Top quark rare production and decay processes

LHCP Conference - 08/06/2021

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Rare top processes status

Sensitivity and precision in top quark measurements increased over the years

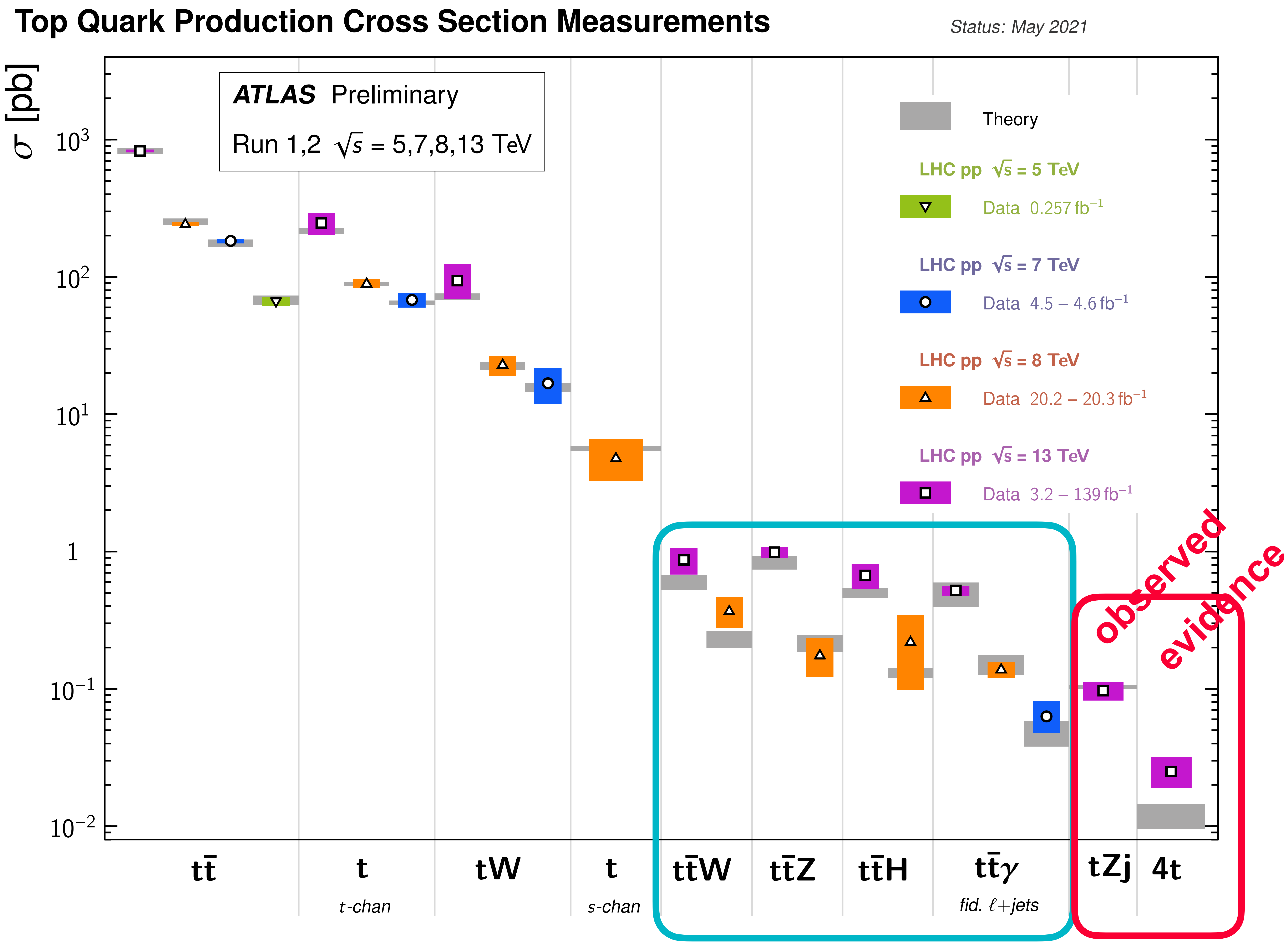
Former rare processes ($t\bar{t}+X$) are now background for new measurements and searches

Approaching the fb frontier

Covered in this talk:

- Latest observation: *tZj*
- Latest evidences: *tttt̄*, *tγ* (CMS)
- Searches:
  - flavour-changing neutral currents
  - lepton flavour violation

$t\bar{t}$+X covered by J. Thomas-Wilsker

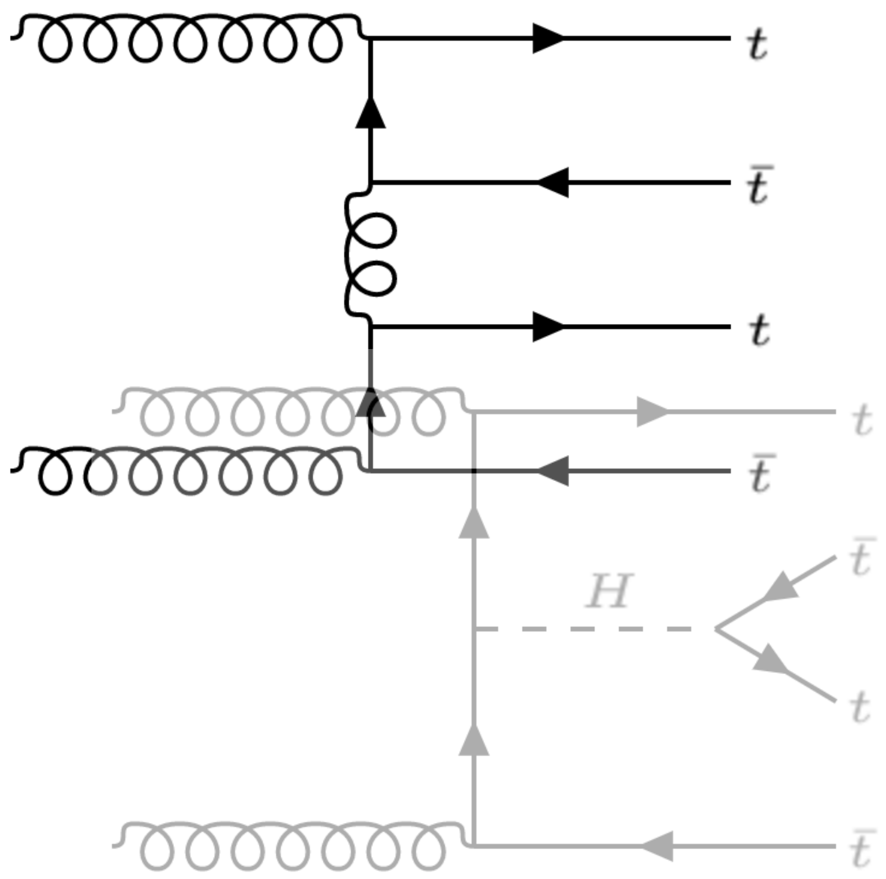


Nikhef

Measurements

Rare top production: $t\bar{t}t\bar{t}$

More details in A. Kong's talk



Massive final state ~700 GeV

Sensitive to magnitude and CP nature of top quark Yukawa coupling

Sensitive to presence of New Physics e.g. 2HDM

Small predicted $\sigma(t\bar{t}t\bar{t})$ = 12 ± 2.4 fb at 13 TeV, NLO in QCD+EW (JHEP 02 (2018) 031)

Various lepton (ℓ = e, μ) multiplicity final states probed by ATLAS and CMS

Same-charge di-lepton pair (2ℓSS), multi-lepton (ML)

small branching fraction (**12%**)

lower backgrounds:

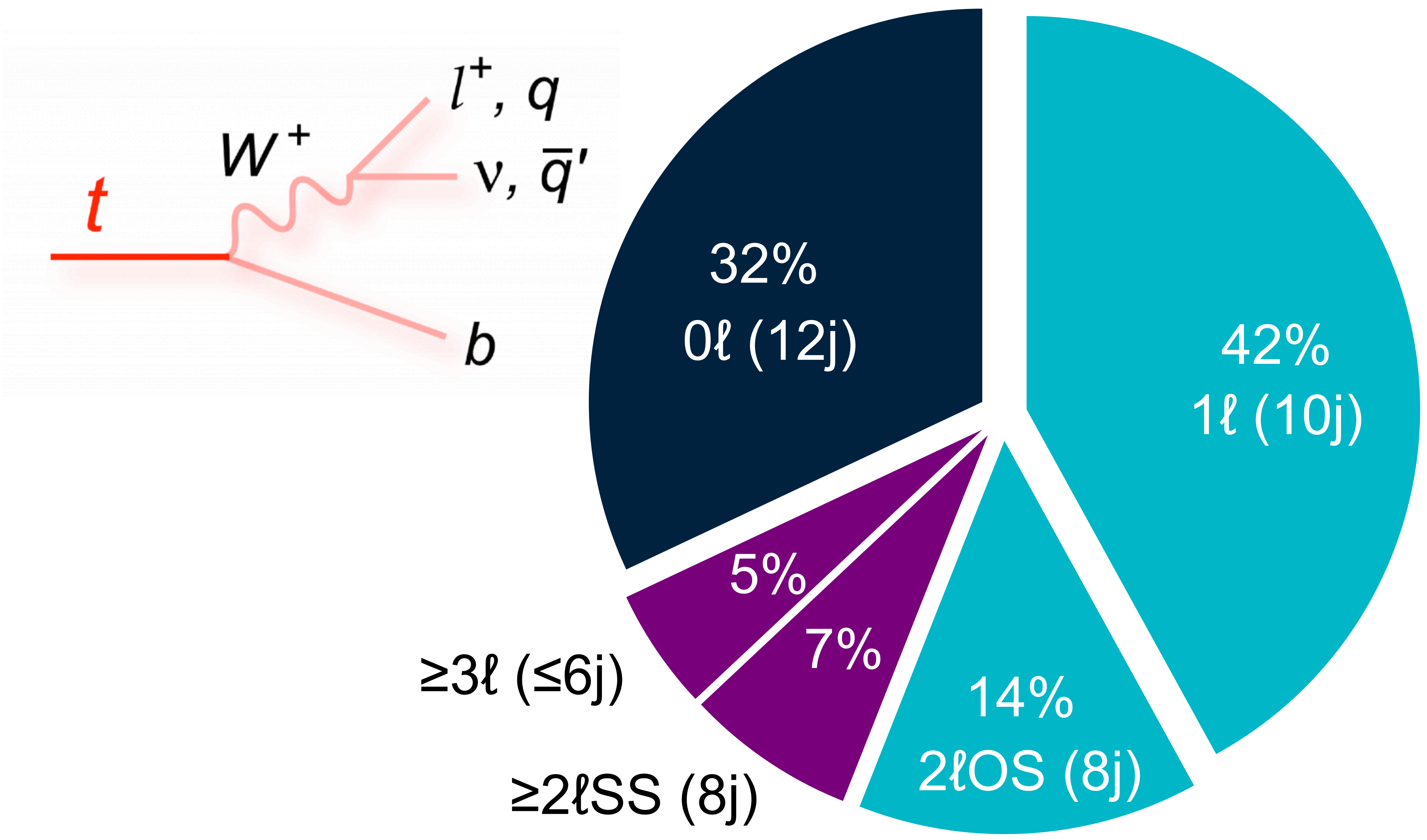
$t\bar{t}W$, $t\bar{t}Z$, non-prompt leptons, charge mis-identification

Single lepton (1ℓ), opposite-charge pair (2ℓOS)

larger branching fraction (**56%**)

large irreducible background:

$t\bar{t}$ + additional jets



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$t\bar{t}t\bar{t}$ 2ℓSS and ML

Full-Run 2 search: 2.6σ obs. (2.7σ exp.) [137 fb^{-1}]

(Eur. Phys. J. C (2020) 80:75)

Signal region (SR)

≥4 jets, ≥2 *b*-jets, H_T^{jets} > 300 GeV, E_T^{miss} > 50 GeV, *Z*-veto in ML channel

Background modelling

$t\bar{t}Z$, $t\bar{t}W$ corrections:

- N_{jets} based on dilepton $t\bar{t}$ data/MC
- heavy flavour jet multiplicity (also $t\bar{t}H$) from σ($t\bar{t}bb$) / σ($t\bar{t}jj$)
- $t\bar{t}Z$, $t\bar{t}W$ constrained by the fit

Data-driven estimation of non-prompt leptons

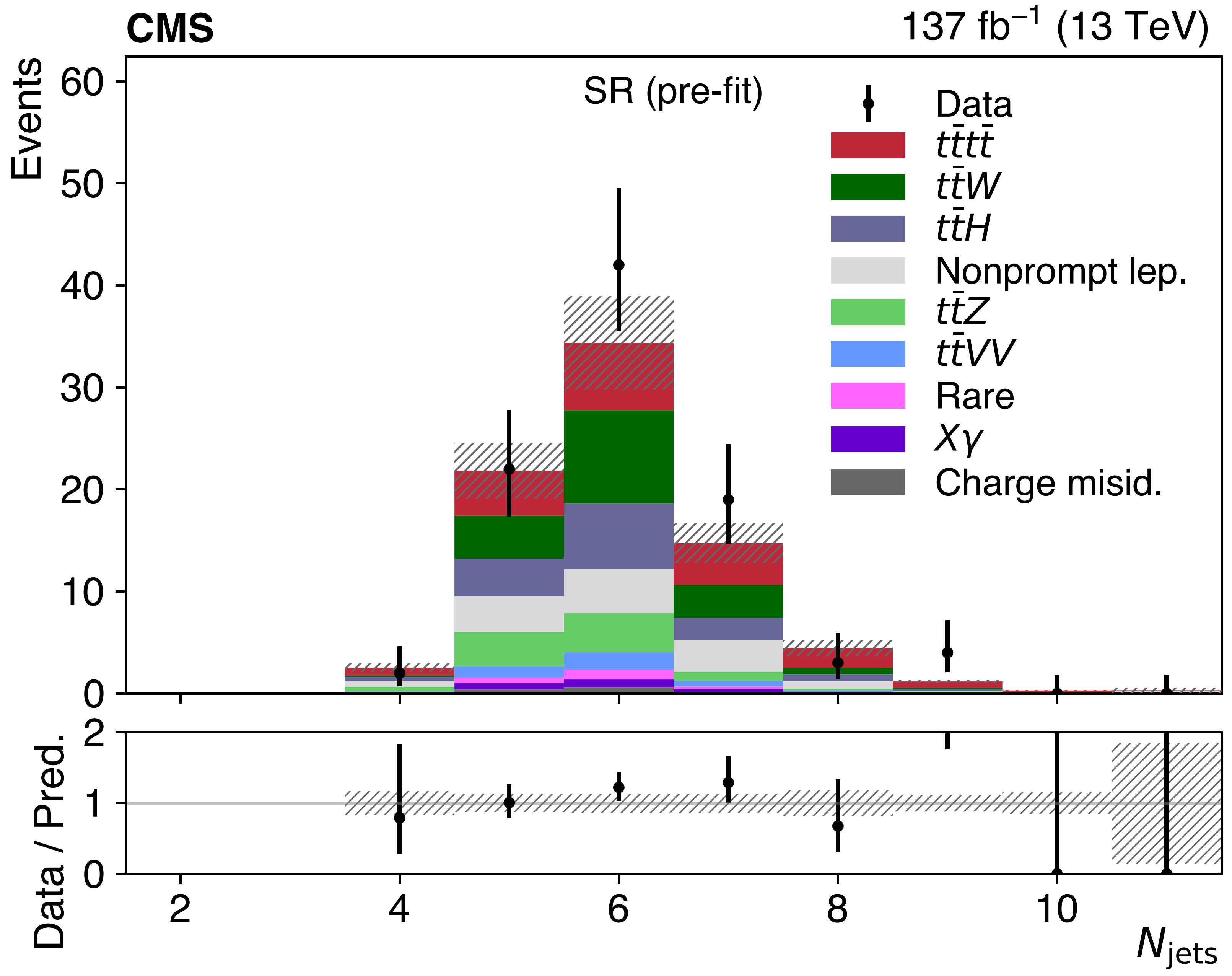
Signal extraction

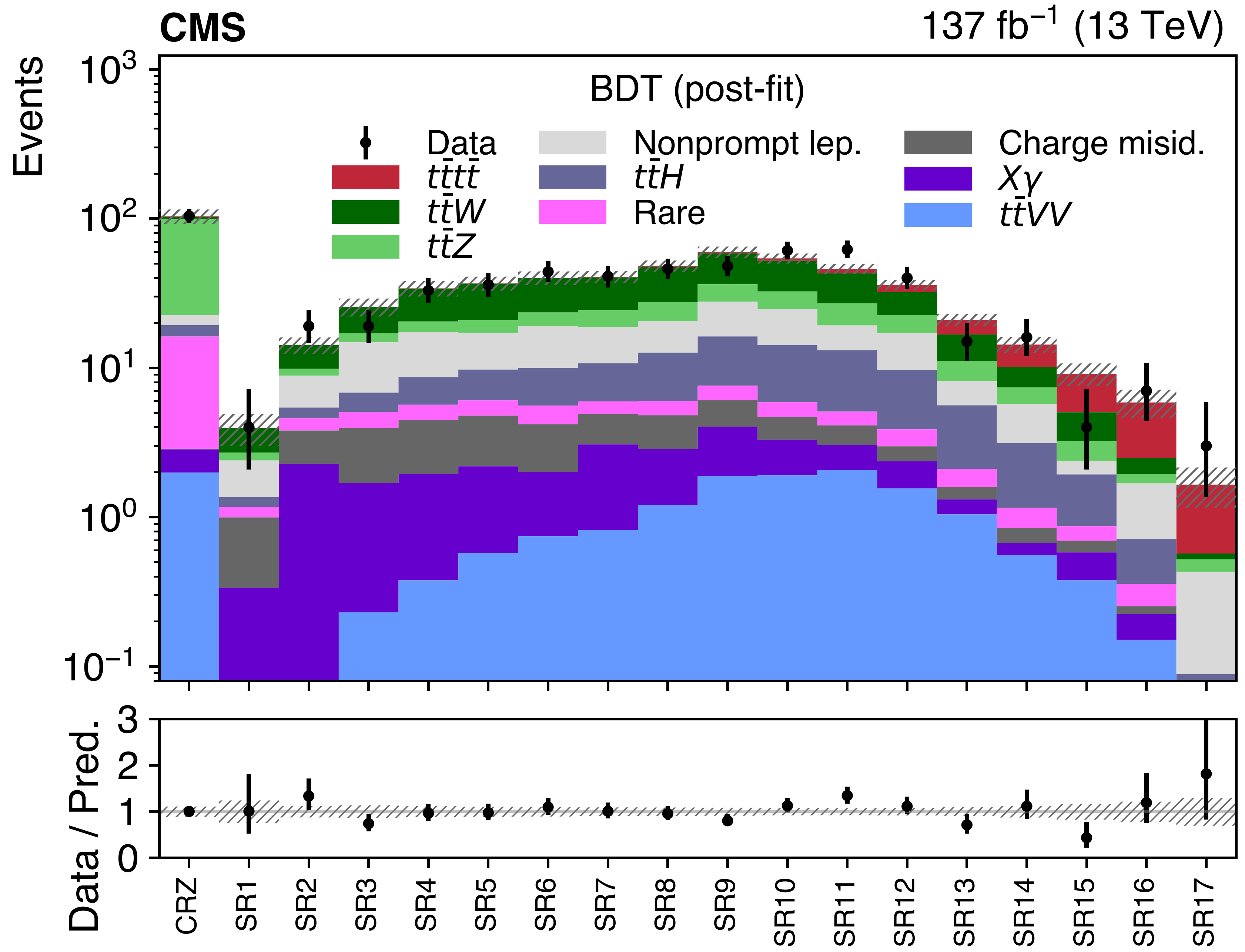
SR divided in 17 regions depending on the BDT score

Simultaneous fit of CRZ and SR(s): measured σ($t\bar{t}t\bar{t}$) = $12.6^{+5.8}_{-5.2}$ fb

Dominant uncertainties:

additional *b*-jets modelling (11% impact on σ($t\bar{t}t\bar{t}$)), JES (9%), JER (6%)





$t\bar{t}t\bar{t}$ 2ℓSS and ML

First evidence: 4.3σ obs. (2.4σ exp.) [139 fb^{-1}]

(Eur. Phys. J. C (2020) 80:1085)

Signal region

≥6 jets, ≥2 *b*-jets, H_T > 500 GeV, *Z*-veto in ML channel

Background modelling

Five control regions to normalise

- the non-prompt lepton background
- the $t\bar{t}W$ background

Data-driven charge mis-identification estimation

Signal extraction

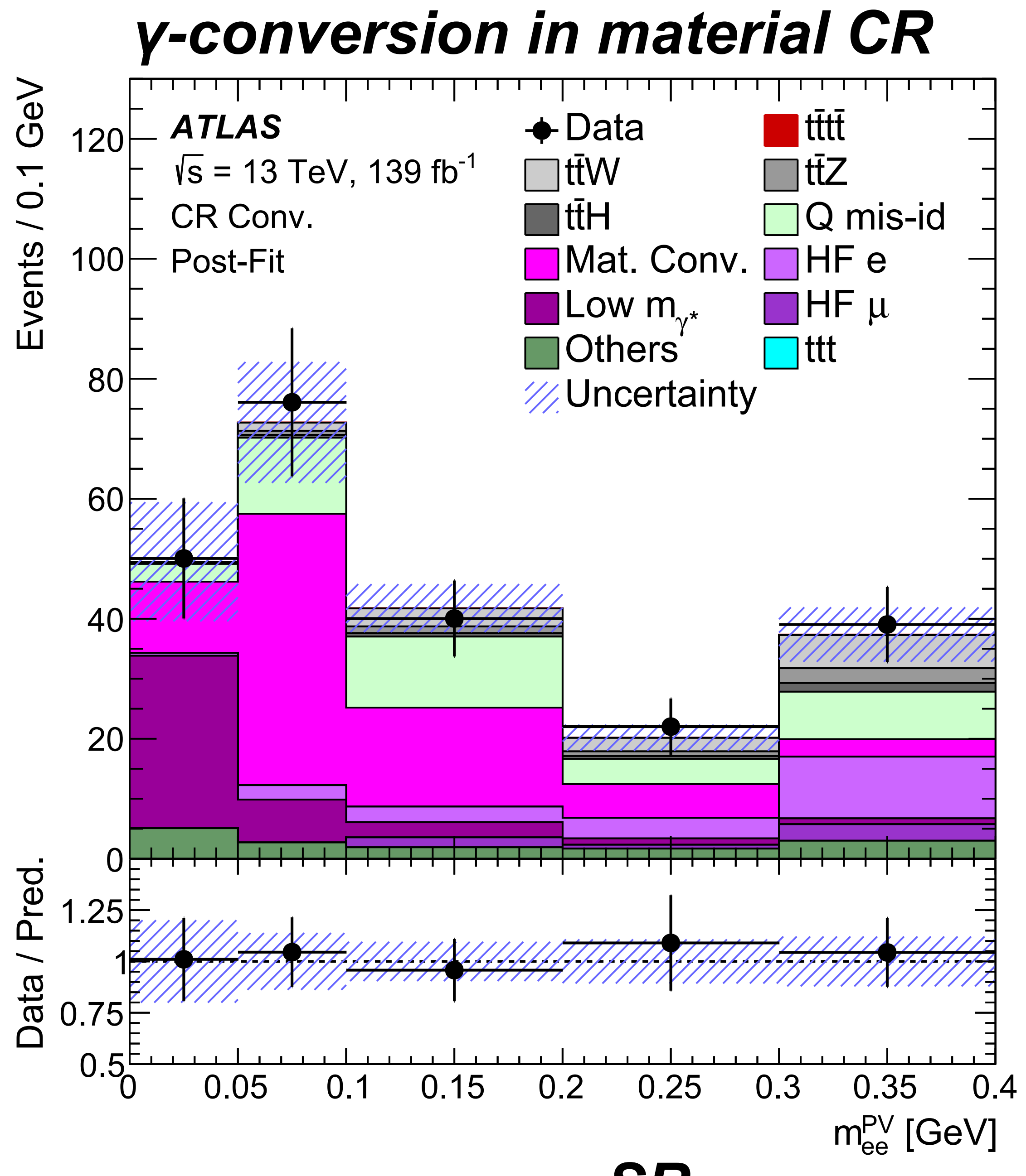
Simultaneous SR+CR fit

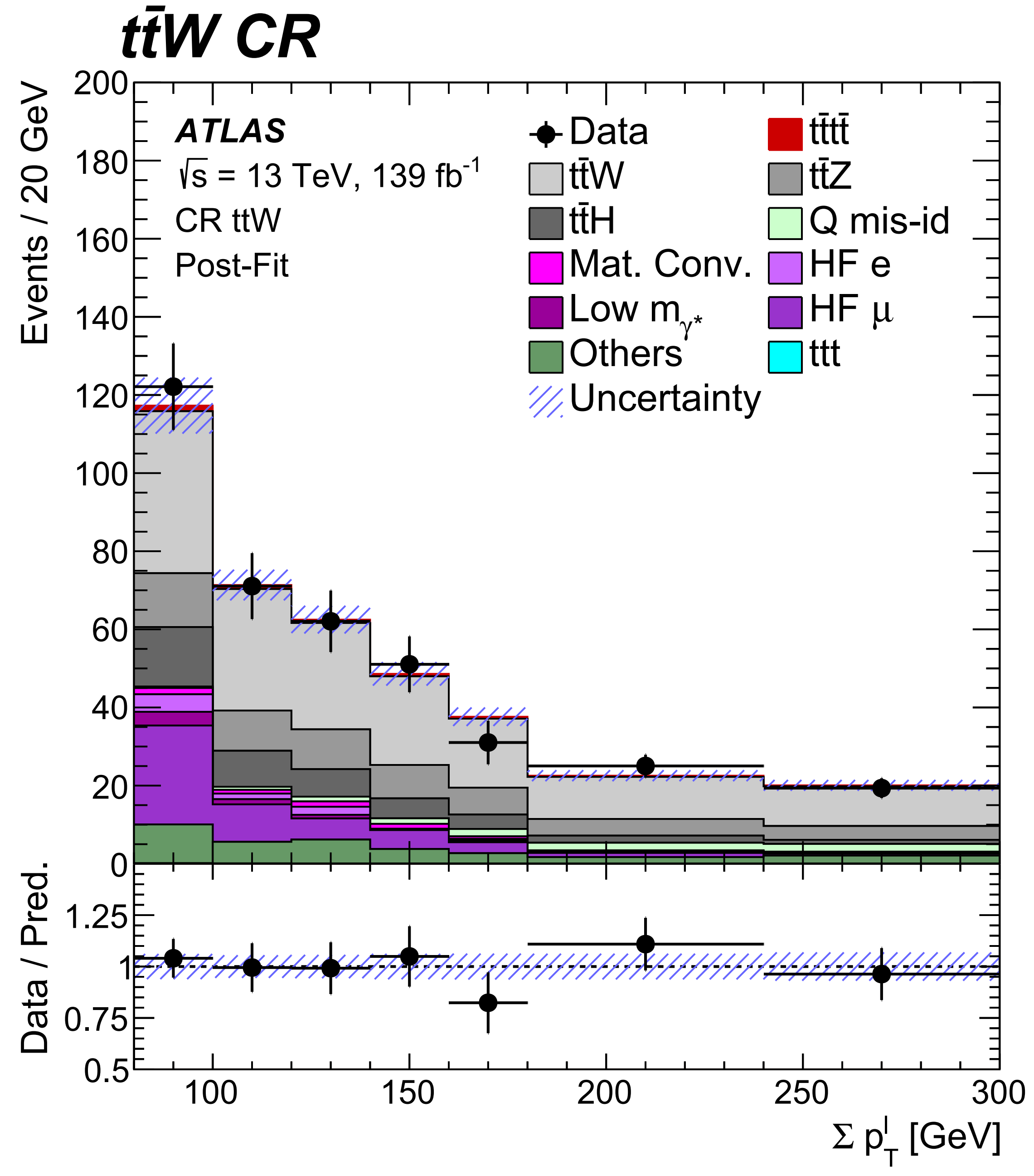
BDT discriminant distribution fit in SR

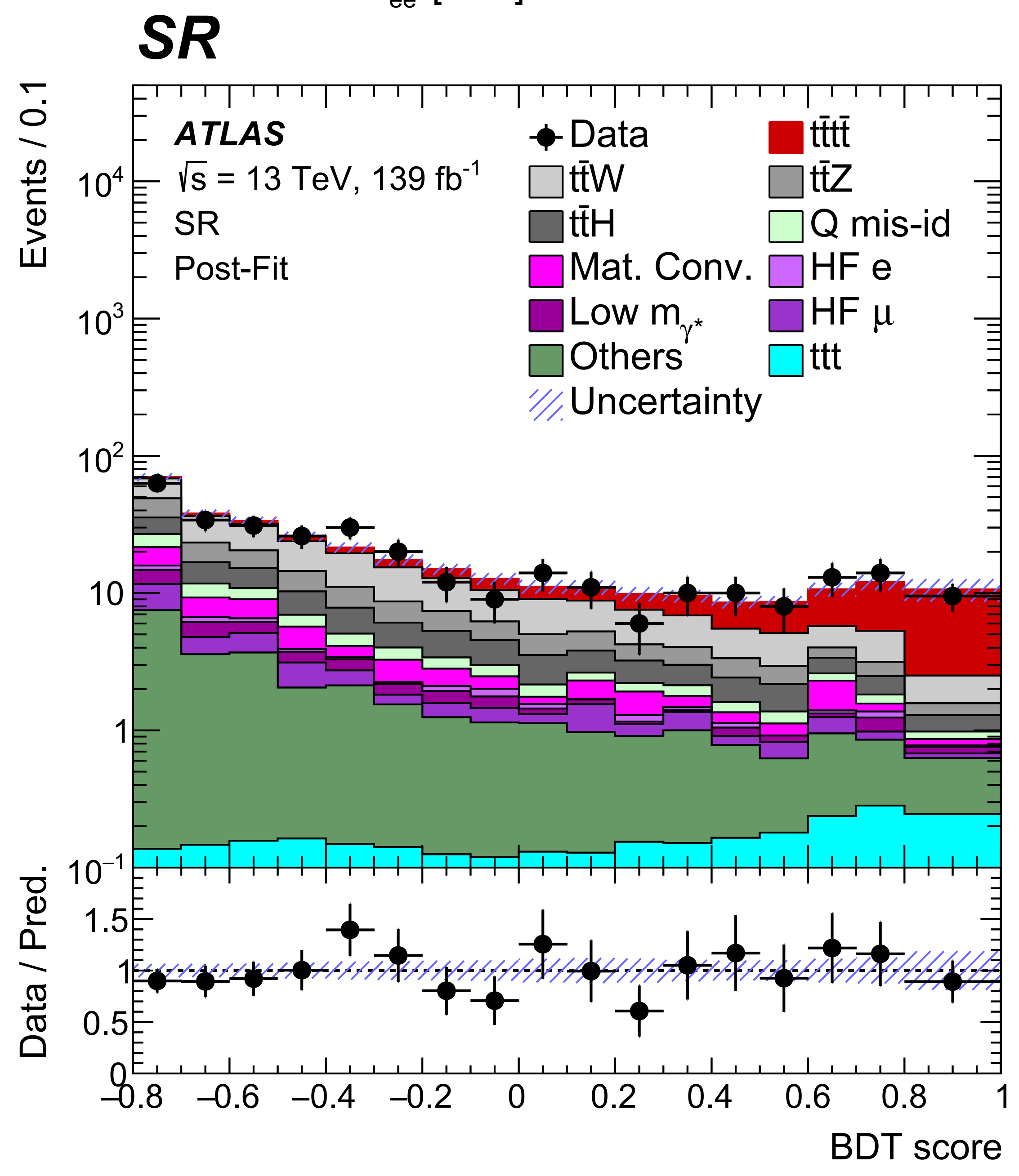
Measured σ($t\bar{t}t\bar{t}$) = 24^{+7}_{-6} fb (1.7σ compatible with SM)

Dominant uncertainty:

modelling of $t\bar{t}W$(≥7 jets), $t\bar{t}W$(≥3 *b*-jets)







$t\bar{t}t\bar{t}$ 1ℓ and 2ℓOS

Partial Run-2 dataset search [35.8 fb^{-1}]

(JHEP 11 (2019) 082)

Region definition

1ℓ, ≥ 7 jets or 2ℓOS (*Z*-veto), ≥ 4 jets.

Always ≥ 2 *b*-jets, H_T^{jets} > 500 GeV

Strategy

BDTs to reconstruct the top quarks from jet triplets

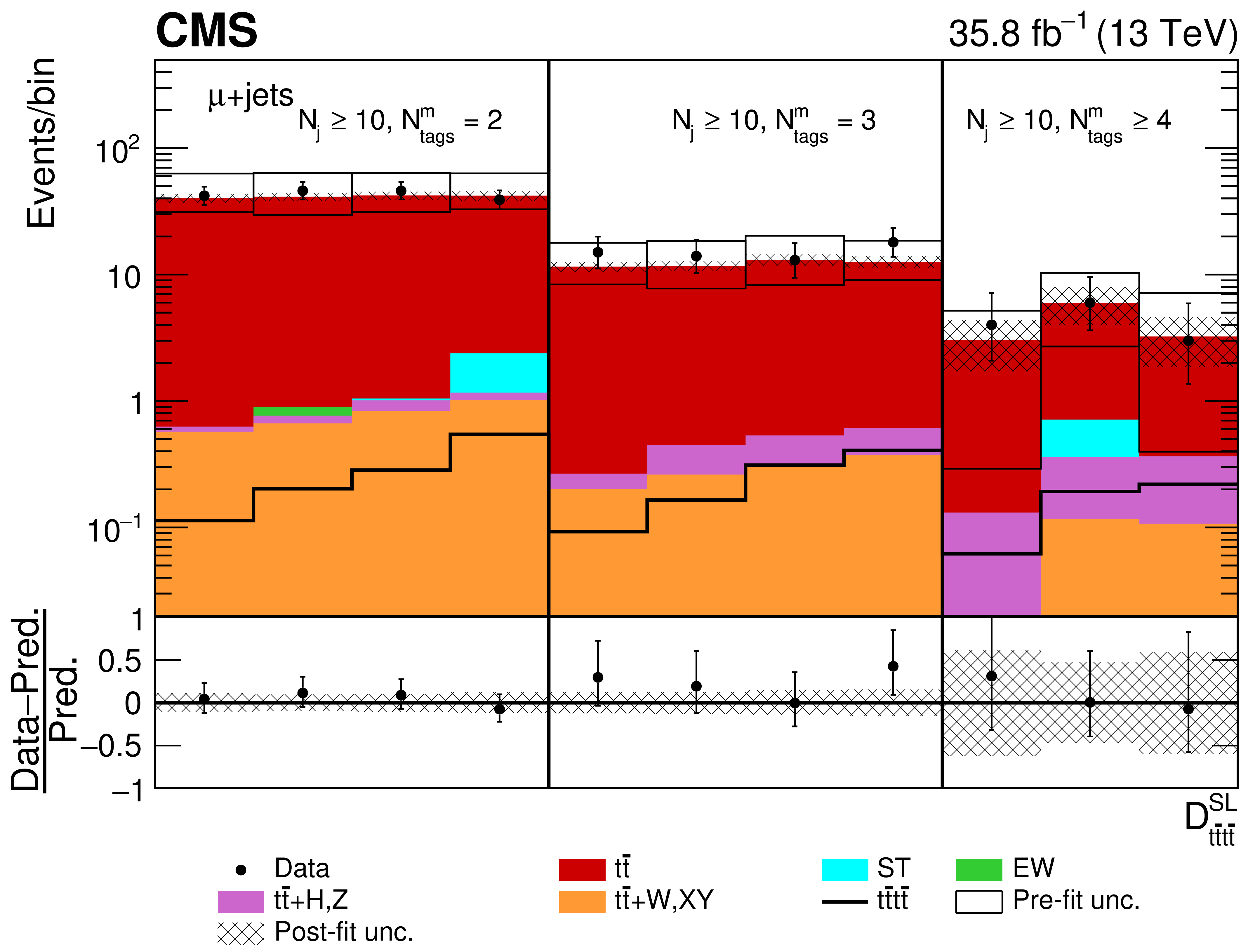
BDTs to the discriminate signal from background

Simultaneous fit of 1ℓ and 2ℓ BDT scores $D_{t\bar{t}t\bar{t}}^{SL}$ and $D_{t\bar{t}t\bar{t}}^{DL}$

Results

σ($t\bar{t}t\bar{t}$) < 48 fb 95%CL

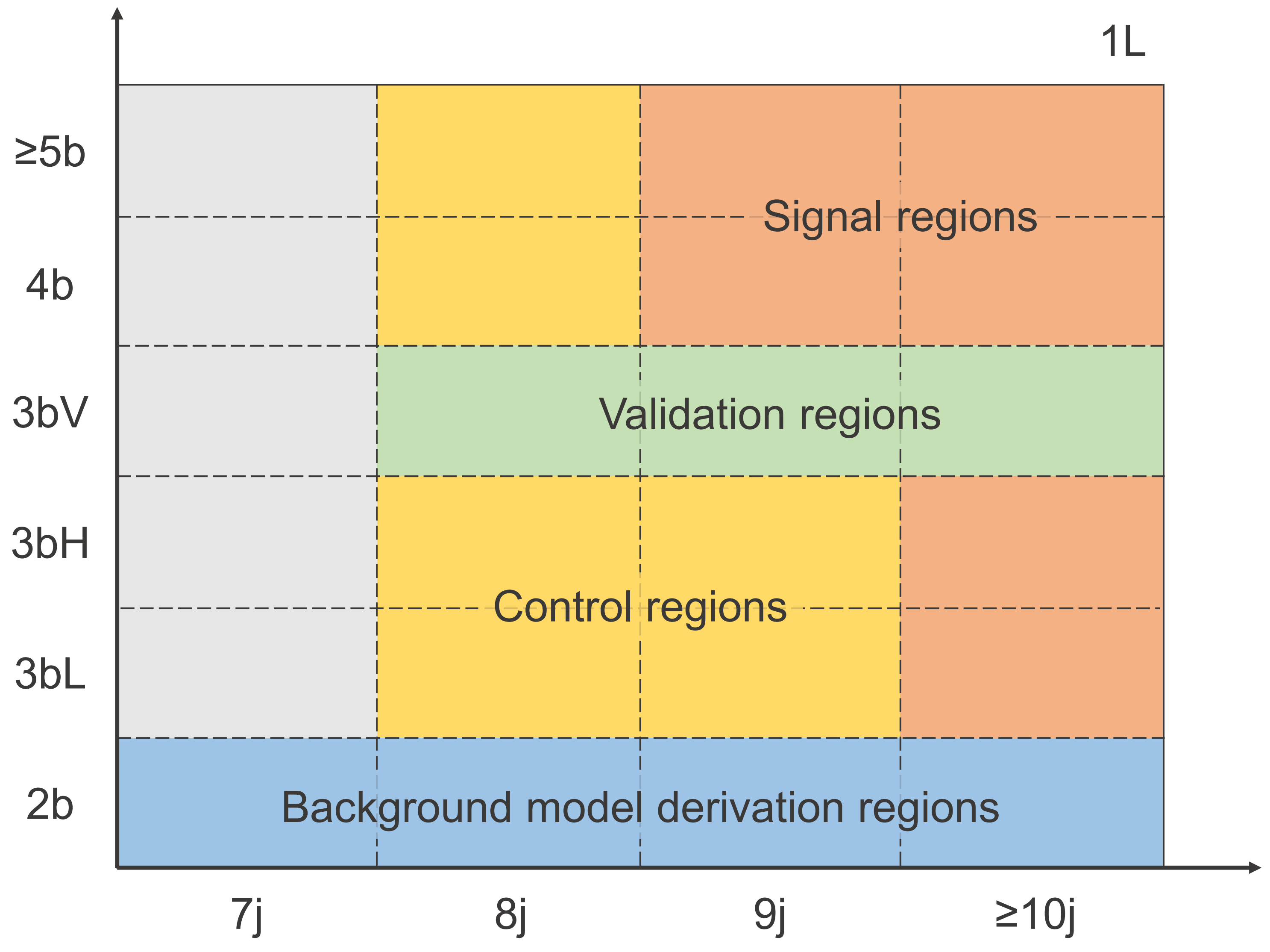
Statistical uncertainty ~ systematic uncertainty



$t\bar{t}t\bar{t}$ 1ℓ and 2ℓOS

Full-Run 2 search: 1.9σ obs. (1.0σ exp.) [139 fb^{-1}]

(ATLAS-CONF-2021-013)



Region definition

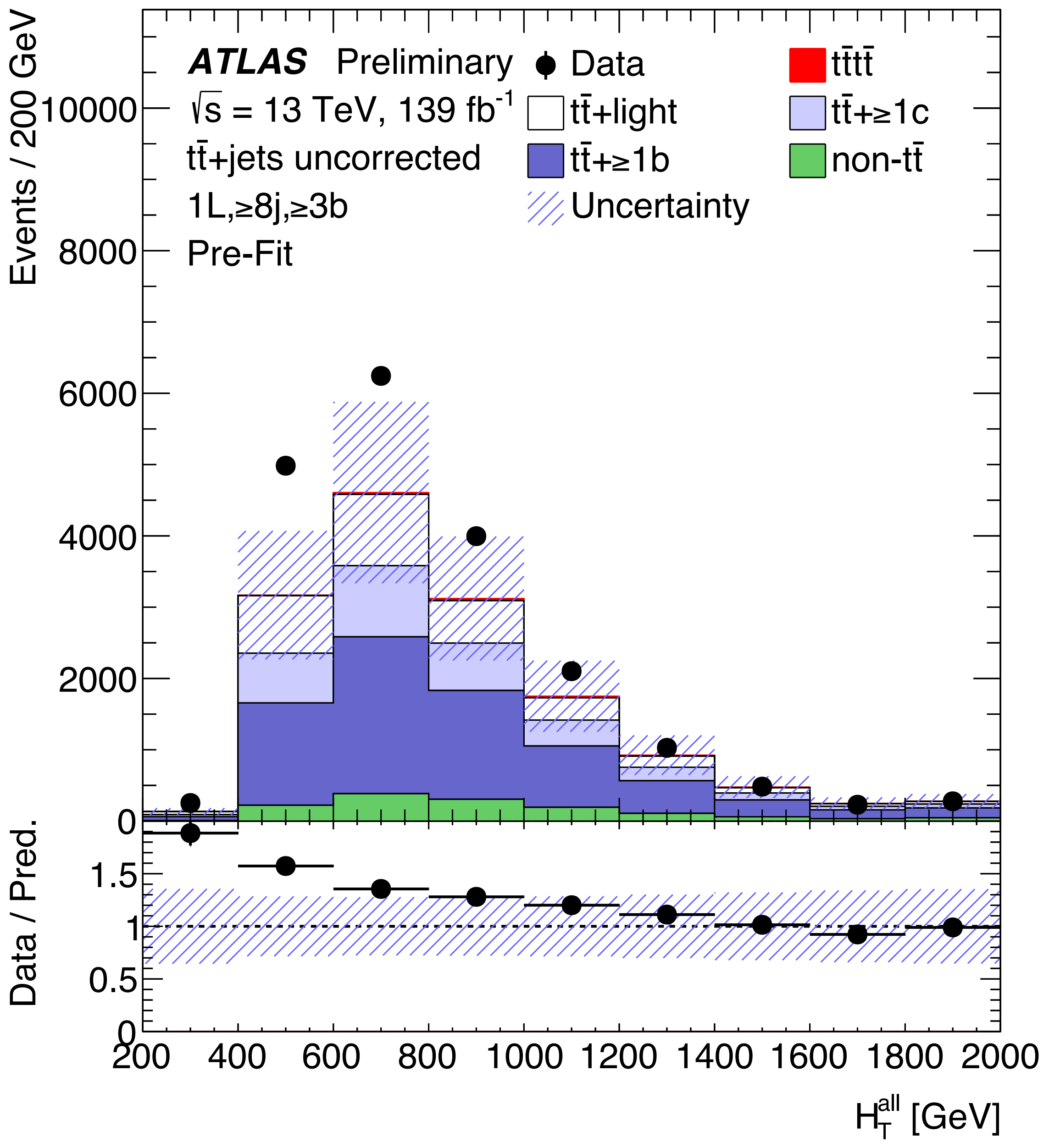
≥ 2 *b*-jets, (1ℓ, ≥ 7 jets) or (2ℓOS, *Z*-veto, ≥ 5 jets)

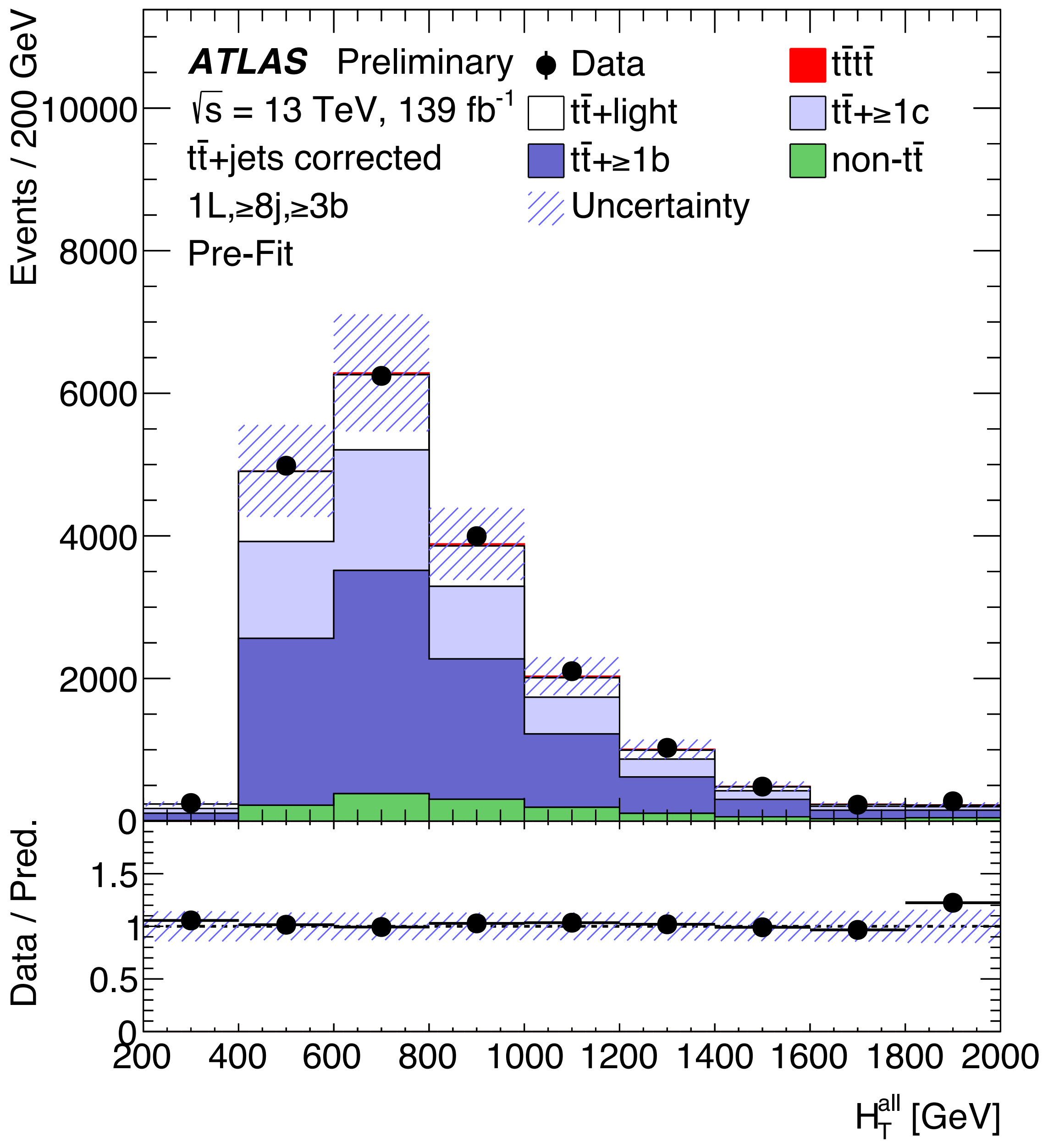
Regions defined by jet and *b*-jet multiplicities

Different *b*-tagging requirements to resolve the flavour composition

Background (= $t\bar{t}$+jets) modelling

- Flavour rescaling. Dedicated fit in ≥8(6) jets for 1(2)ℓ and ≥2 *b* to normalise: $t\bar{t}$+light, $t\bar{t}$+≥1*c*, $t\bar{t}$+≥1*b*
- Kinematic reweighting derived in 2 *b*-jets region





Strategy

BDTs trained in 6 different regions (3 bins in N_{jets} × $N_ℓ$)

6 SRs for 1L, 4 SRs for 2ℓOS

Simultaneous fit of BDT shape in SRs and H_T shape in CRs

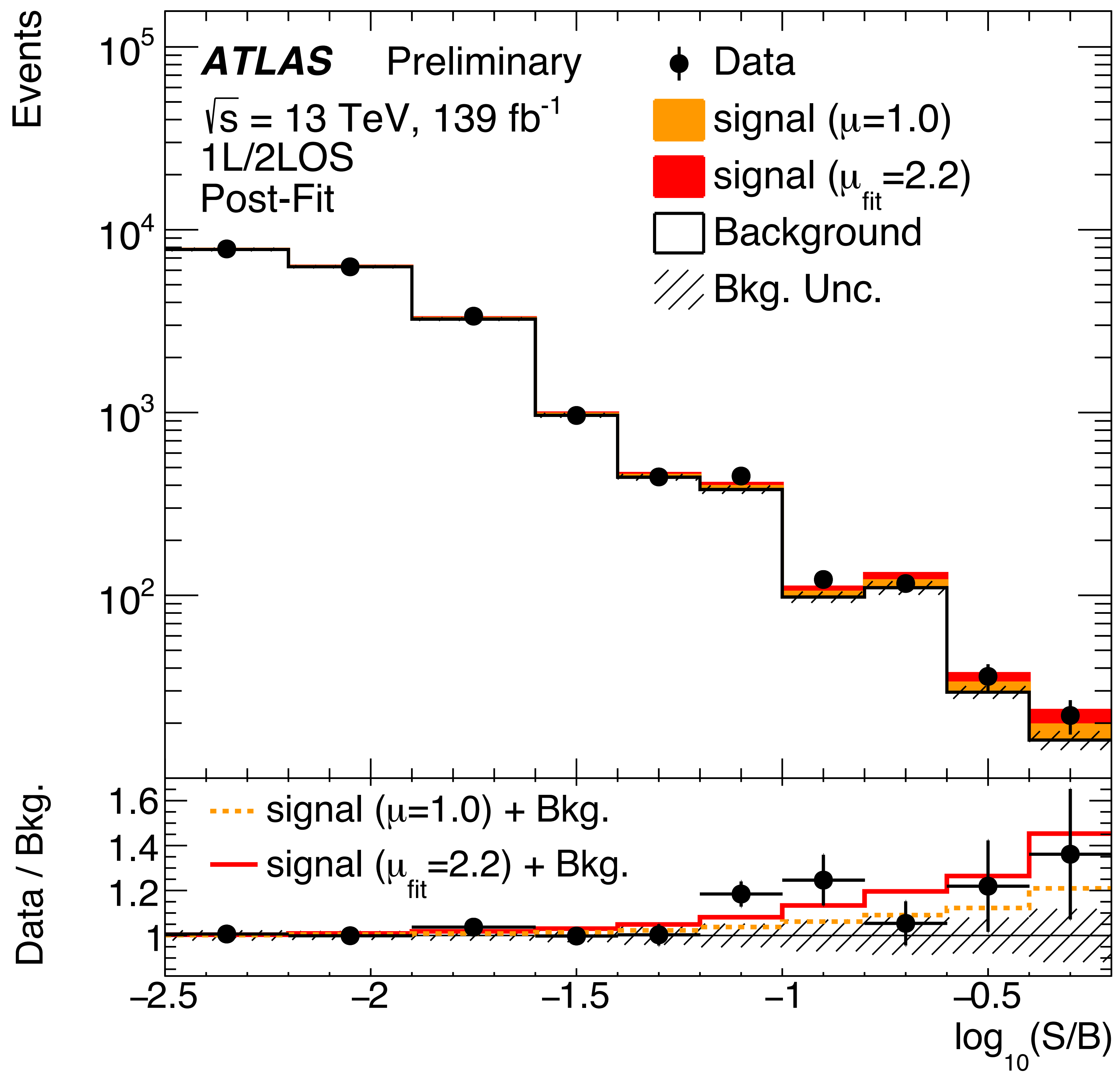
$t\bar{t}t\bar{t}$ 1ℓ and 2ℓOS, combination

Full-Run 2 search: 1.9σ obs. (1.0σ exp.) [139 fb^{-1}]
(ATLAS-CONF-2021-013)

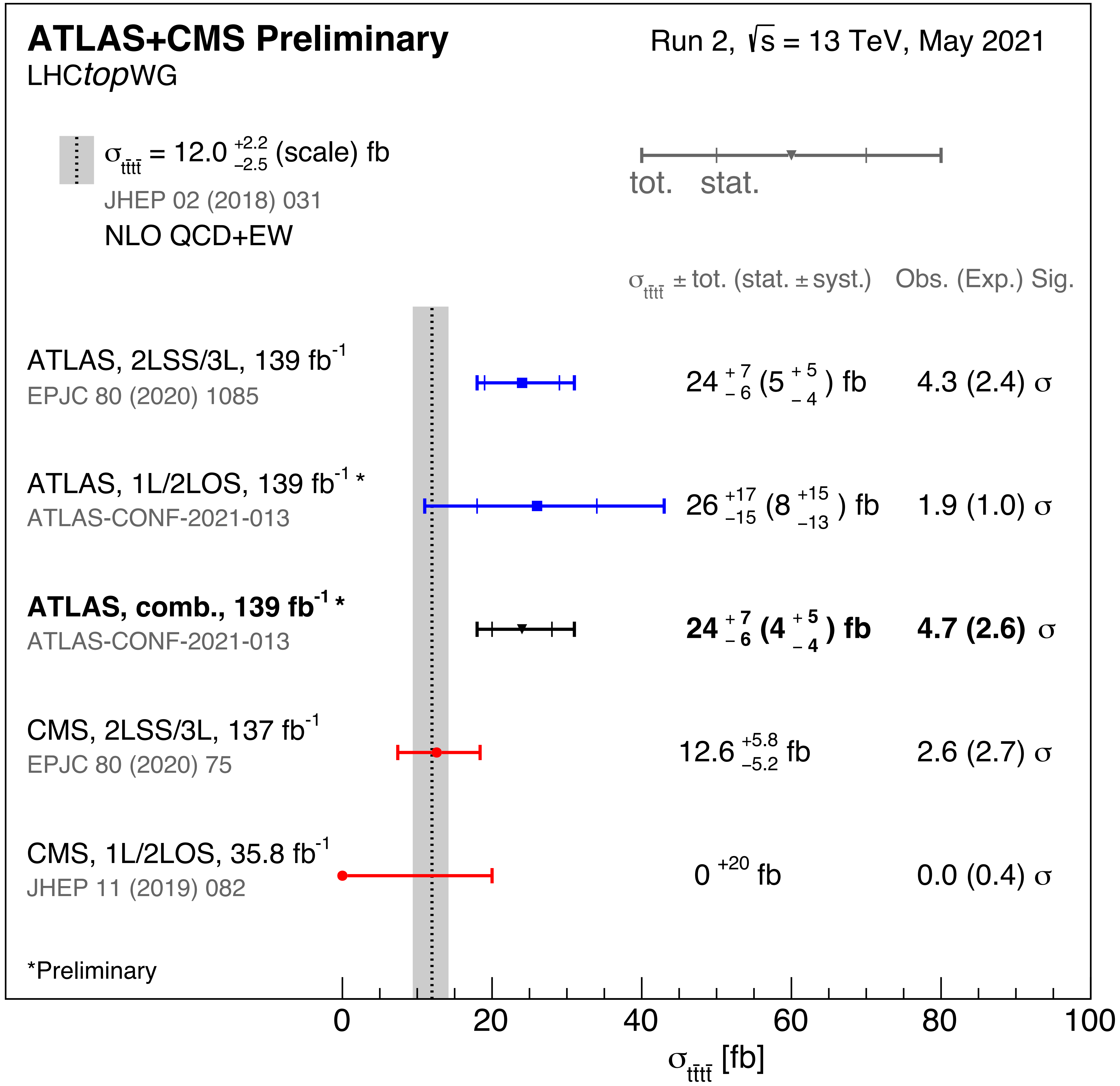
Measured $\sigma(t\bar{t}t\bar{t}) = 26^{+17}_{-15}$ fb

Dominant uncertainties:

$t\bar{t}$+≥1*b* modelling,(±8 fb), $t\bar{t}$+≥1*c* cross-section (±5 fb)



(ATL-PHYS-PUB-2021-013)



Nikhef

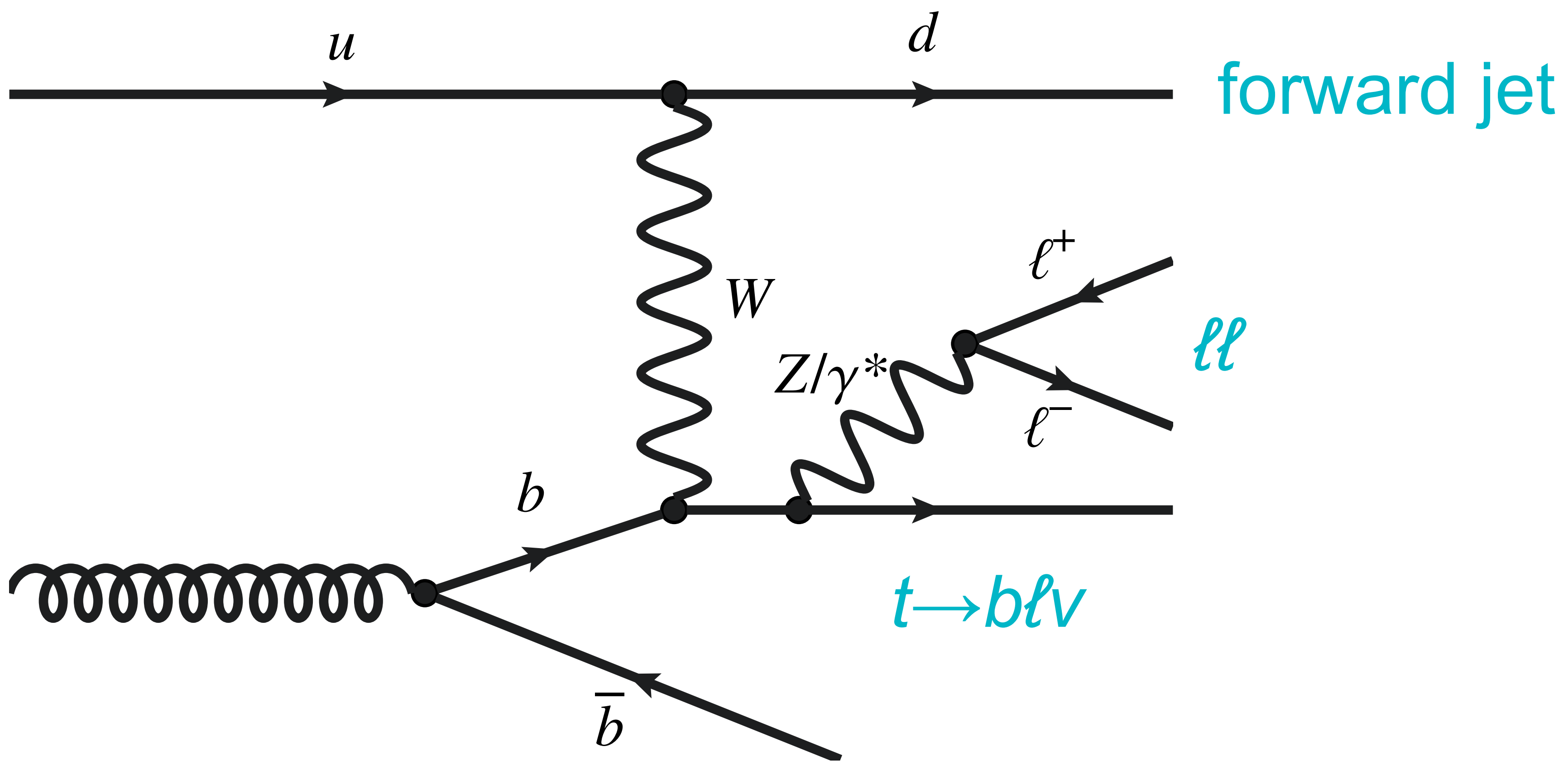
tZq cross section measurement

NEW

More details in G. Gonzalvo Rodriguez's talk

CMS New preliminary result [138 fb^{-1}] (CMS-PAS-TOP-20-010)

ATLAS Observation [139 fb^{-1}] (JHEP 07 (2020) 124)

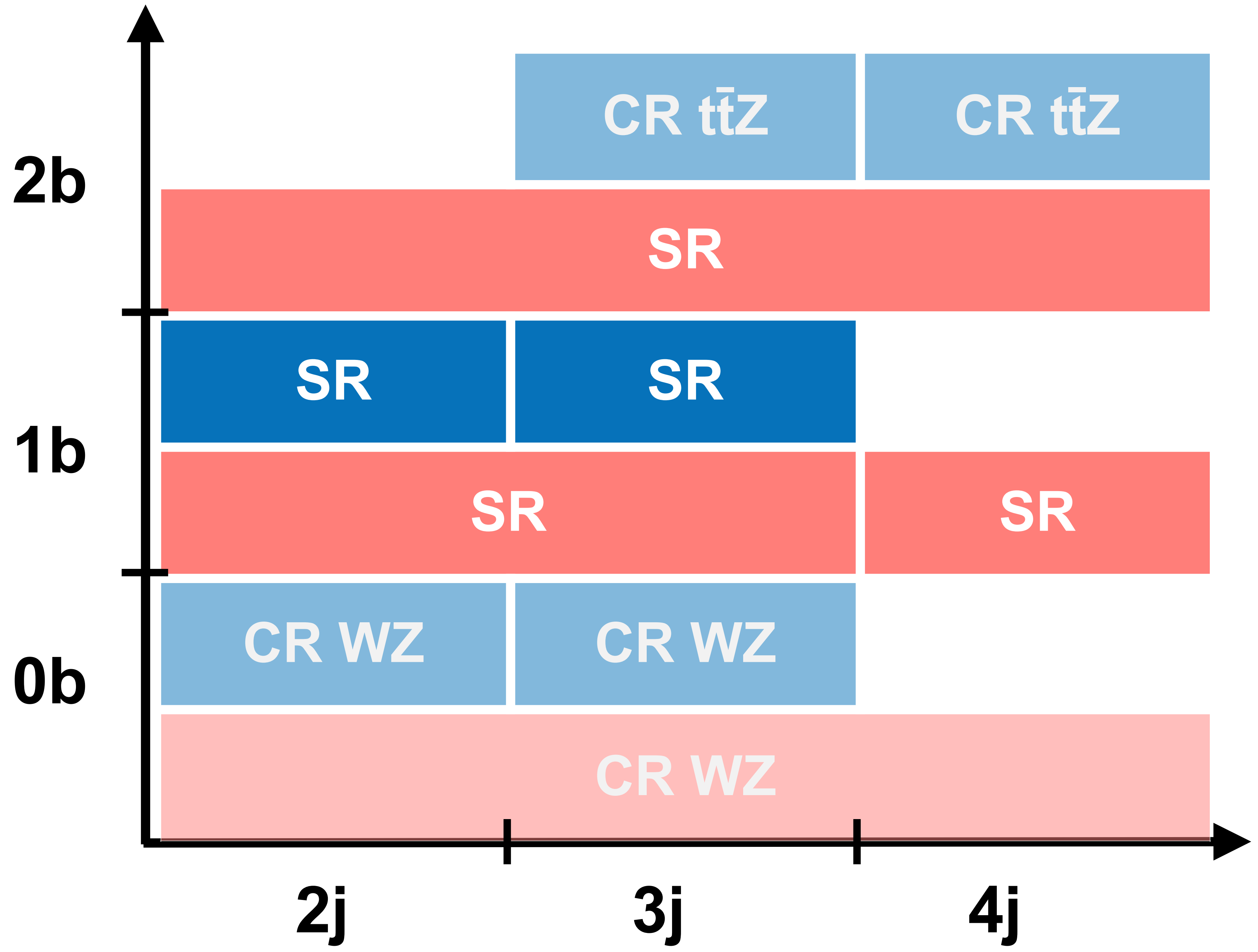


Motivation

Sensitive to *WWZ*, *tt̄Z*, *tbW* couplings, *bW*→*tZ*

Selection

3ℓ, 1 Z candidate, 1 forward jet, 1 *b*-jet



Backgrounds

Non-prompt leptons

- suppressed with object-level MVA
- data-driven estimation. Dedicated CR.
- MC-based shape ("embedded" lepton), normalised in CR

WZ+jets, *tt̄Z*

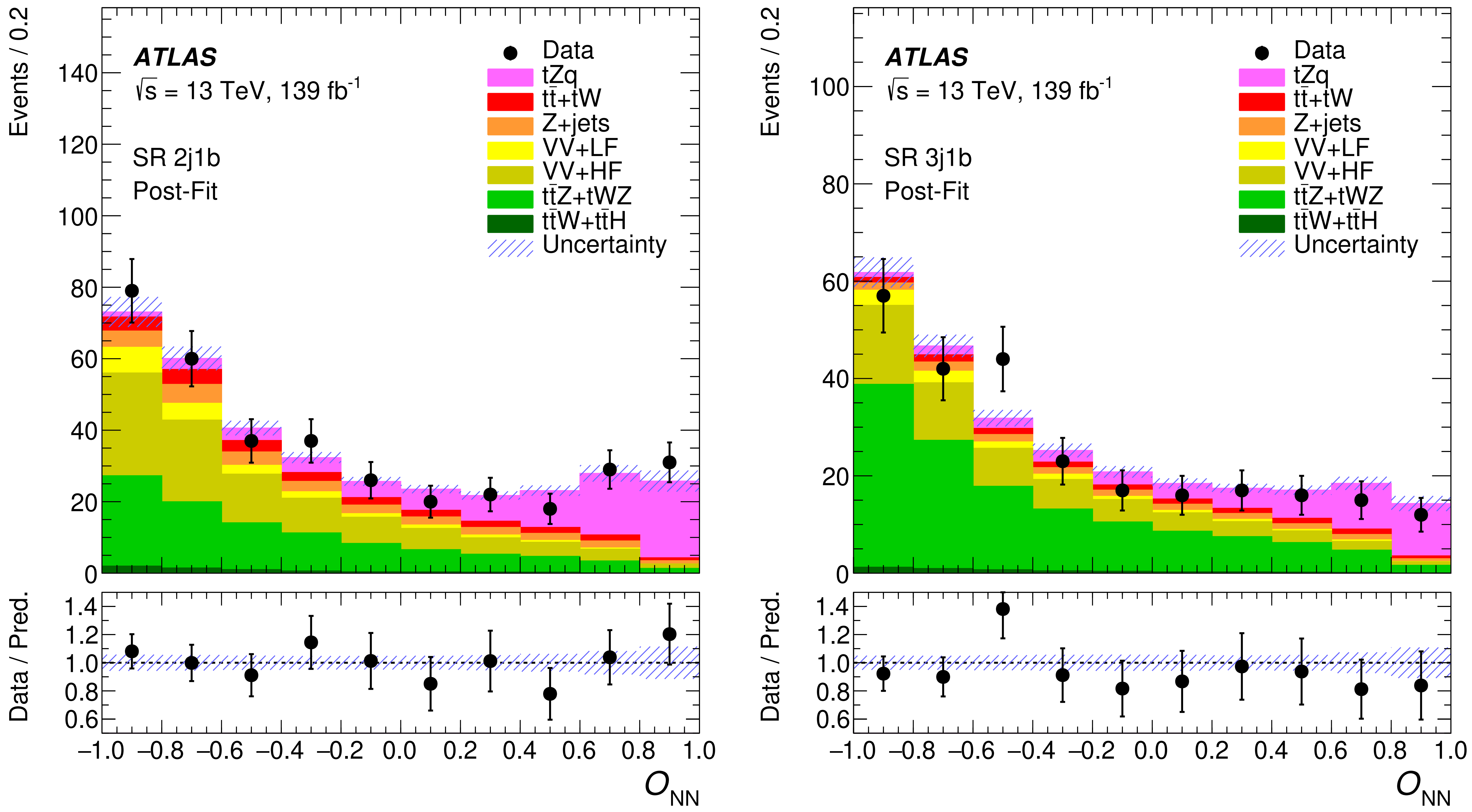
- constrained in CRWZ, CRtt̄Z(4ℓ), low BDT score
- normalised in CRs

Strategy

One BDT / NN per SR, simultaneous fit with CRs

tZq cross section measurement

Observation paper [139 fb^{-1}]
(JHEP 07 (2020) 124)



Result

$\sigma(pp\to t\ell^+\ell^- q)_{\text{ATLAS}}$ = 97 ± 13 (stat) ± 7(syst) fb **(±14%)**

Dominant uncertainties:

non-prompt leptons (3%), JES (2%), lepton selection (2%)

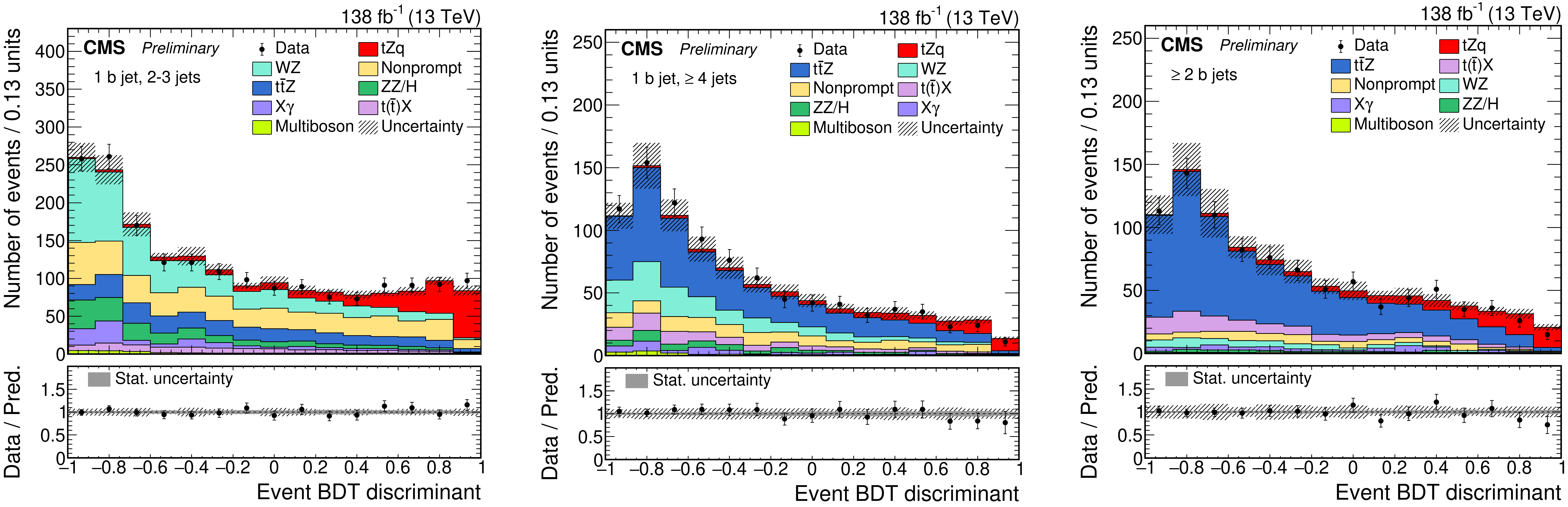
SM prediction

$\sigma(pp\to t\ell^+\ell^- q)$ = 94.2 ± 3.1 fb

tZq cross section measurement

New preliminary result [138 fb^{-1}]

(CMS-PAS-TOP-20-010)



Result

$\sigma(pp \to t\ell^+\ell^- q)_{\text{CMS}} = 87.9\ ^{+7.5}_{-7.3}(\text{stat})^{+7.3}_{-6.0}\ (\text{syst})$ fb **(±11%)**

$\sigma(t) / \sigma(\bar{t}) = 2.4^{+0.6}_{-0.4}$ (stat) $^{+0.3}_{-0.1}$ (syst)

Dominant uncertainties:

tZq modelling (3%), non-prompt leptons (2%), WZ normalisation (2%)

SM prediction

$\sigma(pp \to t\ell^+\ell^- q) = 94.2 \pm 3.1$ fb

tZq differential measurement

NEW

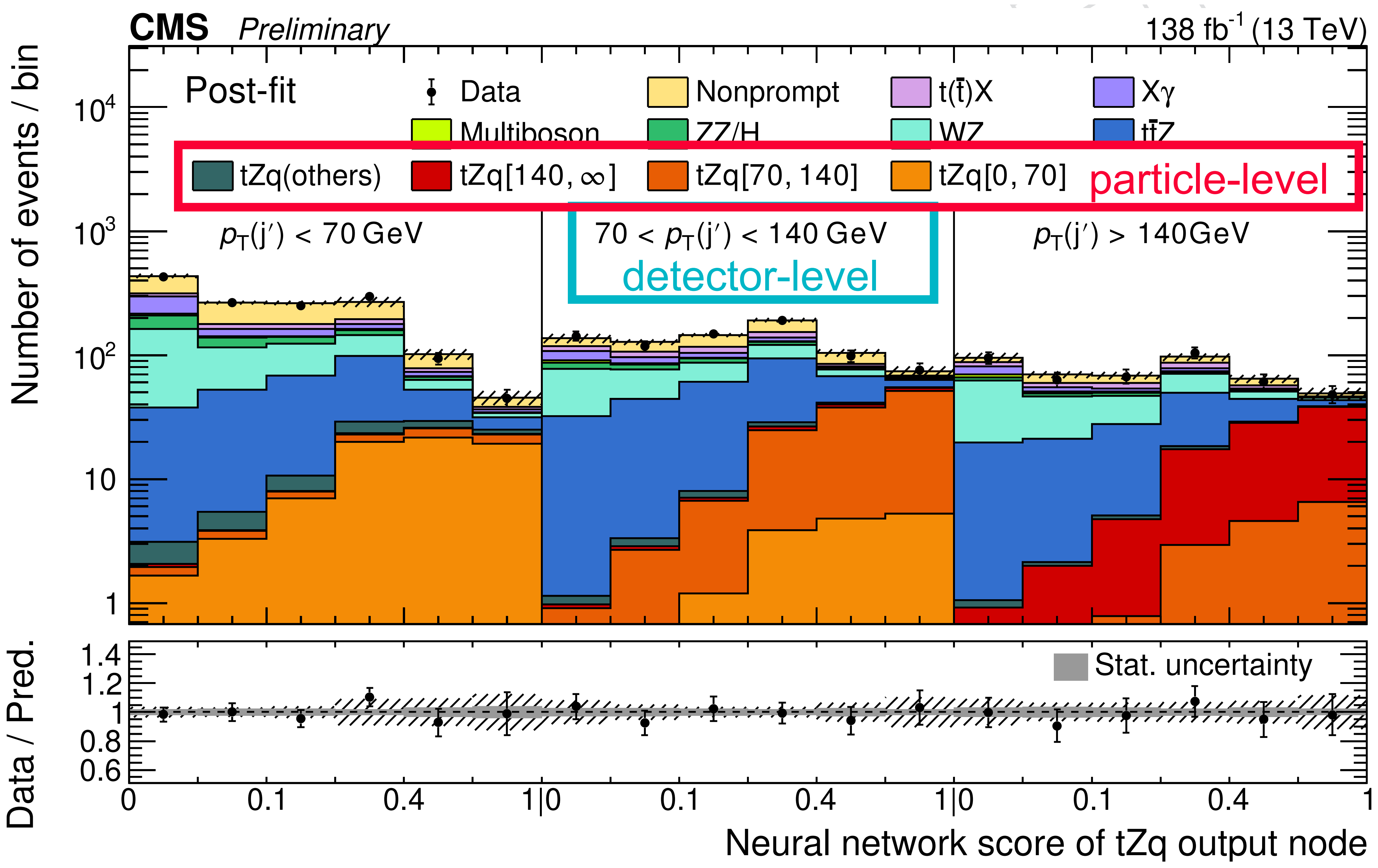
New preliminary result [138 fb^{-1}]
(CMS-PAS-TOP-20-010)

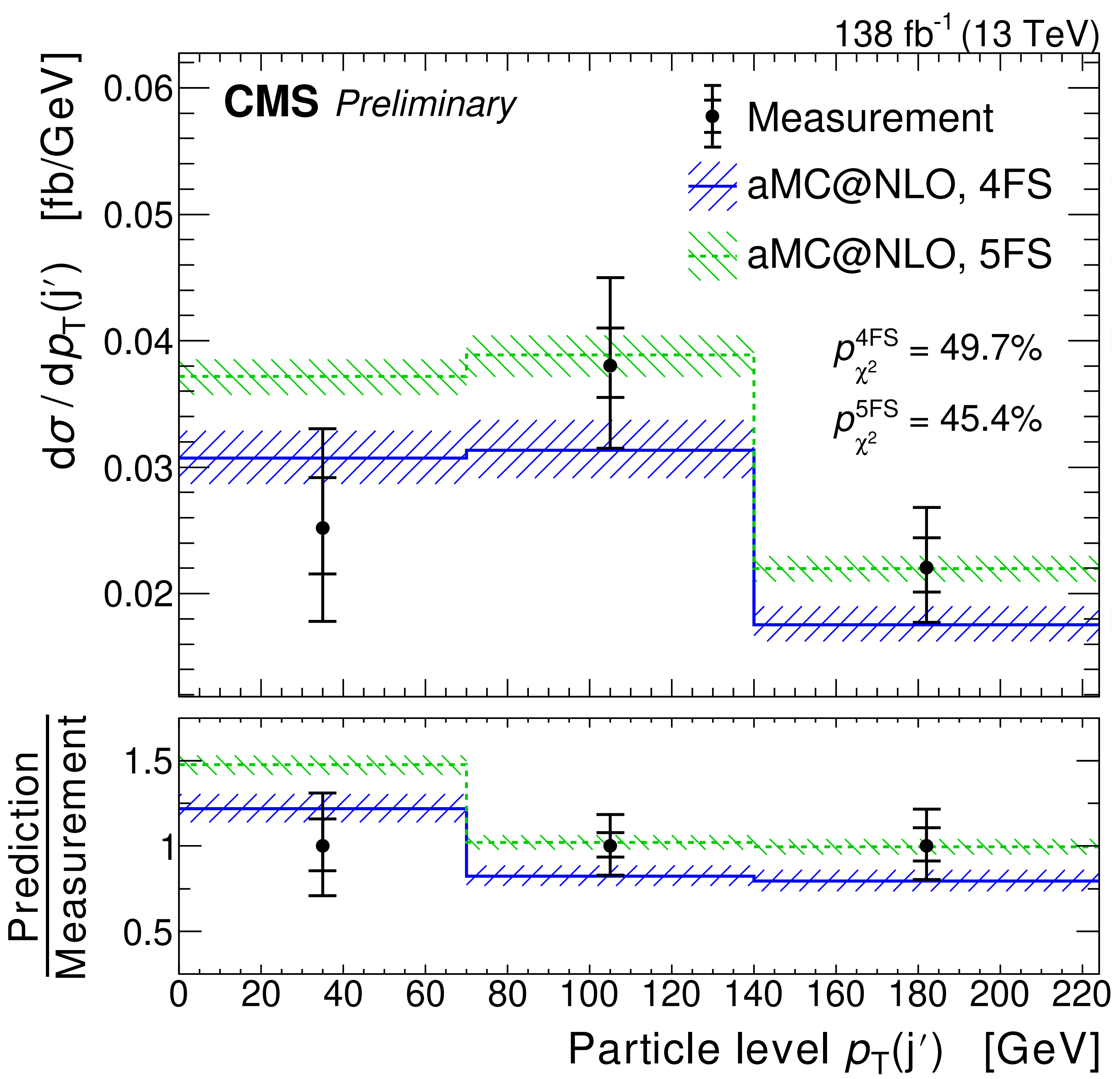
Parton & particle level, 9 variables: $p_T(t)$, $p_T(Z)$, $p_T(\ell_t)$, $m(3\ell)$, $\Delta\Phi(\ell,\ell')$, $\cos(\theta^*_{pol})$, $m(t,Z)$, $p_T(j')$, $|\eta|(j')$

tZq divided into generator-level bin: 4 for lepton variables, 3 for hadronic variables

tZq detector response matrix determined with simulation

Fit of NN output determines the normalisation of the generator-level bins





Results

- Similar goodness-of-fit of 4FS and 5FS in all variables
- Spin asymmetry

$$\frac{d\sigma}{d\cos(\theta^{\star}_{\text{pol}})} = \sigma_{\text{tZq}}\left(\frac{1}{2} + A_{\ell}\cos(\theta^{\star}_{\text{pol}})\right)$$

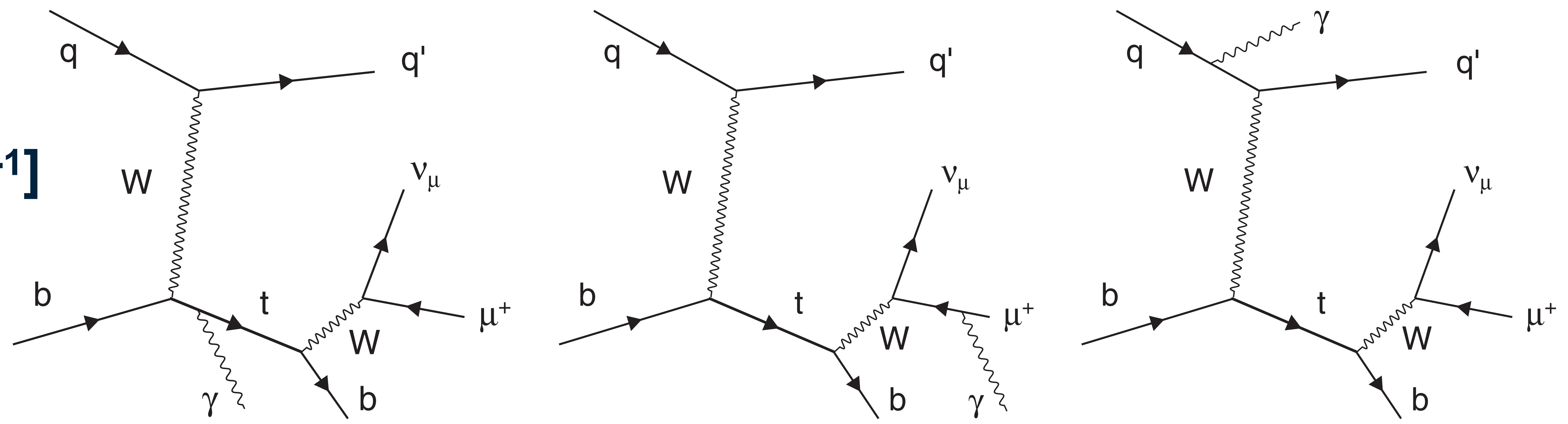
$A_\ell = 0.58_{-0.16}^{+0.15} \pm 0.06$

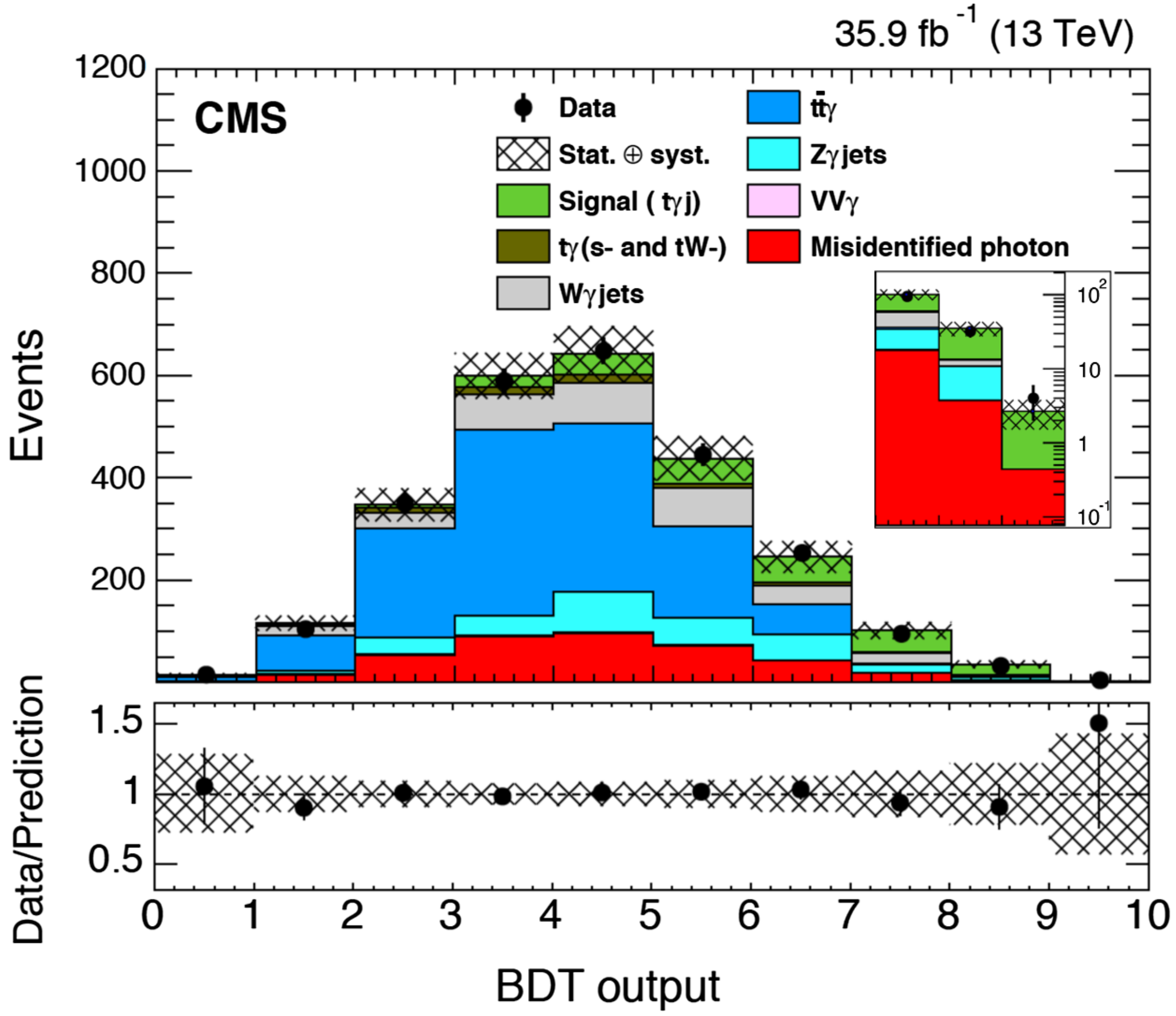
compatible with SM prediction
$A^{4/5FS} = 0.437 / 0.454 \pm 0.005$

$t\gamma$ evidence

First evidence: 4.4σ obs. (3.0σ exp.) [35.9 fb^{-1}]

(Phys. Rev. Lett. 121 (2019) 221802)





Motivation: sensitive to magnetic dipole moment

Selection: 1μ, 1γ, 1 *b*-jet, 1 forward jet

Backgrounds

$t\bar{t}\gamma$ (×9 $t\gamma$), $V\gamma$ (×2 $t\gamma$)

Signal extraction

BDT shape fit

$\sigma(pp \rightarrow t\gamma j)B(t\rightarrow\mu\nu b)$ = 115 ± 17 (stat) ± 30 (syst) fb

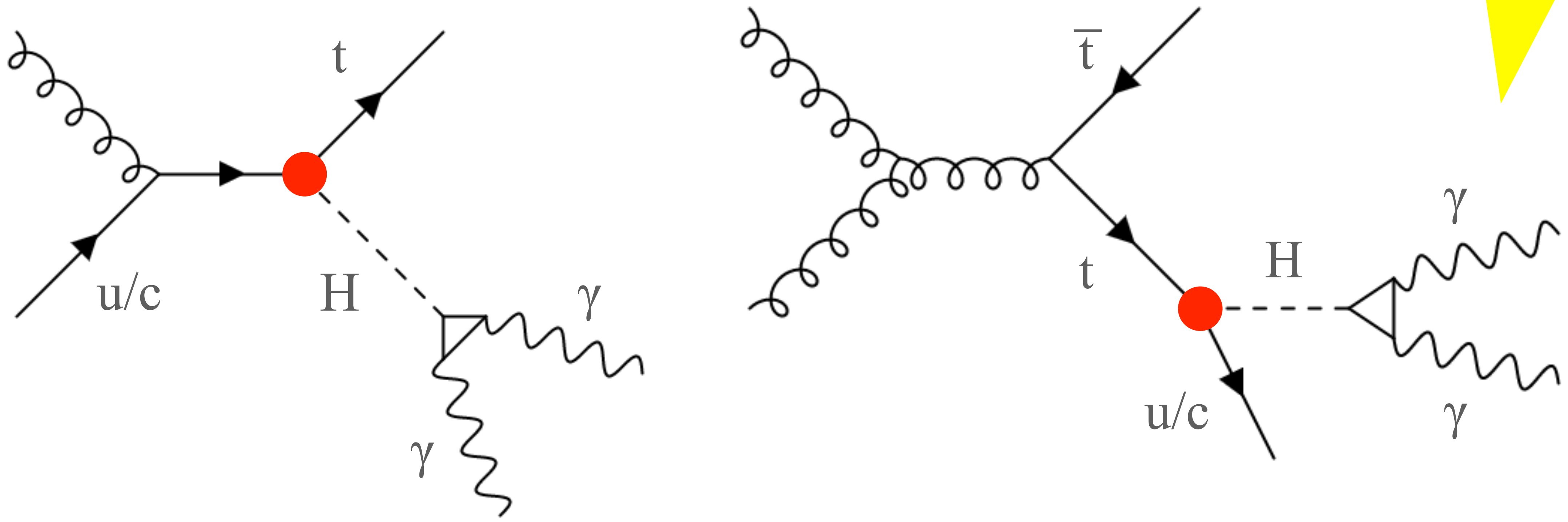
Expected $t\gamma$ events 154 ± 24, observed 220 ± 63

Dominant uncertainty: JES(12%)

Searches

Search for the FCNC *tHq* interaction

***tHq* (*q* = *u*,*c*), production & decay, H→γγ [137 fb^{-1}]**
(CMS-PAS-TOP-20-007)



Motivation: SM prediction B($t \rightarrow Hq$)~10^{-16},
any excess = evidence for new physics

Signal region

2 photons, 100 < $m_{\gamma\gamma}$ < 180 GeV

leptonic: ≥1 jet, ≥1ℓ

hadronic: ≥3 jet, ≥1 *b*-jet

Backgrounds

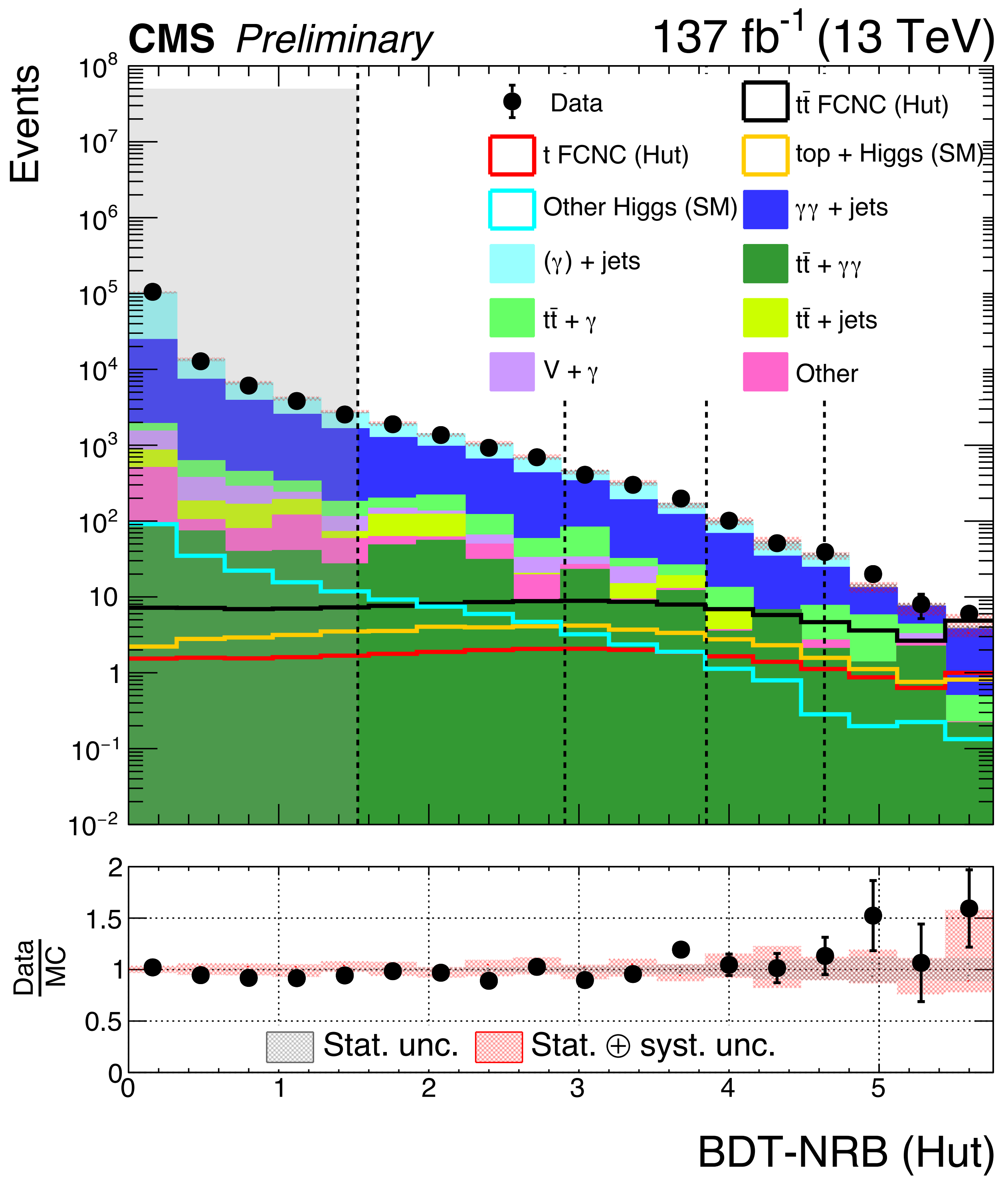
- resonant: $t\bar{t}H$, *VH*, VBF, *ggH*, $b\bar{b}H$, *tH*
- non-resonant: γ(γ)+jets, $t\bar{t}$+γ(γ), *V*+γ
  data-driven estimation

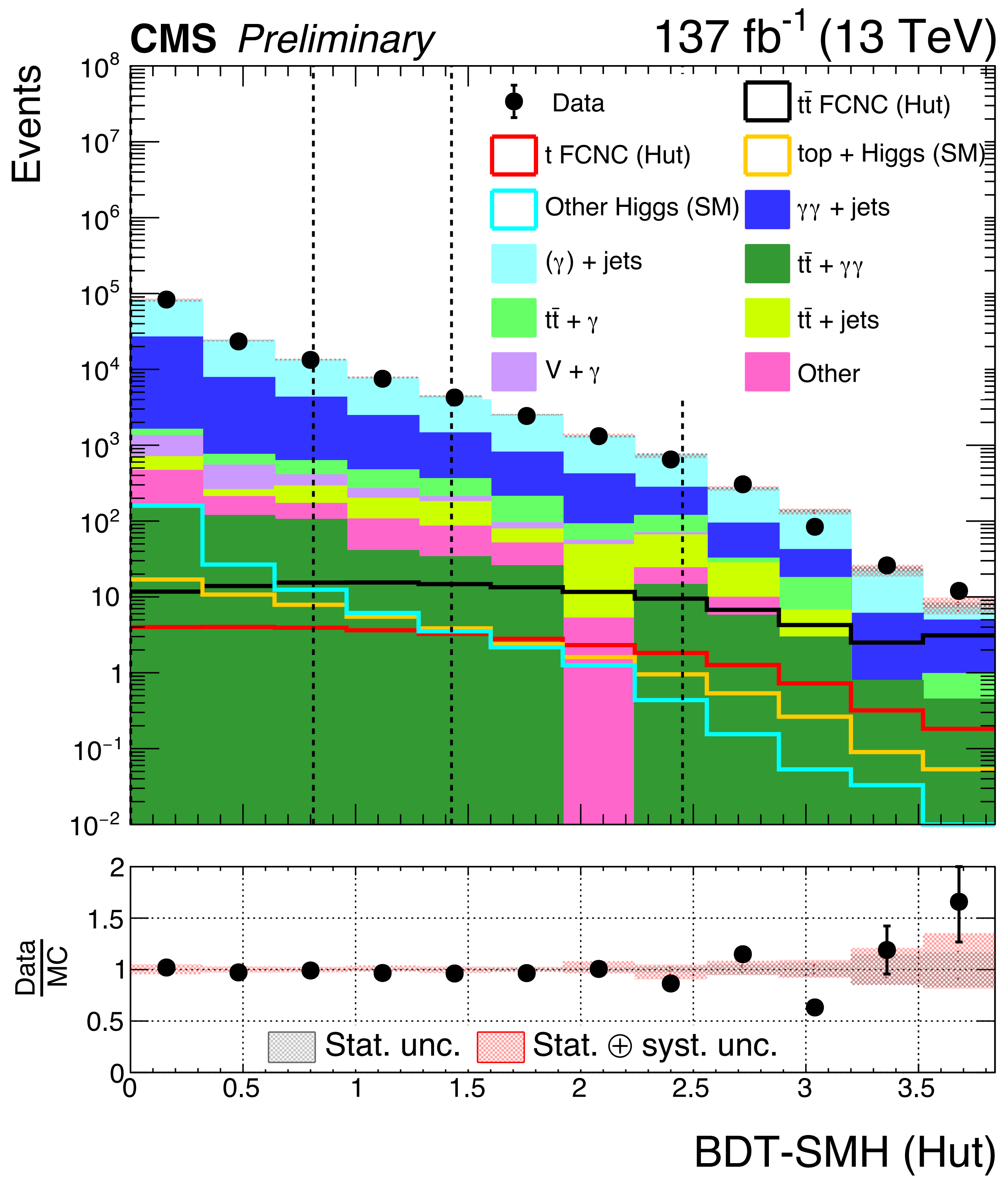
Strategy

8 BDTs: (*u*, *c*) × (lep, had) × (res, non-res bkg)

7 categories defined by BDT score per *q* = *u, c* flavour

14 $m_{\gamma\gamma}$ distributions to fit



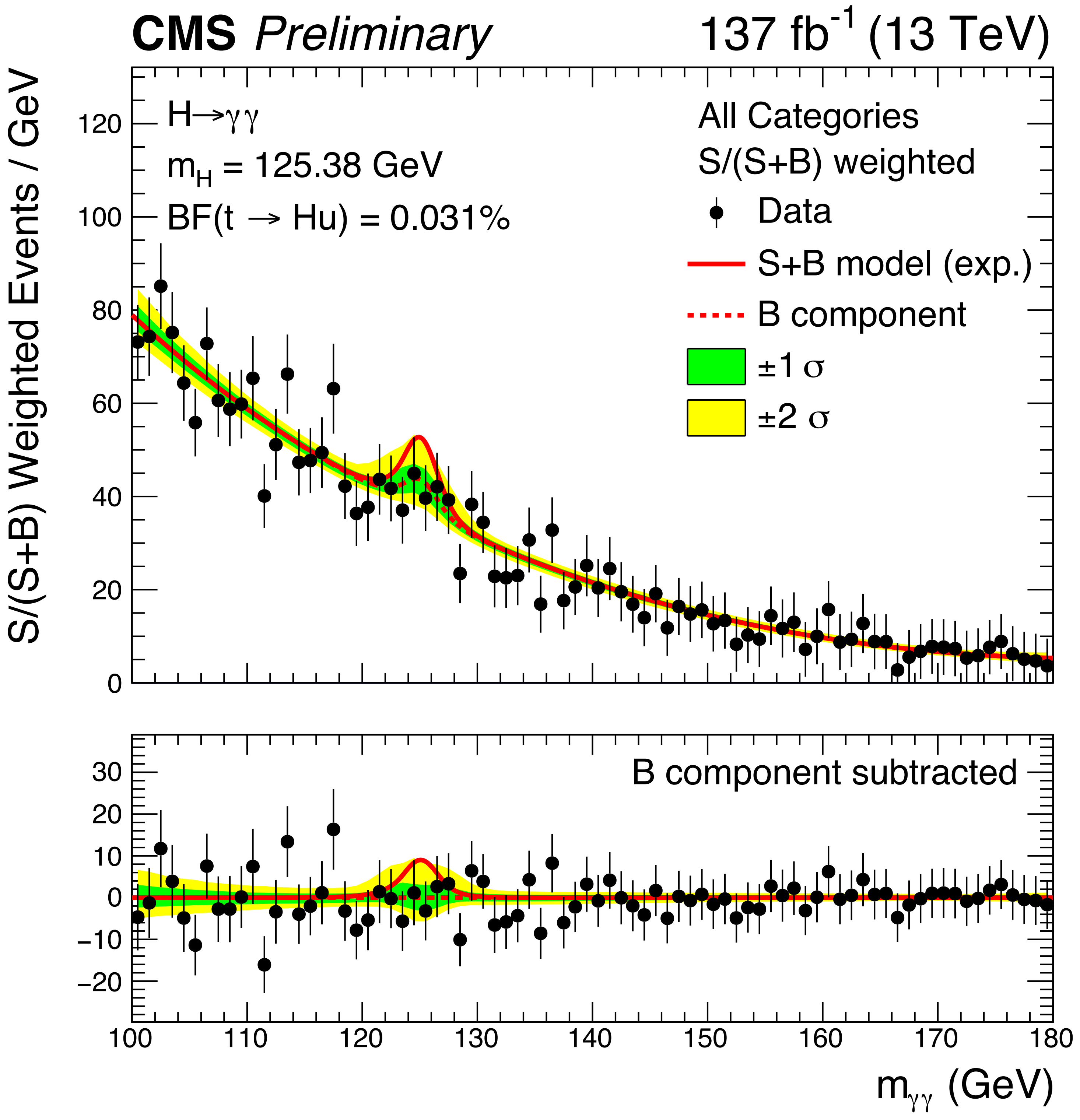


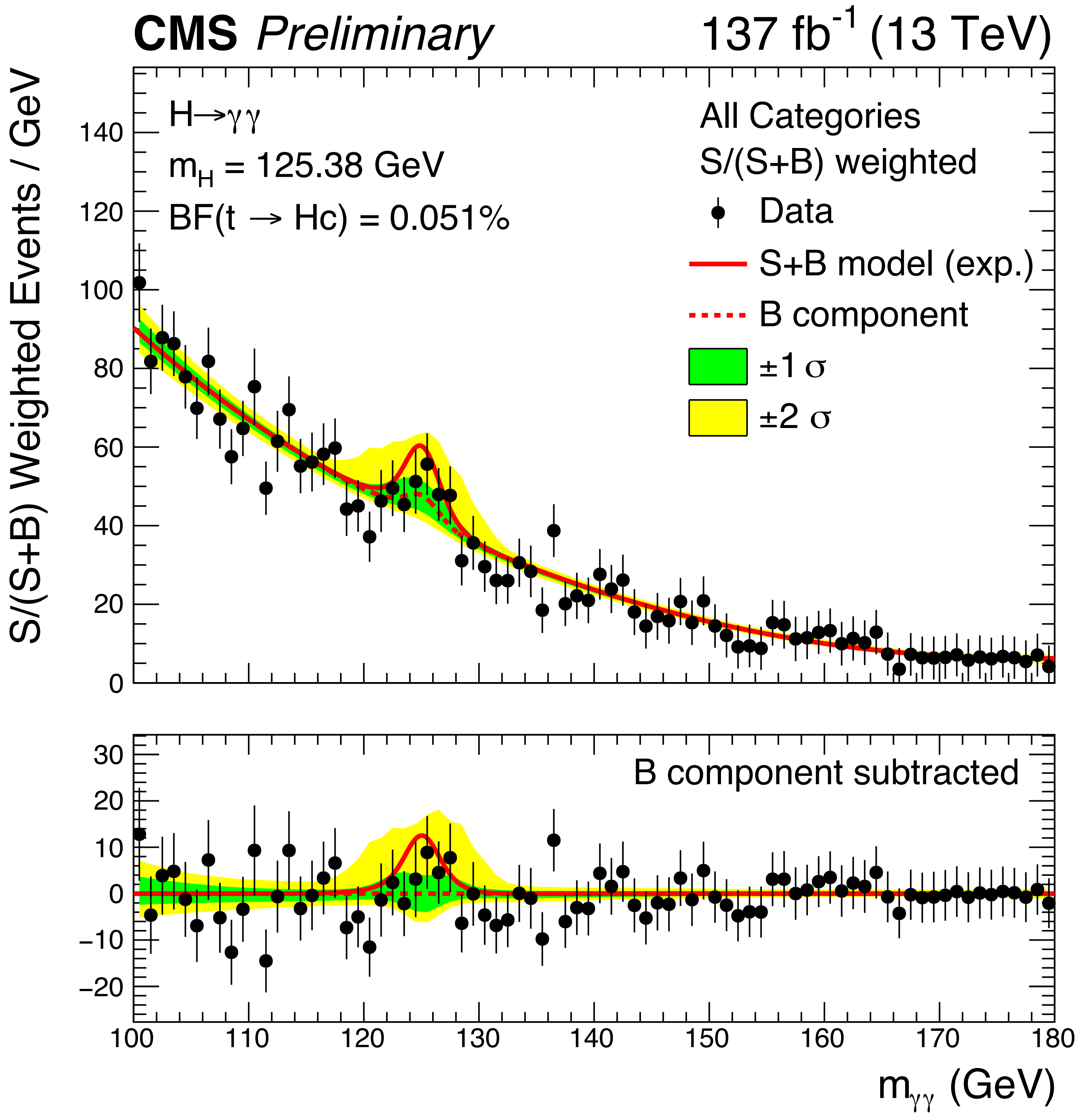
Search for the FCNC *tHq* interaction

NEW

tHq (*q* = *u*,*c*), production & decay, H→γγ [137 fb^{-1}]

(CMS-PAS-TOP-20-007)





Results

Data compatible with absence of signal

95% CL upper limits:

- B(*t*→*Hu*) < 1.9×10^{-4} (exp. 3.1×10^{-4})
- B(*t*→*Hc*) < 7.3×10^{-4} (exp. 5.1×10^{-4})

Dominant uncertainties:

b-tagging, *γ* identification

FCNC *tHq* summary

Searches with 36 fb^{-1}

t→H(γγ)q JHEP 10 (2017) 129

t→H(ML)q Phys. Rev. D 98, 032002

t→H(b$\bar{b}$, ττ)q JHEP 05 (2019) 123

Most stringent bound from *t→H(b$\bar{b}$, ττ)q*

B(*t→Hu*) < 1.2×10^{-3}

B(*t→Hc*) < 1.1×10^{-3}

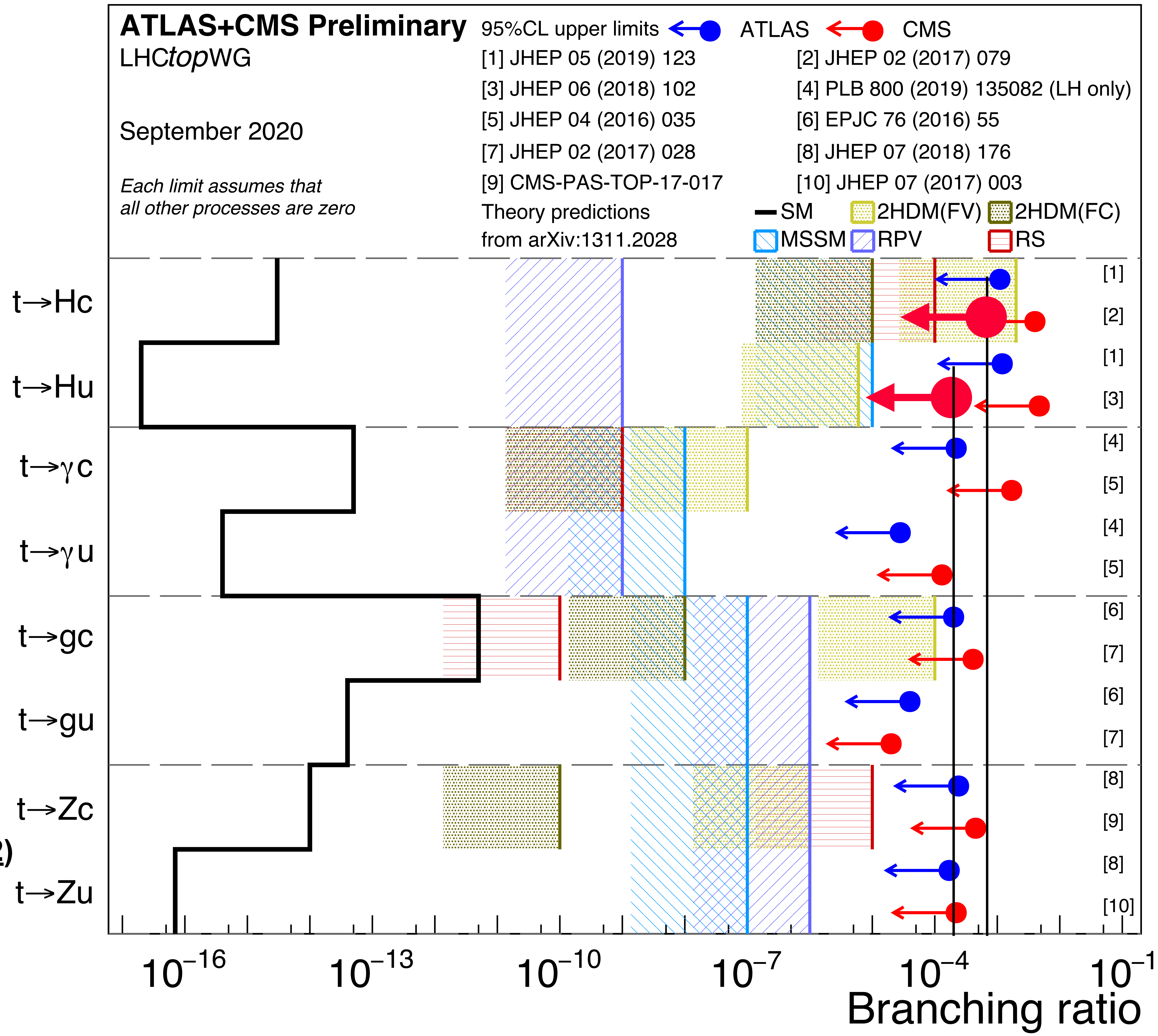
New CMS-PAS-TOP-20-007

B(*t→Hu*) < 1.9×10^{-4}

B(*t→Hc*) < 7.3×10^{-4}

Previous bound from *t→H(b$\bar{b}$)q* (JHEP 06 (2018) 102)

B(*t→Hq*) < 4.7×10^{-3}



Search for CLFV in top production and decay

NEW

tℓℓ'q interaction ℓ = e,μ, q = u,c [137 fb^{-1}]

(CMS-PAS-TOP-19-006)

Motivation: CLFV suppressed in SM with massive neutrinos. LFV underlying mechanism unknown.

Signal process

tℓℓ'q interaction described by EFT operators such as

$$O_{\mathrm{lq}}^{(1)ijkl} = (\bar{\mathrm{l}}_i \gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k \gamma^\mu \mathrm{q}_l)$$

grouped in 3 classes:

$$O_{\mathrm{vector}} = O_{\mathrm{lq}} + O_{\mathrm{lu}} + O_{\mathrm{eq}} + O_{\mathrm{eu}}$$

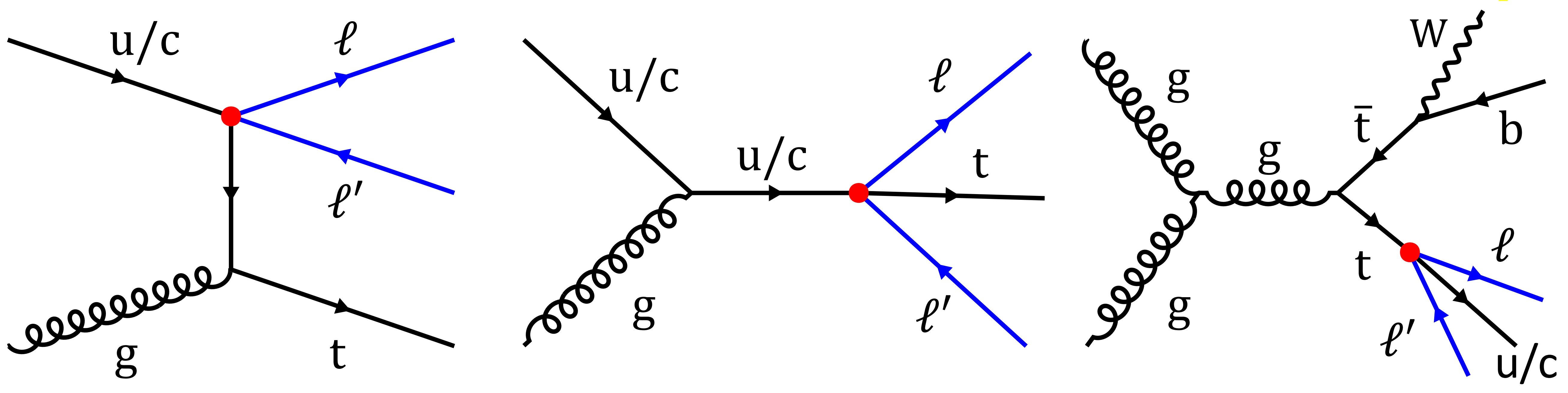
$$O_{\mathrm{scalar}} = O_{\mathrm{lequ}}^{(1)}$$

$$O_{\mathrm{tensor}} = O_{\mathrm{lequ}}^{(3)}$$

No SM interference

q = *u*, *c* considered separately

EFT vertex in both single top production and $t\bar{t}$ decay



Signature / SR

Always one hadronic top decay

2ℓOS (1*e*, 1*μ*), 1 *b*-jet

Backgrounds

t$\bar{t}$ (90%), *tW*

modelled with MC events

Search for CLFV in top production and decay

NEW

tℓℓ'q interaction ℓ = e,μ, q = u,c **[137 fb^{-1}]**

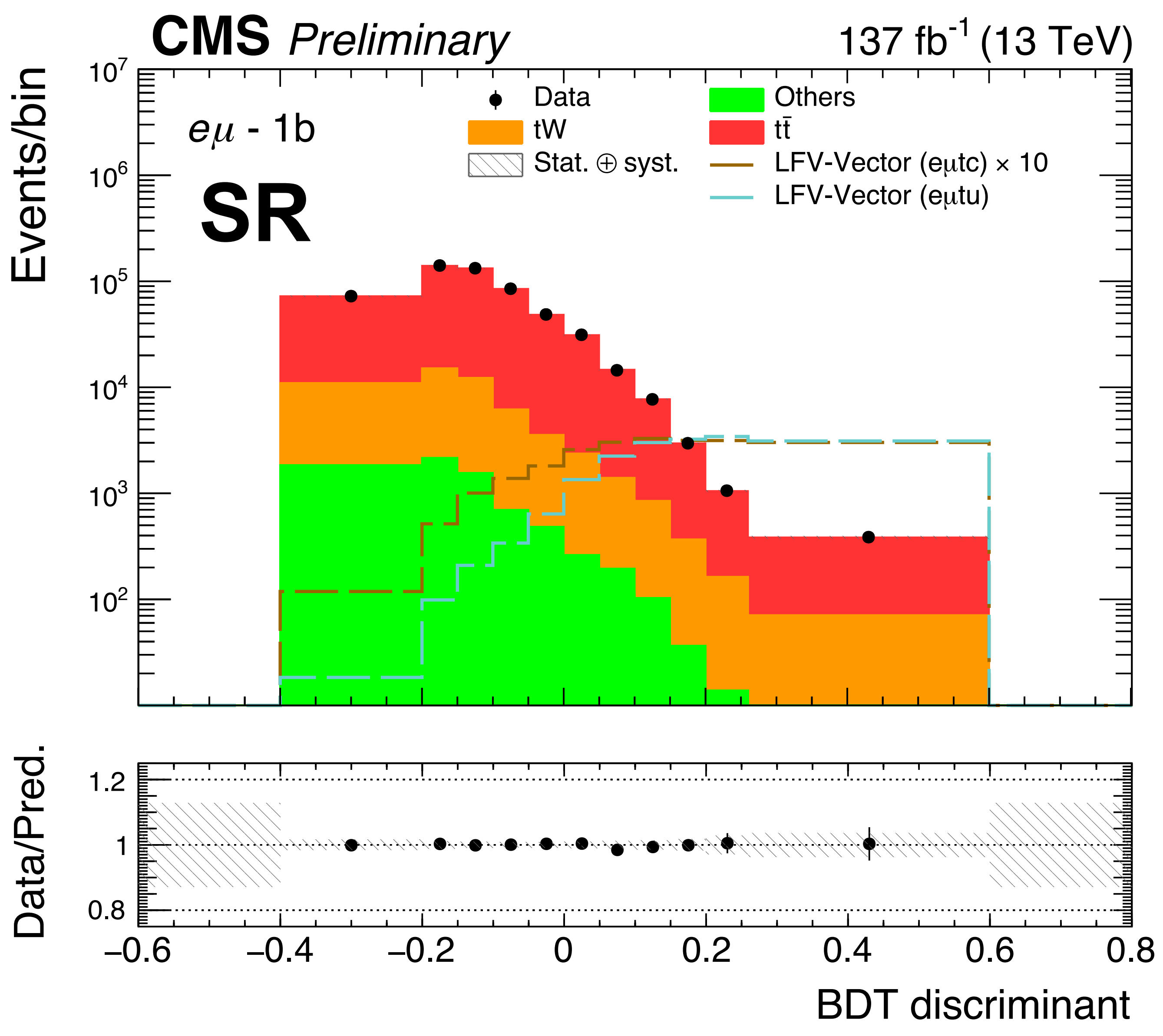
(CMS-PAS-TOP-19-006)

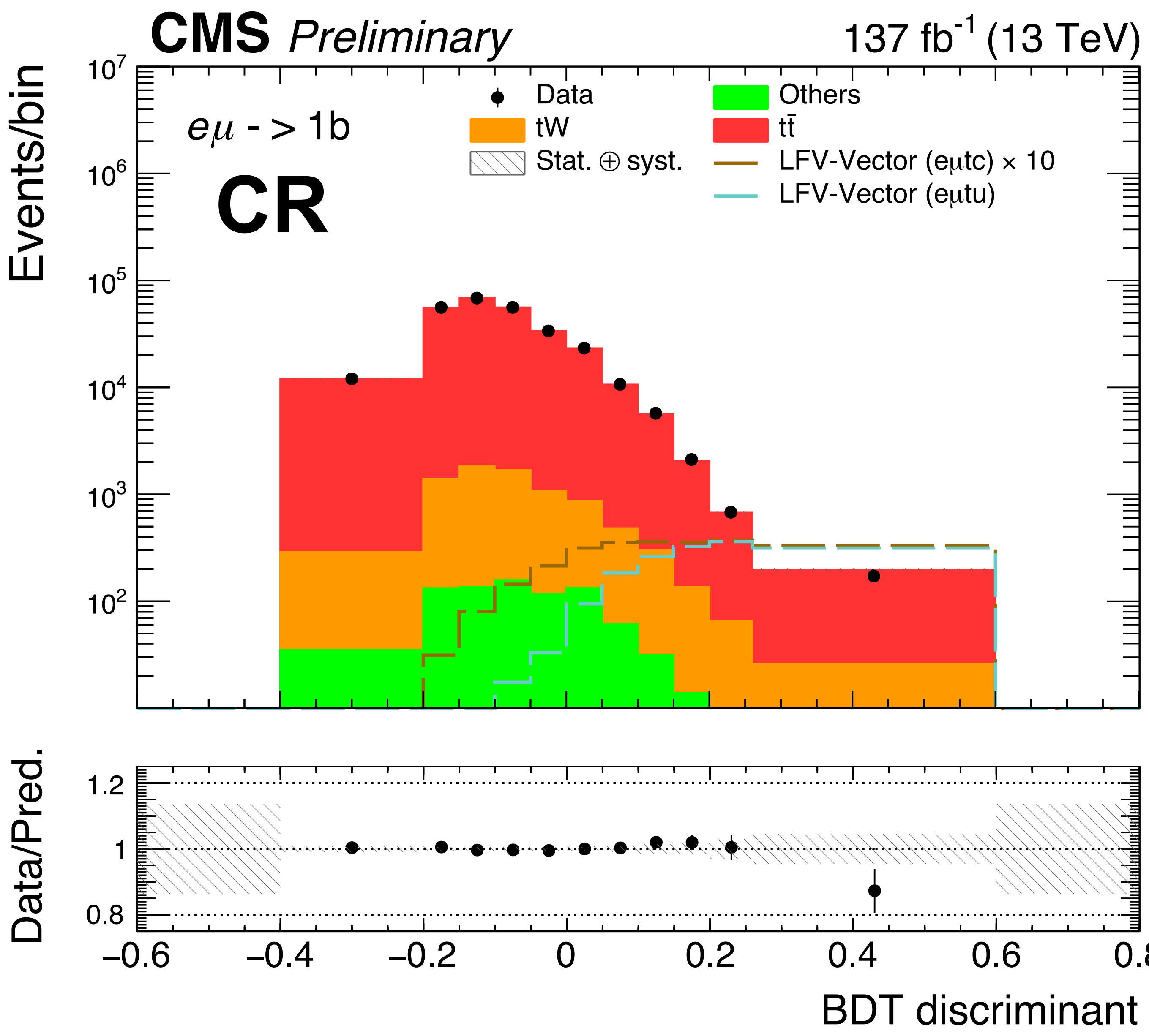
Strategy

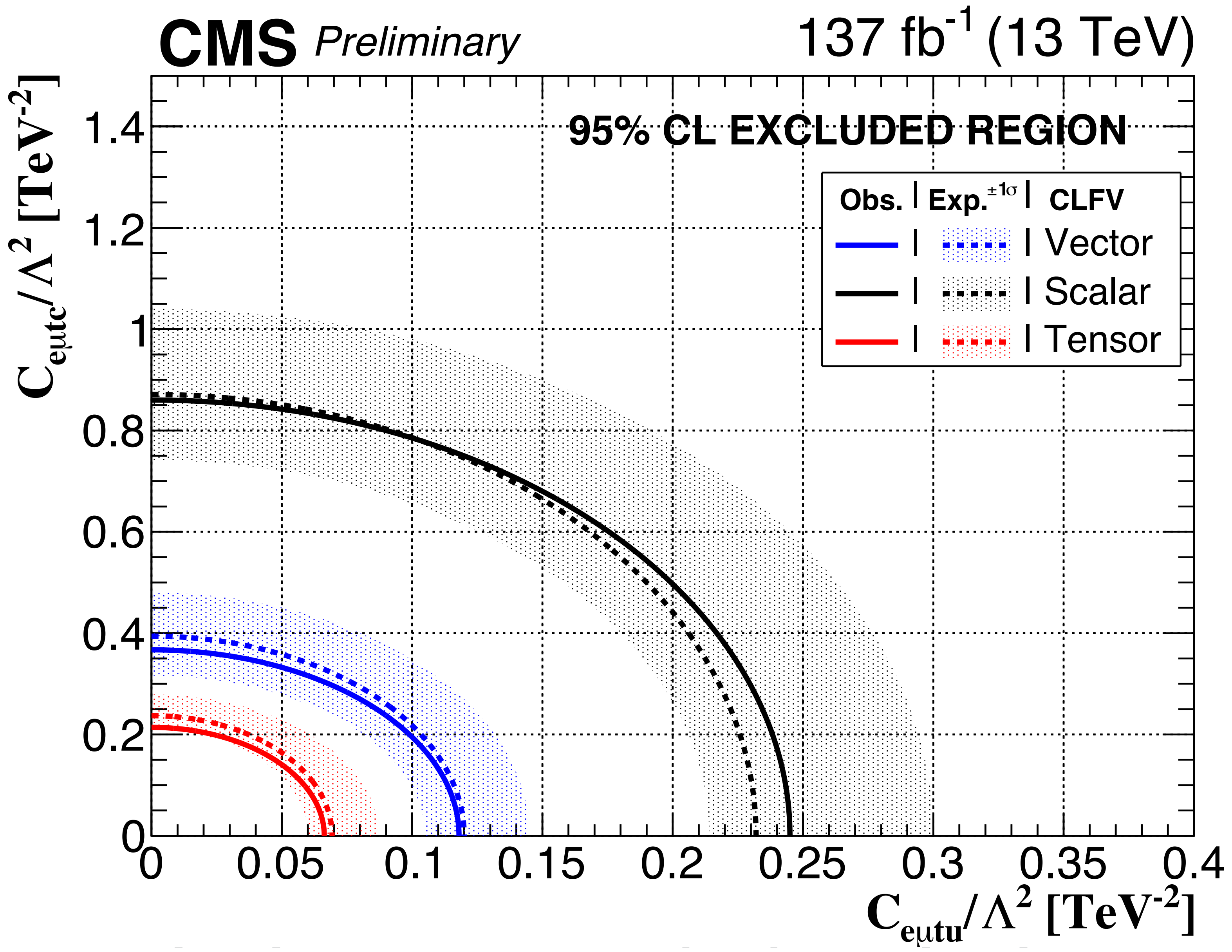
One BDT trained in SR for all categories

BDT applied also in CR (2 *b*-jets)

SR+CR BDT shape fit for one operator at a time







Results

Data consistent with SM expectation

Upper limits set on the Wilson coefficients

Dominant uncertainty: *b*-tagging

Nikhef

CLFV in top processes

$t\ell\ell'q$ interaction $\ell = e,\mu$, $q = u,c$ [137 fb^{-1}]

(CMS-PAS-TOP-19-006)

Results

Limits on the Wilson coefficients translate into

$B(t \to e\mu\ u/c)_{scalar} < 0.07 / 0.89 \times 10^{-6}$

$B(t \to e\mu\ u/c)_{vector} < 0.14 / 1.3 \times 10^{-6}$

$B(t \to e\mu\ u/c)_{tensor} < 0.25 / 2.6 \times 10^{-6}$

to be compared with previous ATLAS result

$B(t \to e\mu q) < 6.6 \times 10^{-6}$

$t\ell\ell'q$ interaction $\ell = e,\mu$, $q = u,c$ [79.8 fb^{-1}]

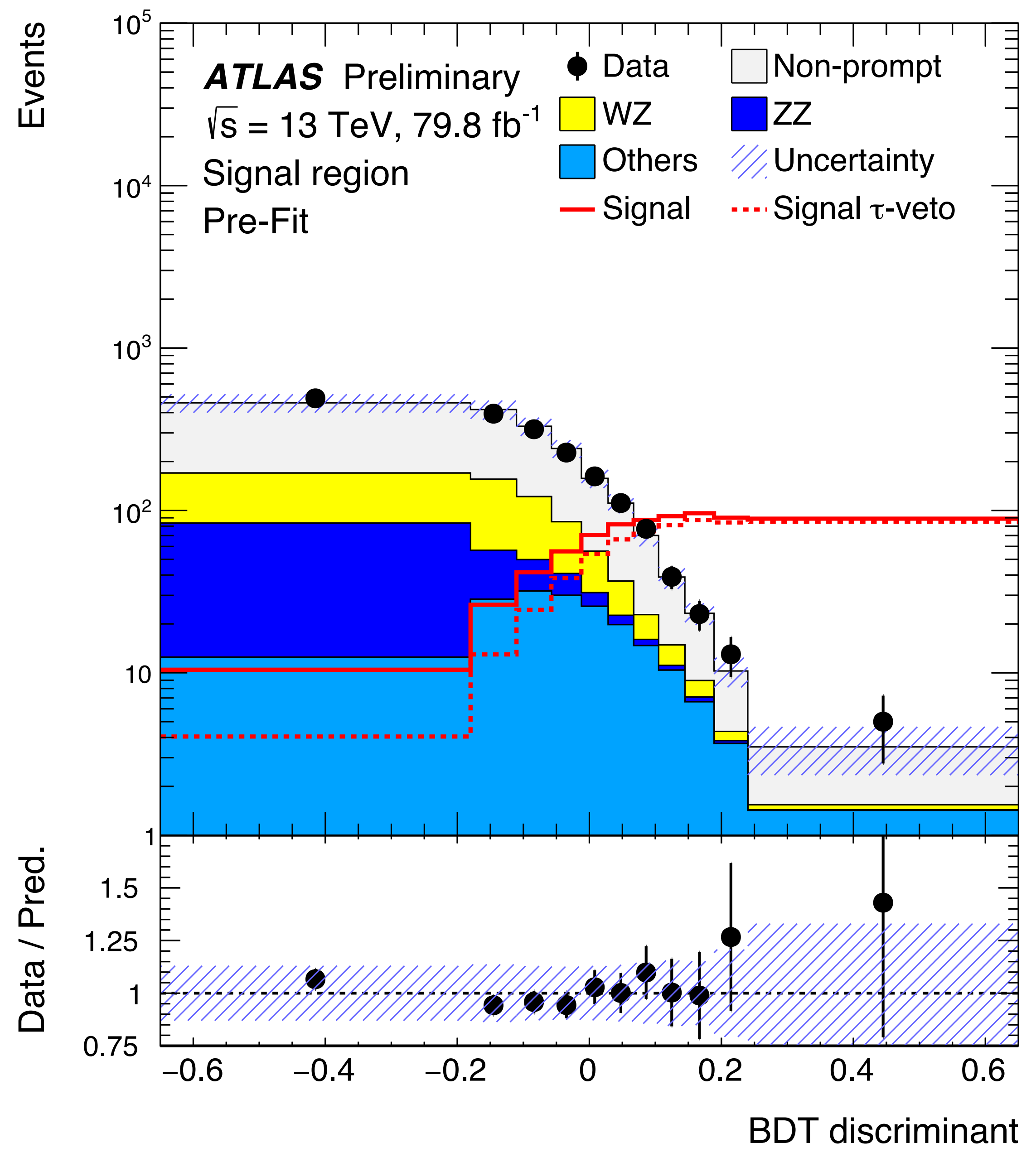
(ATLAS-CONF-2018-044)

Remarks

Upper limit on inclusive process

Decay only, 3ℓ final state

Different EFT basis, no EFT interpretation



Summary

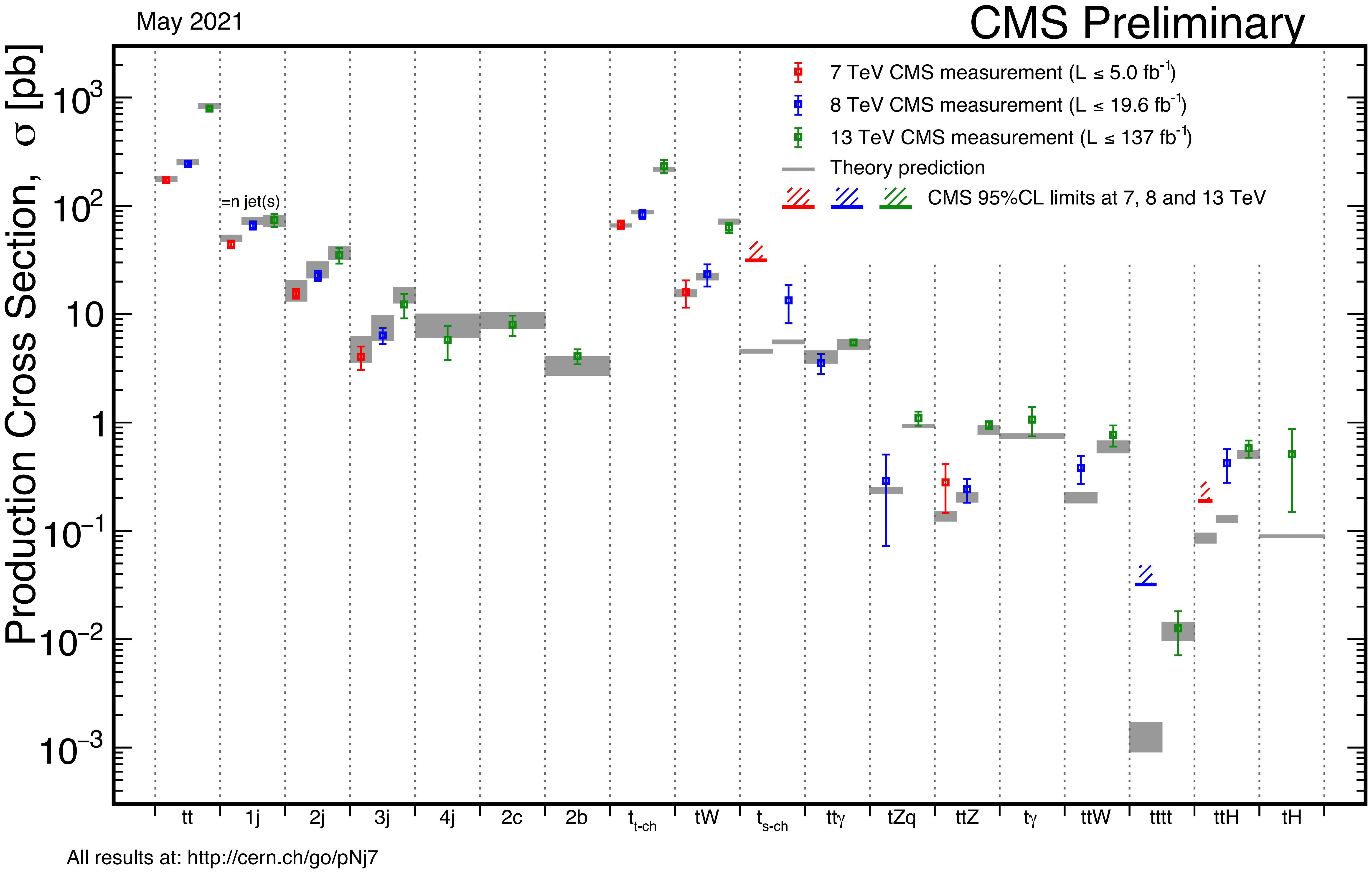
New results in the investigation of SM rare top processes:

- $t\bar{t}t\bar{t}$ evidence
- tZq differential measurement
- $t\gamma$ evidence

Still to do: *tH*, *tWZ*

Top processes as fertile ground for BSM searches:

- FCNC
- CLFV
- LFU (*previous talk by Svan Menke*)



BACKUP

$t\bar{t}t\bar{t}$ 2ℓSS and ML

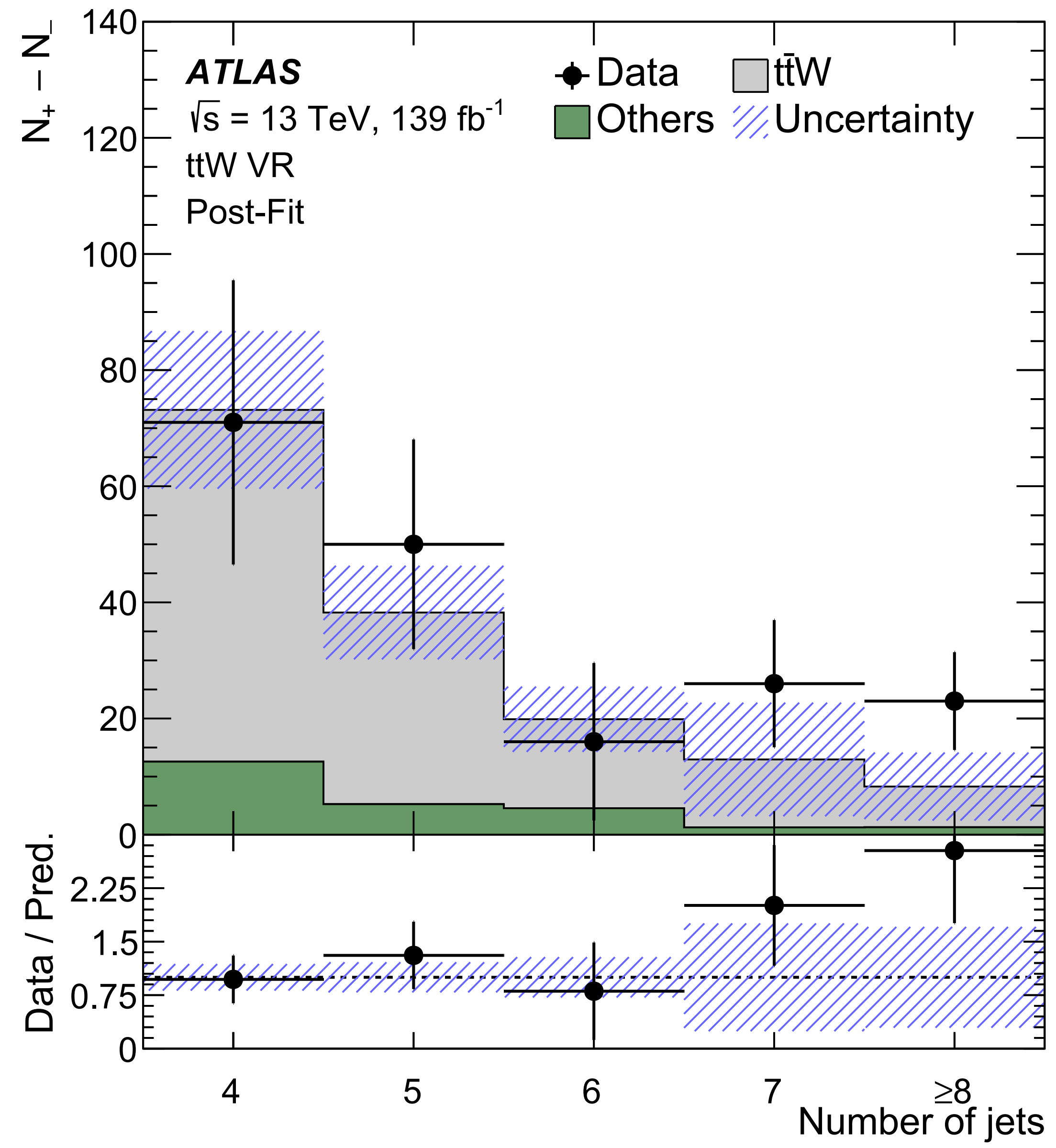
First evidence: 4.3σ obs. (2.4σ exp.)

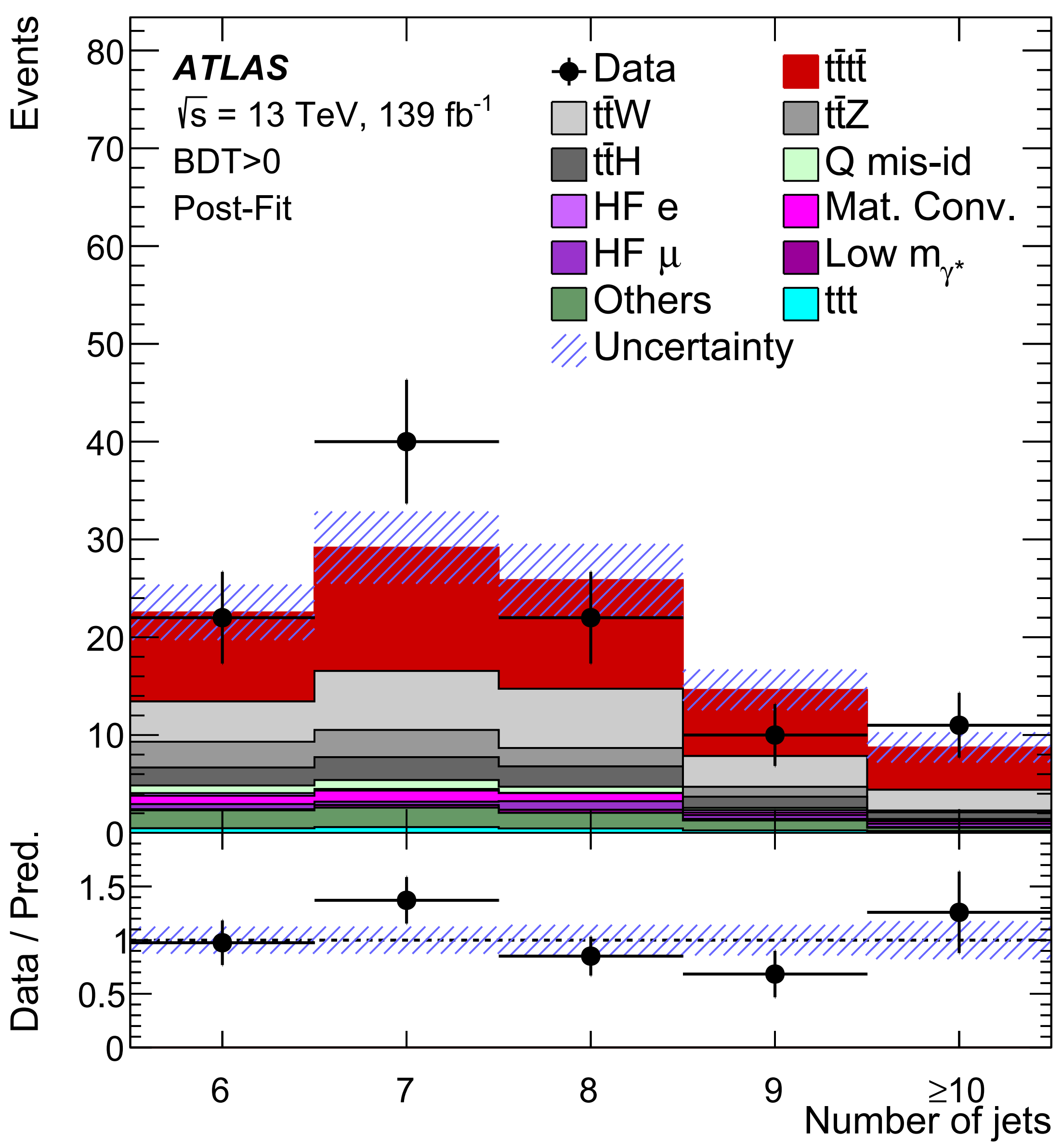
(Eur. Phys. J. C (2020) 80:1085)

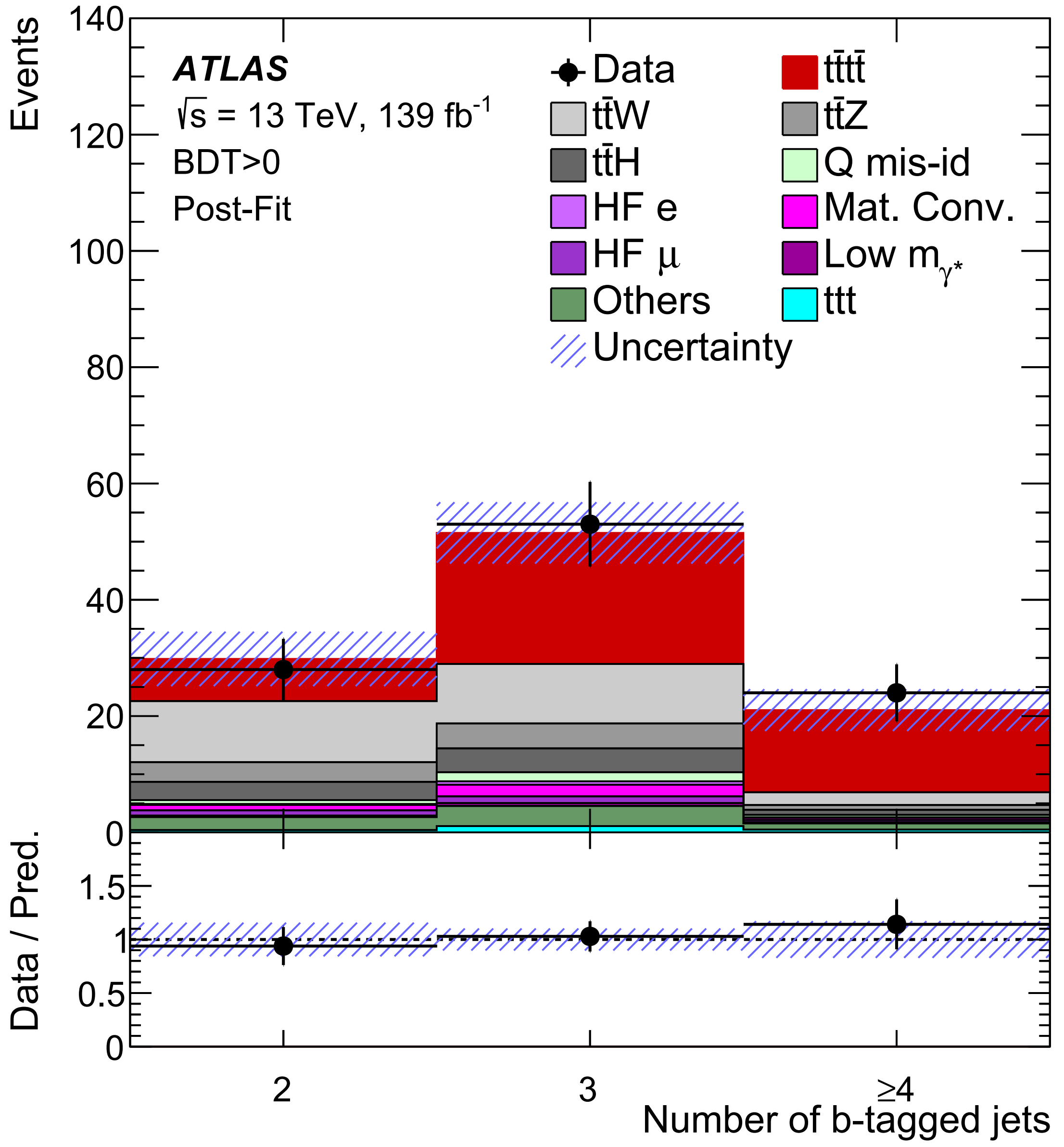
Region	Channel	N_j	N_b	Other requirements
SR	2LSS/3L	≥ 6	≥ 2	$H_T > 500$
CR Conv.	$e^{\pm}e^{\pm} \| \| e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1 \text{ GeV}]$
				$200 < H_T < 500$ GeV
CR HF e	$eee \| \| ee\mu$	–	$= 1$	$100 < H_T < 250$ GeV
CR HF μ	$e\mu\mu \| \| \mu\mu\mu$	–	$= 1$	$100 < H_T < 250$ GeV
CR ttW	$e^{\pm}\mu^{\pm} \| \| \mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1 \text{ GeV}]$, $\|\eta(e)\| < 1.5$
				For $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$
				For $N_b \geq 3$, $H_T < 500$ GeV

Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m(\gamma^*)}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

$t\bar{t}W$ Validation Region







$t\bar{t}t\bar{t}$

First evidence: 4.3σ obs. (2.4σ exp.) [139 fb^{-1}]

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Full-Run 2 search: 1.9σ obs. (1.0σ exp.) [139 fb^{-1}]

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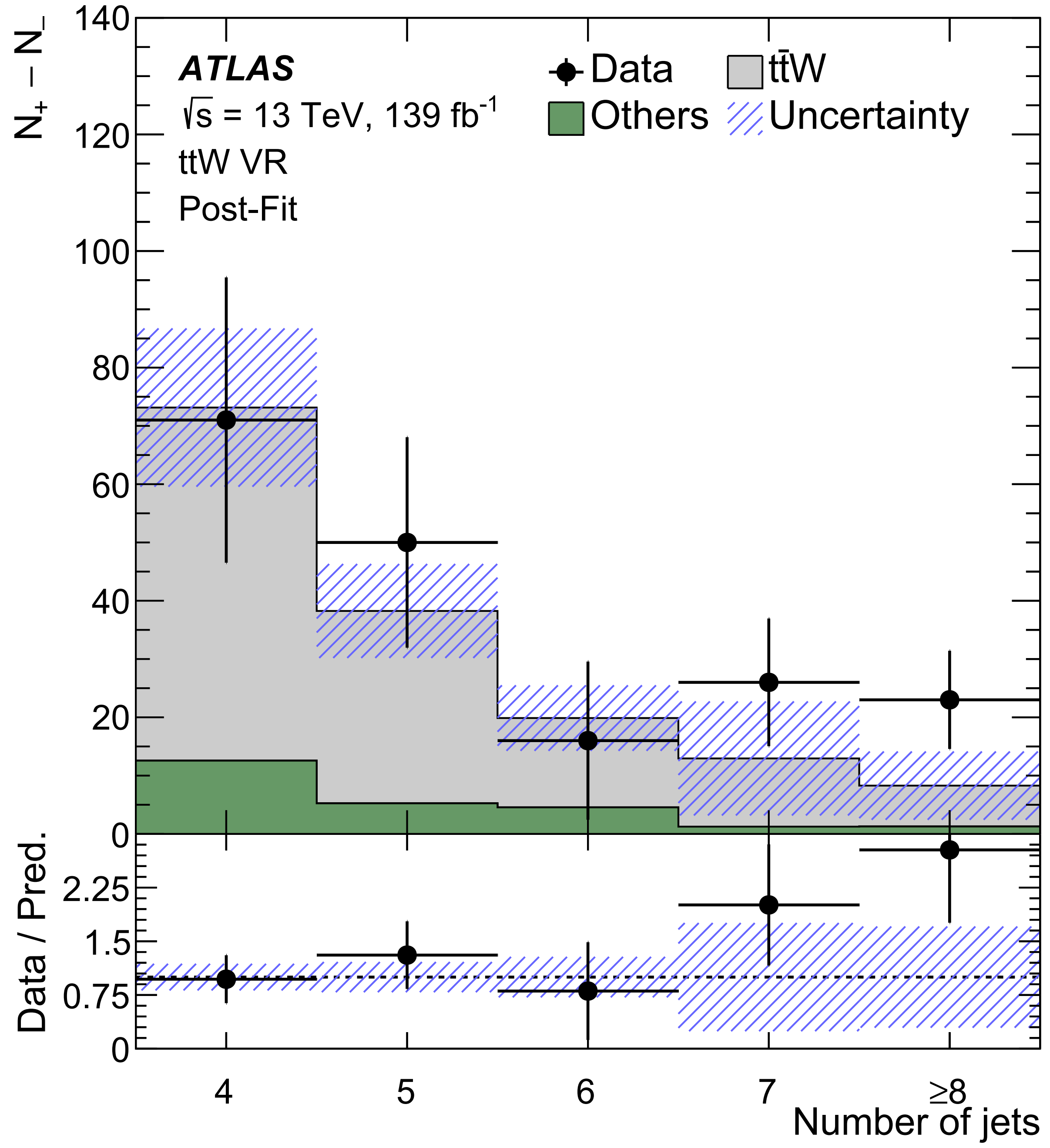
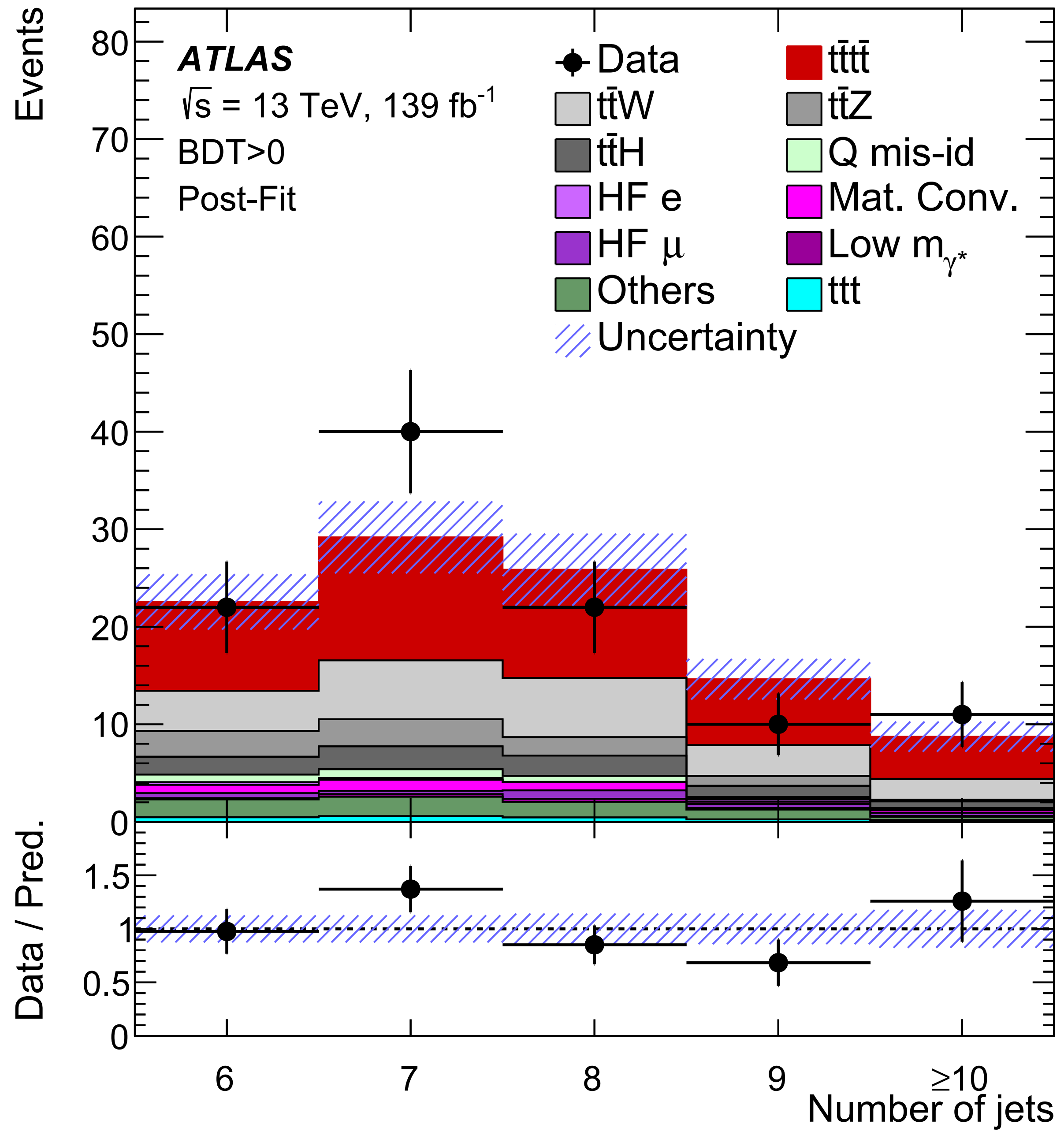
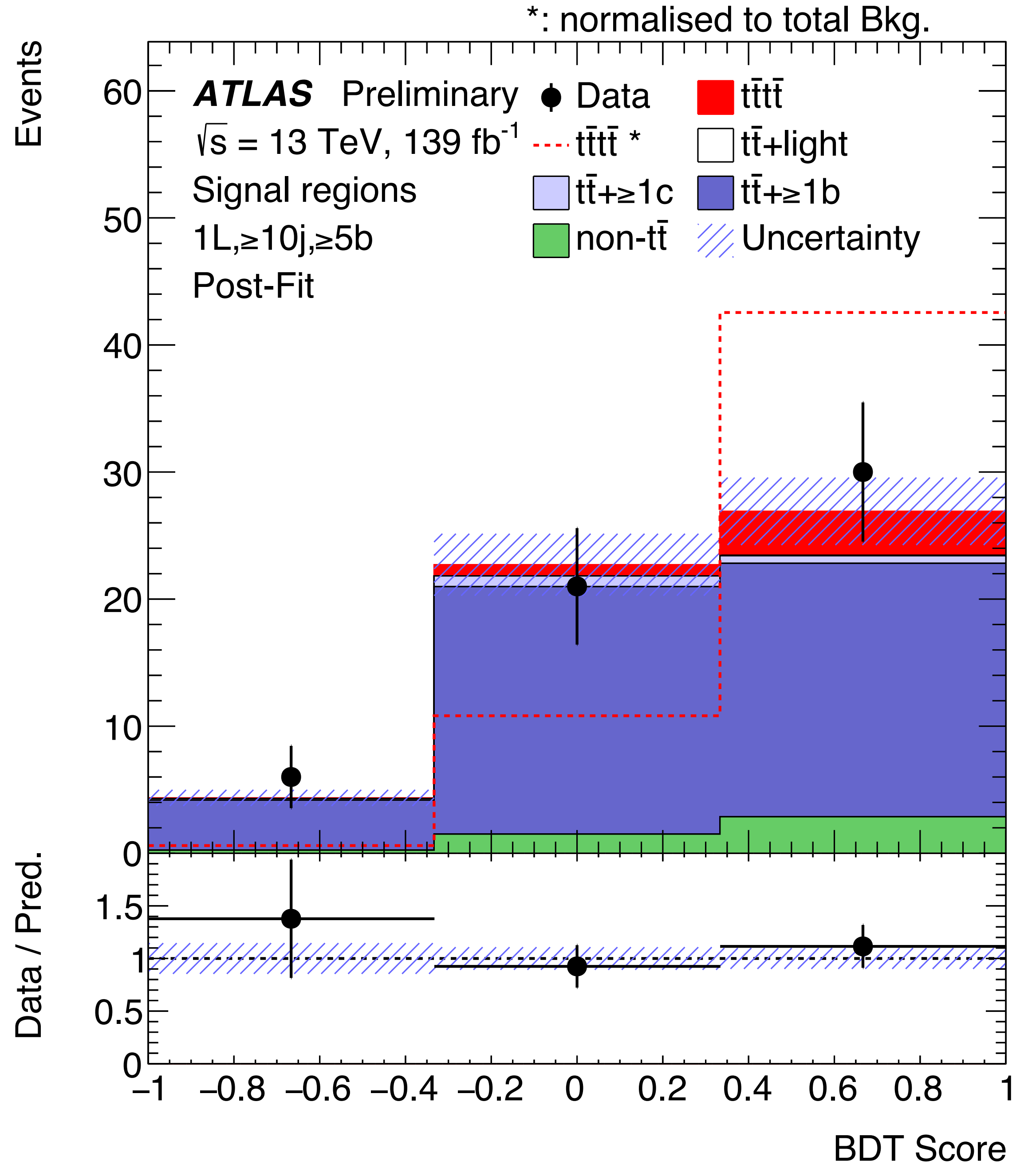
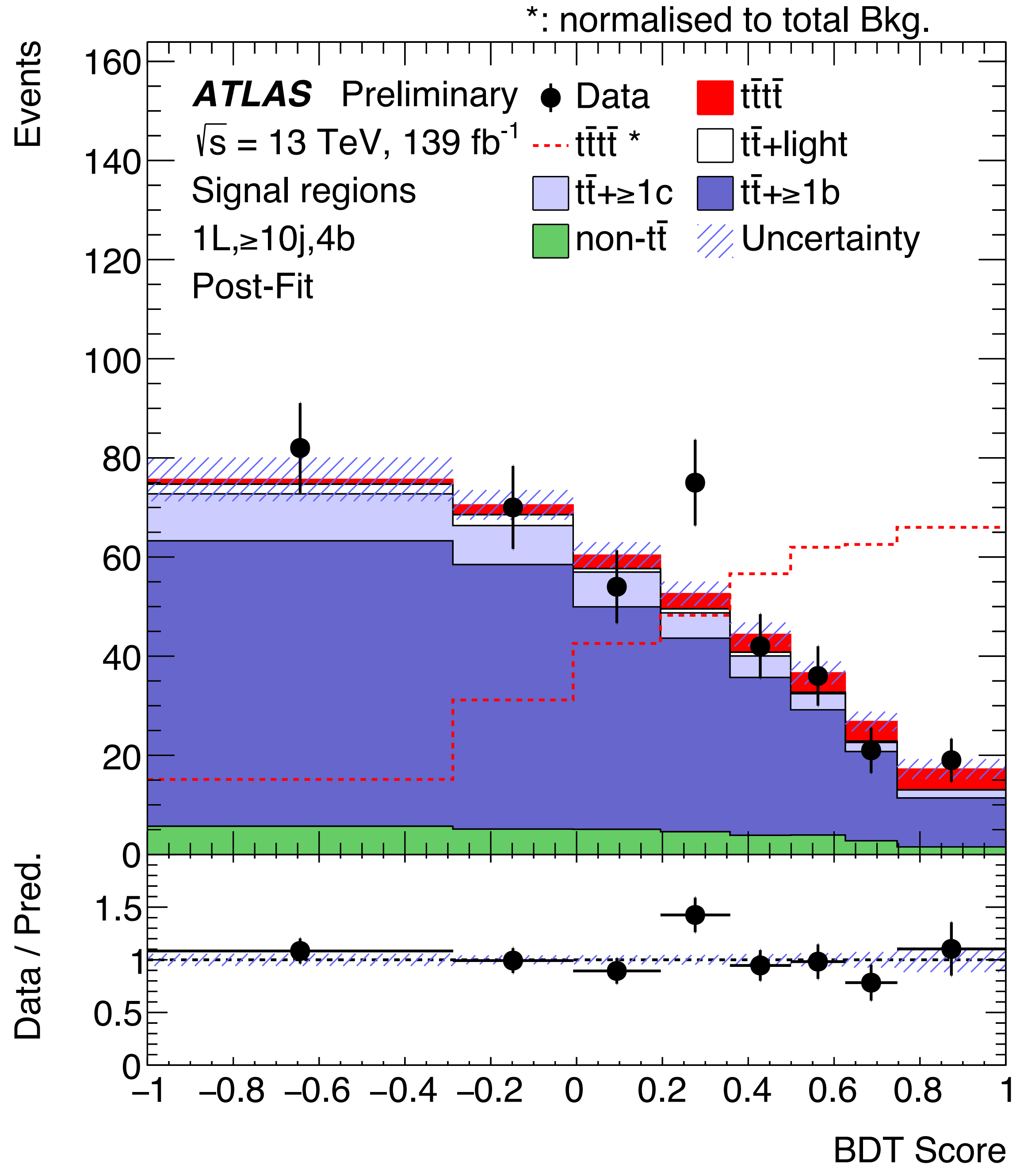
$\mu_{1\ell} = 2.9^{+1.8}_{-1.5}$

$\mu_{2\ell OS} = 1.3^{+1.7}_{-1.5}$





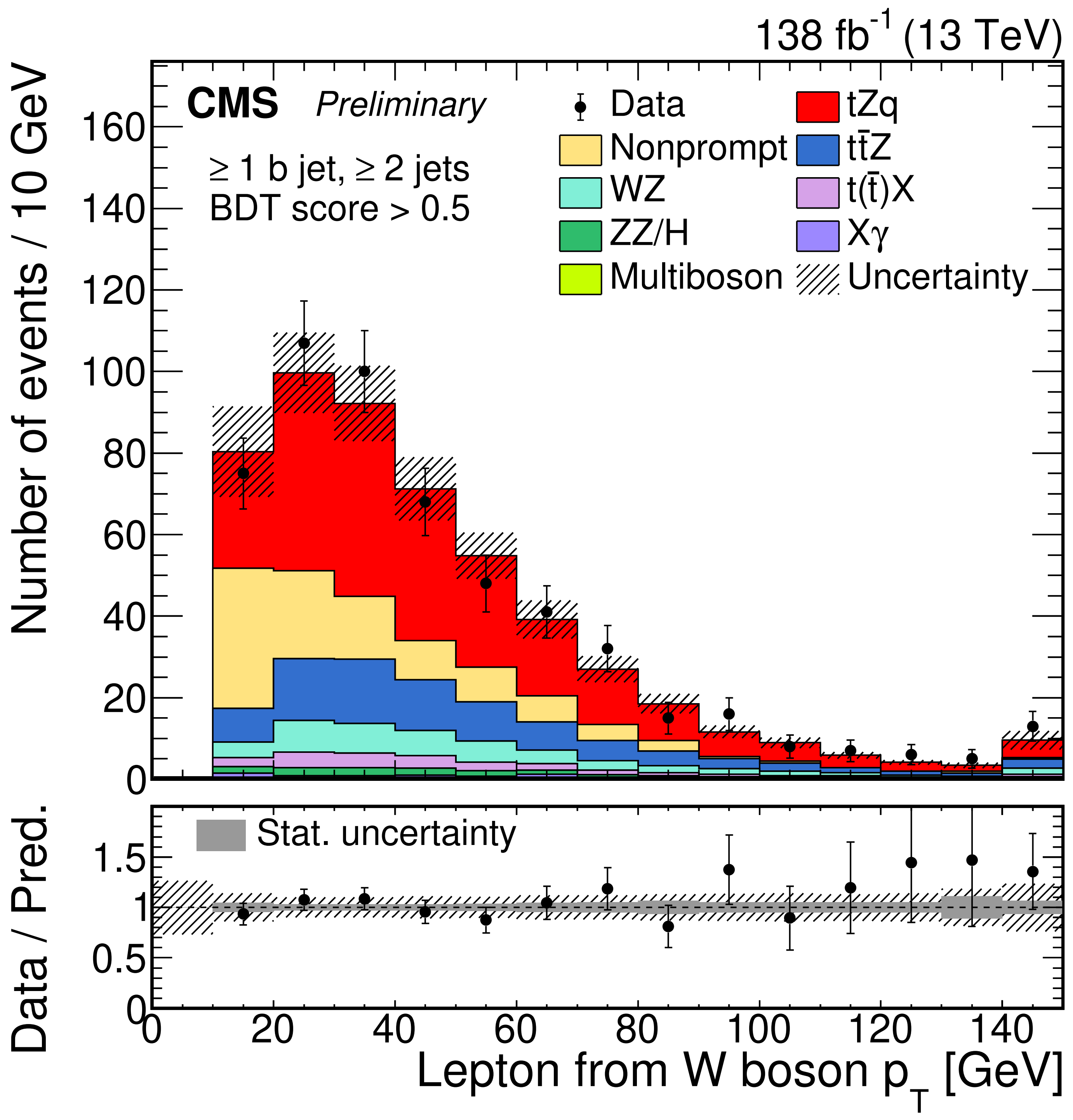


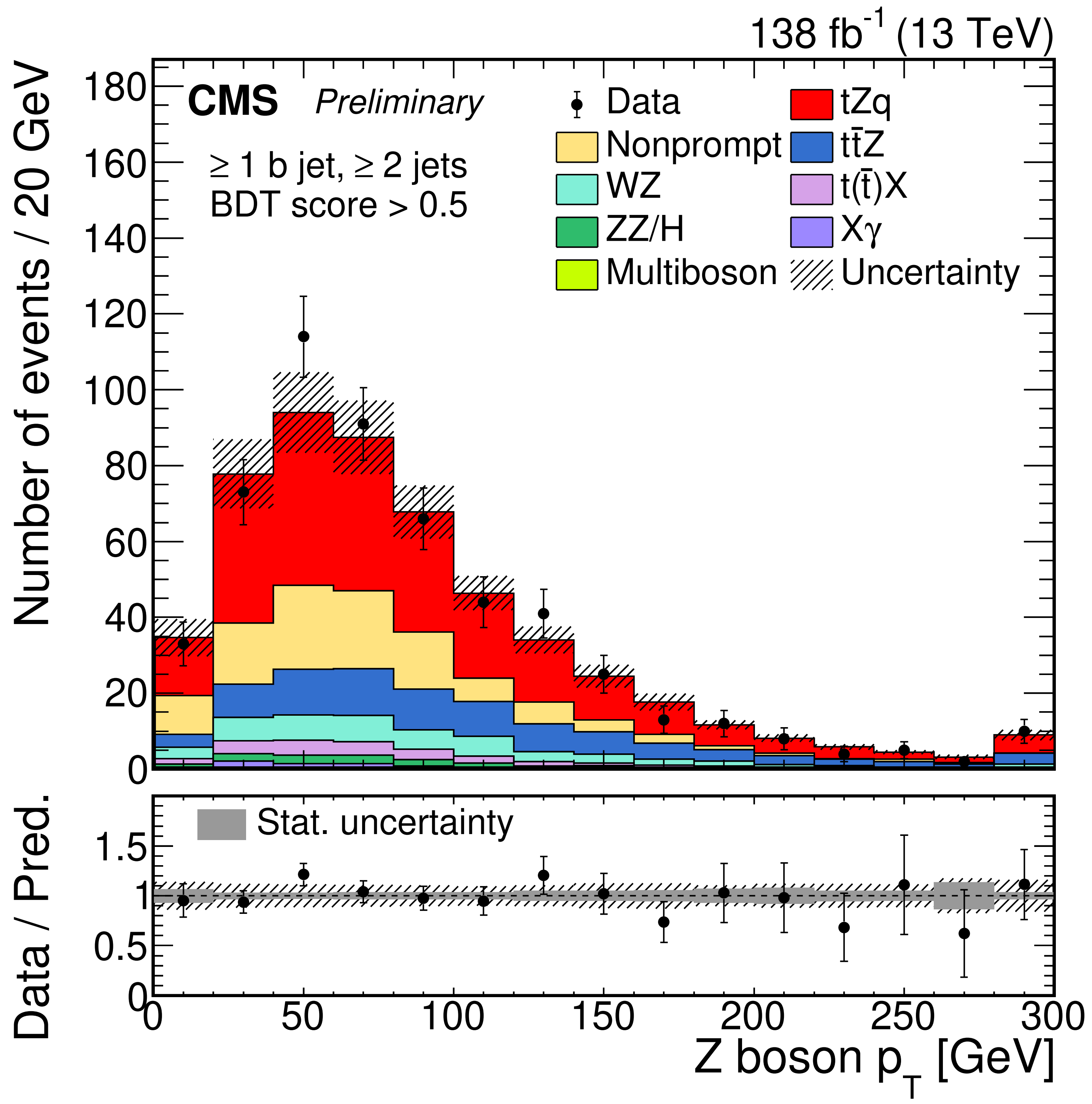


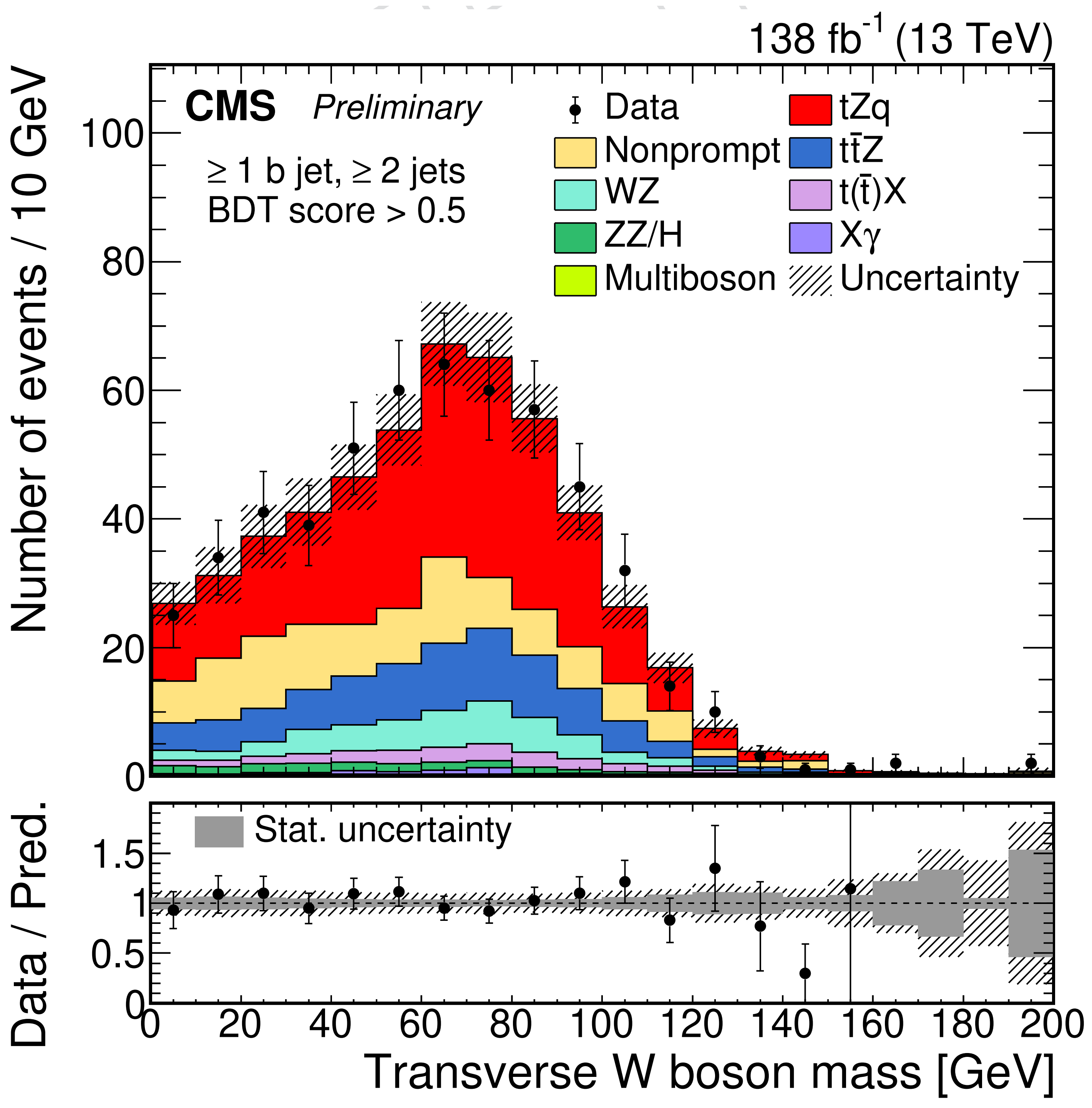
tZq differential

New preliminary result [138 fb^{-1}]

(CMS-PAS-TOP-20-010)







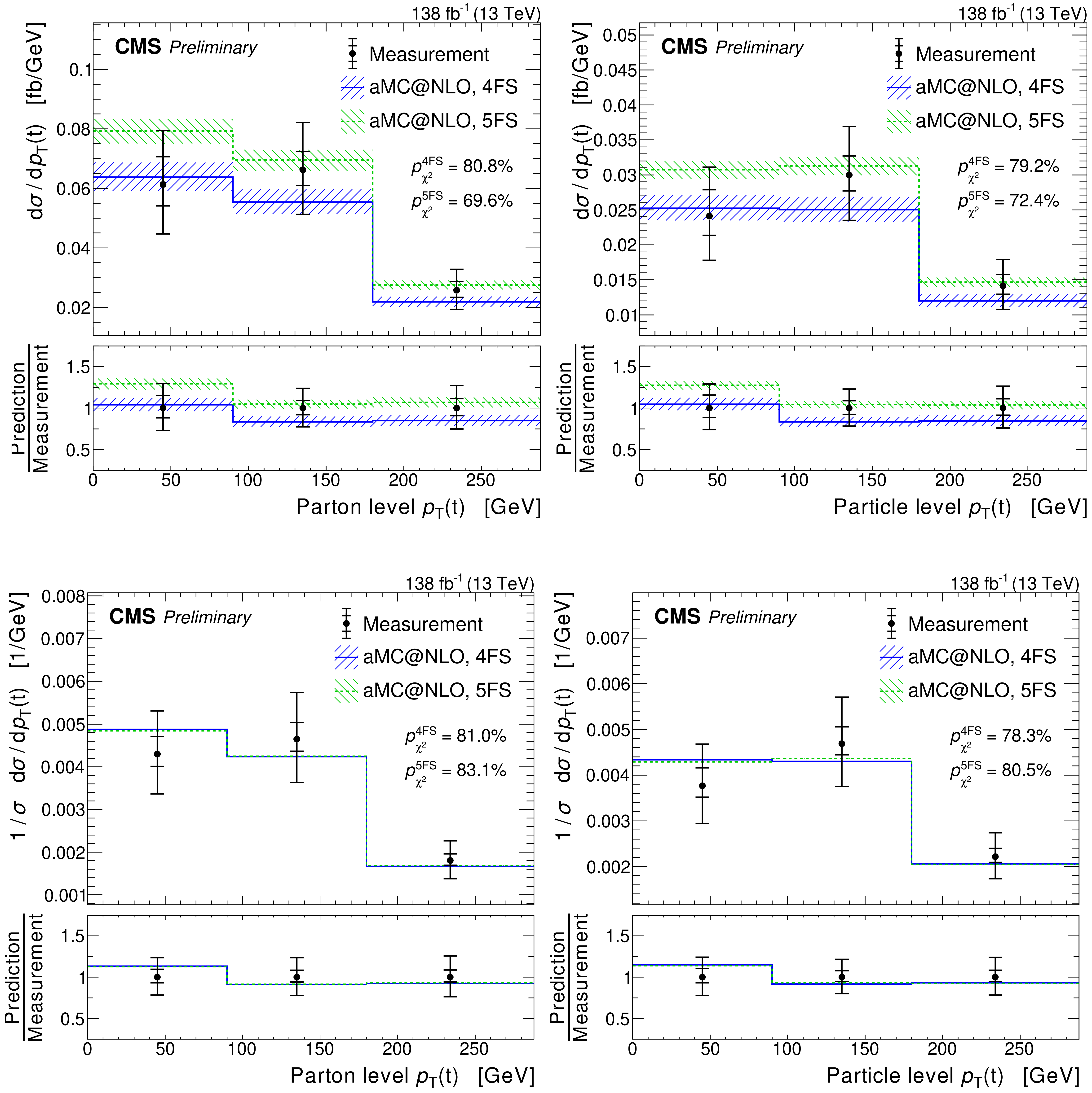
tZq differential

New preliminary result [138 fb^{-1}]

(CMS-PAS-TOP-20-010)

χ^2 test p-values

Observable	parton level absolute 4FS	parton level absolute 5FS	parton level normalized 4FS	parton level normalized 5FS	particle level absolute 4FS	particle level absolute 5FS	particle level normalized 4FS	particle level normalized 5FS
$p_T(Z)$	97.0	81.8	98.9	97.5	97.1	87.1	99.1	98.6
$\Delta\phi(\ell,\ell')$	70.1	47.2	61.1	56.0	73.2	58.8	64.8	65.8
$p_T(\ell_t)$	95.0	72.0	93.4	91.3	95.4	73.0	94.0	93.3
$m(3\ell)$	6.4	1.8	5.0	4.2	6.7	2.2	3.8	3.4
$p_T(t)$	80.8	69.6	81.0	83.1	79.2	72.4	78.3	80.5
$m(t,Z)$	67.5	49.1	59.8	54.6	68.7	65.2	61.3	71.2
$\cos(\theta^{\star}_{pol})$	82.3	56.0	74.7	78.3	87.5	66.5	83.5	88.4
$p_T(j')$	-	-	-	-	49.7	45.4	40.3	32.8
$\|\eta\|(j')$	-	-	-	-	51.6	30.9	46.2	28.2



Nikhef

tZq differential

New preliminary result [138 fb^{-1}]

(CMS-PAS-TOP-20-010)