$t\bar{t}V$ production as a background in ATLAS and CMS

Elizaveta Shabalina

University of Göttingen

Many thanks to Marco Peruzzi, Josh Thomas-Wilsker and Didar Dobur (CMS) for their help in preparation of the talk

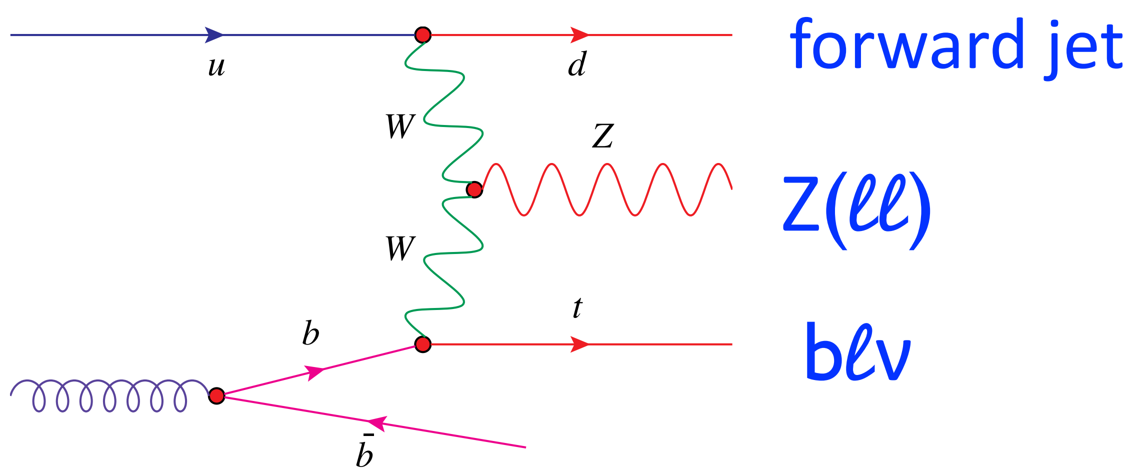
Introduction

- Many searches of rare processes including top quarks are performed in the multilepton final states
- Such final states have significant contributions from associated production of top quark pair with vector bosons
  - $t\bar{t}Z$ and $t\bar{t}W$ are rare processes by themselves and not yet very well measured
- Normalisation of these processes are often free parameters of the fit or large prior uncertainty is assigned to it
- MC simulation:
  - Pythia 8 for parton shower with respective ATLAS and CMS tunes
  - $t\bar{t}Z$: MadGraph5_aMC@NLO NLO ME (no additional partons)
  - $t\bar{t}W$: MadGraph5_aMC@NLO NLO ME with up to 1 (0) additional partons at NLO for CMS (ATLAS)
  - new nominal in ATLAS ttH multilepton analysis: Sherpa 2.2.1 MePs@Nlo with up to 1 additional parton at NLO and up to 2 partons at LO

Measurements of tZq production

tZq measurement

ATLAS-CONF-2019-043
Phys. Rev. Lett. 122 (2019) 132003



Selection

- 3 leptons
  - opposite sign same flavour pair within Z mass window
- 2 to 4 jets
- 1 or 2 b-tags

	2J	3J	4J
2b		CR ttZ (A)	CR ttZ (A) SR (CMS)
1b	SR	SR	SR (CMS)
0b	CR WZ	CR WZ	

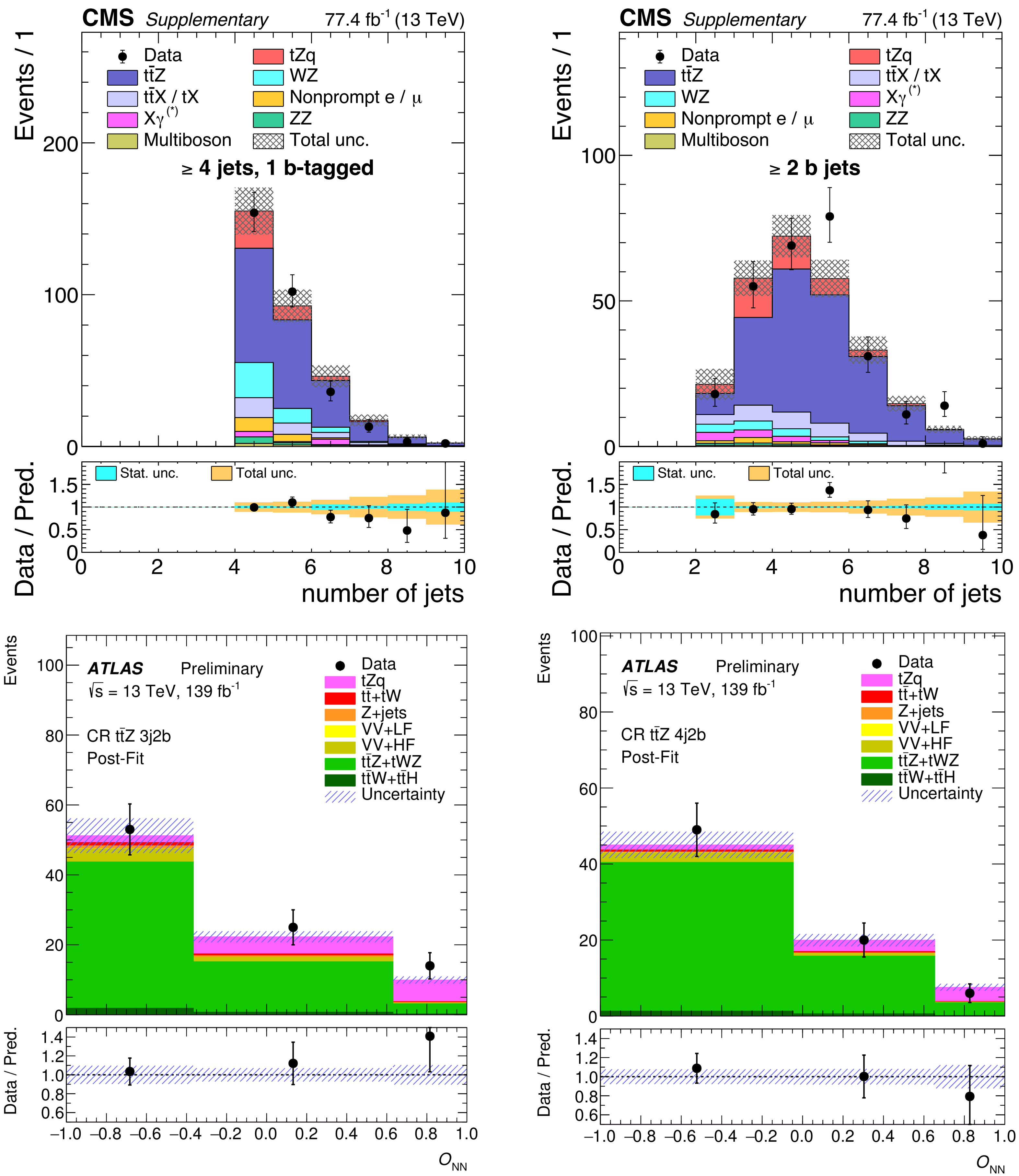
Backgrounds

- non-prompt leptons
  - Data driven (CMS)
  - MC-based shape, free floating normalisation (ATLAS) from 2 dedicated CRs
- WZ+b-jets
- ttZ
  - dominant background in 4j1b and 4j2b CMS SR regions

ttZ systematics

- normalisation
  - 12% (15%) prior A(CMS)
- shape
  - ISR scale variation in parton shower
  - μ_R and μ_F scale variations by 2 and 1/2 in ME
  - (A) MG5_MC@NLO vs Sherpa LO with additional jets
  - (CMS) FSR scale variation in parton shower

ttZ dominated regions

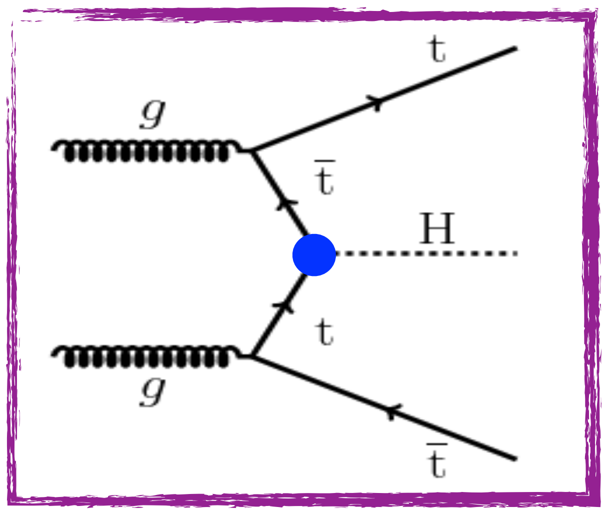


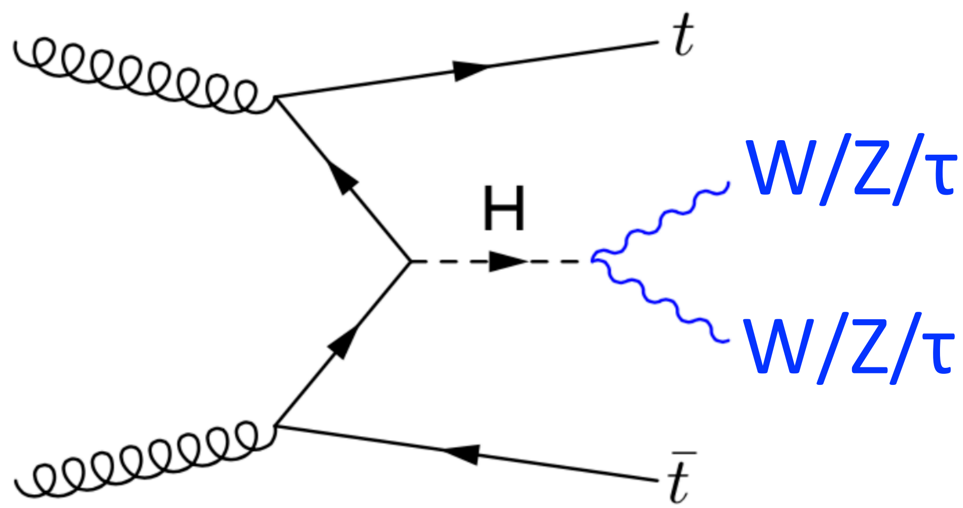
- Postfit distributions
- Small pull towards higher values is observed for $t\bar{t}Z$ normalisation by both collaborations (exact values are not public)
- For ATLAS it is driven by some data/MC tension in 3j region
- Modelling of $t\bar{t}Z$ with one lost jet from $t\bar{t}$ is important

Measurements of ttH in multilepton final state

ttH

ATLAS-CONF-2019-045
CMS-HIG-18-019-pas
CMS: JHEP 08 (2018) 066

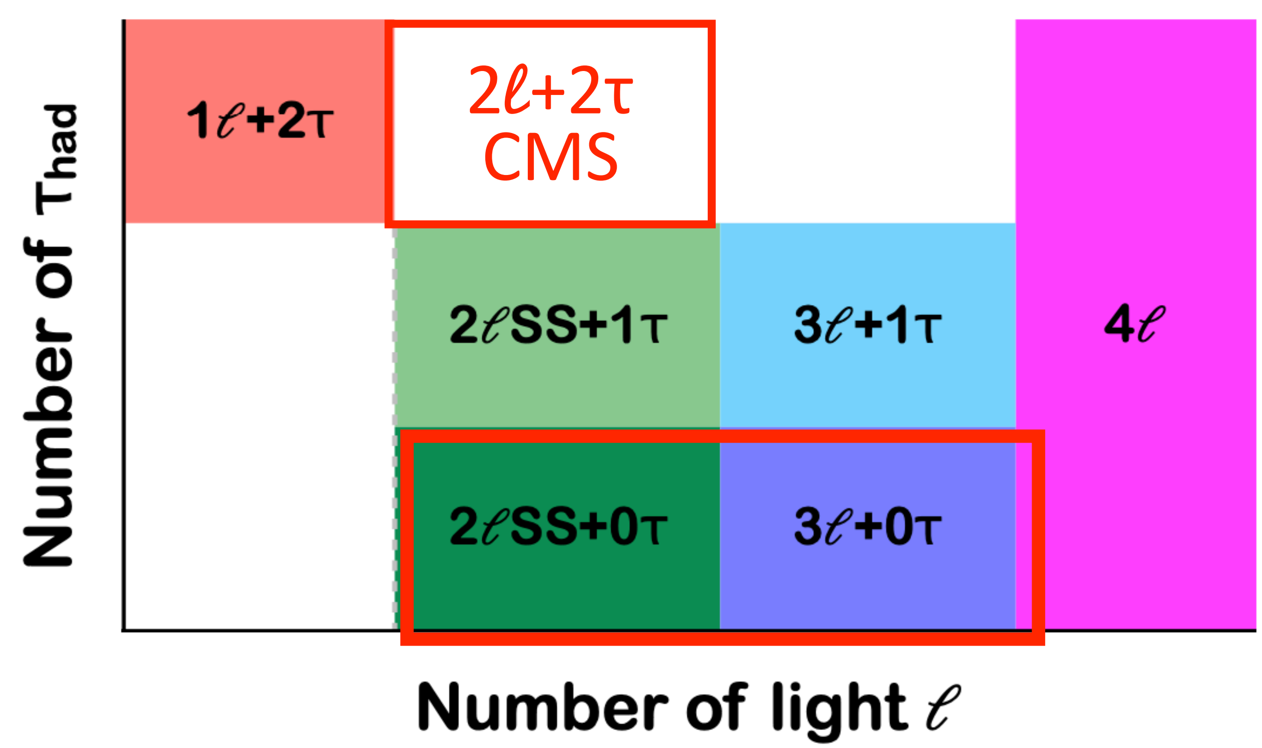




Leptonic decays of W/Z bosons and τ decays

Dilepton or single lepton decay of tt pair

- Backgrounds
  - irreducible
    - **t̄tZ/W**, VV
  - reducible
    - non-prompt ℓ, charge misID electrons, and electrons from photon conversions



ttV normalisation

tt(Z/γ*): NLO in QCD with off shell contribution with $m(\ell^+\ell^-)>1$ GeV (YR4)

ttW: NLO in QCD with the leading NLO EW corrections (YR4)

ttV normalisation

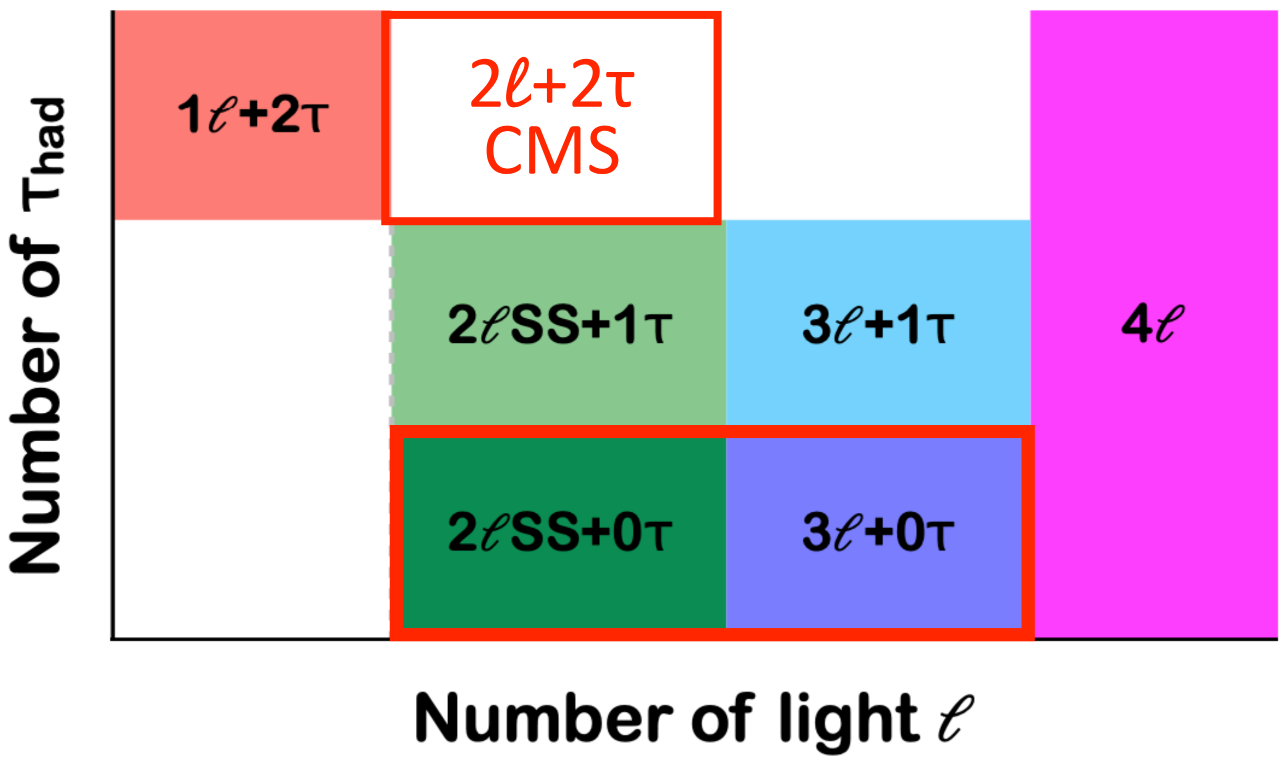
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

tt(Z/γ*): NLO in QCD with off shell contribution with $m(\ell^+\ell^-)>1$ GeV (YR4)

ttW: NLO in QCD with the leading NLO EW corrections (YR4)

- Study motivated by observed tension between prediction and data
- Baseline: MadGraph5_aMC@NLO MC w/o extra jets
  - identify effects not included in baseline simulation
- Source 1: QCD corrections
  - ttW+0j@NLO ➜ $t\bar{t}$ W+0,1j@NLO accounts for missing QCD corrections in higher order XS
  - Sherpa 2.2.5 using the MEPS@NLO cross-checked with the NLO MadGraph5_aMC@NLO 2.2.1 with FxFx, both with 1 jet @NLO
  - Yields a factor 1.11
- Source 2: missing EW corrections [1711.02116]
  - "subleading" NLO EWK corrections, not included in YR4 XS, can be large primarily because of the large NLO3 term driven by the ttW+1-jet diagrams with a Higgs boson exchanged in the t-channel
  - Yields a factor 1.09
- **Overall normalisation factor of 1.2 is applied on top of YR4 on ttW cross section ONLY in new ATLAS ttH multilepton analysis**

ttH



- Most sensitive channels
  - 2ℓSS and 3ℓ
- Similar strategy in ATLAS and CMS analysis

Basic selection (simplified)

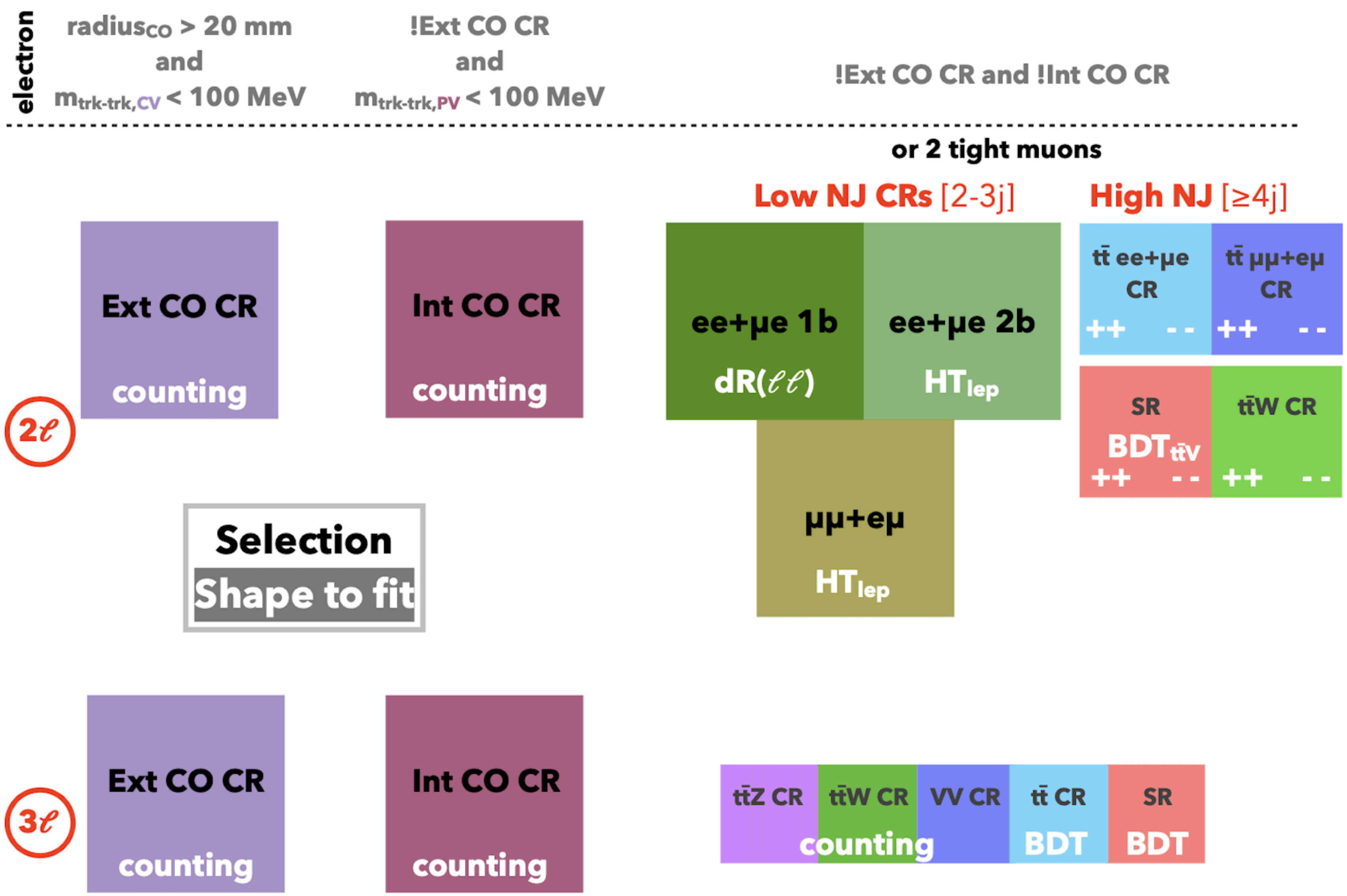
2ℓSS	3ℓ
≥4j, ≥1bj	≥2j, ≥1bj $\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV

- MVA discriminants are trained in regions after basic selection
- Lower jet multiplicity regions (nj=3 in CMS and 2≤nj≤3 in ATLAS) are used to control backgrounds

- Different CRs between ATLAS and CMS are motivated by different fake lepton background estimate
- CMS: data-driven fake factor method
- ATLAS: MC-based template method with 4 free parameters in the fit for various components:
  - HF electron, HF muon
  - material conversions
  - internal conversions

Signal extraction

- BDTs are trained to separate ttH from ttV and ttH from tt+jets (i.e. non-prompt background)
  - **CMS:** discriminant in subcategories based on lepton flavor, charge and b-tagging



ATLAS:

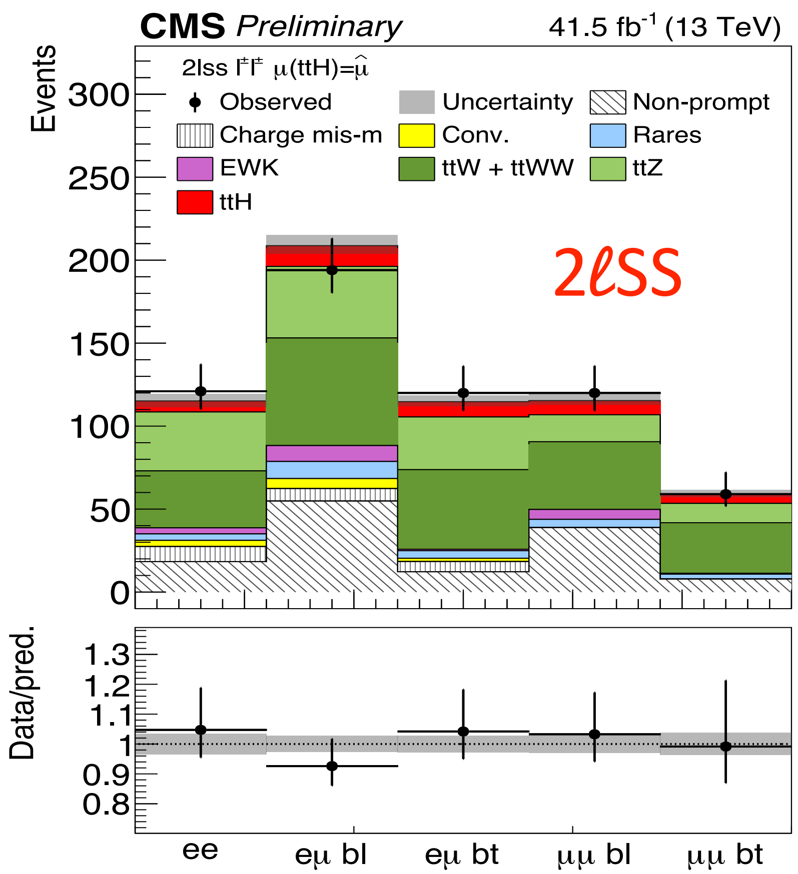
17 control subcategories based on lepton flavour, charge and b-tagging and to control the conversions

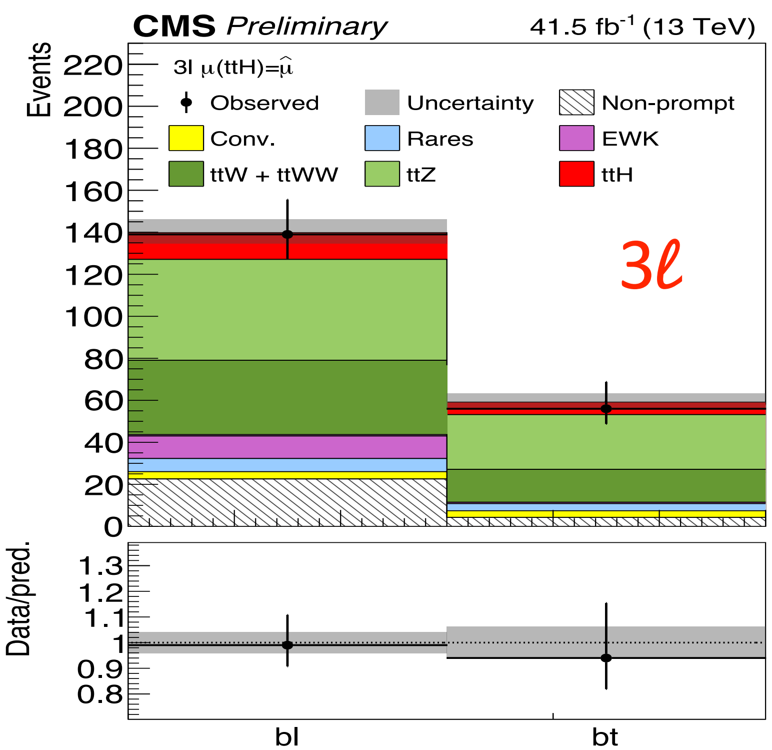
3 signal regions

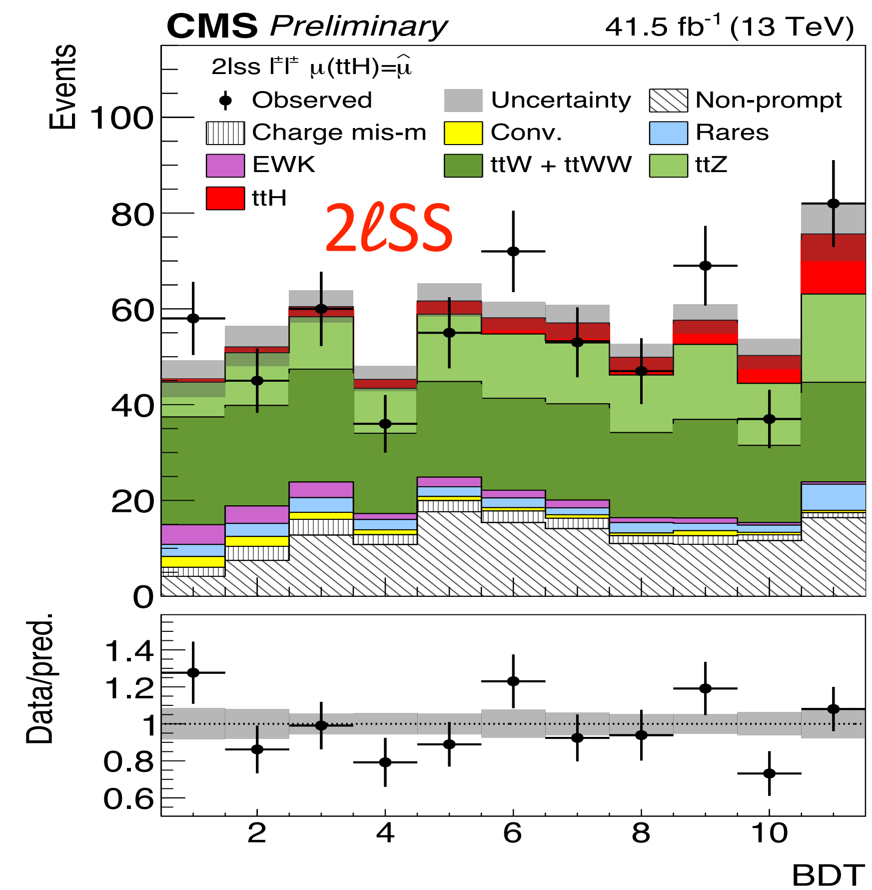
CMS: 2017 analysis

Signal regions postfit

CMS-HIG-18-019-pas





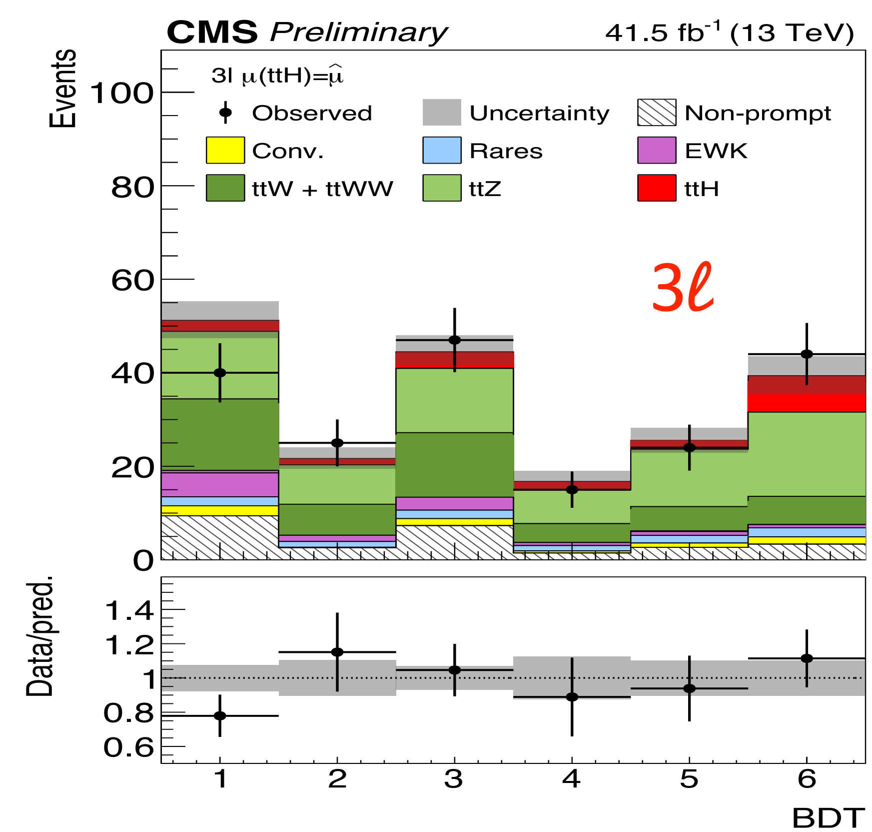


Category	$2\ell ss$	3ℓ
$t\bar{t}H$	43.0 ± 7.1	18.8 ± 4.8
$t\bar{t}W + t\bar{t}WW$	218.5 ± 13.7	51.0 ± 5.3
tH	2.4 ± 0.1	0.9 ± 0.1
$WZ + ZZ$	< 0.05	12.0 ± 1.7
$t\bar{t}Z/\gamma^*$	138.2 ± 7.6	74.1 ± 6.3
Misidentified	132.1 ± 10.0	26.8 ± 4.0
Conversions	11.6 ± 3.0	6.6 ± 1.3
Signal flip	22.8 ± 2.3	< 0.05
Other	26.7 ± 3.9	9.7 ± 2.2
SM expectation	595.3 ± 20.6	200.0 ± 10.8
Observed data	614	195

ttV: ~60%

2ℓSS: 24%

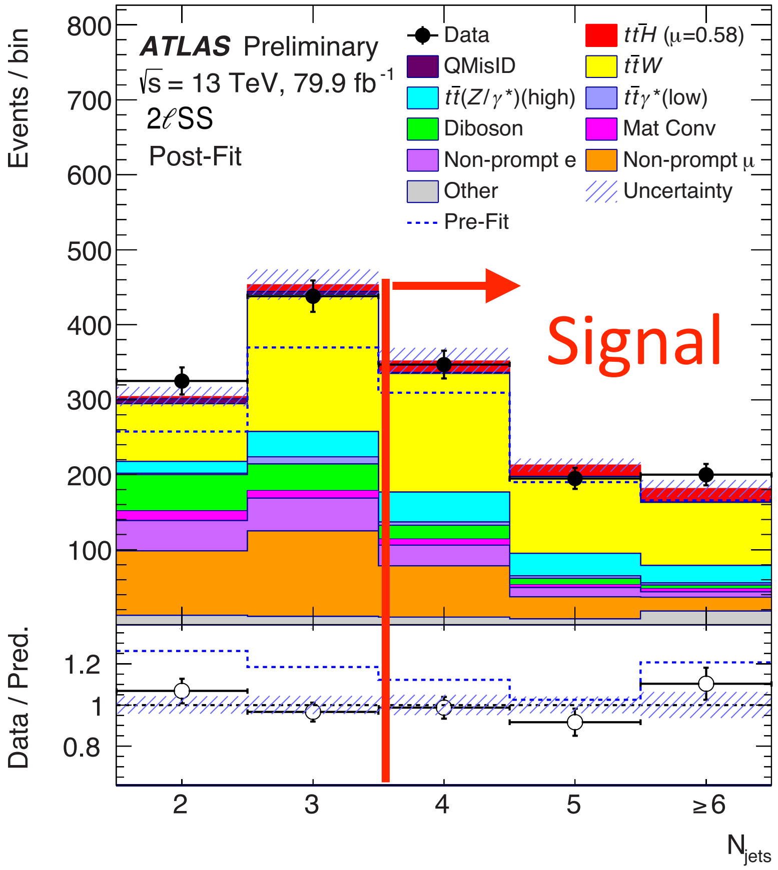
3ℓ: 16%

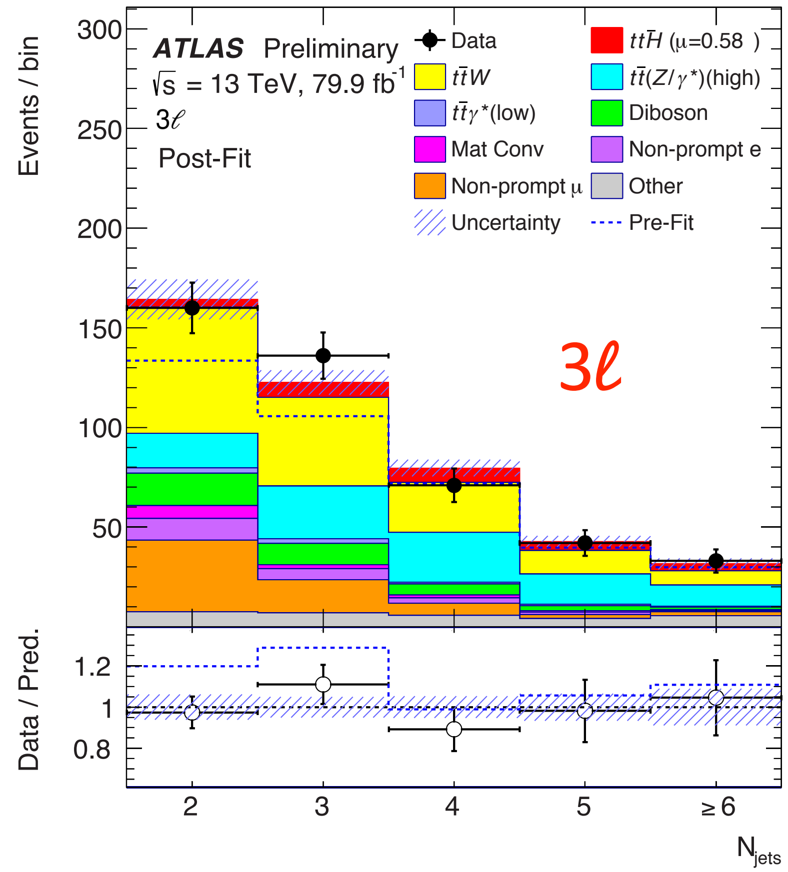


ATLAS control regions

2ℓSS

ATLAS-CONF-2019-045

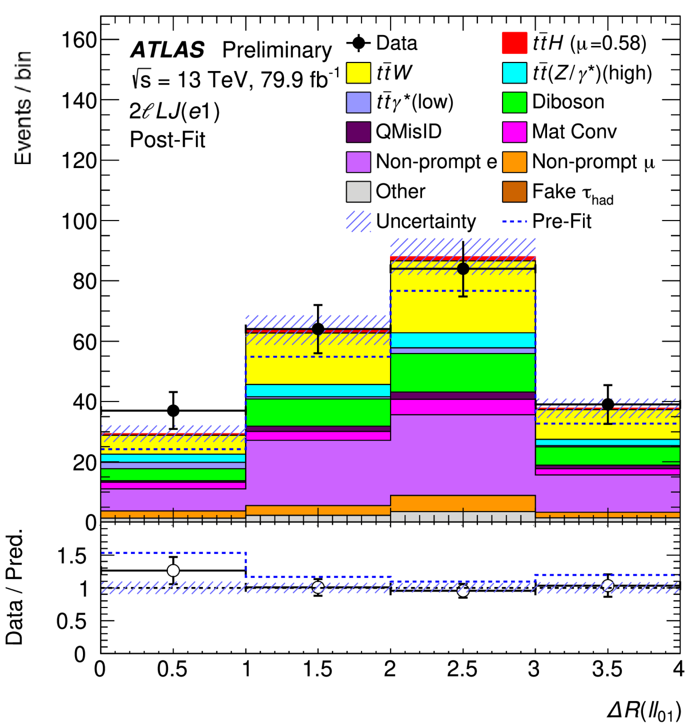


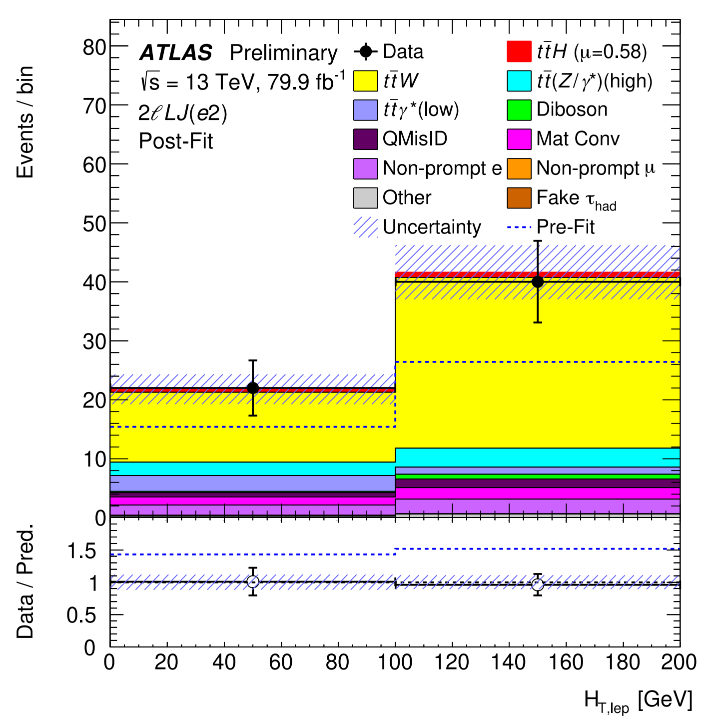


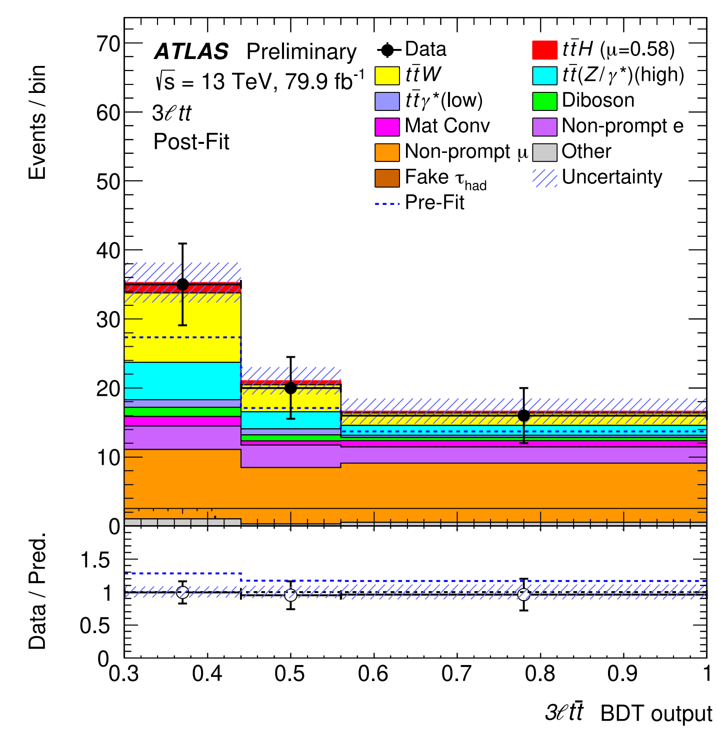
Plots after basic selection including low jet multiplicity

Prefit distributions show tension between data and prediction

variables used in the fit in control regions







CMS: fit setup and results

- 7 categories
  - 2lSS and 3l split into subcategories based on lepton flavour, lepton charge and b-tagging
- Control regions
  - no CRs included in 2016 analysis
  - ttW CR in 2017 analysis (nj=3)
  - ttZ CR via inverting Z window veto
  - Diboson CR via b-tag veto

- ttV systematics
  - shape: μ_R and μ_F scale variations by 2 and 1/2 (7 variations)
  - normalisation:
    - 2016: Gaussian constraint: ~12% (ttZ), ~14% (ttW) and cross check with free floating
    - 2017: free floating

	baseline	free floating
2016 results	$\mu_{t\bar{t}H} = 1.23^{+0.45}_{-0.43}$	$\mu_{t\bar{t}H} = 1.04^{+0.50}_{-0.36}$

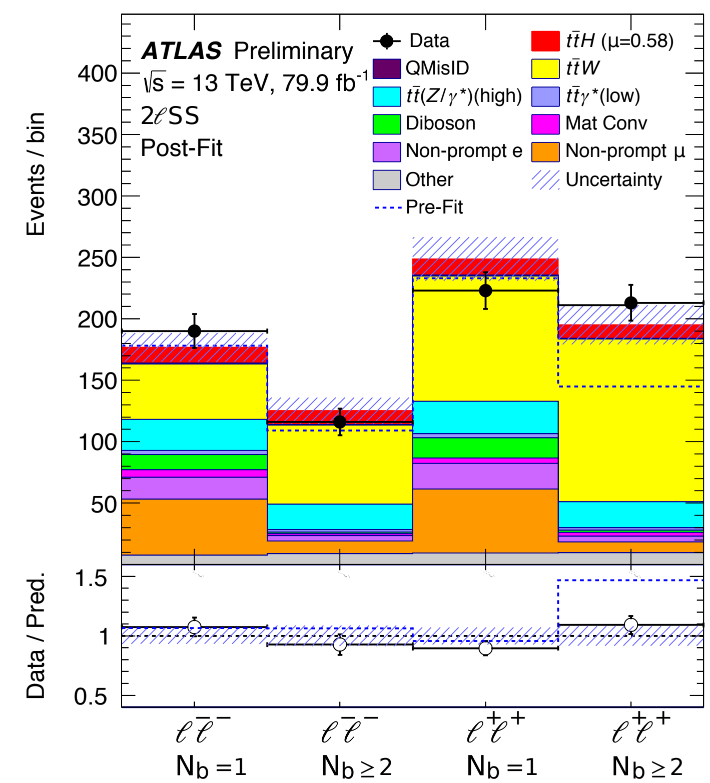
no information on SFs or pulls in given by 20% effect on POI suggests significant increase of the background yield

- 2017 SFs $\quad \mu_{t\bar{t}W} = 1.42^{+0.34}_{-0.33} \quad \mu_{t\bar{t}Z} = 1.69^{+0.39}_{-0.33}$

ATLAS: fit setup and systematics

- 25 categories (including τ channels)
  - 17 categories in 2lSS and 3l control backgrounds including ttZ, ttW and VV
    - 13 use event counts
    - 4 use kinematic variables to discriminate ttW from tt+jets
  - 8 signal categories with BDT in 2ℓSS and 3ℓ and 1ℓ2τ_{had} to separate ttH

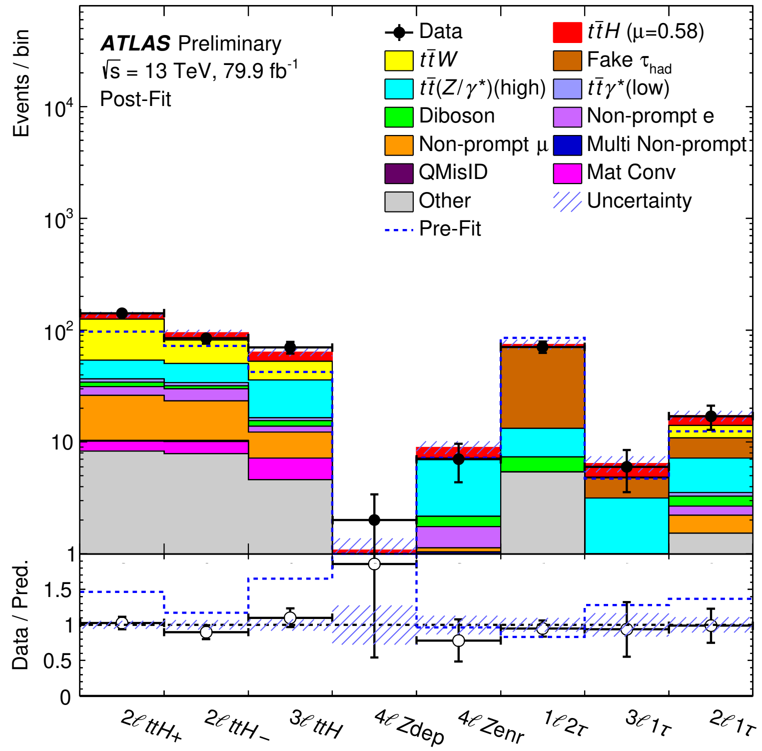
- ttV systematics
  - MC-based shape:
    - μ_R and μ_F scale variations by 2 and 1/2 simultaneously
    - radiation modelling: Sherpa vs MG_aMC@NLO
  - Data-based shape uncertainties to cover prediction vs data disagreement:
    - modelling of b-jets multiplicity
    - W charge asymmetry

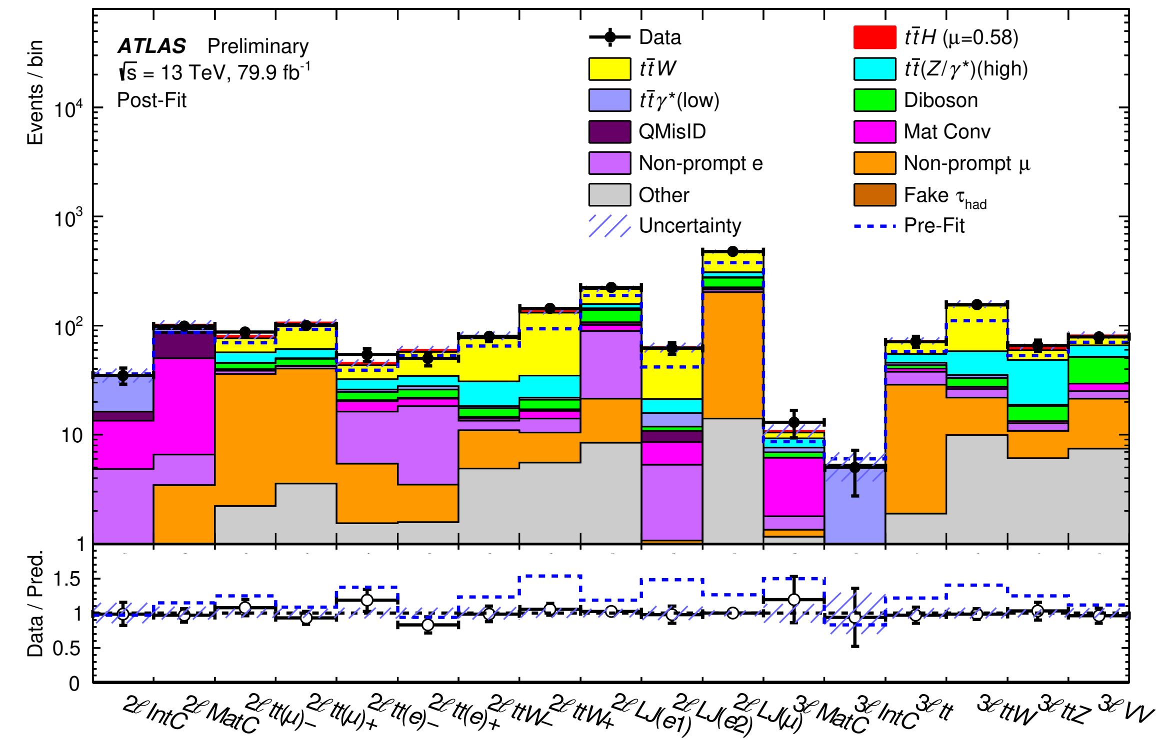


ttW normalisation : 3 free parameters to minimise impact of observed data/MC disagreement in CRs

ATLAS: results

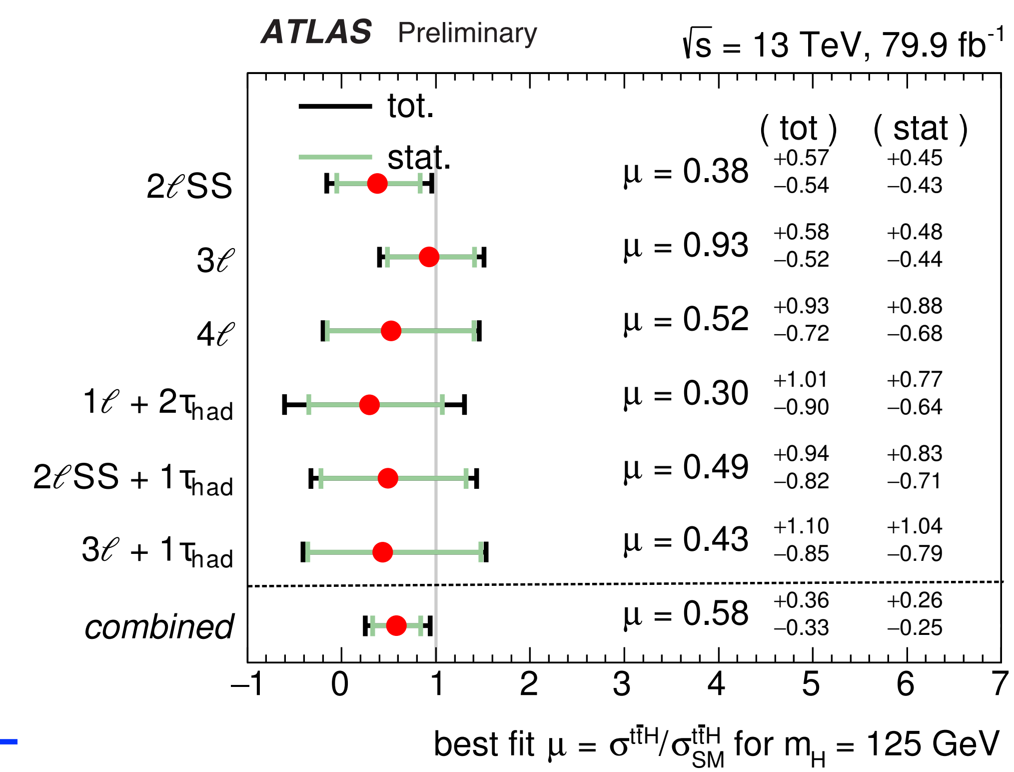
Signal regions — 2015-2017 data — **Control regions**



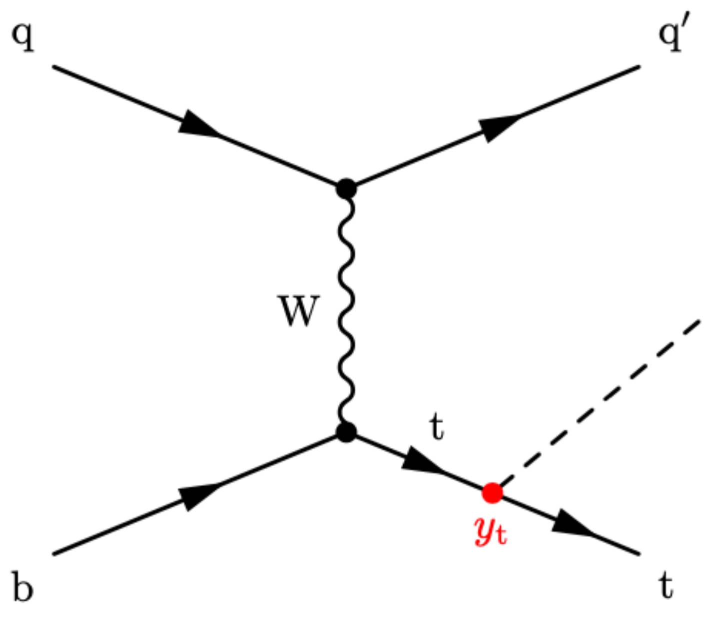


Fit setup	Baseline	Alternative
$\mu_{t\bar{t}H}$	$0.58^{+0.36}_{-0.33}$	$0.70^{+0.36}_{-0.33}$
NF (2ℓ LNJ)	$1.56^{+0.30}_{-0.28}$	$1.39^{+0.17}_{-0.16}$
NF (2ℓ HNJ)	$1.26^{+0.19}_{-0.18}$	
NF (3ℓ)	$1.68^{+0.30}_{-0.28}$	

$1.67^{+0.20}_{-0.19}$ wrt to YR4



CMS tH search



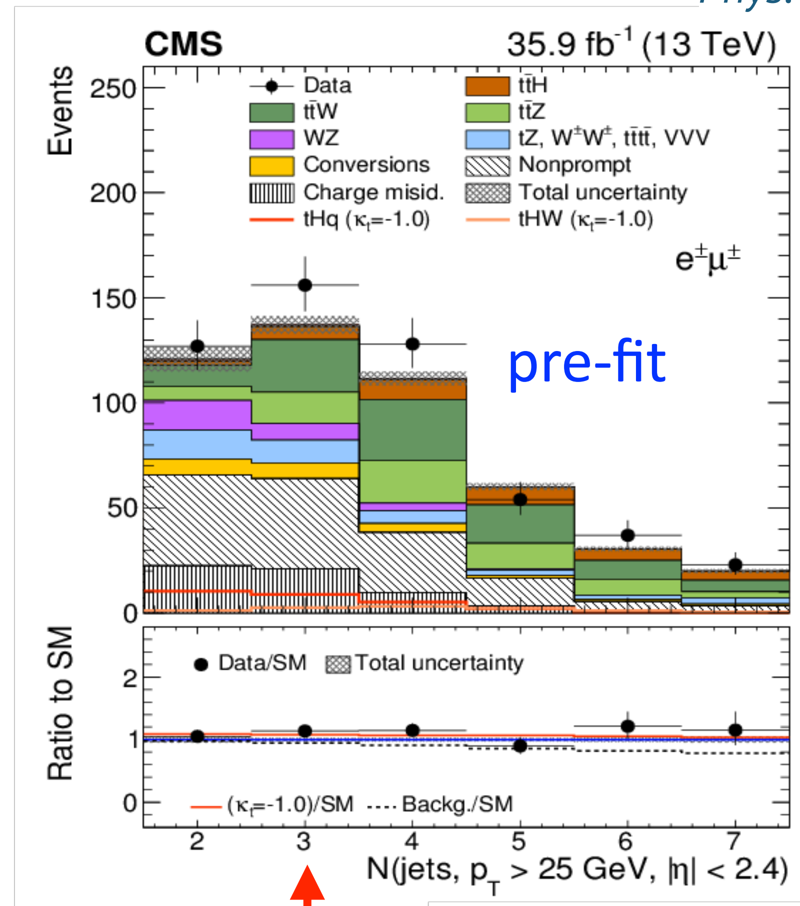
forward jet

$H \to WW$

$t \to b\ell\nu$

- 2ℓSS or 3ℓ channels
  - ≥1 b-jet, 1 forward untagged jet
  - 50% overlap with ttH ML in 2ℓSS
  - 80% overlap with ttH ML in 3ℓ
- Sensitive to same backgrounds as ttH ML but with lower jet multiplicity
  - ttV treated with a Gaussian prior as in ttH ML

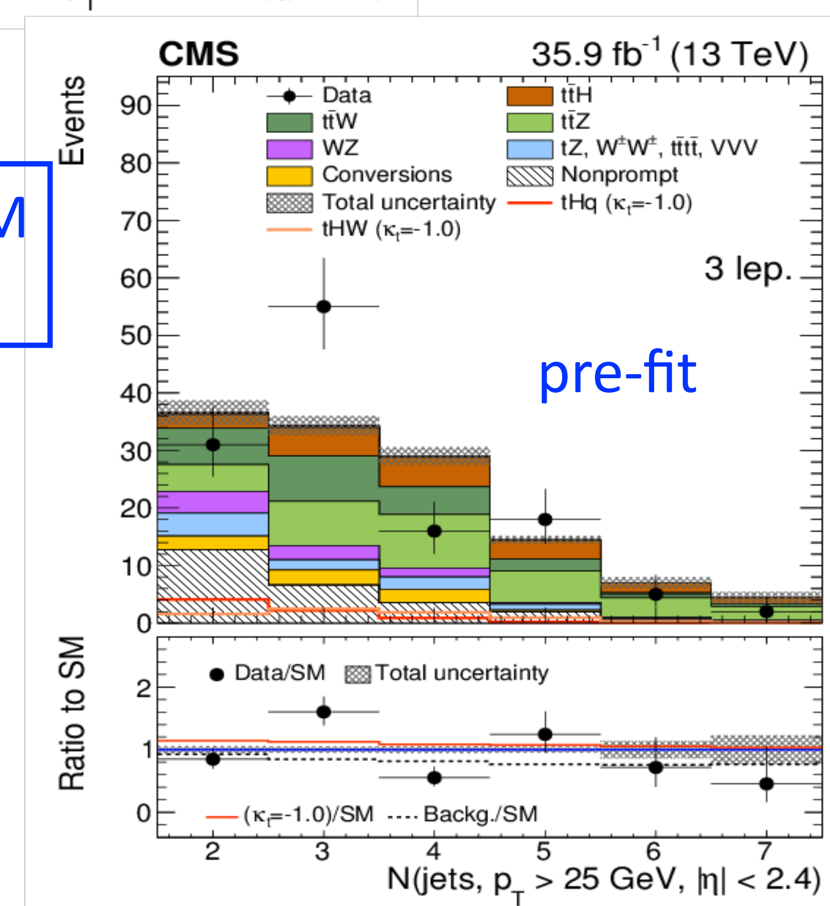
Phys. Rev. D 99 ,9 (2019) 092005



pre-fit

clear excess of data in nj=3,4 which leads to increase of the background with floating ttV in ttH ML analysis

ttW CR in ttM ML analysis

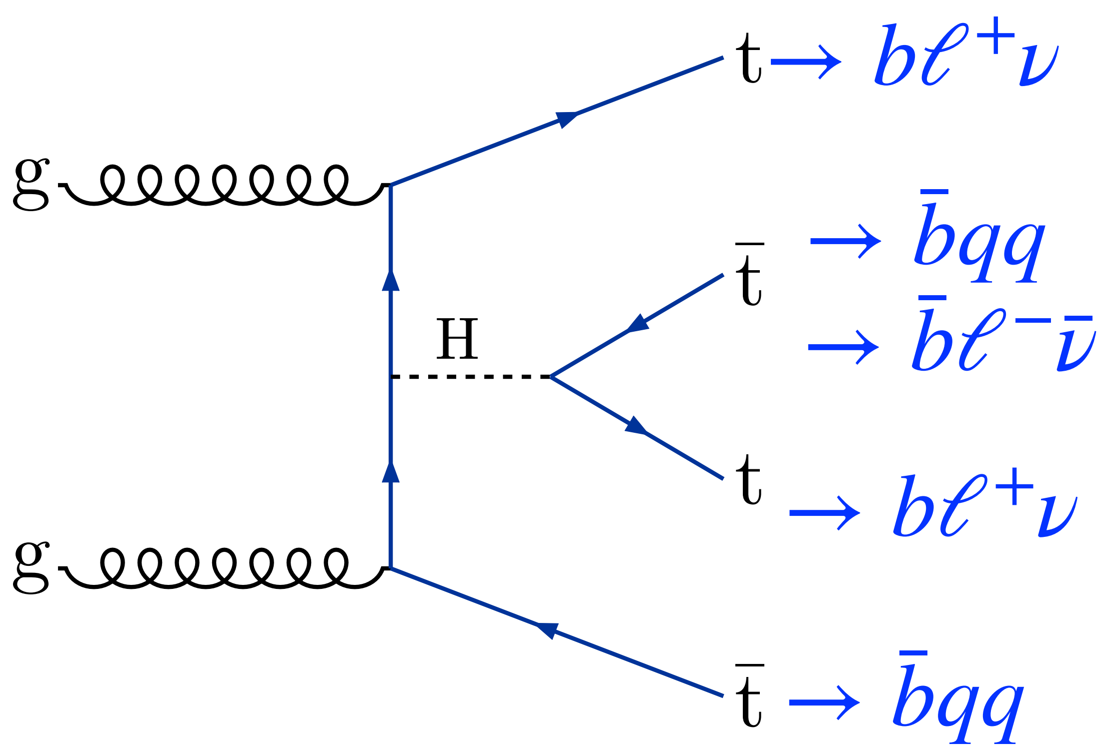


pre-fit

Searches for 4-top quark production in multilepton final state

SM 4-top search

CMS arXiv:1908.06463
ATLAS JHEP 12 (2018) 039 *



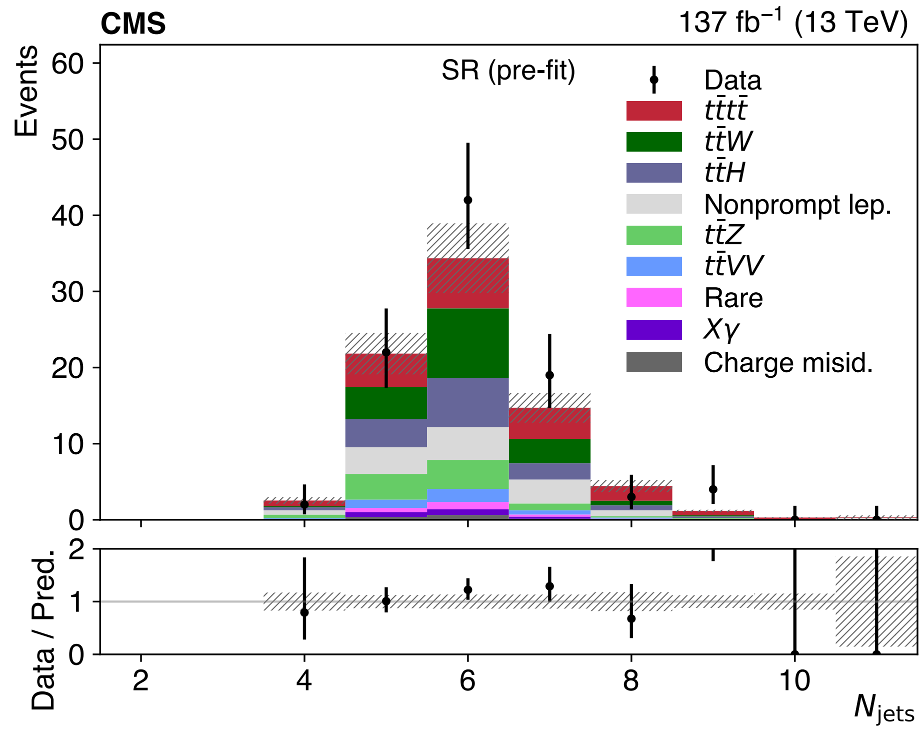
N_ℓ	N_b	N_{jets}	Region
		≤5	CRW
2	2	6	SR1
		7	SR2
		≥8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥8	SR7
	≥ 4	≥5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥7	SR11
	≥ 3	4	SR12
		5	SR13
		≥6	SR14
Inverted resonance veto			CRZ

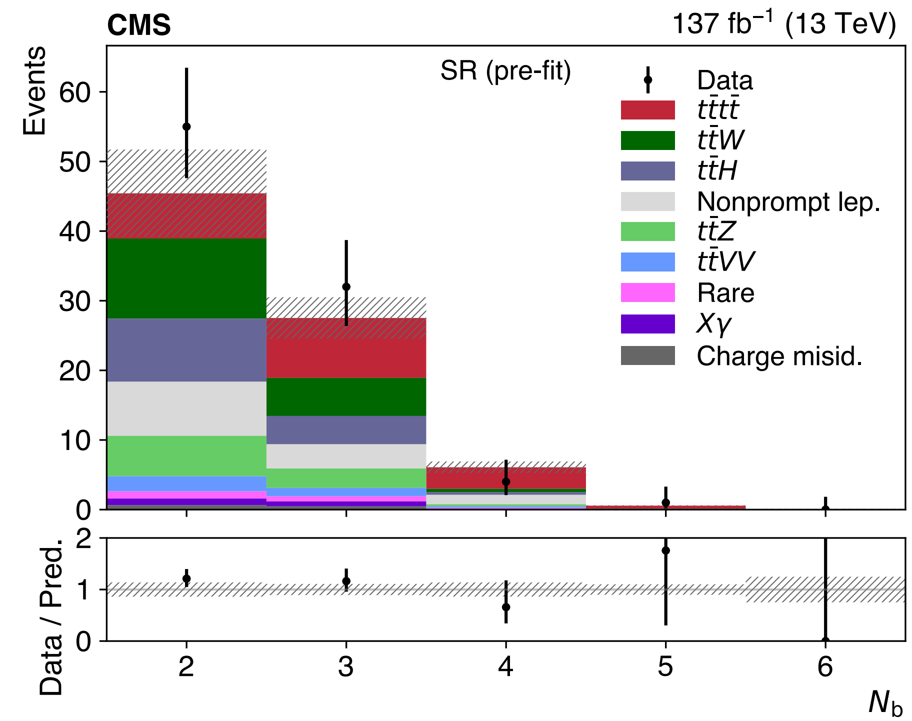
- 2ℓSS and 3ℓ channel signature
  - 4 b-jets from 4 top quarks
  - 4 or 2 jets from W
- Baseline selection
  - ≥2 jets, ≥2 b-jets
  - H_T>300 GeV
  - E_T^{miss} > 50 GeV
  - 30 GeV $Z(\ell^+\ell^-)$ mass window cut

BDT option of analysis does not have ttW CR

*optimised for BSM search

ttW/ttZ corrections





prefit plots in SR after ttV correction

Corrections of ttW, ttZ simulation (MG5_aMC@NLO+Pythia8)

with extra jets

- compare light-flavour jet multiplicity in dilepton $t\bar{t}$ events in data and MG5_aMC@NLO+Pythia8
- derive correction and apply as weight to ttV
- weights vary between 1.46 and 0.77 for 1 to 4 additional jets

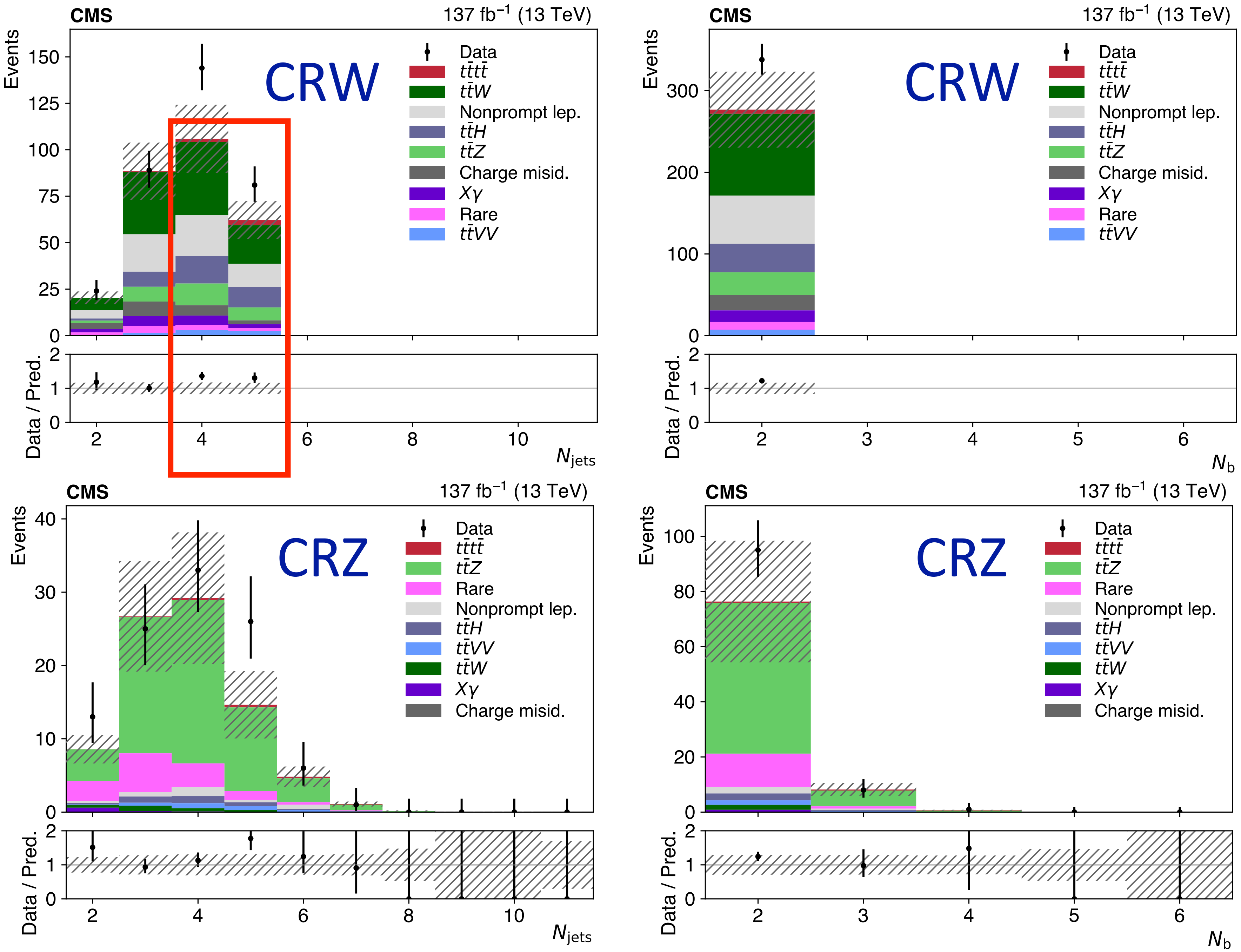
with extra b-jets

- factor of 1.7±0.6 is applied to improve modelling of extra heavy flavour jets
- value is based on measured ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ ratio
- 70% increase of events with additional $b\bar{b}$ pair

Uncertainties on corrections are included in systematics

4-top search: ttW/ttZ CR

Prefit plots



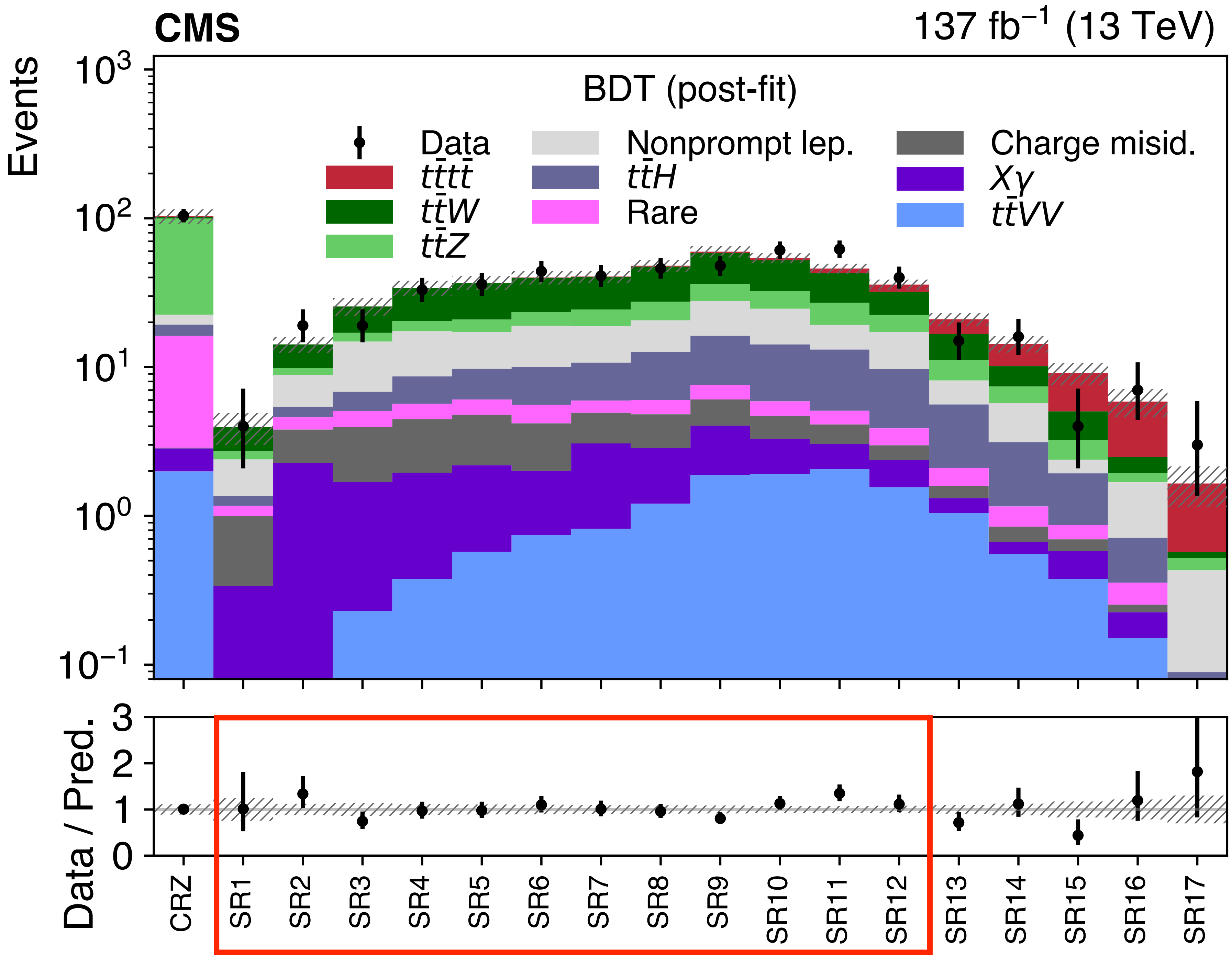
- ttW CR: excess of data over prediction for nj=4,5
- ttZ CR: excess in nj=5

Systematics

- Normalisation: 40% Gaussian prior
- Shape: μ_R and μ_F scale variations by 2 and 1/2

Fit scales ttZ and ttW normalisations by 1.3 ± 0.2

4-top search result

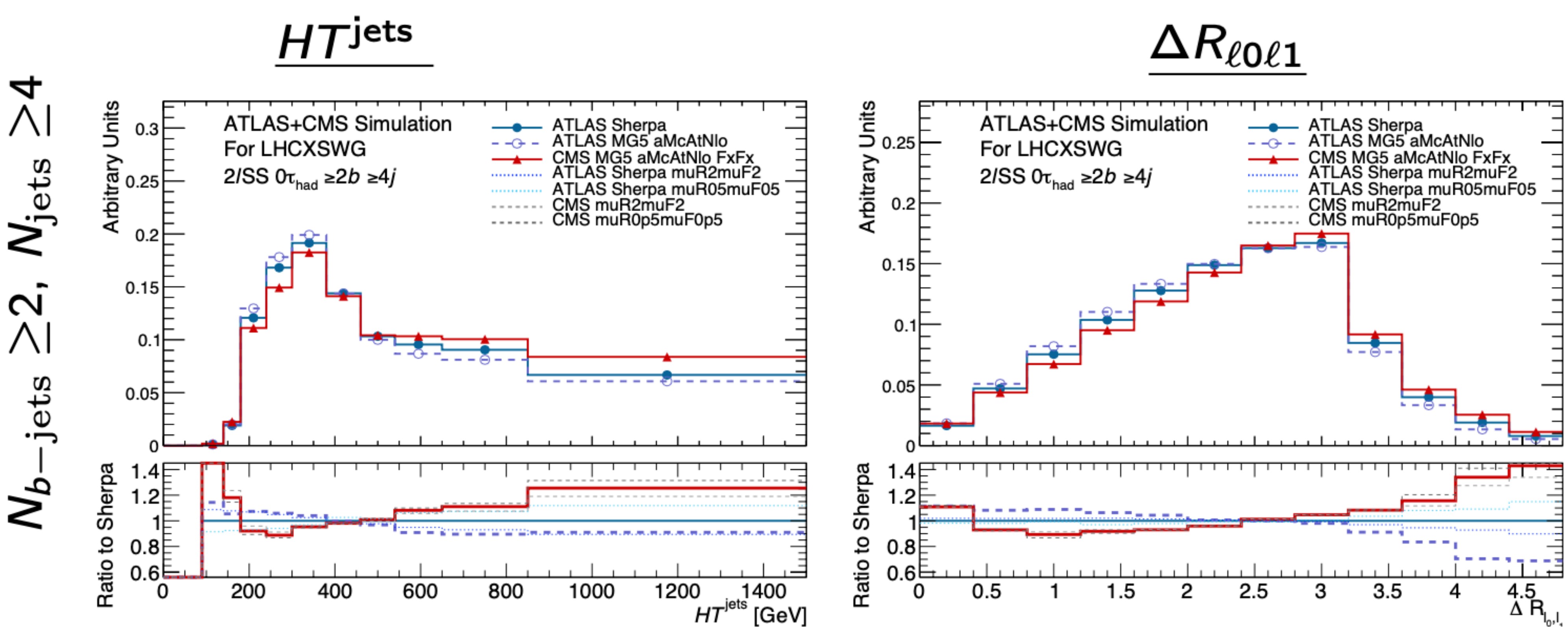


- In BDT analysis ttW is constrained by regions with low BDT score

ttV modelling in ATLAS and CMS

- Within LHCHiggsWG CMS and ATLAS started combine effort to compare ttW at truth level (see talk by K.Grevtsov)
- First step: compare generators and systematic variations used in the current analysis using the selection inspired by the 2ℓSS selection:
  - nj=3 or nj ≥4, nb=1 or nbj ≥2

Exp	Generator	ME order	PS	PDF	Tune
●	Sherpa 2.2.1	MEPs@Nlo (0,1j@NLO+2,3@LO)	Sherpa	NNPDF3.0 NNLO	Sherpa default
●	MG5_aMC FxFx	NLO (0,1j@NLO+ 1,2j@LO)	Pythia 8	NNPDF3.0 NNLO	CMS TuneCUETP8M1
○	MG5_aMC	NLO (0j@NLO+ 1j@LO)	Pythia 8	NNPDF3.0 NLO	A14



Summary and conclusions

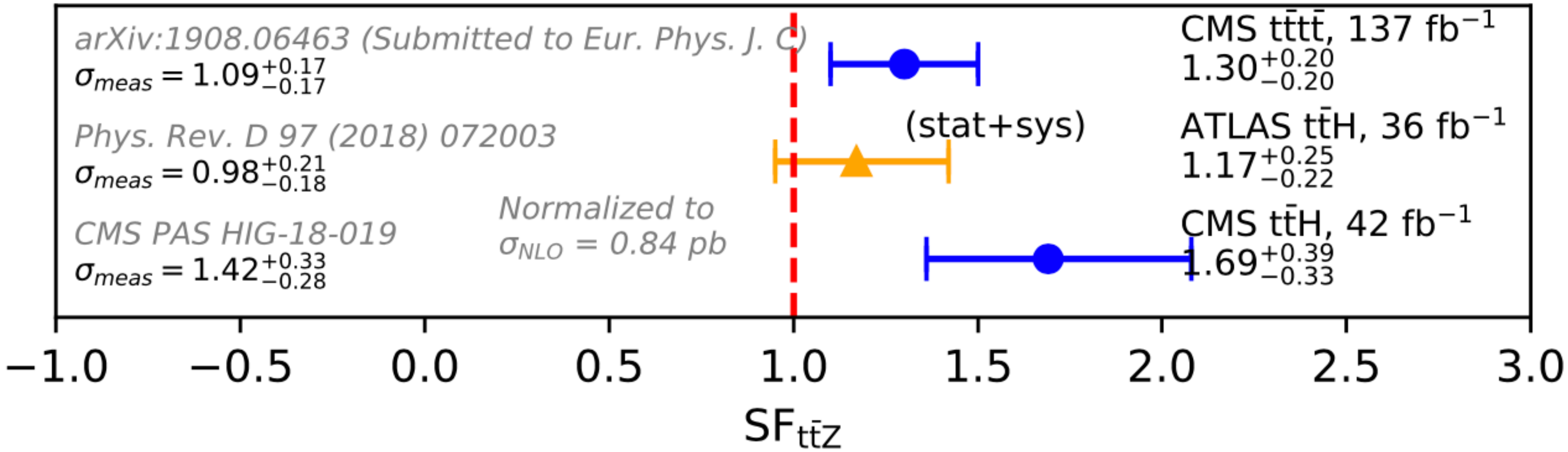
- Measurements involving top quarks in the multilepton final state are strongly affected by ttZ and ttW backgrounds
- tZq measurement
  - on-shell ttZ with one or no jet lost
- ttH (tH) multilepton analysis
  - off-shell ttZ with lost or extra jets
  - ttW with lost jets in the control regions and bulk ttW in signal regions
- 4-top quark search
  - off-shell ttZ with extra jets and b-jets
  - ttW with extra jets and b-jets
- To make progress we need theory predictions for ttV processes accompanied by extra jets and b-jets
  - ttW differential measurements are extremely challenging due to significant contribution of lepton fakes with large uncertainties
  - extensive studies of ttV modelling by different generators are necessary

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

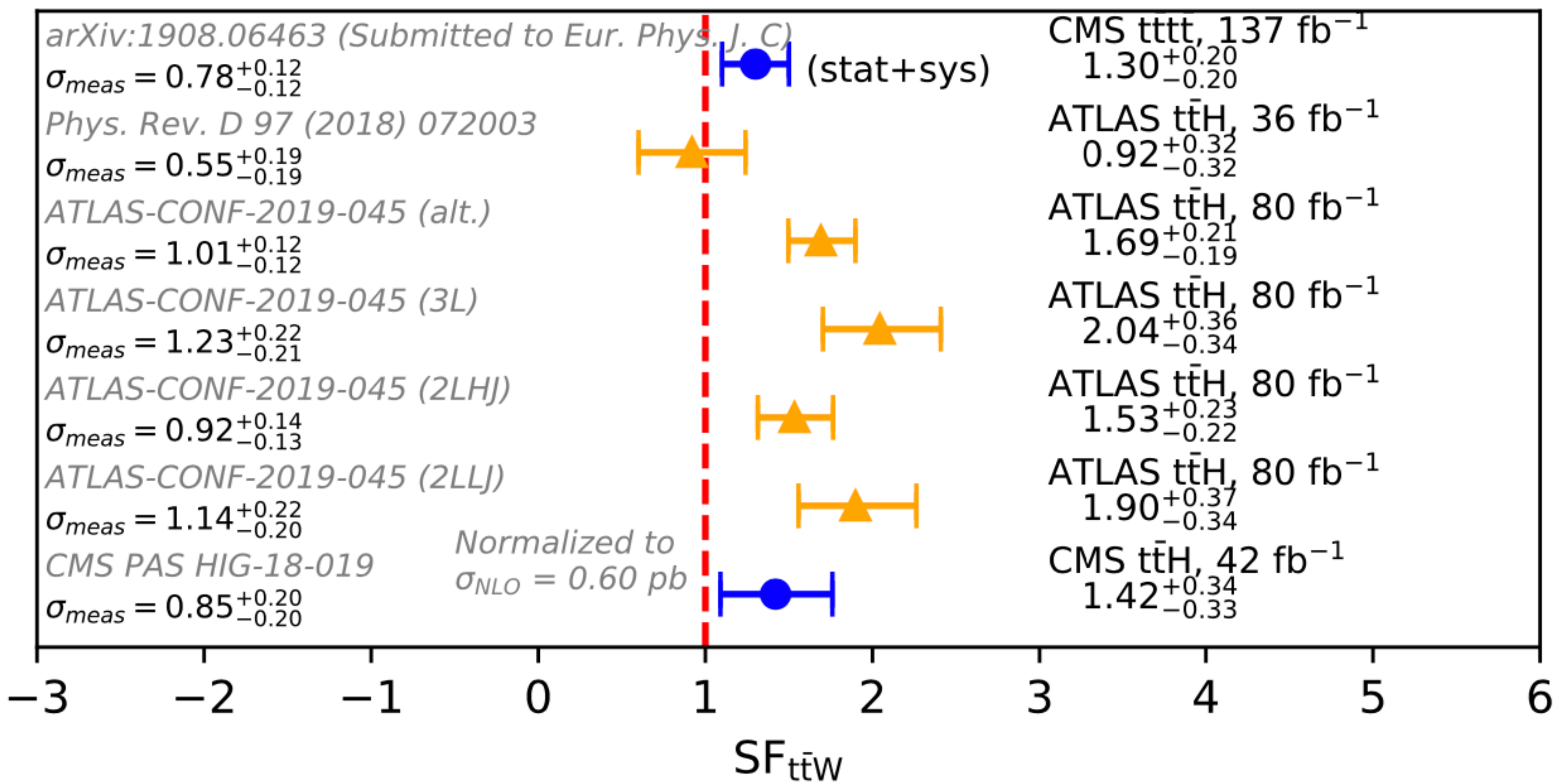
Summary of scale factors

Plots by D.Dobur

$t\bar{t}Z$



$t\bar{t}W$

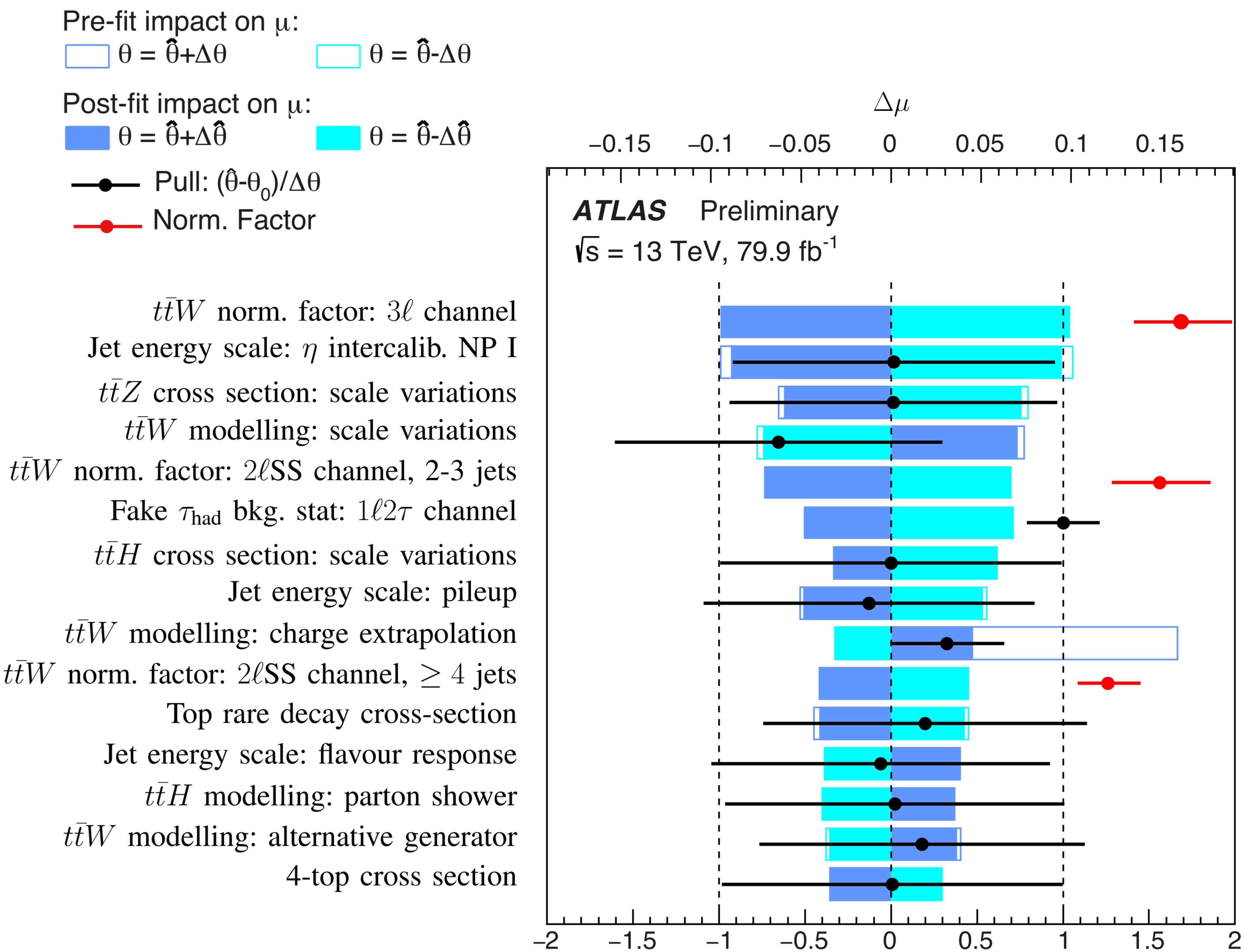


Backup

Atlas tZq regions

Common selections			
Exactly 3 leptons (e or μ) with $\|\eta\| < 2.5$ $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 20$ GeV, $p_T(\ell_3) > 20$ GeV $p_T(\text{jet}) > 35$ GeV			
SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 2 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 3 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$
SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 3 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 4 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$

ATLAS ttH ML ranking



ATLAS: ttH ML

- W-boson charge asymmetry taken as additional uncertainty