Giancarlo Panizzo
on behalf of the ATLAS Collaboration

Prospects for measurements of the four-top-quark production cross section at the ATLAS experiment at the HL-LHC

DIS2022 - Santiago

2-6 May 2022

Main references

Short title	Journal Reference	$\sqrt{s}$	L	Links
Extrapolation of ATLAS sensitivity to the measurement of the Standard Model four top quark cross section at the HL-LHC	ATLAS PUB NOTE	14 TeV	up to 3 ab^{-1}	ATL-PHYS-PUB-2022-004
Evidence for $t\bar{t}t\bar{t}$ production in the multilepton final state in proton–proton collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	EPJC	13 TeV	139 fb^{-1}	Eur. Phys. J. C 80 (2020) 1085
Measurement of the $t\bar{t}t\bar{t}$ production cross section in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector	*JHEP*	*13 TeV*	*139 fb^{-1}*	*JHEP 11 (2021) 118*

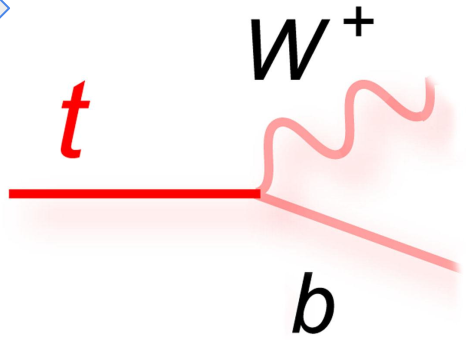
(see also previous talks on HL-LHC)

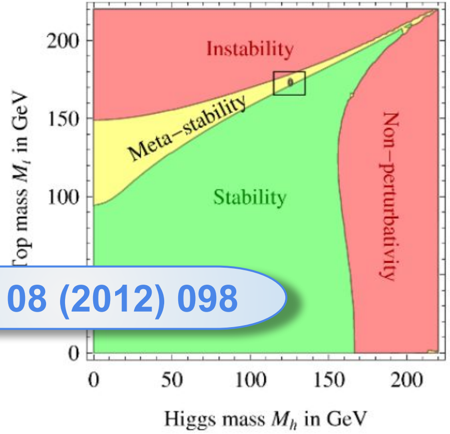
Introduction

The Top quark

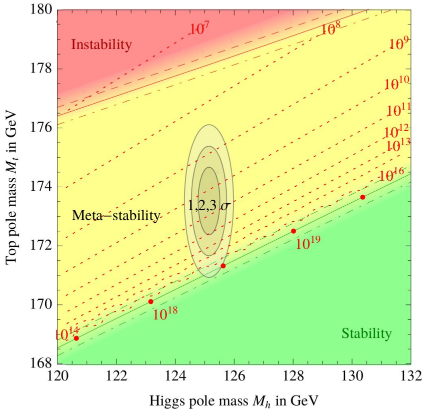
- Heaviest known elementary particle:
  - unique quark at the *W*, *Z* and Higgs bosons mass scale
    - connection to EW Symmetry Breaking in underlying BSM *theories*?
  - Yukawa coupling $y_t \sim 1$
    - important role in EW corrections

Decays before hadronising:





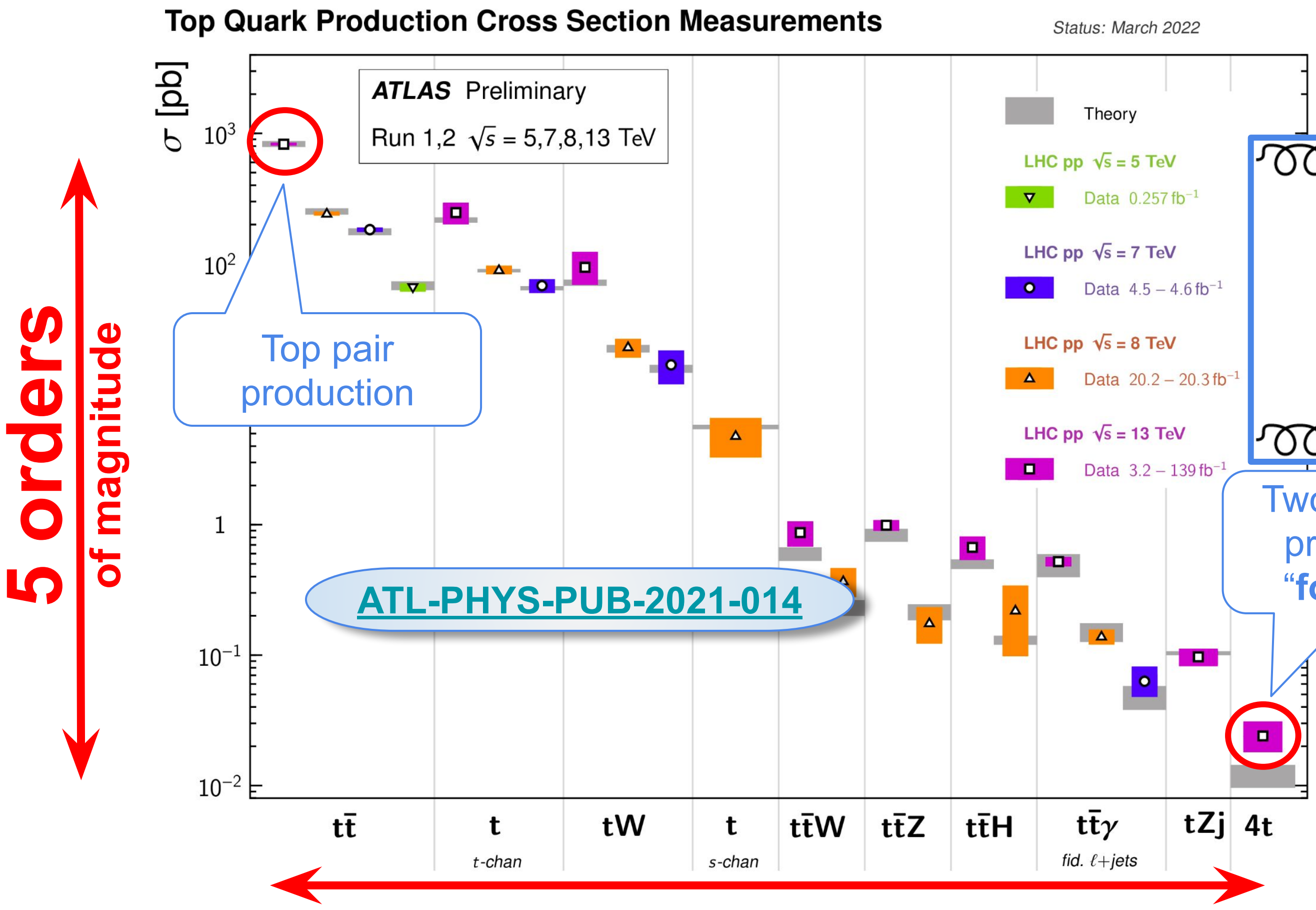
JHEP 08 (2012) 098

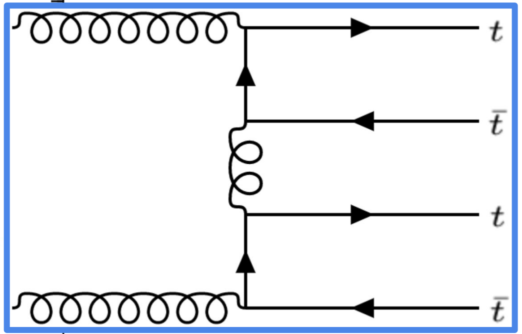


Top mass as key ingredient in SM vacuum stability

JHEP 12 (2013) 089

Four Tops and High Luminosity





Two Top pairs production: **"four tops"**

Summary of ATLAS 139 fb^{-1}/ 13 TeV results:

Eur. Phys. J. C 80 (2020) 1085

Four tops SS+multilepton, evidence

Introduction

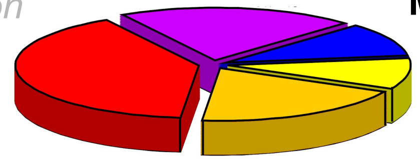
Eur. Phys. J. C 80 (2020) 1085

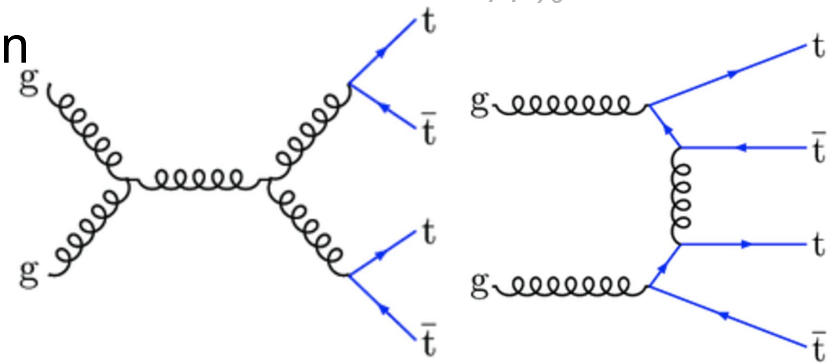
Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

- **First Evidence in ATLAS**
- High jet and *b*-jet multiplicities
- Single lepton/ opposite sign dileptons
  - larger Branching Fraction (56%)
  - large irr. background ($t\bar{t}$+jets)
- Same sign (SS) leptons and multilepton
  - smaller BF (7+5)%
  - **lower backgrounds**

  $t\bar{t}W,\ t\bar{t}Z,$ non-prompt leptons, charge mis-ID





Analysis strategy

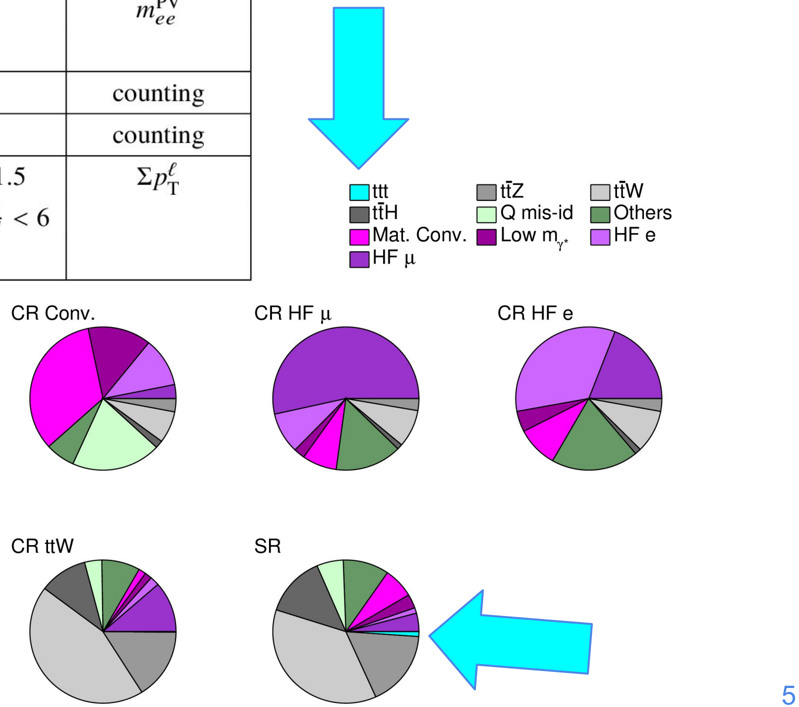
Eur. Phys. J. C 80 (2020) 1085

Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

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

- **Template method** for main backgrounds (except Qmis-id)
  - dedicated control/validation regions(especially *ttW*+jets)
- Simultaneous **profile likelihood fit** in CR/SR with dedicated discriminating variables



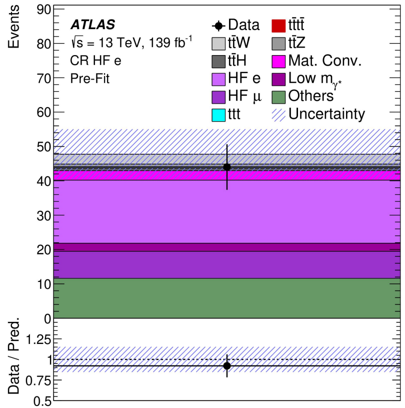
Fit results: CR, pre-fit

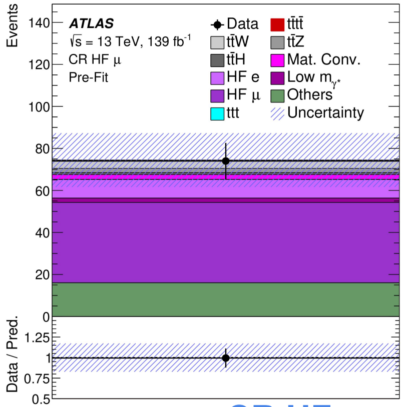
[Eur. Phys. J. C 80 (2020) 1085]

Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

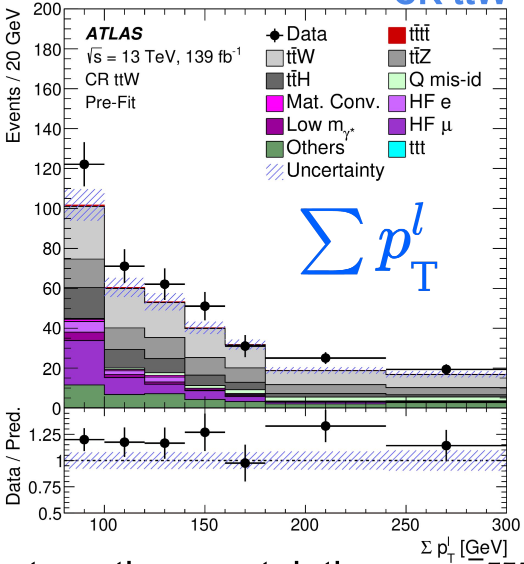
CR HF e



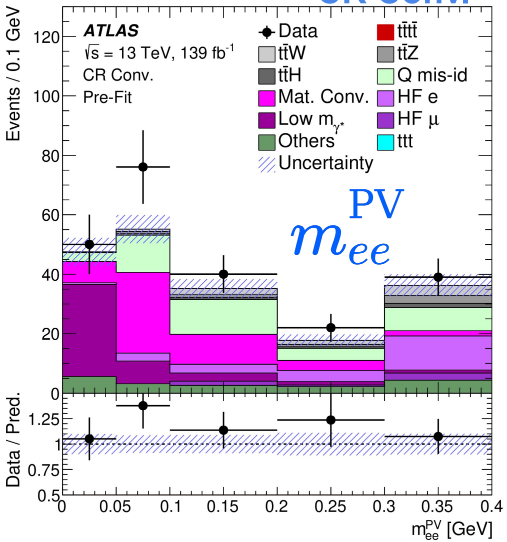


CR HF mu

CR ttW



CR Conv.



- Systematic uncertainties on $t\bar{t}W$ addressing mismodeling between MC and data in the VR (see next):
  - 125% on +7 jets
  - 300% on +8 jets
  - 50% on +3b, ≥4b

- Additional 50% uncertainty to $t\bar{t}Z$ and $t\bar{t}H$ with 3 and ≥4b jets
- 100% uncertainty on 3-top cross section and additional 50% on ttt+b

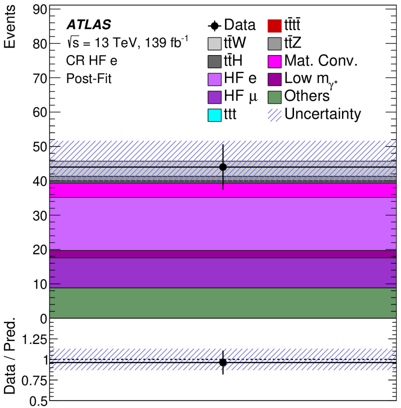
Fit results: CR, post-fit

Eur. Phys. J. C 80 (2020) 1085

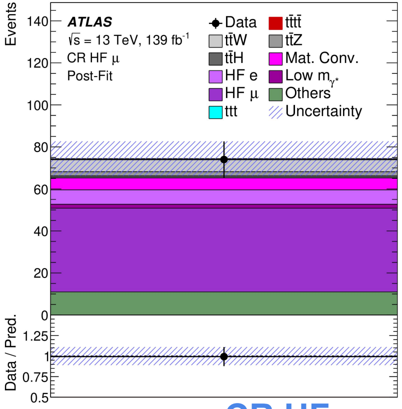
Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

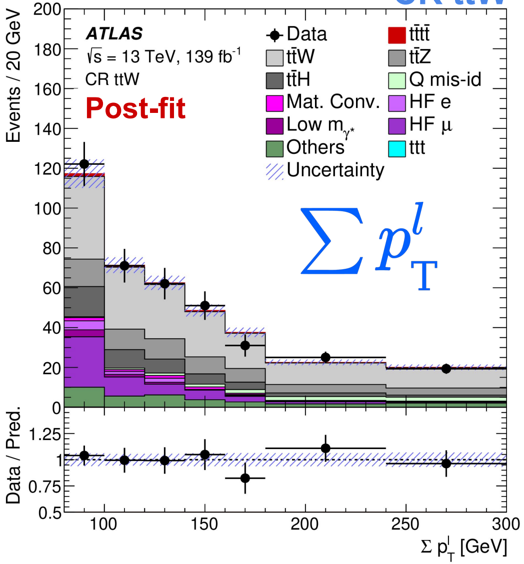
CR HF e



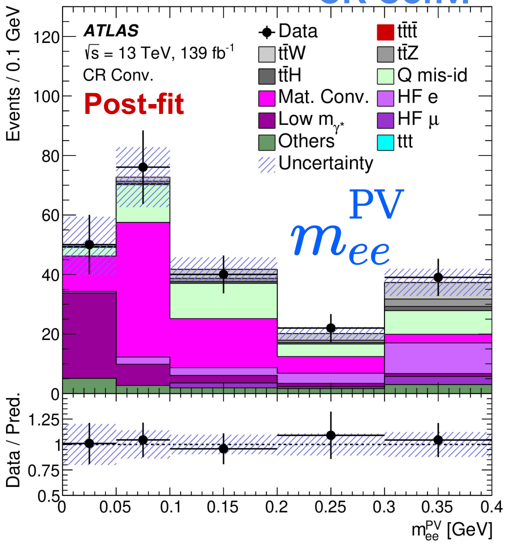
CR HF mu



CR ttW



CR Conv.



- Normalization factors extracted:

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

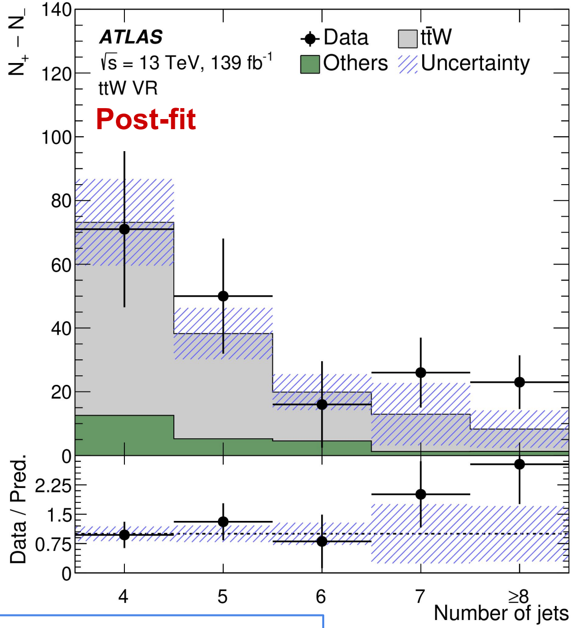
Fit results: *ttW*+jets validation

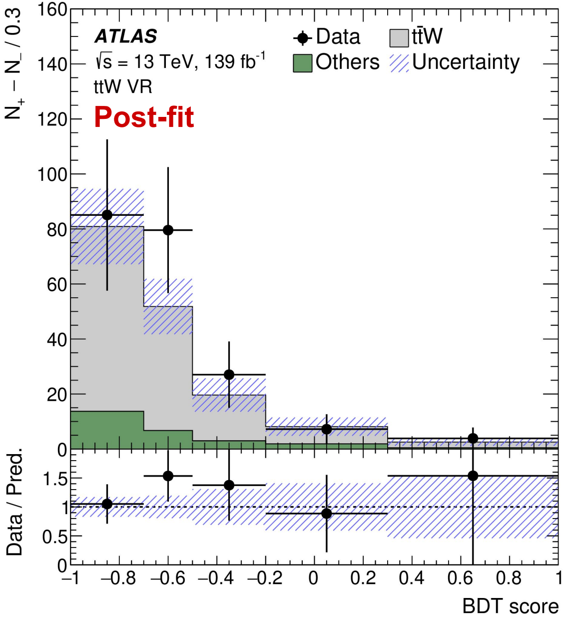
Eur. Phys. J. C 80 (2020) 1085

Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

- Dedicated *ttW* validation region
- Difference between events with positive/negative charge sum $N_+ - N_-$ (suppress all charge symmetric backgrounds)





Very good agreement in EXTREME regions

Fit results: signal region

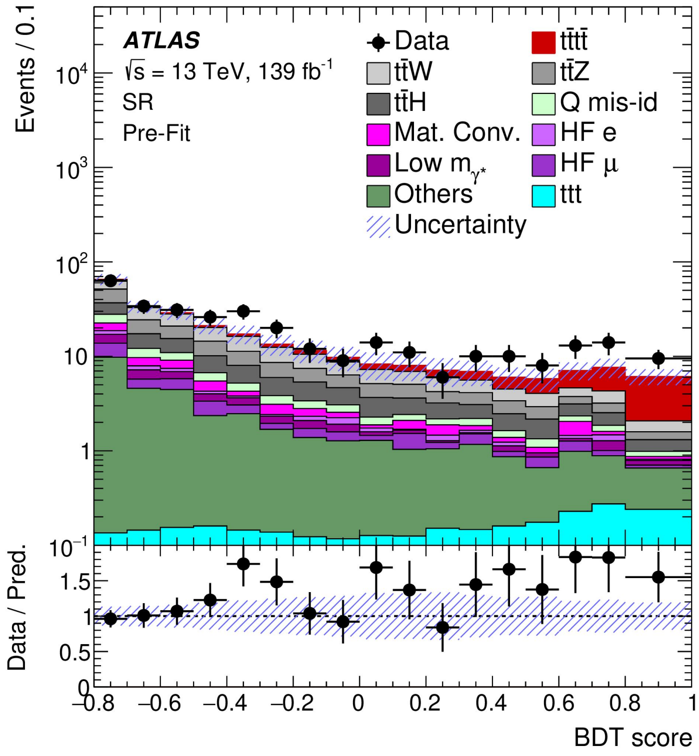
Eur. Phys. J. C 80 (2020) 1085

Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

- **Observed (expected) significance** w.r.t. background-only hypothesis **4.3 (2.4)** standard deviations
- Measured cross section: 24^{+7}_{-6} fb
  - consistent within 1.7σ with SM expectation σ_{4t}=12.0 ± 2.4 fb
- **Combined with 1L/2OSL channel,**

  4.7 (2.8) standard deviations



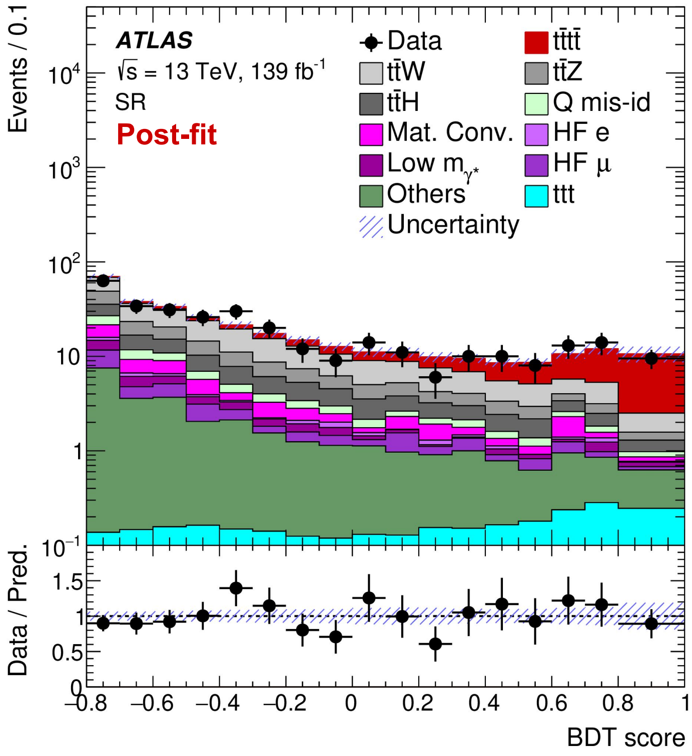
Fit results: signal region

Eur. Phys. J. C 80 (2020) 1085

Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

- **Observed (expected) significance** w.r.t. background-only hypothesis
  4.3 (2.4) standard deviations
- Measured cross section: 24^{+7}_{-6} fb
  - consistent within 1.7σ with SM expectation σ_{4t}=12.0 ± 2.4 fb
- **Combined with 1L/2OSL channel,**
  4.7 (2.8) standard deviations



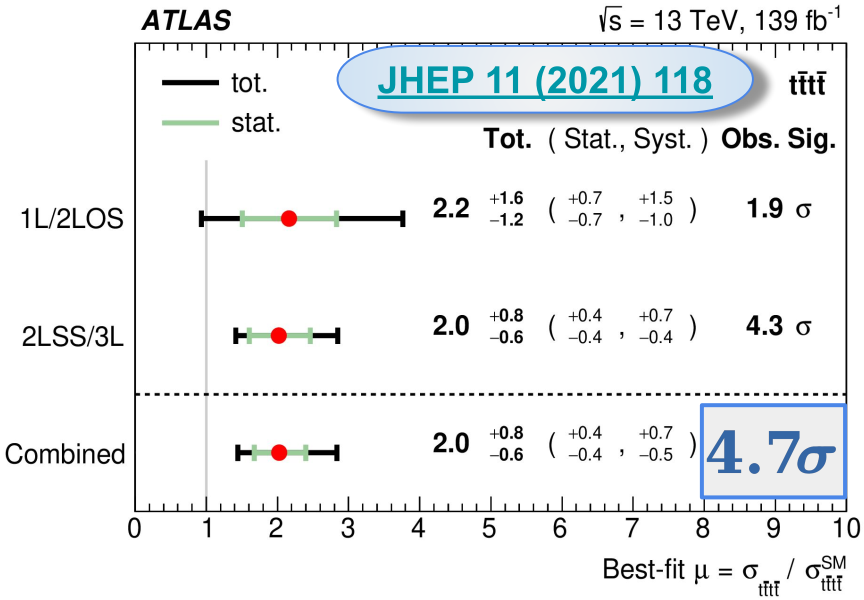
Fit results: signal region

[Eur. Phys. J. C 80 (2020) 1085]

Four tops SS+multilepton, evidence

13 TeV / pp collisions / 139 fb^{-1}

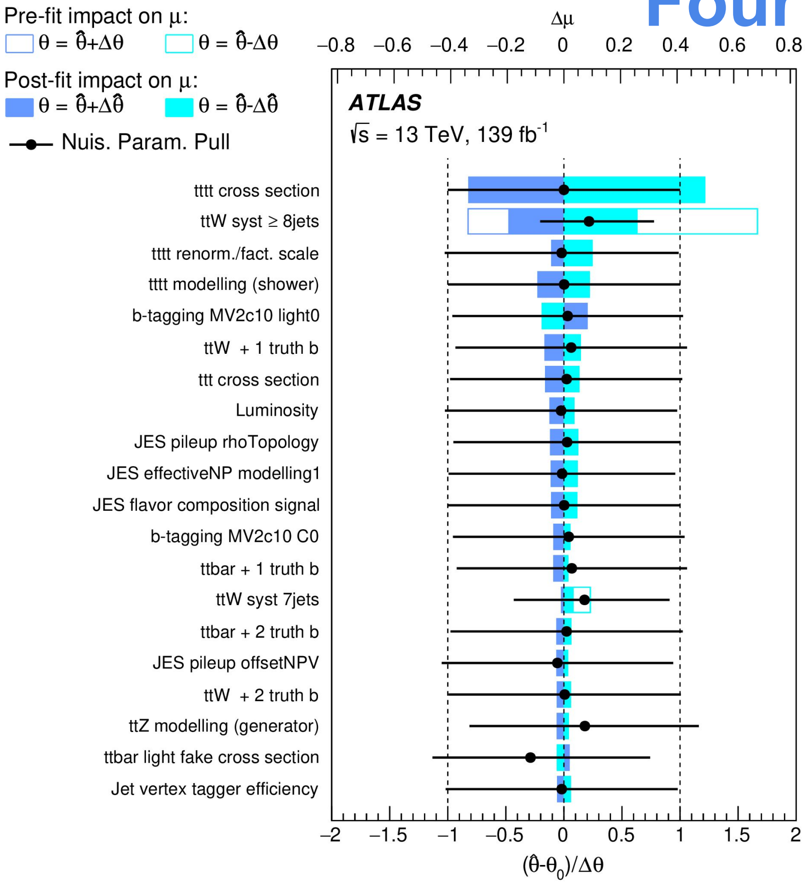
- **Observed (expected) significance** w.r.t. background-only hypothesis
  4.3 (2.4) standard deviations
- Measured cross section: 24^{+7}_{-6} fb
  - consistent within 1.7σ with SM expectation σ_{4t}=12.0 ± 2.4 fb
- **Combined with 1L/2OSL channel,**
  4.7 (2.8) standard deviations



Systematic uncertainties

Eur. Phys. J. C 80 (2020) 1085

Four tops SS+multilepton, evidence



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		
$t\bar{t}W$+jets modelling	+0.26	−0.27
$t\bar{t}t$ modelling	+0.10	−0.07
Non-prompt leptons modelling	+0.05	−0.04
$t\bar{t}H$+jets modelling	+0.04	−0.01
$t\bar{t}Z$+jets modelling	+0.02	−0.04
Other background modelling	+0.03	−0.02
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-flavour 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
Jet flavour tagging (*c*-jets)	+0.03	−0.01
Other experimental uncertainties	+0.03	−0.01
Total systematic uncertainty	+0.70	−0.44
Statistical	+0.42	−0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.83	−0.60

Prospects @HL-LHC/ 14 TeV:

ATL-PHYS-PUB-2022-004

Extrapolation of ATLAS results

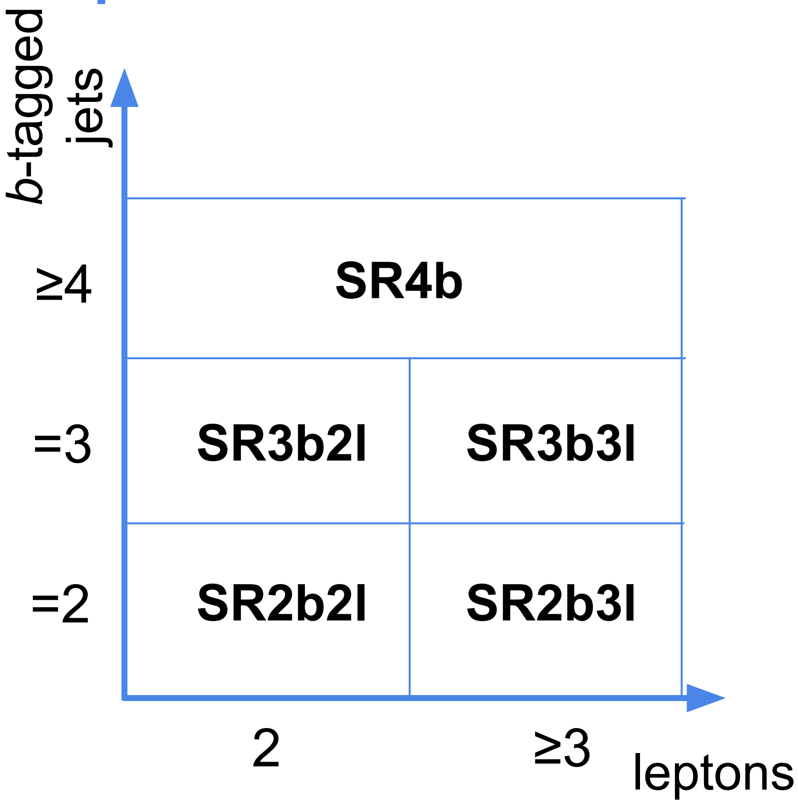
HL-LHC extrap. strategy

ATL-PHYS-PUB-2022-004

Extrapolation of ATLAS results

14 TeV / pp collisions / HL-HLC

- Adapt **luminosity assumptions** (up to 3 ab^{-1})
- Split into 5 SR to account for increased statistical power, fit H_T (compatible results @Run2)
- Scale cross sections 13 TeV→14 TeV:
  - Signal: 1.3 x
  - *tt*, *ttH*, *ttW*, *ttZ*: 1.4 x
- Fix backgr. NF to Run2 fitted values

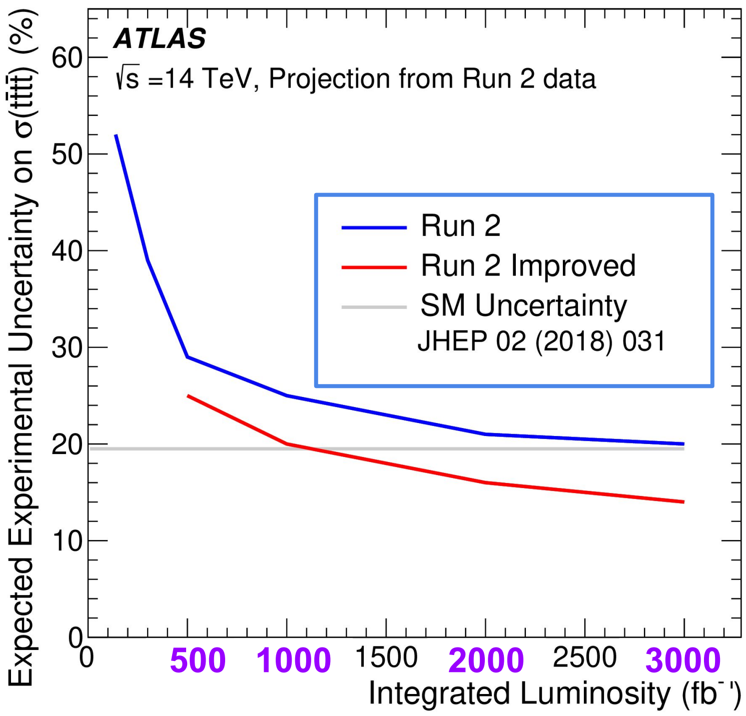


Systematics

ATL-PHYS-PUB-2022-004

Extrapolation of ATLAS results

- Run 2 prescriptions + possible reductions:
  - *ttW*+≥7j: from NF post-fit uncertainty
- Two syst. uncertainties scenarios:
  - **“Run 2”** ***(conservative)***
  - **“Run 2 Improved”**
    - theoretical: halved
    - ttV+jets HF tagging: scale down the nuisance parameters from the current analyses
    - syst. driven by intrinsic detector limitations: revised only in presence of detailed simulation studies of the upgraded detector



Systematics, summary

ATL-PHYS-PUB-2022-004

Extrapolation of ATLAS results

14 TeV / pp collisions / HL-HLC

Uncertainty source	Treatment in the "Run 2 Improved" model
Signal modelling	
$t\bar{t}t\bar{t}$ cross section	Half of Run 2
$t\bar{t}t\bar{t}$ modelling	Half of Run 2
Background modelling	
$t\bar{t}W$+jets modelling	
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
Jets multiplicity modelling	Scaled by Run 2 pulls
Additional heavy flavour jets	Scaled by luminosity
$t\bar{t}t$ modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Non-prompt leptons modelling	Scaled by luminosity
$t\bar{t}H$+jets and $t\bar{t}Z$+jets modelling	
Cross section	Half of Run 2
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
PDF	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Other background modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Charge misassignment	Same as Run 2
Template fit shape uncertainties	
Mat. Conv., γ^*, and HF non-prompt leptons	Scaled by luminosity
Other fake leptons	Half of Run 2
Additional heavy flavour jets	Half of Run 2
Instrumental	
Jet uncertainties	Same as Run 2
Jet flavour tagging (light-flavour jets)	Half of Run 2
Luminosity	Same as Run 2
Jet flavour tagging (b-jets)	Half of Run 2
Jet flavour tagging (c-jets)	Half of Run 2
Other experimental uncertainties	Same as Run 2

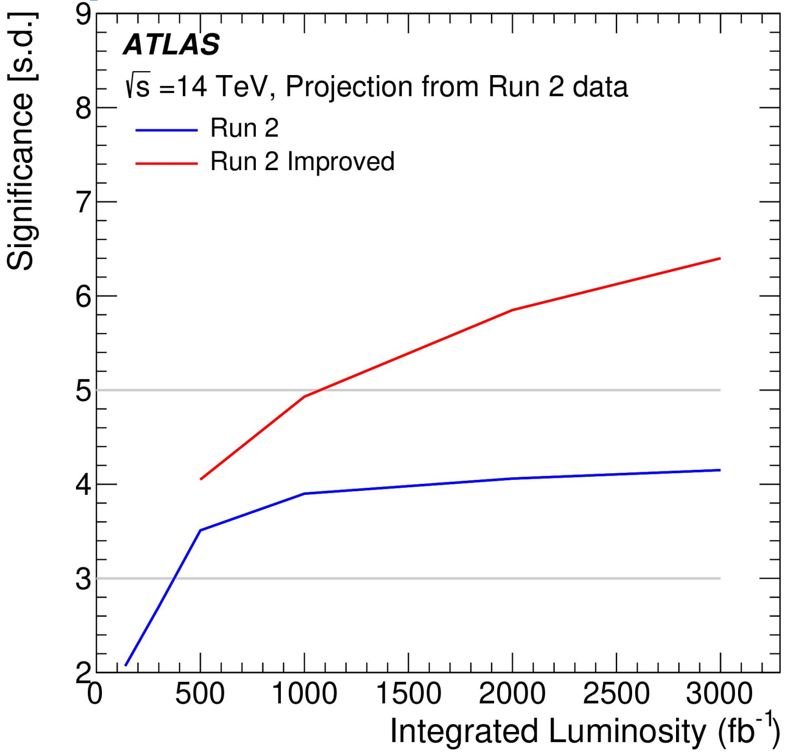
HL-LHC extrap. results

ATL-PHYS-PUB-2022-004

Extrapolation of ATLAS results

14 TeV / pp collisions / HL-HLC

- Expected total uncertainty on the cross section of **14%** (20%) for "**Run2 Improved**" ("Run2")
- Experimental precision is expected to be **significantly better** than the precision of the current SM prediction
- *Expected* significance can reach $6.4\ \sigma$ under "Improved" systematic assumptions
- improvement in sensitivity of the "Improved" scenario wrt "Run 2"driven by smaller unc:
  - on the *ttt* cross section
  - related to *ttV*+jets with heavy-flavour jets
  - jet flavour tagging.



Summary

- Extrapolation relies on knowledge of ATLAS Run2 measurements of $t\bar{t}t\bar{t}$ in **2SS+multilepton** (and 1L/2OSL) decay channels
- Their combination measures

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

with a significance of

$$4.7(2.6)\sigma \text{ Obs. (Exp.)}$$

- **HL-LHC extrapolation** based on 2SS+multilepton channel **alone**
- Two different syst. assumptions:
    - Conservative
    - Run 2 Improved (more optimistic)
    - *Expected* significance can reach $6.4\ \sigma$ under "improved" systematic assumptions at 3 ab^{-1}

- Expected total uncertainty on the cross section of **14%** (20%) for "**Run2 Improved**" ("Run2") (experimental precision **significantly better** than the precision of the current SM prediction)

Backup

Summary of ATLAS 139 fb^{-1}/ 13 TeV results:

JHEP 11 (2021) 118

Four tops 1L+2OSL, combination with SS

Four tops 1L+2OSL

JHEP 11 (2021) 118

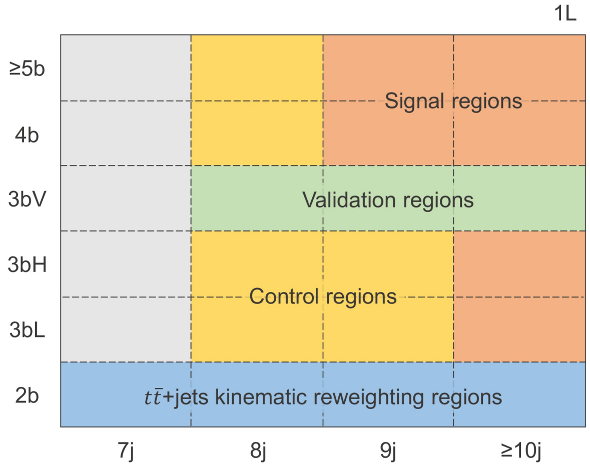
13 TeV / pp collisions / 139 fb^{-1}

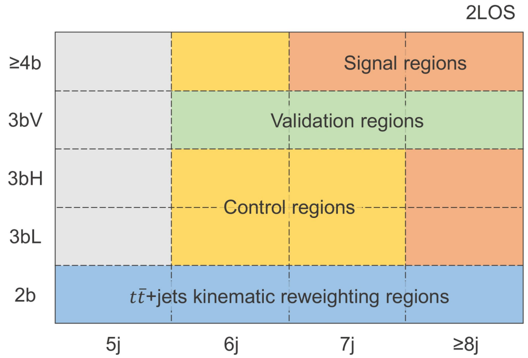
- Single lepton/ opposite sign dileptons
  - larger Branching Fraction (56%)
  - large irr. background $t\bar{t}$+jets:
    - 1+3 steps data-driven correction method
    - dedicated control/validation regions
- Simultaneous **profile likelihood fit** in CRs (H_T) and SRs (BDT)

$$\mu = 2.2 \pm 0.7(\text{stat})^{+1.5}_{-1.0}(\text{syst}) = 2.2^{+1.6}_{-1.2}$$

$$\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}\ \text{fb}$$

1.9(1.0)σ Obs. (Exp.) significance





Four tops 1L+2OSL

JHEP 11 (2021) 118

13 TeV / pp collisions / 139 fb^{-1}

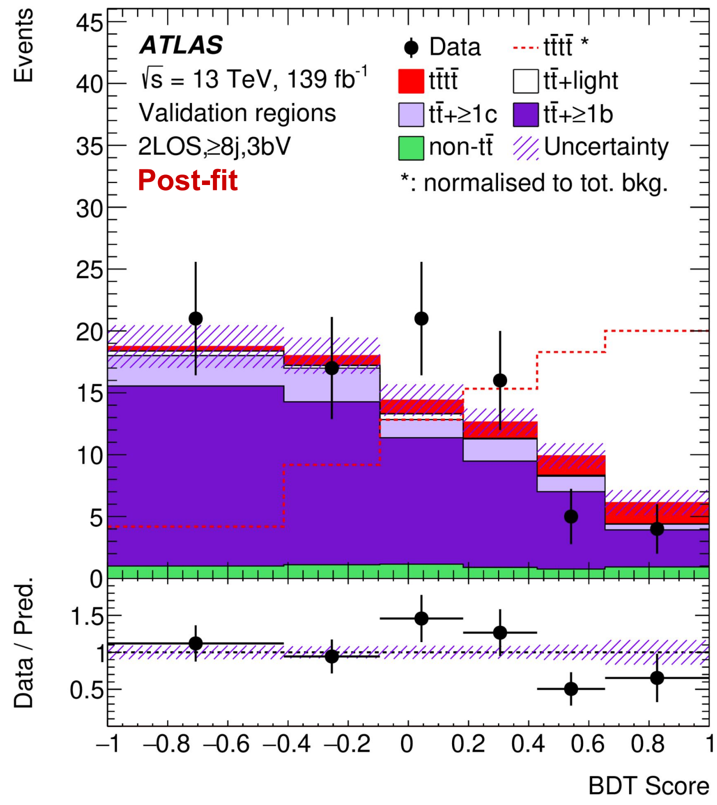
- Single lepton/ opposite sign dileptons
  - larger Branching Fraction (56%)
  - large irr. background $t\bar{t}$+jets:
    - 1+3 steps data-driven correction method
    - dedicated control/validation regions

- Simultaneous **profile likelihood fit** in CRs (H_T) and SRs (BDT)

$$\mu = 2.2 \pm 0.7(\text{stat})^{+1.5}_{-1.0}(\text{syst}) = 2.2^{+1.6}_{-1.2}$$

$$\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}\ \text{fb}$$

$1.9(1.0)\sigma$ Obs. (Exp.) significance



Four tops 1L+2OSL

JHEP 11 (2021) 118

13 TeV / pp collisions / 139 fb^{-1}

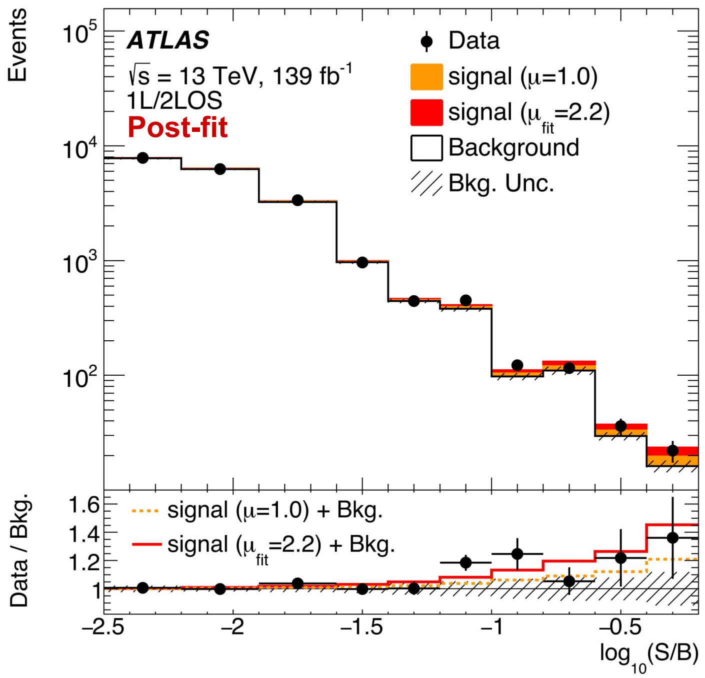
- Single lepton/ opposite sign dileptons
  - larger Branching Fraction (56%)
  - large irr. background $t\bar{t}$+jets:
    - ➢ 1+3 steps data-driven correction method
    - ➢ dedicated control/validation regions

- Simultaneous **profile likelihood fit** in CRs (H_T) and SRs (BDT)

$$\mu = 2.2 \pm 0.7(\text{stat})^{+1.5}_{-1.0}(\text{syst}) = 2.2^{+1.6}_{-1.2}$$

$$\sigma_{t\bar{t}t\bar{t}} = 26^{+17}_{-15}\ \text{fb}$$

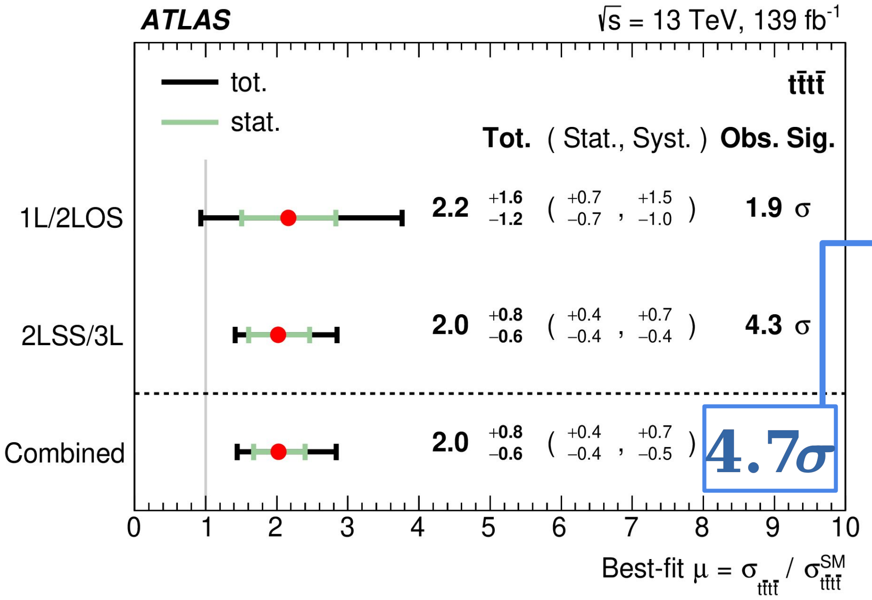
$1.9(1.0)\sigma$ Obs. (Exp.) significance



Combination and extrap. strategy

JHEP 11 (2021) 118

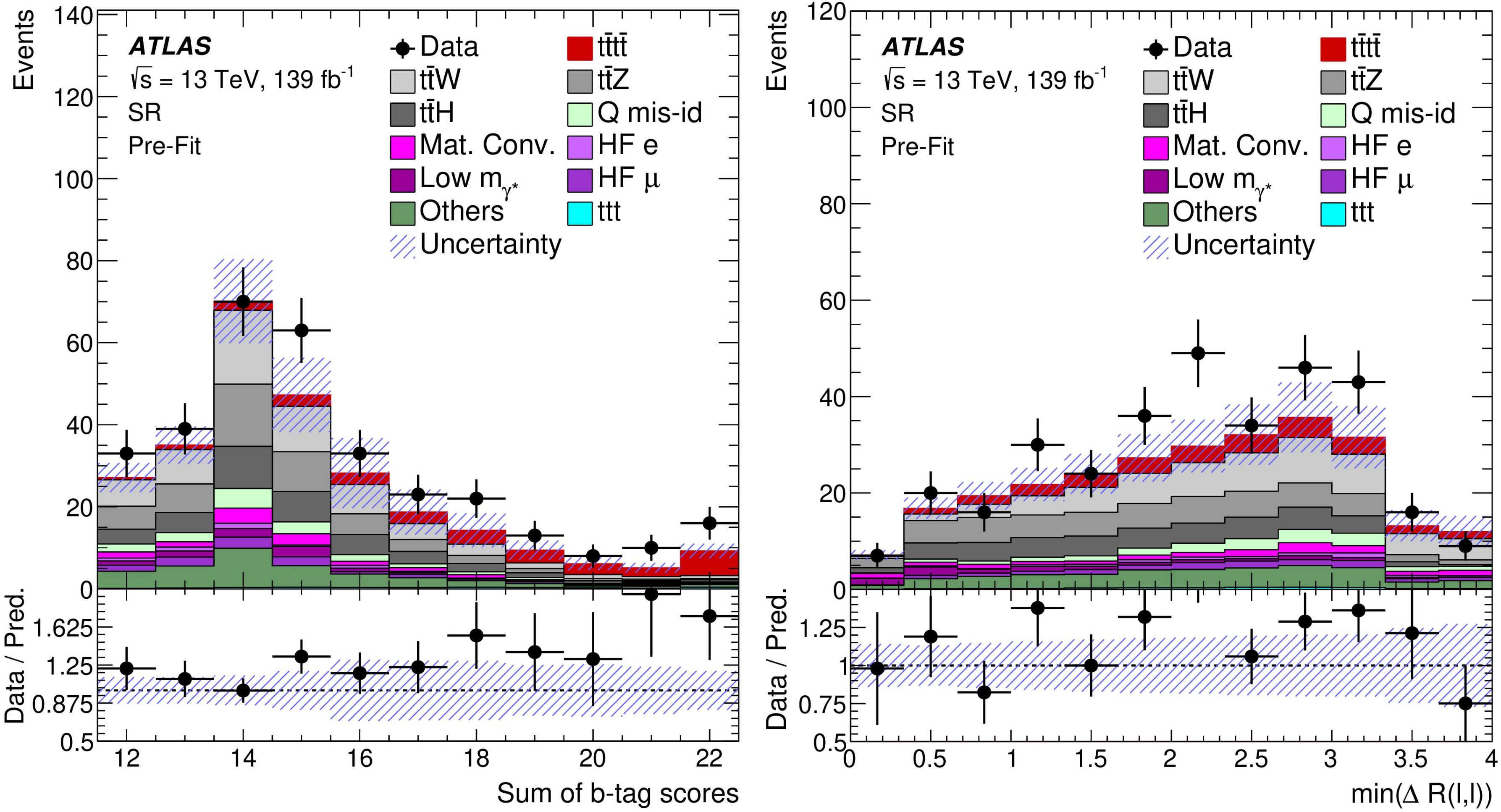
13 TeV / pp collisions / 139 fb^{-1}

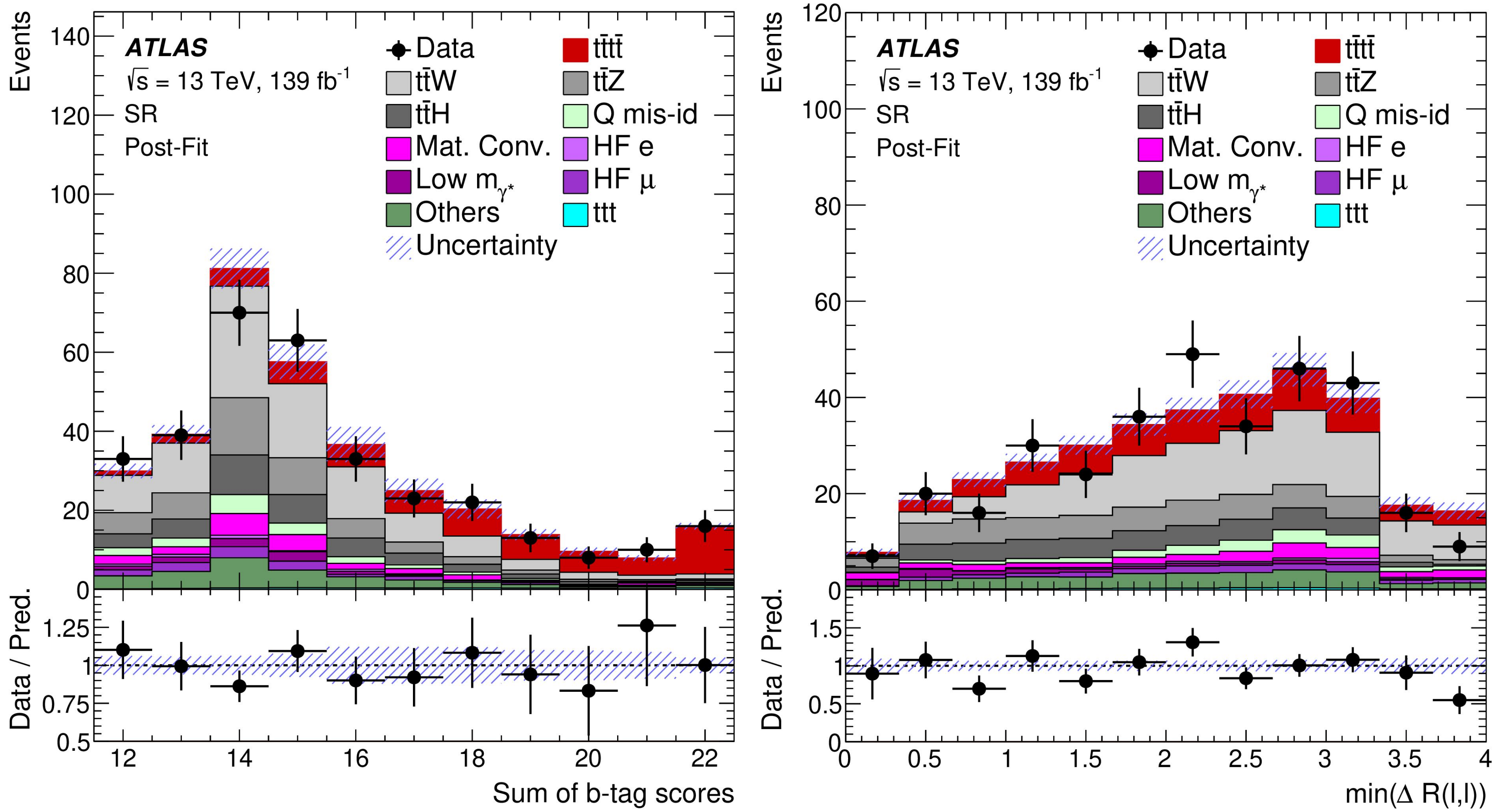


- The two analyses, combined, increase the **obs. significance** (*wrt 2.6 expected*)
- Simple, conservative assumption for HL-LHC extrapolation:
  - study only the 2SS+multilepton channel (exact for early results)

Run 2 syst. unc.

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		
$t\bar{t}W$+jets modelling	$+0.26$	-0.27
$t\bar{t}t$ modelling	$+0.10$	-0.07
Non-prompt leptons modelling	$+0.05$	-0.04
$t\bar{t}H$+jets modelling	$+0.04$	-0.01
$t\bar{t}Z$+jets modelling	$+0.02$	-0.04
Other background modelling	$+0.03$	-0.02
Charge misassignment	$+0.01$	-0.02
Instrumental		
Jet uncertainties	$+0.12$	-0.08
Jet flavour tagging (light-flavour 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
Jet flavour tagging (c-jets)	$+0.03$	-0.01
Other experimental uncertainties	$+0.03$	-0.01
Total systematic uncertainty	$+0.70$	-0.44
Statistical	$+0.42$	-0.39
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	$+0.05$	-0.04
$t\bar{t}W$ normalisation	$+0.04$	-0.04
Total uncertainty	$+0.83$	-0.60


ATLAS
√s = 13 TeV, 139 fb⁻¹
SR
Pre-Fit
Data
tt̄tt̄
tt̄W
tt̄Z
tt̄H
Q mis-id
Mat. Conv.
HF e
Low mγ*
HF μ
Others
ttt
Uncertainty
Events
Data / Pred.
Sum of b-tag scores
min(Δ R(l,l))



ATLAS
√s = 13 TeV, 139 fb-1
SR
Post-Fit
Data
tt̄tt̄
tt̄W
tt̄Z
tt̄H
Q mis-id
Mat. Conv.
HF e
Low mγ*
HF μ
Others
ttt
Uncertainty
Events
Data / Pred.
Sum of b-tag scores
min(Δ R(l,l))

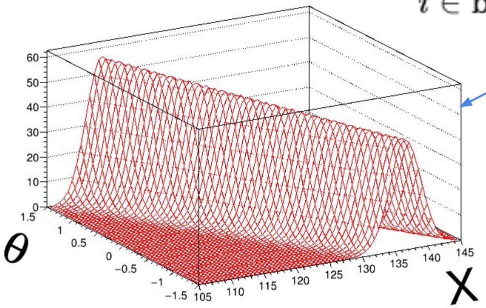
Profile Likelihood approach

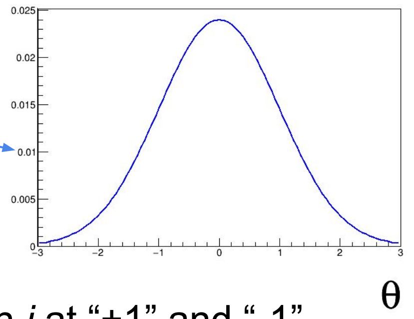
Courtesy of Michele Pinamonti

Intermezzo

- The profile likelihood is a way to include systematic uncertainties in the likelihood
  - systematics included as "***constrained***" **nuisance parameters**
  - the idea behind is that systematic uncertainties on the measurement of μ come from ***imperfect knowledge*** of parameters of the model (S and B prediction)
    - still some *knowledge* is implied: "$\theta = \theta_0 \pm \Delta\theta$"

$$\mathcal{L}(\mathbf{n}, \boldsymbol{\theta}^0 | \mu, \boldsymbol{\theta}) = \prod_{i \in \text{bins}} \mathcal{P}(n_i | \mu \cdot S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta})) \times \prod_{j \in \text{systs}} \mathcal{G}(\theta_j^0 | \theta_j, \Delta\theta_j)$$





➢ usually θ_0=0 and $\Delta\theta$=1 (convention)

➢ define effect of systematic *j* on prediction *x* in bin *i* at "+1" and "-1"

➢ then interpolate & extrapolate for any value of θ

  - external / *a priori knowledge* interpreted as "**auxiliary/subsidiary measurement**", implemented as constraint/penalty term, i.e. probability density function *(usually Gaussian, interpreting "±Δθ" as Gaussian standard deviation)*