Evidence for Four-Top-Quark Production

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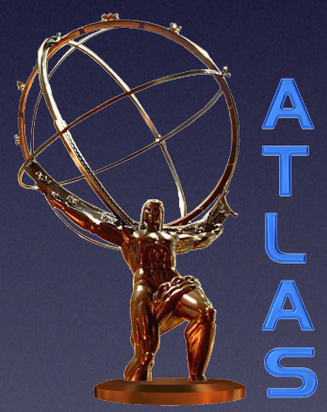


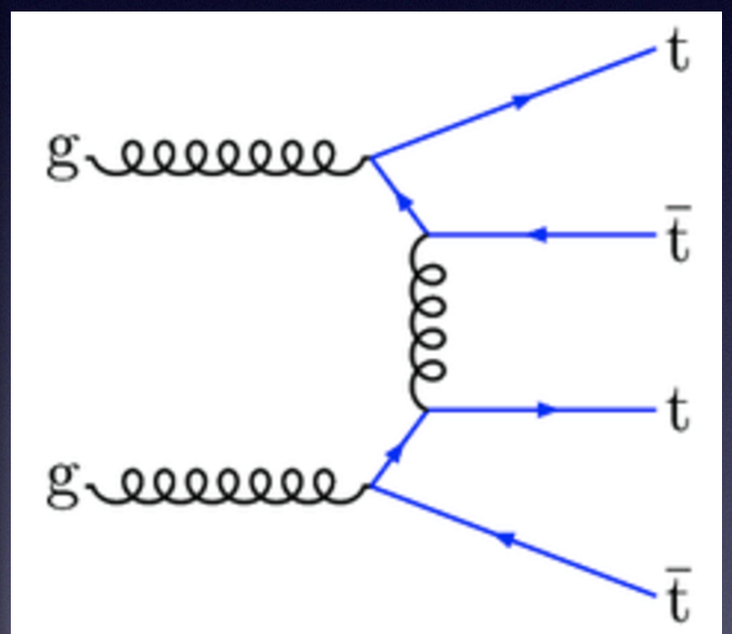
13th International Workshop on Top Quark Physics
September 18, 2020

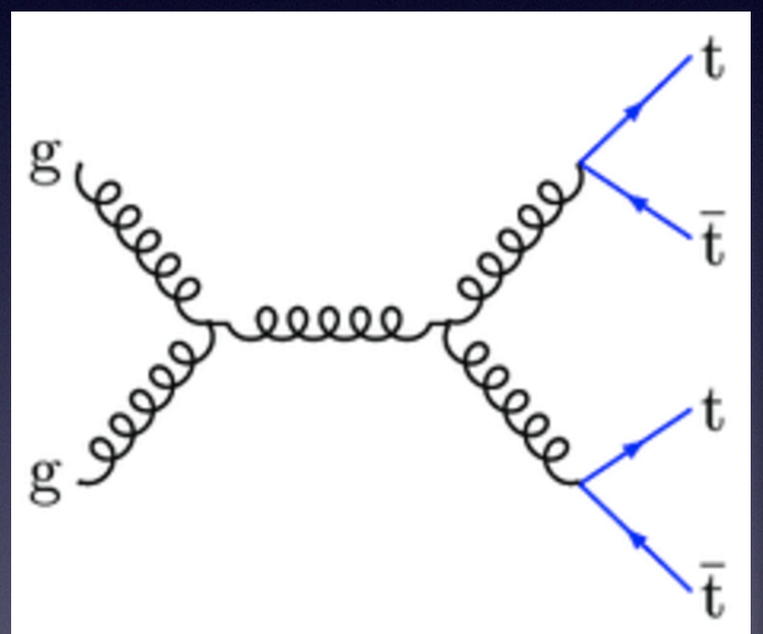
Four-Top-Quark Production

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

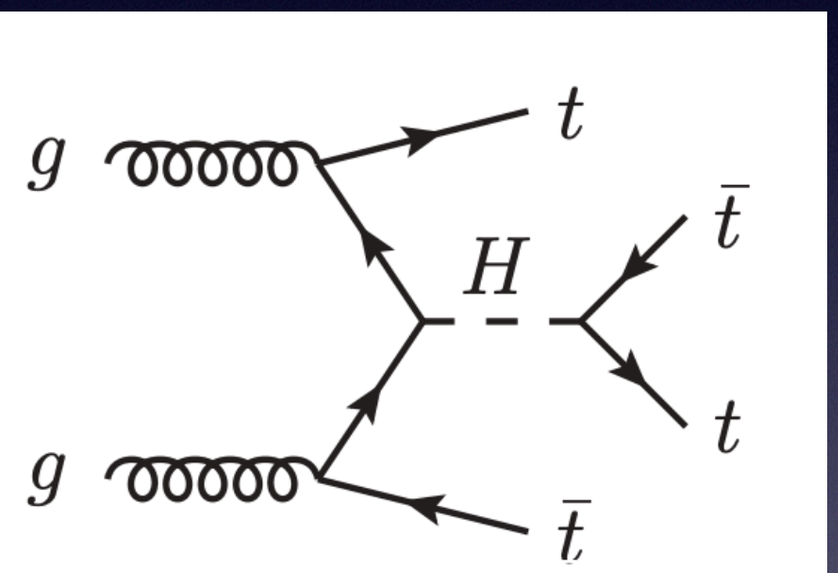
JHEP 02 (2018) 031

Leading SM diagrams





Higgs Yukawa contribution

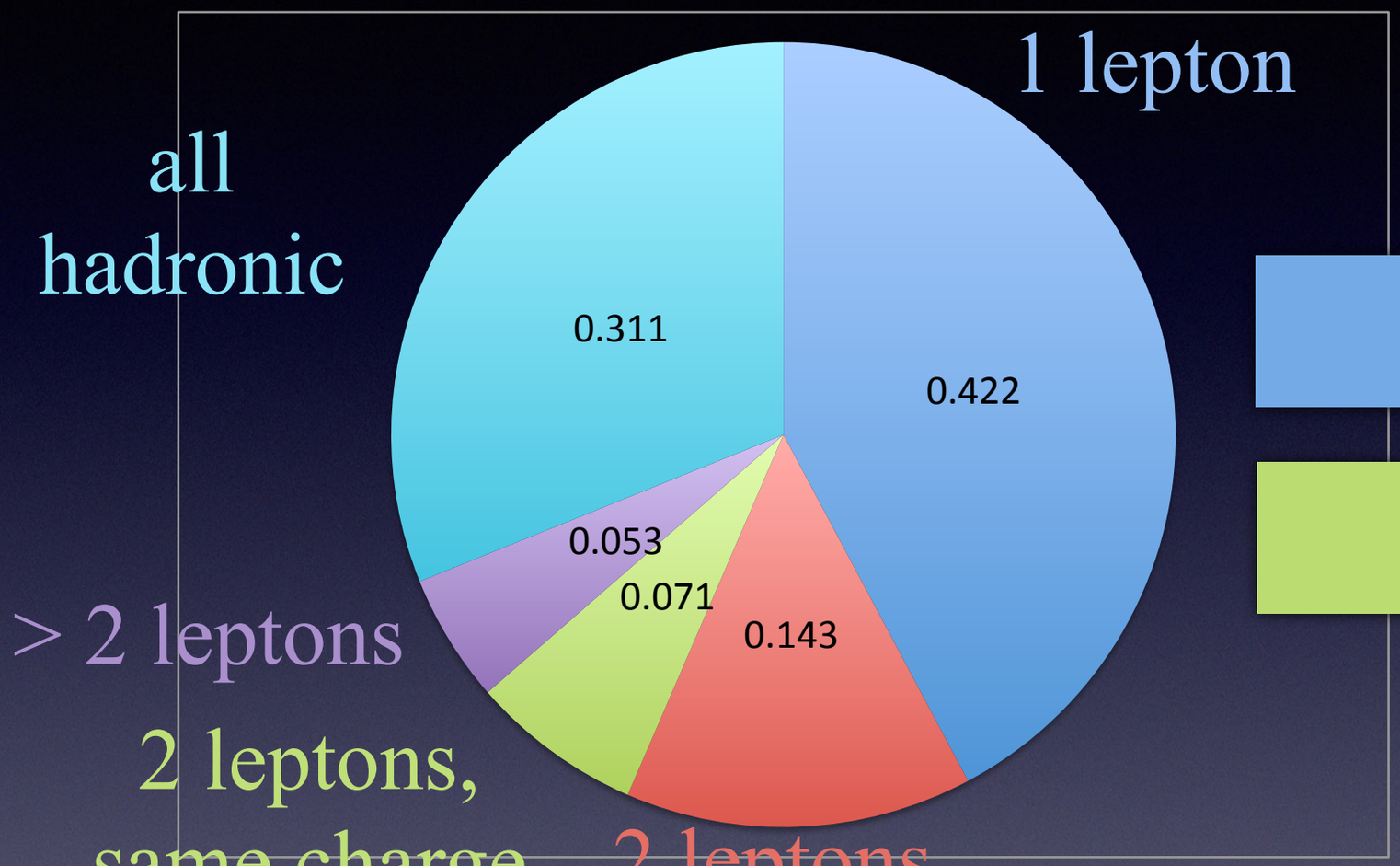


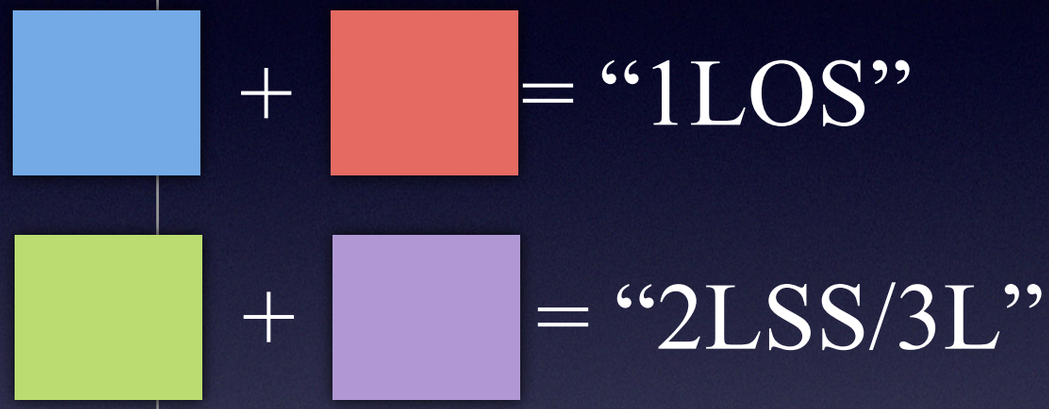
Phys. Rev. D 95, 053004 (2017)

- 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



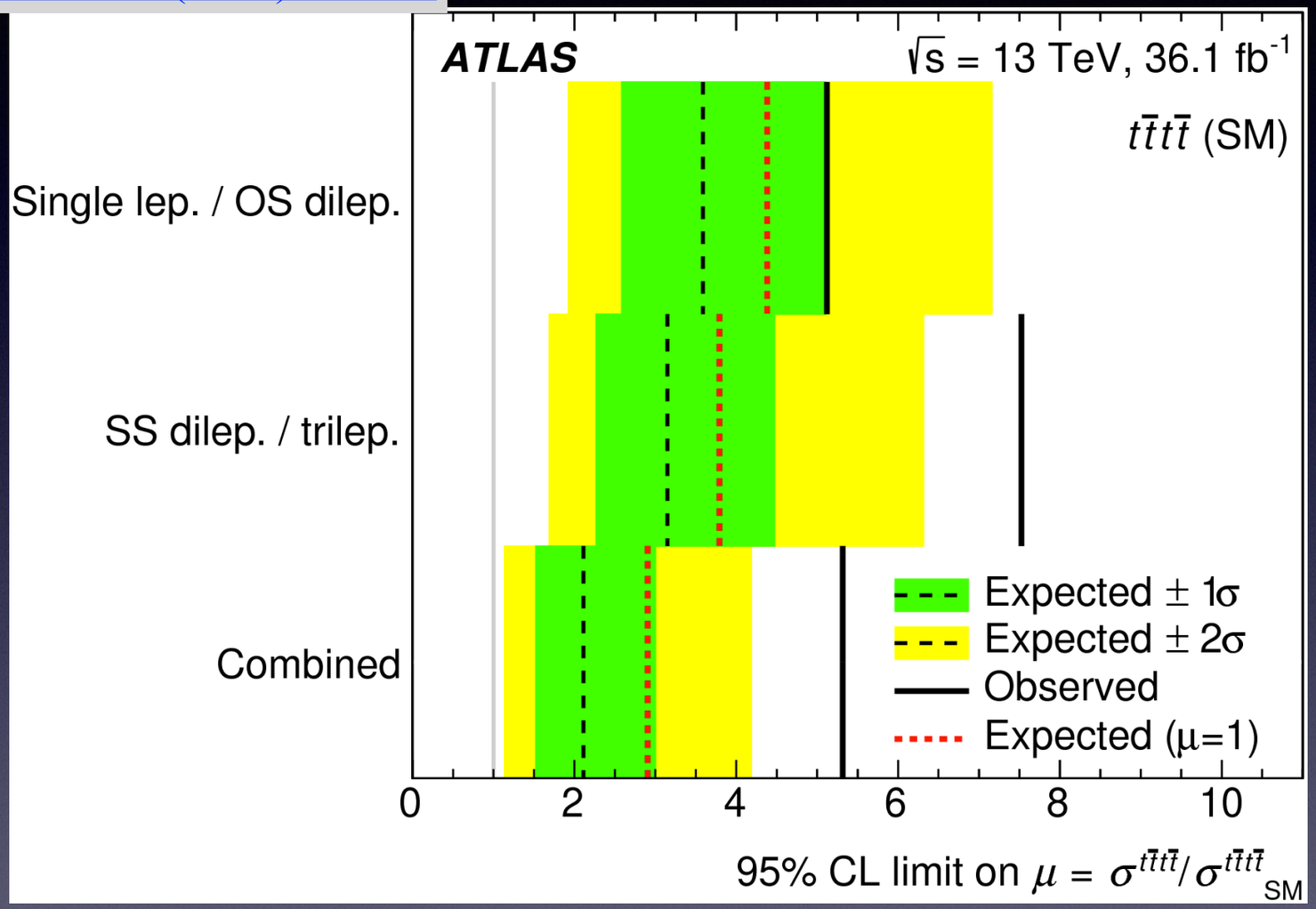


- 2LSS/3L has highest sensitivity due to strong background suppression

Previous ATLAS Search

- 36 fb^{-1} sample using 1LOS plus 2LSS/3L channels

Phys. Rev. D 99 (2019) 052009



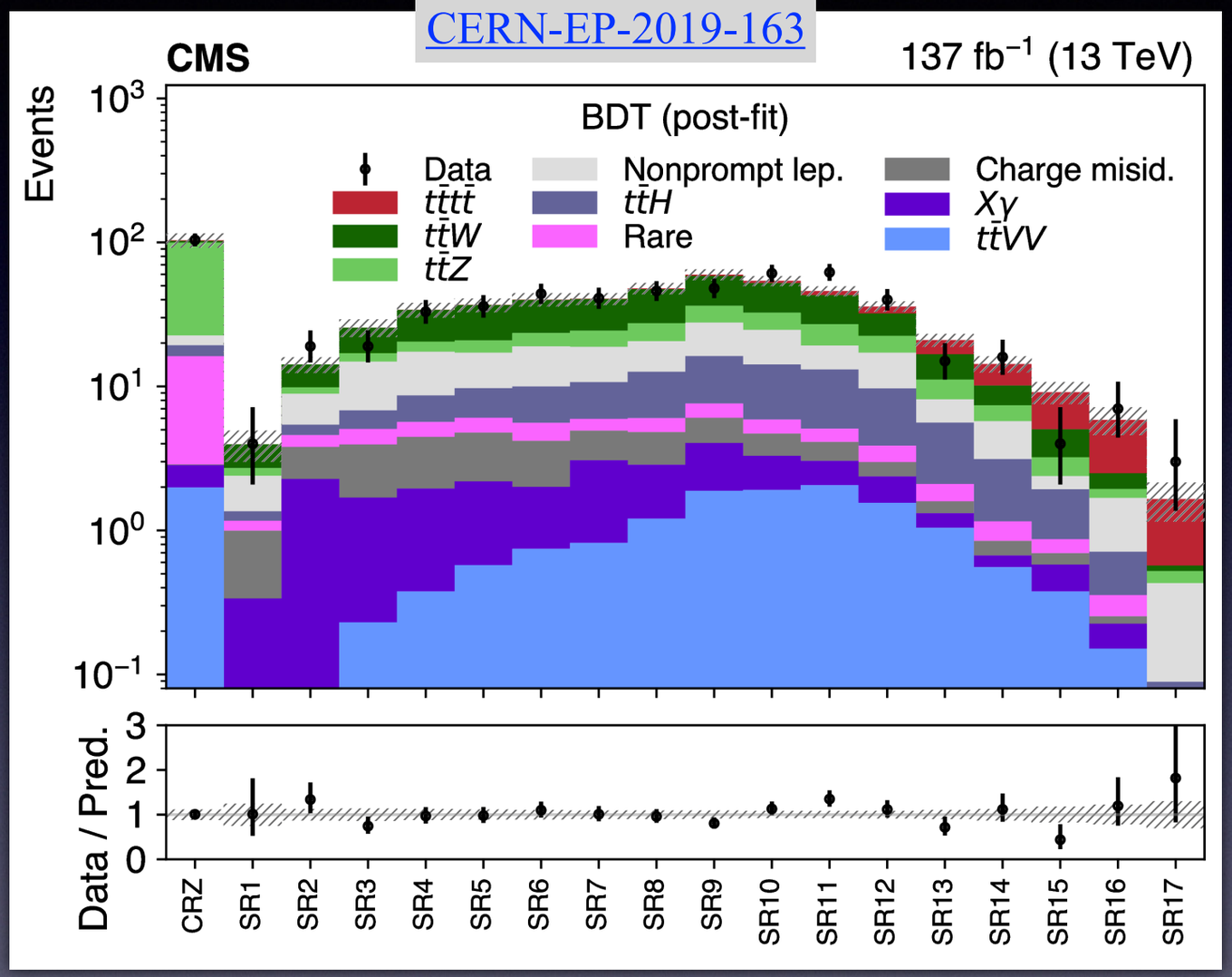
$$\sigma_{t\bar{t}t\bar{t}} = 28.5^{+12}_{-11}\ \text{fb}$$

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

CMS Search

- 137 fb^{-1} sample using 2LSS/3L channels

CERN-EP-2019-163



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

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

see K. Schweiger's talk for details

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]
- 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

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

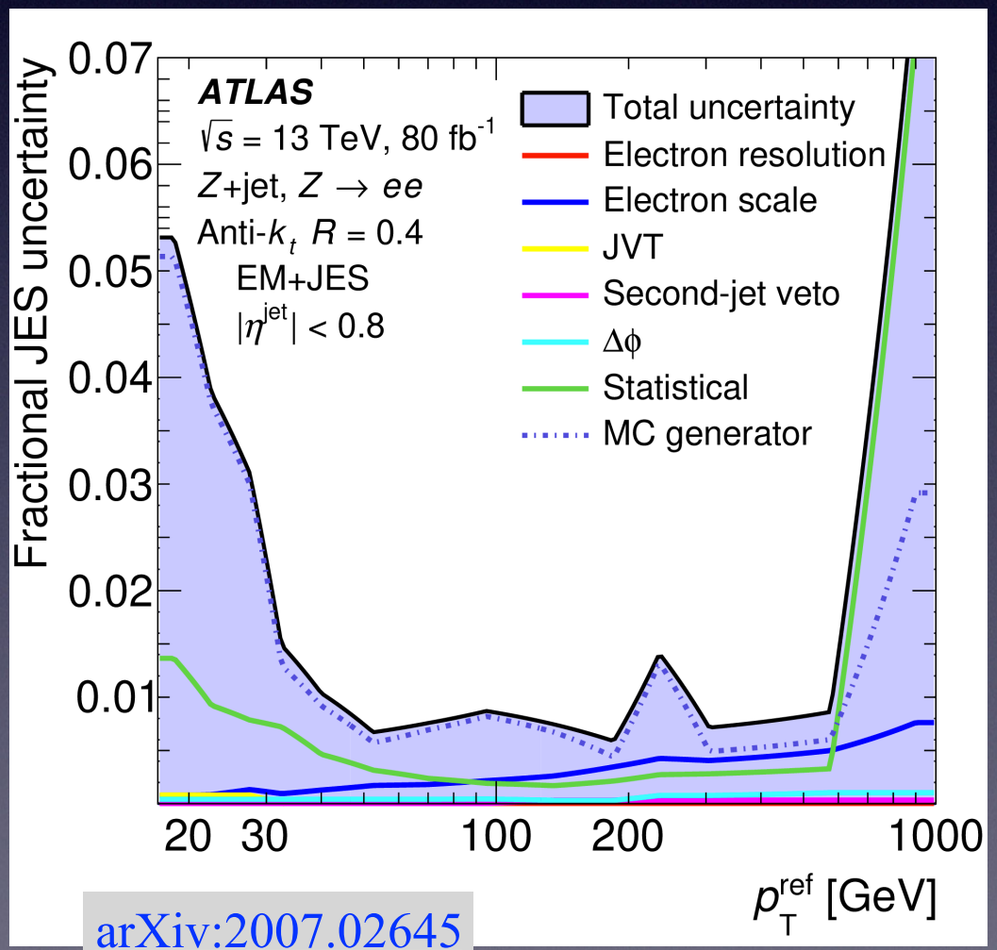
Trilepton: $\left| m_{\ell^+\ell^-} - 91 \text{ GeV} \right| > 10$ GeV

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

Jets and *b*-jets

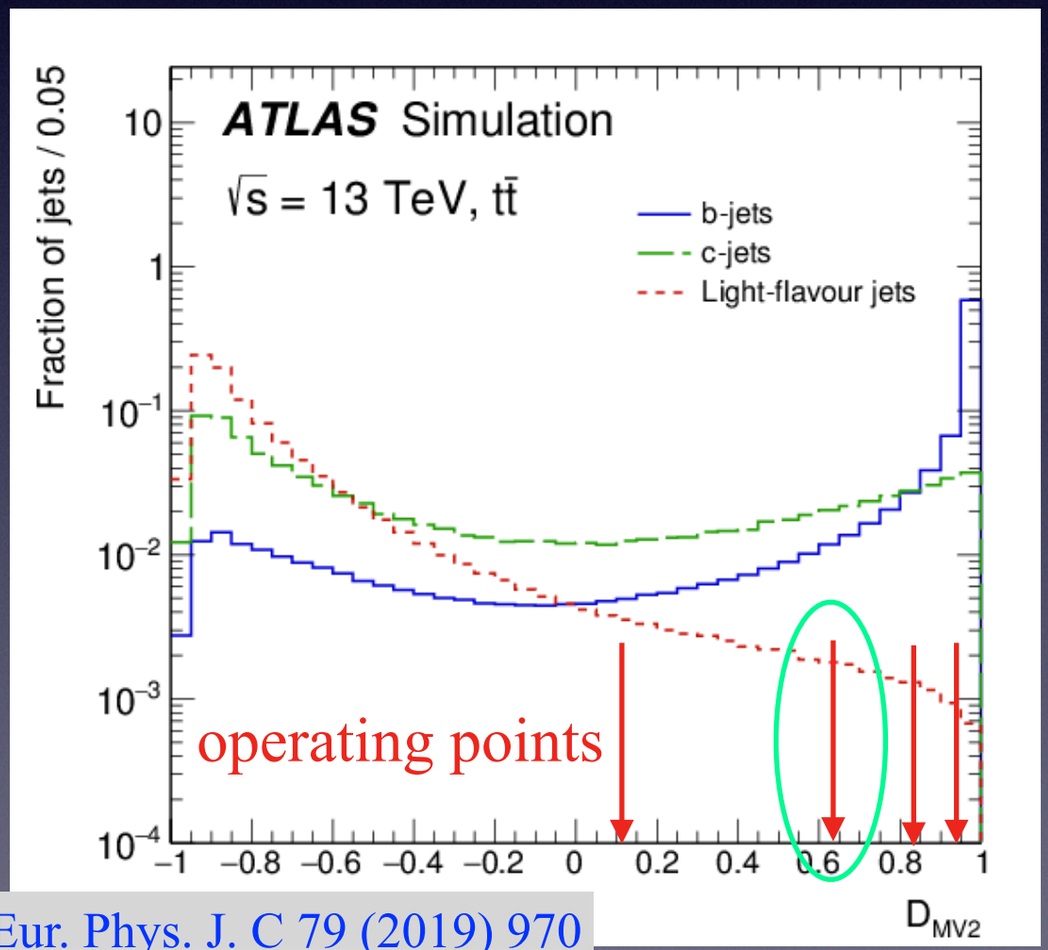
- Jet reconstruction and *b*-jet identification are crucial

Jet energy calibration at ~1% level in relevant p_T range



arXiv:2007.02645

- MV2c10 BDT based on track IPs and secondary vertices



Eur. Phys. J. C 79 (2019) 970

Backgrounds

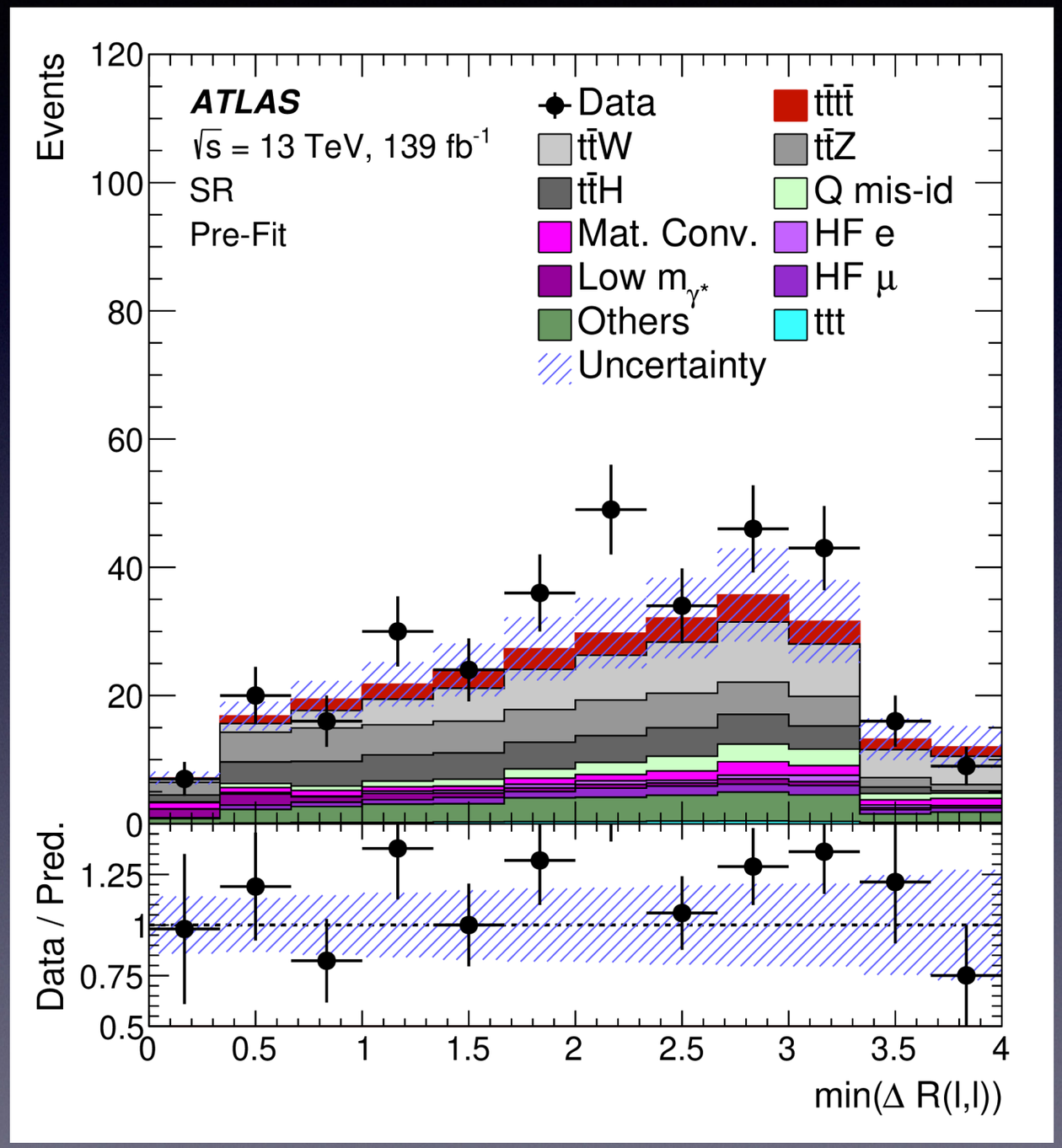
- Several reducible and irreducible backgrounds contribute to the SR yield

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 $Z \to ee$
Fake/non-prompt leptons
several sources considered

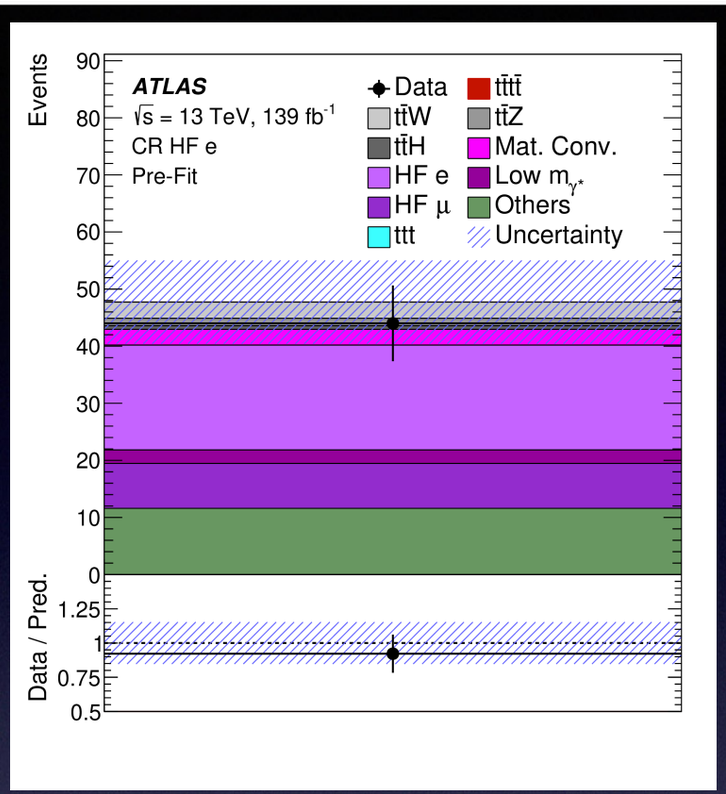


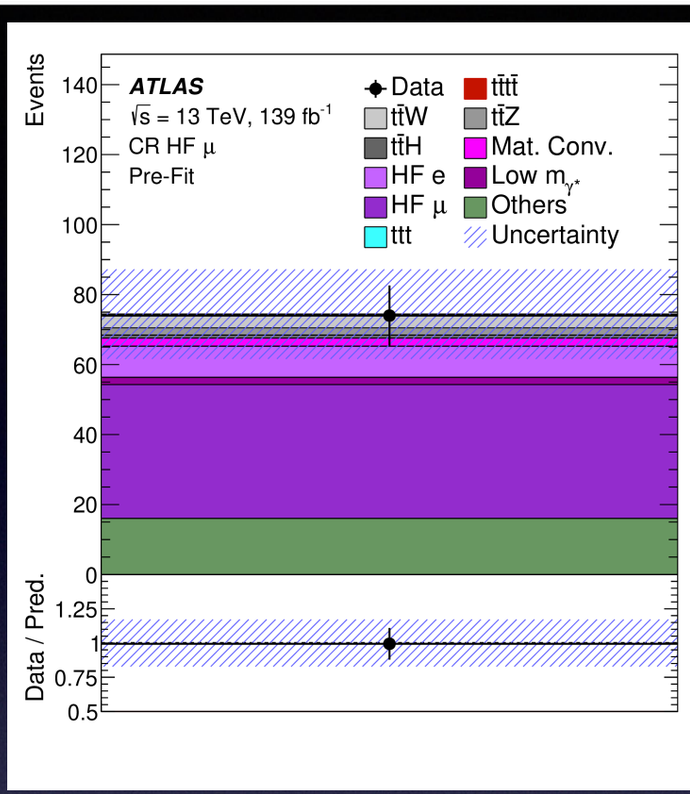
Control Regions

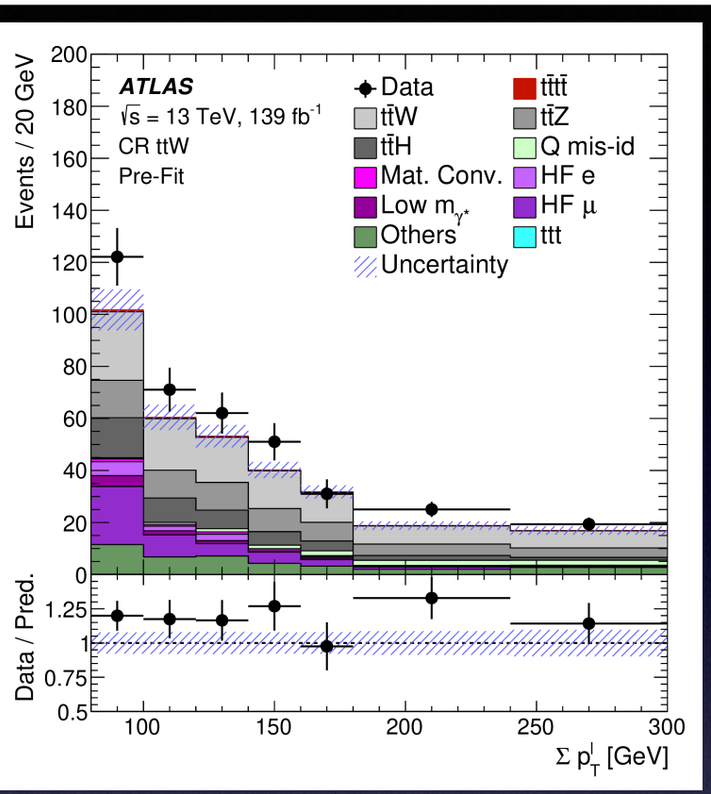
- The fake/non-prompt lepton rate is difficult to simulate precisely
  - highly sensitive to material and response effects
- Control regions enriched in different sources of fake/non-prompt leptons are defined:
  - since $t\bar{t}W$ is a significant contributor in all regions, an additional CR is defined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

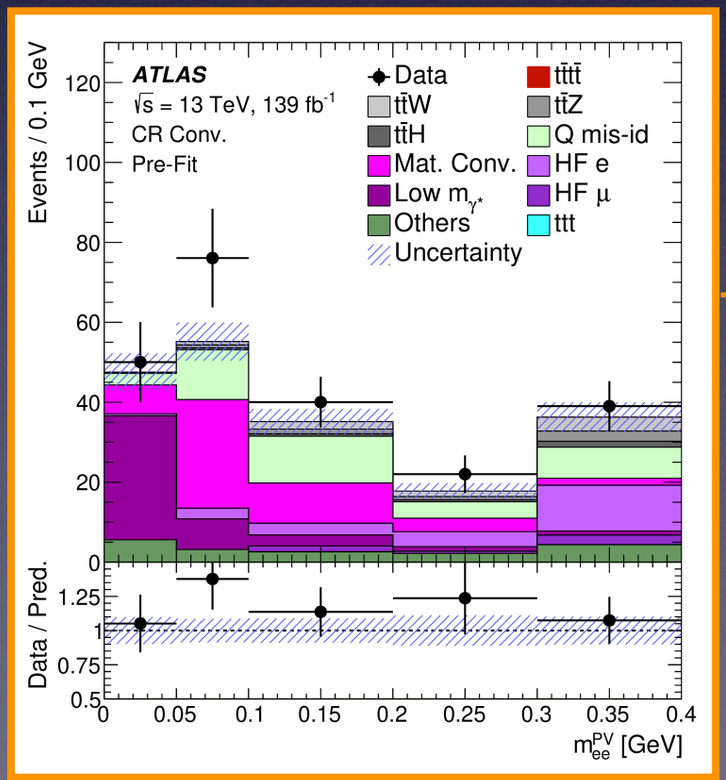
Region	Channel	N_j	N_b	Other requirements	Fitted variable
SR	2LSS/3L	≥ 6	≥ 2	$H_{\mathrm{T}} > 500$	BDT
CR Conv.	$e^{\pm}e^{\pm}\|\|e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{\mathrm{CV}} \in [0, 0.1\ \mathrm{GeV}]$ $200 < H_{\mathrm{T}} < 500$ GeV	m_{ee}^{PV}
CR HF e	$eee \,\|\|\, ee\mu$	-	$= 1$	$100 < H_{\mathrm{T}} < 250$ GeV	counting
CR HF μ	$e\mu\mu \,\|\|\, \mu\mu\mu$	-	$= 1$	$100 < H_{\mathrm{T}} < 250$ GeV	counting
CR ttW	$e^{\pm}\mu^{\pm}\|\|\mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{\mathrm{CV}} \notin [0, 0.1\ \mathrm{GeV}]$, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_{\mathrm{T}} < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_{\mathrm{T}} < 500$ GeV	$\Sigma p_{\mathrm{T}}^{\ell}$

Control Regions





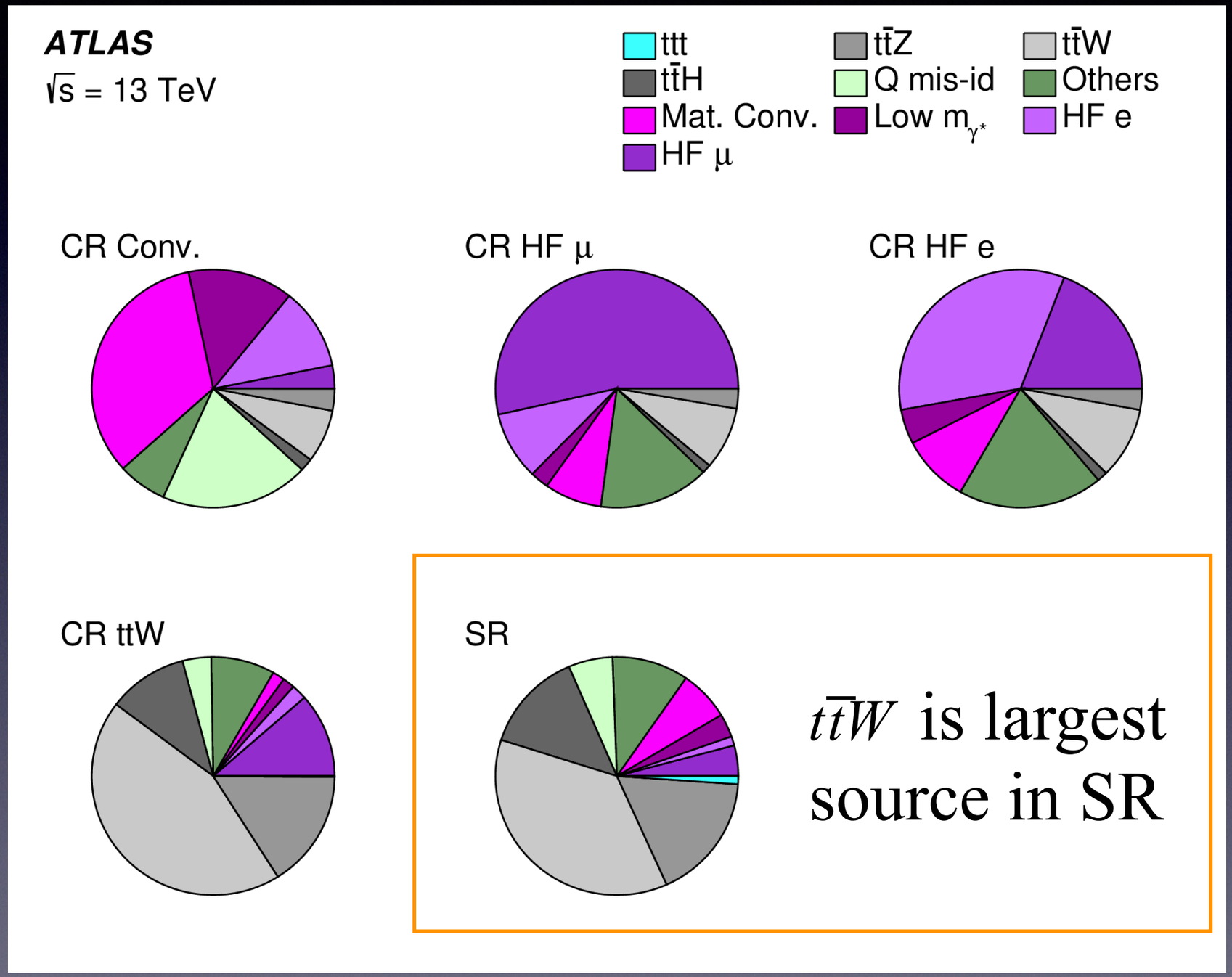




- Binned in mass of *e* track and nearest track evaluated at PV
  - small for virtual photons, larger for material conversions
- Allows contributions from these sources to be distinguished

Composition of Analysis Regions

- Post-fit sample composition

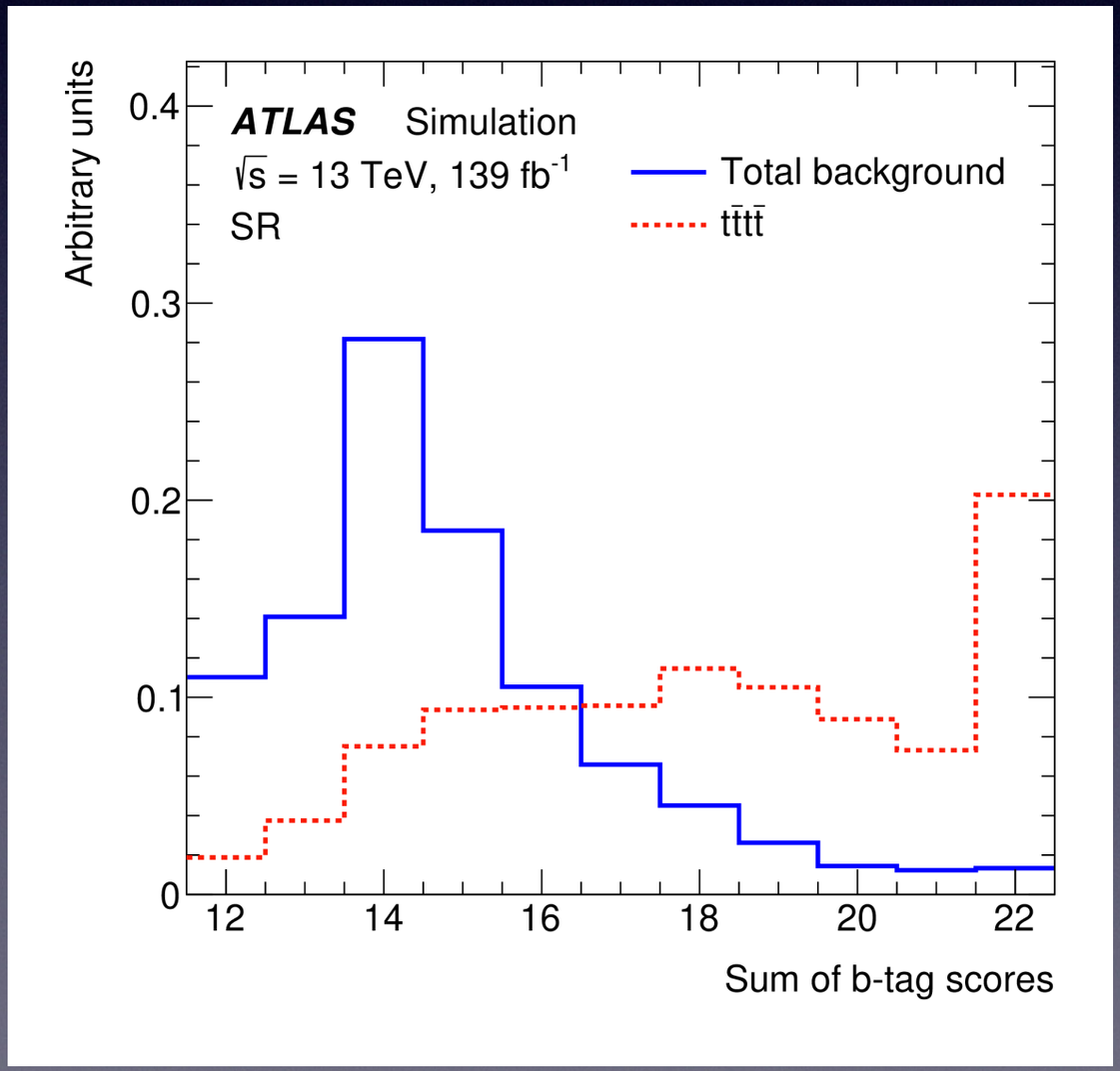


Signal/background Discrimination

- 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

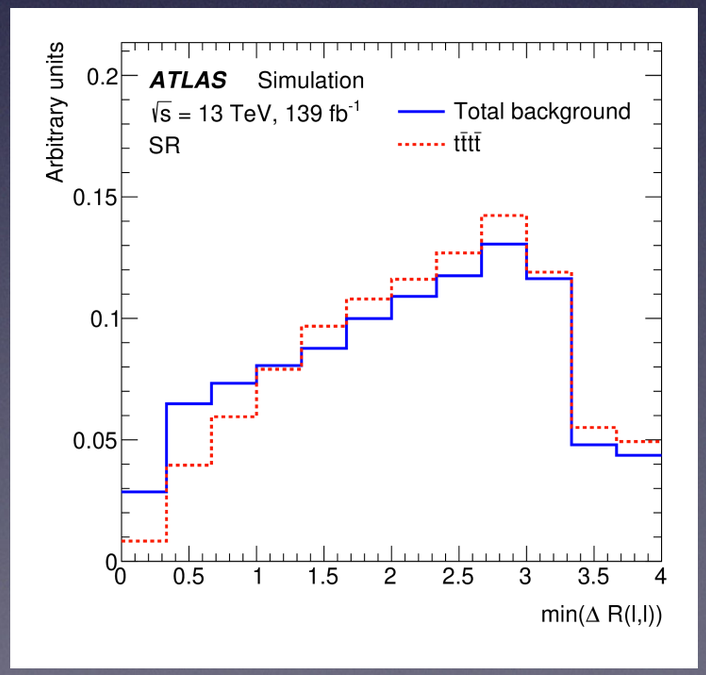
- Sum is taken over all jets
- Provides better S/B discrimination than "tag-and-count" method
  - integers correspond to well-calibrated working points

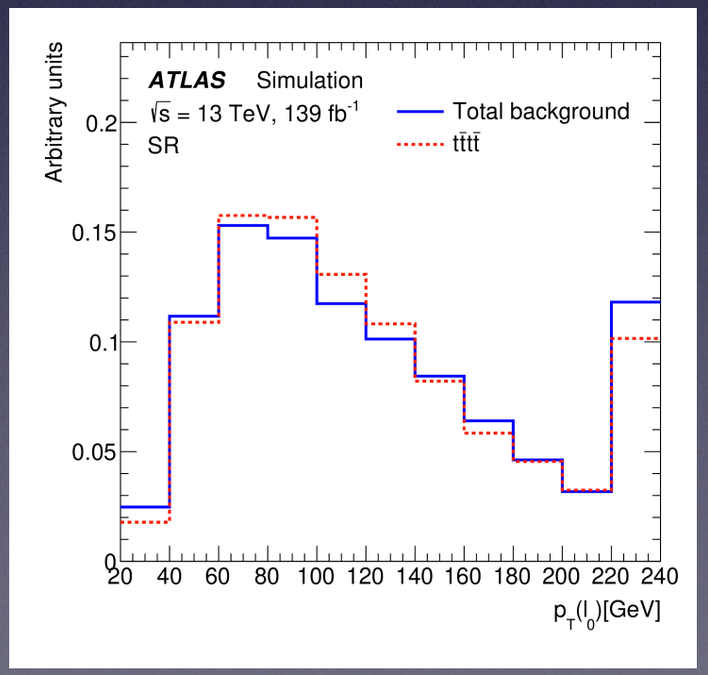


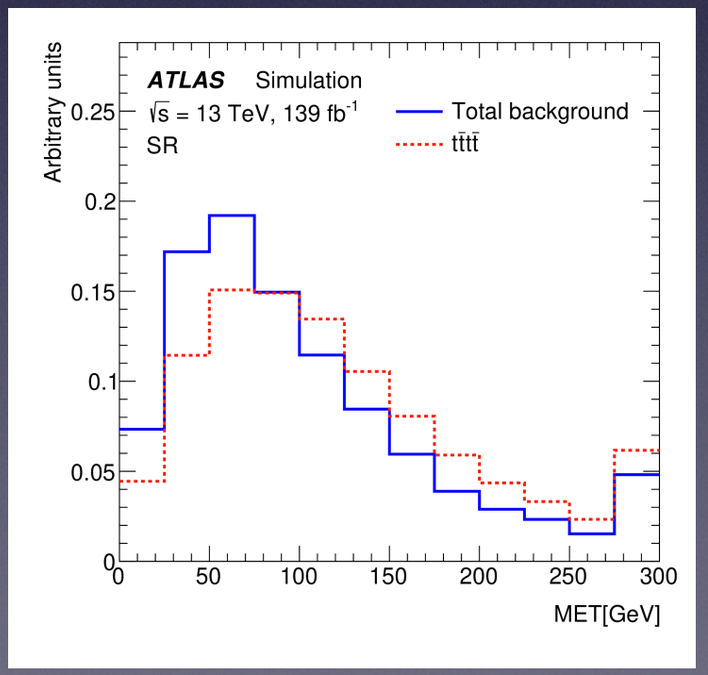
Multivariate Analysis

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

$\min\left(\Delta R_{\ell\ell}\right)$	leading lepton p_T	E_T^{miss}	leading jet p_T
subleading jet p_T	$H_T - p_T\left(j_1\right)$	sixth-leading jet p_T	$\sum_{i\neq j}\Delta R_{\ell_i\ell_j}$
leading b-jet p_T	$\max\left(\Delta R_{\ell b-\text{jet}}\right)$	$\min\left(\Delta R_{jb-\text{jet}}\right)$	

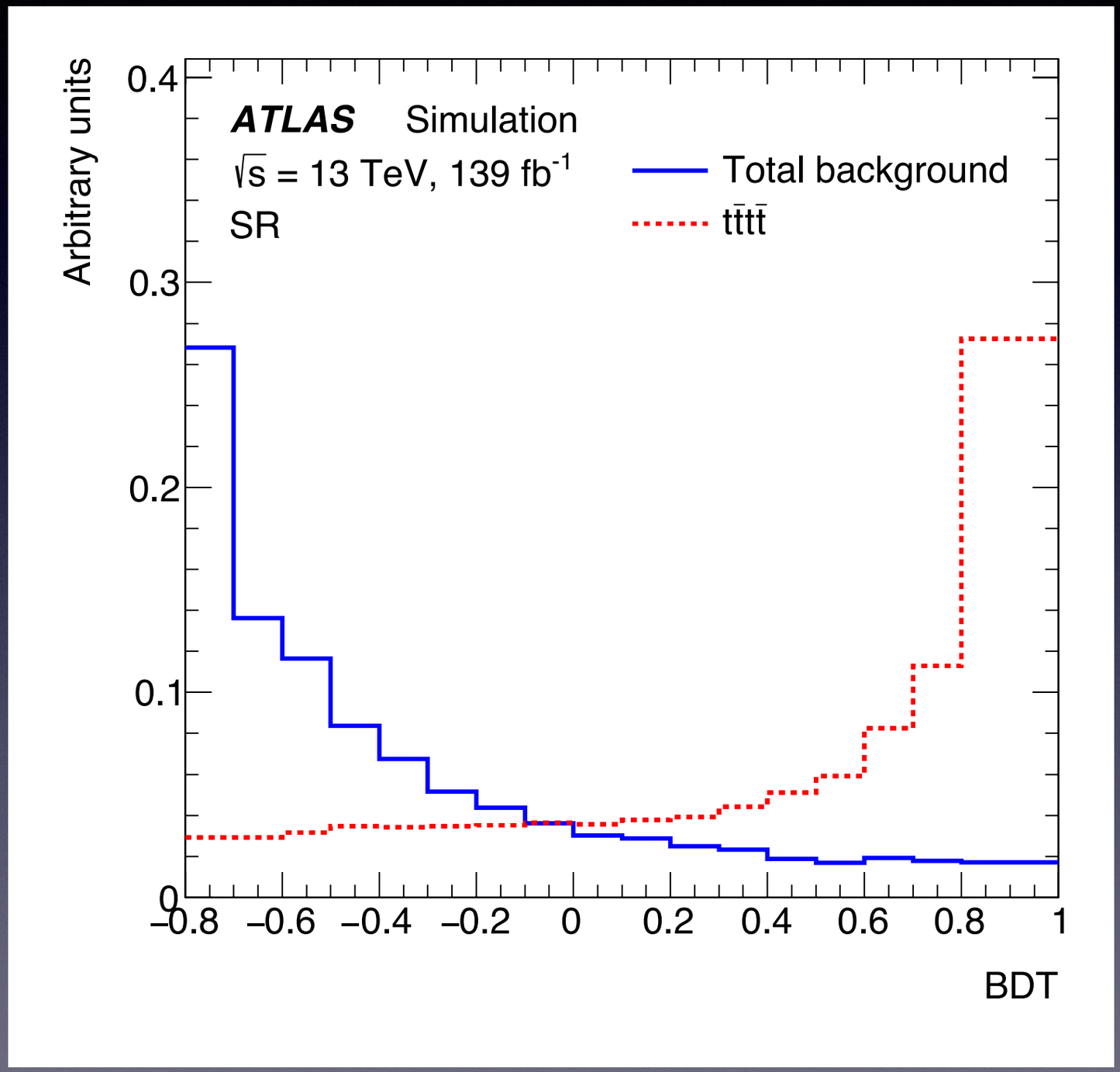




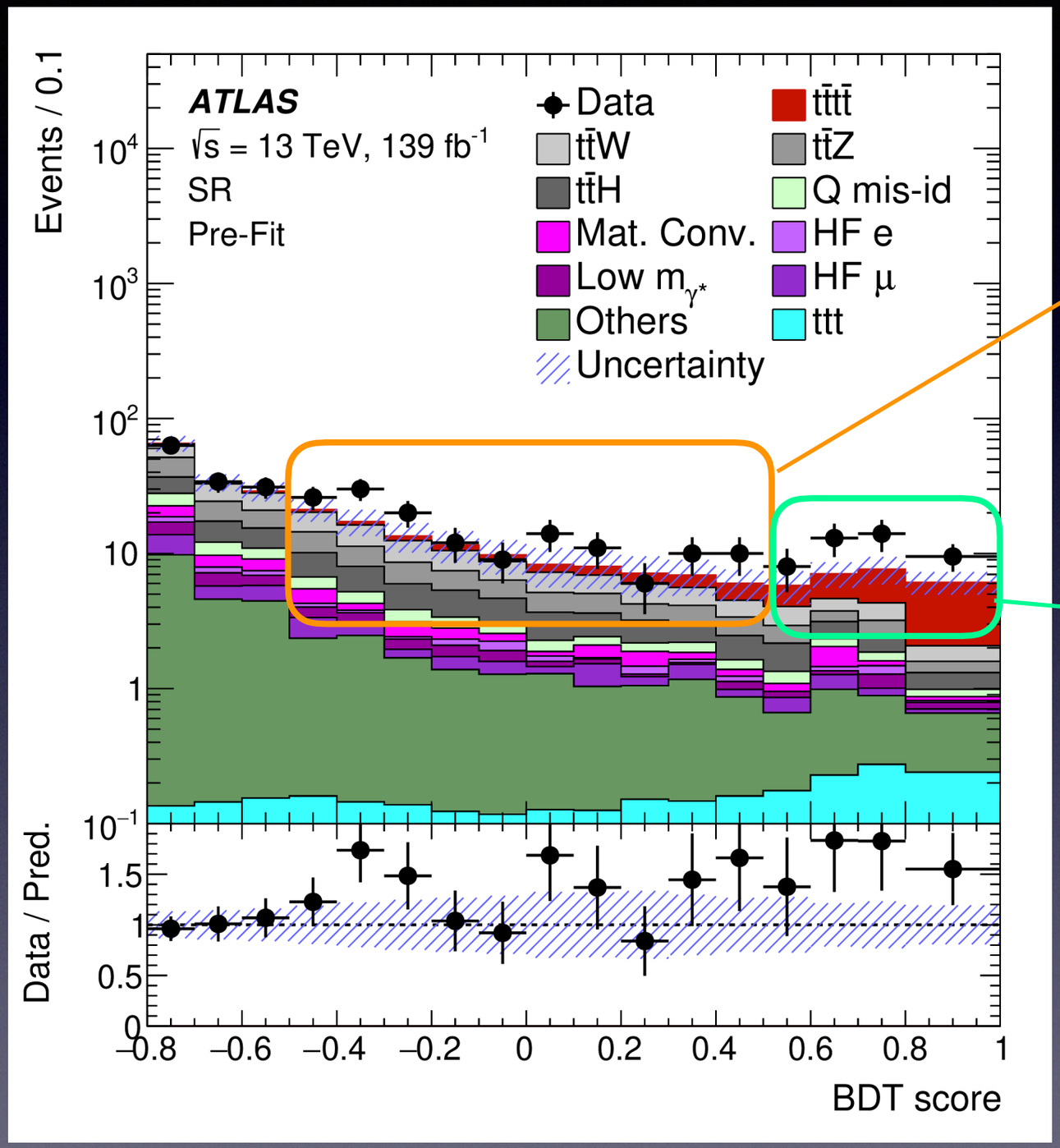


Multivariate Analysis

- 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

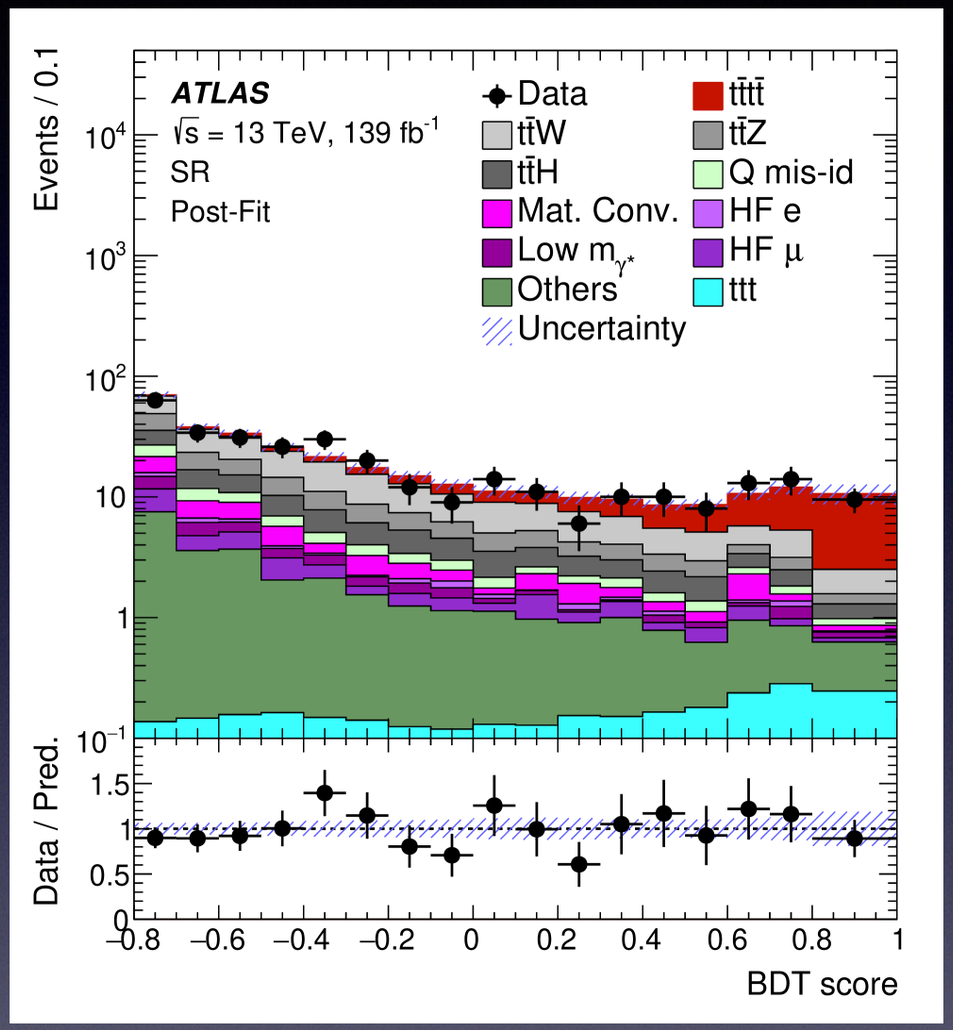
- Simultaneous fit of signal and control regions
- Parameter of interest:

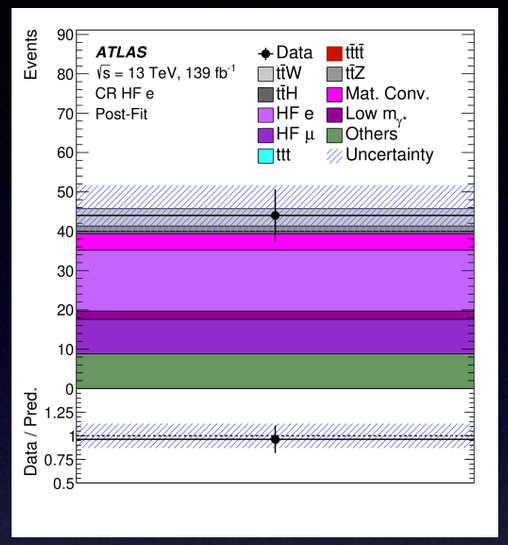
$$\mu \equiv \frac{\sigma_{t\bar{t}t\bar{t}}\left(\text{obs.}\right)}{\sigma_{t\bar{t}t\bar{t}}\left(SM\right)}$$

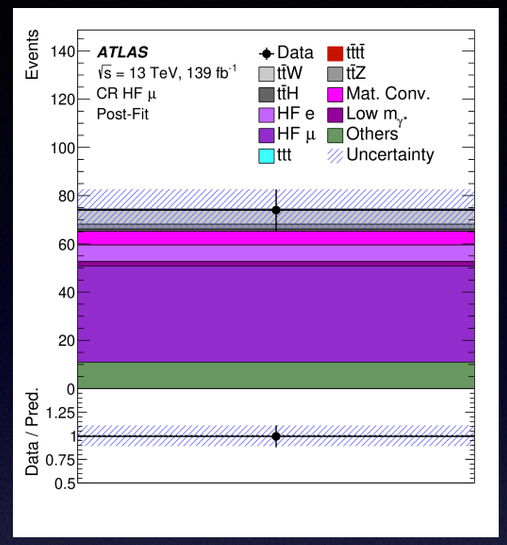
- Key background normalizations allowed to float:
  - Non-prompt e and μ from heavy-flavor decay
  - Non-prompt e from conversions
  - $t\bar{t}W$ (nominal cross section is 601 fb, calculated at NLO w/ EW corrections) JHEP 07 (2012) 052 JHEP 06 (2015) 184 arXiv: 1610.07922
- Other backgrounds constrained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

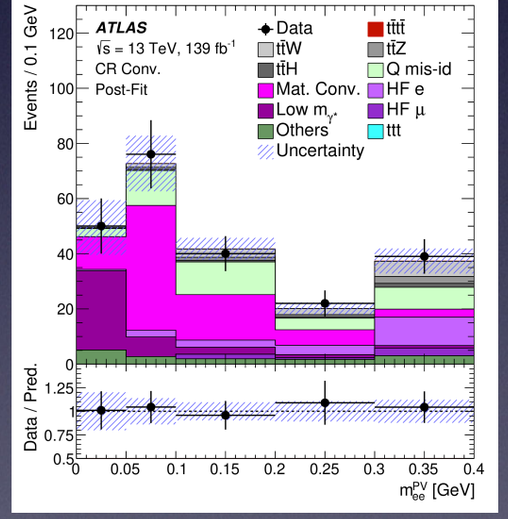
Results

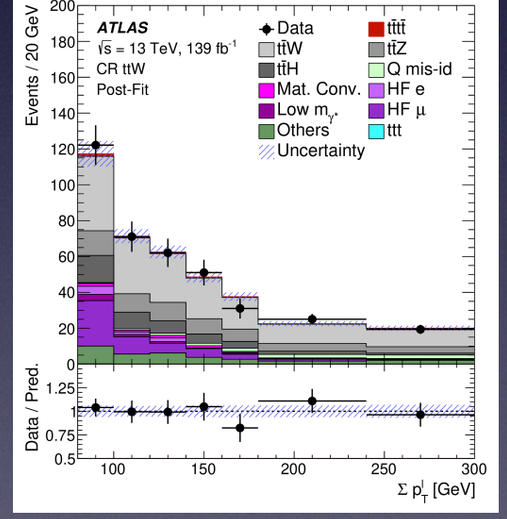
- Fitted distributions in the signal and control regions











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

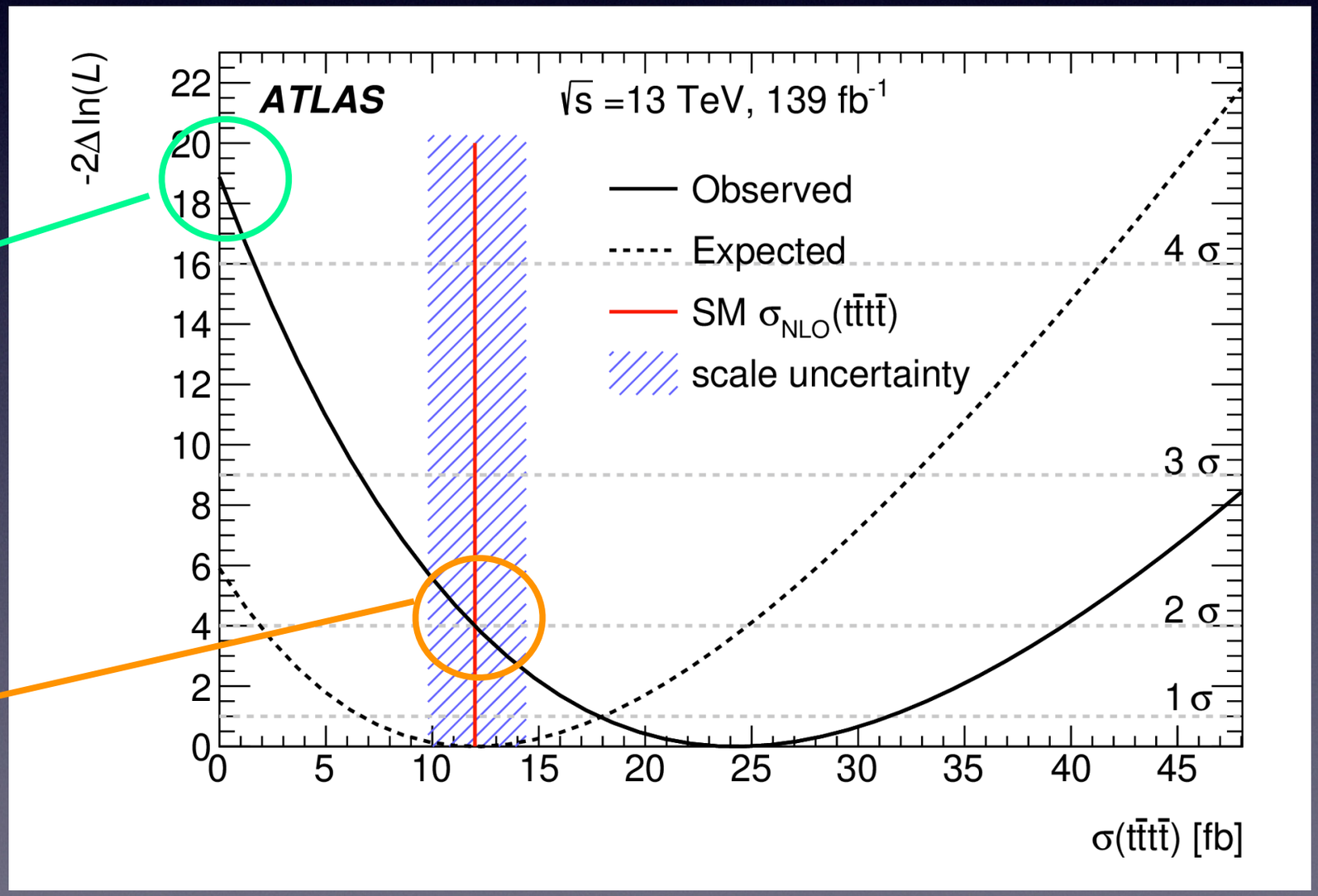
- Excess at high BDT in signal region results in

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

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

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

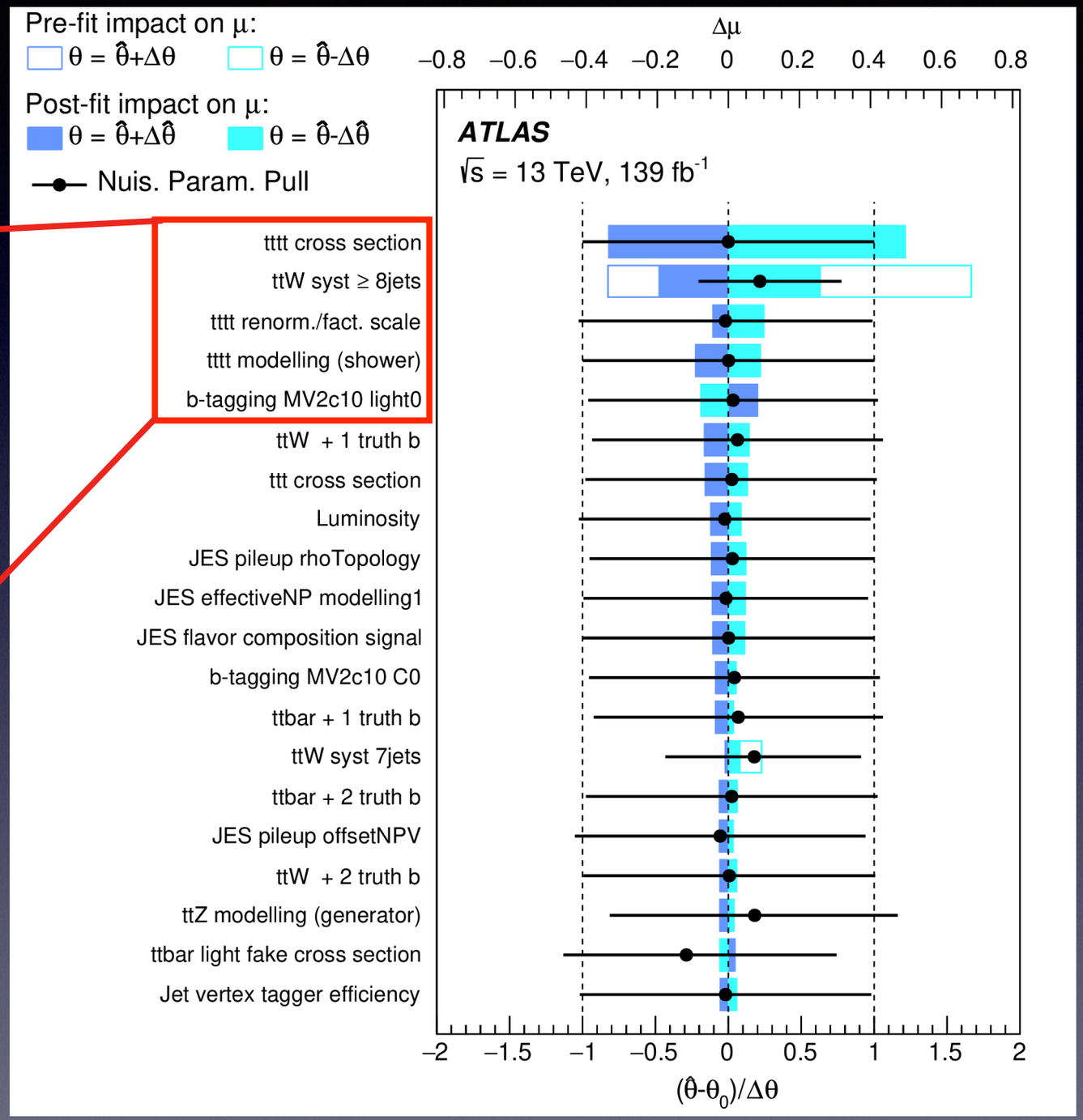
*ttW syst ≥ 8jets

tttt renorm./fact. scale

tttt modelling (shower)

b-tagging MV2c10 light0

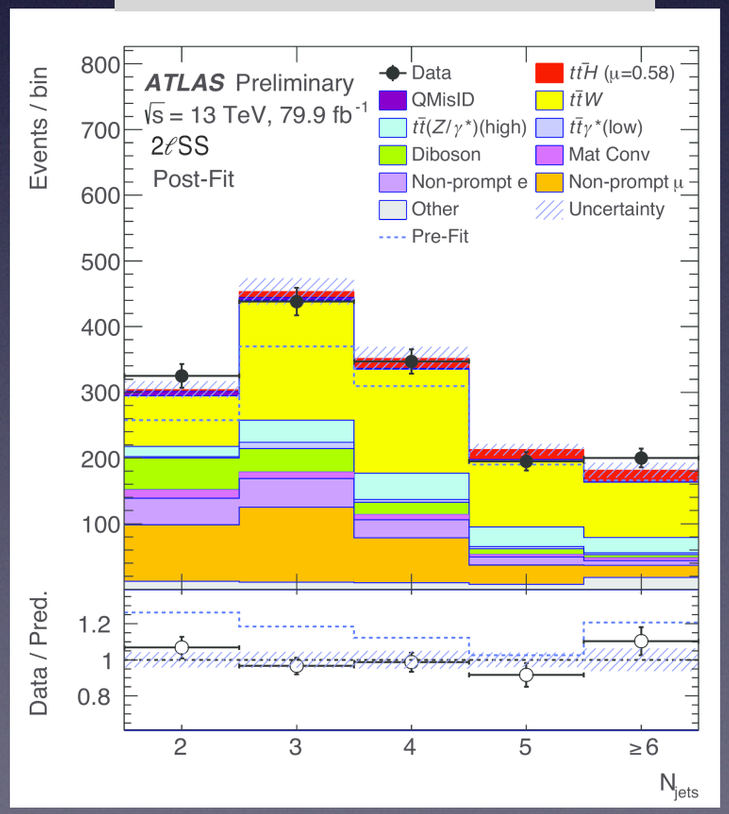
*details in coming slides

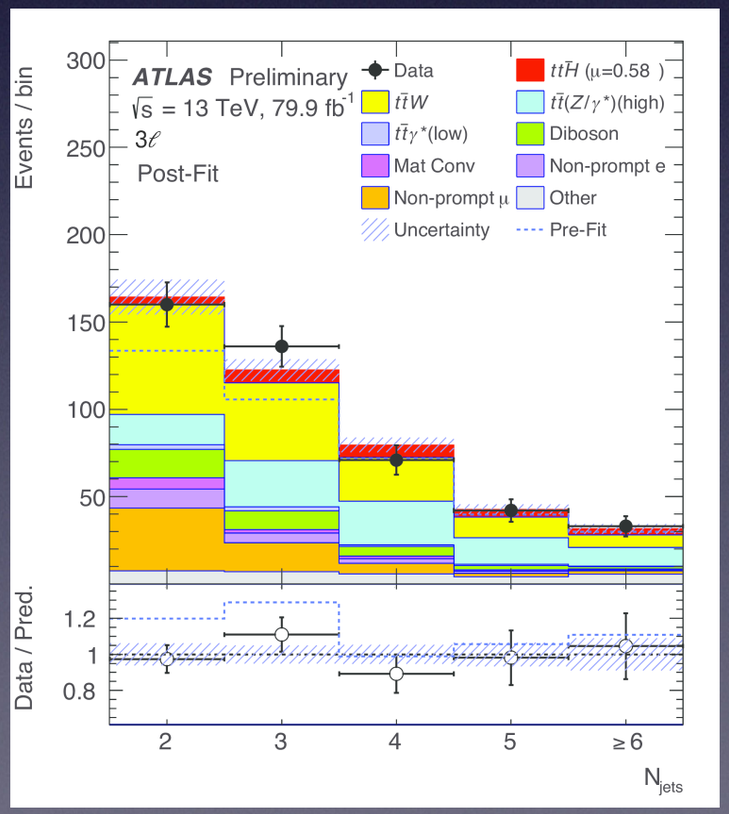


Investigation of $t\bar{t}W$

- 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.q. $t\bar{t}H$ search in multi-lepton final state:

ATLAS-CONF-2019-045





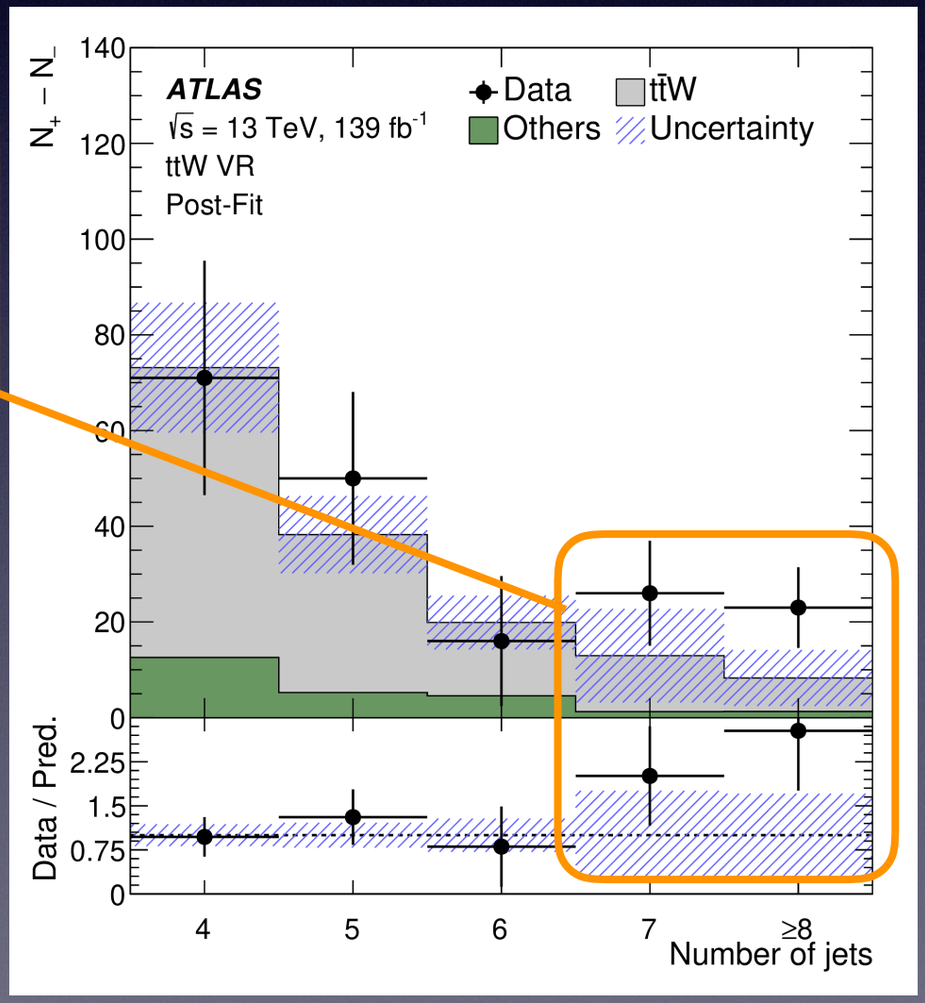
$t\bar{t}W$ normalization factors are 1.3 - 1.7 (depending on jet and lepton multiplicity)

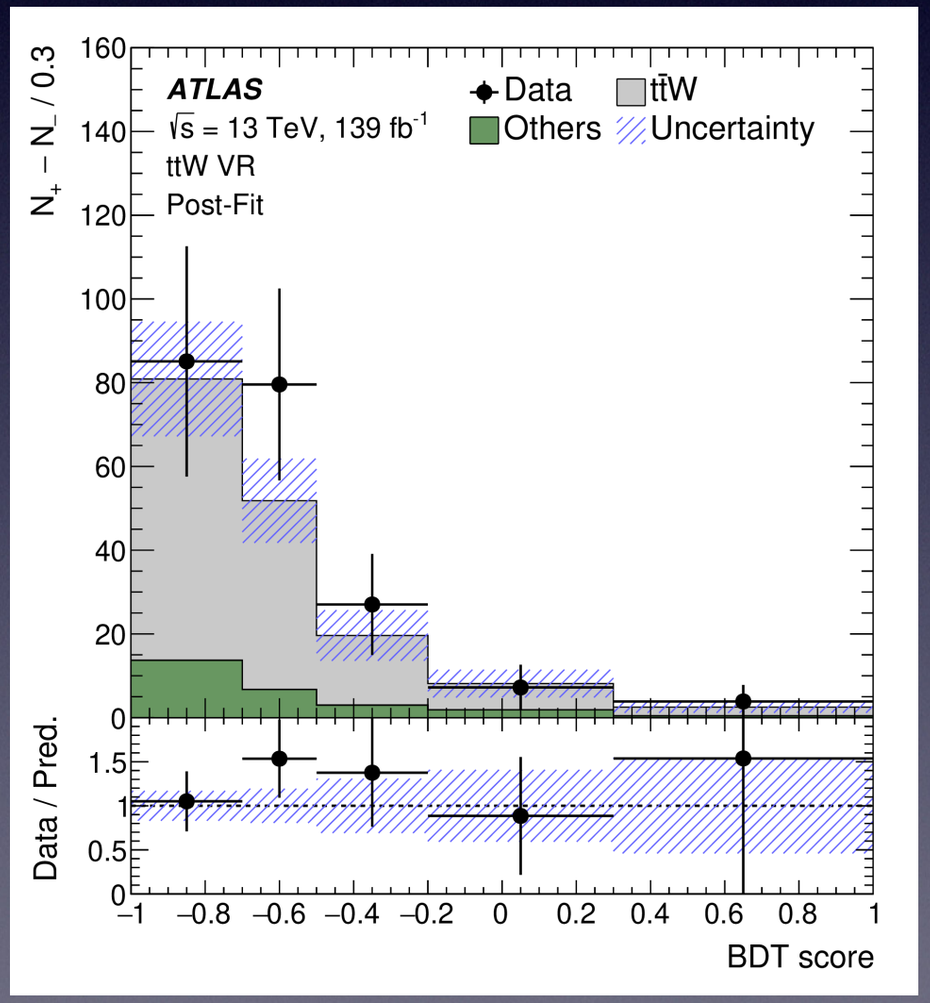
Investigation of $t\bar{t}W$

- 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

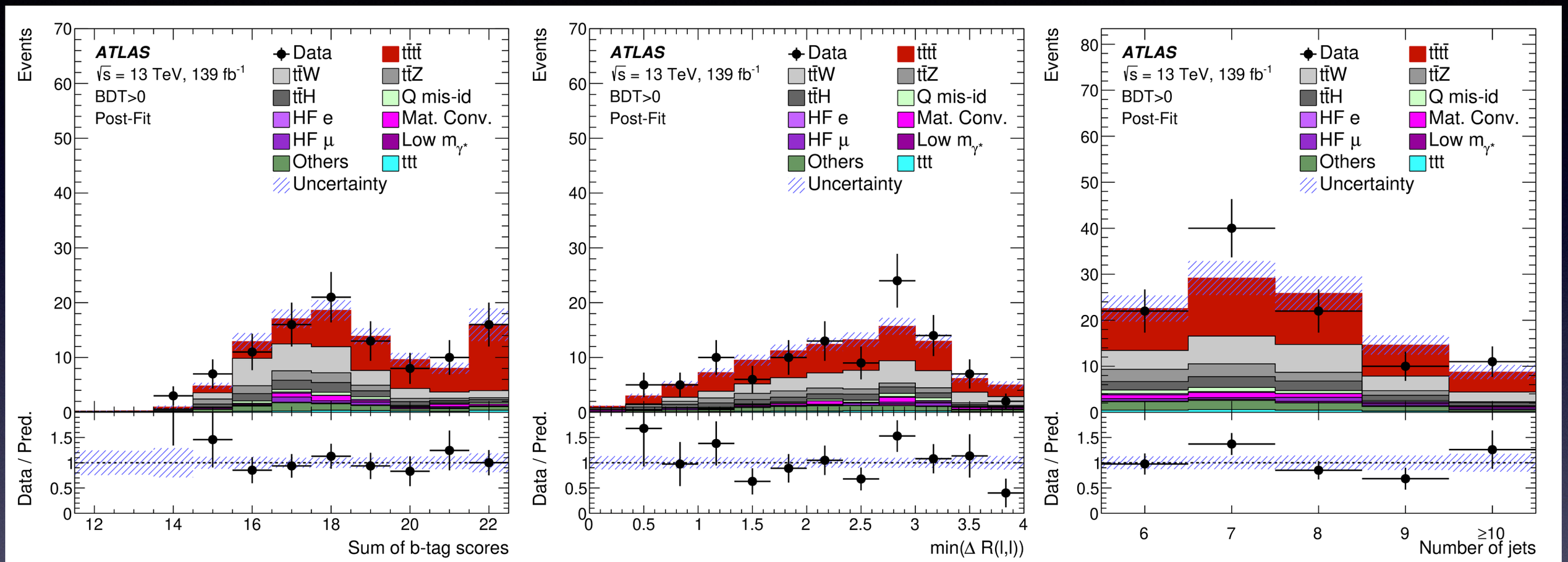
see G. Bevilacqua's talk and on NLO calculation





Cross Checks

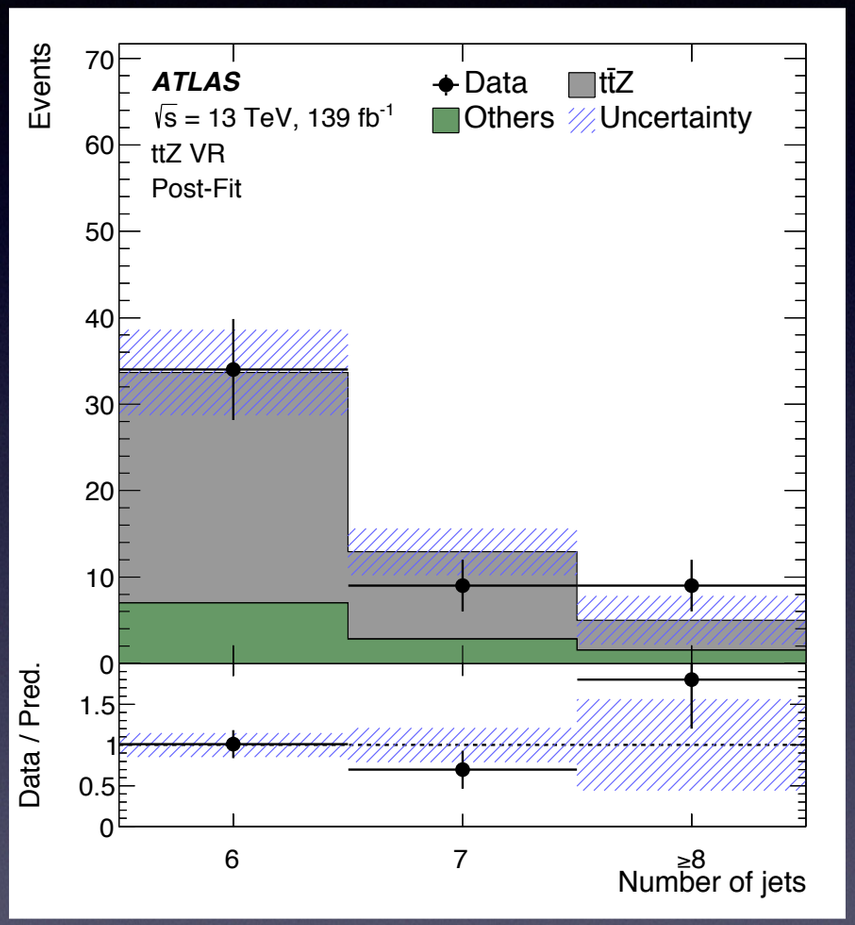
- Kinematic distributions for events with BDT > 0

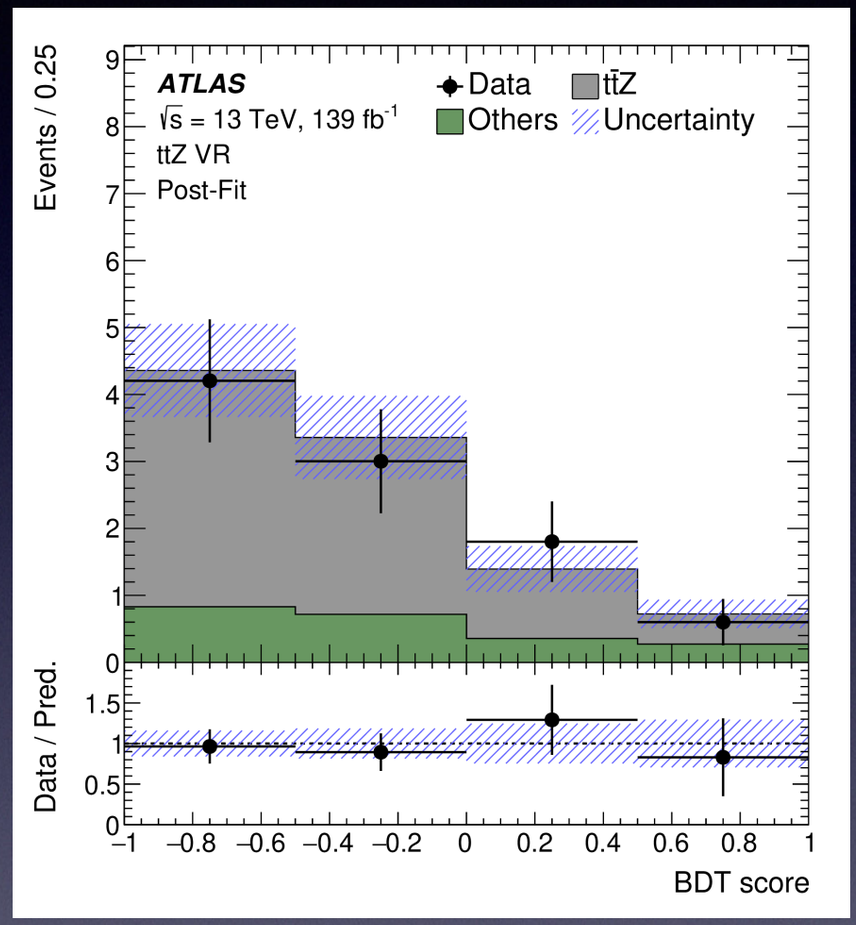


Excess over background consistent with $t\bar{t}t\bar{t}$

Cross Checks

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





- 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

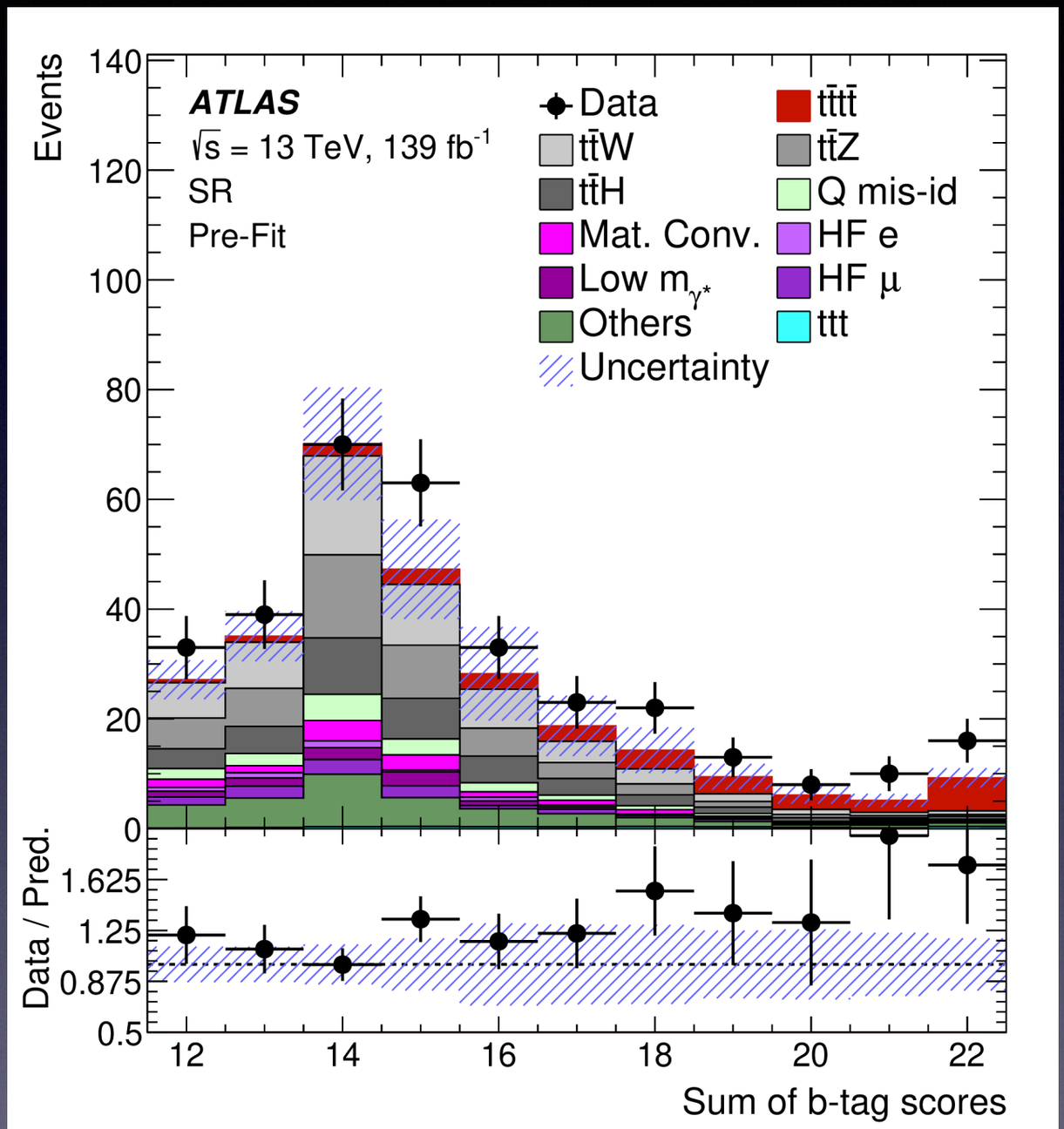
- ATLAS reports evidence for four-top-quark production

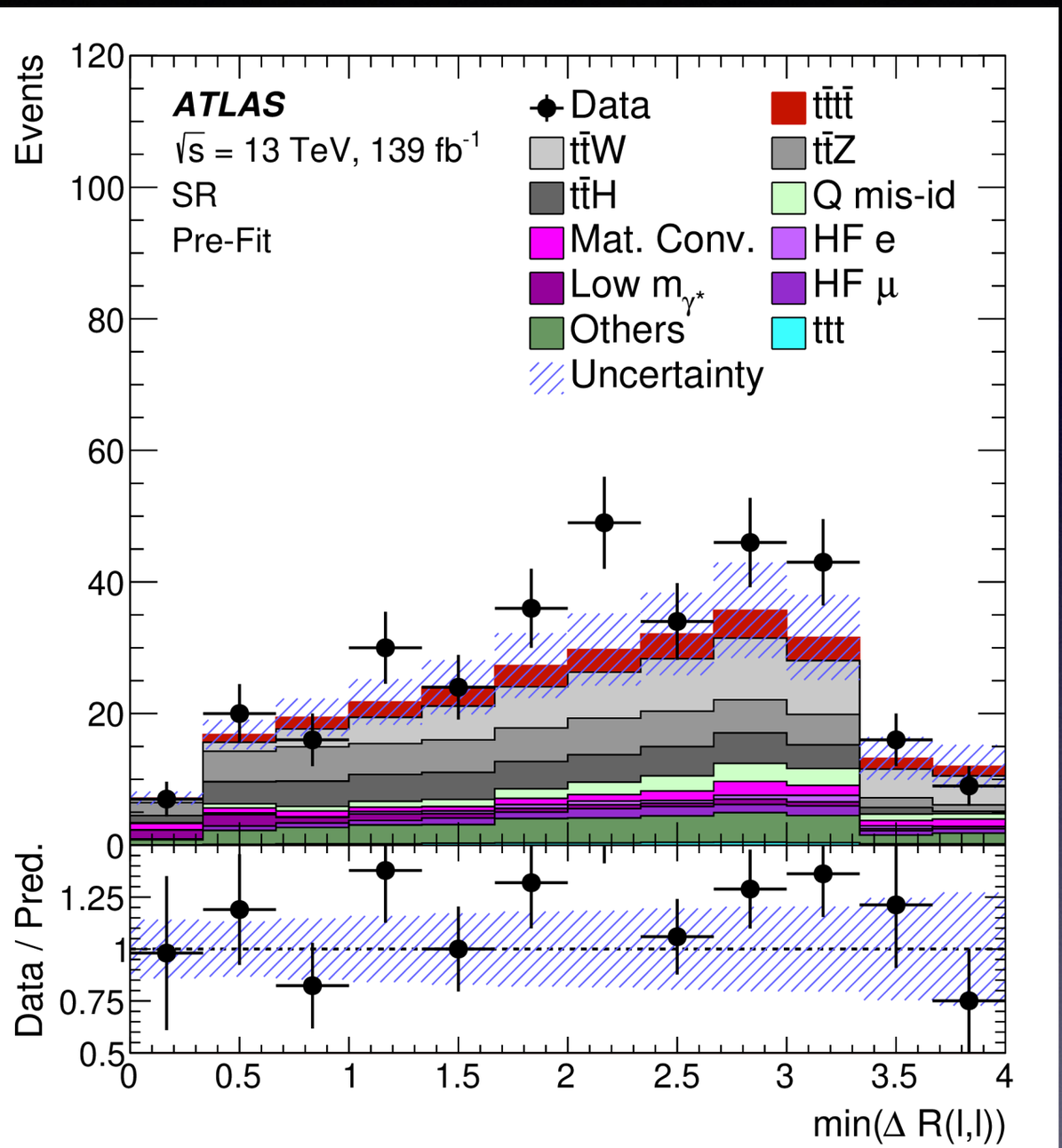
$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat}) \,^{+5}_{-4}(\text{syst}) \text{ fb} = 24^{+7}_{-6} \text{ fb}$$

- 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 (submitted to EPJC)

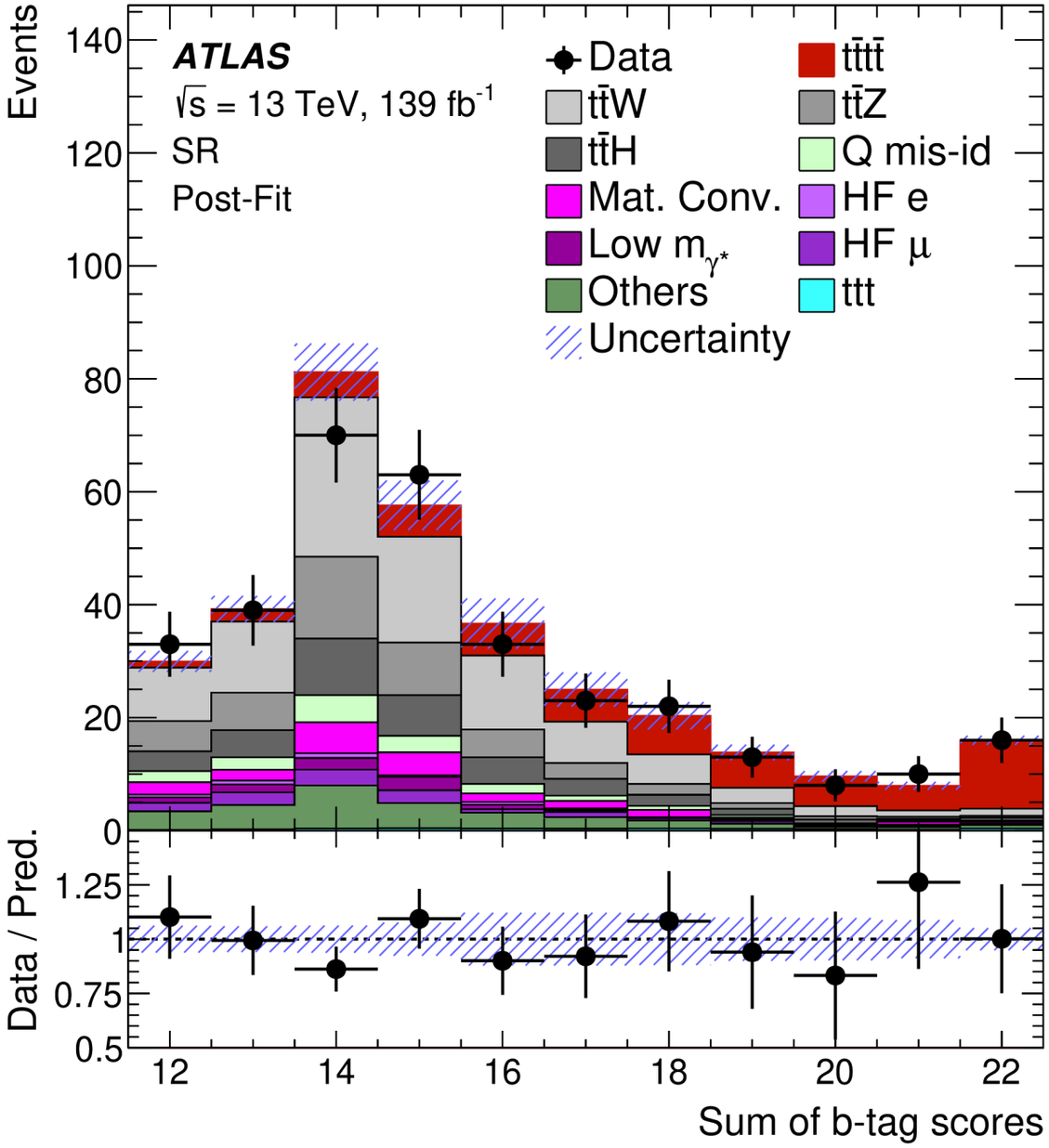
Backup

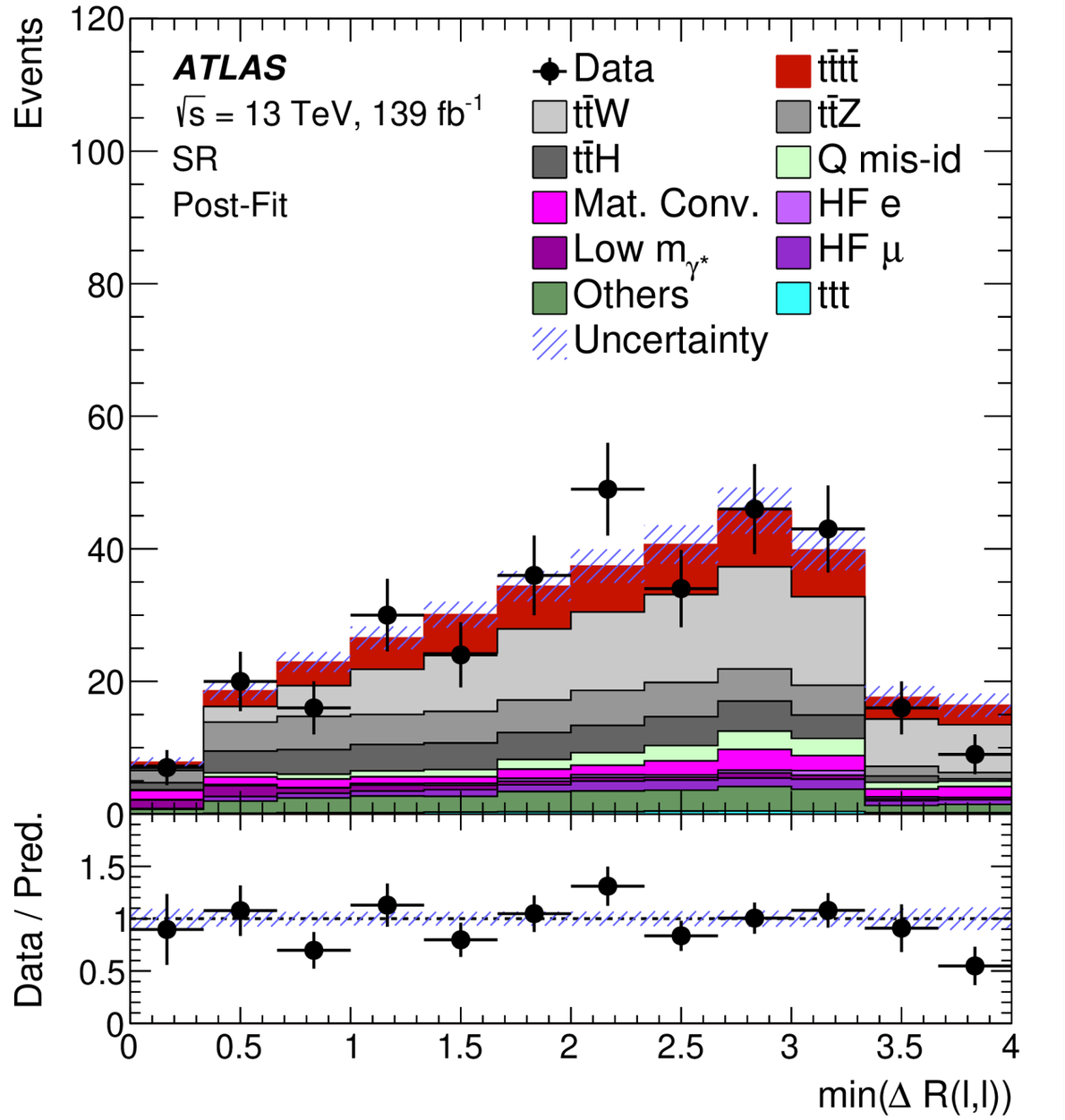
Pre-fit Variable Comparisons



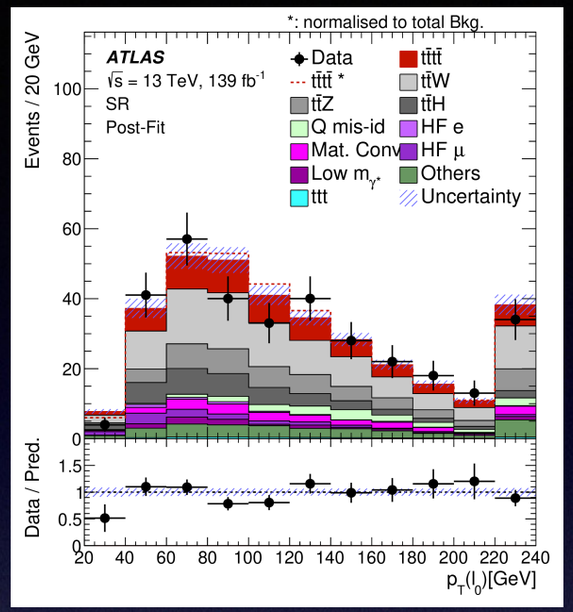


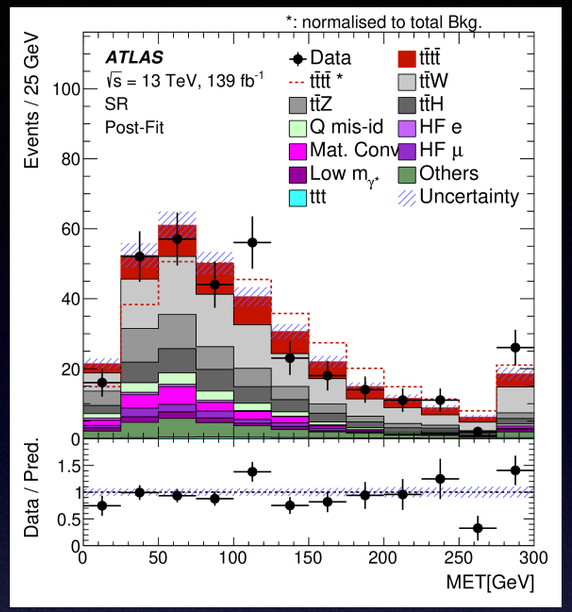
Post-fit Variable Comparisons

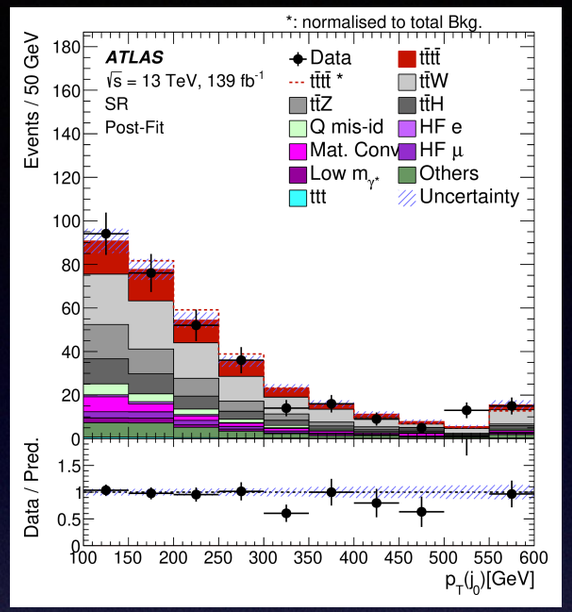


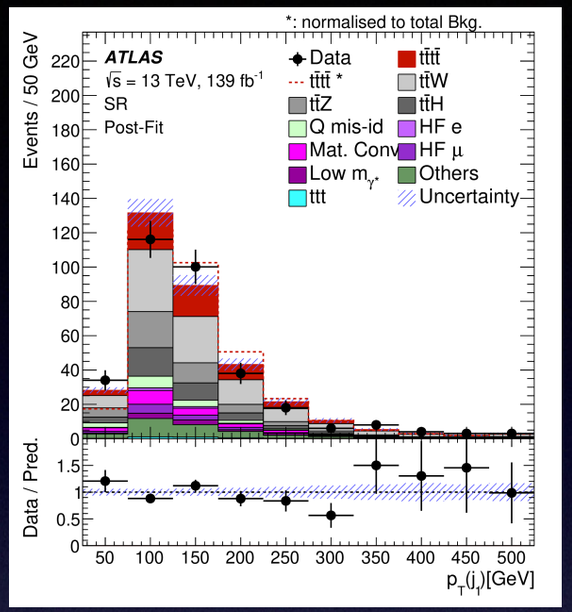


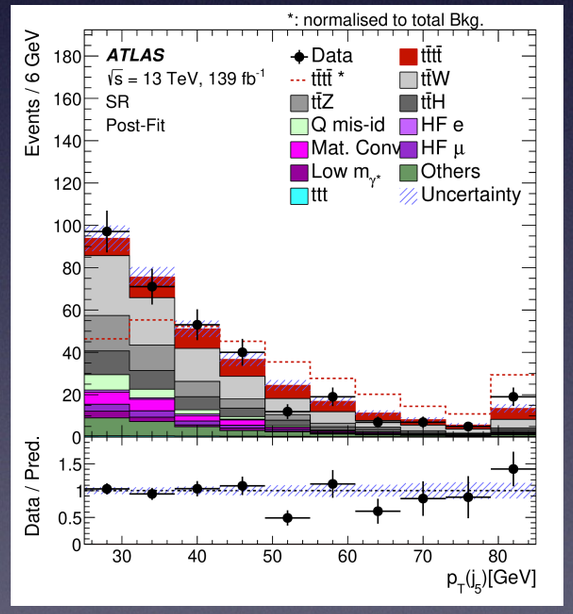
Post-fit Variable Comparisons

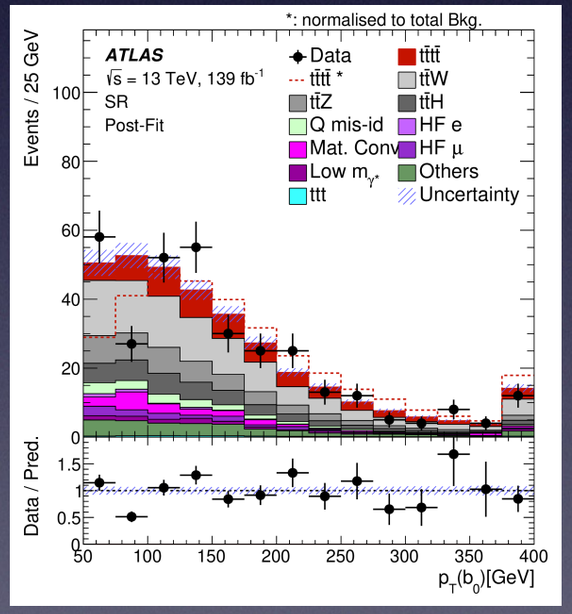


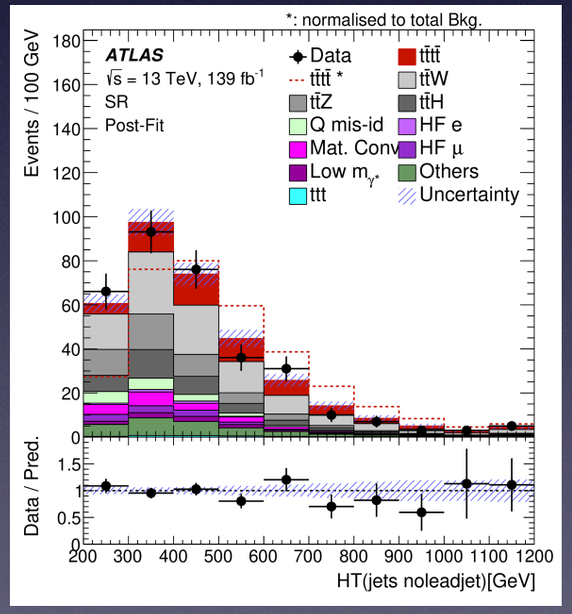


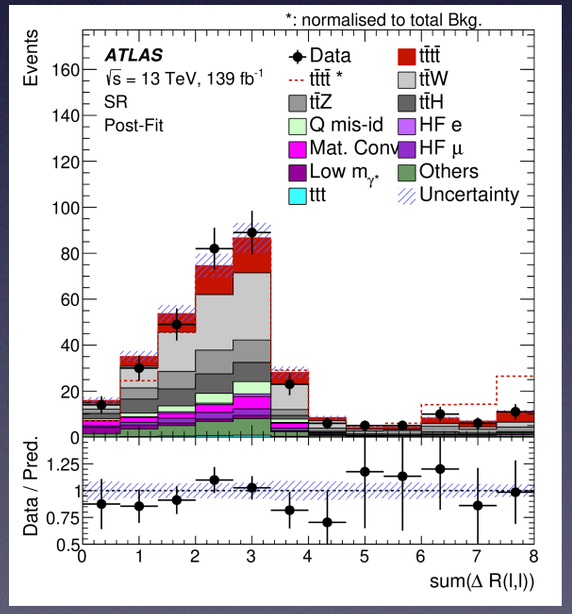












Post-fit Yields

	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