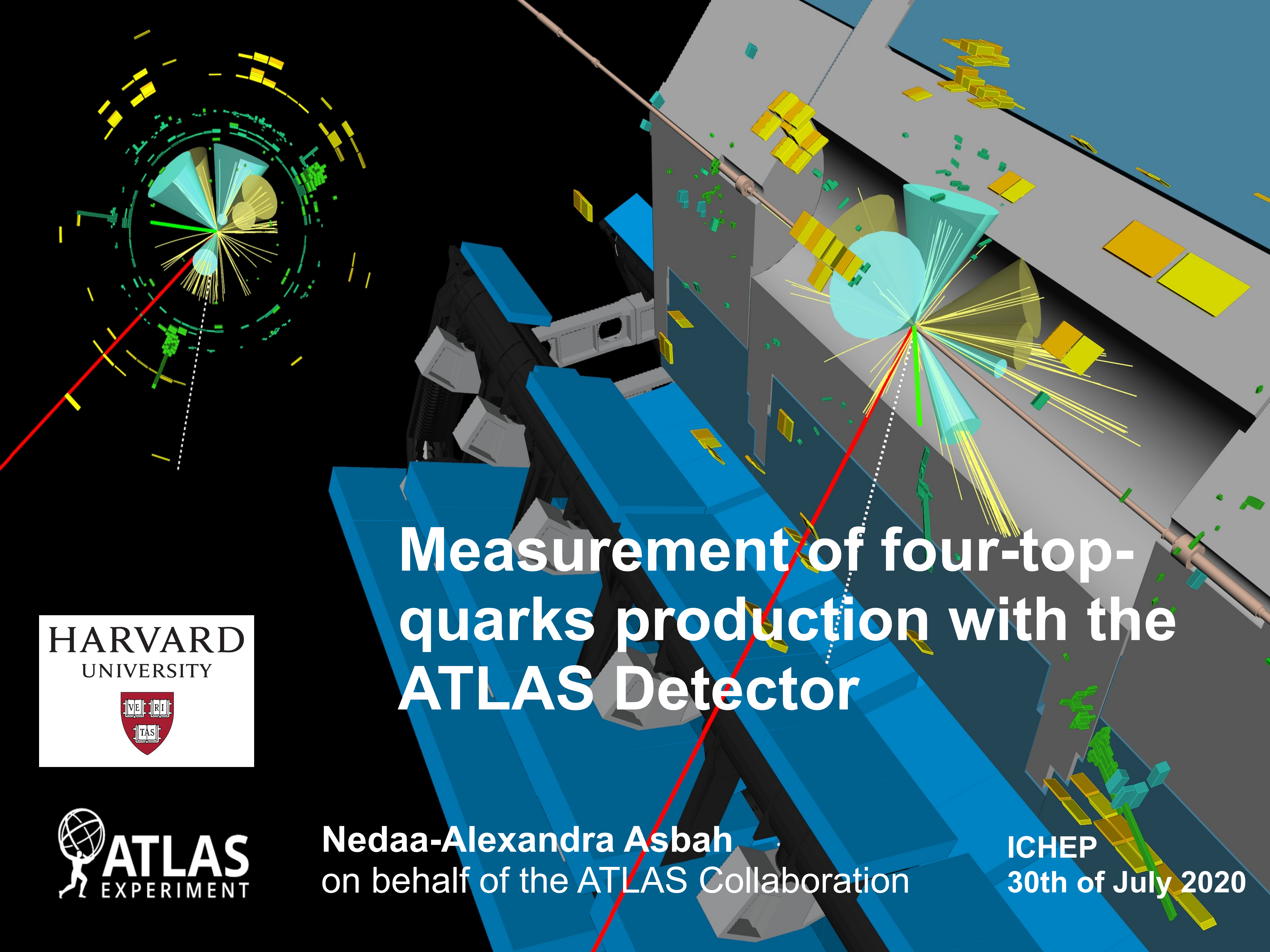


Measurement of four-top-quarks production with the ATLAS Detector

HARVARD UNIVERSITY

ATLAS EXPERIMENT

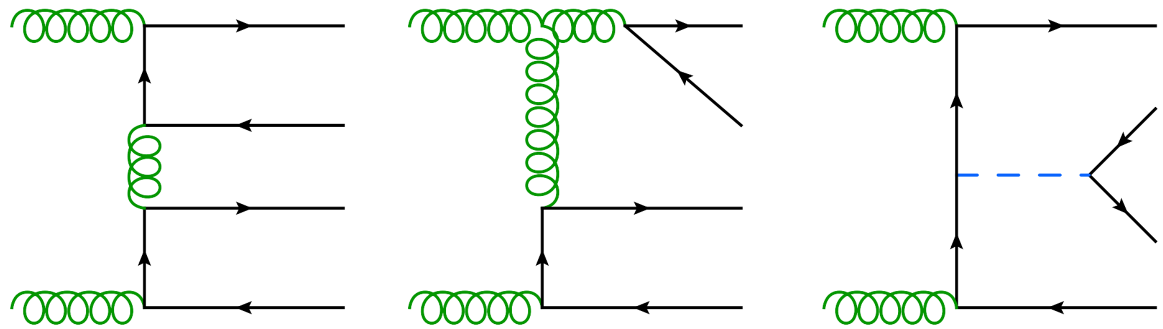
Nedaa-Alexandra Asbah
on behalf of the ATLAS Collaboration

ICHEP
30th of July 2020

Predictions for 4tops

- **Very complicated process**
  - at LO 72 gg+12 qq' initiated diagrams
- **Sensitive to top-Yukawa coupling (y_t)**
  - non-SM value of y_t can change dramatically the production via an off-shell Higgs

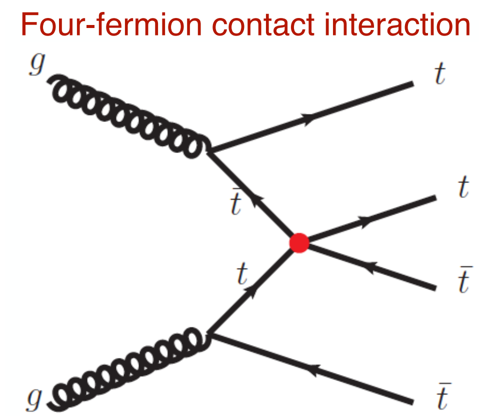
arXiv:1611.05032 [hep-ph]

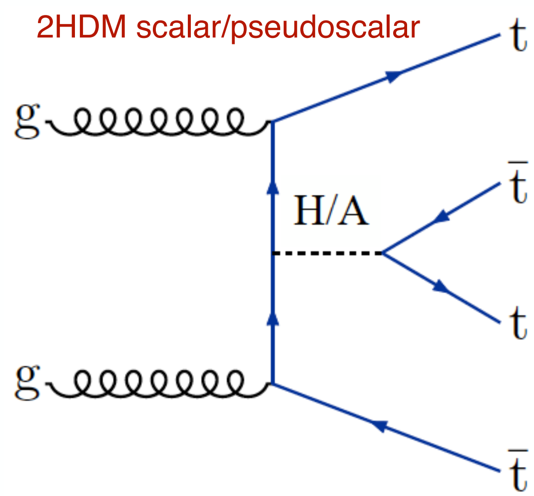


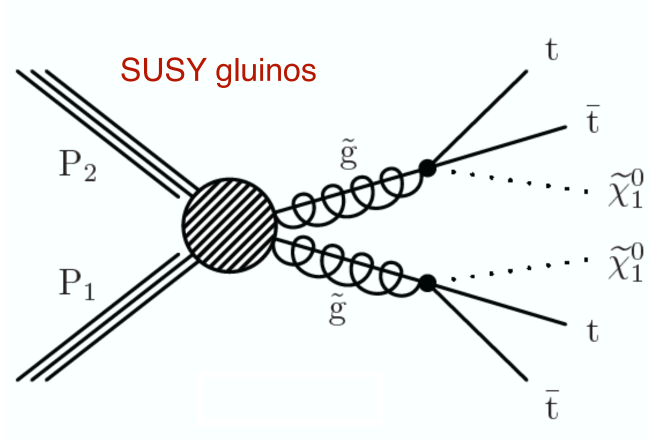
Leading: $O(\alpha_S^4)$

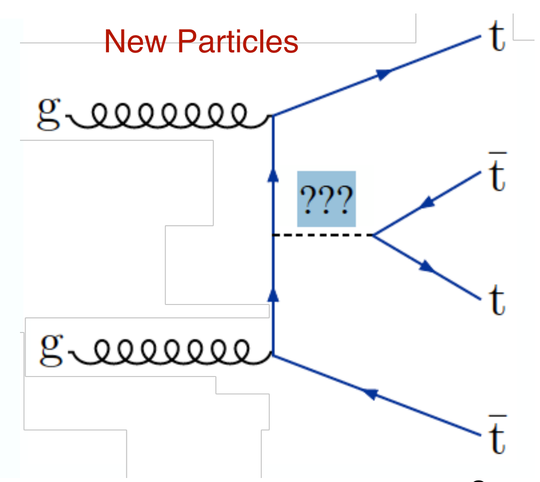
Sub-Leading: $O(\alpha_S^2 y_t^4)$, $O(\alpha_S^2 \alpha^2)$

- **Extremely high energy scale production makes it naturally sensitive to many BSM models**
  - EFTs, including four-fermion contact interaction
  - Higgs physics: 2HDM scalar/ pseudoscalar
  - SUSY: gluinos, sgluons
  - New particles coupling to top quark



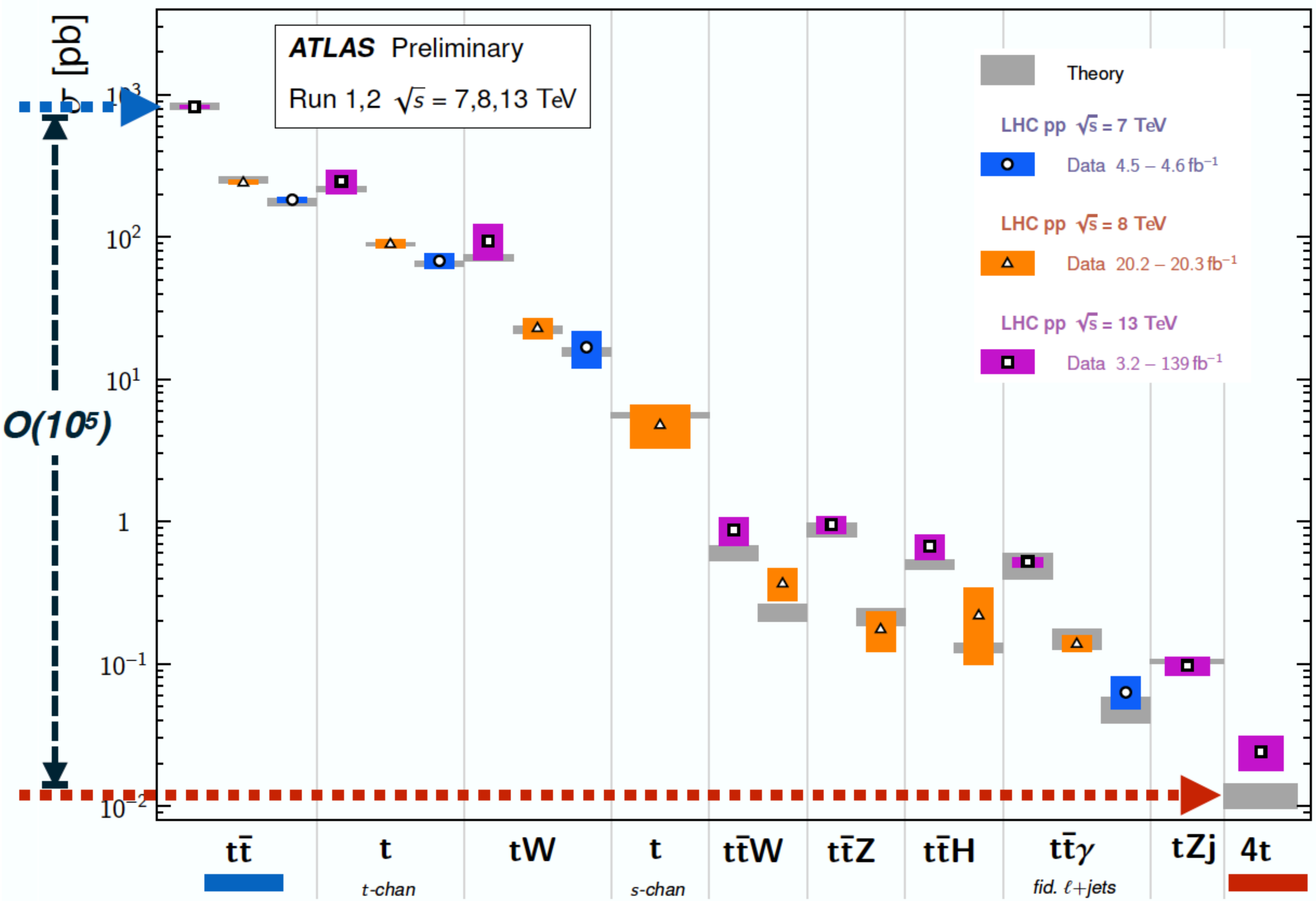






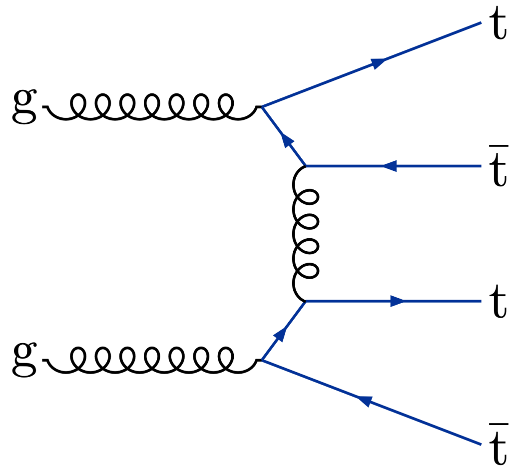
Production of 4tops

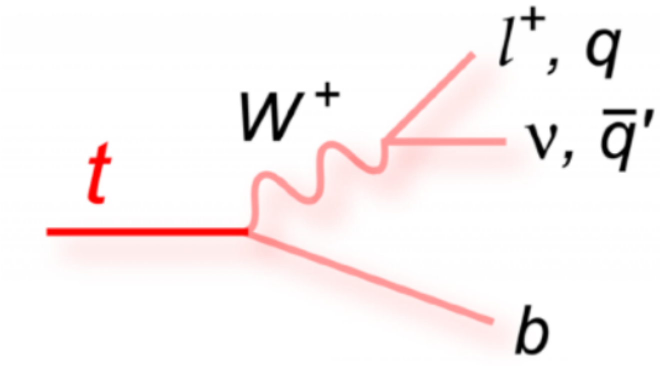
- **Very tiny cross section in the SM**
  - σ ^{NLO}(tttt) = 11.97 fb at NLO QCD + NLO QED at 13 TeV arXiv:1611.05032 [hep-ph]
- O(100M) $t\bar{t}$ events
- O(1k) $t\bar{t}\,t\bar{t}$ events



Signatures

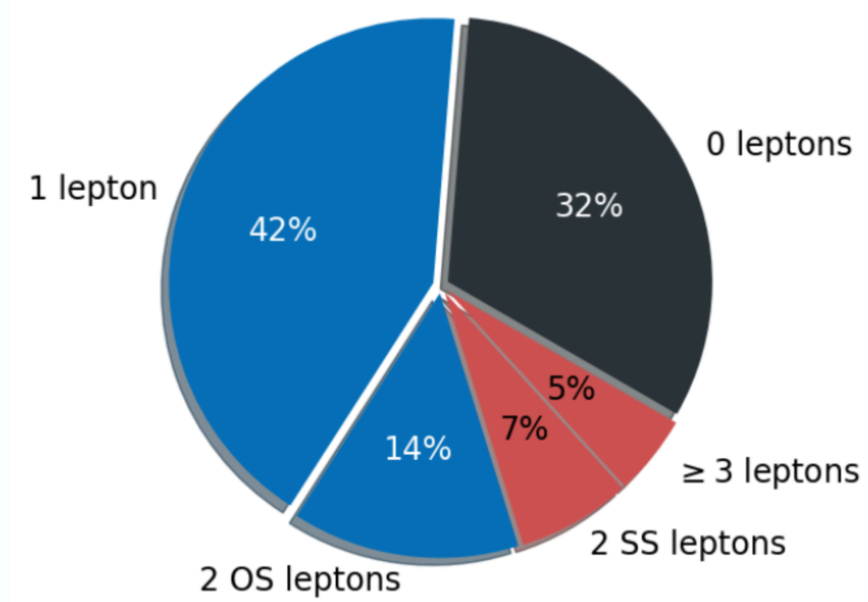
- The t→Wb decay means the detector signature is defined by:
  - The presence of several (up to 4) b-quarks,
  - The decays of the W bosons.





- Channels are split according to:
  - **1ℓ/2ℓOS: 1ℓ** (42%) / **2ℓOS** (14%) Phys. Rev. D99 (2019) 052009
    - Dominant branching fraction, but large irreducible background from tt+jets, tt+heavy flavour jets
    - Uses 36 fb^{-1} of Run 2 dataset
  - **2ℓSS/3ℓ: 2ℓSS** (7%) / **3ℓ** (5%) ATLAS-CONF-2020-013
    - Low branching fraction, but small background (ttW, ttZ, non-prompt leptons, charge misidentification)
    - Most sensitive channel
    - Uses 139 fb^{-1} of Run 2 dataset

NEW!



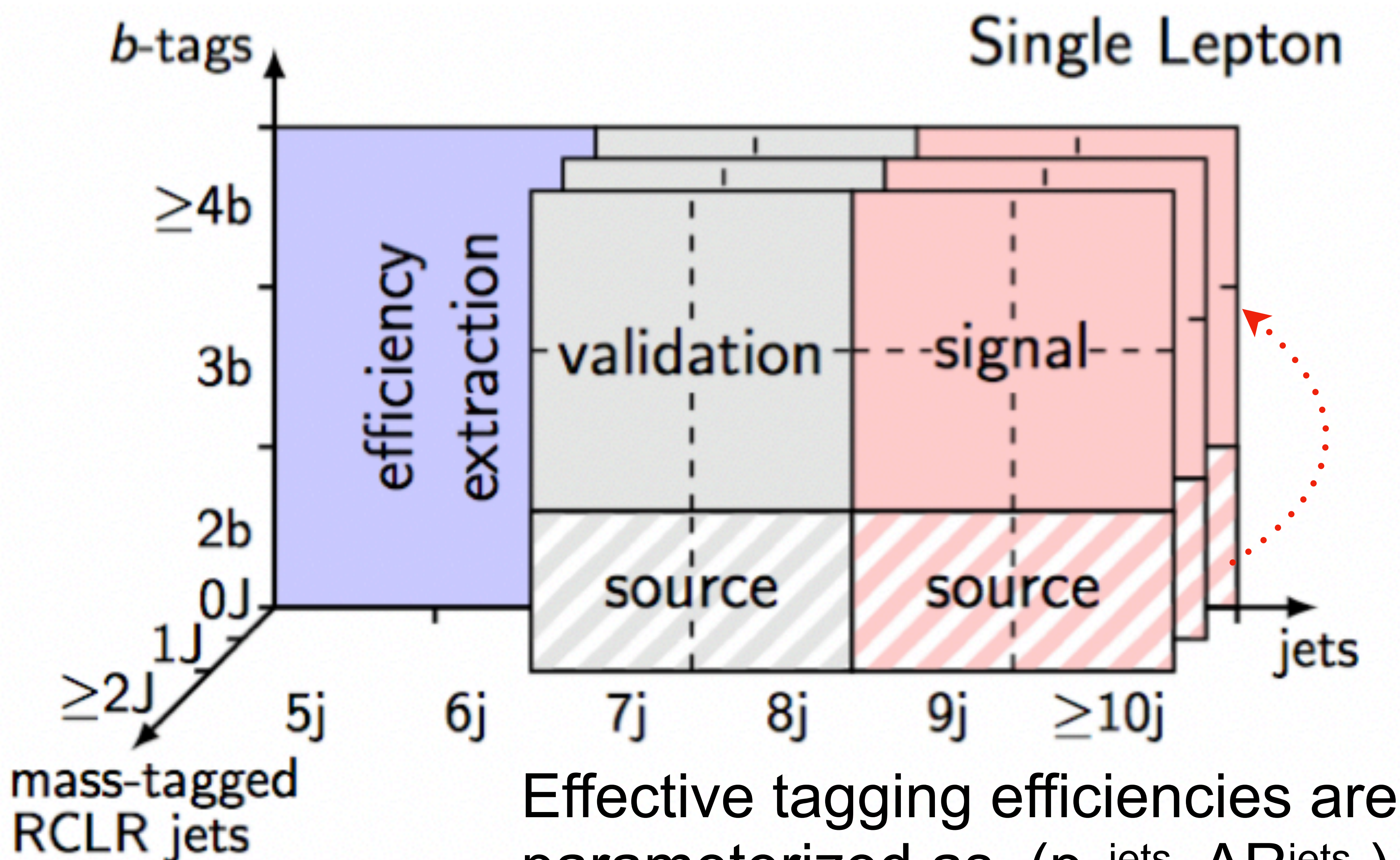
1ℓ/2ℓOS Channel: Analysis Strategy

- ATLAS result : Phys. Rev. D99 (2019) 052009
- Uses **36 fb^{-1}** of Run 2 dataset
- Event Selection:
  - 1 e/μ or 2 e/μ
  - $N_{jets} \geq 5$ (1L), $N_{jets} \geq 4$ (2L)
  - $N_b \geq 2$

Channel	**1L (expected 10 jets and 4 b-jets)**	**OS (expect 8 jets and 4 b-jets)**
Pre-selection	$E^{\text{miss}} > 20$ GeV $E^{\text{miss}} + m^{W} > 60$GeV	$m_{ll} > 30$ GeV $\lvert m_{ll} - 91 \rvert > 9$ GeV

1ℓ/2ℓOS Channel: Analysis Strategy

- Events are categorized according to **number of R=0.4 jets**, **b-tagged jets**, and **large radius jets** (R=1.0 reclustered)
- $t\bar{t}b\bar{b}$ background in signal regions estimated using **data-driven method**
  - extract effective tagging efficiency from **low N_{jets}**, apply to low **N_{tags} source regions** to promote events to higher **N_{tags} SRs**



Effective tagging efficiencies are parameterized as (p_T^{jets}, ΔR^{jets})

1ℓ/2ℓOS Channel: Signal Extraction

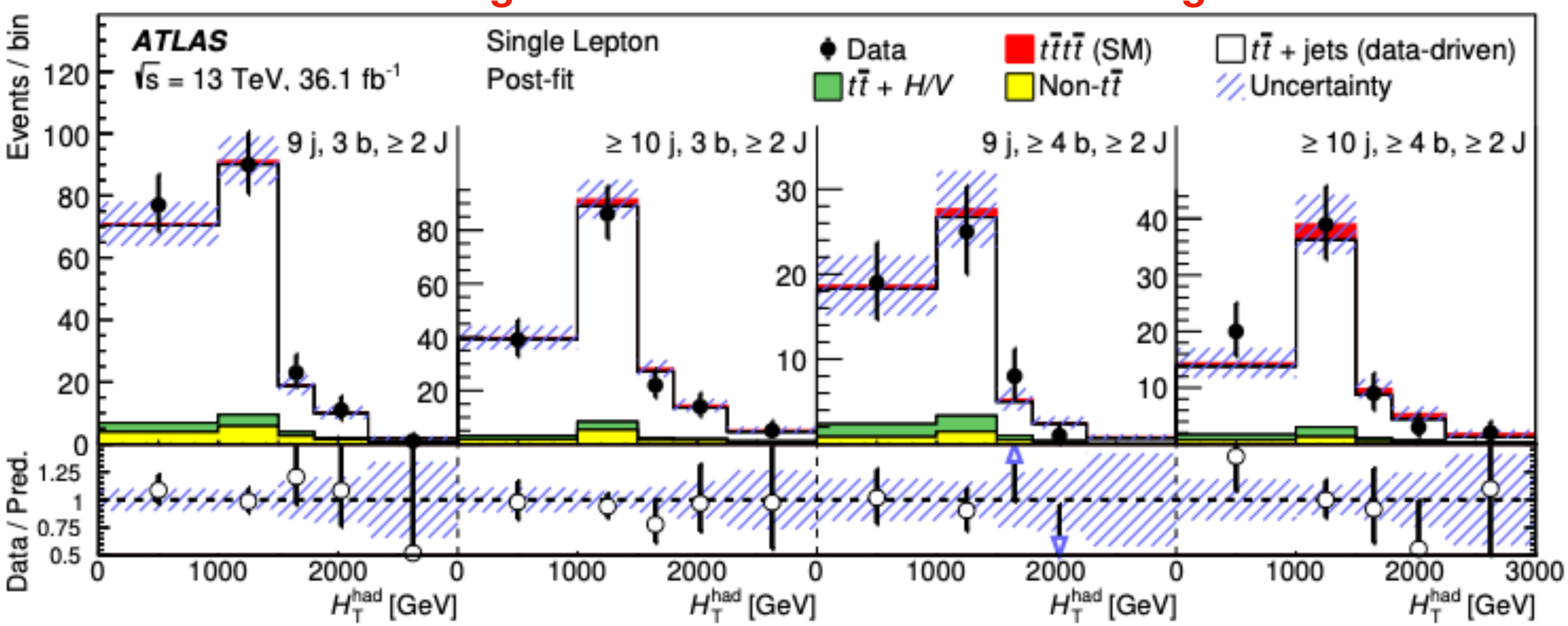
- Simultaneous fit to the H_T distribution in multiple signal regions (total of 20 regions: 12 regions in the single-lepton channel and 8 regions in the dilepton channel)

$$H_T^{had} = \sum^{jets} P_T$$

- tt+jets (data-driven)
- tttt SM signal
- tt+H/V
- Non-tt

Example in the single lepton channel in 9 jets & ≥ 10 jets

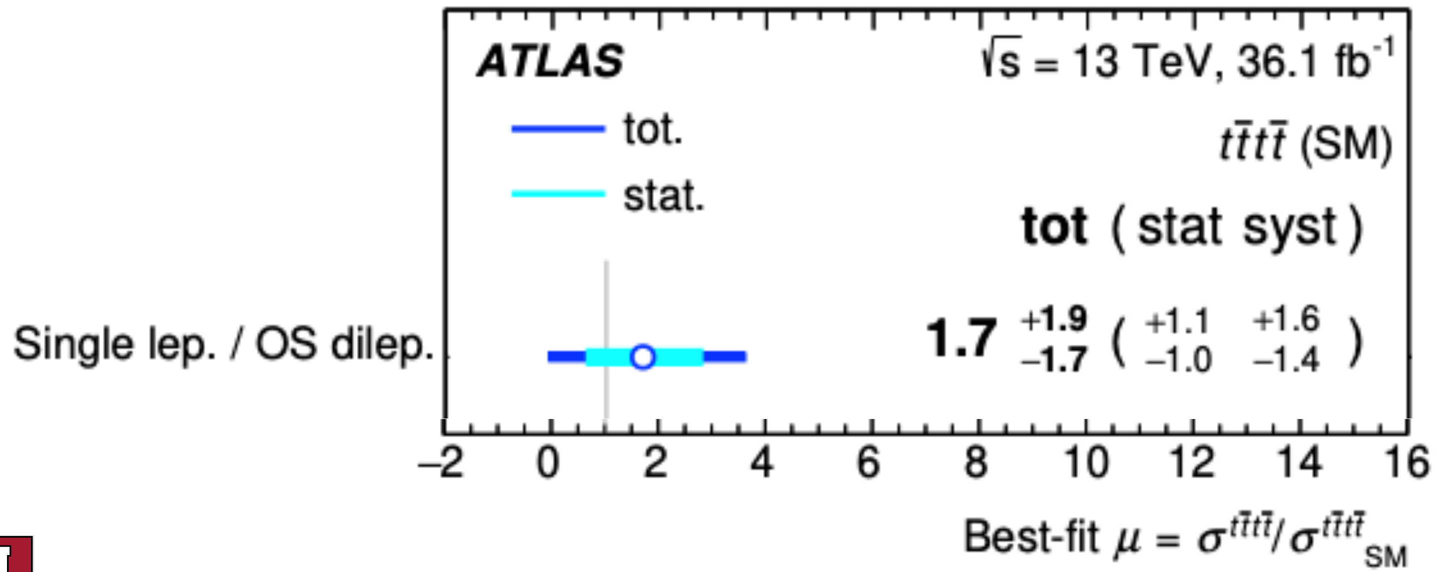
3b regions **4b regions**



Phys. Rev. D99 (2019) 052009

1ℓ/2ℓOS Channel: Results

- No significant excess of events above the SM background prediction, excluding the SM tttt production is found
- In the case of tttt production with SM kinematics, an observed (expected) 95% C.L. upper limit on the production cross section of 47 fb (33 fb) is obtained, corresponding to an upper limit on σ(tttt) relative to the SM prediction of 5.1 (3.6).
- The SM fitted signal strength μ, after combination of the single-lepton and dilepton channels, is measured to be $1.7^{+1.9}_{-1.7}$
- The systematic uncertainties related to the ttbar model are the dominant ones
- Stay tuned for the updated results using the full run 2 dataset



Phys. Rev. D99 (2019) 052009

2ℓSS/3ℓ Channel: Analysis Strategy

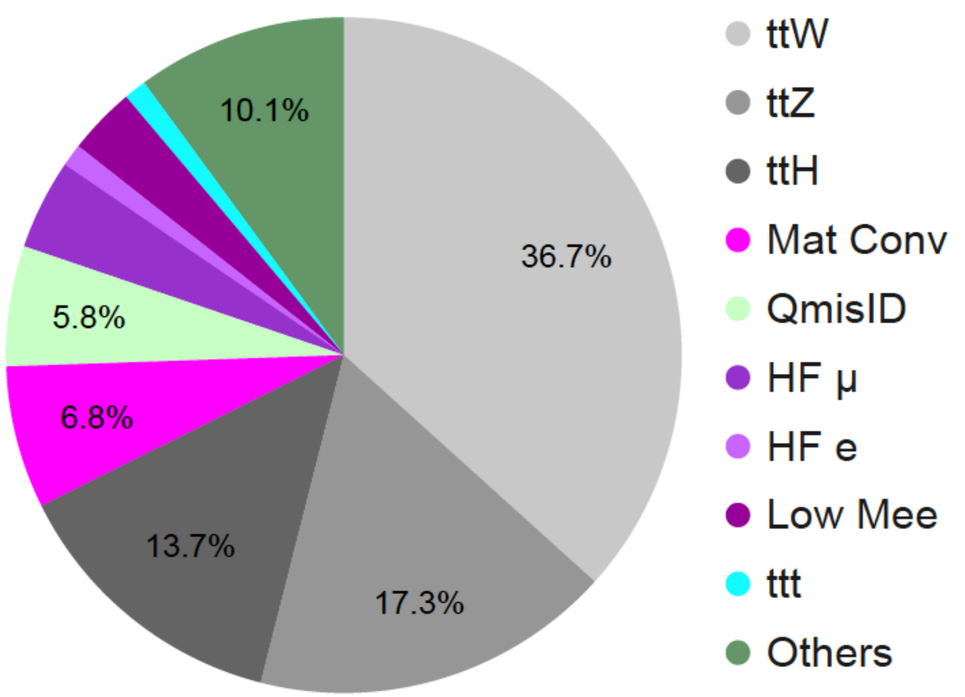
NEW!

- **New ATLAS result:** ATLAS-CONF-2020-013
- Uses full Run 2 dataset: **139 fb^{-1}**
- Targets clean leptonic signatures where at least two of the W bosons decay leptonically

- Selection requirements:
  - 2 same-sign leptons *or* 3 leptons (ℓ=e,μ)
  - **≥ 6 jets** (p_T > 25 GeV)
  - **≥ 2 b-tagged jets** (77% efficiency working point)
  - H_T > 500 GeV ;

$$H_T = \sum^{leptons} P_T + \sum^{jets} P_T$$

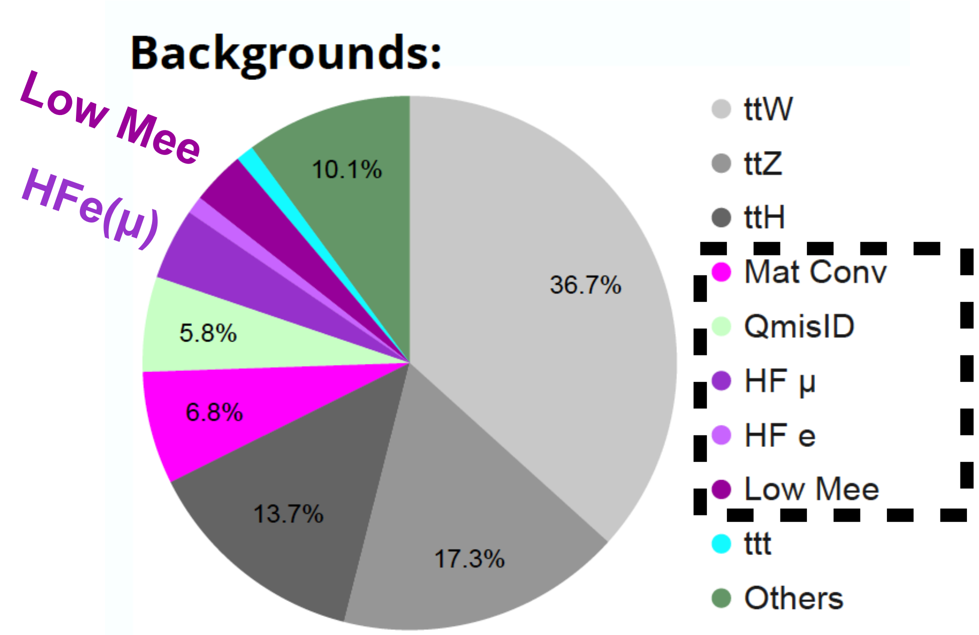
Backgrounds:



2ℓSS/3ℓ Channel: Backgrounds

- **Reducible backgrounds**:

  Fake/non-prompt leptons & charge misidentified leptons

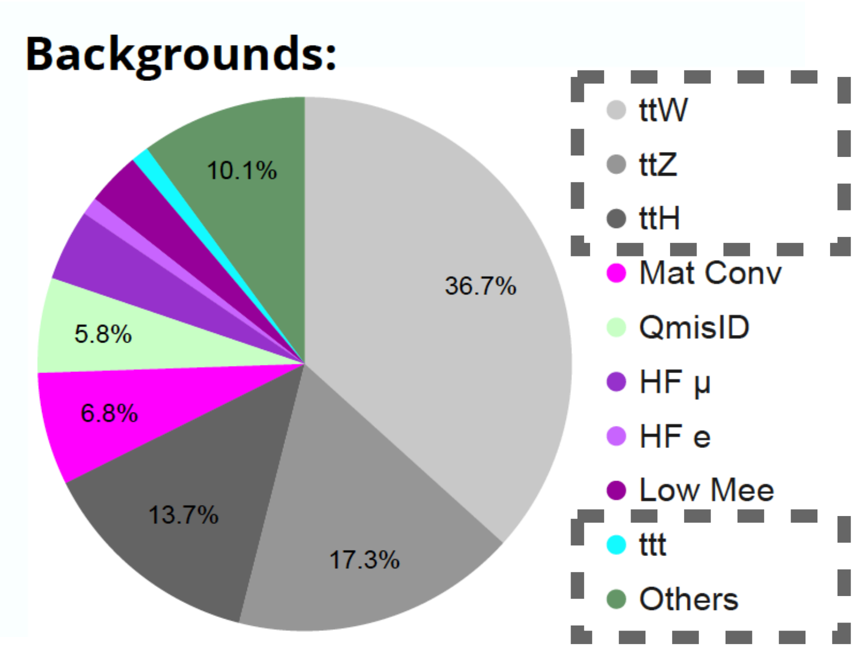


- Main fake/non-prompt backgrounds are:
  - electrons (muons) from heavy-flavour decay, **HFe(μ)**
  - electrons from ɣ conversion in detector, **Mat. Conv. (6.8%)**
  - a virtual photon leading to an e+e− pair, **Low Mee**
- Charge mis-assignment, **Q mis-ID (5.8%)**:
  - Relevant for the 2ℓSS channel
  - Charge of electron is mis-measured due to:
    - Bremsstrahlung photon emission followed by its conversion
    - Mis-measured track curvature

2ℓSS/3ℓ Channel: Backgrounds

- **Irreducible backgrounds**: Leptons from W, Z or leptonic τ decays
  - **ttW (36.7%)**, **ttZ (17.3%)**, and **ttH (13.7%)**
    - Processes with SS and multi-lepton+jets signatures (with additional light and b-tagged jets)
  - **Smaller backgrounds: (10% Others) + ttt**

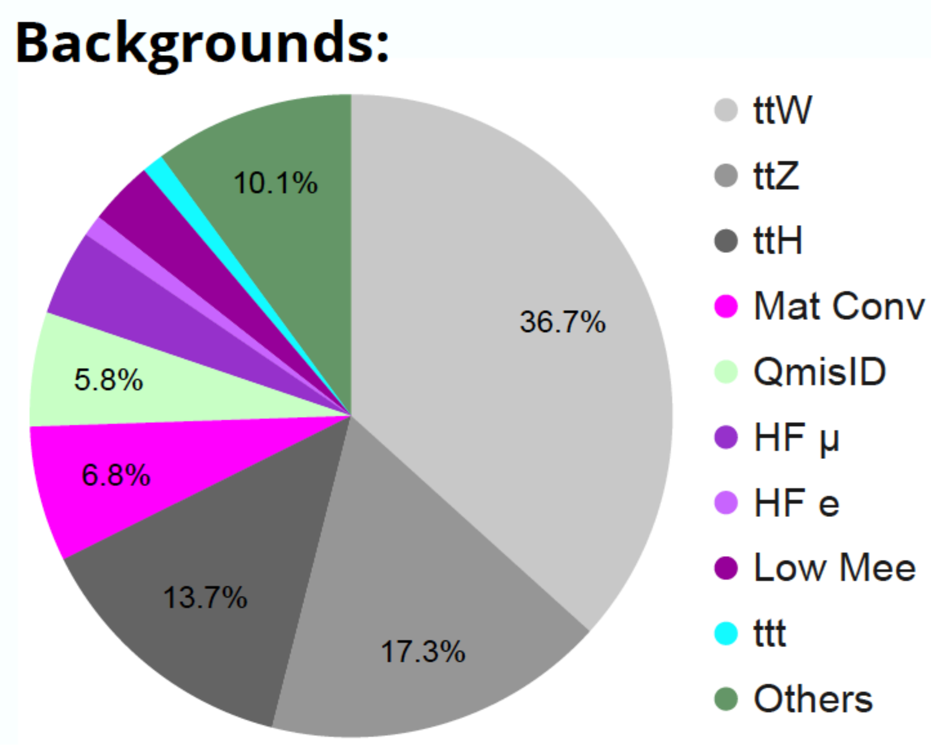
  Diboson, triboson, VH+jets, ttWW, tWZ, tZq



- Evaluated using MC normalised to SM cross sections, except ttW which is floating in the fit

2ℓSS/3ℓ Channel: Template fit

- **Template Method** is used to determine the major backgrounds
  - Background shapes are estimated from MC
  - Normalisation is obtained from the fit
  - Dedicated control regions are defined to constrain normalisation factors and the modeling is validated in the validation regions



- Analysis Regions:
  - 1 Signal region
  - 4 Control regions
    - Each region has a dominating component or a variable with discriminating power between components (**ttW**, **HFe(μ)**, **Material Conversion** and **Low Mee**)

Region	Channel	N_j	N_b	Other requirements	Fitted variable
CRttbarCO2l	$e^{\pm}e^{\pm} \| \| e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$M_{ee}@CV \in [0, 0.1\ \text{GeV}]$ $200 < H_{\text{T}} < 500$ GeV	M_{ee}@PV
CR1b3Le	$eee \| \| ee\mu$	-	$= 1$	$100 < H_{\text{T}} < 250$ GeV	counting
CR1b3Lm	$e\mu\mu \| \| \mu\mu\mu$	-	$= 1$	$100 < H_{\text{T}} < 250$ GeV	counting
CRttW2l	$e^{\pm}\mu^{\pm} \| \| \mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$M_{ee}@CV \notin [0, 0.1\ \text{GeV}]$, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_{\text{T}} < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_{\text{T}} < 500$ GeV	$\Sigma p_{\text{T}}^{\ell}$

2ℓSS/3ℓ Channel: Template fit

- **Results of the Template Fit**
  - Normalization factors obtained from the fit:

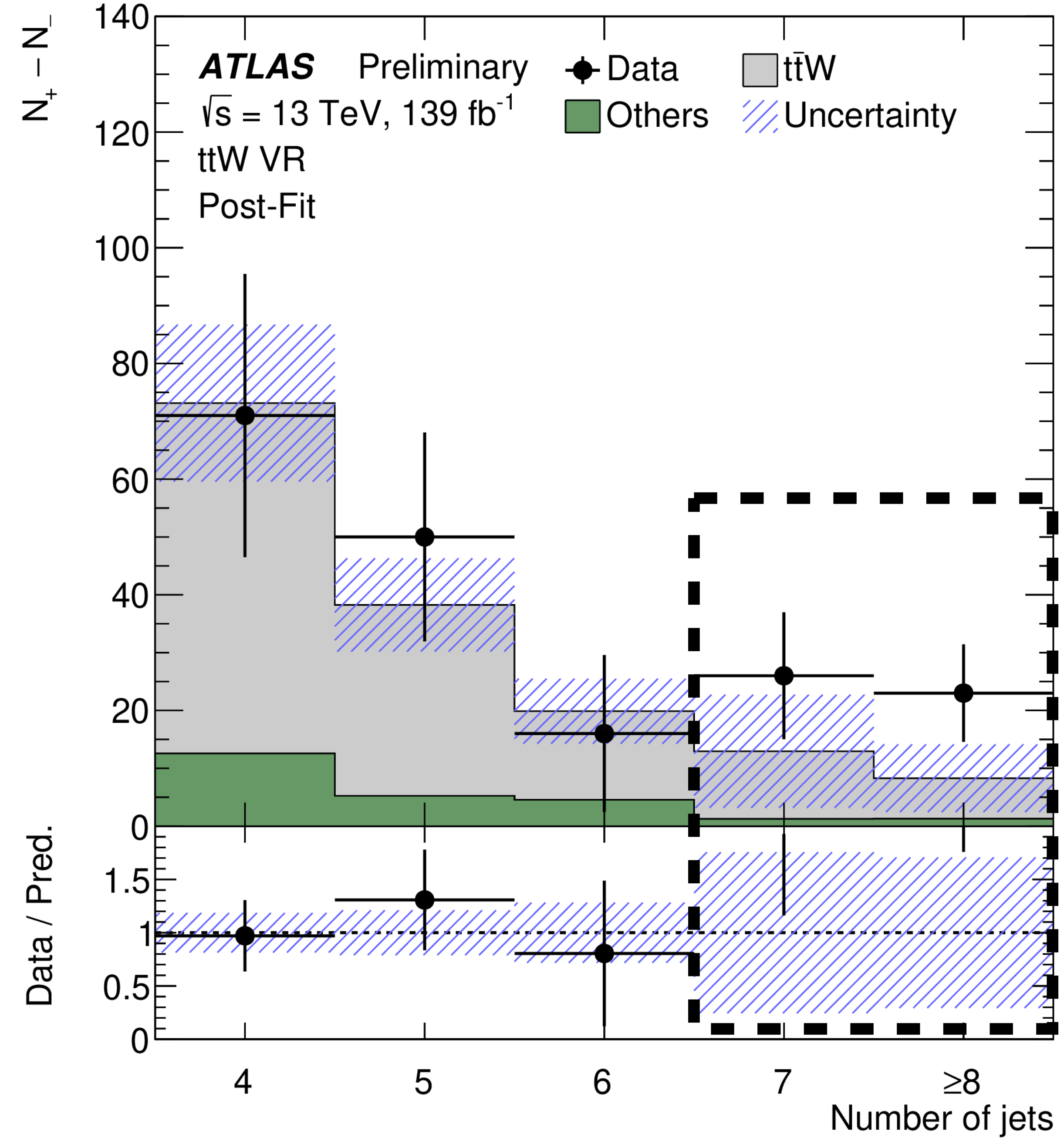
Parameter	$NF_{t\bar{t}W}$	$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } M_{ee}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

  - The factors are compatible with unity except for NF_{ttW} and $NF_{\text{Mat. Conv.}}$
  - The high NF_{ttW} is compatible with previous ATLAS ttH(H→multi-leptons) result [ATLAS-CONF-2019-045]
  - More details in the next slides

2ℓSS/3ℓ Channel: Template fit

- **ttW Validation Regions**
  - Use validation region to check ttW+jets normalisation and modeling
  - Uncertainties:
    - **Additional jets**: Uncertainty of 125% (300%) is assigned to events with =7 (≥8) jets
      - Based on VR mismodeling
    - **Additional b-jets**: Uncertainty of 50% each is assigned to events with 3 or ≥4 truth b-jets
      - Based on tt+HF measurement and data/MC agreement in ttɣ

ttW Validation Region: ≥4jets ≥2b-tagged

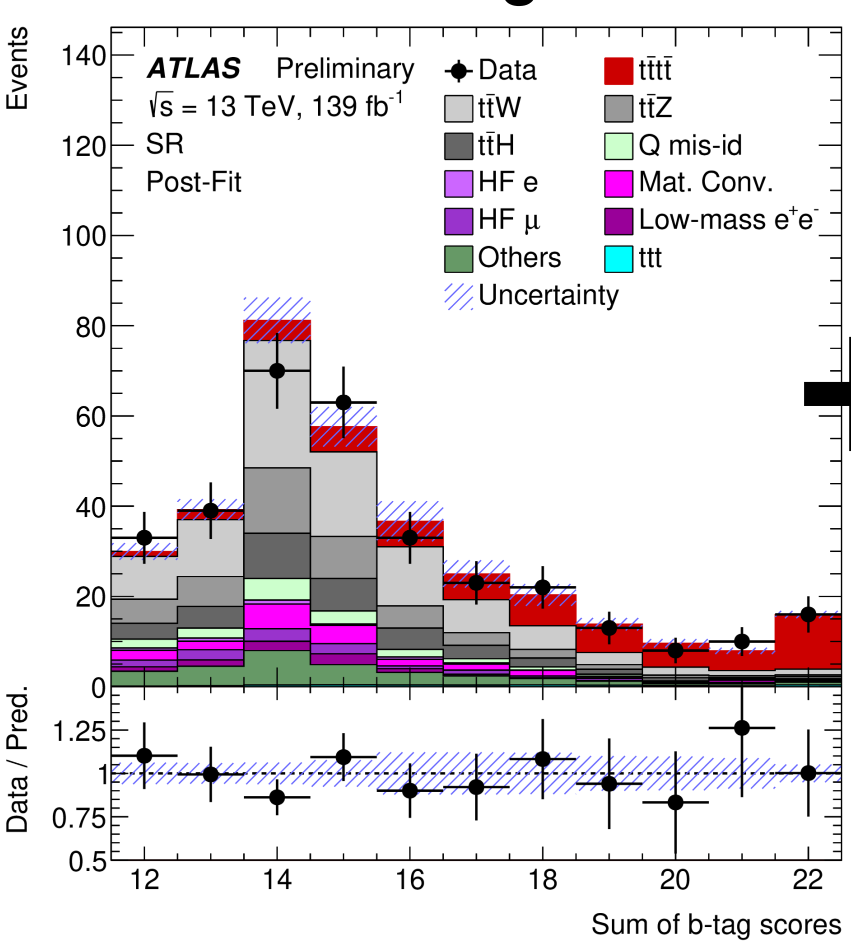


ATLAS-CONF-2020-013

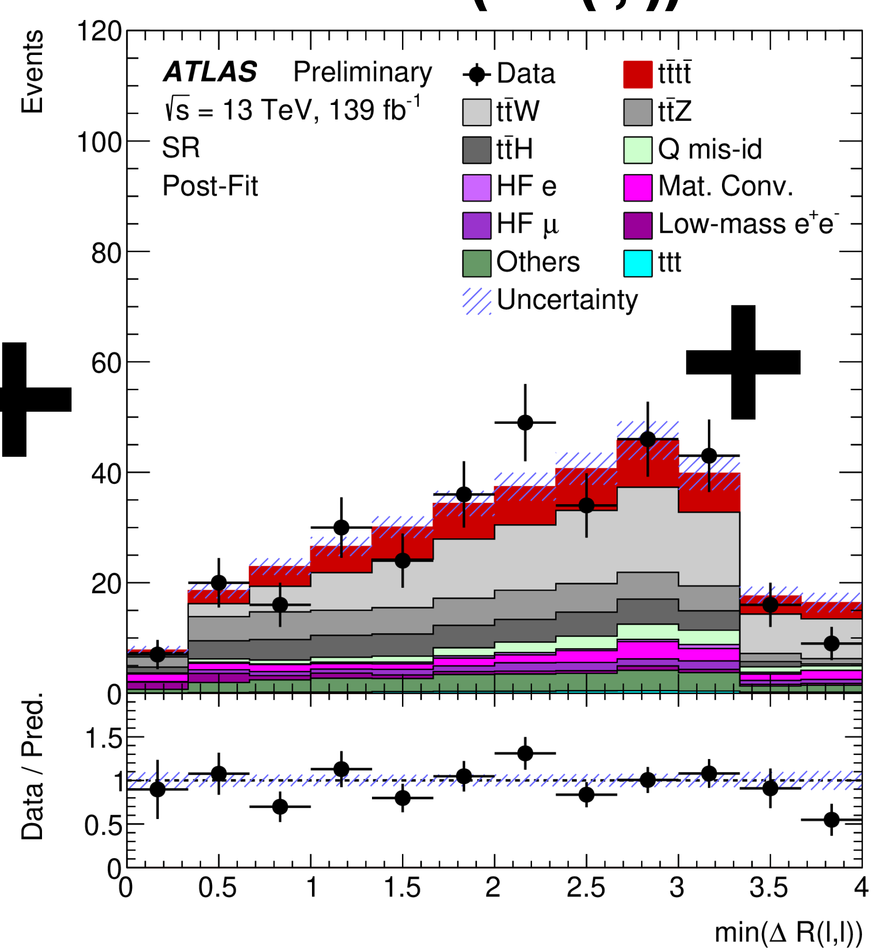
2ℓSS/3ℓ Channel: Signal Optimization

- Signal is separated from background based on a multivariate discriminant built in the signal region by combining input observables into a BDT:
- 12 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
  - BDT training is performed inclusively in **lepton flavour and multiplicity** for events in the SR

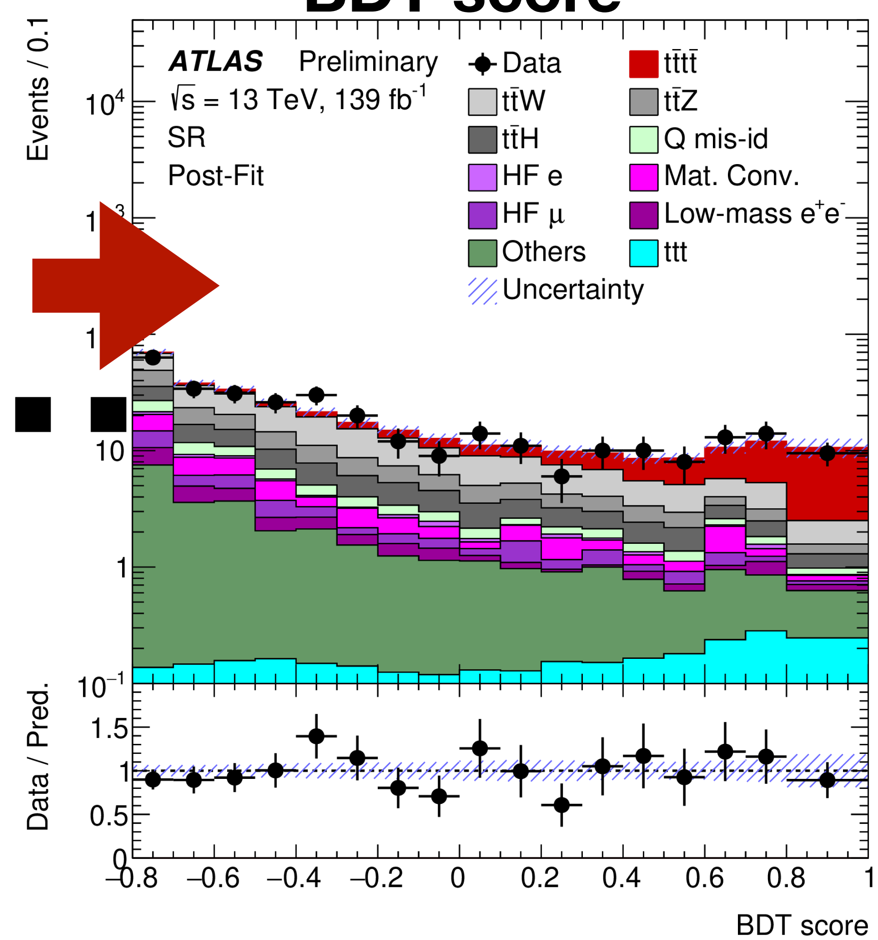
Sum of b-tag scores



min (ΔR(l,l))



BDT score



ATLAS-CONF-2020-013

2ℓSS/3ℓ Channel: Systematics

- The dominant systematics uncertainties on the signal strength are:
  - **The theoretical uncertainty on signal**
  - **Data statistics**
  - **Modelling of ttW+jets**
  - **Uncertainty on ttt production**
    - 10% of tttt cross sections and estimated from MC, but similar BDT shape
  - **Instrumental**
    - B-tagging: Uncertainties on the b-tagging efficiencies, mainly the light mis-tagging rate
    - Jet Energy Scale: Uncertainties related to pile-up subtraction and the modelling of additional jets in the di-jet balance analysis
  - **Non-prompt lepton normalisation and modelling**
    - Shape uncertainty derived from data/MC (dis)agreement in a fake-enriched region

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

ATLAS-CONF-2020-013

2ℓSS/3ℓ Channel: Results

- The tttt production cross section is measured via a binned likelihood fit of the BDT score distribution in the signal region and of the discriminating variables in the four control regions
- The measured tttt signal strength is found to be:

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

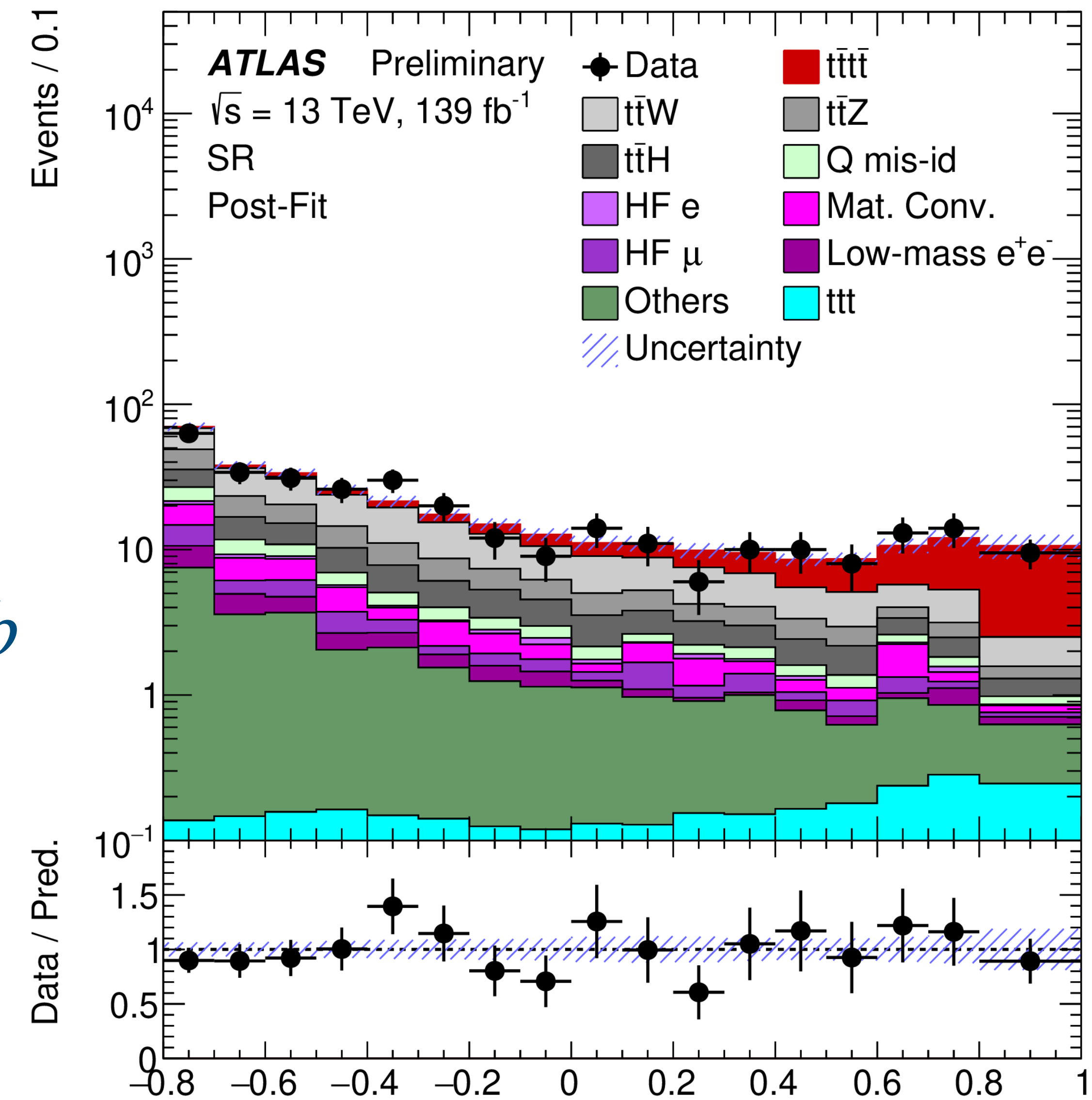
- Cross section:

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

- 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



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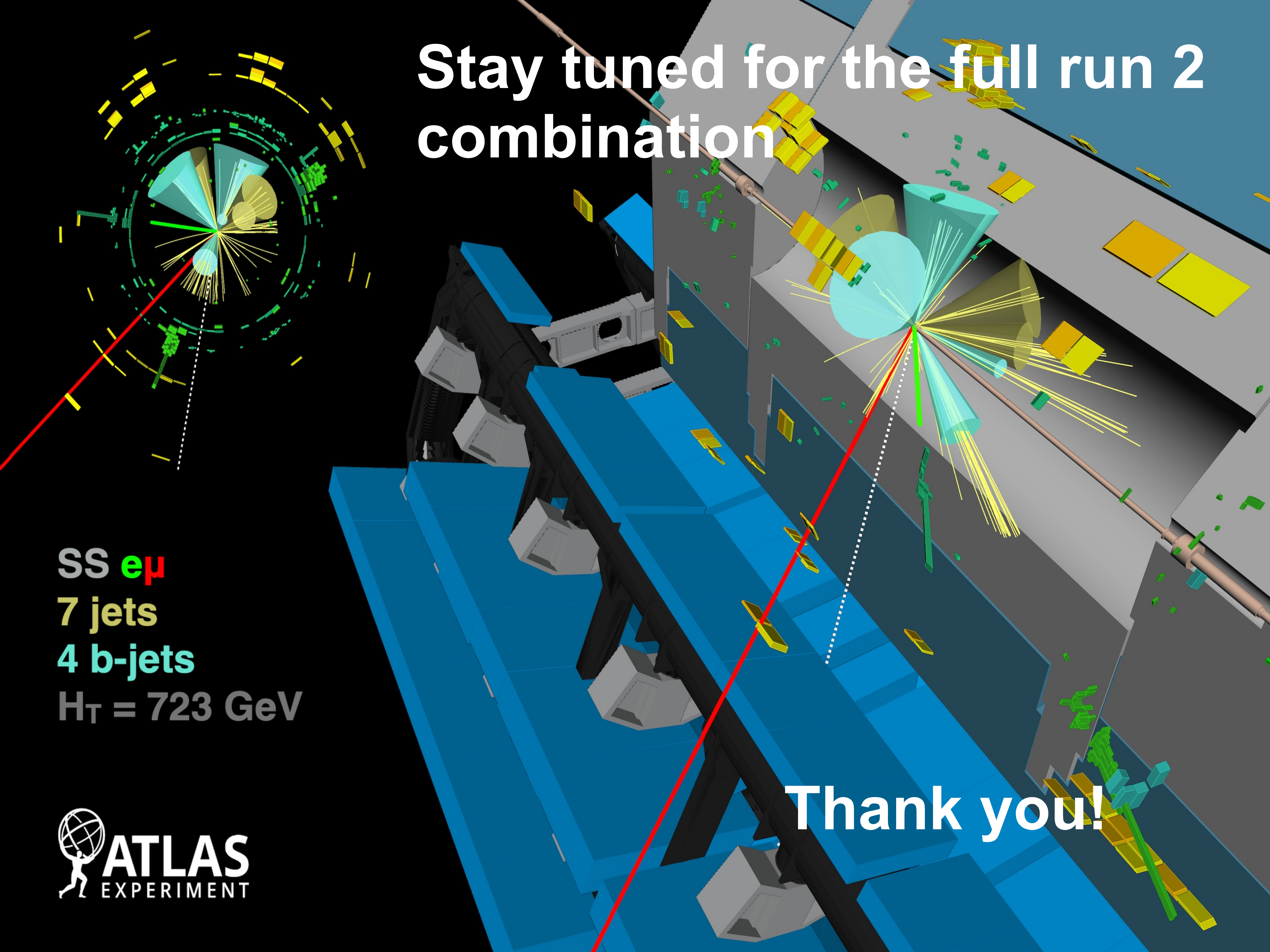
- Several tests were done to check the stability & consistency of the result

Stay tuned for the full run 2 combination



Thank you!

BACKUP SLIDES

1ℓ/2ℓOS Channel: Systematic Uncertainties

- The post-fit impact of the largest sources of systematic uncertainty on the signal strength μ is shown
- The systematic uncertainties are the dominant ones:
  - The largest contributions are due to the uncertainty associated with the choice of tt+jets parton shower and hadronization model and the NLO generators (tt+jets modeling)
  - The second largest contribution is due to the large statistical uncertainties associated with the background prediction

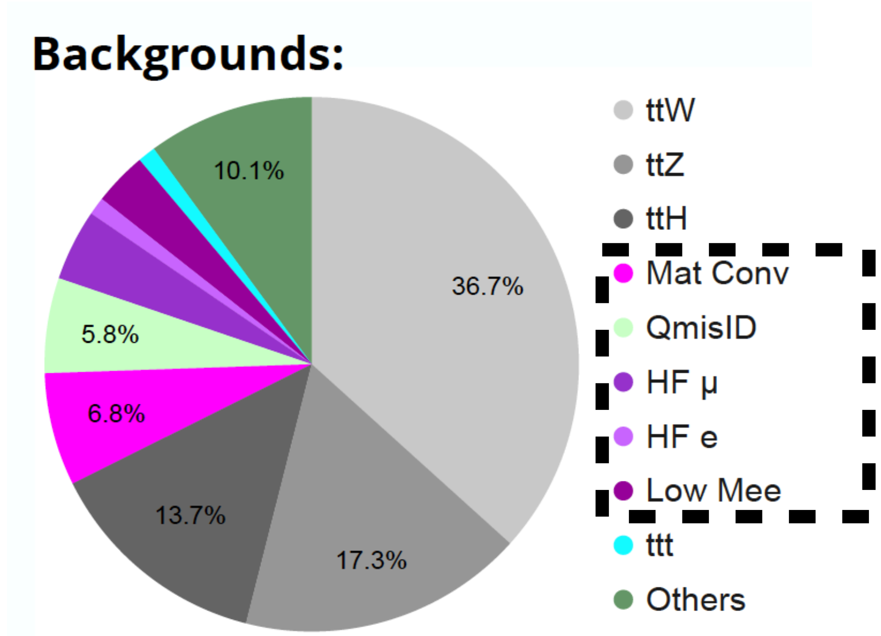
Breakdown of the contributions to the uncertainties on μ

Uncertainty source	$\pm\Delta\mu$	
$t\bar{t}$+jets modeling	+1.2	–0.96
Background-model statistical uncertainty	+0.91	–0.85
Jet energy scale and resolution, jet mass	+0.38	–0.16
Other background modeling	+0.26	–0.20
b-tagging efficiency and mis-tag rates	+0.33	–0.10
JVT, pileup modeling	+0.18	–0.073
$t\bar{t} + H/V$ modeling	+0.053	–0.055
Luminosity	+0.050	–0.026
Total systematic uncertainty	+1.6	–1.4
Total statistical uncertainty	+1.1	–1.0
Total uncertainty	+1.9	–1.7

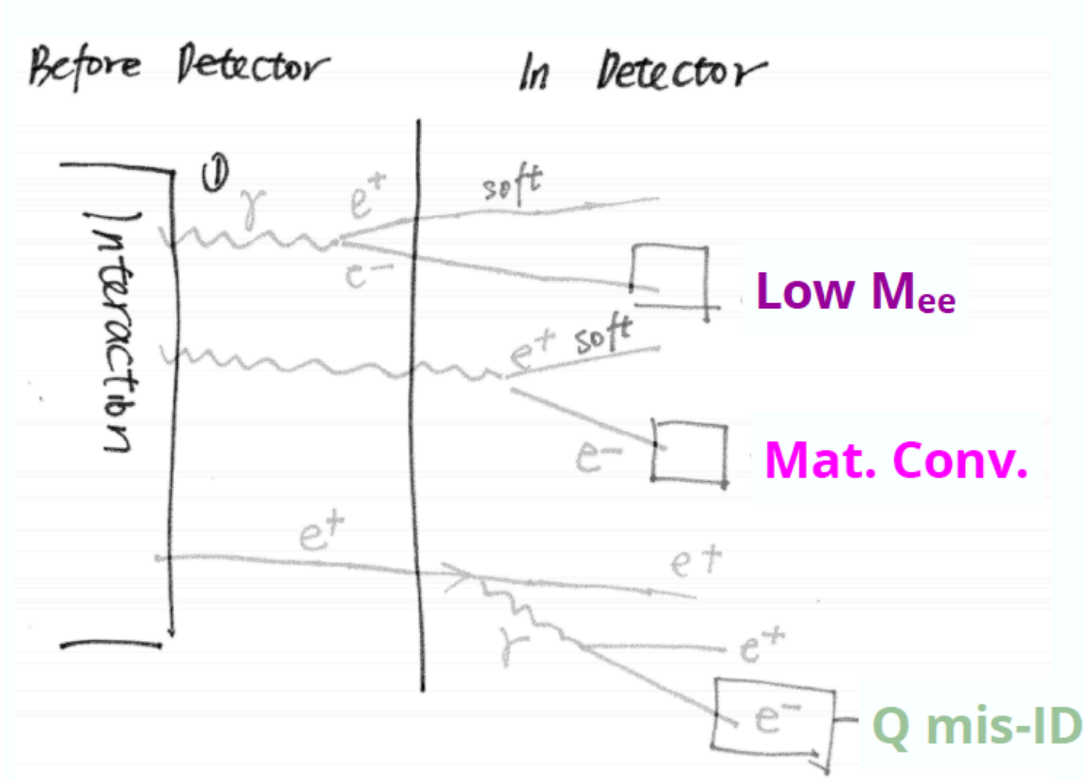
Phys. Rev. D99 (2019) 052009

2ℓSS/3ℓ Channel: Backgrounds

- **Reducible backgrounds**: Fake/non-prompt leptons & charge misidentified leptons



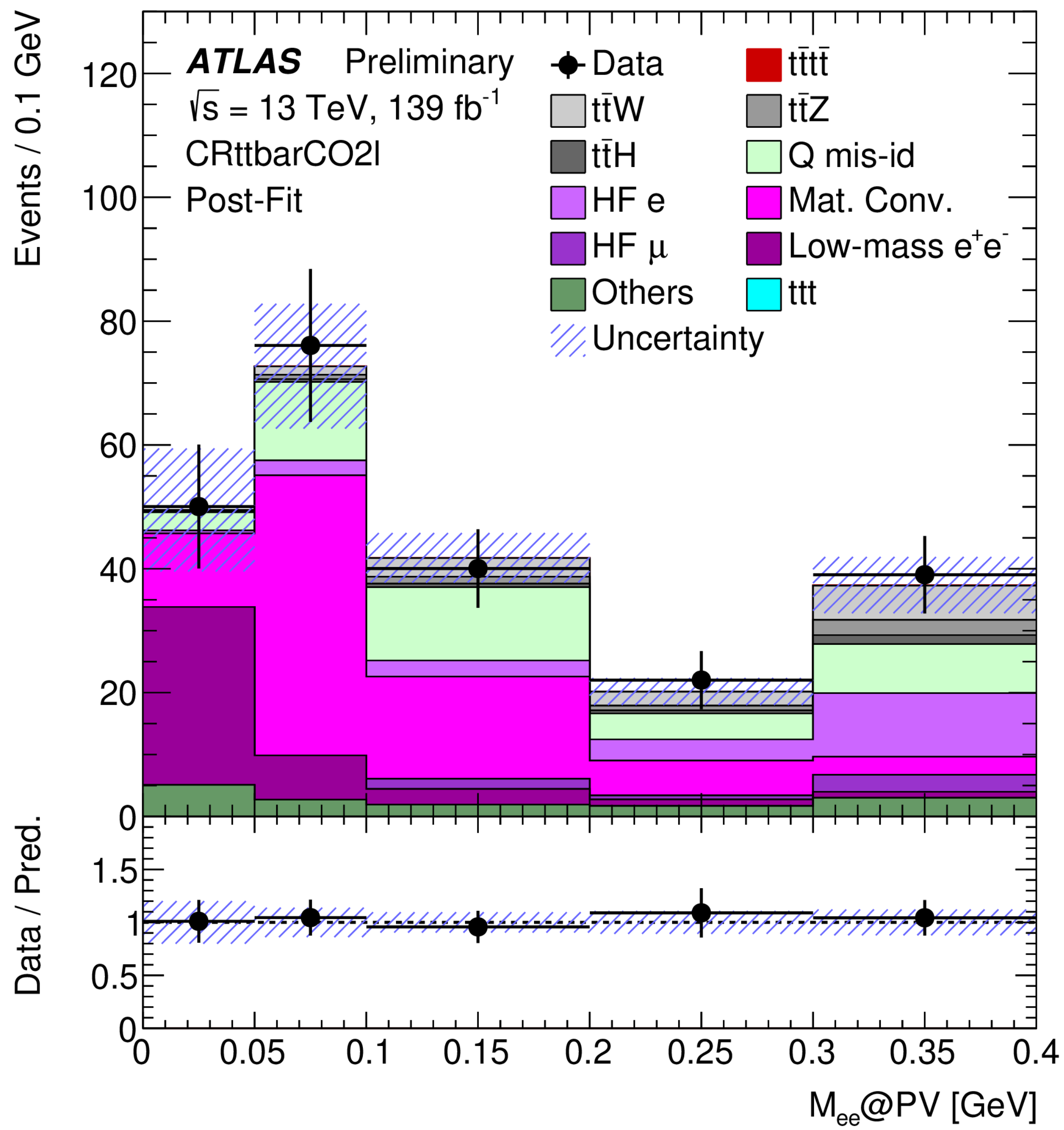
- Main fake/non-prompt backgrounds are:
  - electrons (muons) from heavy-flavour decay, **HFe(μ)**
  - electrons from ɣ conversion in detector, **Mat. Conv.**
  - a virtual photon leading to an e+e− pair, **Low Mee**
- Charge mis-assignment, **Q mis-ID**:
  - Relevant for the 2ℓSS channel
  - Charge of electron is mis-measured due to:
    - Bremsstrahlung photon emission followed by its conversion
    - Mis-measured track curvature

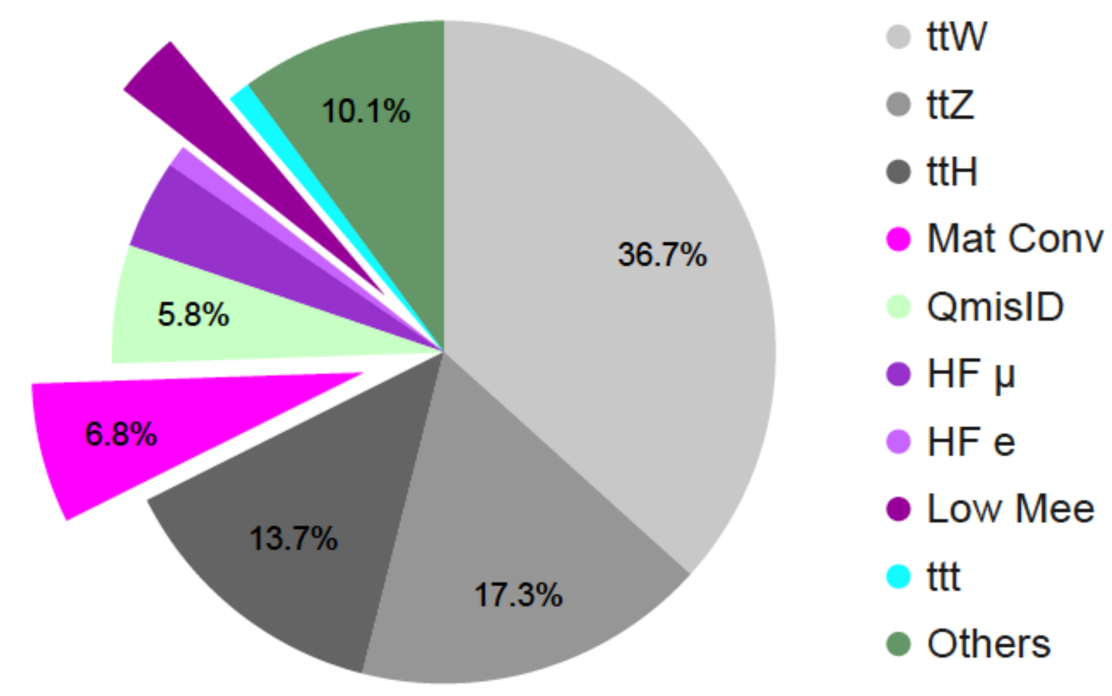


Sketch from Josh McFayden

2ℓSS/3ℓ Channel: Background

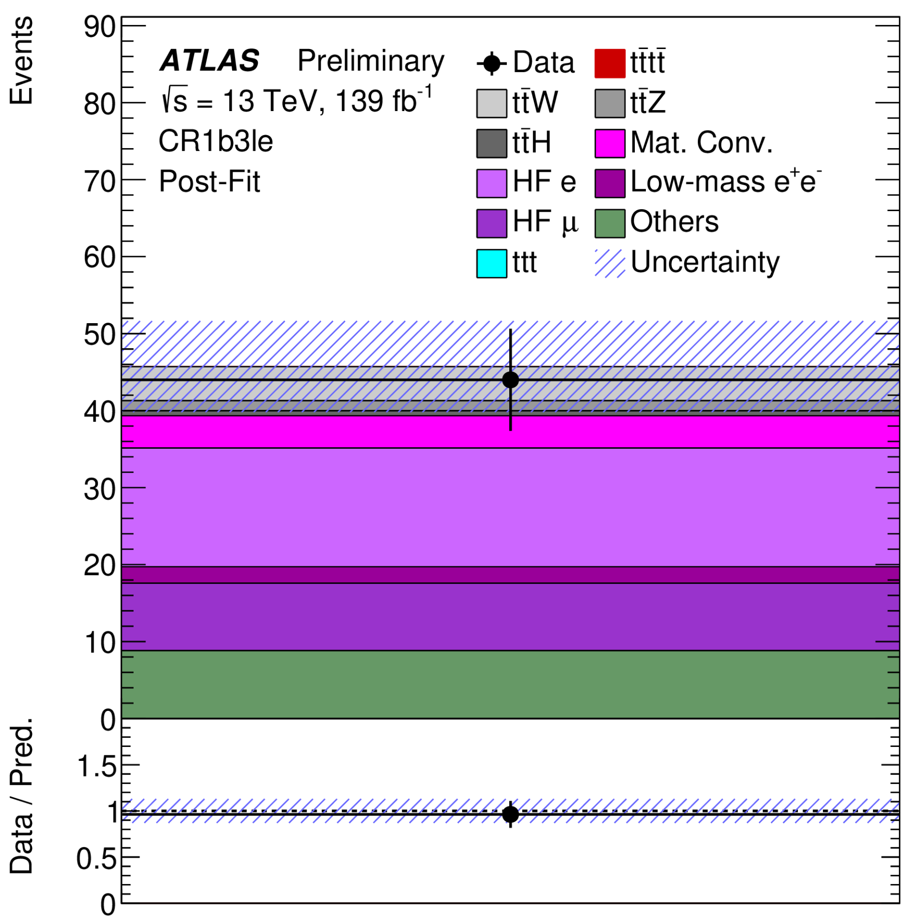
- **Control Regions: CRttbarCO2l**
  - Enriched in **Mat. Conv.** and **Low M_{ee}** events.
  - Look at the invariant mass between the electron track and its closest track

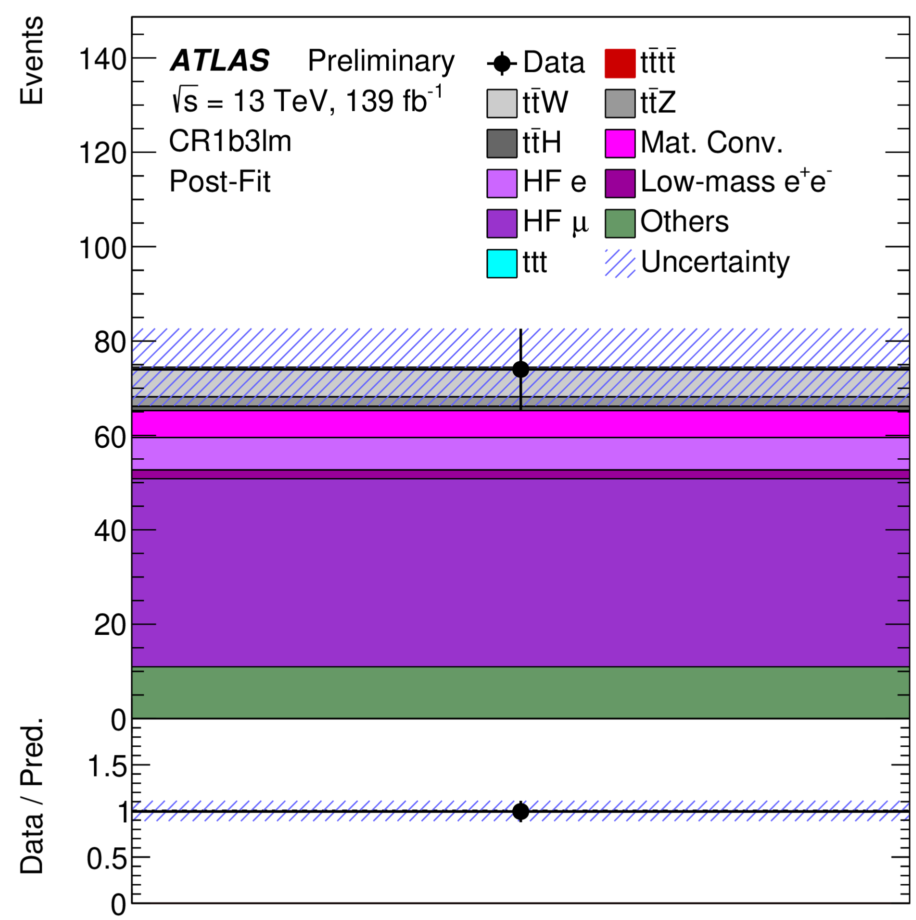


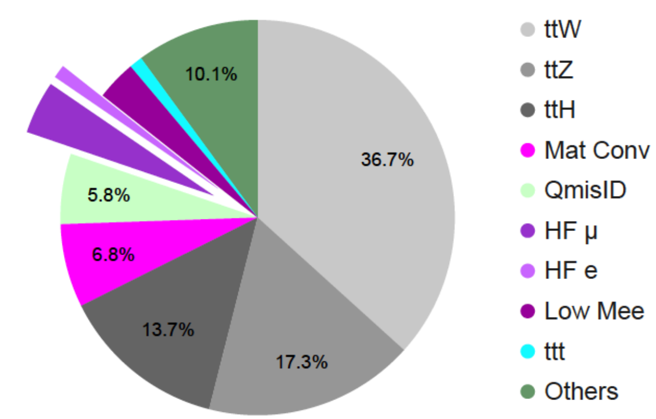


2ℓSS/3ℓ Channel: Background

- **Control Regions: CR1b3le & CR1b3lm**
  - Enriched in background events with **leptons from heavy-flavour**
  - Requiring 3 leptons: eee and eeμ (μμμ and μμe) for CR1b3le (CR1b3lm),
  - Exactly one b-tagged jet & $100 < H_T < 250$ GeV

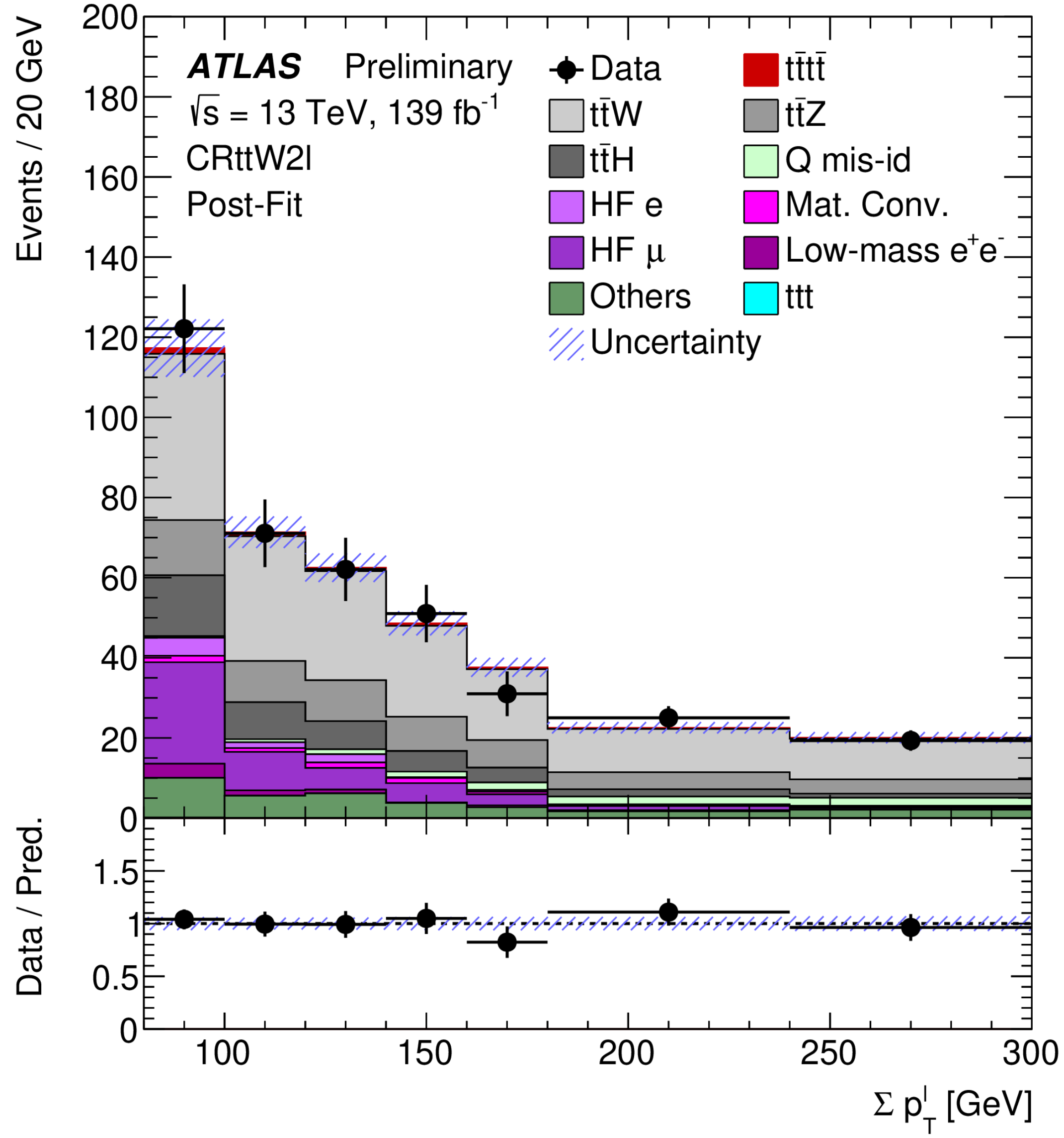


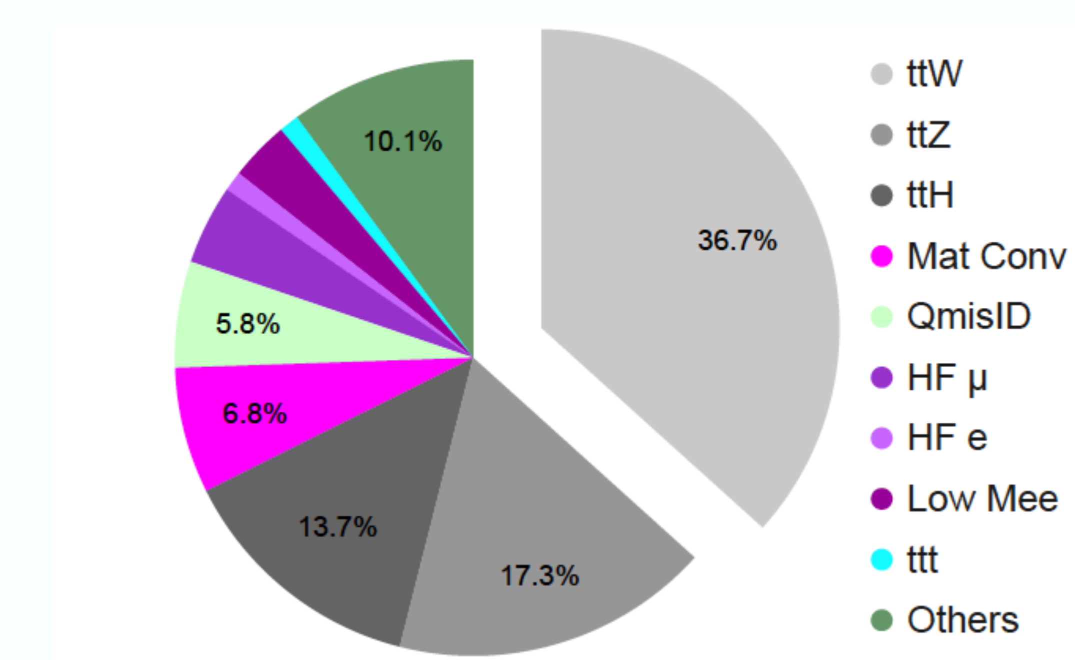




2ℓSS/3ℓ Channel: Background

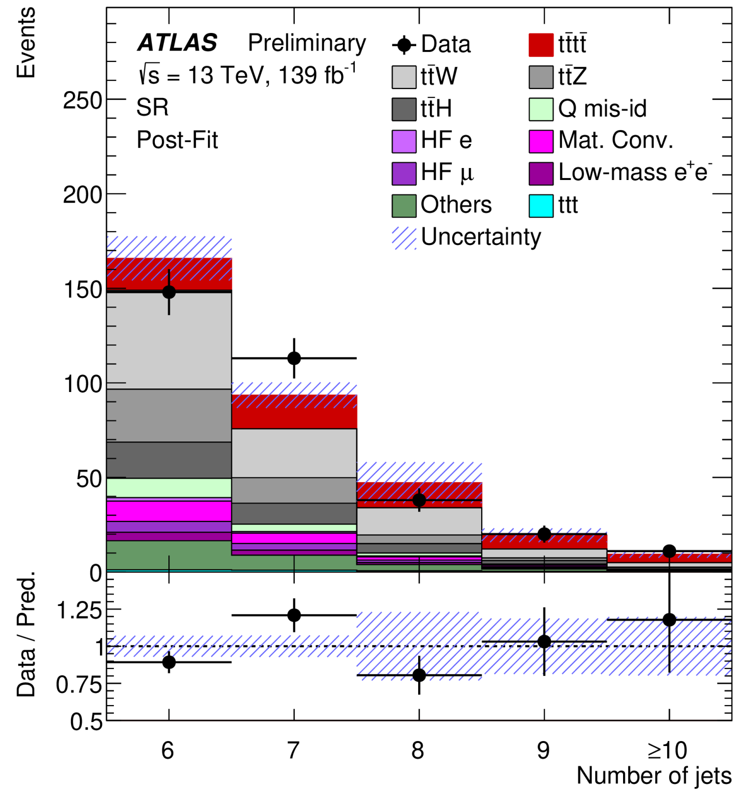
- **Control Regions: CRttW2l**
  - Enriched in **ttW+jets** events
  - Selecting eμ and μμ events with at least four jets and two b-jets which are neither in other CRs nor in the SR.
  - Looked at the sum of the lepton $p_T = \sum p_T^l$ which gives a good discrimination from the other backgrounds in the template fit

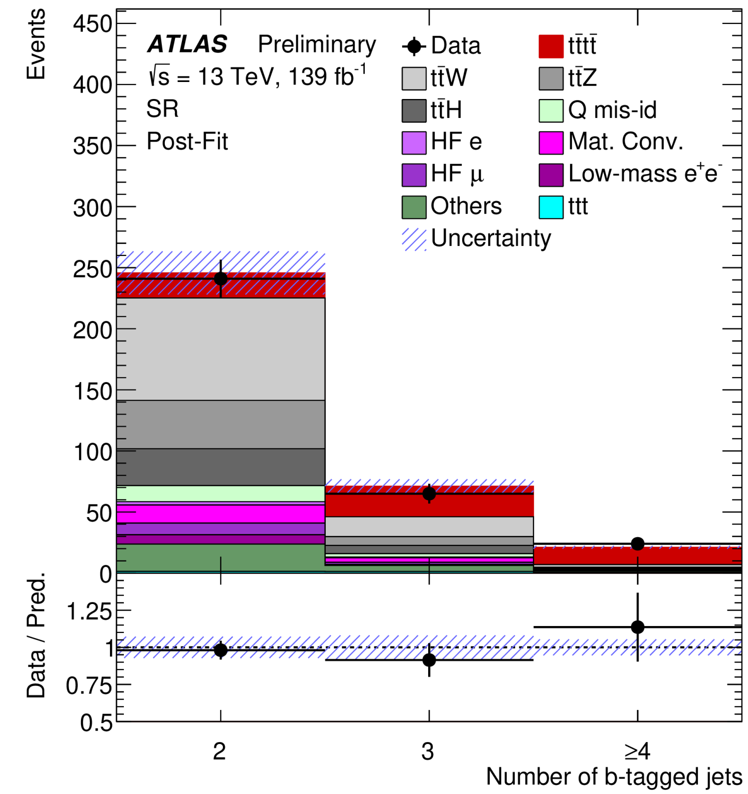


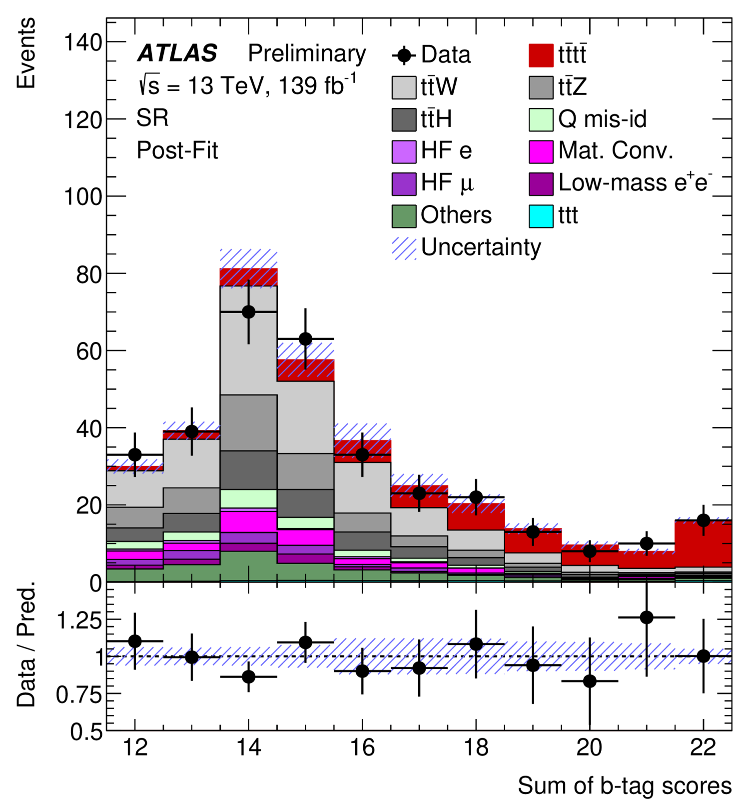


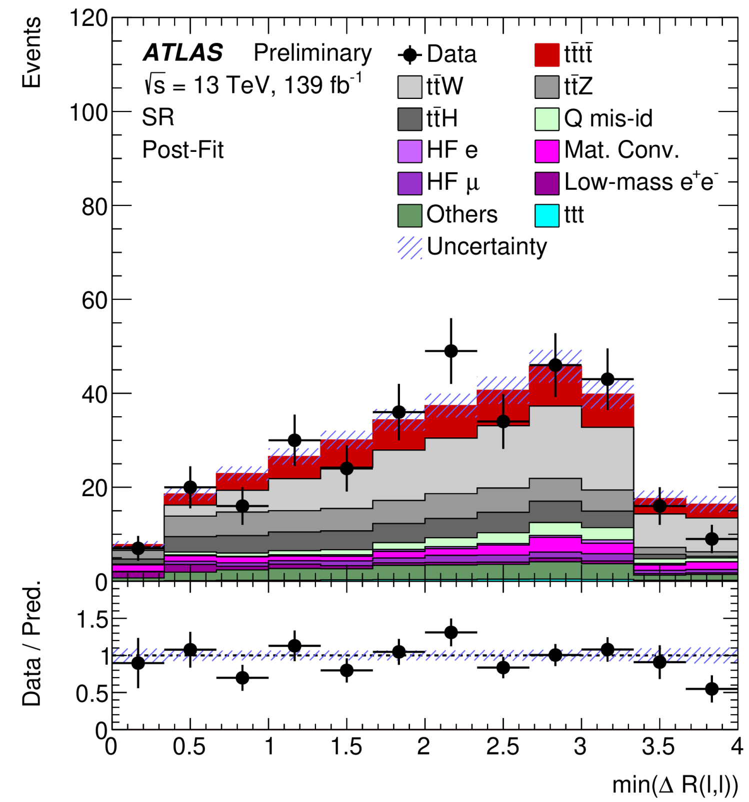
2ℓSS/3ℓ Channel: Results

Good Data/MC agreement seen in the input variables to the BDT



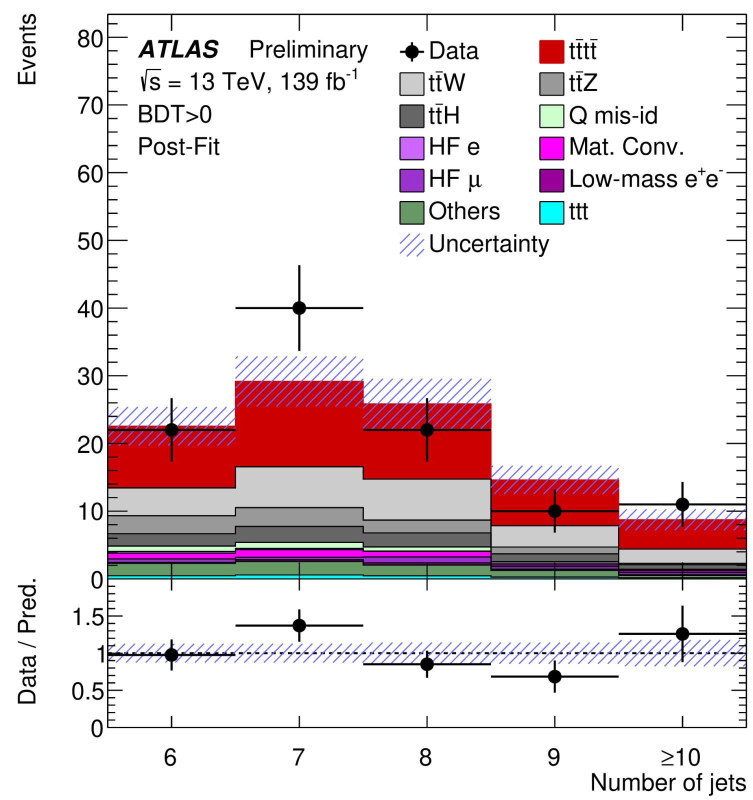


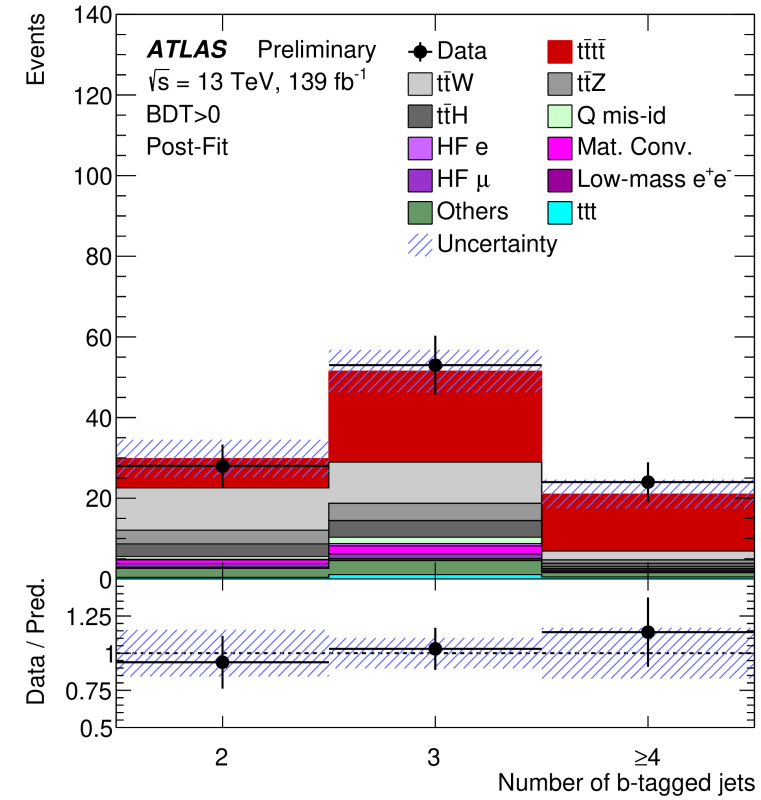


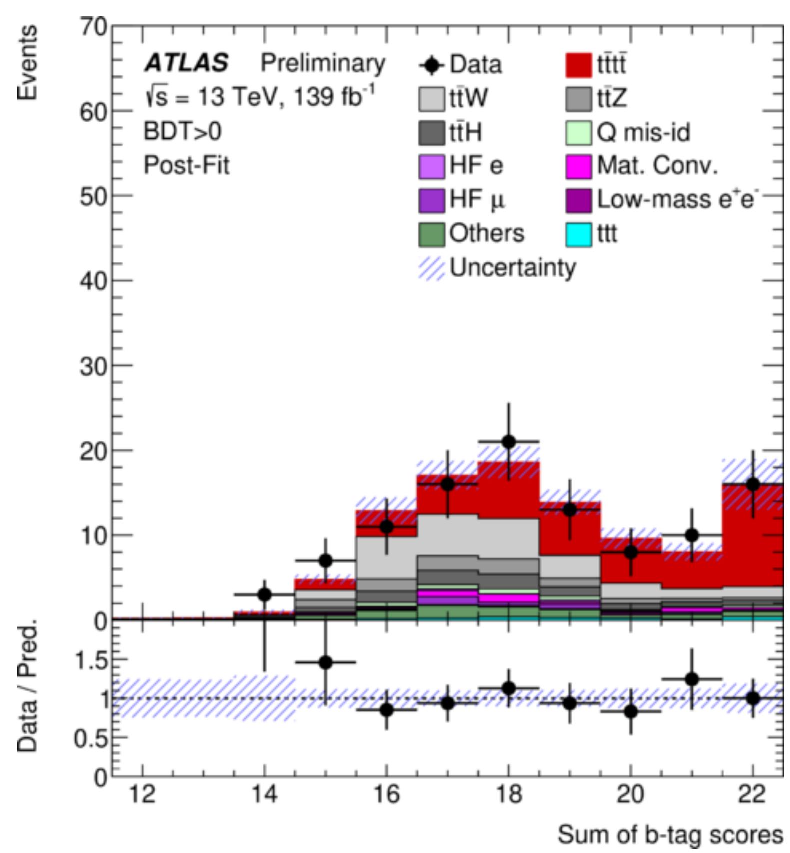


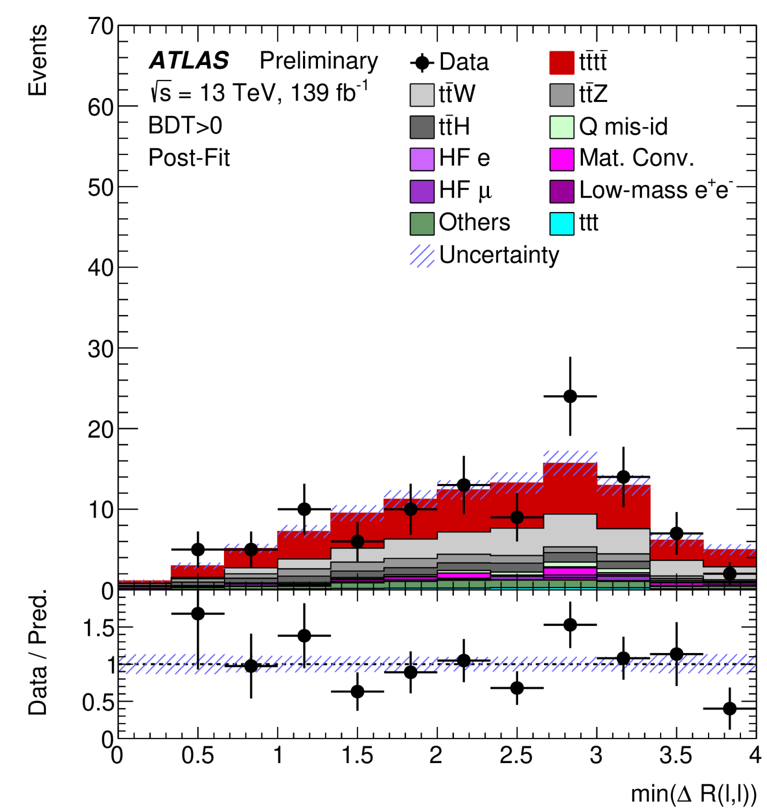
2ℓSS/3ℓ Channel: Results

Good Data/MC agreement is also seen in the input variables to the BDT when requiring BDT > 0





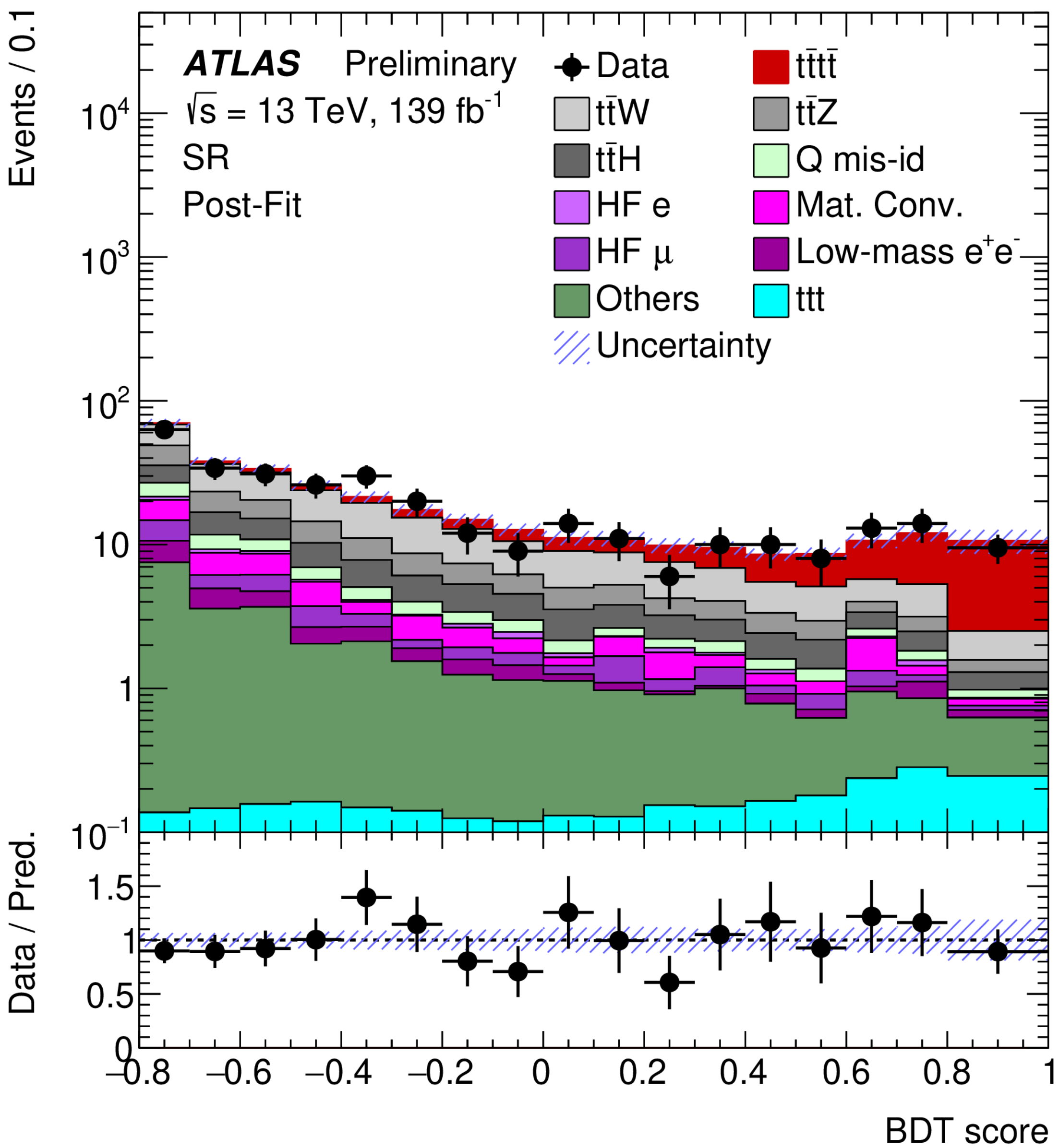




2ℓSS/3ℓ Channel: Results

- The stability of the result is checked in several ways
- Using a H_T-based fit instead of the BDT
- Splitting the signal region in to 2ℓSS and 3ℓ events
- Using only positively/negatively charged SS lepton pairs
- Fitting different data-taking years

- All the above tests showed compatible results



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