Inclusive and differential cross section measurements of $t\bar{t}Z$ production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, including EFT and spin correlations interpretations

Lucia Keszeghová (Comenius University)

on behalf of the ATLAS collaboration

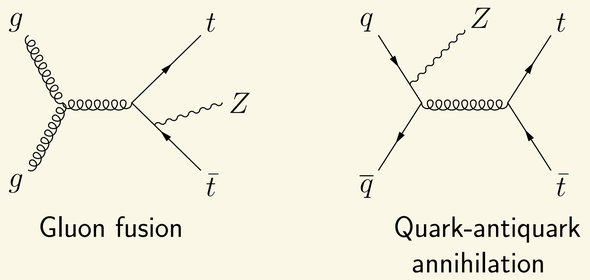
Introduction

Why $t\bar{t}Z$?

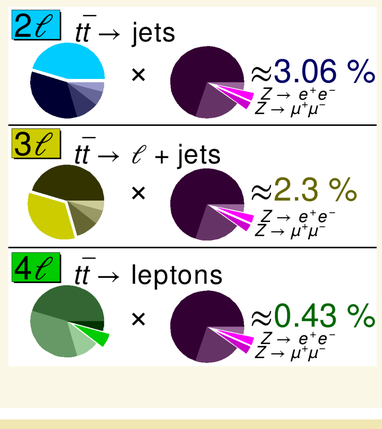
1. precise $t\bar{t}Z$ measurements probe the coupling of the top quark to Z boson
   → indirect search for the Physics beyond the Standard Model (BSM)
   → sensitivity to some Effective Field Theory (EFT) Wilson coefficients
2. $t\bar{t}Z$ as background
   → other top quark measurements ($t\bar{t}H$, $t\bar{t}W$) + BSM searches
3. differential $t\bar{t}Z$ measurements → Monte Carlo (MC) tuning

$t\bar{t}Z$ production

$\sigma^{t\bar{t}Z,\,13\,\mathrm{TeV}}_{\mathrm{NLO+NNLL+EW}} = 0.86^{+0.07}_{-0.08}(\mathrm{scale}) \pm 0.03(\mathrm{PDF} + \alpha_S)\,\mathrm{pb}$ [1]



$t\bar{t}Z$ decay



Refined $t\bar{t}Z$ analysis - ATLAS-CONF-2023-065 [2]

- based on the full Run II dataset (140 fb^{-1})
- improves the previous ATLAS analysis [3]

	Previous	Refined
Inclusive decay channels	3ℓ,4ℓ	2ℓ,3ℓ,4ℓ
Neural network (NN)	✗	✓
Unfolding method	iterative Bayesian	profile-likelihood
EFT interpretation	✗	✓
Spin correlations	✗	✓
Combination possible	✗	✓

Inclusive cross section measurement

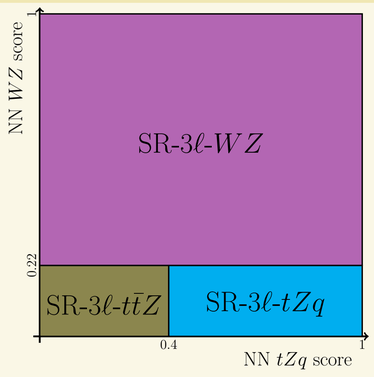
Analysis strategy

- 2ℓ, 3ℓ and 4ℓ decay channels
- signal-background separation: **NN** → looser selection criteria
- signal strength extracted with **profile-likelihood fit**
- NN output:
  1. is used for definition of regions (SRs)
  2. distributions are fitted in signal regions
- treatment of main backgrounds:
  1. 2ℓ: $\mathcal{N}_{Z+\mathrm{c/b}}$ fitted from 2ℓ SRs, data-driven $t\bar{t}$
  2. 3ℓ & 4ℓ: dedicated WZ & ZZ regions
  3. fakes: **Fake Factor method** & fake control regions

Results

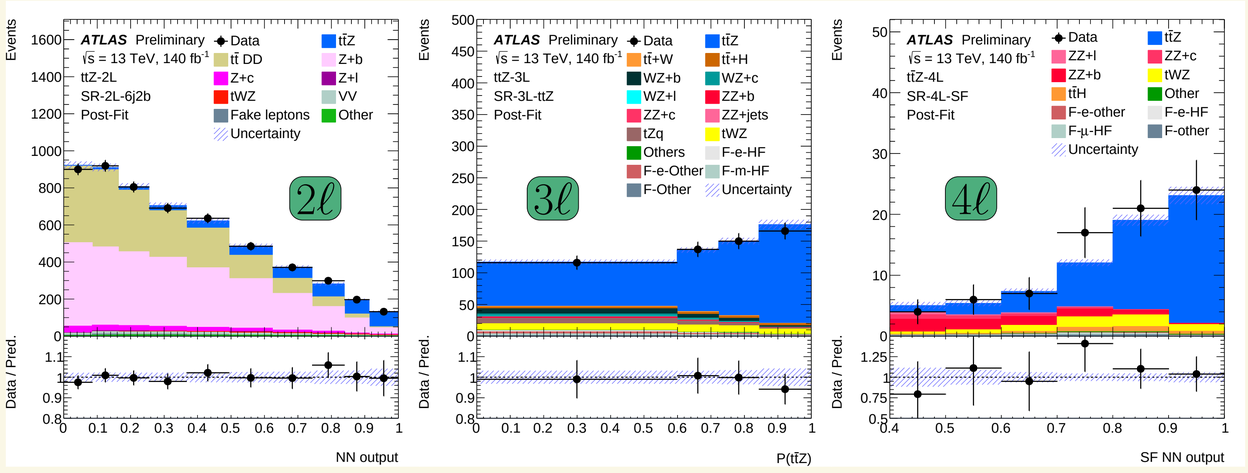
	$\sigma_{t\bar{t}Z}$ [pb]	Relative uncertainty
Theory	$0.86^{+0.07}_{-0.08}(\mathrm{scale}) \pm 0.03(\mathrm{PDF} + \alpha_S)$ [1]	≈ 10%
Previous analysis	$0.99 \pm 0.05(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})$ [3]	≈ 10%
Combination $(2\ell + 3\ell + 4\ell)$	$0.86 \pm 0.05\,\mathrm{pb} = 0.86 \pm 0.04\,(\mathrm{stat.}) \pm 0.04\,(\mathrm{syst.})$	≈ 6.5%
↪ Dilepton	$0.84 \pm 0.11\,\mathrm{pb} = 0.84 \pm 0.06\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})$	≈ 13%
↪ Trilepton	$0.84 \pm 0.07\,\mathrm{pb} = 0.84 \pm 0.05\,(\mathrm{stat.}) \pm 0.05\,(\mathrm{syst.})$	≈ 8.4%
↪ Tetralepton	$0.97^{+0.13}_{-0.12}\,\mathrm{pb} = 0.97 \pm 0.11\,(\mathrm{stat.}) \pm 0.05\,(\mathrm{syst.})$	≈ 18%

⇒ **35% improvement, systematics reduced by 50%**



Leading systematics

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and E_T^{miss}	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_F and μ_R scales	1.6
Leptons	1.6
Z+jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14	1.0
Luminosity	1.0



Spin correlation interpretation

- $t\bar{t}$ spin correlations extracted from angular distributions - **1st time from $t\bar{t}Z$ events**
- observables based on **the angle** between the charged lepton or down-type quark from $t/\bar{t}$ decay
- angular distributions → coefficients $\mathcal{O}$ of the spin density matrix
- **template fit** at detector level:

$$\mathcal{O} = f_{\mathrm{SM}} \cdot \mathcal{O}_{\mathrm{spin-on}} + (1 - f_{\mathrm{SM}}) \cdot \mathcal{O}_{\mathrm{spin-off}}$$

- $\mathcal{O}$: POI = 1 for SM-like correlations, = 0 for no correlations
- $\mathcal{O}_{\mathrm{spin-on}}$: SM-like template
- $\mathcal{O}_{\mathrm{spin-off}}$: $\nexists$ spin correlations

$f_{\mathrm{SM}}^{\mathrm{obs.}} = 1.20 \pm 0.63\,(\mathrm{stat.}) \pm 0.25\,(\mathrm{syst.}) = 1.20 \pm 0.68\,(\mathrm{tot.})\,(1.8\sigma)$

⇒ no-spin hypothesis rejected with significance 1.8σ

Coefficient	Expression
c_{rr}	$-9\langle\cos\theta_r^+ \cdot \cos\theta_r^-\rangle$
c_{kk}	$-9\langle\cos\theta_k^+ \cdot \cos\theta_k^-\rangle$
c_{nn}	$-9\langle\cos\theta_n^+ \cdot \cos\theta_n^-\rangle$
c_{rk}	$-9\langle\cos\theta_r^+ \cdot \cos\theta_k^- + \cos\theta_r^- \cdot \cos\theta_k^+\rangle$
c_{kn}	$-9\langle\cos\theta_k^+ \cdot \cos\theta_n^- + \cos\theta_k^- \cdot \cos\theta_n^+\rangle$
c_{rn}	$-9\langle\cos\theta_r^+ \cdot \cos\theta_n^- + \cos\theta_r^- \cdot \cos\theta_n^+\rangle$
c_r	$-9\langle\cos\theta_k^+ \cdot \cos\theta_n^- - \cos\theta_k^- \cdot \cos\theta_n^+\rangle$
c_k	$-9\langle\cos\theta_n^+ \cdot \cos\theta_r^- - \cos\theta_n^- \cdot \cos\theta_r^+\rangle$
c_n	$-9\langle\cos\theta_r^+ \cdot \cos\theta_k^- - \cos\theta_r^- \cdot \cos\theta_k^+\rangle$
b_r^+	$3\langle\cos\theta_r^+\rangle$
b_r^-	$3\langle\cos\theta_r^-\rangle$
b_k^+	$3\langle\cos\theta_k^+\rangle$
b_k^-	$3\langle\cos\theta_k^-\rangle$
b_n^+	$3\langle\cos\theta_n^+\rangle$
b_n^-	$3\langle\cos\theta_n^-\rangle$

Results for individual angular distributions

Distribution	Channel	Expected values	Observed values
$\cos\varphi$	$3\ell + 4\ell$	$1^{+1.39}_{-1.38}$	$-0.09^{+1.34}_{-1.28}$
$\cos\theta_r^+ \cdot \cos\theta_r^-$	$3\ell + 4\ell$	$1^{+1.83}_{-1.82}$	$1.17^{+1.80}_{-1.76}$
$\cos\theta_k^+ \cdot \cos\theta_k^-$	$3\ell + 4\ell$	$1^{+1.78}_{-1.78}$	$1.39^{+1.72}_{-1.73}$
$\cos\theta_n^+ \cdot \cos\theta_n^-$	$3\ell + 4\ell$	$1^{+1.87}_{-1.86}$	$-1.05^{+2.06}_{-1.96}$
$\cos\theta_r^+ \cdot \cos\theta_k^- + \cos\theta_r^- \cdot \cos\theta_k^+$	$3\ell + 4\ell$	$1^{+1.93}_{-1.93}$	$0.36^{+1.99}_{-1.93}$
$\cos\theta_r^+$	$3\ell + 4\ell$	$1^{+1.81}_{-1.80}$	$1.56^{+1.86}_{-1.98}$
$\cos\theta_r^-$	$3\ell + 4\ell$	$1^{+1.82}_{-1.78}$	$1.81^{+1.63}_{-1.68}$
$\cos\theta_k^+$	$3\ell + 4\ell$	$1^{+1.69}_{-1.67}$	$2.00^{+1.65}_{-1.70}$
$\cos\theta_k^-$	$3\ell + 4\ell$	$1^{+1.68}_{-1.68}$	$2.31^{+1.68}_{-1.68}$

Differential cross section measurement

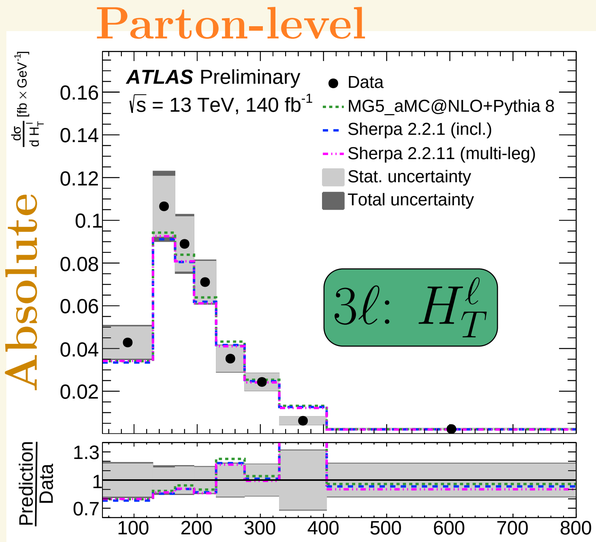
Unfolding procedure

- performed in 3ℓ & 4ℓ channels
- **profile-likelihood unfolding** → the same setup as in the inclusive measurement ($3\ell + 4\ell$ regions, free-floating backgrounds, treatment of systematics, fake control regions)
- **Tikhonov regularisation** (discretized second derivative) is used for variables which require reconstruction of hadronic top

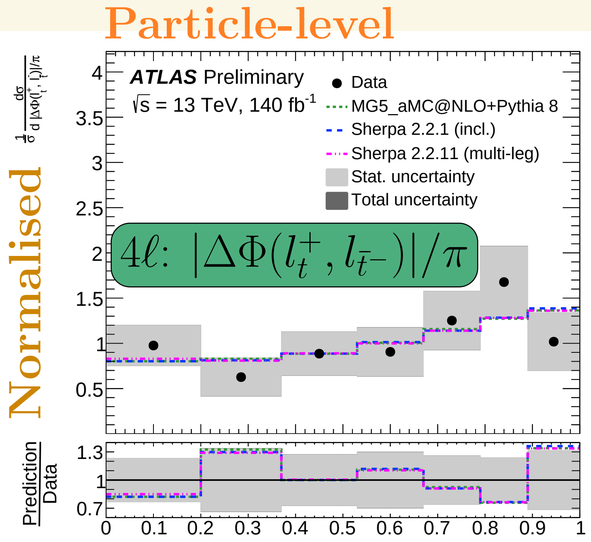
Channel	Variables
3ℓ	N_{jets}, H_T^{ℓ}, $\lvert\Delta\phi(Z, t_{\mathrm{lep}})\rvert$, $\lvert\Delta y(Z, t_{\mathrm{lep}})\rvert$, $p_T^{\ell,\mathrm{non-}Z}$
4ℓ	N_{jets}, H_T^{ℓ}, $\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$
$3\ell + 4\ell$ unregularised	p_T^Z, $\lvert y^Z\rvert$, $\cos\theta_Z^*$
$3\ell + 4\ell$ regularised	$\lvert\Delta\Phi(t\bar{t}, Z)\rvert$, $m^{t\bar{t}}$, $m^{t\bar{t}Z}$, p_T^t, $p_T^{\bar{t}}$, $\lvert y^{t\bar{t}Z}\rvert$

- unfolded to particle & parton level (except for N_{jets})
- both absolute & normalised measurements
- all measurements **statistically** dominated

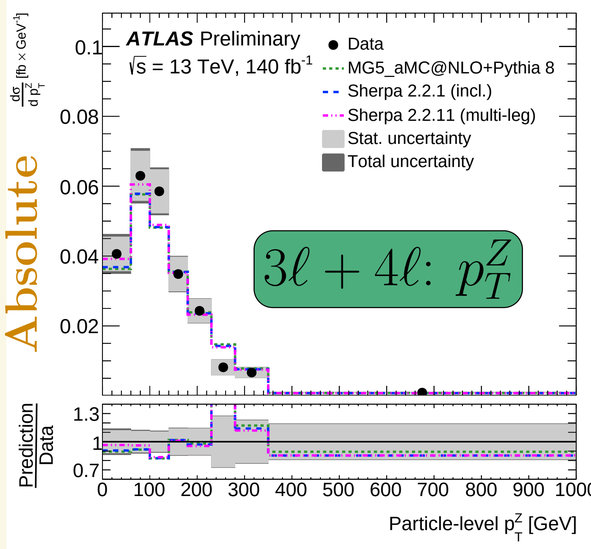
Parton-level



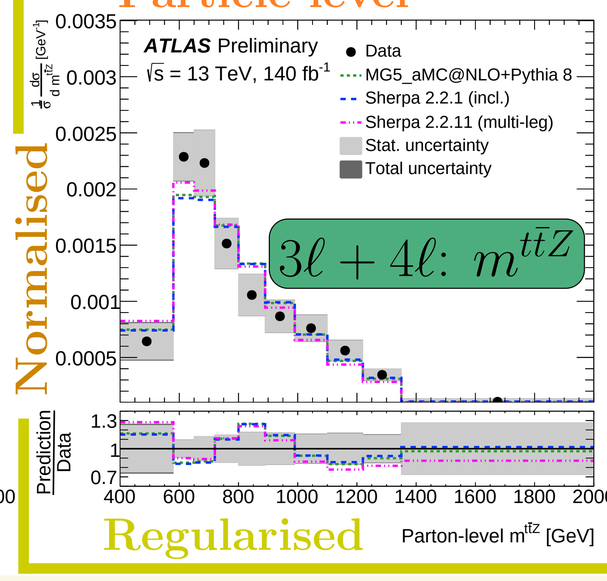
Particle-level



Parton-level



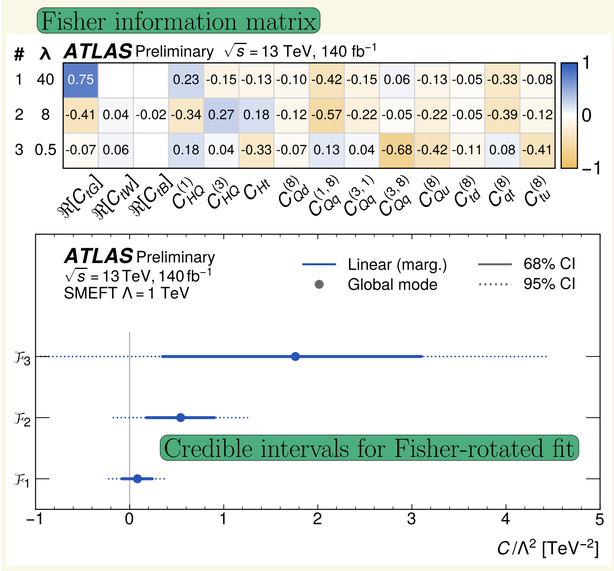
Particle-level

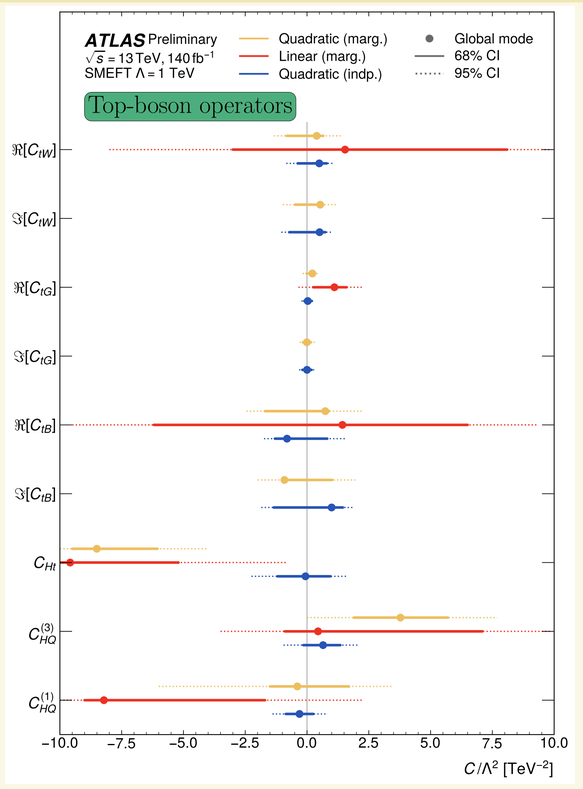


SMEFT interpretation

- 20 dimension-6 SMEFT operators considered: top-boson operators & four-quark operators
- EFT fits performed on **normalised particle-level differential distributions**
- results **compatible with the SM**

Fisher information matrix





References

[1] A. Kulesza et al. "Associated production of a top quark pair with a heavy electroweak gauge boson at NLO+NNLL accuracy". In: *European Physical Journal C* 79.3 (Mar. 2019). DOI: 10.1140/epjc/s10052-019-6746-z.

[2] ATLAS Collabotation. "Inclusive and differential cross section measurements of $t\bar{t}Z$ production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, including EFT and spin correlations interpretations". In: *https://cds.cern.ch/record/2873519* (2023). All figures including auxiliary figures are available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-065.

[3] ATLAS Collabotation. "Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a Z boson at $\sqrt{s} = 13$ TeV with the ATLAS detector". In: *European Physical Journal C* 81 (2021). DOI: 10.1140/epjc/s10052-021-09439-4. arXiv: 2103.12603 [hep-ex].