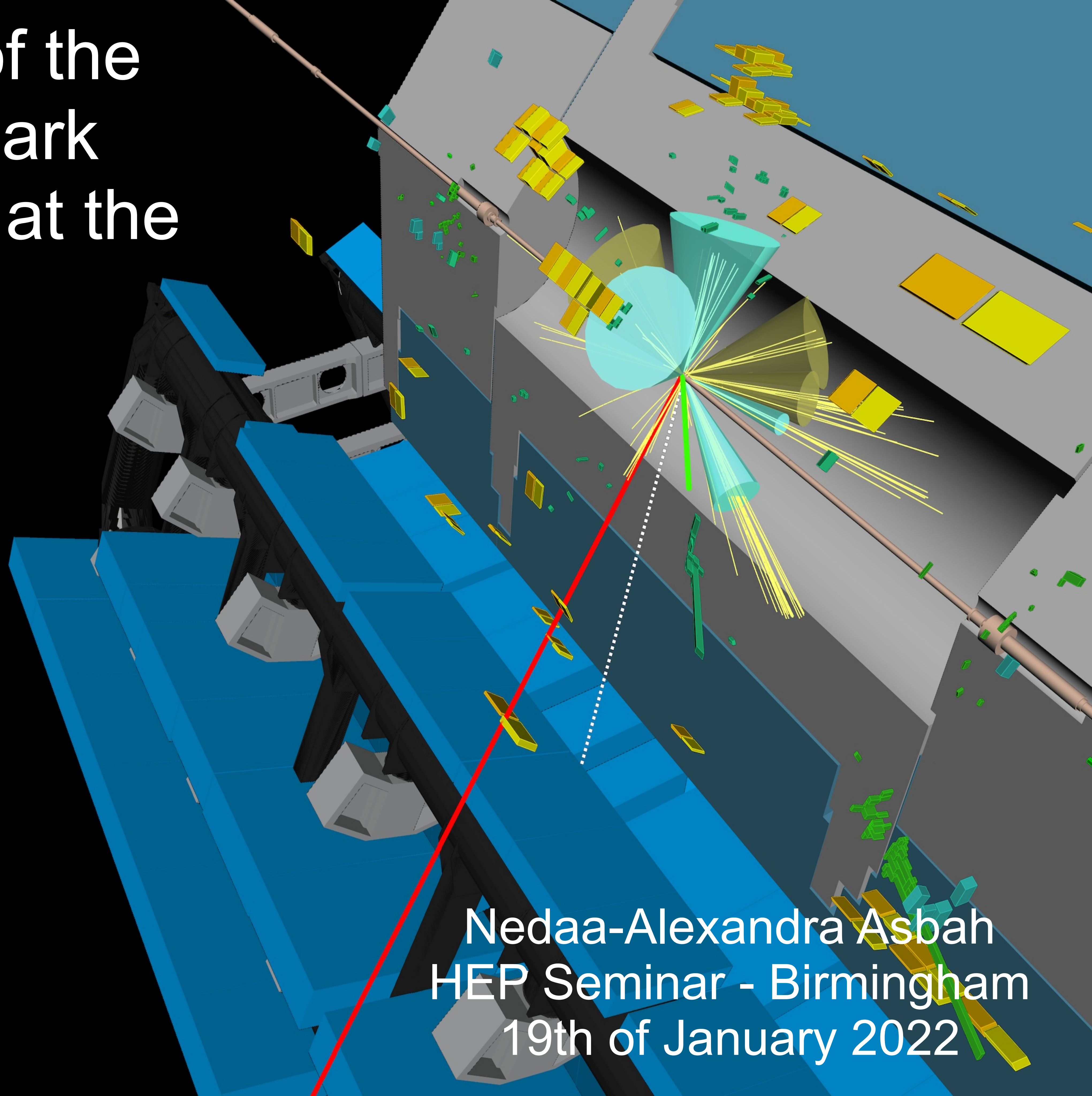
Evidence of the four-top-quark production at the LHC

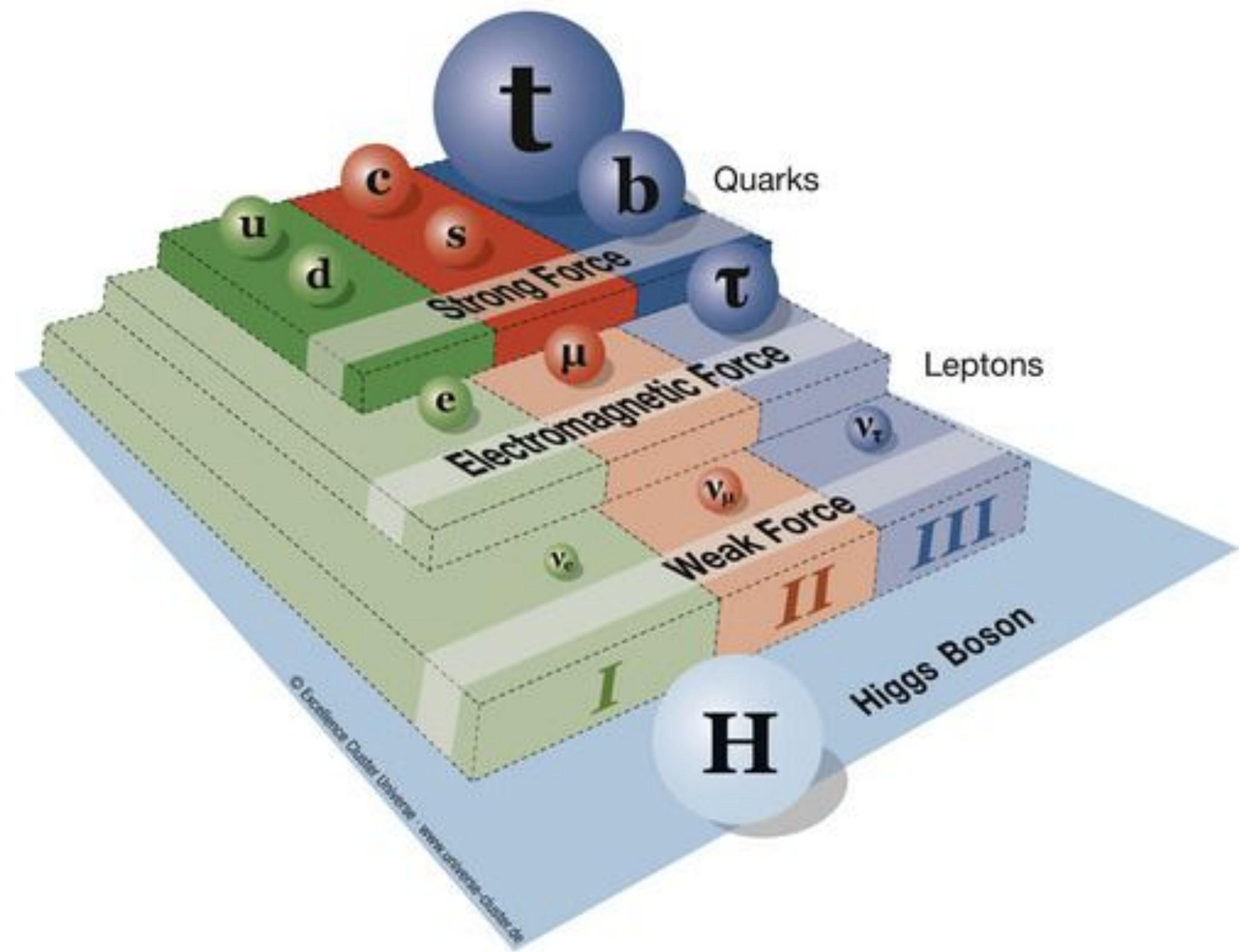


Nedaa-Alexandra Asbah
HEP Seminar - Birmingham
19th of January 2022

Top-quark

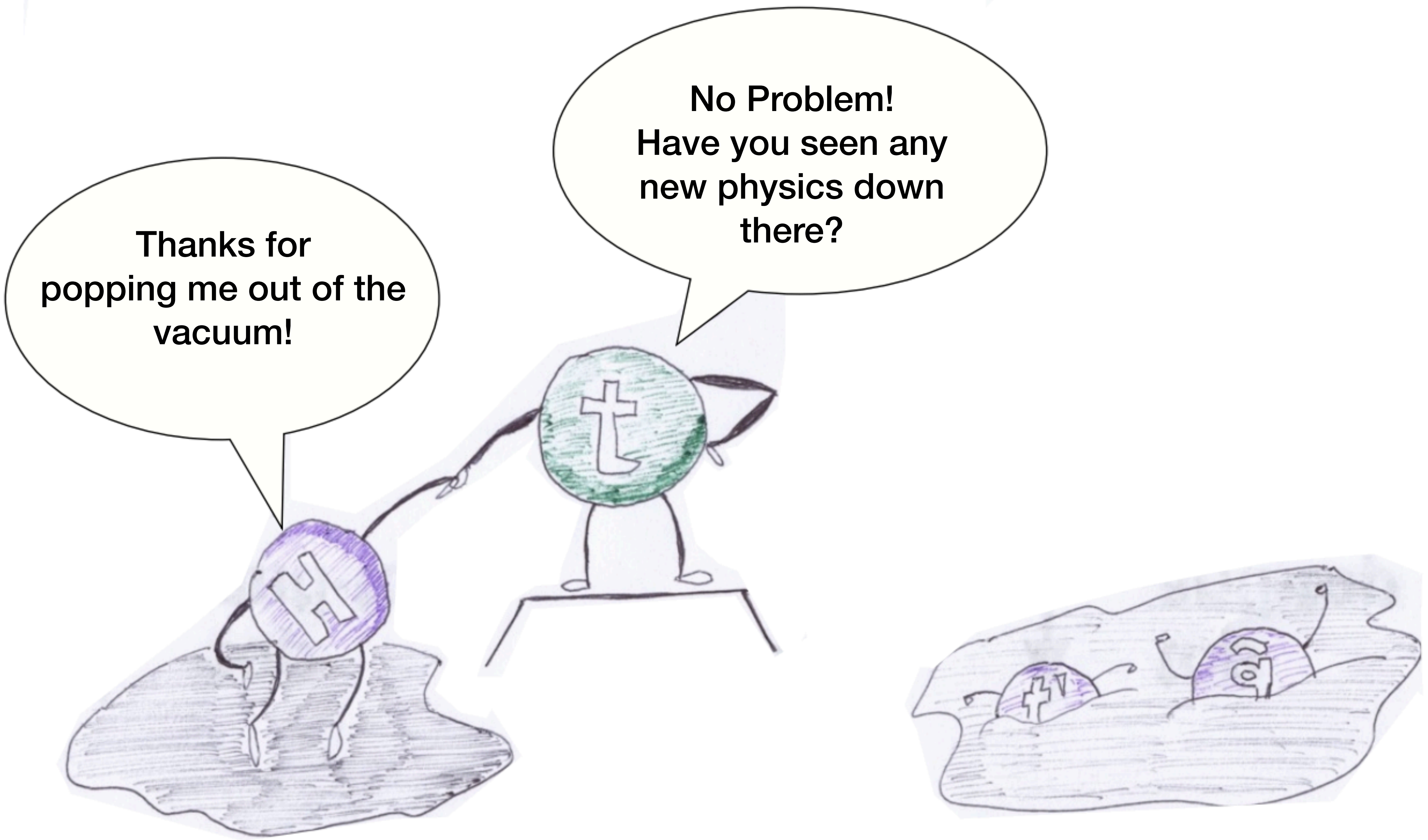
- Top-quark is the **heaviest** of all known fundamental particles m_{top} ~ 170 GeV
  - a bizarrely steep mass hierarchy
  - Even heavier than the **Higgs boson**
  - Unique role as a result of its mass
  - Many models predict that the top is special in order to explain its mass

- Leaves us wondering:
  - Is the top mass from the Higgs mechanism?
  - Is there a hidden connection with the EWSB mechanism?
  - Does it have any connection to Higgs compositeness?



Top-quark

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



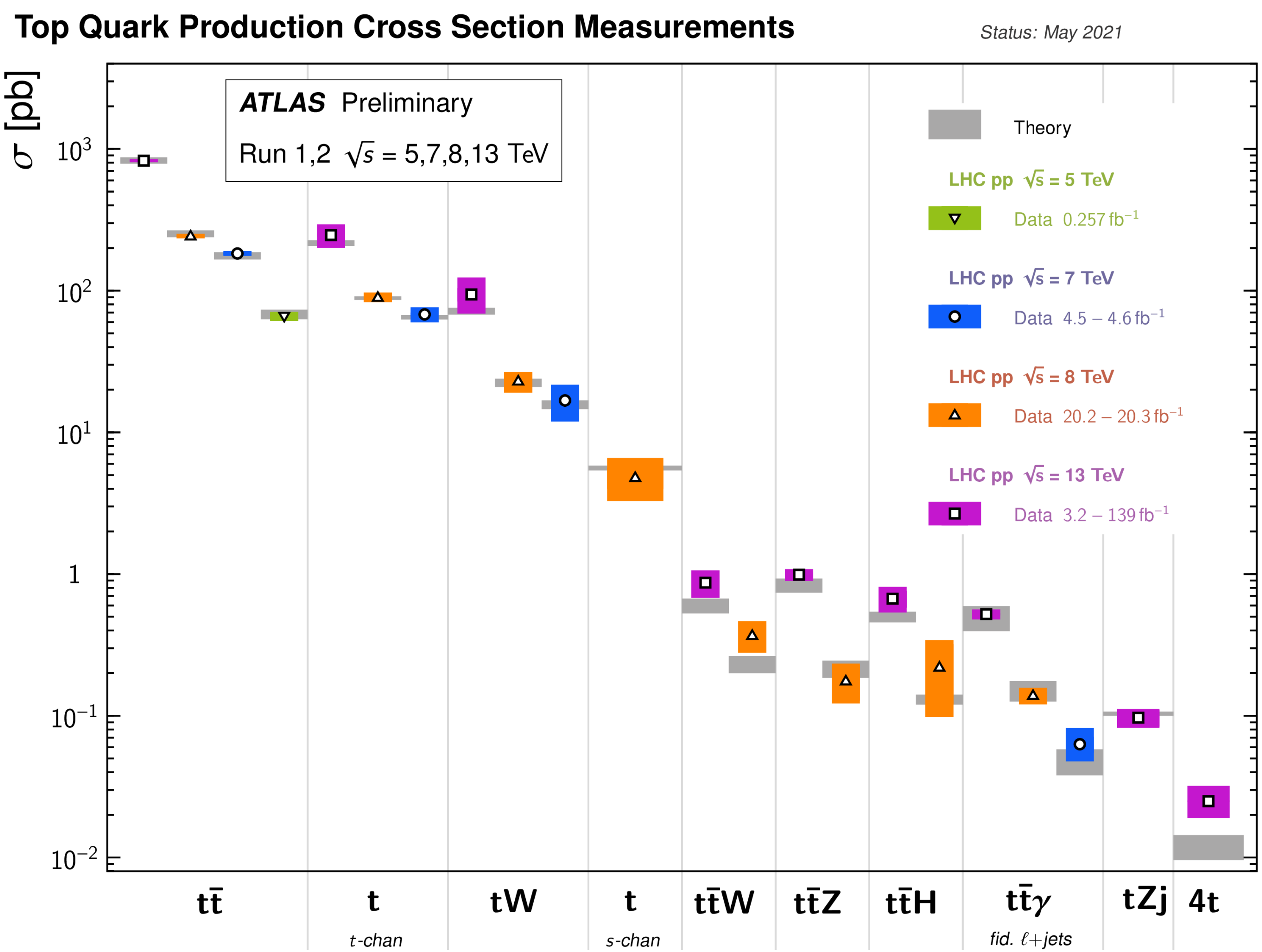
Top-quark

- 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 Production Cross-section Measurements

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

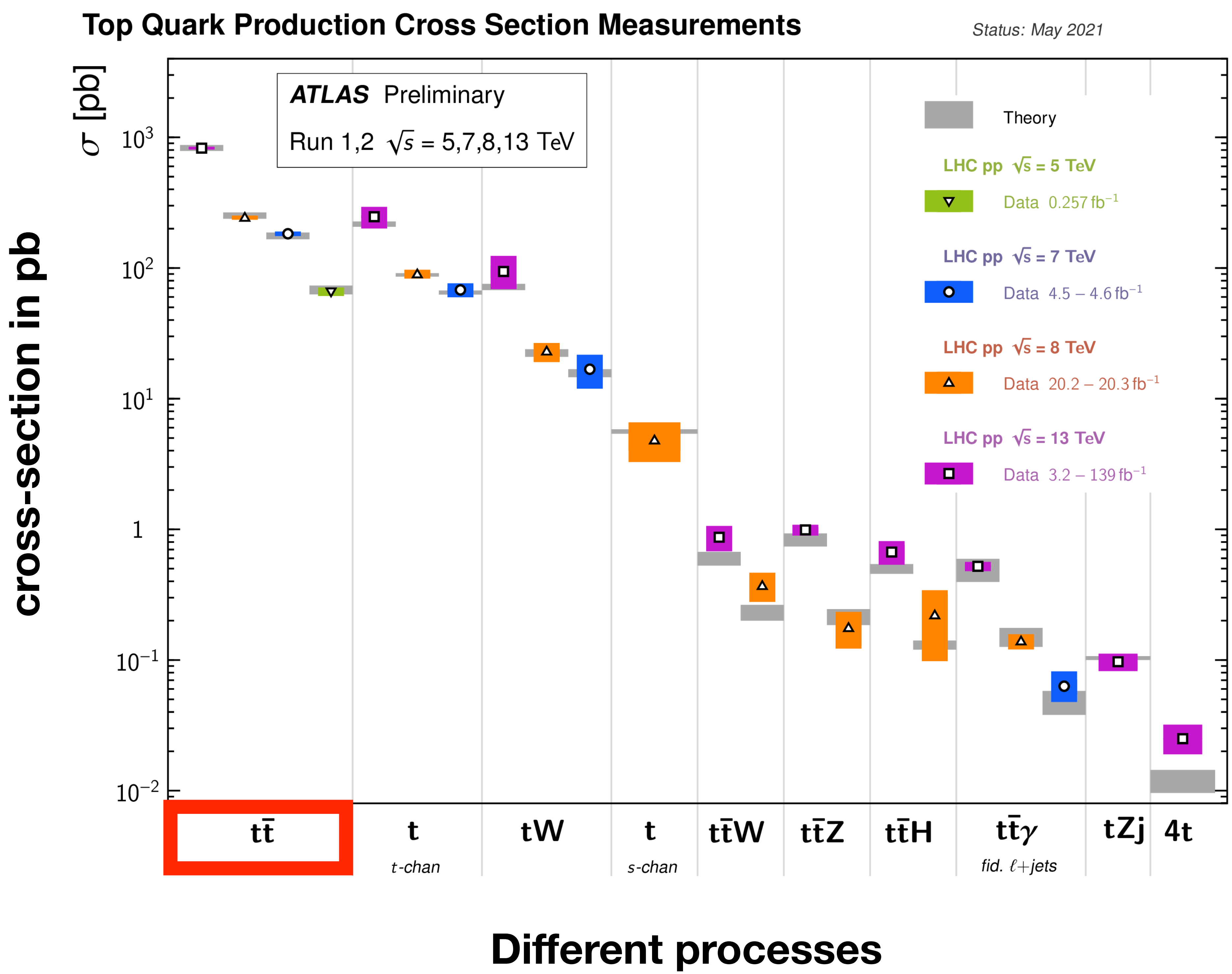
cross-section in pb



Different processes

Top-quark Production Cross-section Measurements

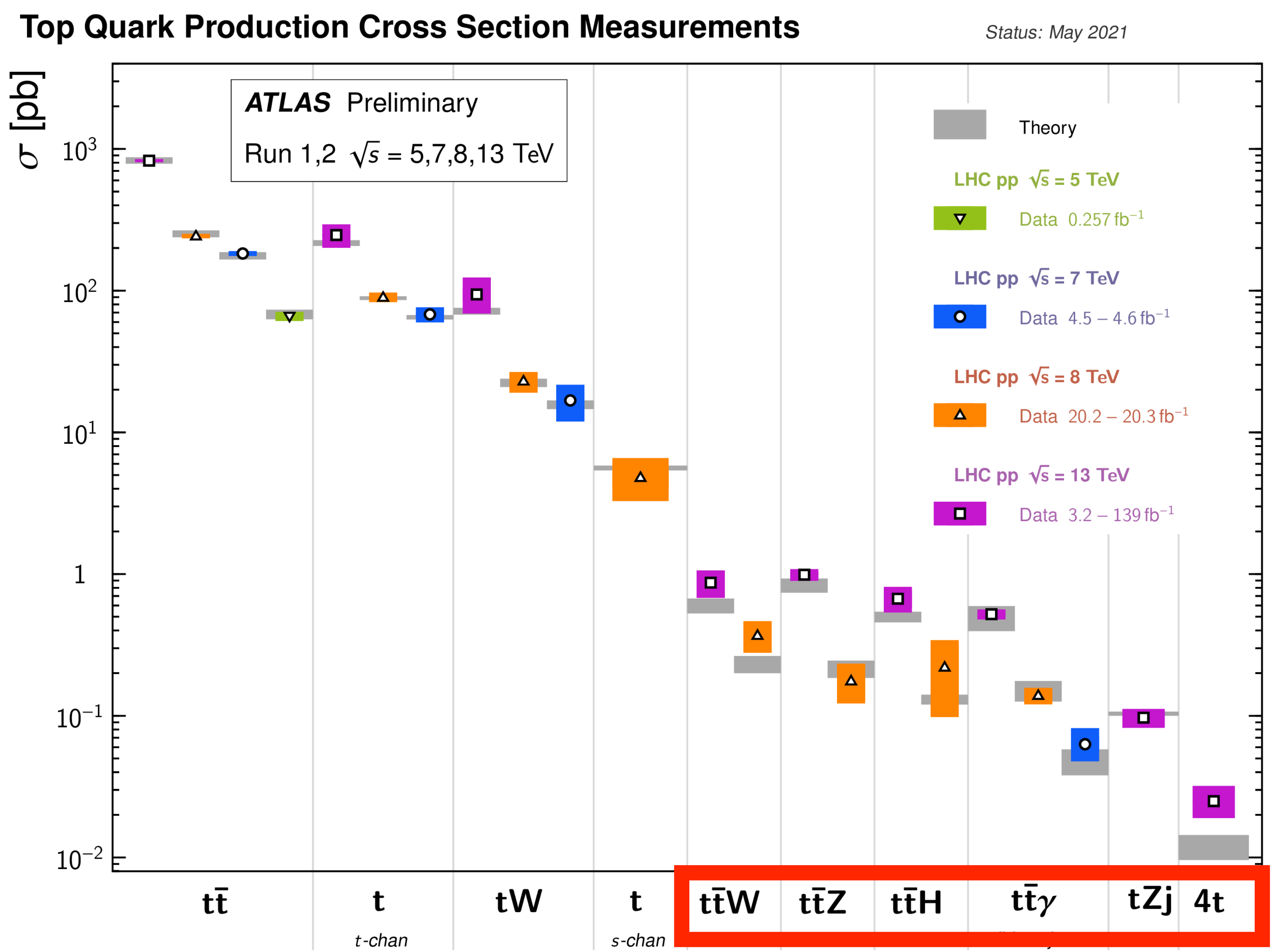
- $t\bar{t}$ production is produced abundantly at the LHC and extremely well studied (total and differential cross sections)



Top-quark Production Cross-section Measurements

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

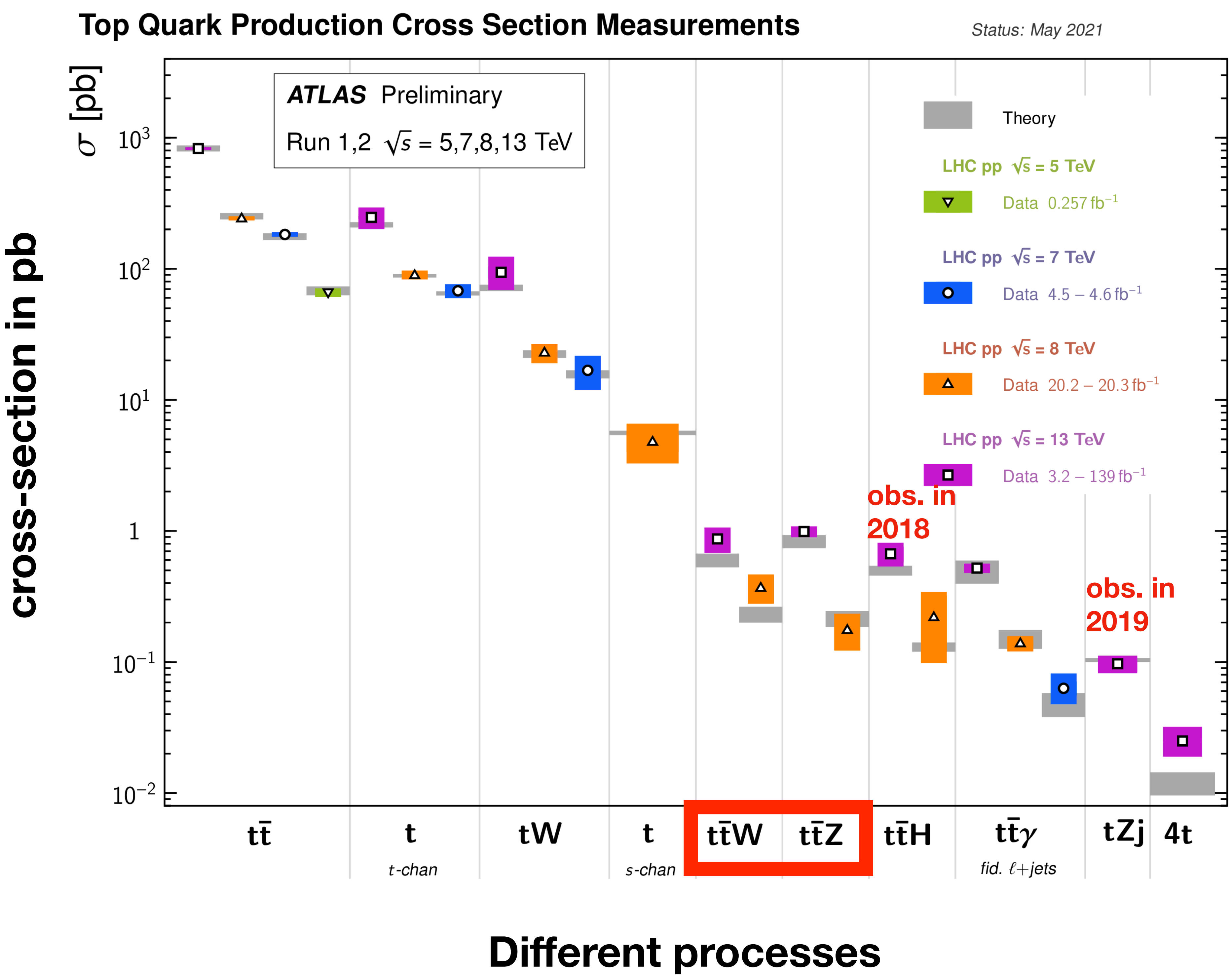
cross-section in pb



Different processes

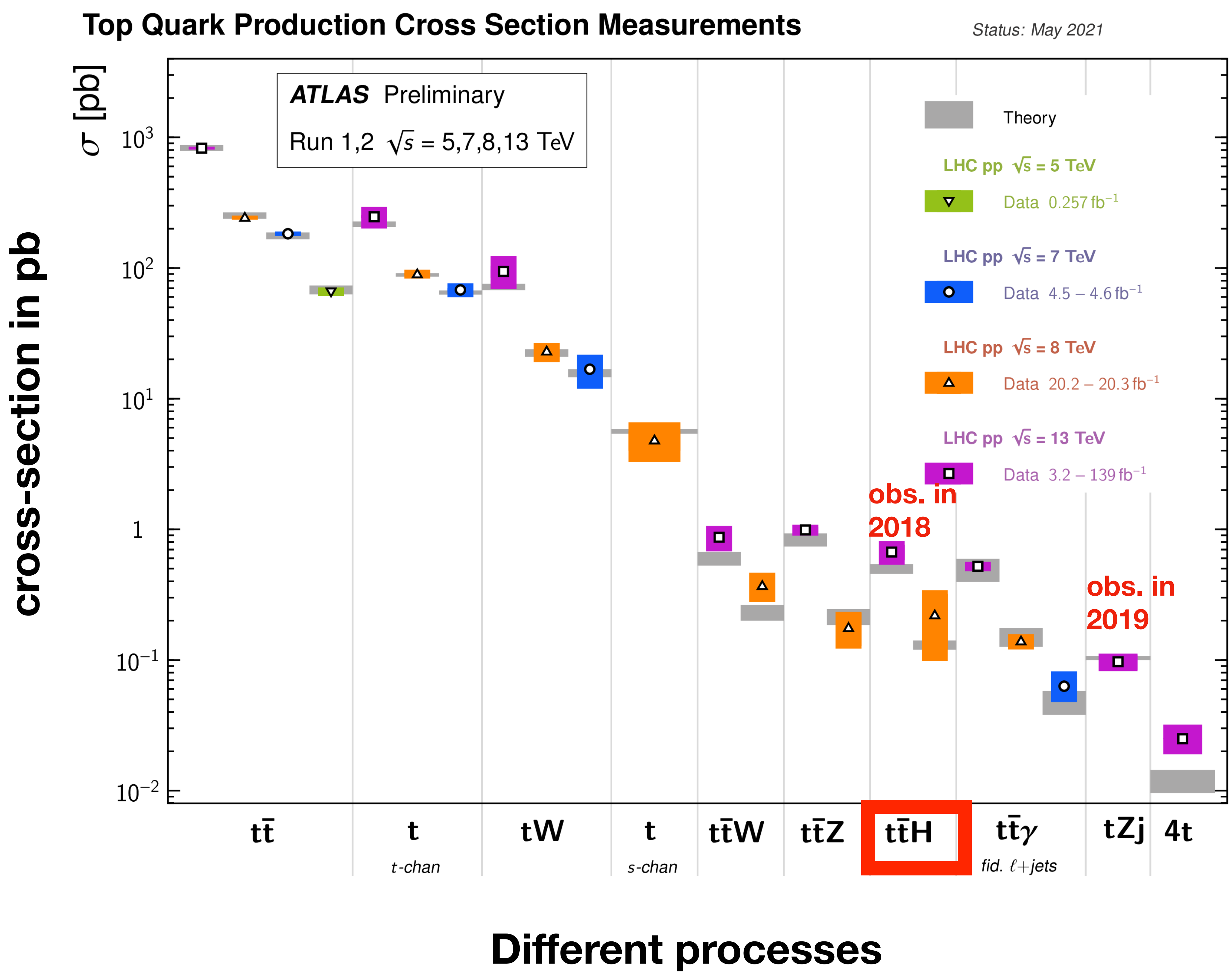
Top-quark Production Cross-section Measurements

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



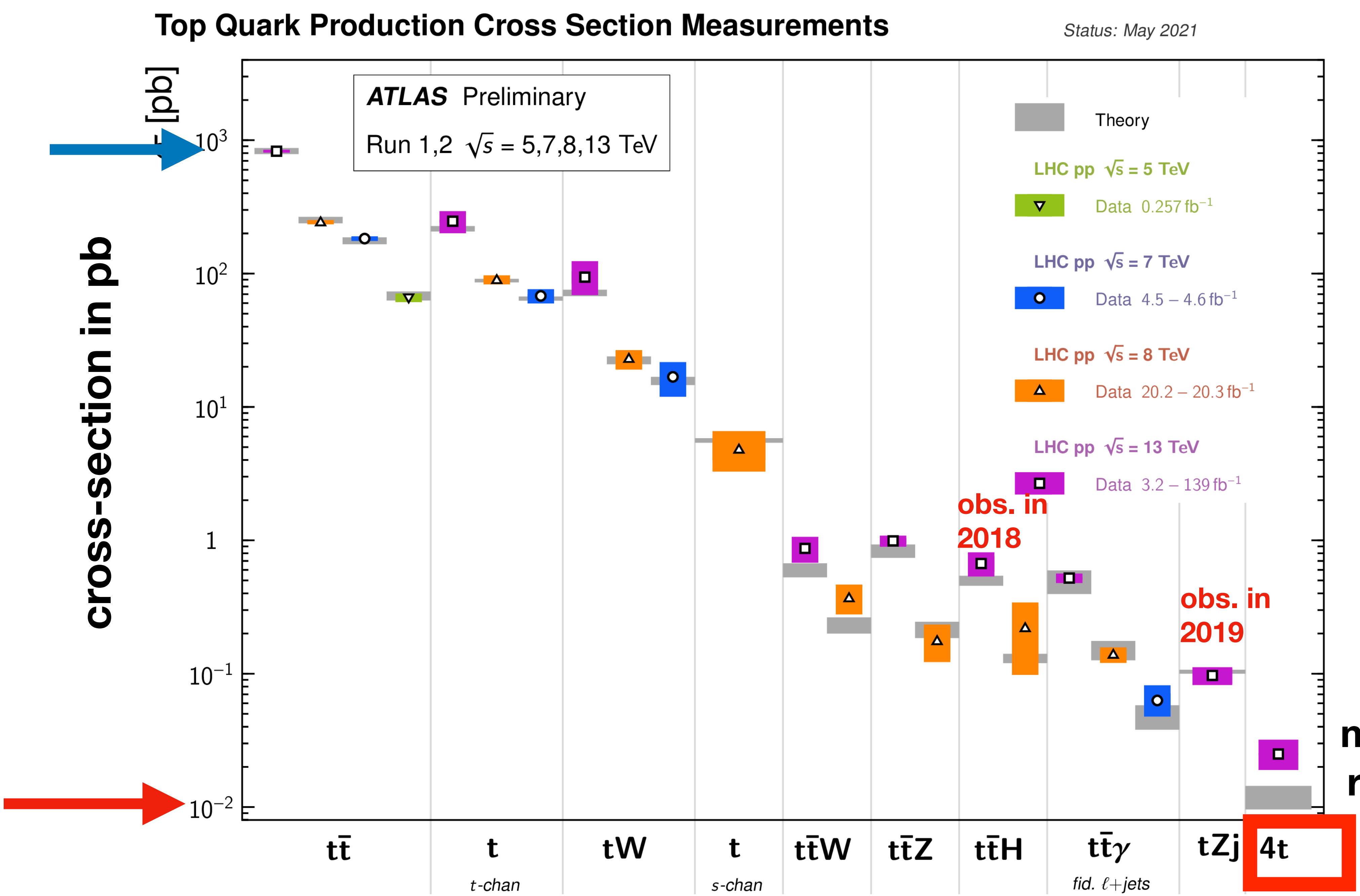
Top-quark Production Cross-section Measurements

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



Top-quark Production Cross-section Measurements

- Today I will talk about $t\bar{t}t\bar{t}$
- **Very tiny cross section in the SM**
- $\sigma_{SM}(t\bar{t}t\bar{t})$ = 11.97 fb at NLO QCD + NLO QED at **13 TeV** JHEP 02, 031 (2018)



minimum energy required is ~700 GeV

Different processes

Predictions for four-tops

- **Rare process** predicted by the SM and has **never been observed**
- Very complicated process: 72 gg + 12 $q\bar{q}$ initiated diagrams at LO
- Sensitive to top-Yukawa coupling (y_t)
  - A non-SM value of y_t can change dramatically the production via an off-shell Higgs

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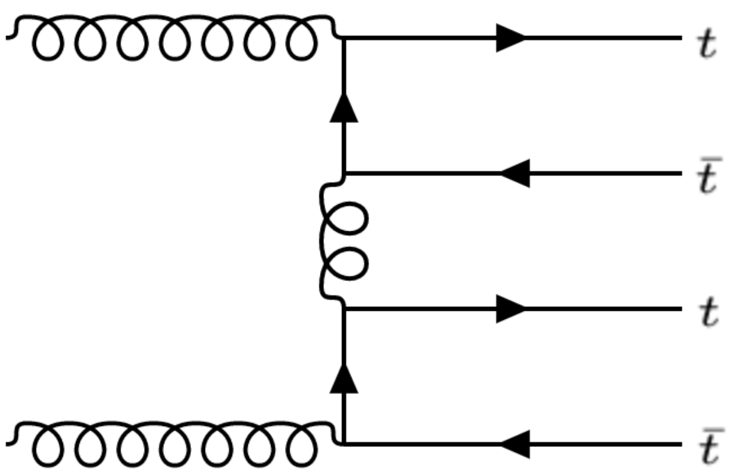

Leading: $O(\alpha_S^4)$

arXiv:1611.05032 [hep-ph]

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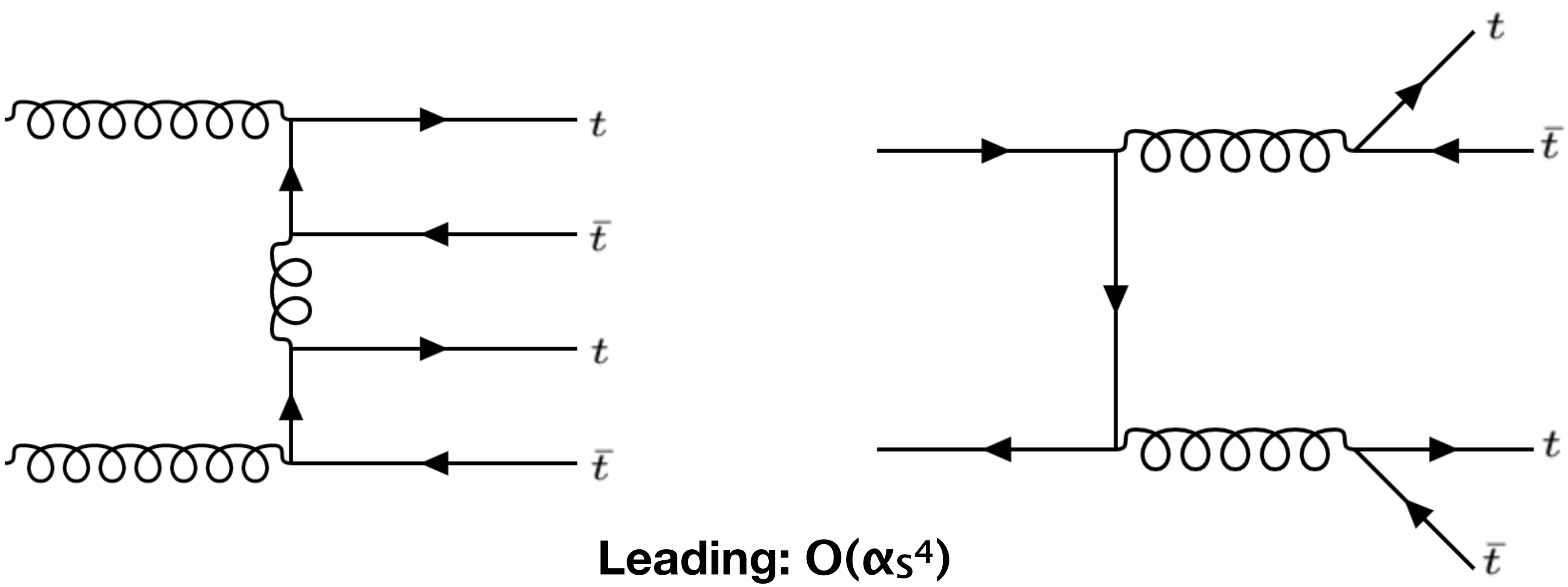

Leading: O(α_S^4)

The production of $t\bar{t}t\bar{t}$ is predominantly a QCD process of order O(α_S^4)

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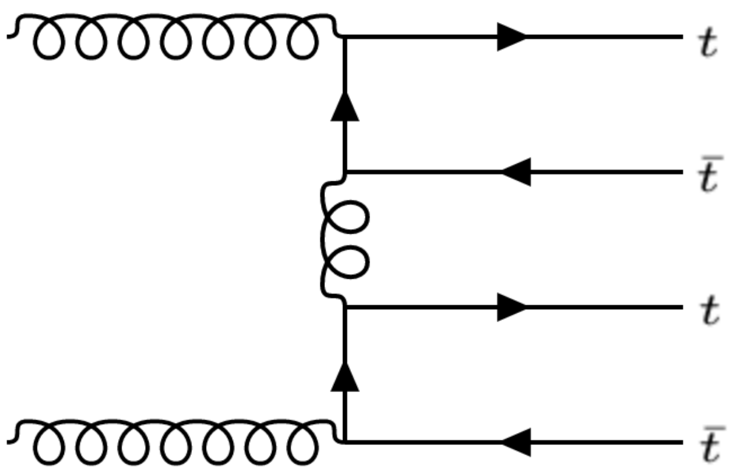
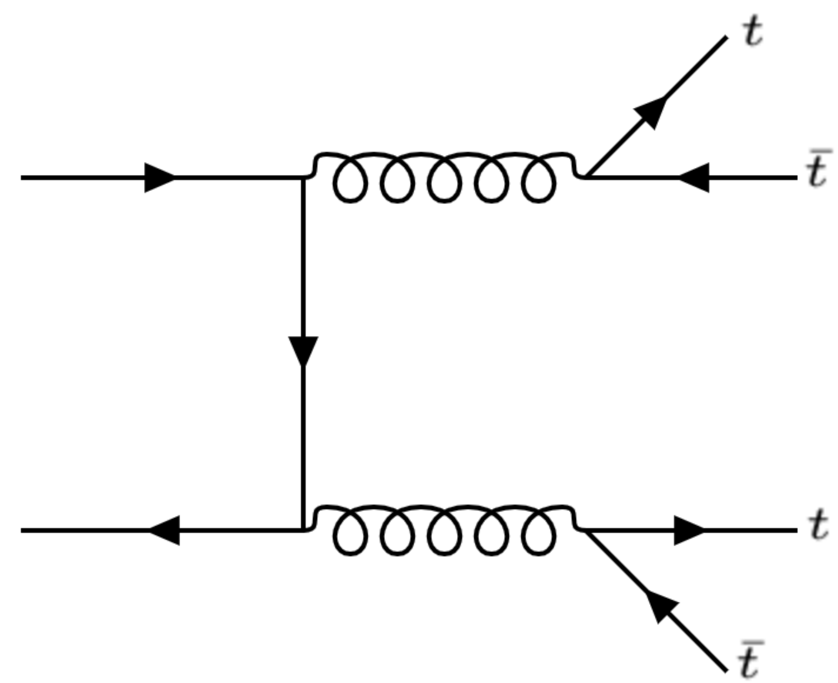
Predictions for four-tops

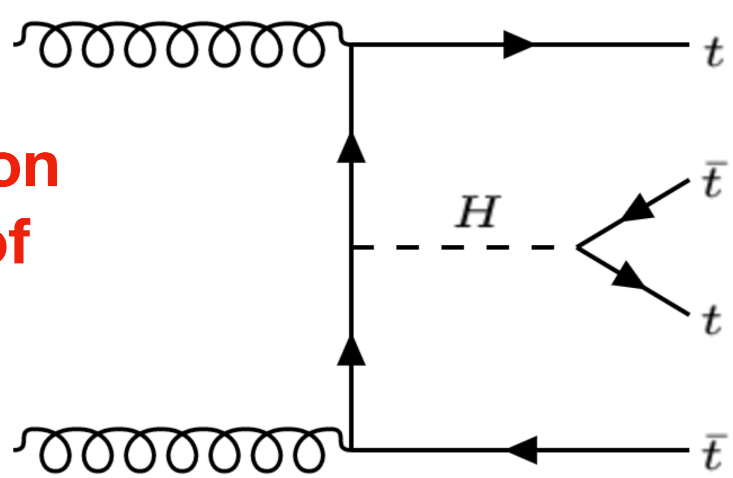
- Rare process predicted by the SM and has never been observed
- Very complicated process: 72 gg + 12 $q\bar{q}$ initiated diagrams at LO
- **Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson**
  - four top quarks can be produced via an offshell SM Higgs boson





The production of $t\bar{t}t\bar{t}$ is predominantly a QCD process of order O(α_S^4)

A sub-leading Higgs boson exchange contribution of order O($\alpha_S^2 y_t^4$)

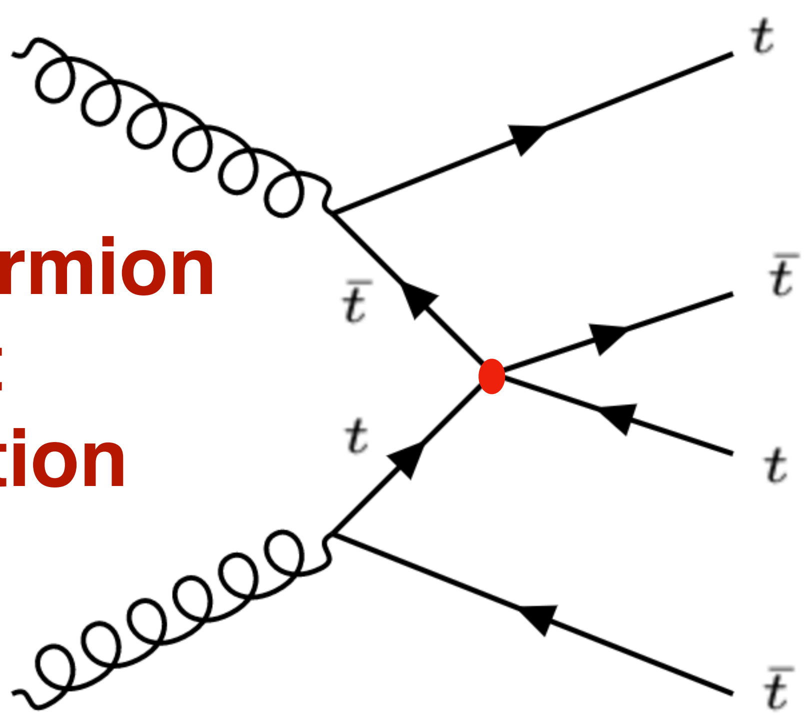


arXiv:1611.05032 [hep-ph]

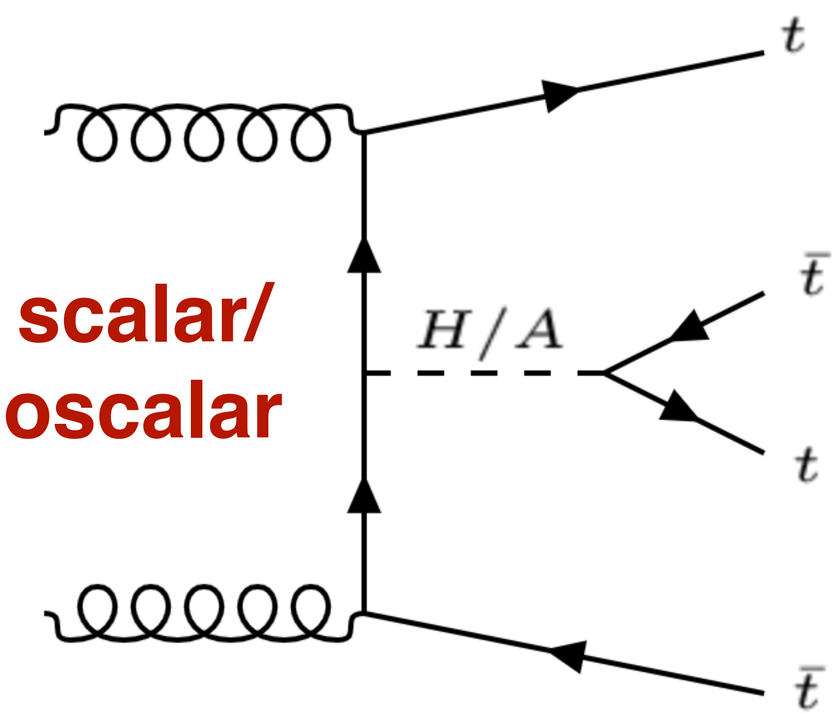
Predictions for four-tops

- **Sensitive to many BSM models**

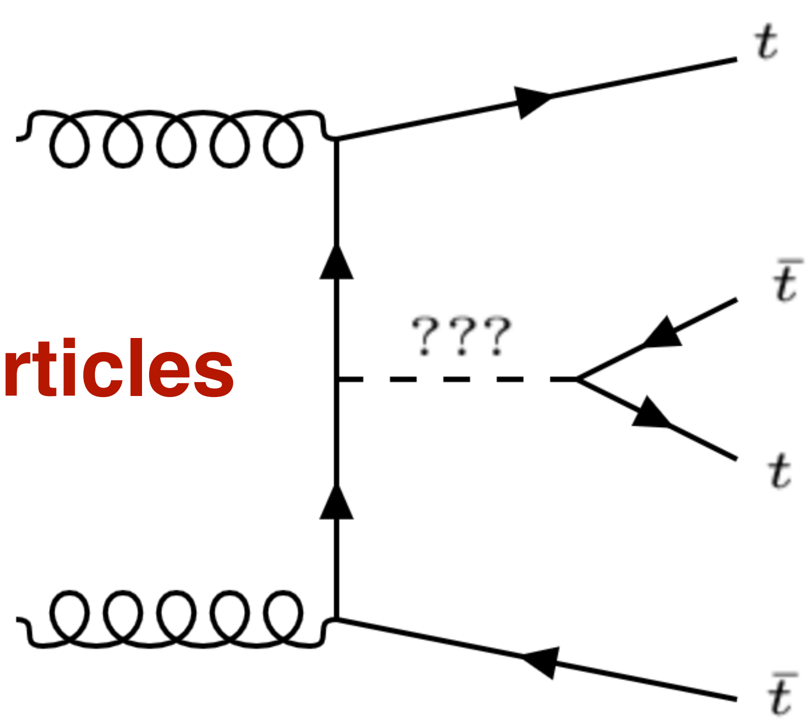
Four-fermion contact interaction



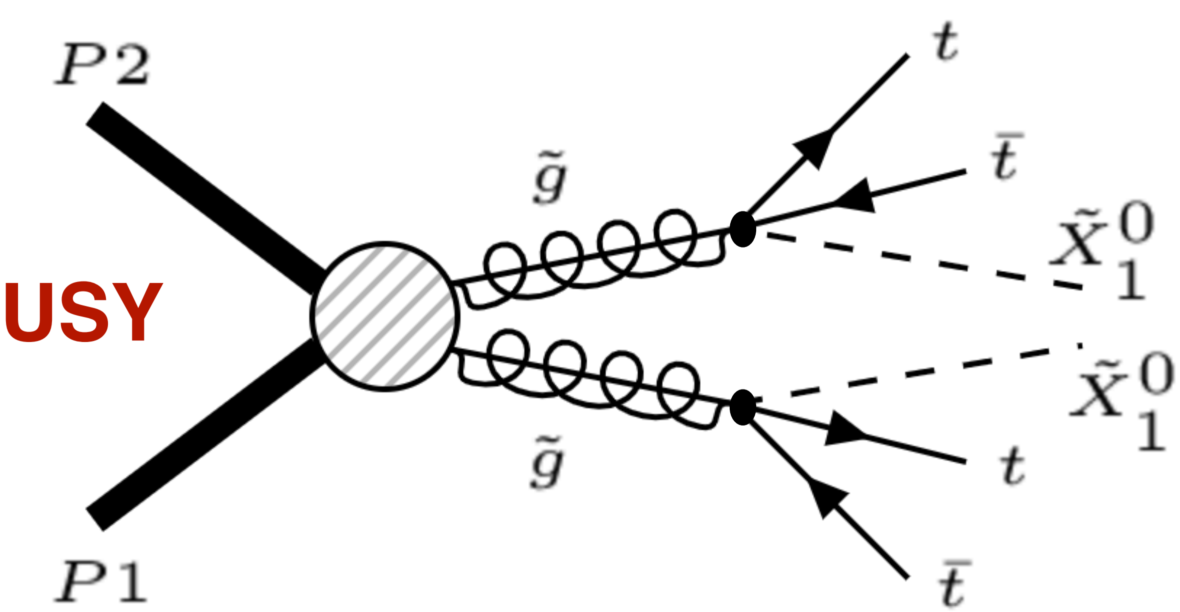
2HDM scalar/ pseudoscalar



New Particles

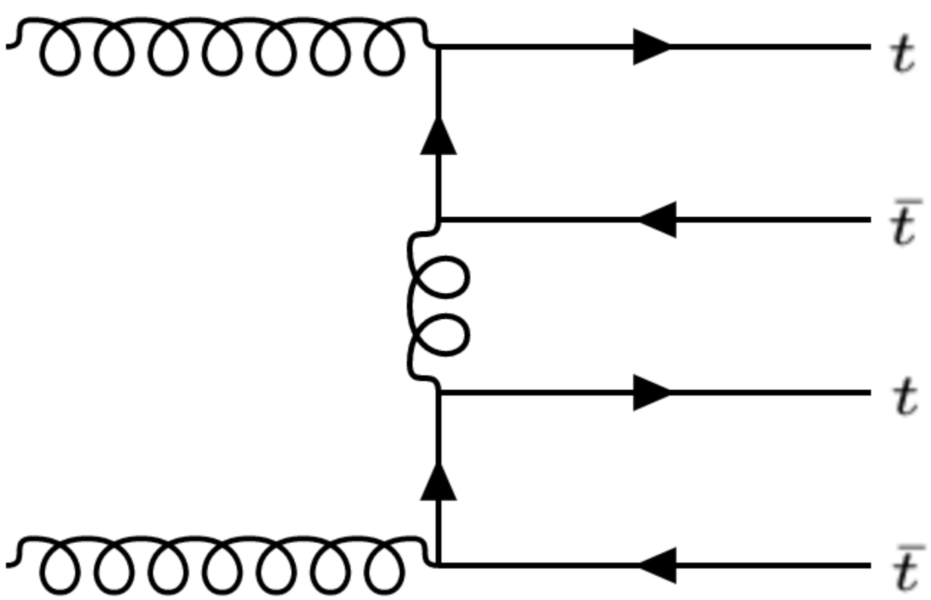


SUSY



Signatures

- We have **four-tops** in our final state
- Each **top** decays to **Wb** and the detector signature is defined by:
  - The presence of four b-quarks
  - The decays of the W bosons



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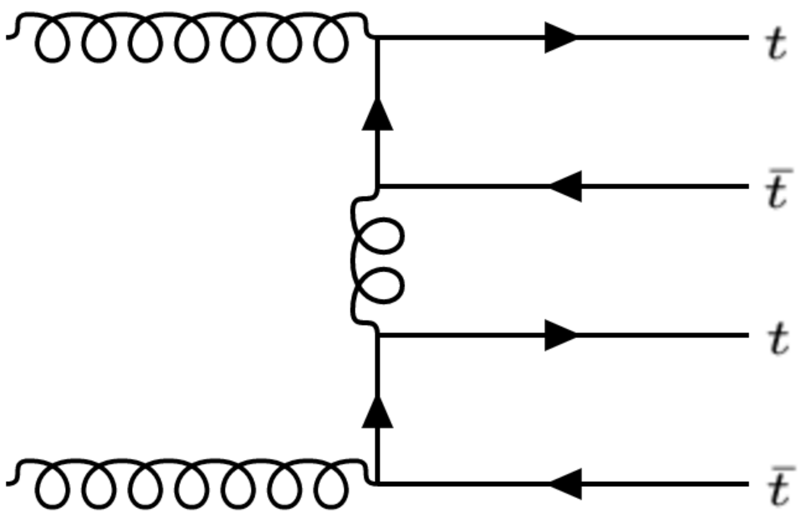

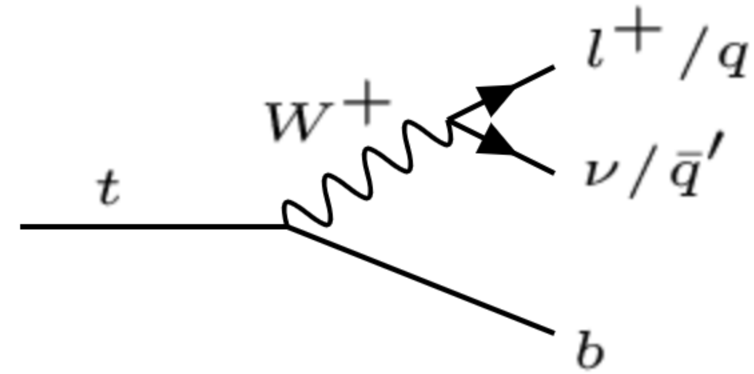

- $W \to q\bar{q}$ 2/3
- $W \to \tau\nu$ 1/9
- $W \to e\nu$ 1/9
- $W \to \mu\nu$ 1/9

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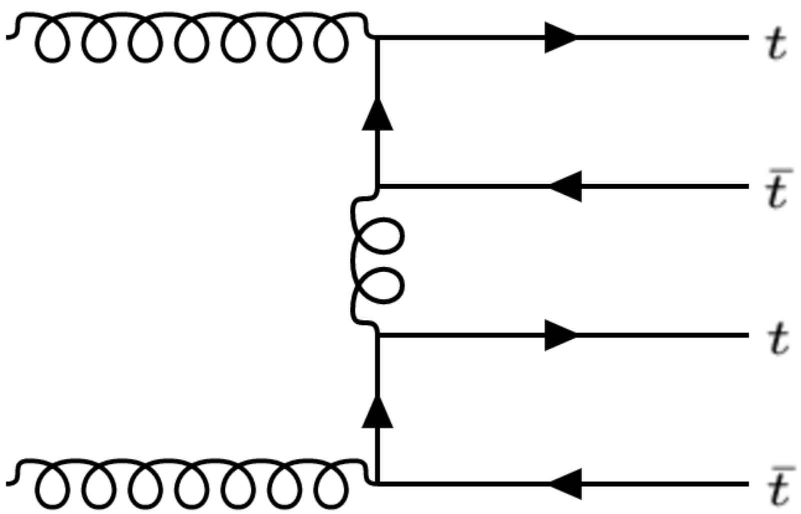

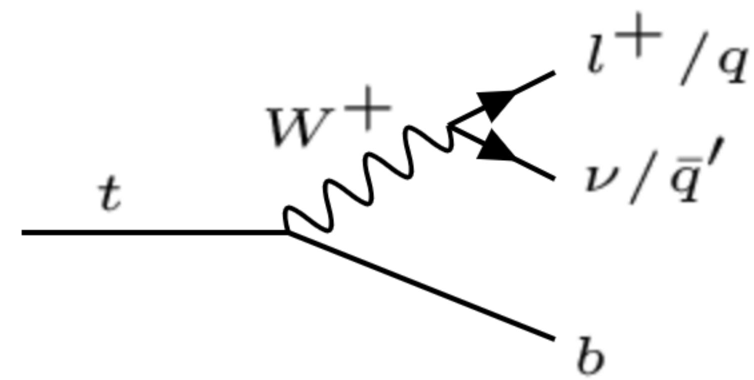

- $W \to q\bar{q}$ 2/3
- $W \to \tau\nu$ 1/9
    - $\tau \to q\bar{q}$ (65%)
    - $\tau \to \mu\nu$ (17.5%)
    - $\tau \to e\nu$ (17.5%)
- $W \to e\nu$ 1/9
- $W \to \mu\nu$ 1/9

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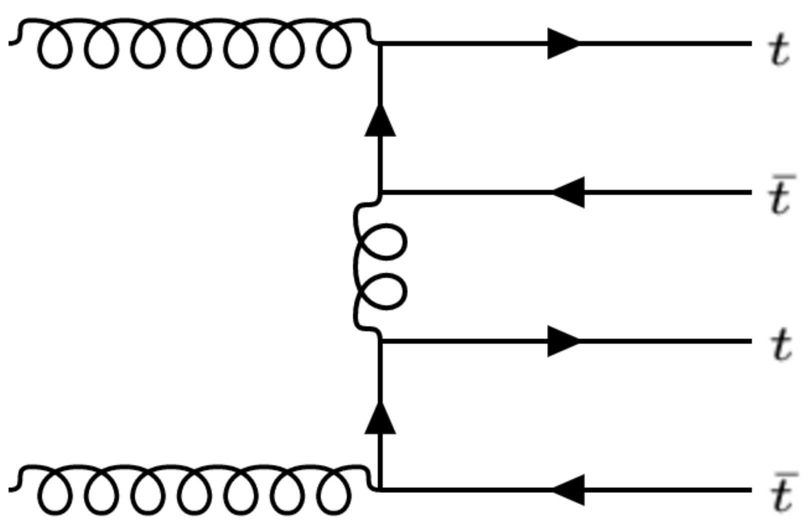

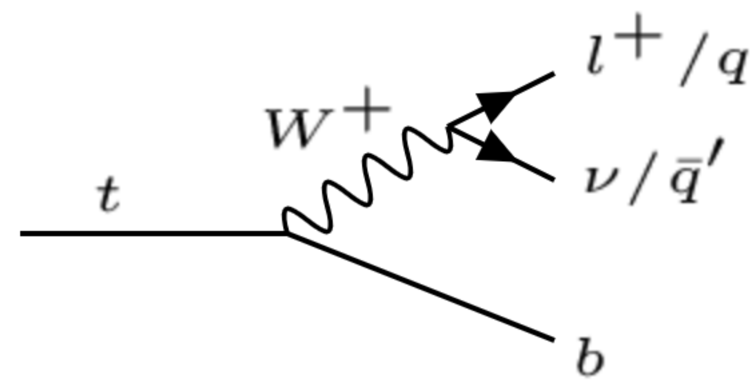

- $W \to q\bar{q}$ 2/3
- $W \to \tau\nu$ 1/9
    - $\tau \to q\bar{q}$ (65%)

~75% hadronically

- $W \to e\nu$ 1/9
- $W \to \mu\nu$ 1/9
    - $\tau \to \mu\nu$ (17.5%)
    - $\tau \to e\nu$ (17.5%)

~25% e or μ

Signatures

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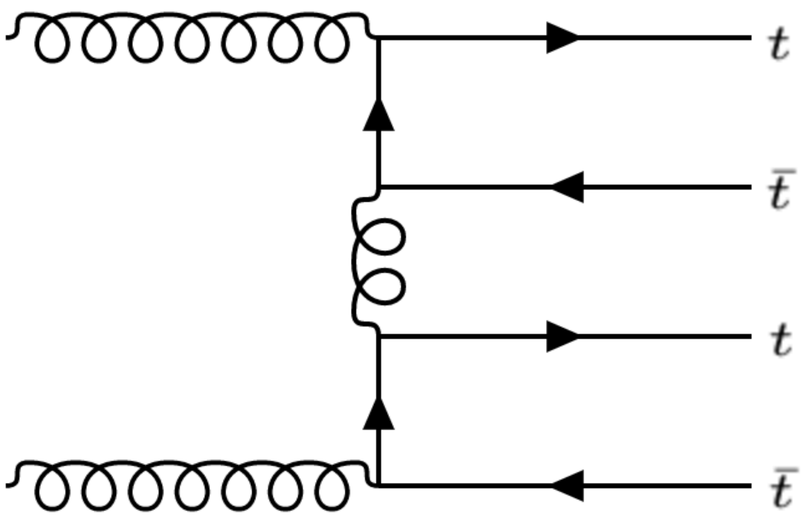
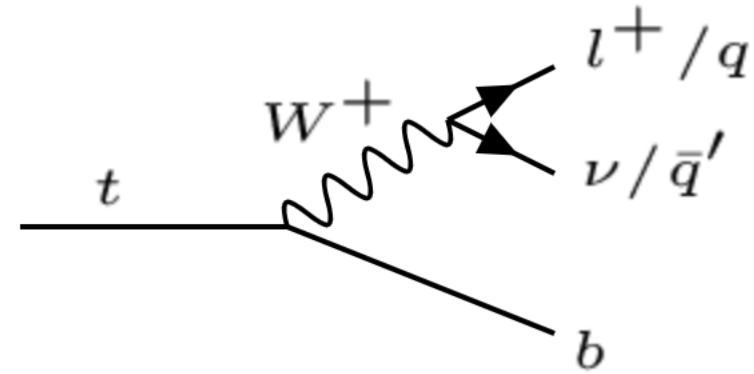
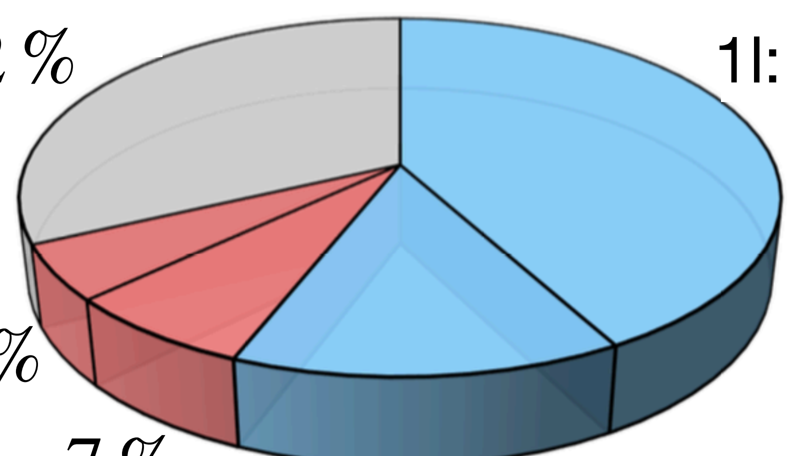


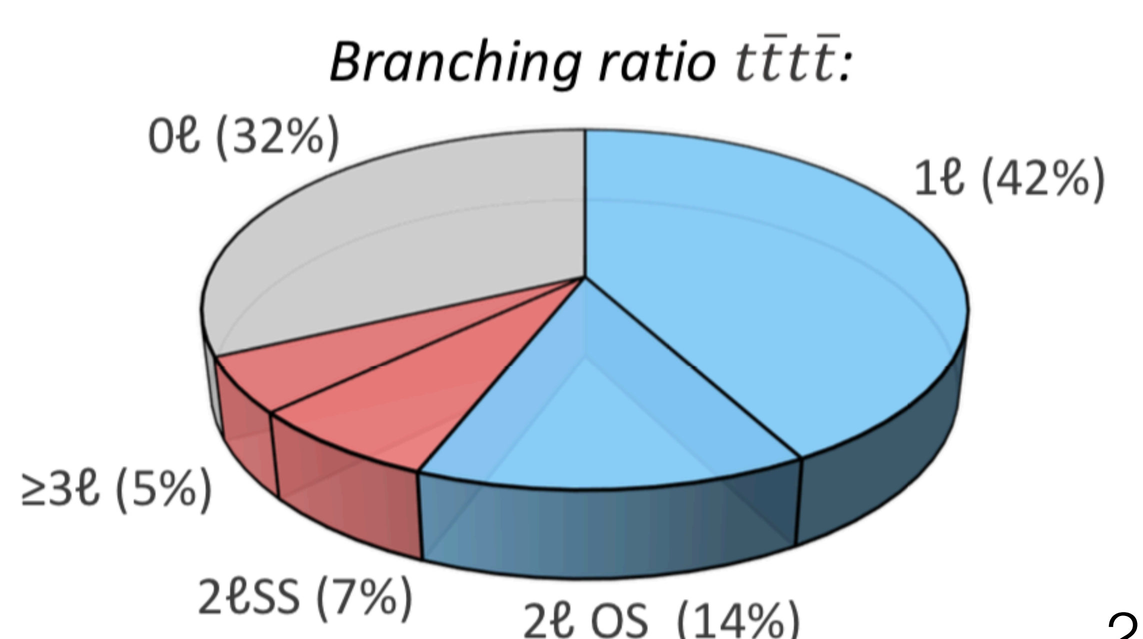


Branching ratio $t\bar{t}t\bar{t}$:



Signatures

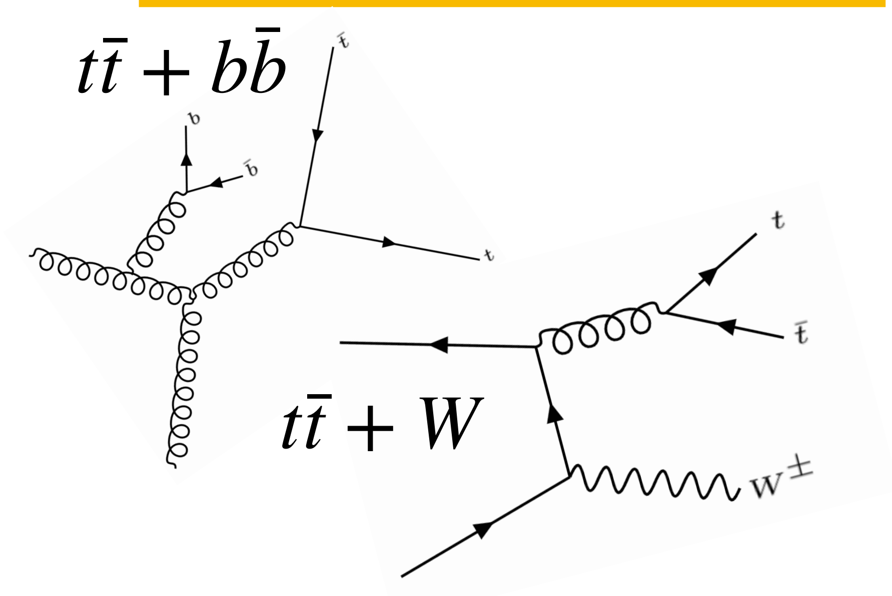
- Channels are split according to:
  - **2ℓSS/3ℓ: 2ℓSS** (7%) / **3ℓ** (5%) Eur. Phys. J. C (2020) 80:1085
    - Small branching fraction
    - Small background (ttW, ttZ, non-prompt leptons, charge misidentification)
    - Most sensitive channel
  - **1ℓ/2ℓOS: 1ℓ** (42%) / **2ℓOS** (14%) JHEP 11 (2021) 118
    - Dominant branching fraction
    - Large irreducible background from tt+jets (tt+heavy flavour jets)
  - **0ℓ (32%)**
    - Experimentally very challenging
      - Large multi-jet background
    - Not yet explored in ATLAS



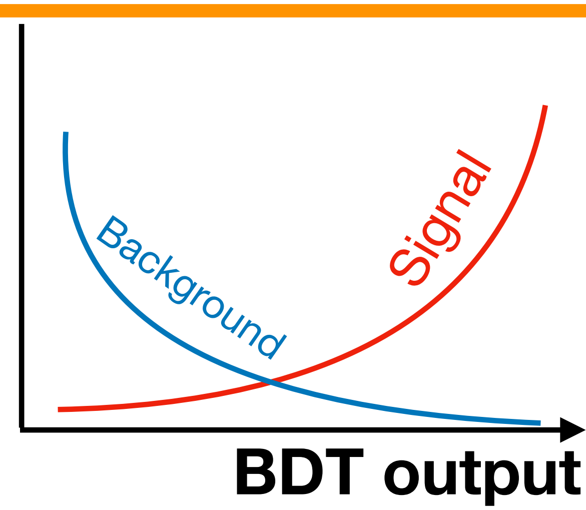
Search Strategy

Event Selection and Analysis regions

Control Region to estimate the main background



Use BDT in the **Signal Region** to separate the signal from the background



Validation Region to validate the model

Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \sigma_{t\bar{t}t\bar{t}}/\sigma^{SM}_{t\bar{t}t\bar{t}}$

Extract measured cross section and compare to theory!

Event Selection and Analysis regions

Control Region to estimate the main background

Use BDT in the Signal Region to separate the signal from the background

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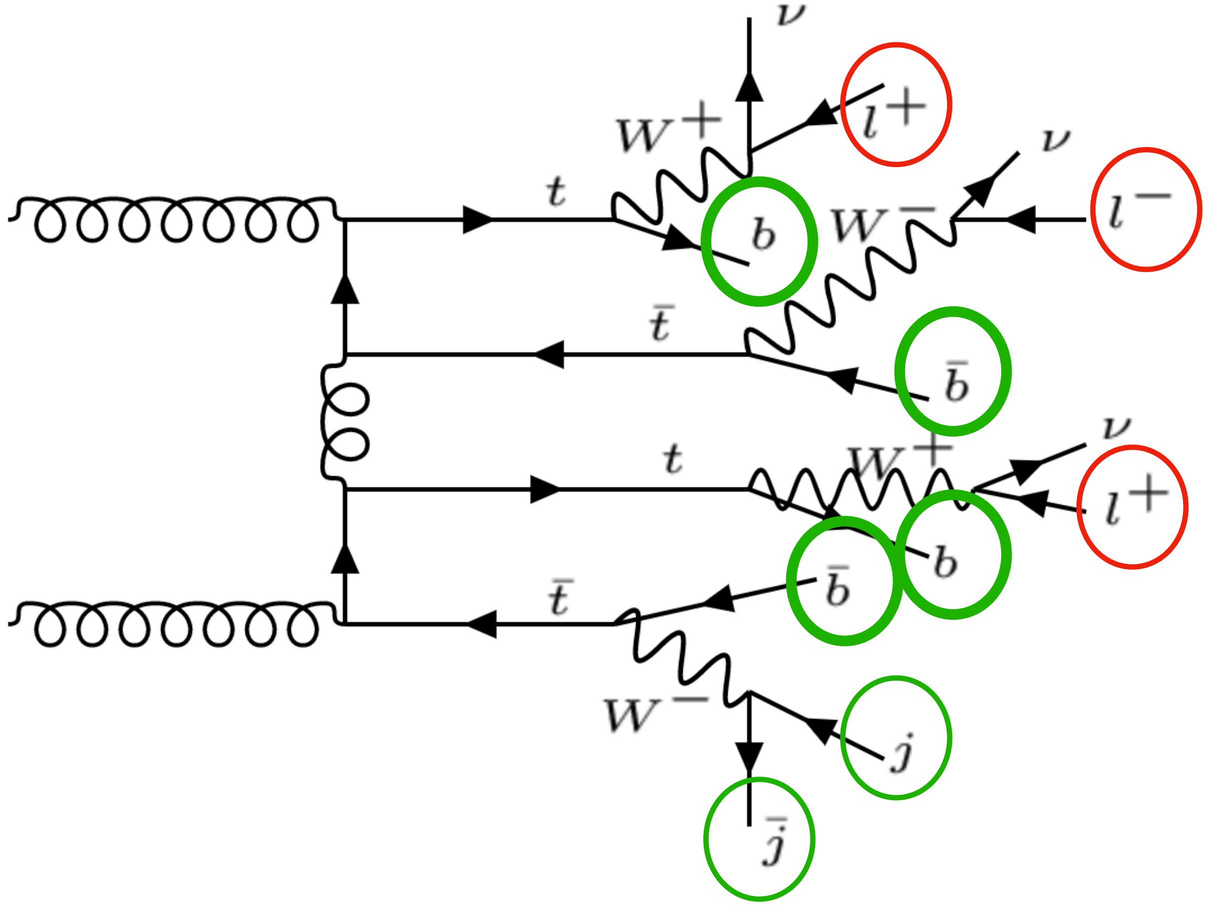
Extract measured cross section and compare to theory!

Event Selection

- Focus on interesting events & maximize the statistical significance of a potential signal excess
- Reduce major backgrounds (maximizing the significance of an excess)
- **Using full Run 2 dataset: 139 fb^{-1}**
- Selection requirements in the **2ℓSS/3ℓ** (signal region):
  - 2 same-sign leptons *or* 3 leptons (ℓ=e,μ)
  - **≥ 6 jets** (p_T > 25 GeV)
  - **≥ 2 b-tagged jets**
    - efficiency of identifying b-jets is 77%
  - H_T > 500 GeV ; $H_T = \sum^{leptons} P_T + \sum^{jets} P_T$

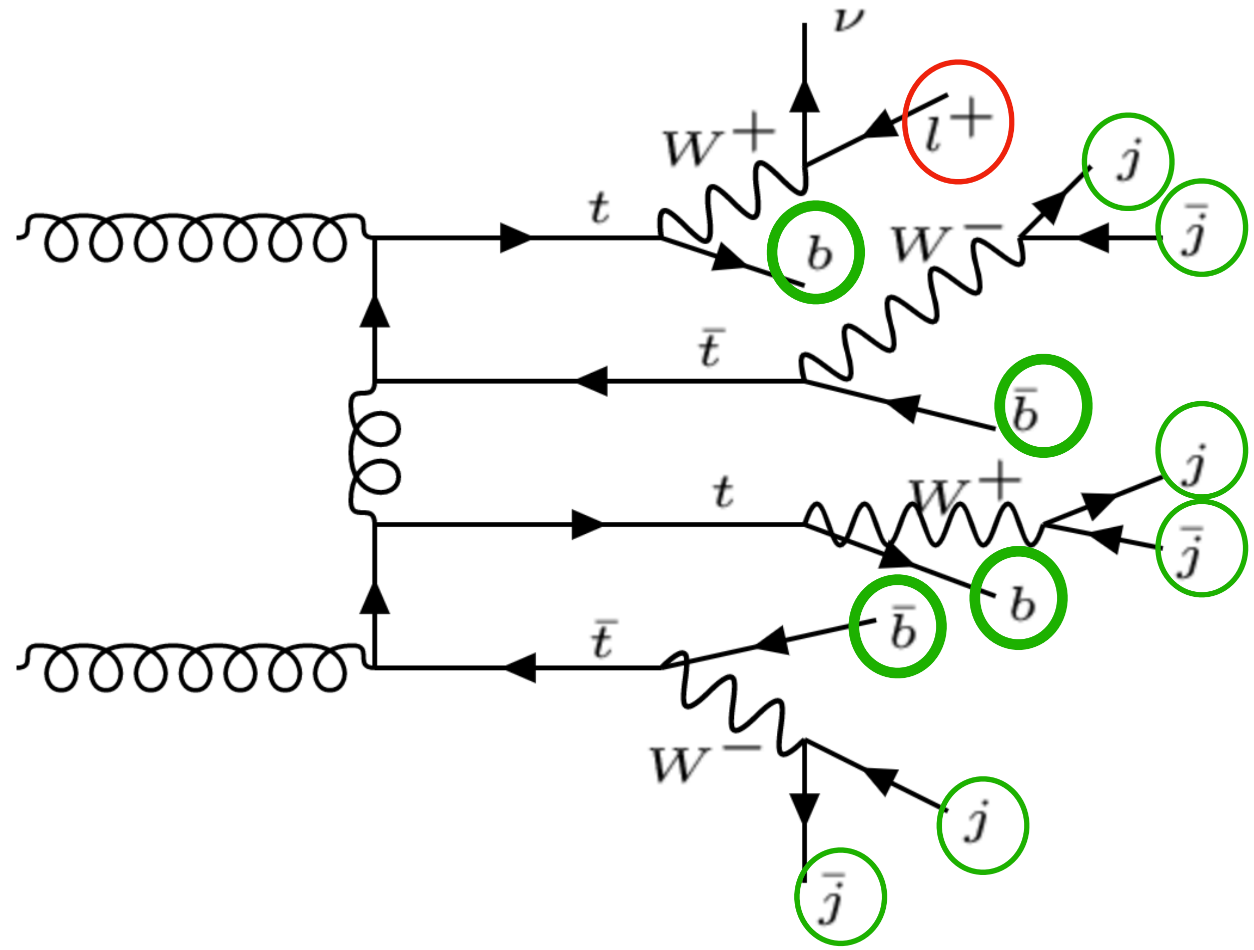
Example from the 3l channel



Event Selection

- Selection requirements in the **1ℓ/2ℓOS**:
  - Expect 10 (8) jets in 1L (2lOS) and 4 b-jets at truth level
  - Targeting events with high **jet** and **b-jet** multiplicities
- Event pre-Selection:
  - 1 e/μ or 2 e/μ
  - N_{jets} ≥7 (1L), N_{jets} ≥5 (2L)
  - N_b ≥2

Example from the 1l channel



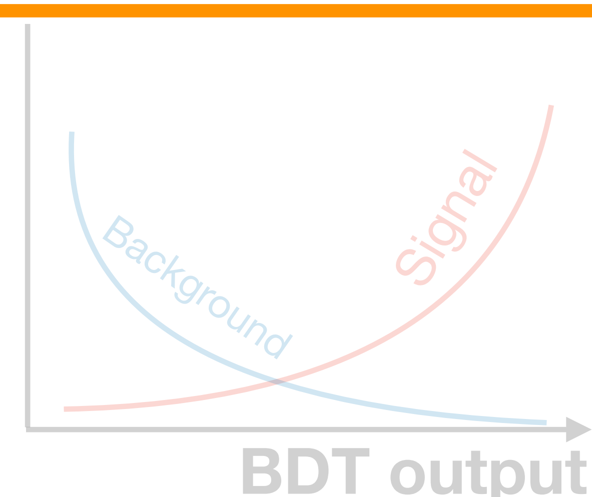
Analysis regions

Event Selection and Analysis regions

Control Region to estimate the main background

Use BDT in the **Signal Region** to separate the signal from the background

Validation Region to validate the model



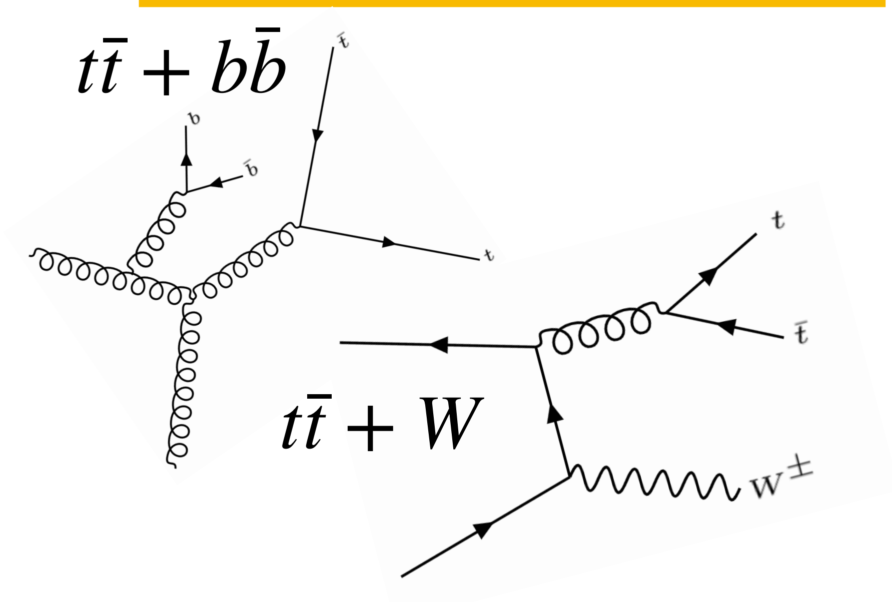
Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \sigma_{t\bar{t}t\bar{t}} / \sigma^{SM}_{t\bar{t}t\bar{t}}$

Extract measured cross section and compare to theory!

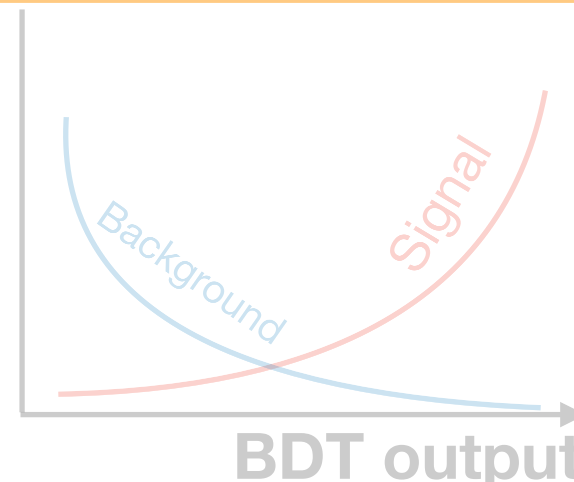
Control Regions

Event Selection and Analysis regions

Control Region to estimate the main background



Use BDT in the **Signal Region** to separate the signal from the background



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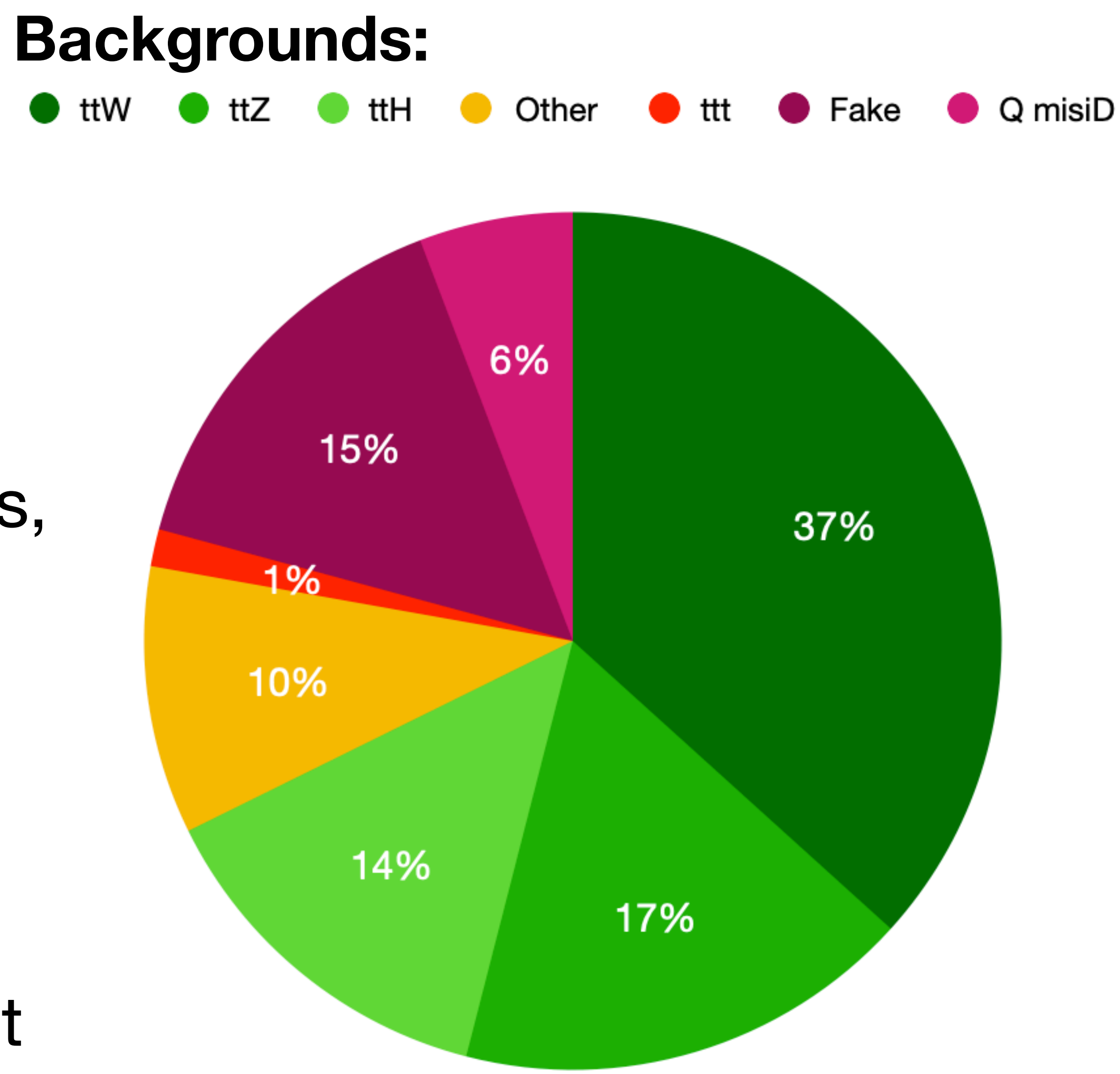
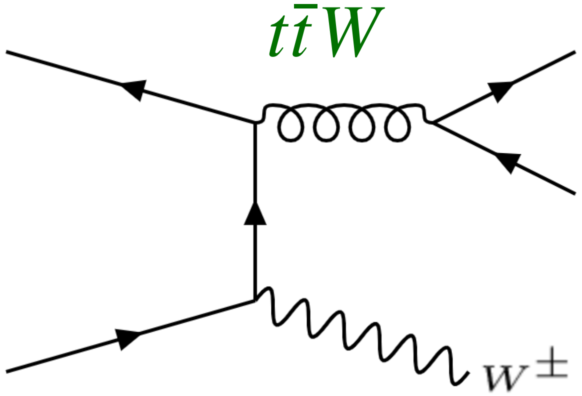
Extract measured cross section and compare to theory!

Backgrounds in 2ℓSS/3ℓ Channel

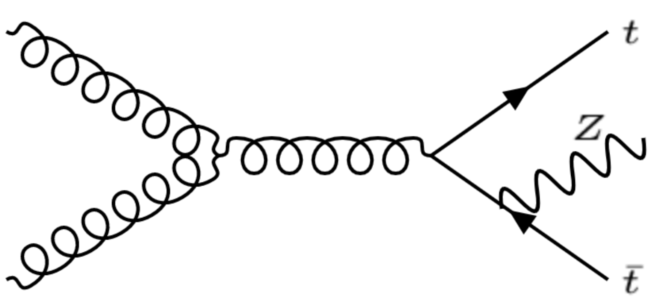
- **Irreducible backgrounds**:
  - Leptons from W, Z or leptonic τ decays
    - $t\bar{t}W$ **(37%)**, $t\bar{t}Z$ **(17%)**, and $t\bar{t}H$ **(14%)**
    - **Others (10%):** Diboson, triboson, VH+jets, ttWW, tWZ, tZq
    - ttt **(1%)**
- Evaluated using MC normalised to SM cross sections, except $t\bar{t}W$ which is floating in the fit
  - **Defined a dedicated Control Region for $t\bar{t}W$**



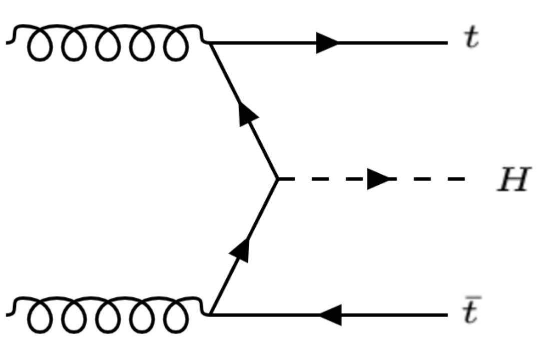
$t\bar{t}W$



$t\bar{t}Z$

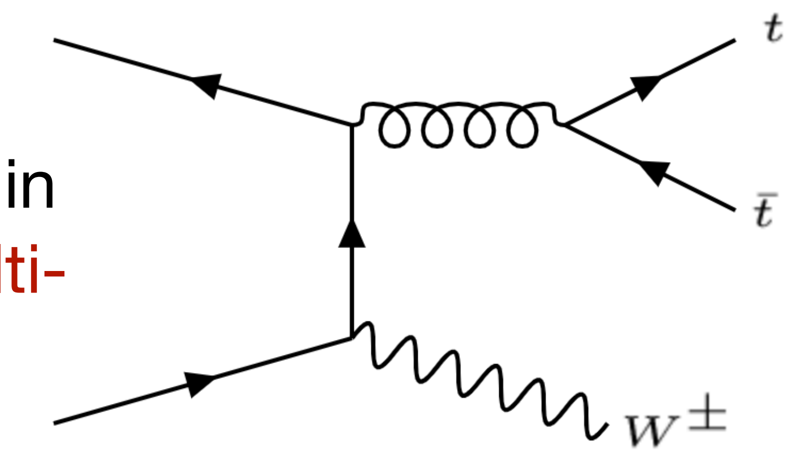


$t\bar{t}H$



Backgrounds in 2ℓSS/3ℓ Channel

- The motivation to float the $t\bar{t}W$ background comes from:
  - the large $t\bar{t}W$+jets background normalisation factor found in recent measurements in a similar phase space ttH(H→multi-leptons)
  - the effect of missing electroweak corrections in the MC simulation



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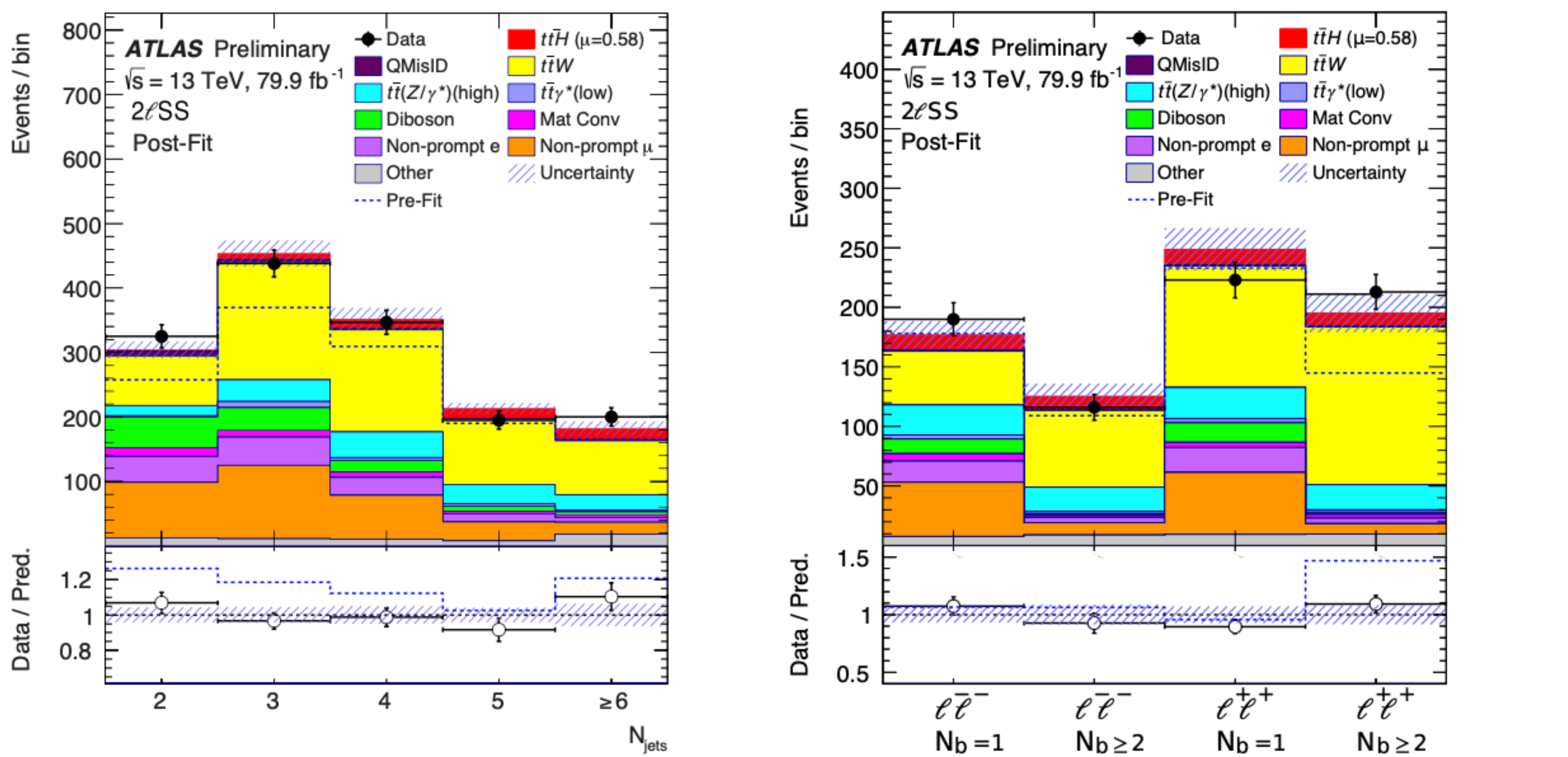
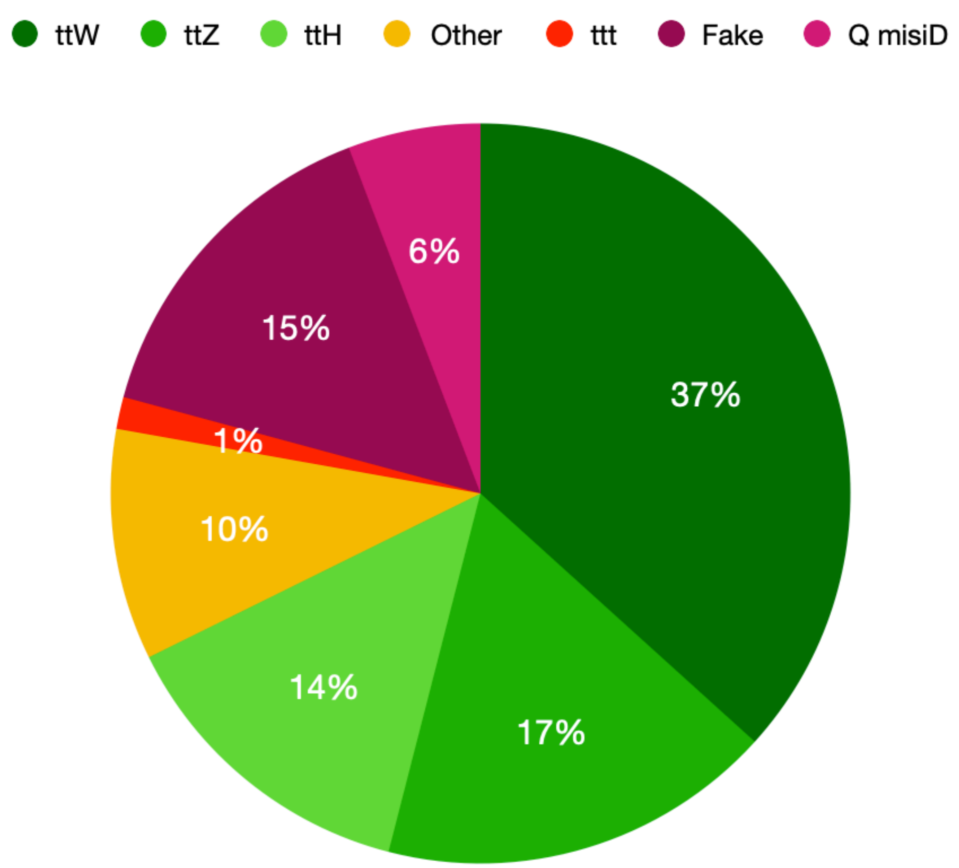
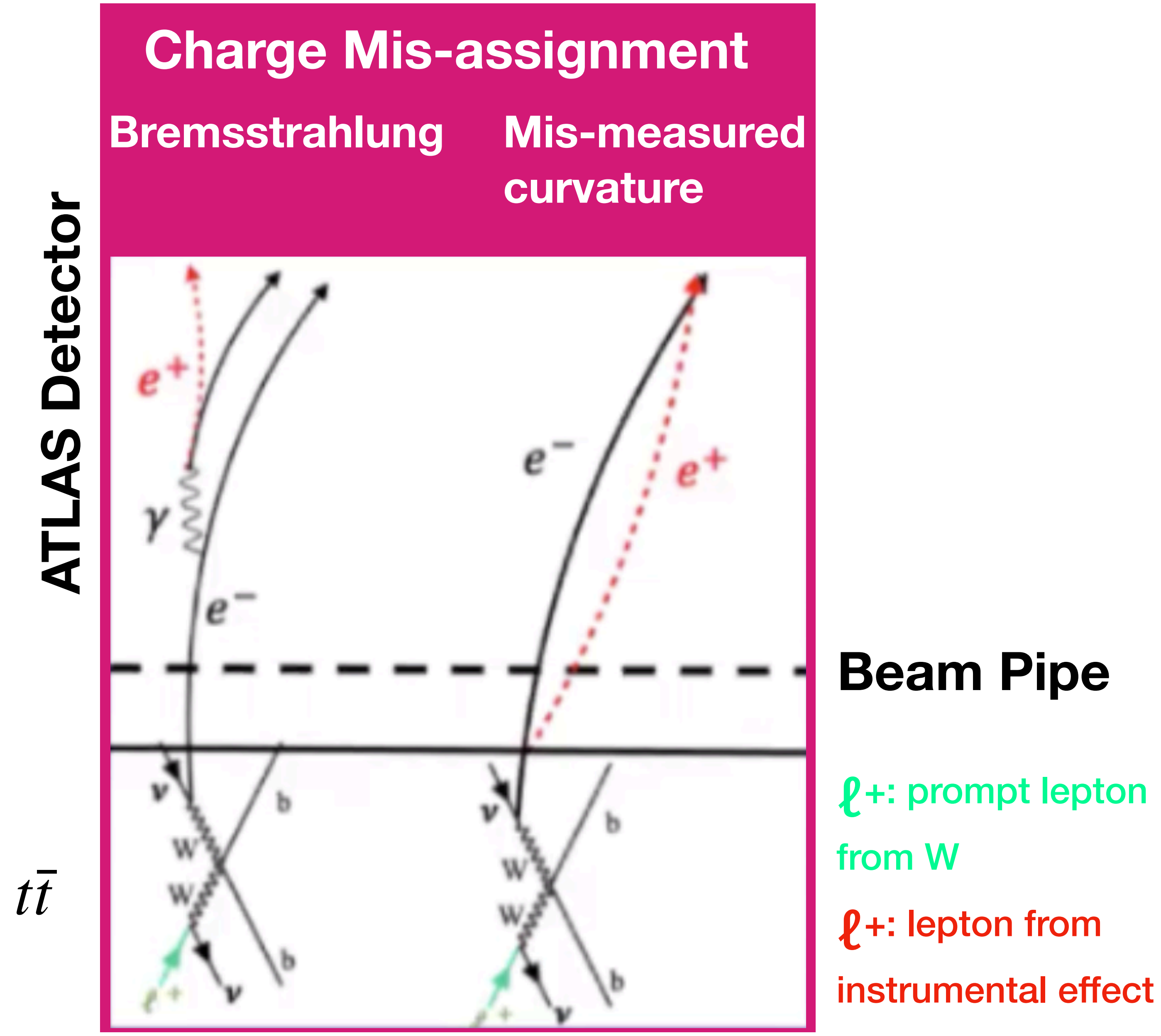


Backgrounds in 2ℓSS/3ℓ Channel

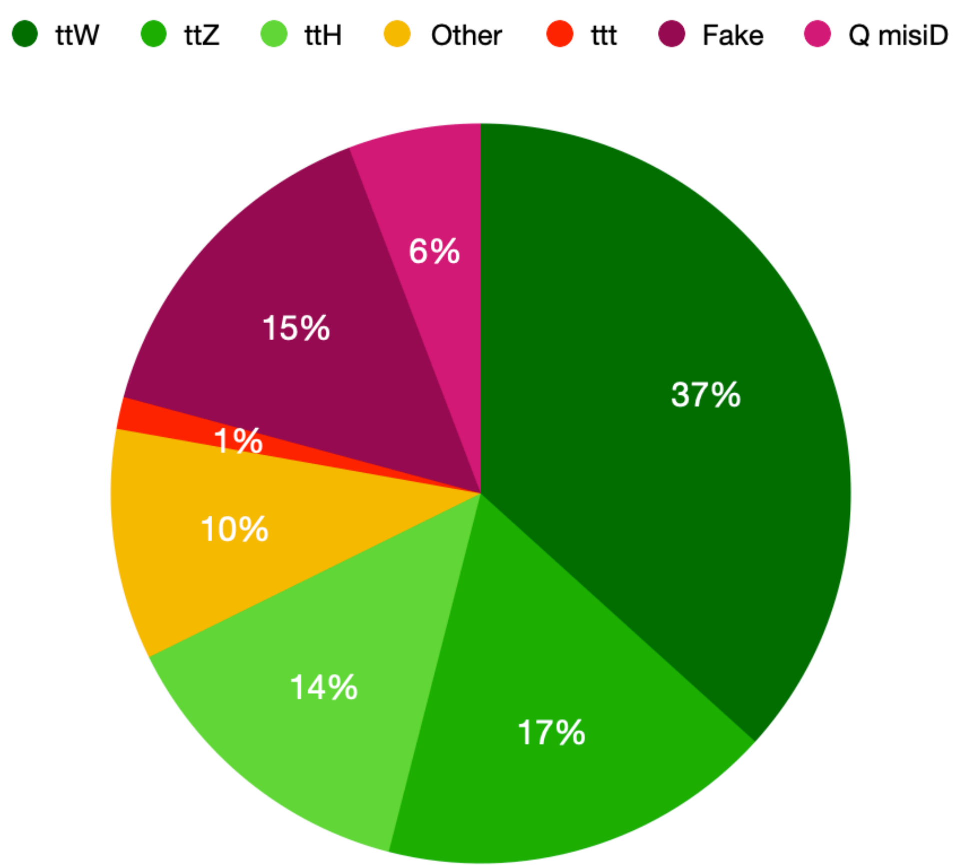
- **Reducible backgrounds** (3 dedicated control regions):
  - **Charge mis-assignment (6%)** and relevant for the 2ℓSS channel
    - Charge of electron is mis-measured, caused by:
      - Bremsstrahlung photon emission followed by its conversion
      - Mis-measured track curvature

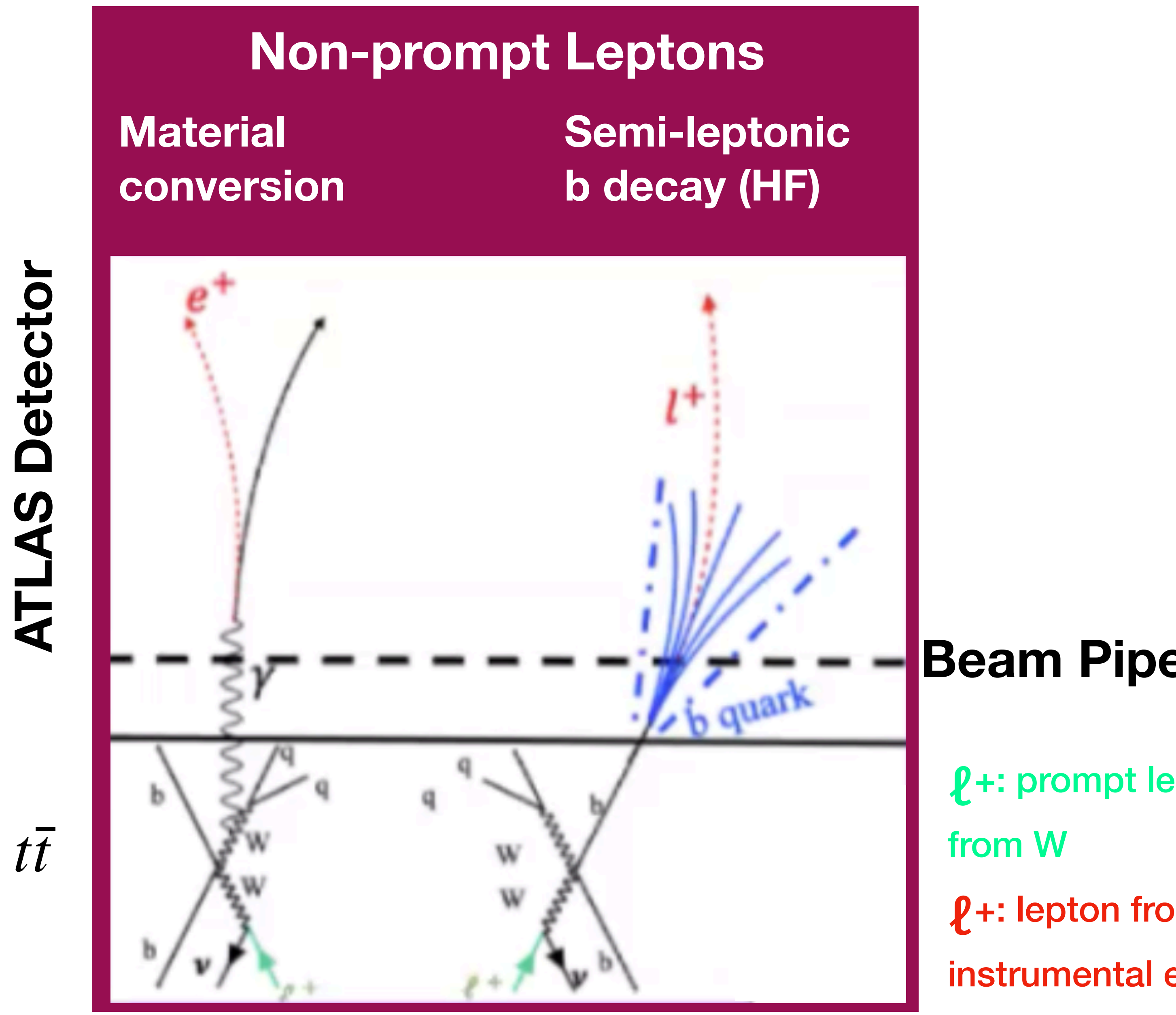




Backgrounds in 2ℓSS/3ℓ Channel

- **Fake and non-prompt backgrounds (15%)**:
  - electrons from ɣ conversion in detector
  - a virtual photon ɣ* leading to an e+e− pair (Low M_{ee})
  - electrons (muons) from heavy-flavour (HF) decay





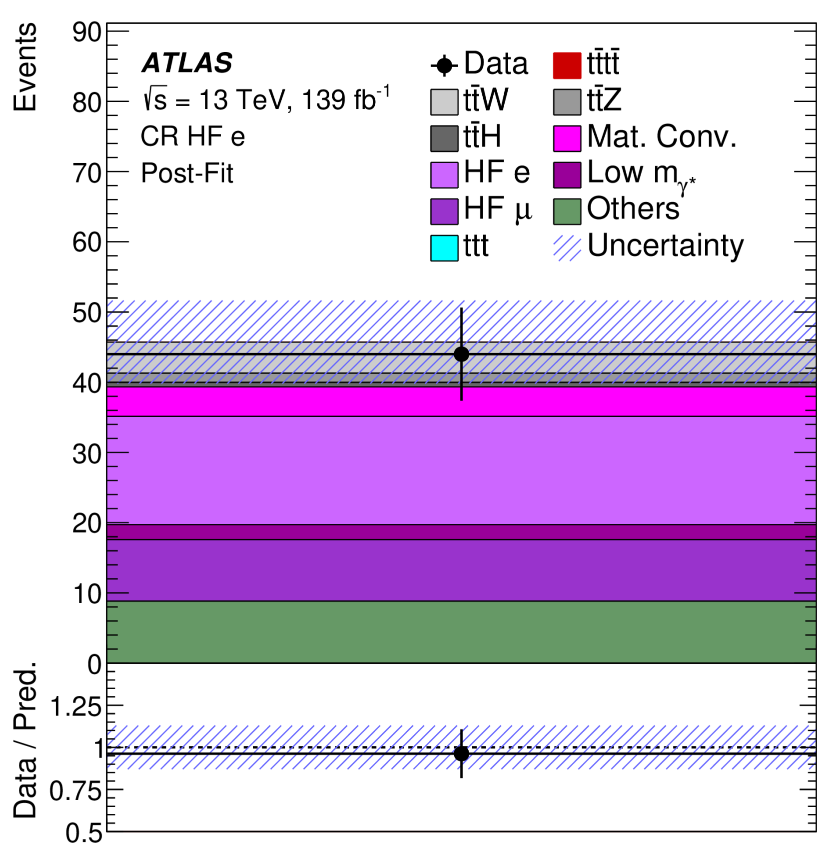
ℓ+: prompt lepton from W

ℓ+: lepton from instrumental effect

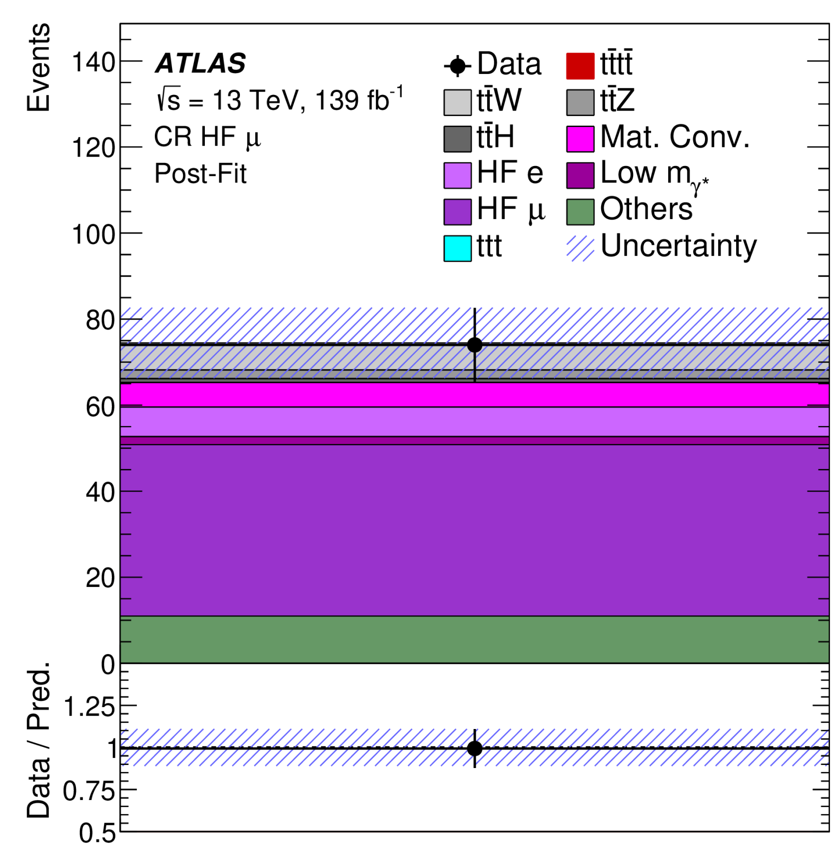
Backgrounds in 2ℓSS/3ℓ Channel

- **Template Method** is used to determine the major backgrounds
  - Background shapes are estimated from MC
  - Normalisation is obtained from the fit
  - Fit is performed in 1 Signal Region 4 Control regioins
    - Dedicated Control Regions are defined to constrain normalisation factors and the modeling is validated in the validation regions

Electron from Heavy Flavour



Muon from Heavy Flavour



Backgrounds in 2ℓSS/3ℓ Channel

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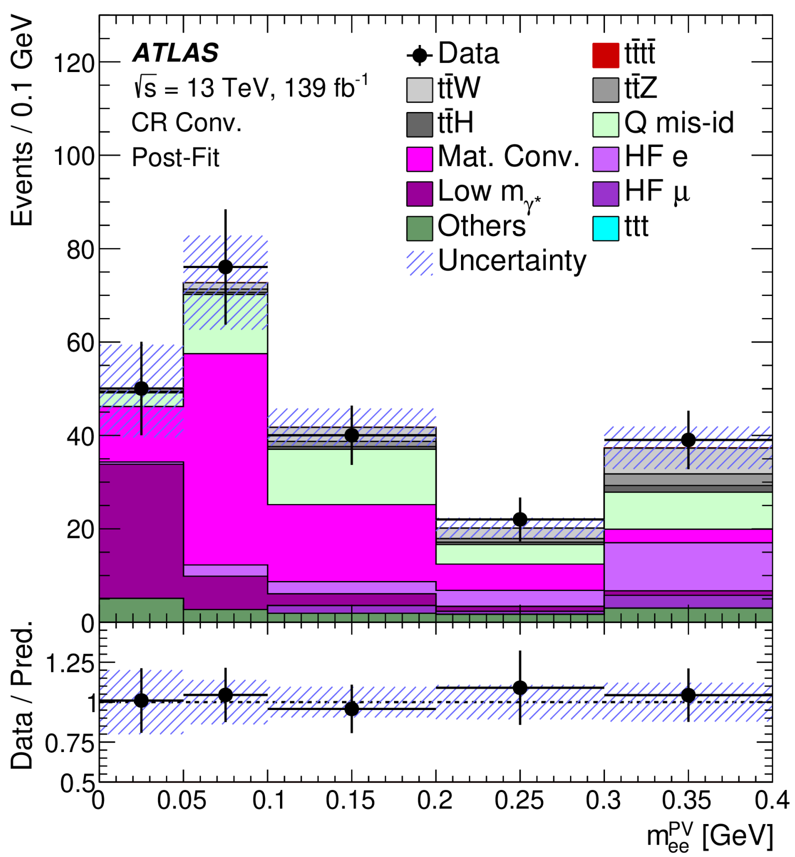
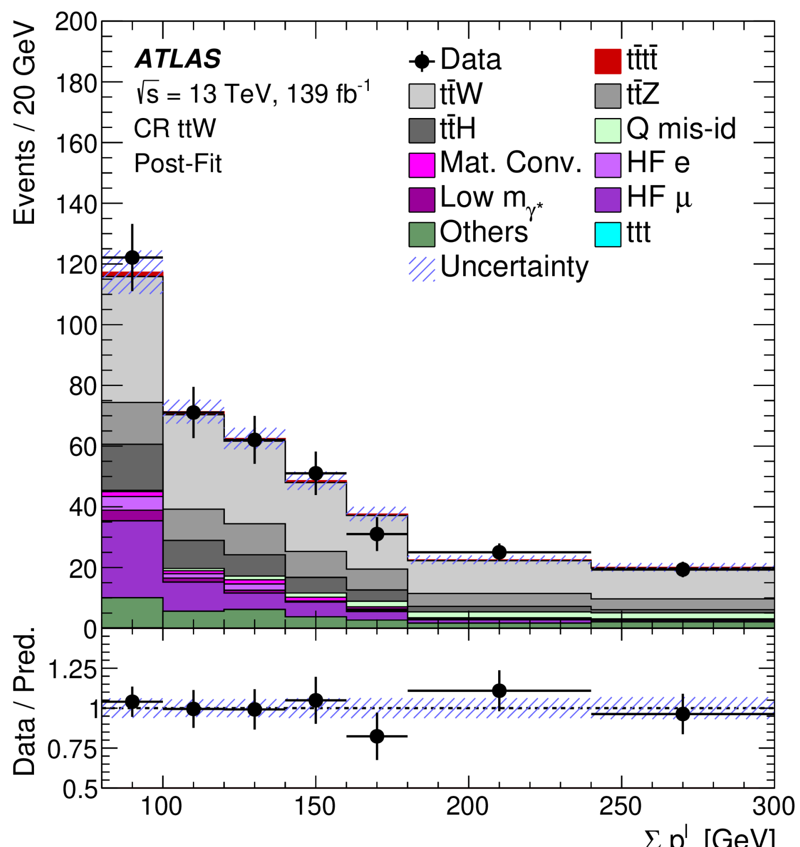
Low-mass e^+e^-

Material Conversion



$t\bar{t}W$



Backgrounds in 2ℓSS/3ℓ Channel

- **Results of the Template Fit**
  - The factors are compatible with unity except for NF_{ttW} and $NF_{Material\ Conversion}$

Fake and non-prompt backgrounds

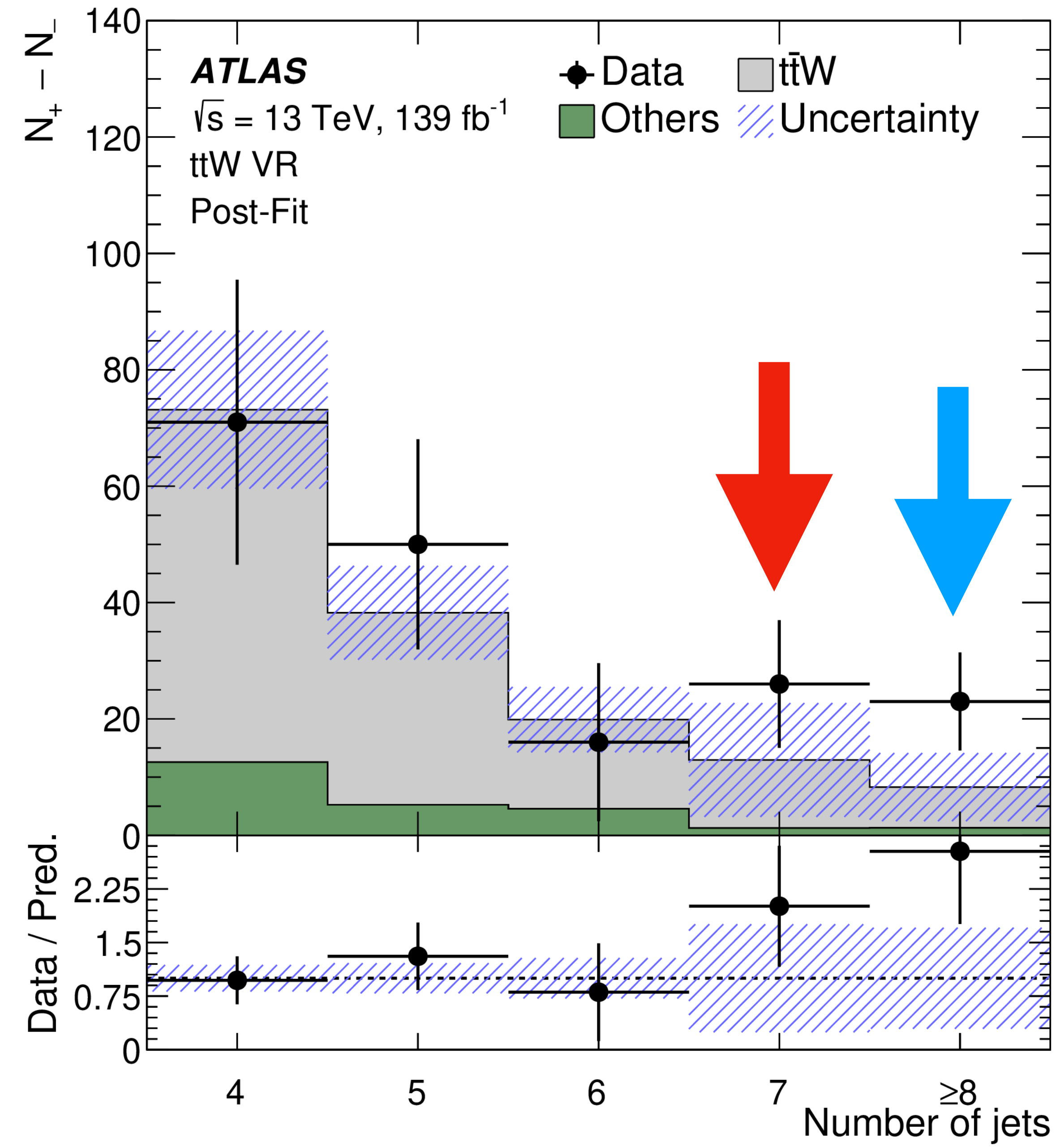
Parameter	$\boxed{NF_{t\bar{t}W}}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	$\boxed{1.6 \pm 0.3}$	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

  - The high NF_{ttW} is compatible with previous ATLAS ttH(H→multi-leptons) results and results from CMS

2ℓSS/3ℓ Channel: $t\bar{t}W$ Validation Region

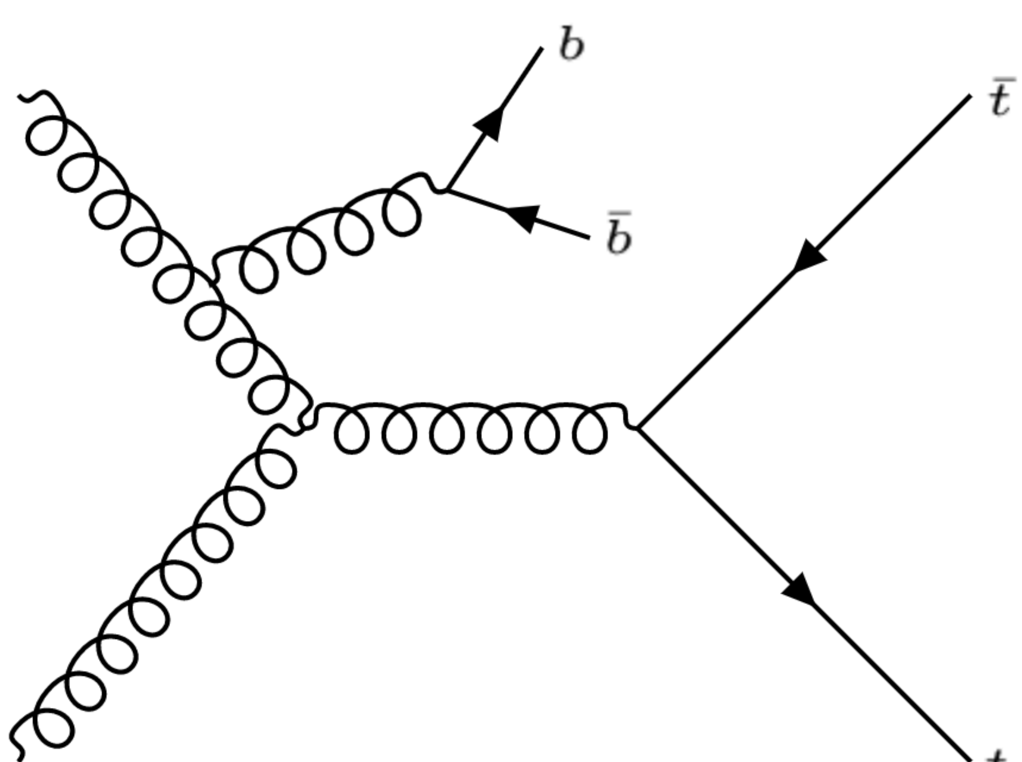
- Use Validation Region to check $t\bar{t}W$+jets normalisation and modeling
  - **Additional jets**: Uncertainty of 125% is assigned to events with 7 jets and 300% is assigned to events with ≥8 jets
    - Based on Validation Region mismodeling

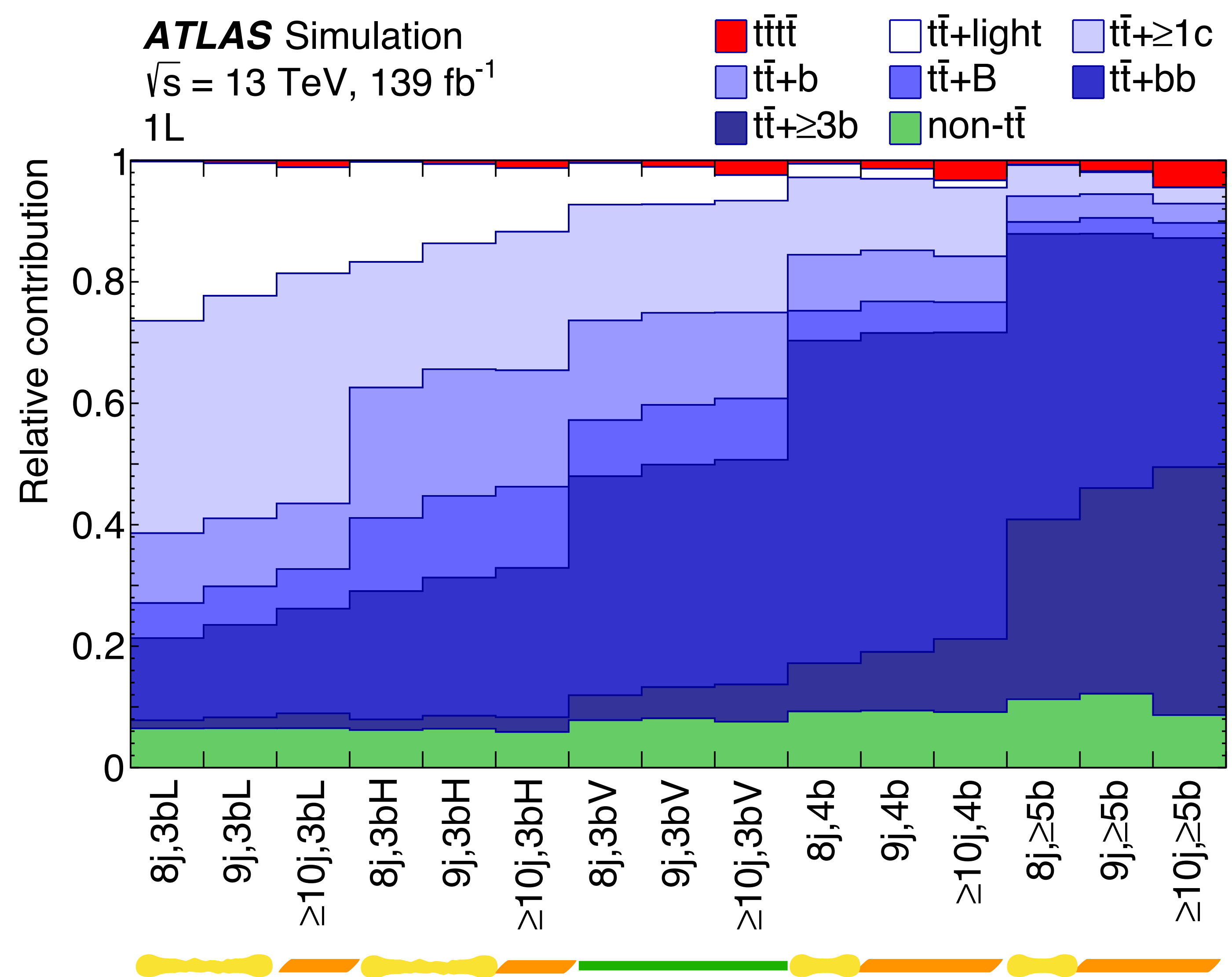
$t\bar{t}W$ **Validation Region**: ≥4jets ≥2b-tagged



Backgrounds in the 1ℓ/2ℓOS Channel

- Dominated by background coming from $t\bar{t}$+jets; mainly $t\bar{t}+b\bar{b}$
- Small contribution from non-ttbar background:
  - Single-top, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}H$, V+jets, VV, $t\bar{t}WW$, ttt, tZ, and tWZ

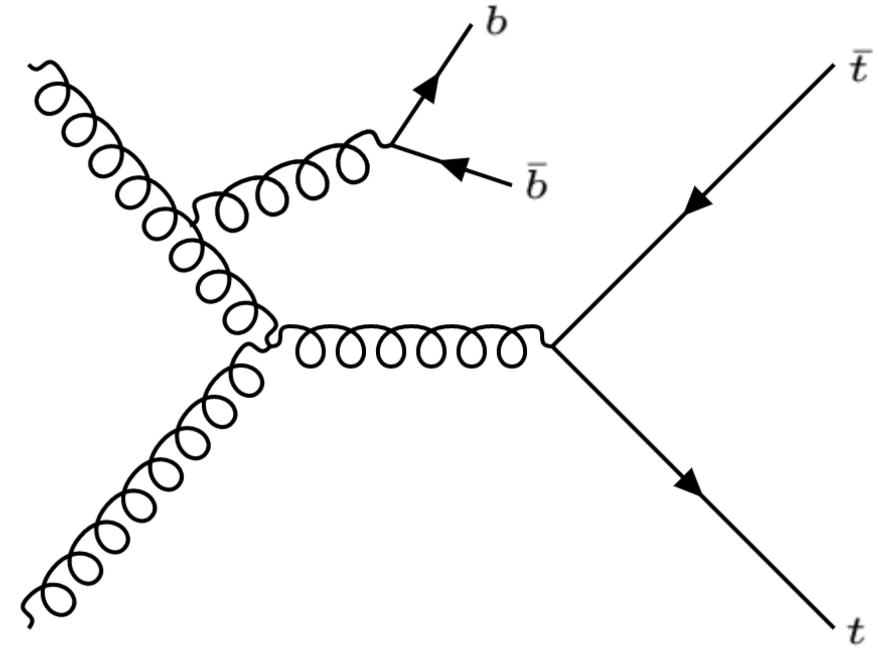




6 Control Regions
6 Signal Regions
3 Validation Regions

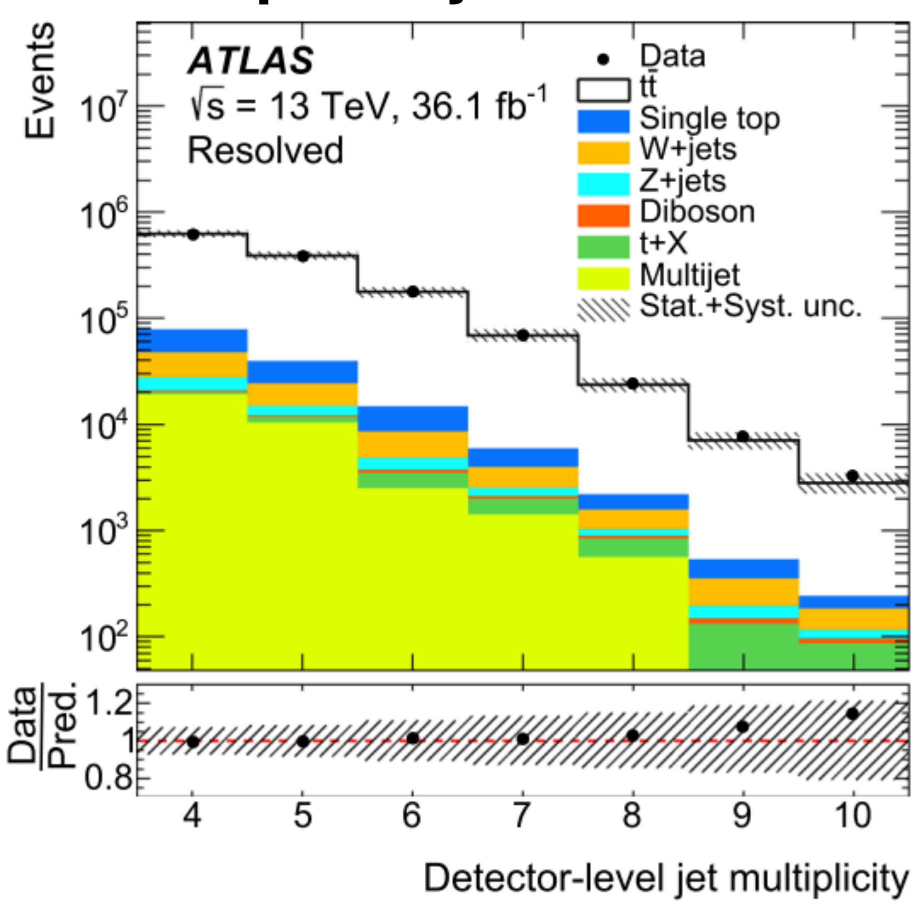
Backgrounds in the $1\ell/2\ell$OS Channel

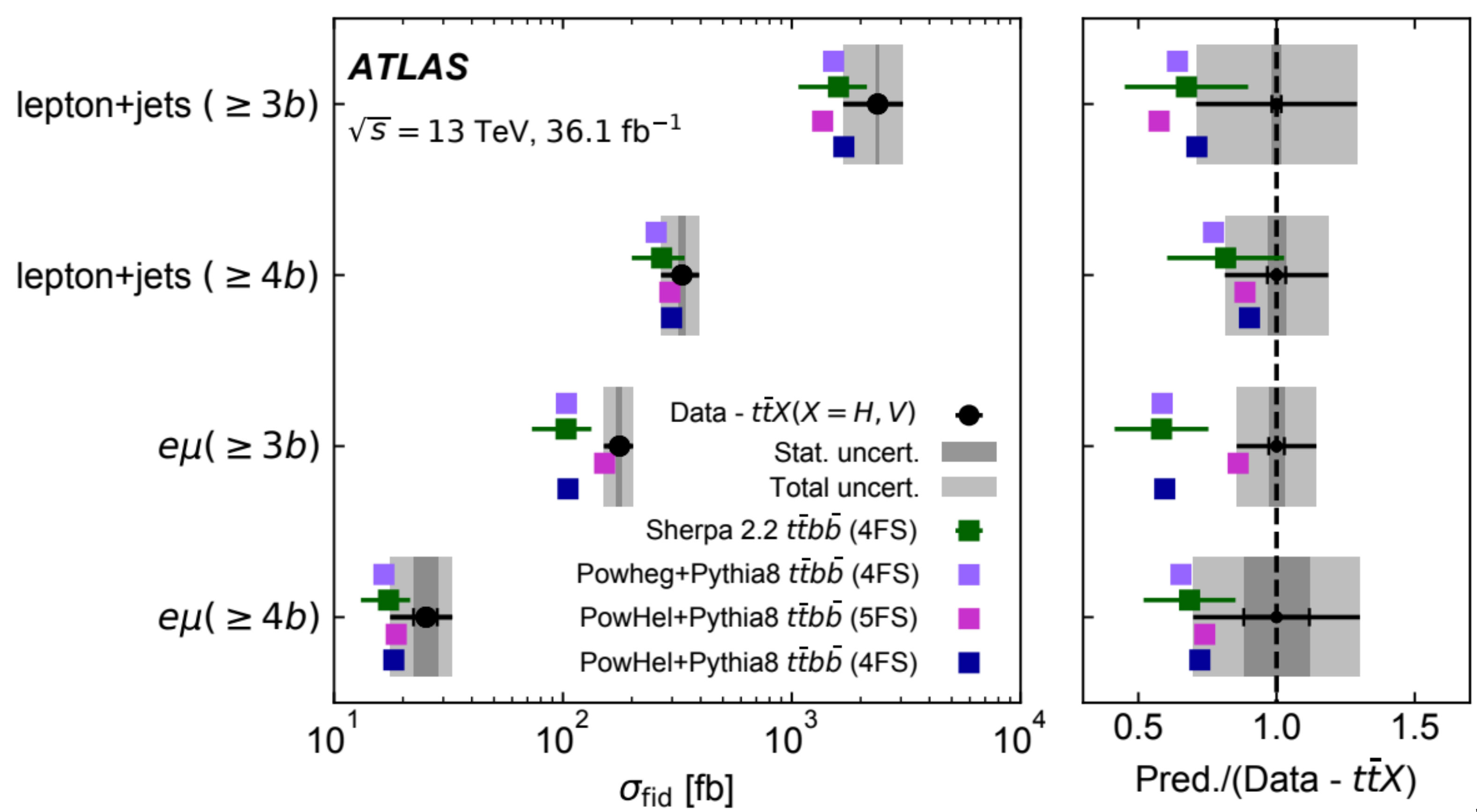
- $t\bar{t}$+jets is a challenging background to model
  - Many additional jets are produced in the parton shower with limited precision
  - Modelling of HF jets (b/c) is even more challenging



$t\bar{t}$+$b\bar{b}$ is underestimated by the current MC simulations

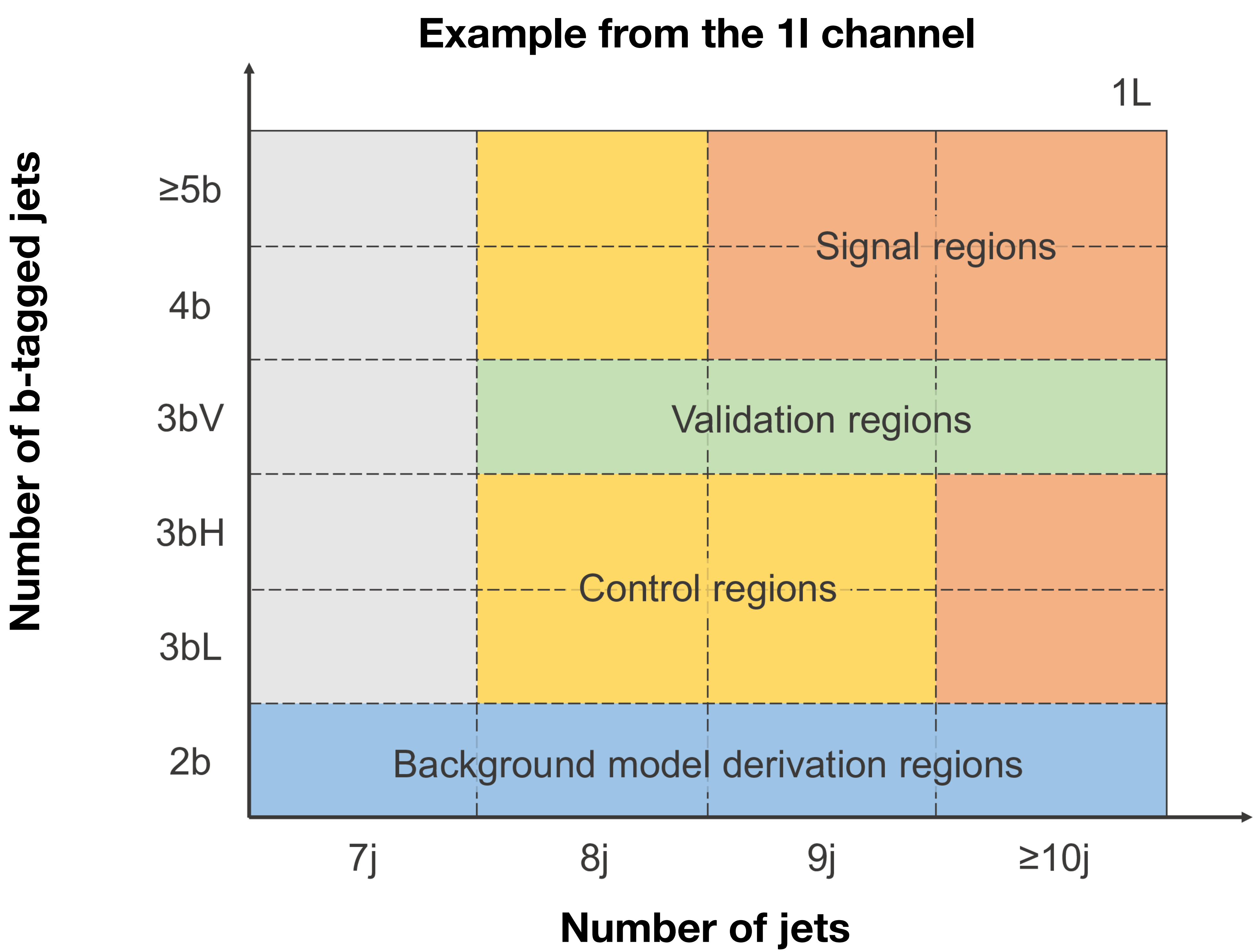
lepton +jets Channel





Regions in the 1ℓ/2ℓOS Channel

- Events are categorized according to the number of **jets** and **different *b*-tagging** requirements
  - Both number of b-tags & their quality (<u>L</u>ow or <u>H</u>igh)



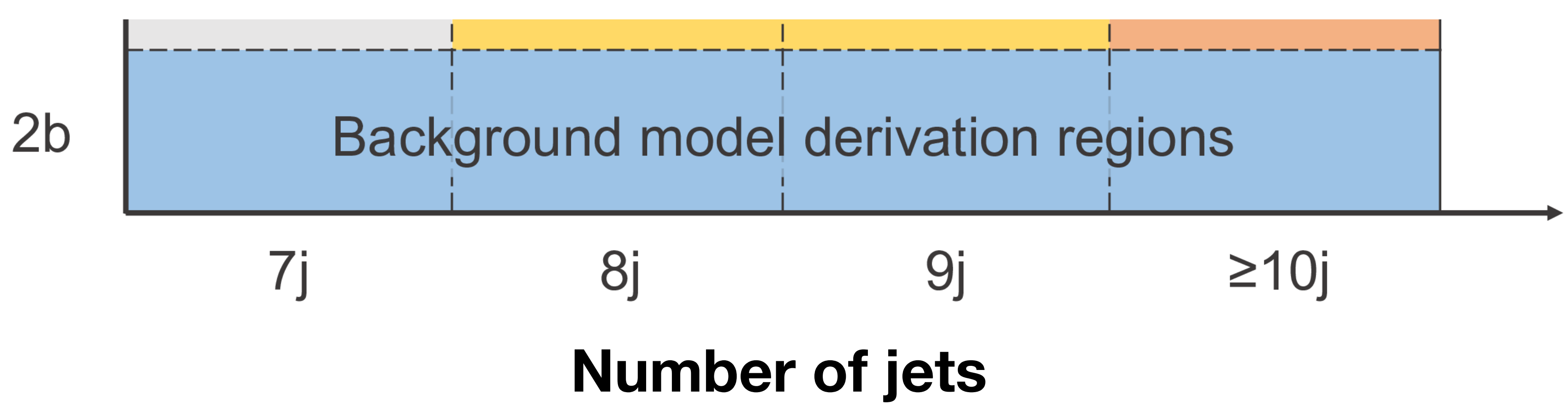
Regions in the 1ℓ/2ℓOS Channel

- Events are categorized according to the number of **jets** and **different *b*-tagging** requirements

  - Both number of b-tags & their quality (Low or High)

Example from the 1l channel

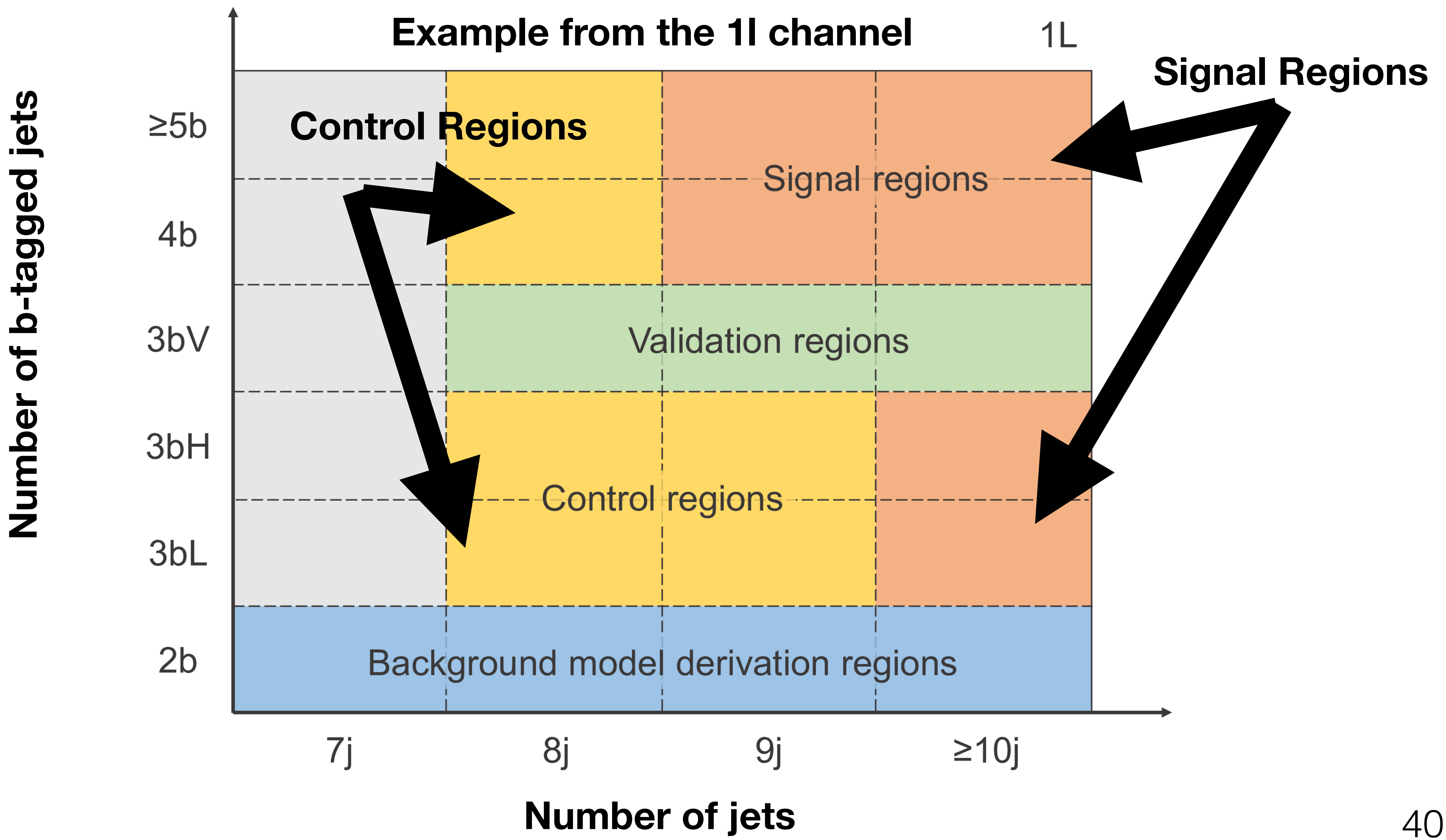
Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	$= 2$	-
3bL	≤ 2	$= 3$	-
3bH	$= 3$	$= 3$	$= 3$
3bV	$= 3$	$= 3$	≥ 4
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	$= 4$	-
≥5b (1L)	-	≥ 5	-



1ℓ/2ℓOS Channel: Analysis Regions

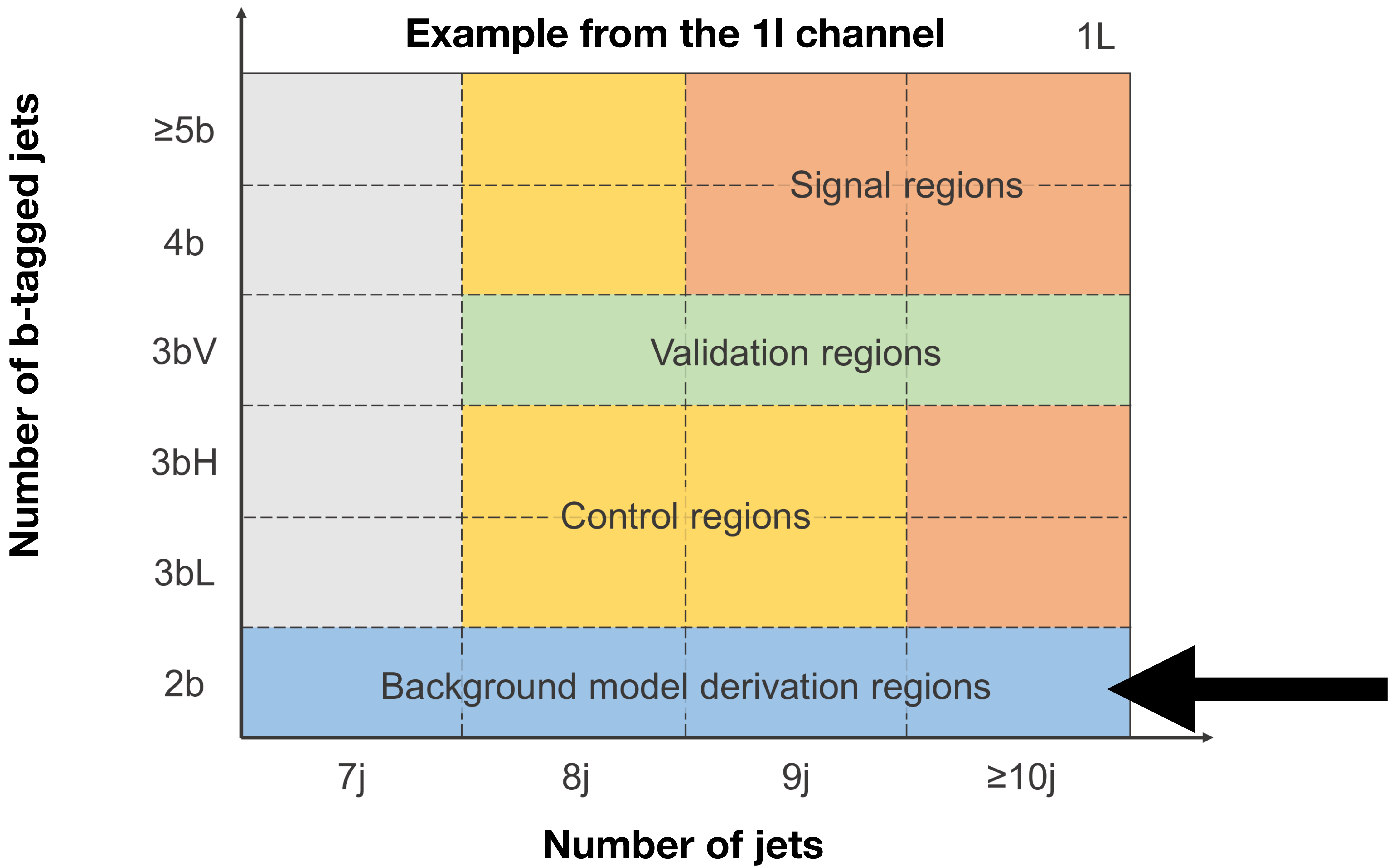
- 12 **Signal** and **Control** regions will be used as input for the binned profile likelihood fit

  - H_T^{all} (lepton+jets activities) distributions are used in Control Regions



1ℓ/2ℓOS Channel: Analysis Regions

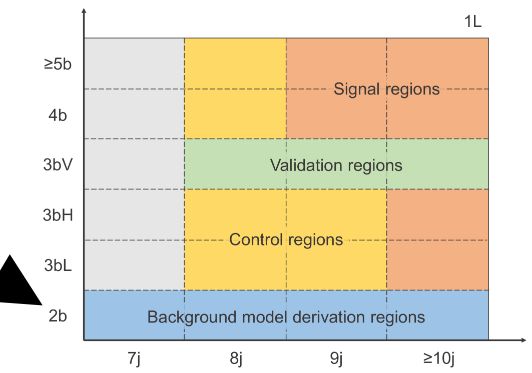
- Events with 2-bjets are used to derive pre-fit corrections factors applied to the $t\bar{t}$+jets MC simulations



1ℓ/2ℓOS Channel: $t\bar{t}$+jets Backgrounds

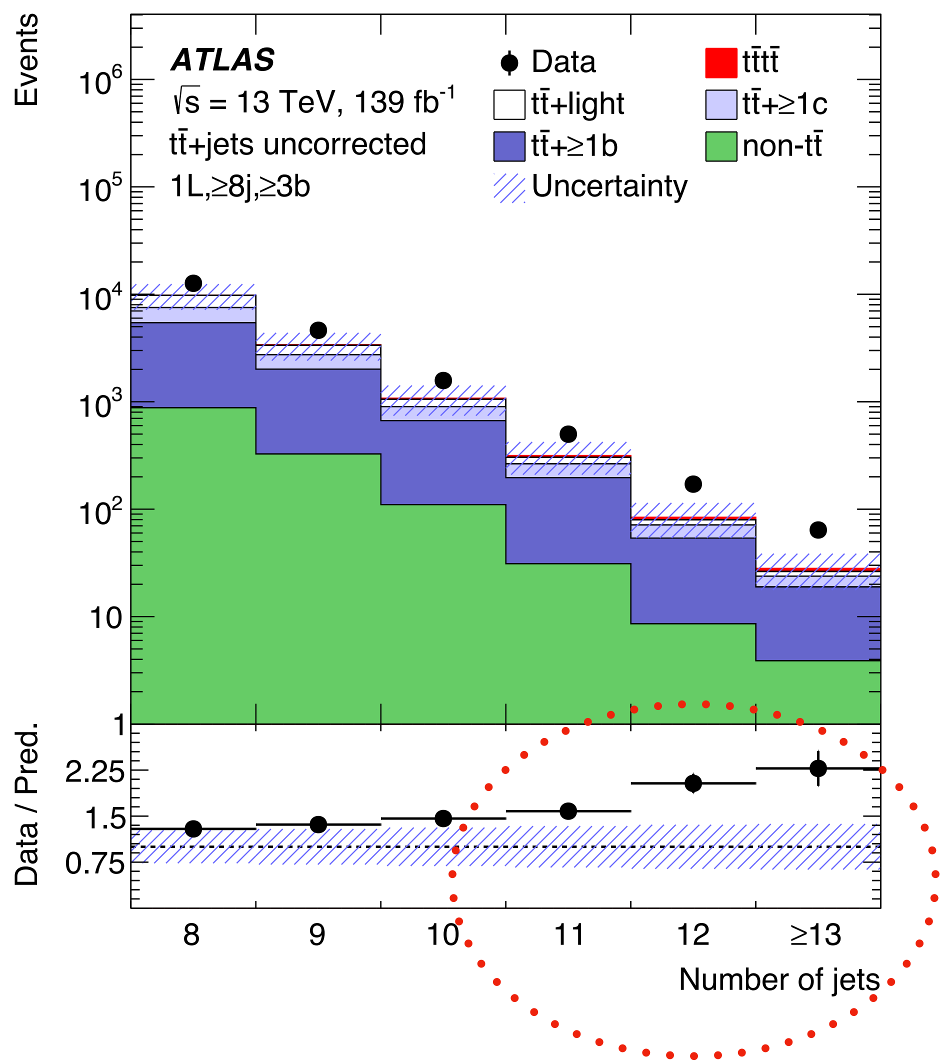
- MC known to mismodel the $t\bar{t}$+jets background at high-H_T and high-b jet multiplicity (mostly noticeable in N_{jets} and H_T)

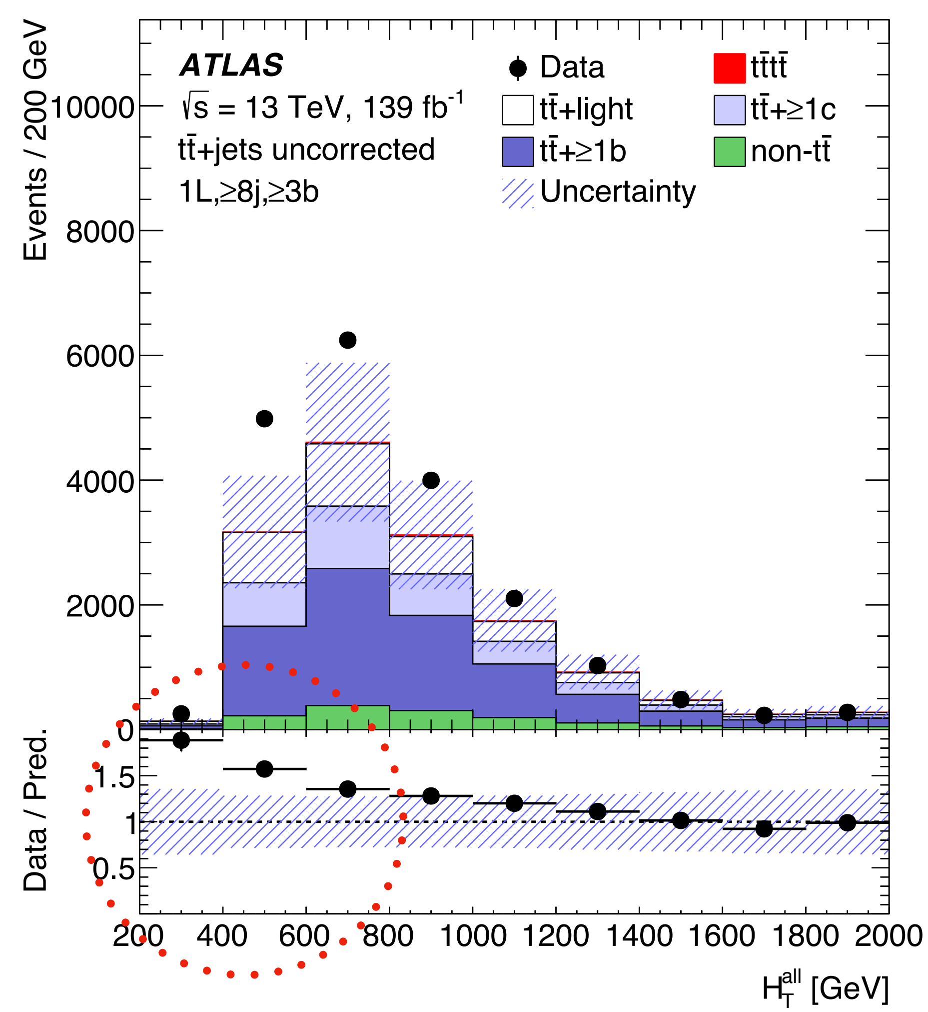
- Developed techniques to tackle MC mismodeling in 2 b-tagged regions



  - Derived rescaling factors at pre-fit level
  - Designed a 3-step sequential re-weighting to target different type of mismodeling

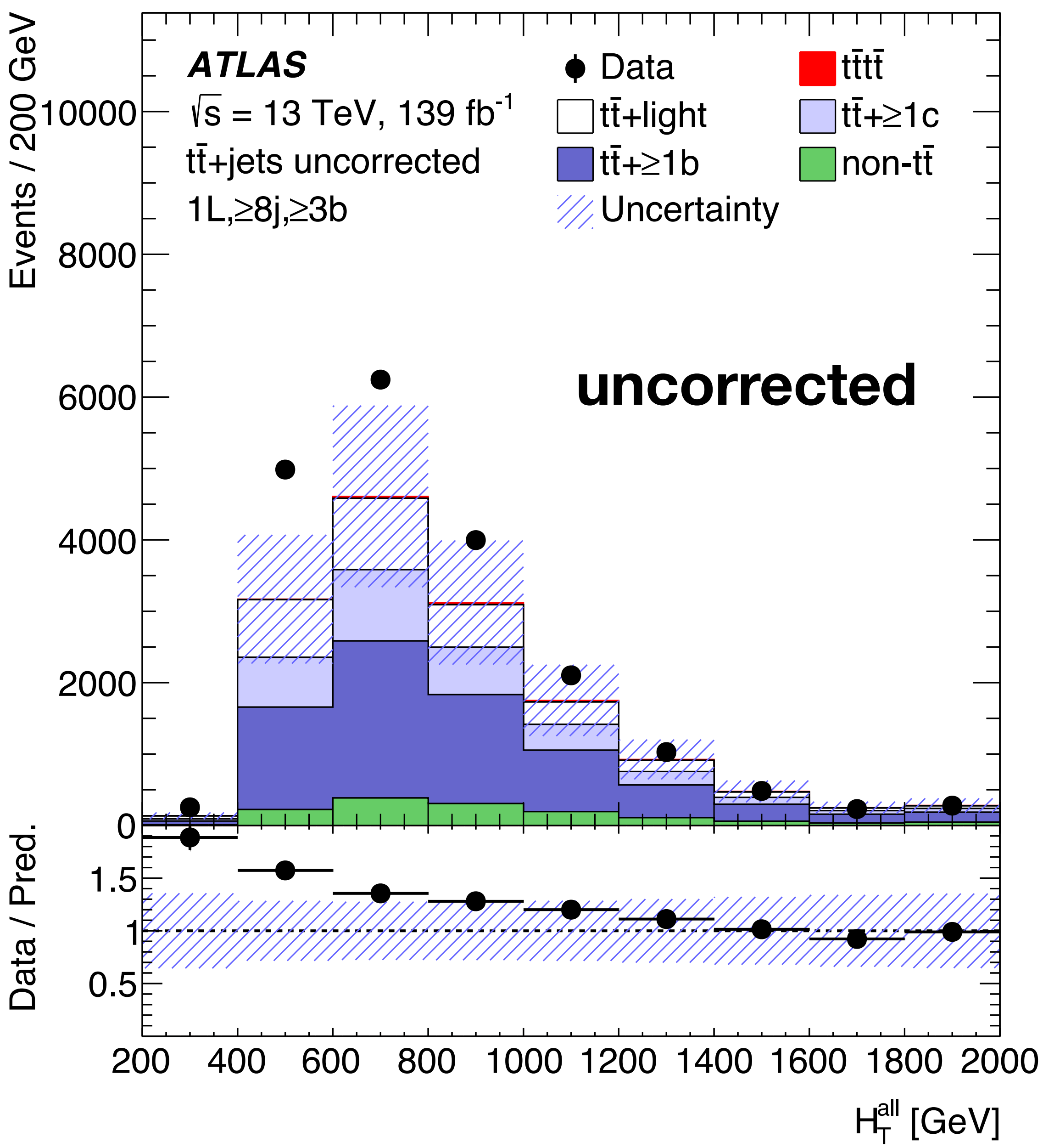
- N_{jet} → H_T^{all} → ΔR_{avg}^{jets}

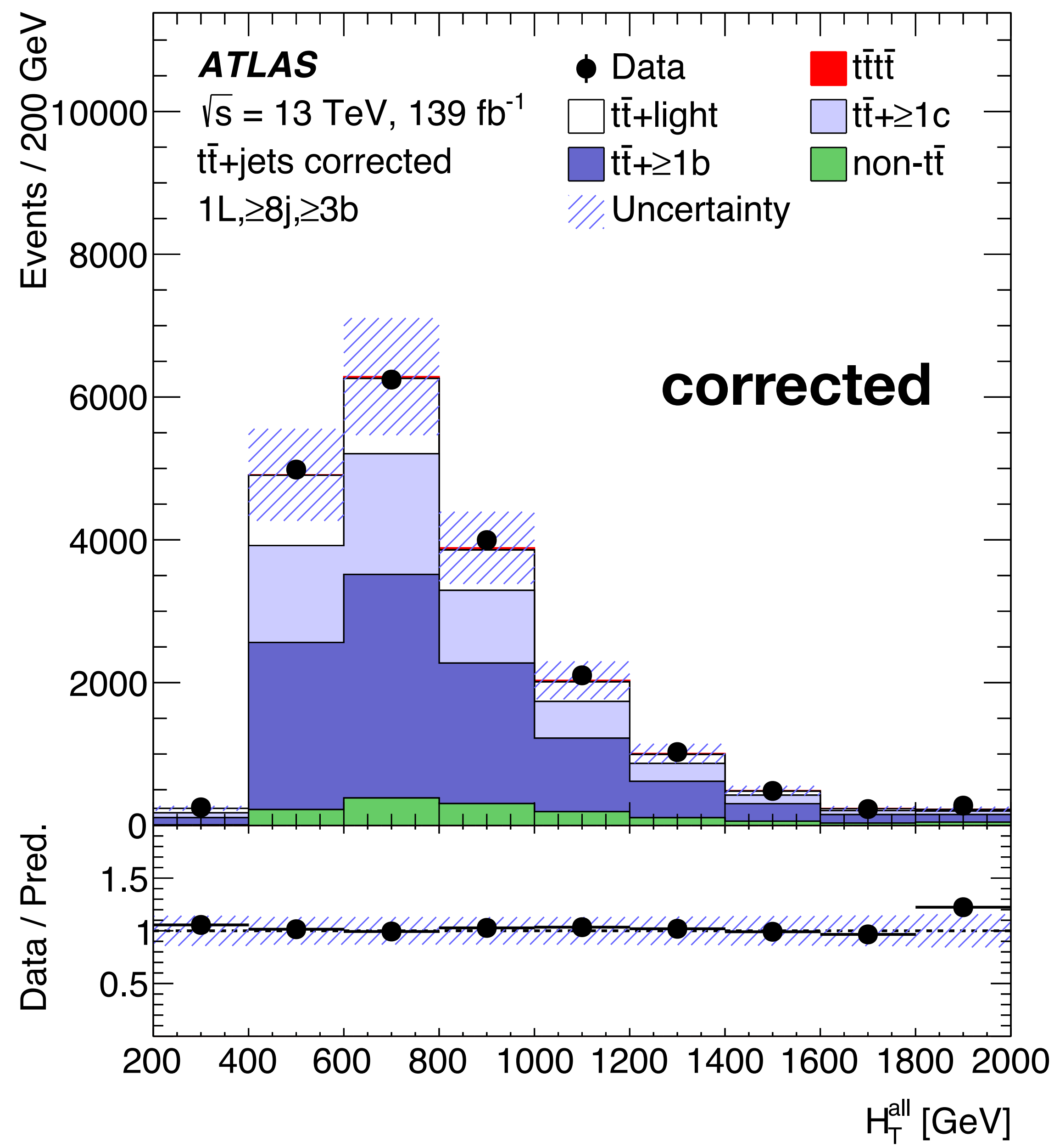




1ℓ/2ℓOS Channel: $t\bar{t}$+jets Backgrounds

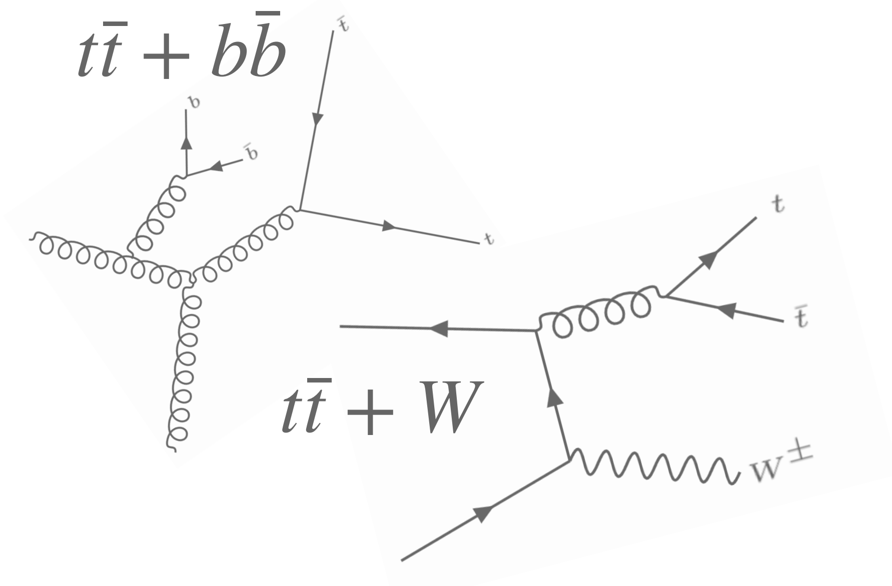
- Better Data/MC agreement after correcting the $t\bar{t}$+jets background



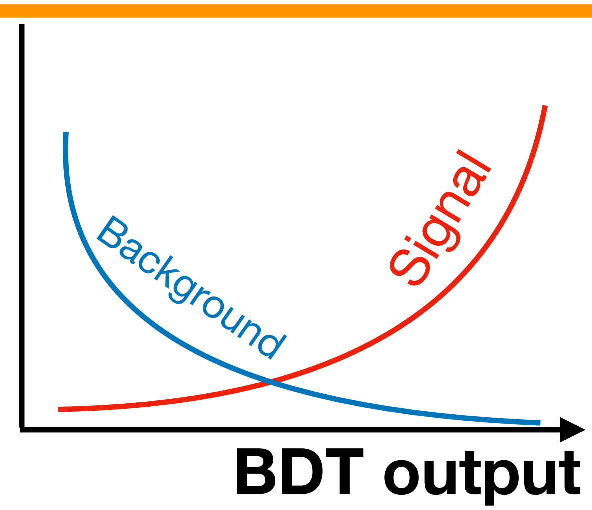


Event Selection and Analysis regions

Control Region to estimate the main background



Use BDT in the **Signal Region** to separate the signal from the background



Validation Region to validate the model

Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \sigma_{t\bar{t}t\bar{t}} / \sigma^{SM}_{t\bar{t}t\bar{t}}$

Extract measured cross section and compare to theory!

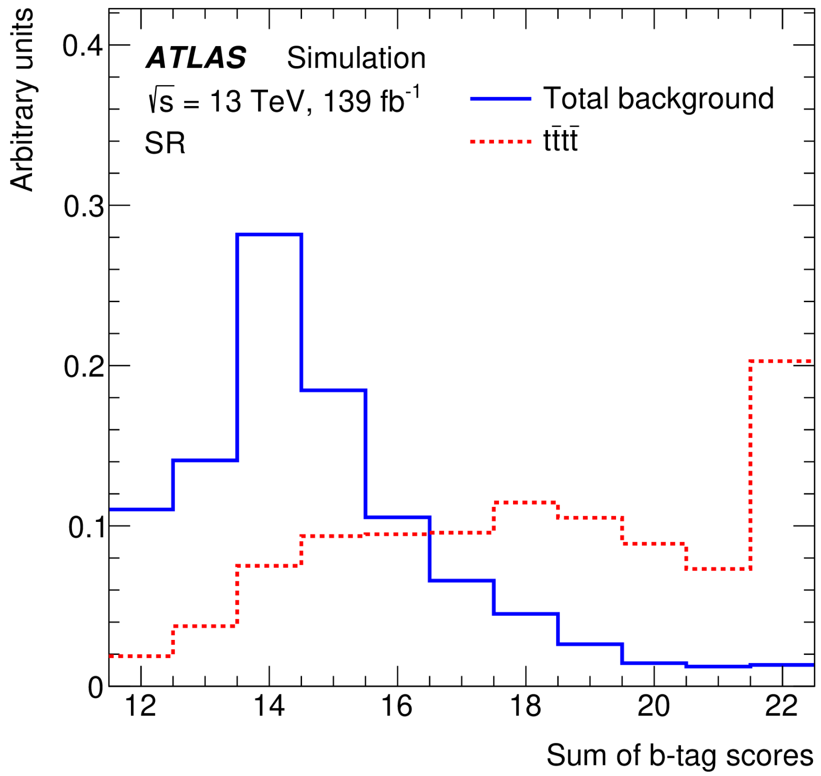
Use of BDT in the Signal Region

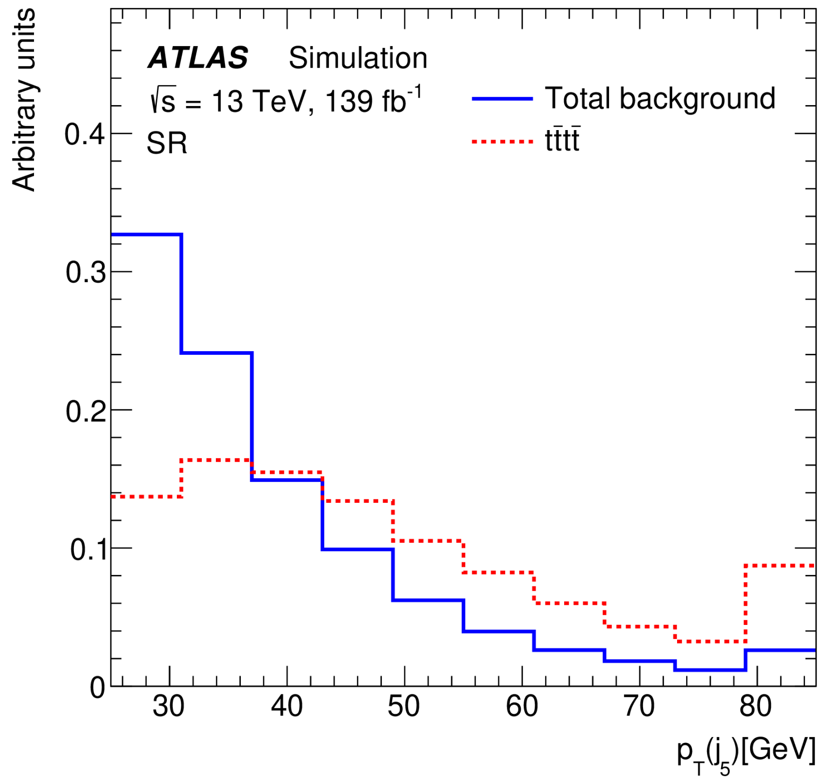
- Signal is separated from background based on a multivariate discriminant built in the signal region by combining many **input observables** into a BDT:

- **Observables** are selected based on their **discrimination power** and the requirement of good modelling

  - b-tagging information: **Sum of the pseudo-continuous b-tagging discriminant score**

  - **Lepton and jet kinematics**





Sum of b-tag scores **+** **$p_T(j_5)$** **+...**

Use of BDT in the Signal Region

- Signal is separated from background based on a multivariate discriminant built in the signal region by combining many **input observables** into a BDT:
- **Observables** are selected based on their **discrimination power** and the requirement of good modelling
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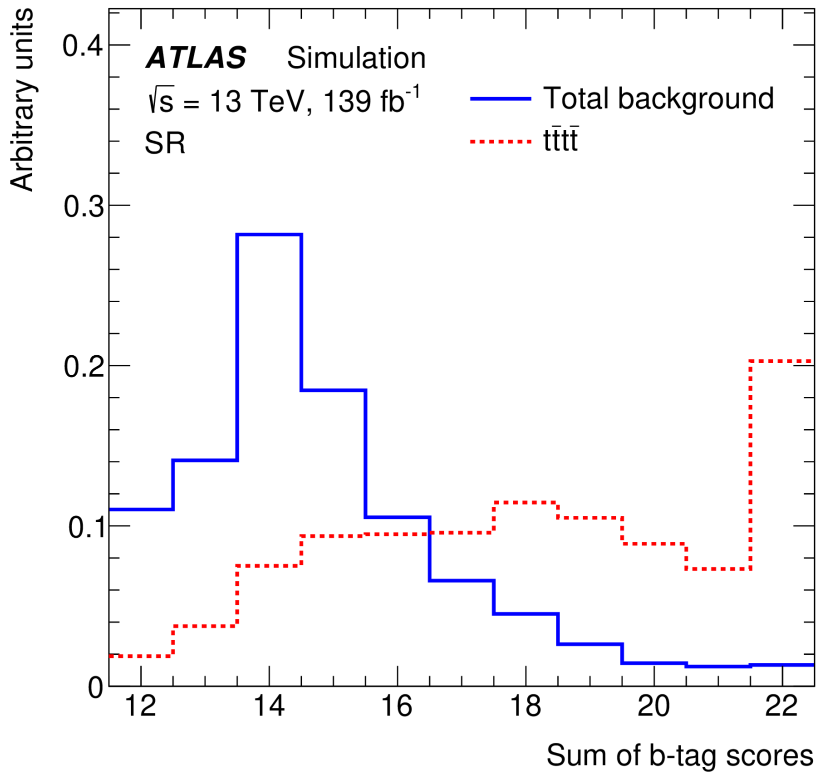
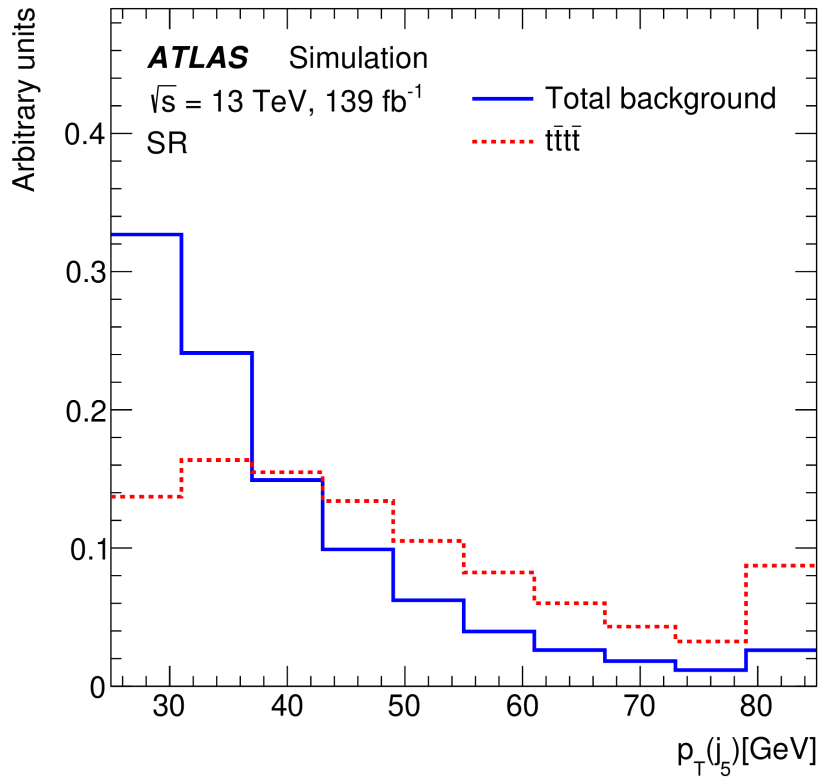
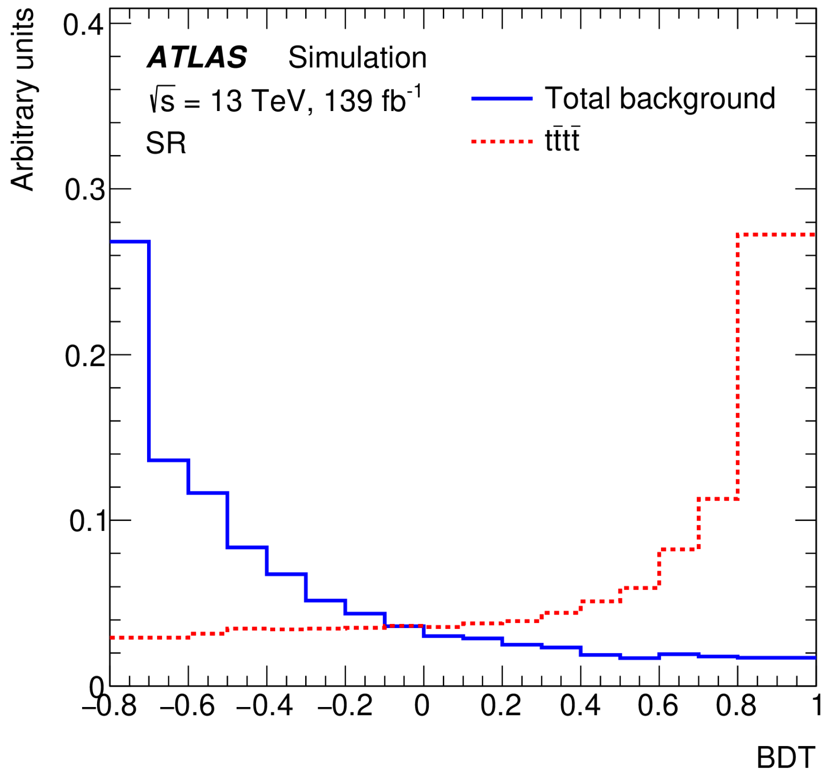






Sum of b-tag scores **+** **$p_T(j_5)$** **+...=** **BDT score**

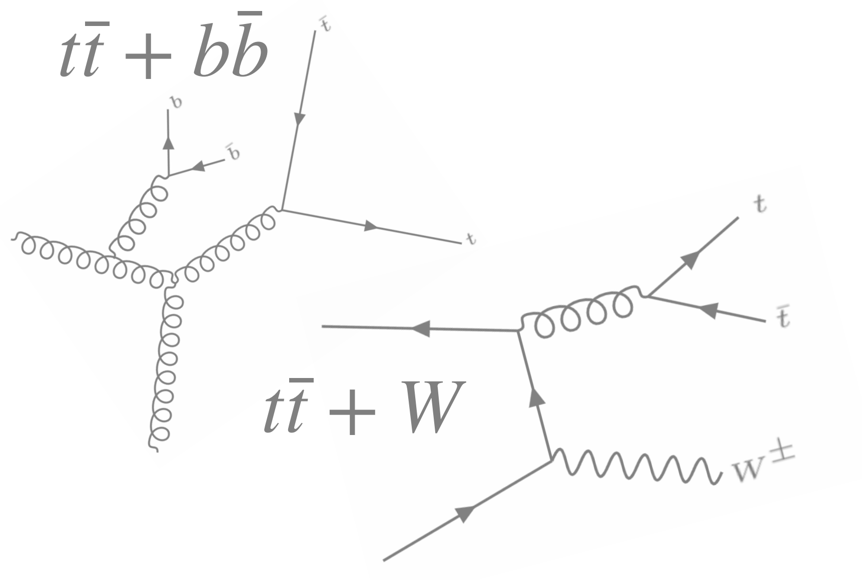
Profile Likelihood Fit

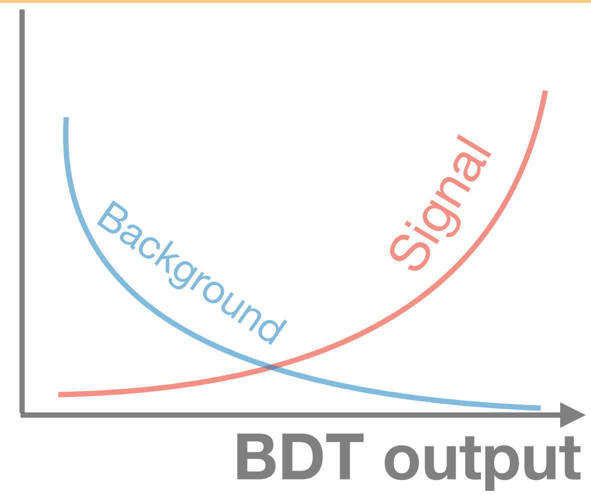
Event Selection and Analysis regions

Control Region to estimate the main background

Use BDT in the **Signal Region** to separate the signal from the background

Validation Region to validate the model





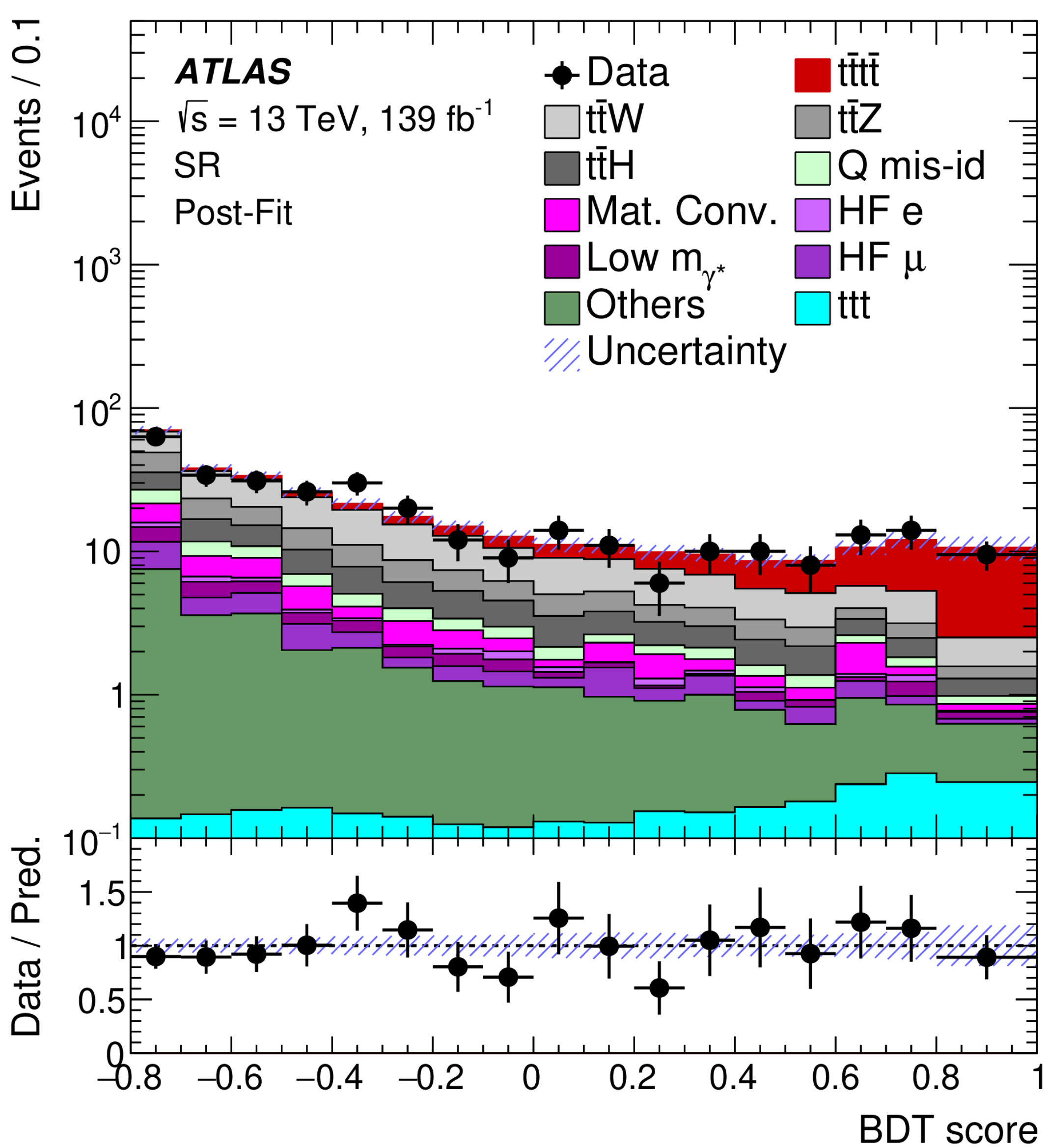
Perform a fit in the Control and Signal Regions to extract the signal strength $\mu = \sigma_{t\bar{t}t\bar{t}}/\sigma^{SM}_{t\bar{t}t\bar{t}}$

Extract measured cross section and compare to theory!

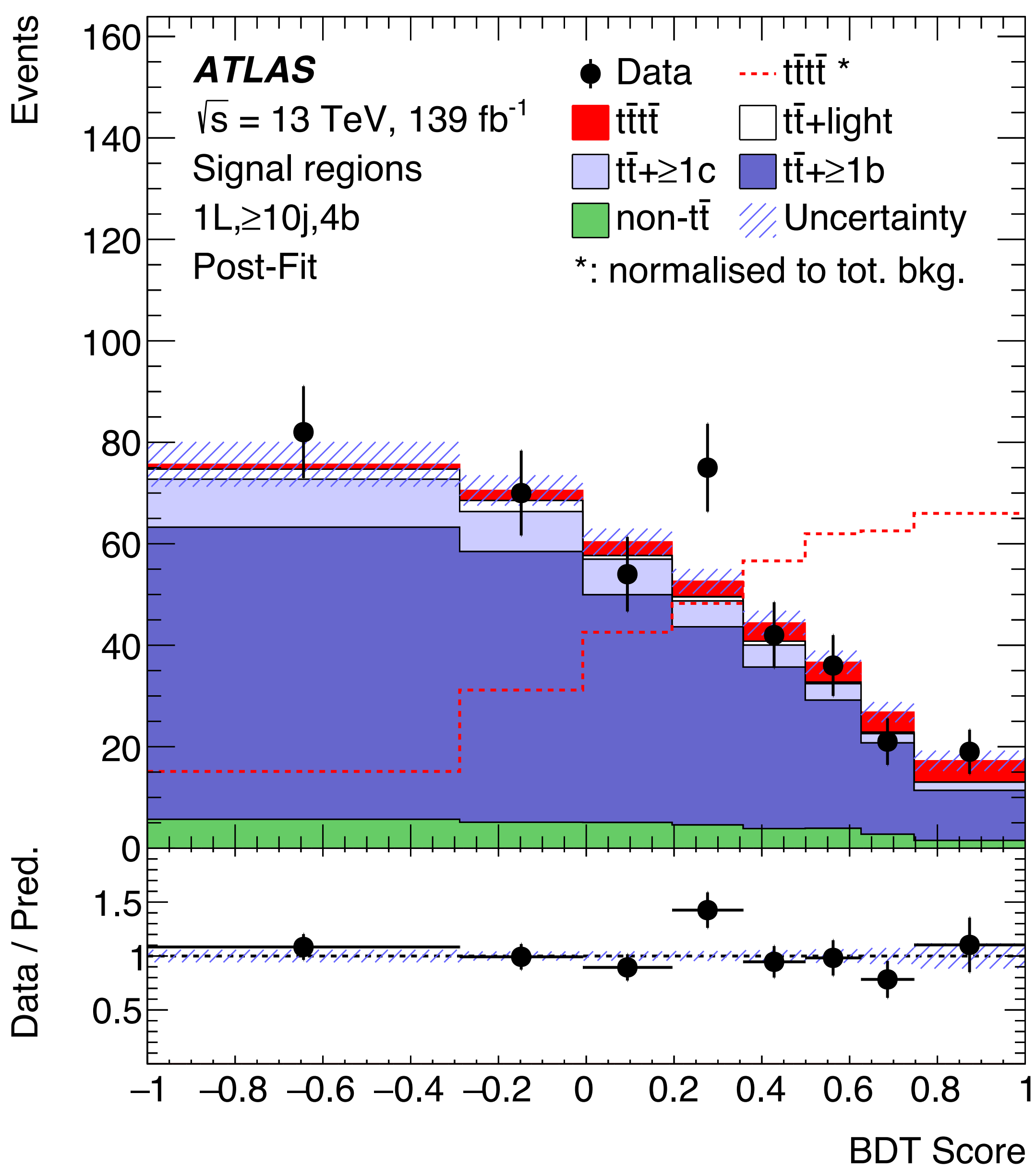
Results: post-fit plots

- A simultaneous profile likelihood fit is performed in the Control Regions and Signal Regions
  - The systematic uncertainties in both the signal and background predictions are included as nuisance parameters in the likelihood function

2ℓSS/3ℓ Channel



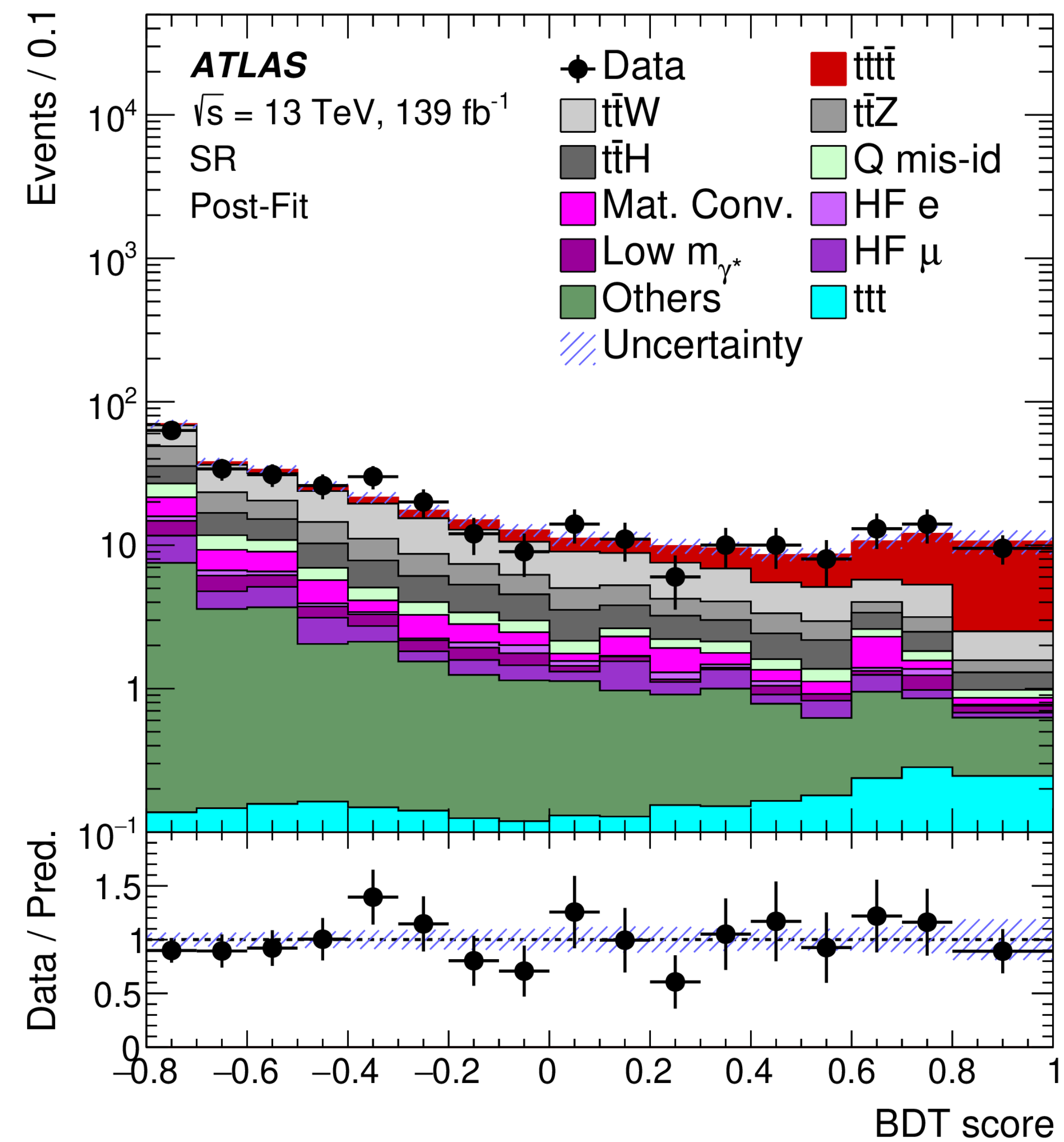
1ℓ Channel



Results: 2ℓSS/3ℓ Channel

- The measured $t\bar{t}t\bar{t}$ signal strength is found to be:

$$\mu = 2.0^{+0.4}_{-0.4}(stat)\ \ ^{+0.7}_{-0.5}(syst)\ \ = 2.0^{+0.8}_{-0.6}$$



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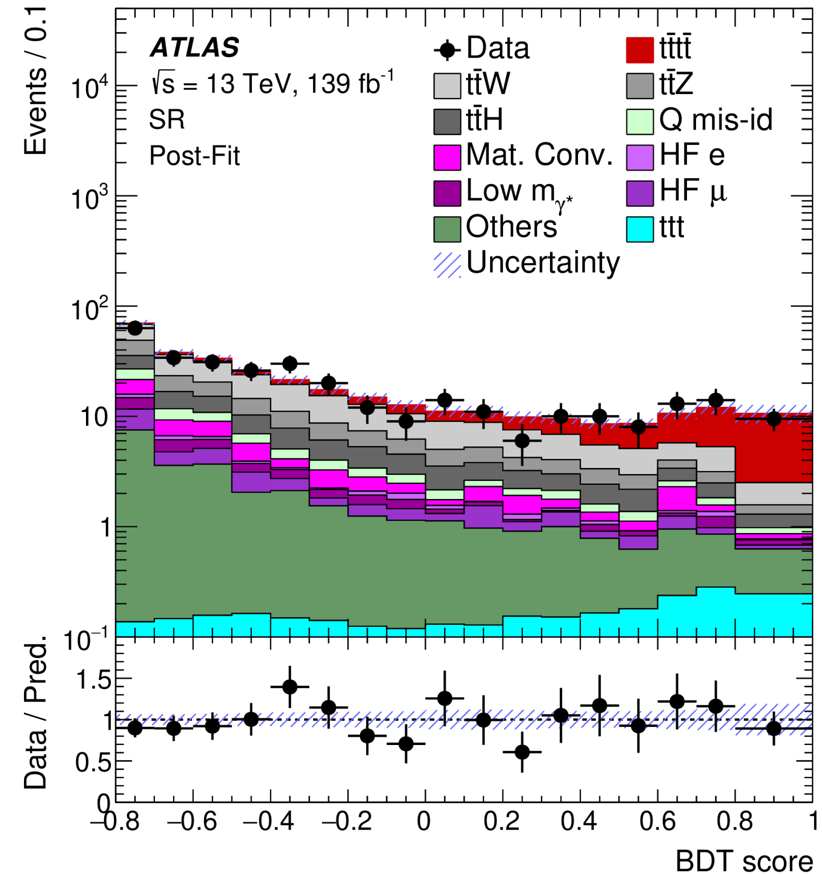
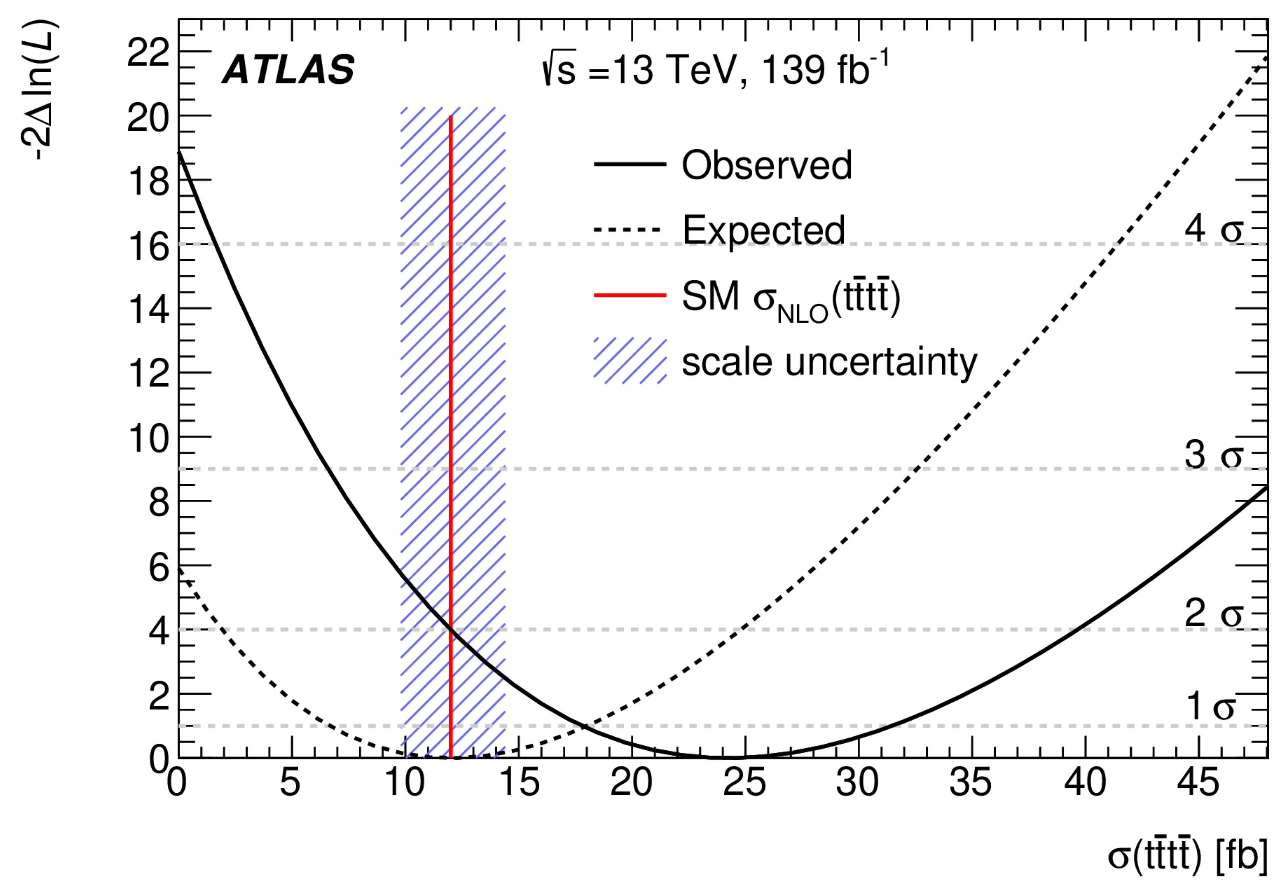
- Cross section:
  $\sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(stat)\ \ ^{+5}_{-4}(syst)\, fb = 24^{+7}_{-6}\ fb$

- Compared to the theoretical predication of $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2\ fb$





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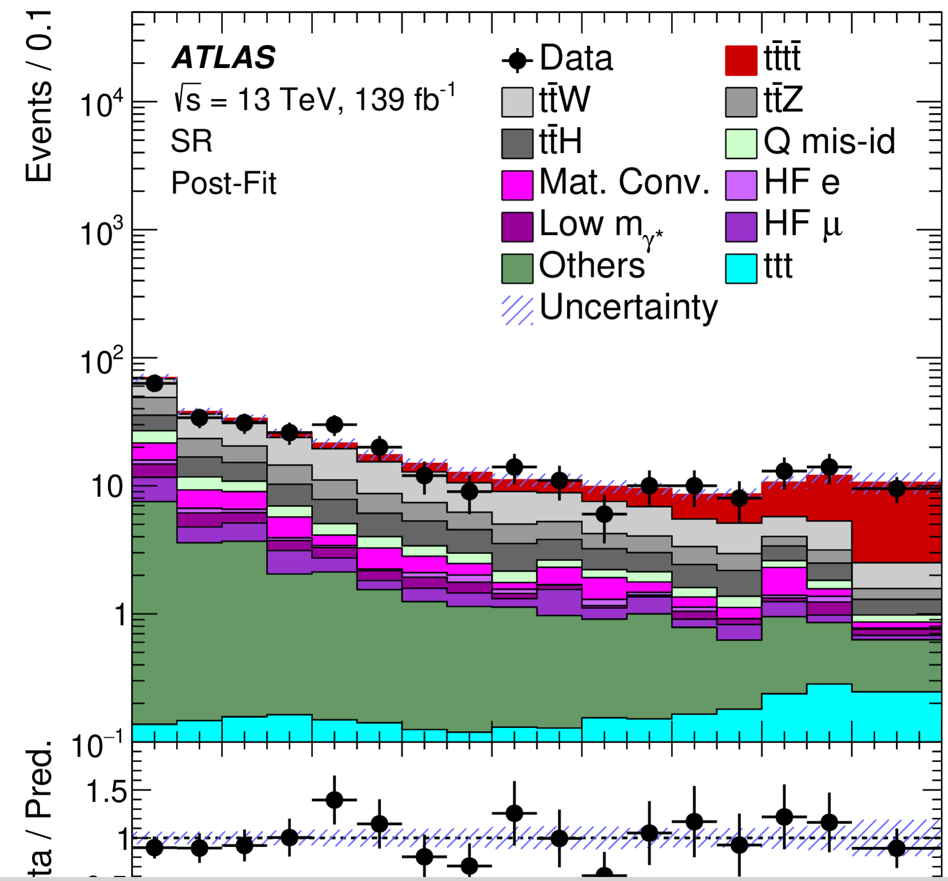
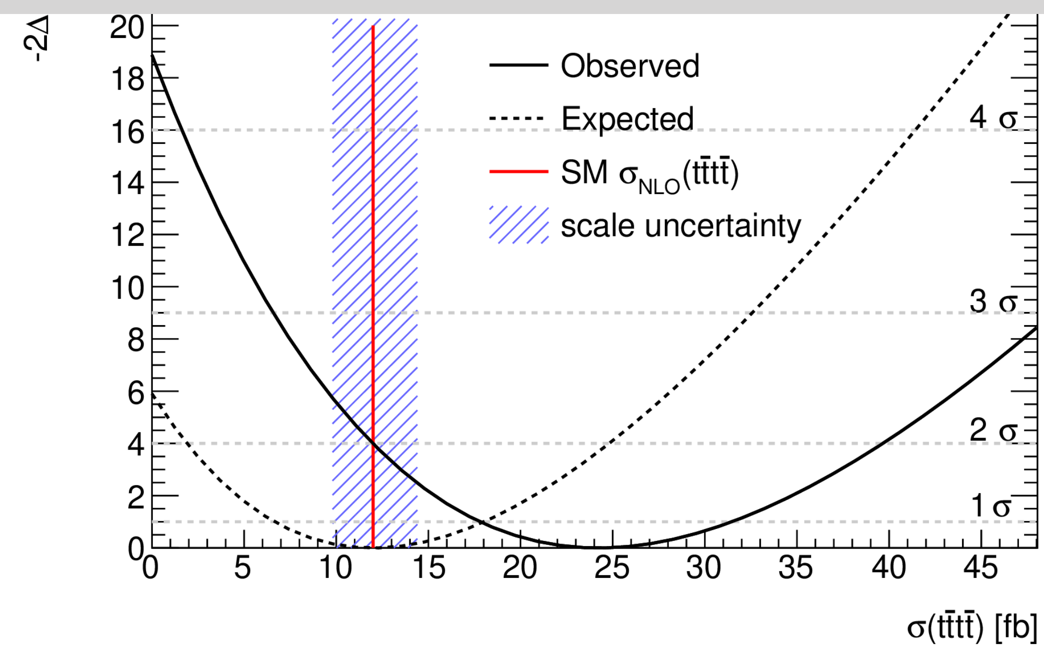


Strong 4.3σ (2.4σ expected) evidence!!!!



Results: 2ℓSS/3ℓ Channel

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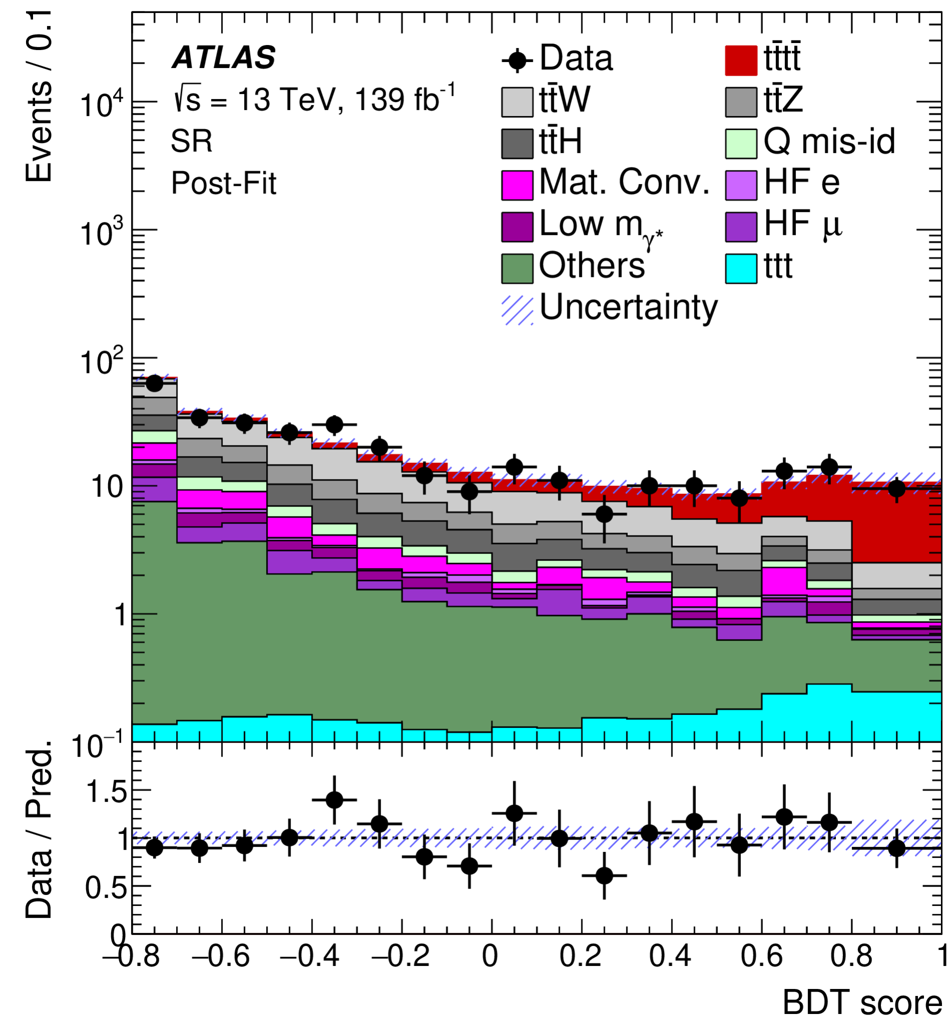
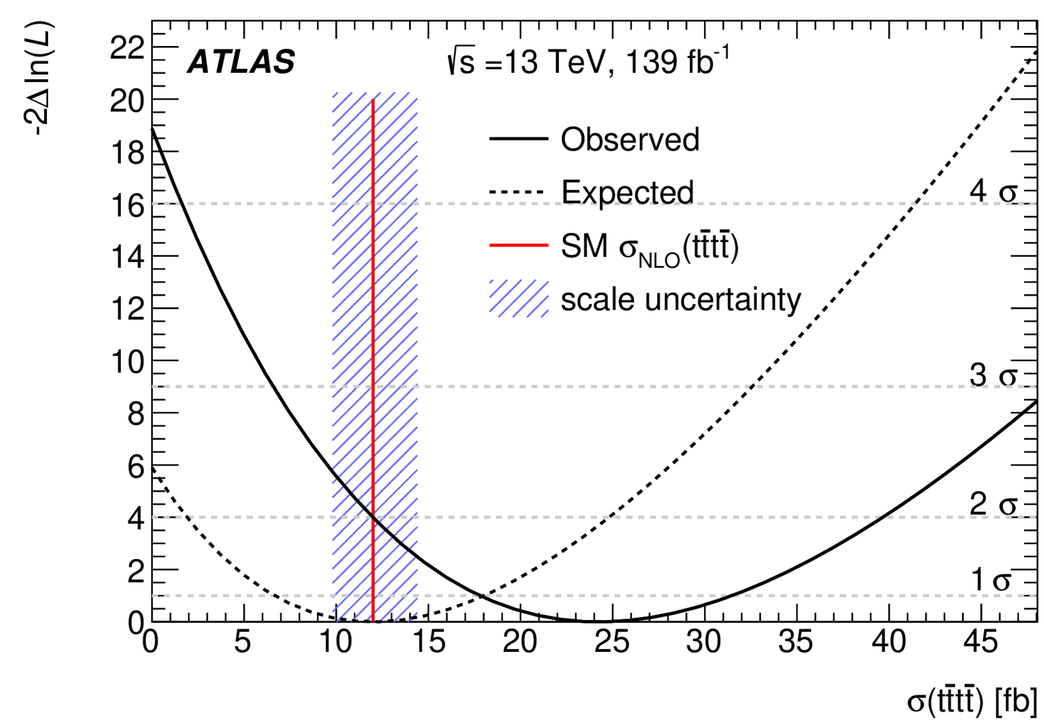
- Cross section:
$$\sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(stat)\ ^{+5}_{-4}(syst)\,fb = 24^{+7}_{-6}\,fb$$
- Compared to the theoretical predication of $\sigma(t\bar{t}t\bar{t}) = 12 \pm 2\,fb$
- **Strong 4.3σ (2.4σ expected) evidence**
  - Consistent to 1.7σ with the Standard Model
  - Extensive tests were done to check the stability & consistency of the result





2ℓSS/3ℓ Channel: Uncertainties

- The dominant systematics uncertainties on the signal strength are:
  - Theoretical uncertainty on the signal
  - Data statistics
  - $t\bar{t}W$ modeling
  - ttt modeling
  - Instrumental
    - B-tagging and Jet Energy Scale
  - Non-prompt lepton normalisation and modelling

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

- The measured $t\bar{t}t\bar{t}$ signal strength is found to be:

$$\mu = \sigma_{t\bar{t}t\bar{t}}/\sigma^{SM}_{t\bar{t}t\bar{t}} = 2.2^{+0.7}_{-0.7}(stat.)\ ^{+1.5}_{-1.0}(syst) = 2.2^{+1.6}_{-1.2}$$

- Cross section:

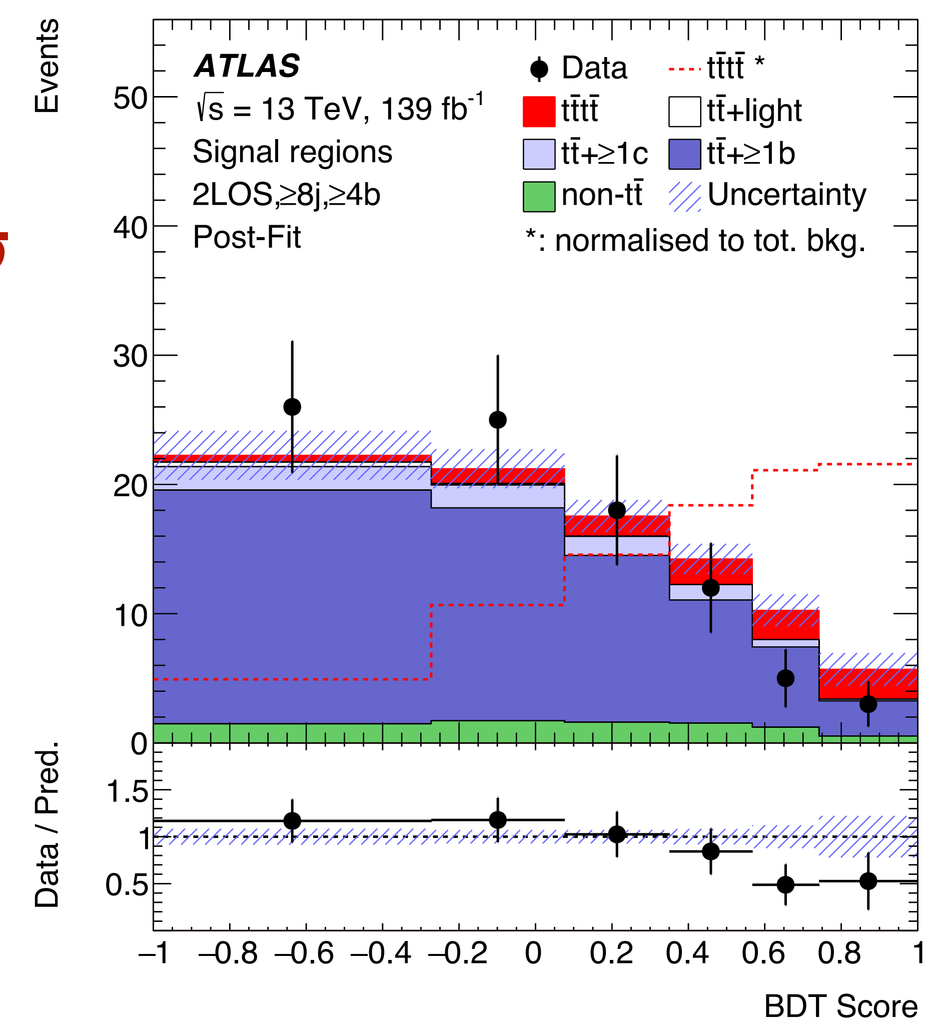
$$\sigma(t\bar{t}t\bar{t}) = 26 \pm 8(stat)\ ^{+15}_{-13}(syst.)\, fb = 26^{+17}_{-15}\, fb$$

- Compared to the theoretical predication of

$$\sigma(t\bar{t}t\bar{t}) = 12 \pm 2.4\, fb$$

- **Observed (expected) significance: 1.9 (1.0) σ**

2ℓOS Channel



$1\ell/2\ell$OS Channel: Uncertainties

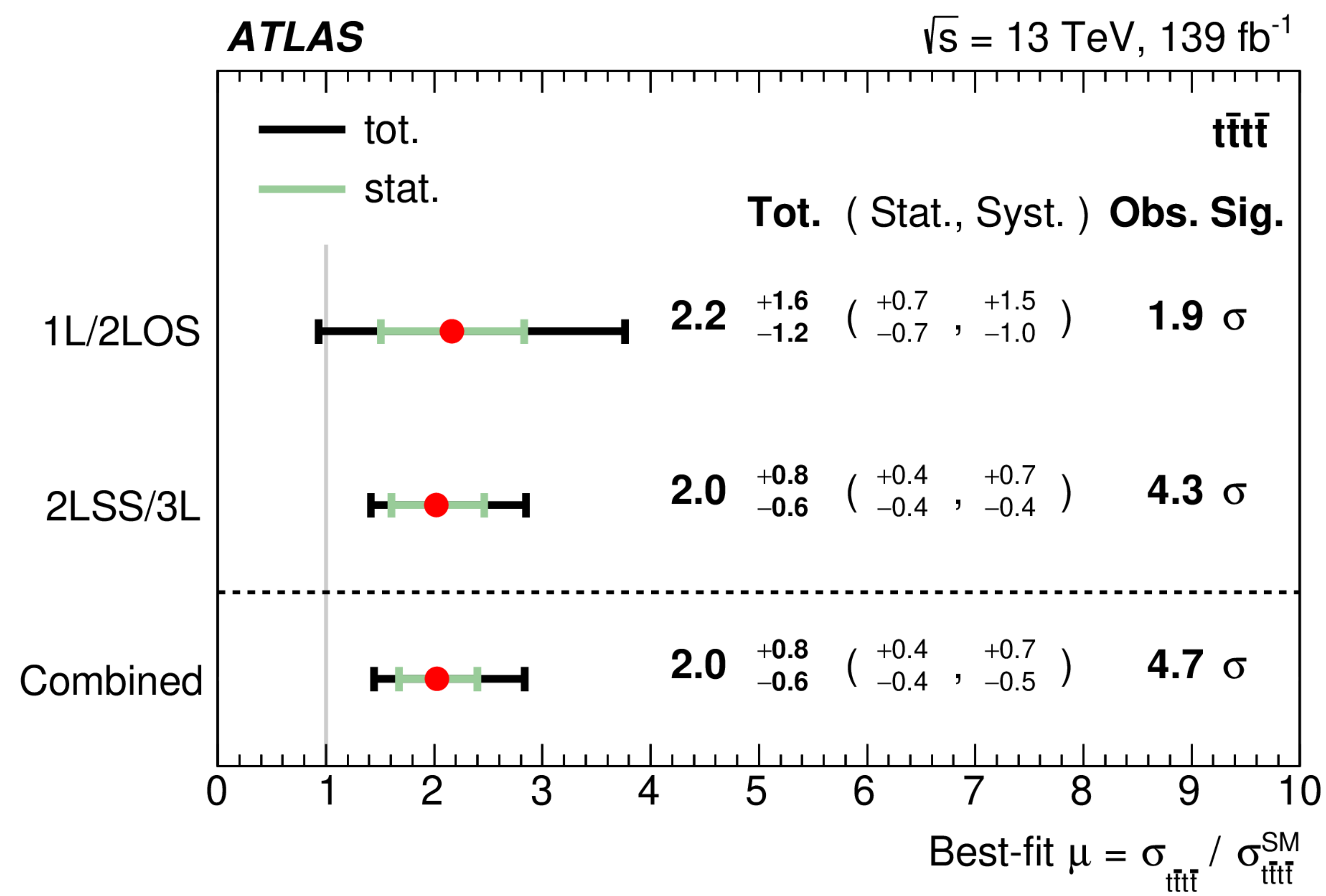
- The dominant systematics uncertainties are coming from the four-top signal and $t\bar{t}$+jets background modelling uncertainties

- Substantial impact from JES uncertainties and from the b-tagging efficiencies on light jets

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

Combination of 2ℓSS/3ℓ and 1ℓ/2ℓOS Channels

- 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**



Combination of 2ℓSS/3ℓ and 1ℓ/2ℓOS Channels

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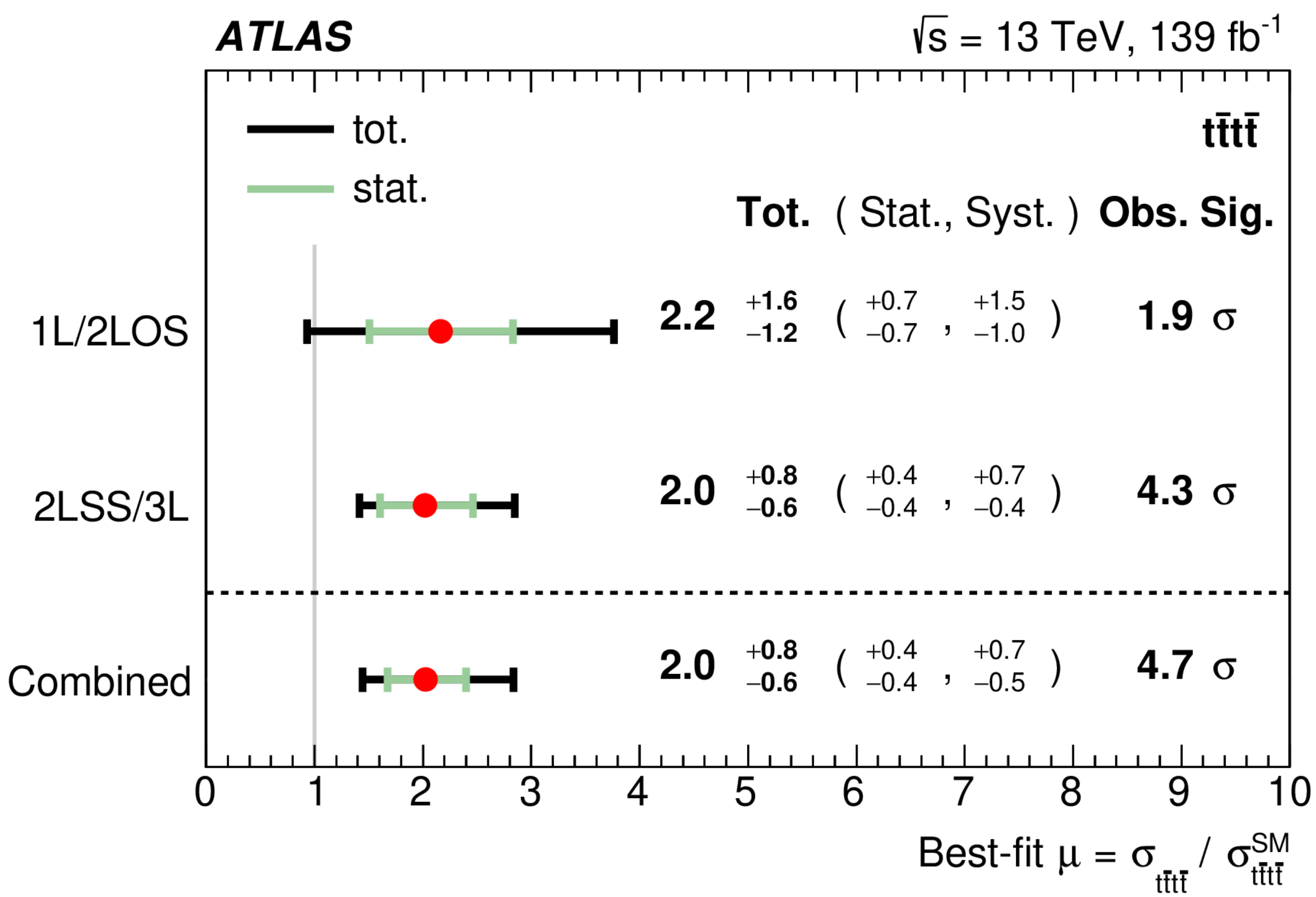
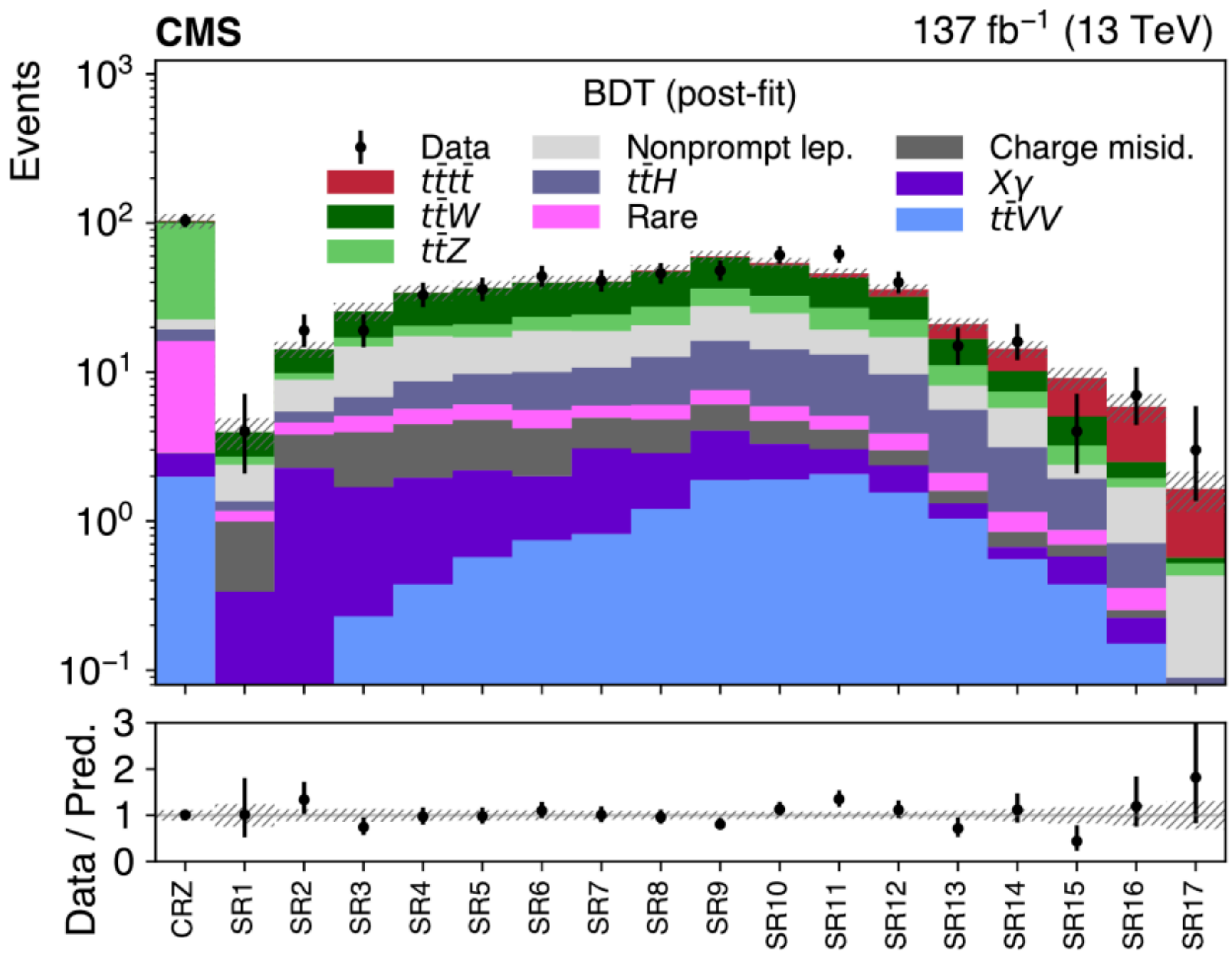
- Observed (expected) significance:
  4.7 (2.6) σ



ATLAS finds further confirmation of evidence for four top-quark process

Results from CMS

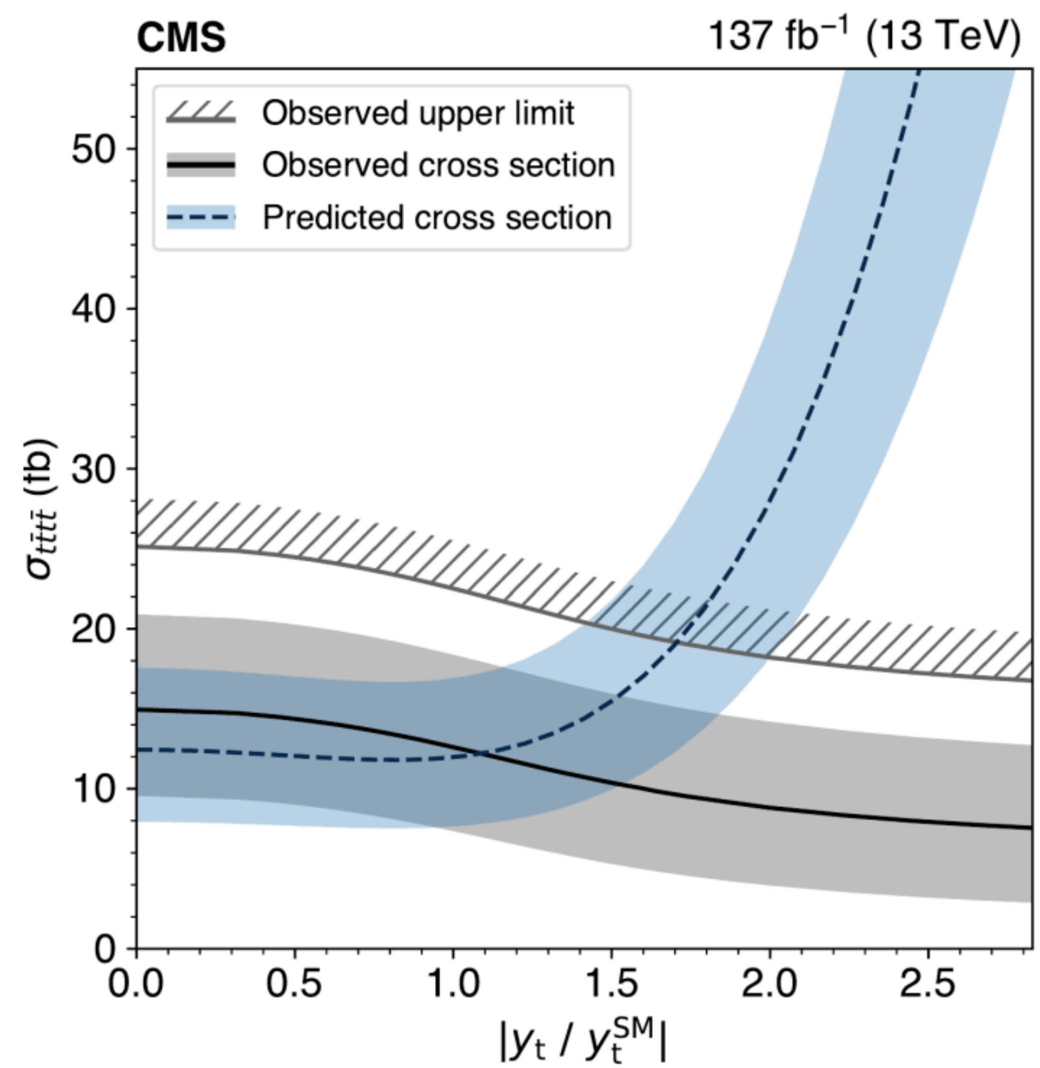
- Similarly CMS published results for 2ℓSS/3ℓ channel using the full run 2 data-set (Eur. Phys. J. C 80 (2020) 75)
  - Used BDTs to separate signal from background
  - Events split in many signal regions
  - Observed (expected) significance: **2.6** (**2.7**) **σ**
  - Measured cross-section : $12.6^{+5.8}_{-5.2}$ fb



Limits on top-Yukawa coupling

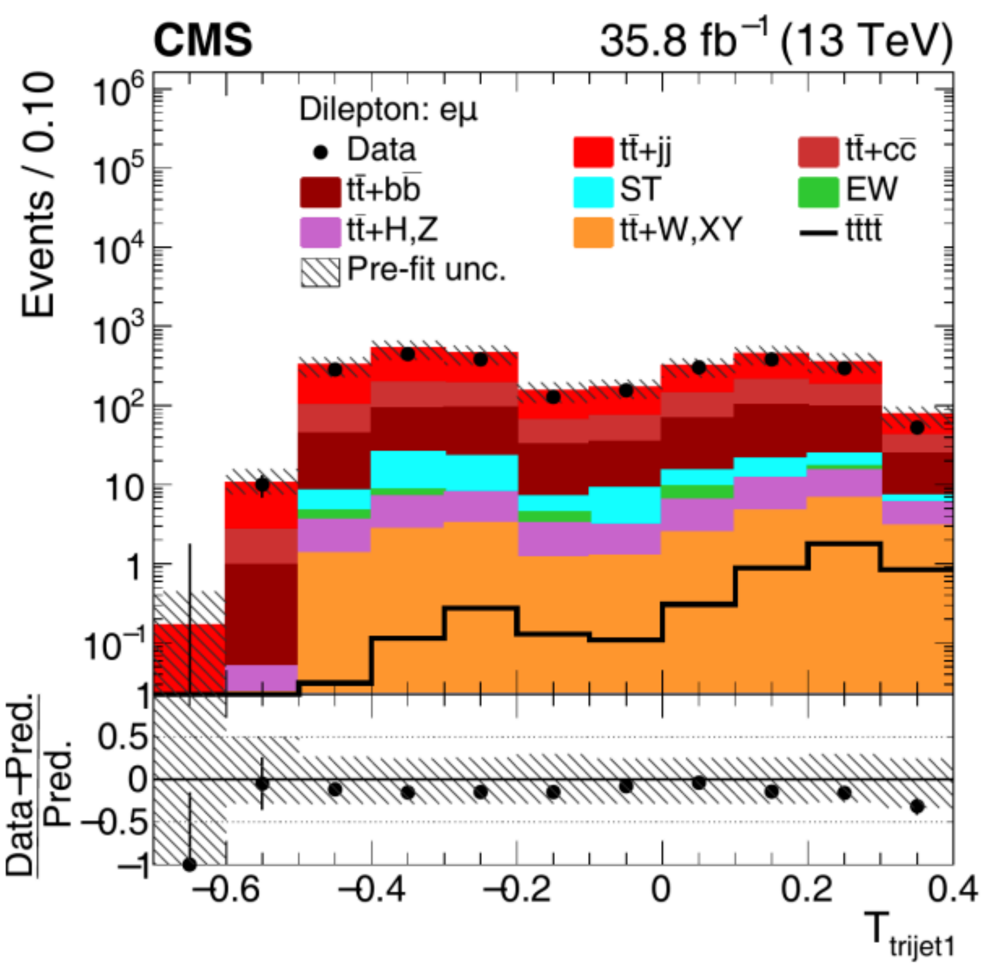
$$|y_t/y_t^{SM}| < 1.7$$

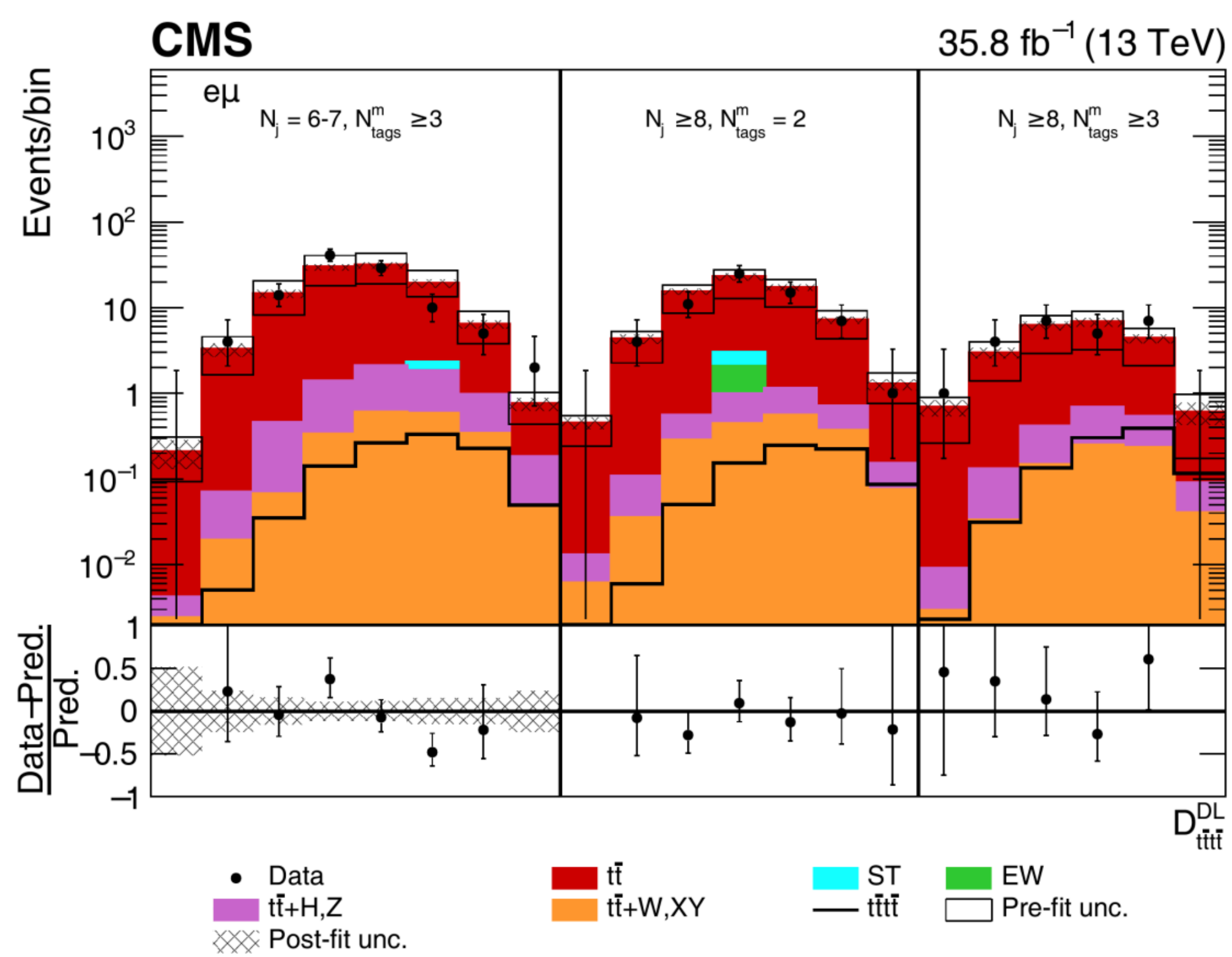
upper limit ranges from [1.4, 2.0]



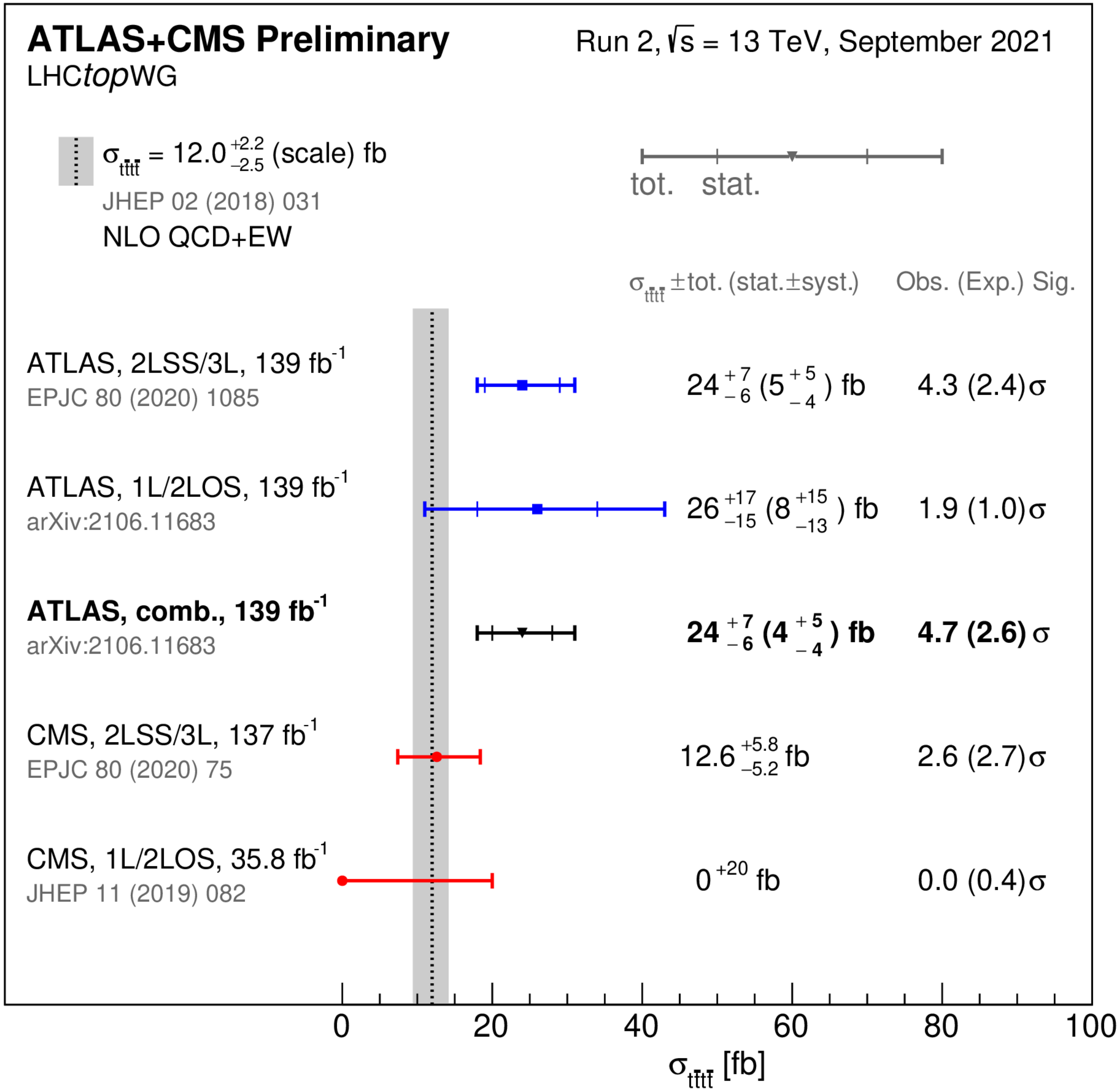
Results from CMS

- Also published results for the 1ℓ/2ℓOS Channel using 36 fb^{-1} of run 2 data-set (JHEP 11 (2019) 082)
- Events split in several categories for 1ℓ and 2ℓOS
  - using (b-)jet multiplicity and different b-tagging working points
  - BDT discriminants in signal regions to separate signal from backgrounds
    - includes a BDT identifying 3-jets groups from hadronic top, N_{jets}, topology variables
  - Observed (expected) significance: **0.0** (**0.4**) **σ**

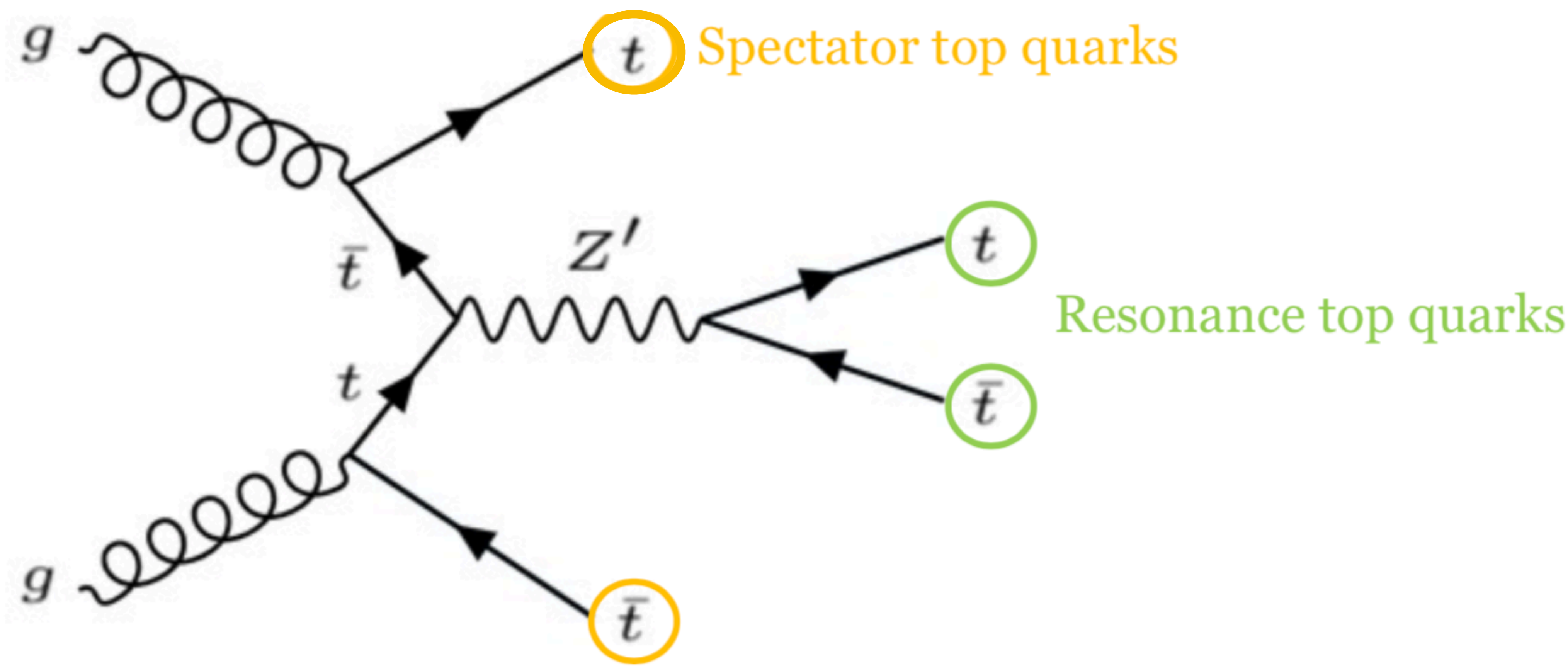




Summary of ATLAS and CMS measurements



Search for heavy resonances in four-top-quark final state



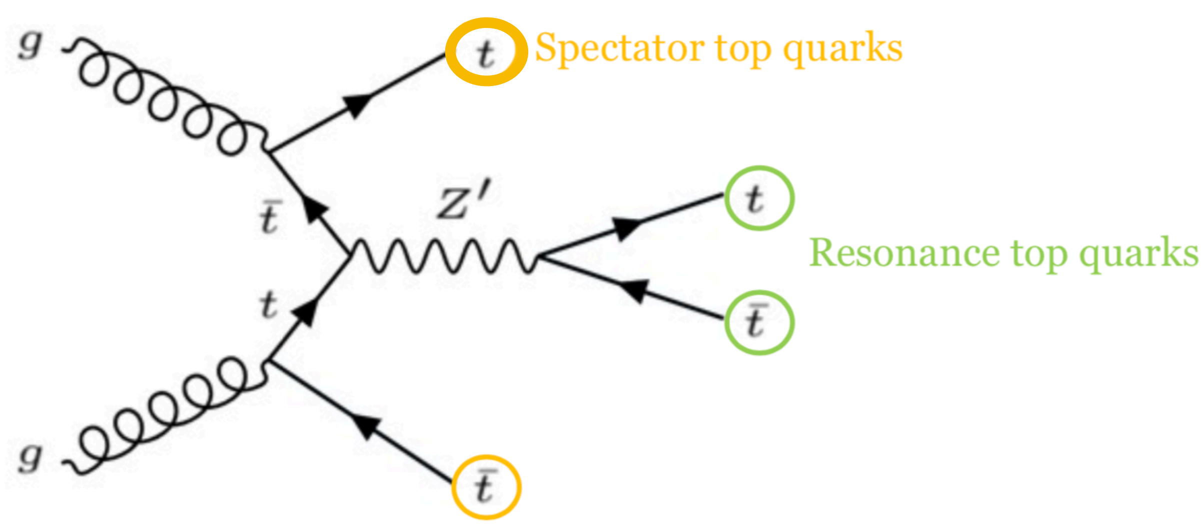
ATLAS-CONF-2021-048

Motivation

- In many BSM theories, new "top-philic" vector resonances are predicted
  - Associated production $t\bar{t}Z'$ is then favored over $q\bar{q}$ annihilation
- Decay of the resonance to $t\bar{t}$ leads to $t\bar{t}t\bar{t}$ **final states**
- Consider a color singlet vector particle (Z') which dominantly couple to $t\bar{t}$

$$\mathscr{L}_{int} = c_t \bar{t}\gamma_\mu(\cos\theta P_L + \sin\theta P_R)tZ'^\mu$$

Z'-top coupling **Chirality parameter**

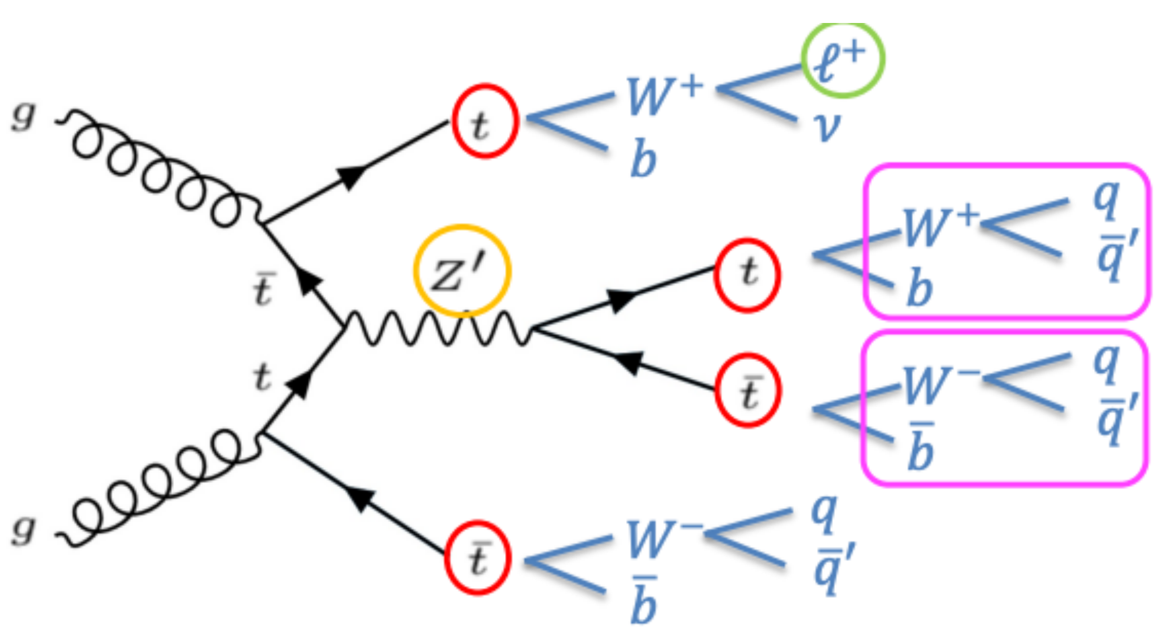


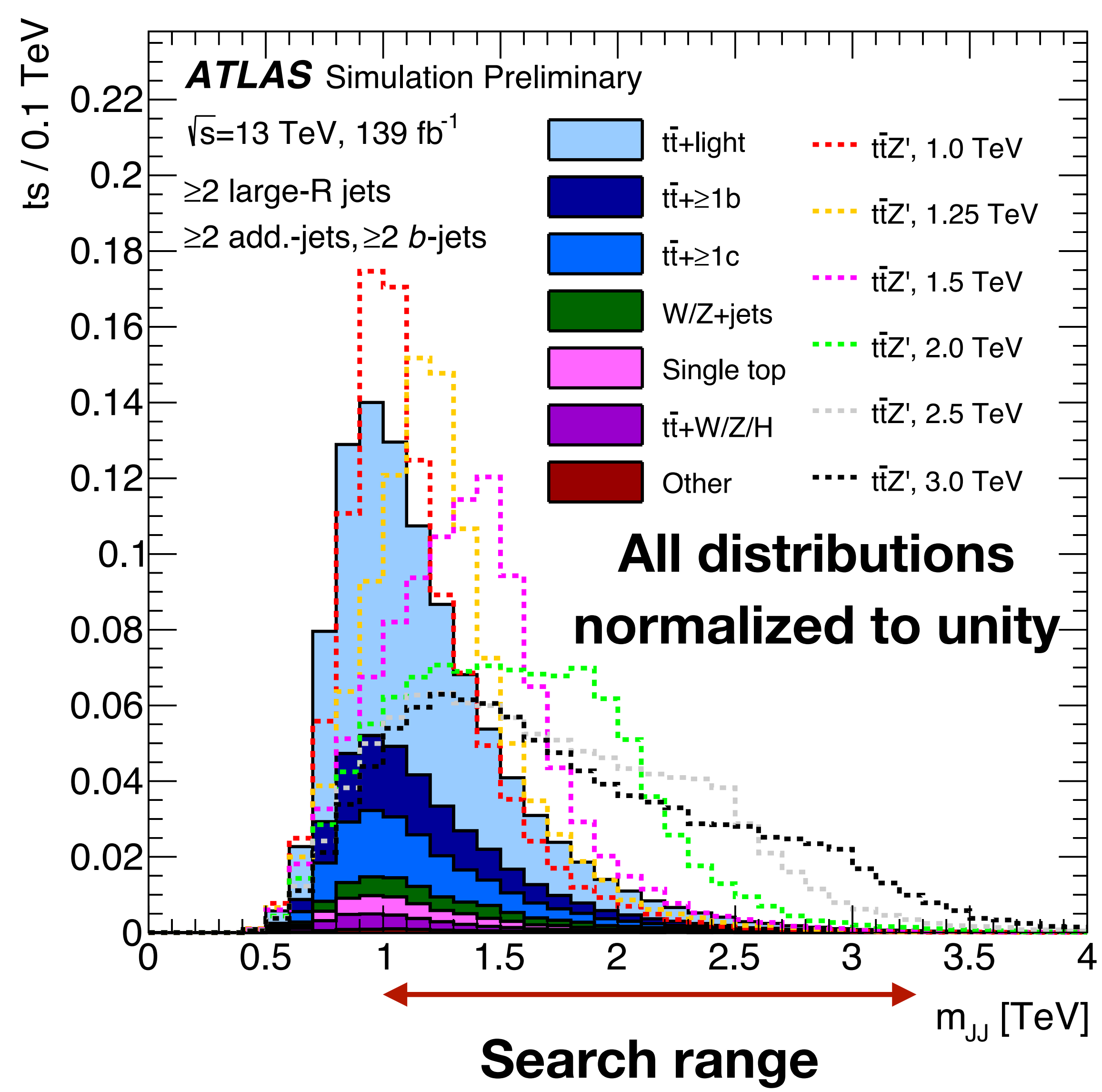
Free parameters:

- Resonance mass: $m_{Z'} = [1, 1.25, 1.5, 2.0, 2.5, 3.0]$ TeV
- Coupling to top quarks: $c_t = 1$ (4% relative width)
- Chirality parameter: $\theta = \pi/4$ ($t\bar{t}Z'$ production insensitive to θ) Phys. Rev. D 94, 035023 (2016)
  - Loop-induced production of the Z' resonance is strongly suppressed

Reconstruction

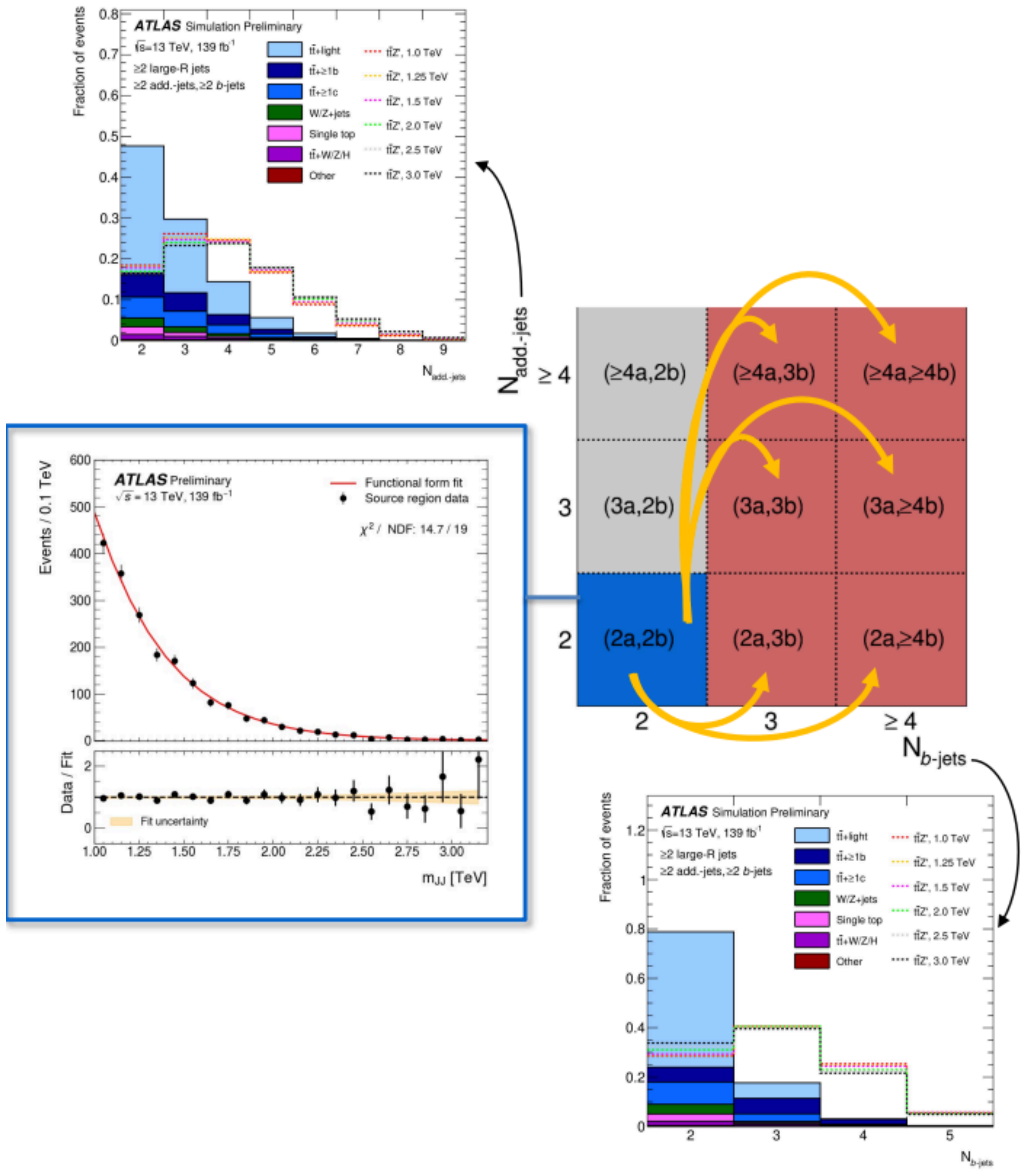
- Focus on **1 lepton** channel using ATLAS 139 fb^{-1} Run-2 data
- Strategy: Use reclustered large-R jets to reconstruct the resonance, targeting **fully hadronic decay**
  - **Invariant mass** of the top candidates (m_{JJ}) is the main discriminant





Background Estimation

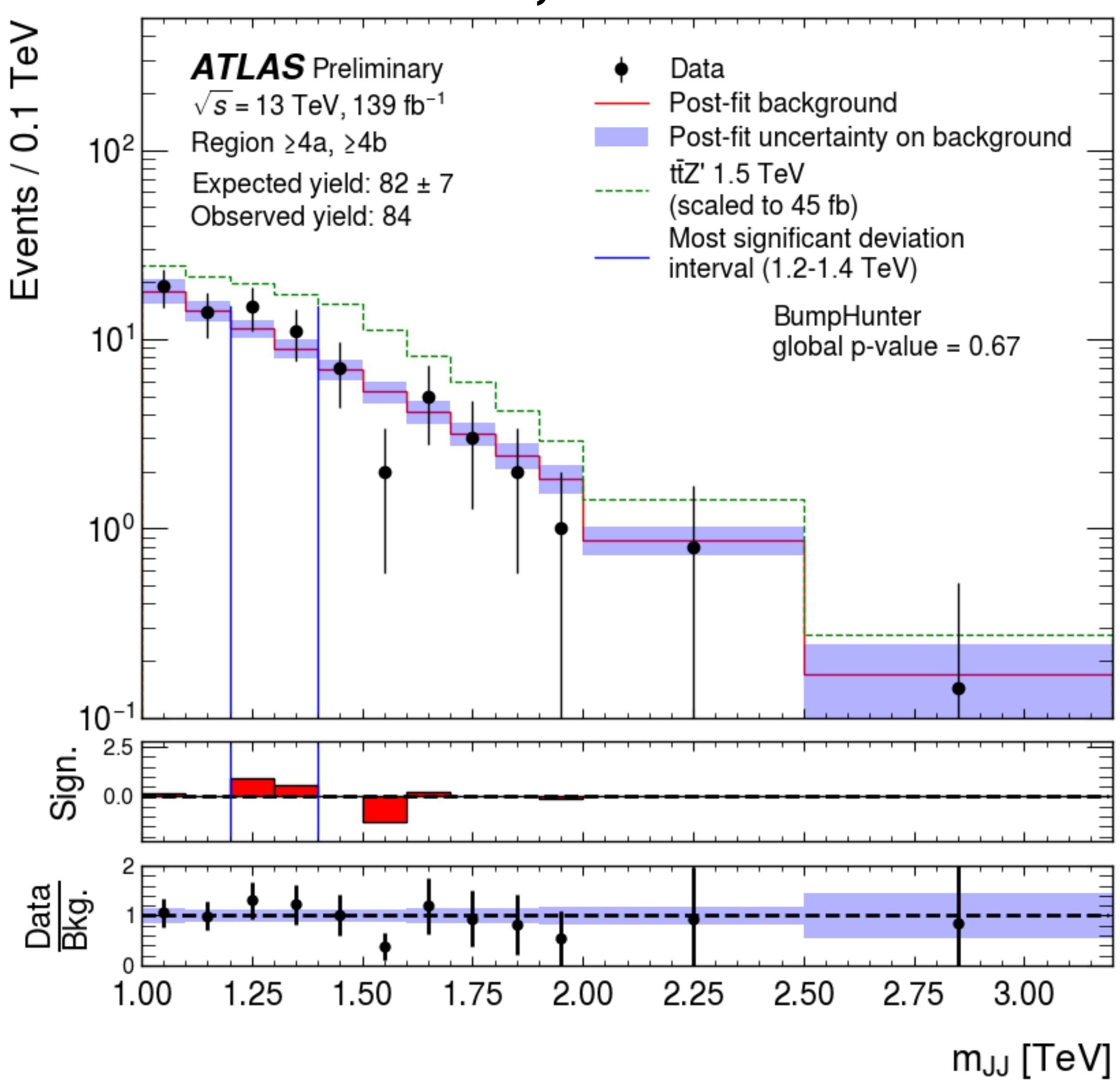
- Region definition based on number of **additional jets** ($N_{\text{add.-jets}}$) and number of **b-jets** ($N_{\text{b-jets}}$)
- Functional form fit to data m_{JJ} distribution in source region, extrapolated to signal regions by ratios of fits to MC m_{JJ} distributions



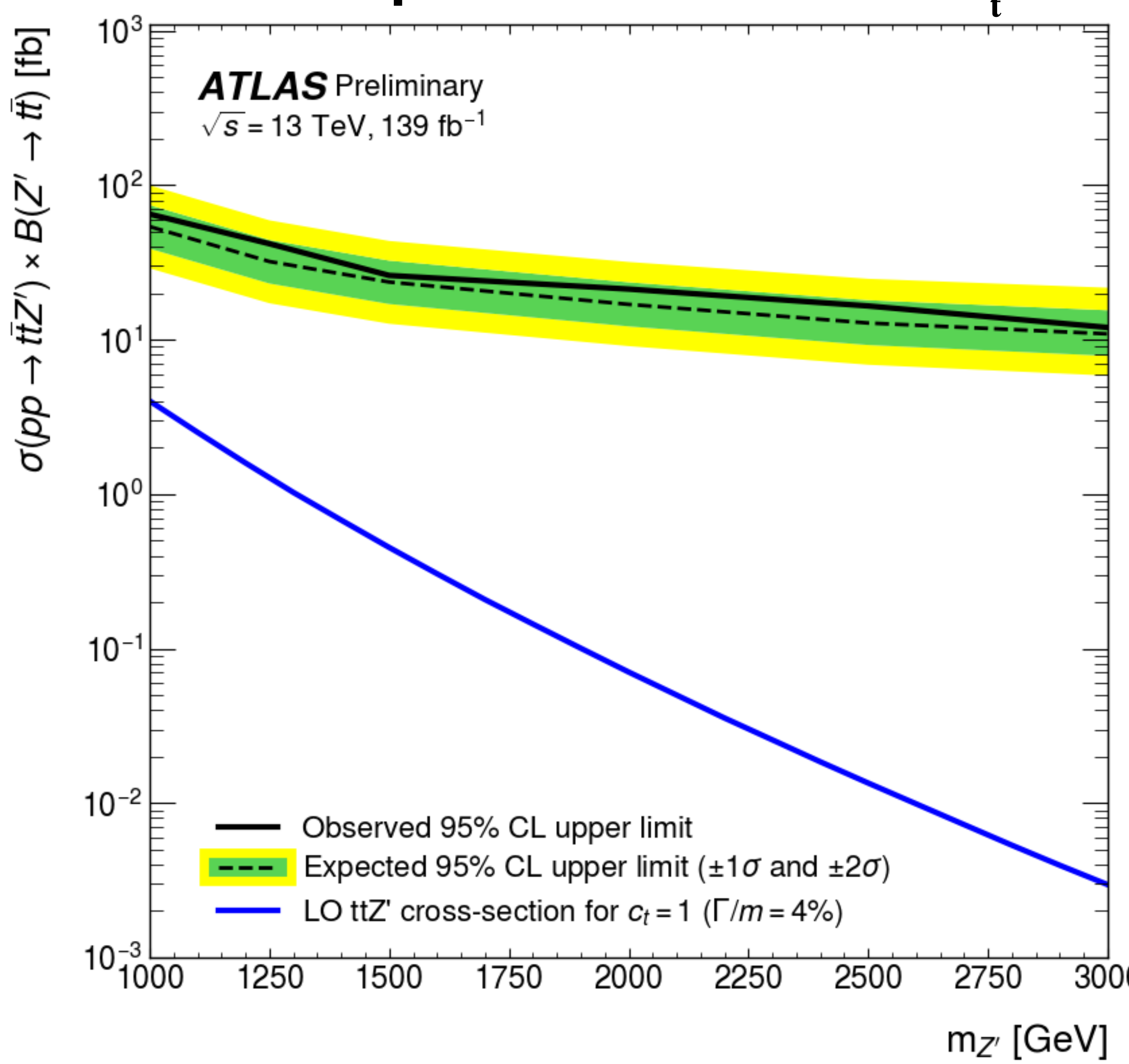
Results

- Good agreement between data and estimated background
  - no significant **bumps detected**
- Limits set on simplified model as a function of Z' mass
  - Observed (expected) limits range from **65 (54) fb** at 1 TeV to **12 (11) fb** at 3 TeV

≥4a, ≥ 4b

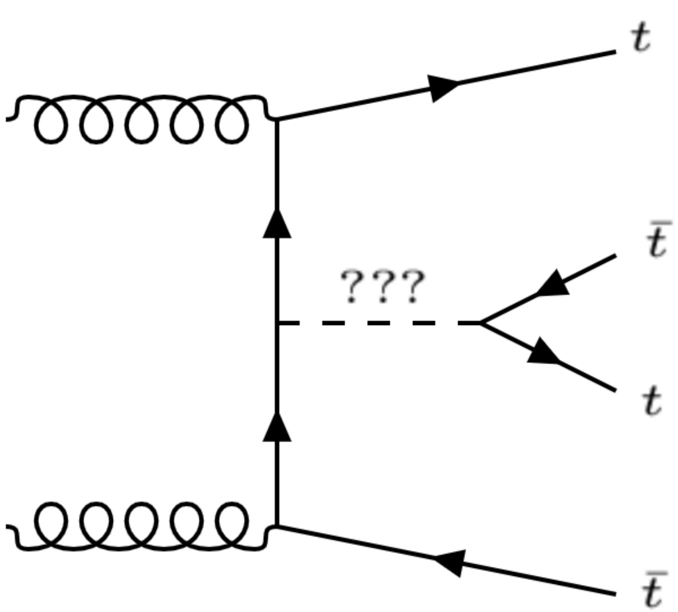


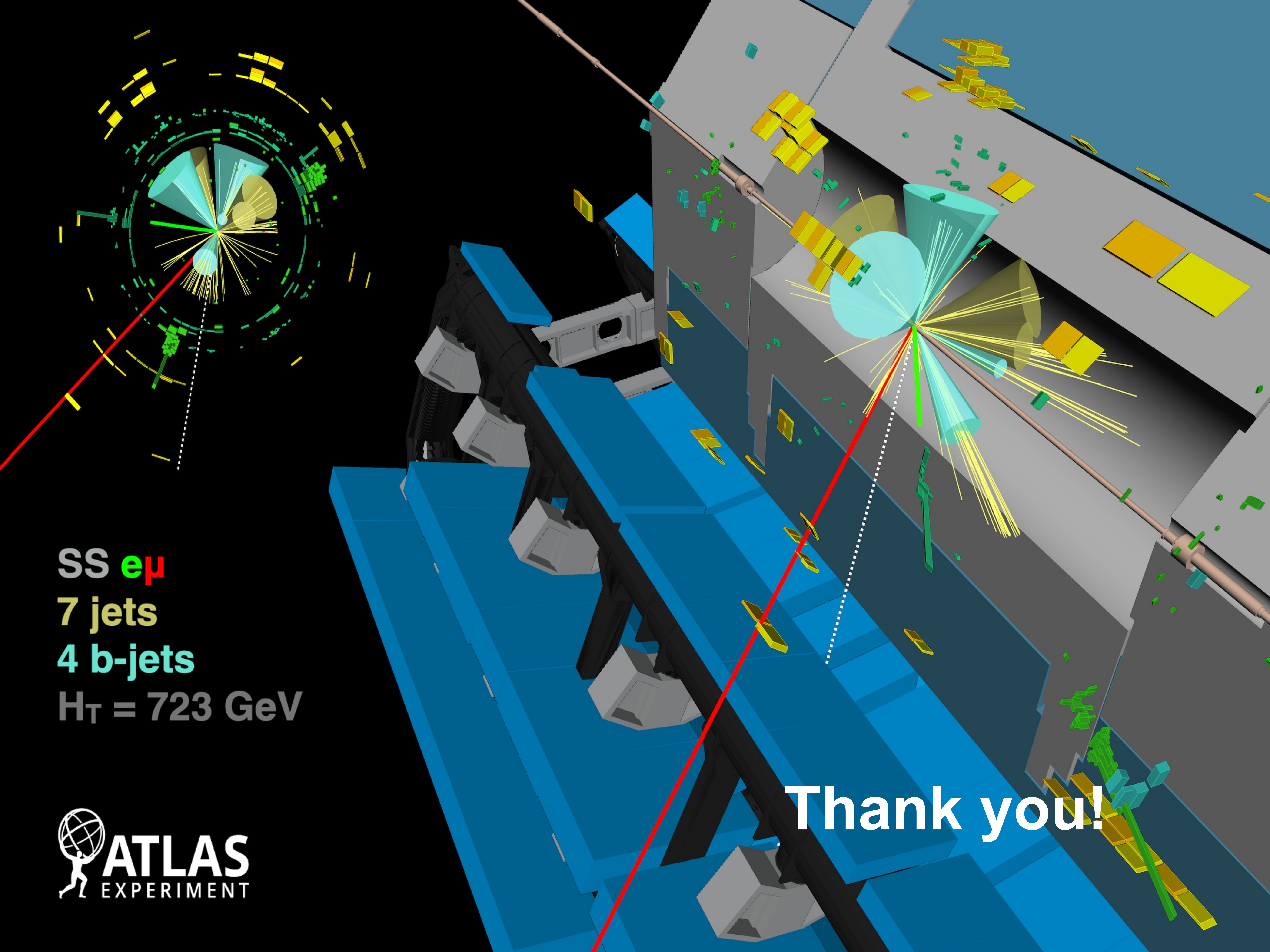
No mass point exclusion with c_t=1



Outlook

- We’ve found exciting results using the full run 2 data-set
- A slight excess in the measured four-top cross section, but still compatible with the SM prediction within 2 σ
- Efforts have started to both improve upon the latest result
  - Run 3 will double our dataset, and could lead to discovery (5 σ) of the four-top process
  - Will greatly benefit from better modeling of $t\bar{t}W$ & $t\bar{t}bb$ processes, & from new techniques to better constrain these backgrounds
- Have started exploring Beyond-the-SM interpretations such as EFT or new resonances




SS eμ
7 jets
4 b-jets
H_T = 723 GeV
ATLAS
EXPERIMENT
Thank you!

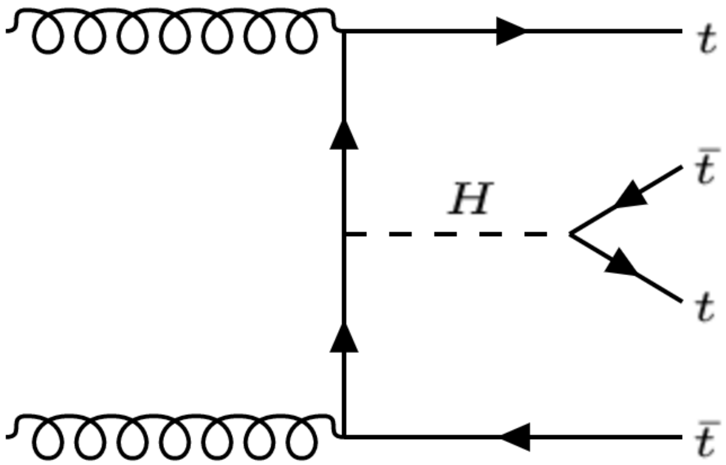
Beyond the tttt measurement back-up

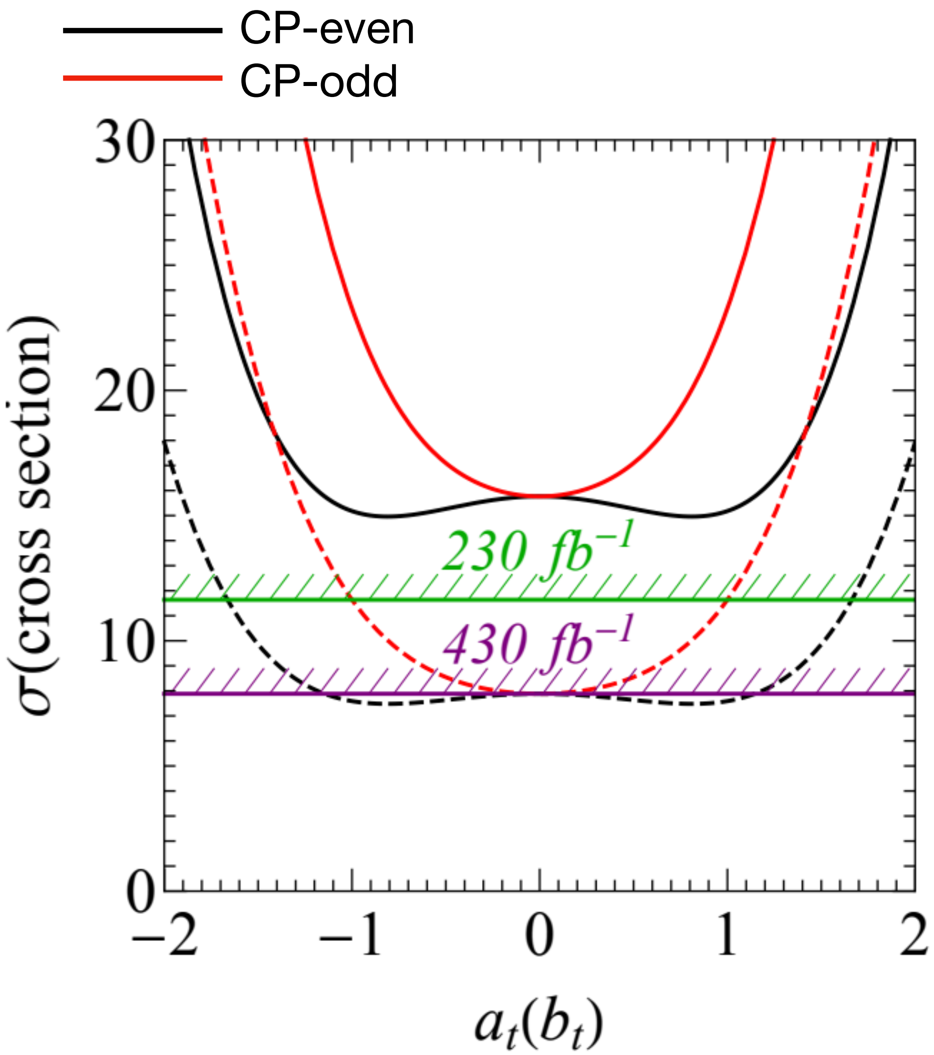
Top-Higgs Yukawa Coupling

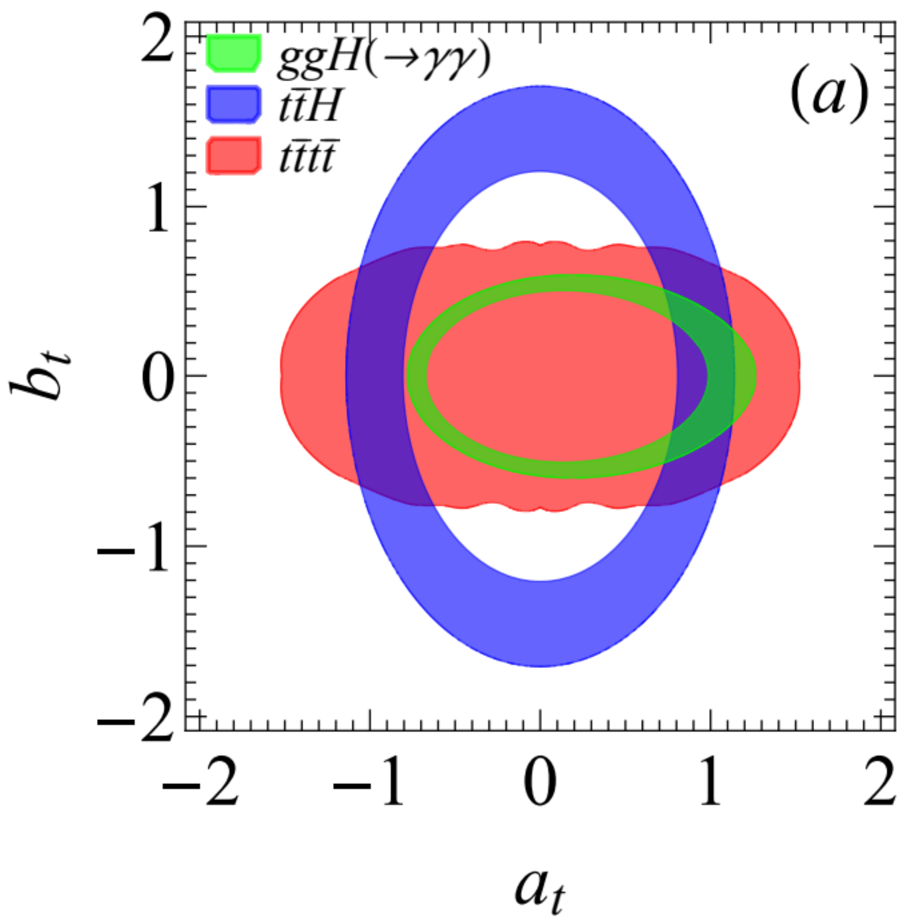
- Sensitive to top Yukawa coupling
- off-shell Higgs does not depend on the Higgs width/BR assumptions
- Sources of CP violation?
  - The general top-quark Yukawa coupling is parameterized as following

$$\mathscr{L}_{Htt} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)t$$

$$\sigma_{(t\bar{t}t\bar{t})_{13\ TeV}} = 9.998 - 1.522a_t^2 + 2.883b_t^2 + 1.173a_t^4 + 2.713a_t^2b_t^2 + 1.827b_t^4$$







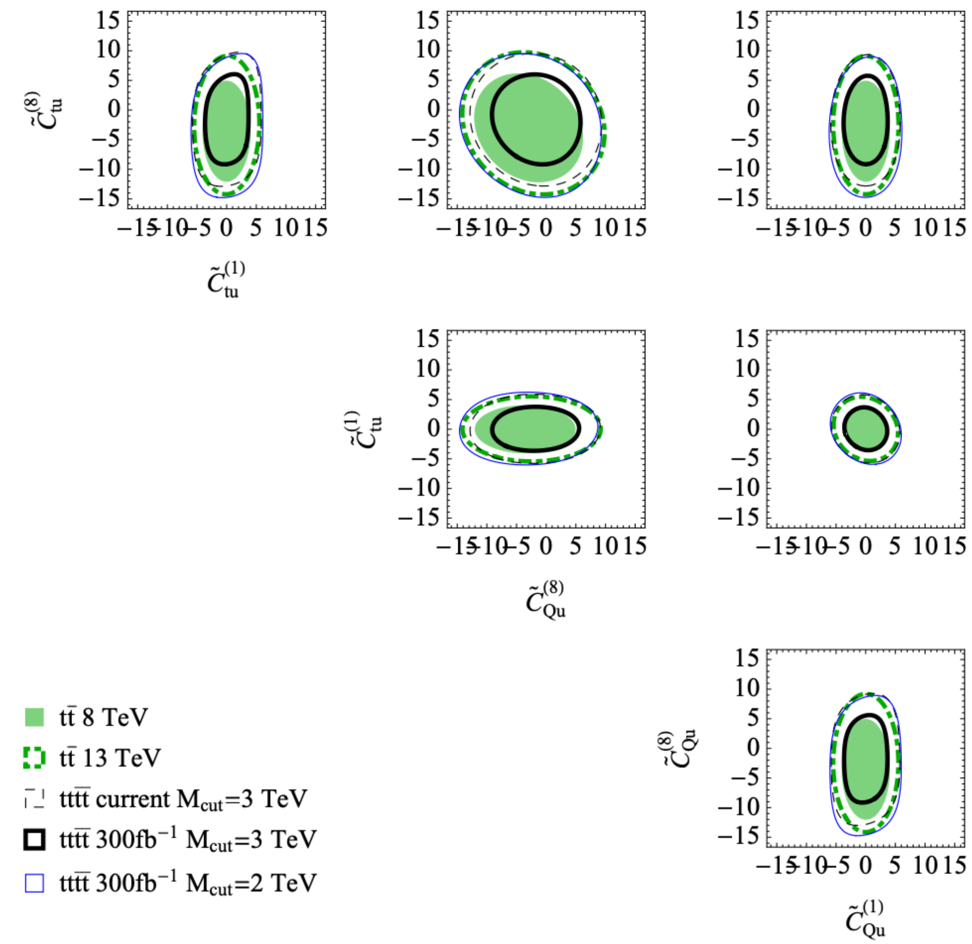
EFT

- Effective operators as higher dimensional terms

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + \ldots$$

- dimension 6-operators that mainly contribute to tttt production

$$\mathcal{O}^1_{tt} = (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$
$$\mathcal{O}^1_{QQ} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L)$$
$$\mathcal{O}^1_{Qt} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R)$$
$$\mathcal{O}^8_{Qt} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{t}_R\gamma_\mu T^A t_R)$$
$$\mathcal{O}^8_{QQ} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma_\mu T^A Q_L)$$



https://arxiv.org/pdf/1708.05928.pdf

- also sensitive to heavy-light type operators
  - Full set of 14 operators

$$\begin{aligned}
\mathcal{O}^{(8,3)}_{Qq} &= (\bar{Q}_L\gamma_\mu T^a\tau^i Q_L)(\bar{q}_L\gamma^\mu T^a\tau^i q_L) & \mathcal{O}^{(1,3)}_{Qq} &= (\bar{Q}_L\gamma_\mu \tau^i Q_L)(\bar{q}_L\gamma^\mu \tau^i q_L)\\
\mathcal{O}^{(8,1)}_{Qq} &= (\bar{Q}_L\gamma_\mu T^a Q_L)(\bar{q}_L\gamma^\mu T^a q_L) & \mathcal{O}^{(1,1)}_{Qq} &= (\bar{Q}_L\gamma_\mu Q_L)(\bar{q}_L\gamma^\mu q_L)\\
\mathcal{O}^{(8)}_{td} &= (\bar{t}_R\gamma_\mu T^a t_R)(\bar{d}_R\gamma^\mu T^a d_R) & \mathcal{O}^{(1)}_{td} &= (\bar{t}_R\gamma_\mu t_R)(\bar{d}_R\gamma^\mu d_R)\\
\mathcal{O}^{(8)}_{tu} &= (\bar{t}_R\gamma_\mu T^a t_R)(\bar{u}_R\gamma^\mu T^a u_R) & \mathcal{O}^{(1)}_{tu} &= (\bar{t}_R\gamma_\mu t_R)(\bar{u}_R\gamma^\mu u_R)\\
\mathcal{O}^{(8)}_{tq} &= (\bar{t}_R\gamma_\mu T^a t_R)(\bar{q}_L\gamma^\mu T^a q_L) & \mathcal{O}^{(1)}_{tq} &= (\bar{t}_R\gamma_\mu t_R)(\bar{q}_L\gamma^\mu q_L)\\
\mathcal{O}^{(8)}_{Qd} &= (\bar{Q}_L\gamma_\mu T^a Q_L)(\bar{d}_R\gamma^\mu T^a d_R) & \mathcal{O}^{(1)}_{Qd} &= (\bar{Q}_L\gamma_\mu Q_L)(\bar{d}_R\gamma^\mu d_R)\\
\mathcal{O}^{(8)}_{Qu} &= (\bar{Q}_L\gamma_\mu T^a Q_L)(\bar{u}_R\gamma^\mu T^a u_R) & \mathcal{O}^{(1)}_{Qu} &= (\bar{Q}_L\gamma_\mu Q_L)(\bar{u}_R\gamma^\mu u_R)
\end{aligned}$$

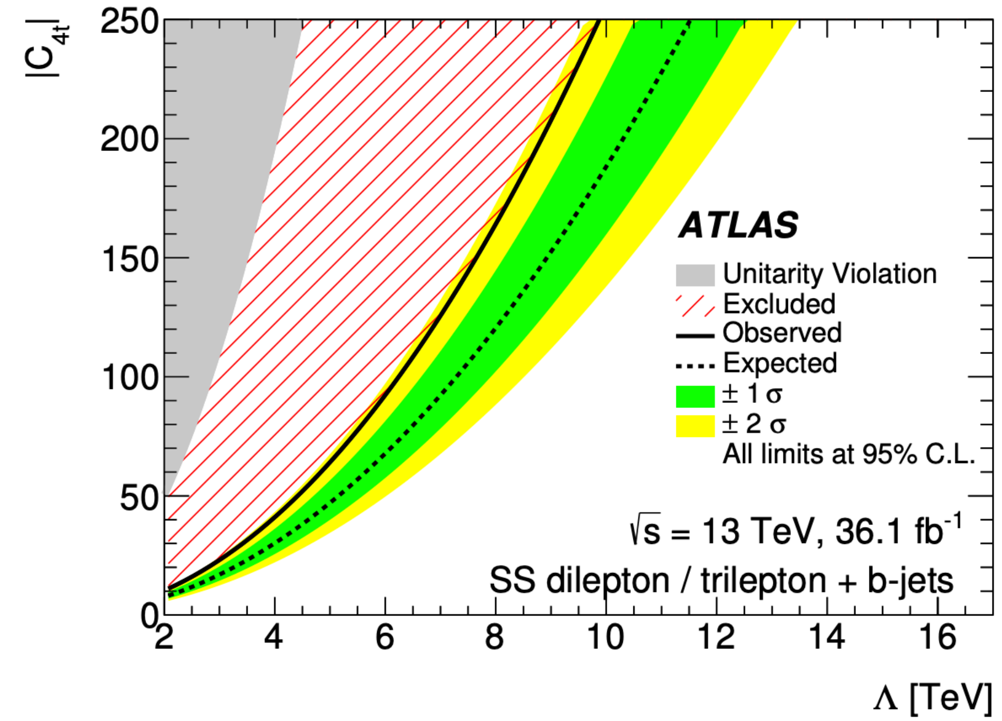
EFT past results

- CMS has set limit on four major dimension-6 operators that mainly contribute to tttt
- using 36 fb^{-1} of run 2 data (arxiv.1906.02805)
- observed (expected) 95% CL upper limit on cross-section, 33 (20) fb

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	$[-2.0, 1.9]$	$[-2.2, 2.1]$
$\mathcal{O}^1_{\mathrm{QQ}}$	$[-2.0, 1.9]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{\mathrm{Qt}}$	$[-3.4, 3.3]$	$[-3.7, 3.5]$
$\mathcal{O}^8_{\mathrm{Qt}}$	$[-7.4, 6.3]$	$[-8.0, 6.8]$

- ATLAS set limit on the pure right-handed operator $\mathcal{O}^1_{t\bar{t}}$ using 36 fb^{-1} of run 2 data (JHEP12(2018)039)
- observed (expected) limit on Wilson coefficient

$$|C_{4t}|/\Lambda^2 < 1.9\ \mathrm{TeV}^{-2}(1.6\ \mathrm{TeV}^{-2})$$



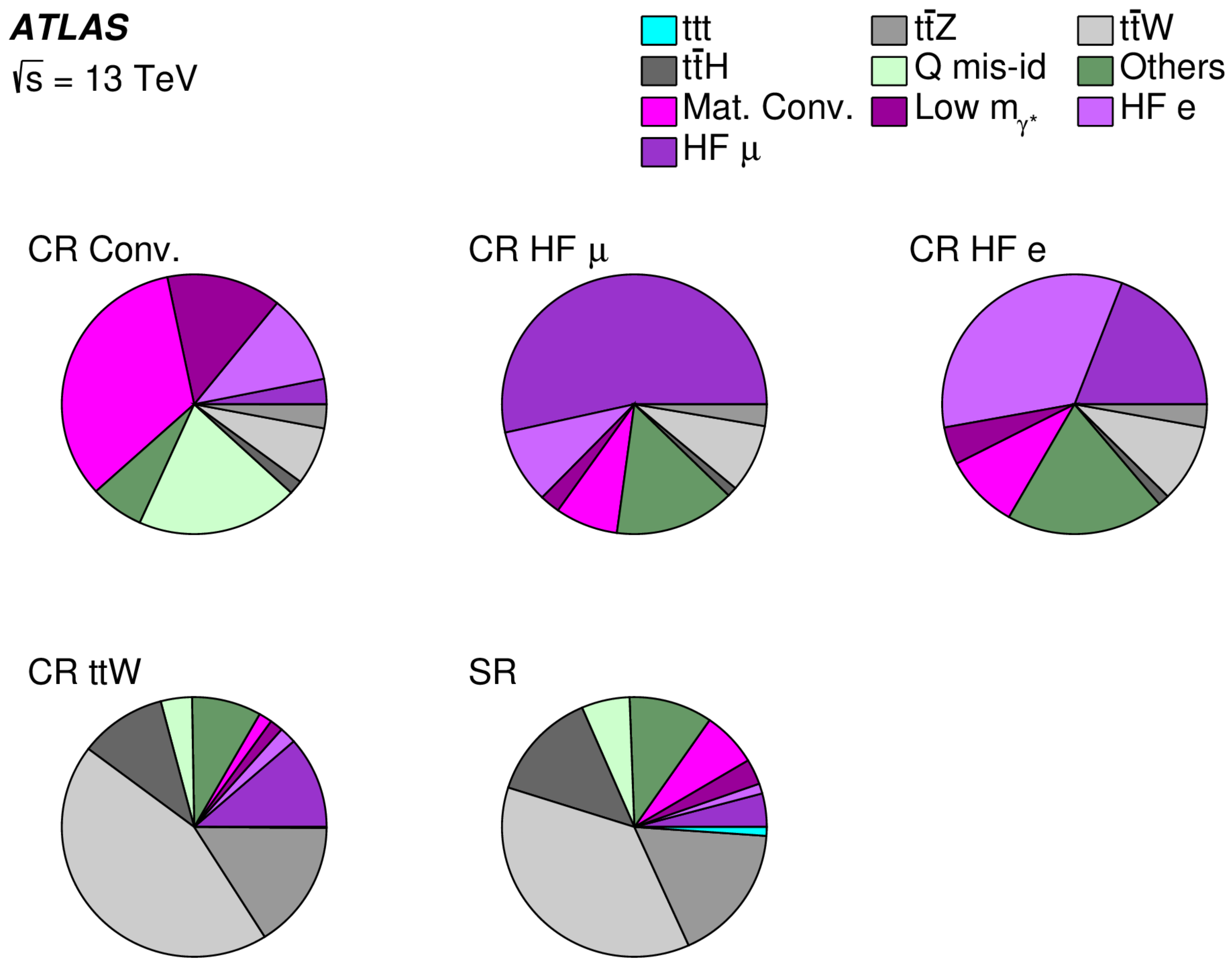
2ℓSS/3ℓ Channel back-up

2ℓSS/3ℓ Channel: Selection in the different regions

Table 1 Summary of the signal and control regions used in the template fit. The variable m_{ee}^{CV} (m_{ee}^{PV}) is defined as the invariant mass of the system formed by the track associated with the electron and the closest track at the conversion (primary) vertex. N_j (N_b) indicates the jet (b-tagged jet) multiplicity in the event. H_{T} is defined as the scalar sum of the transverse momenta of the isolated leptons and jets

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

2ℓSS/3ℓ Channel: Background composition



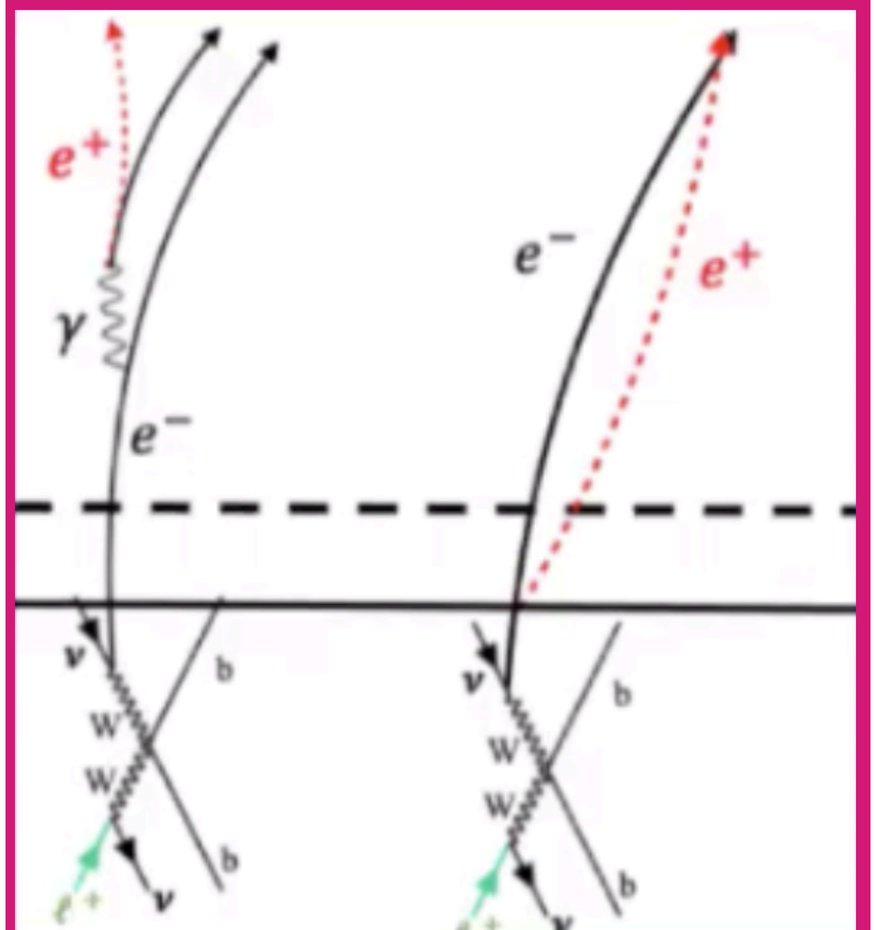
2ℓSS/3ℓ Channel: Background composition

ATLAS Detector

$t\bar{t}$

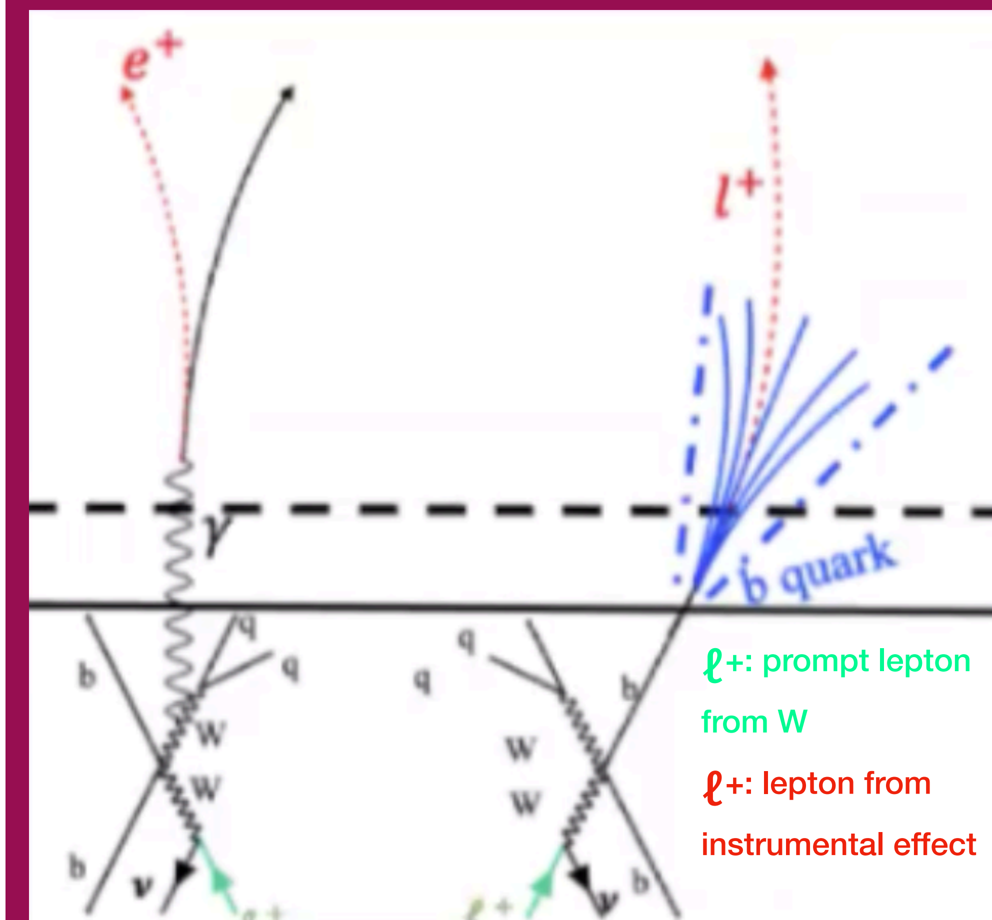
Charge Mis-identification

Bremsstrahlung | **Mis-measured curvature**



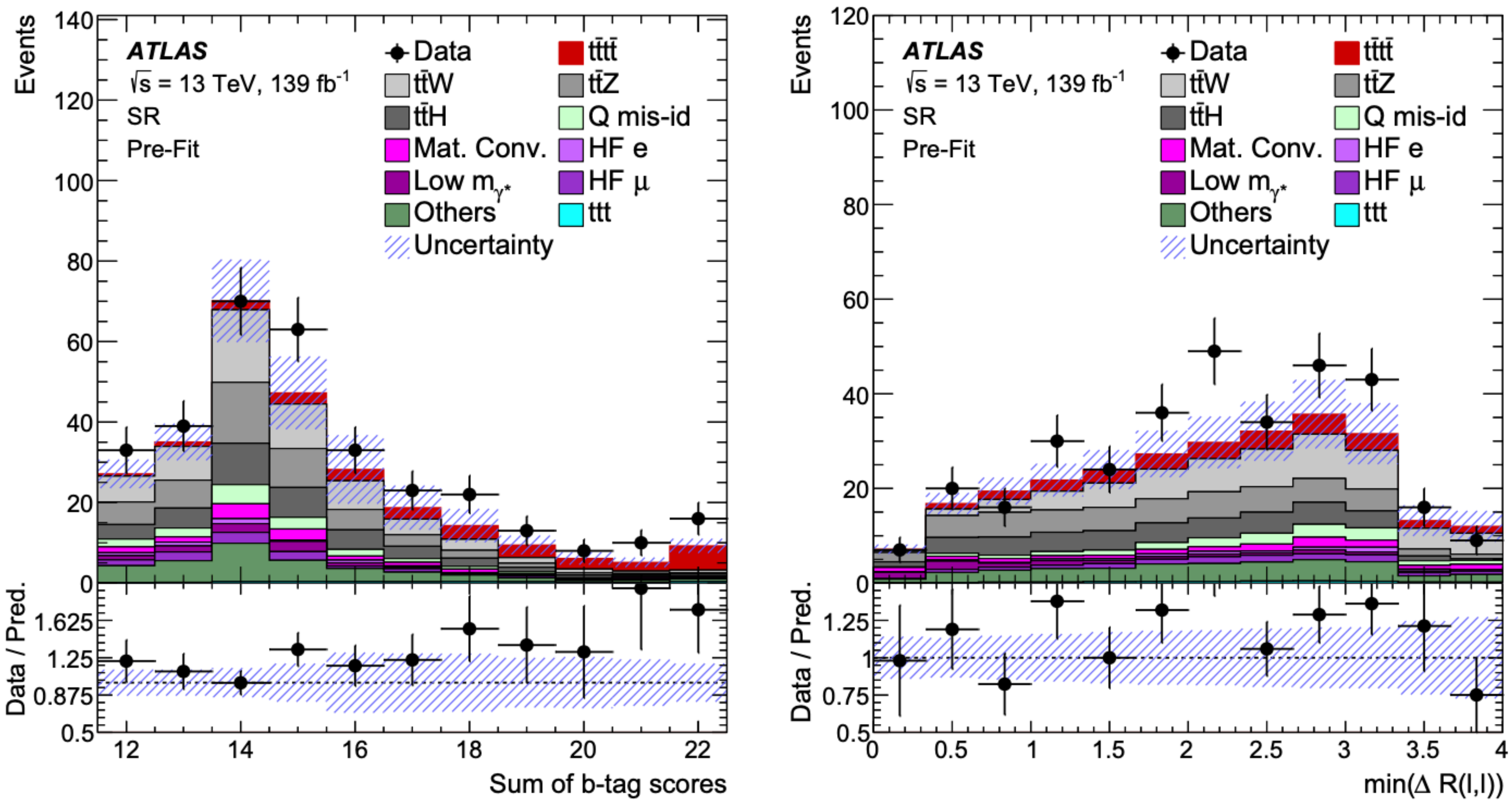
Non-prompt Leptons

Material conversion | **Semi-leptonic b decay (HF)**

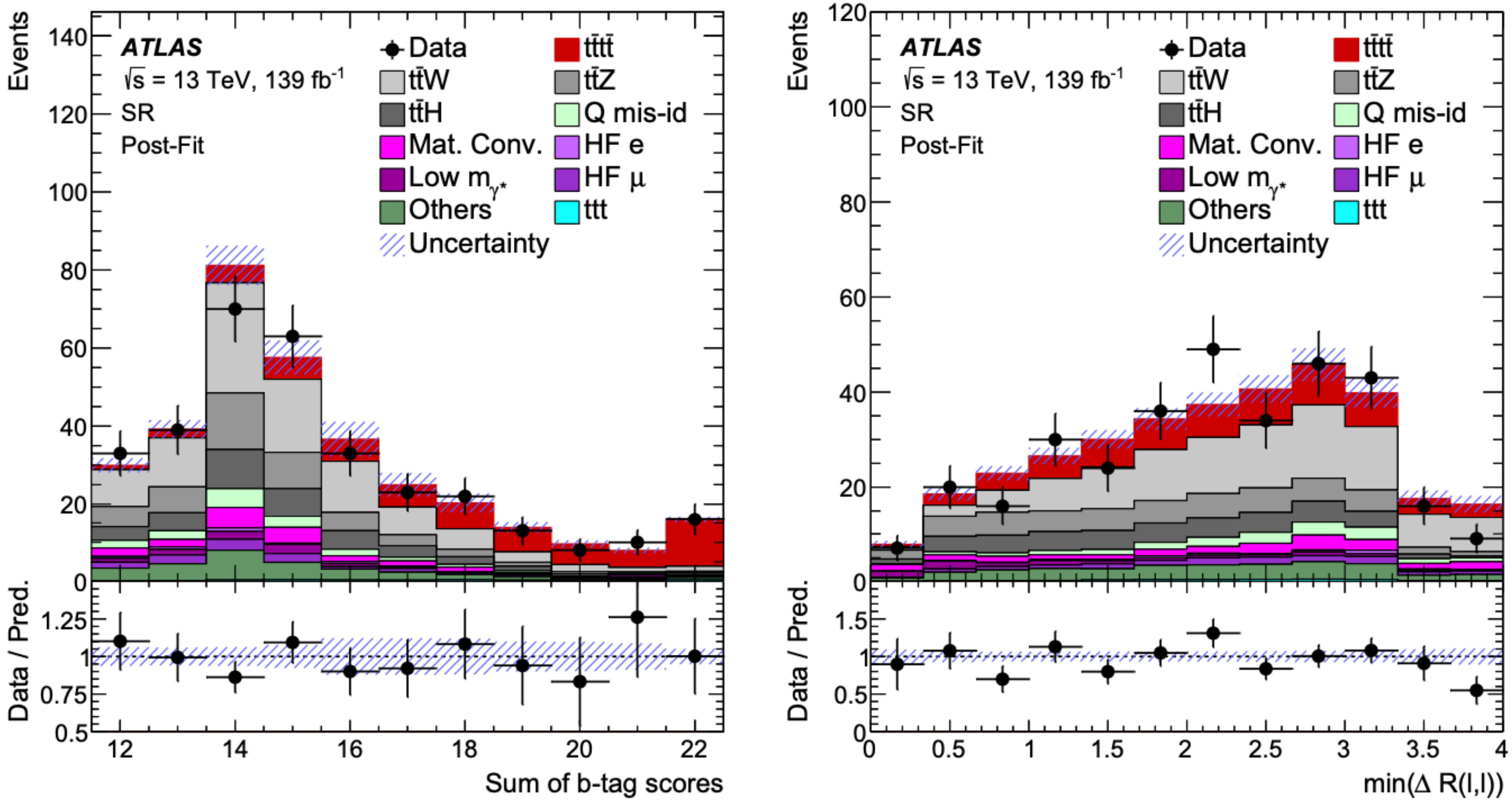


Beam Pipe

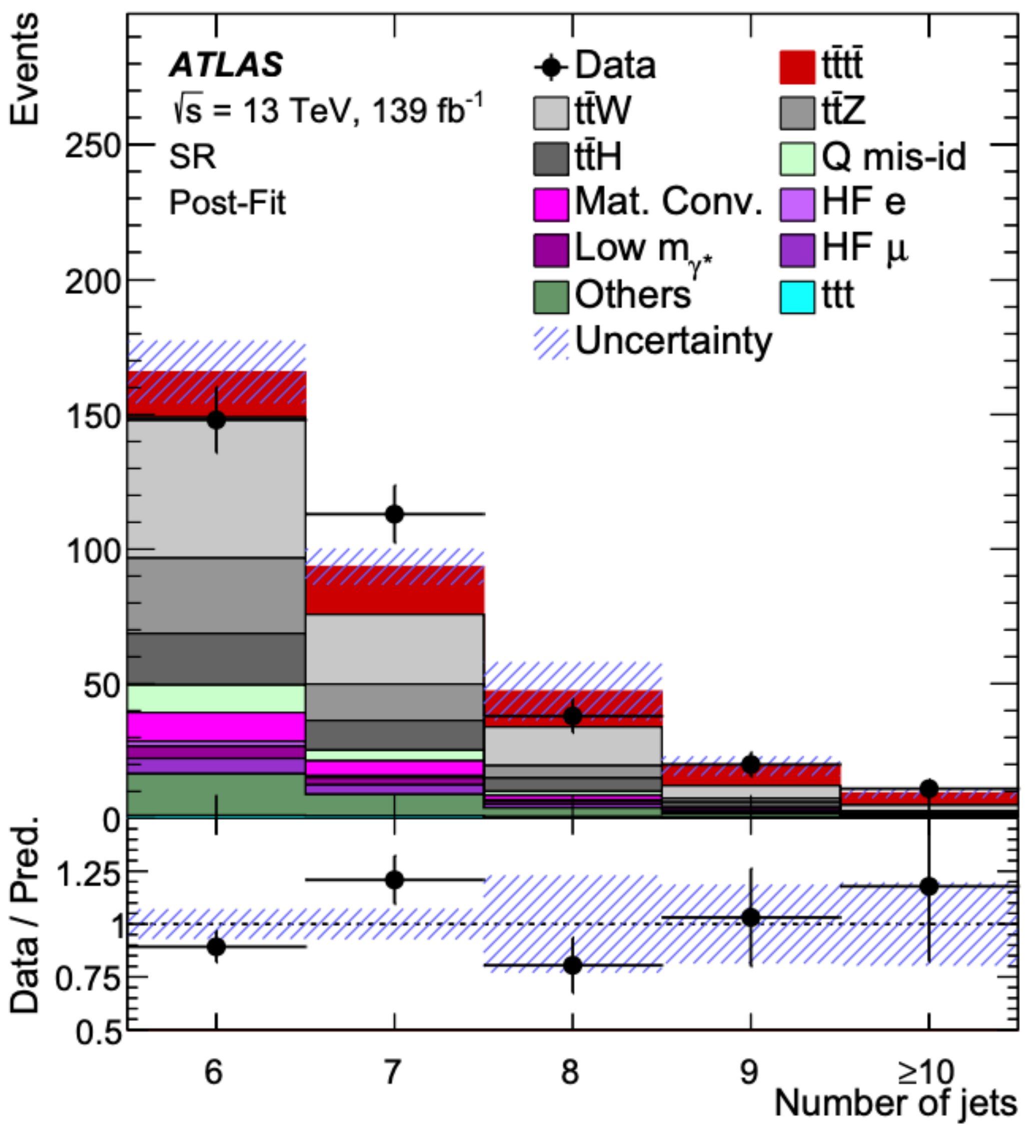
2ℓSS/3ℓ Channel: pre-fit plots (input variables to the BDT)

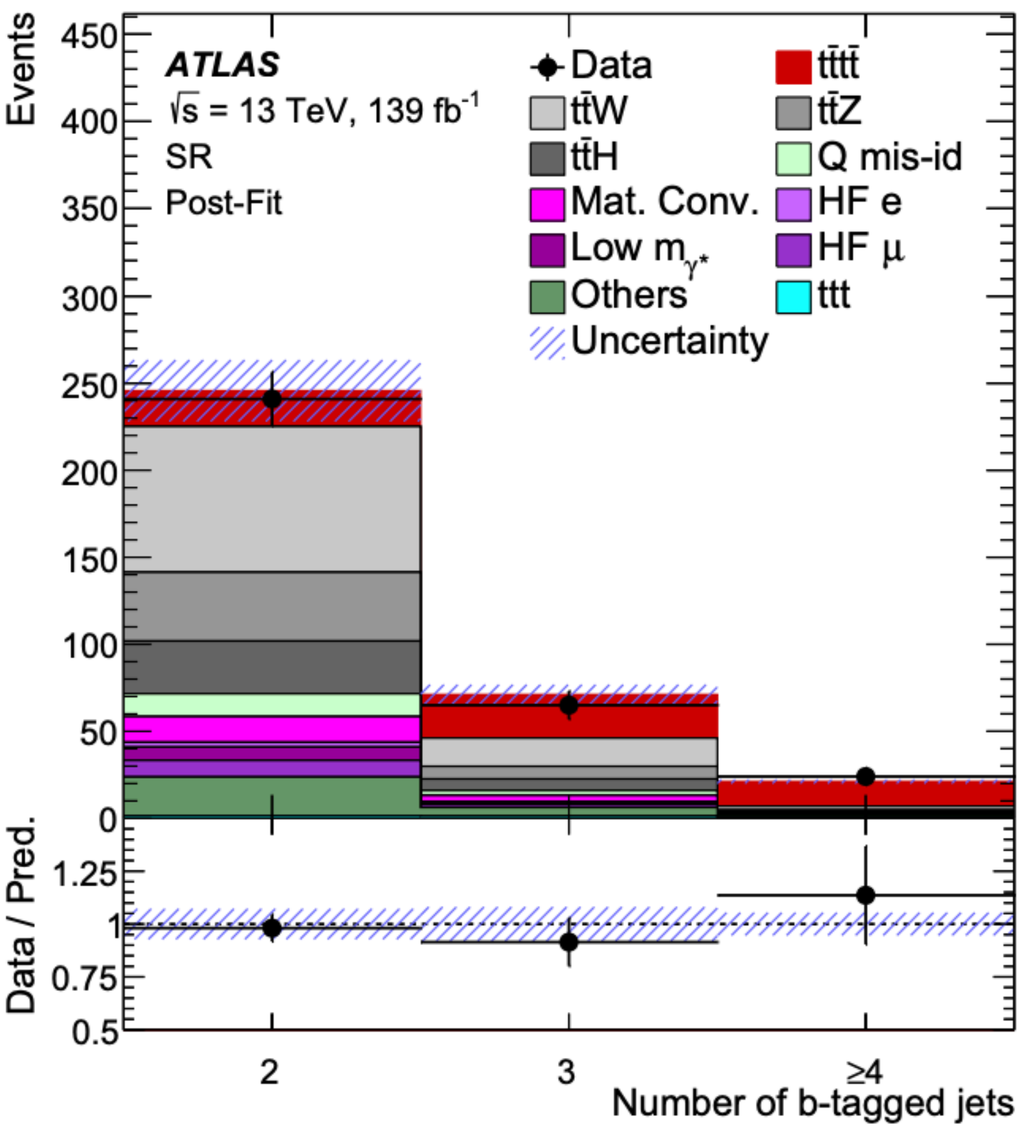


2ℓSS/3ℓ Channel: post-fit plots (input variables to the BDT)

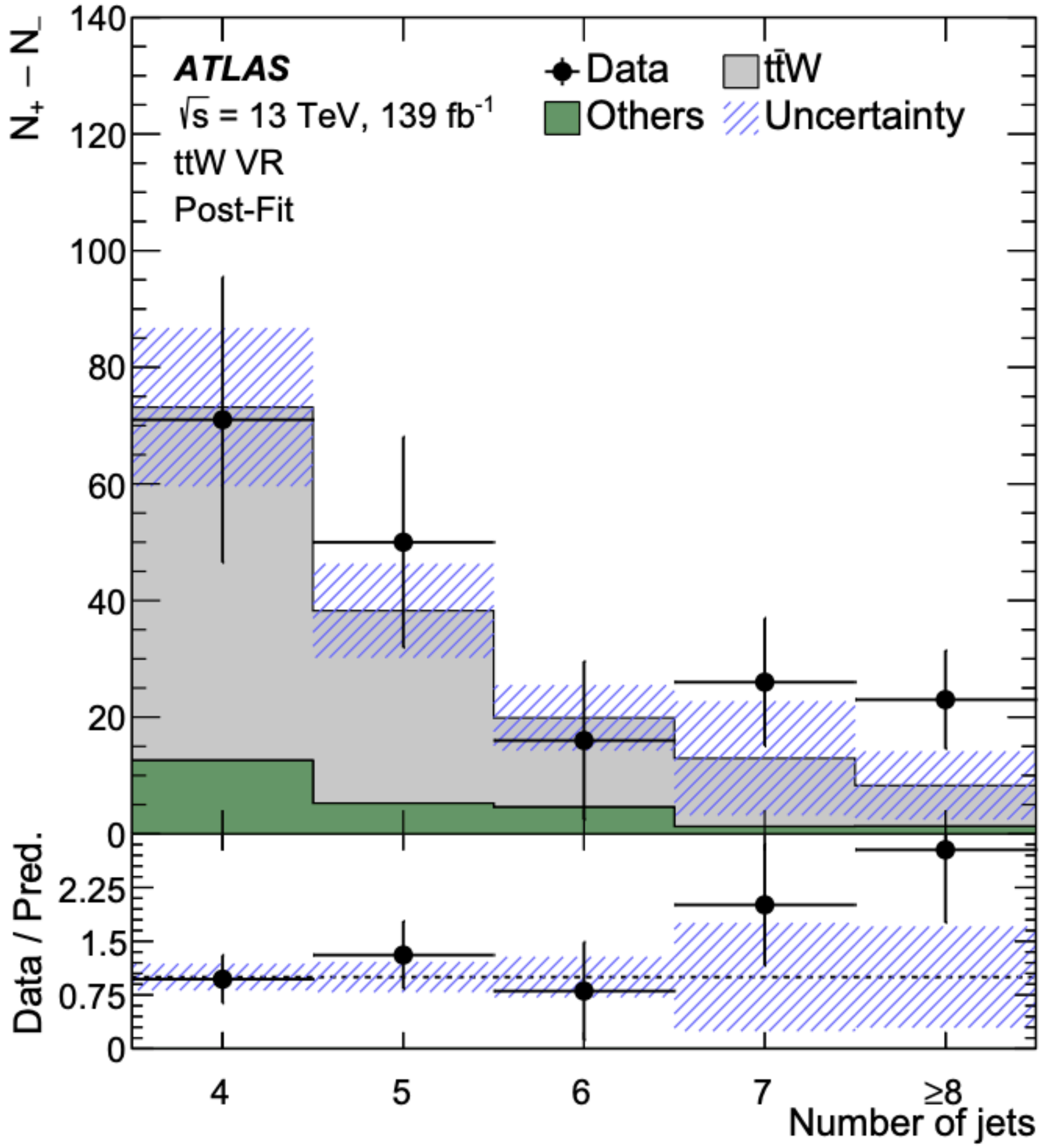


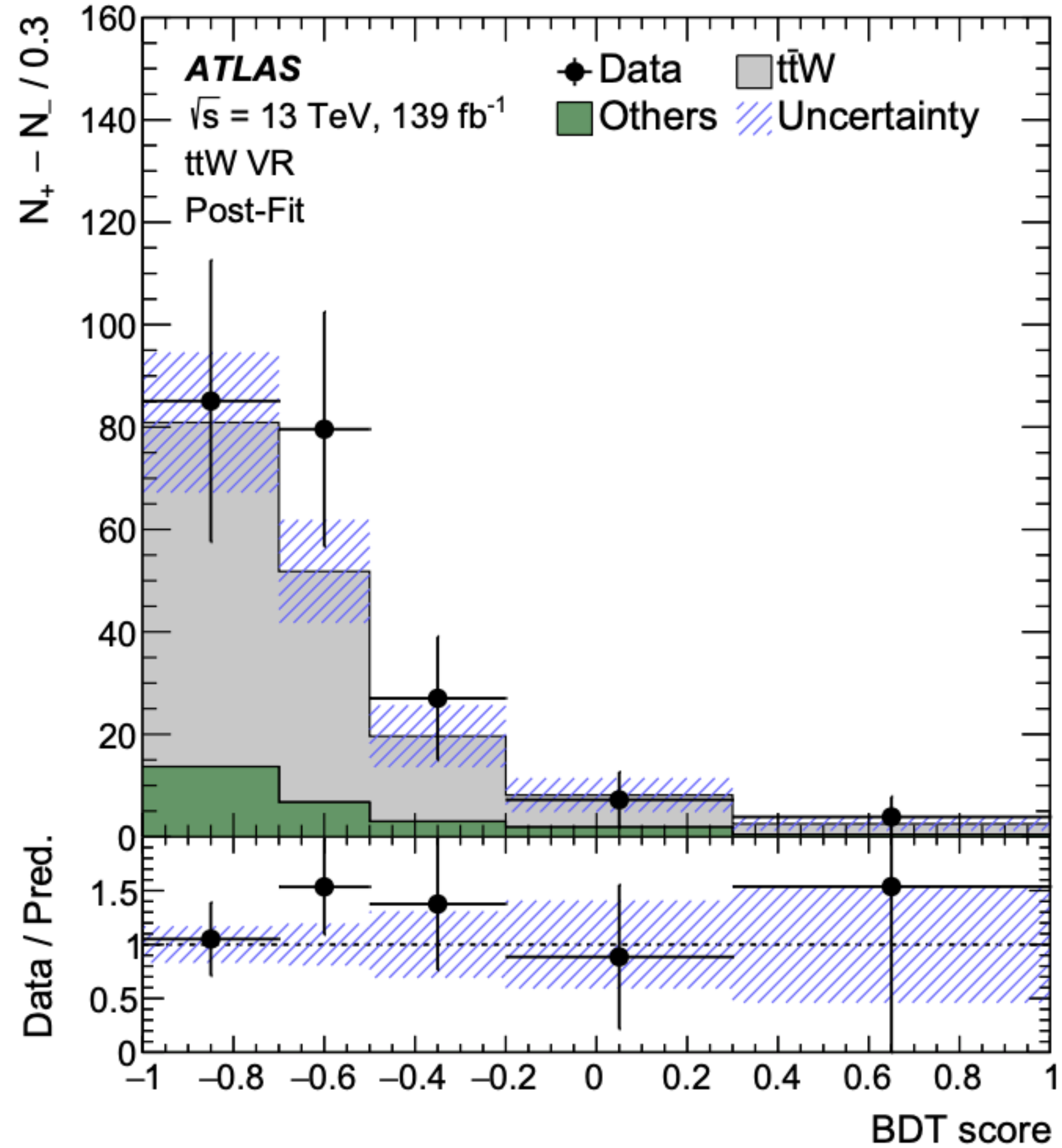
2ℓSS/3ℓ Channel: post-fit plots (input variables to the BDT)



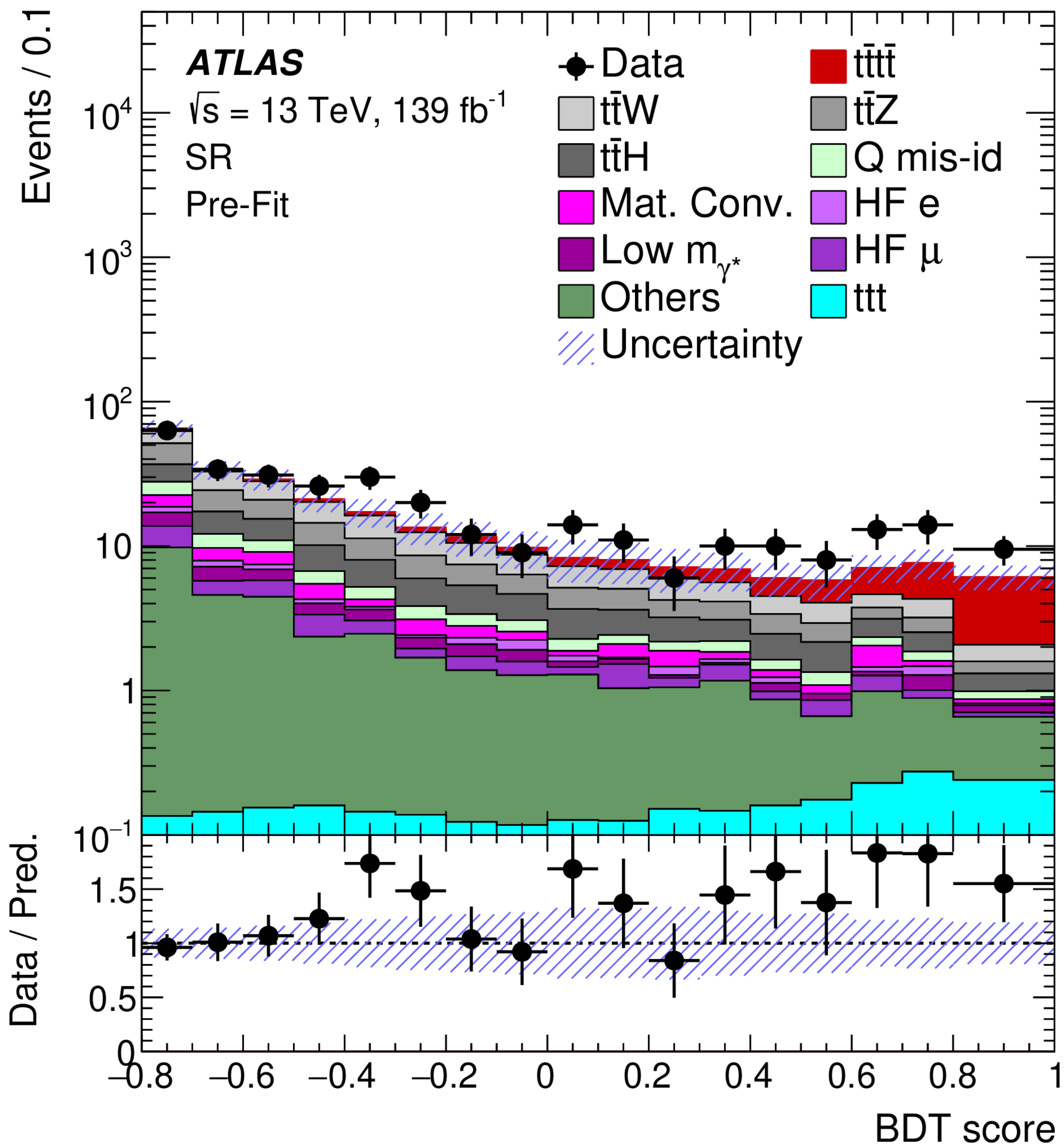


2ℓSS/3ℓ Channel: ttW Validation Region

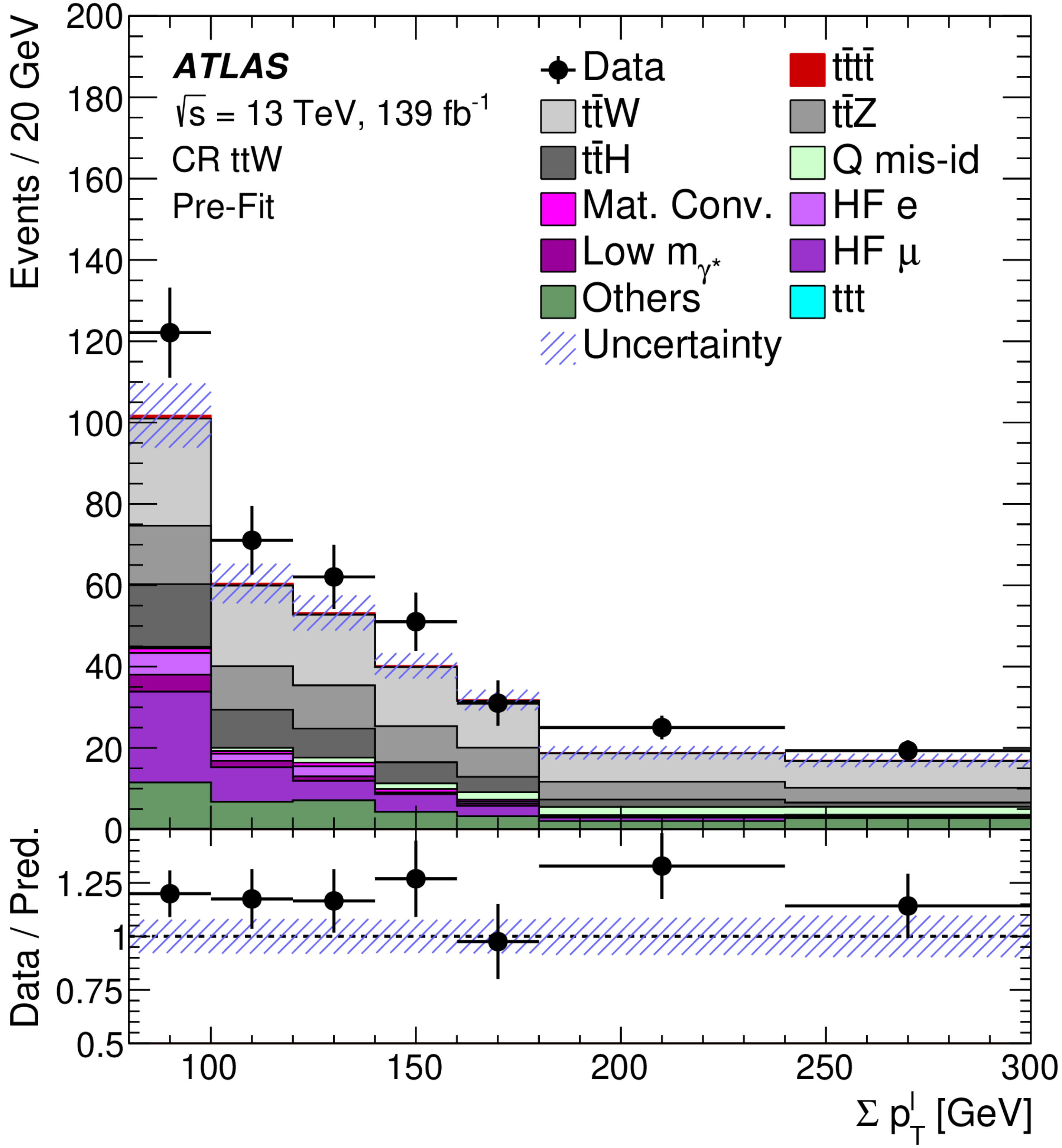




2ℓSS/3ℓ Channel: SR pre-fit



2ℓSS/3ℓ Channel: ttW pre-fit



Results from CMS - 2ℓSS/3ℓ Channel

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

1ℓ/1ℓOS Channel back-up

1ℓ/1ℓOS Channel: tt+bb backgrond

$t\bar{t}$+$b\bar{b}$ measurements from CMS

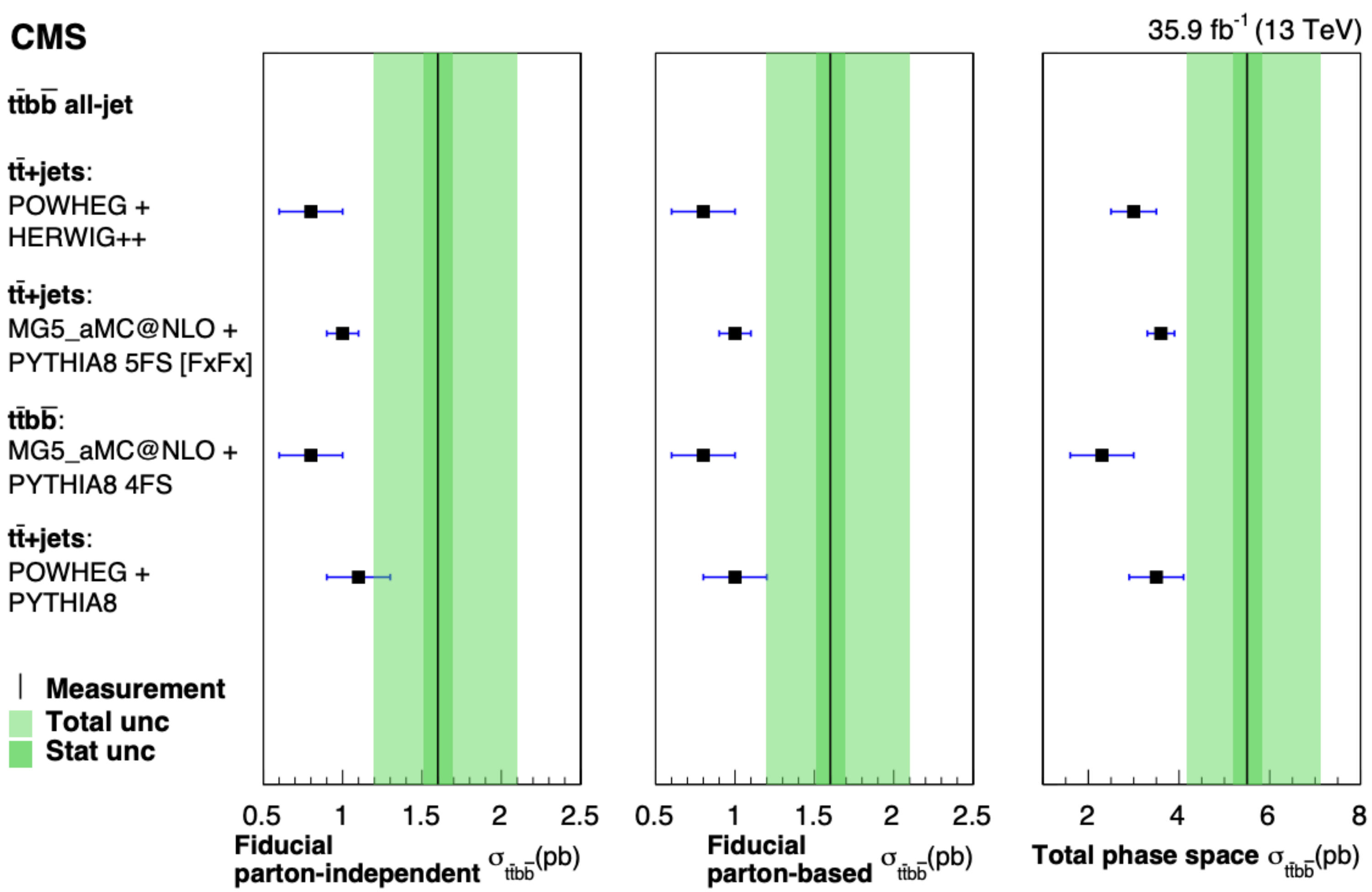
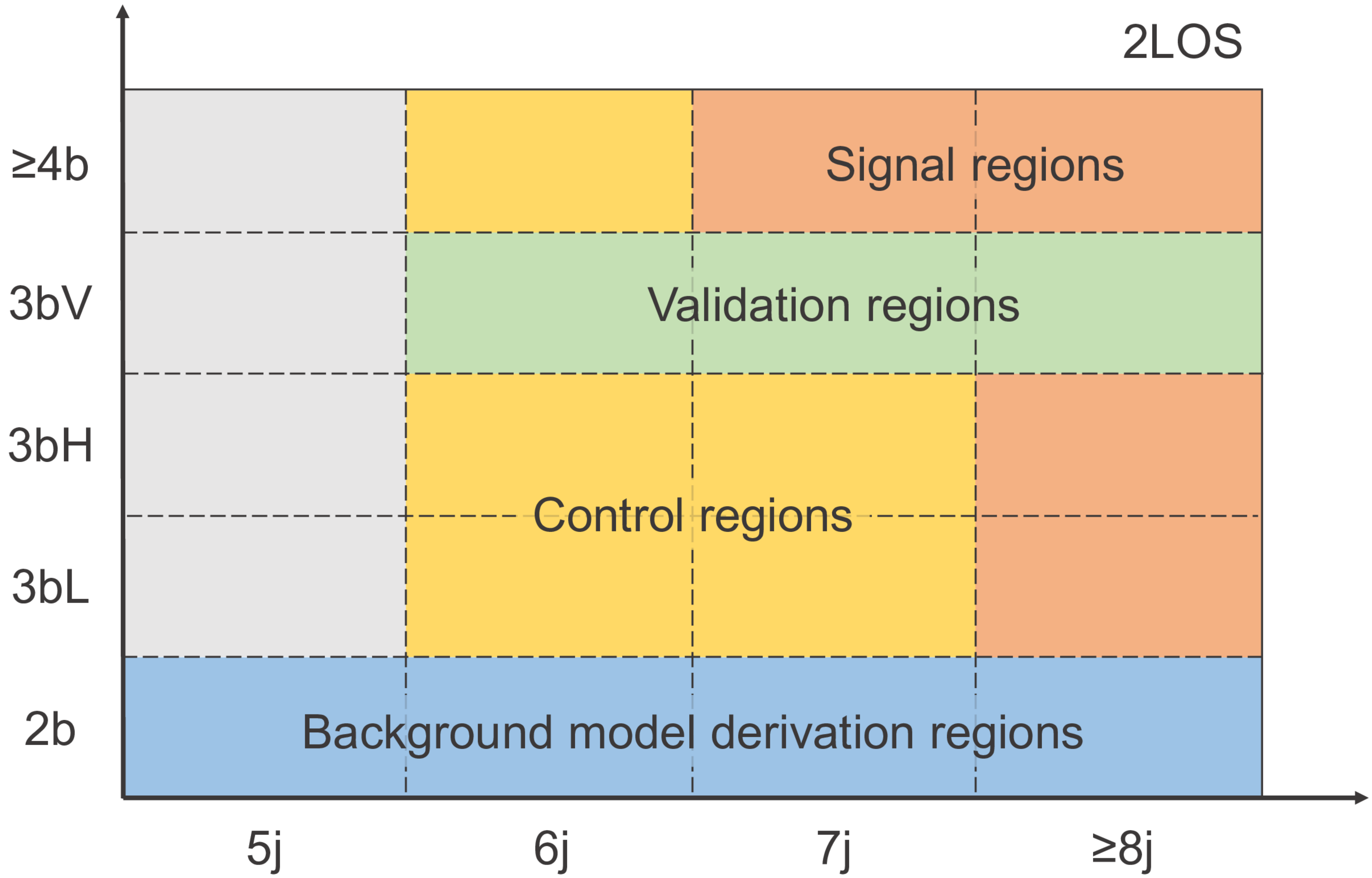
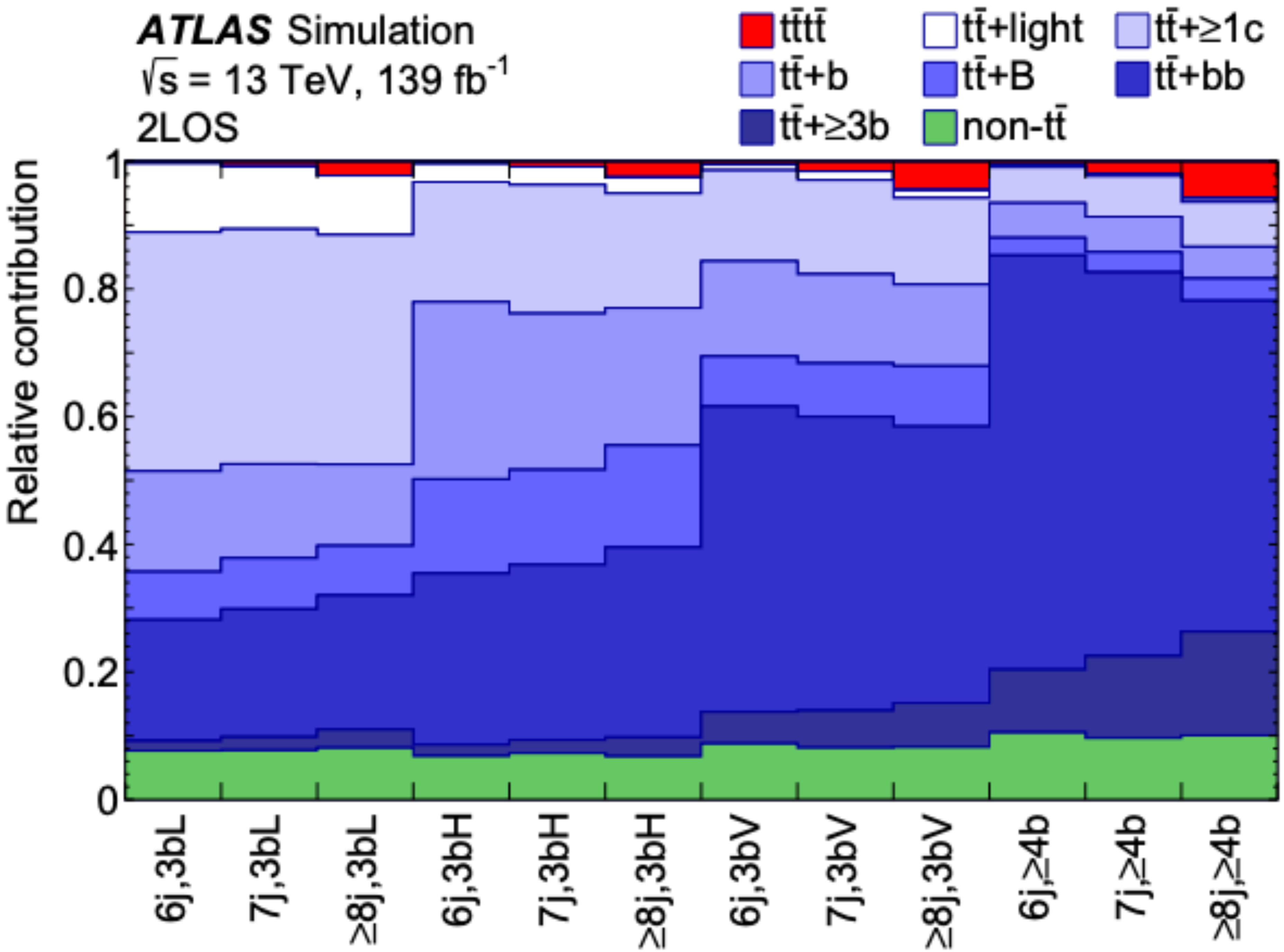


Figure 3: Comparison of the measured $t\bar{t}b\bar{b}$ production cross sections (vertical lines) with predictions from several Monte Carlo generators (squares), for three definitions of our $t\bar{t}b\bar{b}$ regions of phase space: fiducial parton-independent (left), fiducial parton-based (middle), total (right). The dark (light) shaded bands show the statistical (total) uncertainties in the measured value. Uncertainty intervals in the theoretical cross sections include the statistical uncertainty as well as the uncertainties in the PDFs and the μ_R and μ_F scales.

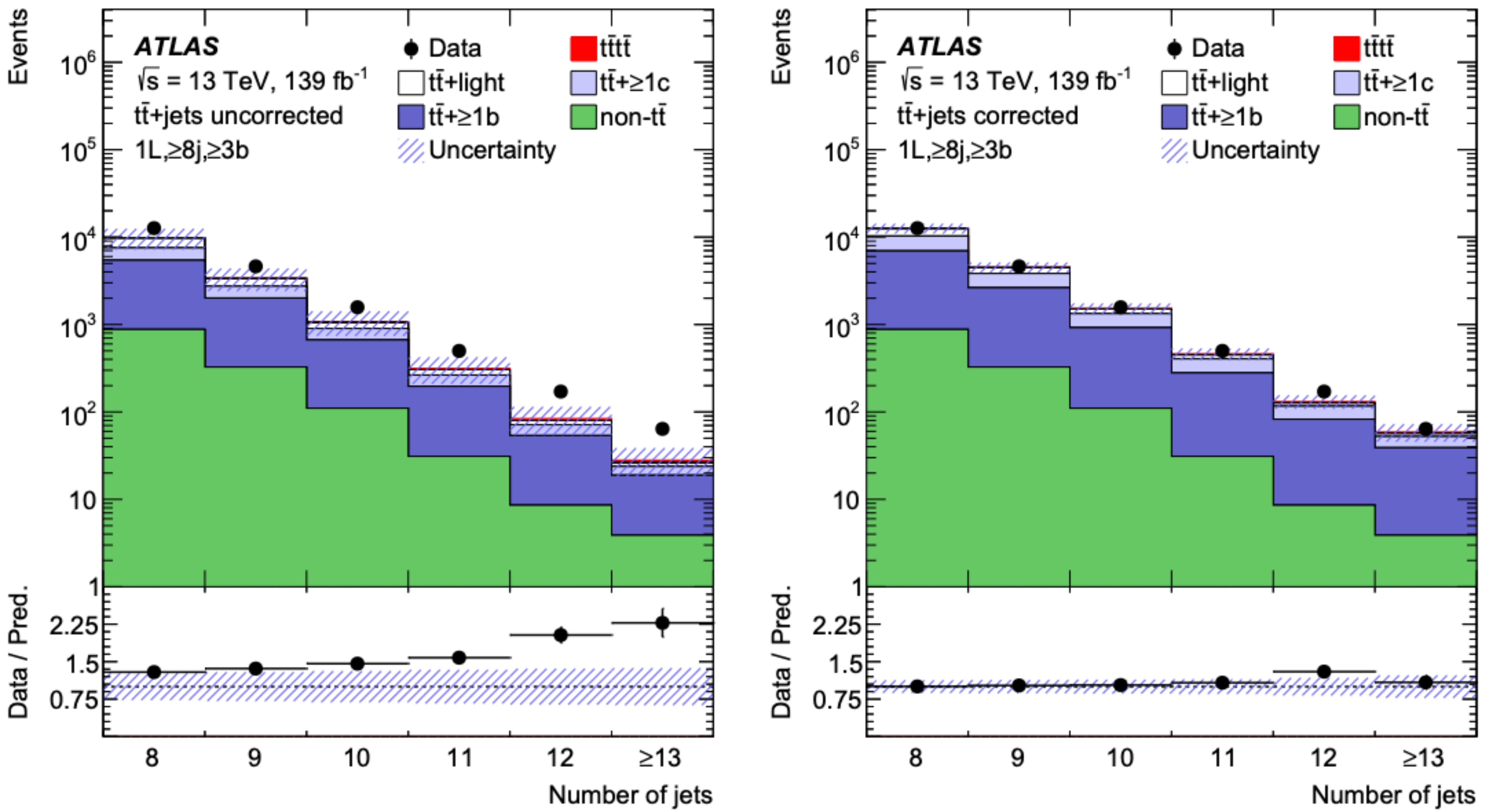
$1\ell/1\ell$OS Channel: Analysis Regions



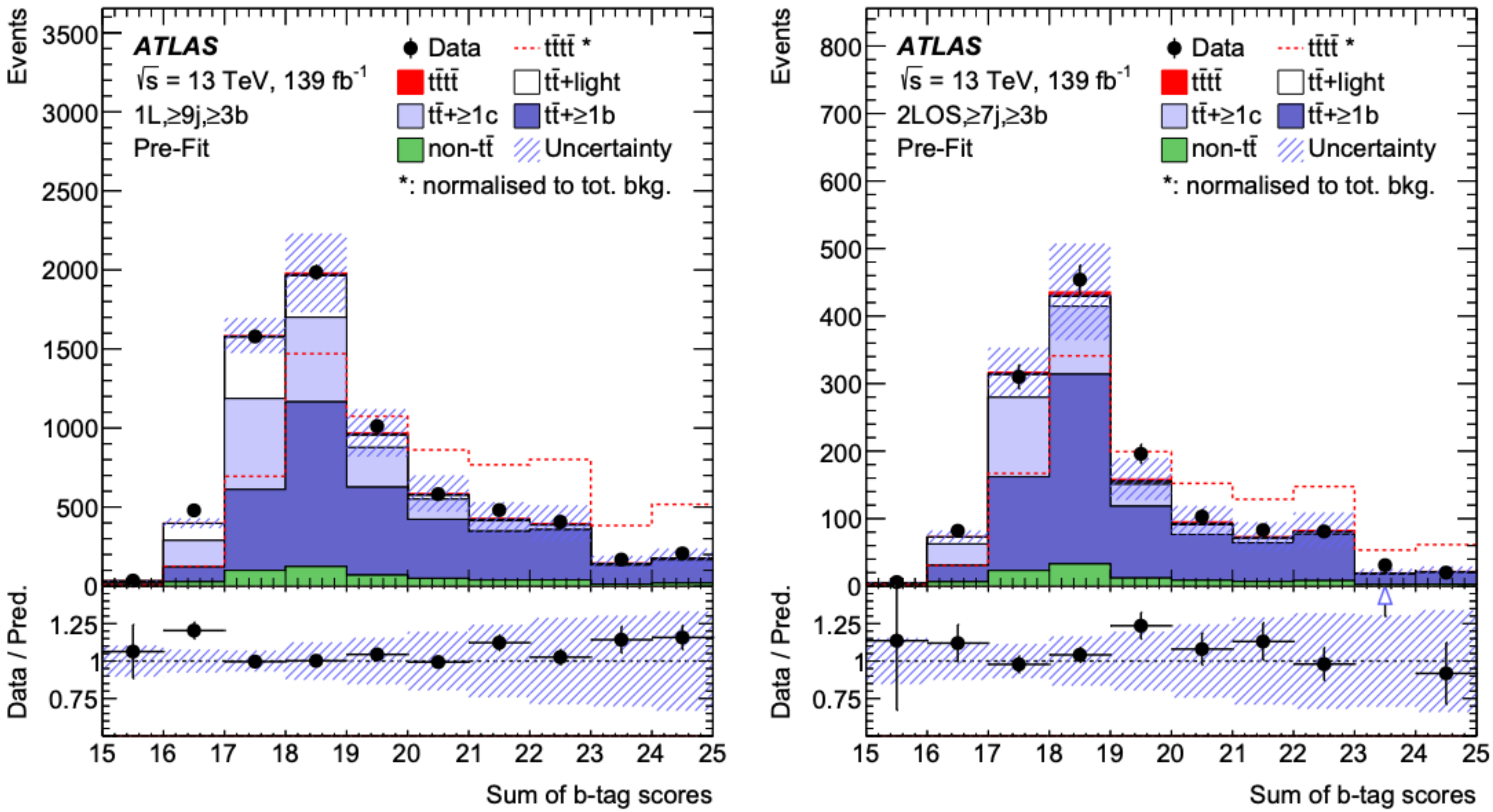
1ℓ/1ℓOS Channel: Analysis Regions



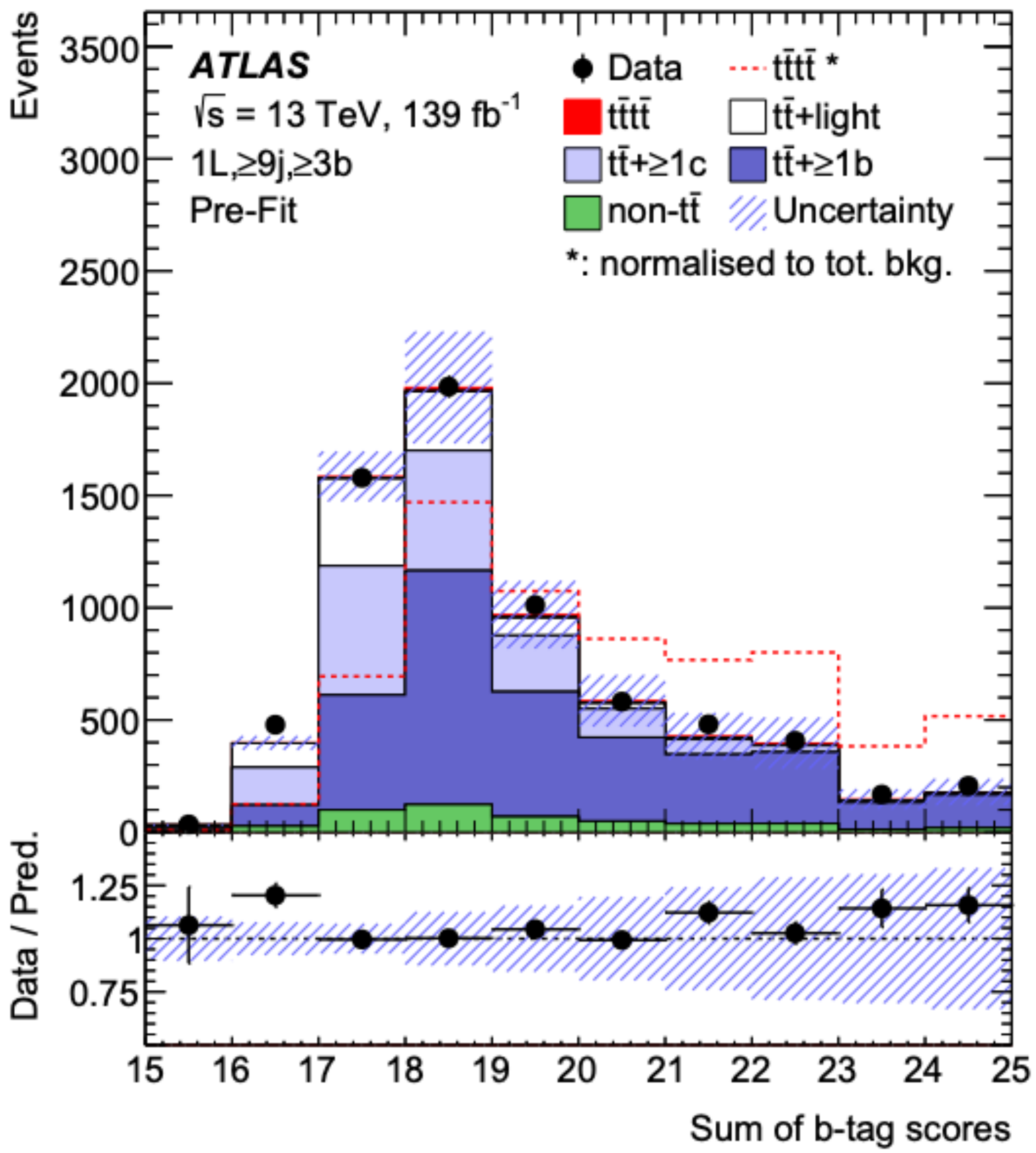
1ℓ/1ℓOS Channel: Effect of the re-weighting

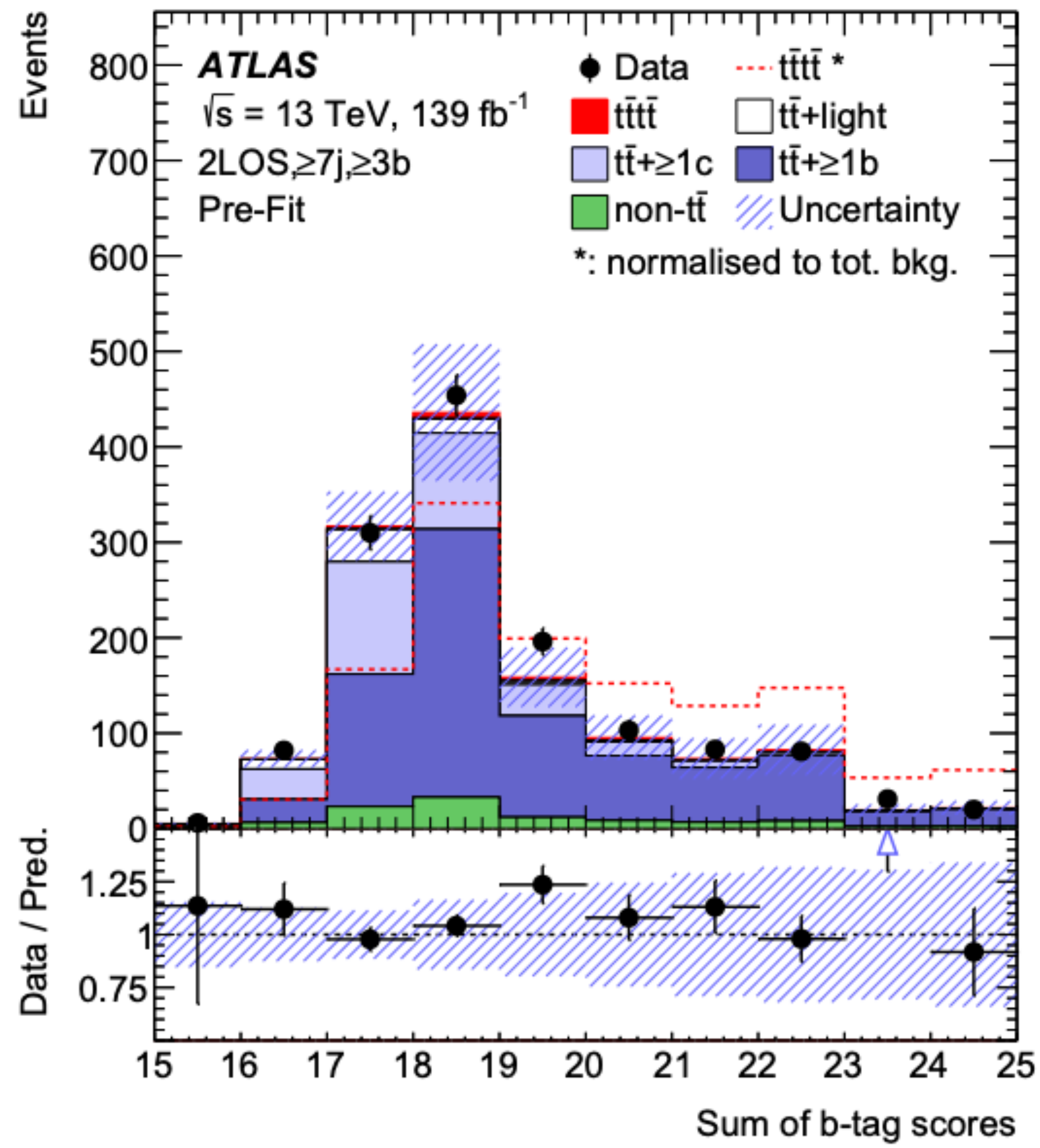


1ℓ/1ℓOS Channel: pre-fit plots (input variables to the BDT)

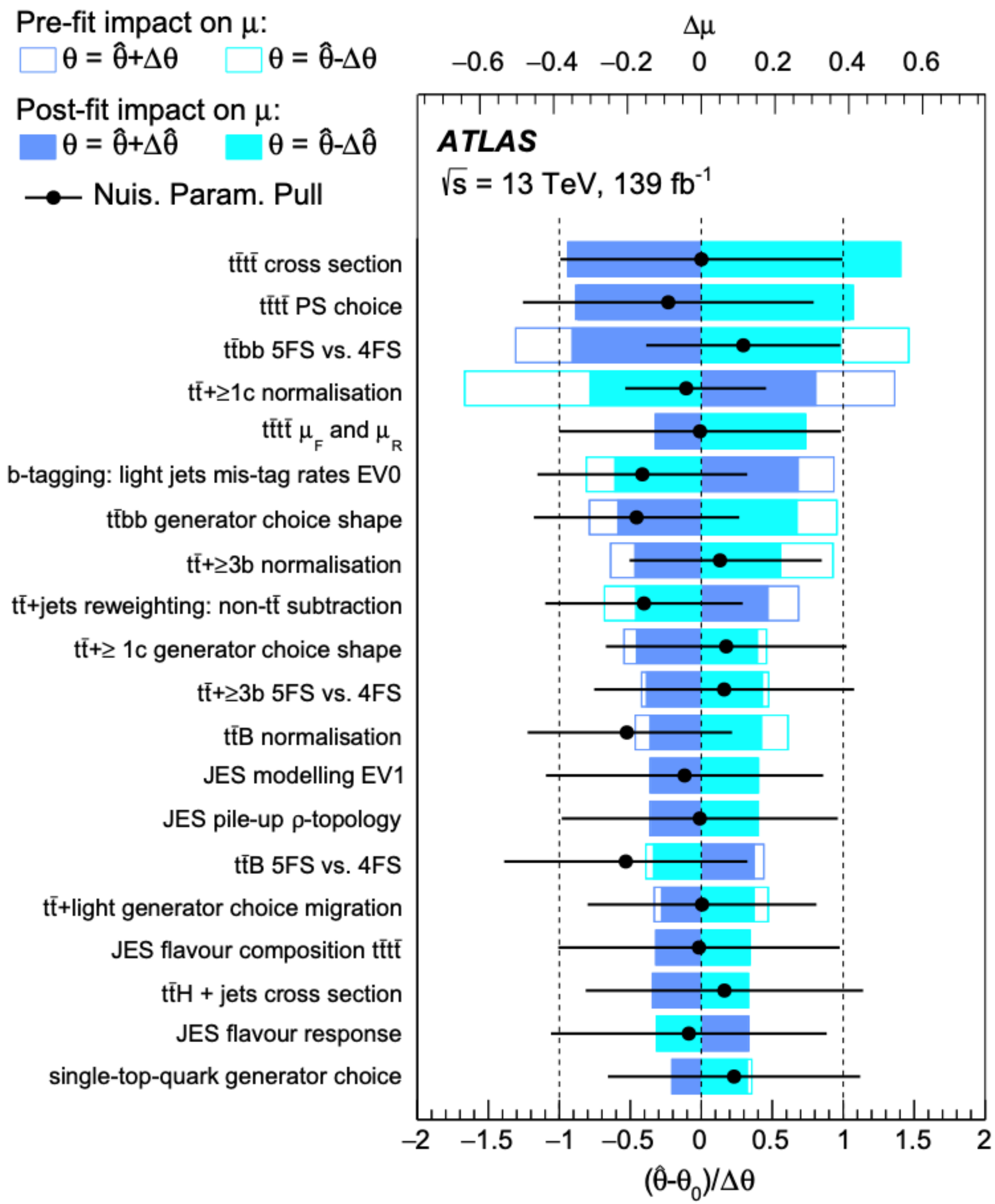


1ℓ/1ℓOS Channel: pre-ft plots (input variables to the BDT)





1ℓ/1ℓOS Channel: Ranking of systematics

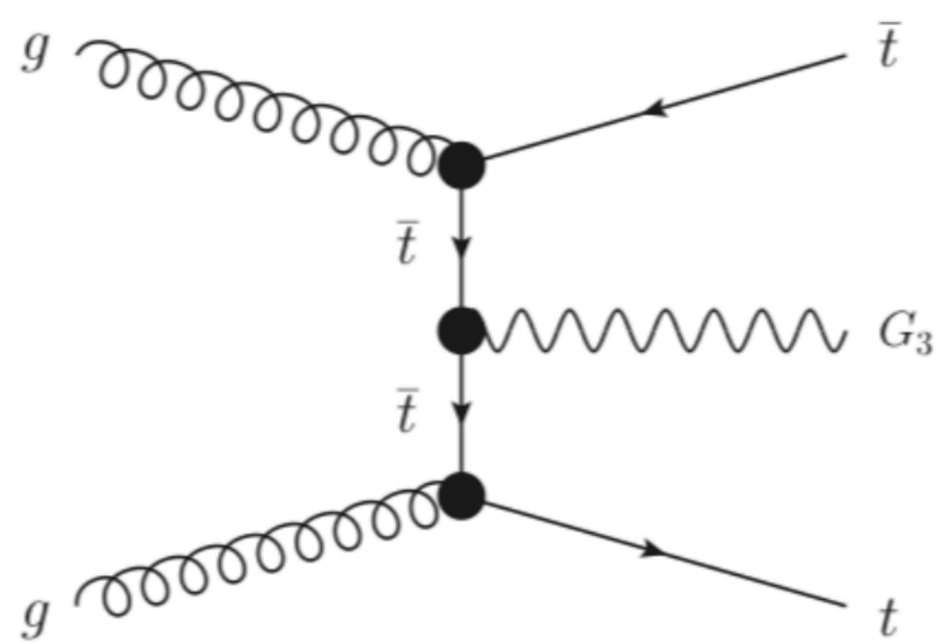


BSM 4tops Search back-up

Benchmark Signal Model

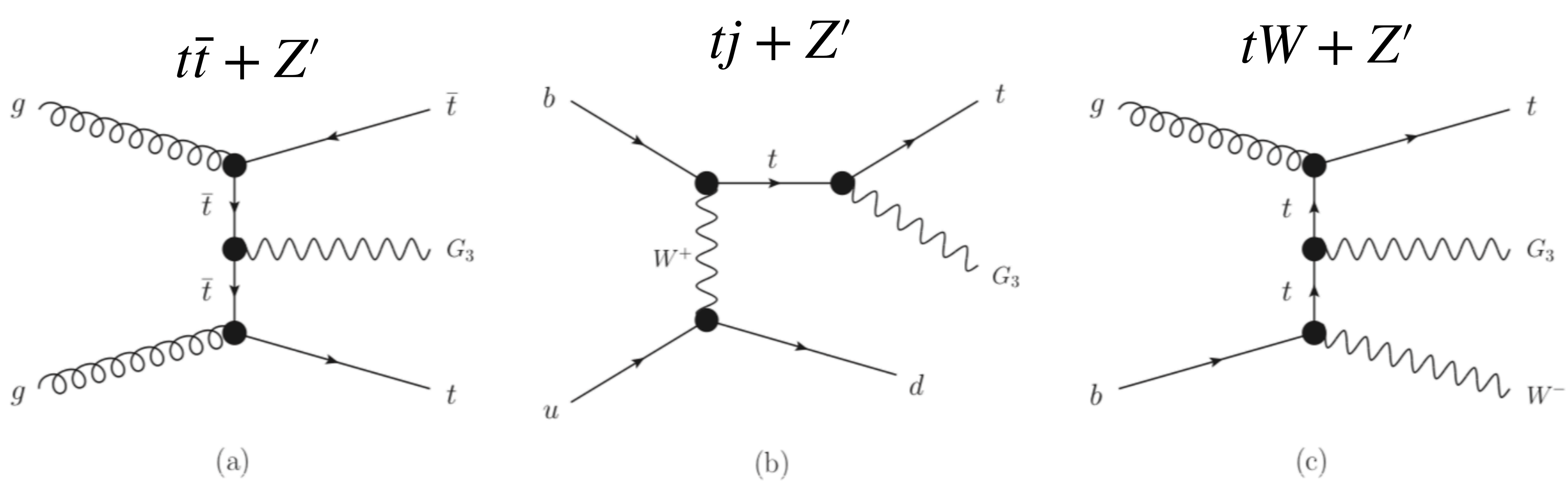
- Consider a color singlet vector particle (Z'), with mass ≫ m_{top}, leading to a narrow resonance: *Probing TeV scale Top-Philic Resonances with Boosted Top-Tagging at the High Luminosity LHC*
- Using a model independent approach and focus on a two body decay of Z' into $t\bar{t}$ with $M_{Z'}$ in the TeV range
- Can produce top-philic resonances at tree-level and one-loop
- We focus on tree-level production such as: $t\bar{t} + Z'$, $tW + Z'$ and $tj + Z'$ with $Z' \to t\bar{t}$

$t\bar{t} + Z'$



Benchmark Signal Model

- The largest contribution at the LHC comes from the four top-quark final state
  - $tj + Z'$ production is smaller than $t\bar{t} + Z'$ roughly by a factor of 2 while $tW + Z'$ production is smaller by a factor 4

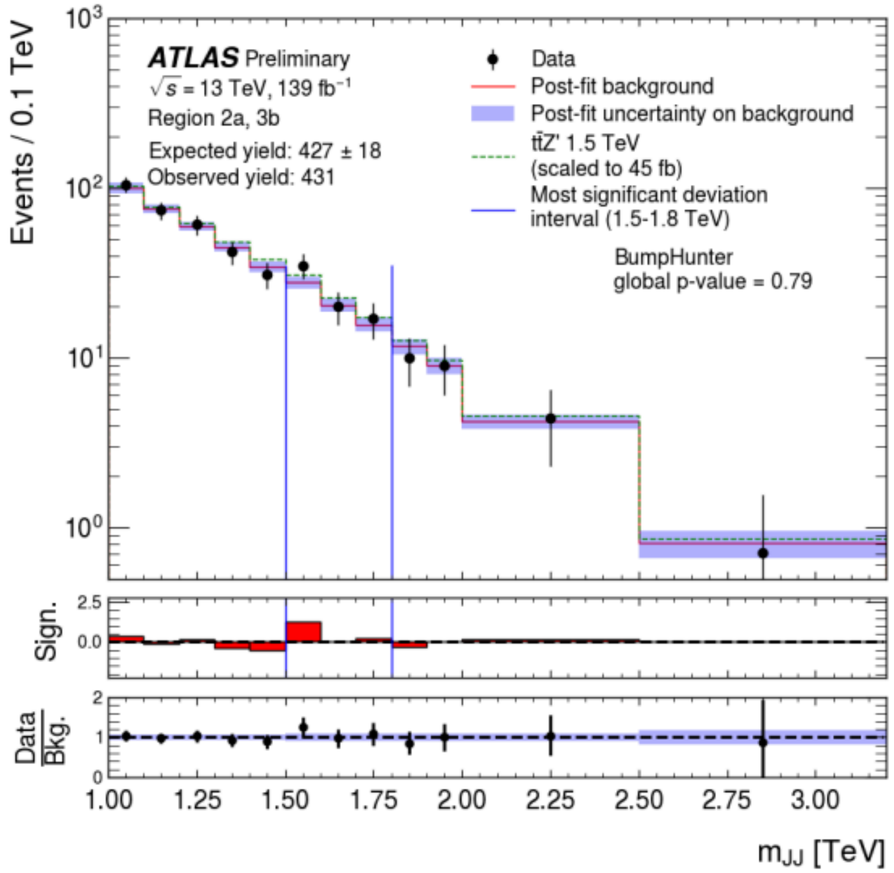


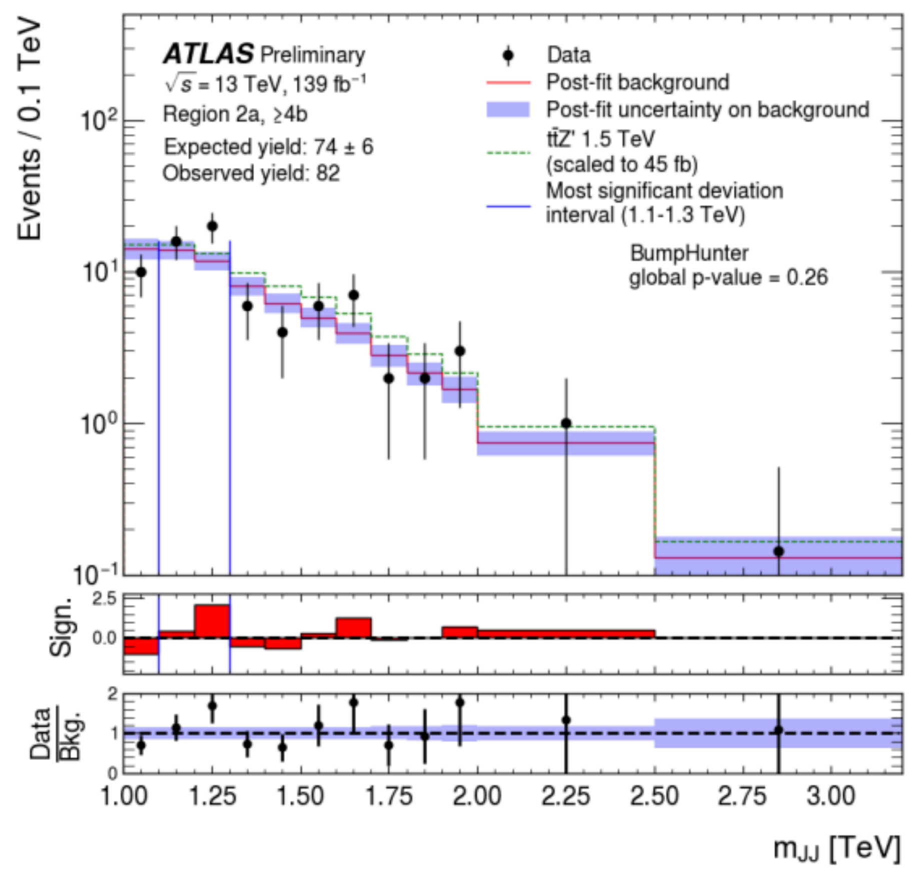
So far only considering $t\bar{t} + Z'$

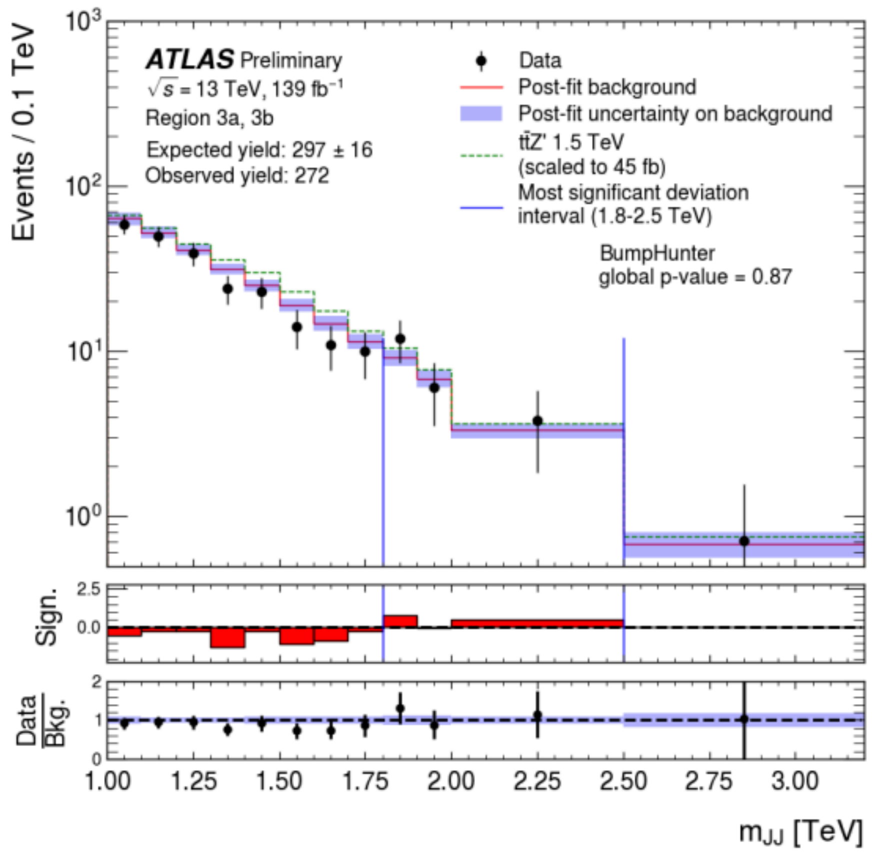
1/2

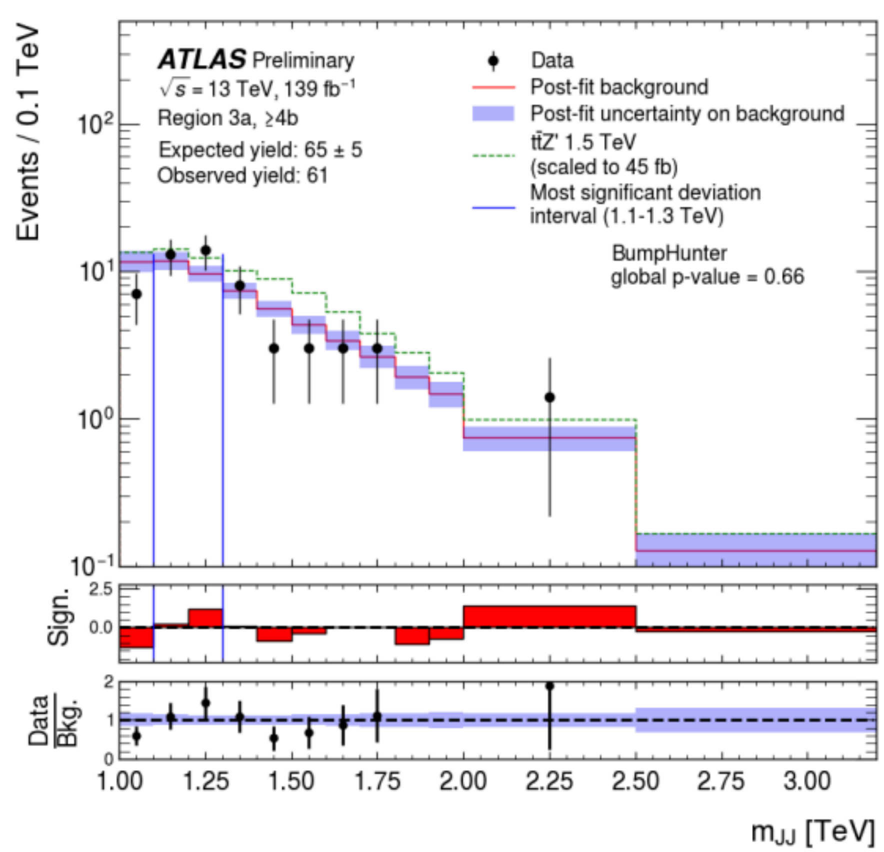
1/4

BumpHunter Results

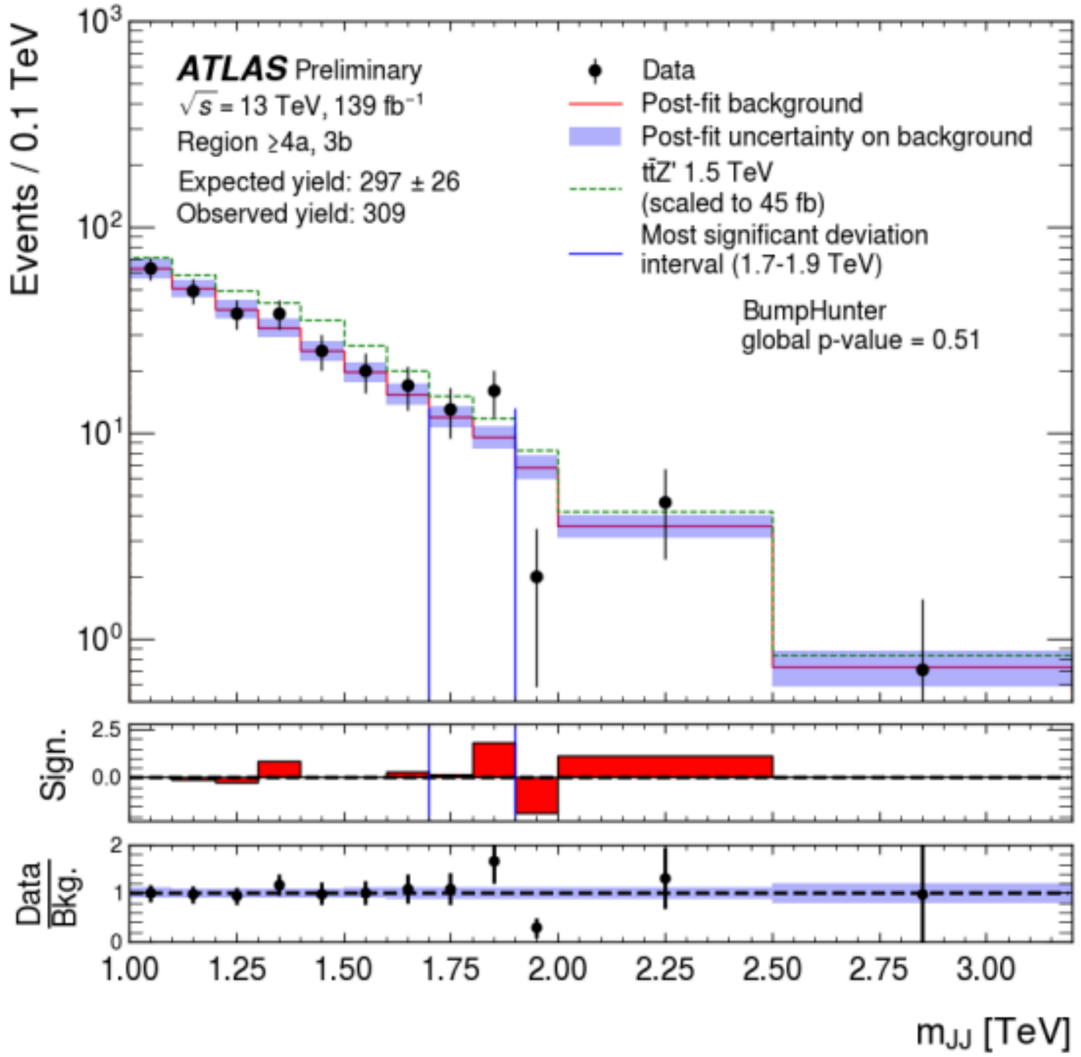


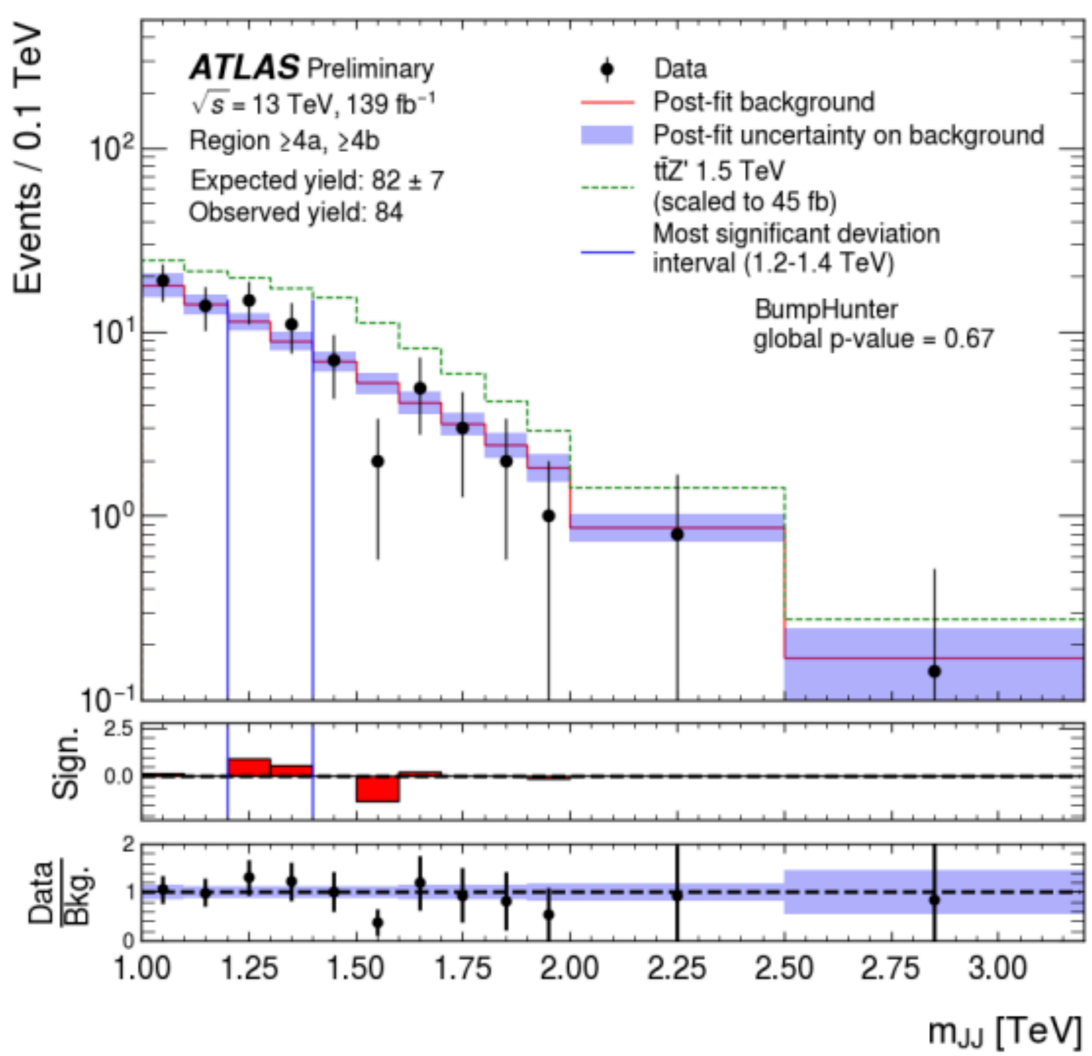






BumpHunter Results





Uncertanties

Uncertainty categories	Relative contribution to the total uncertainty [%]	
	1.5 TeV	3 TeV
$t\bar{t}$+jets modeling	68	50
Signal bias	45	25
Functional fit and extrapolation	34	33
Jet energy scale and resolution	29	18
Single-top-quark modeling	9.4	7.7
Flavor tagging	8.7	3.6
Minor backgrounds modeling	5.1	5.6
Other uncertainties	0.4	2.0
Luminosity	0.3	0.1
Total systematic uncertainty	92	74
Statistical uncertainty	39	67