Extrapolation of ATLAS sensitivity to Standard Model four top quark cross section measurement at the HL-LHC

ATLAS EXPERIMENT

Top Working Group Plenary
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Nedaa-Alexandra Asbah
Harvard University

Frédéric Déliot
CEA-Saclay

Zhi Zheng
SLAC

HARVARD UNIVERSITY

cea DE LA RECHERCHE À L'INDUSTRIE

université PARIS-SACLAY

SLAC NATIONAL ACCELERATOR LABORATORY

Motivation

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- **Goal:**
  - Perform extrapolation studies for the measurement of the SM four-top-quark (tttt) production cross-section
    - based on the latest **SS/ML results** (139 /fb of Run 2 data-set)
    - in the context of the HL-LHC with 3000 /fb at 14 TeV
      - also showed results for 500/fb, 1000/fb and 2000/fb
  - Last PUB Note (2019 Yellow Report) was based on the extrapolation of the 36/fb result using smearing functions

- **Target:**
  - within the **Snowmass** efforts

Outline

- Summary of the 139 /fb analysis at 13 TeV
- Extrapolation Studies
  - Caveat: results won't be shown (not approved yet)
- Conclusions

Summary of the 139 /fb analysis at 13 TeV

Summary of the 139 /fb analysis at 13 TeV

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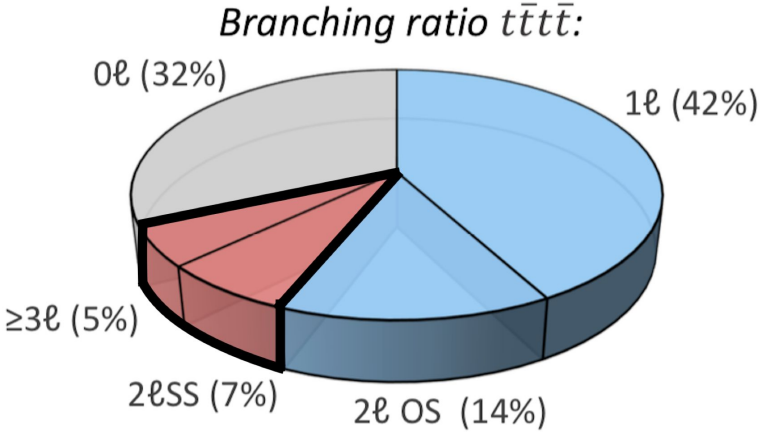
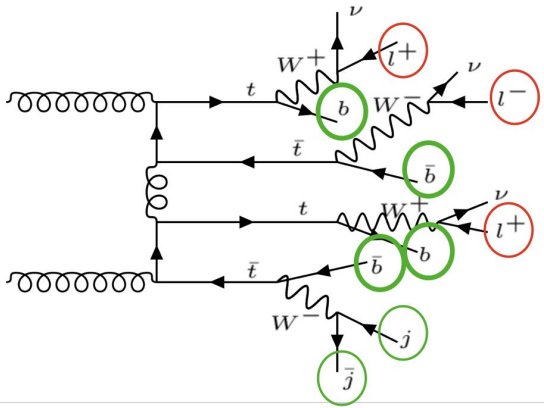
- Extrapolation studies based on the recent SS/ML results using the full Run 2 data-set [Eur. Phys. J. C (2020) 80:1085]

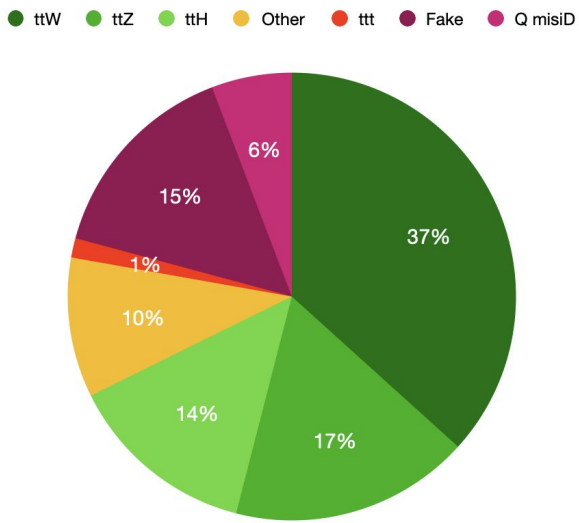
- Selection requirements in the **Signal Region**:
  - 2 same-sign leptons or 3 leptons (ℓ=e,μ)
  - ≥ 6 jets (pT > 25 GeV)
  - ≥ 2 b-tagged jets (efficiency of identifying b-jets is 77%)
  - HT > 500 GeV

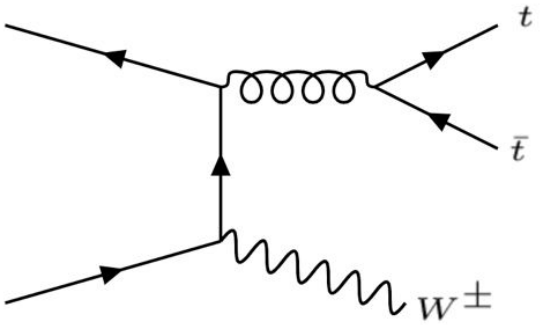


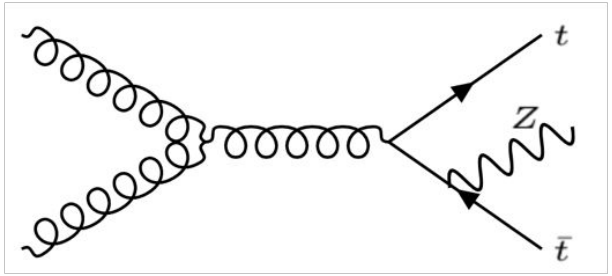


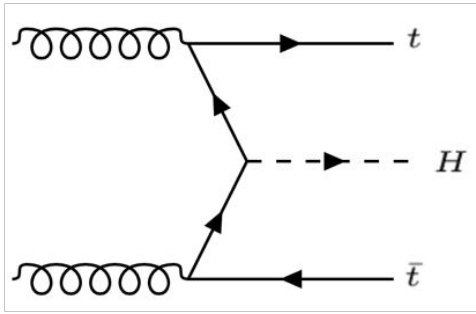
Main background processes

- Backgrounds:
  - Fake and non-prompt leptons (15%)
  - Charge mis-assignment (6%)
  - Leptons from W, Z or leptonic τ decays
    - **ttW (37%)**, ttZ(17%), and ttH (14%)
    - Others (10%): Diboson, triboson, VH+jets, ttWW, tWZ, tZq
    - ttt(1%)









Template Method

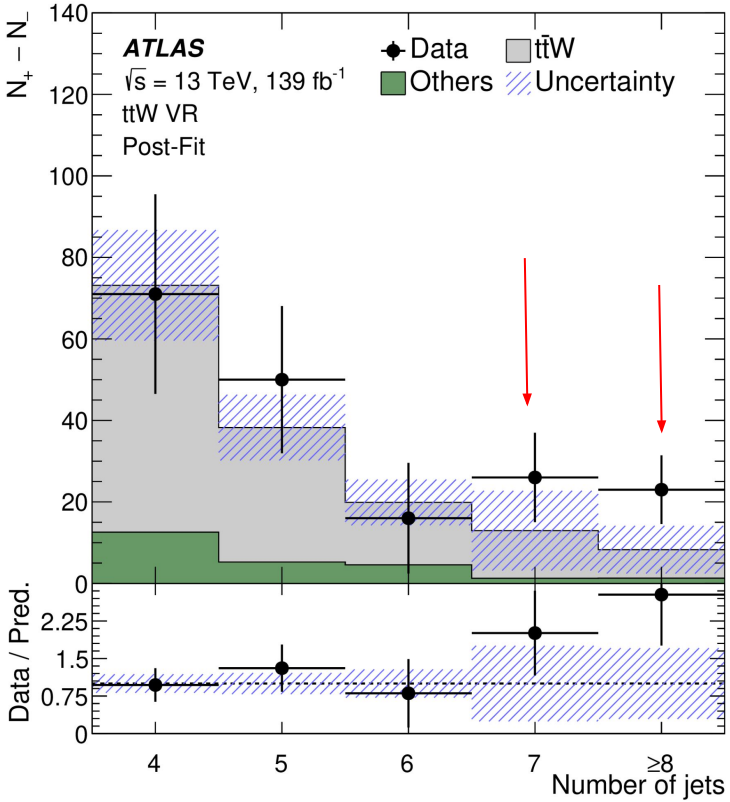
- **Five analysis regions**:
  - 1 Signal Region
  - 4 Control Regions

- **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

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

ttW Validation region

- Use Validation Region to check ttW+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



Results

- Signal is separated from background based on a multivariate discriminant built in the signal region by combining input observables into a **BDT**
- The measured tttt signal strength is found to be:

$$\mu = \sigma_{t\bar{t}t\bar{t}}/\sigma^{SM}_{t\bar{t}t\bar{t}} = 2.0^{+0.4}_{-0.4}(stat)\ ^{+0.7}_{-0.5}(syst) = 2.0^{+0.8}_{-0.6}$$

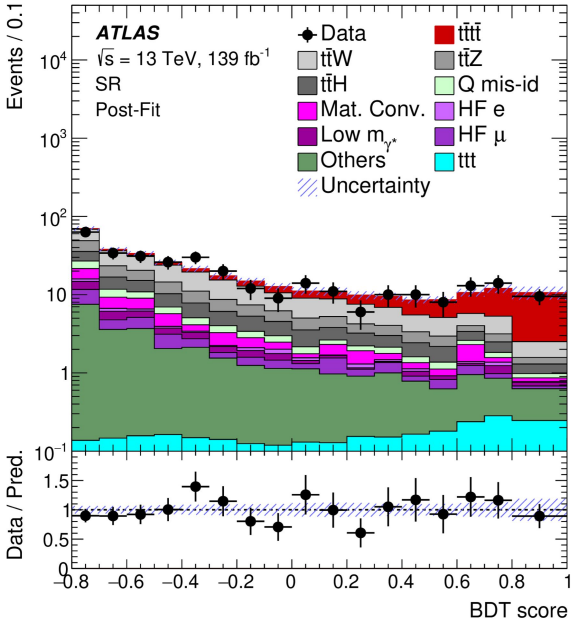
- Cross section:

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

- Compared to the theoretical prediction 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



List of uncertainties

- The dominant systematics uncertainties on the signal strength are:
  - Theoretical uncertainty on the signal
  - Data statistics
  - ttW 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

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Extrapolation Studies

Extrapolation Studies

- The expected cross-section of tttt at 14 TeV is 15.83 +18%/ -21% fb (JHEP 02 (2018) 031)
- Extrapolation studies are performed with the setup that uses **HT as fitted variations** in five signal regions
  - easier to extrapolate than the result using the BDT score
  - Almost the same significances as with the BDT
    - **The significance for HT will be reported in the note**

Signal regions

- Definition of the **five signal** regions:

Channel	Selection criteria
Common	$N_j \geq 6$, $N_b \geq 2$ and $H_T > 500$ GeV
SR2b2l	SS events with $N_b = 2$
SR2b3l	multilepton events with $N_b = 2$
SR3b2l	SS events with $N_b = 3$
SR3b3l	multilepton events with $N_b = 3$
SR4b	events with $N_b \geq 4$

HL-LHC recommendations

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- Looked into several extrapolation scenarios based on how to scale the systematics with the assumption agreed for the **2019 Yellow Report**
- Followed the recommendations explained in the High Lumi LHC Systematics
  - It was assumed for the YR that progress in theory would be such that the **modelling uncertainties could be halved** (ATL-PHYS-PUB-2019-005)
  - No dedicated studies for HL-LHC expected performance, **except for HF** (see next slide)
    - "Systematics driven by intrinsic detector limitations **are left unchanged**, or revised according to detailed simulation studies of the upgraded detector."

HL-LHC recommendations

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- The recommended way to apply flavor tagging uncertainties is to **scale down** the nuisance parameters from the current analyses
- No scale factors for **JES & JER** should be applied
- **MET**: In analysis where the soft-term uncertainty is highly ranked, the scale factor can be assumed to be 0.

Different scenarios

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- Scale scenario (in each case, fit redone with MC)
    - Asimov fit
    - For each case: scale statistical uncertainty with luminosity

Different scenarios

- **Model 1: “Run 2”**
  - **Instrumental systematics are kept as Run 2**
  - **Fake normalization injected from Run 2**
  - **ttW +7/8 jets systematics are scaled by Run 2 pulls**

- The post-fit value of the NP associated with the systematic uncertainty taken from Run 2:
  - **ttW+7jets** is **0.18** +0.73/-0.61 (with a 125% input uncertainty, this corresponds to **22%** increase in ttW+7jets)
  - **ttW+≥8jets** is **0.22** +0.56/-0.42 (with a 300% input uncertainty, this corresponds to **65%** increase in ttW+≥8jets)

Different scenarios

- **Model 2: "Run 2 Improved"**
  - Instrumental systematics are kept as Run 2
    - FTAG related systematics are halved
  - Fake syst, ttV + jets are scaled by lumi
    - The uncertainties on the fake/non-prompt lepton and charge misassignment backgrounds that are fitted to data in control regions are scaled down according to the assumed luminosity
    - Same for ttV+HF because this uncertainty is based a tt+HF measurement
  - ttW +7/8 jets systematics are scaled by the Run 2 pulls
  - Uncertainties related to the theoretical predictions are assumed to be halved compared to their values used in the 139/fb

Systematics treatment in Model 2 "Run 2 Improved"

- Blue- keep the same
- Red- halved
- Orange - Scaled by lumin
  - $1/(L/L_{ref})^{-0.5}$
- Purple-ttW 7/8 systematics
  - scaled by Run 2 pulls

Systematic uncertainty	Components
Luminosity (N)	1
Pile-Up reweighting	1
Physics Objects	
Electron	7
Muon	12
Jet energy scale and resolution	39
Jet vertex fraction	1
Jet flavor tagging	85
E_T^{miss}	3
Total (Experimental)	144
Electron charge misassignment	2
Template Fit uncertainties	
Material conversions	1
Internal conversions	1
HF non-prompt leptons	2
Other fake leptons	2
Additional heavy flavor jets	2
Total (reducible background)	10

Systematic uncertainty	Componen
$t\bar{t}t\bar{t}$ **modeling**	
Cross section (N)	1
Renormalization and factorization scales	1
Parton shower and hadronization model	1
PDF	1
$t\bar{t}H$ **modeling**	
Cross section (N)	1
Renormalization and factorization scales	1
Parton shower and hadronization model	1
PDF	1
Additional heavy flavor jets	2
$t\bar{t}W$ **modeling**	
Renormalization and factorization scales	1
Generator	1
Jets multiplicity modeling	2
Additional heavy flavor jets	2
$t\bar{t}Z$ **modeling**	
Cross section (N)	1
Renormalization and factorization scales	1
Generator	1
PDF	1
Additional heavy flavor jets	2
Other background modeling	
Cross section (N)	5
Additional heavy flavor jets	3
Total (Signal and background modeling)	30
Total (Overall)	189

Extrapolation Studies

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- Things we plan to show/report on
  - The yields for the sum of the five signal regions in the case of the “Improved Run 2” scenario
  - List of the main uncertainties in the signal strength obtained after extrapolation of the Run 2 analysis to the HL-LHC in the scenario “Run 2 improved”
  - The obtained expected significance for the tttt cross section resulting from the fit in the control and signal regions assuming the two scenarios for the scaling of systematic uncertainties is reported for 500, 1000, 2000, and 3000 /fb

Conclusions

- Presented projections for the measurement of the Standard Model four-top-quark production cross-section in the context of the High-Luminosity LHC with 3000 /fb at 14 TeV
- Presented two extrapolation scenarios (Run 2, Improved Run 2)
  - Stay tuned for the results!