Observation of 4-top-quarks and the determination of the Higgs boson width….

Paul Jackson (University of Adelaide)

on behalf of the ATLAS Collaboration

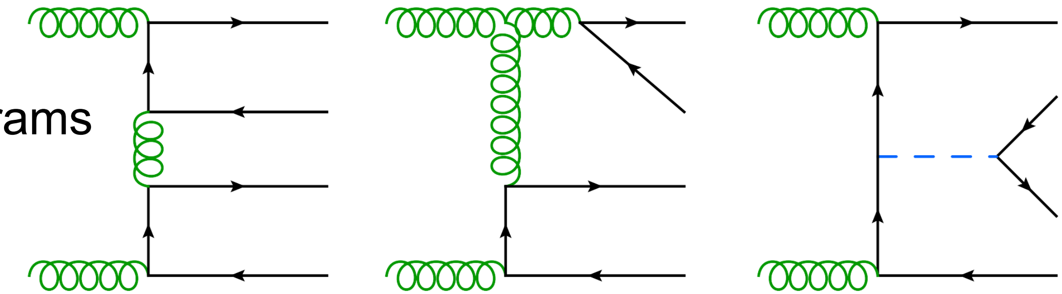
July 18th, 2024

ICHEP 2024 | PRAGUE

…..and a brief lesson in the songs of ‘The Four Tops’

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

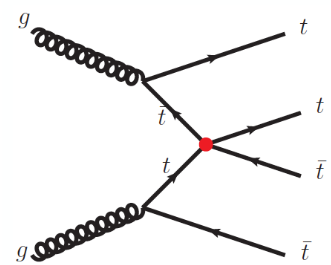
Very complicated process,
at LO 72 gg and 12 qq' initiated diagrams



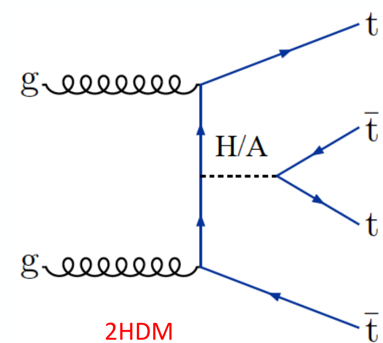
Leading: $O(\alpha_S^4)$

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

- **Sensitive to top-Yukawa coupling (y_t)**
  - **non-SM value can dramatically change the production via off-shell Higgs**



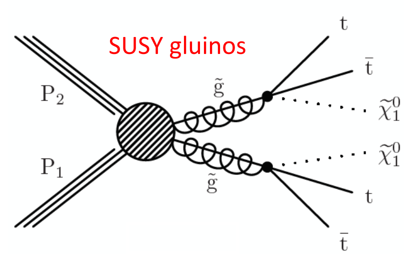
Four-fermion contact interaction



2HDM scalar/pseudoscalar

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

SUSY gluinos



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ATLAS EXPERIMENT

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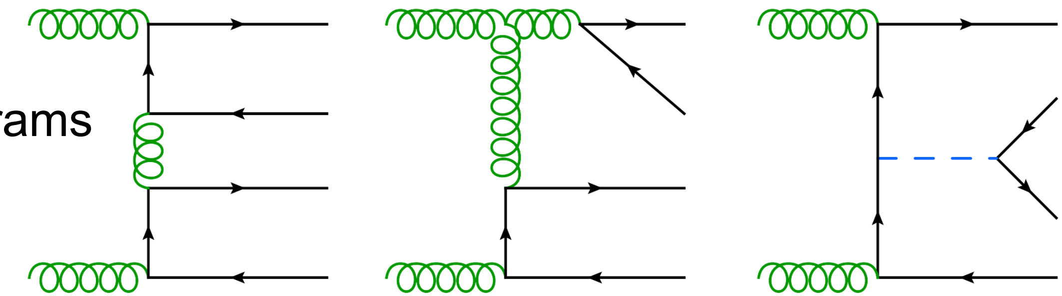

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From the Four Tops fourth studio album 'Reach Out'

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$t\bar{t}t\bar{t}$ production

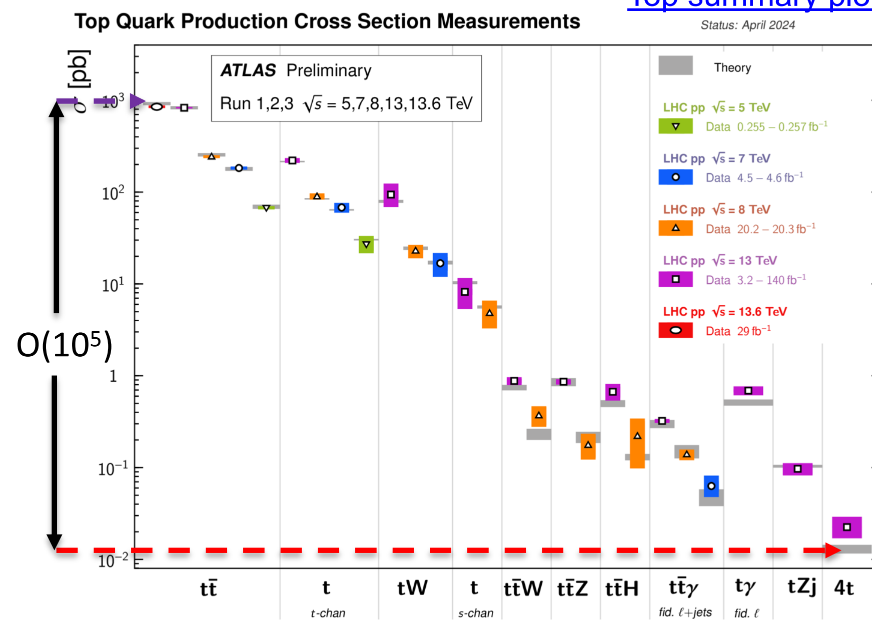
[Eur. Phys. J. C 83 (2023) 496](#)
[Eur. Phys. J. C 84 (2024) 156](#)

[Top summary plots](#)

One of the heaviest LHC final states

NLO QCD: $\sigma(t\bar{t}t\bar{t})$ = 12 fb ±20% [JHEP 02 (2018) 031]
NLO+NLL: $\sigma(t\bar{t}t\bar{t})$ = 13.4 fb ±11% [PRL 131 (2023) 211901]

O(100M) tt events and O(1k) tt tt events



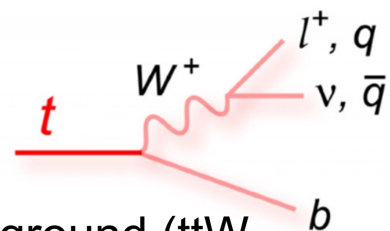
Signatures:

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.

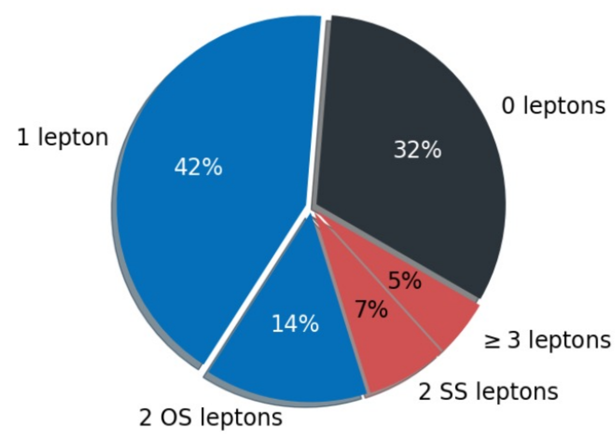
1ℓ/2ℓOS: 1ℓ (42%) / **2ℓOS** (14%)

- Dominant branching fraction, but large irreducible background from tt+jets, tt+heavy flavour jets



2ℓSS/3ℓ: 2ℓSS (7%) / **3ℓ** (5%)

- Low branching fraction, but small background (ttW, ttZ, non-prompt leptons, charge misidentification)
- *Most sensitive channel*



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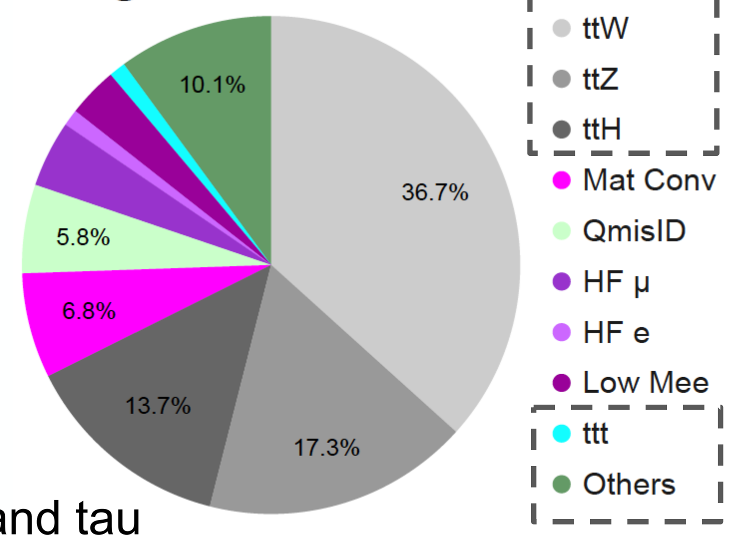
$t\bar{t}t\bar{t}$: 2lSS/3l channel strategy

- Targets clean leptonic signatures where at least 2 W bosons decay leptonically
- Selection requirements:
  - 2 same-sign leptons *or* 3 leptons (ℓ=e,μ)
  - **≥ 6 jets** (pT > 25 GeV)
  - **≥ 2 b-tagged jets**
  - H_T > 500 GeV

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

Backgrounds:



- Irreducible backgrounds: Leptons from W, Z and tau
  - **ttW (36.7%)**, **ttZ (17.3%)**, and **ttH (13.7%)**
    - Processes with SS and multi-lepton+jets (with additional light and b-tagged jets)
  - **Smaller backgrounds: (10% Others) + ttt** Diboson, triboson, VH+jets, ttWW, tWZ, tZq

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

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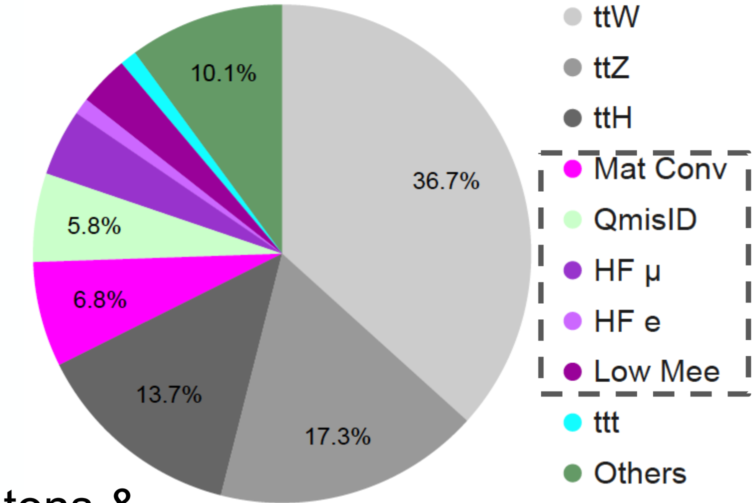

- Reducible backgrounds: fake/non-prompt leptons & charge misidentified leptons
  - electrons(muons) from heavy-flavour decay, HF e/μ
  - Electrons from γ conversions in detector, Mat Conv
  - a virtual photon leading to an e^+e^- pair, Low M_{ee}
- Charge mis-assignment, **charge mis-ID (5.8%)**:
  - Relevant for the 2lSS channel (mostly for electrons)

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$t\bar{t}t\bar{t}$ background estimation

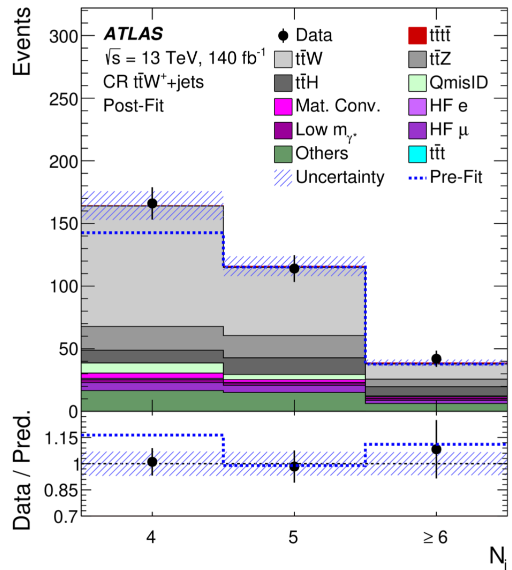
- $t\bar{t}Z$+jets and $t\bar{t}H$+jets background:

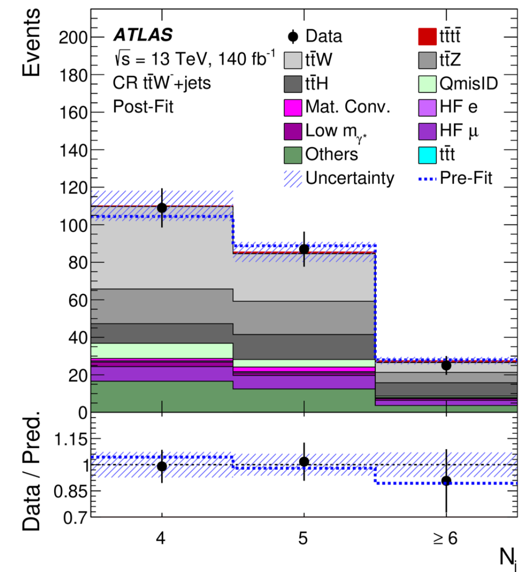
- From simulation

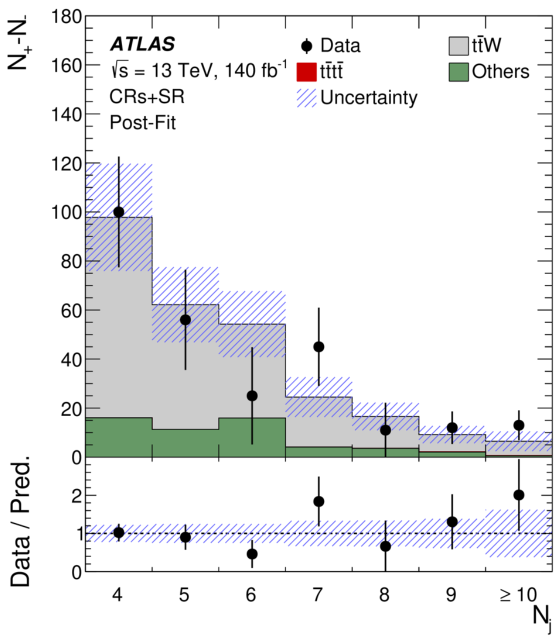
- $t\bar{t}W$+jets background:

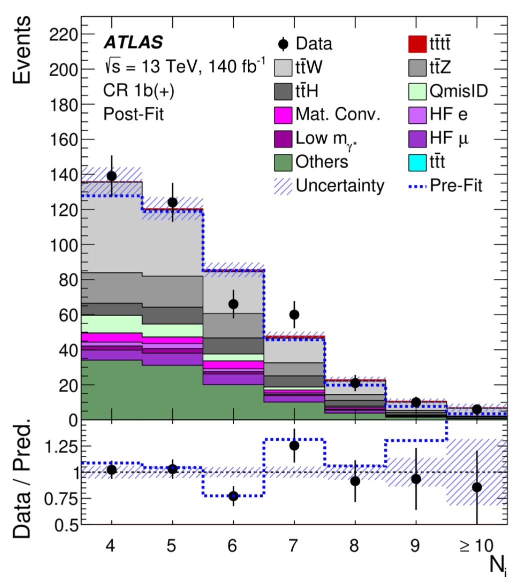
- Njets dependence fitted to data using 4 free parameters
- 4 control regions with 1 b-tag jet and with low H_T, split by charge

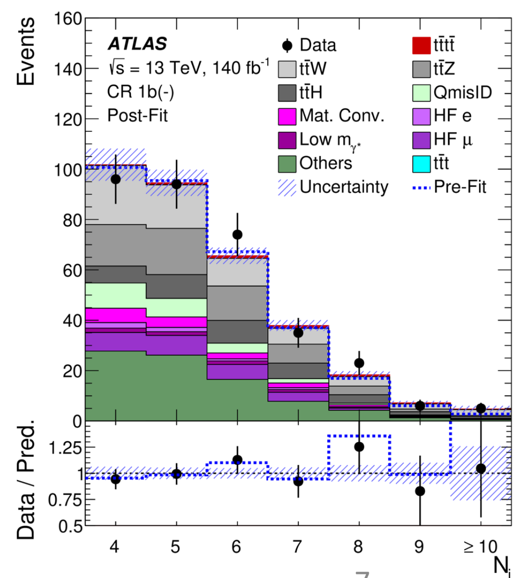
$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^+(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^-(4\mathrm{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$











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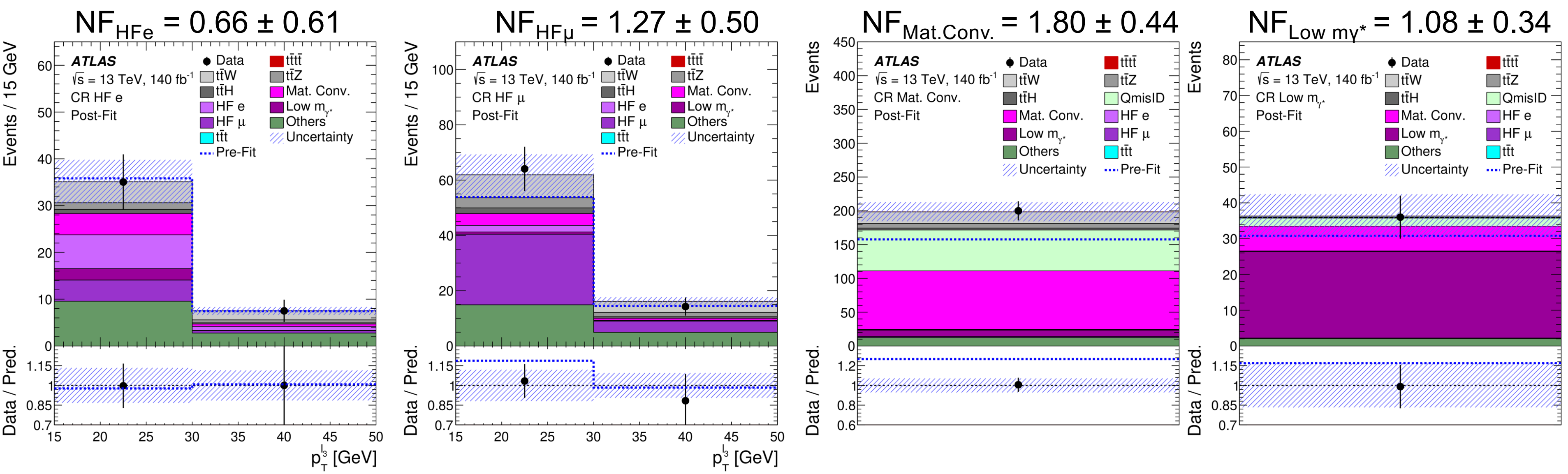
$t\bar{t}t\bar{t}$ background estimation

- Fake/non-prompt lepton background
  - Shape from MC, normalisation from data using control regions enriched in fakes (low jets multiplicity, low H_T (from jets))
- Charge mis-ID
  - Charge flip rate from data



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

- Production cross section measured via a simultaneous profile likelihood fit of the GNN score in the signal region and of discriminating variables in 8 control regions
- The measured tttt signal strength is found to be:

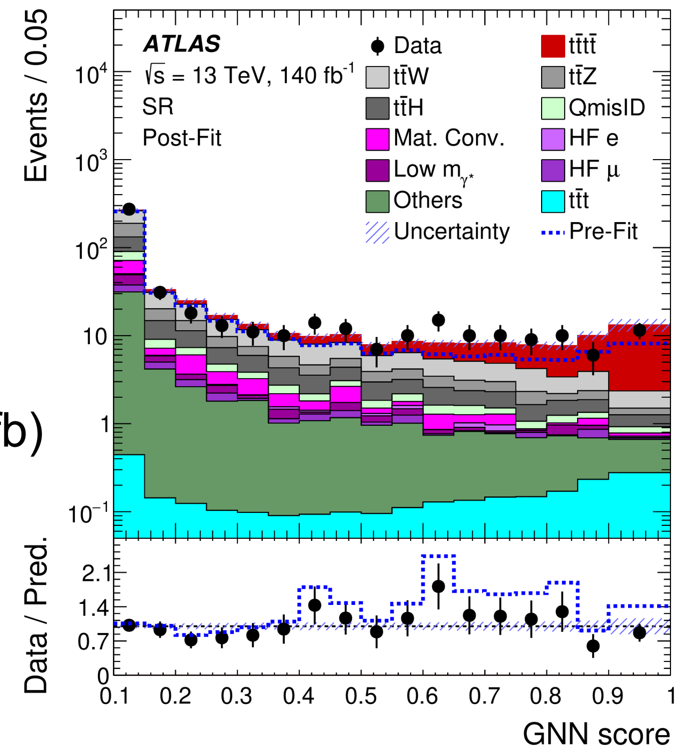
$$\mu = 1.9 \pm 0.4(\text{stat})\ ^{+0.7}_{-0.4}(\text{syst})$$

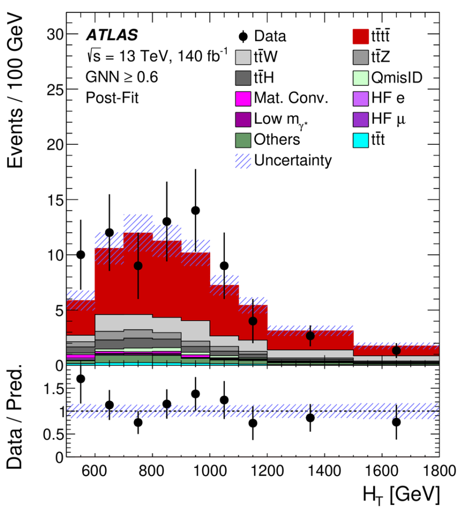
- Cross section:

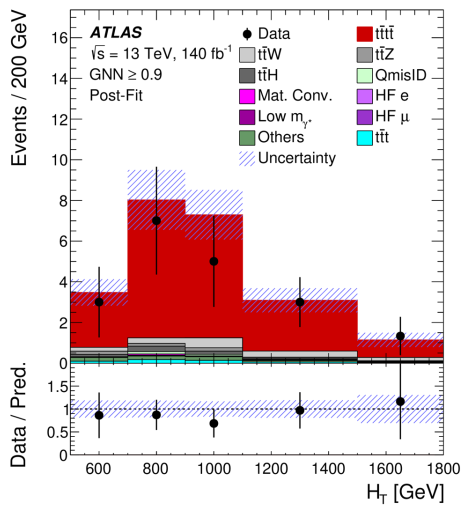
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\ ^{+4.6}_{-3.4}(\text{syst})\ \text{fb}$$

Compatible at 1.8 sigma with the SM prediction (12 fb)
Largest systematic uncertainties on signal modelling

Expected significance: 4.3 σ (wrt 12 fb) /4.7σ (wrt 13.4 fb)
Observed significance 6.1 σ







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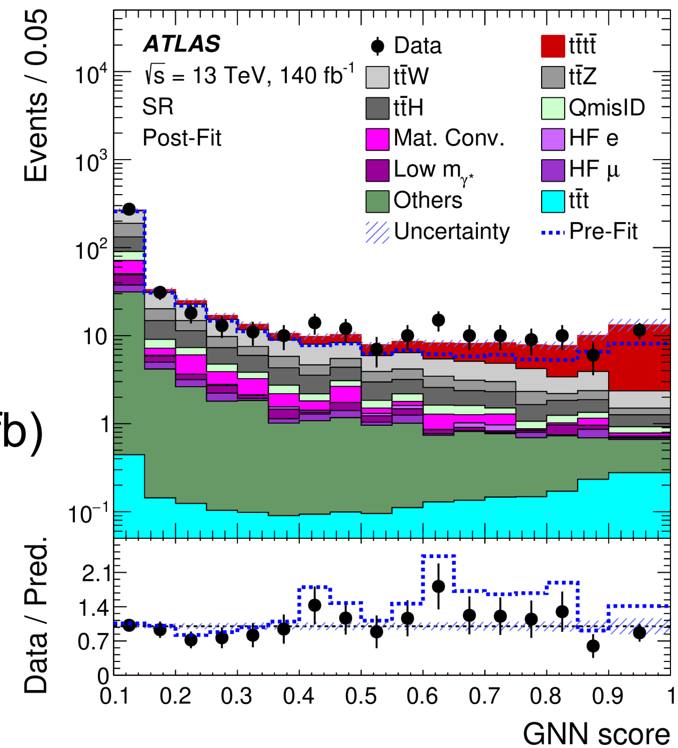

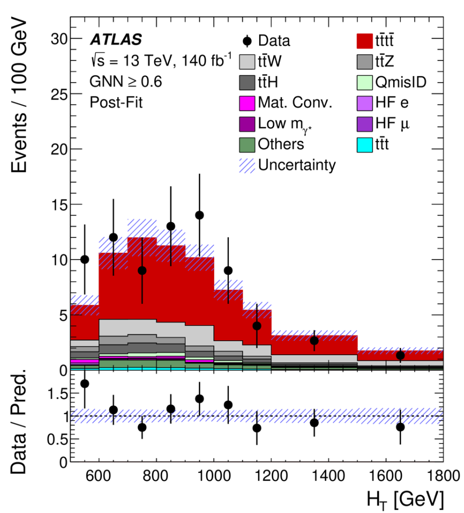

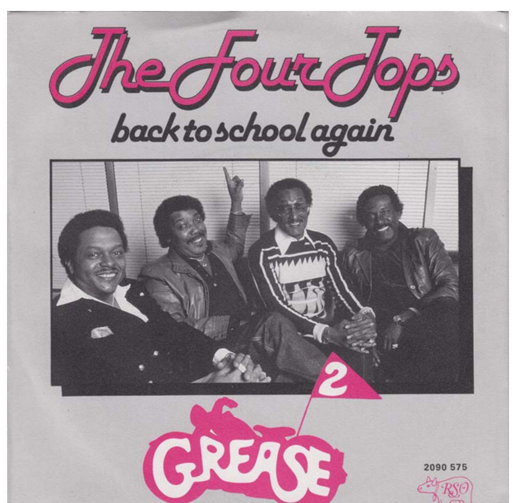

Main gain in sensitivity due to:
- updated lepton and jet selection and uncertainties
- use of the GNN discriminant
- improved treatment of the $t\bar{t}t$ background

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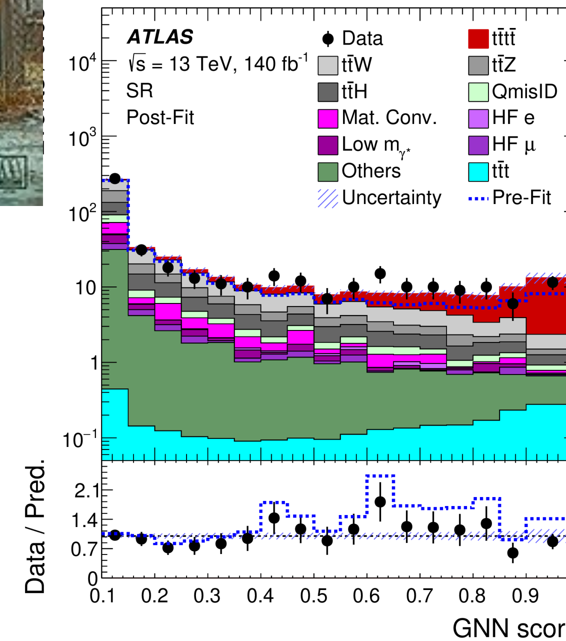
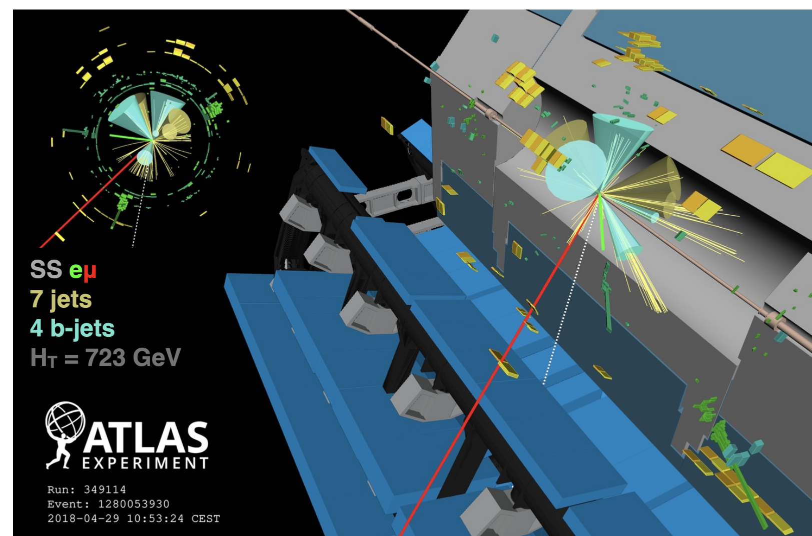
‘It’s the way Nature Planned It’ – The Four Tops (1972)

	Pre-fit		Post-fit	
	SR	GNN≥0.6	SR	GNN≥0.6
$t\bar{t}W$	130 ± 40	9 ± 4	127 ± 35	12 ± 4
$t\bar{t}Z$	72 ± 15	3.4 ± 1.8	79 ± 15	4.4 ± 2.0
$t\bar{t}H$	65 ± 11	4.6 ± 1.3	68 ± 10	5.0 ± 1.4
QmisID	27 ± 4	1.78 ± 0.26	27 ± 4	1.80 ± 0.24
Mat. Conv.	16.5 ± 2.3	0.73 ± 0.25	30 ± 8	1.4 ± 0.5
HF e	3.1 ± 1.0	0.4 ± 0.5	2.3 ± 2.4	0.3 ± 0.4
HF μ	7.1 ± 1.2	0.31 ± 0.15	9 ± 4	0.41 ± 0.22
Low m_{γ^*}	14.1 ± 2.0	0.52 ± 0.19	15 ± 5	0.56 ± 0.22
Others	47 ± 11	3.9 ± 1.2	50 ± 10	4.3 ± 1.2
$t\bar{t}t$	2.9 ± 0.9	1.5 ± 0.5	2.9 ± 0.9	1.5 ± 0.5
Total bkg	390 ± 50	26 ± 5	412 ± 21	32 ± 4
$t\bar{t}t\bar{t}$	38 ± 4	25.2 ± 3.2	69 ± 15	45 ± 10
Total	430 ± 50	51 ± 7	480 ± 19	77 ± 8
Data	482	83	482	83





[Eur. Phys. J. C 83 (2023) 496](https://doi.org/10.1140/epjc/s10052-023-11573-0)
Eur. Phys. J. C 84 (2024) 156

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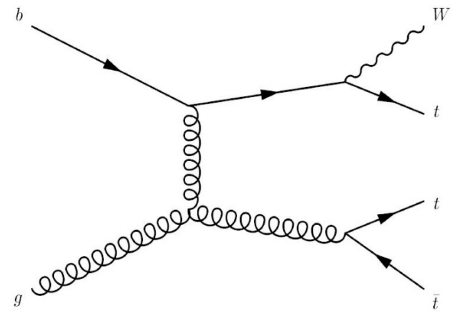
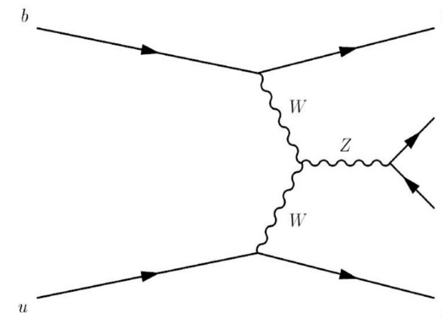
4-top as a path to 3-top

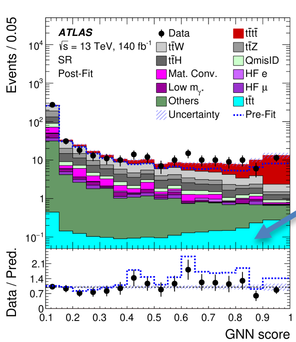
- SM ttt production
  - Cross section ~ 10 times smaller than the tttt process
  - Still very signal like
  - Currently no experimental constraints
- Free floating both tttt and ttt in the fit
  - Very large correlation between the ttt and tttt processes : - 93%

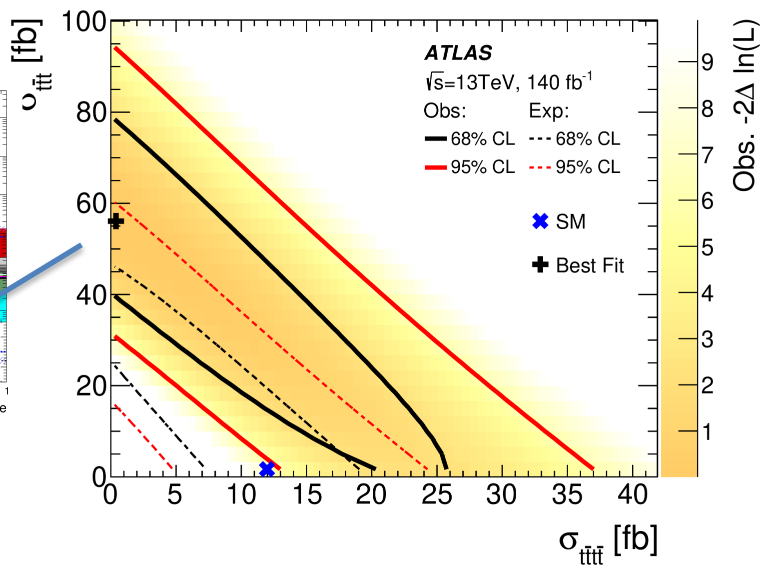


$\sigma(t\bar{t}t\,W) \sim 1$ fb



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





Use the 2D likelihood scan to set limit on $t\bar{t}t$ production

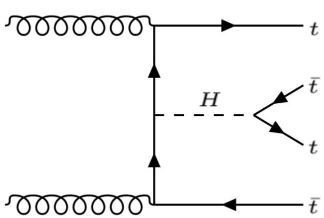
Processes	95% CL cross section interval [fb] with $\mu_{t\bar{t}t\bar{t}} = 1$	95% CL cross section interval [fb] with $\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

4-top to constraint New Physics

ATLAS EXPERIMENT

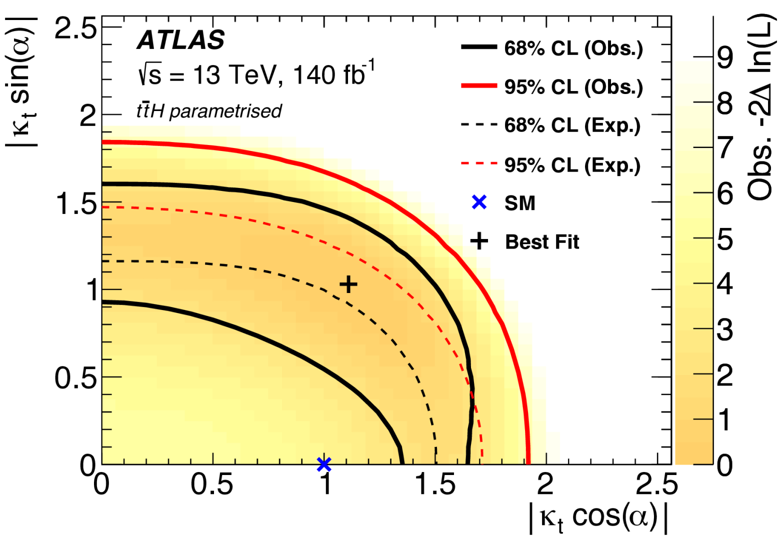
- Top Yukawa coupling

- tttt production sensitive to modification of the Higgs top coupling
- Need to account for the ttH background



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

Obs (exp) limit with α= 0: $|\kappa_t| < 1.9\ (1.6)$



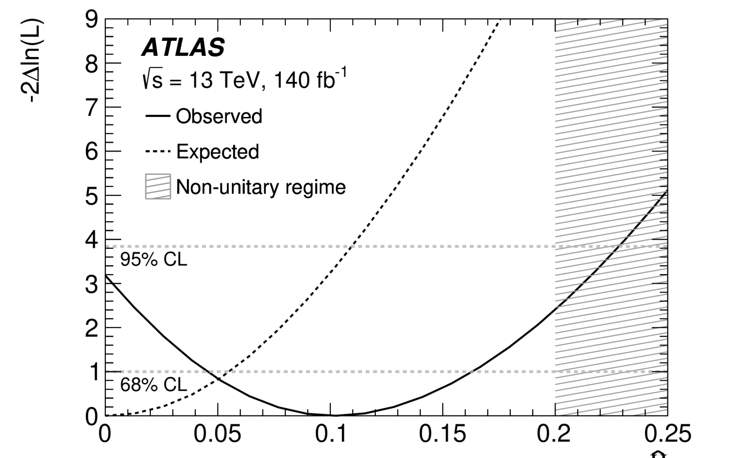
- EFT parameters

- tttt production sensitive to modification of the four heavy fermion operators

Limits of four heavy-fermion operators (one operator at a time)

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
$\mathcal{O}^1_{QQ}$	[−2.5, 3.2]	[−4.0, 4.5]
$\mathcal{O}^1_{Qt}$	[−2.6, 2.1]	[−3.8, 3.4]
$\mathcal{O}^1_{tt}$	[−1.2, 1.4]	[−1.9, 2.1]
$\mathcal{O}^8_{Qt}$	[−4.3, 5.1]	[−6.9, 7.6]

- Also sensitive to self-energy correction of the Higgs boson $\hat{H}$ that affects off-shell Higgs interaction ($\hat{H}$=0 in the SM)



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4-top → Higgs width

Higgs width from the Top Yukawa Coupling

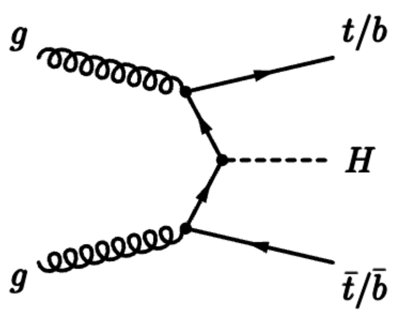
$$\frac{d\sigma}{dm^2} = \frac{g_{i,SM}^2 g_{f,SM}^2 \kappa_i^2 \kappa_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

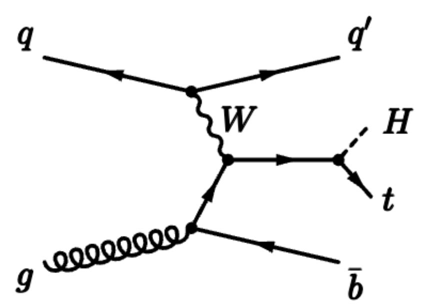
$$\mu_{i\to H\to f} = \frac{\sigma_i \times \mathrm{B}(H \to f)}{\sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)} = \frac{\kappa_i^2 \kappa_f^2}{R_\Gamma}$$

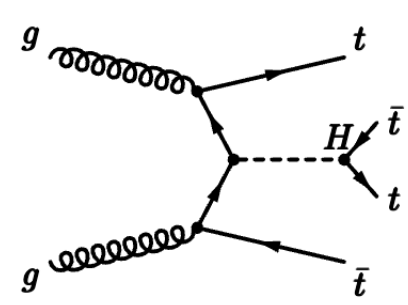
The Higgs total width is a potential indicator of Higgs decays to undetected BSM particles.

Direct measurements from the Higgs lineshape are limited by detector resolution.

Processes with an off-shell Higgs measure Higgs couplings independently of the width.





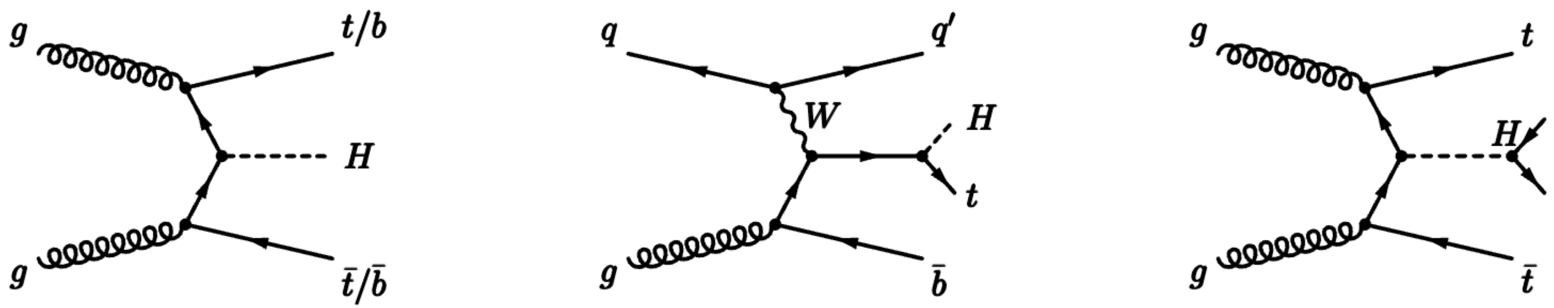


Higgs width from the Top Yukawa Coupling

$$\frac{d\sigma}{dm^2} = \frac{g^2_{i,SM} g^2_{f,SM} \kappa_i^2 \kappa_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \qquad \mu_{i\to H\to f} = \frac{\sigma_i \times \mathrm{B}(H\to f)}{\sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H\to f)} = \frac{\kappa_i^2 \kappa_f^2}{R_\Gamma}$$

This has been exploited in the ZZ* and WW* channels to measure the Higgs width in a combination of on- and off-shell measurements.

The measurement of the top Yukawa coupling in tttt production opens a new channel in the Higgs width measurement program.

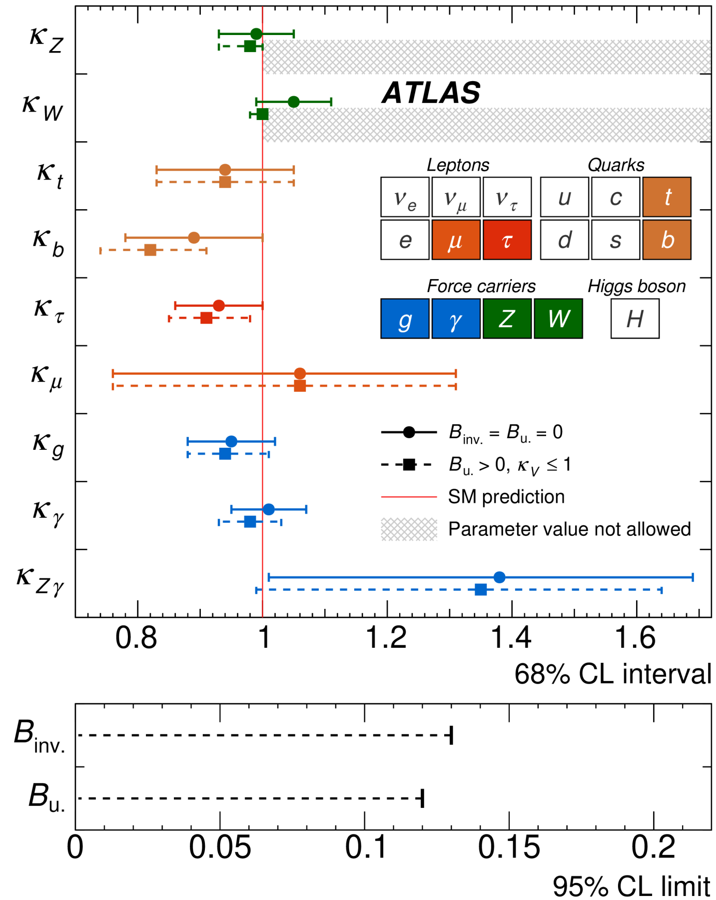


Combination Strategy

Take measurements of the on-shell Higgs production and decay based on the 2022 combination published in Nature, the ttH (ML) channel is removed.

- 15 measurements included covering all major Higgs production and decay modes.

- Measurement of off-shell Higgs production from tttt quark observation (presented earlier)
- All measurements parameterised in the kappa framework with Higgs width left as a free parameter.
- Full statistical combination of the input analyses with systematics correlated as appropriate



Limits on Γ_H and κ_t

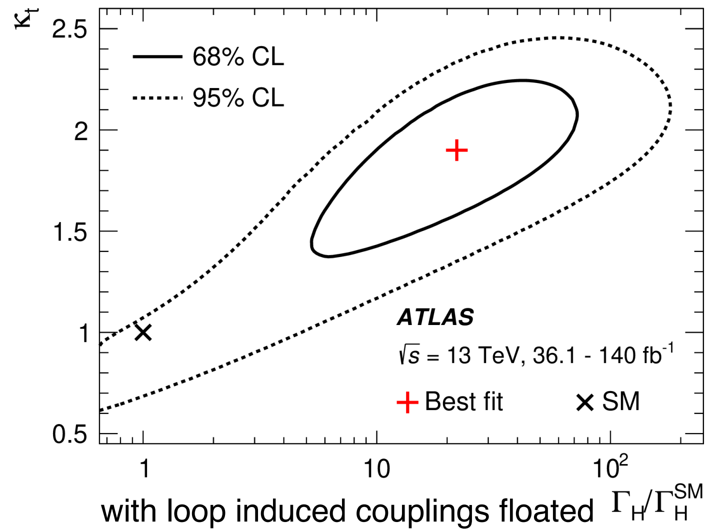
https://arxiv.org/abs/2407.10631
Public Plots

- Observed (expected) 95% CL limit: Γ_H < 445 (75) MeV
- If we parameterize the loop-induced Higgs couplings in terms of the tree level couplings to SM particles, the limit becomes Γ_H < 157 (55) MeV.

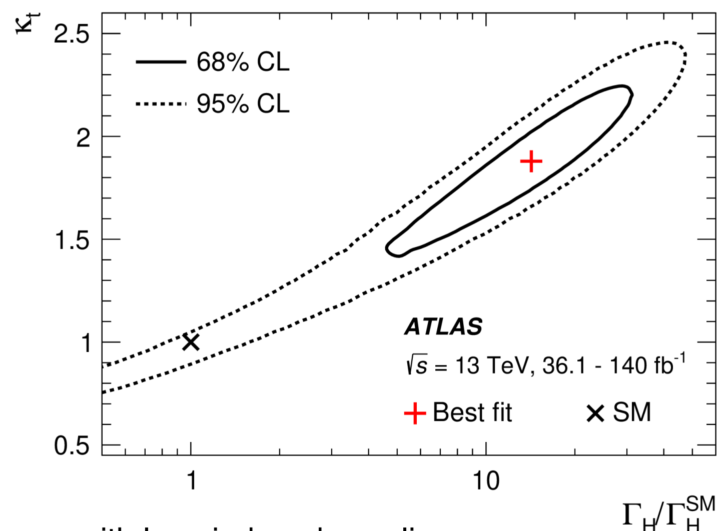
First constraint of the Higgs width based on off-shell measurements of the top Yukawa coupling

Less sensitive than VV* measurements, but no assumption on contributions from new physics to the gluon-gluon fusion loop

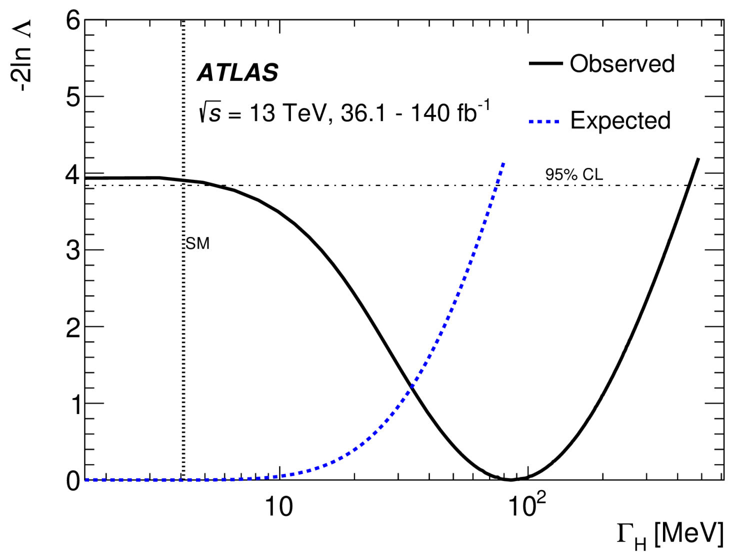
2D limit contours



with loop induced couplings floated



with loop induced couplings parameterized by tree-level



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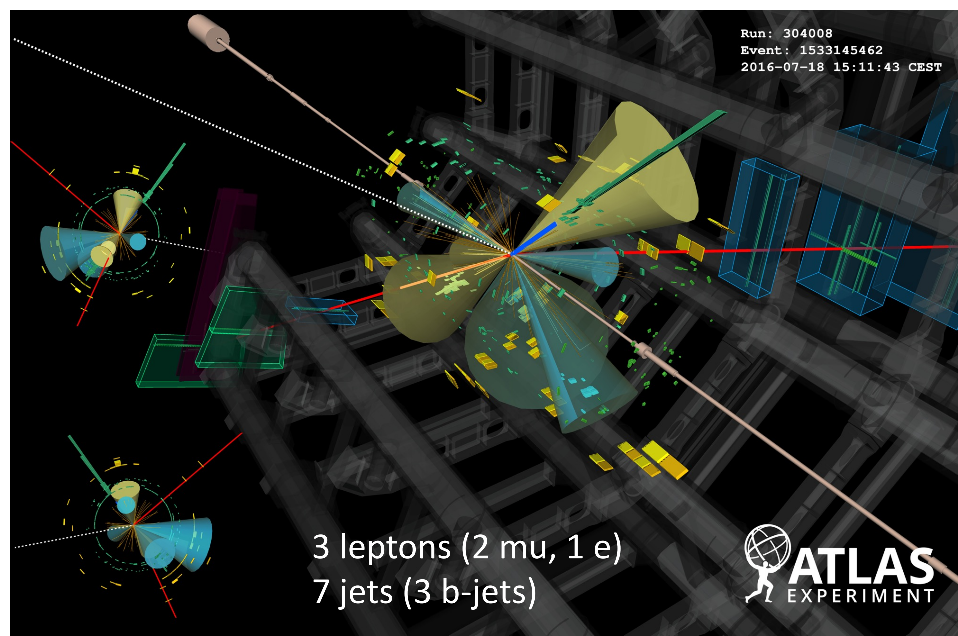
Summary

- ATLAS published an observation of 4-top-quark production in the 2L same-sign and multi-lepton final state in 2023.
- The results have been used to make a measurement of the constraint on the Higgs boson width.
- We look forward to furthering this physics program with the Run 3 data collected throughout the run.



ATLAS EXPERIMENT

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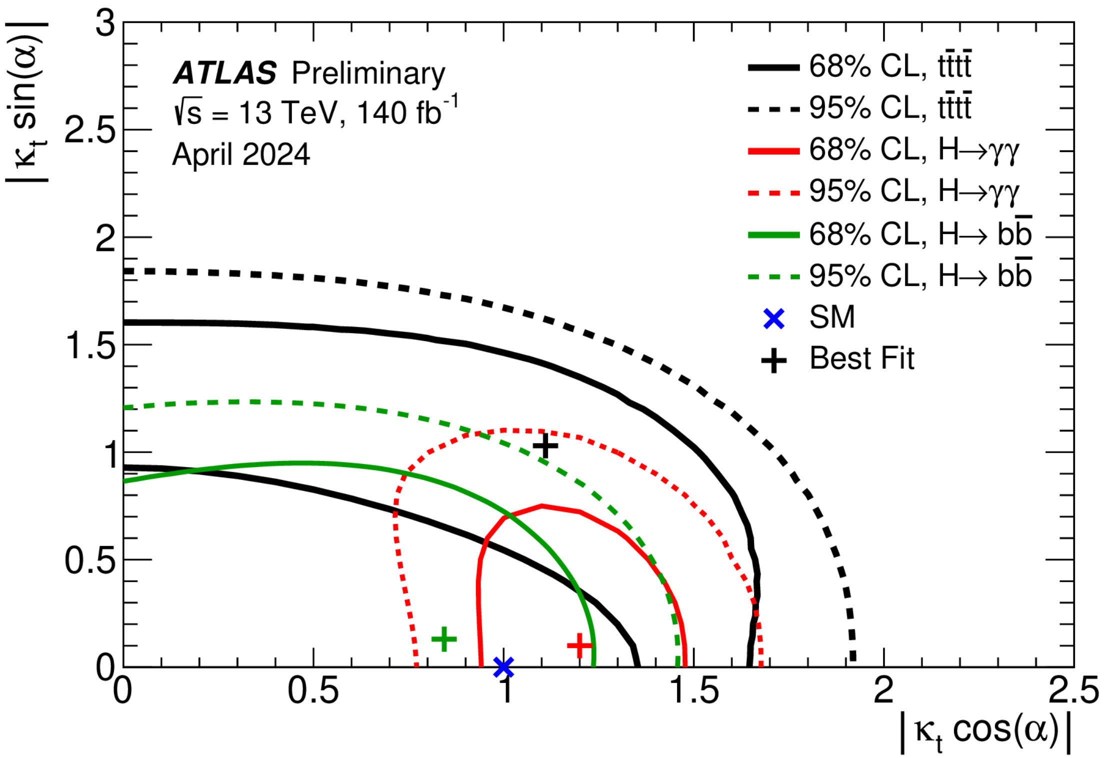
Backup



[2024 Pub note plots]

Summary of the two-dimensional confidence limit contours for $\kappa_t \cos(\alpha)$ and $\kappa_t \sin(\alpha)$ at $\sqrt{s}$ = 13 TeV with the ATLAS experiment. Here, κ_t represents the top-Higgs Yukawa coupling strength modifier in the Kappa formalism, while α describes the admixture of CP-even and CP-odd components in this coupling. The solid lines depict the 68% CL limits, while the dashed lines indicate the 95% CL limits on $\kappa_t \cos(\alpha)$ and $\kappa_t \sin(\alpha)$ from the $t\bar{t}t\bar{t}$ observation, Higgs CP property measurements with $H \rightarrow \gamma\gamma$, and Higgs CP property measurements with $t\bar{t}H(\rightarrow b\bar{b})$. The "+" markers denote the observed best-fit values from these three measurements, while the "×" marker represents the SM expectation (κ_t = 1, α = 0). In the $H \rightarrow \gamma\gamma$ measurement, the rates of the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ processes are constrained by results from combined Higgs boson coupling measurements. All other couplings in these measurements are fixed to the values predicted by the SM. This plot was modified in April 2024 to integrate updated $t\bar{t}t\bar{t}$ results.

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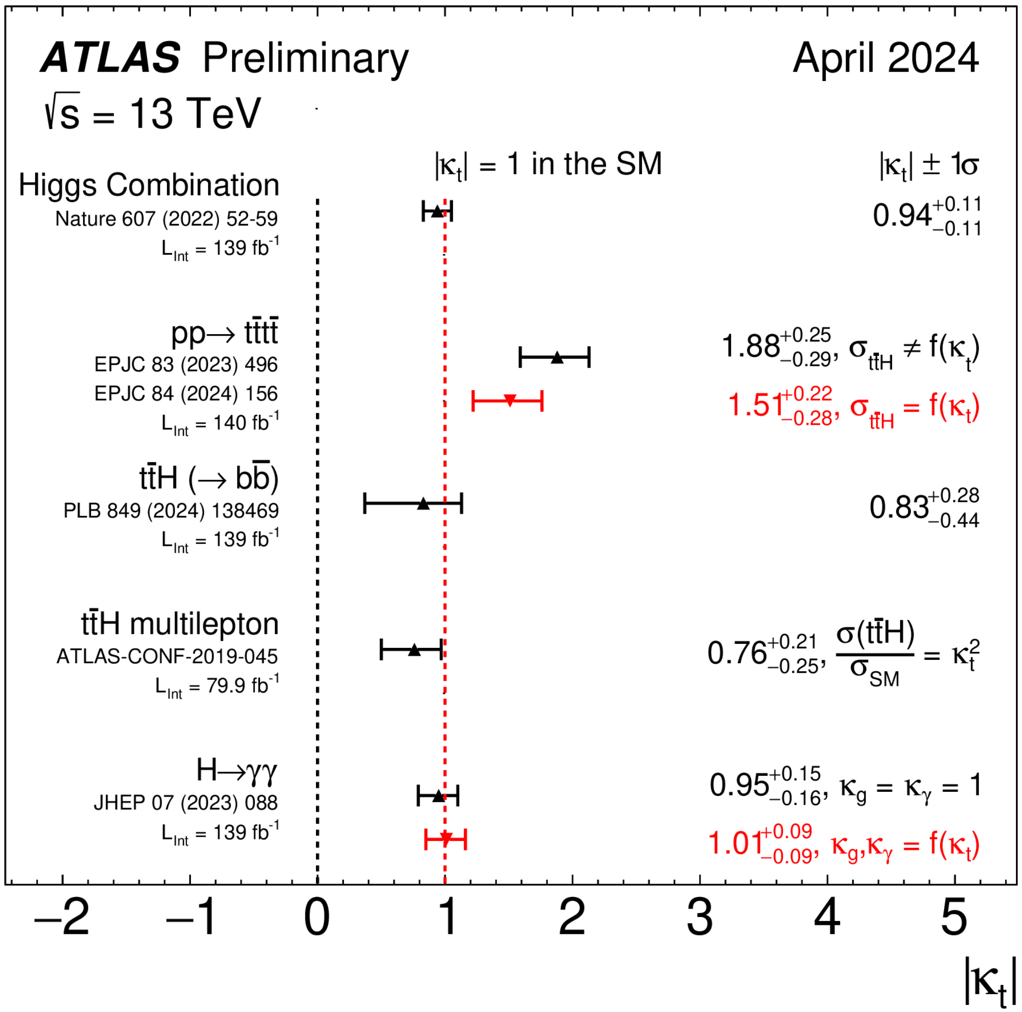

Summary of measurements of the top-Higgs Yukawa coupling modifier in the Kappa formalism, $|\kappa_t|$, at $\sqrt{s}$ = 13 TeV with the ATLAS experiment. The error bars represent 1σ intervals. The black and red points denote alternative parameterizations of $|\kappa_t|$ in the measurements. For the combined Higgs property measurement, $\sigma(t\bar{t}t\bar{t})$ is fixed to the SM expectation, and other coupling modifiers are fit simultaneously. In the $t\bar{t}t\bar{t}$ measurement, values for $|\kappa_t|$ are extracted with $\sigma(t\bar{t}H)$ either parameterized as a function of $|\kappa_t|$ (in red) or profiled (in black). In the $t\bar{t}H$ multilepton measurement, $|\kappa_t|$ is derived from the best-fit value of $\sigma(t\bar{t}H)$ assuming $\sigma(t\bar{t}H) \propto |\kappa_t|^2$. In the $H \rightarrow \gamma\gamma$ measurement, $|\kappa_t|$ is determined either with κ_g and κ_γ parameterized as a function of $|\kappa_t|$ (in red), or with both set to their SM expectation values (in black). All other couplings in these measurements are fixed to the values predicted by the SM. This plot was modified in April 2024 to integrate updated $t\bar{t}t\bar{t}$ results and to update the references for the $t\bar{t}H$ and $H \rightarrow \gamma\gamma$ measurements.