ATLAS and CMS 4-top comparison

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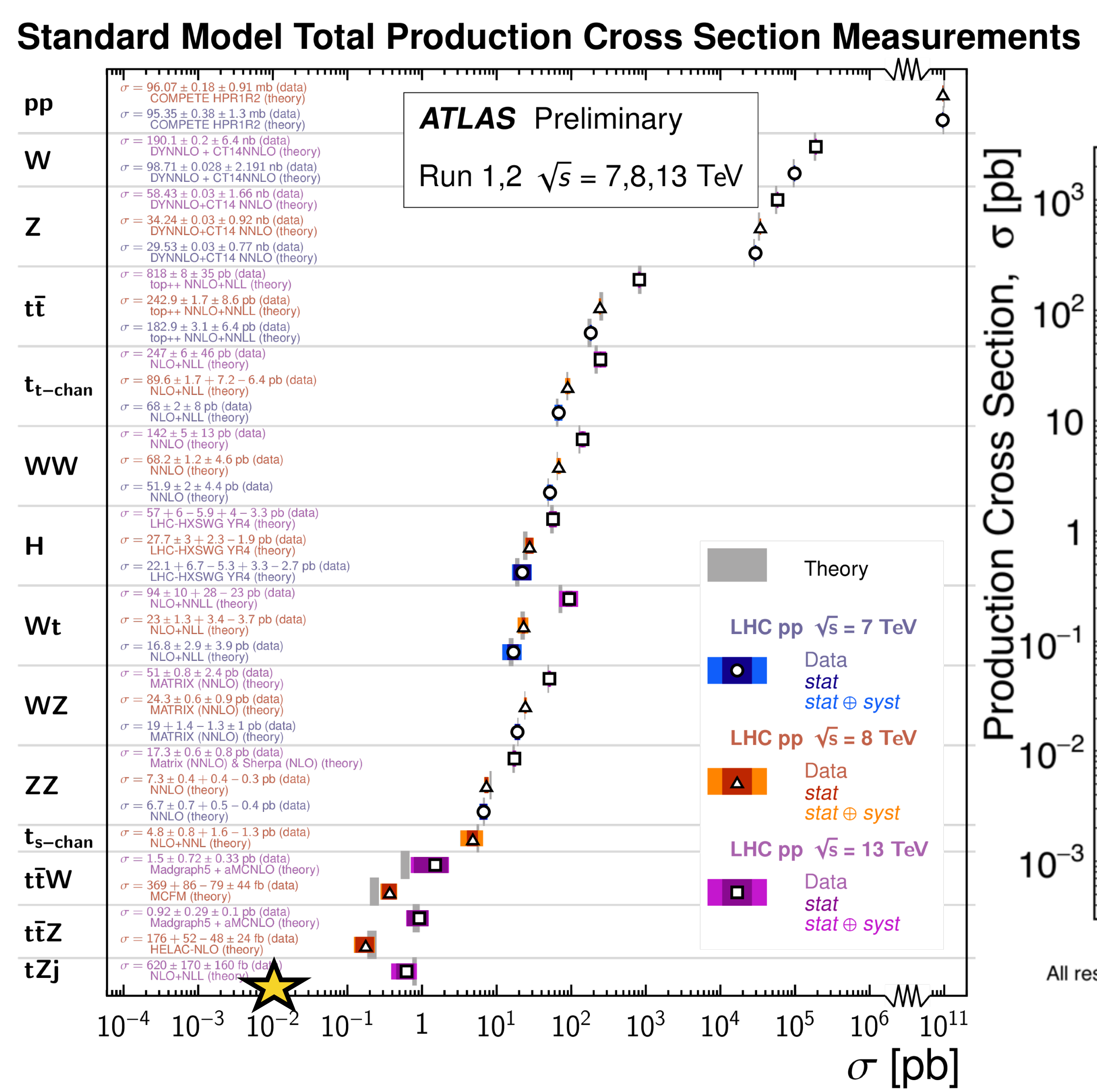
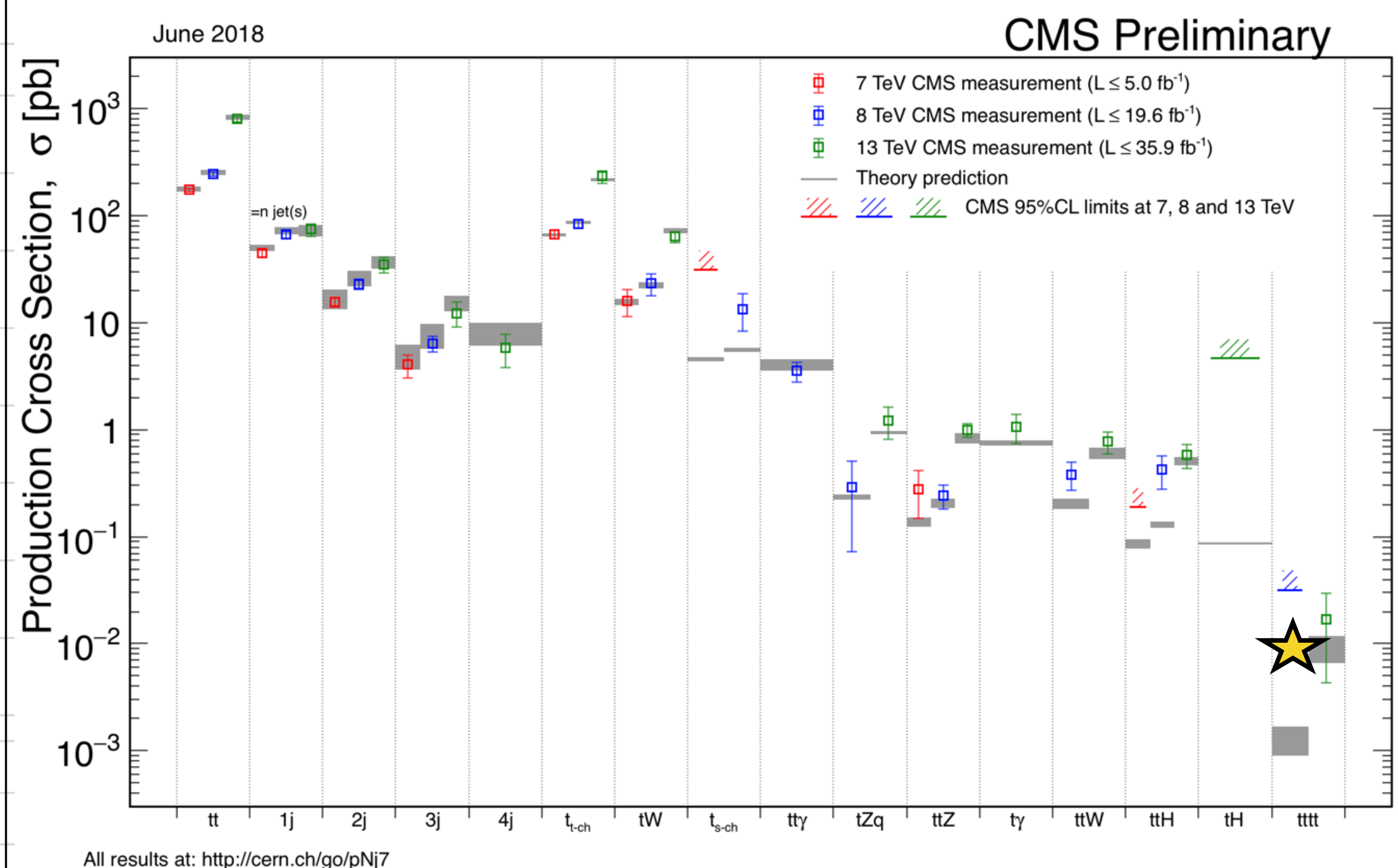
LHC TOP WG Meeting - 20 November 2018

tttt: the next frontier ★

Top quark *pair pair* production: a complex QCD process with large sensitivity to new physics effects





Standard Model prediction

Large theoretical uncertainties in inclusive cross section

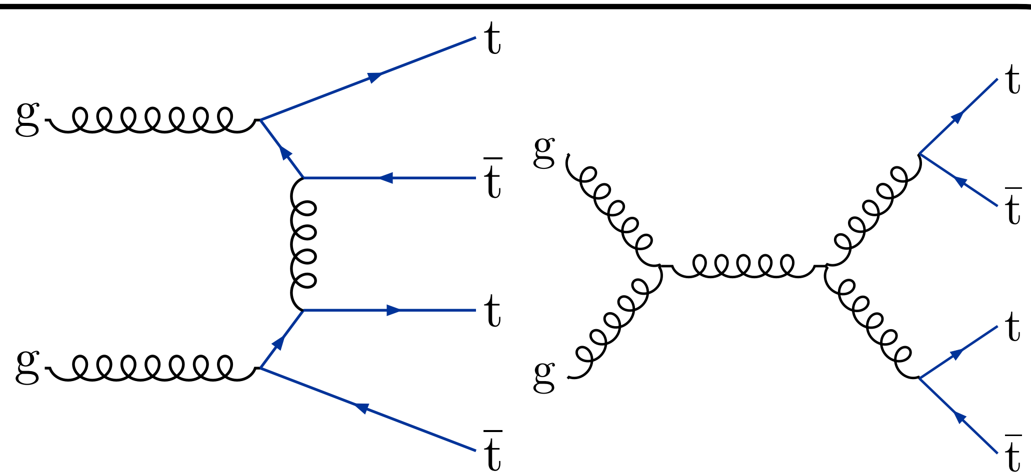
QCD NLO/LO k-factor ranges between 1.2 and 2.0, depending on scale and PDF choices

Large effects (up to 40%) from Leading Order EWK diagrams

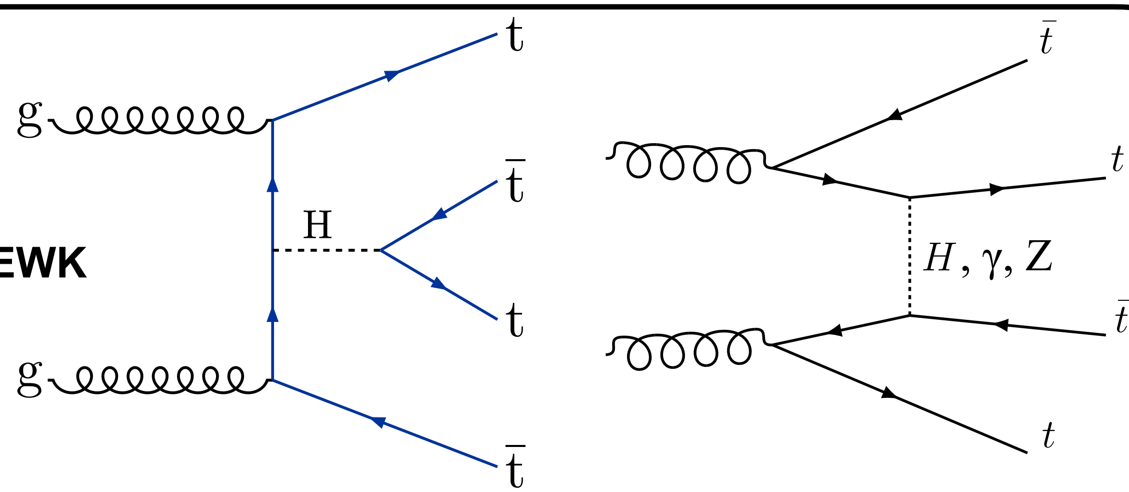
13 TeV prediction currently used by ATLAS and CMS: $\sigma_{NLO}(tttt) = 9.2^{+2.9}_{-2.4}$ fb [1]

Most recent prediction, including EWK NLO effects: $12^{+2.2}_{-2.5}$ fb [2]

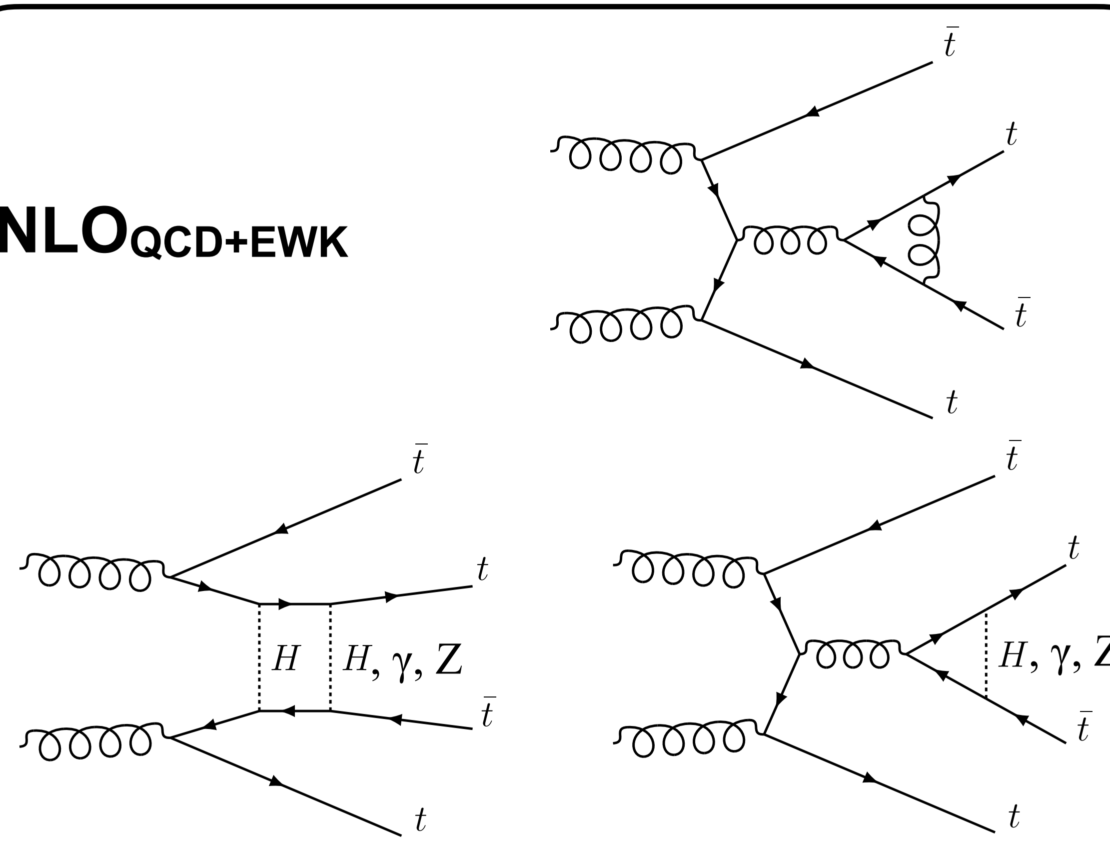
LO$_{QCD}$



LO$_{EWK}$



NLO$_{QCD+EWK}$



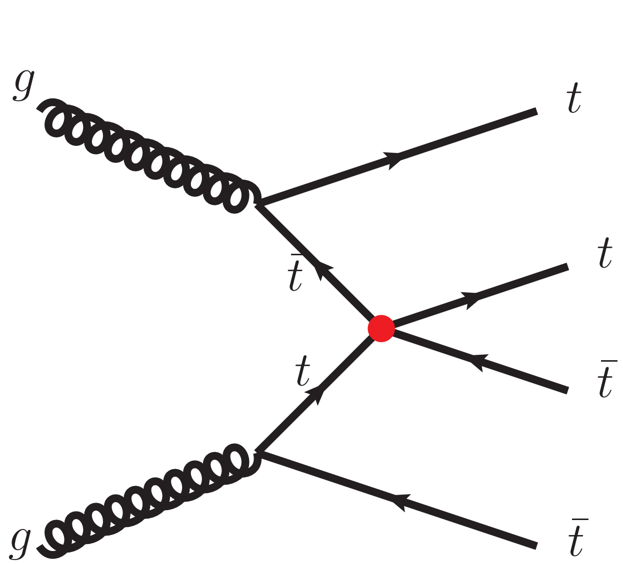
[1] J. Alwall et al., JHEP 1407, 079 (2014) [arXiv:1405.0301]
[2] R. Frederix, et al., JHEP 1802 (2018) 031 [arXiv:1711.0211]

Beyond the Standard Model

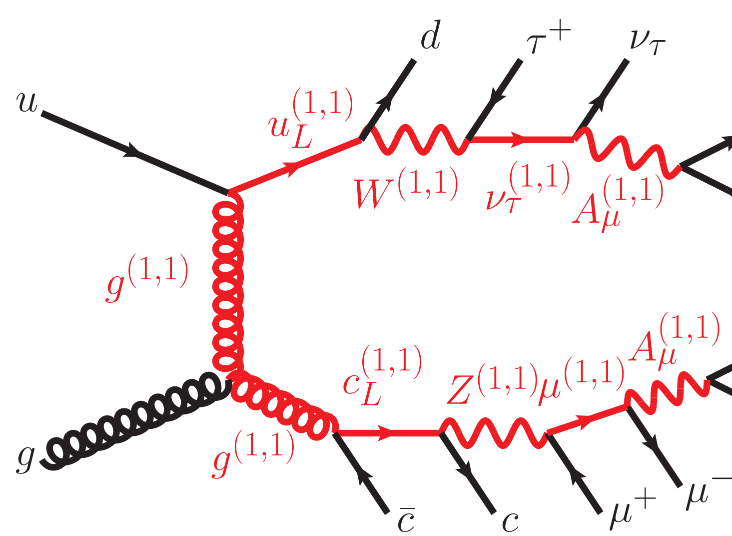
Several new physics couplings and particles can affect tttt production

- Top-Higgs yukawa coupling different from SM
- Four-fermion contact interactions (and other EFTs)
- Extra dimensions (2UED), with a heavy photon $A^{(1,1)}$ decaying to tt
- Scalar/psedo-scalar particles with $m>2*m_t$ and higgs-like couplings (2HDM)
- And more: gluinos, sgluons, low-mass scalars and vectors…

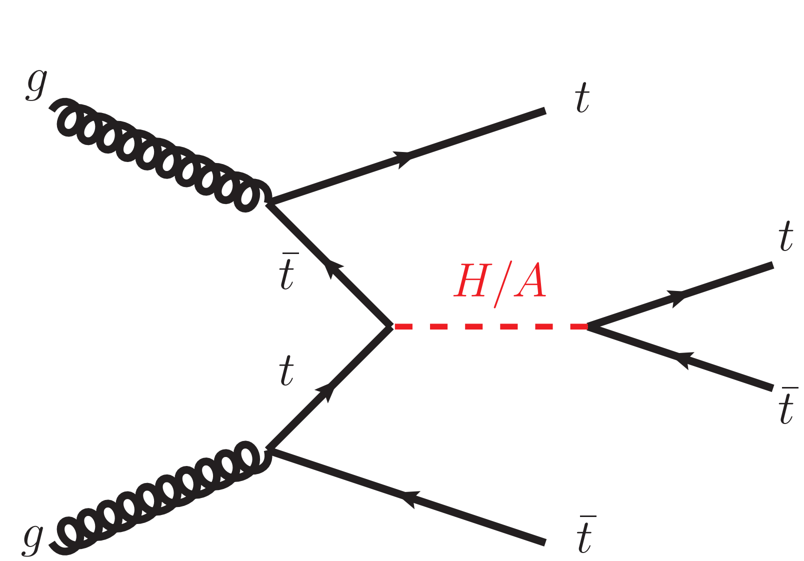
Some of these models generate SM-like kinematics, and can be probed with a cross section limit/measurement. Others have harder kinematics.



Four-fermion contact interaction

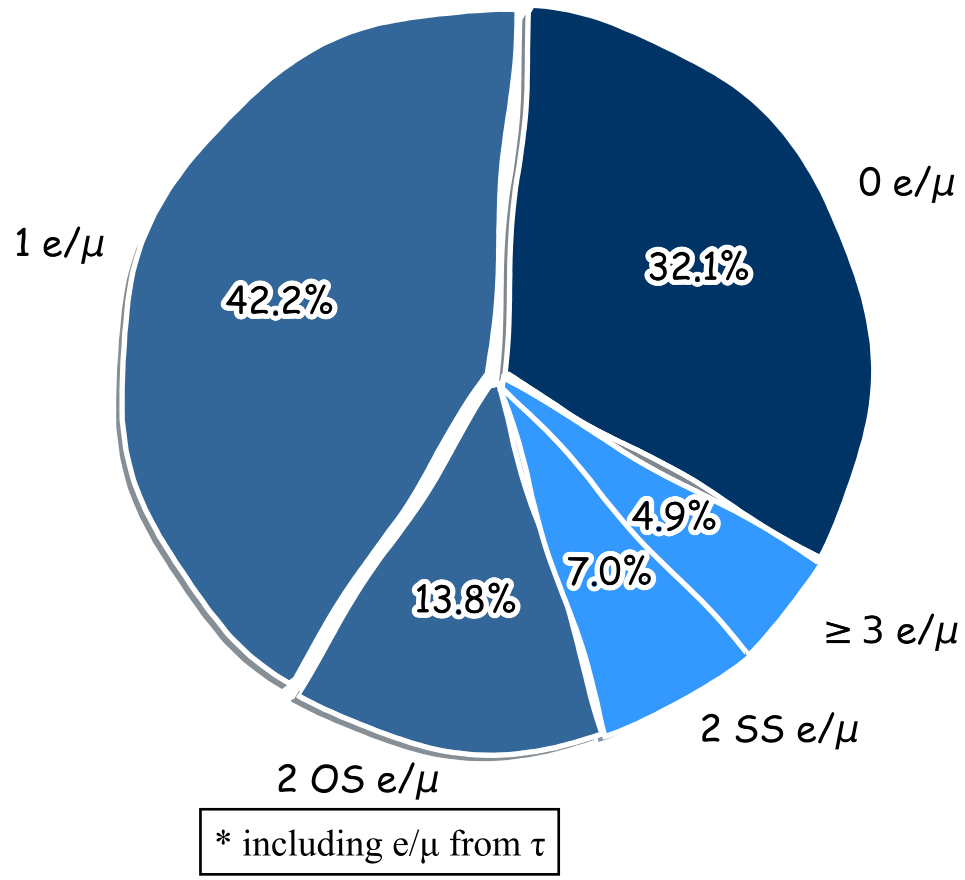


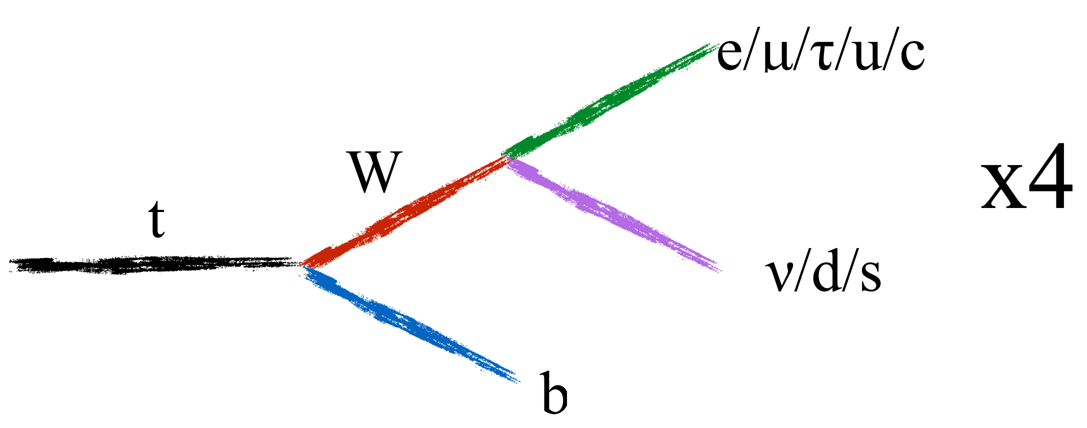
2UED Extra dimensions



2HDM scalar/pseudoscalar

Final States





All-hadronic

Powerful with massive new particles (gluons), not yet explored with SM kinematics

1 lepton and opposite-sign 2 lepton (1L/OS)

Dominant BR, large tt pair-production background (systematics limited)

2 same-sign or ≥ 3 leptons (2LSS)

Comparable branching to OS2L, but reject the tt background (statistically limited)

Status of analyses

Focus on Run 2: large PDF gain at the 4-top threshold

2-3 fb^{-1} of 13 TeV data already surpassed the Run1 results

	ATLAS	CMS
1L/OS	arxiv:1811.02305 (36.1 fb^{-1}) (NEW)	arxiv:1702.06164 (2.6 fb^{-1})
2LSS	arxiv:1807.11883 (36.1 fb^{-1})	arxiv:1710.10614 (35.9 fb^{-1})
Combination	within arxiv:1811.02305	in progress, with 1L/2LOS 36 fb^{-1} analysis

- 1L/2LOS: can compare strategies, but not results (different luminosities)
- 2LSS: full apples-to-apples comparison possible <— Main focus
  - NOTE: CMS is optimized to SM tttt, while ATLAS is a broader search

Significant differences between ATLAS and CMS strategies

Signal regions (different for 1L/OS, quite similar in 2LSS)

Background estimates (different for both analyses)

—> Discuss these in following slides

Shared ingredients of 1L/OS and 2LSS

Before splitting 1L/OS and SS, a few shared ingredients

b-tagging: MVA taggers used in both experiments

CMS “DeepCSV”: 55-70% b-jets, 1-2% light jets (range for jets with p_T 20-400 GeV)

ATLAS “MV2c10”: 77% b-jets, 17% c-jets, 0.7% light jets (measured in tt events)

- ATLAS performance is better than CMS in 2016 (caveat: not a full p_T/η comparison)

Pileup rejection in jets

CMS: “charge-hadron-subtracted” (CHS) jet clustering, using only tracks from PV

ATLAS: “jet vertex tagger” (JVT) selection on jets with $p_T < 60$ GeV

- PU jets are not an issue for either experiment after these methods

tttt simulation:

Madgraph_aMC@NLO for both, but ATLAS uses LO and CMS uses NLO

Then, for 2LSS and 1L/OS, focus on:

- Object selection
- Signal region definition
- Background estimates
- Systematics
- Results and interpretations

2LSS: Object Selection

Same-sign analyses are susceptible to Fake/Non-Prompt and Charge Misidentified leptons

Instrumental backgrounds, difficult to simulate and carry large uncertainties

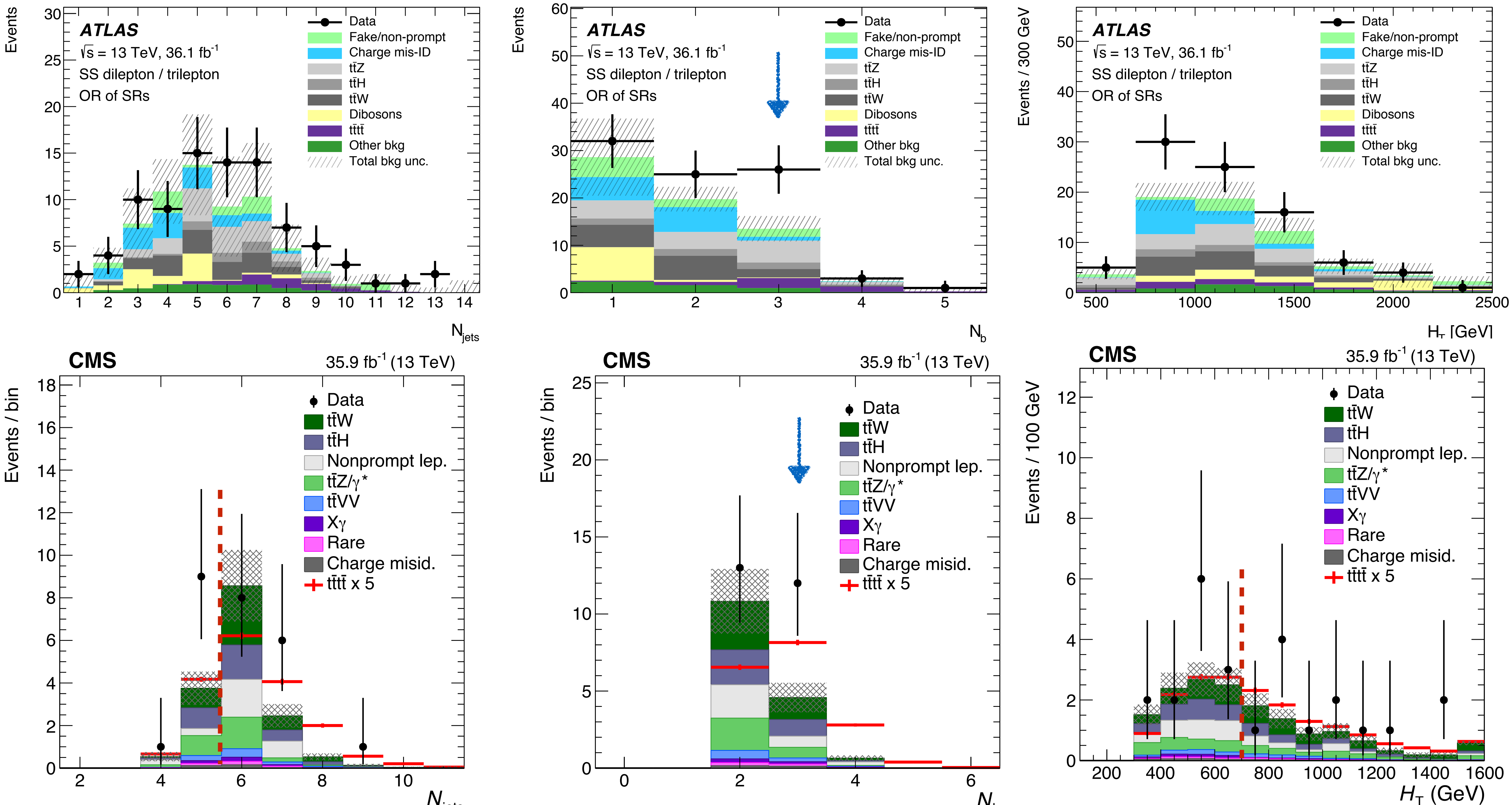
	ATLAS	CMS
Lepton ID	e ID (MVA), μ ID (cut-based), impact parameter: similar sets of variables	
Lepton ISO	**MiniTrackIso** (e, μ), CaloIsoDR02 (e), ΔR(e, **jet**) > 0.4, ΔR(μ, **jet**) > 0.04 + 10/pT(μ)	**MiniIso** AND [pT(lep)/pT(**jet**) > A OR |pT(lep)×pT(**jet**)|/pT(**jet**) > B]
	For CMS, this is the <u>**jet** which includes the lepton</u>. For ATLAS, an <u>additional nearby **jet**</u>.	
Lepton Charge	Include # of Pixel and B-layer <u>hits</u> in MVA ID; <u>reject endcap</u> electrons for same-sign events	Require <u>hit</u> in the first Pixel layer; apply "<u>triple-charge coincidence</u>" cut on the electron track
	Both veto electrons matched to conversion vertices	
Trigger	Single + dilepton (95% efficient)	Dilepton only (92-95% efficient)
jet counting	<u>25 GeV</u>, η < 2.5	<u>40 GeV</u>, η < 2.5
b-jet	25 GeV, η < 2.5	
DY veto (low-mass and Z peak)	Only veto same-sign DY; keep opposite-sign events for vector-like quarks search	<u>Also veto opposite sign DY (reduce ttZ bkg)</u>

Baseline Region Kinematics

Similar baseline selection ("baseline" : sum of all signal regions)

CMS higher jet p_T cut; ATLAS higher HT cut; ==> $N_{jets}^{ATLAS} > N_{jets}^{CMS}$

- Data yield in N(b-jets)=3 is similar to N(b-jets)=2, in both ATLAS and CMS



2LSS: Signal Region selection

CMS

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
Inverted Z veto			CRZ

ATLAS

Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$ 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
SR1b3ℓ	≥ 1	1	3	any	$H_T > 1000$ GeV and $E_T^{miss} > 140$ GeV
SR2b3ℓ	≥ 2	2	3	any	$H_T > 1200$ GeV and $E_T^{miss} > 100$ 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

Signal Regions based on N(jets), N(b-jets), N(leptons), HT and MET

CMS extends further in the counting (≥4 b-jets, ≥8 jets), but has fixed HT/MET (> 300/50 GeV)

ATLAS looks at tails in HT and MET up to 1200 and 140 GeV, to search also for non-SM tttt

No 1-to-1 correspondence, but can still make meaningful comparisons

Acceptance*Efficiency for events entering the OR of all SRs:

- 1.5% for CMS, 1.2% for ATLAS

Total tttt (and background) events predicted in SRs with N(b)>1:

- 4.0 (27.9) events for ATLAS, 4.8 (15.9) events for CMS

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Next slide: pick most sensitive same-sign SRs with comparable S/B and look at backgrounds

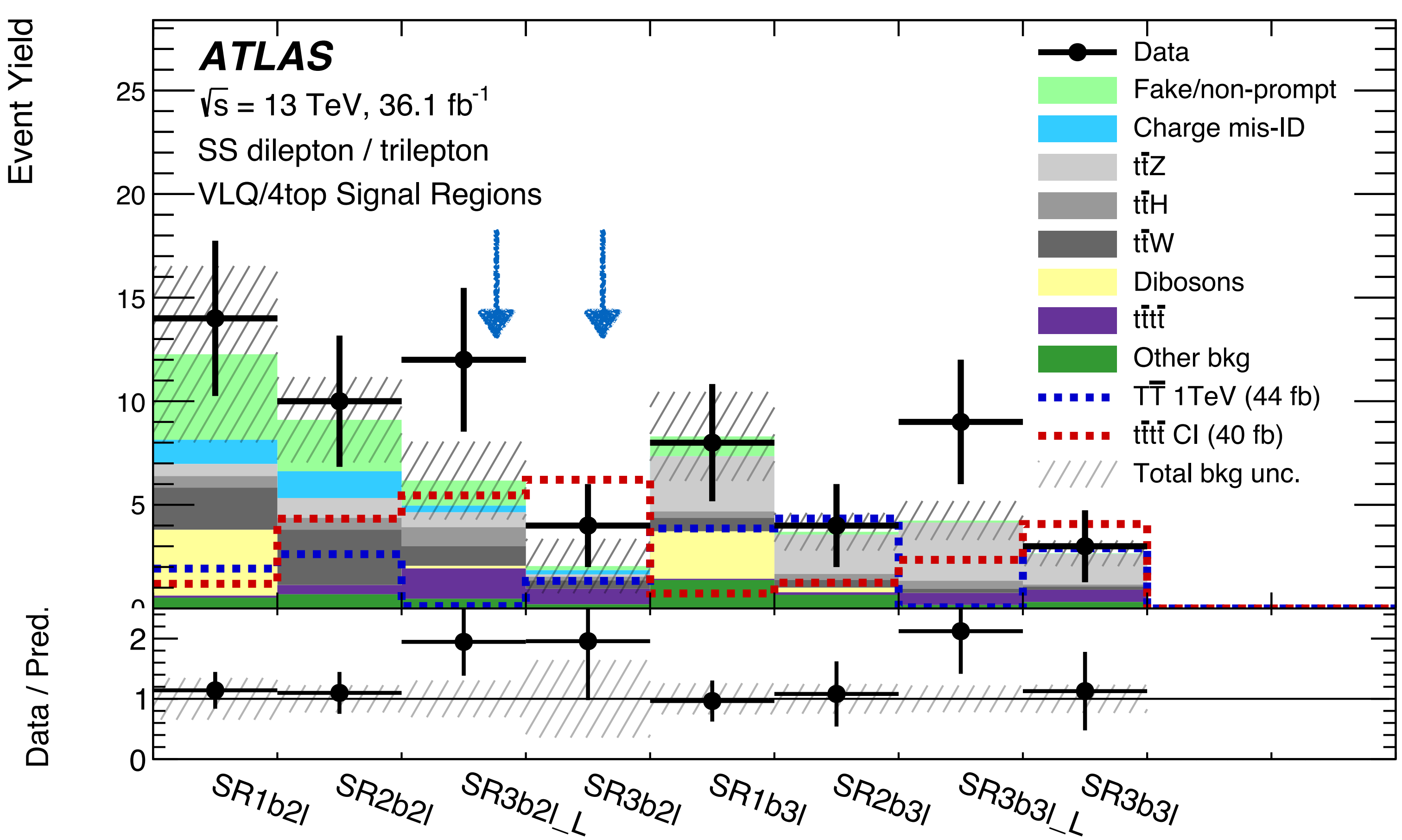
2LSS: Signal Regions

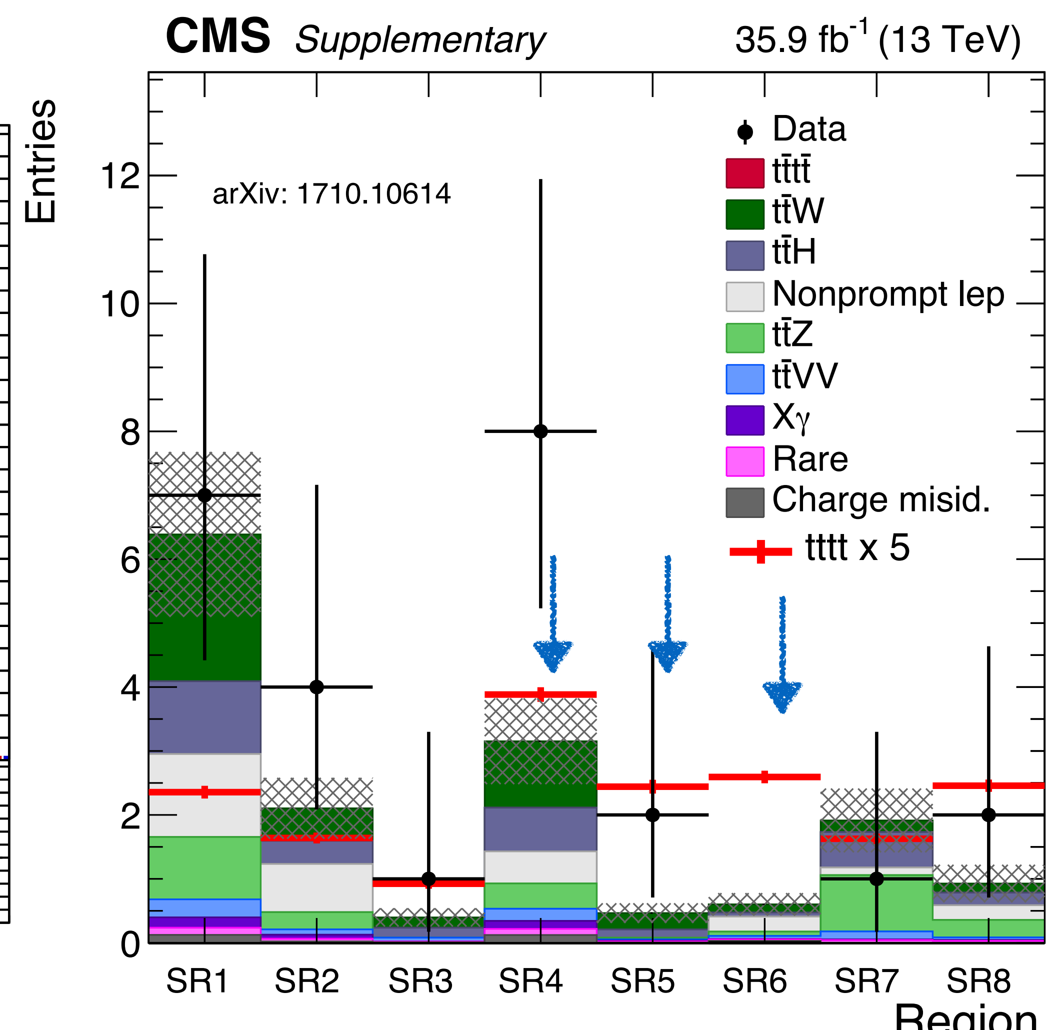
Study backgrounds in similar regions: 2-lepton and ≥3 b-jets

ATLAS (SR3b2l + SR3b2l_L), CMS (SR4+SR5+SR6)

	tttt	Tot Bkg	ttW	ttZ	ttH	Fake/NP	Charge	Others
ATLAS	2.2	6.0	1.4 (23%)	0.8 (13%)	1.1 (18%)	1.4 (23%)	0.5 (8%)	0.8 (13%)
CMS	1.8	4.2	1.4 (33%)	0.5 (12%)	0.9 (21%)	0.7 (17%)	0.1 (2%)	0.5 (12%)

- Comparable S/B and comparable fraction of ttZ and Others
- CMS has relatively larger ttW/ttH (low HT), smaller Fake/NP and Charge misid.





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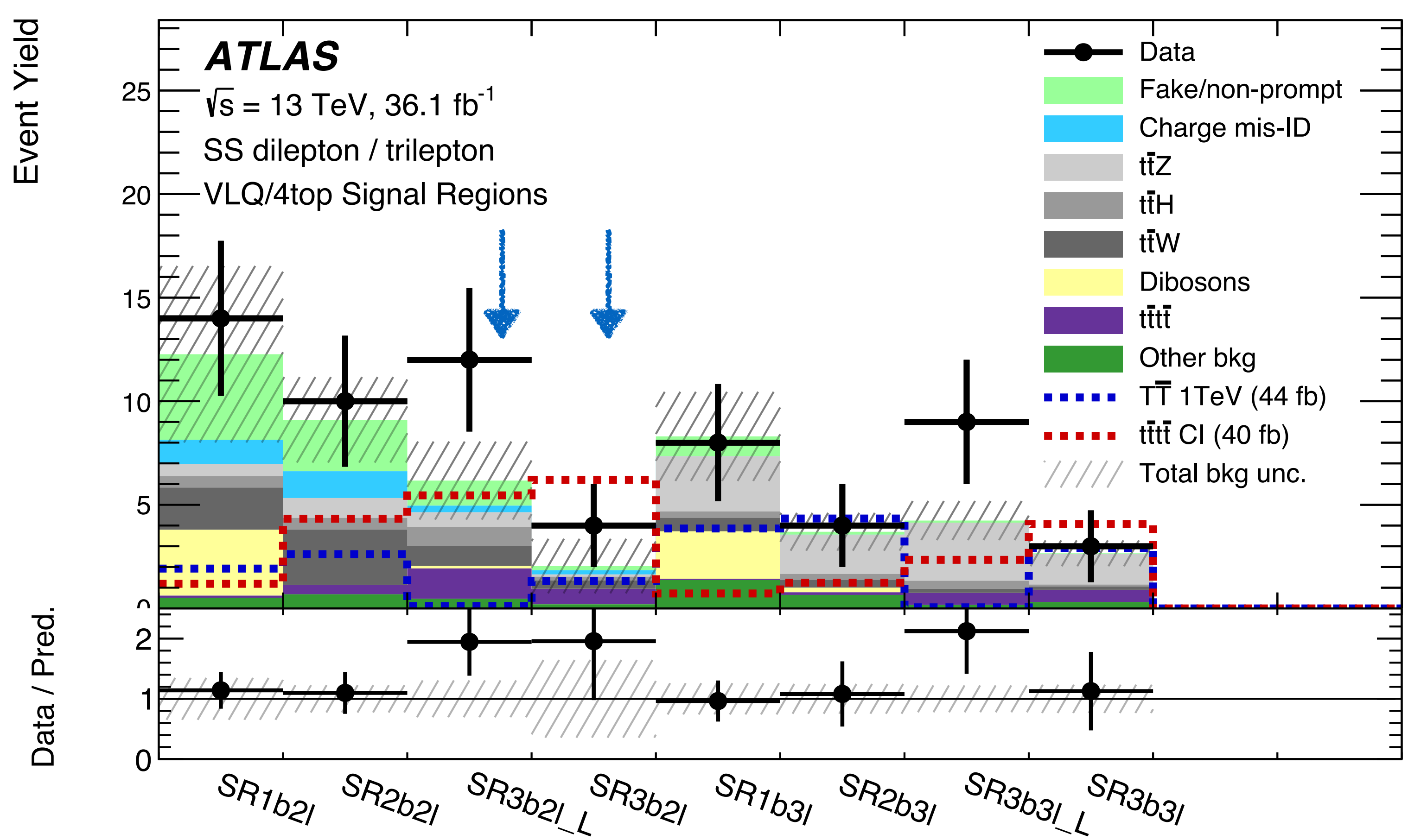
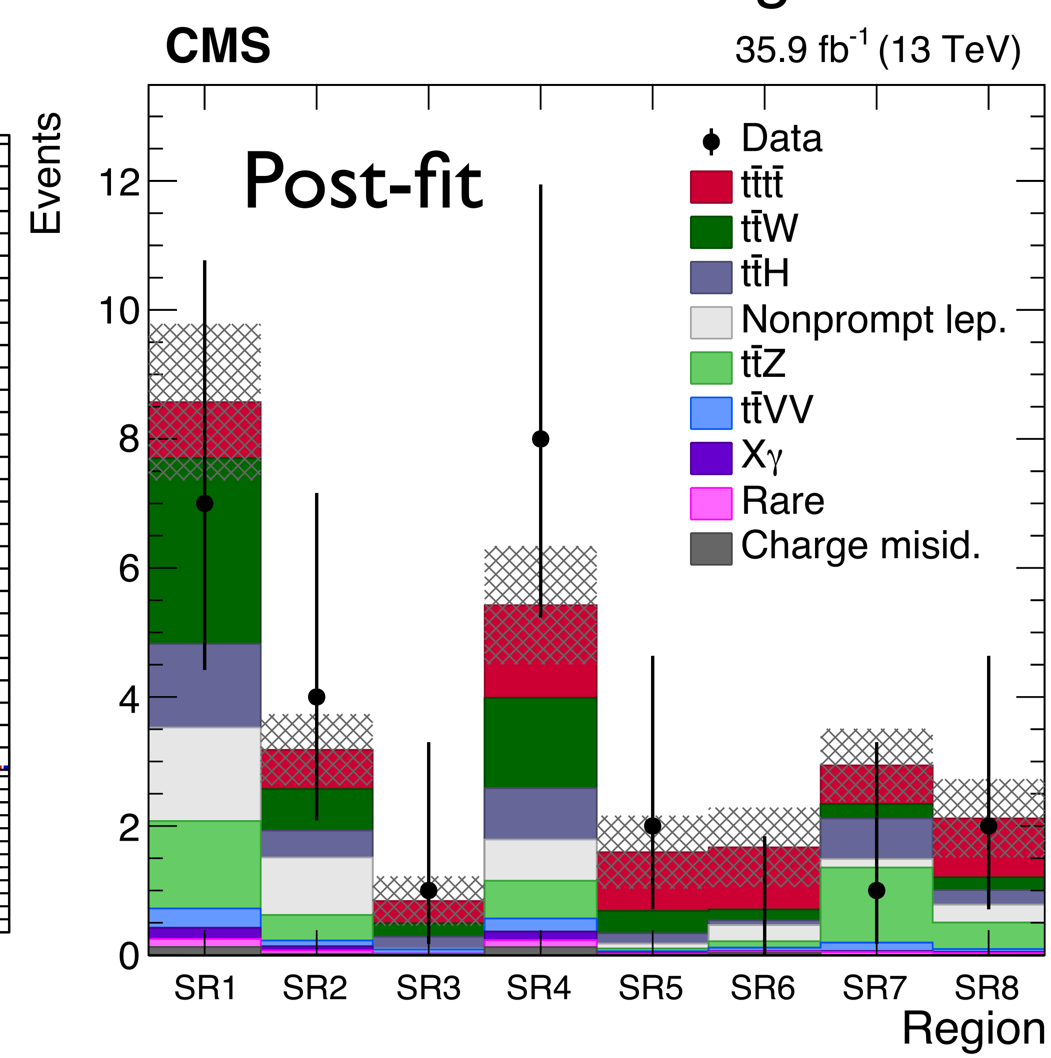
- Comparable S/B and comparable fraction of ttZ and Others
- CMS has relatively larger ttW/ttH (low HT), smaller Fake/NP and Charge misid.
- CMS post-fit: increase of ttW/ttZ/ttH bkgs





2LSS: Background Estimates

No single background dominating the final state

~even mixture of ttW, ttZ, ttH, Fakes, Charge misid., Other rare backgrounds

	ATLAS	CMS
Fake/NonPrompt	**Problem**: 4D binning the efficiency for fake leptons measured in data. Efficiency depends on: 1) p_T^{lepton}; 2) η^{lepton}; 3) flavor of mother-parton; 4) p_T or ΔR of mother-parton	
	2D binning in (1,2), then derive 1D corrections for (3) and (4)	Tune ID definition to reduce (3), then combine (1) and (4) in a single variable: $p_T^{lep}+p_T^{iso\text{-}cone}$
	Problem: low statistics yields in Loose ID/ISO control regions	
	Matrix method, with Poisson likelihood to avoid negative yields and obtain asymmetric statistical uncertainty	FakeRate method, with MC used to subtract prompts and to predict Fakes in case of 0 yield
Charge misidentification	Scale OS events by a "flip rate" derived on Data	Derive "flip rate" on MC and validate it in Data
ttW and ttZ	Validate normalization/shape in Validation Regions, then take both from MC	Use dedicated control regions to fit the normalization and validate the shapes. Post-fit normalizations for ttW and ttZ are 1.2 ± 0.3 and 1.3 ± 0.3, consistent with CMS measurements
Other rare bkgs (ttH, VV, VVV, ttVV, ttt)	Take from simulation	

2LSS: Systematics

Analyses are statistically dominated

Systematics will start to play a larger effect in future iterations

Reconstruction uncertainties

Jet energy scale and b-tagging efficiency dominate for both

Lepton ID efficiency is better measured in ATLAS (1-3%) than CMS (4-10%)

Background uncertainties

Different assumptions on ttW, ttZ, ttH cross-sections

ATLAS uses theory uncertainties, CMS uses past measurements

- ATLAS: ±13% (ttW), 12% (ttZ), +6-9% (ttH) based on theory uncertainties
- CMS: ±40% (ttW and ttZ), ±50% (ttH)

Similar uncertainty on other rare samples (±50%) and Fakes (30/50% in CMS/ATLAS)

Total background unc. across SRs: 18-32% (ATLAS), 16-60% (CMS)

For the next generation of tttt, new measurements of ttW/Z/H are available with 20-25% uncertainty (and ~1σ higher than theory)

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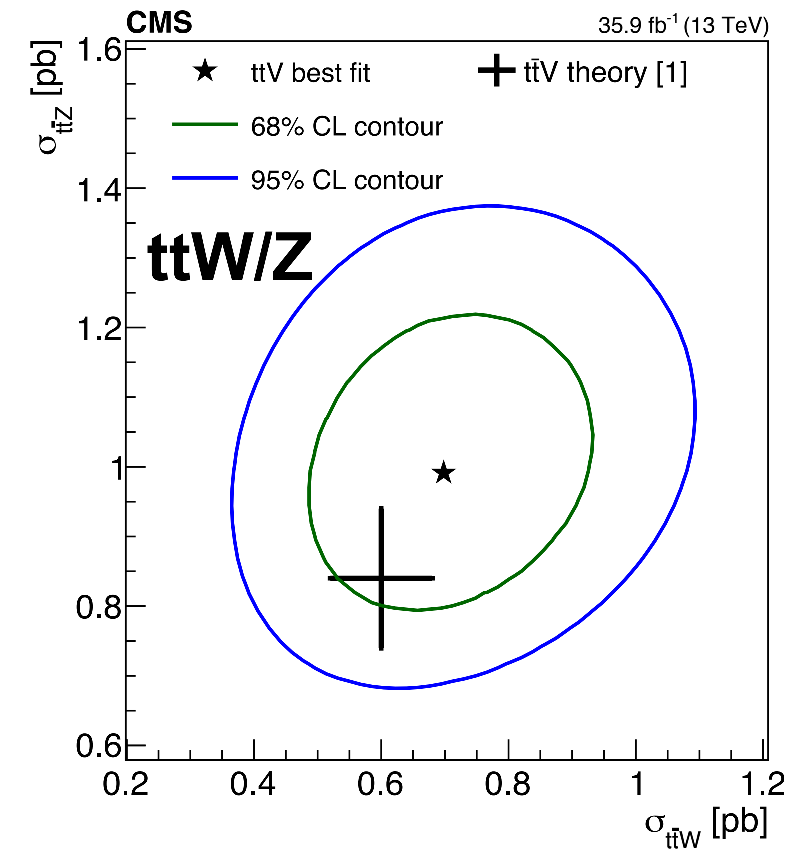

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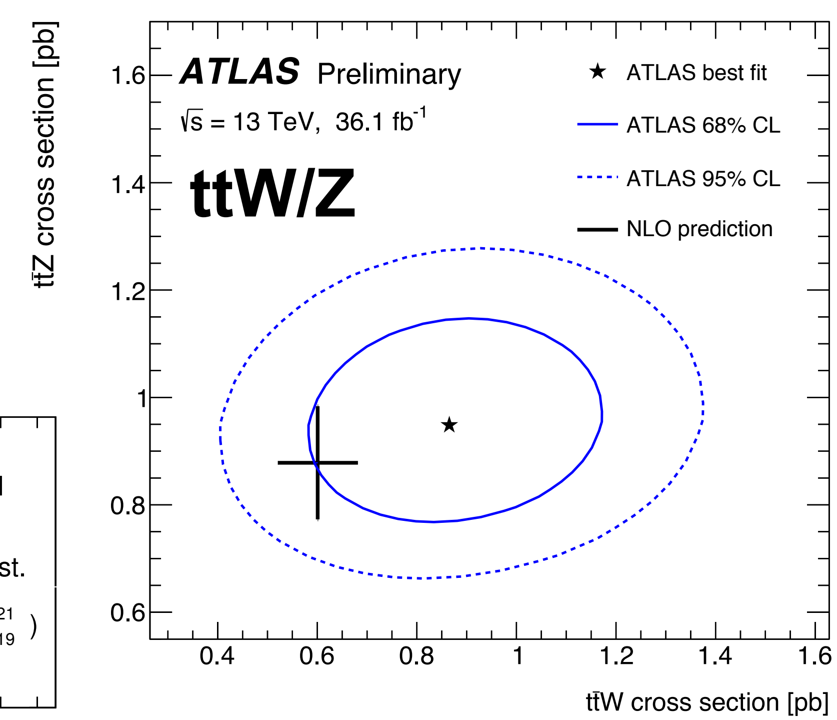
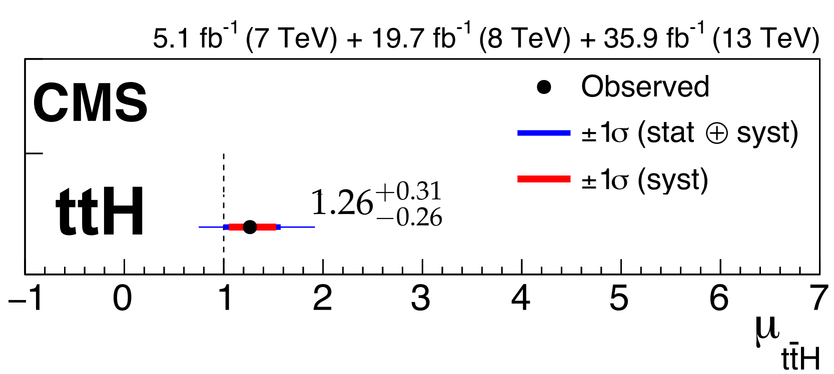
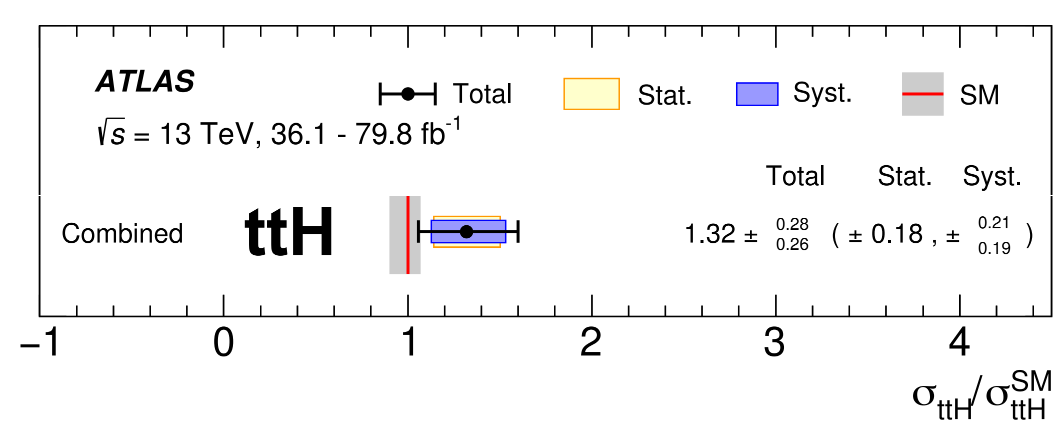






2LSS: Results (SM)

There is an interesting ~2σ excess over the SM in the ATLAS analysis, but CMS only sees 0.6σ above SM. So focus on comparing (expected) results

	95% CL Upper Limit	Signal significance	Cross section best-fit value
ATLAS	69 (29) fb	3.0 (0.9)	$40.5\ ^{+16.6}_{-14.7}$ fb
CMS	42 (21) fb	1.6 (1.0)	$16.9\ ^{+13.8}_{-11.4}$ fb

Expected results are quite similar, since S/B, signal acceptance and background composition are similar

- CMS analysis slightly more sensitive
- But ATLAS analysis not optimized on SM tttt only (for example, no ttZ veto)

Luminosity increase from 2017+2018 datasets will give a strong improvement to these analyses, but strategies must keep improving to avoid suffering from the (worst case) 30-60% uncertainties in background predictions

Notes:

- Observed (Expected)
- Expected upper limit assumes σ(tttt) = 0
- Expected signal significance assumes σ(tttt) = 9.2 fb

2LSS: Results (BSM)

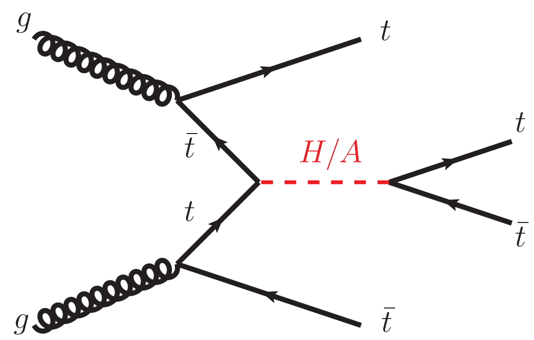
Many interpretations available, but can only comment on a few

New heavy scalars in 2HDM (both in ATLAS tttt and in CMS)

In alignment limit: *h* matches the SM Higgs, and *H/A* couples mainly to tt

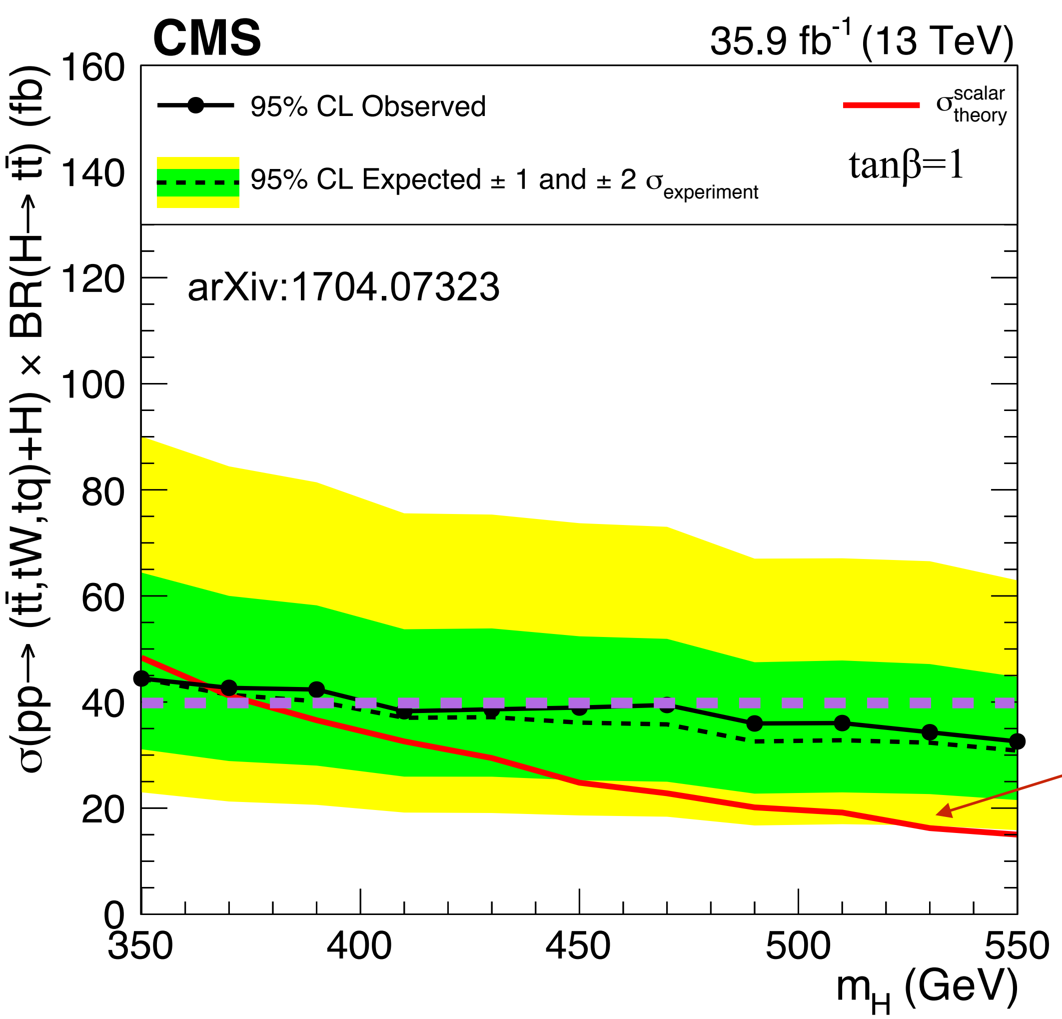
Difficult to constrain through pp—>H/A—>tt due to interference with SM tt

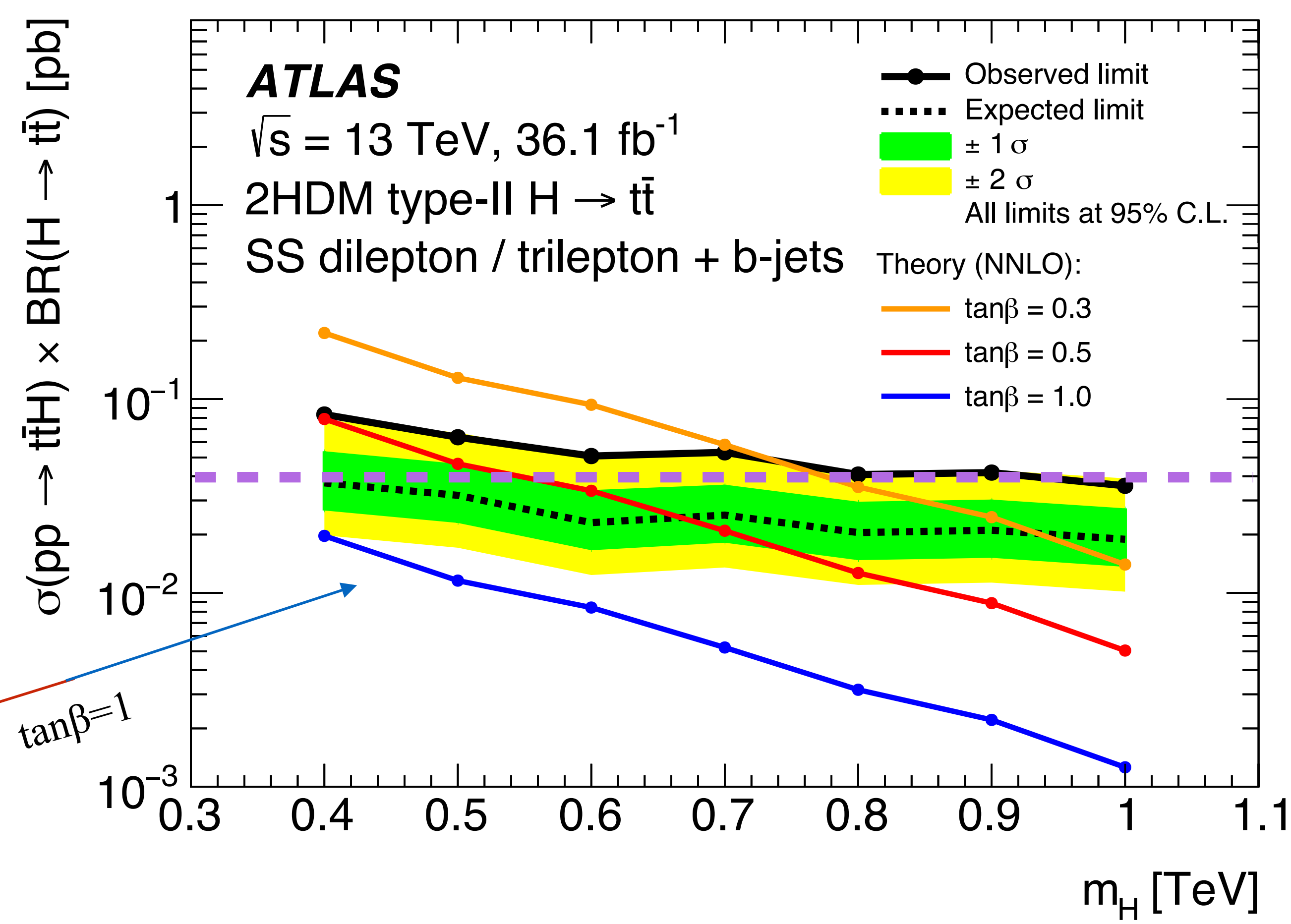
- ttH/A (H/A—>tt) has a visible cross section enhancement on tttt and no interference



ATLAS/CMS have comparable expected limits, but different theory cross section

- Both analyses assume alignment limit and tanβ=1
- CMS adds 3-top production channels (tHq and tHW), which almost double the total cross section
- ATLAS measures 2D, m_H vs tanβ. Also sets limit to models with $m_H = m_A$





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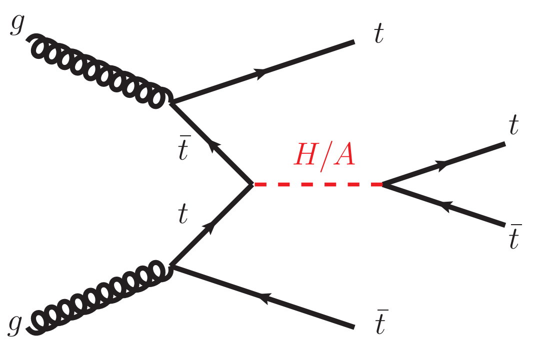

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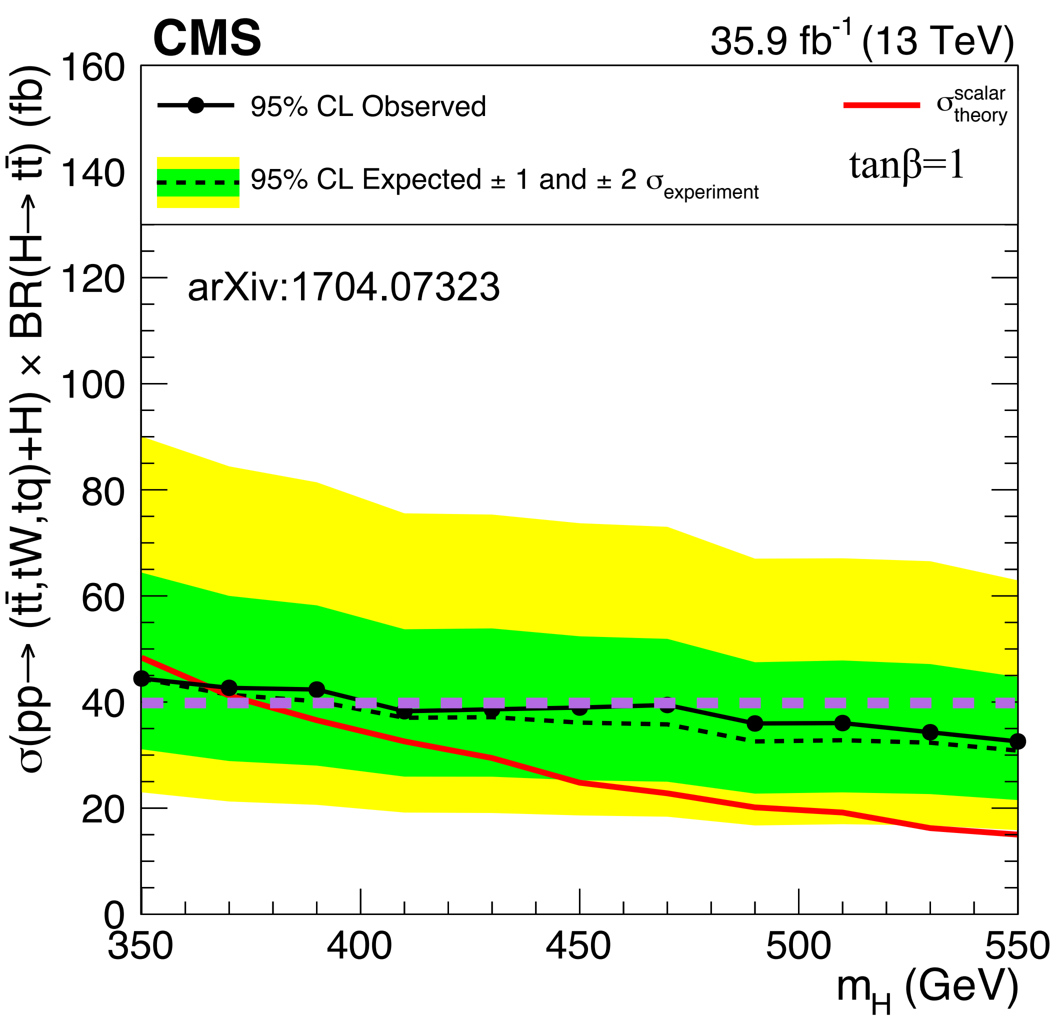

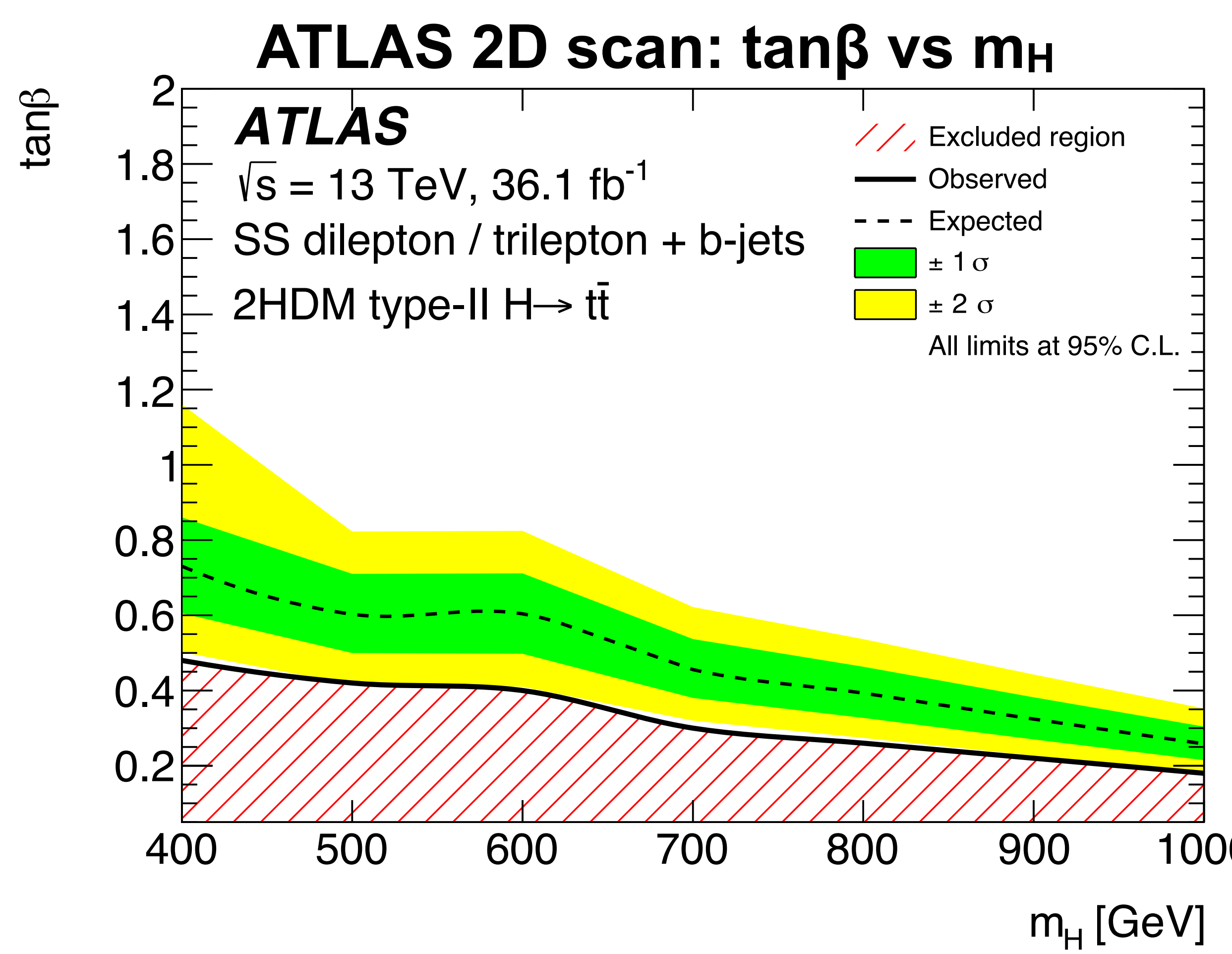

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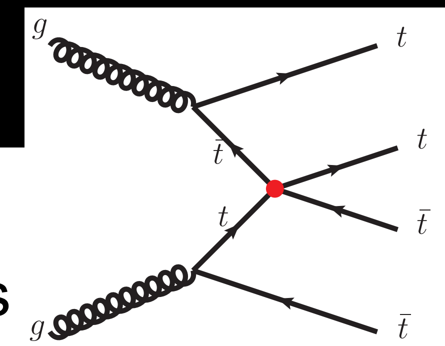


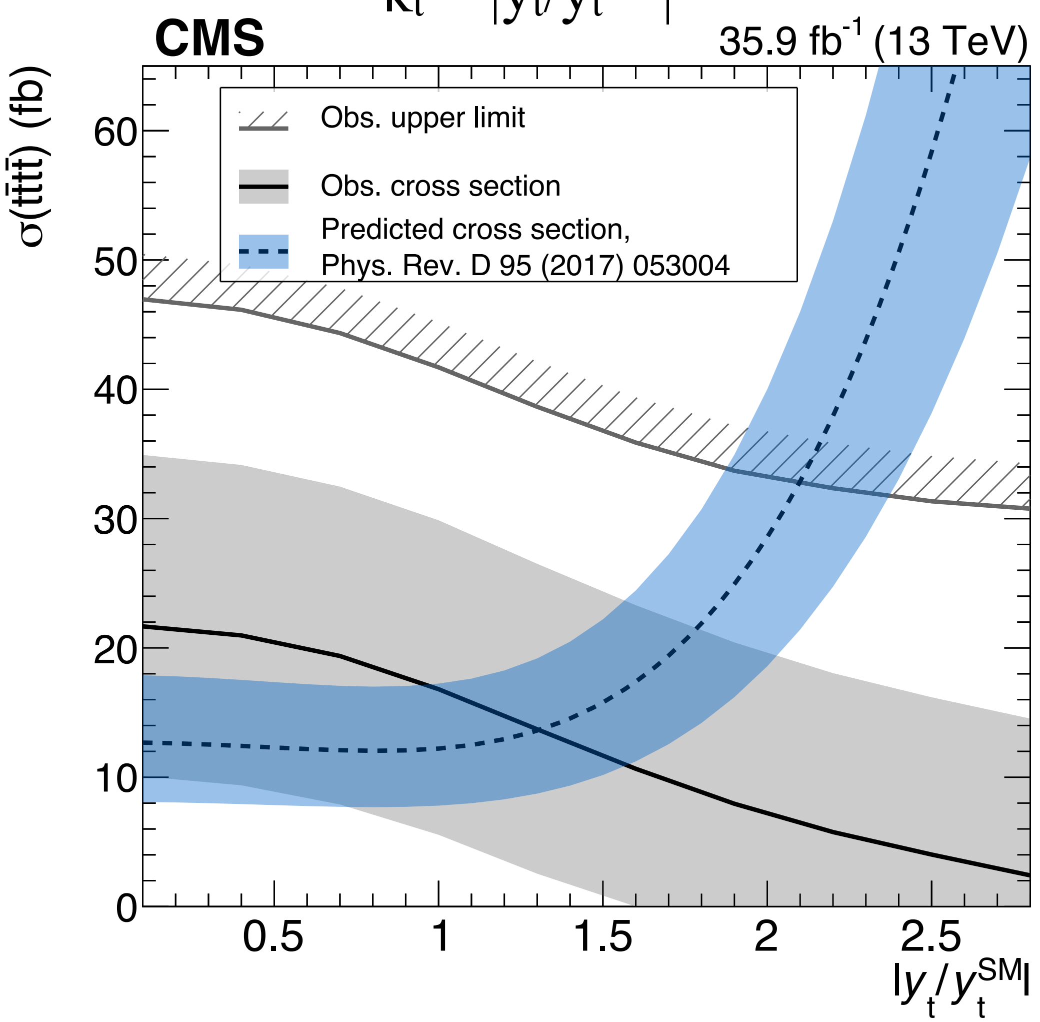
Top Yukawa (CMS) and Contact Interactions (ATLAS)

No new particles, but <u>enhancements of tt-tt couplings</u>, giving SM-like tttt events

y_t: off-shell Higgs production has a ~10% contribution to tttt, which grows as y_t^4

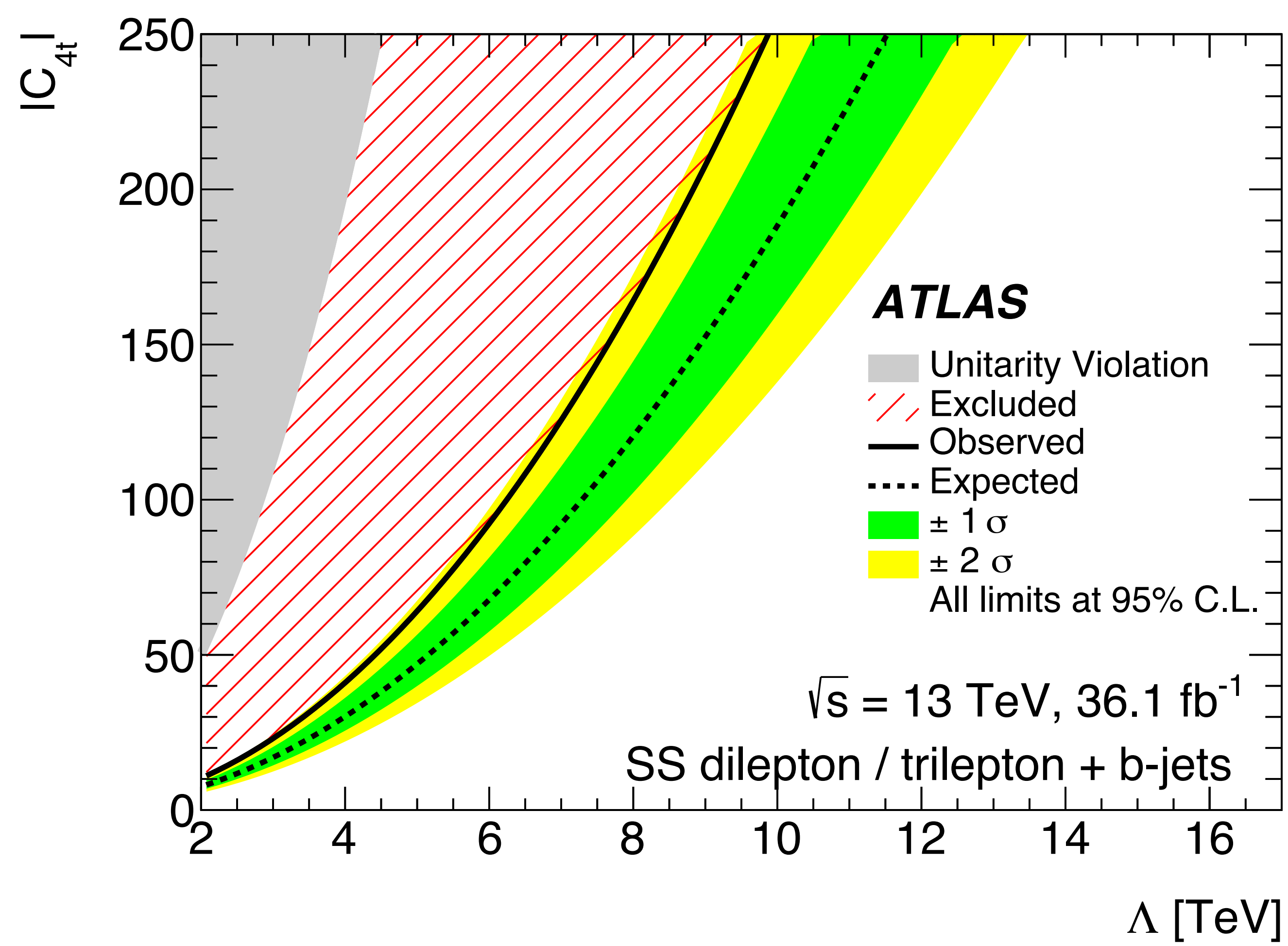
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma^{\rm SM}_{\rm int} + \kappa_t^4\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

$$\kappa_t = |y_t/y_t^{\rm SM}|$$



CI: additional Effective Field Theory four-fermion coupling (SM tttt is a bkg)

$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2}\left(\bar{t}_R\gamma^\mu t_R\right)\left(\bar{t}_R\gamma_\mu t_R\right)$$



Other interpretations possible when considering tt-tt coupling enhancement

Additional EFTs; new low mass particles with large coupling to top quark

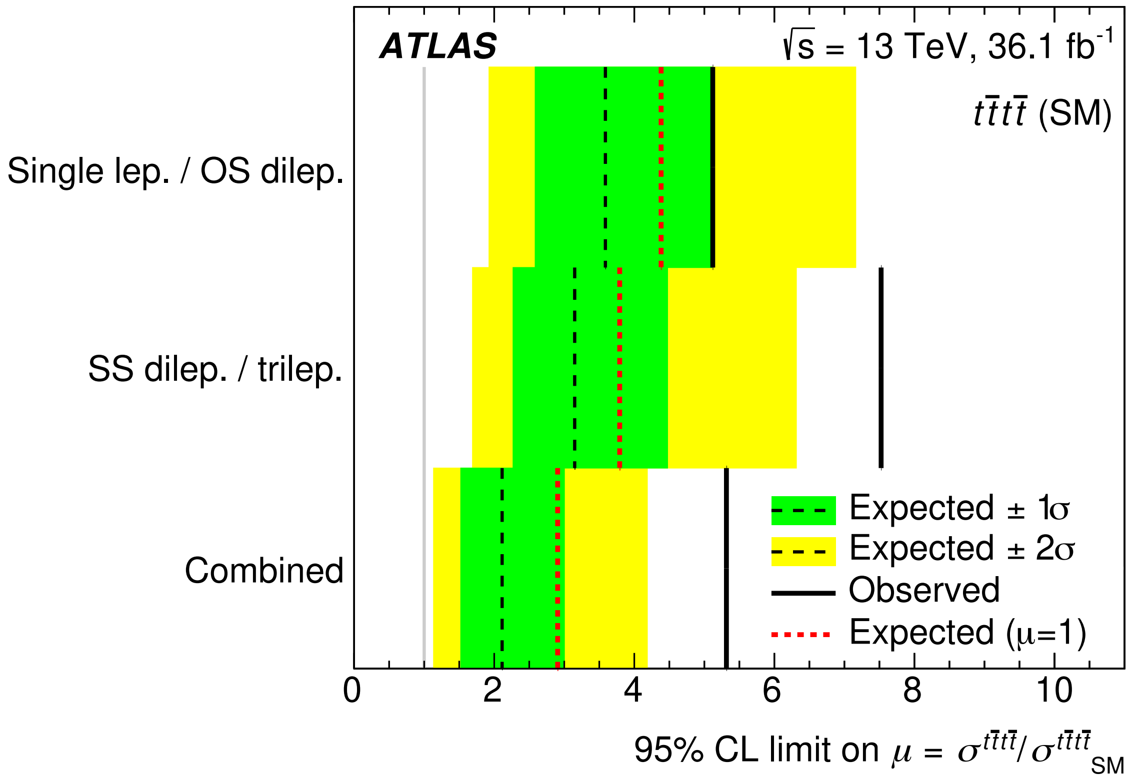
1L/2LOS

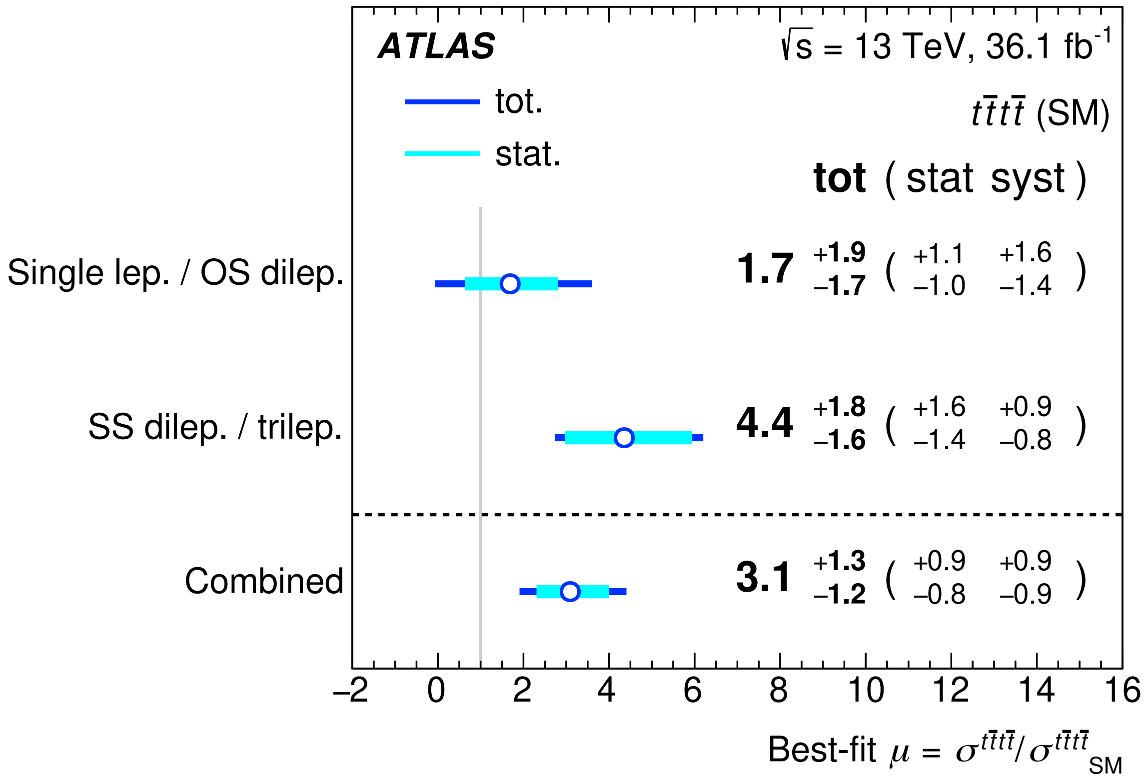
Reminder:

	ATLAS	CMS
1L/OS	arxiv:1811.02305 (36.1 fb^{-1})	arxiv:1702.06164 (2.6 fb^{-1})
2LSS	arxiv:1807.11883 (36.1 fb^{-1})	arxiv:1710.10614 (35.9 fb^{-1})
Combination	within arxiv:1811.02305	in progress, with 1L/2LOS 36 fb^{-1} analysis

ATLAS combination showcases the complementarity w.r.t 2LSS

- 1L/OS has almost same exp. UL as 2LSS, smaller stat. unc. but larger syst. unc.
- Combination improves UL by ~30% w.r.t 2LSS (from 27 to 19 fb UL)





1L/OS: same goals, different strategies

Common goals of 1L/2LOS analyses across ATLAS and CMS

1) reconstruct (i.e. tag) hadronic top decays (qq'b)
2) use event kinematics to separate tttt from tt+(b)jets
3) estimate background from tt+(b)jets

Strategies are so different that it would be challenging to make quantitative comparisons, even if we had 2 analyses at 36 fb^{-1}

Just a qualitative comparison below: discussions and questions welcome

1) reconstruct (i.e. tag) hadronic top decays (qq'b)

Both ATLAS and CMS use R=0.4 jets as inputs

ATLAS clusters R=0.4 jets into R=1.0 jets

- basic trimming: remove R=0.4 jets if $p_T^{0.4}/p_T^{1.0} < 5\%$
- "mass tagged" if R=1.0 jet has: p_T>200 GeV, $\eta < 2.0$, m > 100 GeV

CMS considers all pairs and triplets of R=0.4 jets

- use a BDT to find the best (for 2LOS) or second best (for 1L) triplet
- BDT variables: m(jj), m(jjj), b-tag, ΔR(jjj, "W"), ΔR(jjj, "b"), $p_T^{jjj}/ (\Sigma p_T^j)$

1L/OS: Signal Region definition

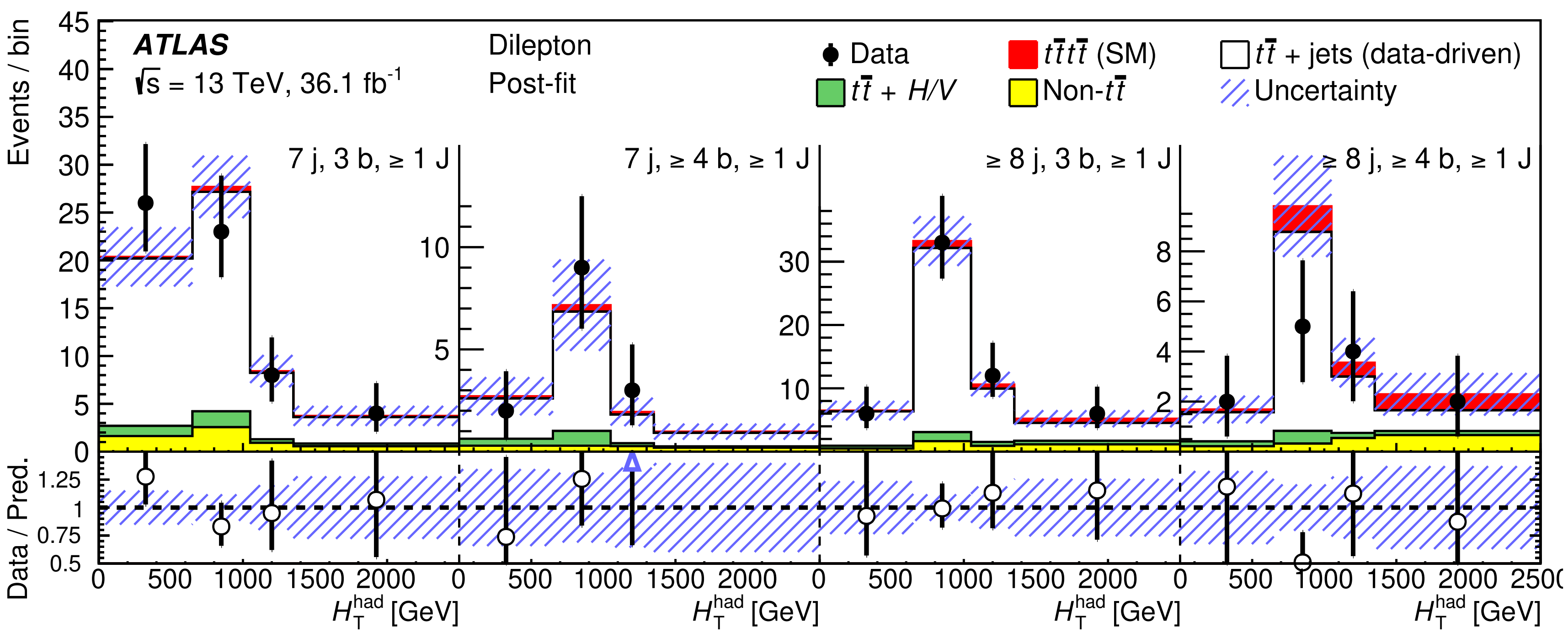
2) use event kinematics to separate tttt from tt+(b)jets

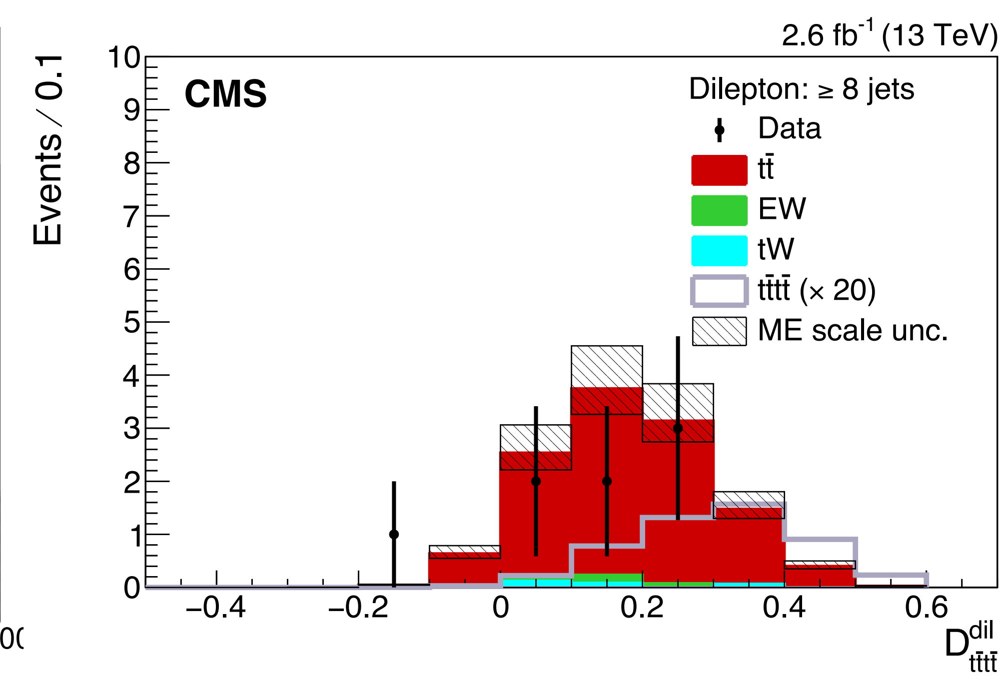
Most powerful variables are N(jets), N(b-jets)

For different N(jets) x N(b-jets) regions, further binning in:

- ATLAS: #(hadronic top tags) and HT
- CMS: BDT (tttt vs tt) with input variables: score of the hadronic top tagger, HT, $HT_{b\text{-jets}}$, $p_T^{j3}+p_T^{j4}$, p_T-weighted N(jets), centrality, sphericity, and a few more

Most sensitive regions in 2LOS analyses for ATLAS and CMS (*different int. lumi.*)





1L/OS: tt background estimate

3) estimate background from tt+(b)jets

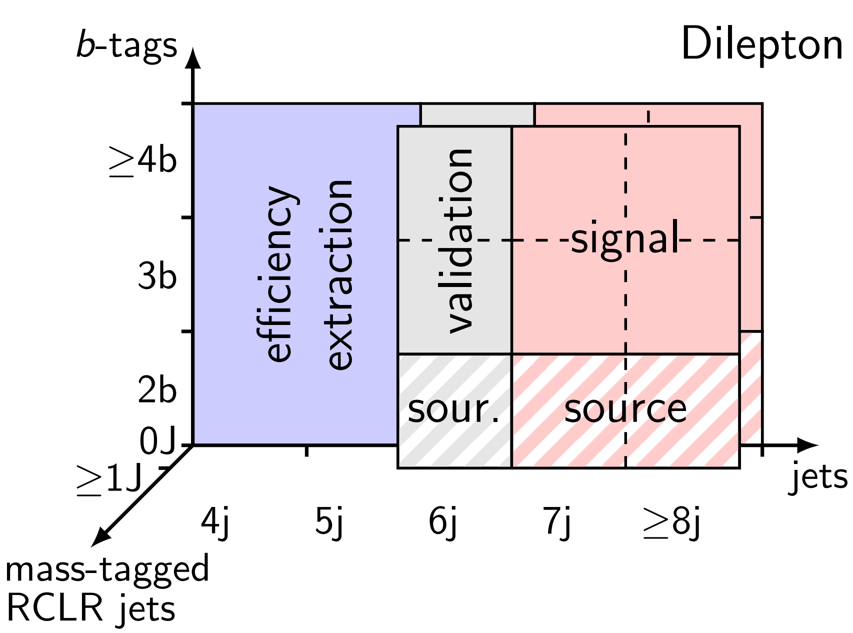
Different ways to use Data control regions to constrain tt

ATLAS:

- @ low N(jets): measure the probability of b-tagging an additional jet (ε_b)
- @ low N(b-jets): normalize tt, and apply ε_b to obtain the tt estimate
- Only profile MC uncertainties across SR: N(jet) ≥ 7, N(b-jet) ≥ 3
- Comment: estimate is based on Data/Data ratios, with MC/MC corrections, reducing the effect of uncertainties on the MC (b-tagging, jet energy scale, renorm/fact scale, ISR/FSR)

CMS:

- Take tt shape from MC, with reconstruction and theory uncertainties
- Profile uncertainties across the bulk of tt: N(jet) ≥ 4, N(b-jet) ≥ 2
- Comment: potentially similar reduction of MC uncertainties, cannot compare without final numbers



Uncertainties and their effect on μ in the ATLAS result

Uncertainty source	$\pm\Delta\mu$	
$t\bar{t}$+jets modeling	+1.2	−0.96
Background-model statistical uncertainty	+0.91	−0.85
Jet energy scale and resolution, jet mass	+0.38	−0.16
Other background modeling	+0.26	−0.20
b-tagging efficiency and mis-tag rates	+0.33	−0.10
JVT, pileup modeling	+0.18	−0.073
$t\bar{t} + H/V$ modeling	+0.053	−0.055
Luminosity	+0.050	−0.026
Total systematic uncertainty	+1.6	−1.4
Total statistical uncertainty	+1.1	−1.0
Total uncertainty	+1.9	−1.7

Conclusions

We are starting to become sensitive to tttt

- Both ATLAS and CMS have an expected significance of ~1 standard deviation using the 2016 dataset, or an expected limit at around $2*\sigma_{SM}$
- Both ATLAS and CMS are observing yields larger (but consistent) with the SM

The most sensitive final states have well established analyses:

same-sign dileptons and ≥ 3 leptons

- Highest S/B, but low statistics and complicated mixture of background processes
- Comparable strategies and results from ATLAS and CMS analyses
- "Easy" gains with statistics, but need to control tt+X/Fakes backgrounds to do better than ±30%

1-lepton and opposite-sign dileptons

- Large branching ratio, but large tt background, challenging to estimate
- Very different strategies, and cannot compare directly until 2016 CMS becomes public

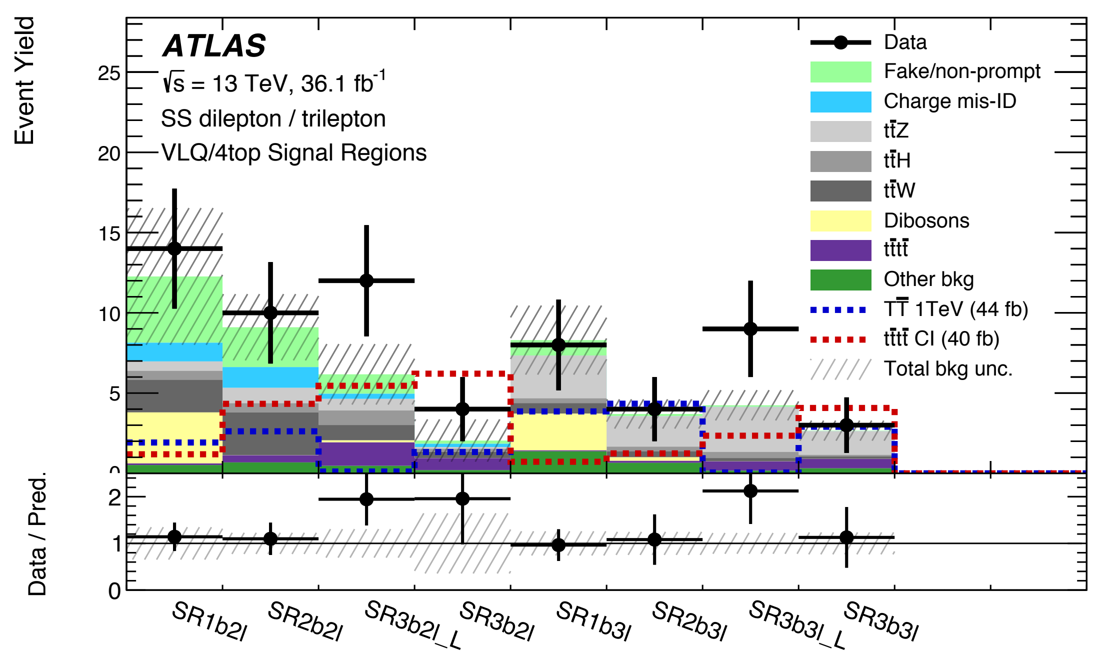
ATLAS and CMS analysts are collaborating towards the HL/HE-LHC Yellow Report, together with some of the many theorists who are continuing to study this final state and finding new ways to think about tttt

Backup

ATLAS Results

Source	$\mathrm{SR}1b2\ell$	$\mathrm{SR}2b2\ell$	$\mathrm{SR}3b2\ell$_L	$\mathrm{SR}3b2\ell$
$t\bar{t}W$	2.04 ± 0.14 ± 0.49	2.68 ± 0.15 ± 0.55	0.95 ± 0.11 ± 0.31	0.40 ± 0.06 ± 0.10
$t\bar{t}Z$	0.58 ± 0.08 ± 0.10	0.95 ± 0.11 ± 0.17	0.72 ± 0.11 ± 0.19	0.11 ± 0.05 $^{+0.13}_{-0.10}$
Dibosons	3.2 ± 1.5 ± 2.4	< 0.5	0.13 ± 0.13 $^{+0.27}_{-0.00}$	< 0.5
$t\bar{t}H$	0.56 ± 0.07 ± 0.07	0.57 ± 0.10 ± 0.09	0.91 ± 0.11 ± 0.22	0.19 ± 0.05 ± 0.07
$t\bar{t}t\bar{t}$	0.10 ± 0.01 ± 0.05	0.44 ± 0.03 ± 0.23	1.46 ± 0.05 ± 0.74	0.75 ± 0.04 ± 0.38
Other bkg	0.52 ± 0.07 ± 0.14	0.68 ± 0.09 ± 0.24	0.47 ± 0.08 ± 0.18	0.20 ± 0.04 ± 0.06
Fake/non-prompt	4.1 $^{+1.6}_{-1.4}$ ± 2.4	2.5 $^{+1.0}_{-0.9}$ ± 1.1	1.2 $^{+0.9}_{-0.7}$ ± 0.6	0.20 $^{+0.46}_{-0.20}$ ± 0.16
Charge mis-ID	1.17 ± 0.10 ± 0.27	1.29 ± 0.10 ± 0.28	0.32 ± 0.04 ± 0.09	0.21 ± 0.04 ± 0.04
Total bkg	12.3 $^{+2.2}_{-2.1}$ ± 3.4	9.1 $^{+1.2}_{-1.1}$ ± 1.2	6.2 $^{+1.0}_{-0.8}$ ± 1.2	2.0 $^{+0.5}_{-0.2}$ ± 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

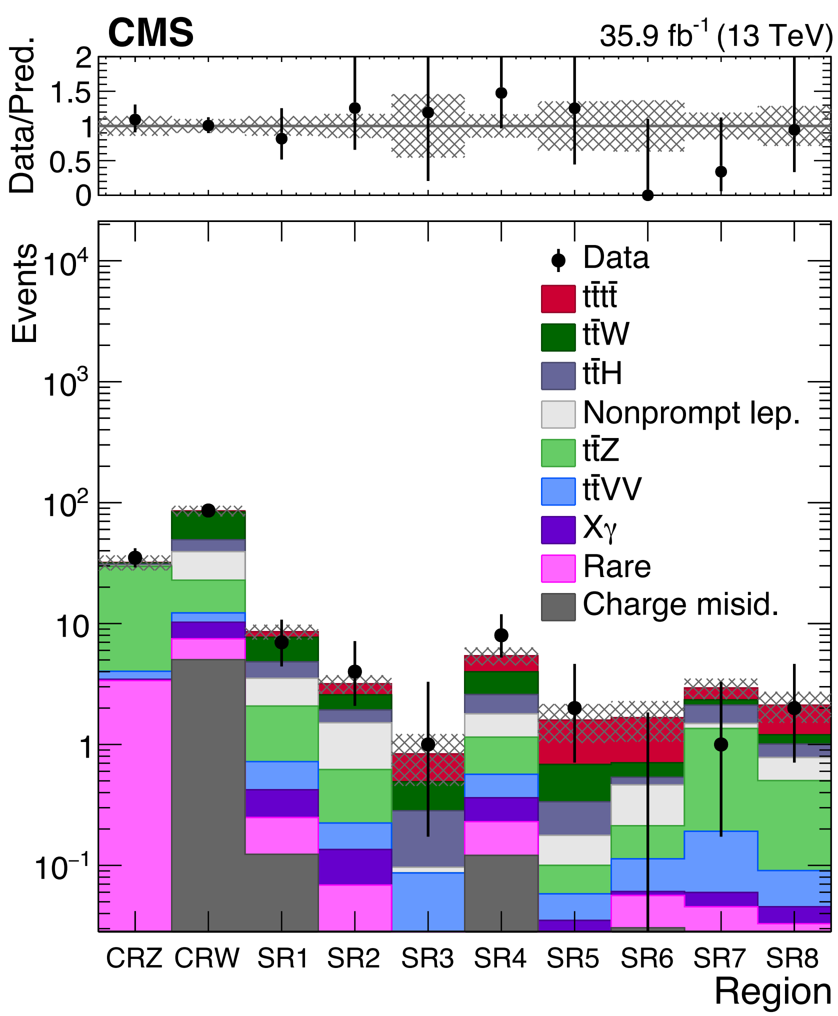
Source	$\mathrm{SR}1b3\ell$	$\mathrm{SR}2b3\ell$	$\mathrm{SR}3b3\ell$_L	$\mathrm{SR}3b3\ell$
$t\bar{t}W$	0.66 ± 0.08 ± 0.20	0.38 ± 0.05 ± 0.11	0.21 ± 0.05 ± 0.09	0.15 ± 0.04 ± 0.05
$t\bar{t}Z$	2.66 ± 0.15 ± 0.43	1.90 ± 0.14 ± 0.42	2.80 ± 0.17 ± 0.58	1.47 ± 0.14 ± 0.28
Dibosons	2.3 ± 0.7 ± 1.7	0.22 ± 0.16 ± 0.27	< 0.5	< 0.5
$t\bar{t}H$	0.30 ± 0.04 ± 0.04	0.28 ± 0.05 ± 0.05	0.38 ± 0.06 ± 0.07	0.10 ± 0.03 ± 0.02
$t\bar{t}t\bar{t}$	0.06 ± 0.01 ± 0.03	0.13 ± 0.02 ± 0.06	0.58 ± 0.04 ± 0.29	0.59 ± 0.03 ± 0.30
Other bkg.	1.37 ± 0.13 ± 0.45	0.65 ± 0.10 ± 0.27	0.17 ± 0.09 ± 0.10	0.31 ± 0.07 ± 0.11
Fake/non-prompt	1.0 $^{+0.6}_{-0.5}$ ± 0.6	0.14 $^{+0.31}_{-0.12}$ ± 0.09	0.00 $^{+0.38}_{-0.00}$ $^{+0.09}_{-0.00}$	0.03 $^{+0.15}_{-0.02}$ ± 0.00
Total bkg	8.3 $^{+0.9}_{-0.8}$ ± 1.8	3.7 $^{+0.6}_{-0.3}$ ± 0.4	4.2 $^{+0.4}_{-0.2}$ ± 0.7	2.7 ± 0.2 ± 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

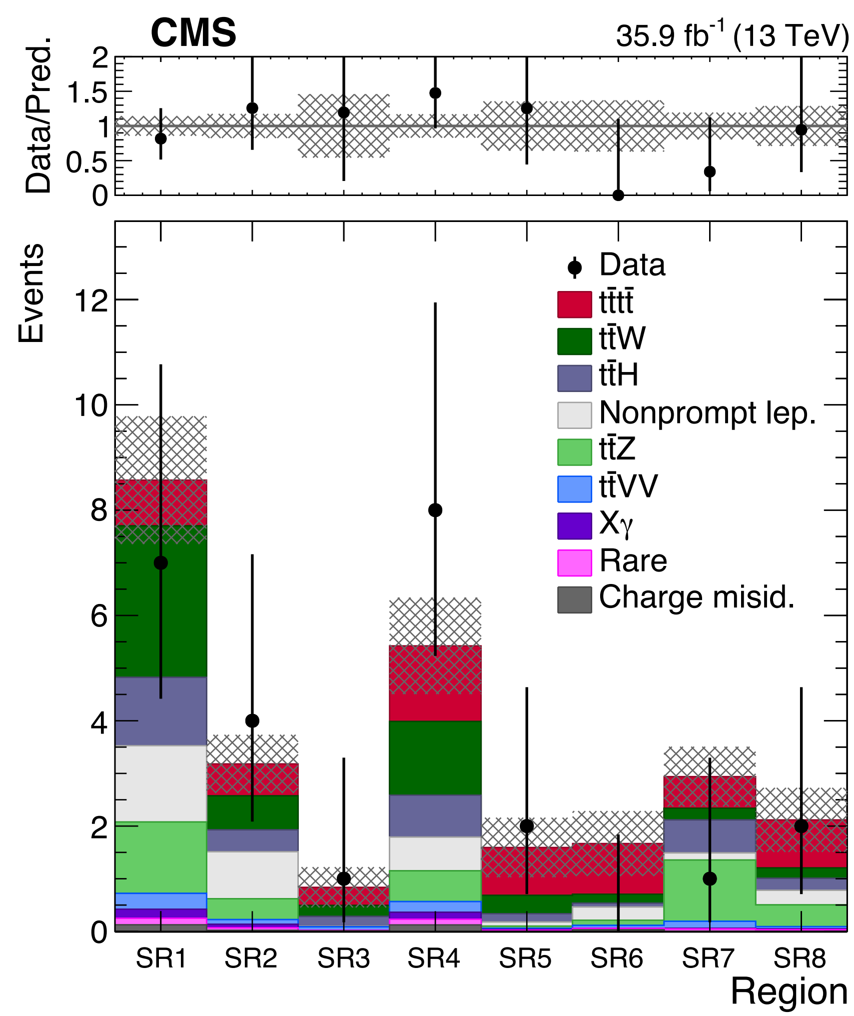


CMS Results: post-fit

N_{leps}	N_b	N_{jets}	Region
2	2	6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8

	SM background	$t\bar{t}t\bar{t}$	Total	Observed
CRZ	31.7 ± 4.6	0.4 ± 0.3	32.1 ± 4.6	35
CRW	83.7 ± 8.8	1.9 ± 1.2	85.6 ± 8.6	86
SR1	7.7 ± 1.2	0.9 ± 0.6	8.6 ± 1.2	7
SR2	2.6 ± 0.5	0.6 ± 0.4	3.2 ± 0.6	4
SR3	0.5 ± 0.3	0.4 ± 0.2	0.8 ± 0.4	1
SR4	4.0 ± 0.7	1.4 ± 0.9	5.4 ± 0.9	8
SR5	0.7 ± 0.2	0.9 ± 0.6	1.6 ± 0.6	2
SR6	0.7 ± 0.2	1.0 ± 0.6	1.7 ± 0.6	0
SR7	2.3 ± 0.5	0.6 ± 0.4	2.9 ± 0.6	1
SR8	1.2 ± 0.3	0.9 ± 0.6	2.1 ± 0.6	2

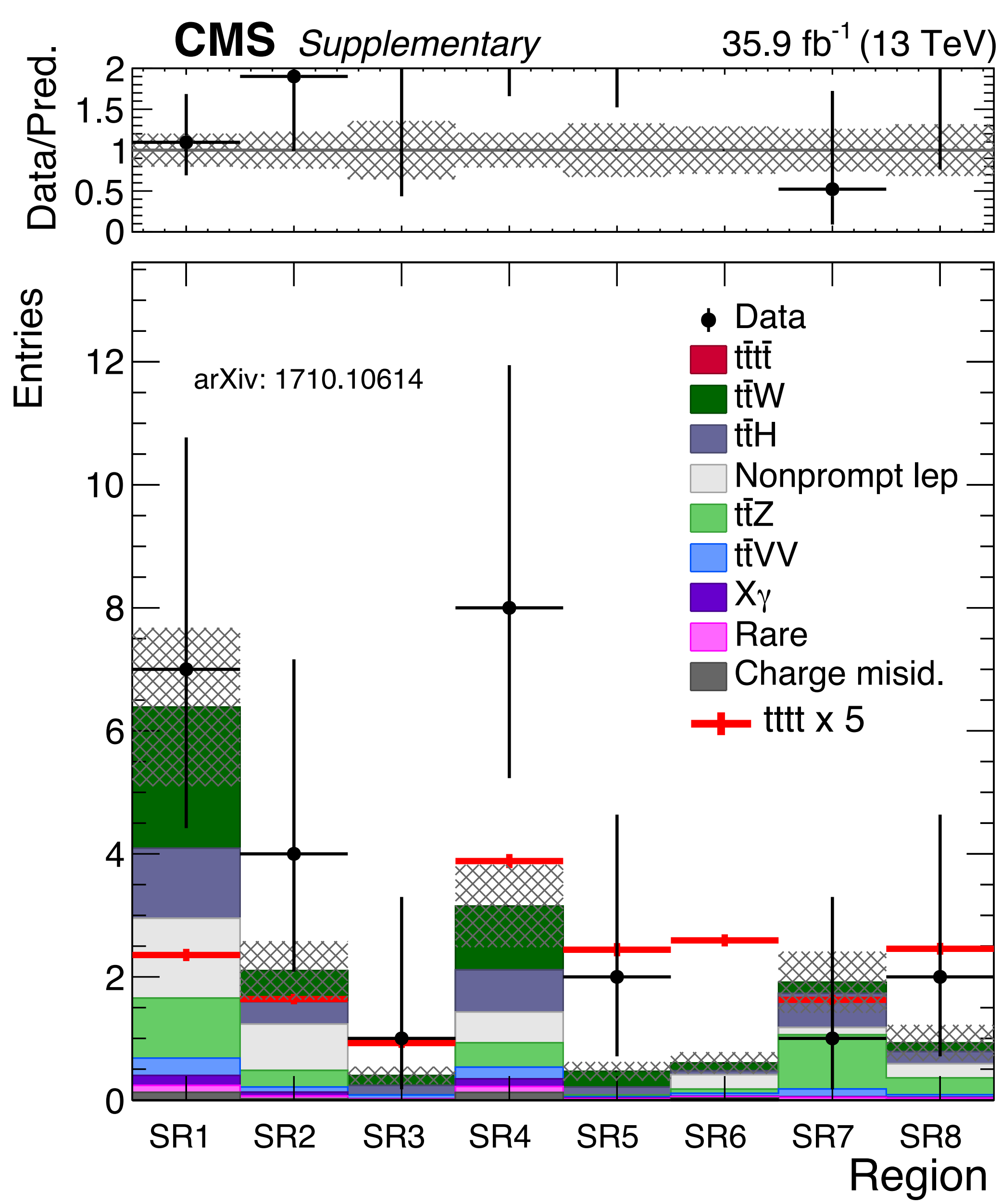




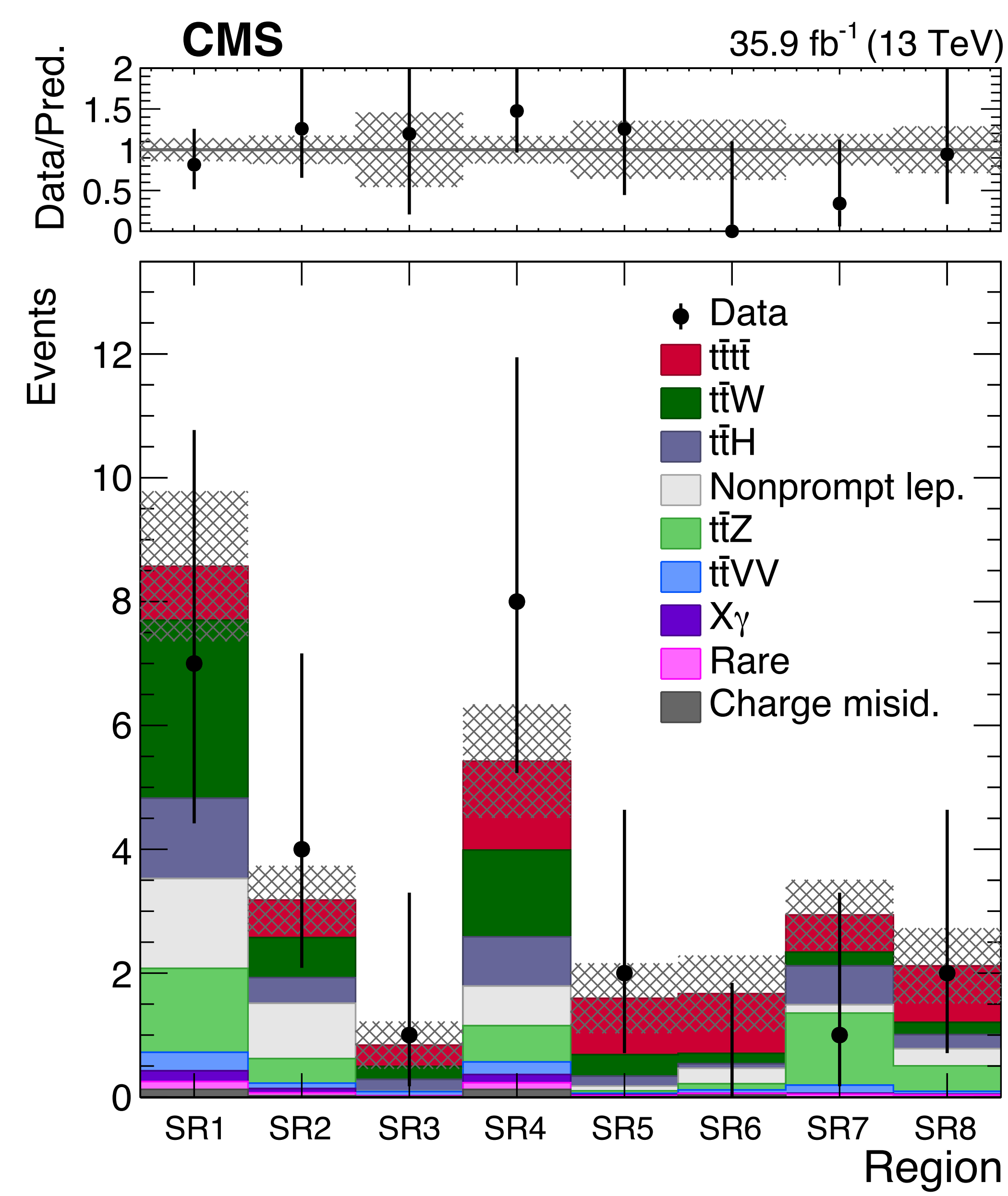
CMS: Pre vs Post-fit

N_{leps}	N_b	N_{jets}	Region
2	2	6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8

Pre-fit, tttt overlaid



Post-fit, tttt stacked



2LSS: Systematics Tables

CMS:
Signal and Background (top 10)
Background (bottom 5)

Source	Uncertainty (%)
Integrated luminosity	2.5
Pileup	0–6
Trigger efficiency	2
Lepton selection	4–10
Jet energy scale	1–15
Jet energy resolution	1–5
b tagging	1–15
Size of simulated sample	1–10
Scale and PDF variations	10–15
ISR/FSR (signal)	5–15
$t\bar{t}H$ (normalization)	50
Rare, $X\gamma$, $t\bar{t}VV$ (norm.)	50
$t\bar{t}Z/\gamma^*$, $t\bar{t}W$ (normalization)	40
Charge misidentification	20
Nonprompt leptons	30–60

ATLAS: Background

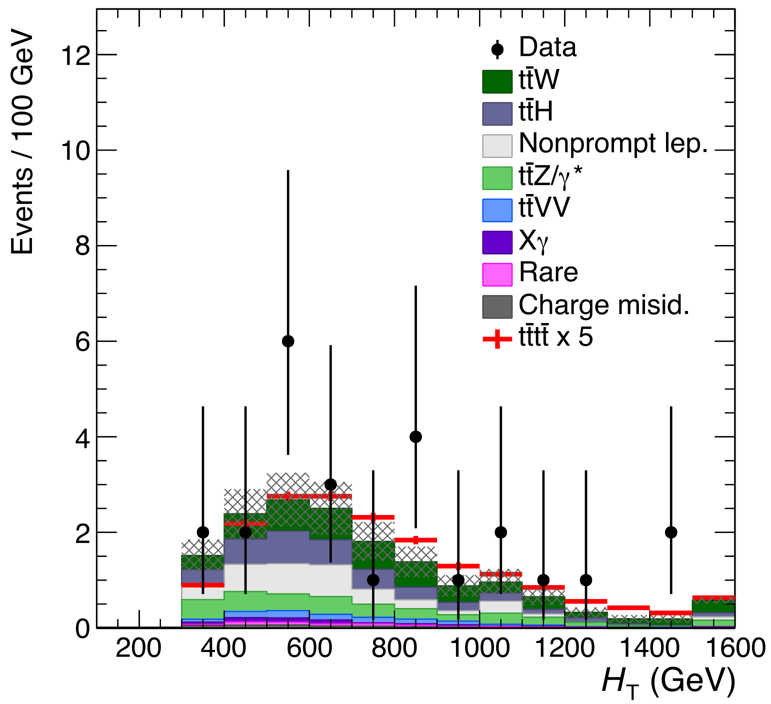
Uncertainty source	SR1$b2\ell$ [%]	SR2$b2\ell$ [%]	SR3$b2\ell$_L [%]	SR3$b2\ell$ [%]	SR1$b3\ell$ [%]	SR2$b3\ell$ [%]	SR3$b3\ell$_L [%]	SR3$b3\ell$ [%]
Jet energy resolution	3	1	5	6	3	5	3	4
Jet energy scale	3	3	9	6	3	5	11	6
b-tagging efficiency	5	3	6	7	3	4	9	9
Lepton ID efficiency	2	1	1	1	3	3	2	3
Pile-up reweighting	5	2	3	3	3	5	1	6
Luminosity	1	1	2	2	2	2	2	2
Fake/non-prompt	20	12	13	8	7	2	3	1
Charge mis-ID	2	3	1	2	-	-	-	-
Cross-section $\times$ acceptance	25	13	22	32	32	26	21	24

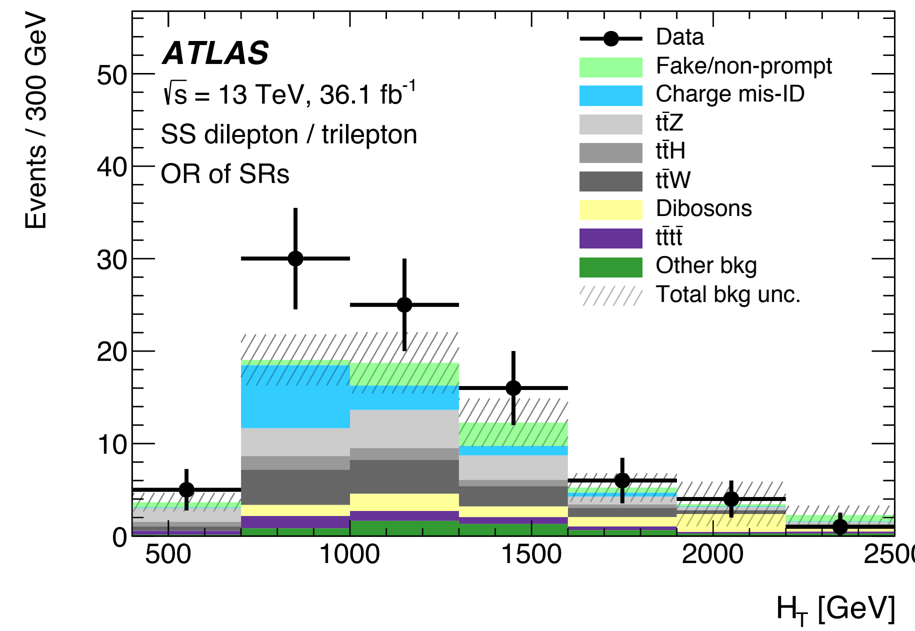
ATLAS: Signal

Uncertainty source	SR1$b2\ell$ [%]	SR2$b2\ell$ [%]	SR3$b2\ell$_L [%]	SR3$b2\ell$ [%]	SR1$b3\ell$ [%]	SR2$b3\ell$ [%]	SR3$b3\ell$_L [%]	SR3$b3\ell$ [%]
Jet energy resolution	< 1	1	6	4	< 1	< 1	24	< 1
Jet energy scale	2	1	23	3	1	1	12	< 1
b-tagging efficiency	6	3	9	8	5	4	7	8
Lepton ID efficiency	2	2	1	2	3	3	2	3
Luminosity	2	2	2	2	2	2	2	2
Pile-up reweighting	3	3	7	3	< 1	< 1	3	2
Expected yield	1.7	2.1	0.08	1.0	3.0	3.2	0.03	1.8

Difference in HT cut

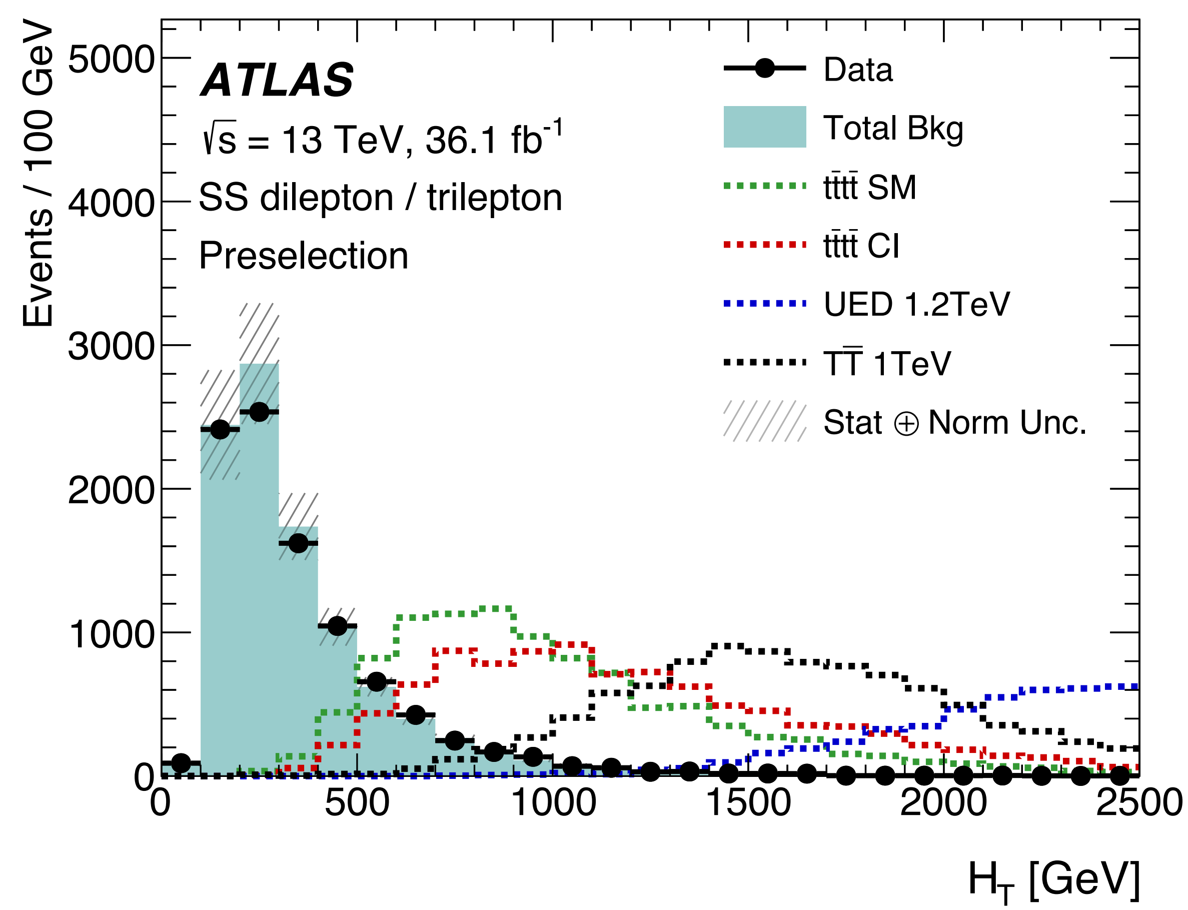
ATLAS seems to cut much harder on HT than CMS





But jet thresholds are different (25/40 GeV in ATLAS/CMS), so HT spectra are also different

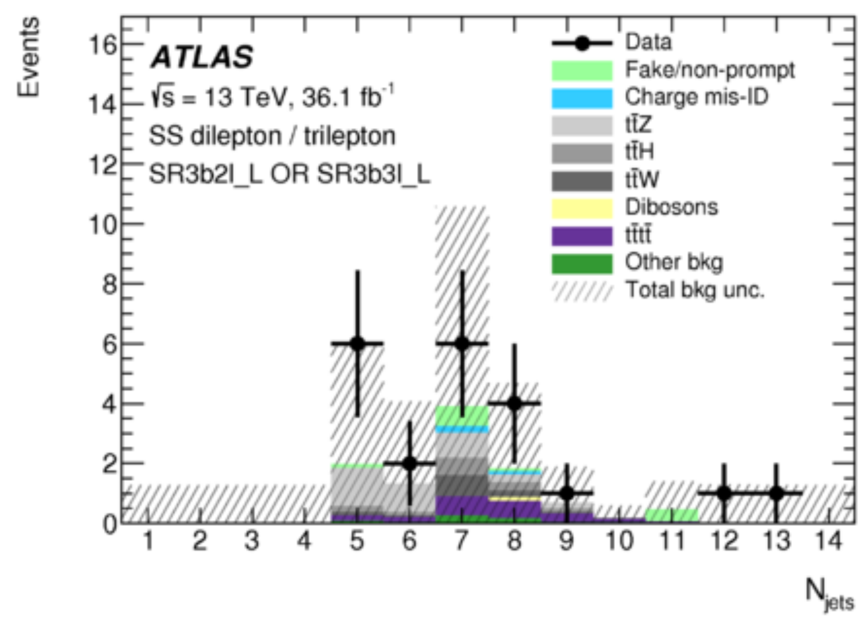
- CMS: tttt peaks at ~500 GeV
- ATLAS: tttt peaks at ~800 GeV

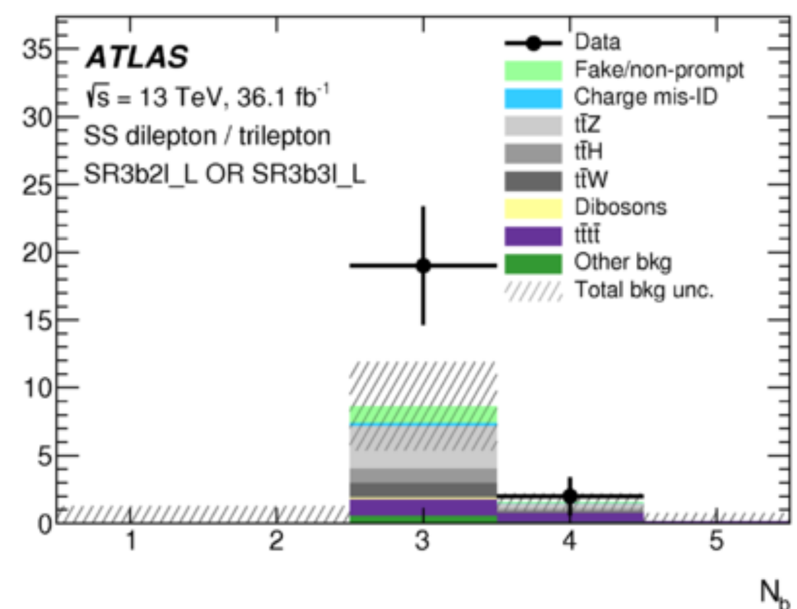


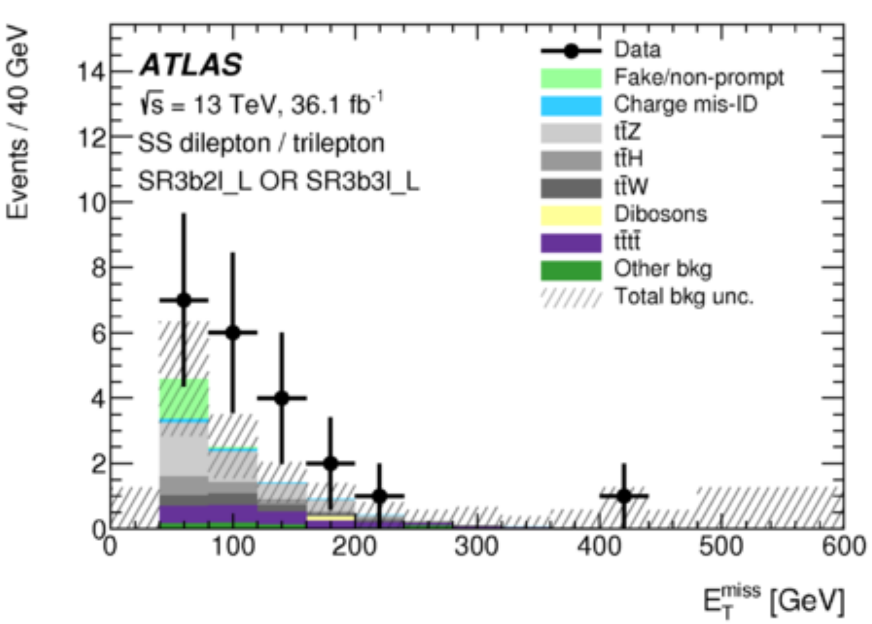
Slide on ATLAS excess

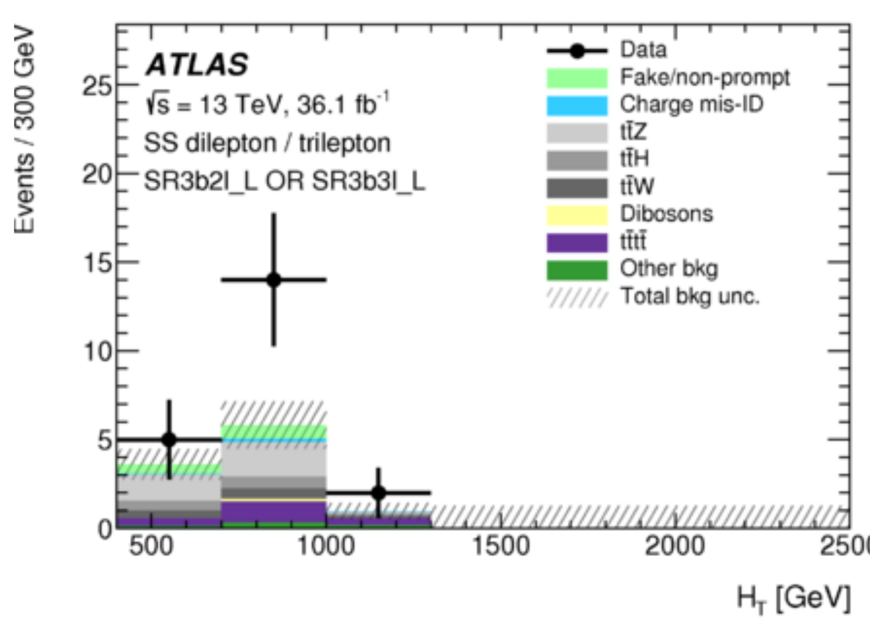
Showing sum of 3b2l regions

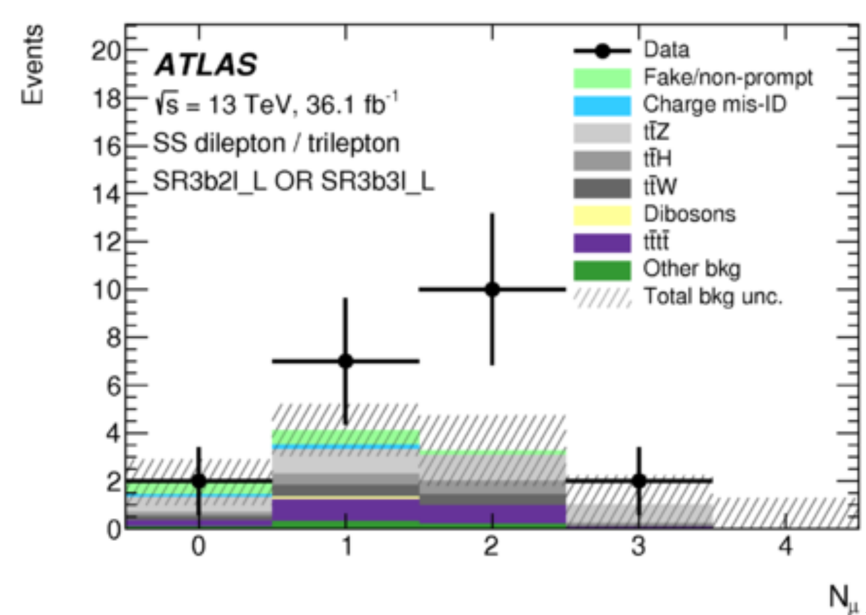
Excess concentrated in events with 3b and 2 muons



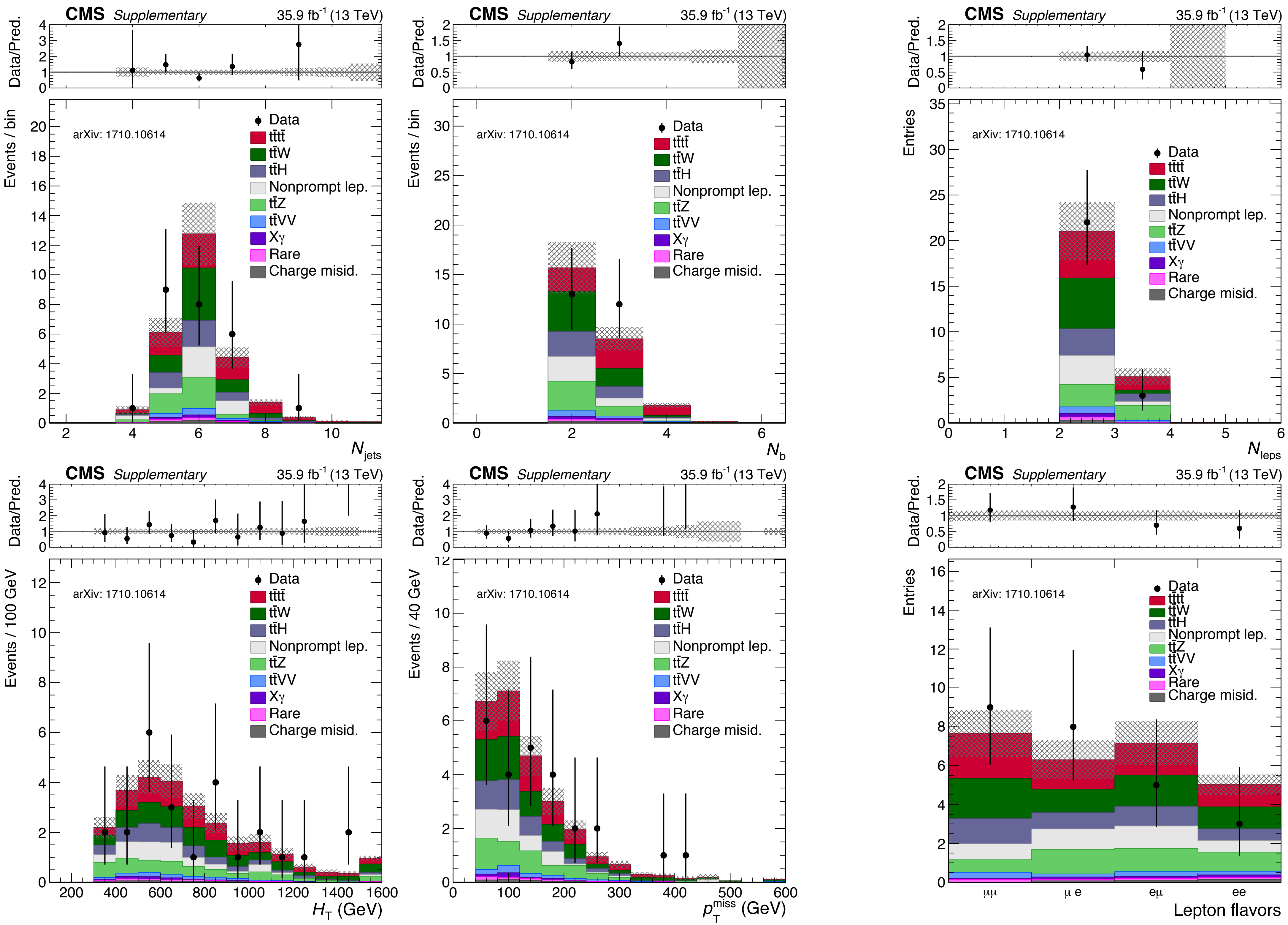








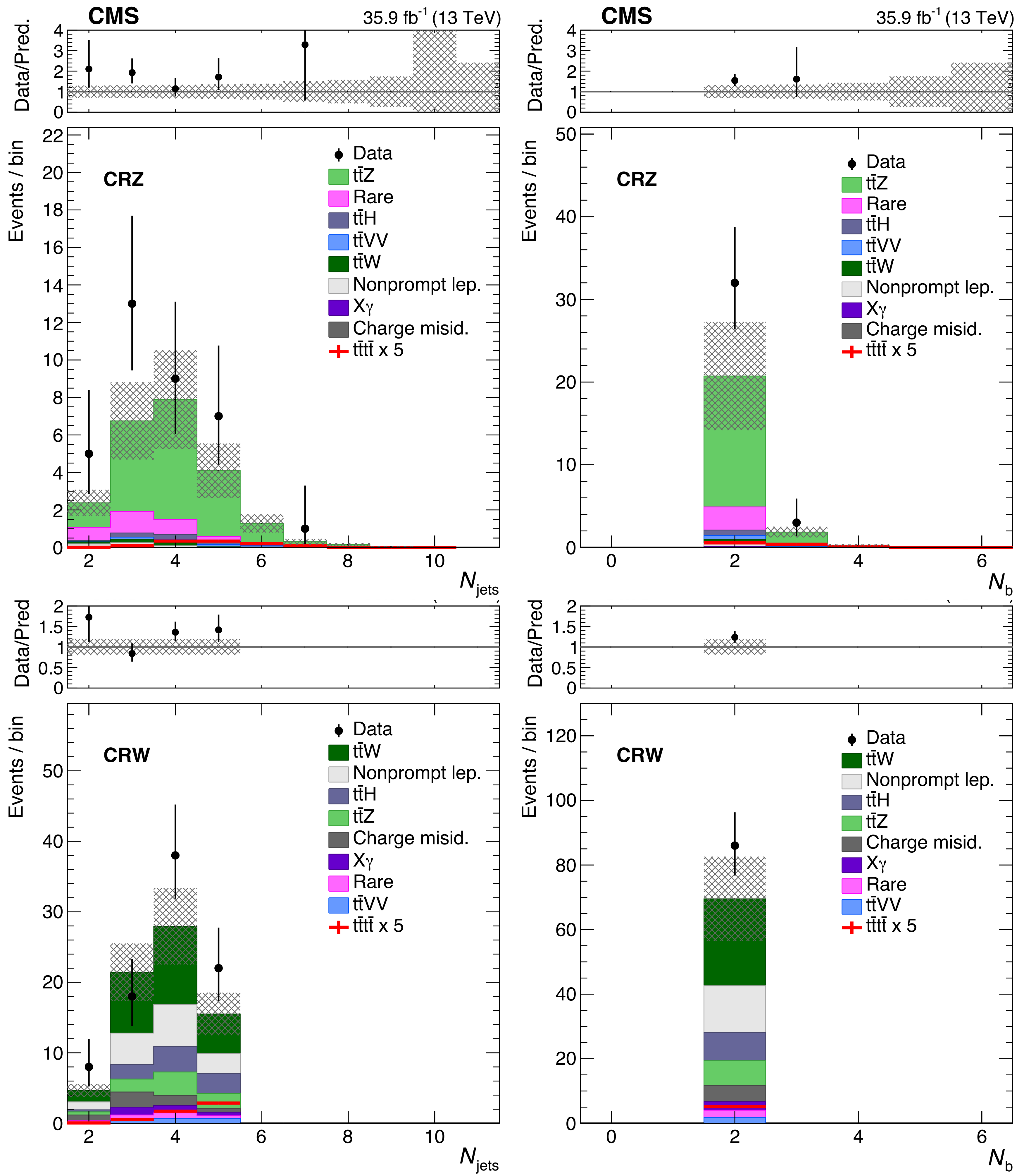
CMS SR kinematics, post-fit



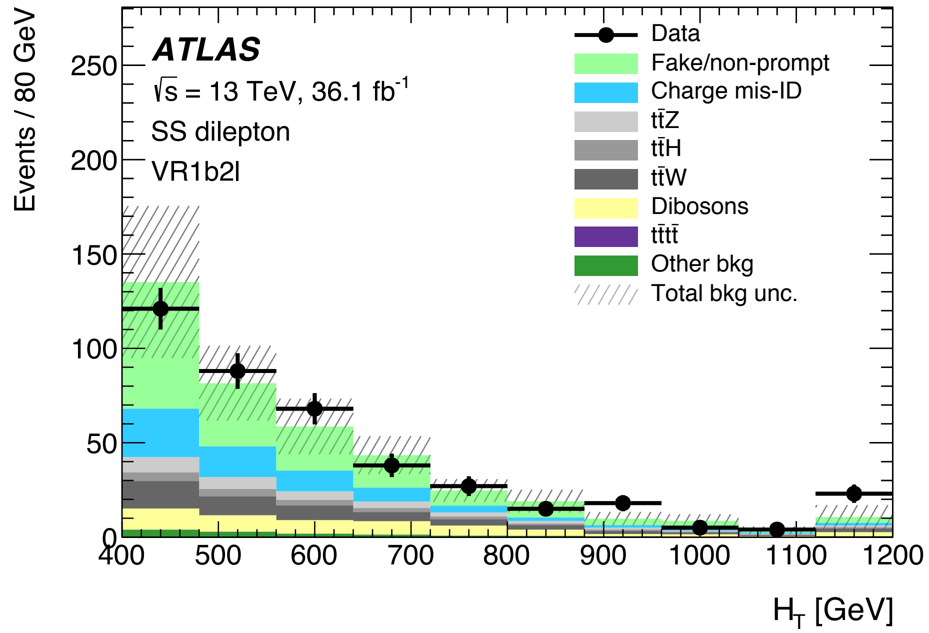
CMS control regions

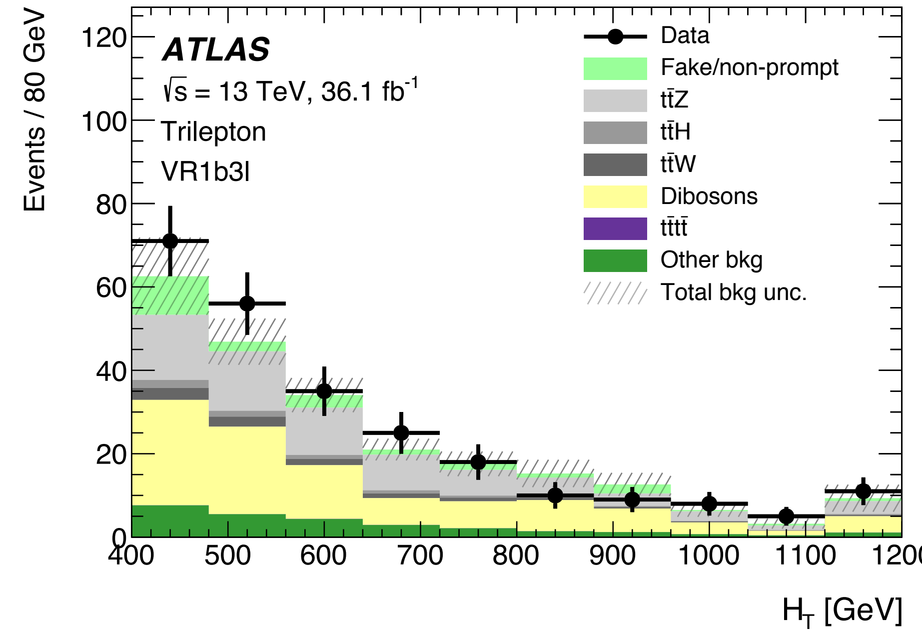
ttZ CR

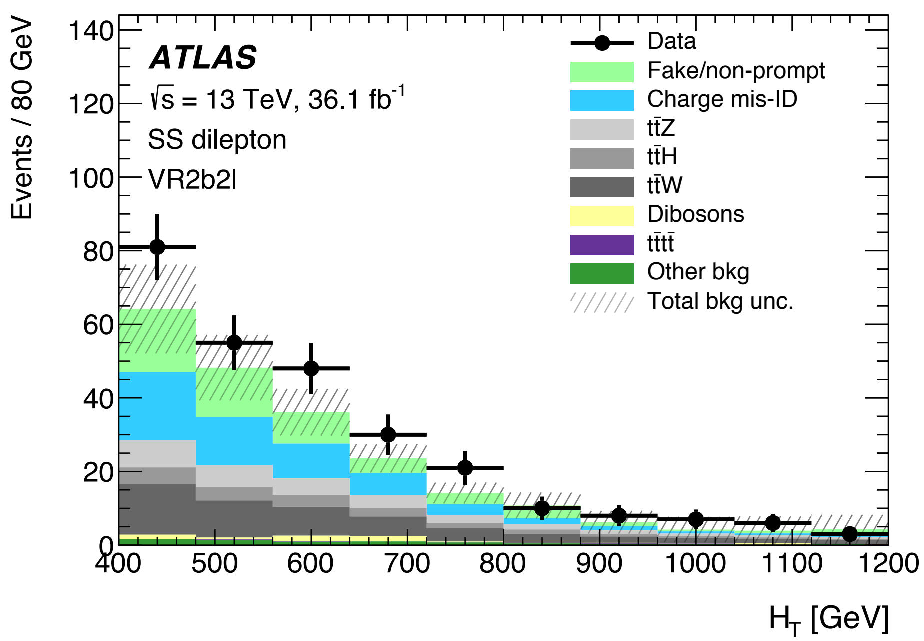
ttW CR

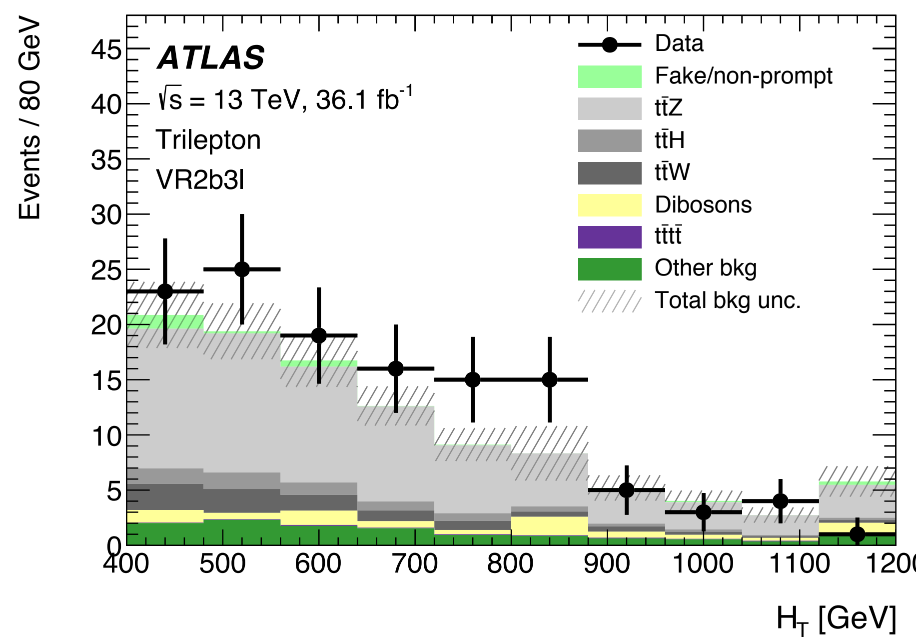


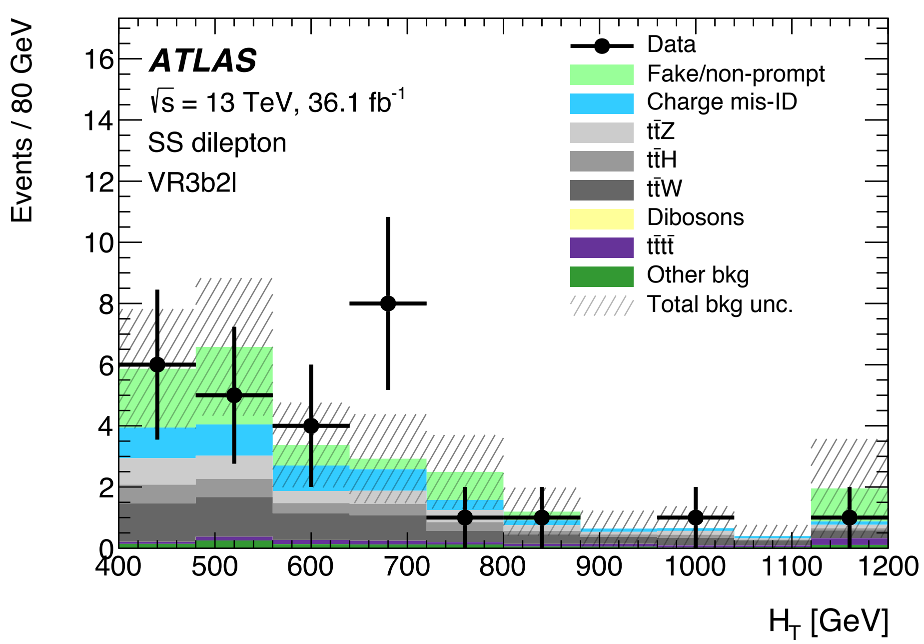
ATLAS validation regions

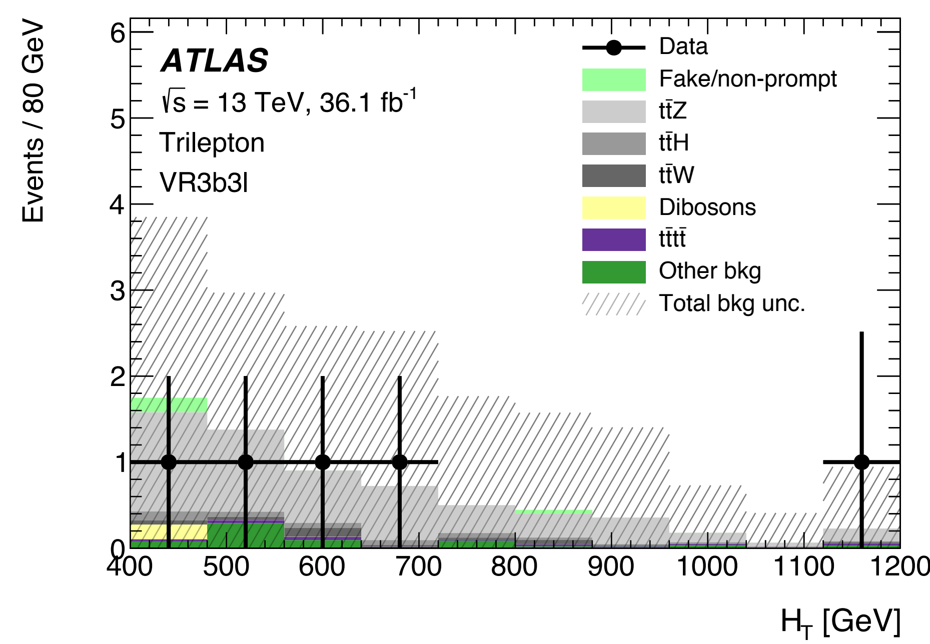












Full list of ATLAS SR and VR

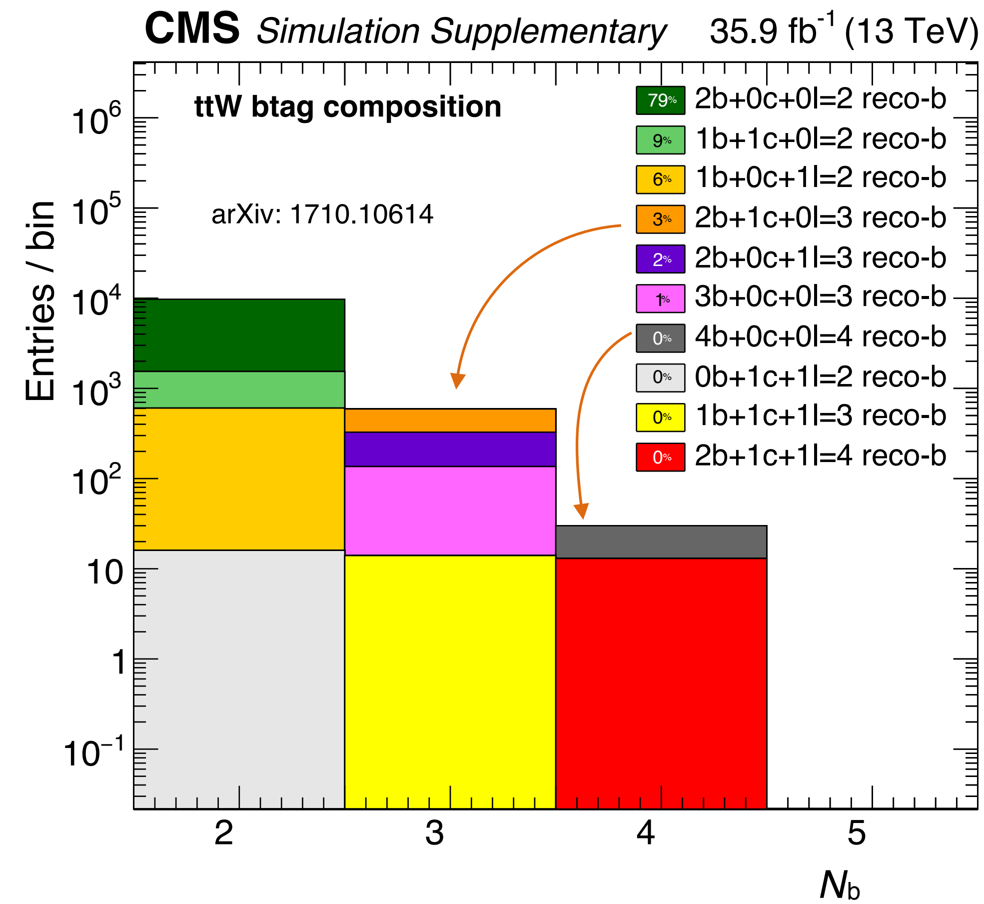
Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$ 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

Where do the extra (b-)jets come from?

Main backgrounds, ttW, ttZ, ttH(WW) have 2 b-jets: why 3 b-tags?

Check ttW at generator level:

- N_b = 3 region dominated by ttW+c
- N_b = 4 region dominated by ttW+bb



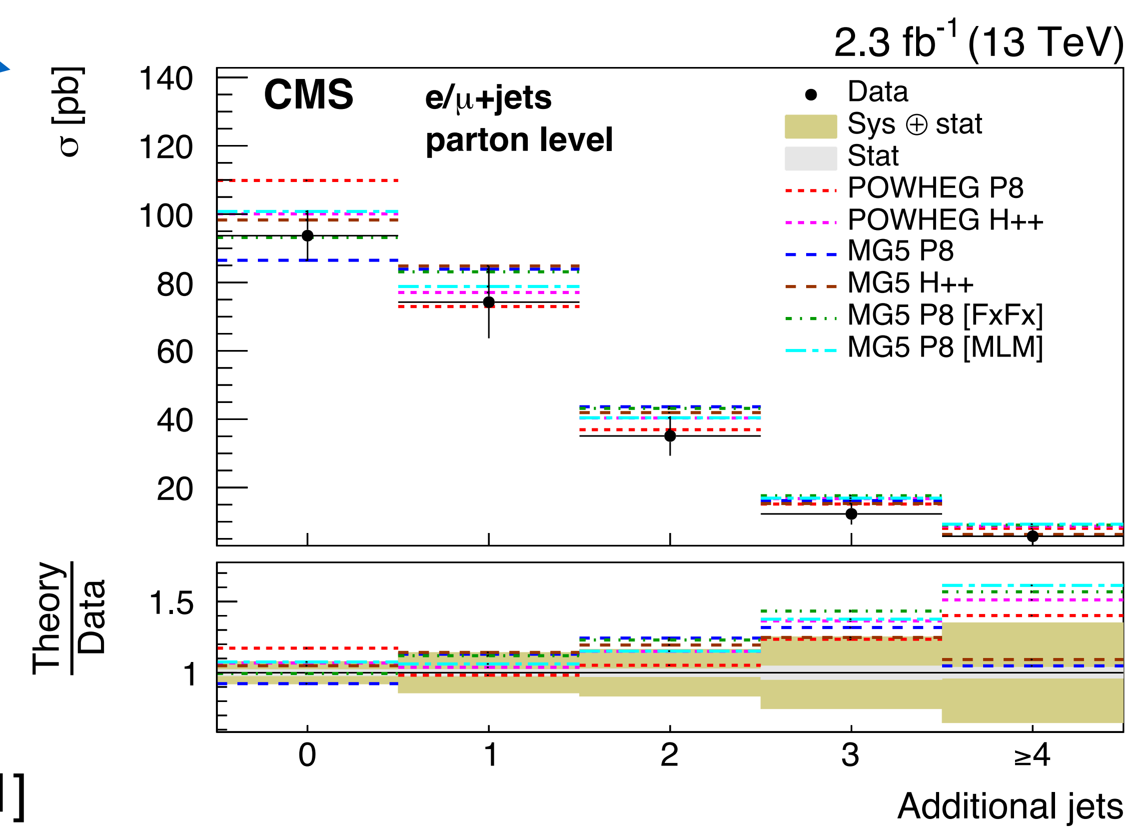
Are ttV+jets and ttV+bb well understood?

Use tt+jets and tt+bb as proxy for ttV

- tt+jets measurement is below theory
- σ(ttbb)/σ(ttjj) measurement is 1 σ above theory (1.7 ± 0.6) [arXiv:1705.10141]

Correct ttV simulation using tt Data/MC for both effects

- tt+jets measured in dilepton tt events
- tt+bb based on public result



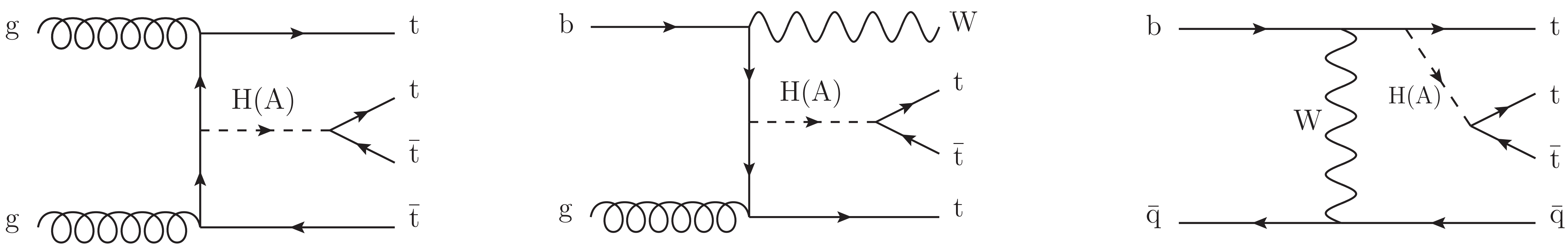
[tt+bb: arXiv:1705.10141, tt+jets: arXiv:1610.04191]

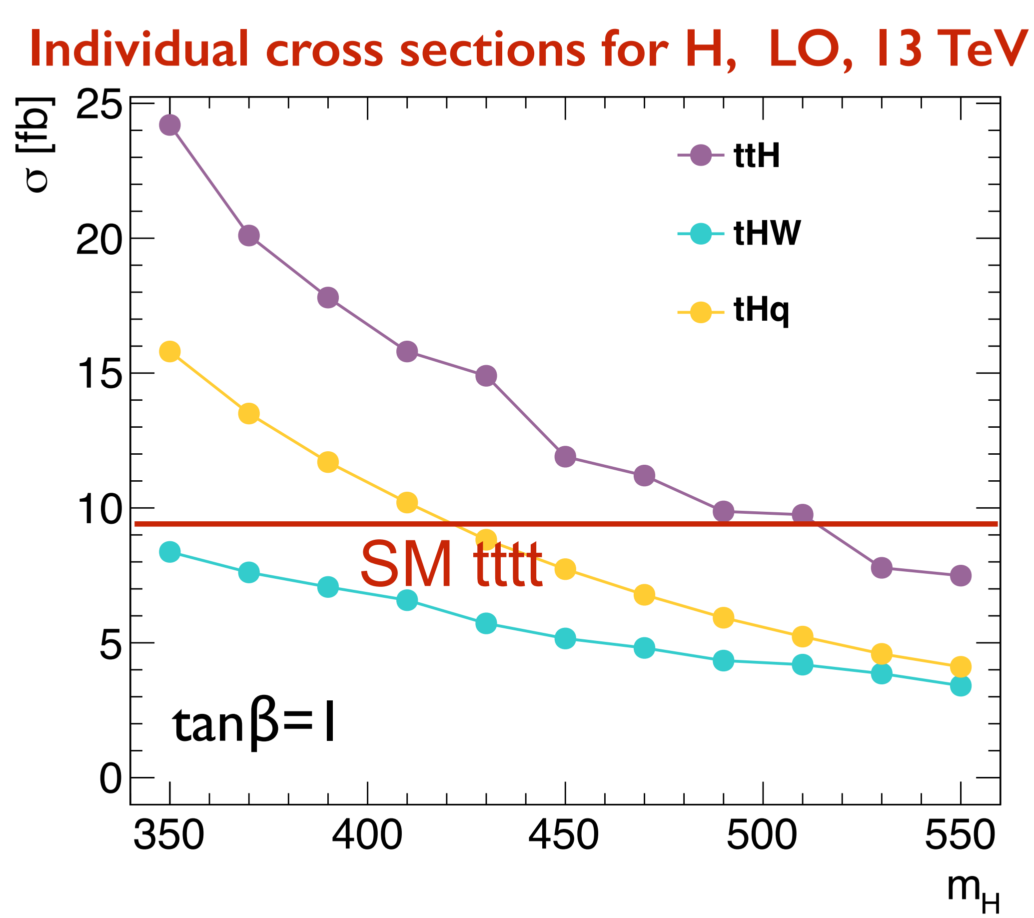
H/A associated production

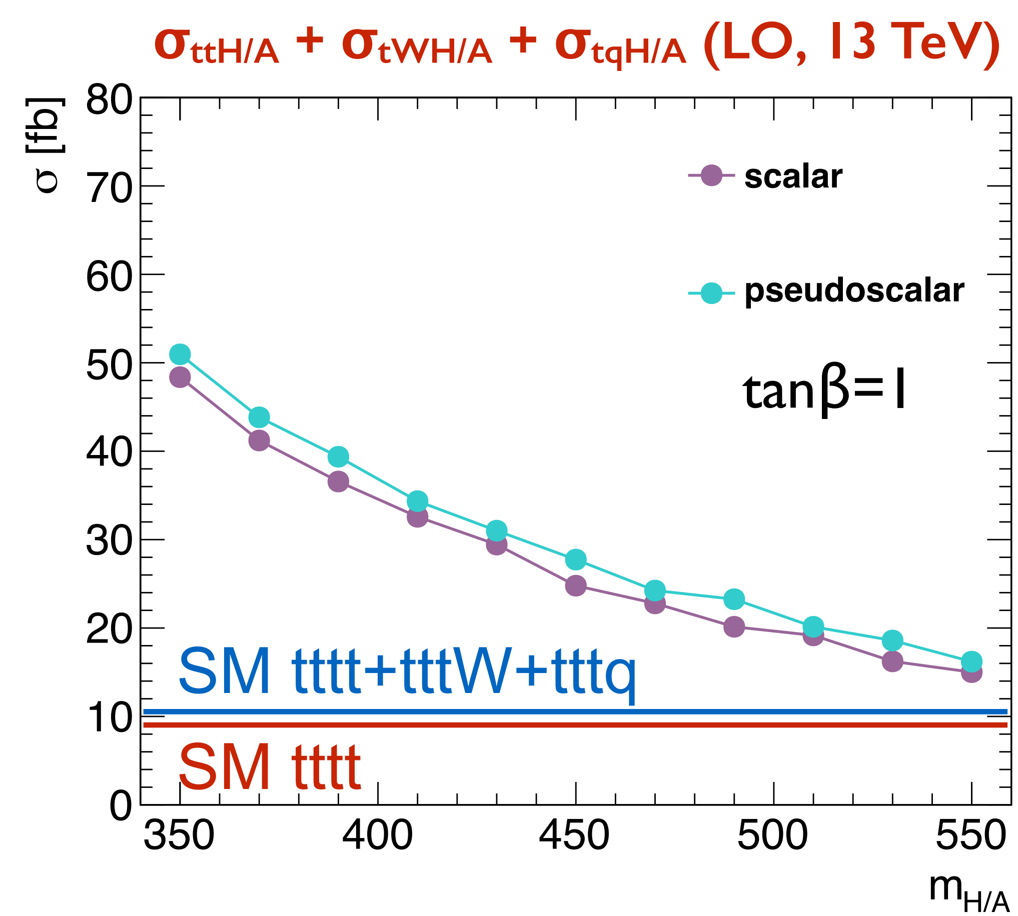
Proposal by N. Craig et al [arXiv:1605.08744]

2HDM predicts enhancement in several <u>top-associated production</u> channels

Can easily probe down to 2*m_t, where enhancement of σ_{tttt} is a factor of > 2.5







More EFTs

Even more generic: Effective Field Theory operators

- http://feynrules.irmp.ucl.ac.be/wiki/4topEFT

First: can set limits based on cross-section enhancement

Next (300 fb^{-1}): can start studying kinematics

$$\mathcal{O}_R = (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$$

$$\mathcal{O}_L^{(1)} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma_\mu Q_L)$$

$$\mathcal{O}_L^{(8)} = \left(\bar{Q}_L \gamma^\mu T^A Q_L\right)\left(\bar{Q}_L \gamma_\mu T^A Q_L\right)$$

$$\mathcal{O}_B^{(1)} = (\bar{Q}_L \gamma_\mu Q_L)(\bar{t}_R \gamma_\mu t_R)$$

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

tttt generation

ATLAS:

LO MG5_aMC@NLO2.2.2+Pythia8, NNPDF2.3 LO PDF, default LO dynamical scale

- Card: import model sm; generate p p > t t~ t t~

value	`dynamical_scale_choice` meaning
-1	default case:
	LO code: transverse mass of the $2 \to 2$ system resulting of a k_T clustering
	NLO code: sum of the transverse mass divide by 2 $\frac{1}{2}\sum_{i=1}^{N}\sqrt{m_i^2+p_{T,i}^2}$.

CMS:

NLO MG5_aMC@NLO2.2.2+Pythia8, NNPDF3.0 NLO PDF, default NLO dynamical scale

- Cards: import model loop_sm-no_b_mass, generate p p > t t~ t t~ [QCD] @0
- Scale: default dynamic scale in both cases (different at LO and NLO)

Some LO/NLO comparisons from arxiv:1711.02116

- Focus on main plot. Ratio is NLO/NLO. LO HT spectrum is softer than NLO one