New results on $t\bar{t}W$ and 4-top production with the ATLAS experiment

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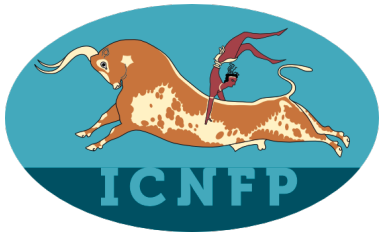
On behalf of the ATLAS collaboration



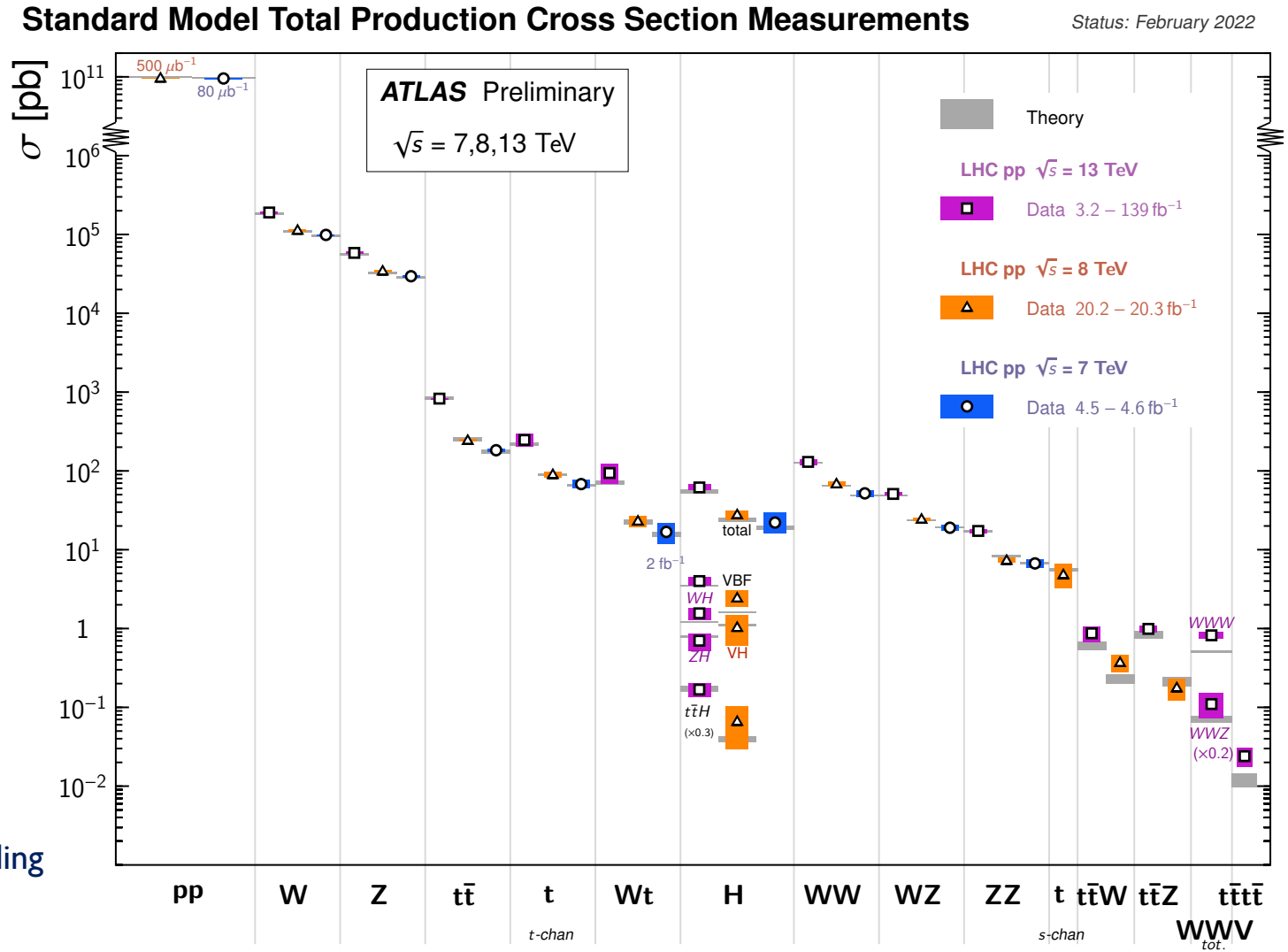
ICNFP2023, 10-23 July 2023

The top quark production at LHC

Top quark is heaviest in the **SM**, with the strongest ties to the Higgs boson

Top production modes:

- $t\bar{t}$bar
- single top(t-chan, s-chan, t + W)
- **$t\bar{t}$ + W**/Z/H/γ
- t + Z/γ
- **multi-top (four-top, three-top)**



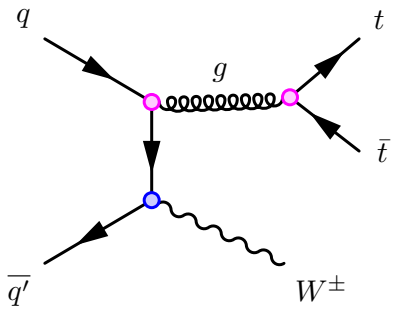
ATL-PHYS-PUB-2022-009

Summary of several SM cross-section measurements, compared to the corresponding theoretical expectations

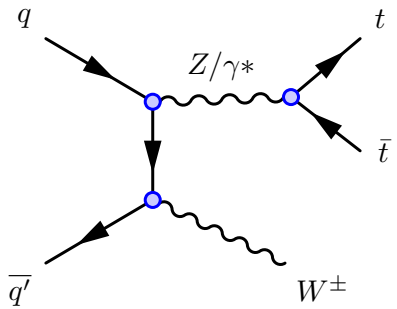
Due to its mass, top quark is expected to have the strongest coupling to the Higgs boson
It is also predicted to have strong couplings to new particles in many **BSM** theories

$t\bar{t}W$ production

Charge-asymmetric production from **PDF**

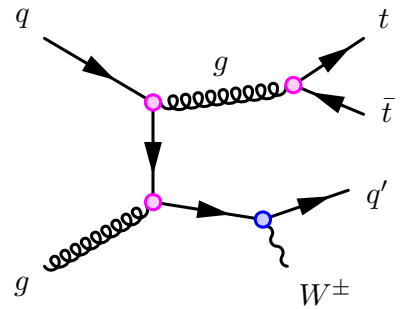


$O(\alpha\alpha_S^2)$

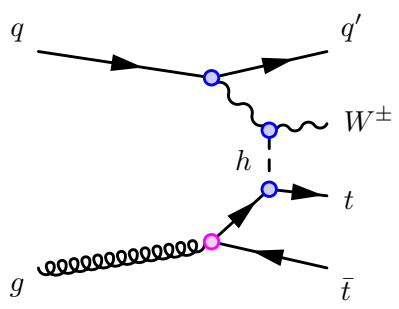


$O(\alpha^3)$

Complex **NLO QCD** and **EW** corrections



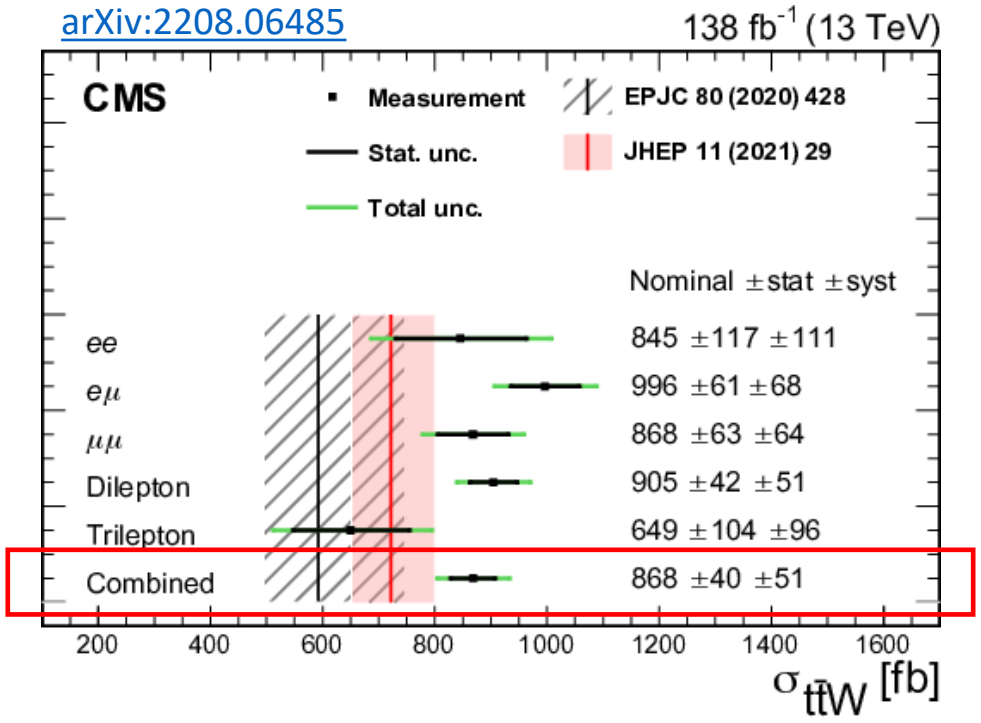
$O(\alpha\alpha_S^3)$



$O(\alpha^3\alpha_s)$

The pink circles correspond to **QCD** couplings and the blue circles correspond to **EWK** couplings

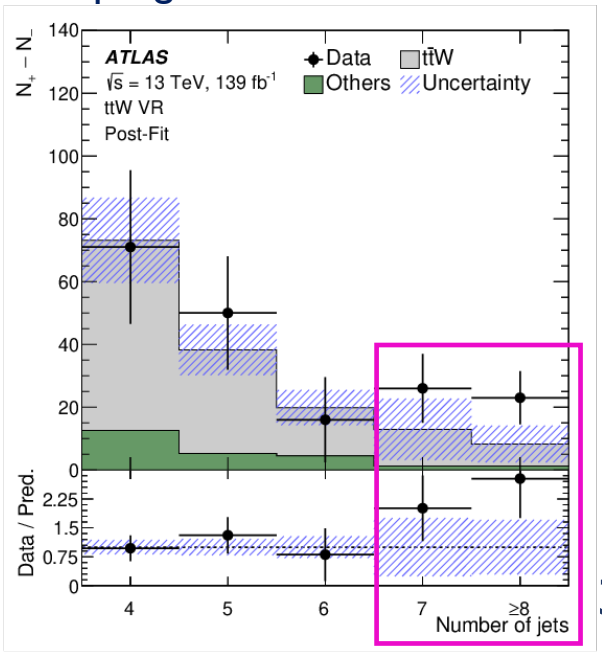
arXiv:2208.06485



ATLAS and **CMS** consistently measure 20-50% higher cross section than **SM** predictions

Largest source of systematic uncertainty in ATLAS four-top evidence analysis due to mismodelling of N_{jets} in $t\bar{t}W$ production

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



Inclusive $t\bar{t}W$ cross section measurement

ATLAS-CONF-2023-019

Simultaneous profile likelihood fit to data in the 56 **SR** and 10 **CR**

$$\sigma_{t\bar{t}W} = 890 \pm 50(\text{stat}) \pm 70(\text{syst})\,\text{fb}$$

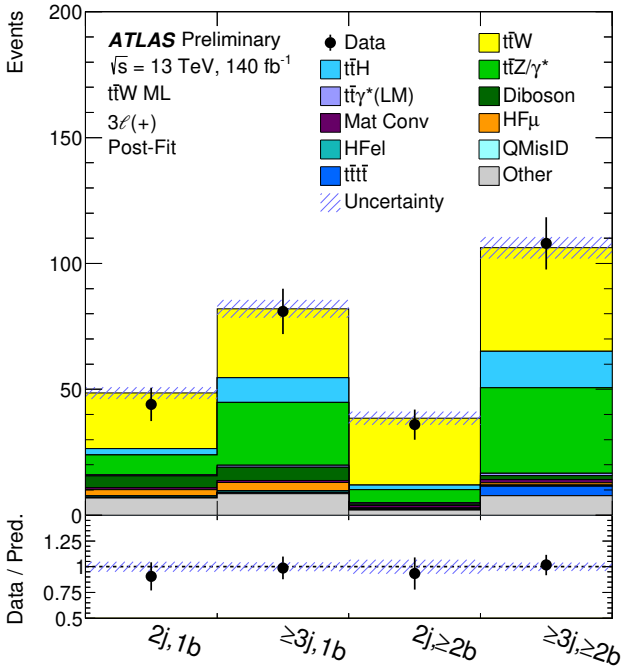
9% relative uncertainty

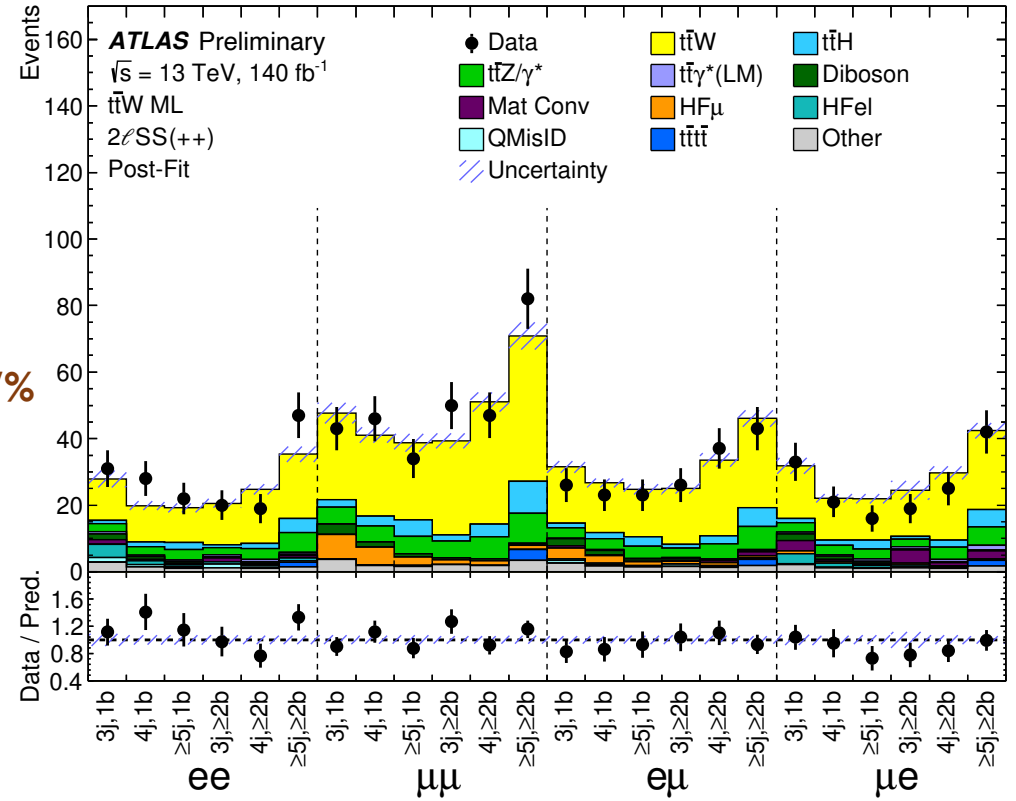
Consistent at **1.5σ** with the **SM** prediction (722 fb±10%)

JHEP11(2021)029

* with the new **NNLO** calculation the sum of $t\bar{t}W^+$ and $t\bar{t}W^-$ will be **745 fb ± 6.7%**

arXiv:2306.16311





Systematic uncertainties:

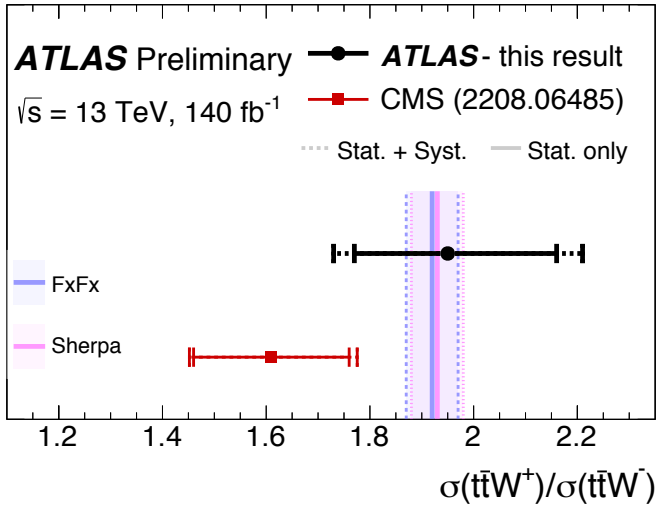
- from $t\bar{t}W$ modeling
- $t\bar{t}H$, $t\bar{t}t\bar{t}$ normalisation
- b-tagging and non-prompt isolation **BDT** calibration

Result use the full ATLAS Run-2 dataset of 140 fb^{-1} at 13 TeV

Inclusive and ratio $t\bar{t}W$ results

Ratio of $t\bar{t}W^+$ to $t\bar{t}W^-$ production rate

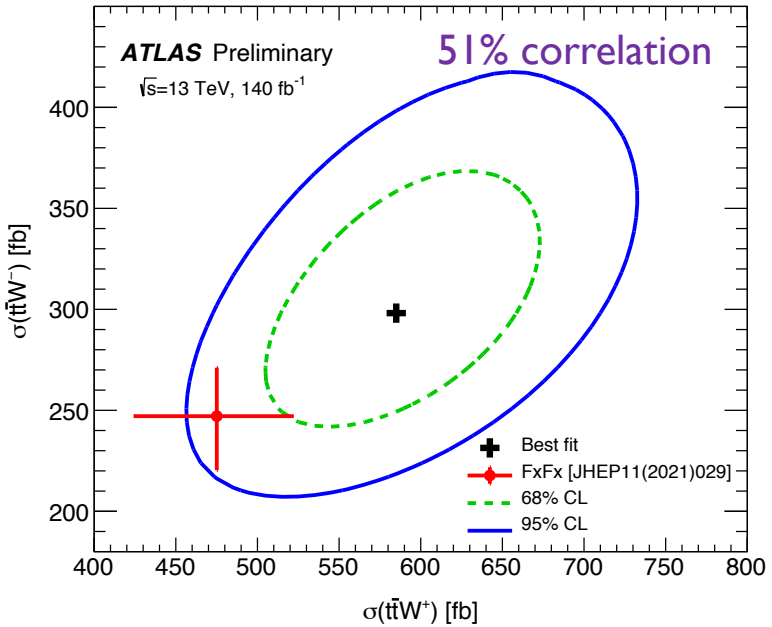
ATLAS-CONF-2023-019



Expect to help improving future **MC** predictions and data measurements sensitive to $t\bar{t}W$ background (like $t\bar{t}t\bar{t}$ production)

$$\frac{\sigma_{t\bar{t}W^+}}{\sigma_{t\bar{t}W^-}} = 1.95 \pm 0.21(\text{stat}) \pm 0.16(\text{syst})$$

consistent with **MC** predictions

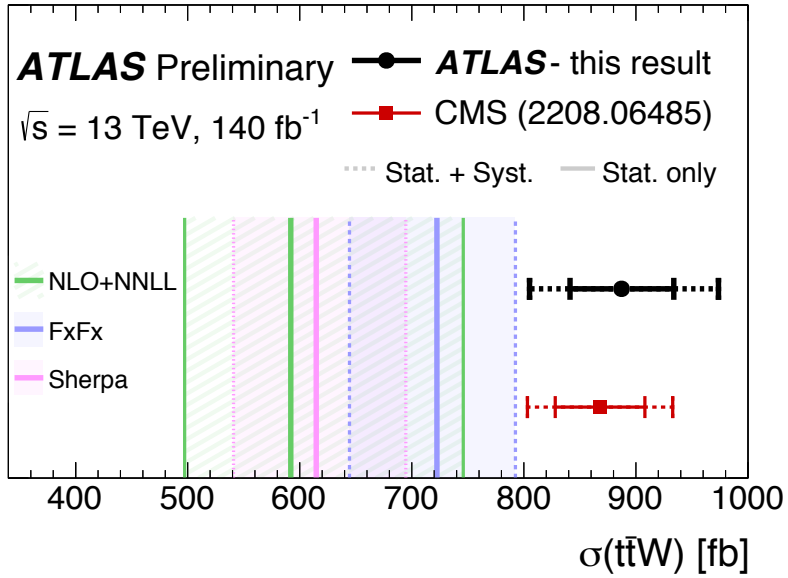


$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

$$A_C^{rel} = 0.32 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$$

Good agreement with **Sherpa** prediction

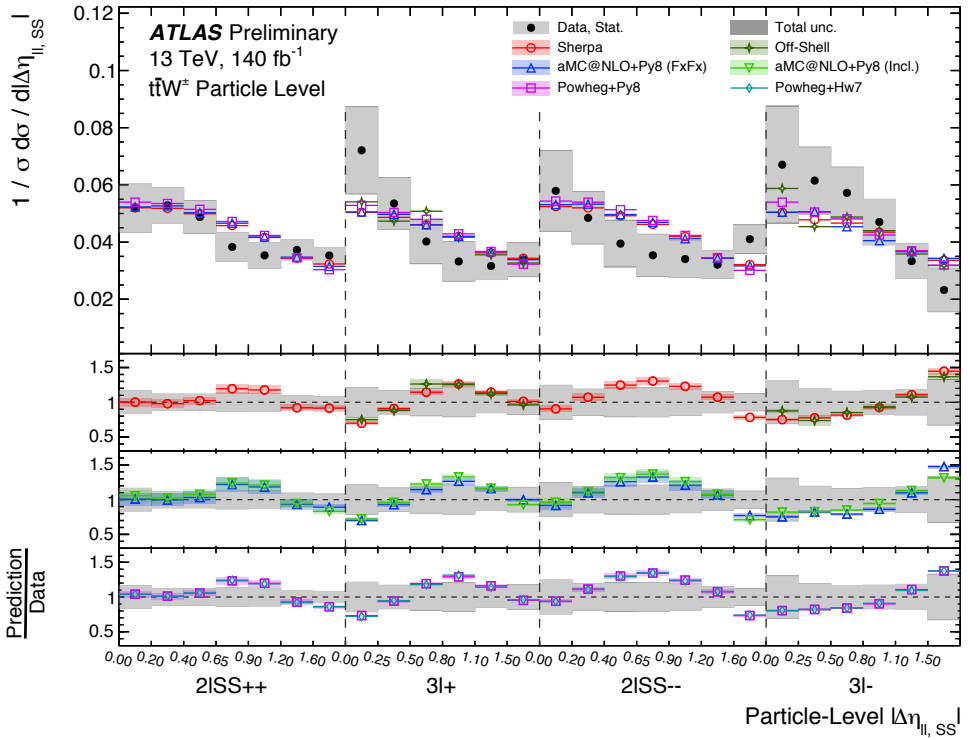
$$A_{C,t\bar{t}W} = 0.322 \pm 0.003(\text{scale}) \pm 0.007(\text{PDF})$$



Differential $t\bar{t}W$ results

ATLAS-CONF-2023-019

Observable	NDF	Sherpa 2.2.10		MG5aMC+Py8 FxFx		MG5aMC+Py8 Incl.		Powheg+Pythia8		Powheg+Herwig7	
		χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
N_{jets}	5	2.4	0.79	4.2	0.52	2.8	0.73	2.9	0.72	2.6	0.76
$H_{\text{T,jets}}$	5	0.7	0.98	1.1	0.95	0.8	0.98	1.5	0.91	2.0	0.85
$H_{\text{T,lep}}$	7	3.6	0.82	3.8	0.80	3.4	0.84	3.4	0.85	3.5	0.84
$\Delta R_{\text{lb, lead}}$	7	2.0	0.96	2.4	0.93	2.6	0.92	2.6	0.92	2.5	0.93
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	7	0.6	1.00	0.7	1.00	0.9	1.00	0.8	1.00	0.9	1.00
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	6	6.5	0.37	7.3	0.29	11.4	0.08	9.5	0.15	9.4	0.15
$M_{\text{jj, lead}}$	6	4.9	0.56	2.7	0.84	7.2	0.30	9.0	0.17	10.9	0.09



Fiducial phase space definition:

- Particle level objects defined starting by quasi-stable object
- Closely follows the detector level definition

Unfolding performed using a profile likelihood approach:

- Main background normalization ($t\bar{t}Z$, VV, non-prompt lepton backgrounds) free floating in the fit
- Tikhonov regularisation with optimised strength for each variable

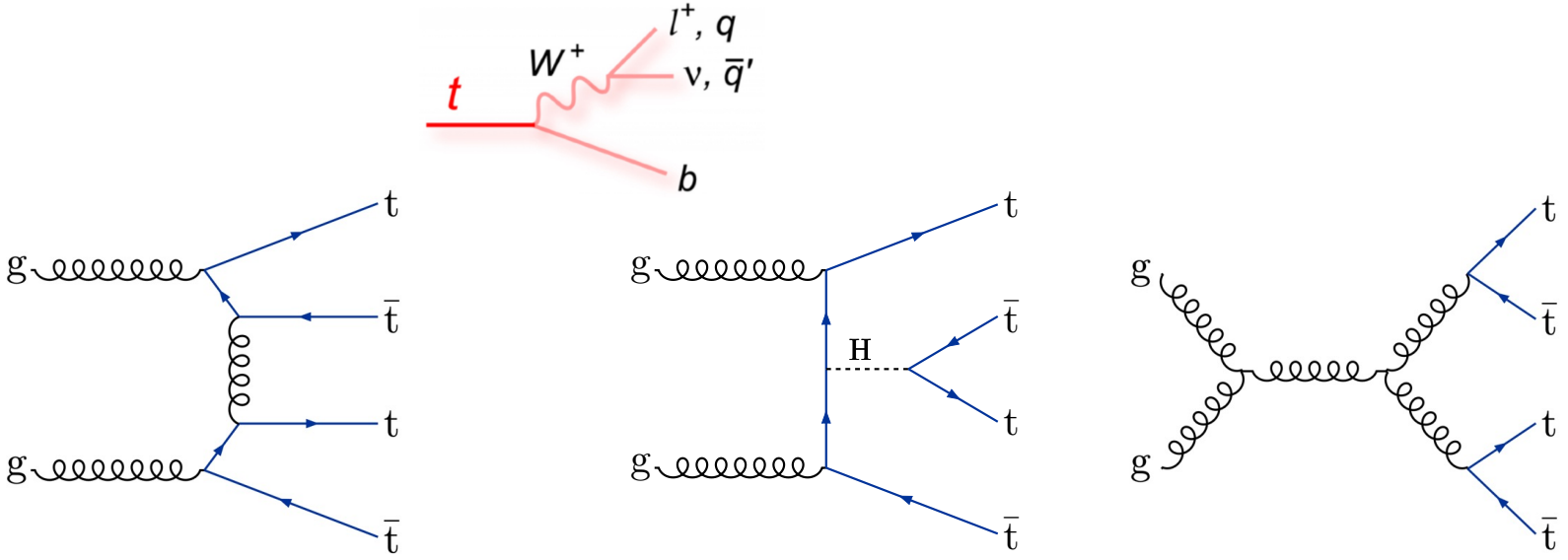
➢ Small tension of $\Delta\eta$ between two leptons

➢ Good quantitative agreement of unfolded data with all MC setups (considering the statistical and systematic correlation)

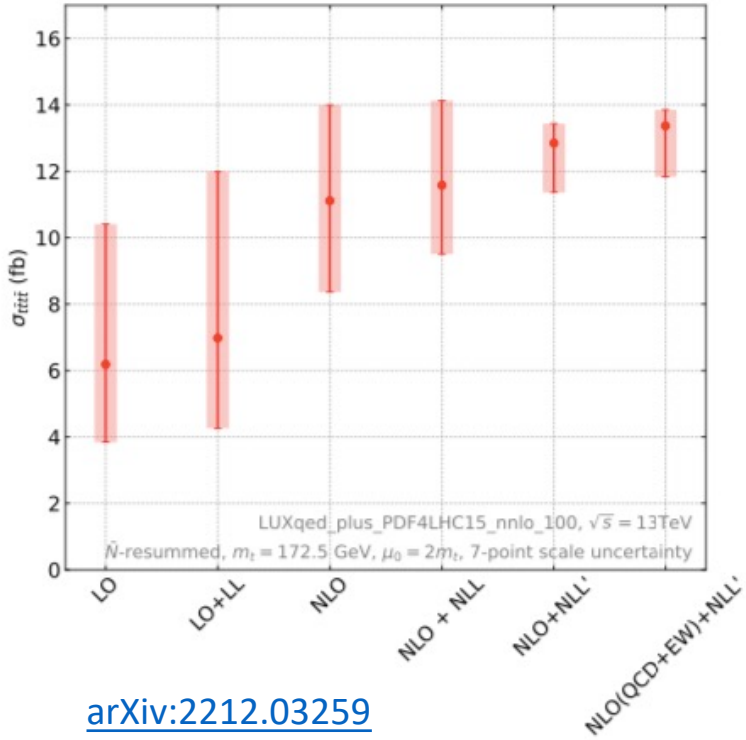
The four-top-quarks production at LHC

Production of four top quarks is very rare

- **NLO QCD:** $\sigma(t\bar{t}t\bar{t}) = \mathbf{12\ fb \pm 20\%}$ [JHEP02(2018)031]
- **NLO+NLL:** $\sigma(t\bar{t}t\bar{t}) = \mathbf{13.4\ fb \pm 11\%}$ [arXiv:2212.03259]



Examples of Feynman diagrams for SM $t\bar{t}t\bar{t}$ production at leading order in QCD and via an off-shell Higgs boson mediator



arXiv:2212.03259

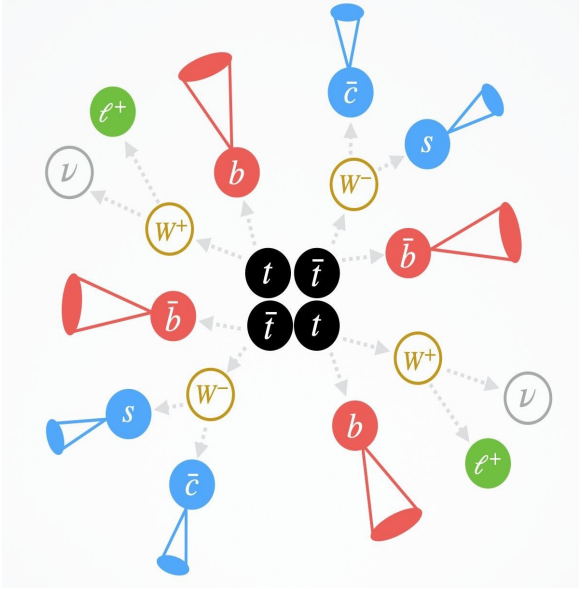
$\sigma_{t\bar{t}t\bar{t}}$ predictions

The four-top decays

Top quark decays to **b quark + W boson**
The most sensitive channel for **four-top** is:

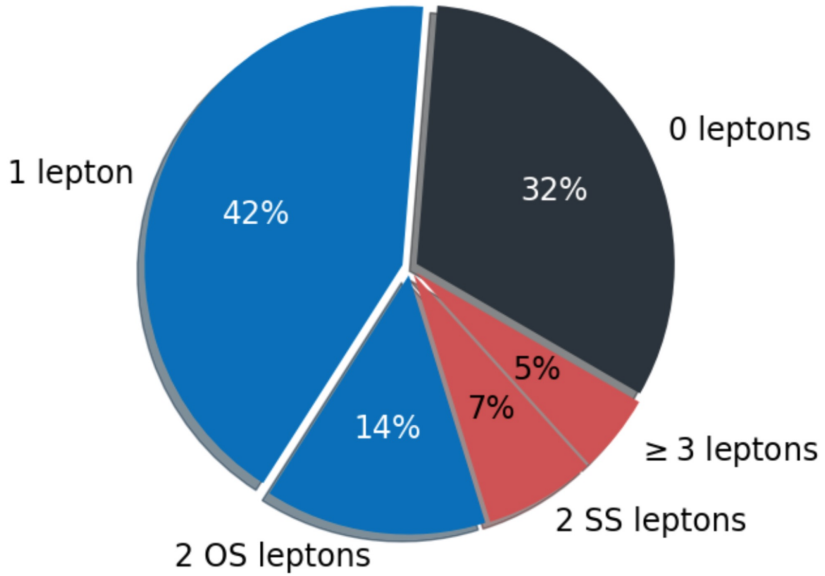
- **Multilepton final state:**
  2 Leptons Same Sign and 3 Leptons (2LSS/3L),
  13% branching ration, highest sensitivity – observation

* 2LSS/3L avoids the ttbar background that's dominant in 1L and 2LOS final states



Signature: high jet, b-jet multiplicities and High H_T

lepton	total jets	light/c jets	b-jets
SS	8	4	4
3L	6	2	



Background composition

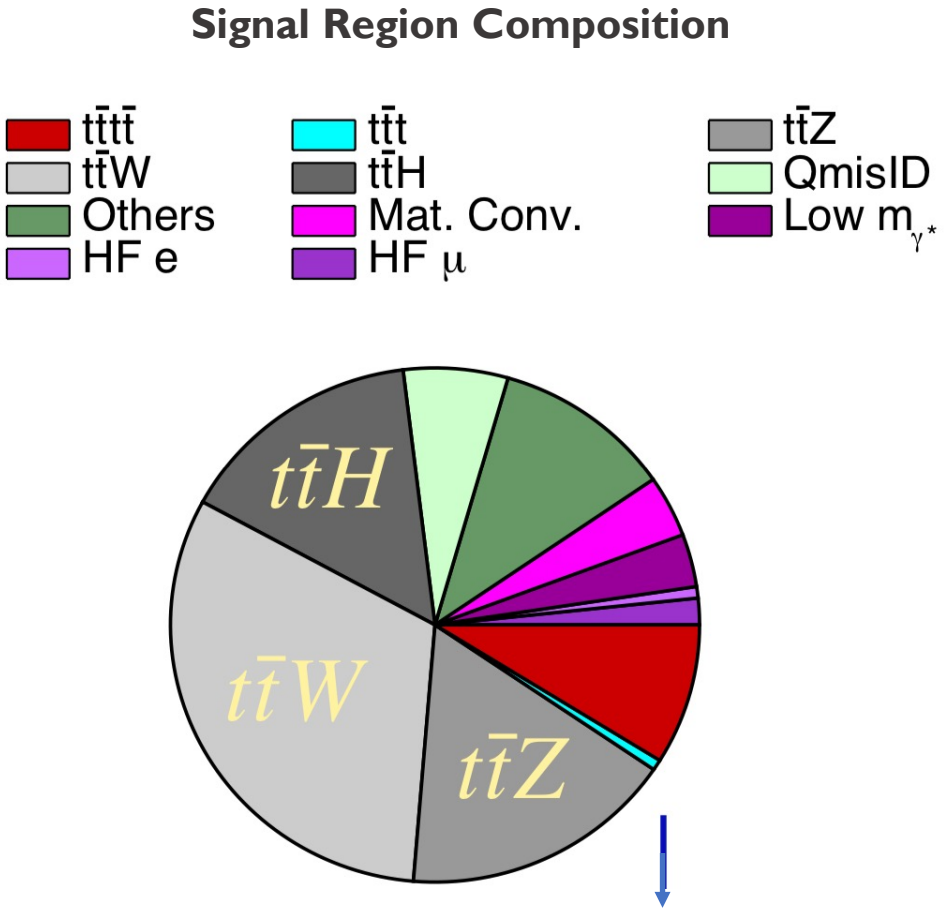
Signal region:
$\geq$ 6 jets $\geq$ 2b-jets and $H_T \geq$ 500 GeV

Main backgrounds:
- **Physical** background (~85%):
  $t\bar{t}Z$ + jets, $t\bar{t}H$ + jets, $t\bar{t}W$ + jets
- **Instrumental** background (~15%):
  Process with electron charge mis-identified
  Events with non prompt or fake leptons

$t\bar{t}W$ is the main background
Key process that is essential to study for its own

	SR
Total bkg	390 ± 50
$t\bar{t}t\bar{t}$	38 ± 4

- Novel **MVA** techniques bring improvement for **S/B** separation



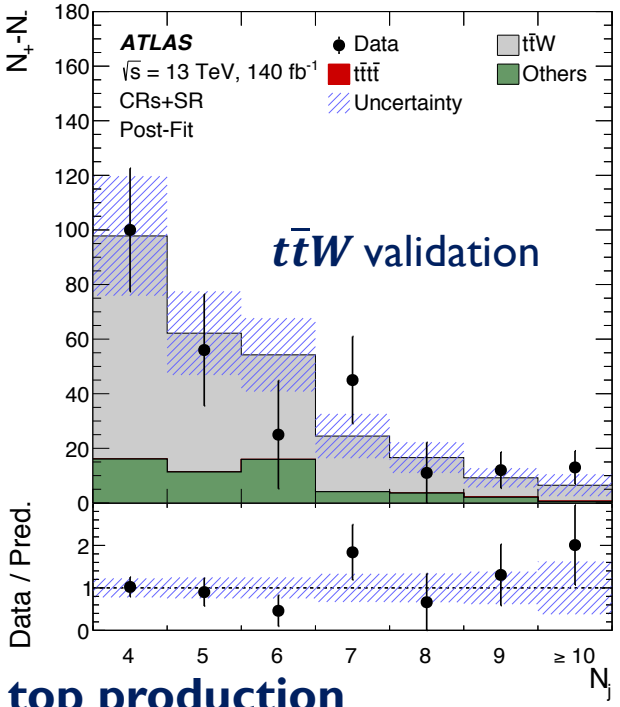
***ttt* is an important background given similar kinematic properties**

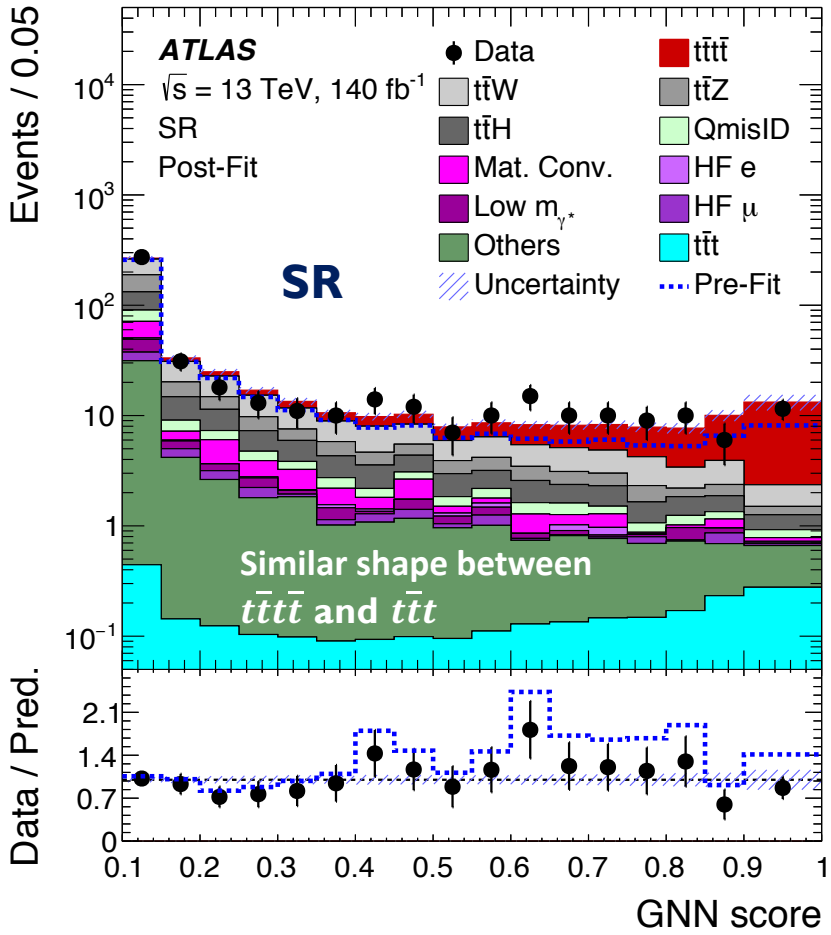
Four top cross section measurement

Eur. Phys. J. C 83, 496 (2023)

Analysis strategies are based on the **SM $t\bar{t}t\bar{t}$** evidence paper with several improvements [EPJC 80 (2020) 1085]

- **Re-optimized object selection**
- **$t\bar{t}W$ data-driven method fitting the N_{jets} dependence**
- **GNN** to extract the signal
- **Updated $t\bar{t}t$ modeling**





- Includes several **BSM** interpretations:
  - Limits on the cross-section of **three top production**
  - Measurement of value and **CP** properties of the **top Yukawa** Coupling
  - **EFT** interpretations for **four fermion** operators and **Higgs Oblique** parameters

Result use the full ATLAS Run-2 dataset of 140 fb^{-1} at 13 TeV

First observation of four-top production

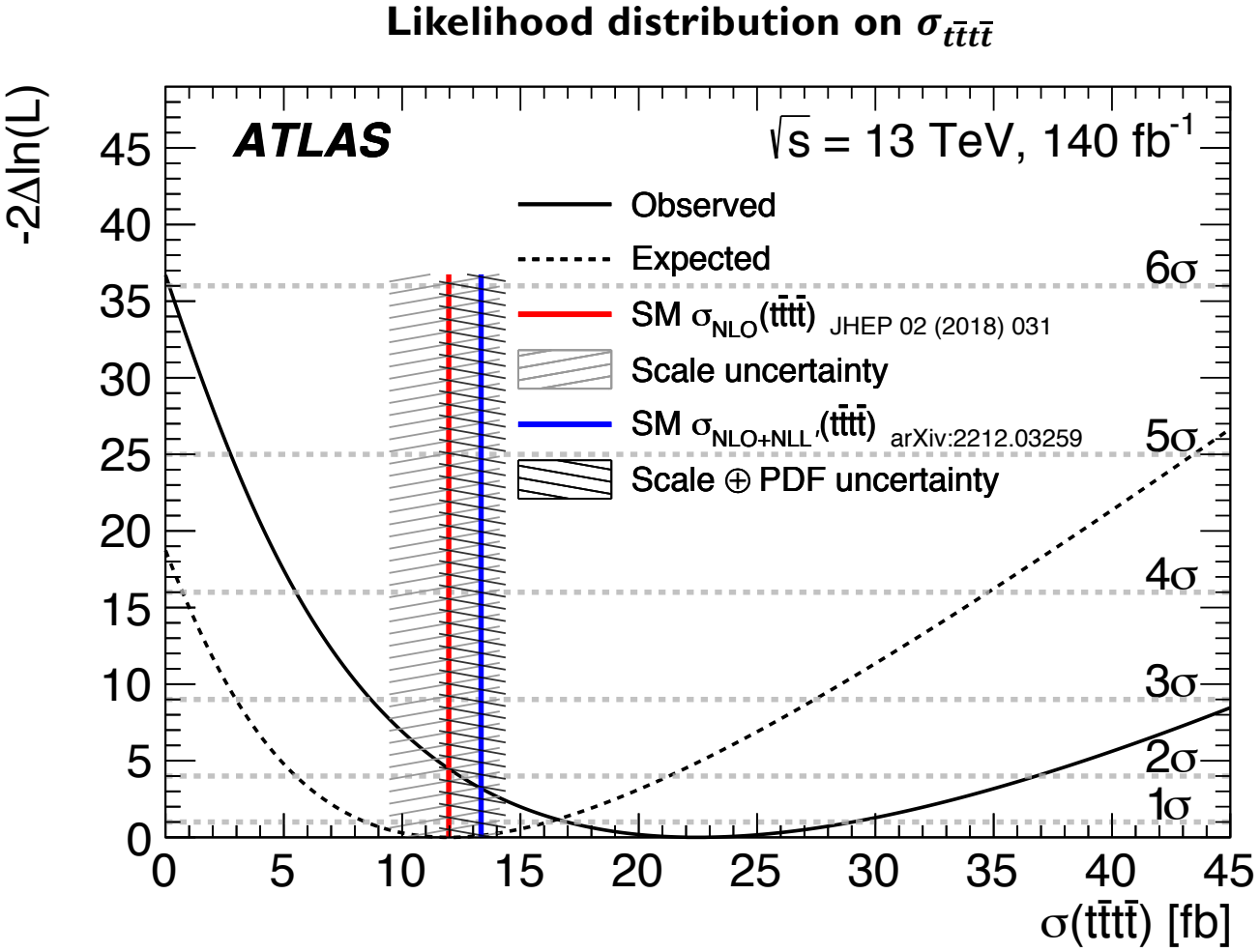
Eur. Phys. J. C 83, 496 (2023)

First observation of $t\bar{t}t\bar{t}$ production with an observed (expected) significance of **6.1σ (4.3σ) with GNN**

- $\mu = 1.9 \pm 0.4(\text{stat})^{+0.7}_{-0.4}(\text{syst}) = 1.9^{+0.8}_{-0.5}$
- $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.6}_{-3.4}(\text{syst})\ \text{fb} = 22.5^{+6.6}_{-5.5}\ \text{fb}$

With BDT: 6.0σ (3.9σ)

- **GNN** gave 10% higher sensitivity compared with the best **BDT** methods!



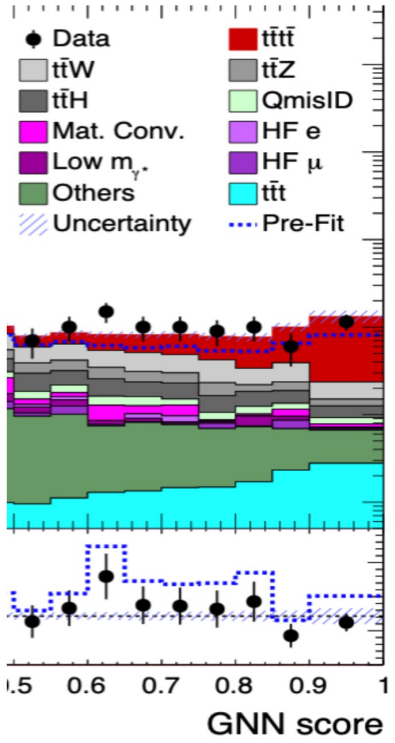
* Consistent with the **SM** within 1.8 standard deviations and with previous **ATLAS** measurement of 24^{+7}_{-6} fb

The interplay between Three top and Four top

Eur. Phys. J. C 83, 496 (2023)

Hard to distinguish three and four top production

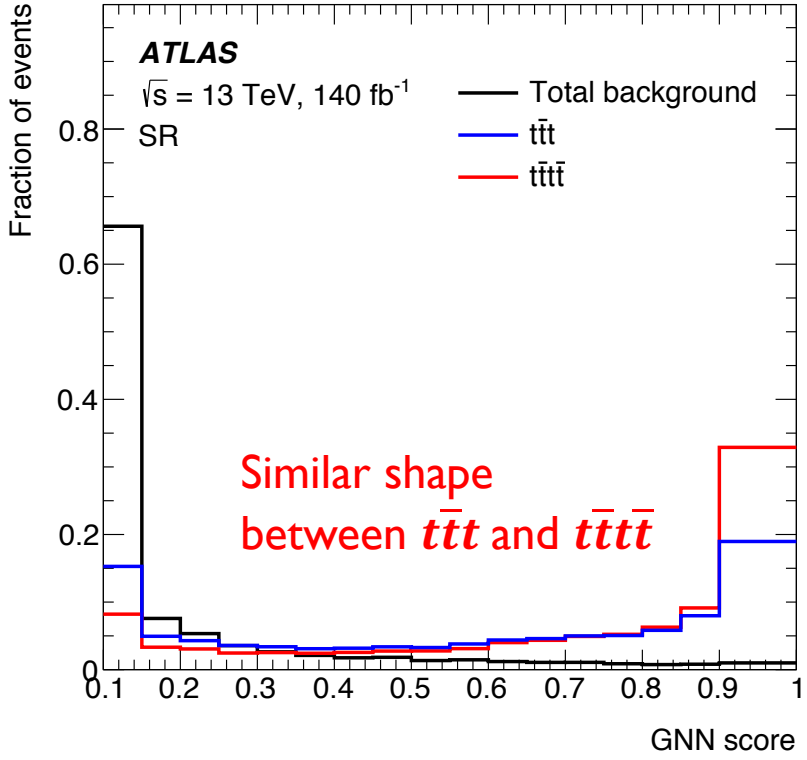
- Cross section ~10 times smaller than the four top process
- Very large correlation between the 2 processes : - 93%

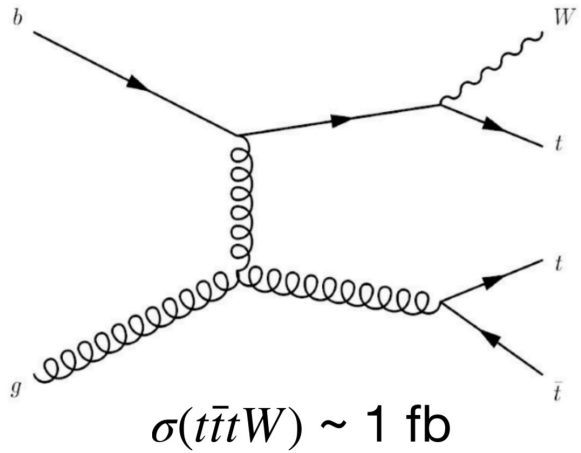


Final state signature is similar to **four-top** signal

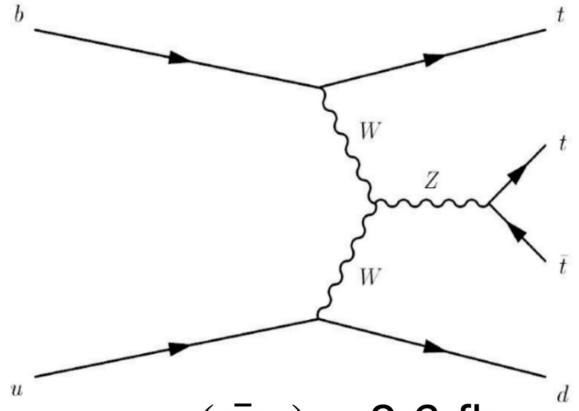
Populates region of high **GNN** score

$t\bar{t}t$





$\sigma(t\bar{t}tW) \sim 1$ fb



$\sigma(t\bar{t}tq) \sim 0.6$ fb

Interpretations

Eur. Phys. J. C 83, 496 (2023)

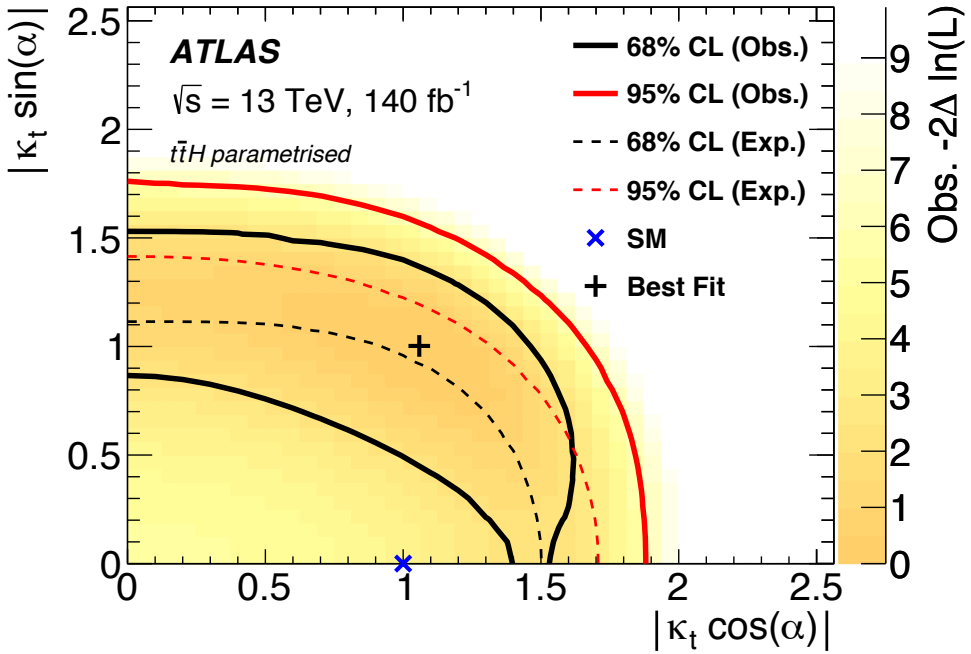
Top Yukawa coupling

Four top production sensitive to modification of the Higgs-top coupling

$$\mathcal{L} = -\frac{1}{\sqrt{2}}\kappa_t y_t \bar{t}\,(\cos\alpha + i\sin\alpha\gamma_5)\,th$$

CP even CP odd

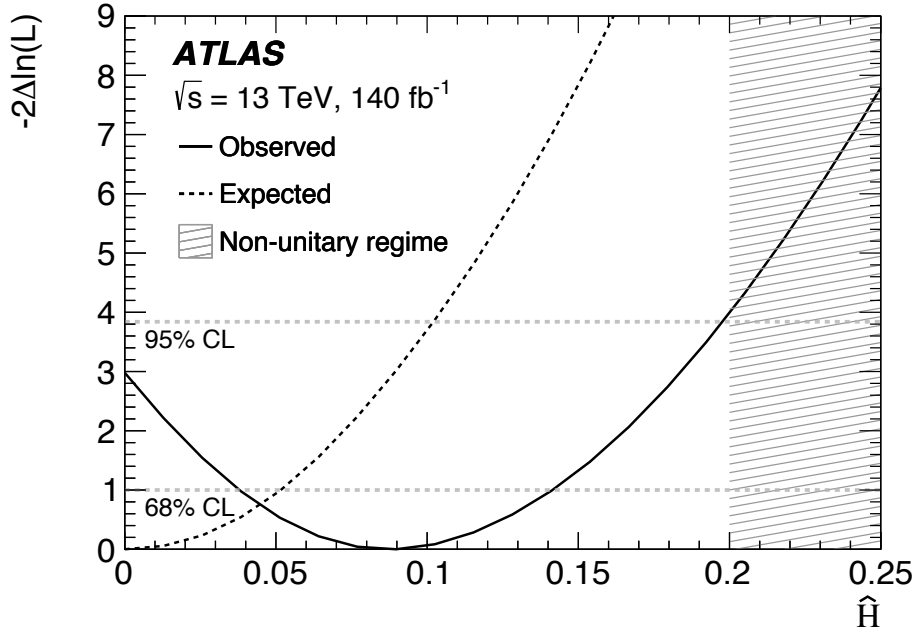
- **CP even, obs (exp) limit with $\alpha = 0$: $|k_t| < 1.8\ (1.6)$** ($t\bar{t}H$ parameterized vs k_t)
- **CP even, obs (exp) limit with $\alpha = 0$: $|k_t| < 2.2\ (1.8)$** ($t\bar{t}H$ free floating)



Higgs oblique parameter

Four top production can constrain dedicated dim-6 operators, e.g the four-fermion operators

Upper limit: $\hat{H} < 0.2$ ($\hat{H} = 0$ in SM)



Limits in EFT parameters

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

Summary

Measure inclusive, fiducial, and the first differential cross sections of $t\bar{t}W^{\pm}$ in multi-lepton final state

- Inclusive cross section is found to be higher than reference theory prediction and consistent with it at **1.5σ** level
- Normalised differential distributions agree with data
  - Expect to help improving future **MC** predictions
  - Will help data measurements sensitive to **$t\bar{t}W$** background

Four-top observation! First time ever! ⭐
Background only hypothesis rejected with a significance of **6.1σ**

- **SM** agreement remains just under **2σ** in all interpretations
- The results are used to set limits on several **BSM** scenarios

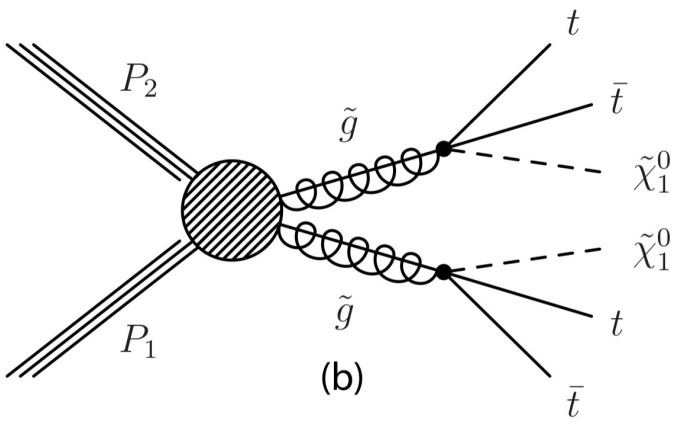
*** Both presented results use the full ATLAS Run-2 dataset of 140 fb^{-1} at 13 TeV**

Thank you for your attention!

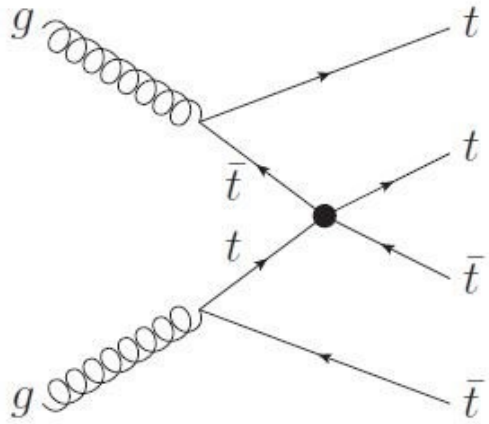
Back up

Exploring BSM

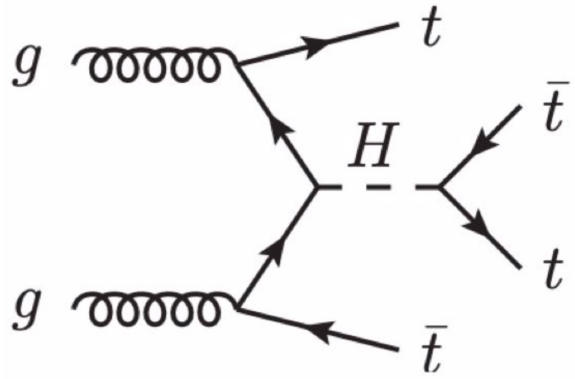
SUSY (gluino/sgluino pair, ..,)



Contact Interaction



2HDM



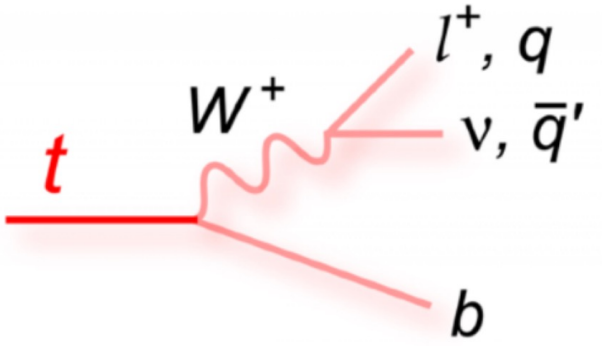
More likely to couple to new physics because of the mass of the top quark?

Measurement of the $t\bar{t}W$

Provides irreducible source of same-sign dilepton pairs

Main backgrounds:

- **Physical** background:
  $t\bar{t}H$, $t\bar{t}Z$, diboson
- **Instrumental** background:
  Fake lepton (template fit), and QmisID (Charge flip rate from data)



- $N_{jets} \geq 2$, among which one is tight b-tagged or two are loose b-tagged
- **3L**: dilepton (**OSSF**) or trilepton inv. mass again from the Z peak

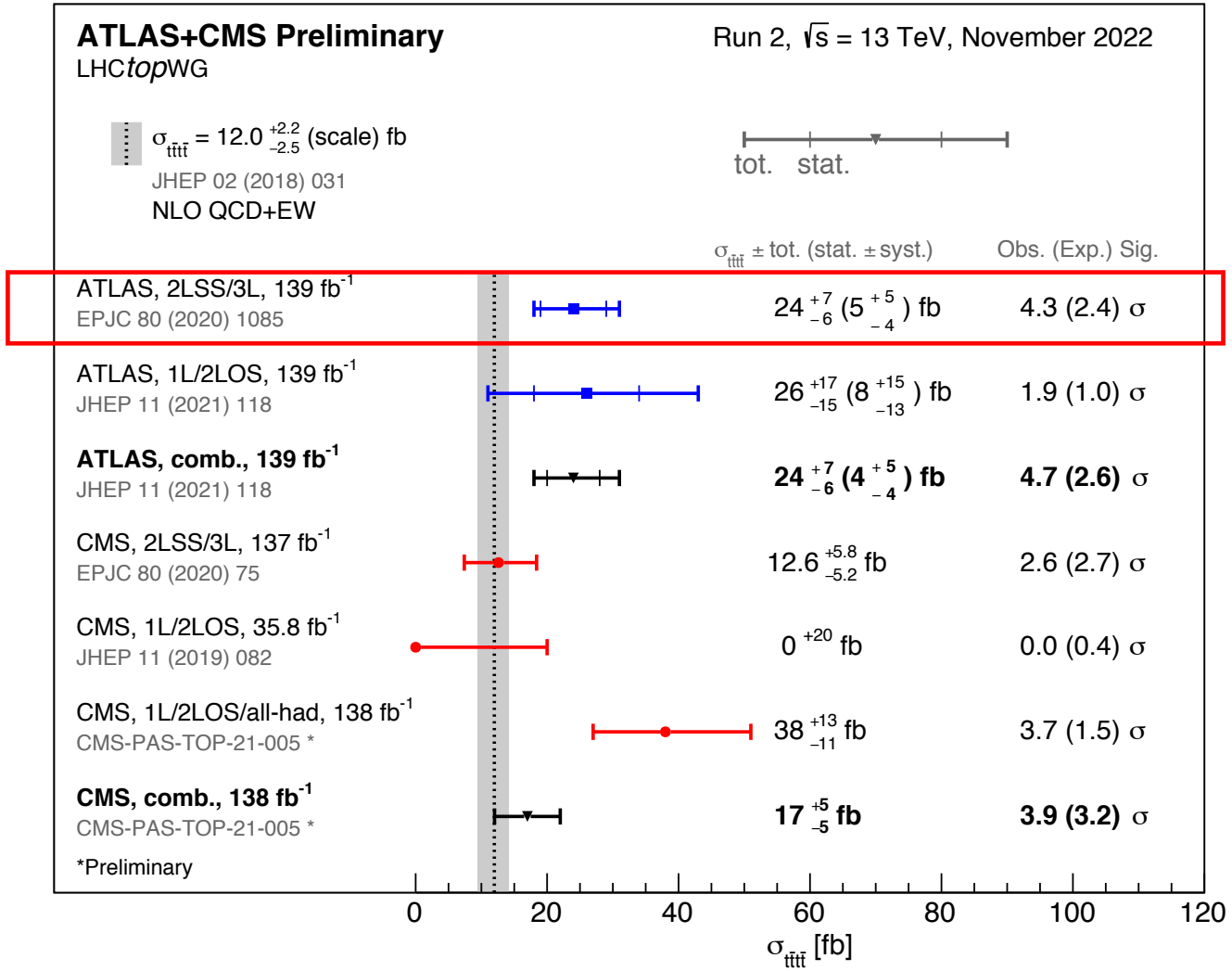
2LSS and **3L SR** split into charge, flavor, jet and b-jet multiplicities

* Both **ATLAS** and **CMS** observe 20-50% larger $\sigma(t\bar{t}W)$ than prediction → non-perturbative **QCD**, **EW** corrections, spin correlations, and off-shell effects, offer only partial explanation of data excess

The publication before the observation

Both **ATLAS** and **CMS** experiments had the combined measurements on four-top with **ATLAS** full Run-2 data

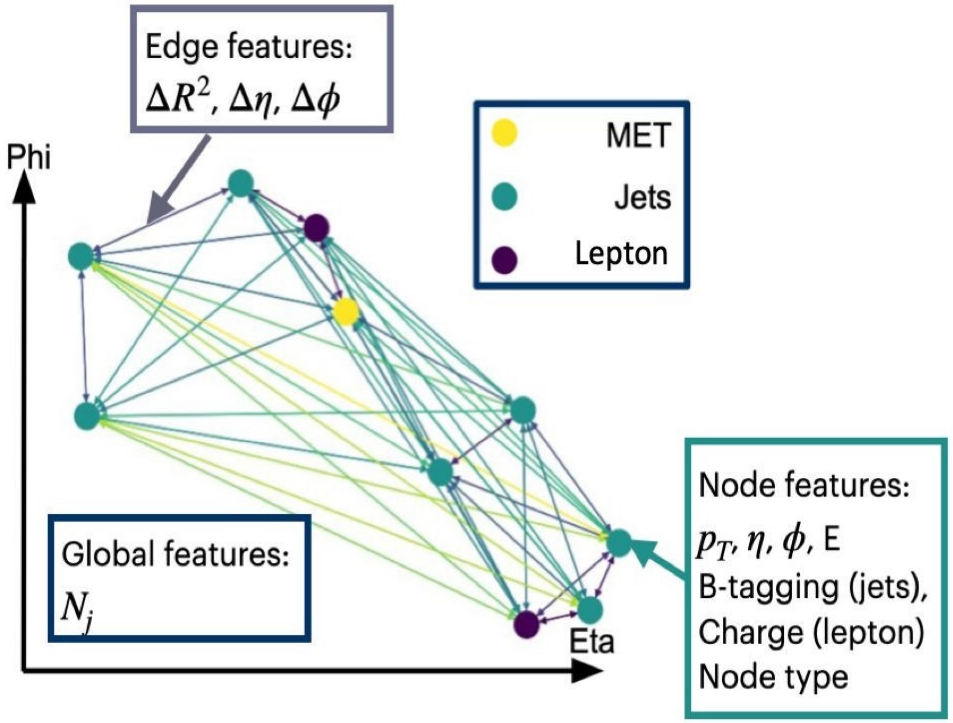
Both ATLAS/CMS experiments declared the evidence of the four-top, and re-optimized their analysis with the same Run2 data in **2LSS/3L** channel for the observation

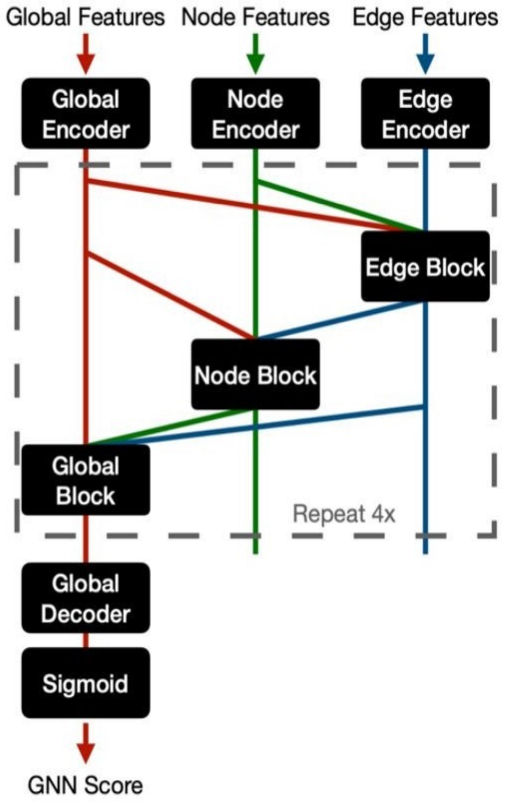


GNN multivariate analysis

The main challenge of the four-top signal extraction is the complicated final state

- The **G**raphic **N**eural **N**etwork (**GNN**, arxiv:1806.01261) combines information about all objects (**jets**, **leptons**, **MET**) from an event into a graph, with **node**, **edge** and **global** properties
- Message passing architecture allows network to learn complex features of the four-top process



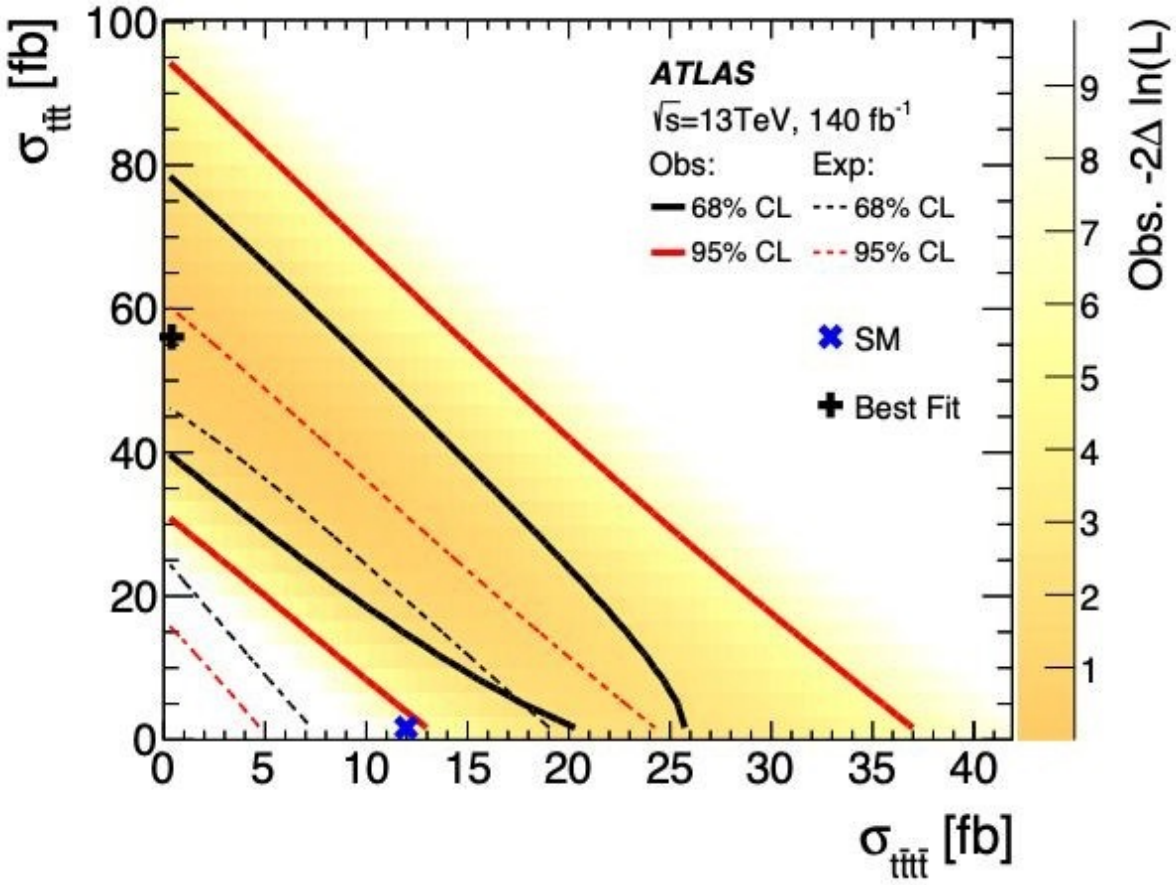


Three-top and Four-top measurements

Eur. Phys. J. C 83, 496 (2023)

- Strong anti-correlations between **three-top** and **four-top** cross-sections
- The simultaneous measurement is compatible with **SM** within **2.1** standard deviation
- Limits are set on **three-top** cross-sections assuming **four top** follows the **SM** or at its best-fit value ($\sigma_{t\bar{t}t\bar{t}}^{SM}$ = 1.67 fb)

Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

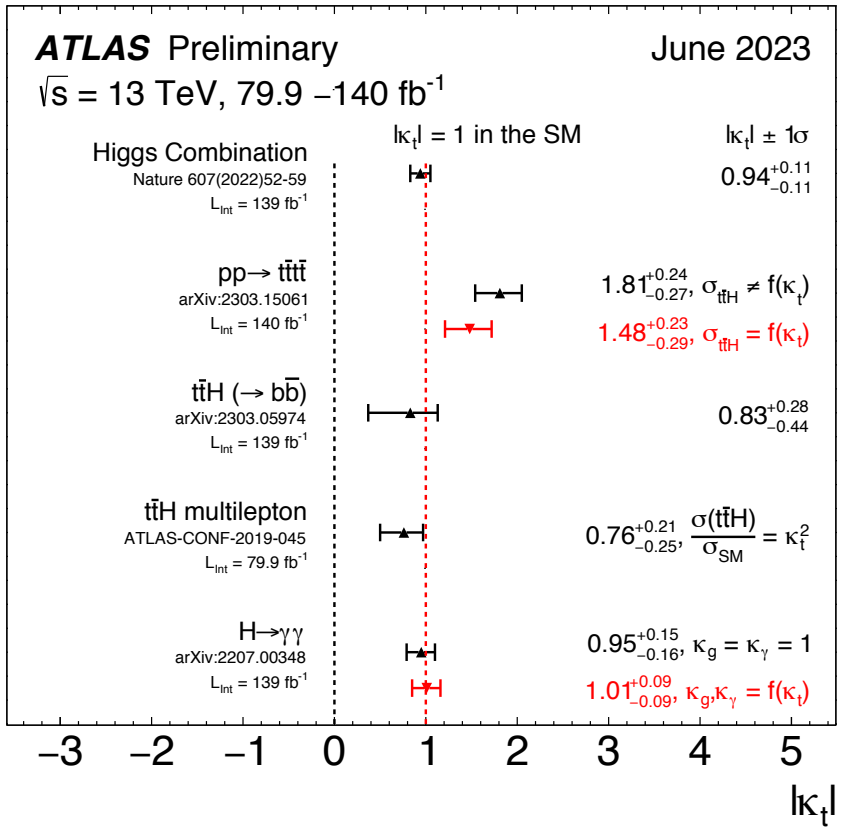


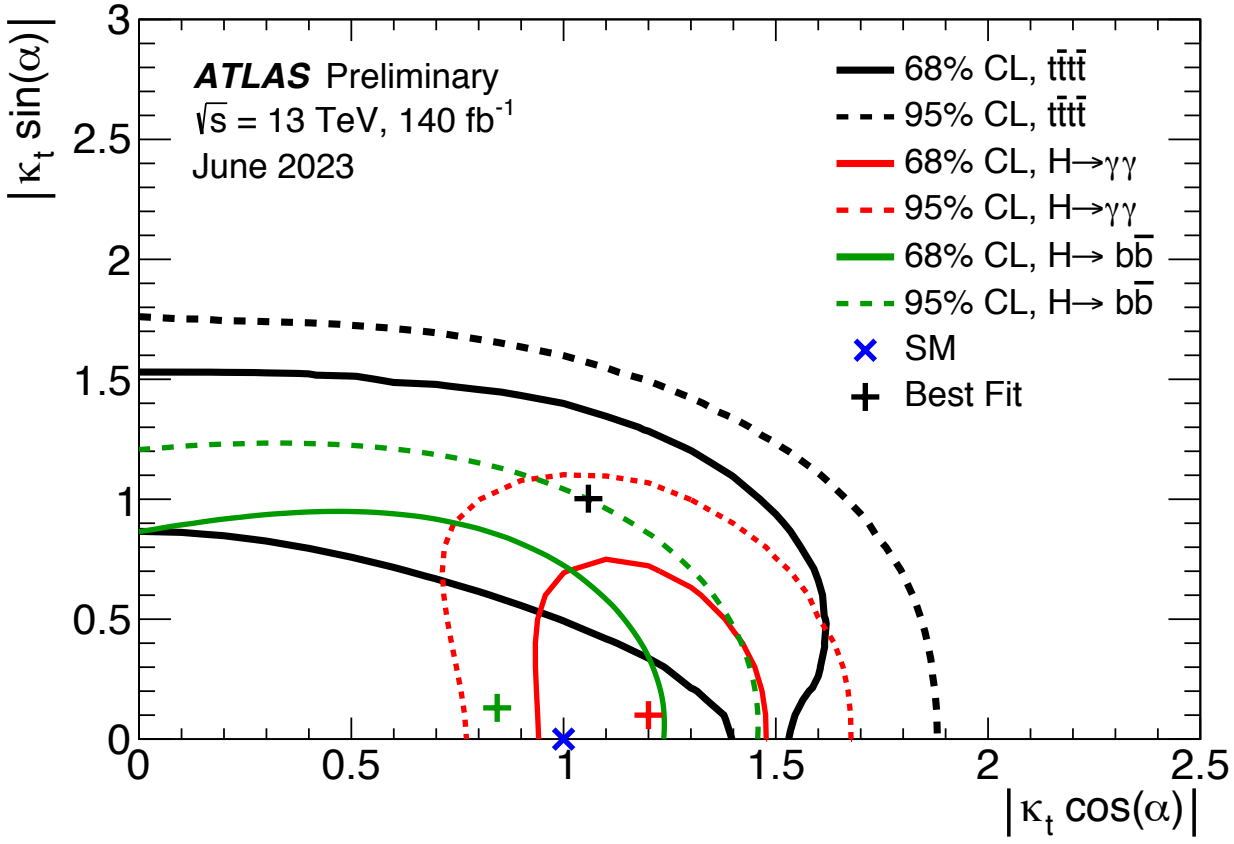
Top Yukawa extraction

ATL-PHYS-PUB-2023-013

The interpretation of the four top cross section in terms of the **Top Yukawa** includes the sensitivity of the $t\bar{t}H$ background

A fit where $t\bar{t}H$ is floated → an indication of the standalone sensitivity of four top





Summary of measurements of the **Top Higgs Yukawa** coupling modifier, $|k_t|$