Four Tops Search in SSML channel at ATLAS

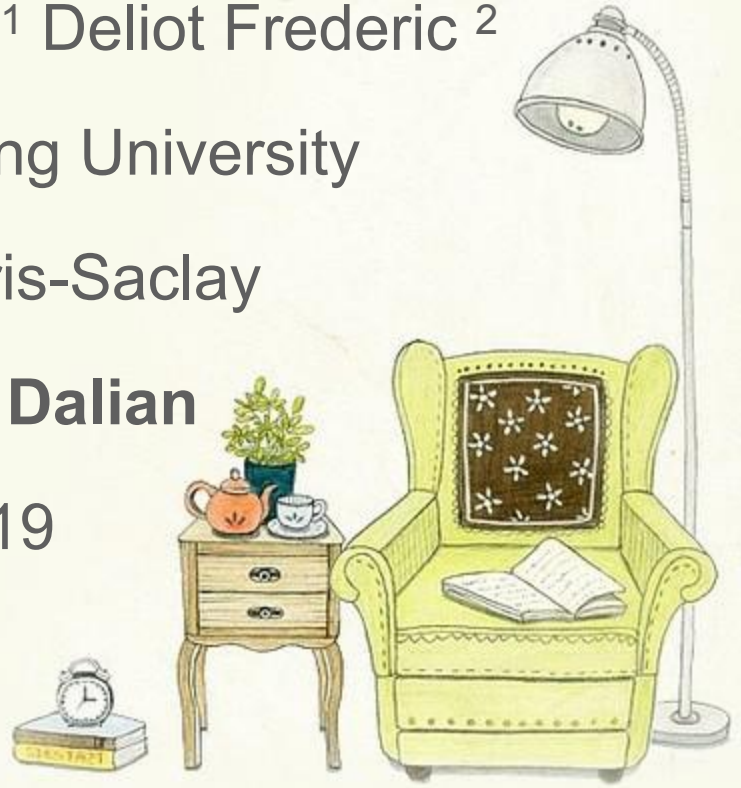
Shuyang Hu [1,2] Liang Li [1] Deliot Frederic [2]

1. Shanghai Jiao Tong University

2. Université Paris-Saclay

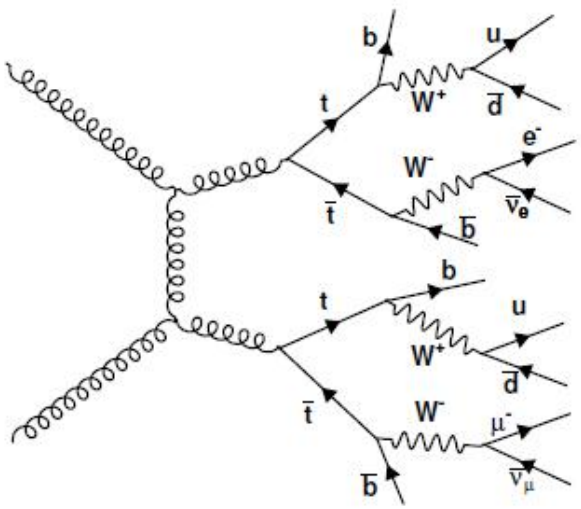
CLHCP 2019, Dalian

27.10.2019

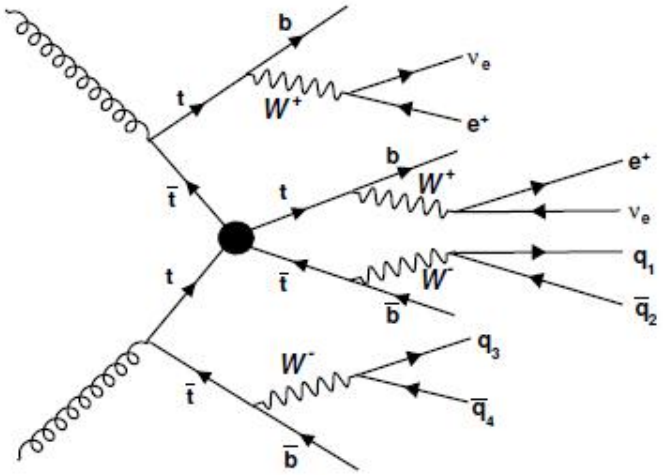


Physics motivation

=> SM prediction of 4tops xsec is very small: ~9.2 fb(NLO) at 13 TeV, not observed yet, rare process search



Example of Standard Model $t\bar{t}t\bar{t}$ event whose decay contains two same-sign leptons.



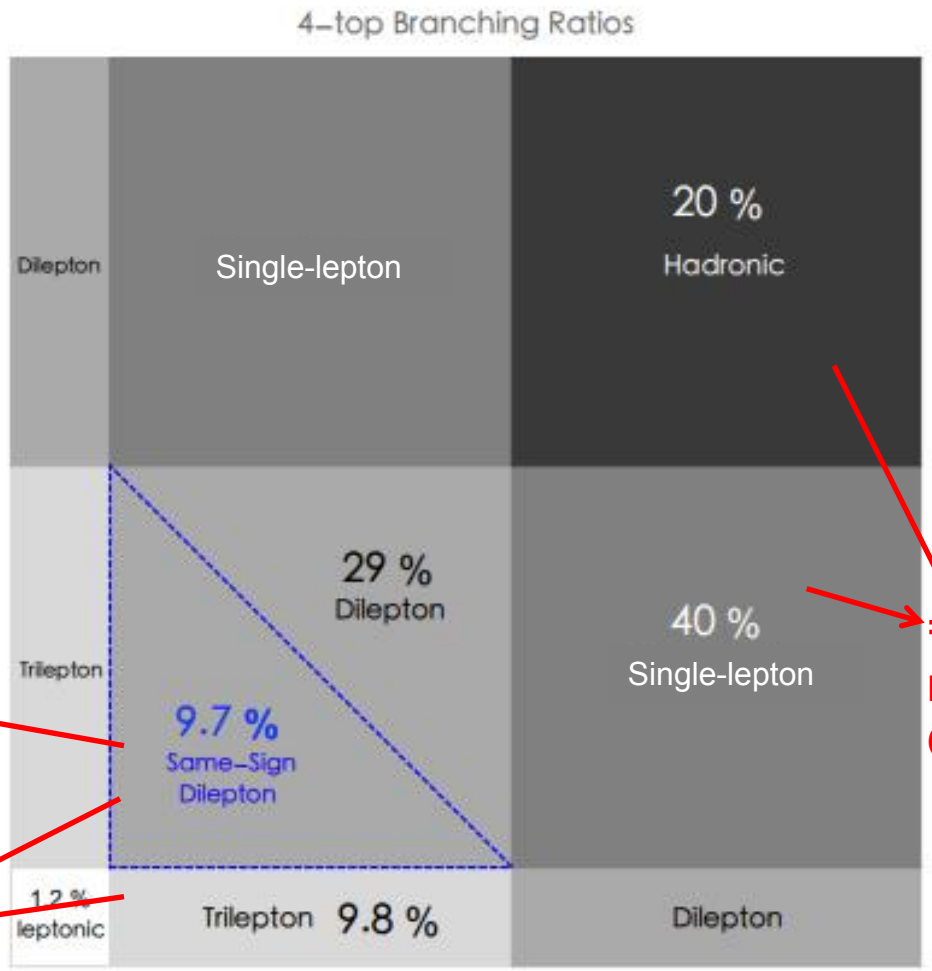
Example of Feynman diagram of $t\bar{t}t\bar{t}$ production via contact interaction.

=> Sensitive to BSM physics like Contact interaction (CI), Vector-like quark (VLQ), 2 Higgs Doublet Model (2HDM) ...

1) Top mass is close to the scale of electroweak symmetry breaking

2) Top has a very clear signiture: t -> b + W, high jet/bjet multiplicity

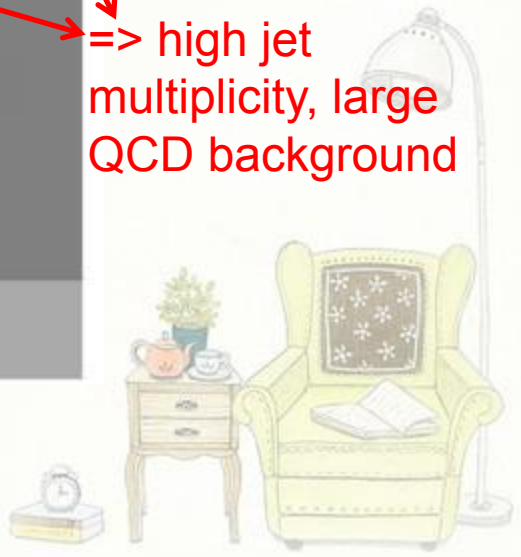
4tops branching ratios



=> Largely reduce the irreducible background from Z boson and tt + X

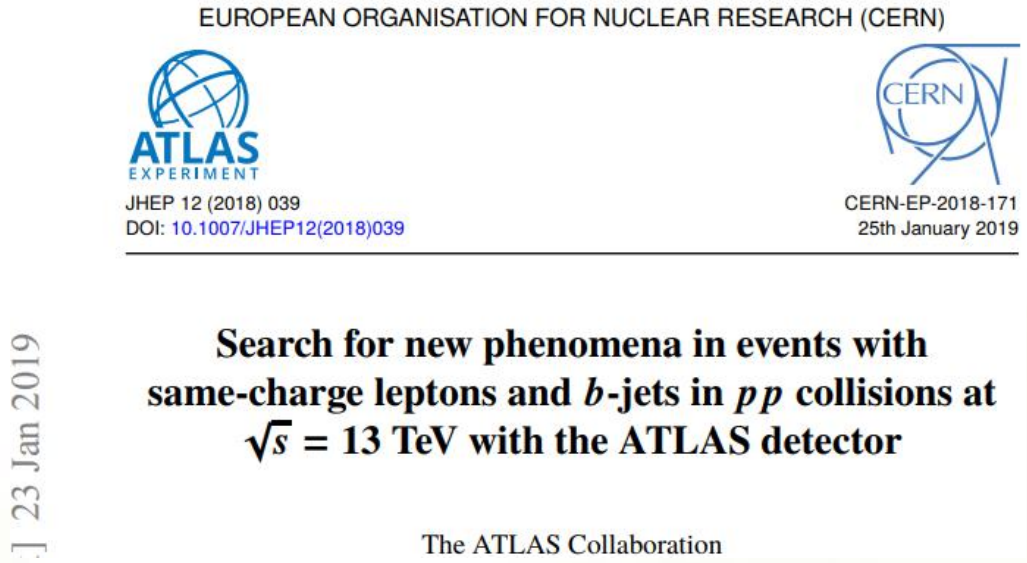
=> What I have been focusing on

=> high jet multiplicity, large QCD background



What has been achieved

=>(SS + 3L) paper:
10.1007/JEHP12(2018)039



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

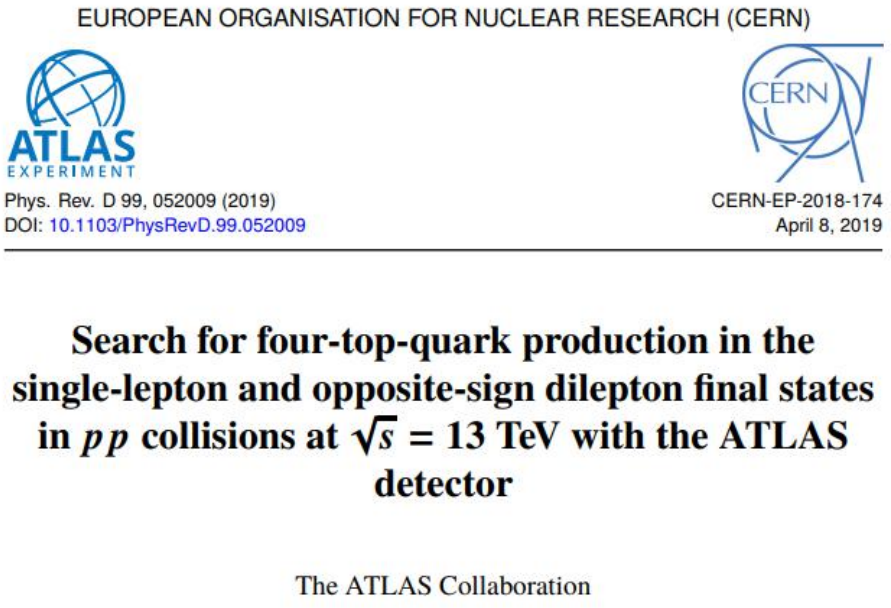
JHEP 12 (2018) 039
DOI: 10.1007/JHEP12(2018)039

CERN-EP-2018-171
25th January 2019

Search for new phenomena in events with same-charge leptons and b-jets in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

=>(1L + OS) paper:
10.1103/PhysRevD.99.052009



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Phys. Rev. D 99, 052009 (2019)
DOI: 10.1103/PhysRevD.99.052009

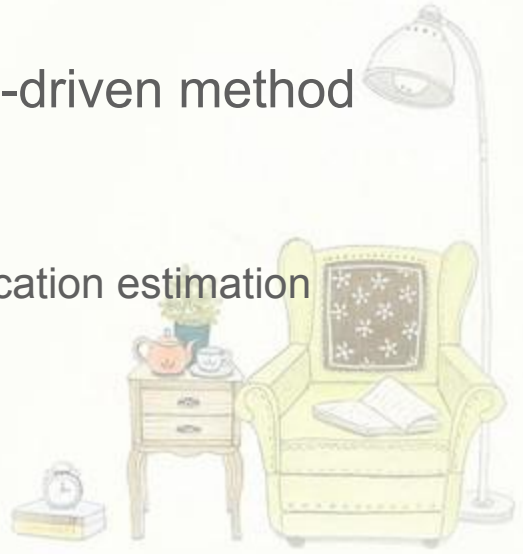
CERN-EP-2018-174
April 8, 2019

Search for four-top-quark production in the single-lepton and opposite-sign dilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

Background Estimation (SS+ML)

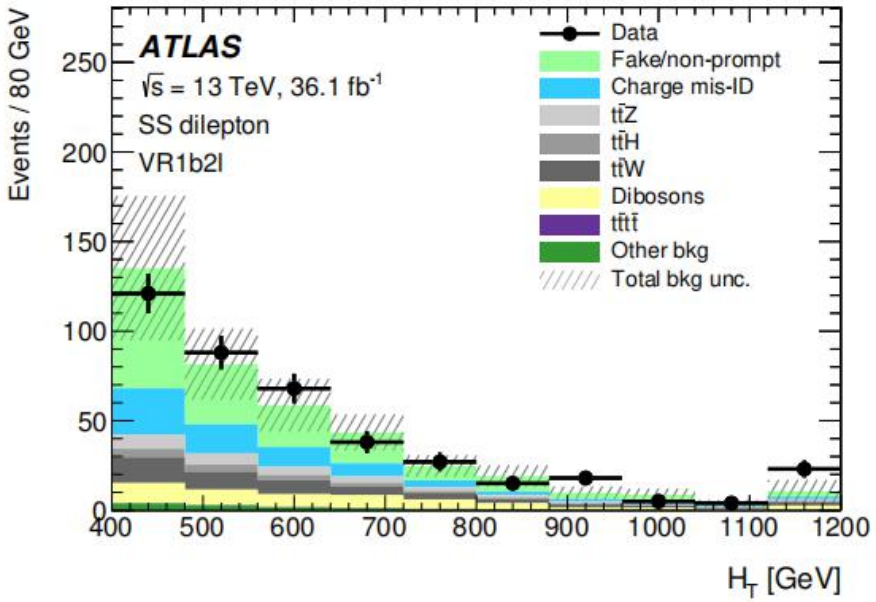
- Signal and irreducible backgrounds are estimated using MC simulation
  - Main irreducible background
    - => ttV, ttH, diboson
  - Other irreducible background
    - => triboson, VH, ttt, ttWW, tZW, tZ
- Reducible backgrounds are estimated using data-driven method
  - => Matrix method for fake estimation
  - => Maximum likelihood fit method for charge mis-identification estimation

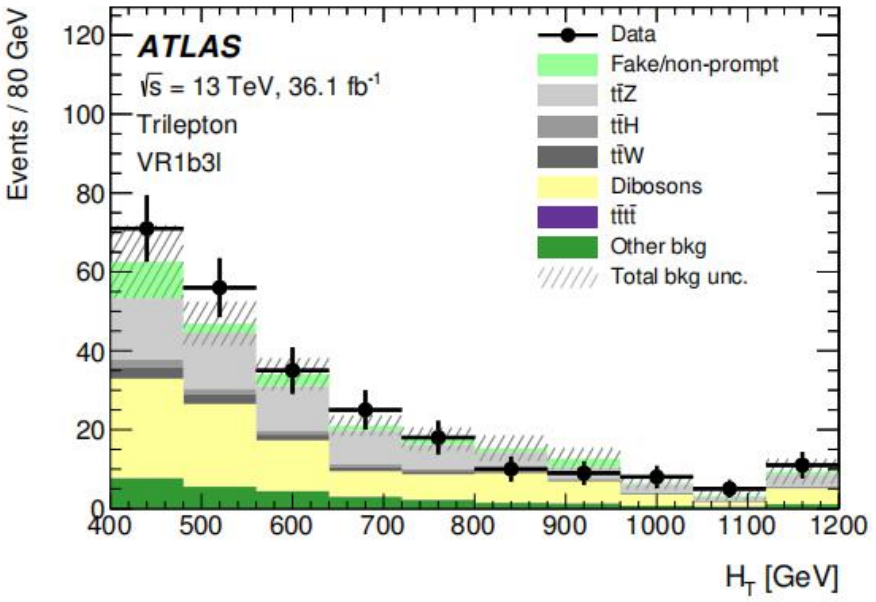


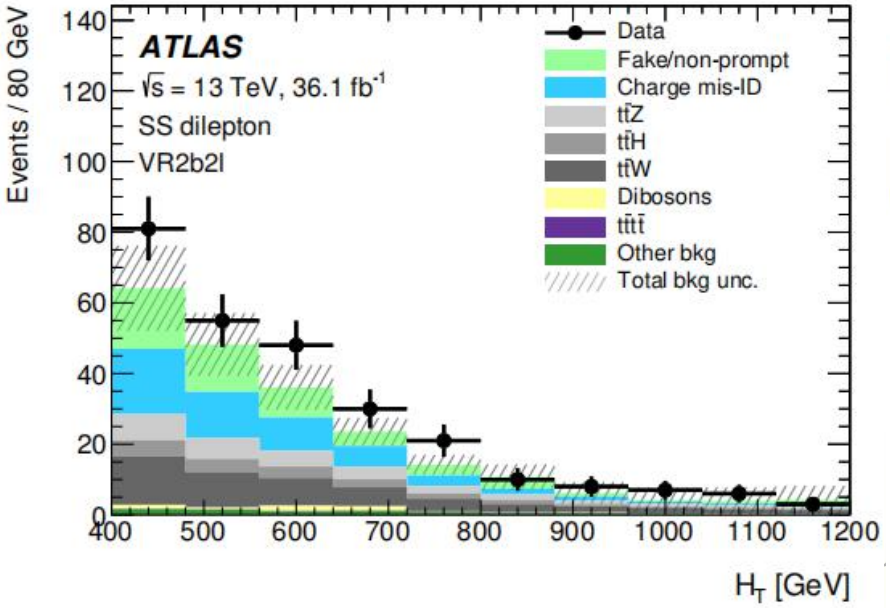
Regions Definition (SS+ML)

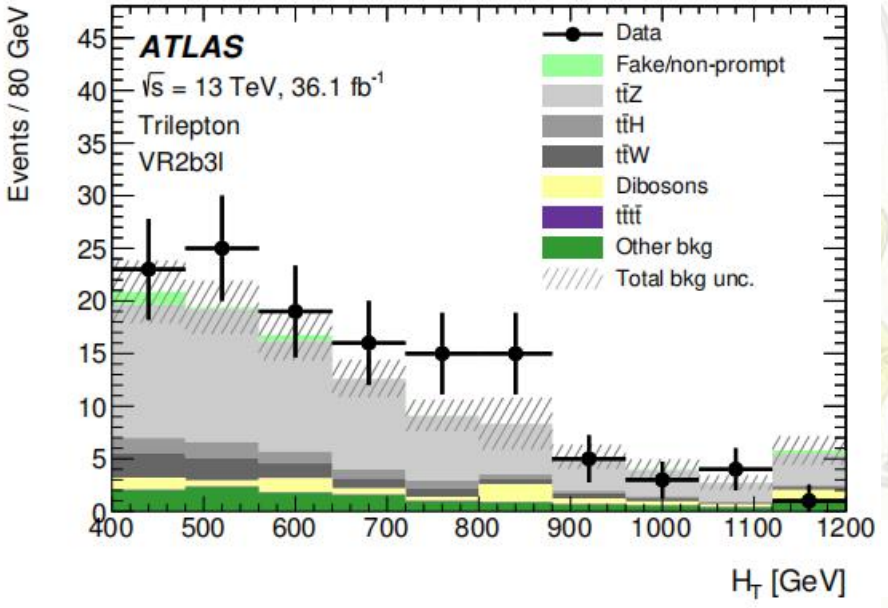
Region name	N_j	N_b	N_ℓ	Lepton charges	Kinematic criteria
VR1b2ℓ	≥ 1	1	2	++ or −−	$400 < H_T < 2400$ GeV or $E_T^{miss} < 40$ GeV
SR1b2ℓ	≥ 1	1	2	++ or −−	$H_T > 1000$ GeV and $E_T^{miss} > 180$ GeV
VR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 400$ GeV
SR2b2ℓ	≥ 2	2	2	++ or −−	$H_T > 1200$ GeV and $E_T^{miss} > 40$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

Data/MC comparison in VRs

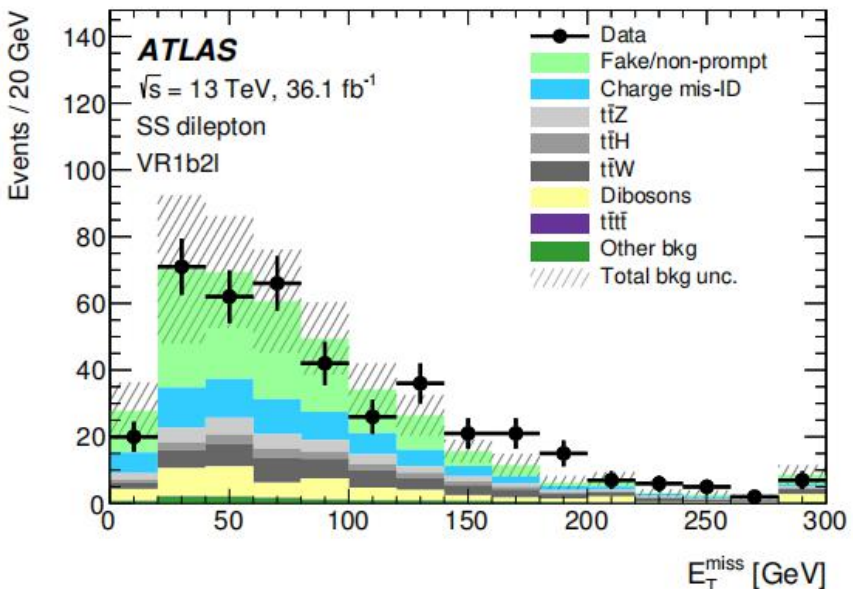


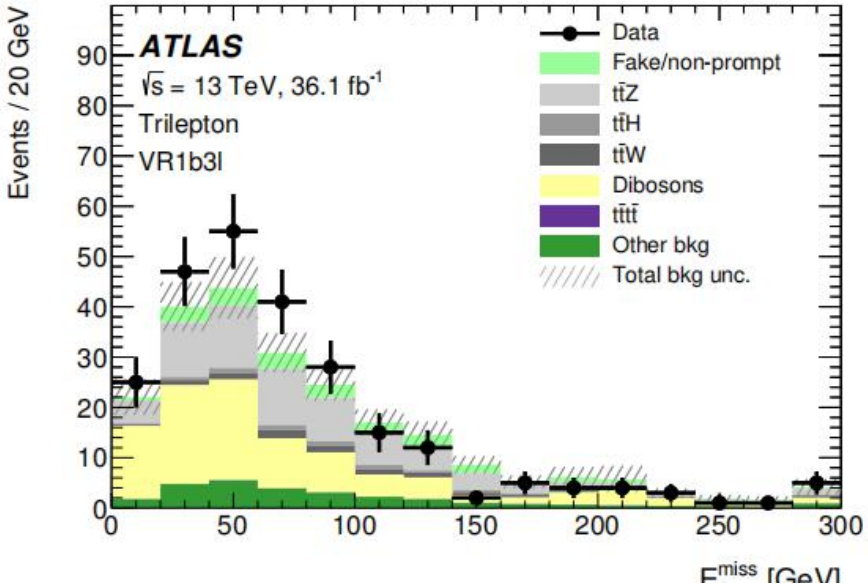


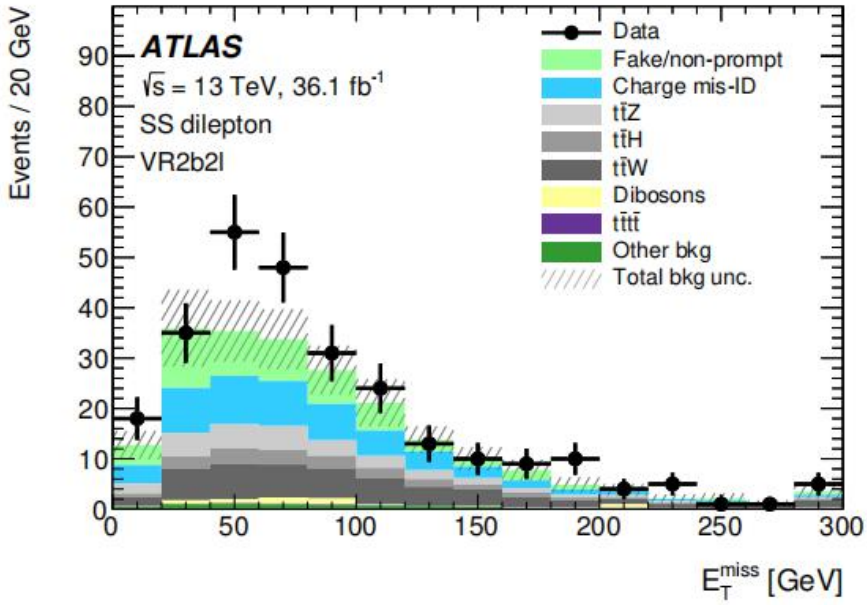


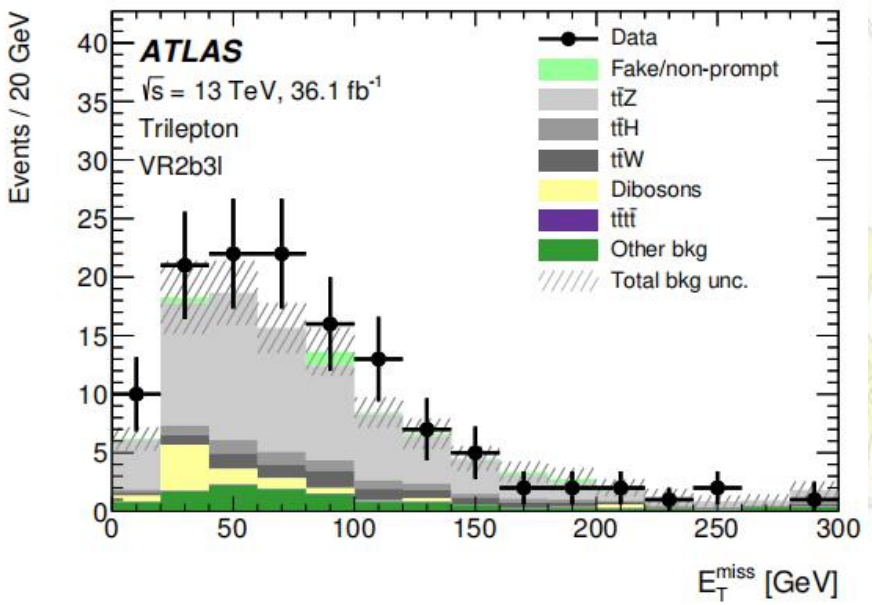


Data/MC comparison in VRs

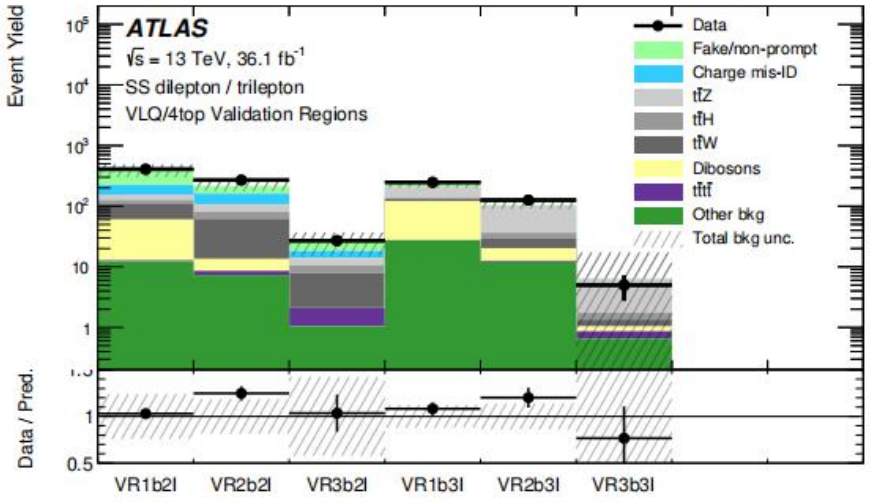


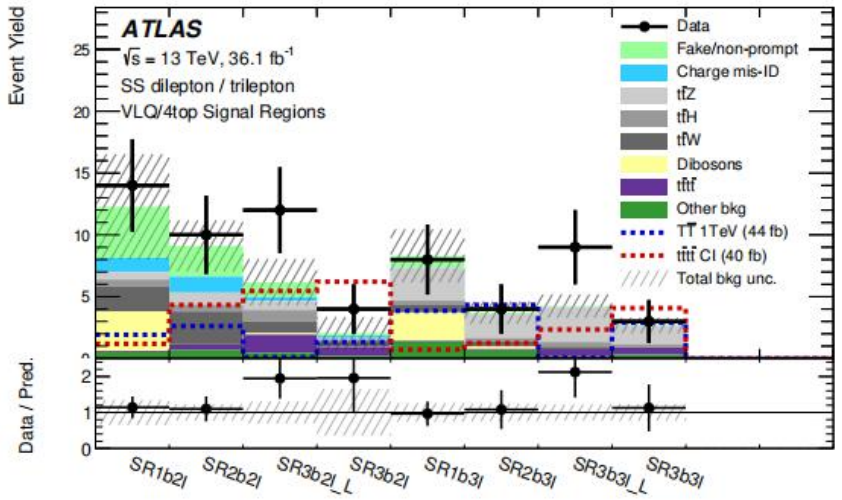






Summary of data/MC comparison in SR/VRs





=> Background estimation is good

=> Combined fit in all SRs to extract the upper limit of POI

Systematic uncertainties

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

Uncertainties of the total background yeilds in the signal regions

Results (SS+ML)

Source	SR1$b2\ell$	SR2$b2\ell$	SR3$b2\ell$_L	SR3$b2\ell$
$t\bar{t}W$	$2.04 \pm 0.14 \pm 0.49$	$2.68 \pm 0.15 \pm 0.55$	$0.95 \pm 0.11 \pm 0.31$	$0.40 \pm 0.06 \pm 0.10$
$t\bar{t}Z$	$0.58 \pm 0.08 \pm 0.10$	$0.95 \pm 0.11 \pm 0.17$	$0.72 \pm 0.11 \pm 0.19$	$0.11 \pm 0.05\ ^{+0.13}_{-0.10}$
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

=> cut based analysis.

Source	SR1$b3\ell$	SR2$b3\ell$	SR3$b3\ell$_L	SR3$b3\ell$
$t\bar{t}W$	$0.66 \pm 0.08 \pm 0.20$	$0.38 \pm 0.05 \pm 0.11$	$0.21 \pm 0.05 \pm 0.09$	$0.15 \pm 0.04 \pm 0.05$
$t\bar{t}Z$	$2.66 \pm 0.15 \pm 0.43$	$1.90 \pm 0.14 \pm 0.42$	$2.80 \pm 0.17 \pm 0.58$	$1.47 \pm 0.14 \pm 0.28$
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

Table 14: Expected and observed 95% CL upper limits on the four-top-quark production cross-section in various models.

Observable	Expected median with 1σ range	Observed
SM cross-section [fb]	$29.0\ ^{+12.2}_{-8.1}$	69.2
CI cross-section [fb]	$20.8\ ^{+12.2}_{-8.1}$	38.6

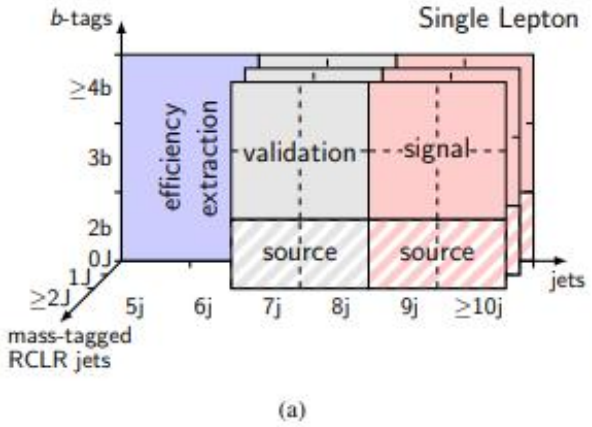
Search strategy (1L+OS)

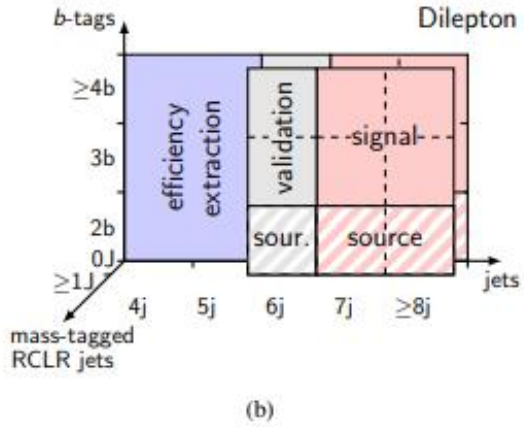
Event selection:

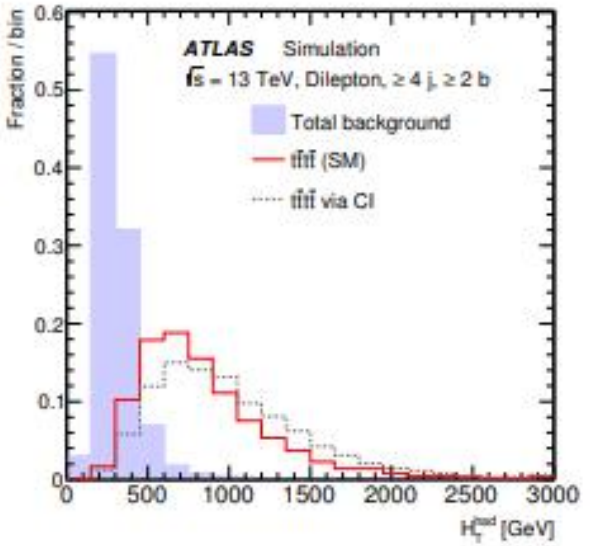
Preselection requirements		
Requirement	Single-lepton	Dilepton
Trigger	Single-lepton triggers	
Leptons	1 isolated	2 isolated, opposite-sign
Jets	≥5 jets	≥4 jets
b-tagged jets	≥2 b-tagged jets	
Other	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV	$m_{\ell\ell} > 50$ GeV
	$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W}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

H_T distribution already provides good discrimination between signal and background.

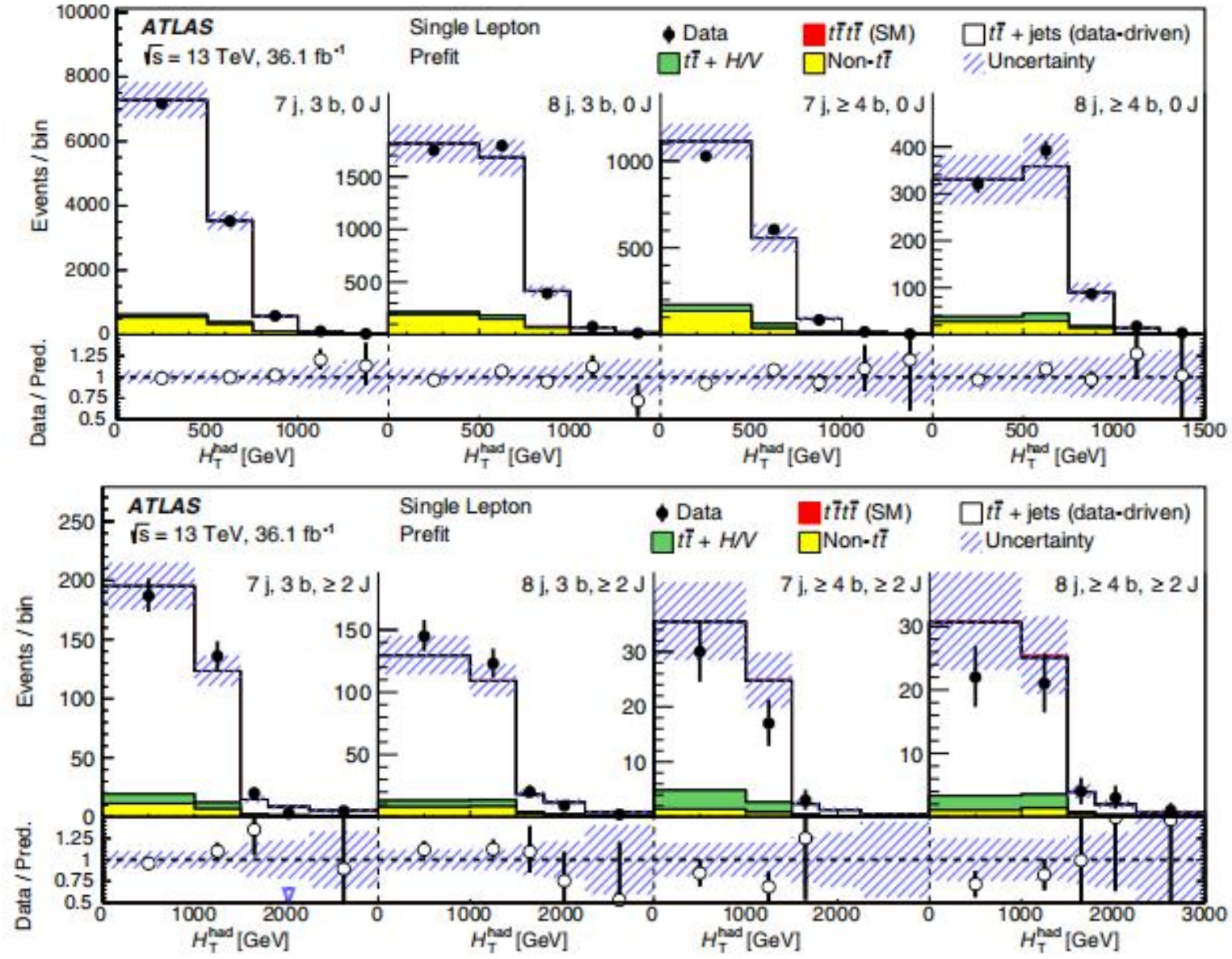
Region definition:



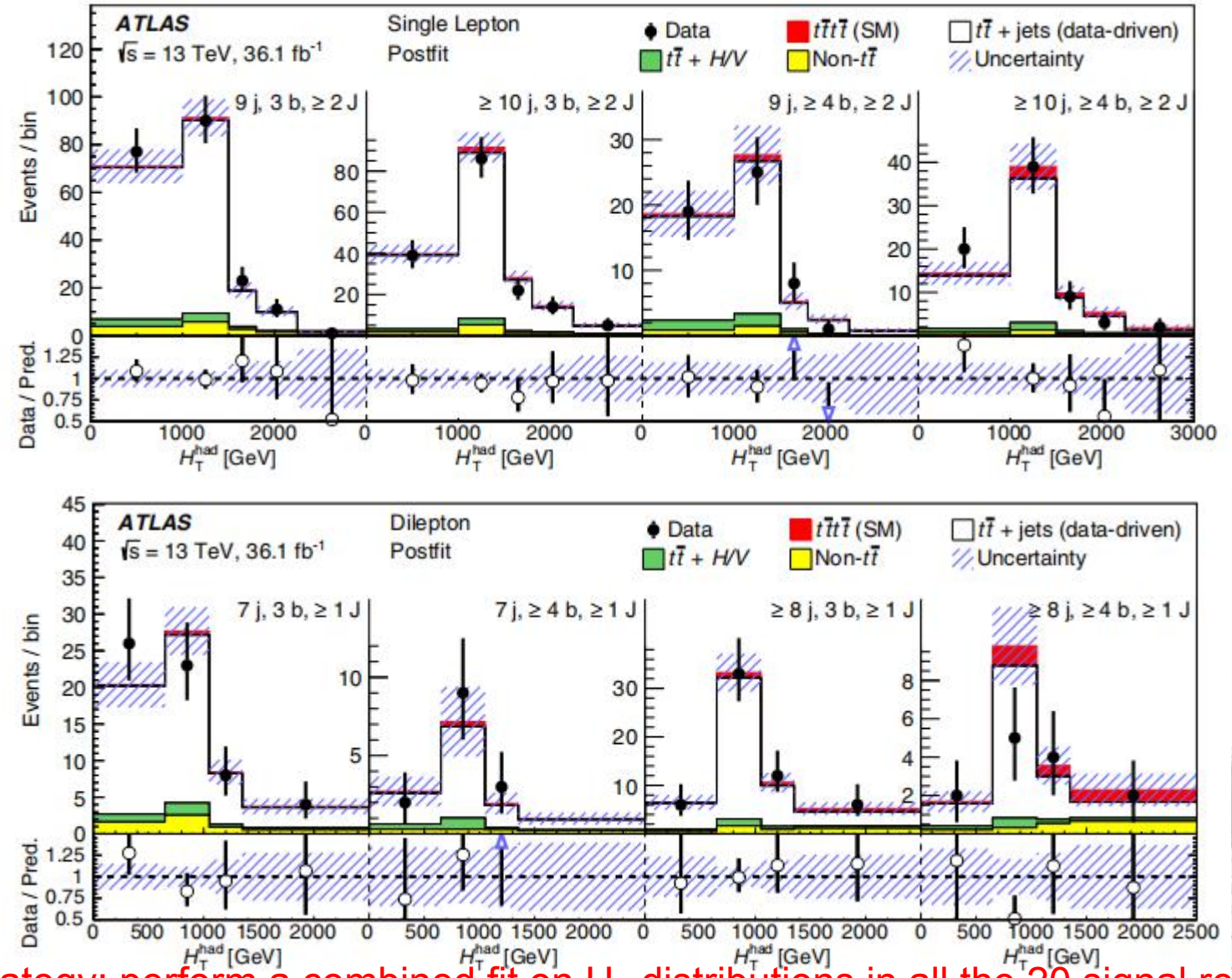




Pre-fit HT distribution in VRs



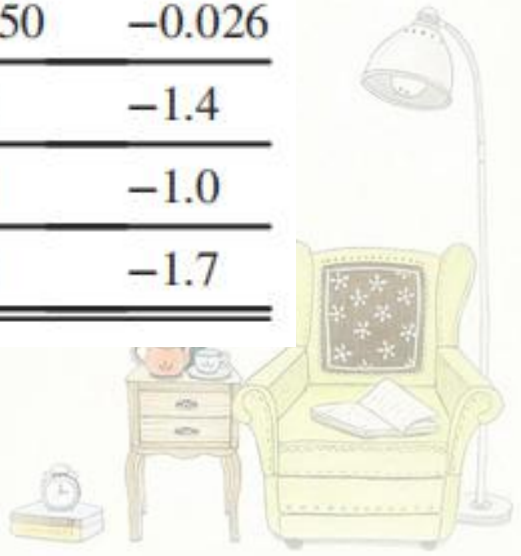
Post-fit HT distribution in SRs



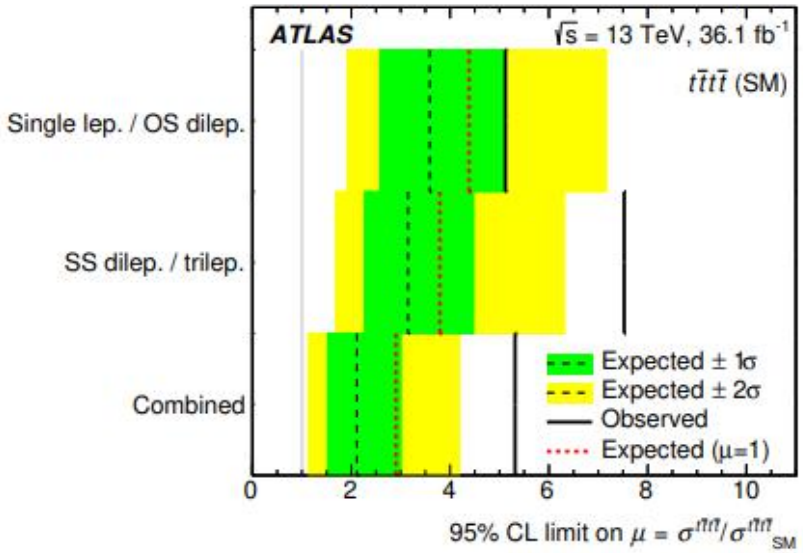
Strategy: perform a combined fit on H_T distributions in all the 20 signal regions.

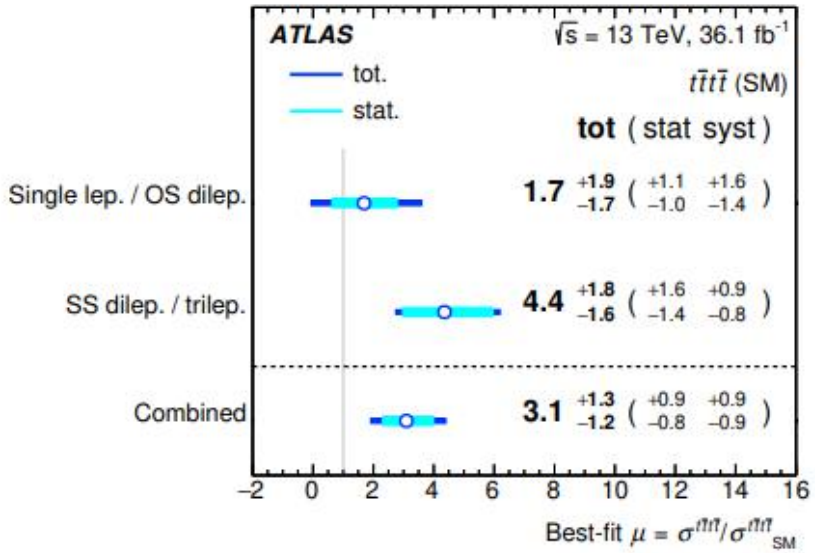
Systematic uncertainties

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 mistag 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



Results (combined)



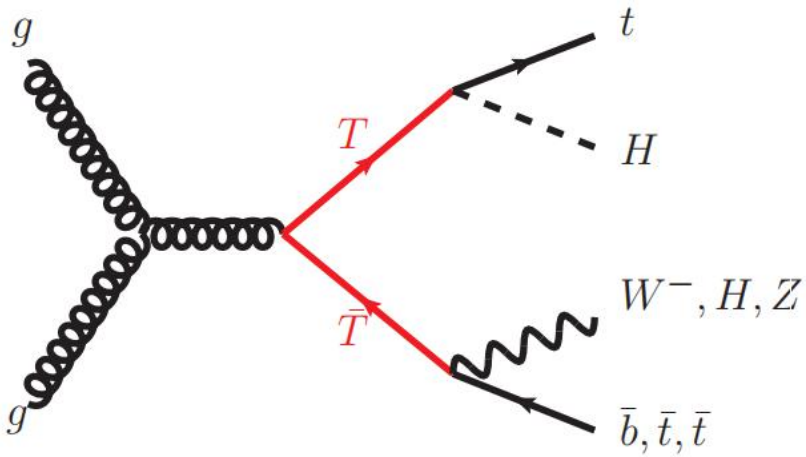


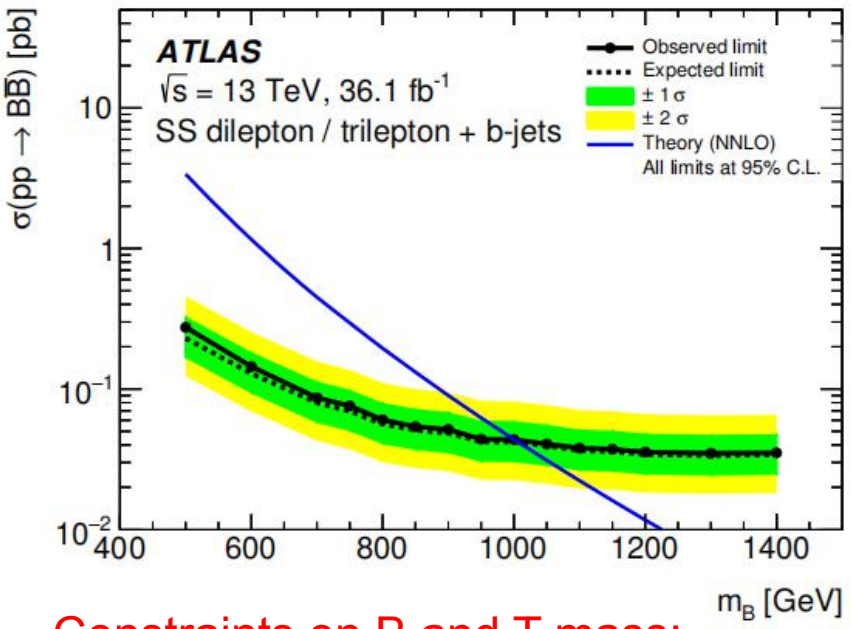
Summary:

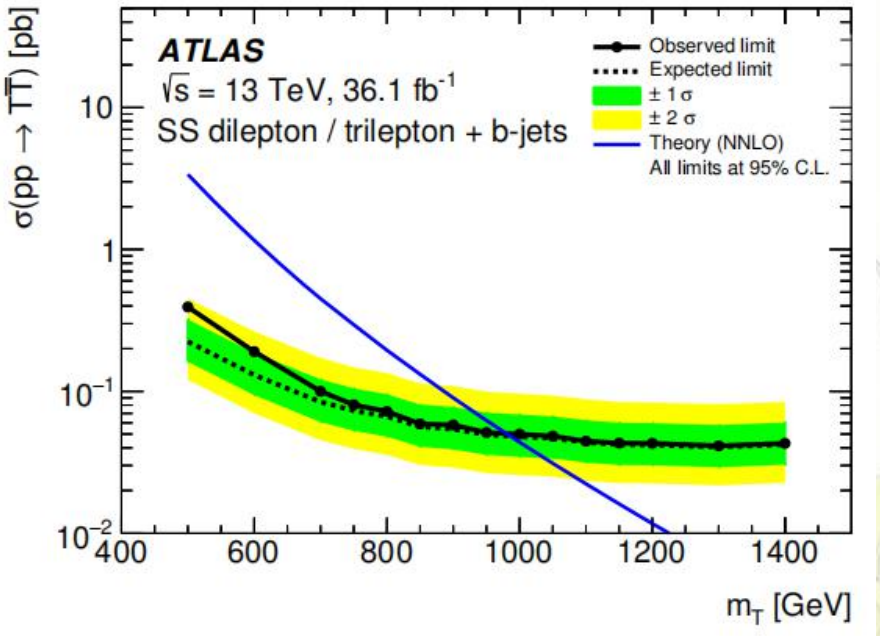
Channel	xSec limit obs (exp)	significance obs (exp)
1L+OS	49 (19) fb	1.0(0.6)
SS+ML	69 (29) fb	3.0(0.8)
Combined	47 (33) fb	2.8(1.0)

BSM searches

VLQ searches







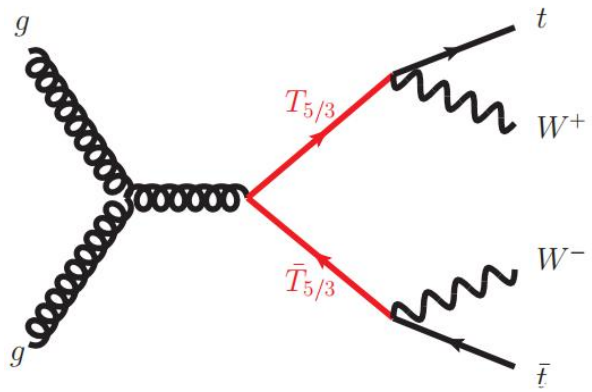
Constraints on B and T mass:

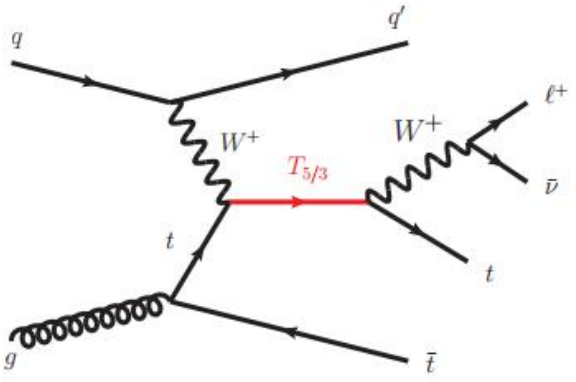
m_B > 1.00 TeV (1.01 TeV)

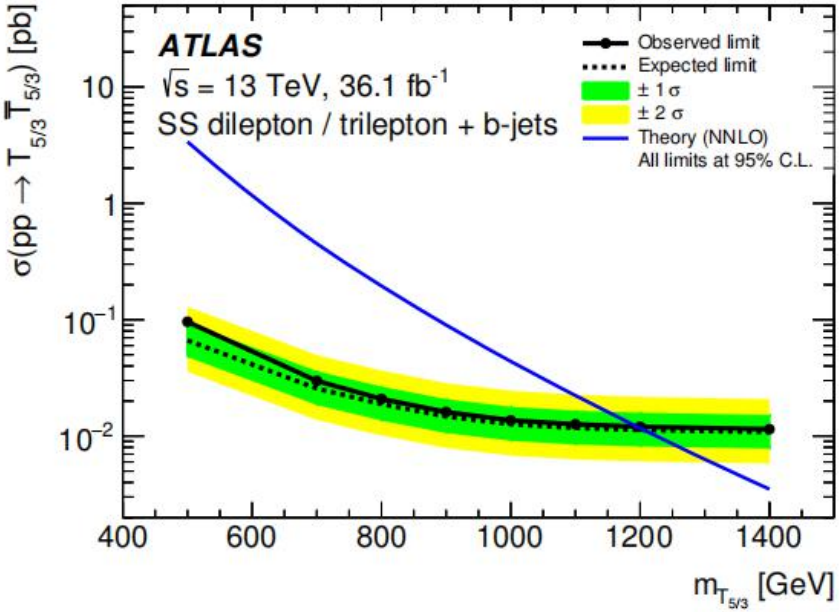
m_T > 0.98 TeV (0.99 TeV)

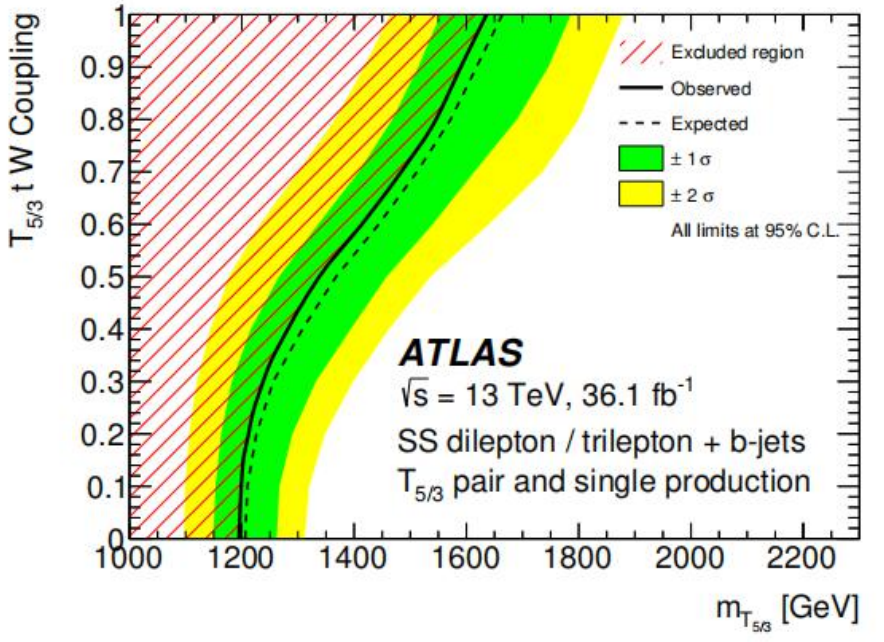
BSM searches

VLQ searches









Constraints on $T_{5/3}$ mass:

$m_{T5/3}$ > 1.19 TeV (1.21 TeV) (assuming no single $T_{5/3}$ production)

Towards full Run-2 4tops analysis

=> Integrated luminosity ~ 140 fb^{-1}, ~4 times of 36.1 fb^{-1}, ~ 2 times improvement in significance expected

=> Event selection optimization

=> Background estimation

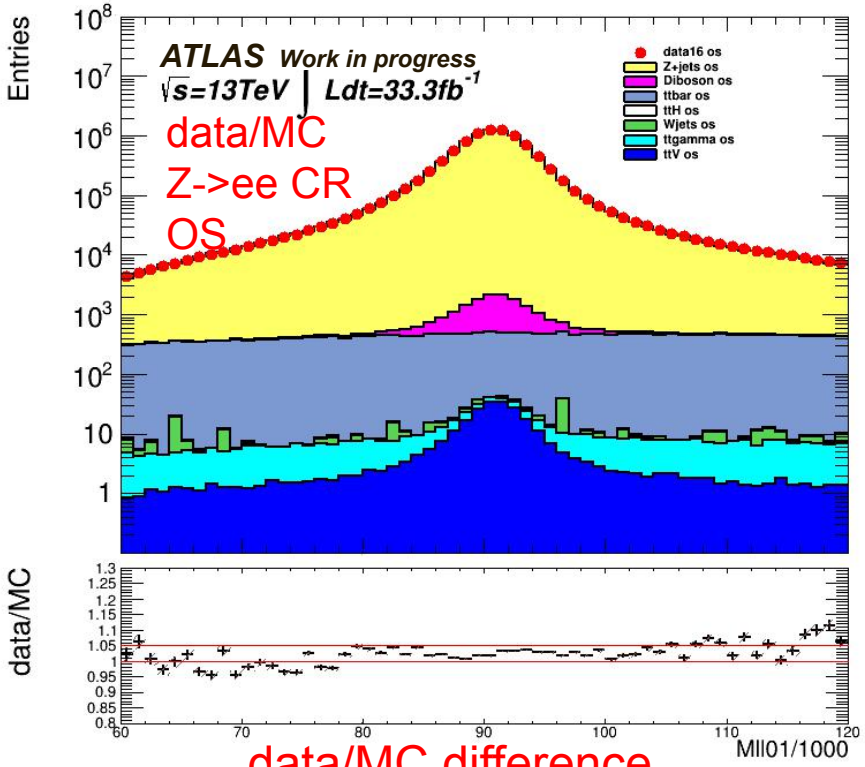
=> Use MVA analysis to improve significance

=> Typical statistical procedure on BDT discriminant to extract the limit on signal strength

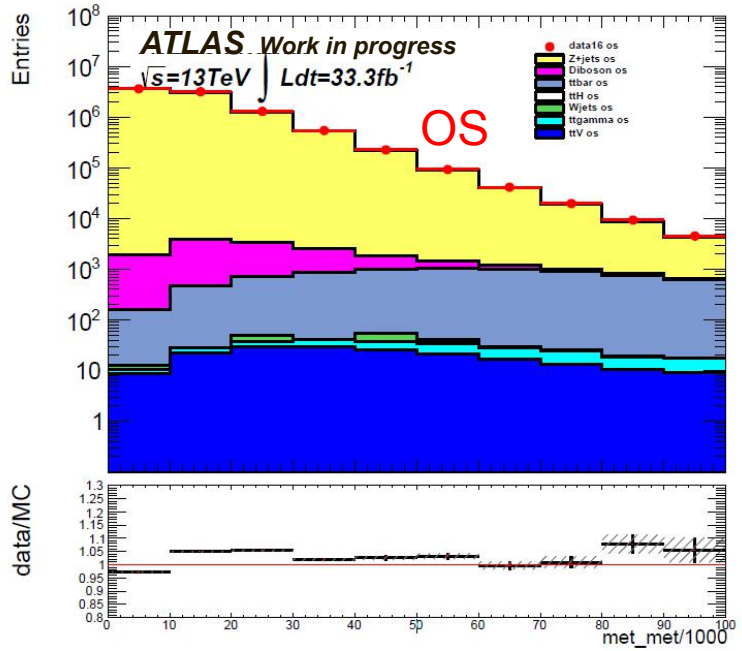
=> Aim at 3 sigma evidence

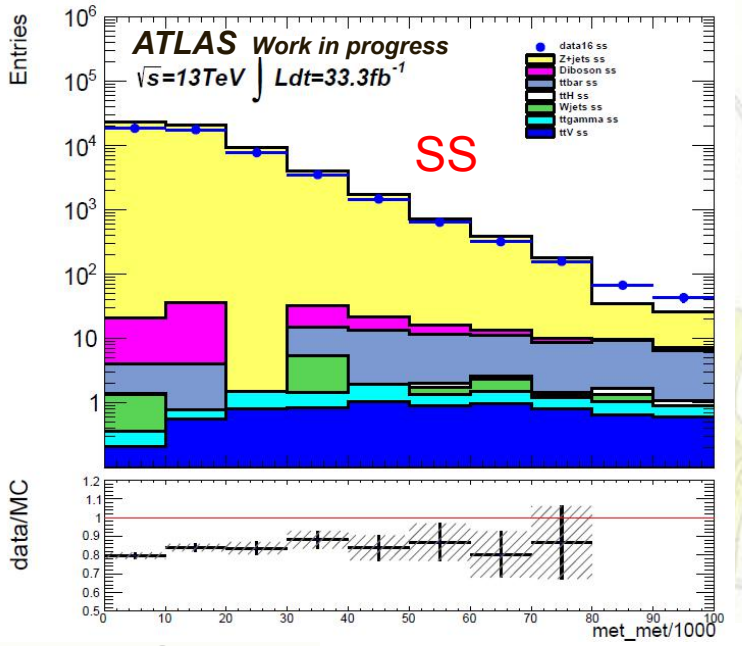
Charge misID study

performed on Z->ee events



data/MC difference
almost below 5 %





QmisID rate extraction using likelihood method

=> pT binning: {28,60,90,130,1000} GeV

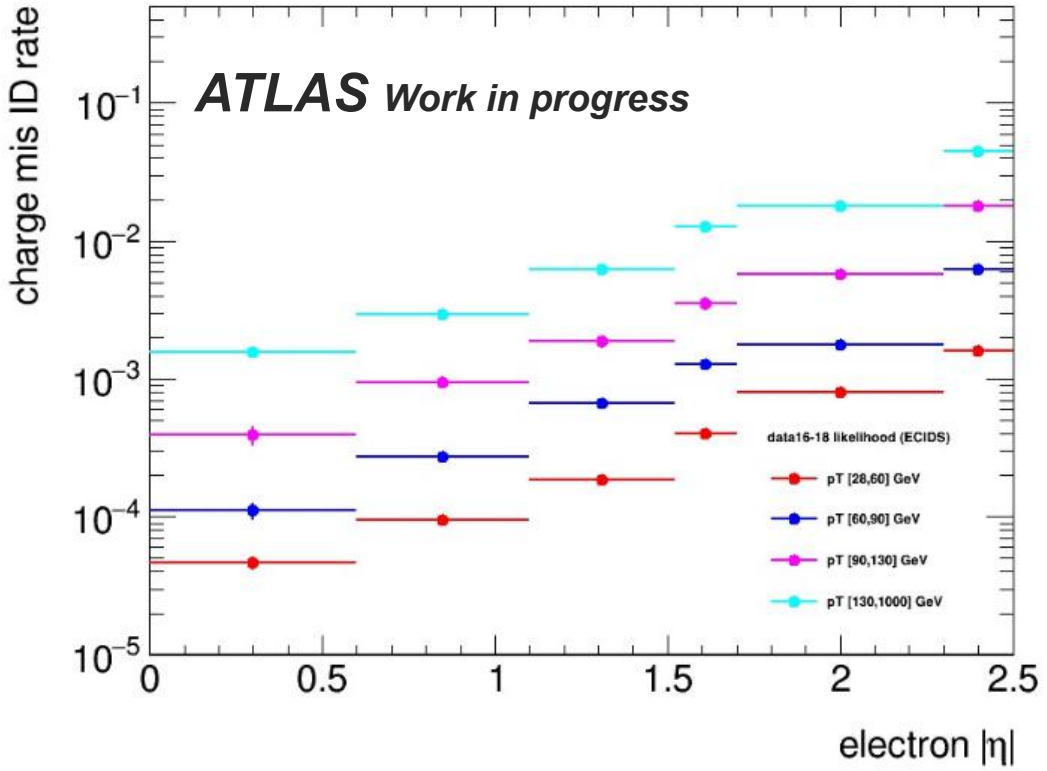
=> |eta| binning: {0,0.6,1.1,1.52,1.7,2.3,2.5}

Performed in Z->ee events in data

=> Minimizing the following function to extract the best fitted QmisID rates

$$-\ln L(\epsilon|N_{ss},N) \approx \sum_{i,j,k,l} \ln[N^{ij,kl}(\epsilon_{i,k}+\epsilon_{j,l})]N_{ss}^{ij,kl} - N^{ij,kl}(\epsilon_{i,k}+\epsilon_{j,l}).$$

extracted rates =>



MVA setup && BDT input

Default settings:

=> BDT model with Gradient boosting

=> 16 input variables:

- H_T, jet/lepton's p_T, missing E_T
- distance between (l,l) (l,j) (l,b)
- Sum over MV2C10 b-tagging socre

=> Training on LO 4tops signal against all backgrounds

=> Application on NLO signal

=> Combined fit on BDT output distribution in all the signal regions

BDT hyper-parameter optimization

Default BDTG setting.

=> stat. only significance

nBtags	nTrees	Shrinkage	nMaxDep	Sample Fraction	Significance
>=2	1000	0.10	4	0.50	3.87443
>=2	1000	0.10	2	0.50	3.9952
>=2	750	0.10	2	0.50	3.89603
>=2	500	0.10	2	0.50	3.84626
>=2	250	0.10	2	0.50	3.93919
>=2	1000	0.05	2	0.50	3.8702
>=2	1000	0.20	2	0.50	3.90817
>=2	1000	0.10	2	0.20	3.80704
>=2	1000	0.10	2	0.35	3.81605
>=2	1000	0.10	2	0.65	3.93425
>=2	1000	0.10	2	0.8	3.86061

~ 3% improvement

Summary

=> Two seperate 4 tops searches (1LOS and SSML) at ATLAS with 36.1 fb^{-1} dataset were reviewed. SM and several BSM scenarios are investigated.

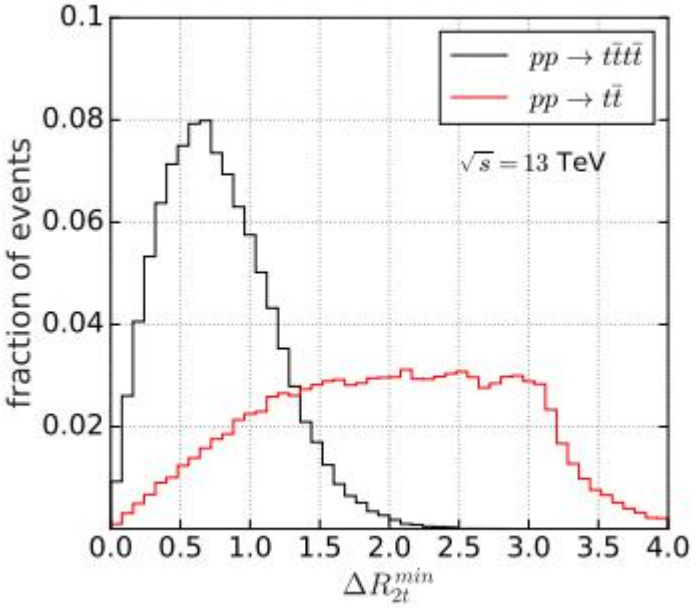
=> In Standard Model SSML channel analysis, the highest significance comes from 3b3l signal region, which is 2.1.

=> Combined result of the upper limit on SM 4tops production cross section observed (expected) is 49(19) fb, which is 5.3(2.1) times the SM prediction. The corresponding signicance is 2.8 (1.0). The excess mainly comes from SSML channel.

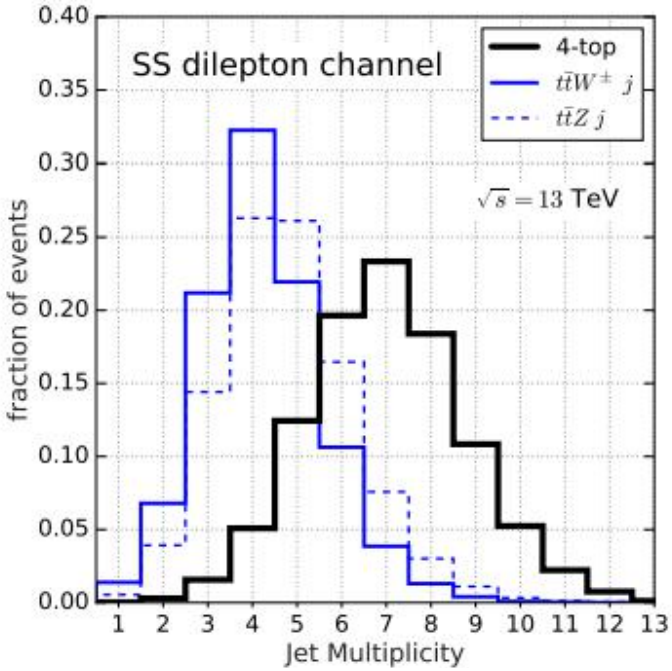
=> Full Run-2 analysis ongoing. Aim at 3 sigma evidence!

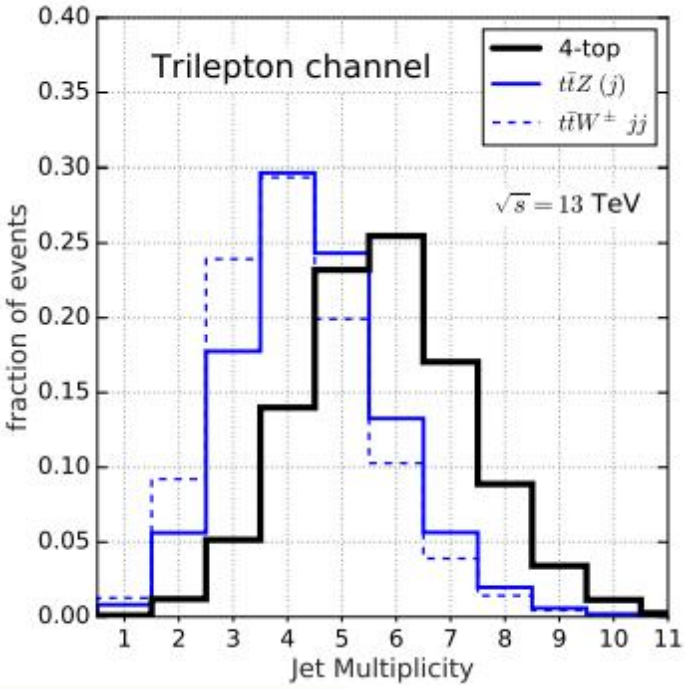
backup

Signal/background features



minimum distance between any top quark pair

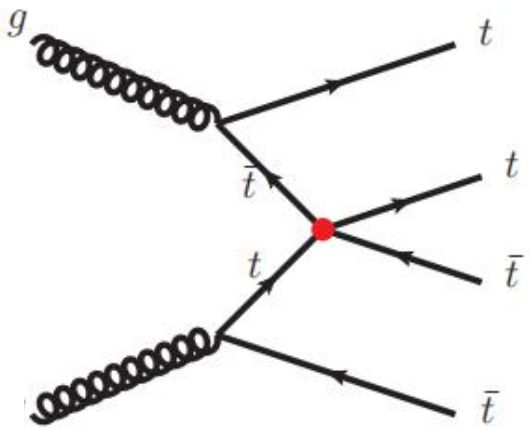


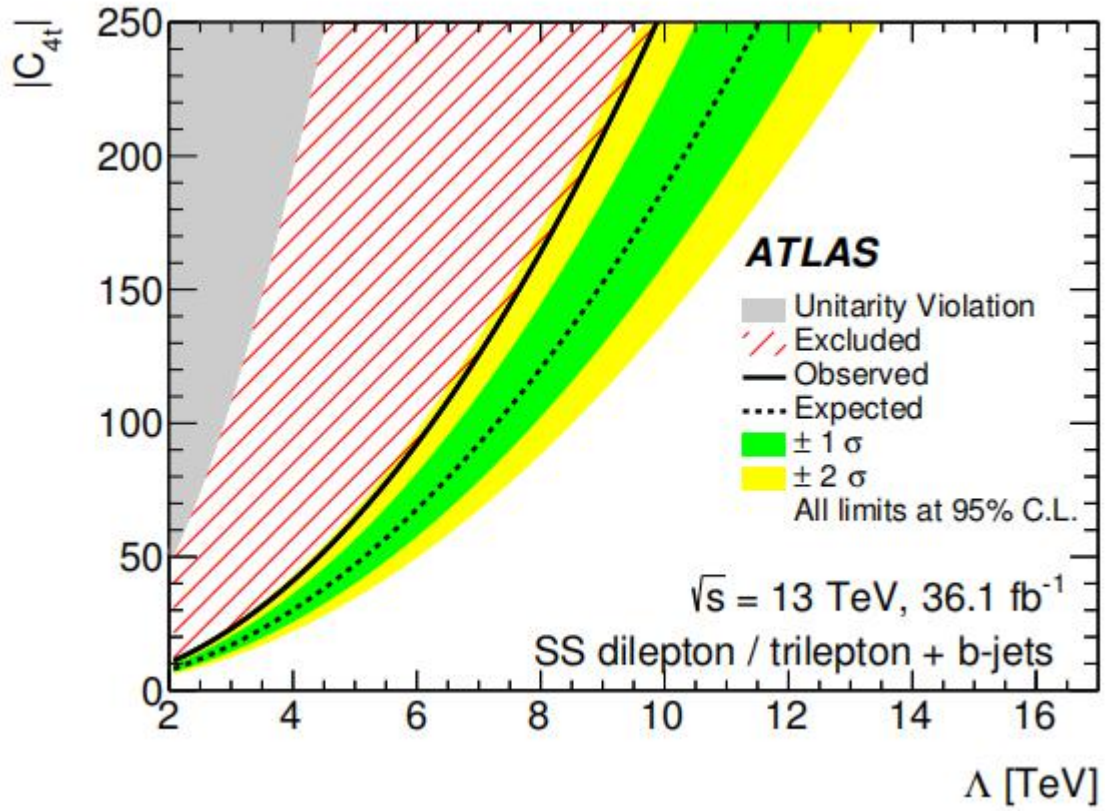


BSM searches

Contact Interaction model

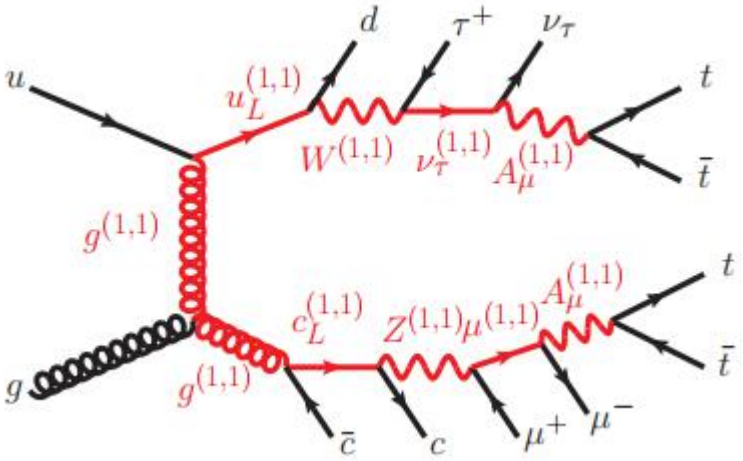
$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2} \left(\bar{t}_R \gamma^\mu t_R\right) \left(\bar{t}_R \gamma_\mu t_R\right)$$

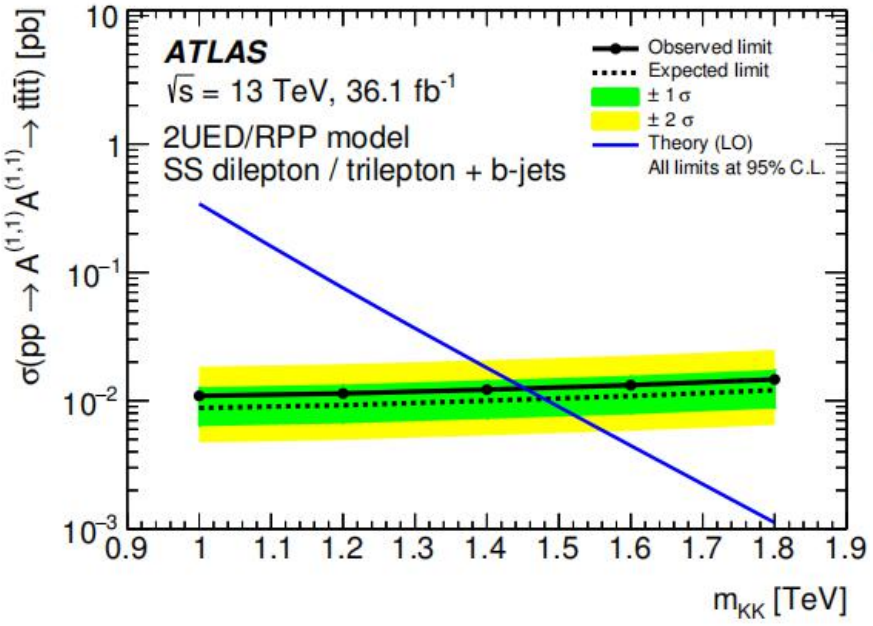


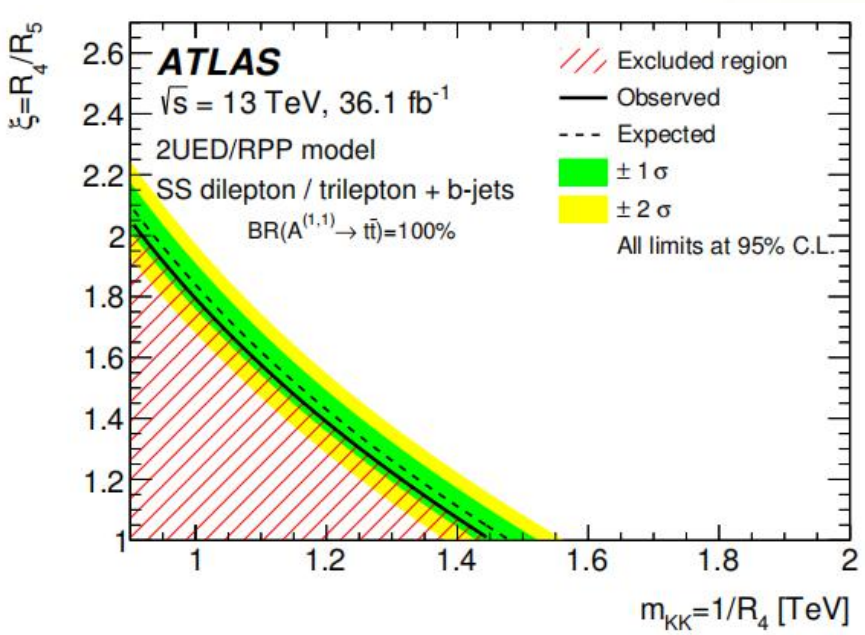


BSM searches

2UED/RPP model





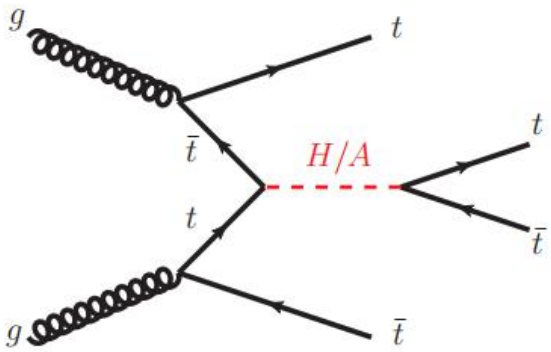


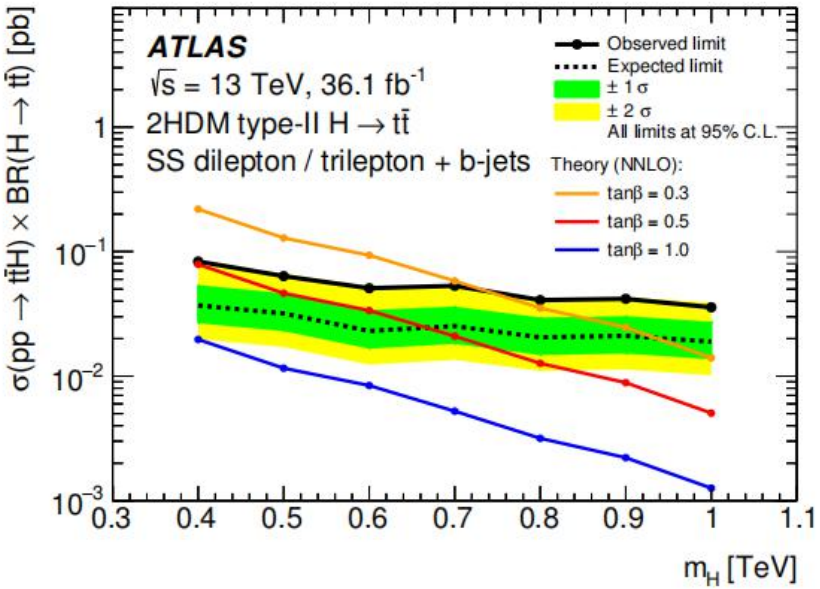
Constraints on Kaluza-Klein mass:

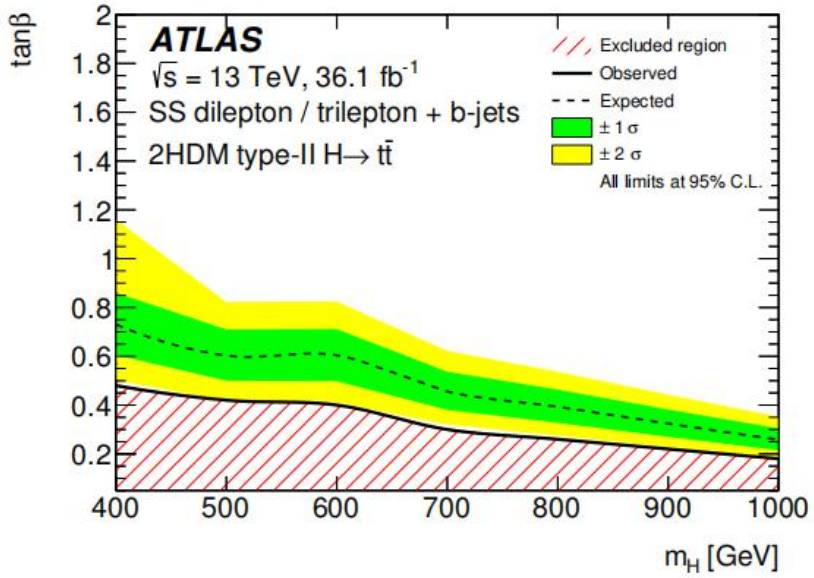
m_{KK} > 1.45 TeV (1.48 TeV) (assuming B($A^{(1,1)}$->tt) = 100%)

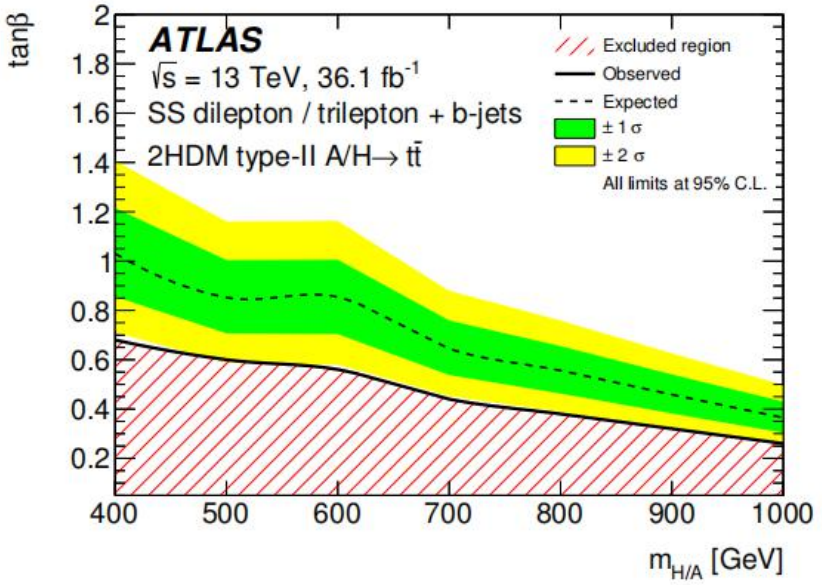
BSM searches

2HDM









Correlation Matrix && BDT output