Top Physics at the LHC and Beyond

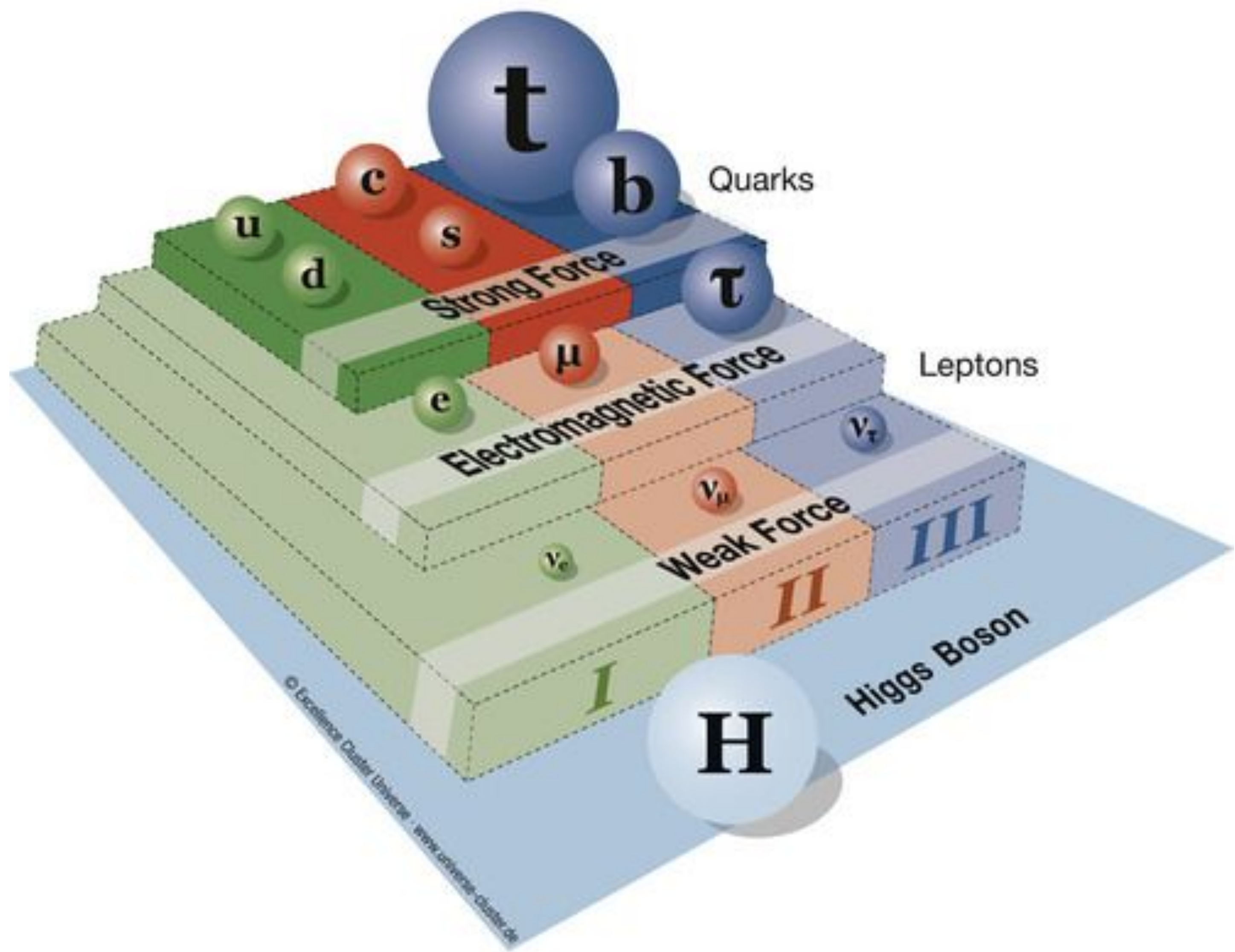
Nedaa-Alexandra Asbah
Harvard University

ECT* workshop 2022- Trento
31.08.2022

Top-quark

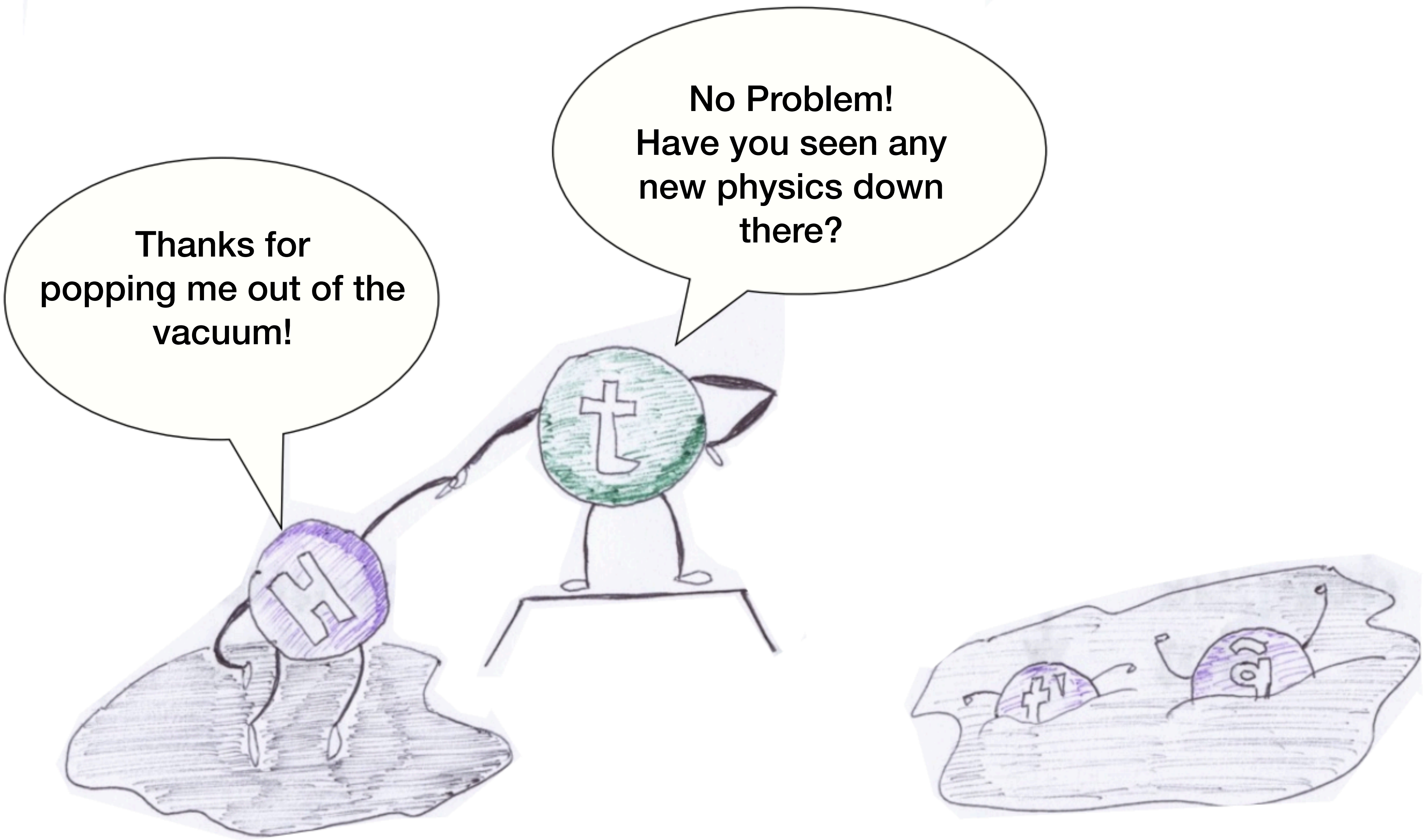
- Top-quark is the **heaviest** of all known fundamental particles m_{top} ~ 170 GeV
  - a bizarrely steep mass hierarchy
  - Even heavier than the **Higgs boson**
  - Unique role as a result of its mass
  - Many models predict that the top is special in order to explain its mass

- Leaves us wondering:
  - Is there a hidden connection with the EWSB mechanism?
  - Is the top quark a fundamental particle?



Top-quark

- Strongly interacts with the Higgs sector
  - Large top yukawa coupling $y_t \sim 1$



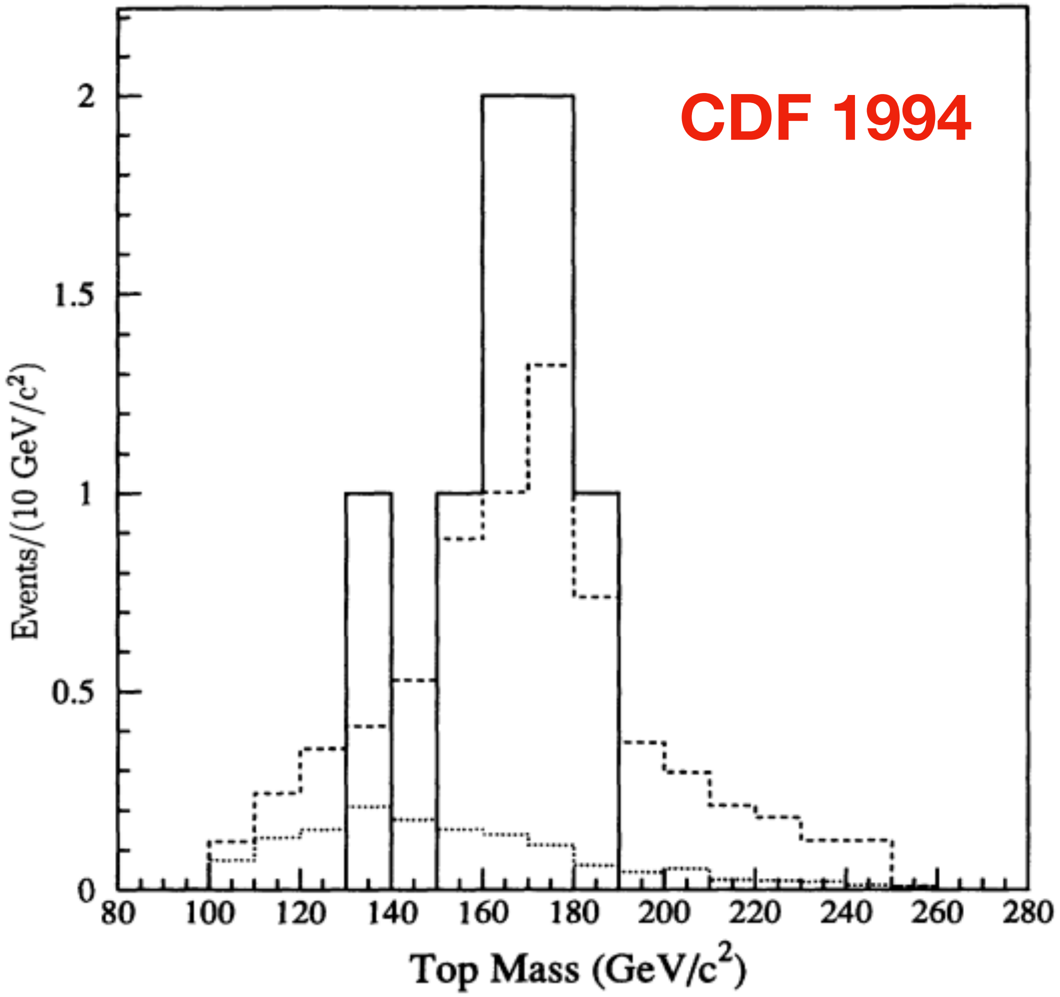
Top-quark

- Short-lived, it decays before hadronizing
  - $\tau_{had} \approx 2 \times 10^{-24} s$
  - $\tau_{top} \approx 0.5 \times 10^{-24} s$
  - Possible to study the properties of a bare quark
- LHC is a top factory & many top-quarks are produced at the LHC
  - About $25{,}000$ $t\bar{t}$ events are produced every hour
- Gateway to **New Physics**
  - Precision SM top-quark properties measurements
  - Search for non-SM top-quark interactions
  - Searches of top-quark partners and other states

Top-quark

- We have been doing Top & SM measurements for a long time!

7 events; l+4jets



Top mass:

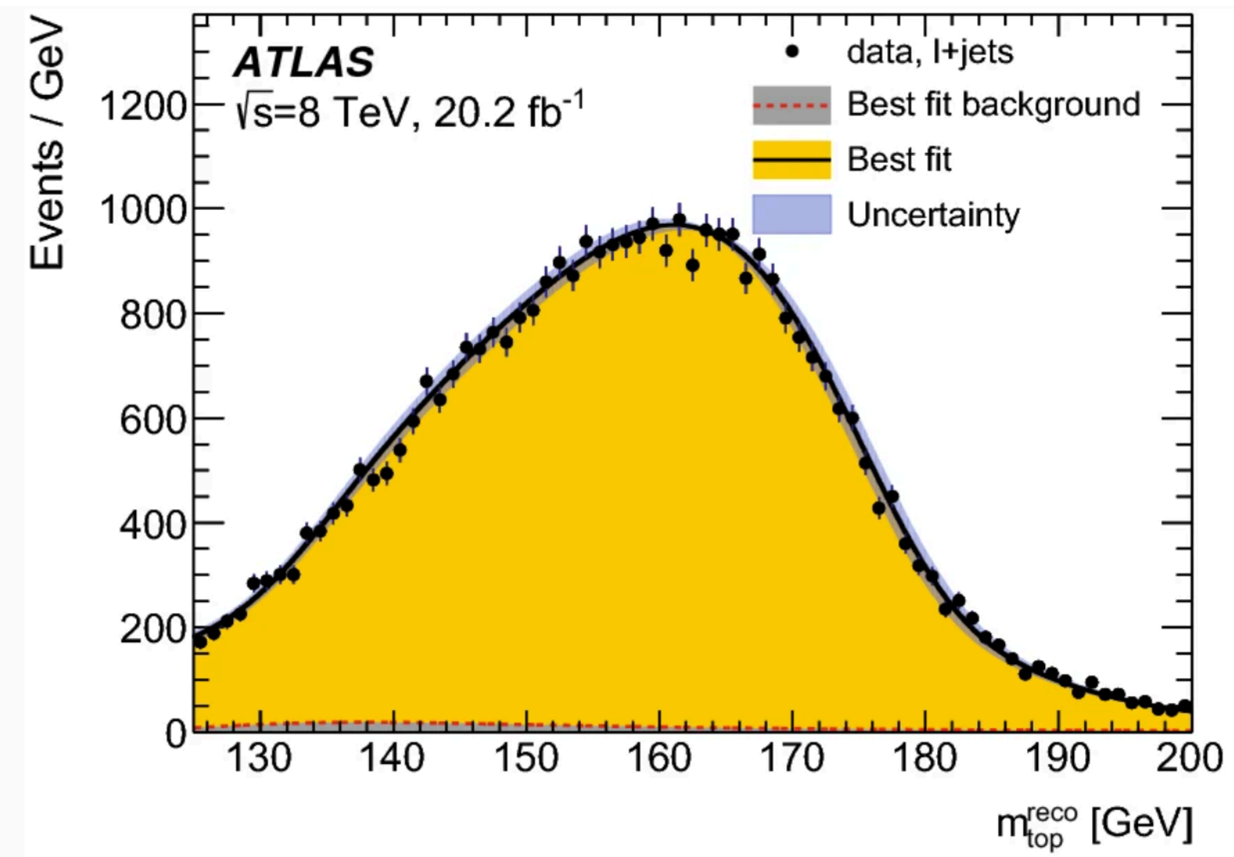
$174 \pm 10^{+13}_{-12}$ GeV/c²

with **9.4% precision**

PRD 50,2966(1994)

~38K events; l+4jets
(at least 2b-tags)

ATLAS 2019



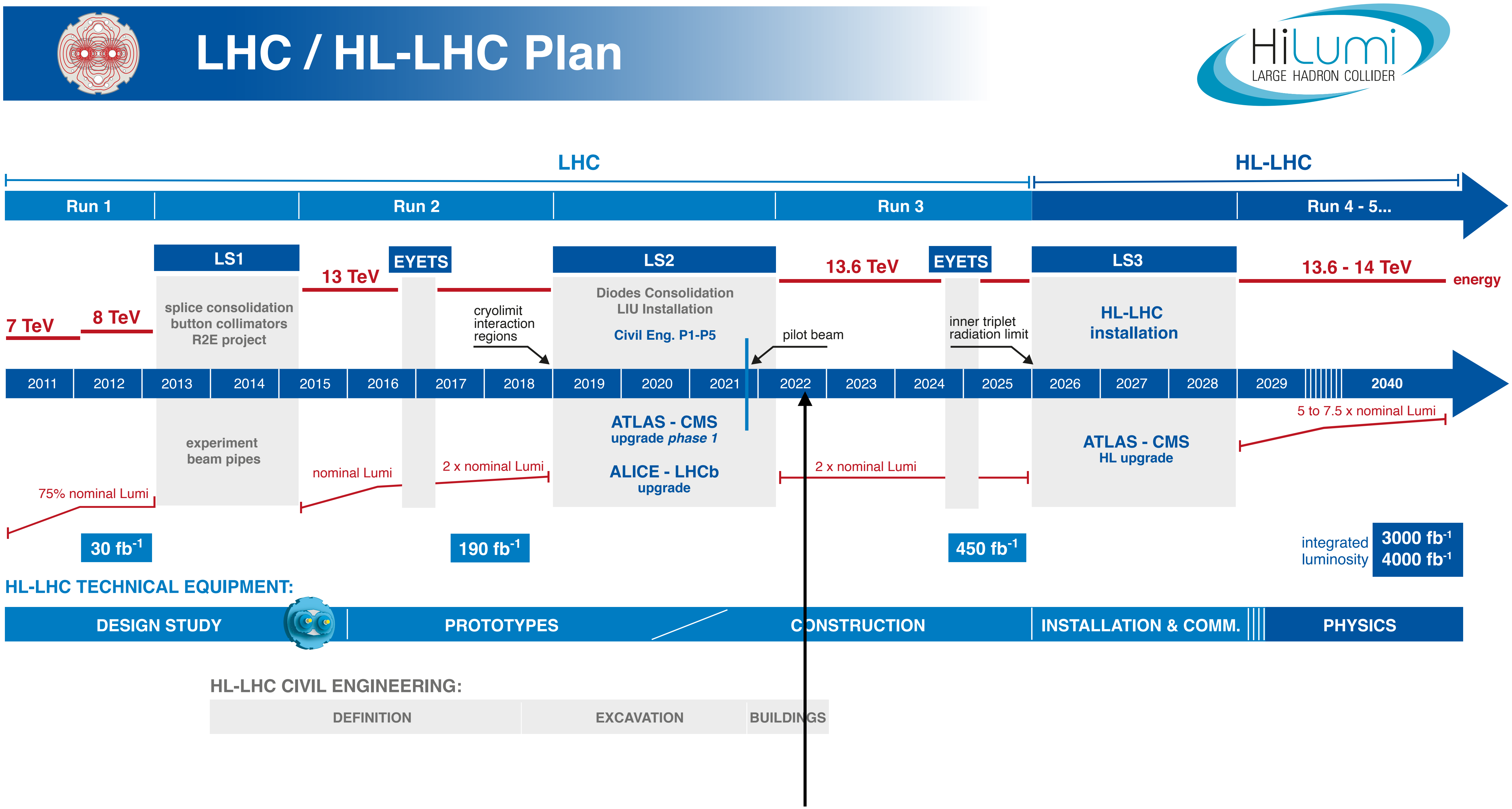
Top mass:

$172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})$ GeV/c²

with **0.5% precision**

Eur. Phys. J. C79(2019) 290

LHC/ HL-LHC Plan (last update February 2022)

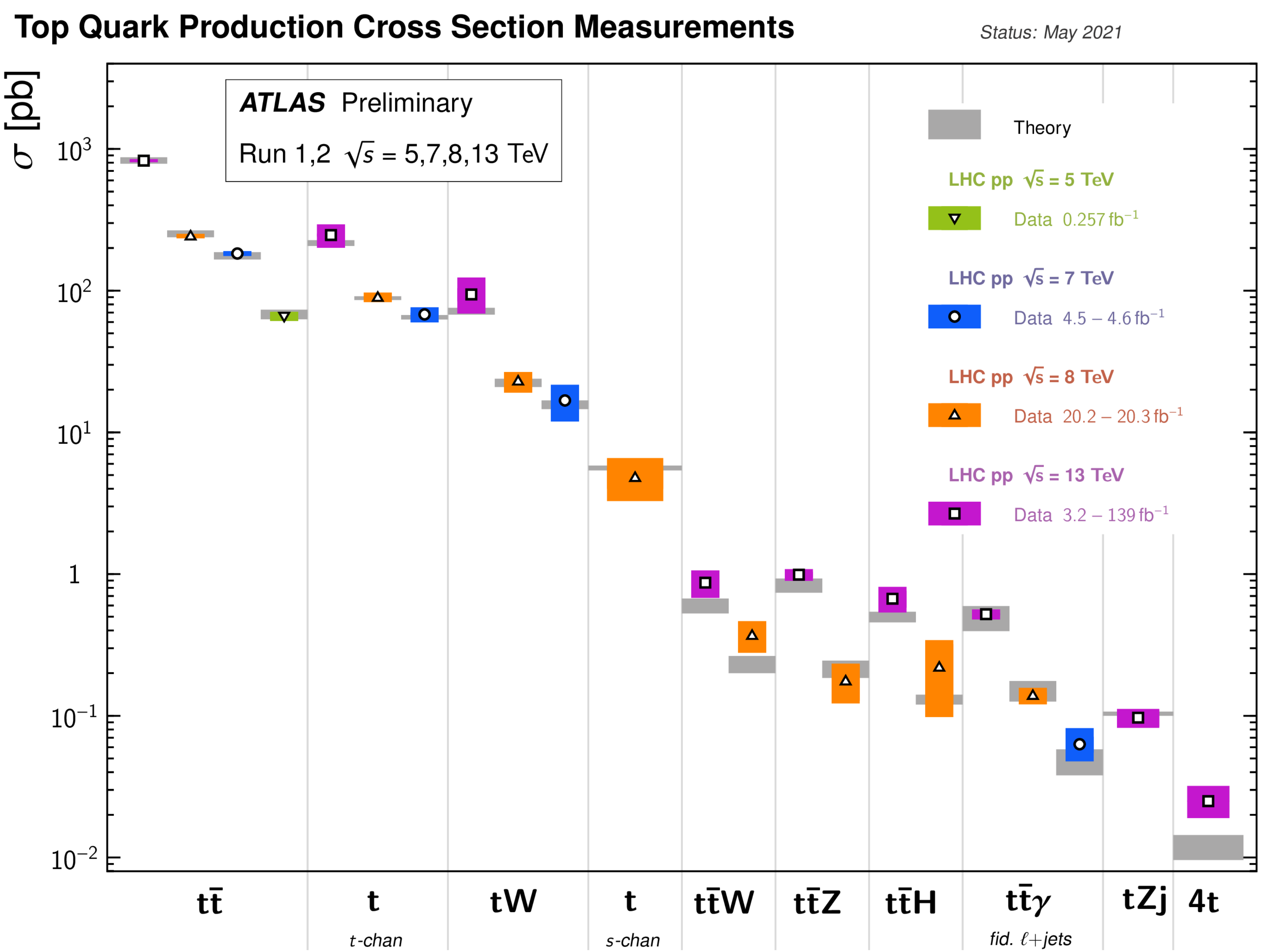


Ongoing - More than 10 fb^{-1} recorded by ATLAS so far!

Top-quark Production Cross-section Measurements

Run 1 @ 7 TeV   Run 1 @ 8 TeV   Run 2 @ 13 TeV   Theory

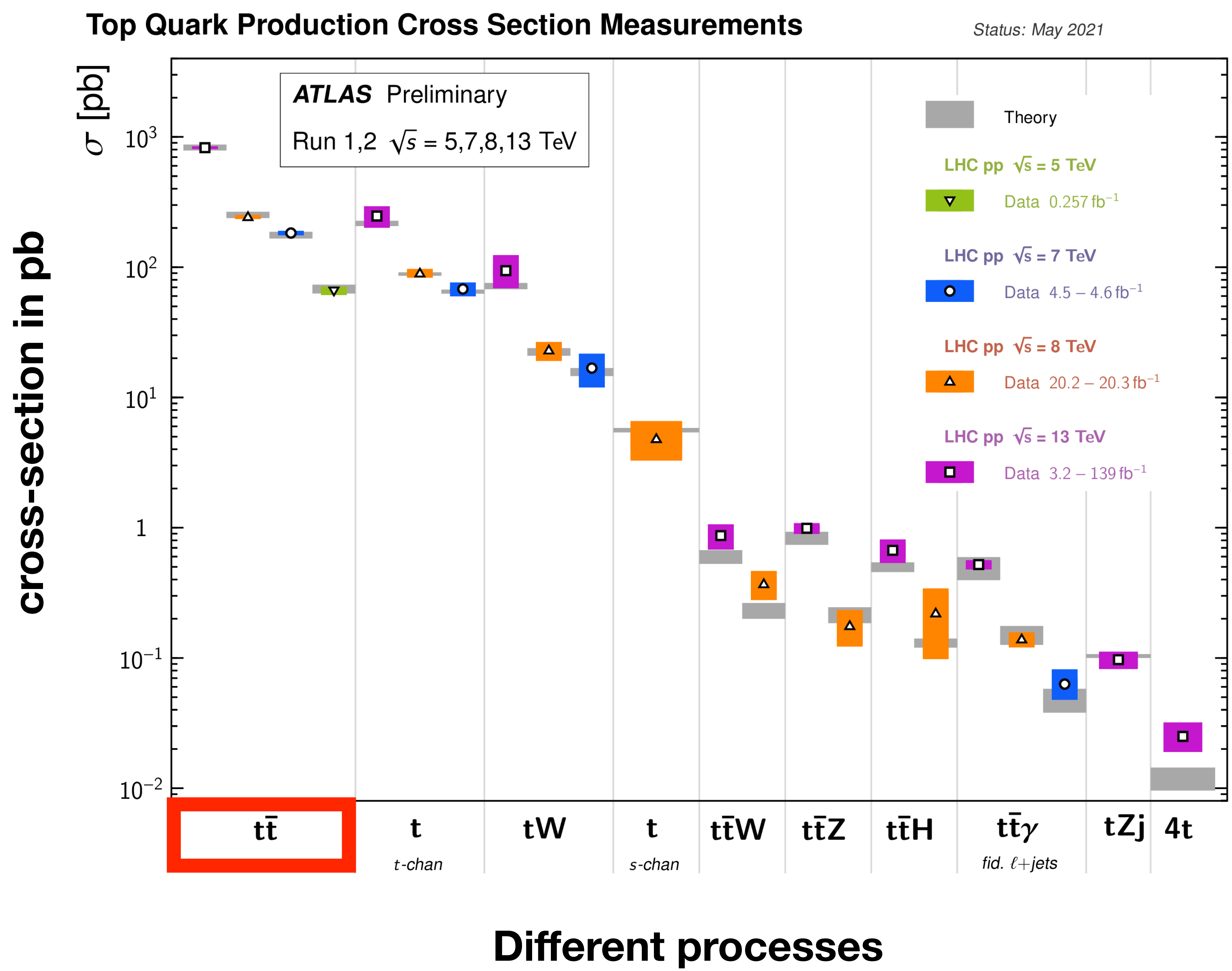
cross-section in pb



Different processes

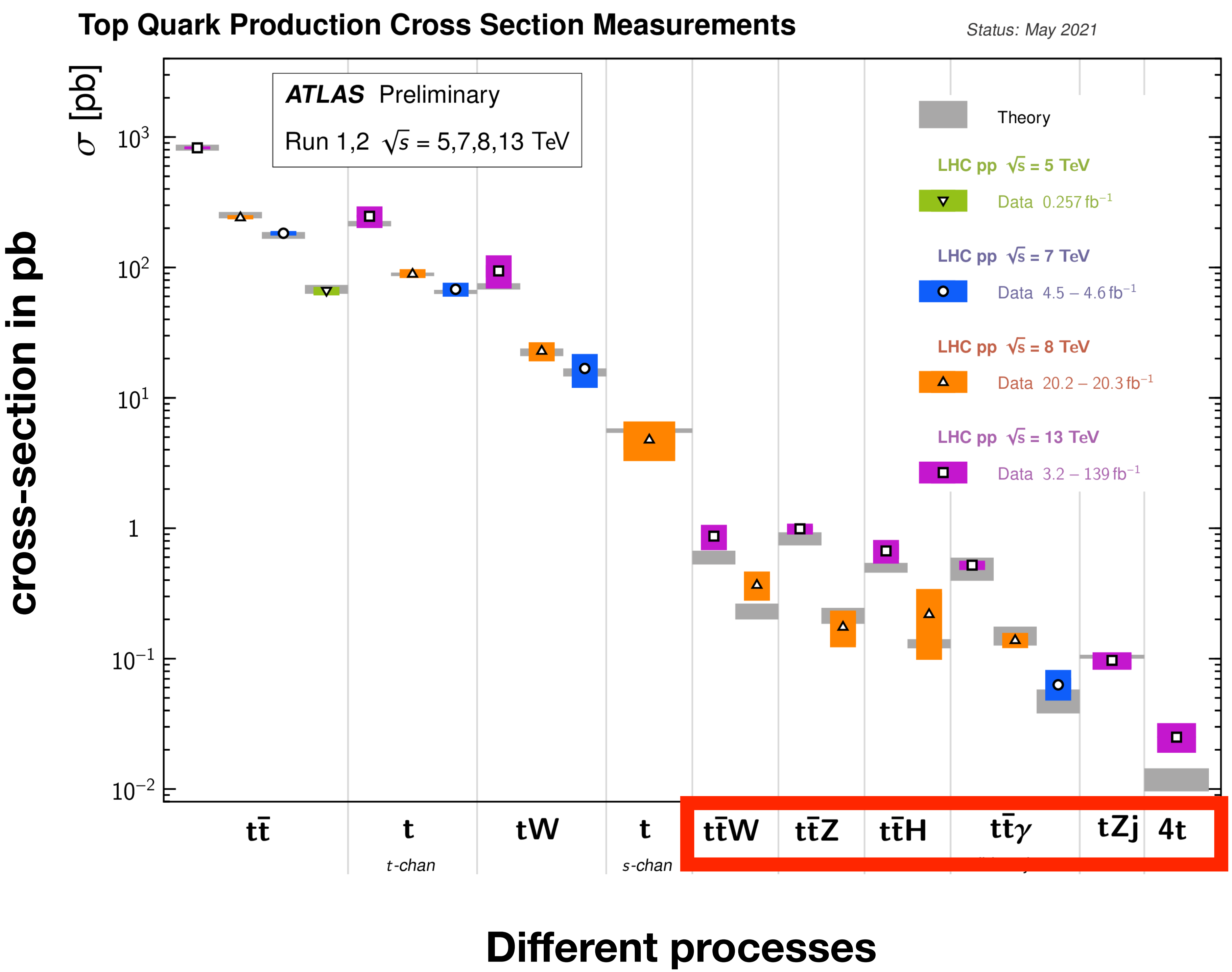
Top-quark Production Cross-section Measurements

- $t\bar{t}$ production is produced abundantly at the LHC and extremely well studied (total and differential cross sections)



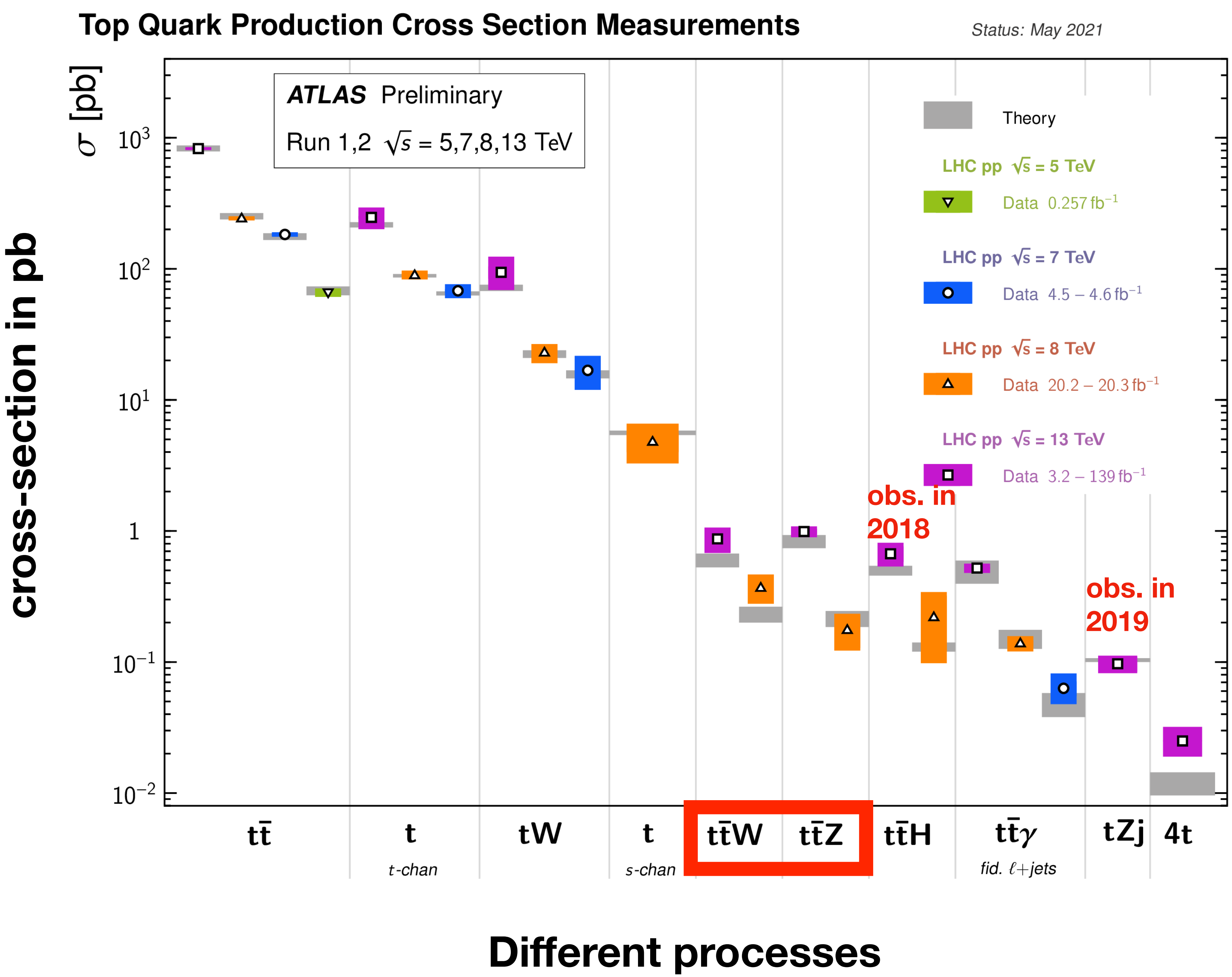
Top-quark Production Cross-section Measurements

- Rare top production modes become fully accessible with Run 2 data
- $t\bar{t}$(t)+X events are related to new physics and important backgrounds for rare SM processes



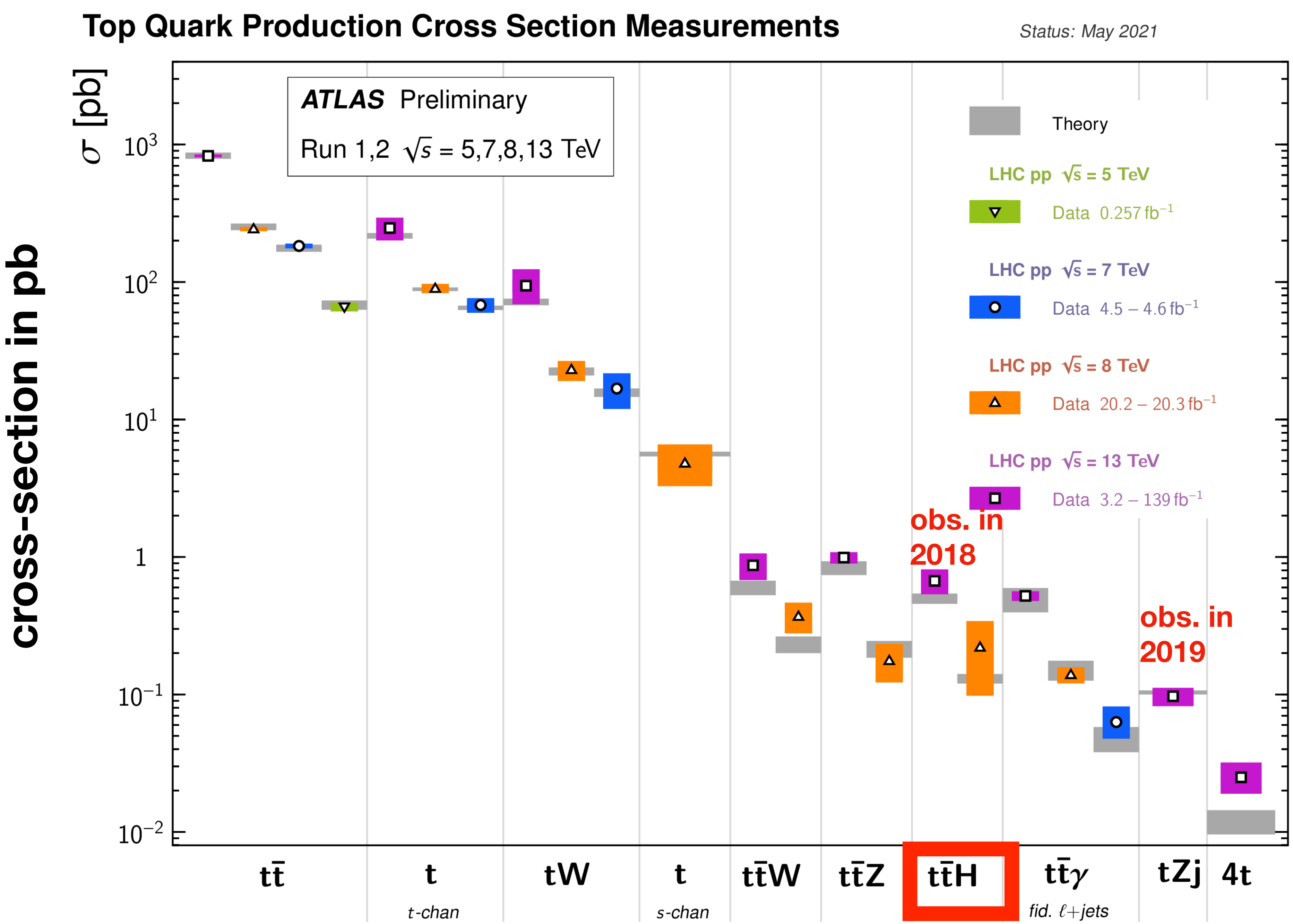
Top-quark Production Cross-section Measurements

- $t\bar{t}Z/t\bar{t}$W are among the most massive signatures that can be studied at the LHC with high precision
- Important backgrounds for searches and measurements



Top-quark Production Cross-section Measurements

- $t\bar{t}$H was recently observed using 80 fb^{-1} of Run 2 data-set [ATLAS-CONF-2019-045]



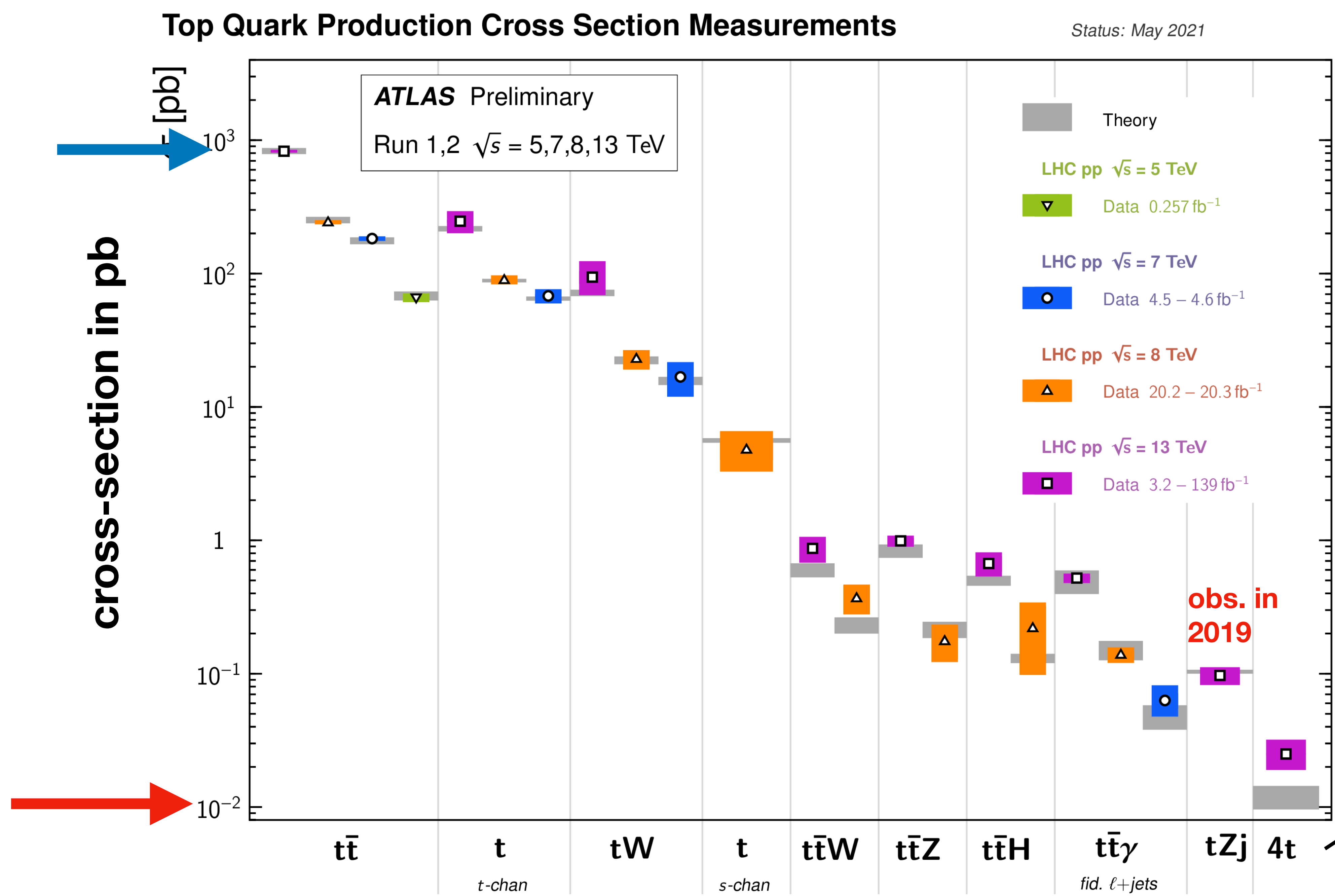
Different processes

Top-quark Production Cross-section Measurements

- Even more rare processes

- $\sigma_{SM}(t\bar{t}t\bar{t})$ = 11.97 fb at NLO QCD + NLO QED at **13 TeV** JHEP 02, 031 (2018)

cross-section in pb



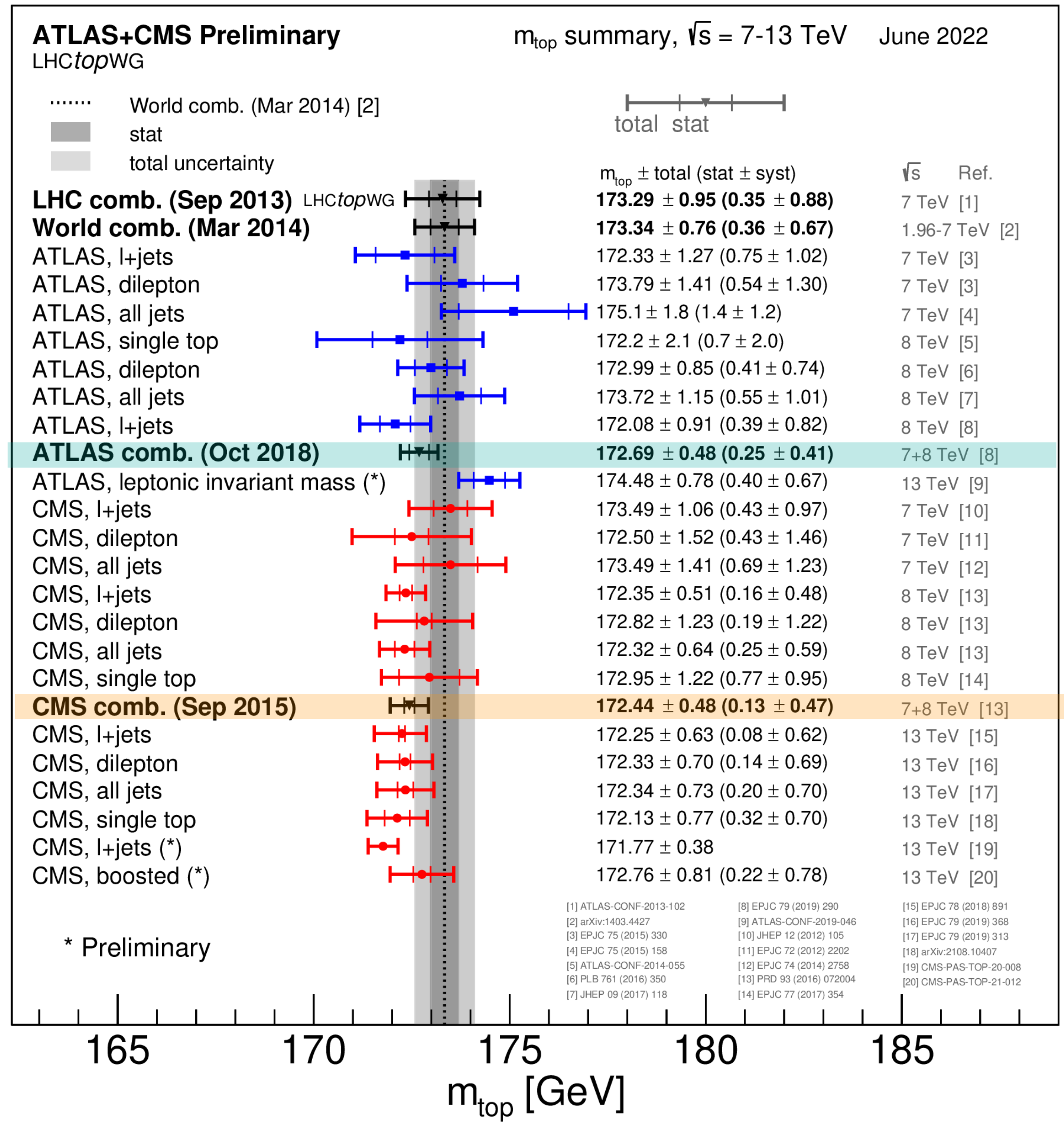
minimum energy required is ~700 GeV

Different processes

Top Mass

- Various methods to measure the top quark mass
  - Top quark mass from template fit
    - Likelihood- or MVA-based reconstruction of event (top quark) kinematics
    - Using one- or more-dimensional template functions which are sensitive to top quark mass
    - Fit to data (with top mass as free parameter) to extract best result
    - Dominant systematic uncertainties: jet-related uncertainties (JES/bJES), hadronisation and ISR/FSR MC modelling

ATLAS/CMS results for direct top quark mass measurements (June 2022)
ATL-PHYS-PUB-2022-032

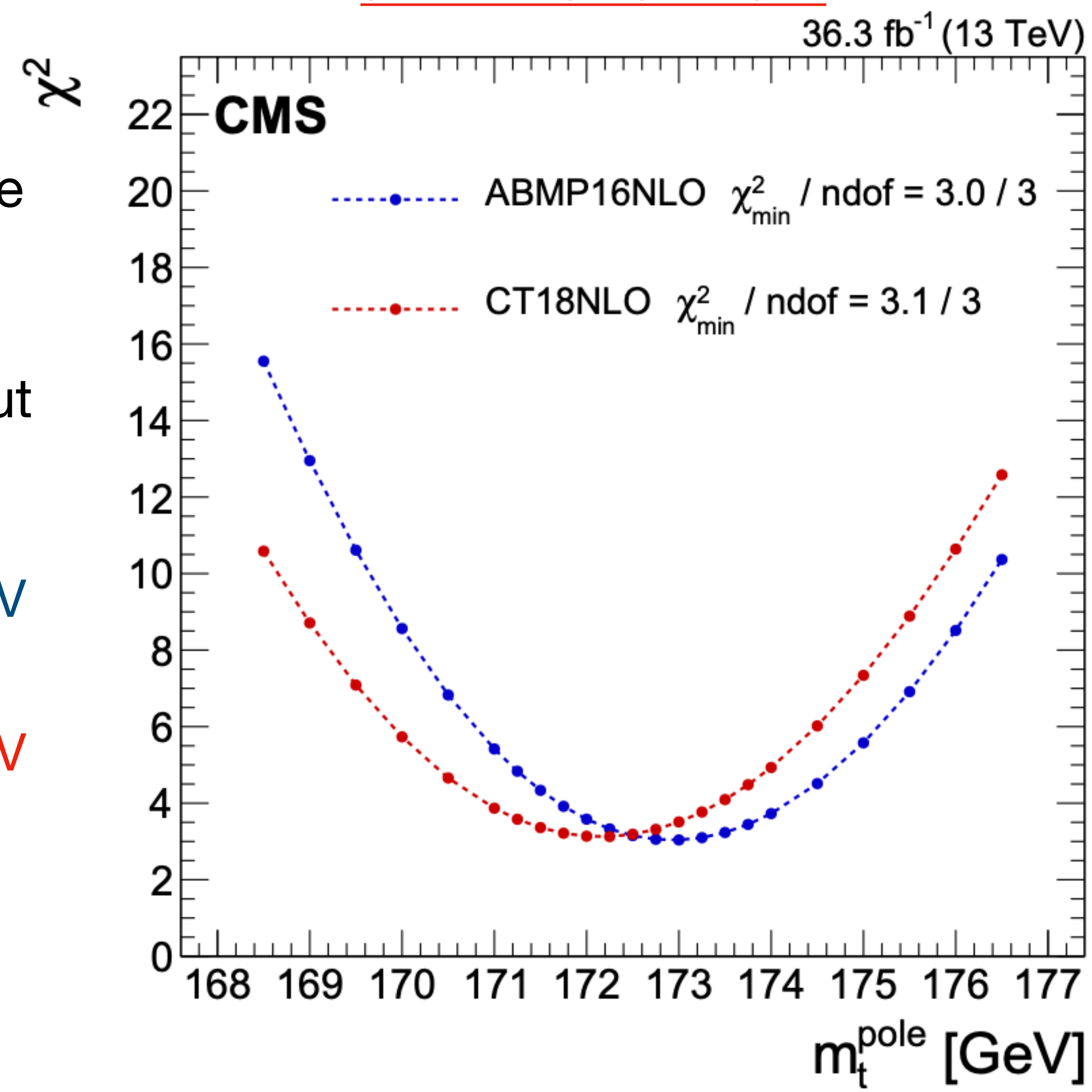


Top Mass

- Top quark mass from $t\bar{t}$+jets cross section:
  - Extract top quark mass from inclusive (or differential) cross section measurements
  - Best value of top quark pole mass is extracted from χ^2 minimisation between the normalized differential cross section at parton level and theoretical $t\bar{t}$+jets MC predictions at NLO (using two different input PDF sets)
  - $m_{top}^{pole} = 172.94 \pm 1.27(fit)^{+0.51}_{-0.43}(scale)$ GeV
  - $m_{top}^{pole} = 172.16 \pm 1.35(fit)^{+0.50}_{-0.40}(scale)$ GeV
  - Dominant systematic uncertainties arise from scale variations (μR, μF), JES and background normalizations

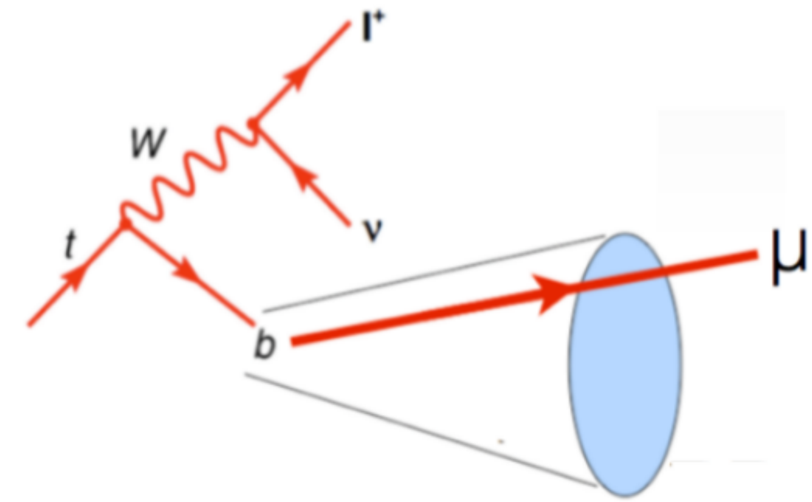
χ^2 **versus** m_t^{pole}

arXiv:2207.02270v1



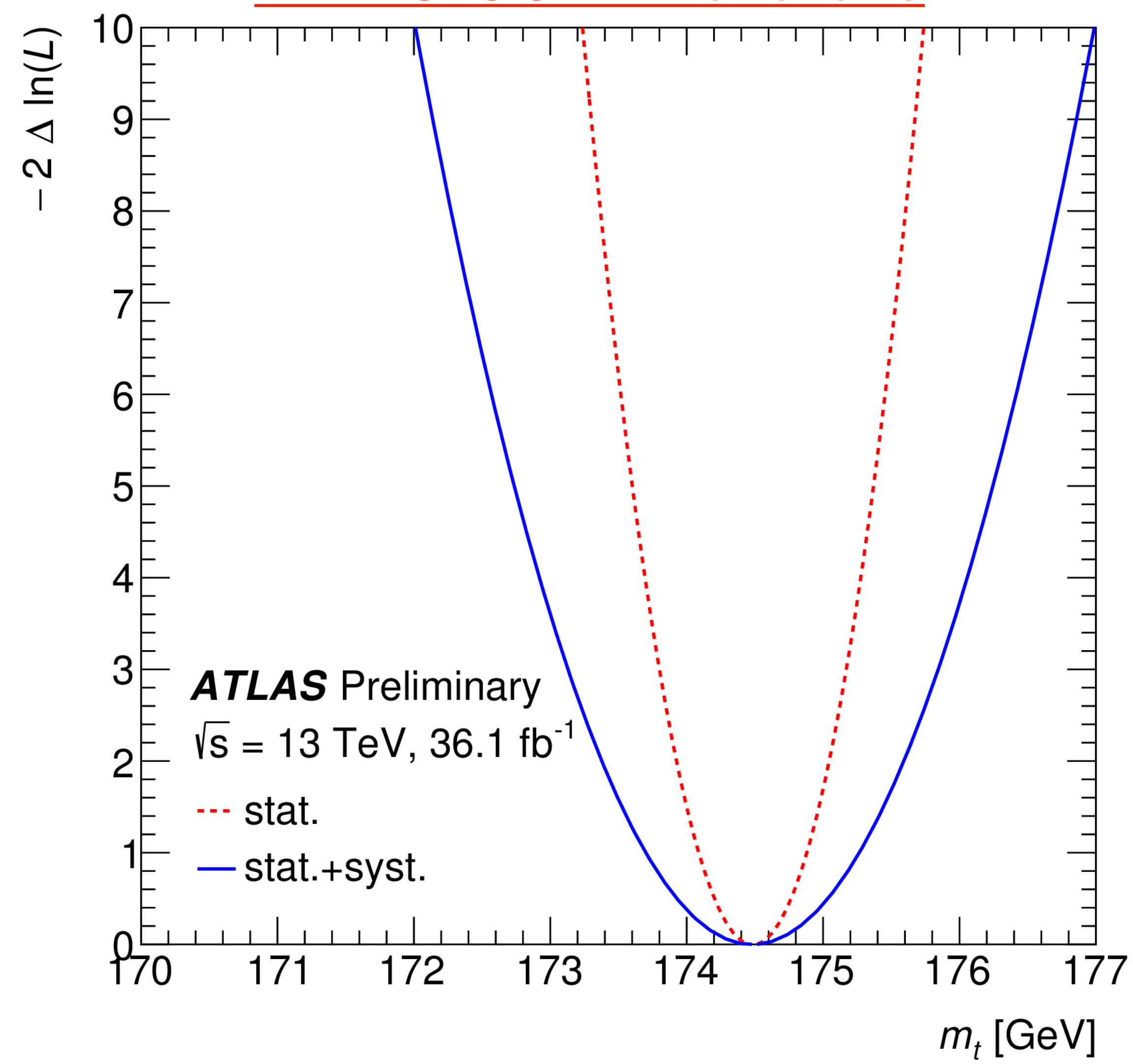
Top Mass

- Top quark mass using "soft muon tags" (SMT)
  - Measurement of m_{top} with 36 fb^{-1} data in lepton+jets channel
  - One lepton (electron/muon) from a W boson and a jet containing a "soft" muon (p_T > 8 GeV) originating from a b-hadron decay (SMT-tagged jet)
  - Using a binned likelihood fit on $m_{l\mu}$ (invariant mass between lepton from W and muon from SMT-jet) to extract top quark mass
  - Best fit value of top quark mass: $m_{top} = 174.48 \pm 0.40(stat.) \pm 0.67(syst.)$ GeV
  - Significantly more precise than previous ATLAS measurements from direct reconstruction of top decay products
  - Dominant systematic uncertainties: branching ratios of b/c-hadron decays to muons, pile-up modeling and b-fragmentation function



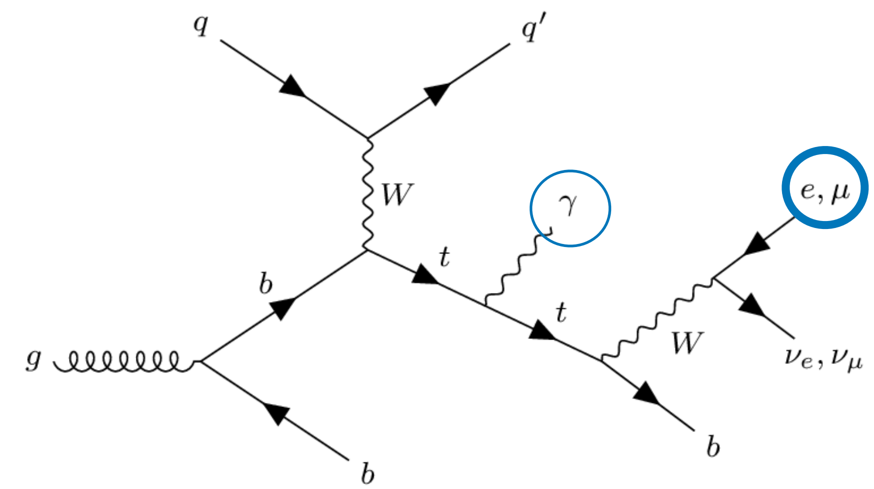
Likelihood scan of m_{top}

ATLAS-CONF-2019-046

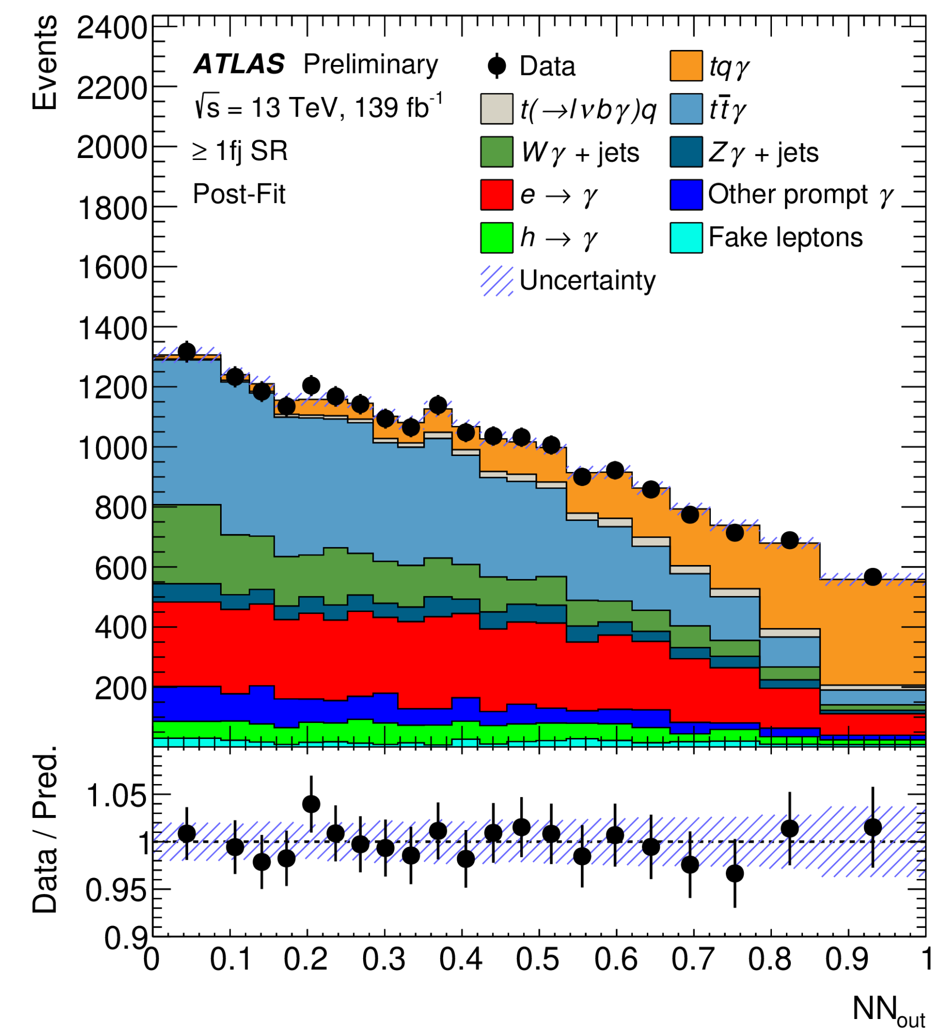


Observation of $tq\gamma$ ATLAS-CONF-2022-013

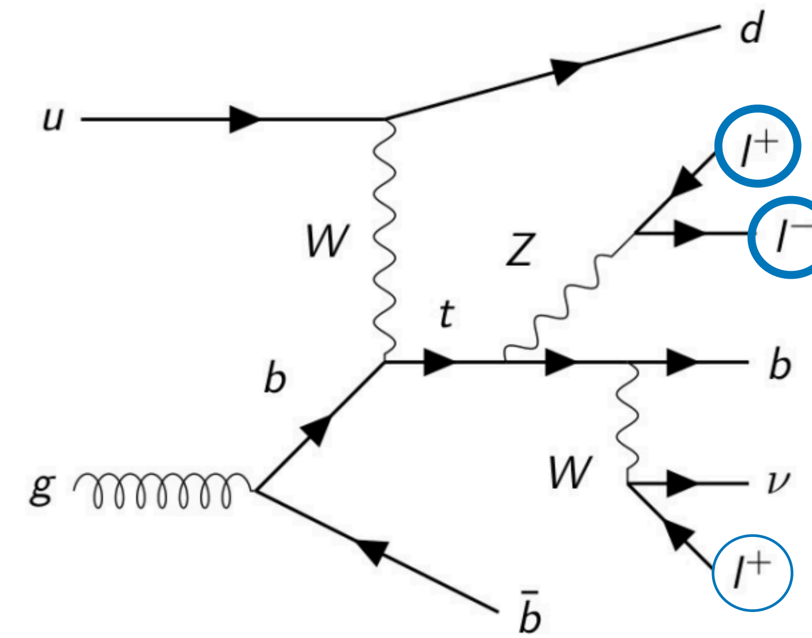
- **Strategy:**
  - Events contain one isolated photon, one isolated lepton (e/μ), one b-tagged jet, and jet in the forward direction
  - Two signal regions are defined with 0 and ≥ 1forward jet
  - Dedicated control regions are defined for the main backgrounds coming from $t\bar{t}\gamma$ and $W\gamma +$ jets
  - Fake photons ($e \to \gamma,\ j \to \gamma$) are estimated using data-driven method
- Signal and backgrounds are separated using a Neural Network
- **Results:**
  - The observed (expected) significance is 9.1σ (6.7σ)
  - Fiducial measurements:
    - parton-level cross section: $580 \pm 19(stat.) \pm 63(syst.)$
    - particle-level cross section: $287 \pm 8(stat.) \pm 31(syst.)$
  - Systematics dominated by modeling of $t\bar{t}\gamma$ and the limited number of MC event for background processes and the $tq\gamma$ signal



Neural network output

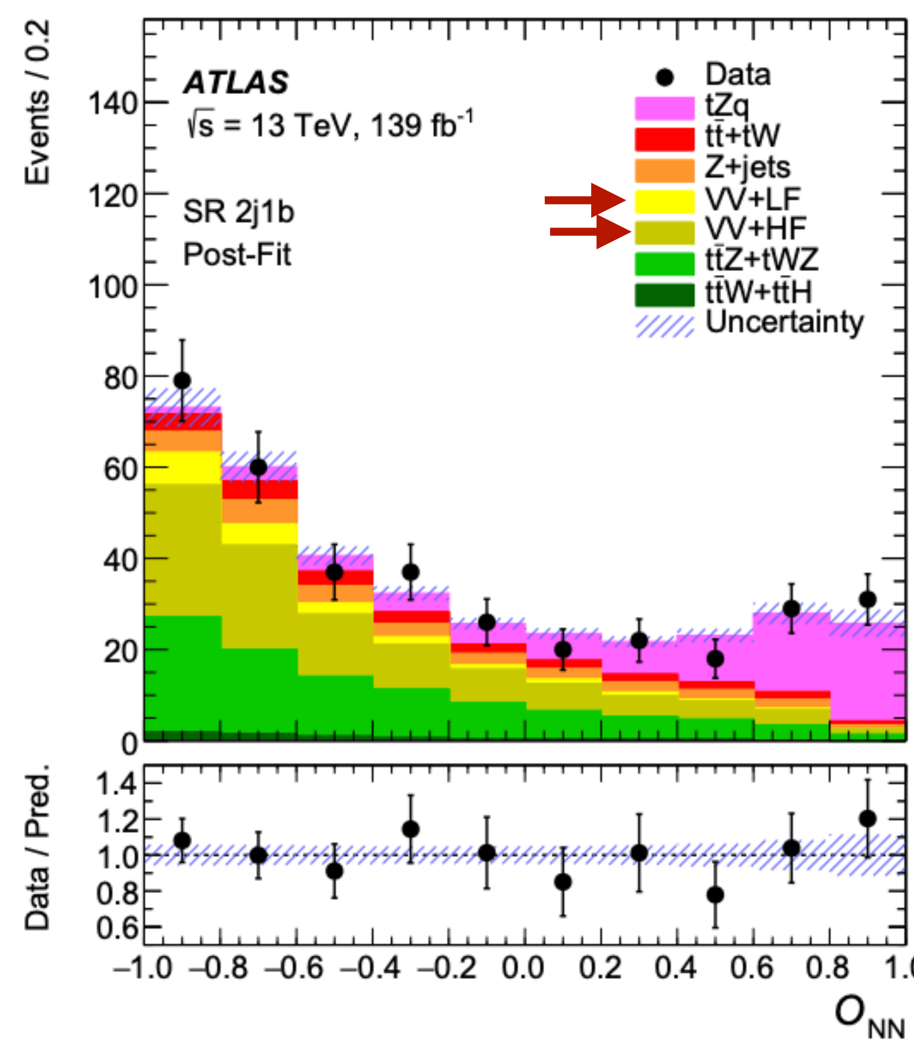


Observation of the electroweak production of tZq JHEP 07 (2020)



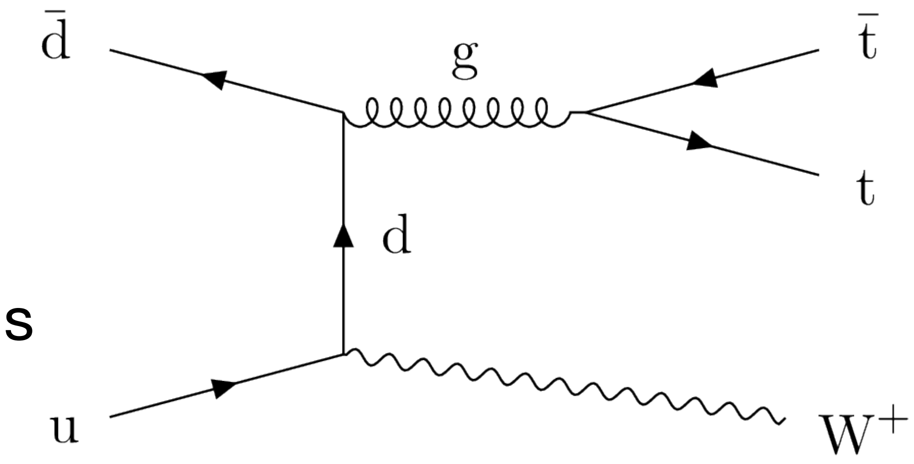
- **Strategy:**
- Events contain three isolated leptons (e/μ)
  - One pair should build a Z mass peak
- Two or three jets, one of which is identified as containing a b-hadron (b-tagged)
- Large background coming from diboson+Heavy Flavour jets (VV+HF)
- Signal and backgrounds are separated using a Neural Network
- Signal fraction is estimated using a profile-likelihood fit
- **Results:**
- Yields a tZq production cross section of **97 ± 13 (stat.) ± 7 (syst.) fb** [SM cross section: 102^{+5}_{-2} fb]
- **Statistically limited**, systematics dominated by prompt lepton background
- **Observation with $> 5\sigma$**

Neural network output

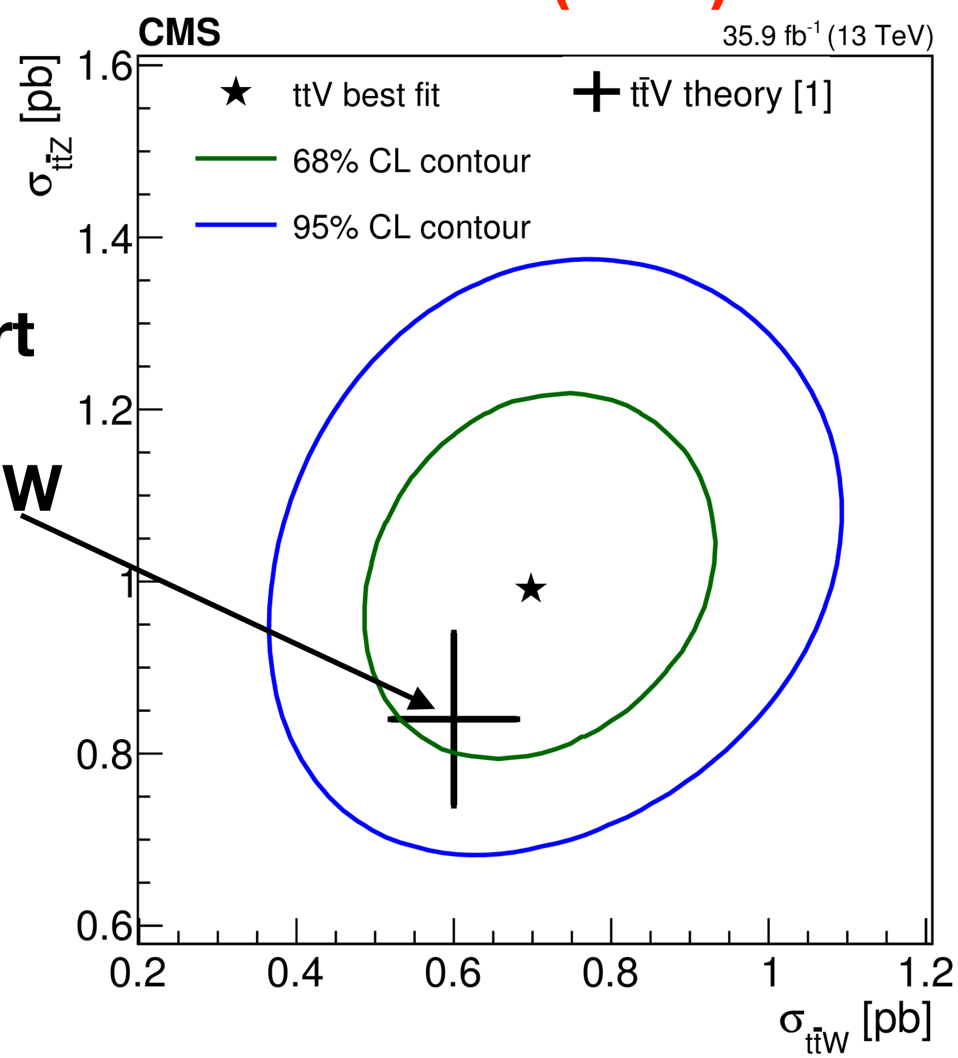


ttW

- W mainly couples to initial state quarks
  - Significant charge asymmetry
- t-W scattering sensitive to top quark coupling to neutral bosons
- Previous ATLAS and CMS measurements with 36 fb^{-1} data
  - higher cross section than prediction

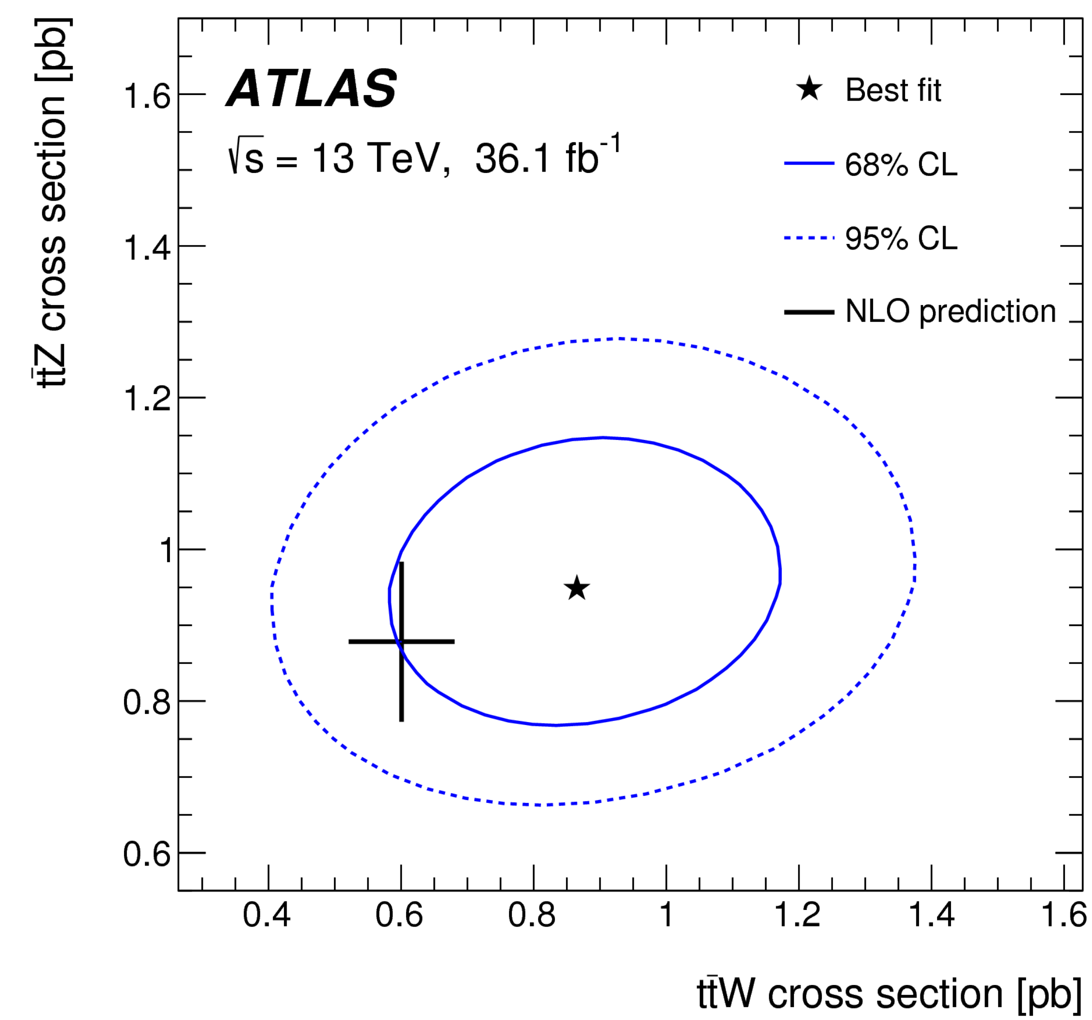


JHEP 08 (2018) 011



Yellow report Prediction NLO QCD+EW

Phys. Rev. D 99 (2019) 072009



- Using 138 fb^{-1} of run 2 data
- Using events with 2 SS or 3 e/μ
- Inclusive measurement compared to 2 predictions: NLO+NNLL [A. Kulesza et al.]; NLO+2j@LO with improved FxFx ME merging [R. Frederix, I. Tsinikos]

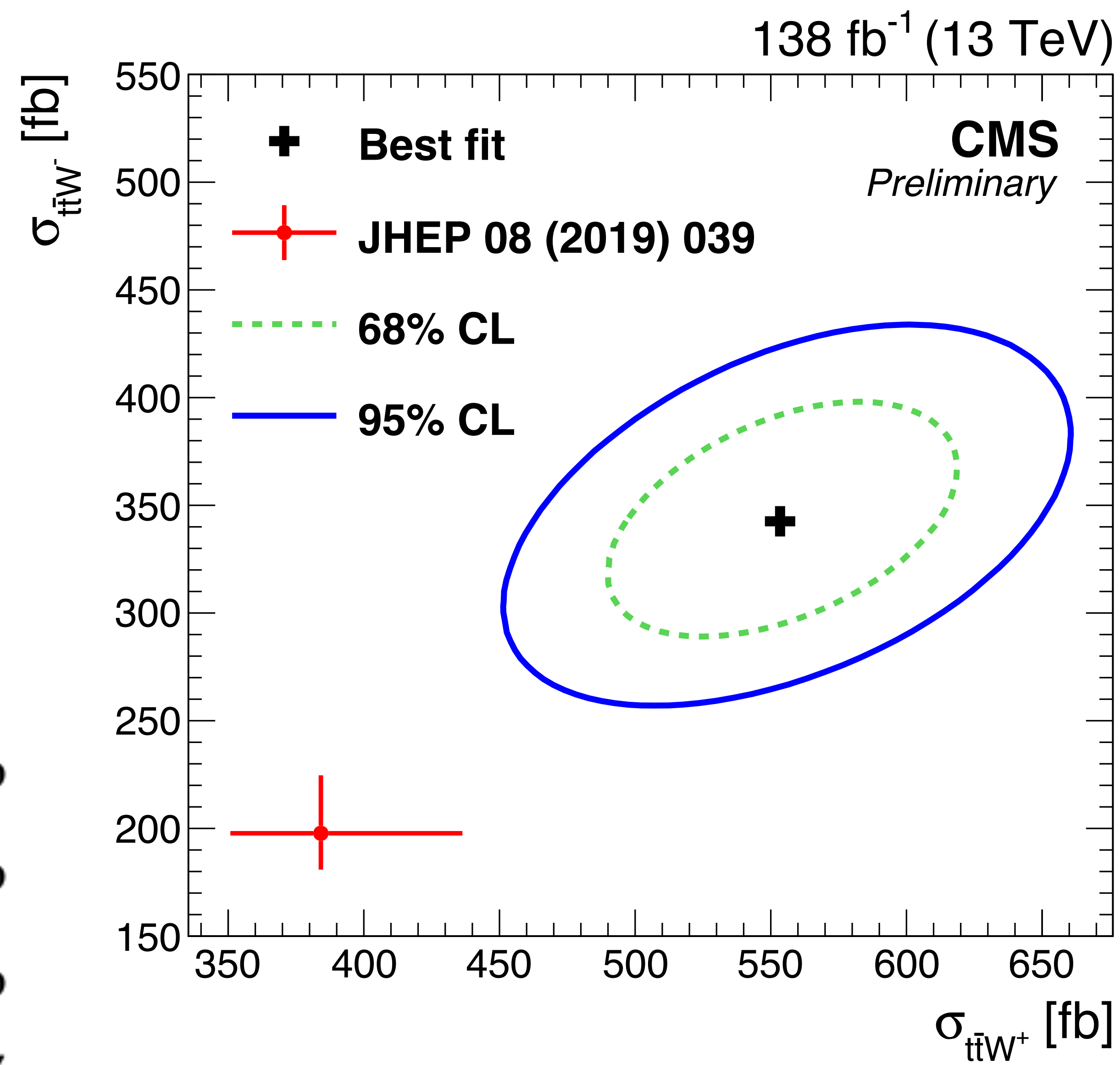
In agreement with SM predictions within 2σ

Measurement

$$\sigma_{t\bar{t}W} = 868 \pm 40\,(\text{stat})^{+52}_{-50}\,(\text{syst})\,\text{fb}$$
$$\sigma_{t\bar{t}W+} = 553^{+30}_{-29}\,(\text{stat})^{+31}_{-30}\,(\text{syst})\,\text{fb}$$
$$\sigma_{t\bar{t}W-} = 343 \pm 26\,(\text{stat}) \pm 25\,(\text{syst})\,\text{fb}$$
$$R_{t\bar{t}W+/t\bar{t}W-} = 1.61^{+0.15}_{-0.14}\,(\text{stat})^{+0.07}_{-0.05}\,(\text{syst})$$

Prediction

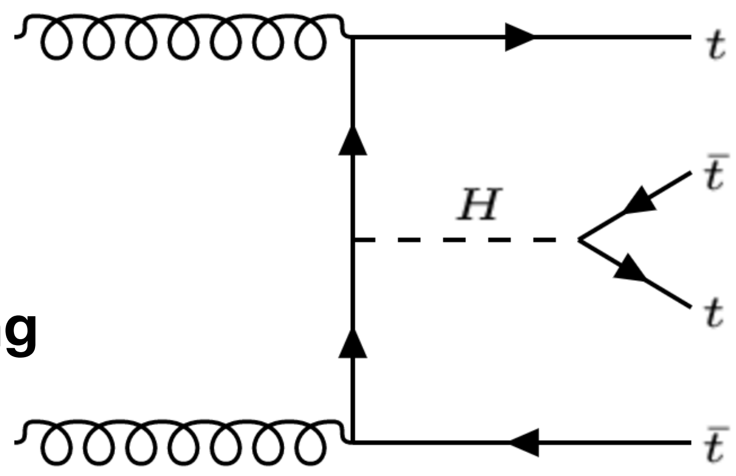
$$\sigma^{\text{theo.}}_{t\bar{t}W} = 592^{+155}_{-96}(\text{scale})^{+12}_{-12}(\text{PDF})\,\text{fb}$$
$$\sigma^{\text{theo.}}_{t\bar{t}W+} = 384^{+52}_{-32}(\text{scale})^{+8}_{-8}(\text{PDF})\,\text{fb}$$
$$\sigma^{\text{theo.}}_{t\bar{t}W-} = 198^{+26}_{-16}(\text{scale})^{+5}_{-5}(\text{PDF})\,\text{fb}$$
$$R^{\text{theo.}}_{t\bar{t}W+/t\bar{t}W-} = 1.94^{+0.37}_{-0.24}$$



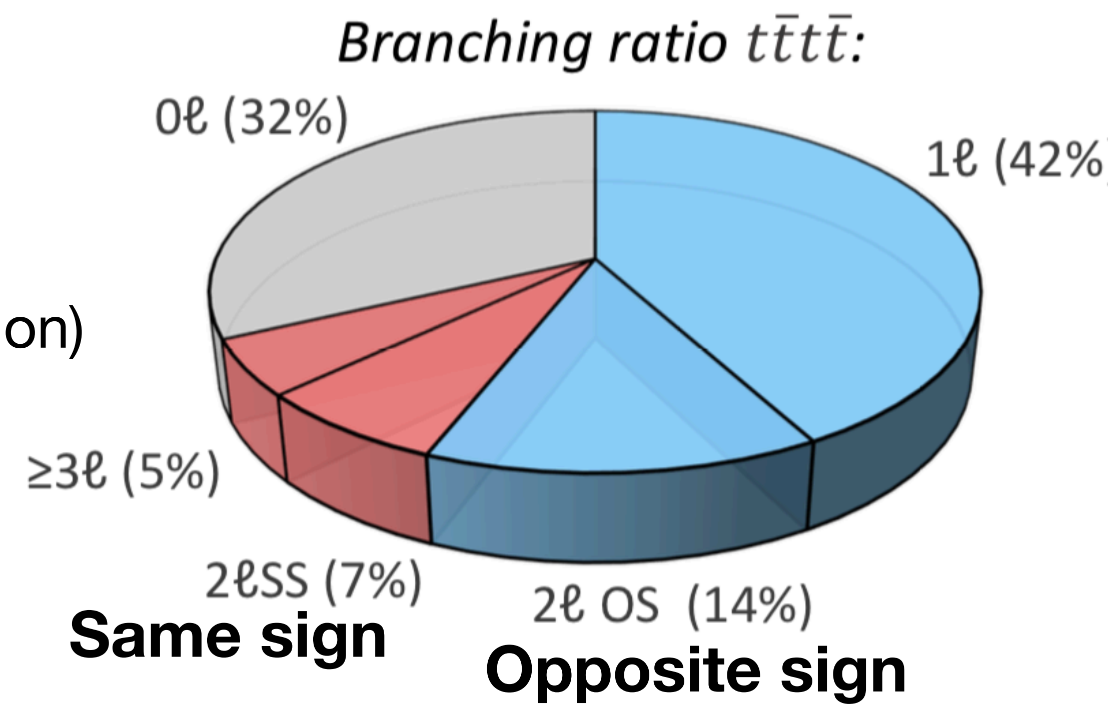
JHEP 08 (2019 039)
A Broggio et al.

Production of four tops

Eur.Phys. J. C (2020)80:10985 JHEP 11 (2021)118



- **Rare process predicted by the SM and has never been observed**
  - $\sigma_{SM}(t\bar{t}t\bar{t})$ = 11.97 fb at NLO (QCD+QED) at **13 TeV**
- **Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson**
- **Sensitive to many BSM models** (EFT, 2HDM SUSY, …)
- Channels are split according to:
  - **2ℓSS** (7%) / **3ℓ** (5%)
    - Small branching fraction & Small background ($t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons, charge misidentification)
    - Most sensitive channel
  - **1ℓ** (42%) / **2ℓOS** (14%)
    - Dominant branching fraction
    - Large irreducible background from **tt+jets** (tt+heavy flavour jets)

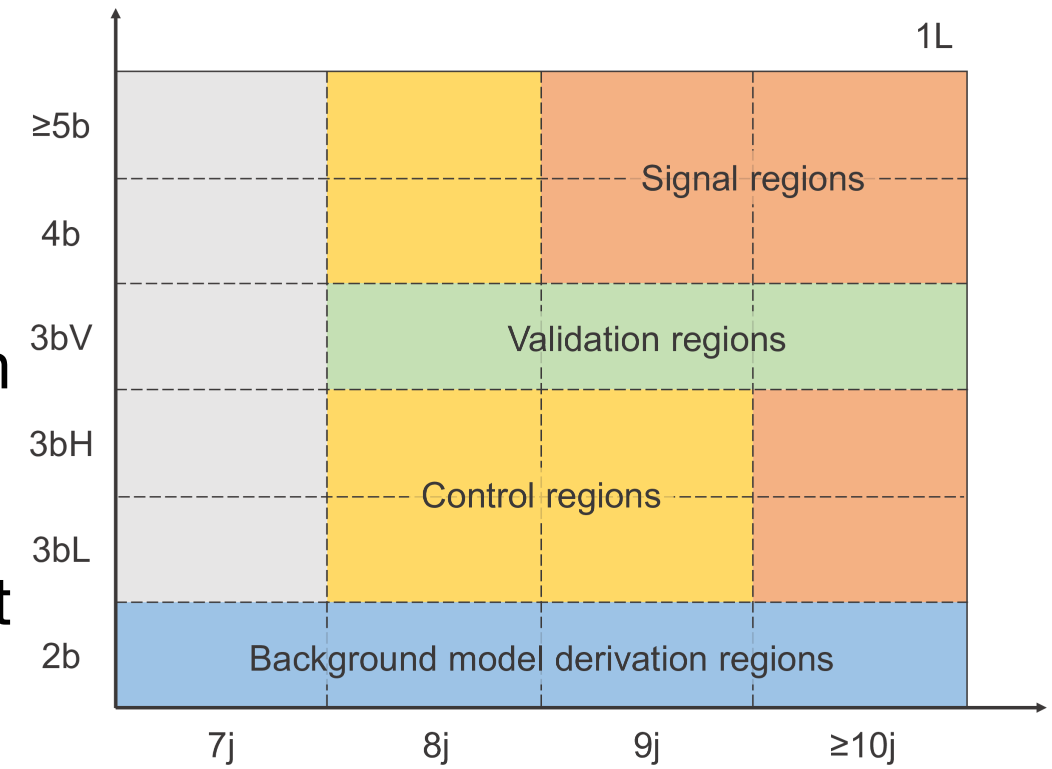


Production of four tops

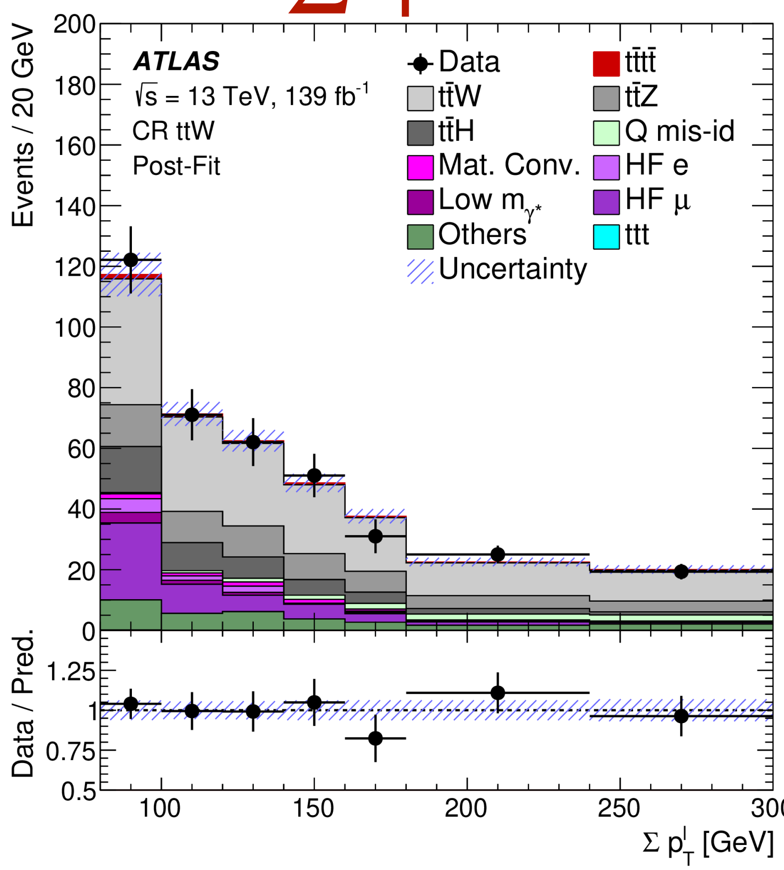
Eur.Phys. J. C (2020)80:10985 JHEP 11 (2021)118

- Targeting events with high **jet** and **b-jet** multiplicities
- Split in multiple regions: Control (CR) signal (SR) and validation (VR) regions
  - Dedicated Control Regions are defined to constrain normalisation factors in **2ℓSS/3ℓ channel**
  - Designed a 3-step sequential re-weighting to target different type of mismodeling in the **1ℓ/2ℓOS**

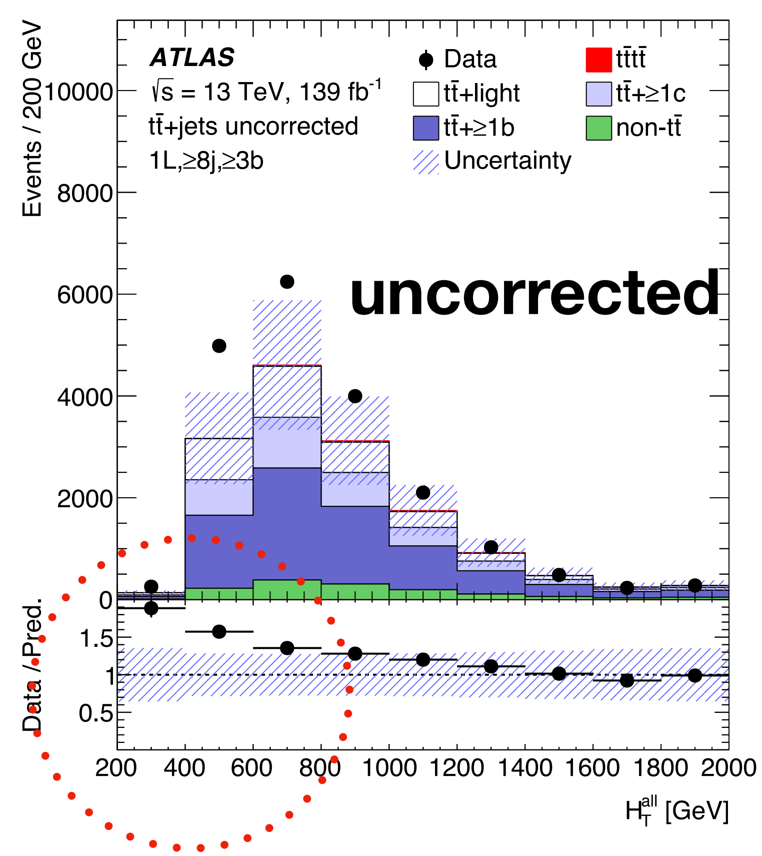
Regions in the 1l channel



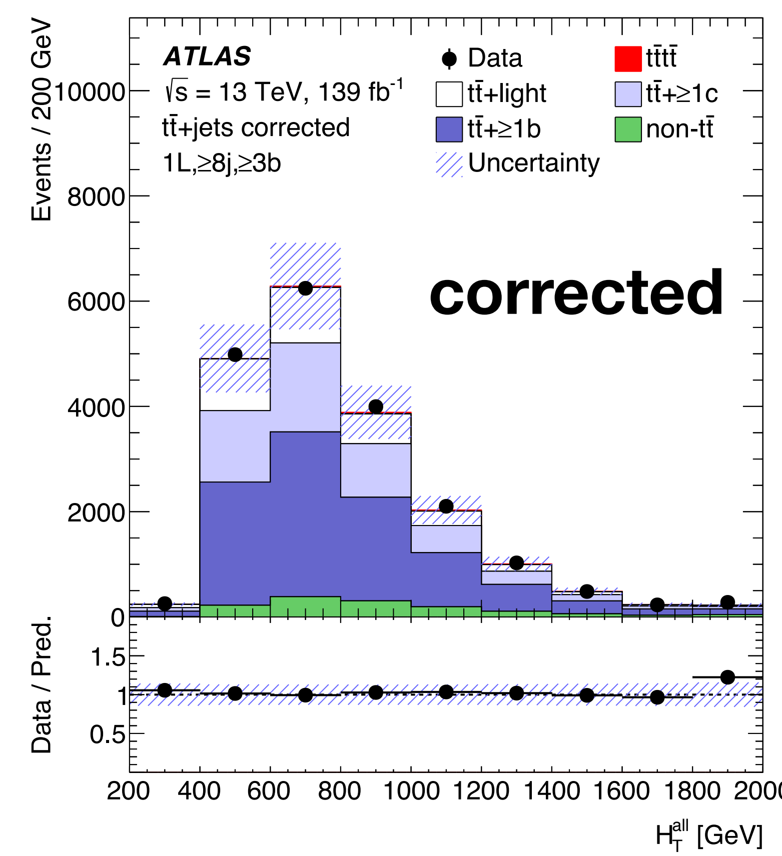
$\sum p_T^{\text{lepton}}$



H_T^{all}



H_T^{all}

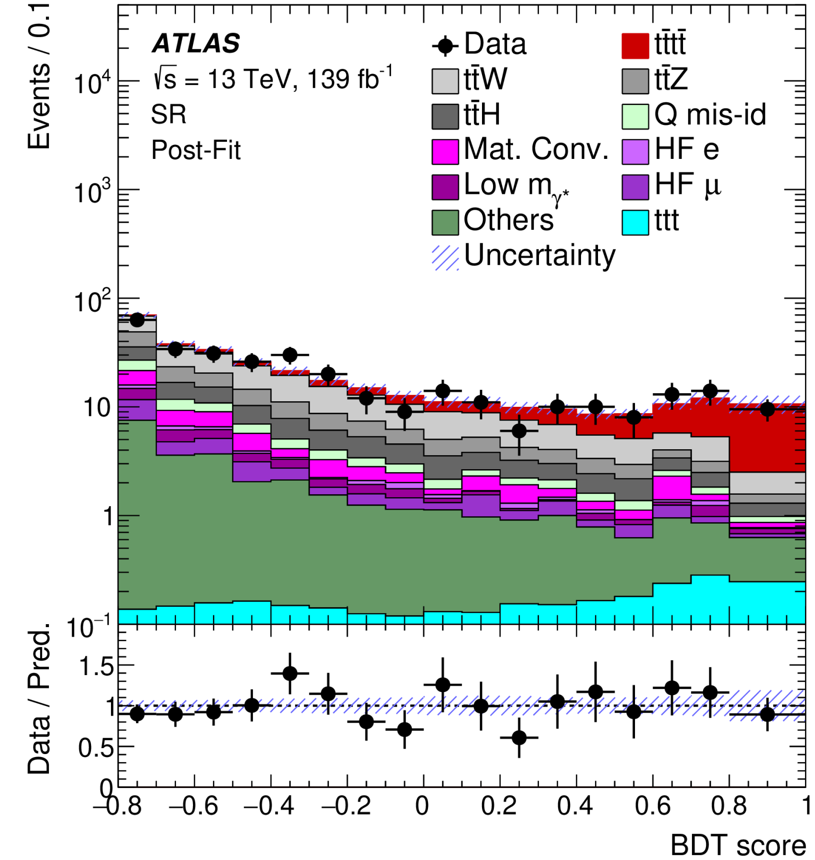


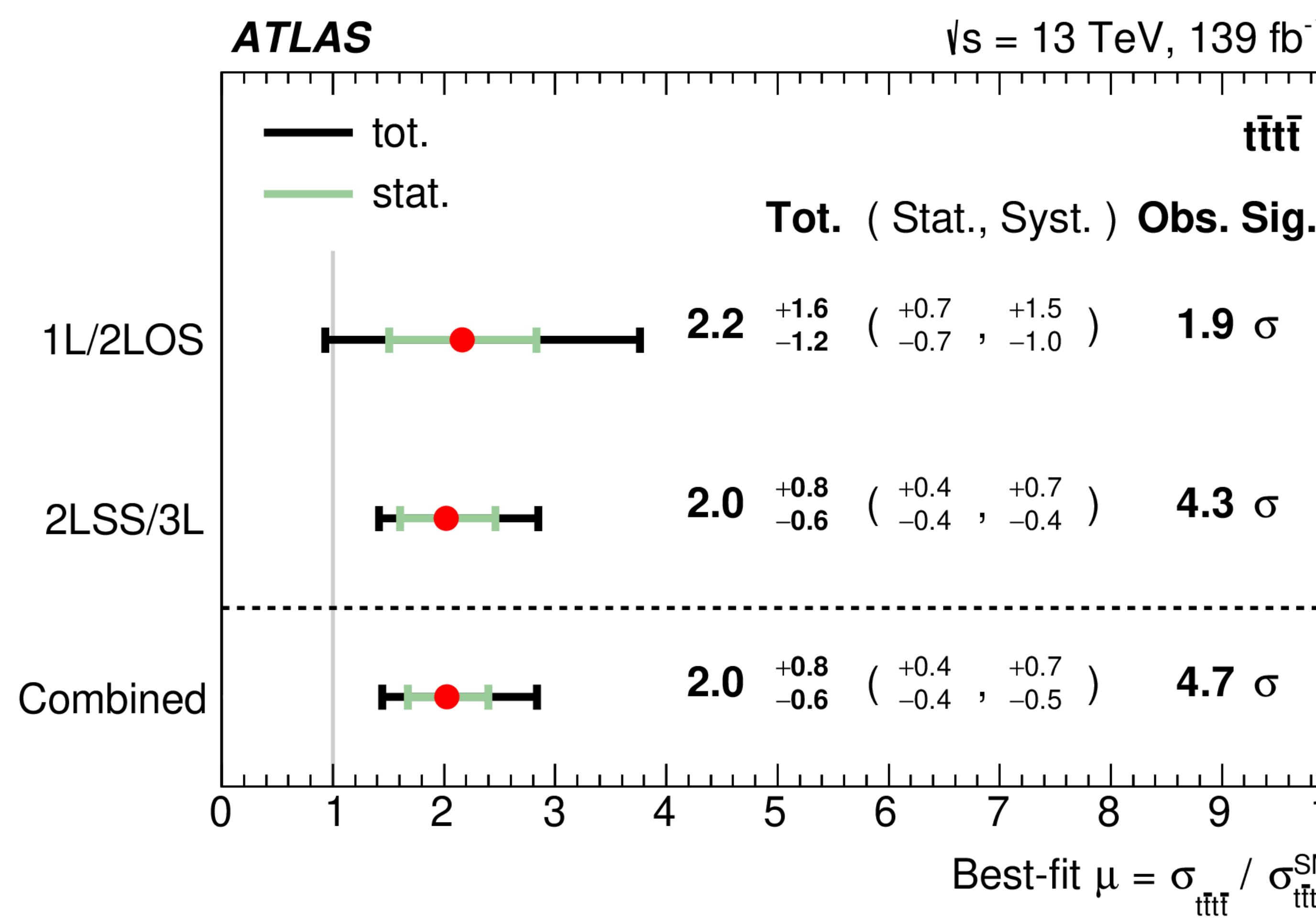
Production of four tops

Eur.Phys. J. C (2020)80:10985 JHEP 11 (2021)118

- Signal is separated from background based on a BDT in the SR
- A simultaneous profile likelihood fit is performed in the CR and SR
- The combined four-top cross-section: $\sigma(t\bar{t}t\bar{t}) = 25^{+7}_{-6}\ fb$
- To be compared to $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4\ fb$
- Compatible with the SM prediction within 2.0 σ
- Observed (expected) significance: **4.7** (**2.6**) **σ**
- The dominant systematics uncertainties:
  - modeling of the four top signal
  - modeling of $t\bar{t}W$ and $t\bar{t}$+jets
  - b-tagging and Jet Energy Scale

BDT score

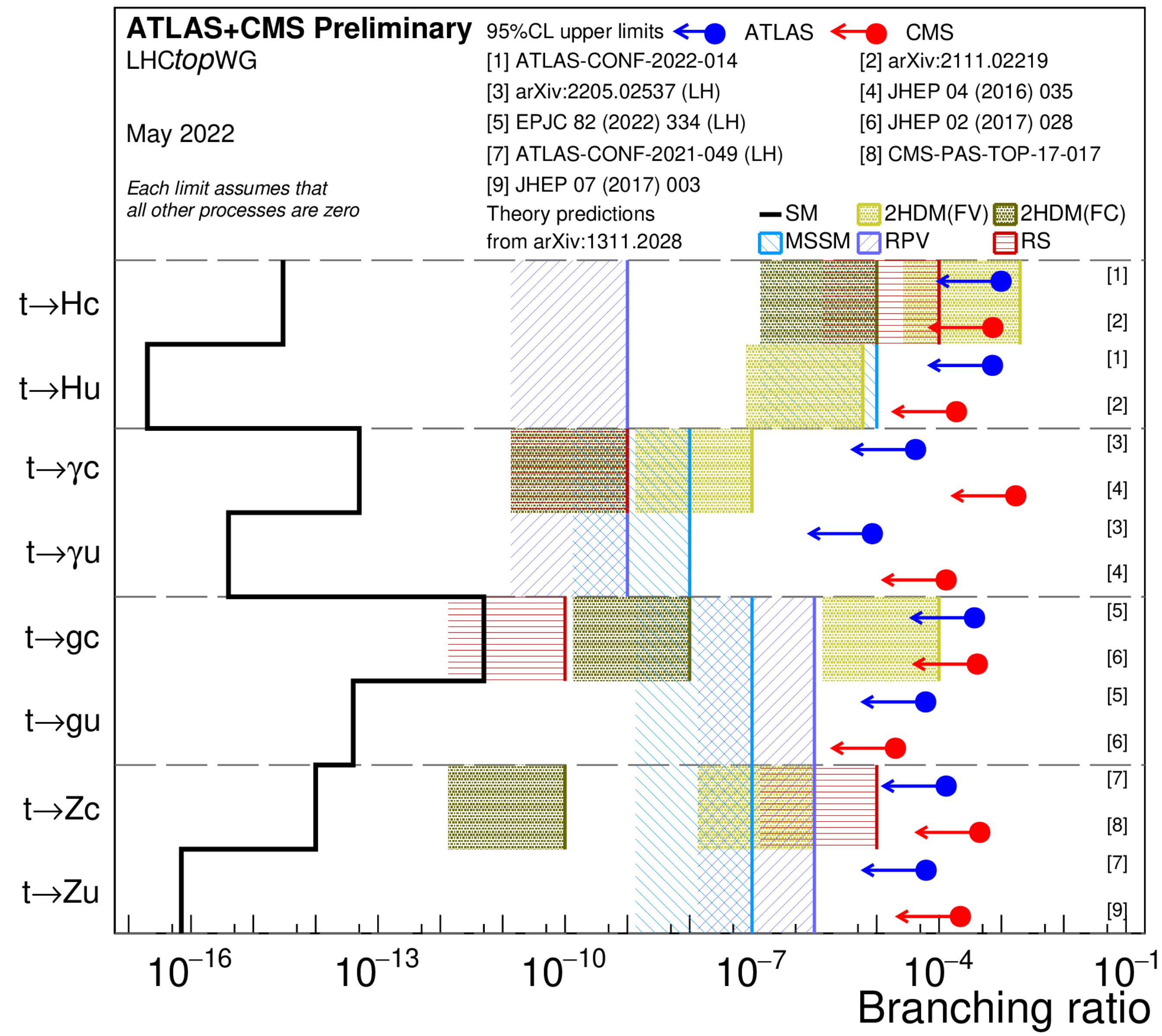




Searches for Flavour Changing Neutral Current (FCNC)

- FCNC in the SM is forbidden at tree-level: heavily suppressed in loops by GIM mechanism BRs ~10^{-14}
- BSM can enhance FCNC up to ~10^{-4}
  - Many potential models: 2HDM, MSSM, RPV SUSY, …
- Any observation of FCNC can hint to new physics
- FCNC probe can be done in both top quark **production**, and **decay**

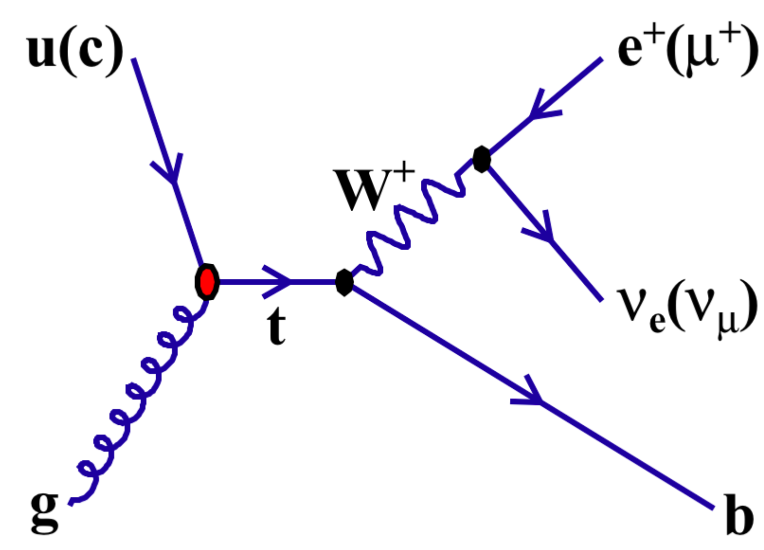
Summary of the current 95% confidence level observed limits on the branching ratios of the top quark decays via FCNC



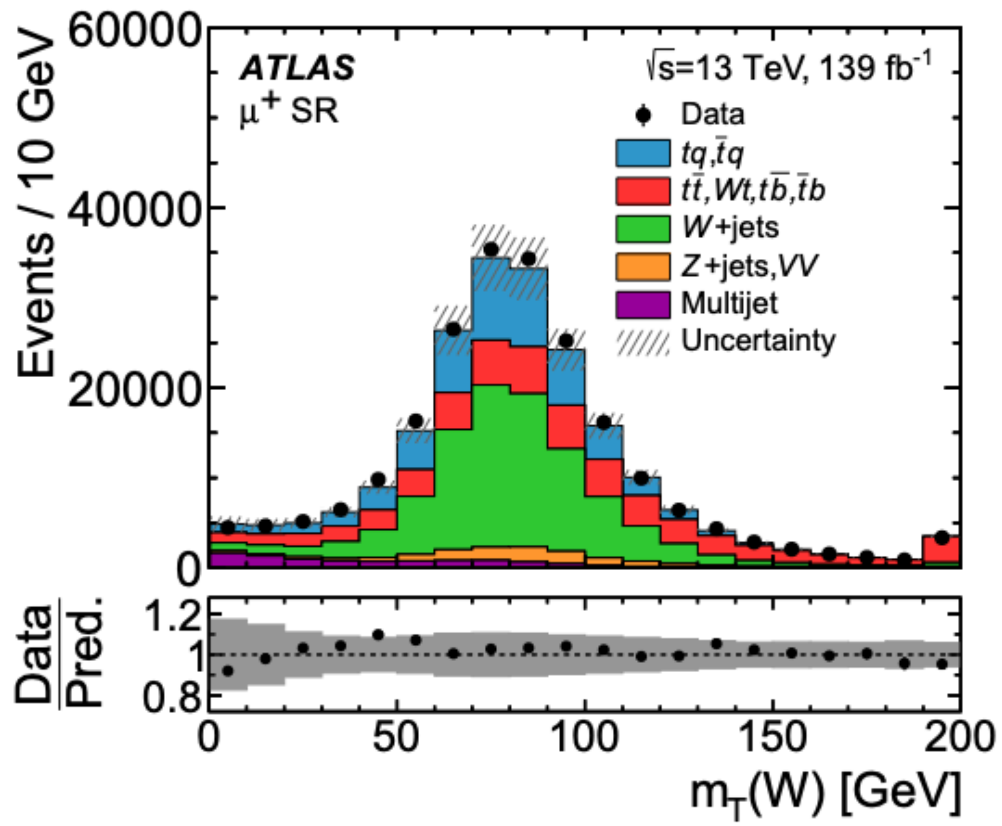
ATL-PHYS-PUB-2022-030

FCNC Search for top-gluon with $t \to l\nu b$ 2112.01302

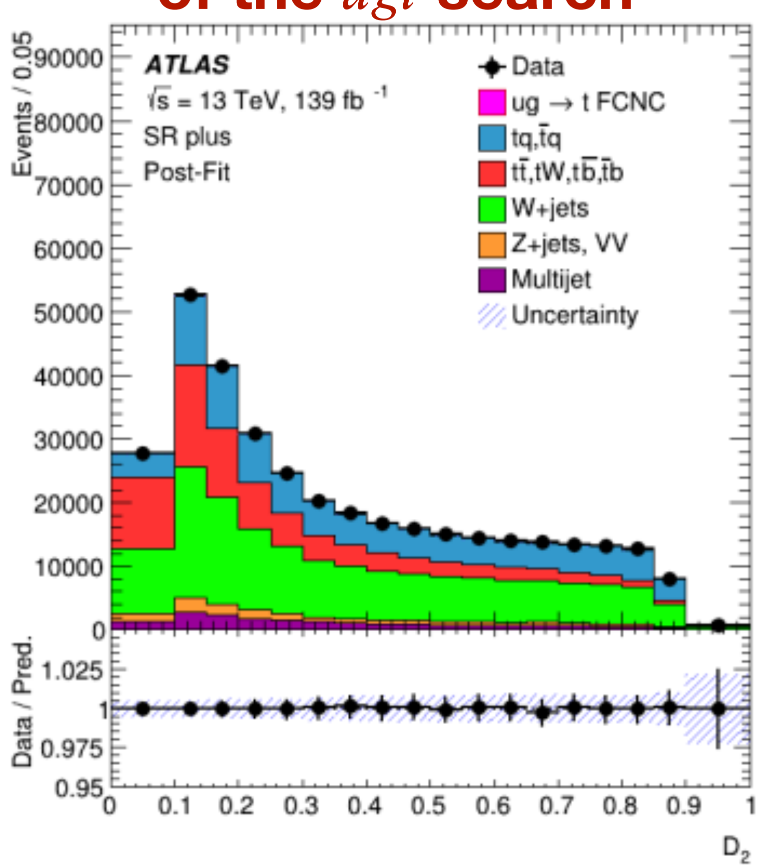
- Target $l + b$-tagged jet and E_T^{miss}
- Main backgrounds: $W + b\bar{b}$, t-channel single-top and $t\bar{t}$ production
  - Multijet contribution determined in a data-driven way by fitting E_T^{miss} and $m_T(W)$
- Neural Network (NN) used to construct two discriminants:
  - D1 targeting top antiquark production $\bar{u}/\bar{c} + g \to \bar{t}$: signal region for tcg and tug in l^- channel
  - D2 aimed at direct top quark production $u + g \to t$: signal region for tug in l^+ channel



$m_T(W)$



NN discriminant D_2 of the ugt search

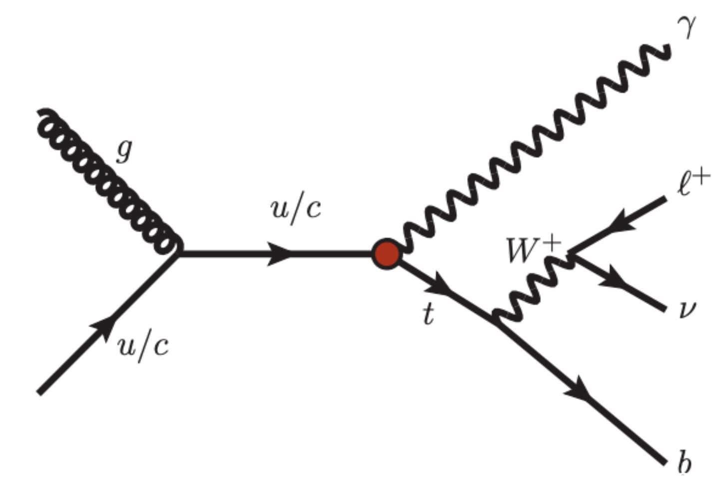


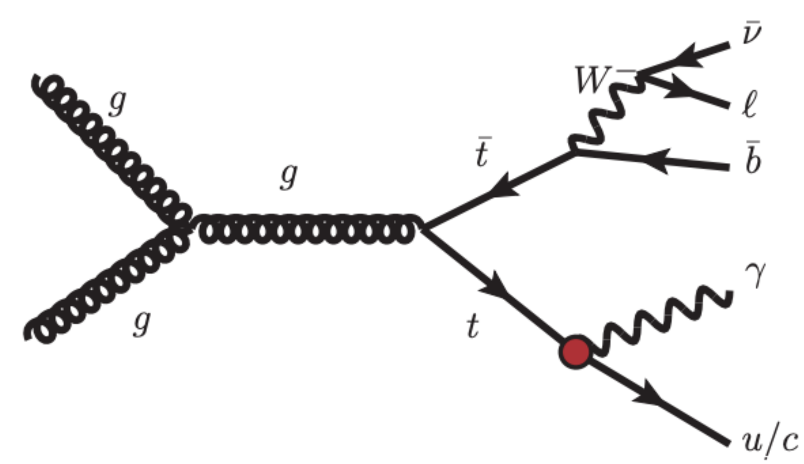
FCNC Search for top-gluon with $t \to l\nu b$ 2112.01302

- Binned maximum-likehood fit performed separately to tug and tcg FCNC processes
- Leading systematic uncertainties related to the W+jets process for the tug fit and the modelling of the parton shower for the tcg fit
- Measured data consistent with background-only hypothesis
- Limits for FCNC tqg couplings set at the 95% CL for cross-sections, branching ratios and further interpreted in terms of EFT coefficients
  - **A factor of three more restrictive than the previous ATLAS results**

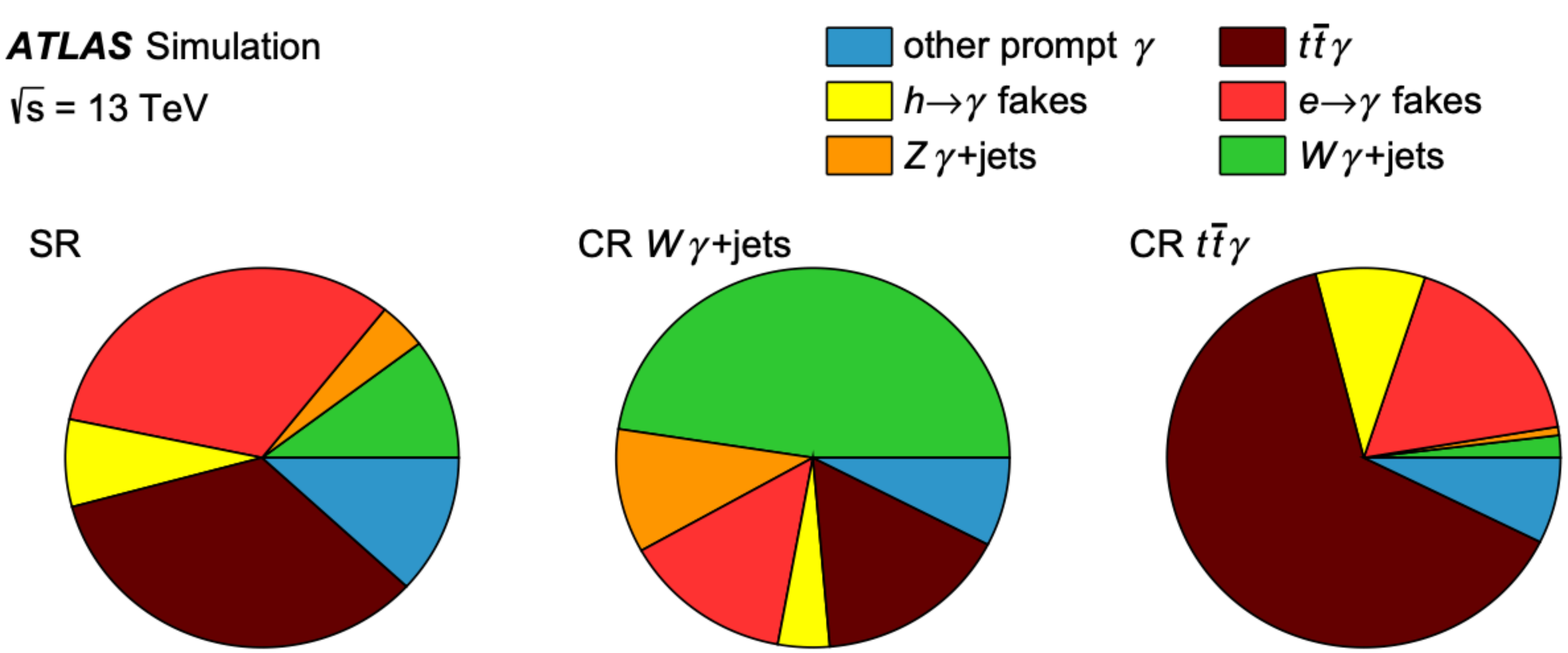
Coupling	$\sigma(q+g \to t)$	$\mathcal{B}(t \to gq)$	$\lvert C_{uG}^{qt}\rvert/\Lambda^2$
tgu	3.0 pb	$0.61\ (0.49) \times 10^{-4}$	0.057
tgc	4.7 pb	$3.7\ (2.0) \times 10^{-4}$	0.14

- Searching for the production and decay mode of FCNCs with a top and a photon
  - Four couplings: $tc\gamma, tu\gamma$ (left- and right-handed)
- Events require one high-momentum photon and a semileptonically decaying top quark
- Main backgrounds arise from prompt photons and misidentified photons
  - Estimated using dedicated CRs and data-driven method

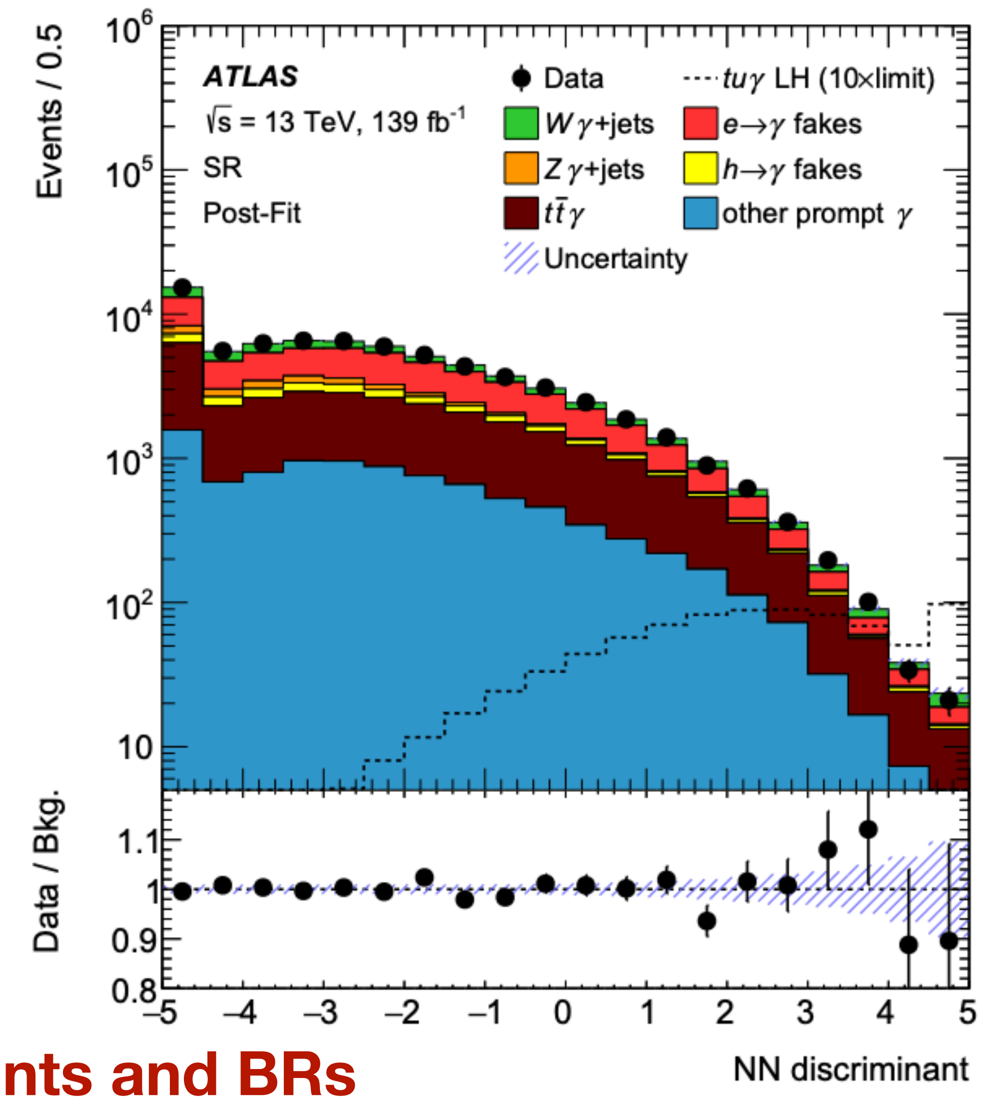




Expected background composition of the SR, CR $W\gamma+$ jets, CR $t\bar{t}\gamma$



NN discriminant in the SR for the $tu\gamma$ coupling



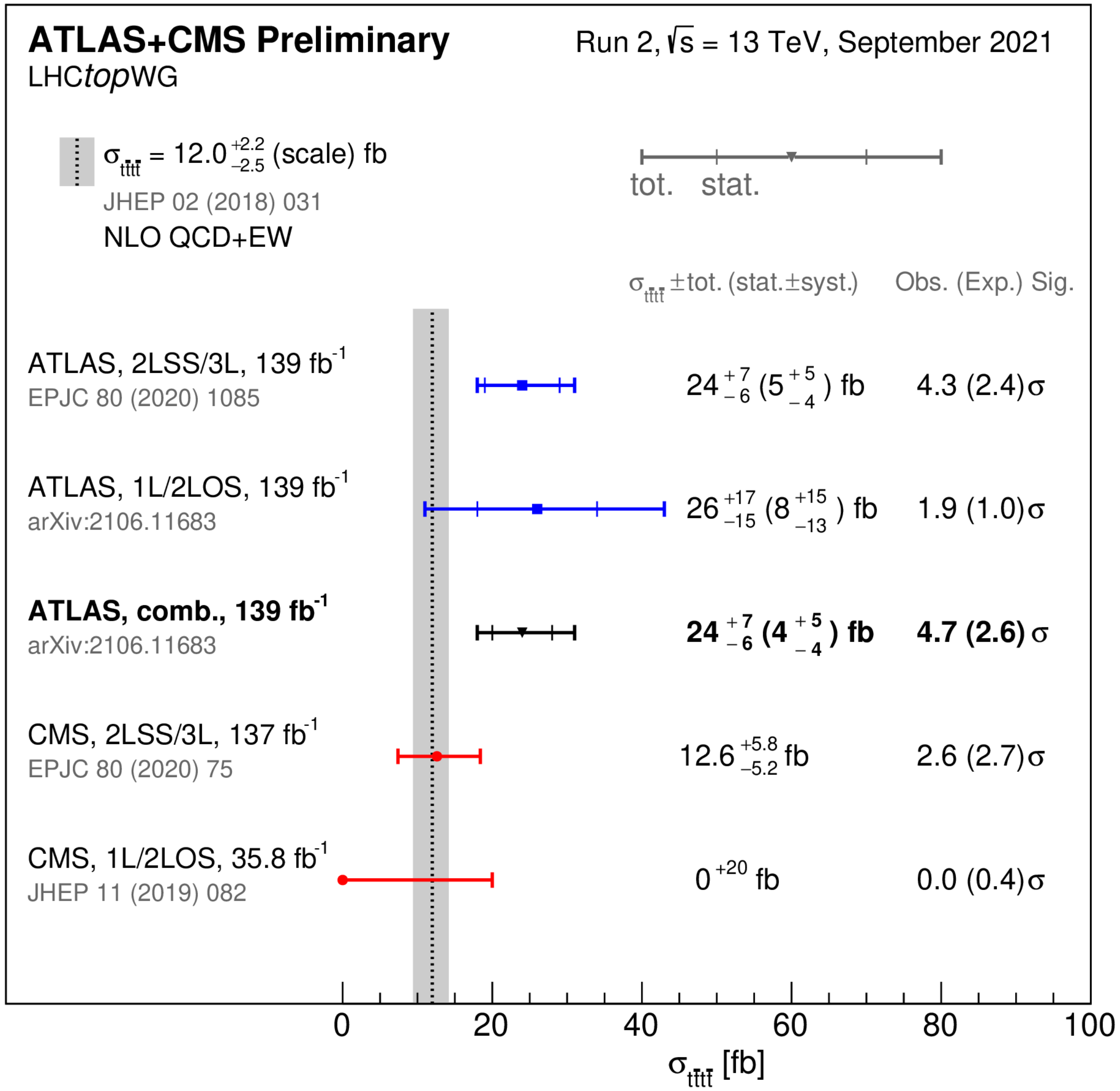
- Two neural networks are trained for $tu\gamma$ and $tc\gamma$
- Observed (expected) upper limits of BR
  - Factor 5 (tuγ LH), 5 (tuγ RH), 9 (tcγ LH), 8 (tcγ RH) improvements in expected limits on B(t → qγ)
  - Factor 3 (tuγ LH), 5 (tuγ RH), 5 (tcγ LH), 4 (tcγ RH) smaller observed upper limits on B(t → qγ)

95% CL limits on the effective coupling constants and BRs

Effective coupling	Coefficient limits		Coupling	BR limits $[10^{-5}]$	
	Expected	Observed		Expected	Observed
$\lvert C_{uW}^{(13)*} + C_{uB}^{(13)*}\rvert$	$0.104^{+0.020}_{-0.016}$	0.103	$t \to u\gamma$ LH	$0.88^{+0.37}_{-0.25}$	0.85
$\lvert C_{uW}^{(31)} + C_{uB}^{(31)}\rvert$	$0.122^{+0.023}_{-0.018}$	0.123	$t \to u\gamma$ RH	$1.20^{+0.50}_{-0.33}$	1.22
$\lvert C_{uW}^{(23)*} + C_{uB}^{(23)*}\rvert$	$0.205^{+0.037}_{-0.031}$	0.227	$t \to c\gamma$ LH	$3.40^{+1.35}_{-0.95}$	4.16
$\lvert C_{uW}^{(32)} + C_{uB}^{(32)}\rvert$	$0.214^{+0.039}_{-0.032}$	0.235	$t \to c\gamma$ RH	$3.70^{+1.47}_{-1.03}$	4.46

Results with Run 2

- Run 2 opened up measurements to **new rare SM processes**
- We've found **exciting results** using the full run 2 data-set
  - Observation of many rare processes with top quarks
  - A slight excess in the measured $t\bar{t}t\bar{t}$ cross section, but still compatible with the SM prediction within 2 σ



What's next for Top physics

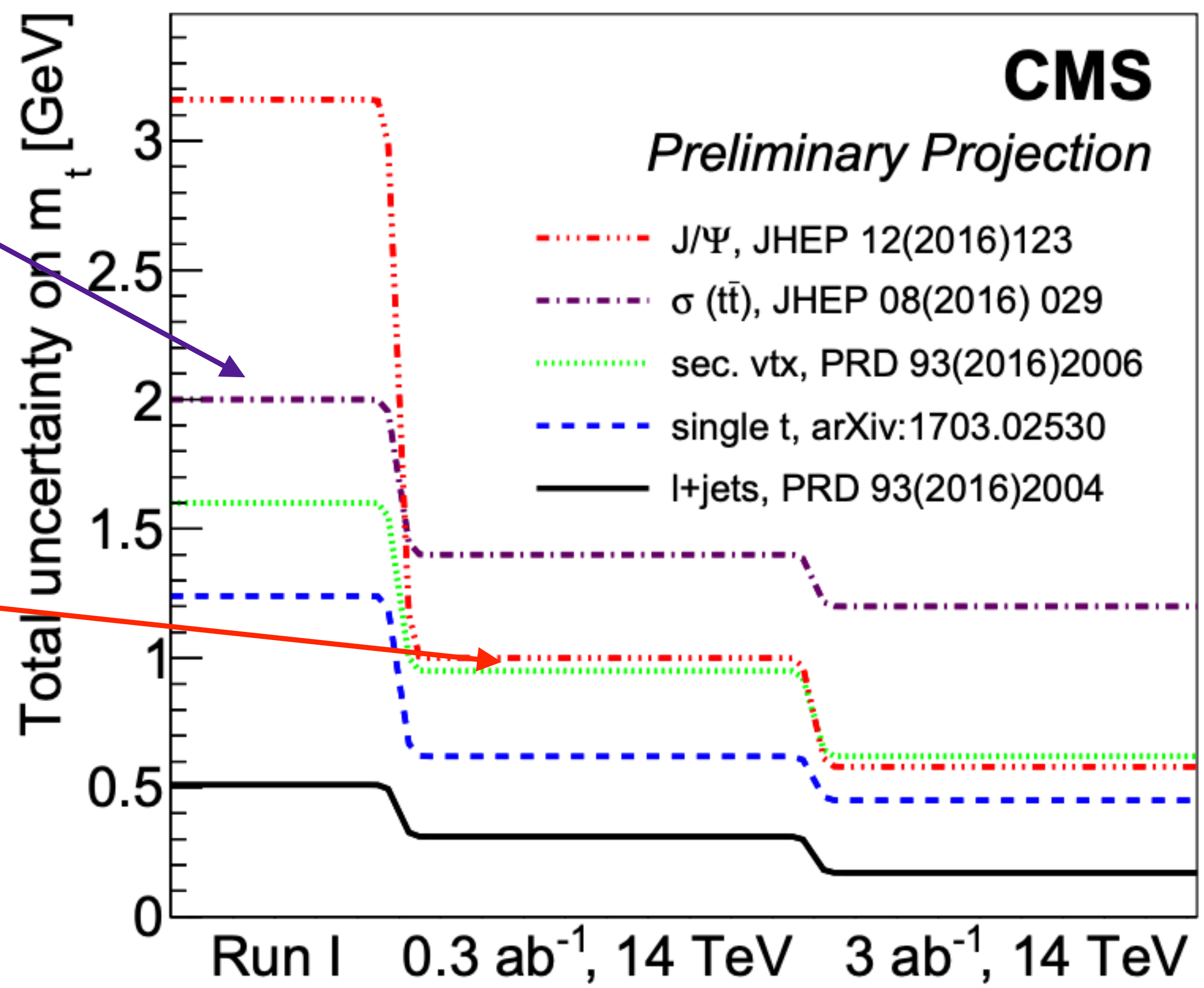
- Why keep doing Top & SM measurements?
    - Teach us about the SM
    - Improves our theoretical calculations, MC modelling, and understanding of CP calibrations and uncertainties
    - Measurements will be important for constraining PDFs, understanding electroweak symmetry breaking (EWSB), and measuring fundamental properties of the SM
    - Can uncover unexpected deviations from the SM
- The HL-LHC will provide the opportunity for more precision, particularly at high energies which are currently limited by statistical uncertainties

Top mass

- Current uncertainties are ~600 MeV, projected to be reduced to 200 MeV at the HL-LHC

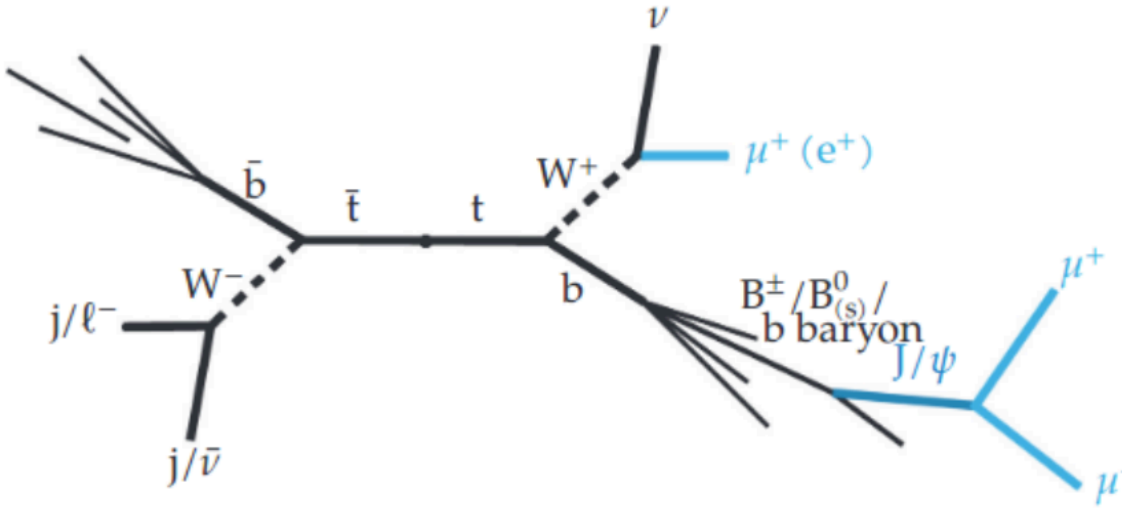
m_{top} **measurement uncertainty for different methods as a function of integrated luminosity**

- Indirect extraction of pole mass, e.g. $\sigma_{t\bar{t}}$
    - limited by theory uncertainty and lumi measurements
- less dependence on JES, e.g. $m(lJ/\psi)$
- Room for more reduction via future techniques



CMS-PAS-FTR-16-006

Top quark mass measurement using $t\bar{t}$ pairs with a J/ψ



- Measurements using $t\bar{t}$ pairs with a $J/\psi \rightarrow \mu\mu$ in final state using the strong correlation between m_{top} and $m(lJ/\psi)$
    - BR $(b \rightarrow J/\psi(\rightarrow \mu\mu) + X)$ ~10^{-3}
        - Will benefit from larger data samples from the HL-LHC
- A reduction of $t\bar{t}$ modeling uncertainties by a factor of two and a reduction of some of the experimental uncertainties by up to a factor two are assumed for these projections
    - Main result of this study is a statistical projection of the measurement
- ATLAS [ATL-PHYS-PUB-2018-042]: **a statistical uncertainty of ~0.14 GeV is expected with a systematic uncertainty of 0.48 GeV**
    - Dominant uncertainties are from **signal modeling** (fragmentation functions / b-hadron fractions) and from **JES/JER**
- CMS [CMS-PAS-FTR-16-006]: **expected to yield an ultimate relative precision below 0.1% at the HL-LHC**

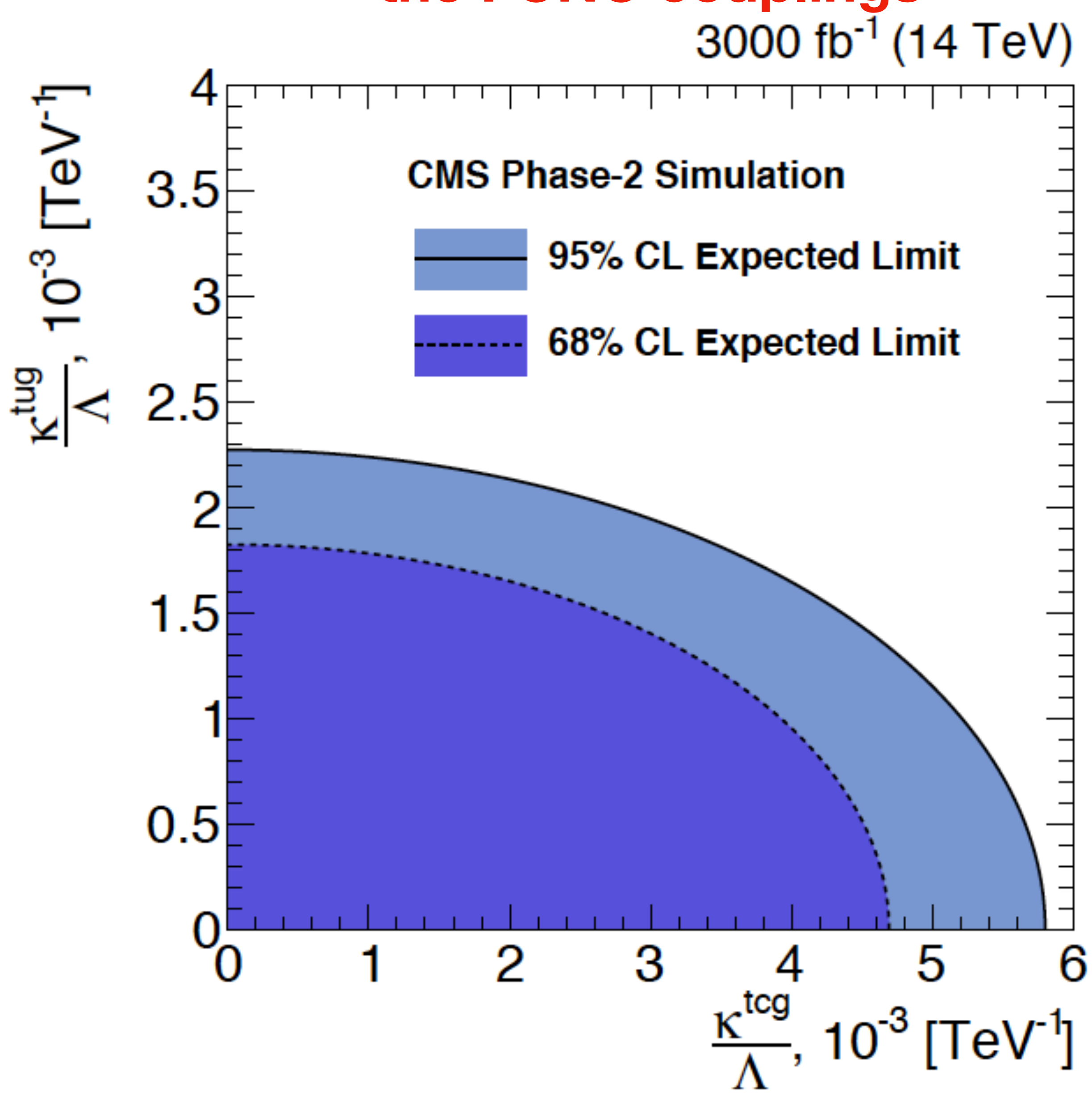
m_{top} measurements will be an important element of HL-LHC

FCNC

- Search prospects for gluon-mediated FCNC in top quark production via tug and tcg vertices were studied with CMS HL-LHC detector
- Dominant uncertainty is normalization of multi-jet background
- Limits on branching fractions:
  - $B(t \rightarrow ug) < 3.8 \times 10^{-6}$
  - $B(t \rightarrow cg) < 32 \times 10^{-6}$

Exploiting full HL-LHC dataset will allow us to improve current limits by an order of magnitude

Two-dimensional expected limits on the FCNC couplings



See back-up for more examples

CMS-PAS-FTR-18-004

Extrapolation Studies for $t\bar{t}t\bar{t}$

- The expected cross-section of tttt at 14 TeV is 15.83 +18%/ -21% fb (JHEP 02 (2018) 031)
  - An increase by a factor of 1.3 with respect to 13 TeV
- Extrapolation studies are performed with the setup that uses HT as fitted variations in five signal regions
  - Easier to extrapolate than the result using the BDT score
  - Almost the same significances as with the BDT

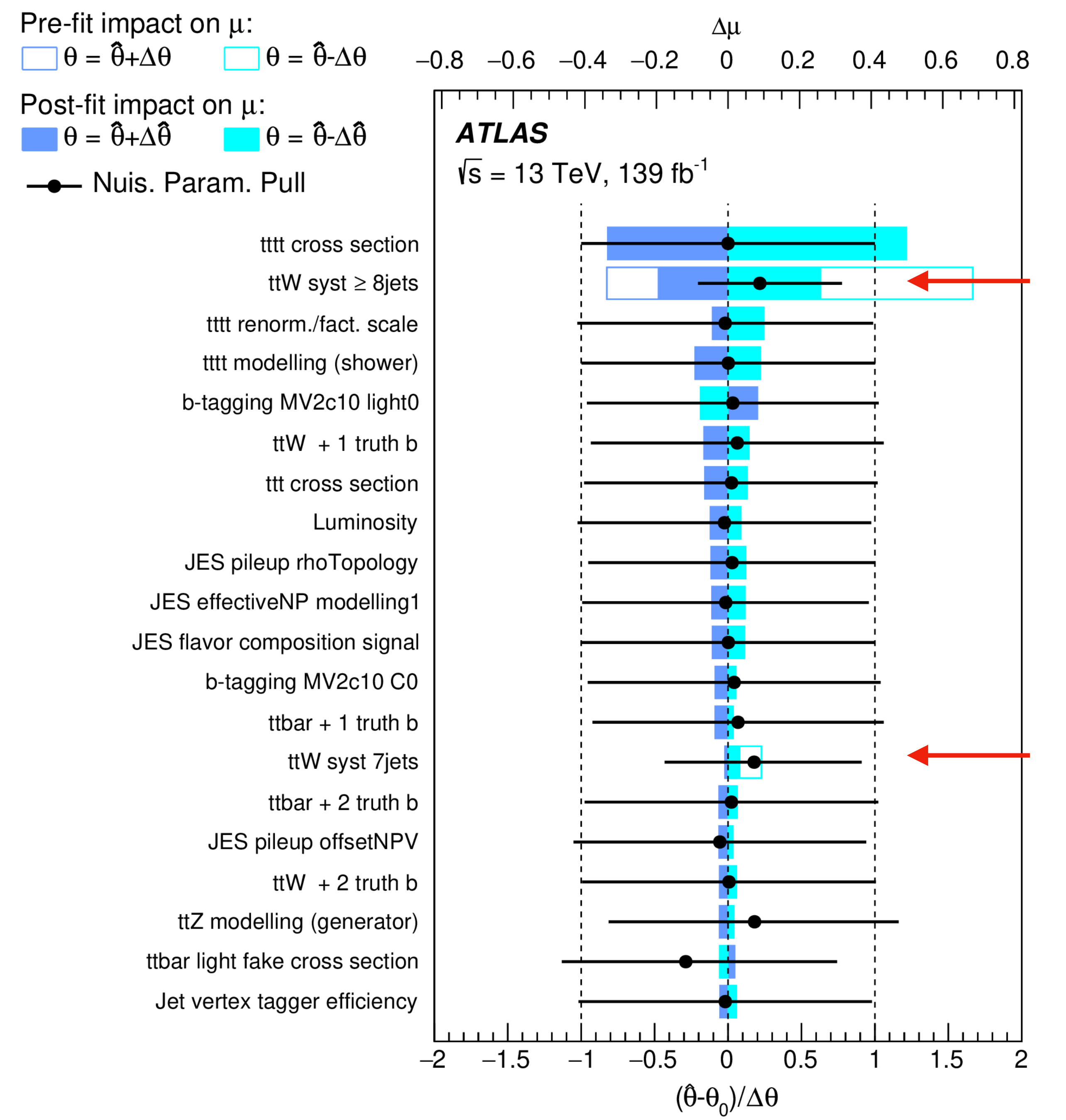
Channel	Selection criteria
Common	$N_j \geq 6$, $N_b \geq 2$ and $H_T > 500$ GeV
SR2b2l	SS events with $N_b = 2$
SR2b3l	multilepton events with $N_b = 2$
SR3b2l	SS events with $N_b = 3$
SR3b3l	multilepton events with $N_b = 3$
SR4b	events with $N_b \geq 4$

Two Different Scenarios

- "**Run 2**" : systematic uncertainties are kept equal to their Run 2 values except uncertainties related to $t\bar{t}W + 7/8$jets (take the post-fit values of the corresponding nuisance parameters from the 139 fb^{-1} result)

- "**Run 2 Improved**": includes the $t\bar{t}W + 7/8$jets scaling and includes a decrease of the systematic uncertainties explained in the previous slide

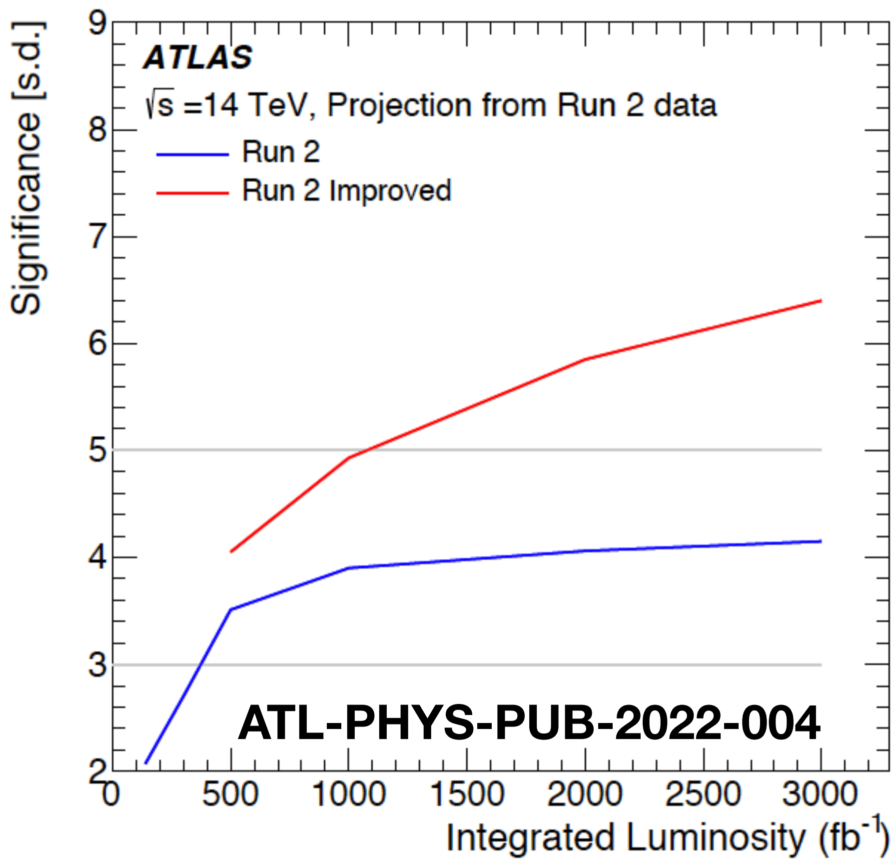
Ranking with 139 fb^{-1}



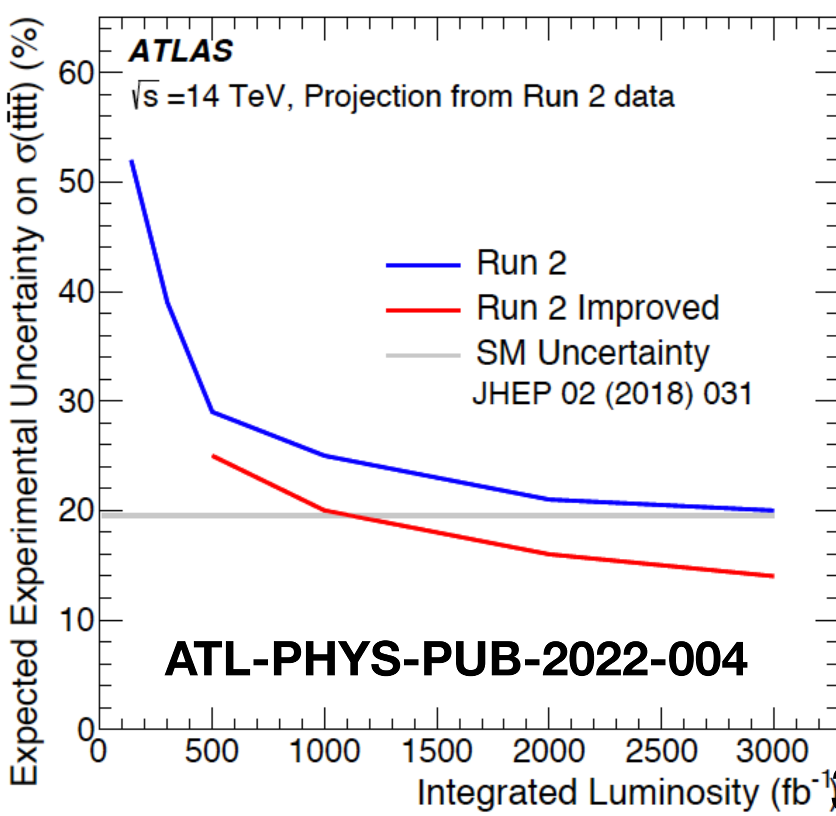
Expected Sensitivity

- A significance of 6.4σ for the SM $t\bar{t}t\bar{t}$ process is expected in the **"Run 2 Improved"** scenario
  - Expecting total uncertainty on the cross section of ~14%
  - Experimental precision is expected to be significantly better than the precision of the current SM computation
- The better sensitivity is driven by:
  - Smaller theoretical uncertainties assumed in the $t\bar{t}$ cross section
  - Better modeling of the $t\bar{t}W/t\bar{t}Z$ + HF jets
  - Smaller b-tagging experimental uncertainties

Expected significance



Expected experimental uncertainty



Sensitivity Studies by CMS

- Based on the run-2 results with 36 fb^{-1}
- Tried various treatment of systematic uncertainties

Source uncert.	*Stat. only*	*Run 2*	*YR18*	*YR18+*
Statistical	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$
Experimental	None	Original	$\max(0.5, (L/L_{ref})^{-0.5})$	$(L/L_{ref})^{-0.5}$
Int. Luminosity	None	Original	0.4	0.4
Data-driven bckgrnd	None	Original	$\max(0.5, (L/L_{ref})^{-0.5})$	$(L/L_{ref})^{-0.5}$
Theory (shapes)	None	Original	0.5	0.5
Bckgrnd cross section	None	Original	0.5	0.5
Signal cross section	None	Original	0.5	0.5

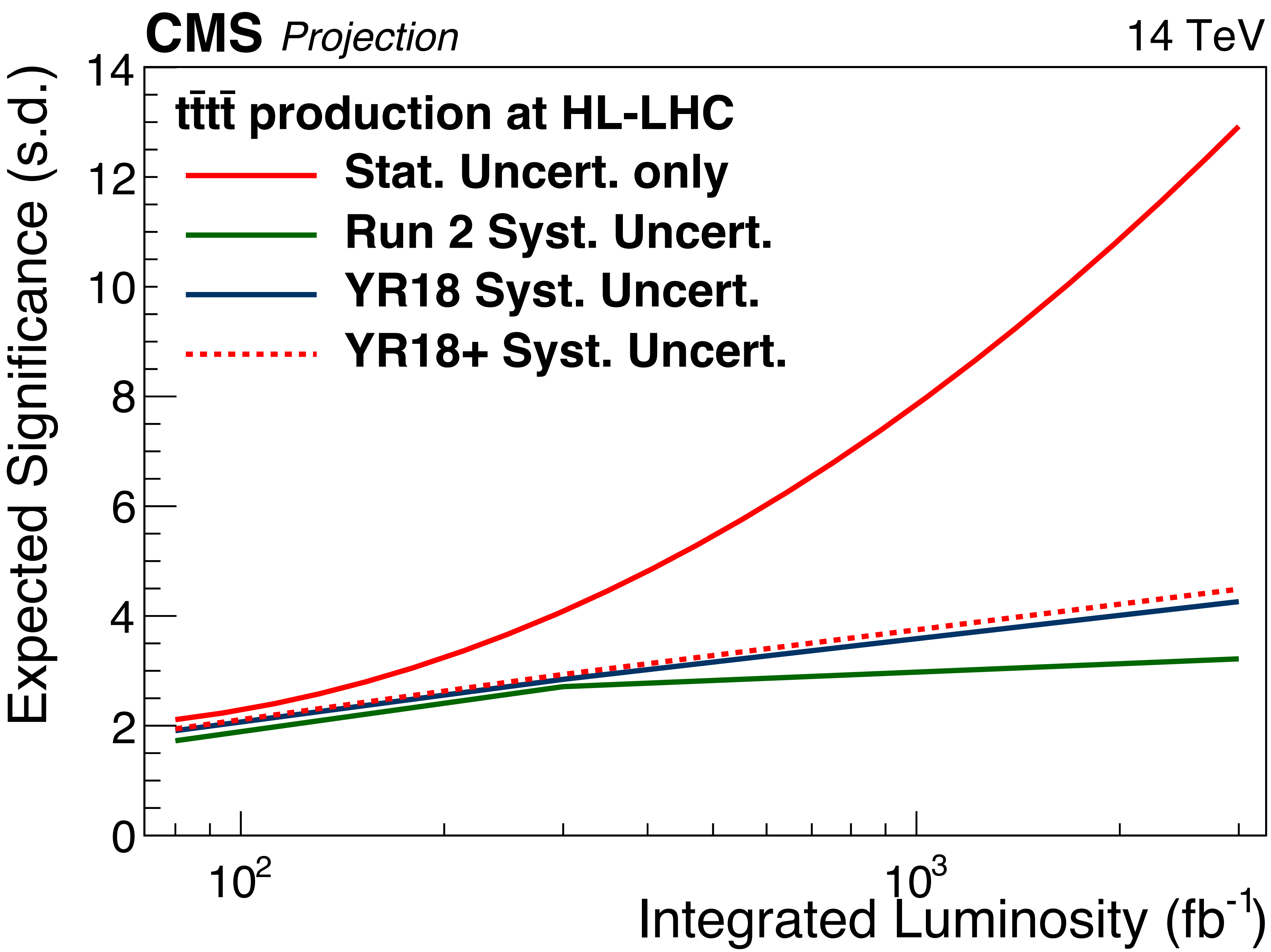
Expected significance of $t\bar{t}t\bar{t}$ signal over a background-only hypothesis

Int. Luminosity	*Stat. only*	*Run 2*	*YR18*	*YR18+*
300 fb^{-1}	4.09	2.71	2.85	2.93
3 ab^{-1}	12.9	3.22	4.26	4.49

CMS-PAS-FTR-18-031

Sensitivity Studies by CMS

- A 4.5σ significance is expected with the most optimistic systematics scenario
- Cross-section can be constrained down to 9% statistical uncertainty and 18% to 28% total uncertainty (depending on the considered systematic uncertainties)



CMS-PAS-FTR-18-031

Conclusions

- HL-LHC will offer a great opportunity for many top measurements & top related searches
- Detector upgrades will allow for better forward jet and lepton reconstruction - essential to improve current measurements
- Will produce currently unachievable measurements
- Improve our understanding and learn more about the SM
- Can uncover unexpected deviations from the SM pointing to new physics
- Improving theoretical uncertainties is a key player to achieve better precision

Thank you!

Extra Material

back-up (SMT- top mass)

Table 5: Impact of main sources of uncertainty on m_t. The last column shows the statistical uncertainty on each of the top quark mass uncertainties.

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
W/Z+jets modelling	0.17	±0.01
Single top modelling	0.01	±0.01
Fake lepton modelling ($t \to W \to \ell$)	0.06	±0.02
Soft muon fake modelling	0.15	±0.03
Jet energy scale	0.12	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.07	±0.05
Jet vertex tagger	< 0.01	±0.01
b-tagging	0.10	±0.01
Leptons	0.12	±0.00
Missing transverse momentum modelling	0.15	±0.01
Pile-up	0.20	±0.05
Luminosity	< 0.01	±0.01
Total systematic uncertainty	0.67	±0.04
Total uncertainty	0.78	±0.03

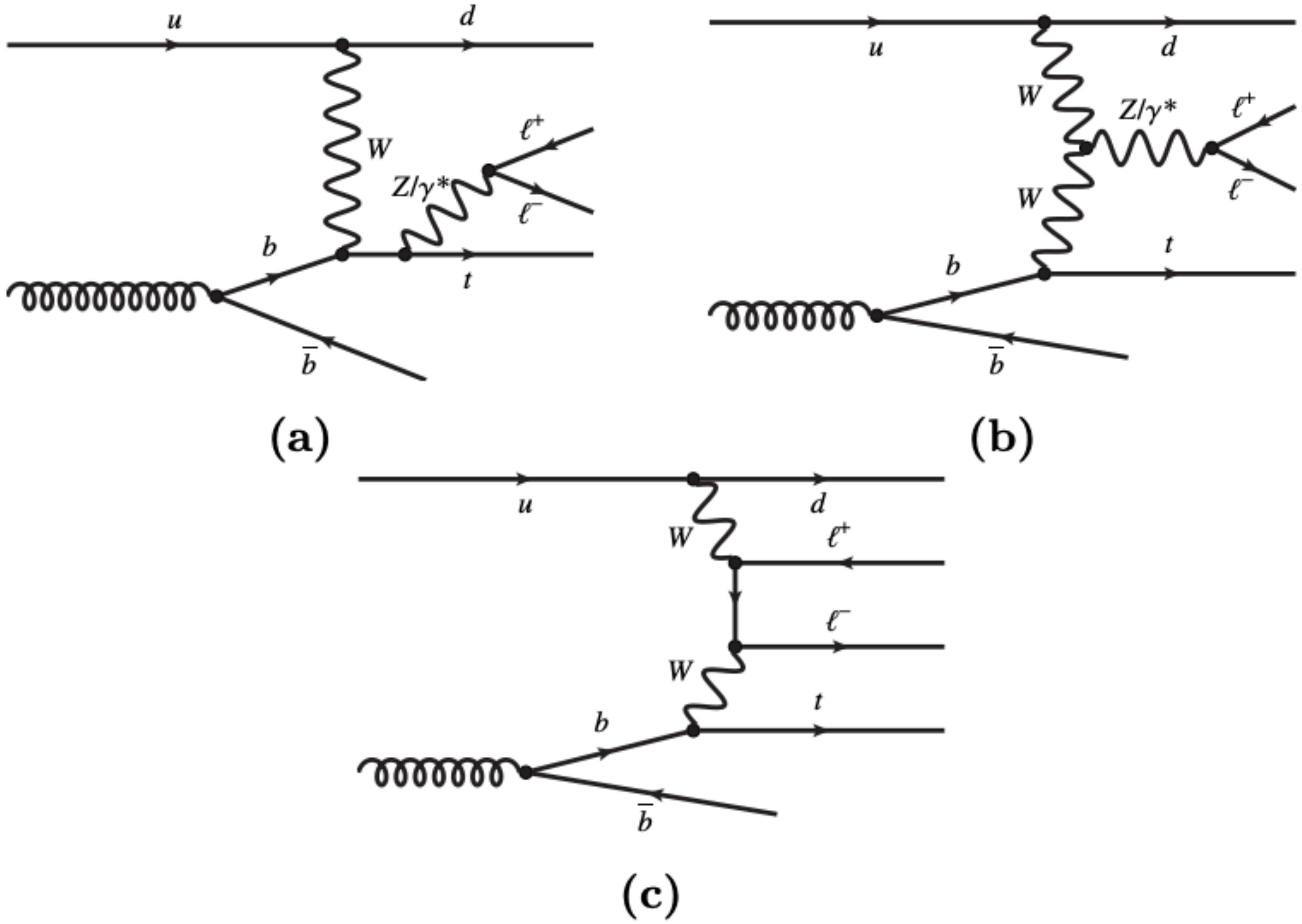


Figure 1. Example Feynman diagrams of the lowest-order amplitudes for the tZq process, corresponding to (a, b) resonant $\ell^+\ell^-$ production and (c) non-resonant $\ell^+\ell^-$ production. In the four-flavour scheme, the b-quark originates from gluon splitting.

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(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, $\|\eta\| < 2.5$

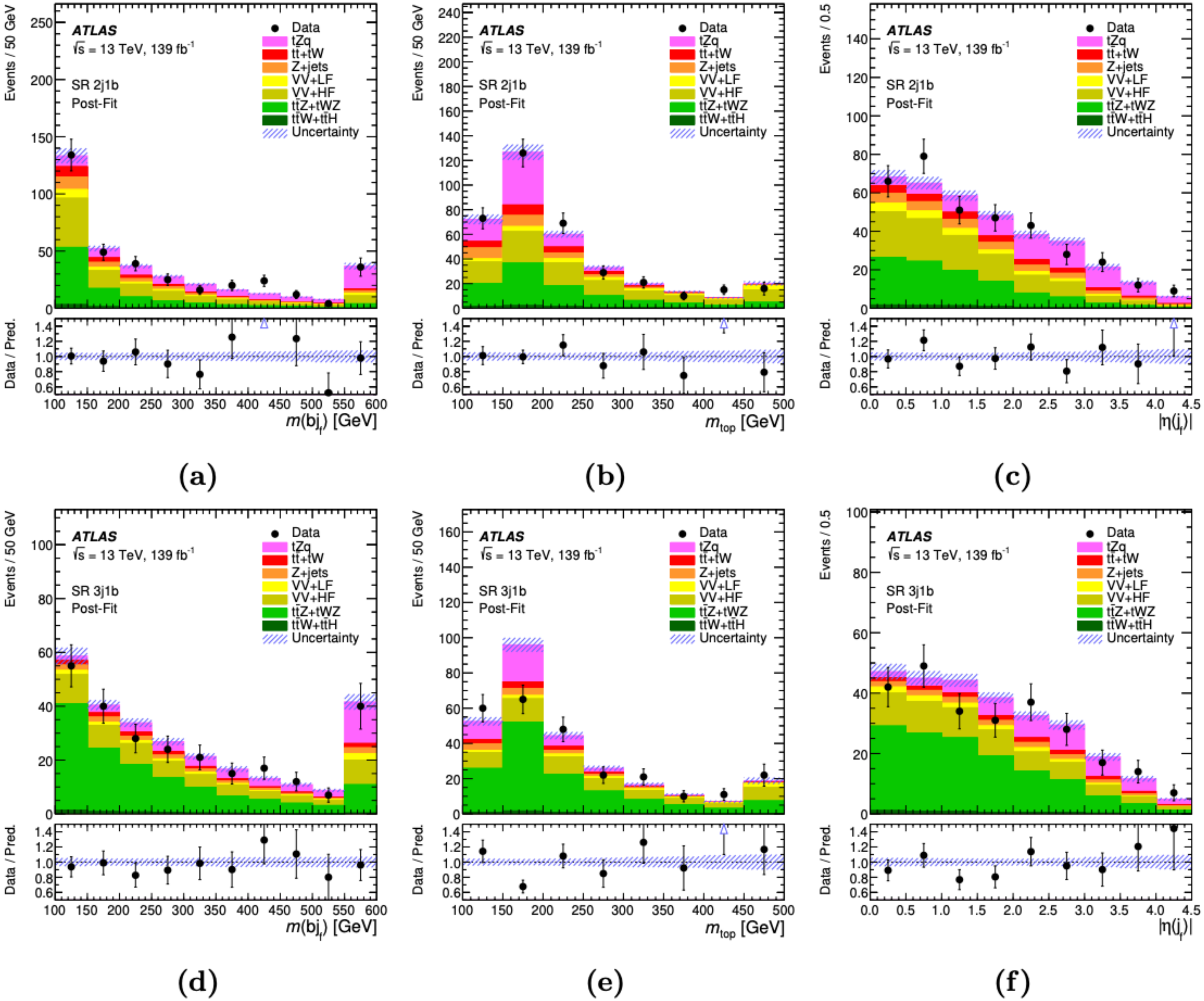
Table 1. Overview of the requirements applied when selecting events in the signal and control regions. OSSF is an opposite-sign same-flavour lepton pair. OSDF is an opposite-sign different-flavour lepton pair.

back-up (tZq)

Variable	Rank		Definition
	SR 2j1b	SR 3j1b	
$m_{b\mathrm{j_f}}$	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\lvert\eta(\mathrm{j_f})\rvert$	3	3	Absolute value of the η of the $\mathrm{j_f}$ jet
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	4	4	Transverse mass of the W boson
b-tagging score	5	11	b-tagging score of the b-jet
H_{T}	6	–	Scalar sum of the p_{T} of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W-boson decay
$\left\lvert\eta(\ell_W)\right\rvert$	8	12	Absolute value of the η of the lepton from the W-boson decay
$p_{\mathrm{T}}(W)$	9	15	p_{T} of the reconstructed W boson
$p_{\mathrm{T}}(\ell_W)$	10	14	p_{T} of the lepton from the W-boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$\lvert\eta(Z)\rvert$	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(\mathrm{j_f}, Z)$	13	7	ΔR between the $\mathrm{j_f}$ jet and the reconstructed Z boson
$E_{\mathrm{T}}^{\mathrm{miss}}$	14	–	Missing transverse momentum
$p_{\mathrm{T}}(\mathrm{j_f})$	15	10	p_{T} of the $\mathrm{j_f}$ jet
$\lvert\eta(\mathrm{j_r})\rvert$	–	5	Absolute value of the η of the $\mathrm{j_r}$ jet
$p_{\mathrm{T}}(Z)$	–	6	p_{T} of the reconstructed Z boson
$p_{\mathrm{T}}(\mathrm{j_r})$	–	9	p_{T} of the $\mathrm{j_r}$ jet

Table 2. Variables used as input to the neural network in SR 2j1b and SR 3j1b. The ranking of the variables in each of the SRs is given in the 2^{nd} and 3^{rd} columns, respectively. The untagged jet is denoted $\mathrm{j_f}$. When two untagged jets are selected, $\mathrm{j_f}$ ($\mathrm{j_r}$) refers to the one for which the invariant mass of this untagged jet and the b-tagged jet is the largest (smallest). The b-tagging score indicates whether the b-jet would also satisfy a tighter b-tagging requirement corresponding to a working point with an efficiency of 60% instead of 70%.

back-up (tZq)



ATLAS
√s = 13 TeV, 139 fb-1
SR 2j1b
SR 3j1b
Post-Fit
Data
tZq
tt̄+tW
Z+jets
VV+LF
VV+HF
tt̄Z+tWZ
tt̄W+tt̄H
Uncertainty
Events / 50 GeV
Events / 0.5
Data / Pred.
m(bjf) [GeV]
mtop [GeV]
|η(jf)|
(a)
(b)
(c)
(d)
(e)
(f)

back-up (tZq)

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pileup modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t} + tW$ and $Z+$jets normalisation	2.1
Total statistical uncertainty	12.9

Table 4. Impact of systematic uncertainties on the tZq cross-section, broken down into major categories. For each category the impact is calculated by performing a fit where the nuisance parameters in the group are fixed to their best-fit values, and then subtracting the resulting uncertainty in the parameter of interest in quadrature from the uncertainty from the nominal fit. For simplicity, the impact is given as the average of the up and down variations. Details of the systematic uncertainties are provided in the text. MC statistics refers to the effect of the limited size of the MC samples. The total systematic uncertainty is a bit larger than the quadratic sum of the individual contributions due to correlations.

back-up (ttZ)

Table 1 The definitions of the trilepton signal regions: for the inclusive measurement, a combination of the regions with pseudo-continuous b-tagging 3ℓ-Z-$1b4j$-PCBT and 3ℓ-Z-$2b3j$-PCBT is used, whereas for the differential measurement only the region 3ℓ-Z-$2b3j$ with a fixed b-tagging WP is employed

Variable	3ℓ-Z-$1b4j$-PCBT inclusive	3ℓ-Z-$2b3j$-PCBT inclusive	3ℓ-Z-$2b3j$ differential
N_ℓ ($\ell = e, \mu$)	$= 3$		
	$\geq$1 OSSF lepton pair with $\lvert m_{\ell\ell}^{Z} - m_Z \rvert < 10$ GeV		
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV		
p_{T} (ℓ_1, ℓ_2, ℓ_3)	$> 27,\ 20,\ 20$ GeV		
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{b\text{-jets}}$	$= 1$@60%	≥ 2@70%	≥ 2@85%
	veto add. b-jets@70%		

Table 2 The definitions of the four tetralepton signal regions. The regions are defined to target different b-jet multiplicities and flavour combinations of the non-Z leptons ($\ell\ell^{\text{non-}Z}$)

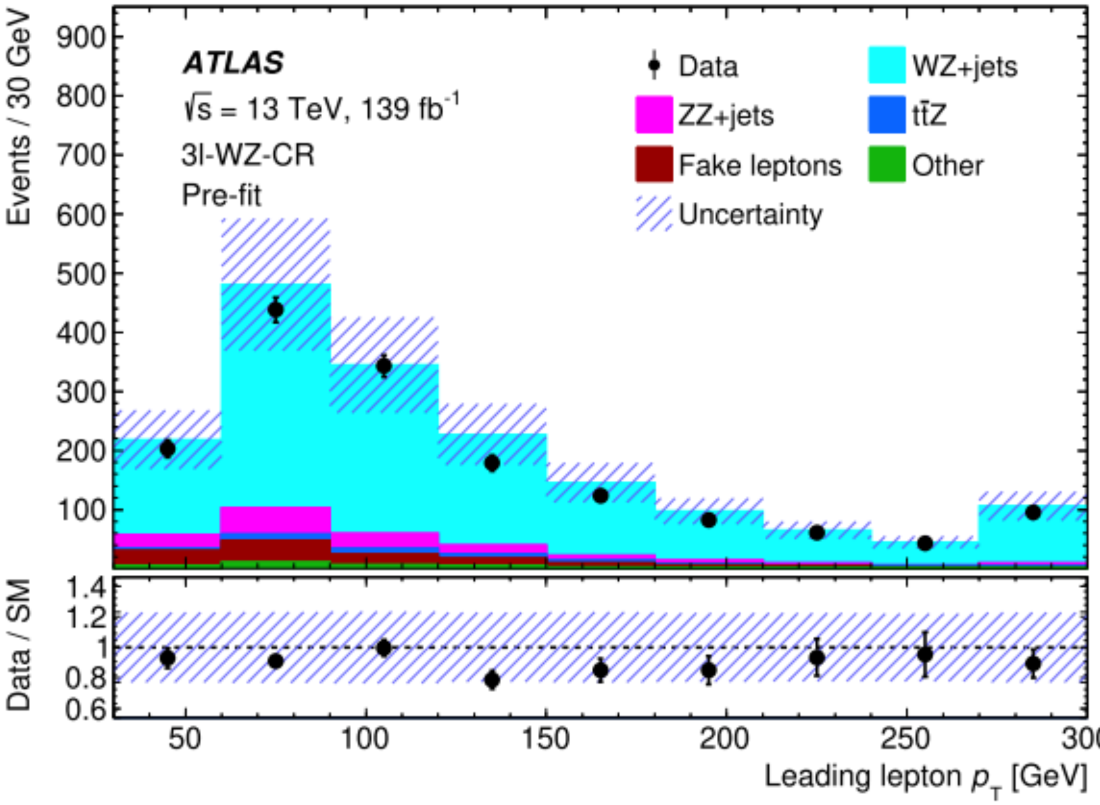
Variable	4ℓ-SF-$1b$	4ℓ-SF-$2b$	4ℓ-DF-$1b$	4ℓ-DF-$2b$
N_ℓ($\ell = e, \mu$)	$= 4$			
	$\geq$1 OSSF lepton pair with $\lvert m_{\ell\ell}^{Z} - m_Z \rvert < 10$ GeV			
	for all OSSF combinations: $m_{\text{OSSF}} > 10$ GeV			
p_{T} (ℓ_1, ℓ_2, ℓ_3, ℓ_4)	$> 27,\ 20,\ 10,\ 7$ GeV			
$\ell\ell^{\text{non-}Z}$	e^+e^- or $\mu^+\mu^-$	e^+e^- or $\mu^+\mu^-$	$e^\pm\mu^\mp$	$e^\pm\mu^\mp$
$E_{\text{T}}^{\text{miss}}$	> 100 GeV, if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z \rvert \leq 10$ GeV	> 50 GeV, if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z \rvert \leq 10$ GeV	–	–
	> 50 GeV, if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z \rvert > 10$ GeV	–		
N_{jets}	≥ 2	≥ 2	≥ 2	≥ 2
$N_{b\text{-jets}}$@85%	$= 1$	≥ 2	$= 1$	≥ 2

back-up (ttZ)

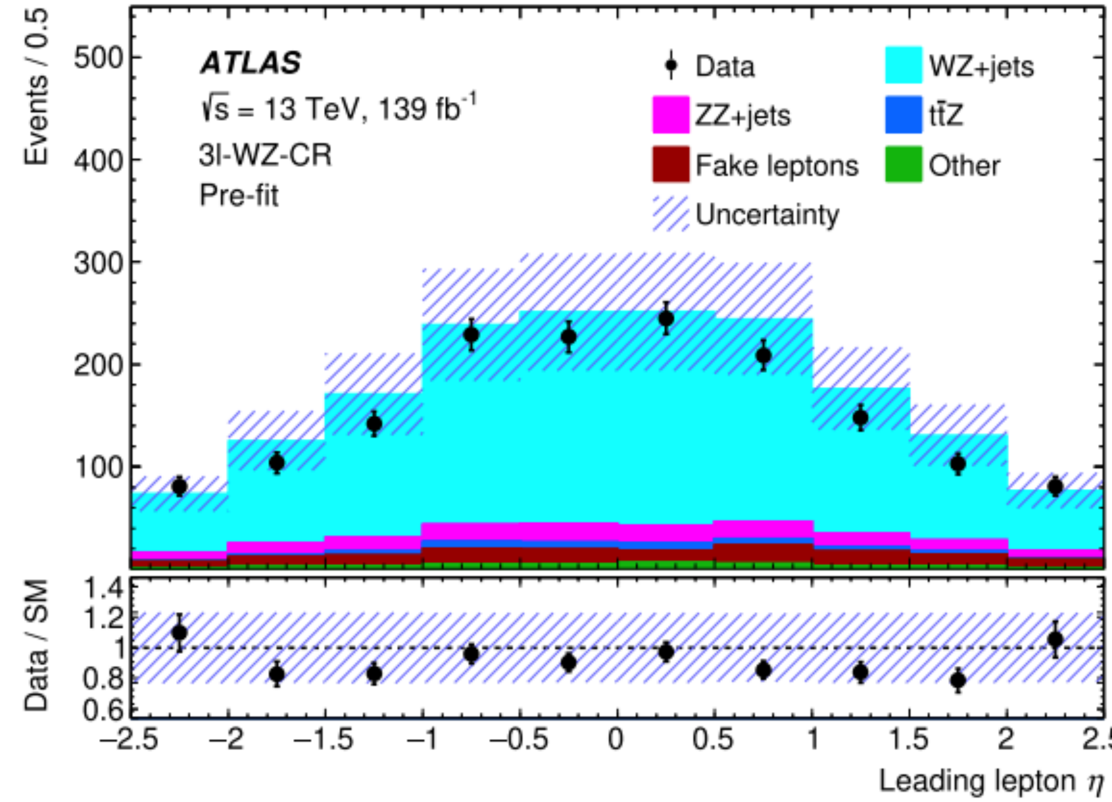
Table 3 Definitions of the control regions targeting the WZ + jets, $WZ \to \ell\ell\ell\nu$ (left) and ZZ + jets, $ZZ \to \ell\ell\ell\ell$ processes (right): the control regions are used to obtain normalisations of the light-flavour components of the WZ/ZZ + jets backgrounds from data

Variable	3ℓ-WZ-CR	4ℓ-ZZ-CR
N_ℓ ($\ell = e, \mu$)	$= 3$	$= 4$
	1 OSSF lepton pair with	2 OSSF lepton pairs with
	$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| < 10$ GeV
p_T ($\ell_1, \ell_2, \ell_3, \ell_4$)	$> 27, 20, 20$ GeV	$> 27, 20, 10, 7$ GeV
N_{jets}	≥ 3	–
$N_{b\text{-jets}}$@85%	$= 0$	–
E_T^{miss}	–	20 GeV $< E_T^{miss} <$ 40 GeV

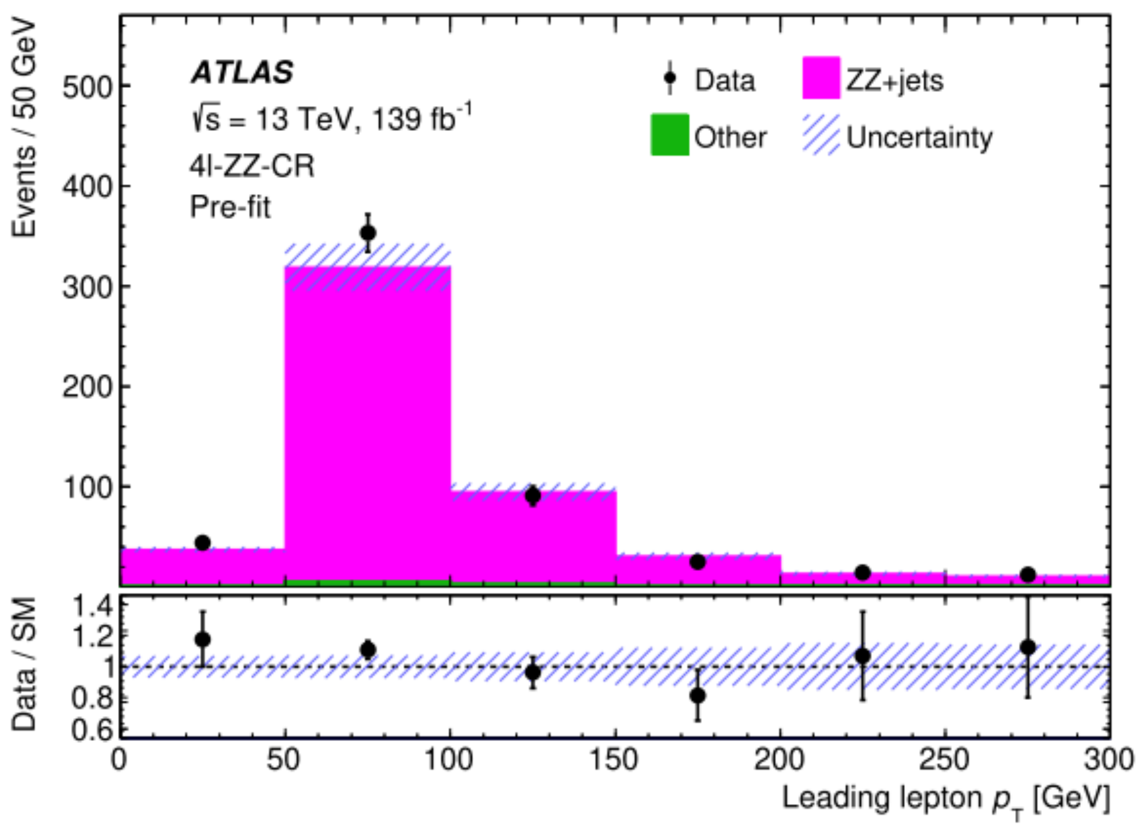
back-up (ttZ)



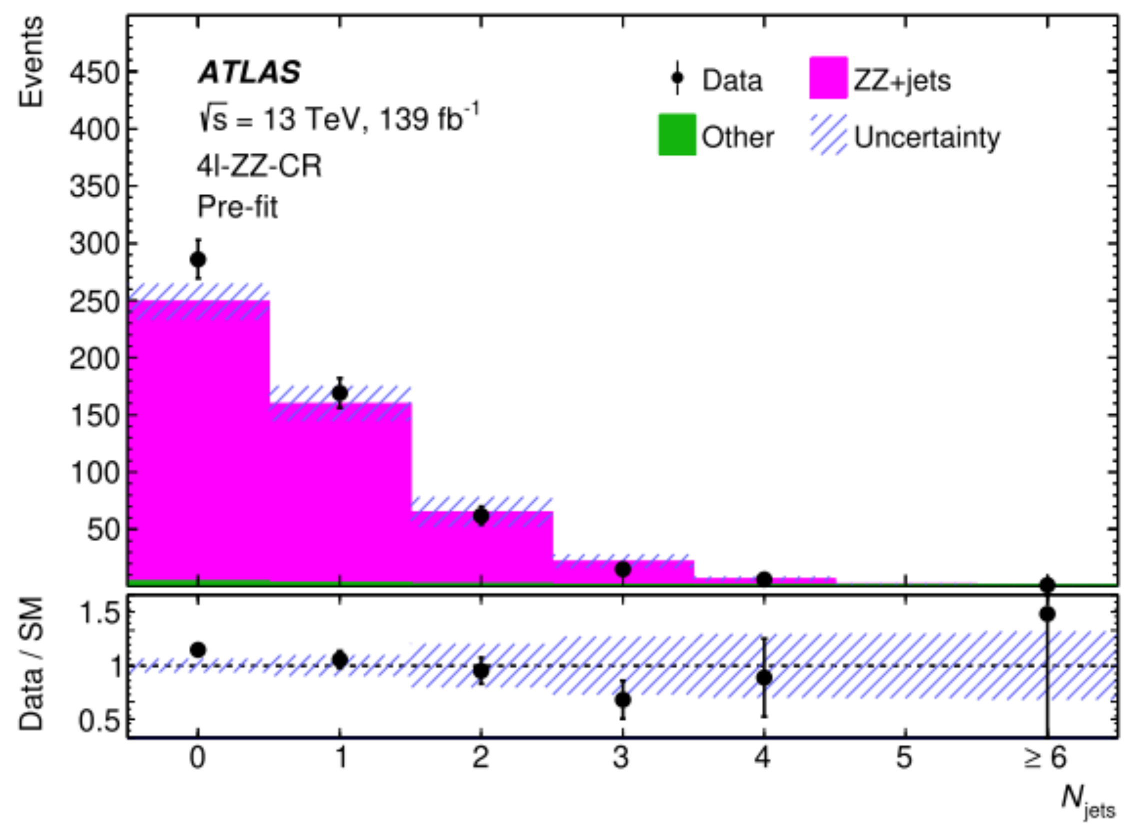
(a)



(b)



(a)



(b)

back-up (ttZ)

Table 7 List of relative uncertainties of the measured inclusive $t\bar{t}Z$ cross section from the combined fit. The uncertainties are symmetrised for presentation and grouped into the categories described in the text. The quadrature sum of the individual uncertainties is not equal to the total uncertainty due to correlations introduced by the fit

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_{f} and μ_{r} scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

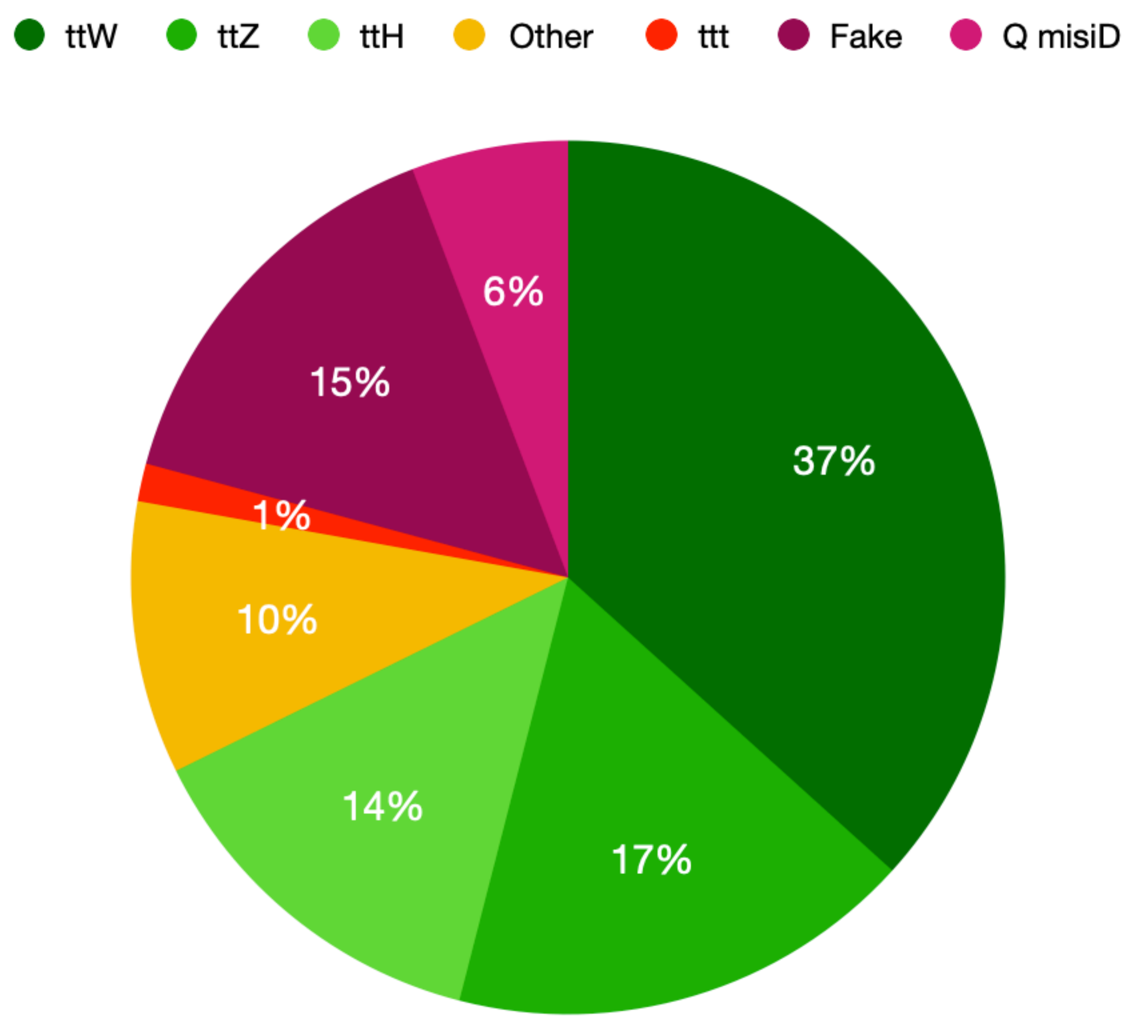
back-up (ttZ)

Table 8 Summary of the variables used for the differential measurements. Some variables are considered for the trilepton or tetralepton signal regions only, as indicated. The jet multiplicity is measured for the two topologies separately, whereas for the variables related only to the kinematics of the Z boson (p_{T}^{Z} and $|y^{Z}|$), the trilepton and tetralepton regions are combined

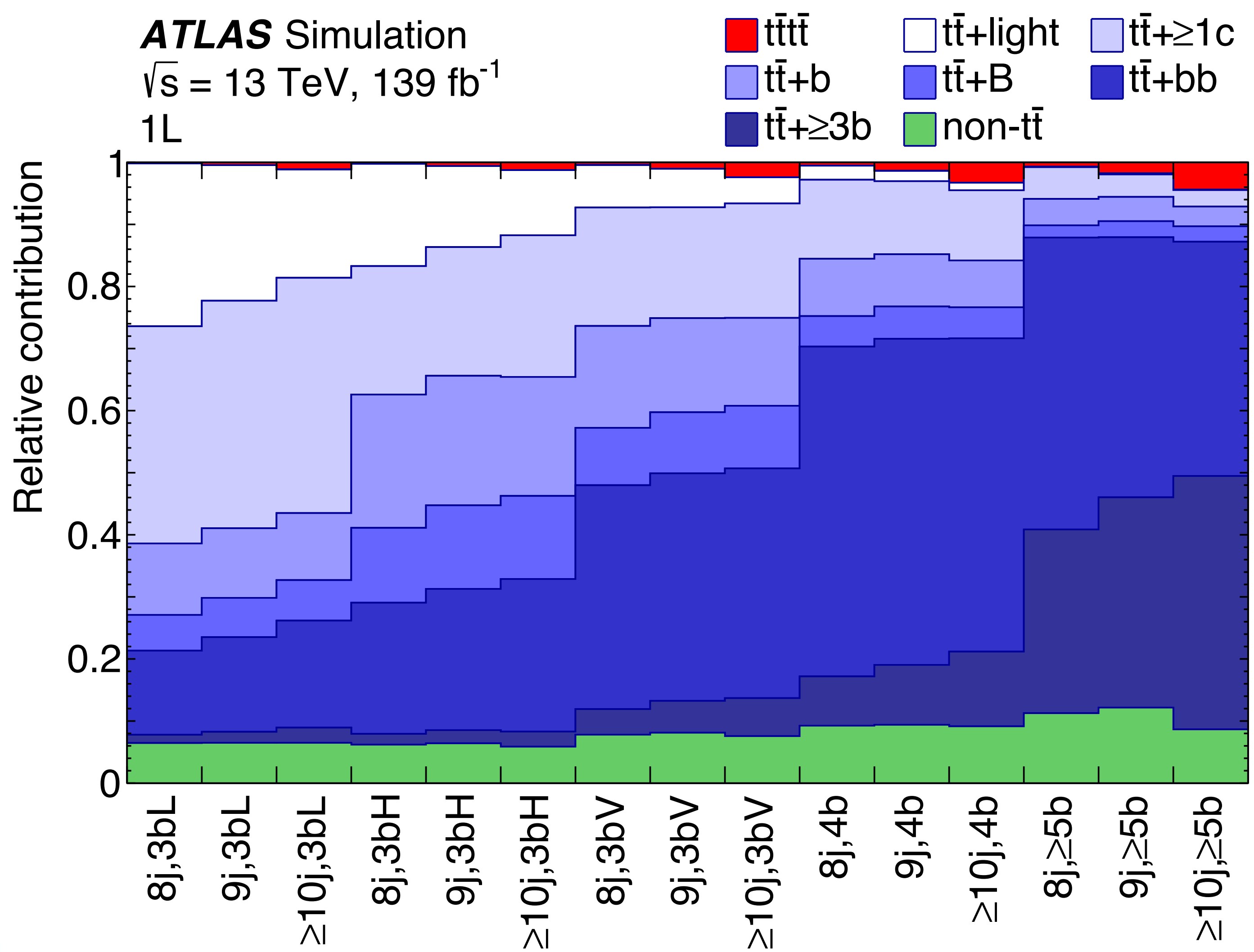
Variable	Definition
$3\ell + 4\ell$	
p_{T}^{Z}	Transverse momentum of the Z boson
$\lvert y^{Z}\rvert$	Absolute value of the rapidity of the Z boson
3ℓ	
N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$
$p_{\mathrm{T}}^{\ell,\text{non-}Z}$	Transverse momentum of the lepton which is not associated with the Z boson
$\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$	Azimuthal separation between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
$\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$	Absolute rapidity difference between the Z boson and the top quark (antiquark) featuring the $W \to \ell\nu$ decay
4ℓ	
N_{jets}	Number of selected jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$
$\lvert\Delta\phi(\ell_t^{+}, \ell_{\bar{t}}^{-})\rvert$	Azimuthal separation between the two leptons from the $t\bar{t}$ system
$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Azimuthal separation between the Z boson and the $t\bar{t}$ system
$p_{\mathrm{T}}^{t\bar{t}}$	Transverse momentum of the $t\bar{t}$ system

backgrounds

in 2ℓSS/3ℓ



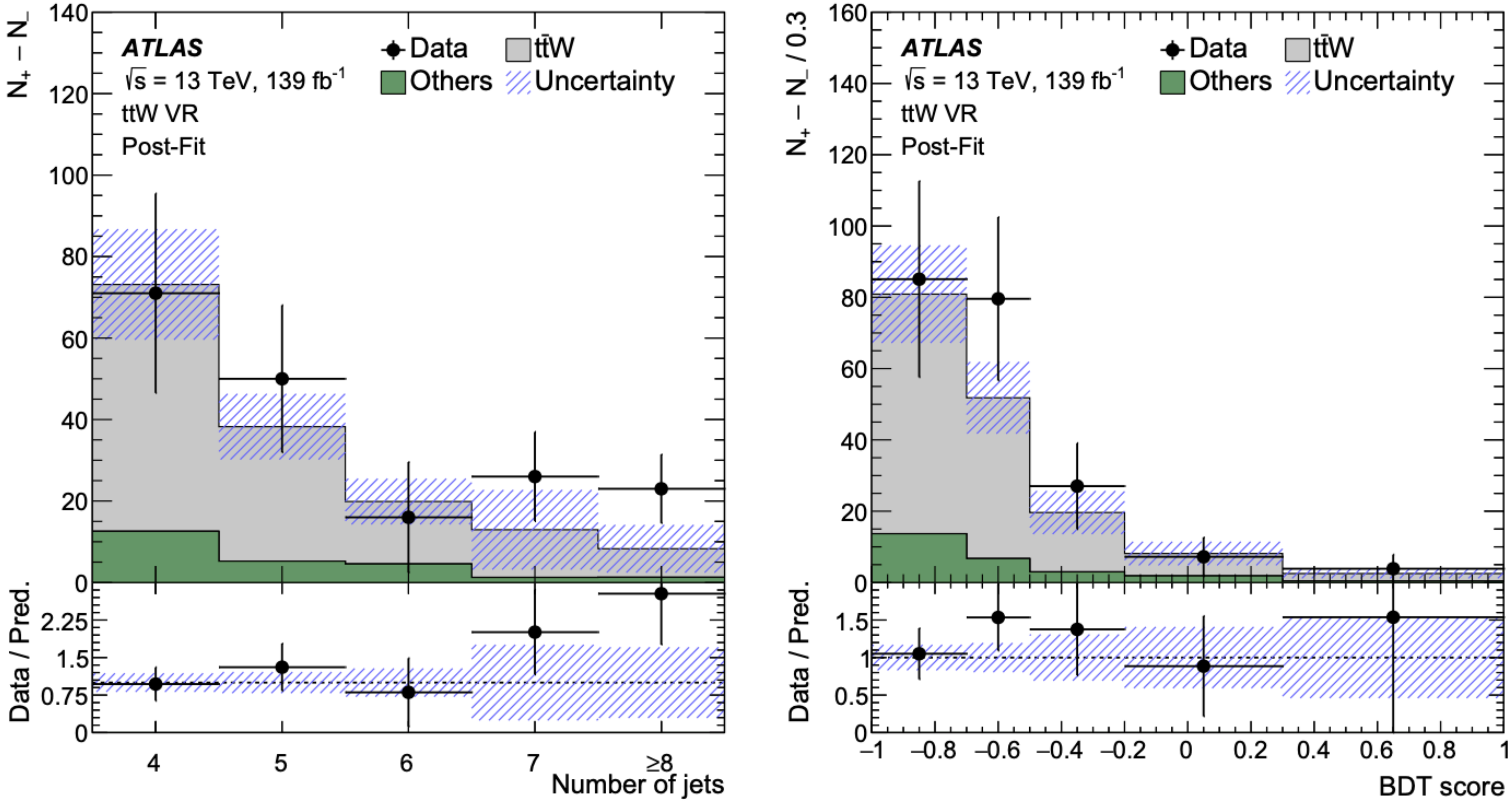
in 1ℓ/2ℓOS



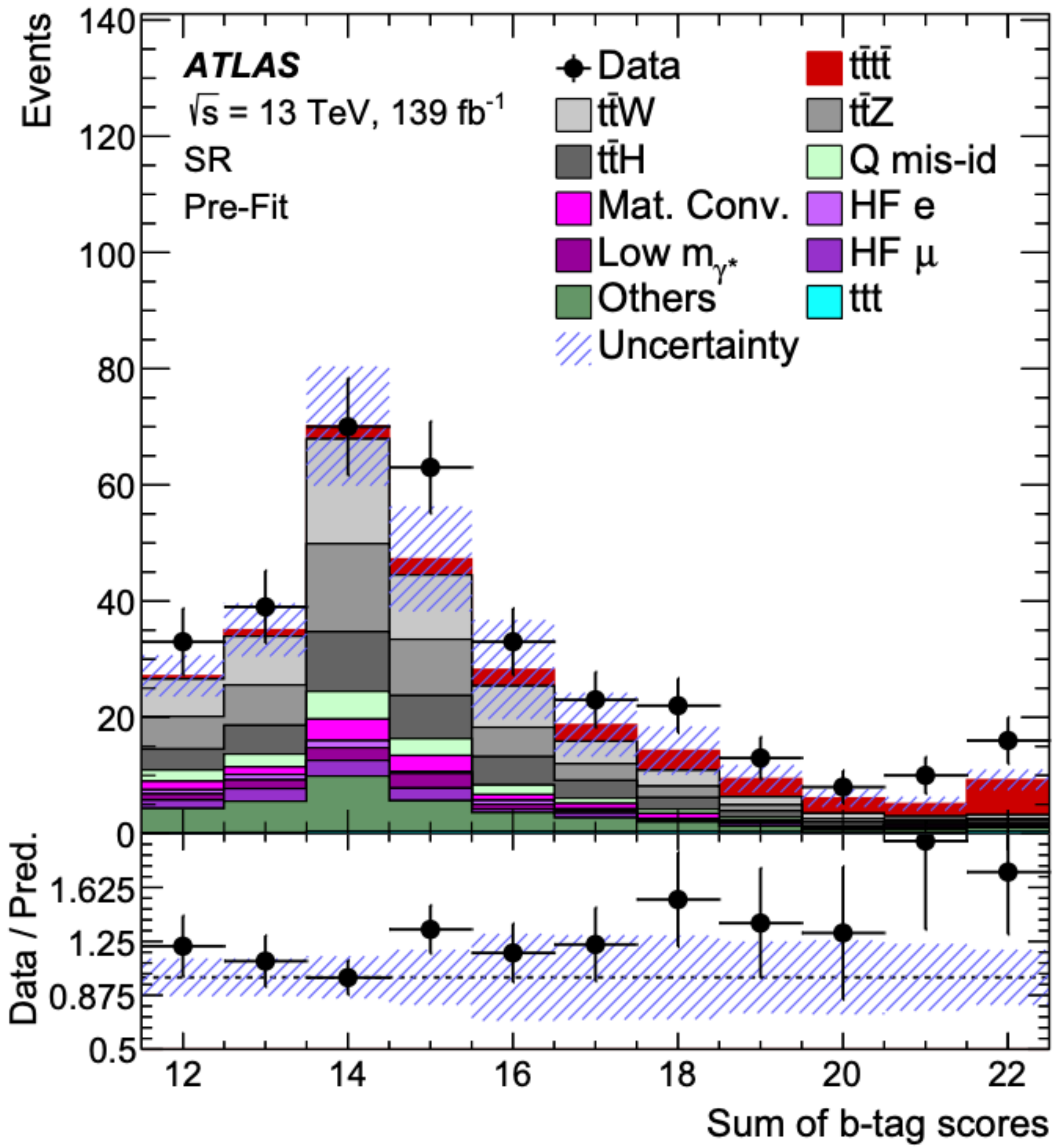
Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

back-up ($t\bar{t}t\bar{t}$)

ttW validation region in 2ℓSS/3ℓ



Sum of b-tag scores as input to the BDT



back-up ($t\bar{t}t\bar{t}$)

Uncertainties

in 2ℓSS/3ℓ

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62

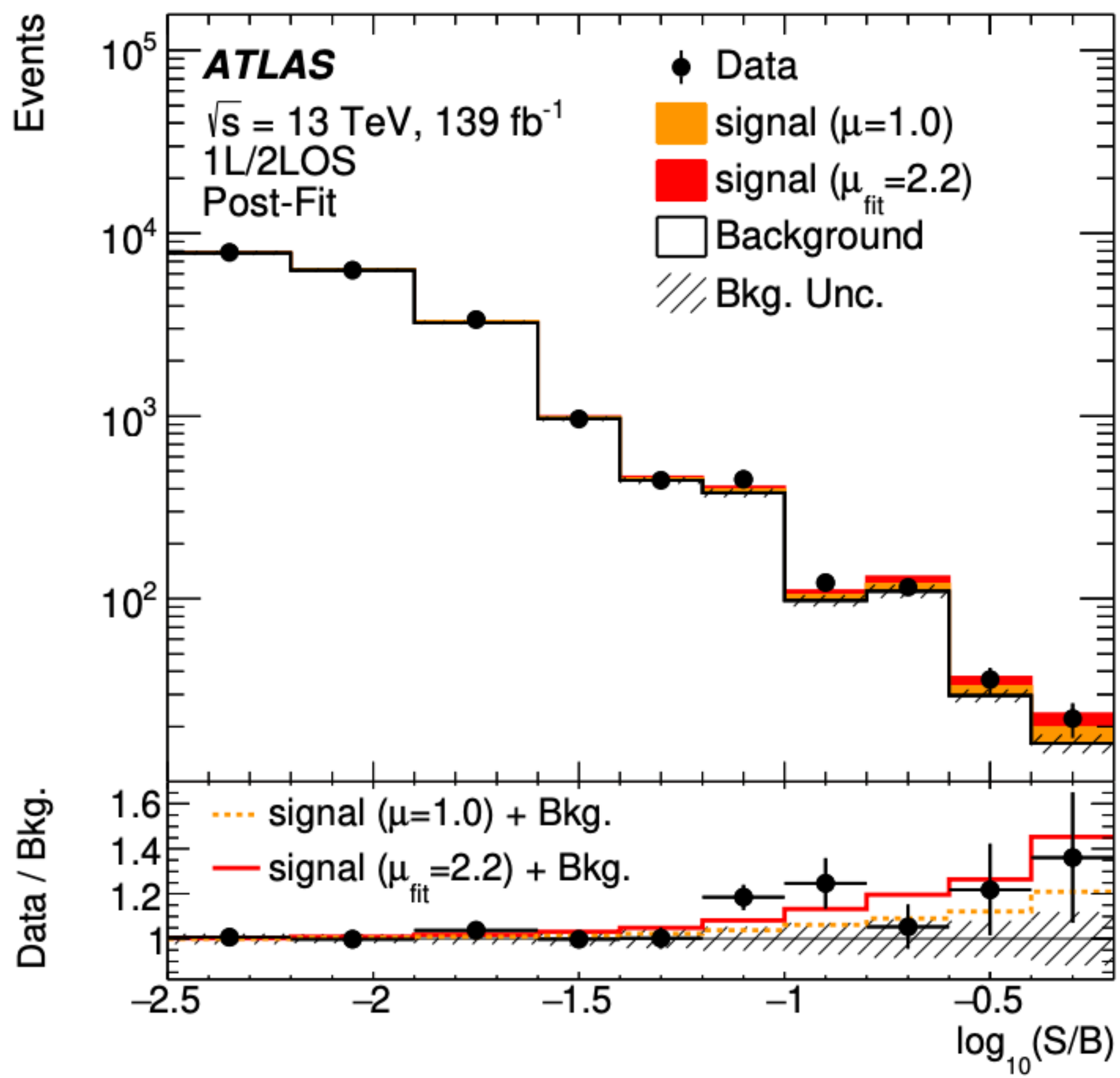
in 1ℓ/2ℓOS

Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	-3
Background Modelling		
$t\bar{t}+\geq 1b$ modelling	+8	-7
$t\bar{t}+\geq 1c$ modelling	+5	-4
$t\bar{t}$+jets reweighting	+4	-3
Other background modelling	+4	-3
$t\bar{t}$+light modelling	+2	-2
Experimental		
Jet energy scale and resolution	+6	-4
b-tagging efficiency and mis-tag rates	+4	-3
MC statistical uncertainties	+2	-2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	-12
Statistical uncertainty	+8	-8
Total uncertainty	+17	-15

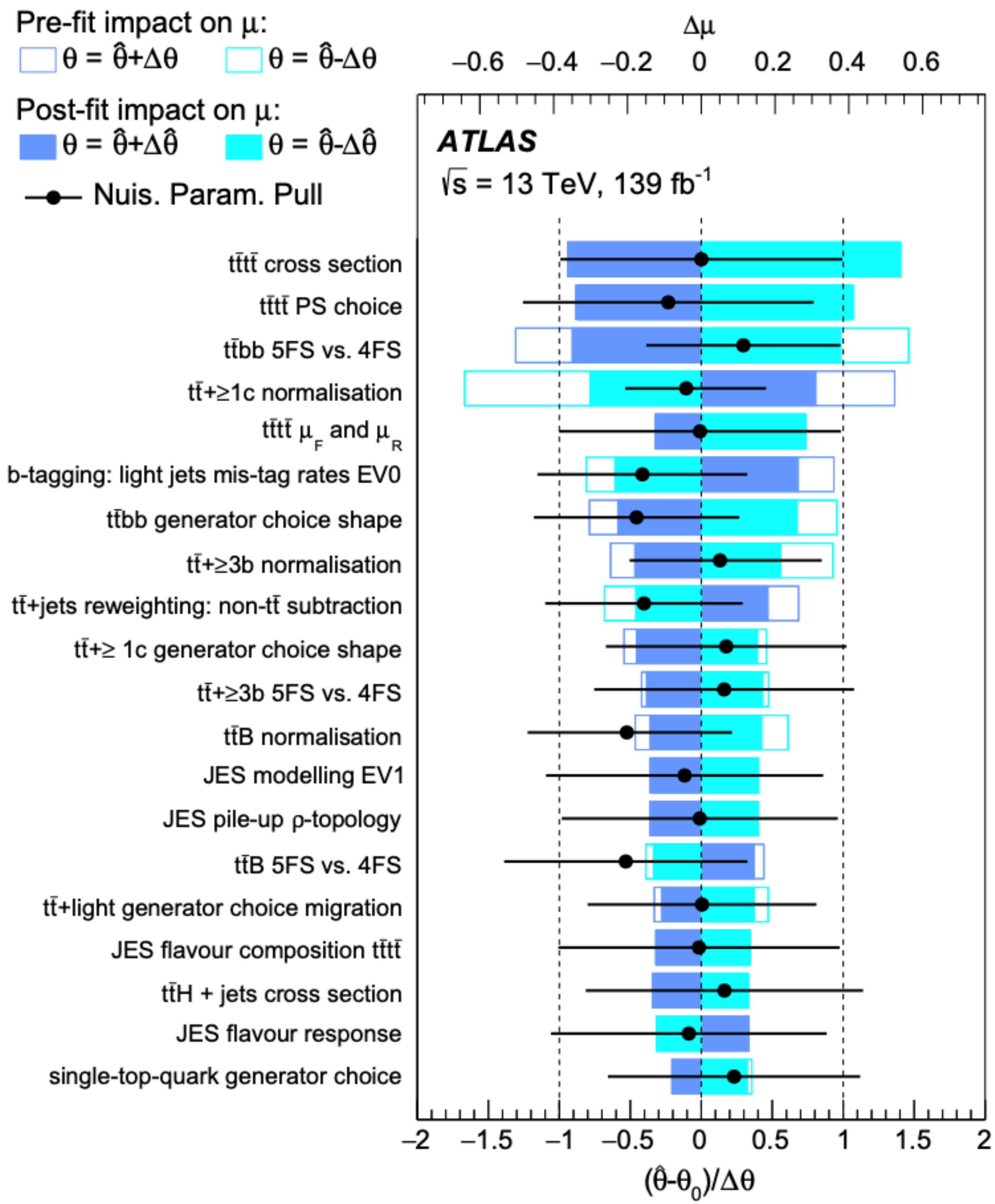
back-up ($t\bar{t}t\bar{t}$)

Observed and expected event yields as function of $\log_{10}(S/B)$ - post-fit

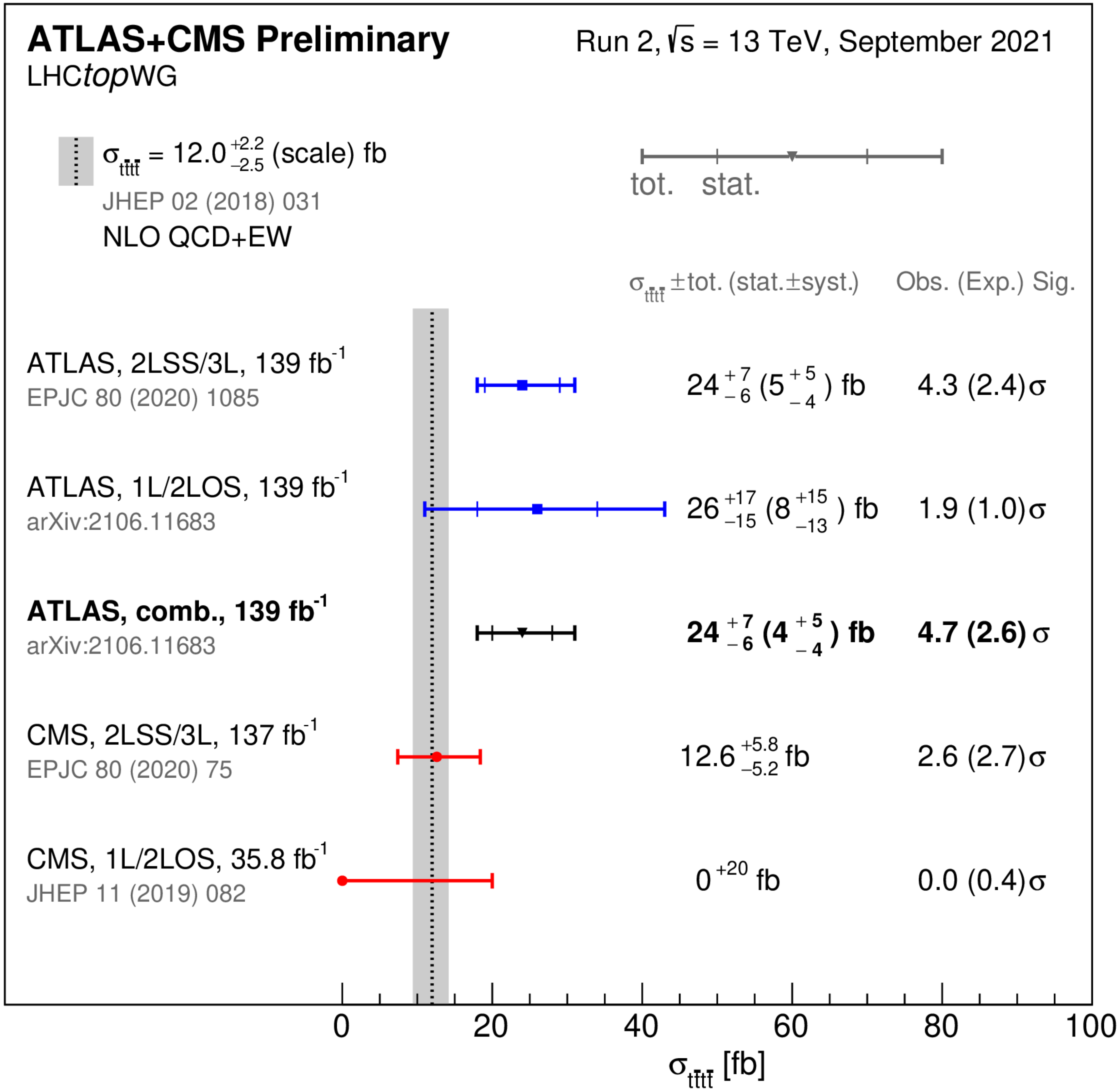
best fit $\mu = 2.2$ and $\mu = 1.0$ are shown



back-up ($t\bar{t}t\bar{t}$)



back-up ($t\bar{t}t\bar{t}$)



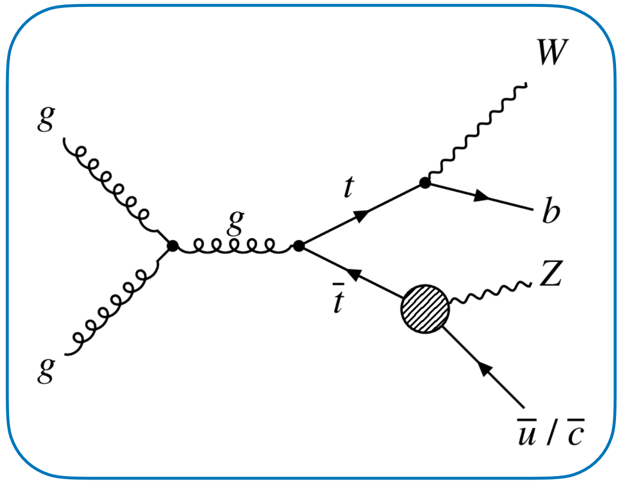
back-up (FCNC, top-gluon with $t \to l\nu b$)

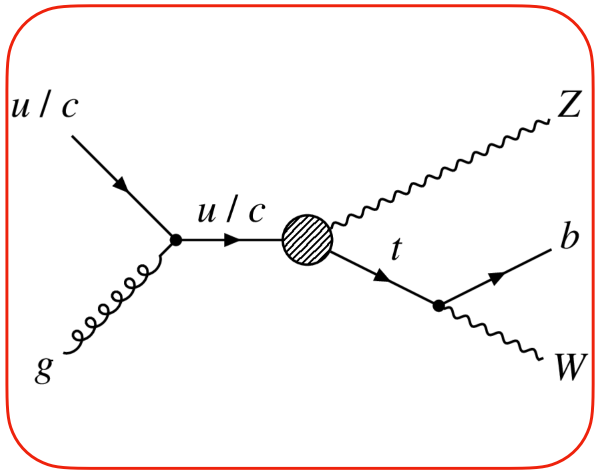
Table 4: Impact of systematic uncertainties on the expected upper limits on the branching ratios of the FCNC decay modes $\mathcal{B}(t \to u+g)$ and $\mathcal{B}(t \to c+g)$. Four scenarios are considered: (1) include only data statistical uncertainties, (2) include the experimental systematic uncertainties in addition, (3) include all systematic uncertainties except for the MC statistical uncertainties and (4) include all uncertainties.

Scenario	Description	$\mathcal{B}_{95}^{\text{exp}}(t \to u+g)$	$\mathcal{B}_{95}^{\text{exp}}(t \to c+g)$
(1)	Data statistical only	1.1×10^{-5}	2.4×10^{-5}
(2)	Experimental uncertainties also	3.1×10^{-5}	12×10^{-5}
(3)	All uncertainties except MC statistical	3.9×10^{-5}	18×10^{-5}
(4)	All uncertainties	4.9×10^{-5}	20×10^{-5}

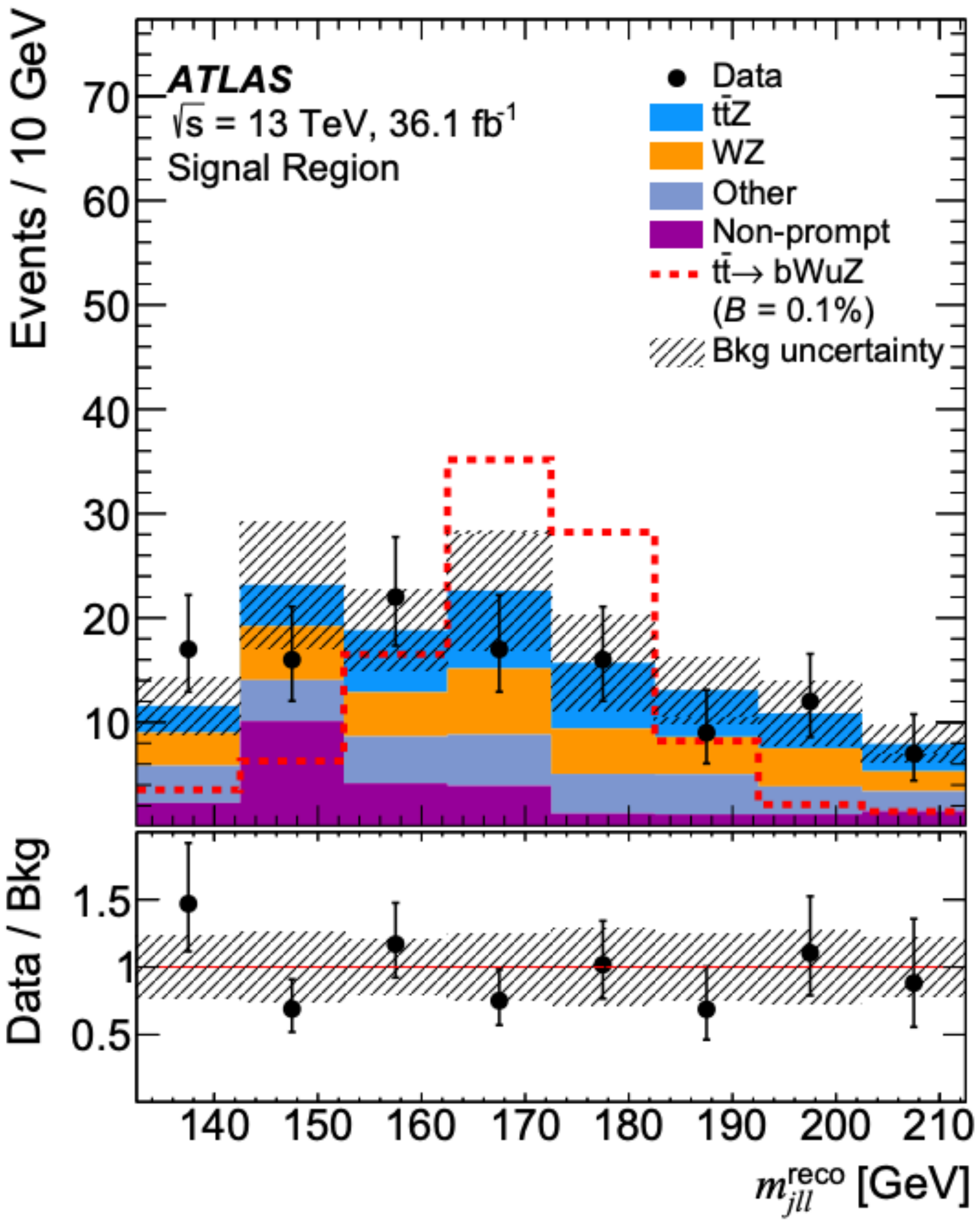
FCNC Search for $t \to Zq$ ATLAS-CONF-2021-049

- **Strategy:**
- Events contain three isolated leptons leptons (e, μ) ≥2 jets, (one b-tagged) and MET
- Only Z boson decays into charged leptons and leptonic W boson decays are considered as signal
- 2 signal regions (SRs) considered targeting FCNC in production and decay:
  - SR1 (ttbar decay): ≥2 jets, 1 b-tag
  - SR2 (tZ production): 1& 2 jets, 1 b-tag
- Events reconstructed via minimisation of kinematic properties of the final state objects under the FCNC top hypothesis
  - Mass veto to ensure orthogonality in 2j events
- Largest background contributions from **Diboson** and $t\bar{t}Z$

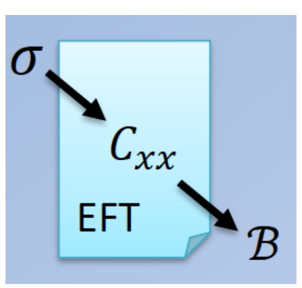




Mass of the FCNC top-quark candidate in SR1

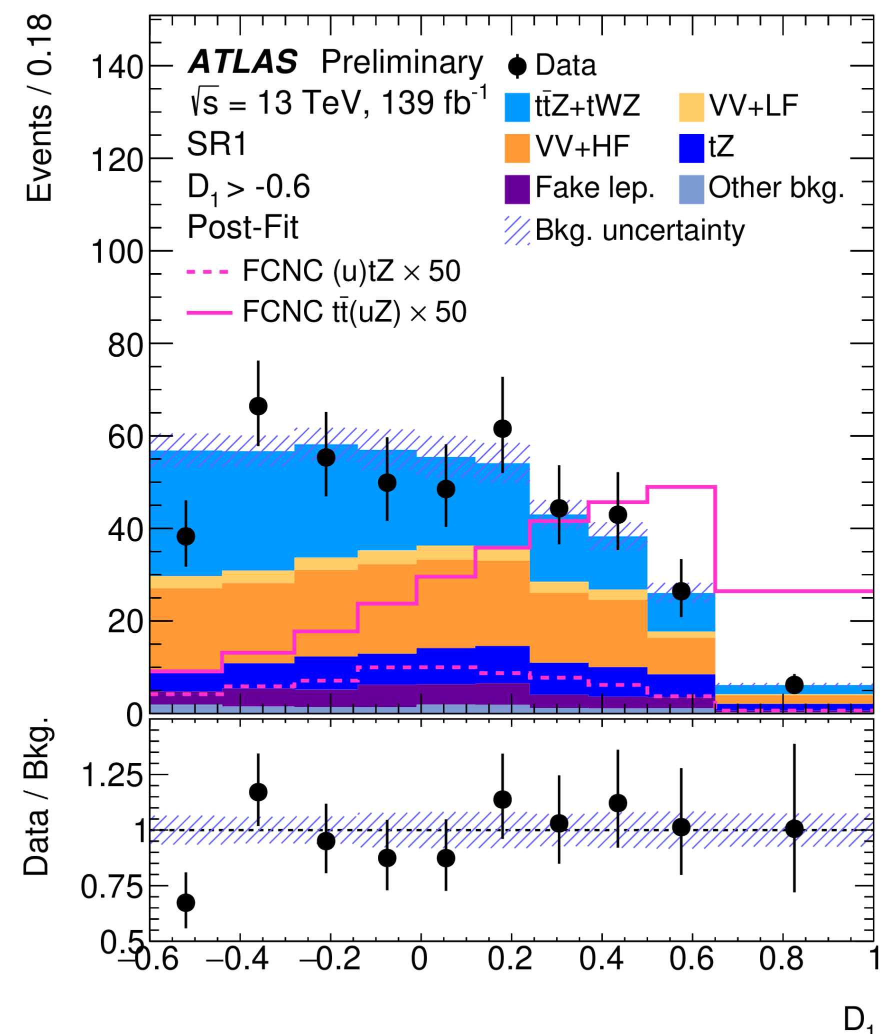


- Gradient BDT used to better separate signal from backgrounds
- Four separate fits performed to extract **LH** and **RH** results for the FCNC **tZu** and **tZc** couplings
- Good agreement between MC predictions and data
- 95% CL upper limits set on branching ratios for both tZu and tZc vertices and for both RH/LH couplings
  - **Improved by a factor of 2-3 on previous limits**
- Limits on relevant EFT Wilson coefficients for vertices also set



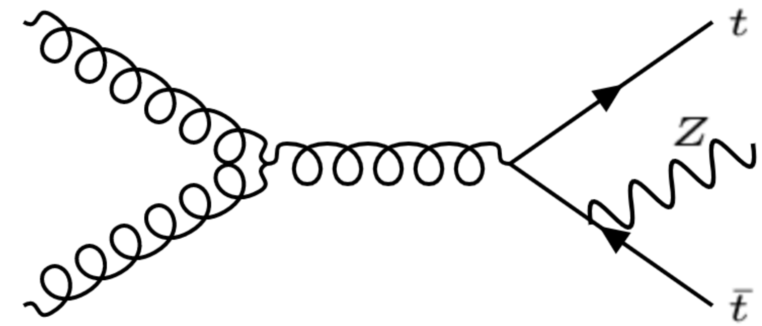
Observable	Vertex	Coupling	Observed	Expected
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZu	LH	6.2	$4.9^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZu	RH	6.6	$5.1^{+2.1}_{-1.4}$
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZc	LH	13	11^{+5}_{-3}
$\mathcal{B}(t \to Zq)\ [10^{-5}]$	tZc	RH	12	10^{+4}_{-3}
$\lvert C_{uW}^{(13)*}\rvert, \lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert, \lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert, \lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert, \lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$

D_1 discriminant in SR1

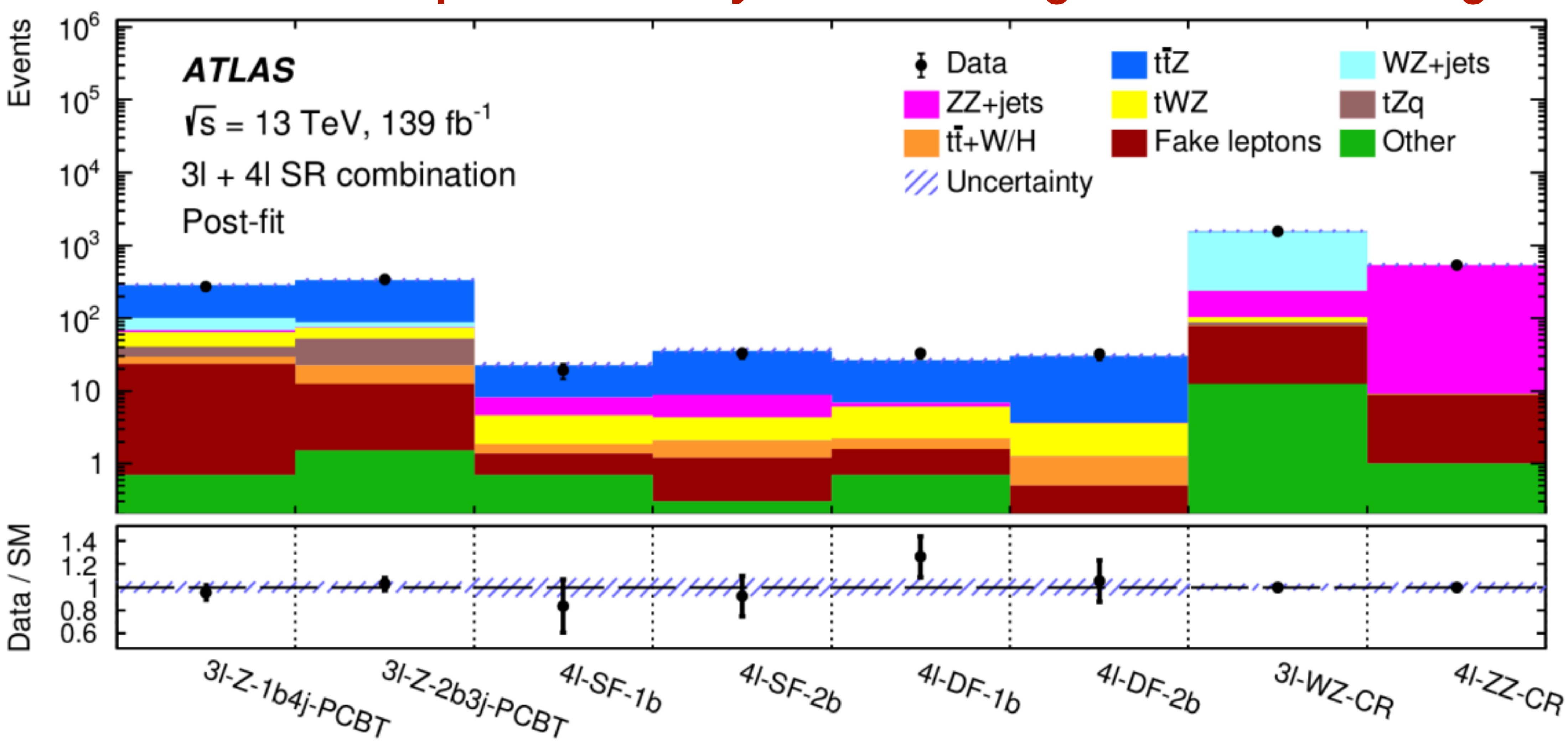


Inclusive & differential $t\bar{t}Z$ production   Eur. Phys. J. C 81 (2021) 737

- Inclusive and differential measurement, targeting 3-lepton and 4-lepton channels (e/μ)
- ≥ 3 jets and ≥ 1 b-jet
- Control regions for WZ and ZZ backgrounds (free-floating)
- Expected cross section: $\sigma^{\text{exp}}_{t\bar{t}Z} = 0.84^{+0.09}_{-0.10}$ pb
- Measured cross-section: $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05(\text{stat.}) \pm 0.08(\text{syst.})$ pb



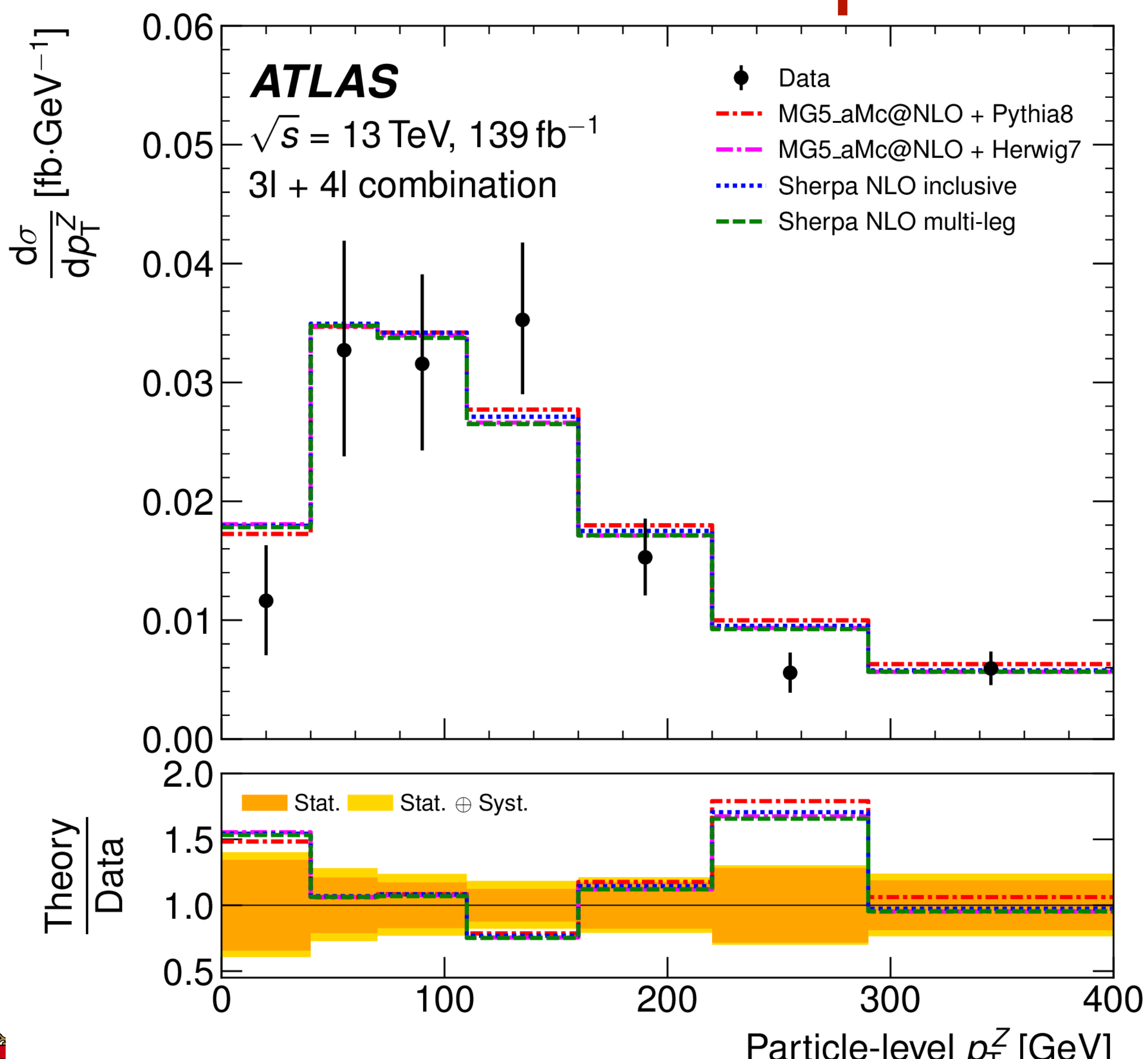
Observed and expected event yields in the Signal and Control regions



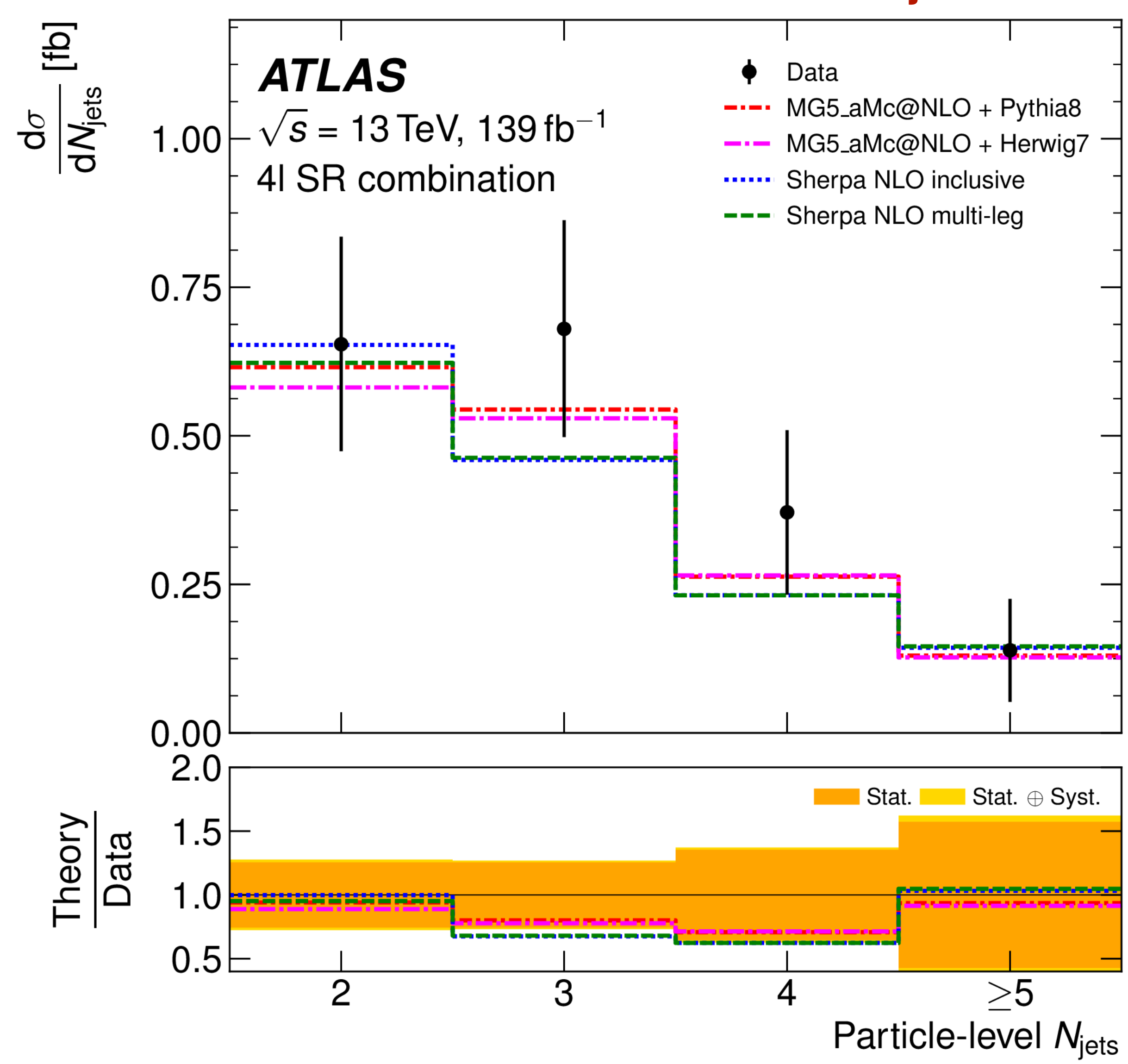
Inclusive & differential $t\bar{t}Z$ production   Eur. Phys. J. C 81 (2021) 737

- 10 observables unfolded to parton and particle level
  - Sensitive to BSM effects and modeling
- Dominated by stat. uncertainty
- Main systematic uncertainties are: Fake leptons, WZ modeling, $t\bar{t}Z$ modeling, and b-tagging

Particle-level p_T^Z



Particle-level N_{jets}



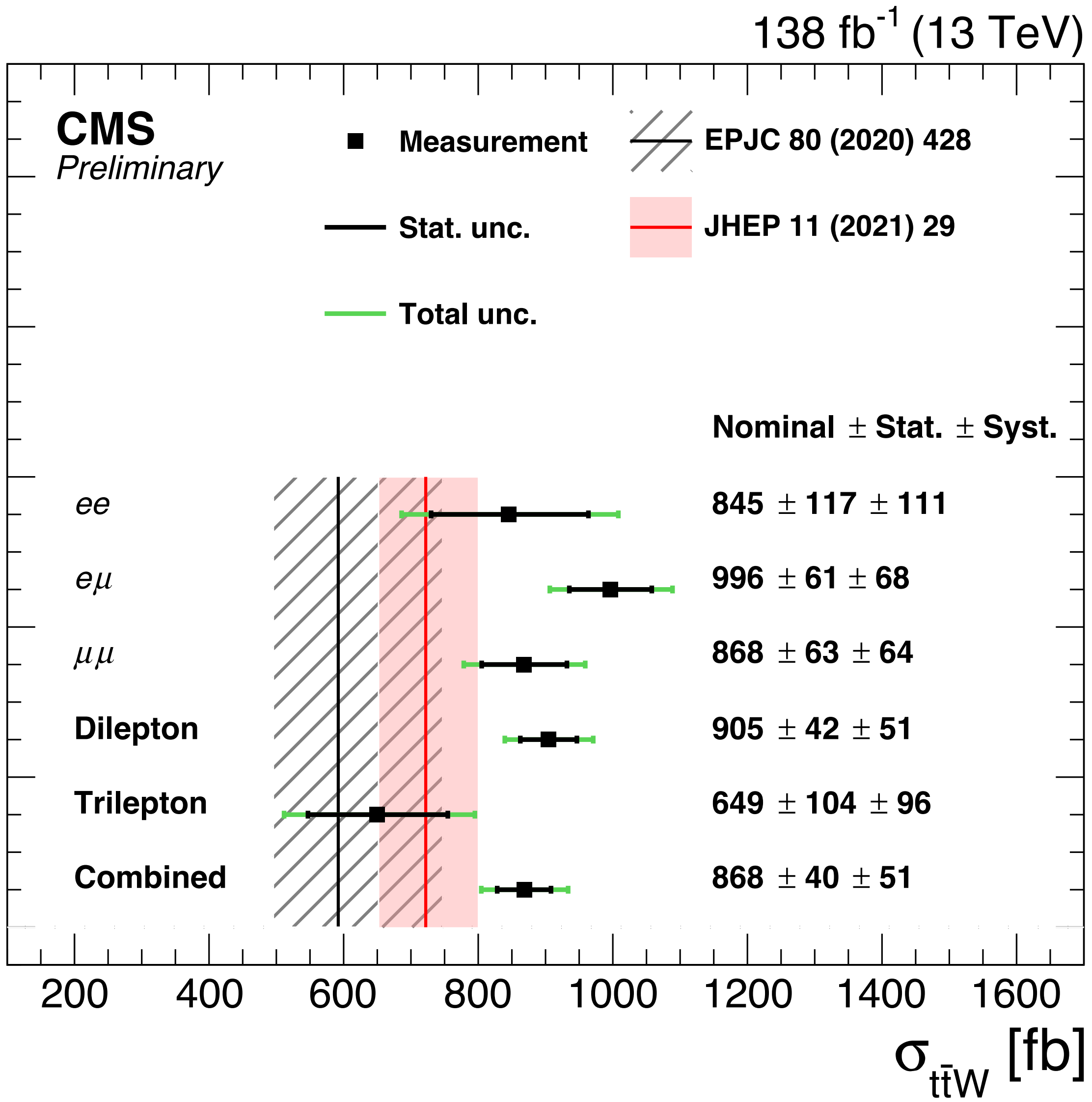
Good agreement with the prediction!

ttW CMS Results

- Precision obtained in the present study is significantly improved with respect to the previous measurement with partial run 2 data-set

- Improvements come from a larger data sample, an improved analysis strategy and improved estimates of dominant background contributions using control regions in data

- Inclusive measurement compared to 2 predictions: NLO+NNLL [A. Kulesza et al.]; NLO+2j@LO with improved FxFx ME merging [R. Frederix, I. Tsinikos]



ttW CMS Results

- Luminosity: overall uncertainty of 1.6%
- Pileup: varying the assumed minimum-bias cross section of 69.2 mb by ±4.6%
- Trigger efficiency: ~2% treated as uncorrelated among data-taking years, as well as between the dileptonic and trileptonic channels
- Lepton efficiency: at most a few percent and assumed to be uncorrelated among lepton flavors and data-taking years
- JES/JER: 21 uncertainty sources corresponding to different detector regions and taking into account the year-to-year correlations
- b-tagging: considered as fully correlated between b and c quark jets, and uncorrelated for other quark flavors
- Non-prompt leptons: overall normalization, uncertainties due to the dependence on the lepton p_T and η, and 20% to cover remaining mismodeling in the validation region

Uncertainty type	Relative value (%)
Experimental	
Integrated luminosity	1.9
Charge misidentification	1.6
b jet identification	1.6
Nonprompt lepton background	1.3
Trigger efficiencies	1.2
Pileup	1.0
Trigger prefiring	0.7
Jet energy scale	0.6
Jet energy resolution	0.4
Lepton efficiencies	0.4

ttW CMS Results

- Signal:
  - Uncertainties on the ISR and FSR in the parton shower
  - Uncertainty due to the color-reconnection model is estimated by using simulated samples produced with alternative models (effect of 1%)
  - PDF uncertainty
  - α_s
- Backgrounds:
  - Normalization uncertainty
  - Varying the normalization and factorization scales (μ_R/μ_F) within a factor of two from their nominal values

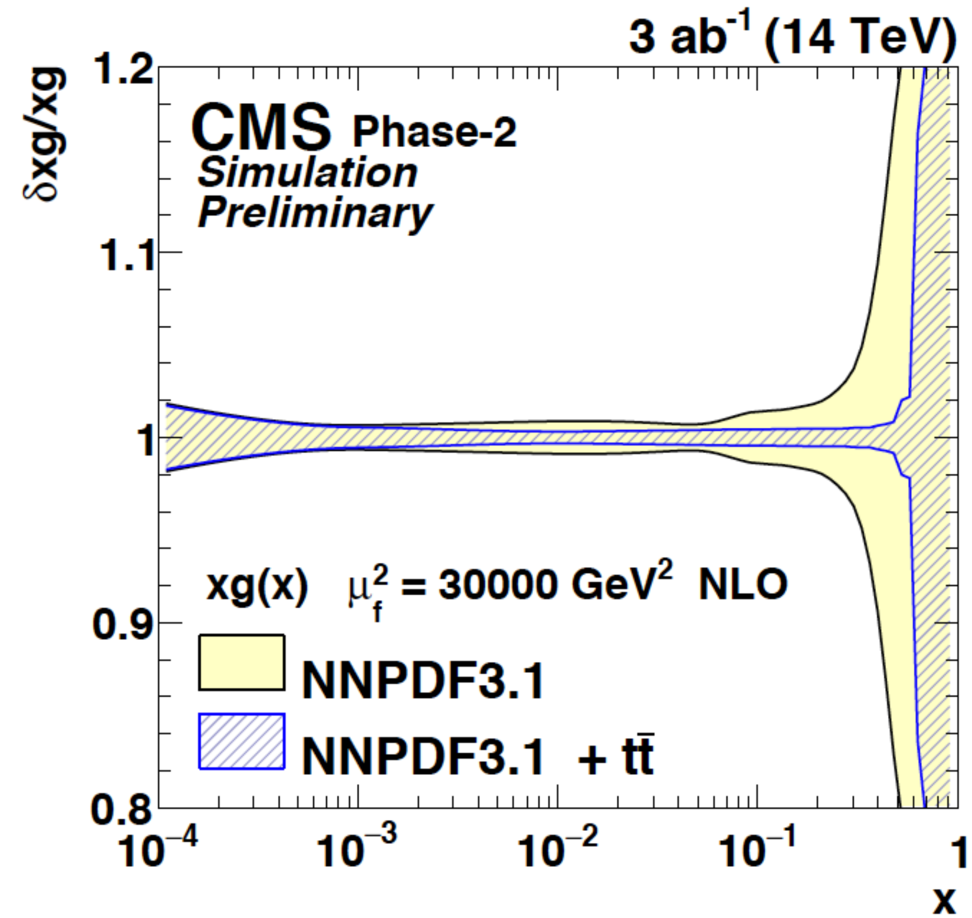
Uncertainty type	Relative value (%)
Normalizations	
$t\bar{t}H$	2.6
VVV	1.2
$t\bar{t}VV$	1.2
Conversions	0.7
$t\bar{t}\gamma$	0.6
ZZ	0.6
Others	0.5
$t\bar{t}Z$	0.3
WZ	0.2
tZq	0.2
tHq	0.2
Modelling	
$t\bar{t}W$ scale	1.8
$t\bar{t}W$ colour reconnection	1.0
ISR/FSR for $t\bar{t}W$	0.8
$t\bar{t}\gamma$ scale	0.4
VVV scale	0.3
$t\bar{t}H$ scale	0.2
Conversions	0.2
Statistical uncertainty	1.8

- **Leading systematics:**
  - **ttH norm (2.6%); lumi (1.9%); ttW scale (1.8%)**
  - **vs. statistical uncertainty 1.8%**

Differential $t\bar{t}$ cross-section measurements

- Done in e/μ+jets channels
- Most significant reduction of uncertainty is expected to come from:
  - Improved jet energy calibration
  - Reduced uncertainty in the b-jet identification
- Final projected uncertainty is estimated below 5%
- Precision in the measurement will profit from the **enormous amount of data** and the **extended η-coverage** of the Phase-2 CMS detector, which enables fine-binned measurements at high rapidity that are not possible with the current detector
- Uncertainties of the gluon distribution are drastically reduced and depend directly on the uncertainty of the integrated luminosity (assumed to be 1%)

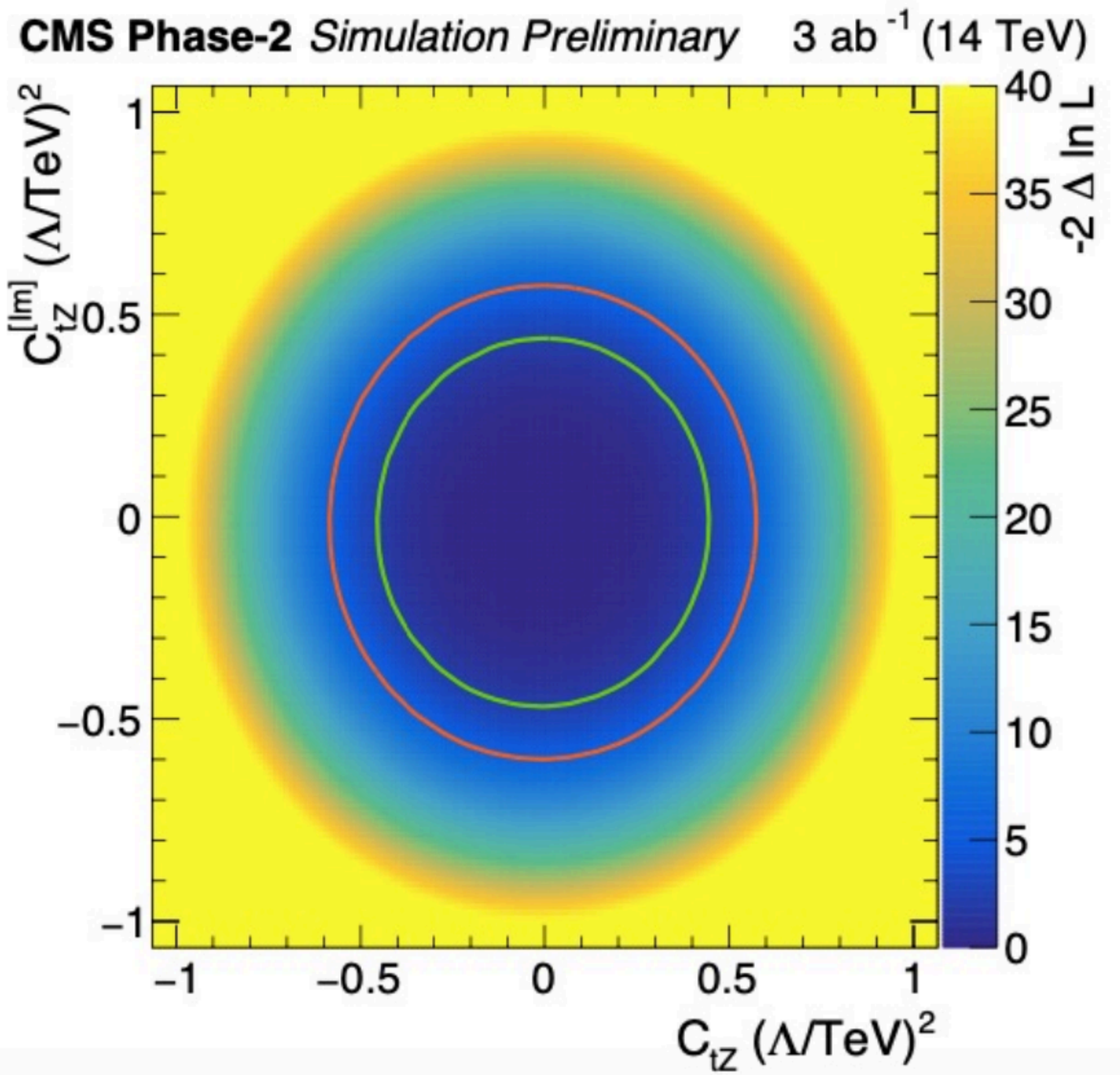
Prospects at HL-LHC of the relative gluon uncertainties of the original and profiled NNPDF3.1 PDF set

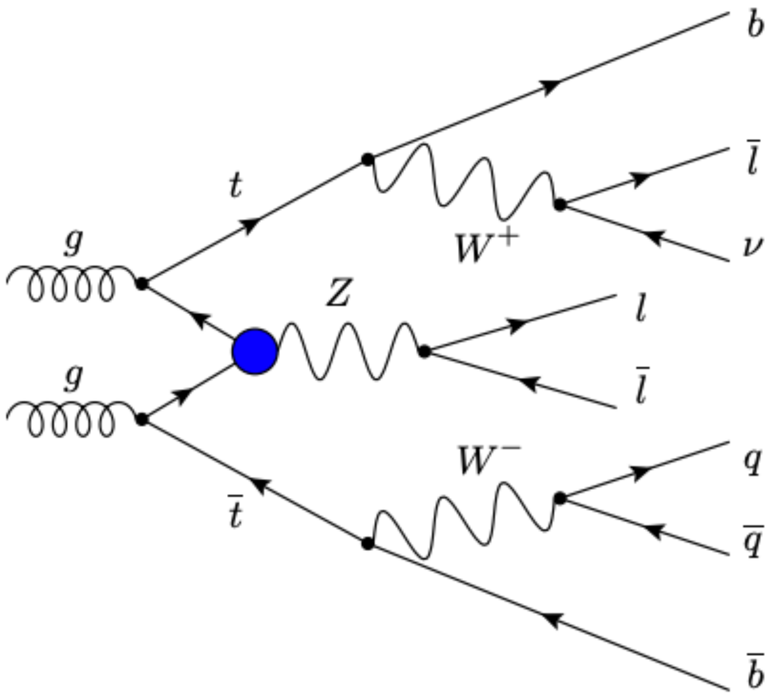


CMS-PAS-FTR-18-015

ttZ and EW top couplings at the HL-LHC

- Expected sensitivity to Wilson coefficients of top quark operators C_{tZ} in the ttZ process





Wilson coefficient C_{tZ} in SMEFT
68 % CL $(\Lambda/\text{ TeV})^2$: [-0.37, 0.36]
95 % CL $(\Lambda/\text{ TeV})^2$: [-0.52, 0.51]

CMS-PAS-FTR-18-036

FCNC - tZq

- Done in the three charged lepton final states
- The dominant sources of uncertainties, in both signal and background estimations, are from the theoretical normalization and the modeling of the background processes MC
- An improvement by a factor of four is expected over the current Run-2 analysis

	-1σ	Expected	$+1\sigma$
$\mathcal{B}(t \to uZ)$	4.9×10^{-5}	6.9×10^{-5}	9.7×10^{-5}
$\mathcal{B}(t \to cZ)$	5.8×10^{-5}	8.1×10^{-5}	12×10^{-5}

Table 6: The expected 95% confidence level upper limits on the top-quark FCNC decay branching ratios are shown together with the $\pm 1\sigma$ bands, which include the contribution from the statistical and systematic uncertainties. Presented limits are extracted from "Asimov data" in the signal and background control regions, defined as the total expected pre-fit background. Systematic uncertainty from the MC statistical uncertainty is considered as well.

Operator	Expected limit
$\lvert C_{uB}^{(31)} \rvert$	0.13
$\lvert C_{uW}^{(31)} \rvert$	0.13
$\lvert C_{uB}^{(32)} \rvert$	0.14
$\lvert C_{uW}^{(32)} \rvert$	0.14

Table 8: Expected 95% CL upper limits on the moduli of the operators contributing to the FCNC decays $t \to uZ$ and $t \to cZ$ within the TopFCNC model for a new-physics energy scale Λ = 1 TeV.

ATL-PHYS-PUB-2019-001

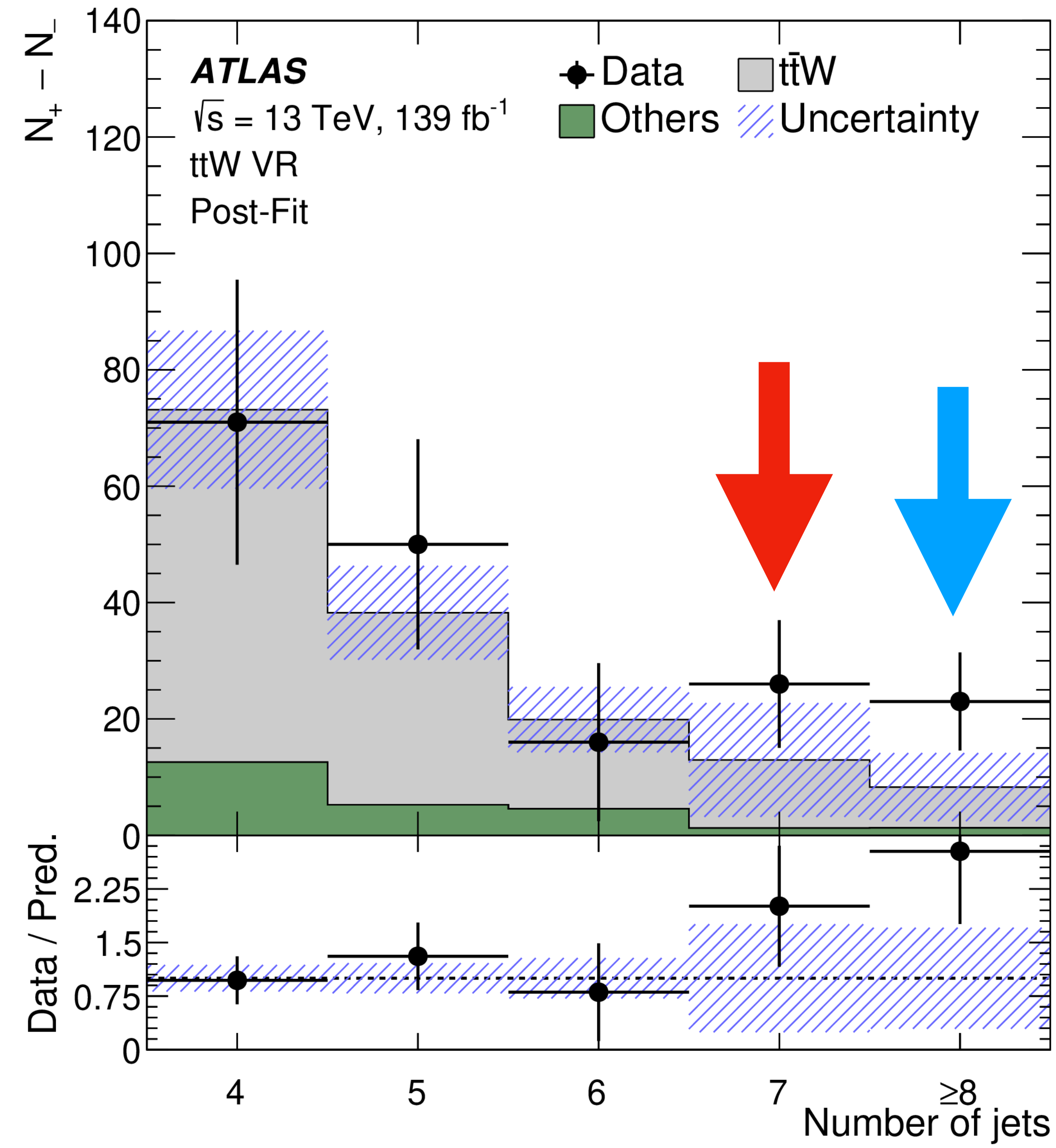
Extrapolation scenarios for 4tops

- Looked into several extrapolation scenarios based on how to scale the systematics with the assumption agreed for the 2019 Yellow Report
- Followed the recommendations explained in the High Lumi LHC Systematics
  - Modelling uncertainties could be halved (ATL-PHYS-PUB-2019-005)
  - No dedicated studies for HL-LHC expected performance, except for HF
    - Recommended way to apply flavor tagging uncertainties is to scale down the nuisance parameters from the current analyses
    - Systematics driven by intrinsic detector limitations are left unchanged, or revised according to detailed simulation studies of the upgraded detector

Run 2 SM $t\bar{t}t\bar{t}$ cross section

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62

$t\bar{t}W$ **Validation Region**: ≥4jets ≥2b-tagged



Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

- The cross-section can be constrained down to 9% statistical uncertainty and 18% to 28% total uncertainty, depending on the considered systematic uncertainties, while a 4.5σ significance is expected with the most optimistic systematics scenario

- The expected sensitivity on the $t\bar{t}t\bar{t}$ cross-section is also used to provide constraints on EFT four top contact interaction operators, setting limits on their Wilson coefficients

CMS-PAS-FTR-18-031