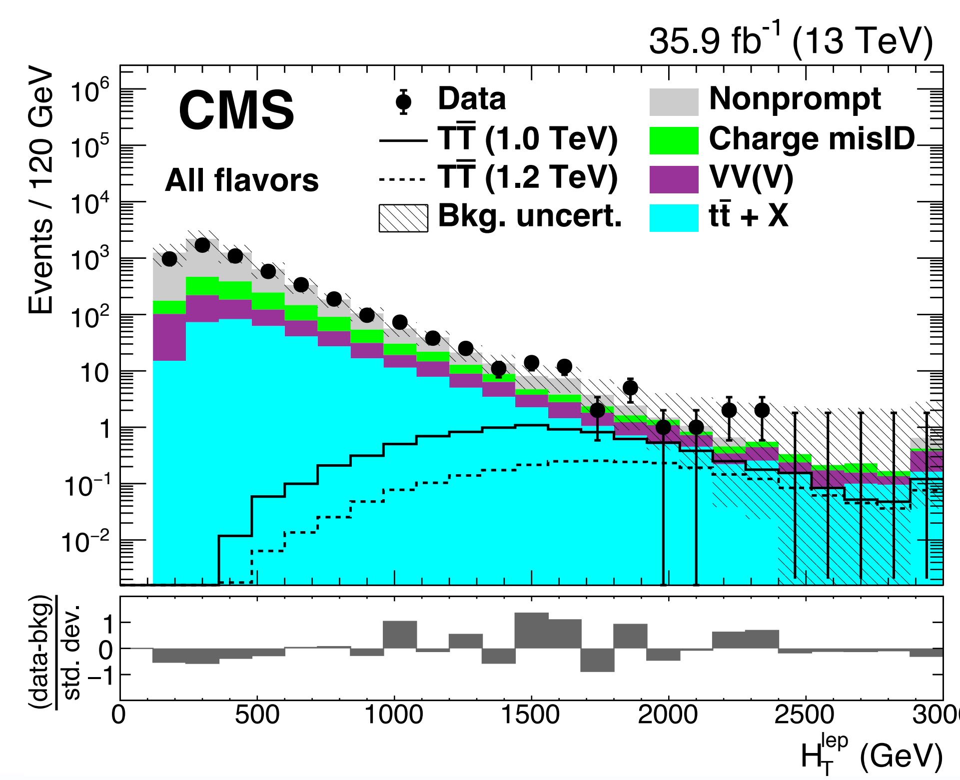
ATLAS: 1803.09678
CMS: 1805.04758

- BSM up-type vector quarks "T" could decay to a SM top + Z, top + H, or bottom + W
- Signature overlaps SM ttW/Z/H, but with even higher multiplicity and higher boost
- ATLAS uses 0ℓ and 1ℓ events with top- and H-tagged jets (combined with 4-top analysis)
- CMS uses top/H-tagged jets in 1ℓ, and lepton+jet M_T or H_T in SS 2ℓ and 3ℓ







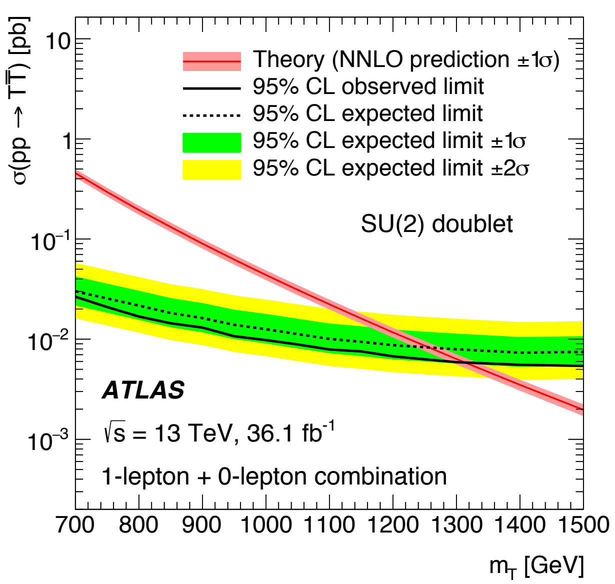


Vector quarks : $t\bar{t}$ + multi-Z / H

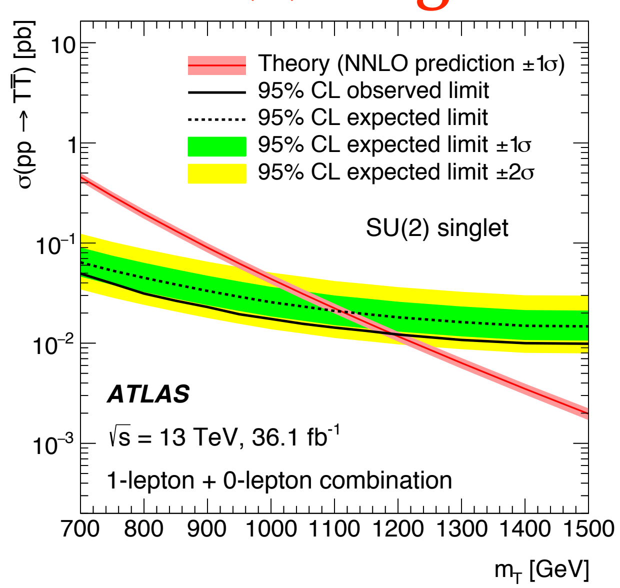
ATLAS: 1803.09678
CMS: 1805.04758

- Despite taking very different approaches, ATLAS and CMS achieve very similar limits, excluding T masses below ~ 1 TeV
- At this mass scale the T decay products are *very* boosted : expect even greater use of top- and Higgs-tagged jets in the future

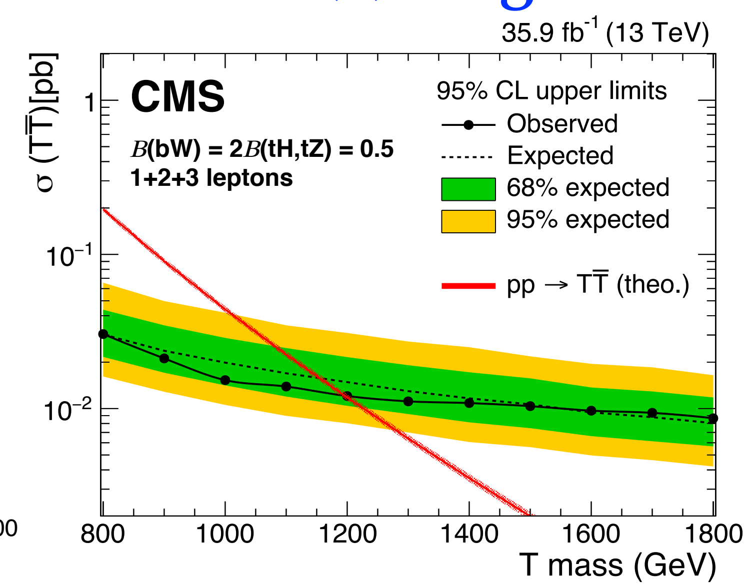
SU(2) doublet



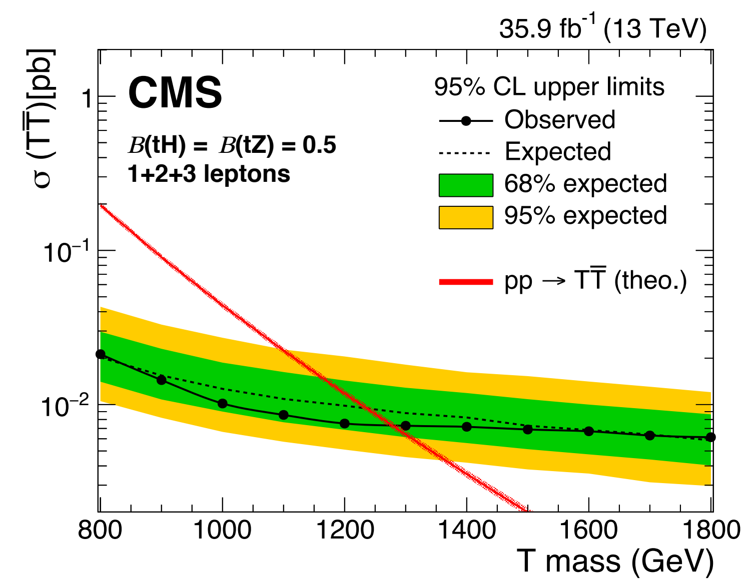
SU(2) singlet



SU(2) singlet



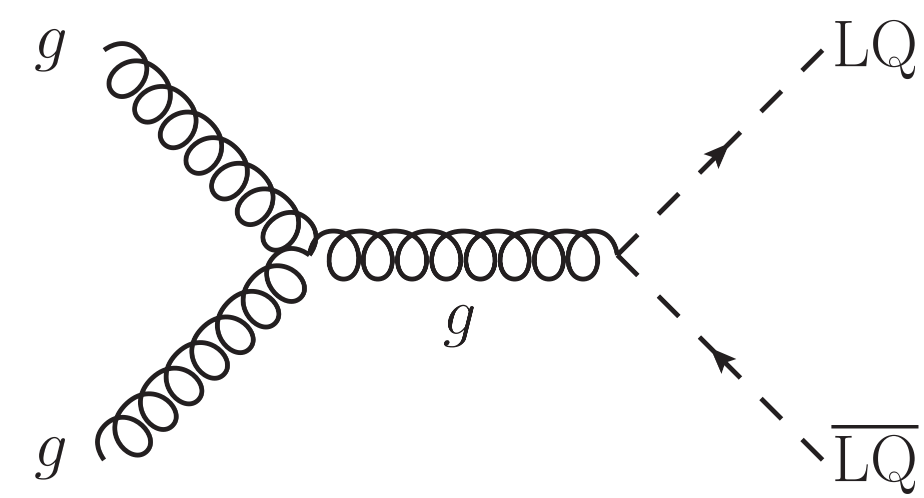
SU(2) doublet



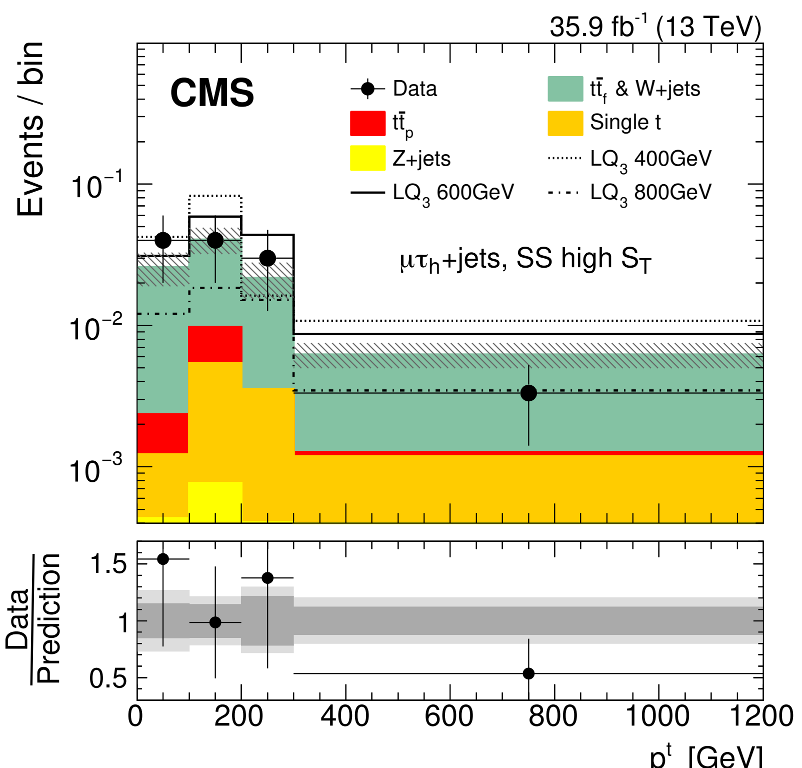
Lepto-quarks : $t\bar{t}$+ττ

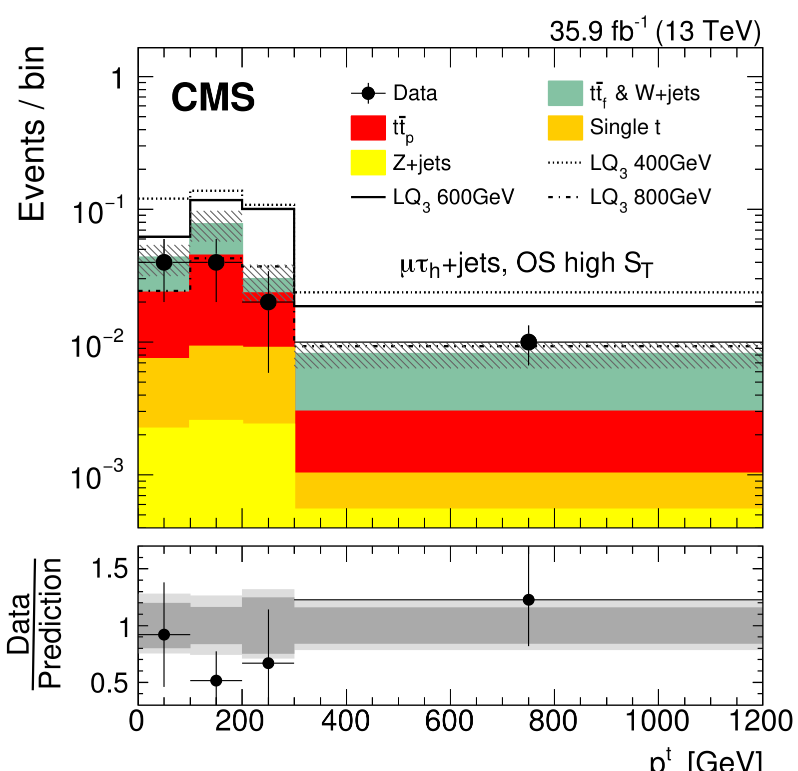
[CMS: 1803.02864](https://arxiv.org/abs/1803.02864)

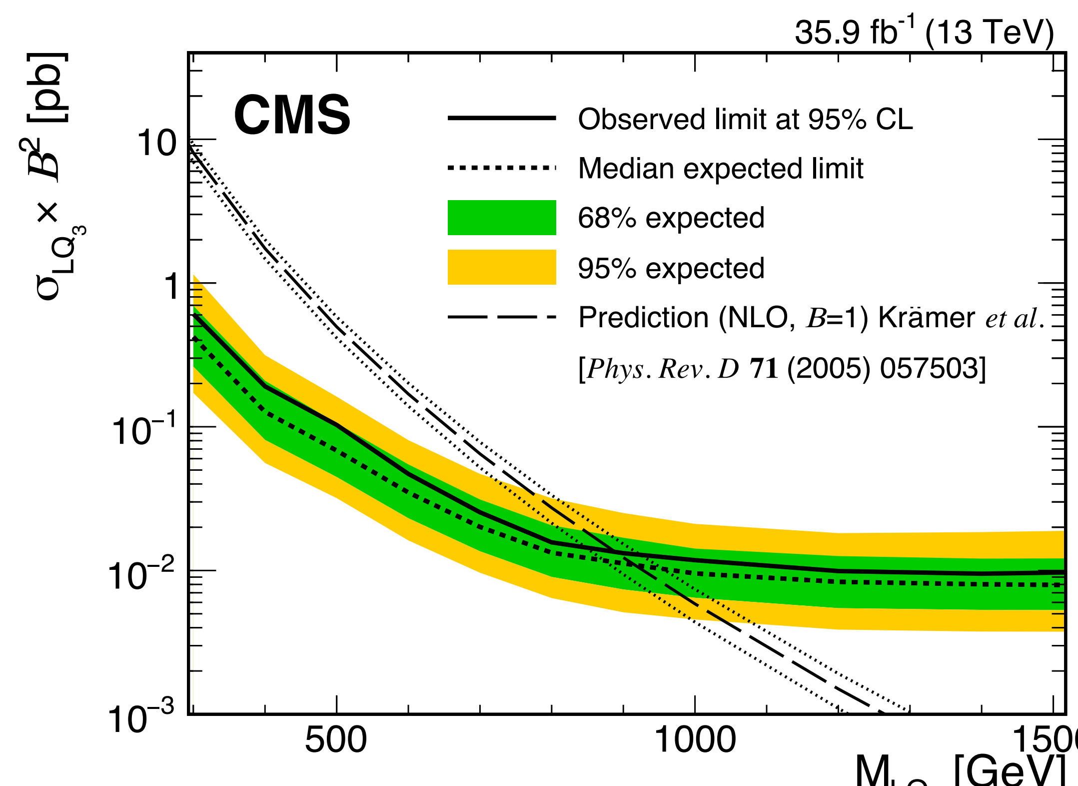
- CMS searches for pairs of LQ → top + τ with $t\bar{t}$ → ℓν + 2 j + 2 b and τ → hadrons



- Categorize by ℓ = e/μ, ℓ + τ charge, scalar Σ p_T of all particles (S_T), and # of τ_h (1 or 2)
- In single-τ_h channel, fit to p_T of reconstructed top → bjj system (p_T^t)
- Combine with counts from 2 τ_h events, exclude LQ masses < 900 GeV



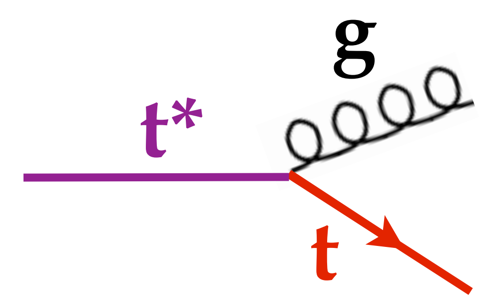




[1] Details and motivation : indico.cern.ch/event/719627/ and indico.cern.ch/event/677667/contributions/2830531/

Excited tops : $t\bar{t}+gg$

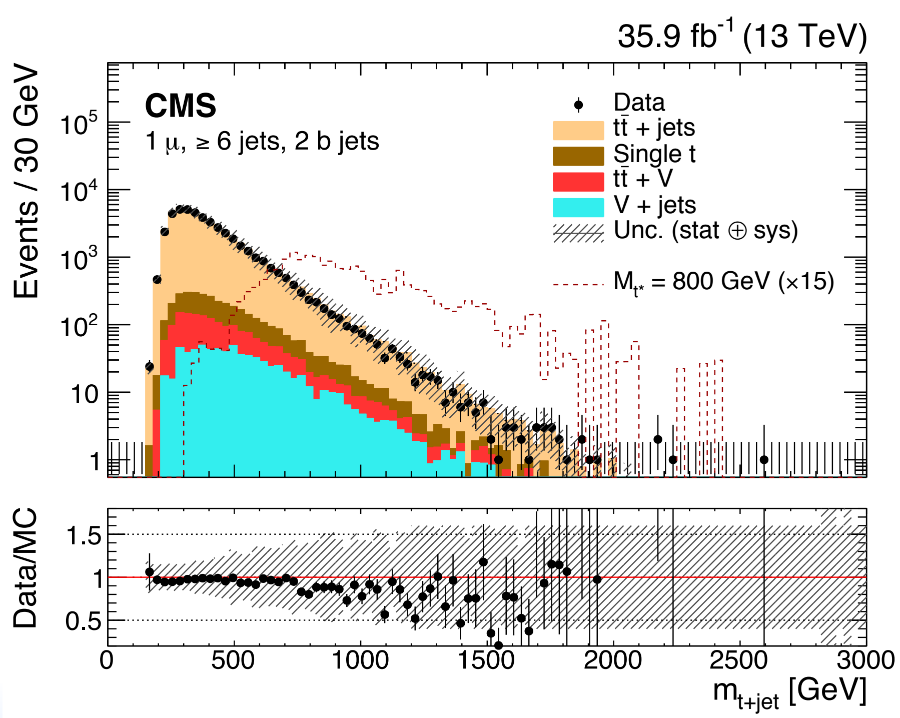
[CMS: 1711.10949]

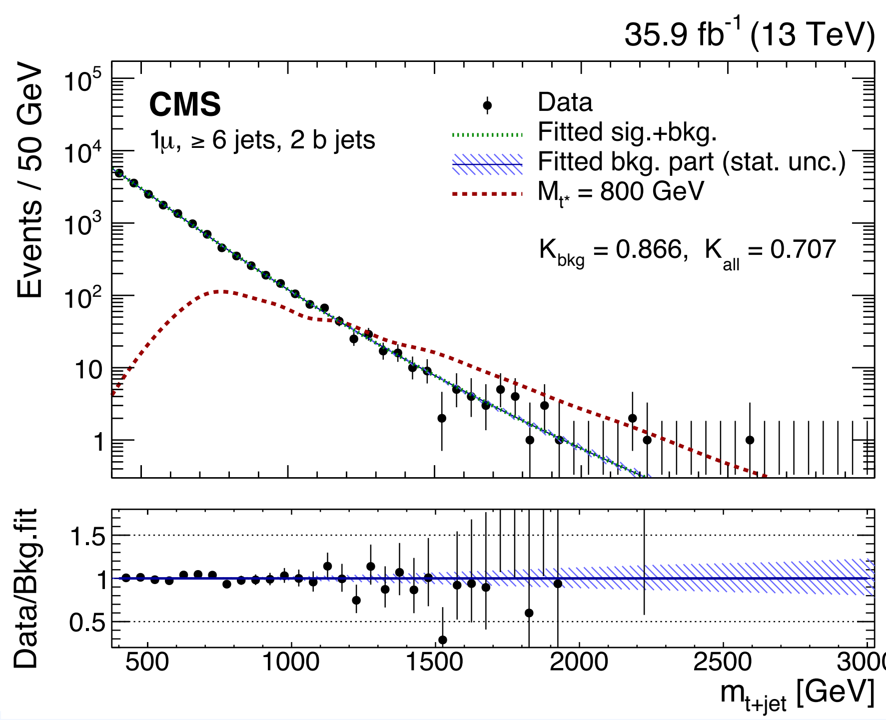


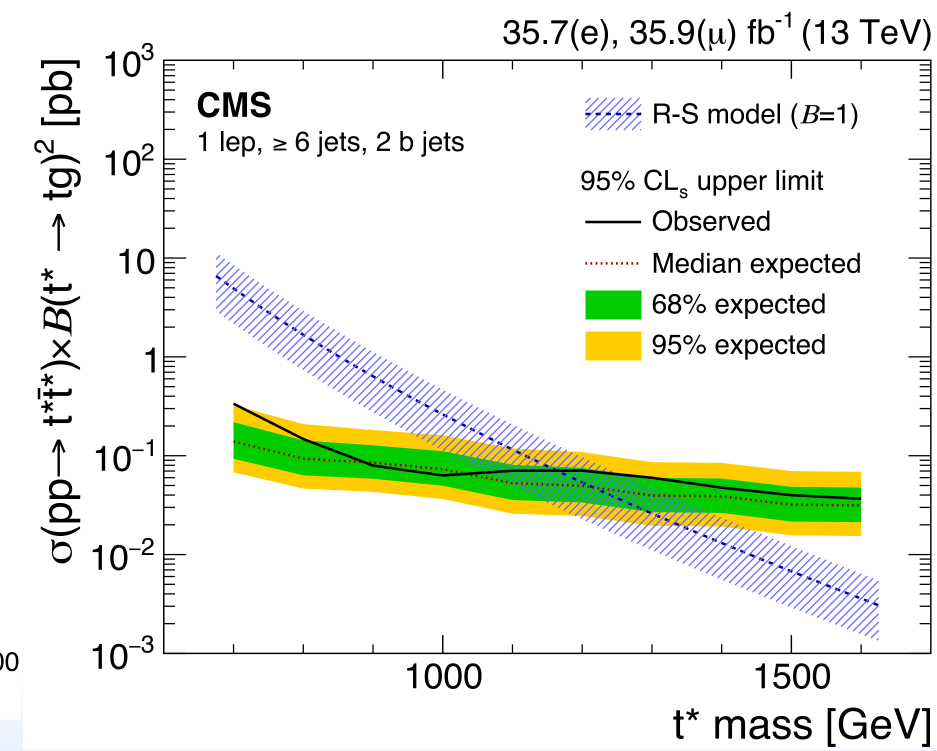
- In any composite top quark model, could have excited top (t*) decaying to ground state + gluon
- CMS searches in $t\bar{t} \to \ell\nu + 2\,j + 2\,b$ events by reconstructing the best-fit t* masses (m_{t+jet})
- In SM backgrounds (including $t\bar{t}$+X!), m_{t+jet} falls logarithmically -- data-only background fit!
- Exclude t* masses < 1.2 TeV

$$S = \left(\frac{m_{qq'} - m_W}{\sigma_W}\right)^2 + \left(\frac{m_{qq'b} - m_t}{\sigma_{t,had}}\right)^2 + \left(\frac{m_{\ell\nu_l b} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{m_{qq'bg} - m_{\ell\nu_l bg}}{\sigma_{t^*}}\right)^2$$

$$f_{bkg}(m) = \frac{1}{m\sqrt{2\pi}} \exp\left(-a_2 \ln^2\left(\frac{m}{m_0}\right)\right)$$







$t\bar{t}$+X results

Final state	SM Xsec	ATLAS		CMS	
		Dataset	Obs. Xsec / Lim.	Dataset	Obs. Xsec / Lim.
$t\bar{t}+\gamma$	151 fb	20 fb^{-1}, 8 TeV	139 ± 18 fb (13%)	20 fb^{-1}, 8 TeV	127 ± 27 fb (21%)
$t\bar{t}$+W	626 fb	3.2 fb^{-1}, 13 TeV	1500 ± 790 fb (53%)	**36 fb^{-1}, 13 TeV**	770 ± 170 fb (22%)
$t\bar{t}$+Z	846 fb		920 ± 290 fb (32%)		990 ± 140 (14%)
$t\bar{t}$H (bb)	294 fb	**36 fb^{-1}, 13 TeV**	247 ± 181 fb (73%)	**36 fb^{-1}, 13 TeV**	212 ± 128 fb (60%)
$t\bar{t}$H (W/Z/τ)	154 fb	**36 fb^{-1}, 13 TeV**	240 ± 43 fb (18%)		189 ± 66 fb (35%)
$t\bar{t}$H ($\gamma\gamma$)	1.2 fb	**36 fb^{-1}, 13 TeV**	0.7 ± 0.8 fb (114%)		2.5 ± 1.0 fb (40%)
$t\bar{t}+t\bar{t}$ *	10.7 fb	**36 fb^{-1}, 13 TeV**	EFT < 16 fb	**36 fb^{-1}, 13 TeV**	SM = 16.9 ± 12.6 fb
$t\bar{t}$+HH/ZZ	- - - - -	**36 fb^{-1}, 13 TeV**	T mass > 0.99 TeV	**36 fb^{-1}, 13 TeV**	T mass > 1.14 TeV
$t\bar{t}+\tau\tau$	- - - - -	- - - - -	- - - - -	**36 fb^{-1}, 13 TeV**	LQ mass > 0.90 TeV
$t\bar{t}$+gg	- - - - -	- - - - -	- - - - -	**36 fb^{-1}, 13 TeV**	top* mass > 1.2 TeV

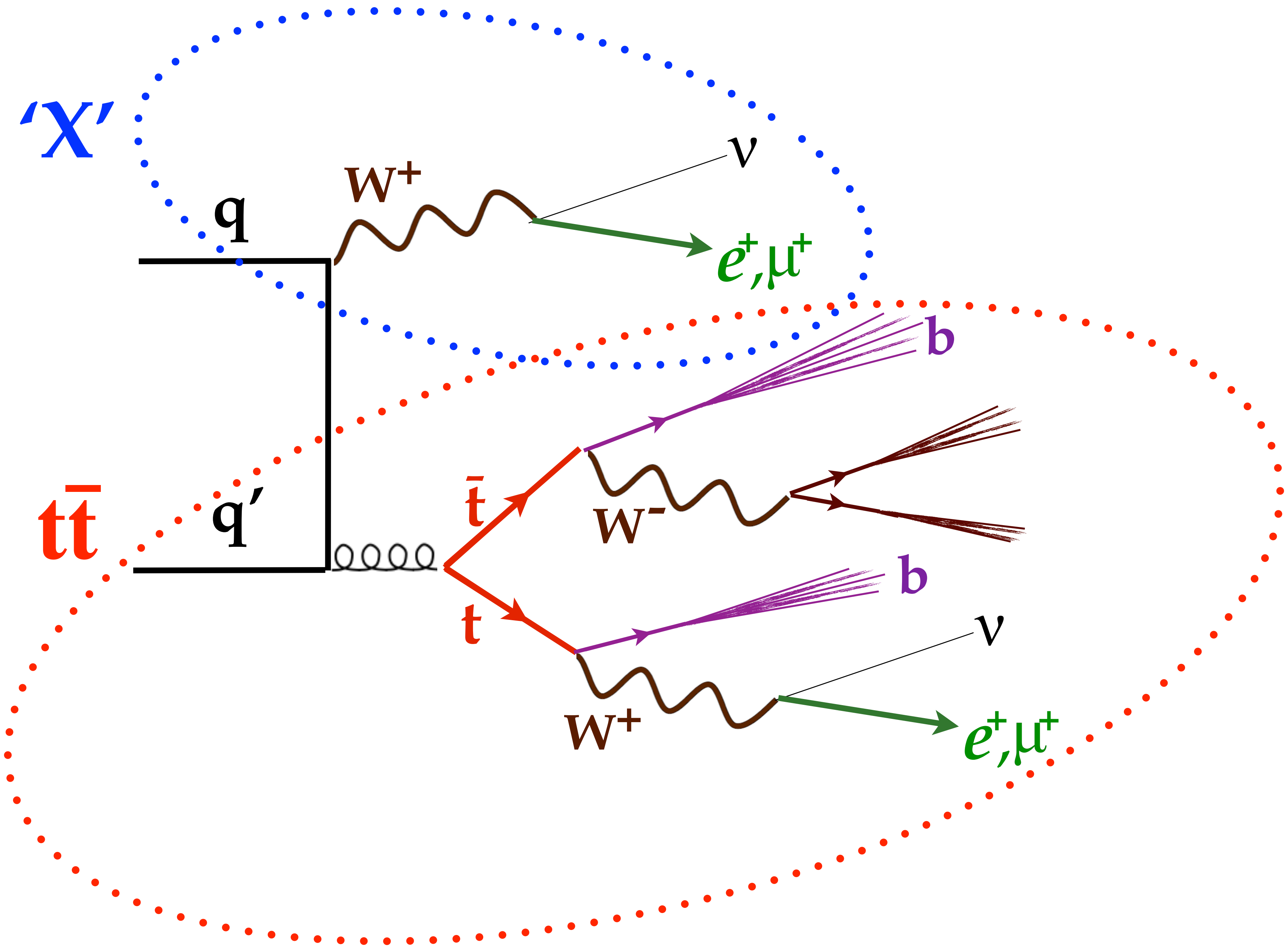
* **ATLAS places limits on higher-energy EFT 4-top production, while CMS searches for SM 4-top events**

Summary

- High-luminosity physics in 13 TeV pp collisions is allowing us to push into unexplored territory of both SM and BSM physics
- For SM $t\bar{t}$+X, increasing use of sophisticated reconstruction techniques to resolve combinatorics of jets, leptons, and p_T^{miss}
- For BSM $t\bar{t}$+X, mass limits on most models are passing the TeV mark -- future analyses increasingly in the boosted regime
- Looking forward to results with 3 - 4 times more data in 2019!

BACKUPS

$t\bar{t}$+X



$t\bar{t}$+Z : probing top-Z coupling

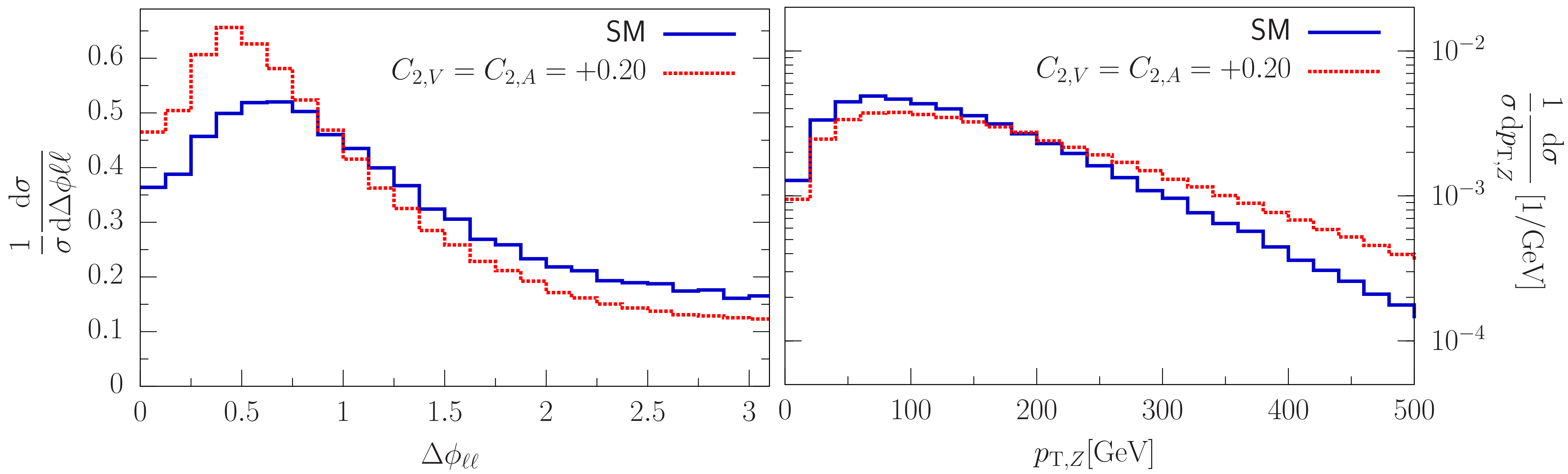


Figure 2: NLO distributions of $\Delta\phi_{\ell\ell}$ and $p_{T,Z}$ for SM $t\bar{t}Z$ couplings and with anomalous dipole couplings $C^Z_{2,V} = C^Z_{2,A} = 0.2$. The distributions are normalized to the overall cross section. The cuts of Eq. (3.2) are applied.

- $t\bar{t}$+Z kinematics sensitive both to vector vs. axial component of top-Z coupling (C_V vs. C_A) and to anomalous dipole couplings

[1] Röntsch and Schulze : arxiv.org/abs/1501.05939

$t\bar{t}$+W and $t\bar{t}$+Z : ATLAS uncertainties

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	19%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

$$\sigma_{t\bar{t}W} = 1.50 \pm 0.72 \text{ (stat.)} \pm 0.33 \text{ (syst.) pb}$$

$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.29 \text{ (stat.)} \pm 0.10 \text{ (syst.) pb}$$

- Dominated by statistical uncertainty

$t\bar{t}$+W and $t\bar{t}$+Z : CMS uncertainties

Source	Uncertainty from each source (%)	Impact on the measured $t\bar{t}W$ cross section (%)	Impact on the measured $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	4	3
Jet energy scale and resolution	2–5	3	3
Trigger	2–4	4–5	5
B tagging	1–5	2–5	4–5
PU modeling	1	1	1
Lepton ID efficiency	2–7	3	6–7
Choice in μ_R and μ_F	1	<1	1
PDF	1	<1	1
Nonprompt background	30	4	<2
WZ cross section	10–20	<1	2
ZZ cross section	20	—	1
Charge misidentification	20	3	—
Rare SM background	50	2	2
$t(\bar{t})$X background	10–15	4	3
Stat. unc. in nonprompt background	5–50	4	2
Stat. unc. in rare SM backgrounds	20–100	1	<1
Total systematic uncertainty	—	14	12

$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}\,(\text{stat})^{+0.13}_{-0.12}\,(\text{syst})\,\text{pb},$$

$$1.23^{+0.19}_{-0.18}\,(\text{stat})^{+0.20}_{-0.18}\,(\text{syst})^{+0.13}_{-0.12}\,(\text{theo})$$

$$\sigma(pp \to t\bar{t}Z) = 0.99^{+0.09}_{-0.08}\,(\text{stat})^{+0.12}_{-0.10}\,(\text{syst})\,\text{pb}.$$

$$1.17\,^{+0.11}_{-0.10}\,(\text{stat})^{+0.14}_{-0.12}\,(\text{syst})^{+0.11}_{-0.12}\,(\text{theo})$$

- Equally limited by systematic and statistical uncertainties
  - Almost equal to theoretical uncertainties on cross section
- “Uncertainties associated with the integrated luminosity, lepton identification, trigger selection efficiencies, nonprompt lepton, and t(t)X backgrounds have the greatest effect”

CMS $t\bar{t}$+W : BDT in SS 2ℓ events