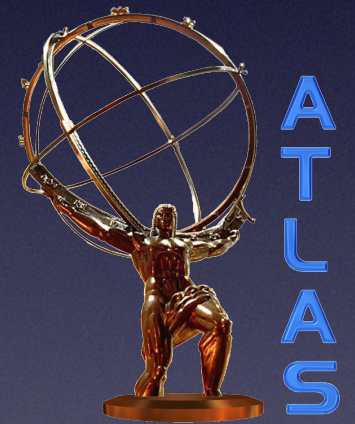


Evidence for Four-Top-Quark Production



Erich W. Varnes
University of Arizona
for the ATLAS Collaboration



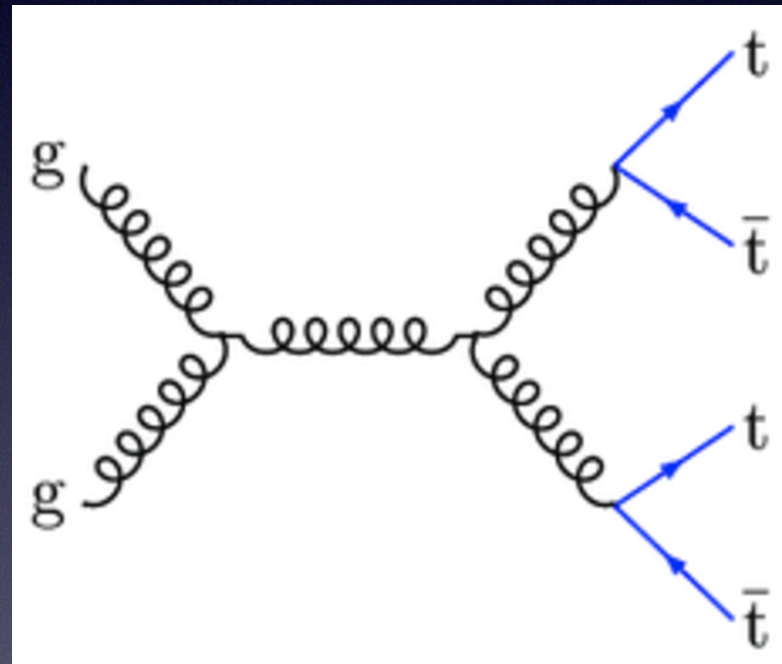
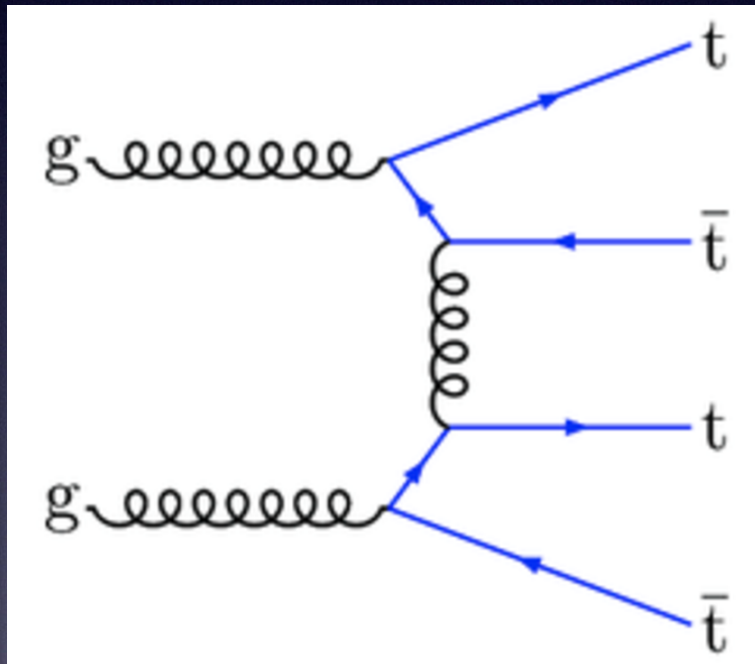
13th International Workshop on Top Quark Physics
September 18, 2020

Four-Top-Quark Production

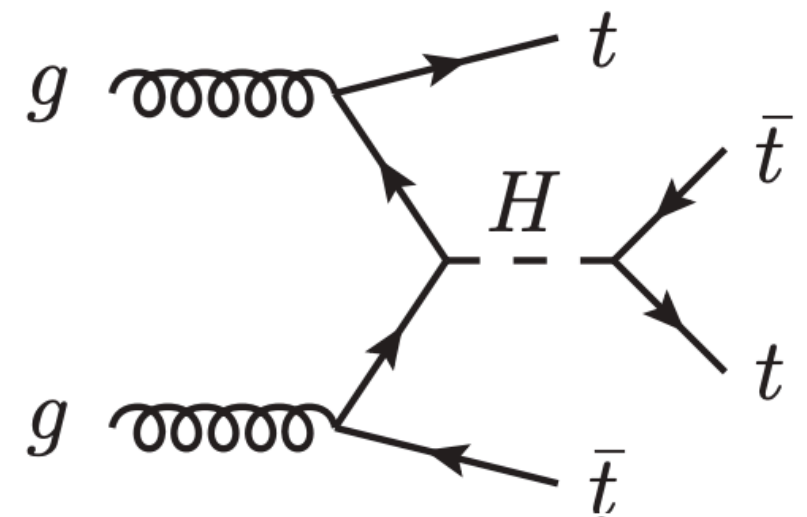
- SM cross section at $\sqrt{s} = 13$ TeV is 12.0 ± 0.24 (scale) fb
 - NLO QCD with EW corrections

[JHEP 02 \(2018\) 031](#)

Leading SM diagrams



Higgs Yukawa contribution

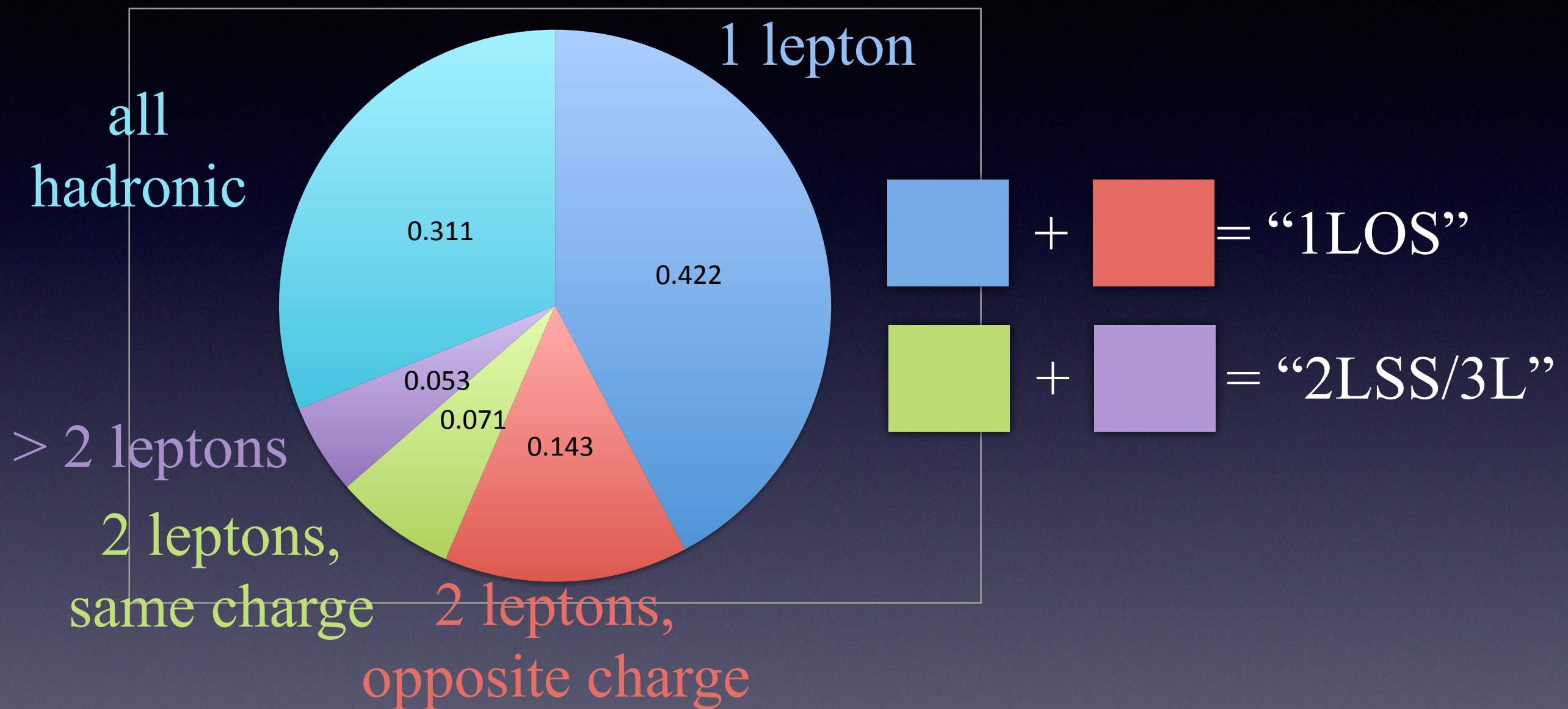


[Phys. Rev. D 95, 053004 \(2017\)](#)

- Not yet observed
- BSM effects can increase cross section
 - e.g. gluino pair production, 2-Higgs-doublet models

Four-Top-Quark Decay

- Final state is determined by W decays

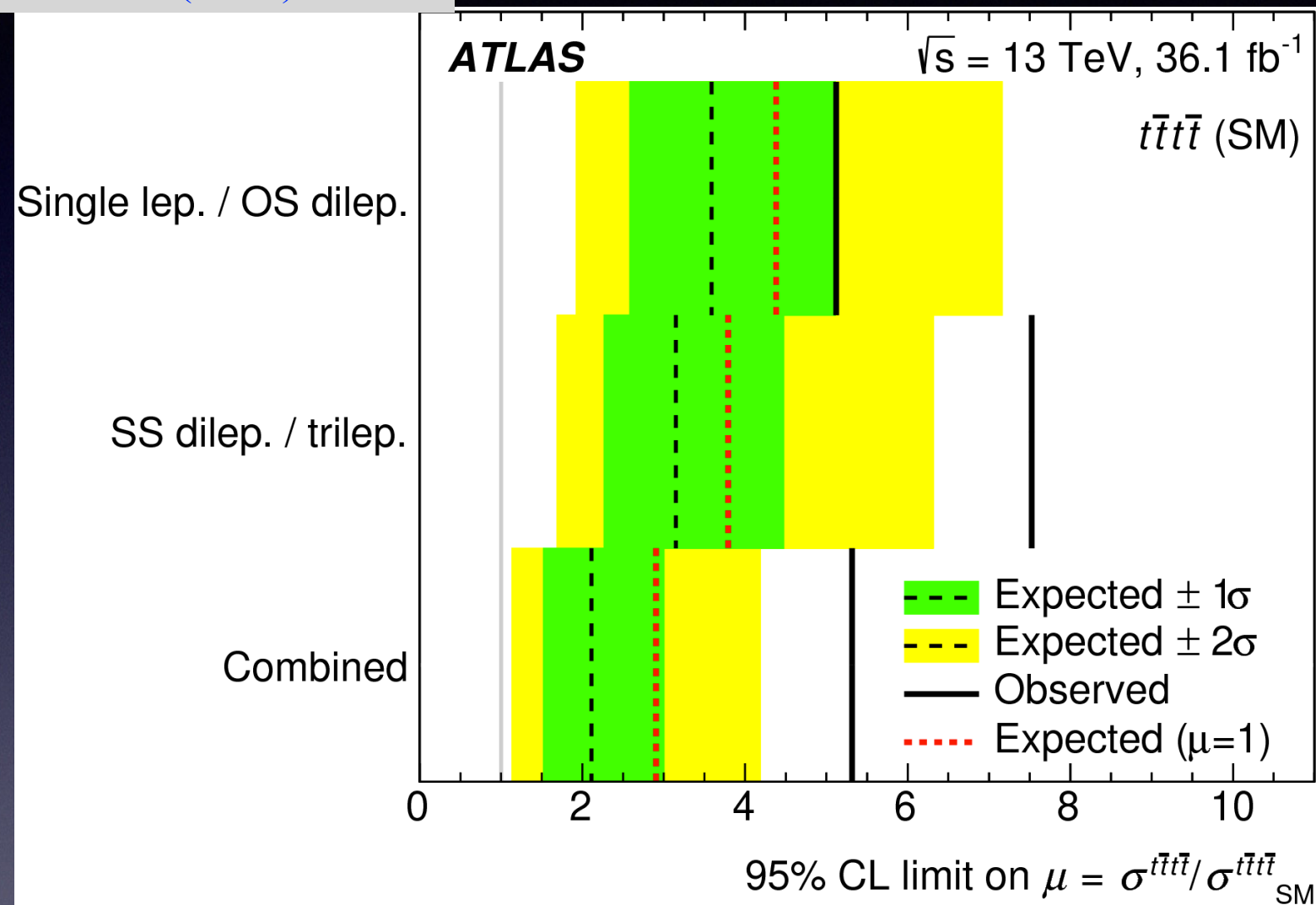


- 2LSS/3L has highest sensitivity due to strong background suppression

Previous ATLAS Search

- 36 fb⁻¹ sample using 1LOS plus 2LSS/3L channels

[Phys. Rev. D 99 \(2019\) 052009](#)

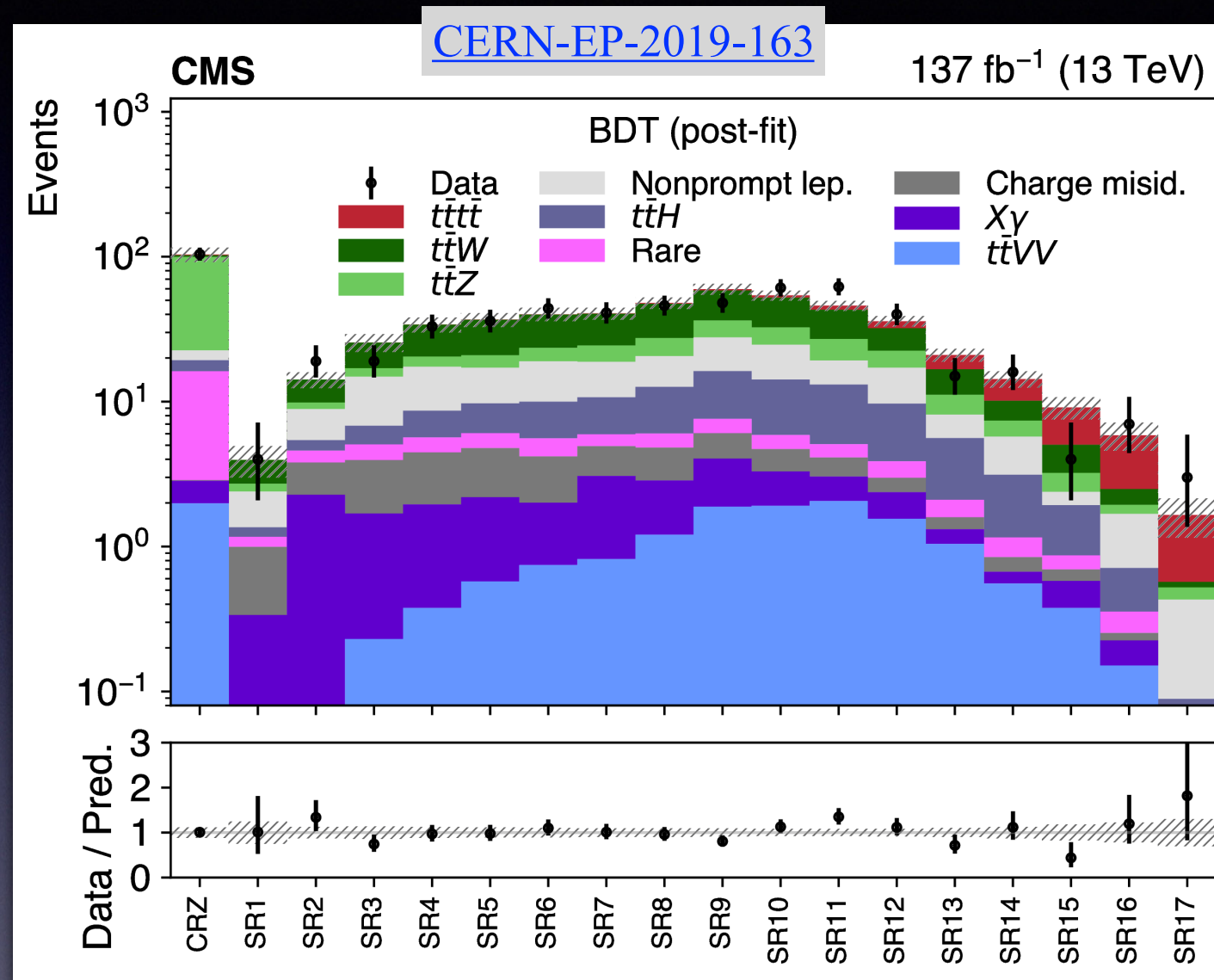


$$\sigma_{t\bar{t}t\bar{t}} = 28.5^{+12}_{-11} \text{ fb}$$

Significance: 2.8 s.d. (1.0 s.d. expected)

CMS Search

- 137 fb⁻¹ sample using 2LSS/3L channels



see K. Schweiger's talk
for details

$$\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2} \text{ fb}$$

Significance: 2.6 s.d. (2.7 s.d. expected)

Event Selection

- Updated ATLAS search is based upon 2LSS/3L channels in 139 fb⁻¹ of pp collision data at $\sqrt{s} = 13$ TeV [arXiv.2007.14858](https://arxiv.org/abs/2007.14858)
- Signal region selection criteria:

Data Quality

Good run
 ≥ 1 primary vertex

Trigger

Single lepton
($p_T > 20 - 26$ GeV)
Dilepton
($p_T > 8 - 24$ GeV)

Objects

Standard ATLAS e and μ ID
 e charge misID suppressed with BDT
Two same-charge leptons or ≥ 3 leptons
 ≥ 6 $R = 0.4$ anti- k_T jets (≥ 2 b -tagged)

Kinematics

$$H_T \equiv \sum_{\text{jets}, \ell} p_T > 500 \text{ GeV}$$

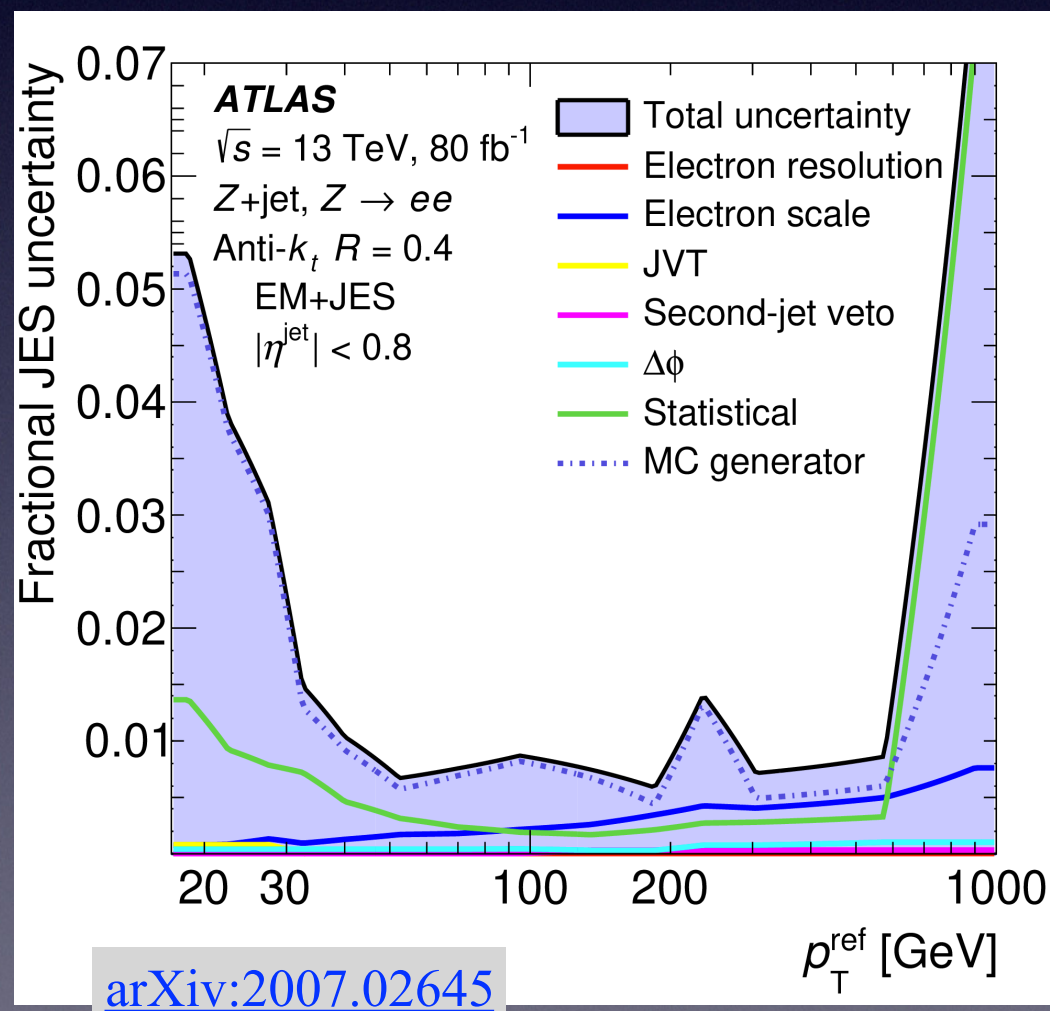
$$\text{Trilepton: } |m_{\ell^+\ell^-} - 91 \text{ GeV}| > 10 \text{ GeV}$$

$$\text{SSee: } m_{ee} > 10 \text{ GeV and } |m_{ee} - 91 \text{ GeV}| > 10 \text{ GeV}$$

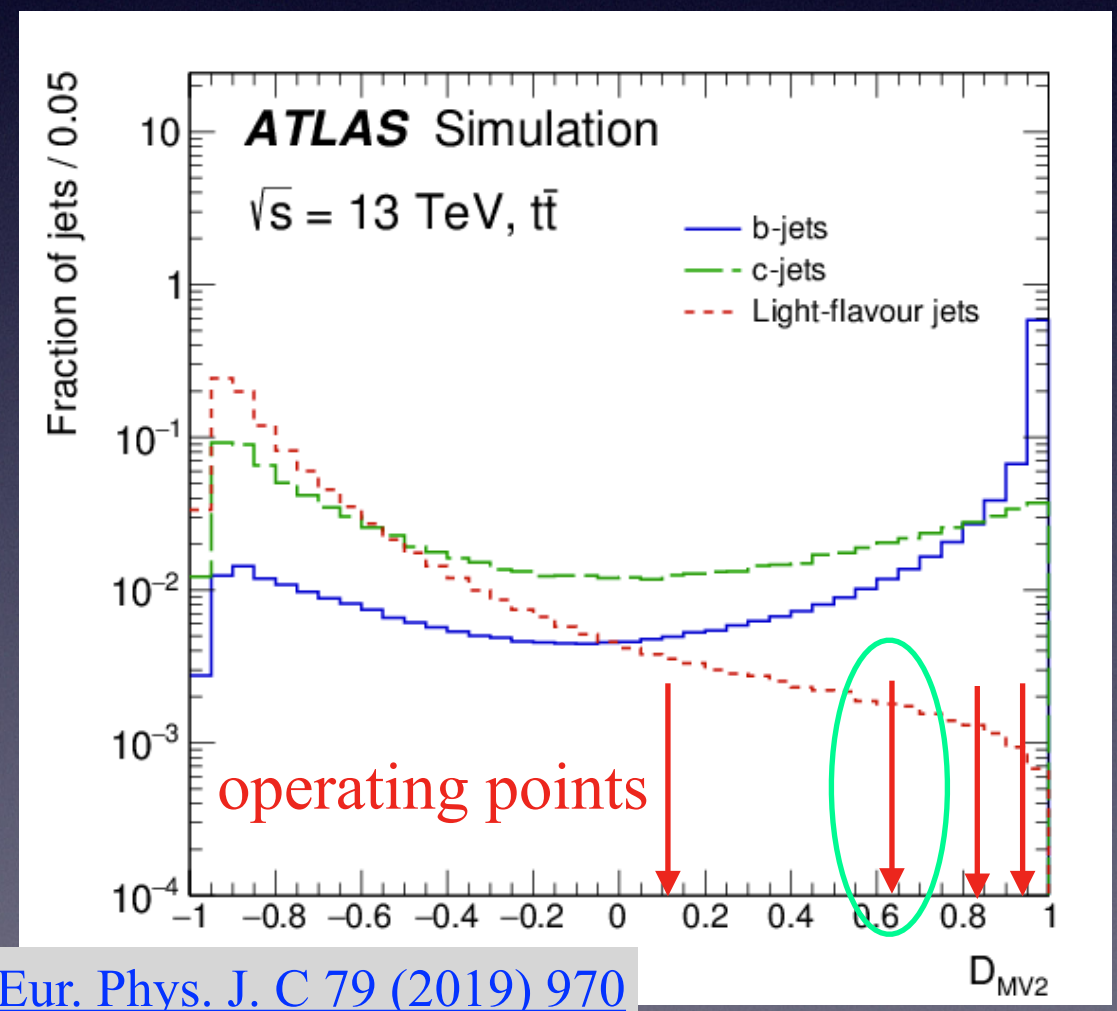
Jets and b -jets

- Jet reconstruction and b -jet identification are crucial

Jet energy calibration at
 $\sim 1\%$ level in relevant p_T
range



- MV2c10 BDT based on track IPs and secondary vertices



Backgrounds

- Several reducible and irreducible backgrounds contribute to the SR yield

Irreducible

Major:

$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, ttt

Minor (“others”):

$t\bar{t}WW$, tWZ , tZq

Reducible

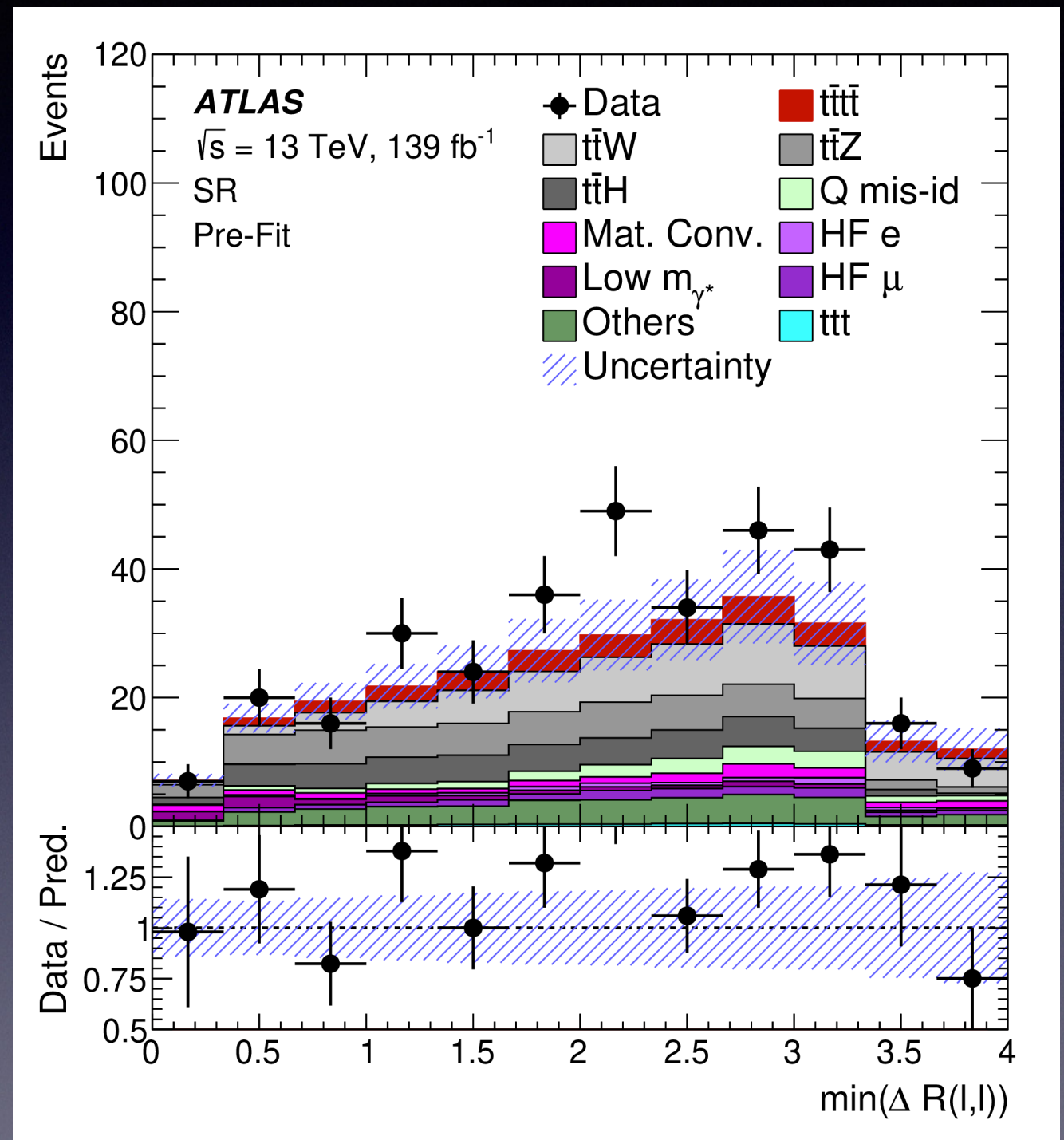
Charge misID

only for SSee

rate estimated from $Z \rightarrow ee$

Fake/non-prompt leptons

several sources considered

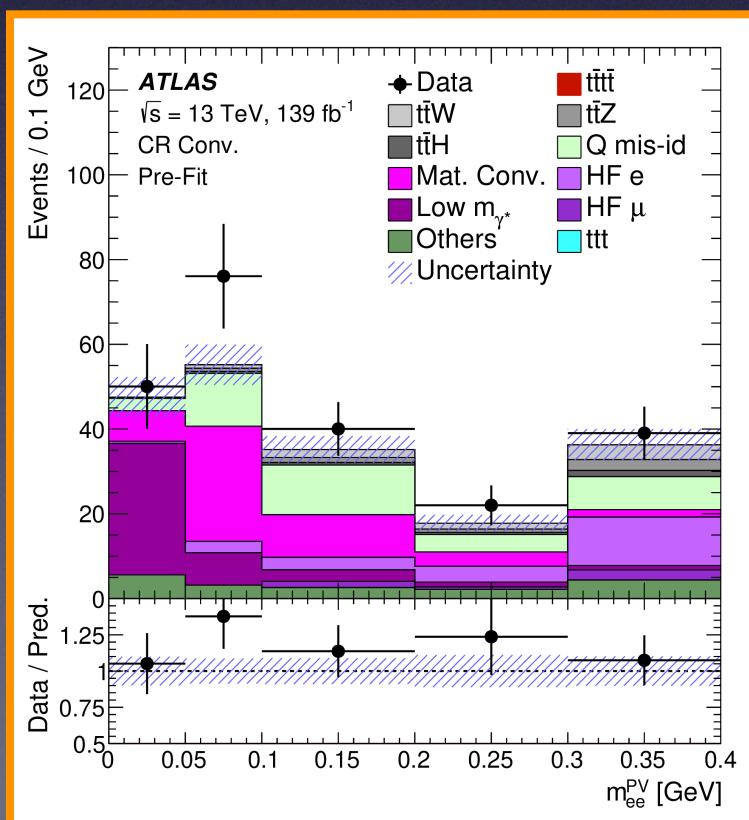
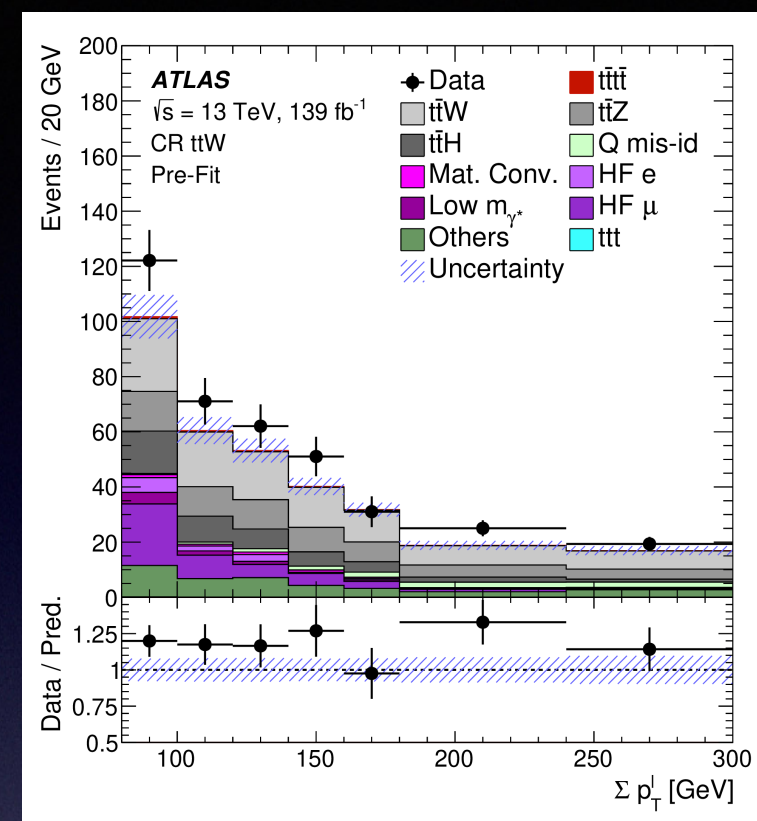
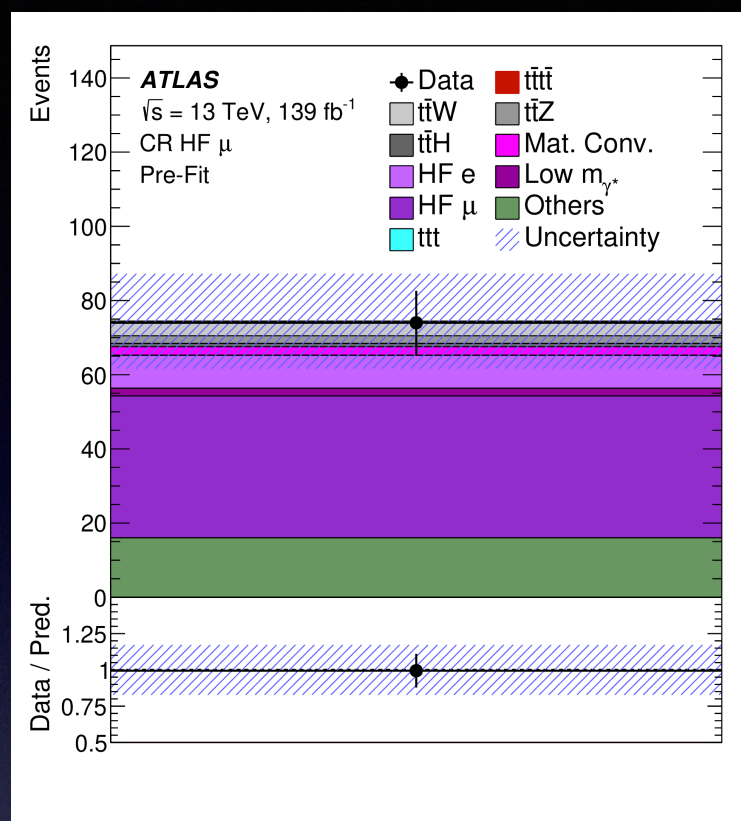
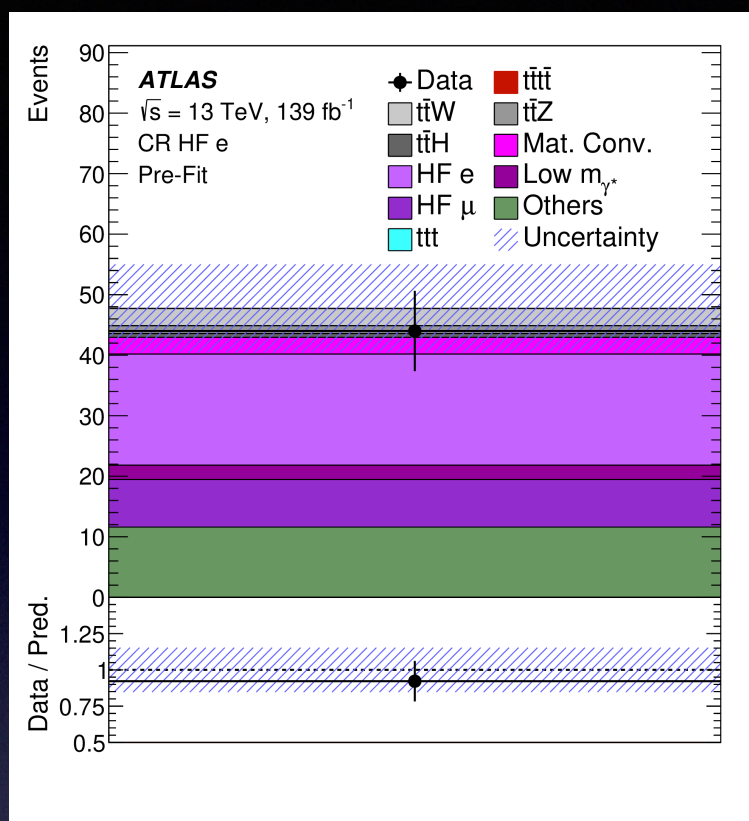


Control Regions

- The fake/non-prompt lepton rate is difficult to simulate precisely
 - highly sensitive to material and response effects
- Control regions enriched in different sources of fake/non-prompt leptons are defined:
 - since $t\bar{t}W$ is a significant contributor in all regions, an additional CR is defined for it

Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_T > 500$	BDT
CR Conv.	$e^\pm e^\pm e^\pm \mu^\pm$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1 \text{ GeV}]$ $200 < H_T < 500 \text{ GeV}$	m_{ee}^{PV}
CR HF e	$eee ee\mu$	-	$= 1$	$100 < H_T < 250 \text{ GeV}$	counting
CR HF μ	$e\mu\mu \mu\mu\mu$	-	$= 1$	$100 < H_T < 250 \text{ GeV}$	counting
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 $N_b = 2, H_T < 500 \text{ GeV}$ or $N_j < 6$ for $N_b \geq 3, H_T < 500 \text{ GeV}$	Σp_T^ℓ

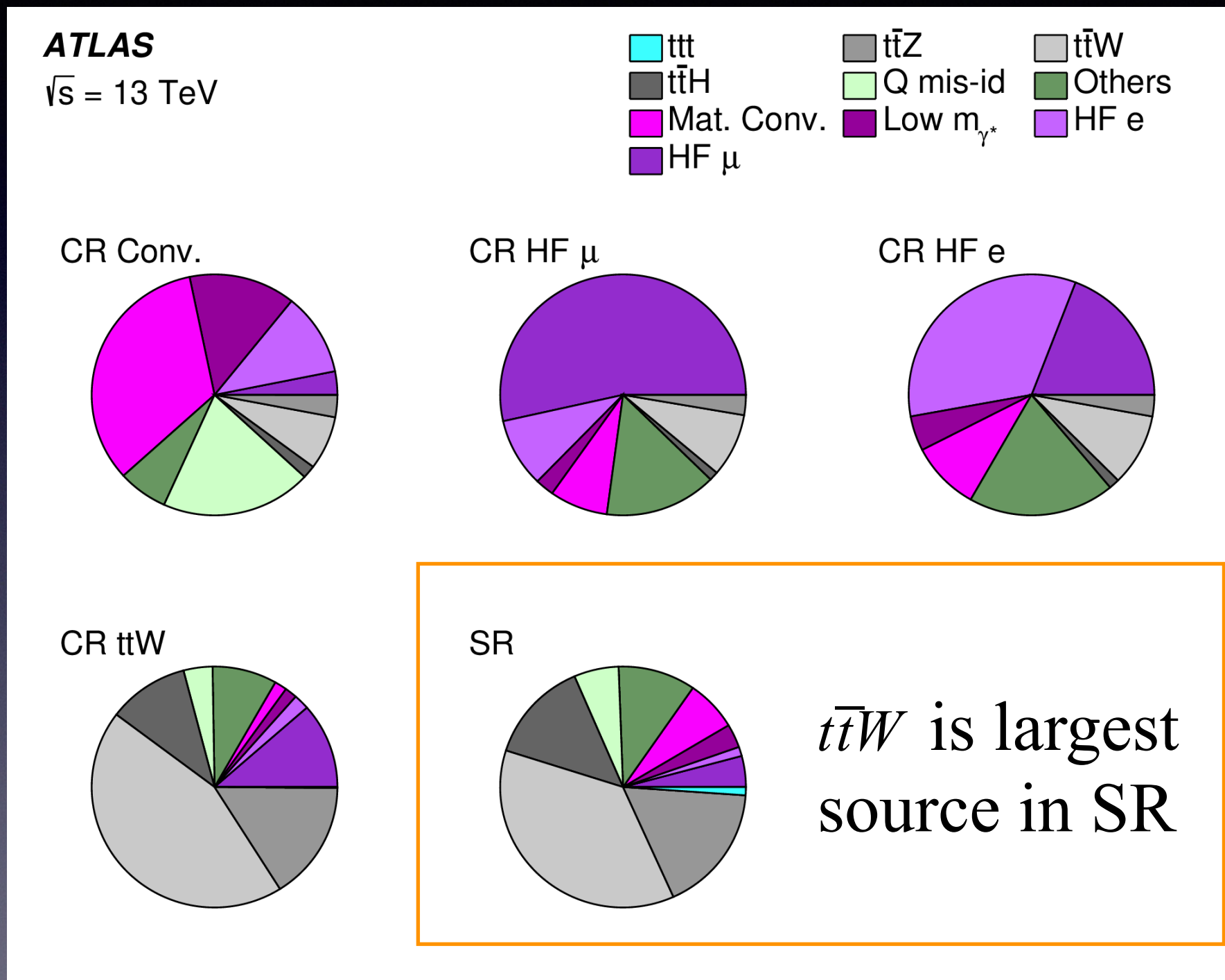
Control Regions



- Binned in mass of e track and nearest track evaluated at PV
 - small for virtual photons, larger for material conversions
- Allows contributions from these sources to be distinguished

Composition of Analysis Regions

- Post-fit sample composition

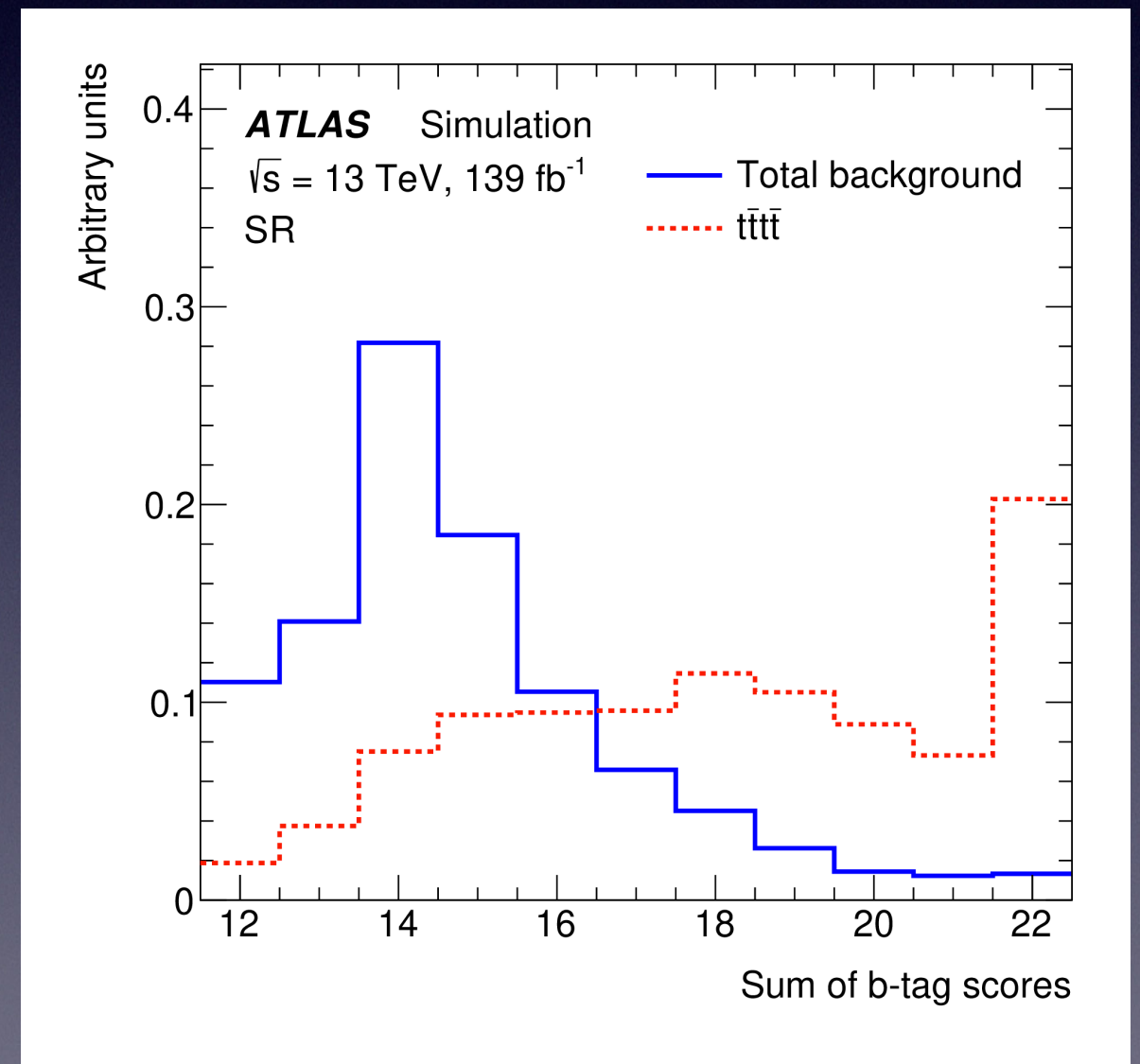


Signal/background Discrimination

- Presence of four b -jets distinguishes four-top signal from background
 - each jet assigned an integer score based on BDT:

Least b -like 1 2 3 4 5 Most b -like

- Sum is taken over all jets
- Provides better S/B discrimination than “tag-and-count” method
 - integers correspond to well-calibrated working points



Multivariate Analysis

- Optimal signal/bkg discrimination obtained with BDT
- Sum of b -tag scores is most powerful variable
- Others are:

$$\min(\Delta R_{\ell\ell})$$

leading lepton p_T

$$E_T^{\text{miss}}$$

leading jet p_T

subleading jet p_T

$$H_T - p_T(j_1)$$

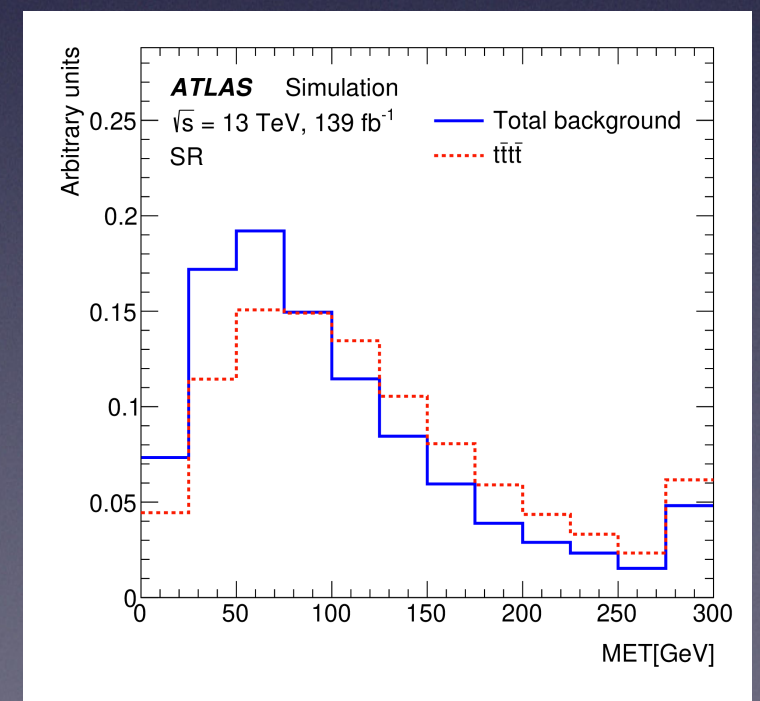
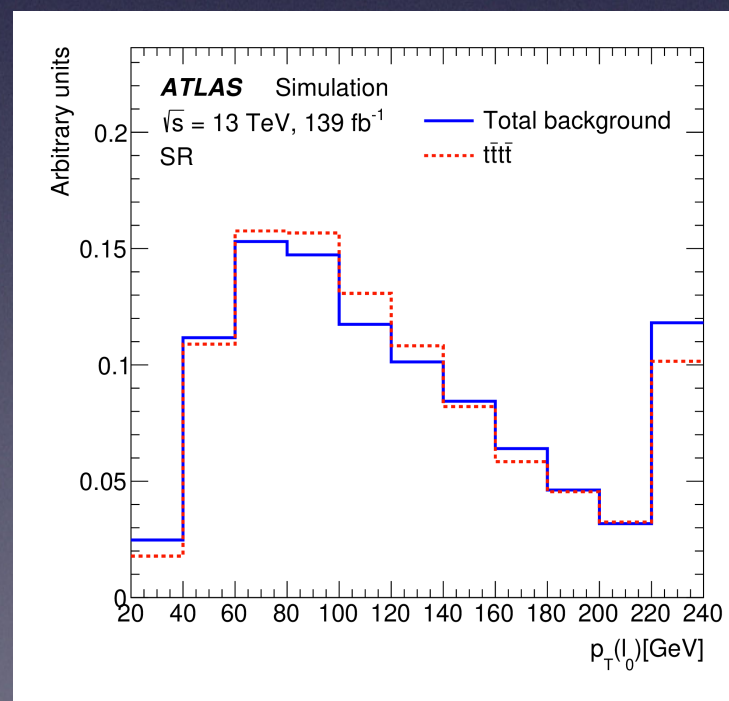
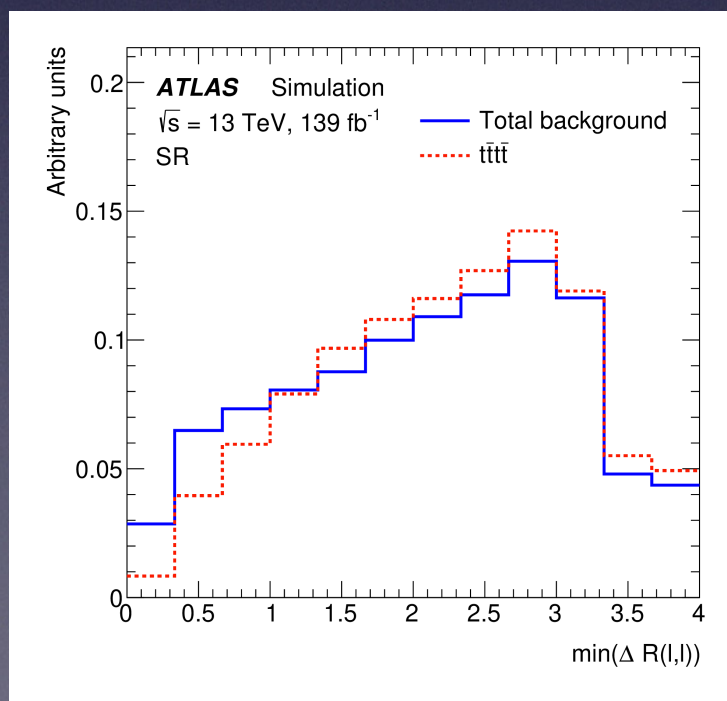
sixth-leading jet p_T

$$\sum_{i \neq j} \Delta R_{\ell_i \ell_j}$$

leading b -jet p_T

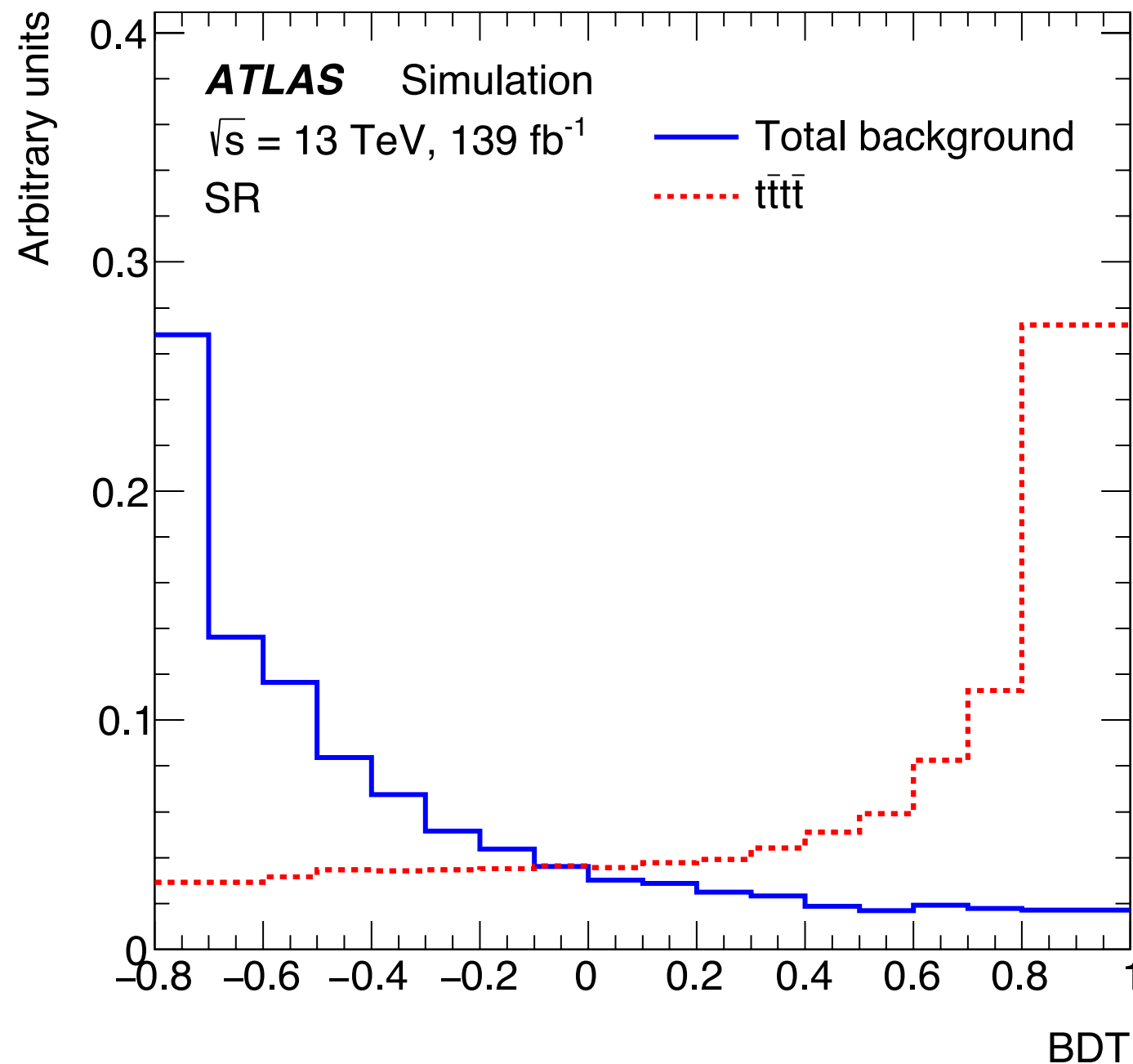
$$\max(\Delta R_{\ell b\text{-jet}})$$

$$\min(\Delta R_{jb\text{-jet}})$$

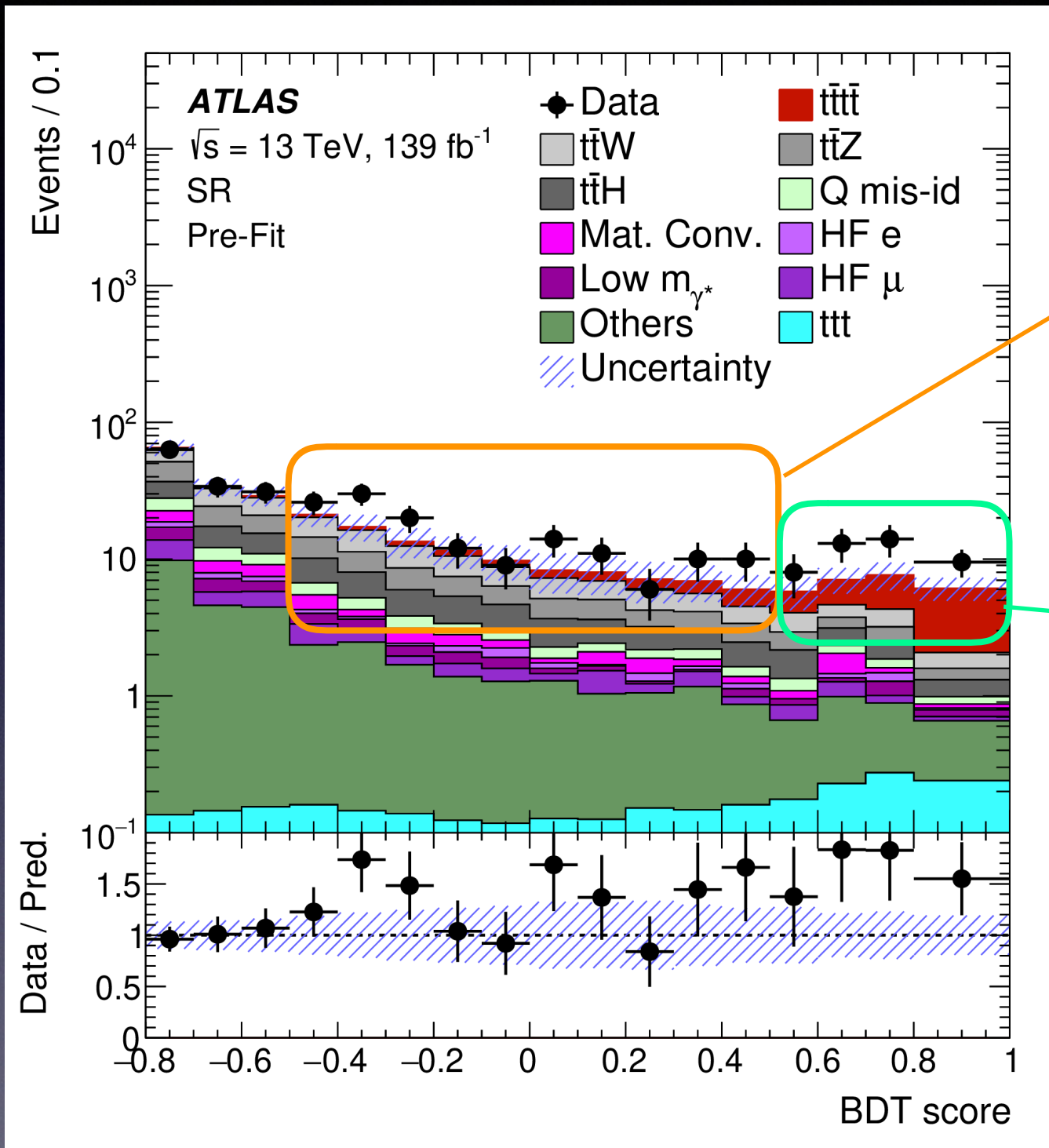


Multivariate Analysis

- Expected BDT performance



Multivariate Analysis



• Two features of note:

1. **Broad excess at intermediate values**

- Background normalization?

2. **Larger excess at high BDT values**

Profile Likelihood Fit

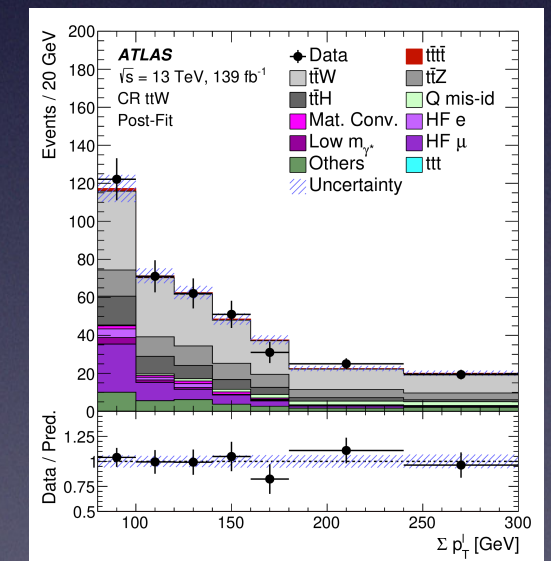
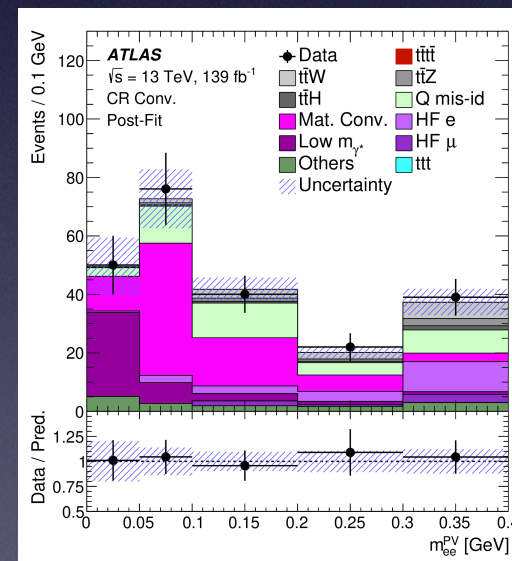
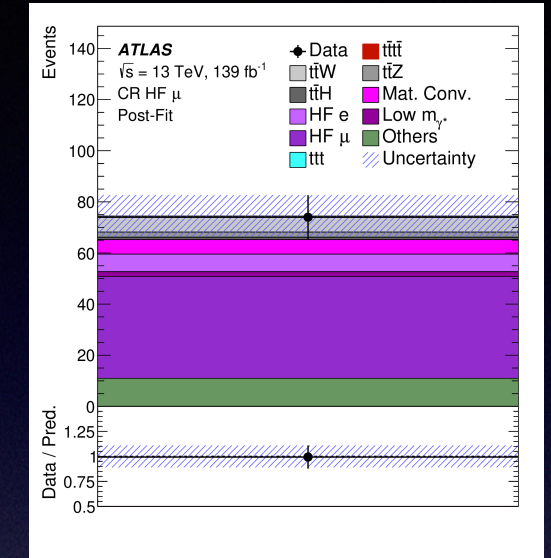
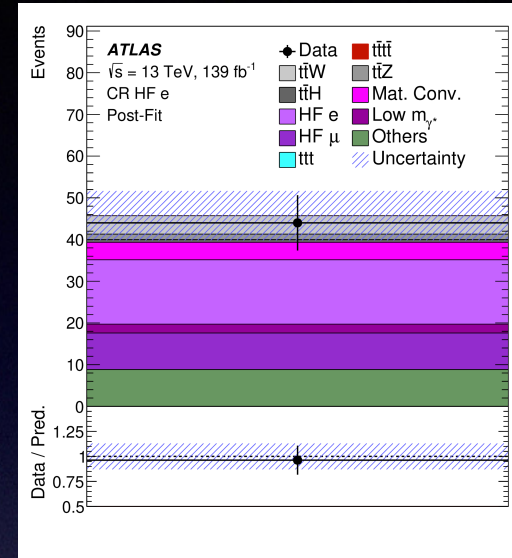
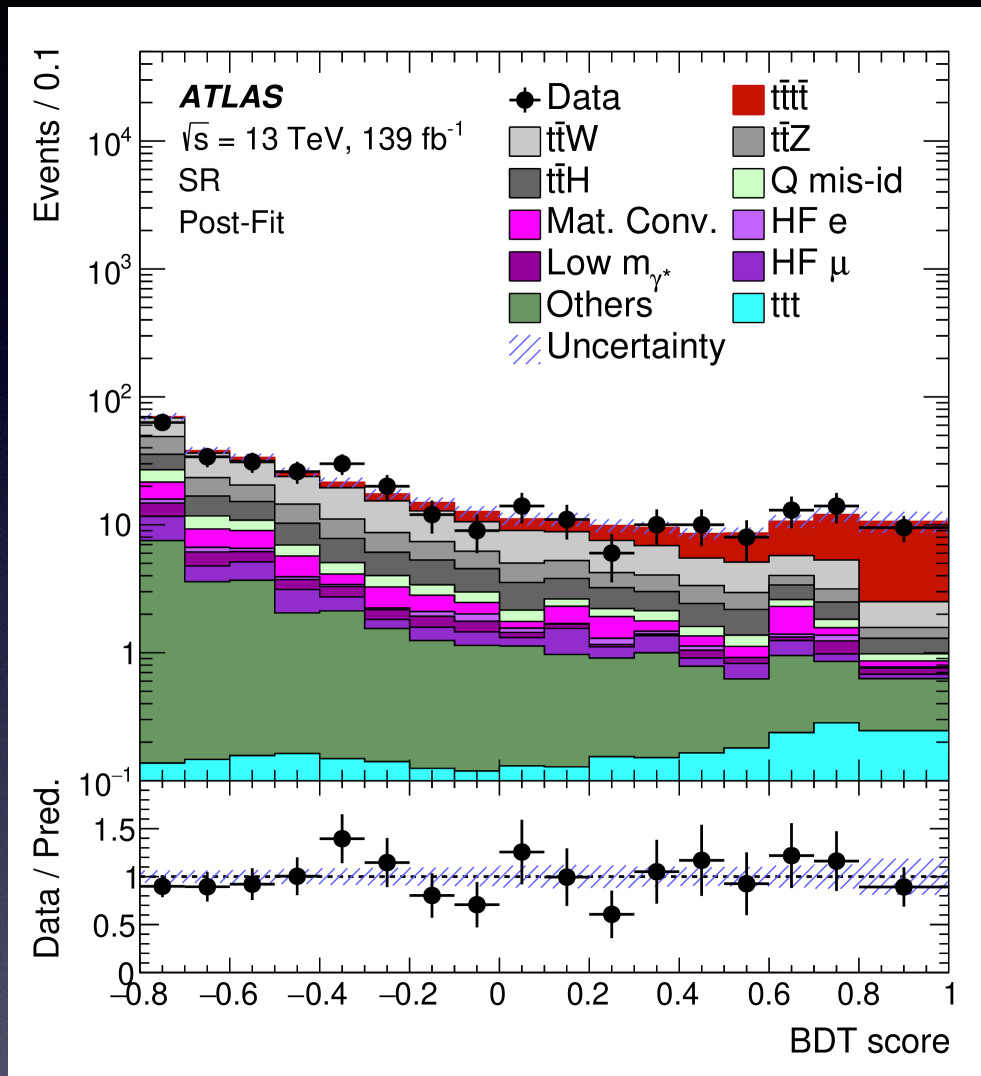
- Simultaneous fit of signal and control regions
- Parameter of interest:

$$\mu \equiv \frac{\sigma_{t\bar{t}\bar{t}\bar{t}}(\text{obs.})}{\sigma_{t\bar{t}\bar{t}\bar{t}}(SM)}$$

- Key background normalizations allowed to float:
 - Non-prompt e and μ from heavy-flavor decay
 - Non-prompt e from conversions
 - $t\bar{t}W$ (nominal cross section is 601 fb, calculated at NLO w/ EW corrections) [JHEP 07 \(2012\) 052](#) [JHEP 06 \(2015\) 184](#) [arXiv: 1610.07922](#)
- Other backgrounds constrained to MC prediction within systematic uncertainties

Results

- Fitted distributions in the signal and control regions



Background normalization factors

details in coming slides

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

Results

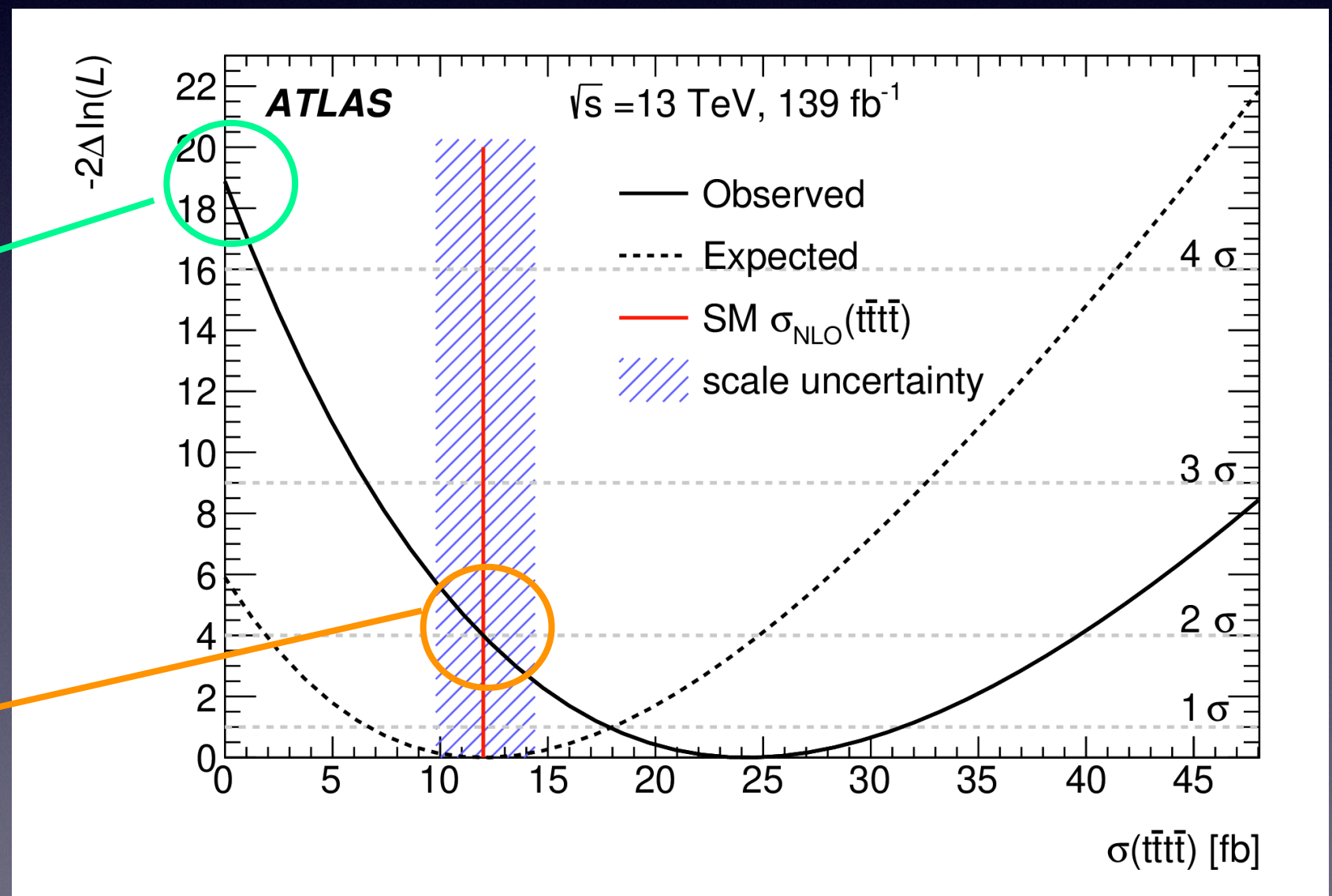
- Excess at high BDT in signal region results in

$$\mu = 2.0 \pm 0.4(\text{stat.})^{+0.7}_{-0.4}(\text{syst.})$$

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat.})^{+5}_{-4}(\text{syst.}) \text{ fb}$$

4.3 s.d. from 0
(2.4 s.d. expected)
Evidence for $t\bar{t}t\bar{t}$
production

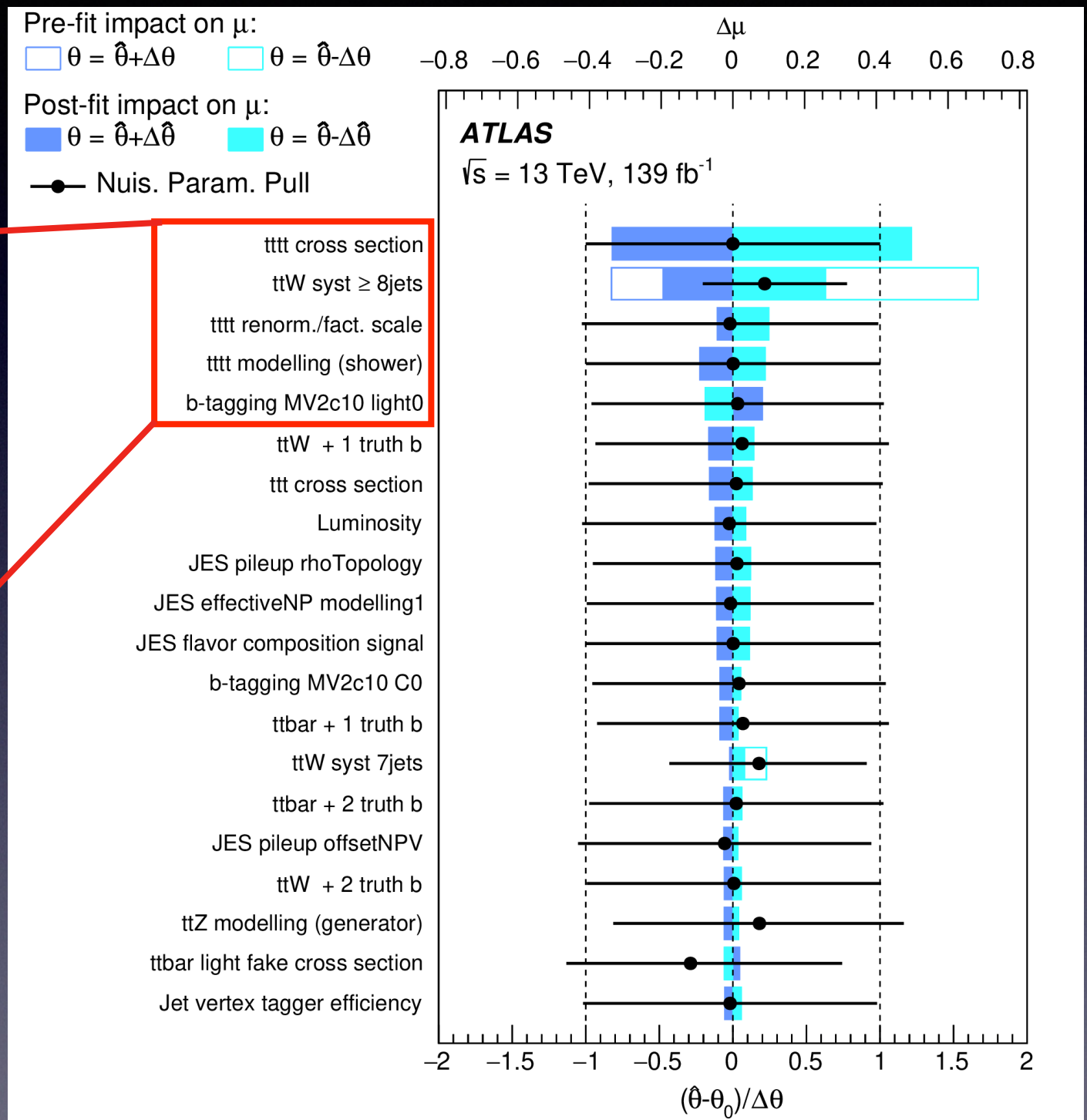
1.7 s.d. from SM



Systematic Uncertainties

tttt cross section
 *ttW syst ≥ 8 jets
 tttt renorm./fact. scale
 tttt modelling (shower)
 b-tagging MV2c10 light0

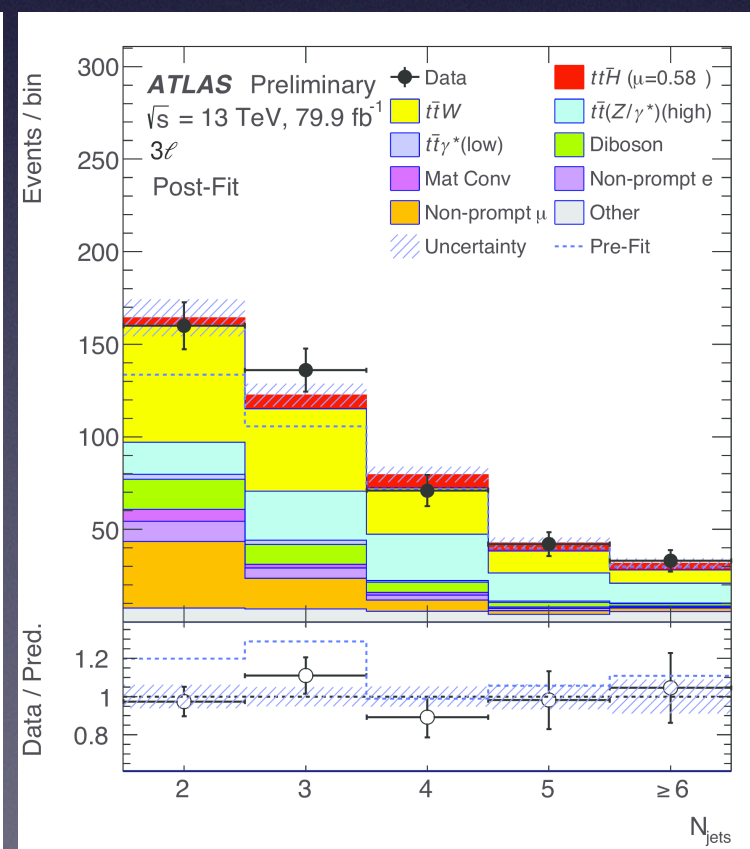
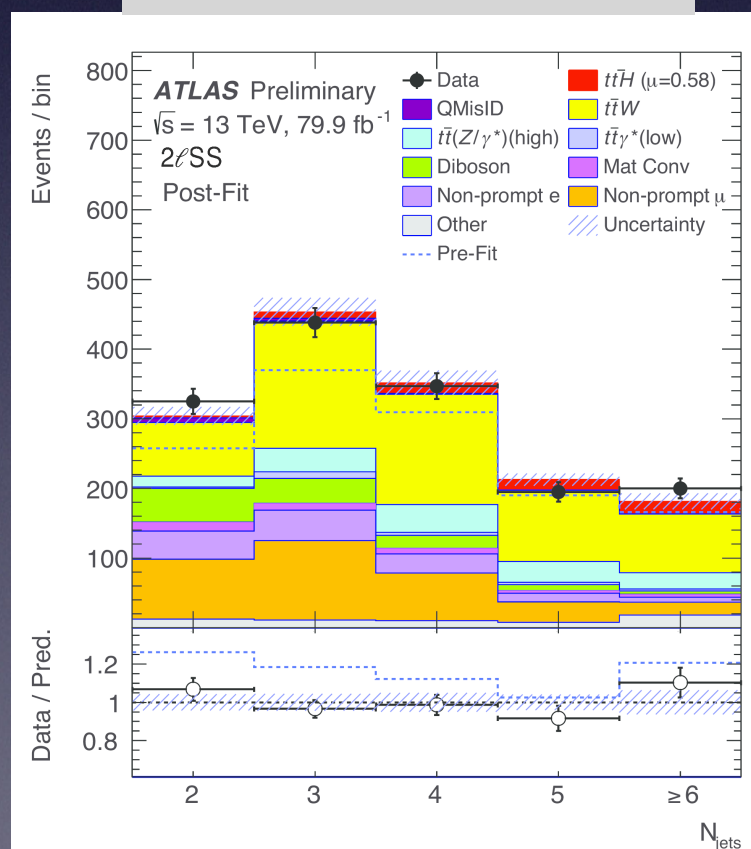
*details in
 coming slides



Investigation of $t\bar{t}W$

- The $t\bar{t}W$ background is of special interest
 - largest single source of events in signal region
 - fit prefers large normalization factor (1.6 ± 0.3)
- Other ATLAS analyses see similar $t\bar{t}W$ normalization factor
 - e.g. $t\bar{t}H$ search in multi-lepton final state:

[ATLAS-CONF-2019-045](#)



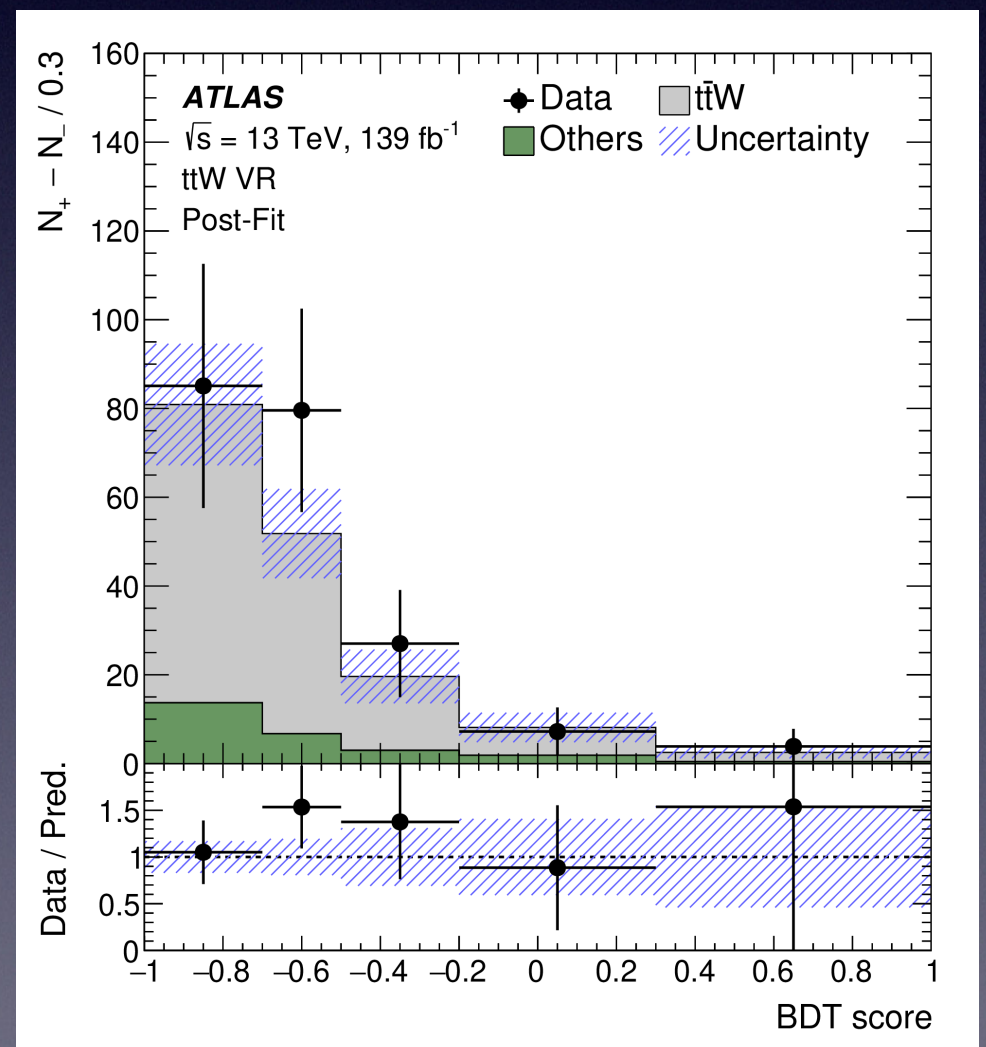
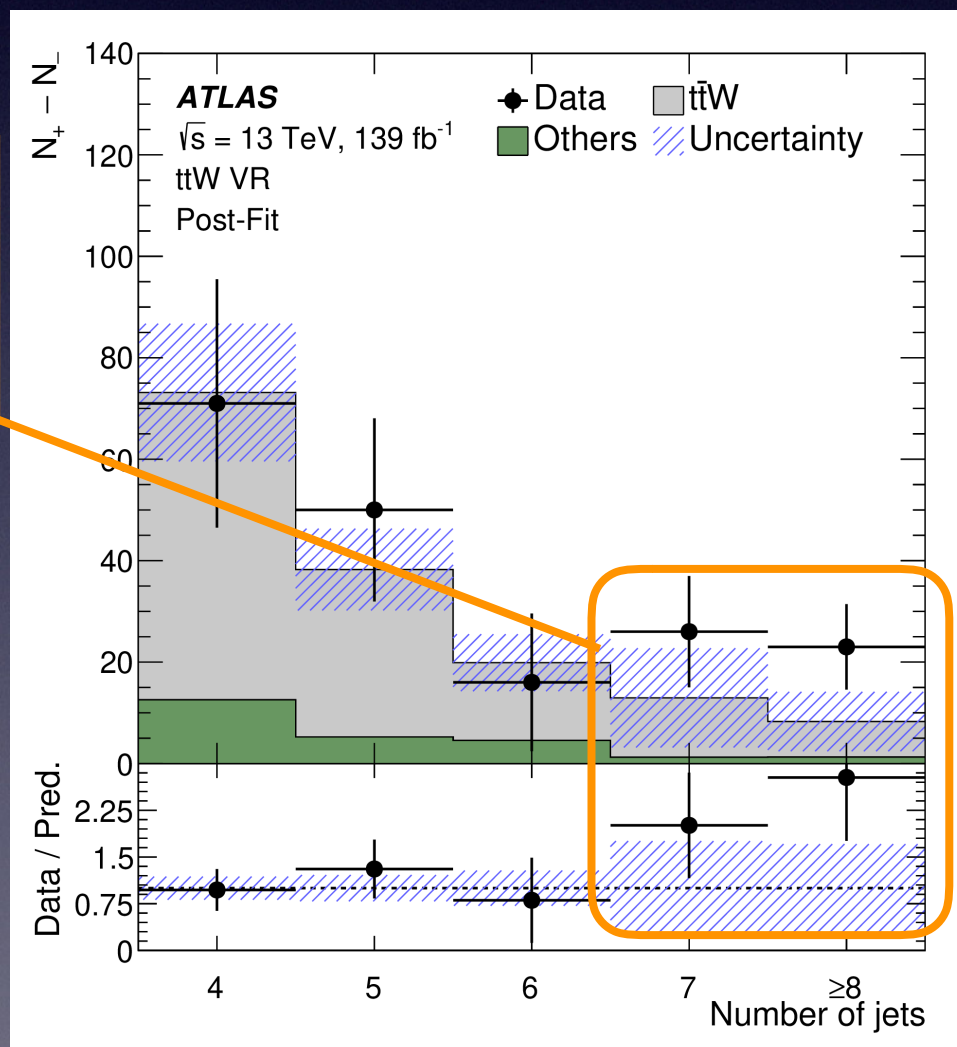
$t\bar{t}W$ normalization factors are 1.3 - 1.7 (depending on jet and lepton multiplicity)

Investigation of $t\bar{t}W$

- Validate $t\bar{t}W$ using the charge asymmetry of the production
 - $t\bar{t}W^+ > t\bar{t}W^-$ due to pp initial state
- Isolate $t\bar{t}W$ in sample with ≥ 4 jets (≥ 2 b -tagged) by considering $N^+ - N^-$:

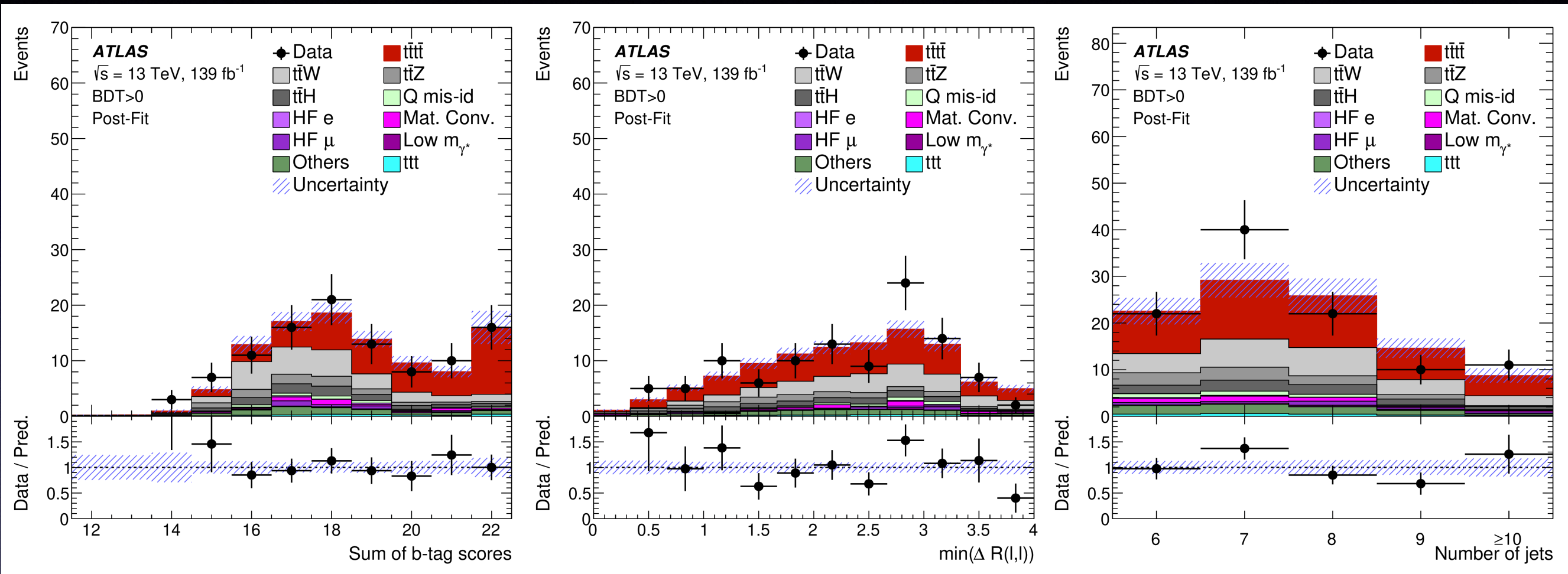
Systematic uncertainties set based on excess

see G. Bevilacqua's talk and on NLO calculation



Cross Checks

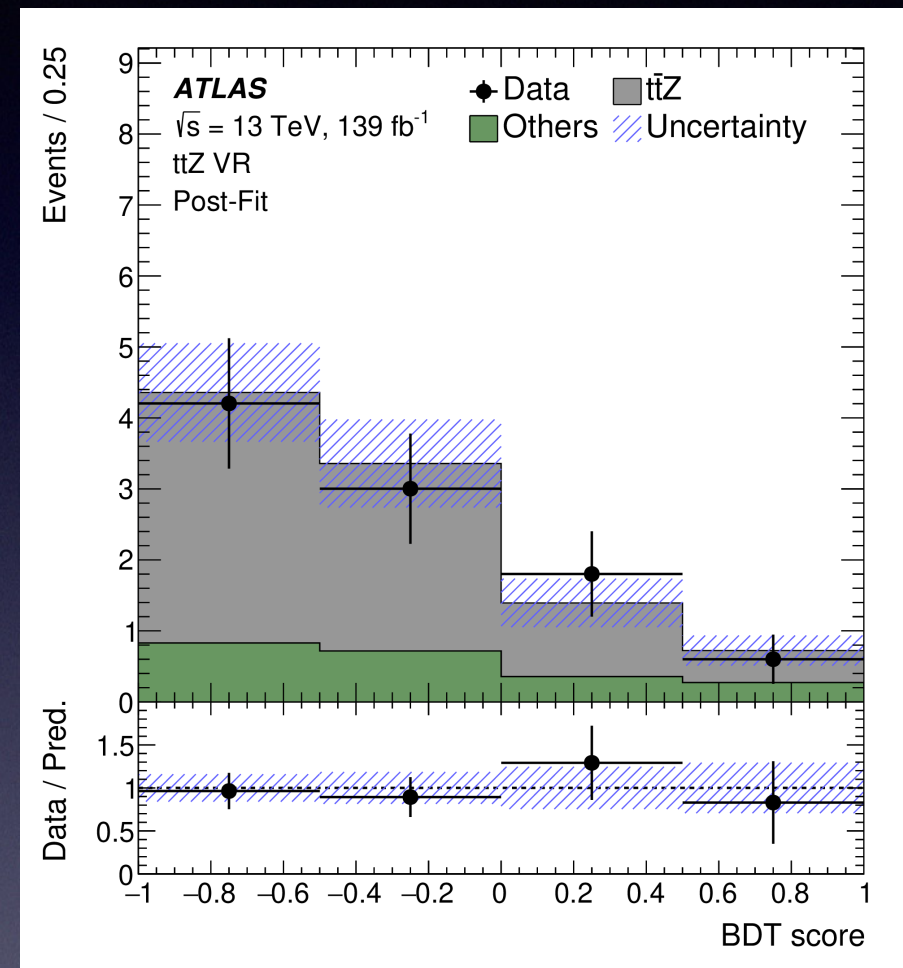
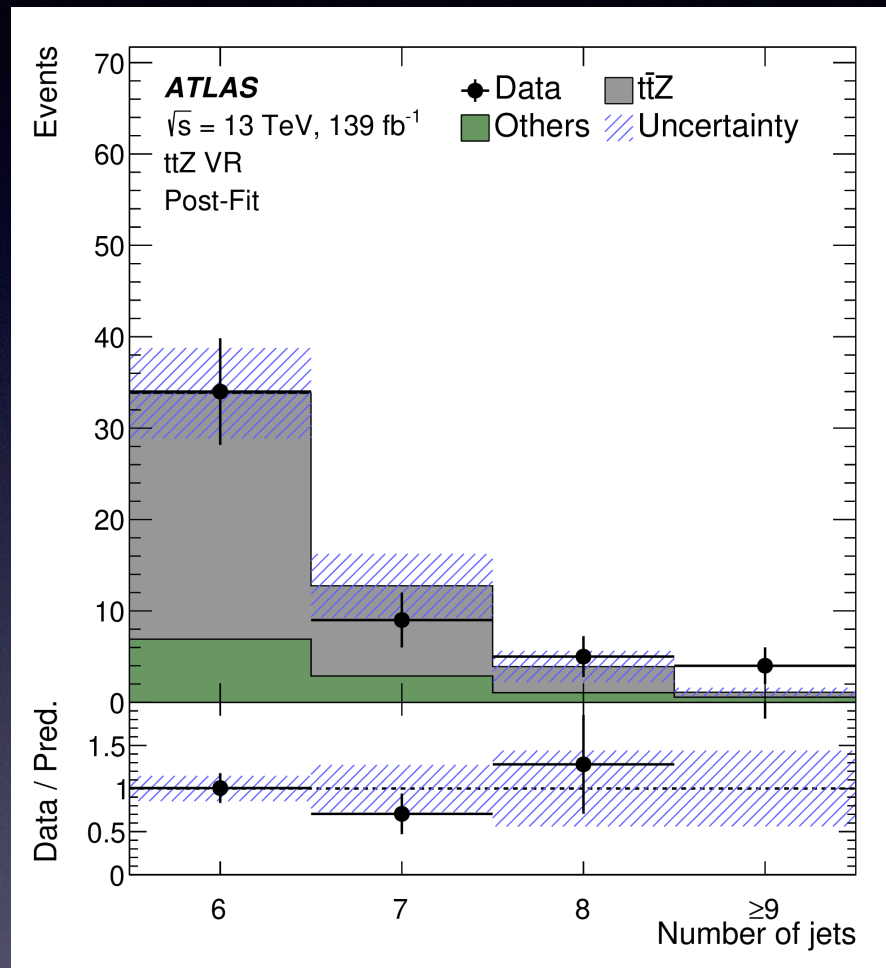
- Kinematic distributions for events with $\text{BDT} > 0$



Excess over background consistent with $t\bar{t}t\bar{t}$

Cross Checks

- Validation region for $t\bar{t}Z$ defined using trilepton events with $|m_{\ell^+\ell^-} - 91 \text{ GeV}| < 10 \text{ GeV}$



- Splitting data sample by run period and fitting H_T rather than BDT score give consistent results

Nothing unexpected observed in cross checks

Summary and Plans

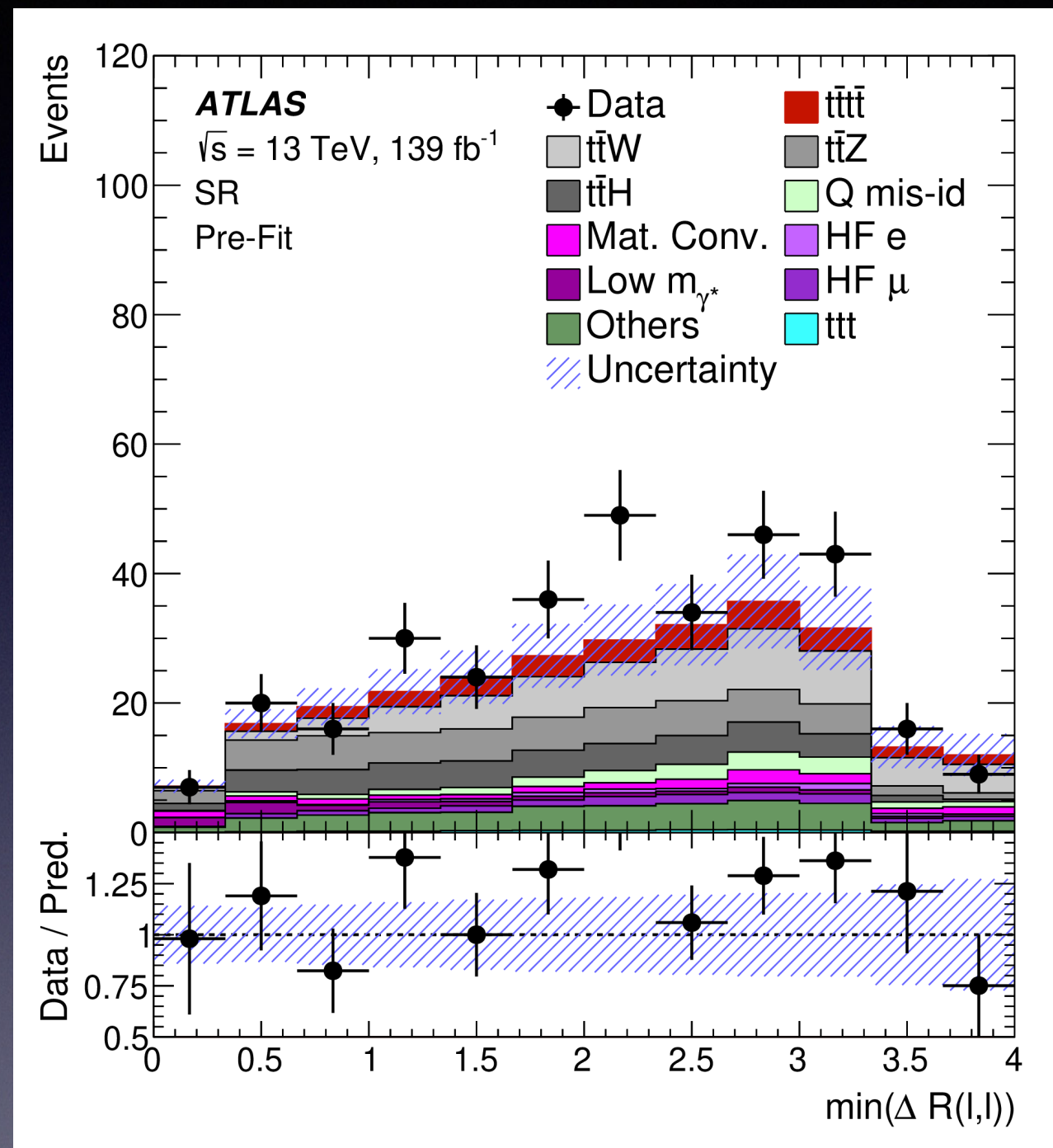
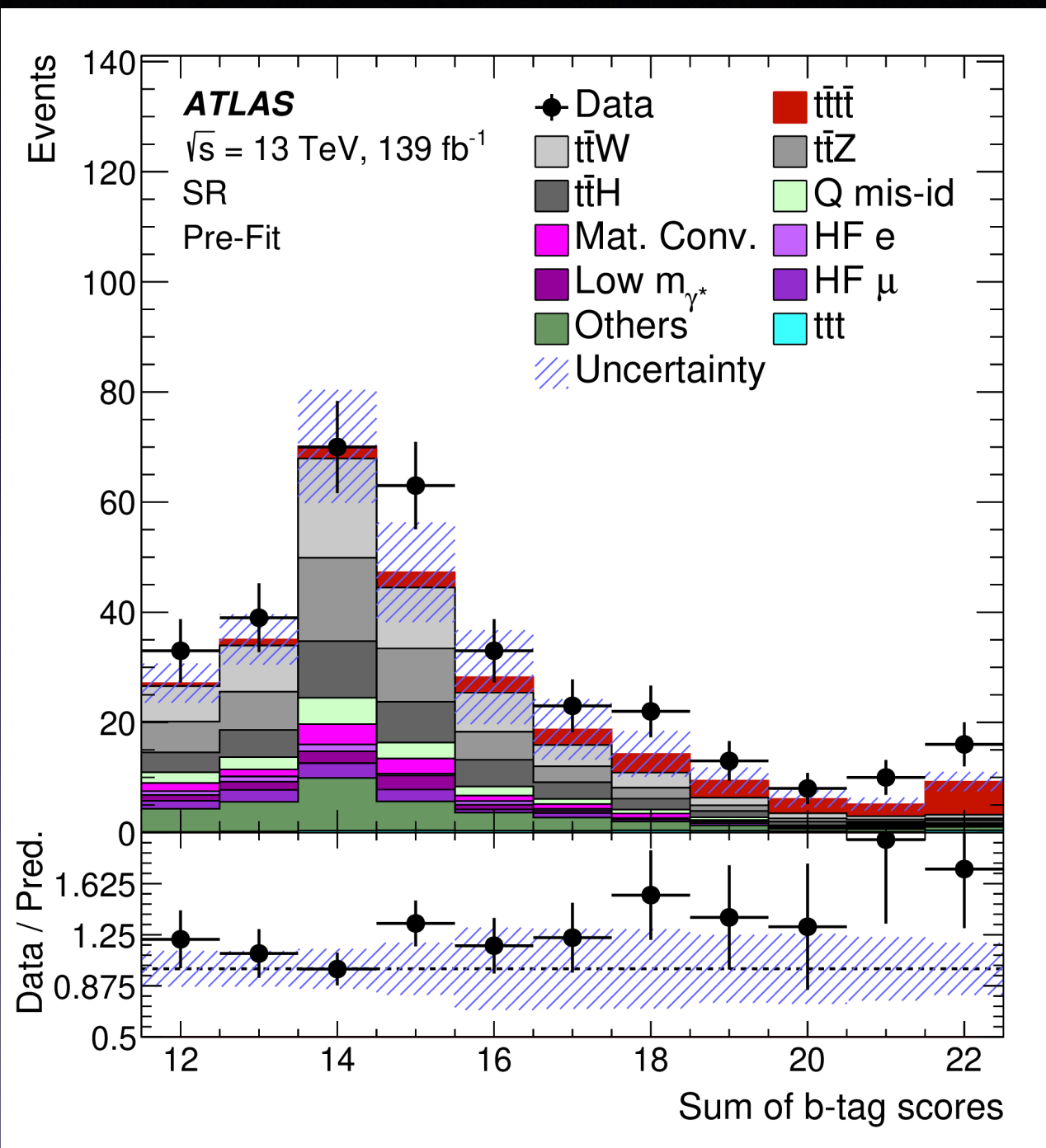
- ATLAS reports evidence for four-top-quark production

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat}) \substack{+5 \\ -4}(\text{syst}) \text{ fb} = 24_{-6}^{+7} \text{ fb}$$

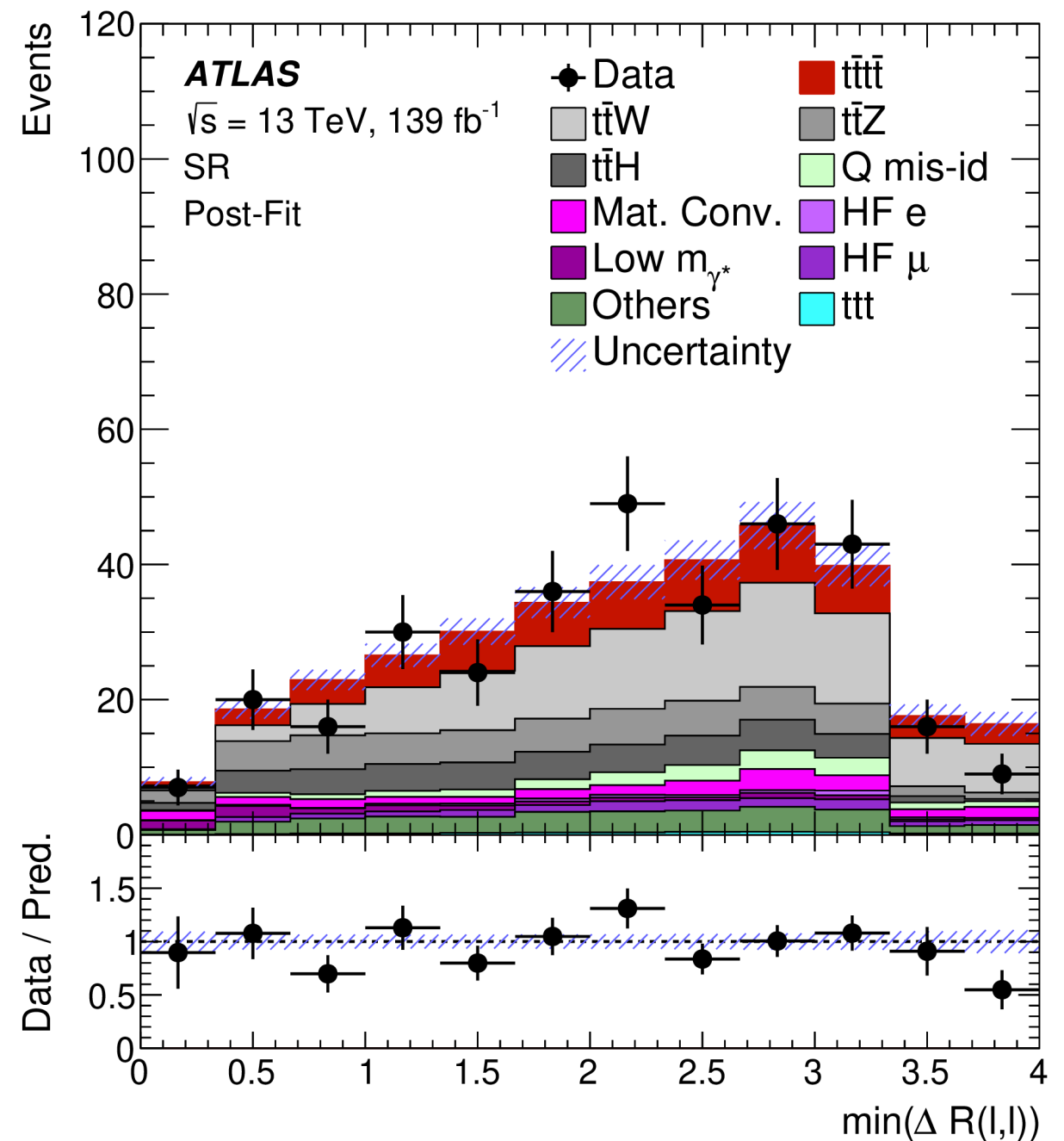
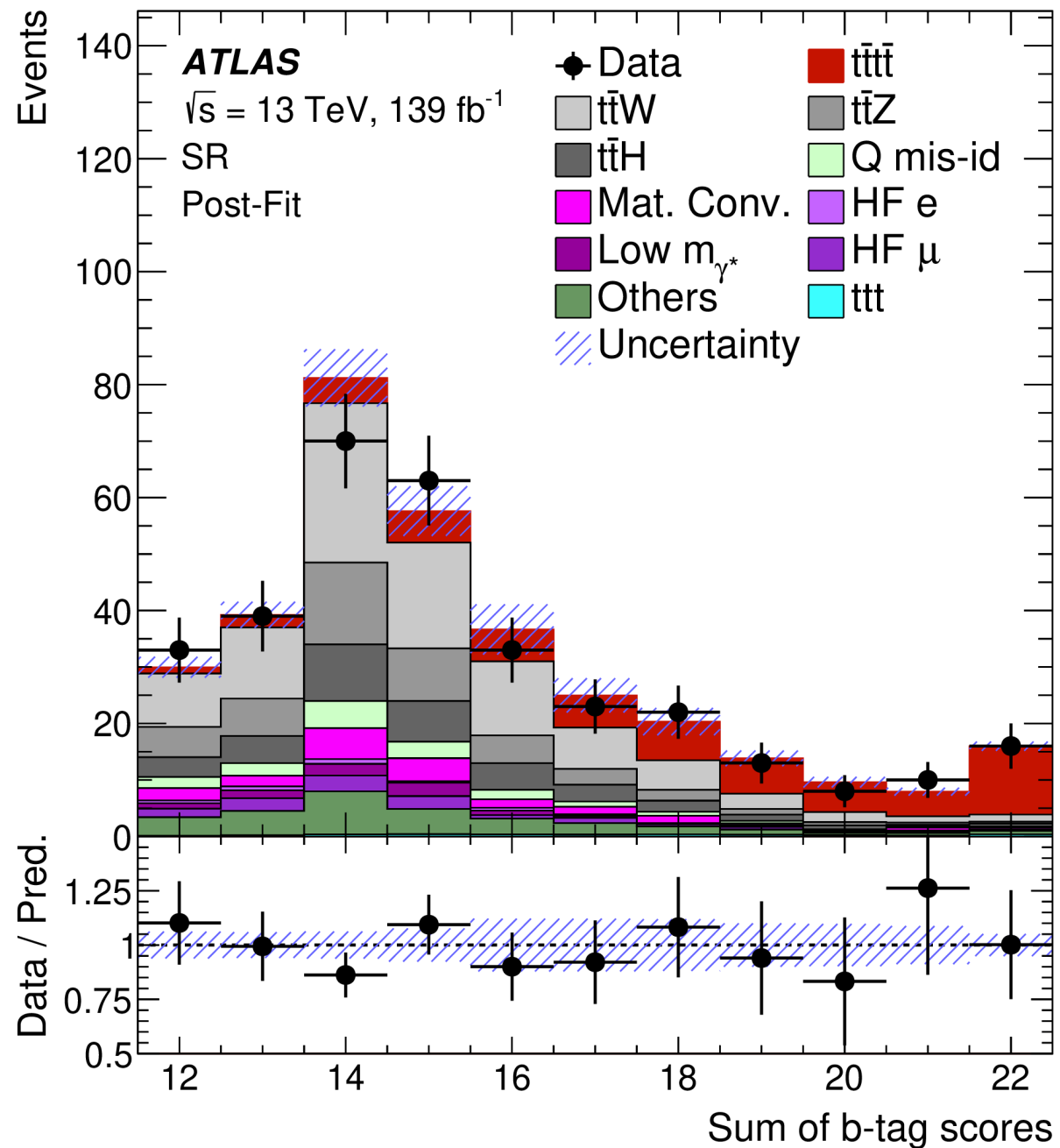
- Significance corresponds to 4.3 s.d. (2.4 expected)
 - consistent with the SM cross section at the 1.7 s.d. level
- Details available in [arXiv.2007.14858](https://arxiv.org/abs/2007.14858) (submitted to EPJC)

Backup

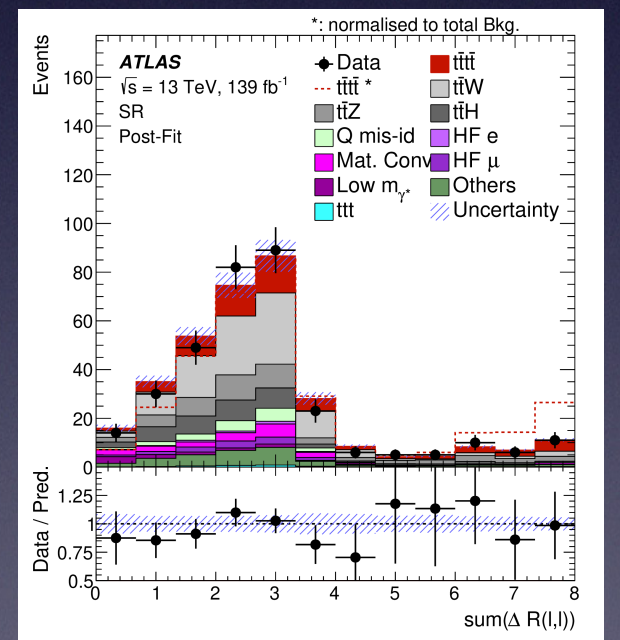
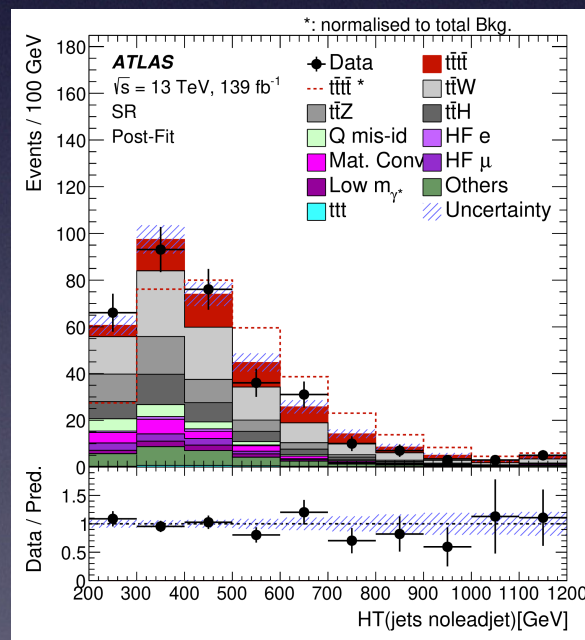
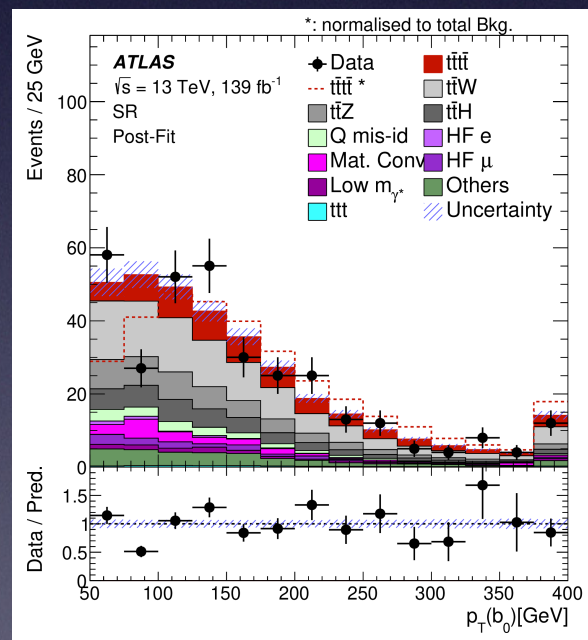
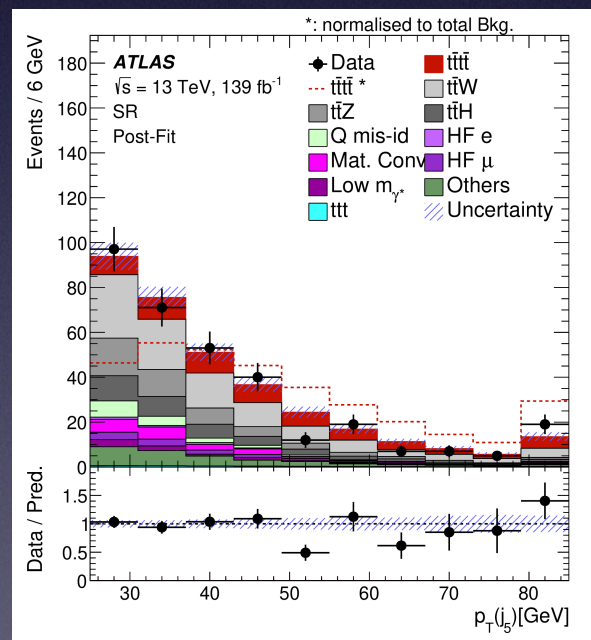
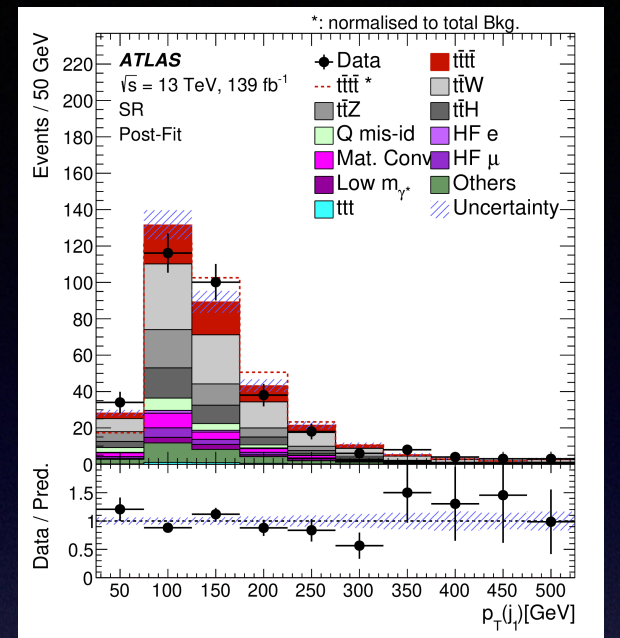
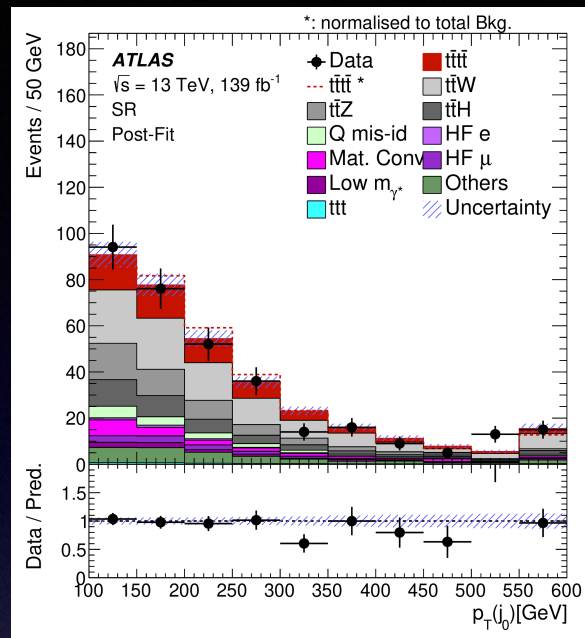
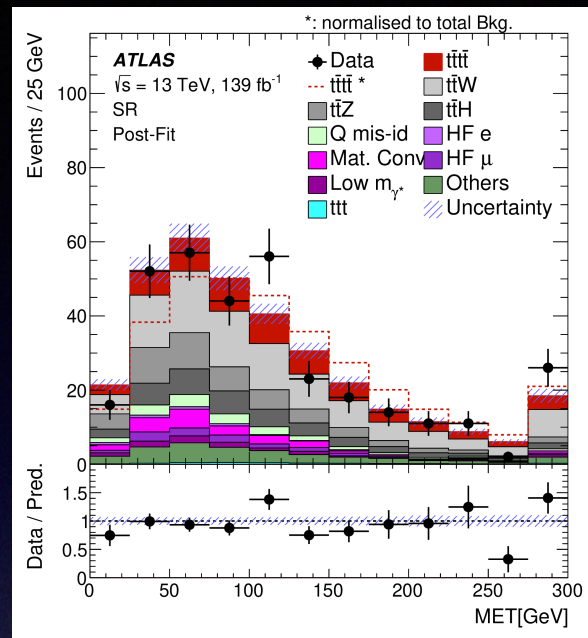
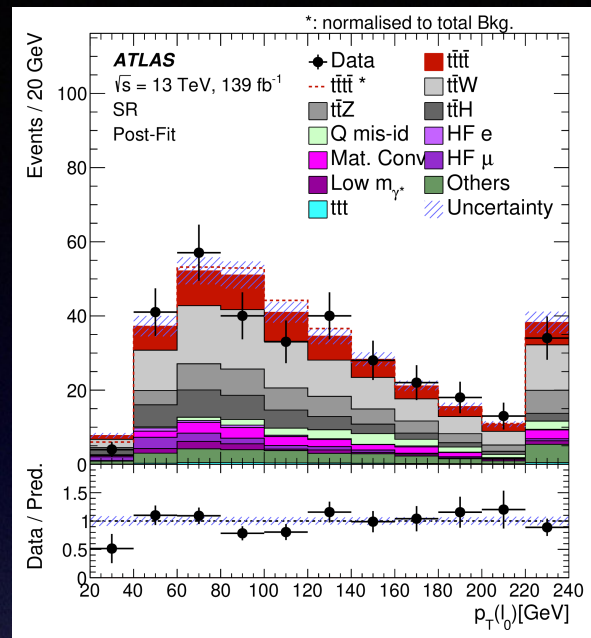
Pre-fit Variable Comparisons



Post-fit Variable Comparisons



Post-fit Variable Comparisons



Post-fit Yields

	SR	SR and BDT > 0
$t\bar{t}W$ +jets	102 ± 26	23 ± 10
$t\bar{t}WW$	7 ± 4	2 ± 1
$t\bar{t}Z$ +jets	48 ± 9	9 ± 2
$t\bar{t}H$ +jets	38 ± 9	8 ± 2
Q mis-id	16 ± 1	2.7 ± 0.2
Mat. Conv.	19 ± 6	3 ± 1
Low m_{γ^*}	9 ± 4	0.9 ± 0.5
HF e	3 ± 3	1 ± 1
HF μ	12 ± 6	3 ± 2
LF	4 ± 5	1 ± 1
Other fake	6 ± 2	2 ± 1
VV,VVV,VH	3 ± 2	0.2 ± 0.2
tZq, tWZ	5 ± 2	1.0 ± 0.4
Other $t\bar{t}X$	3 ± 2	1 ± 1
$t\bar{t}t$	3 ± 3	2 ± 2
Total bkg	278 ± 22	59 ± 10
$t\bar{t}t\bar{t}$	60 ± 17	44 ± 12
Total	337 ± 18	103 ± 10
Data	330	105