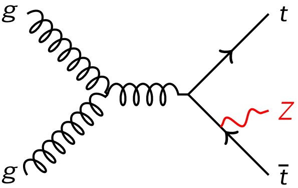
Measurement of the inclusive and differential cross section of a top quark pair in association with a Z boson at 13 TeV with the ATLAS detector

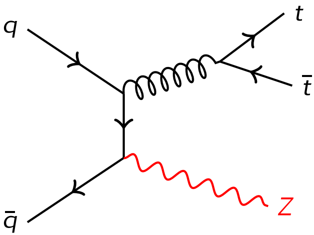
Florian Fischer on behalf of the ATLAS Collaboration

Ludwig-Maximilians-Universität München
– LS Schaile –

13th International Workshop on Top-Quark Physics
– Durham, September 16, 2020 –

- Measurement of $t\bar{t}Z$ cross section a direct access to Z-top quark coupling
  - $\rightarrow$ Test of SM prediction
  - $\rightarrow$ Sensitivity to BSM physics
- $t\bar{t}Z$ is an irreducible background to ...
  - $\rightarrow$ SM measurements ($t\bar{t}t\bar{t}$, tWZ, tZq, ...)
  - $\rightarrow$ BSM searches (e.g. top squark production)





- $\sqrt{s} = 13$ TeV inclusive cross section measurement performed previously by ATLAS (3.2 fb^{-1} Eur.Phys.J.C 77 (2017) 1, 40), (36.1 fb^{-1} Phys.Rev.D 99 (2019) 7, 072009) and CMS (35.9 fb^{-1} JHEP 08 (2018) 011)
- First differential measurement from CMS with 77.5 fb^{-1} JHEP 03 (2020) 056

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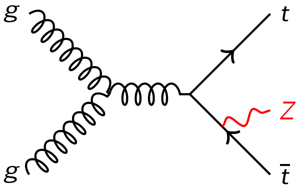

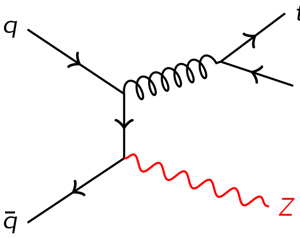

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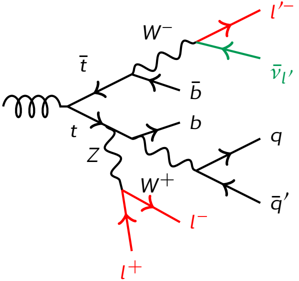
- First differential measurement from CMS with $77.5\,\text{fb}^{-1}$ JHEP 03 (2020) 056
- **First differential measurement by ATLAS and with full LHC Run 2 dataset ($139\,\text{fb}^{-1}$)** ATLAS-CONF-2020-028

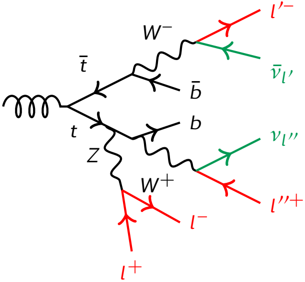
Analysis channels (ATLAS, 139 fb^{-1})

- Exactly 3 or 4 leptons (e, μ)
- OSSF lepton pair with $|m_{\ell\ell} - m_Z| < 10\,\mathrm{GeV}$
- Use of orthogonal signal regions to retain high S/B
  - 3ℓ: varying b-tagging working points based on jet multiplicity
  - 4ℓ: differing in b-jet multiplicity ($1b$, $\geq 2b$), lepton flavour from the $t\bar{t}$ system (ee & $\mu\mu$ vs. $e\mu$) and missing transverse energy

3ℓ

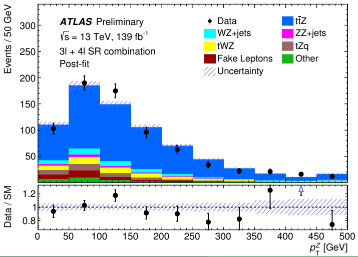


4ℓ



3ℓ+4ℓ SRs

Z boson p_T

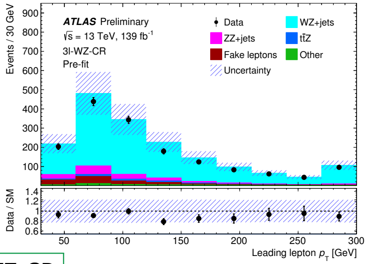


Prompt lepton background:

- WZ/ZZ+light-flavour jets backgrounds estimated in dedicated control regions orthogonal to signal regions by requirements on jet-/b-jet multiplicity and missing transverse energy

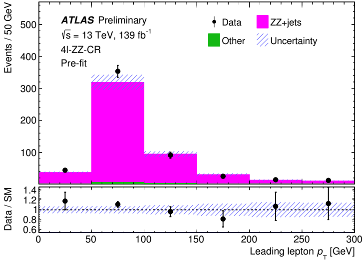
3ℓ-WZ-CR

Leading lepton p_T



4ℓ-ZZ-CR

Leading lepton p_T



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- Other SM backgrounds (tWZ, tZq, $t\bar{t}H$, $t\bar{t}W$, $\ldots$) estimated from Monte Carlo

3ℓ-WZ-CR

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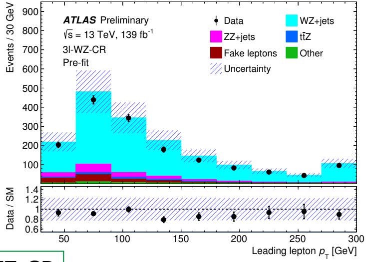
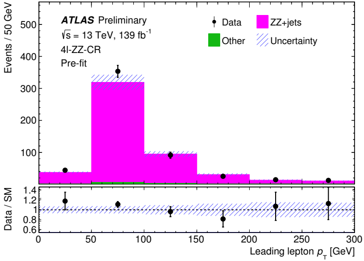


4ℓ-ZZ-CR

Leading lepton p_T



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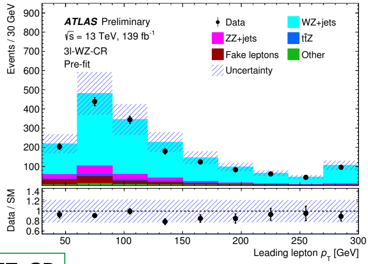

4ℓ-ZZ-CR

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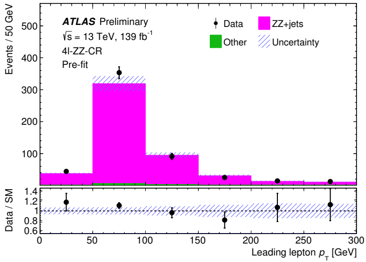


Non-prompt/fake lepton background:

- Leptons from secondary decays
- Objects misidentified as leptons

→ Estimated with fully data-driven matrix method

- Profile-likelihood fit performed based on total yields in each signal/control region
- Free parameters: $t\bar{t}Z$ signal strength and normalisation scales of WZ/ZZ+light-flavour jets backgrounds
- Measured (3ℓ+4ℓ) inclusive cross section:

$$\sigma(pp \to t\bar{t}Z) = 1.05 \pm 0.05\,(\text{stat.})^{+0.09}_{-0.08}\,(\text{syst.})\,\text{pb} = 1.05 \pm 0.10\,\text{pb}$$

- Agreement with theoretical prediction:

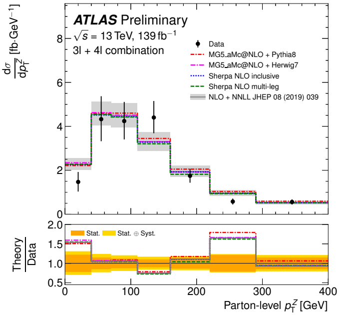
$$\sigma_{t\bar{t}Z}^{\text{NLO+NNLL}} = 0.863^{+0.07}_{-0.09}\,(\text{scale})\ \pm 0.03\,(\text{PDF} + \alpha_s)\ \text{pb}$$ Eur. Phys. J. C 79, 249 (2019)

Dominant systematics:

$t\bar{t}Z$ parton shower	3.1 %
tWZ modelling	2.9 %
b-tagging	2.9 %
WZ/ZZ modelling	2.8 %
tZq modelling	2.6 %

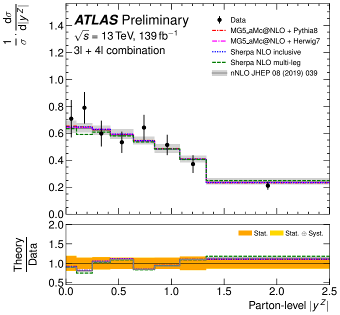
- Employed Iterative Bayesian Unfolding method Nucl. Instrum. Meth. A 362 (1995) 487
- Unfolded 9 variables sensitive to $t\bar{t}Z$ production
- Extrapolation to **parton level** (t, $\bar{t}$, Z before decay) and **particle level** (stable particles: $c\tau \geq 5\,\mathrm{mm}$)
- Measurements of absolute and normalised cross sections

Absolute σ, parton-level Z-p_T



$3\ell + 4\ell$

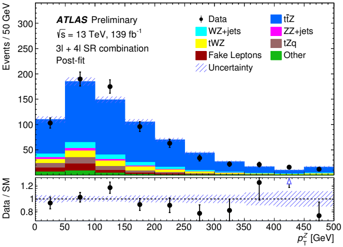
Normalised σ, parton-level Z-rapidity

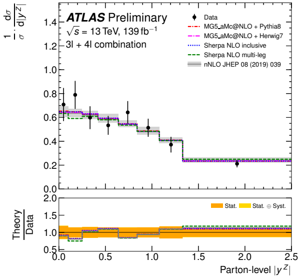


- Custom theoretical predictions (NLO+NNLL) by the authors of JHEP 08 (2019) 039

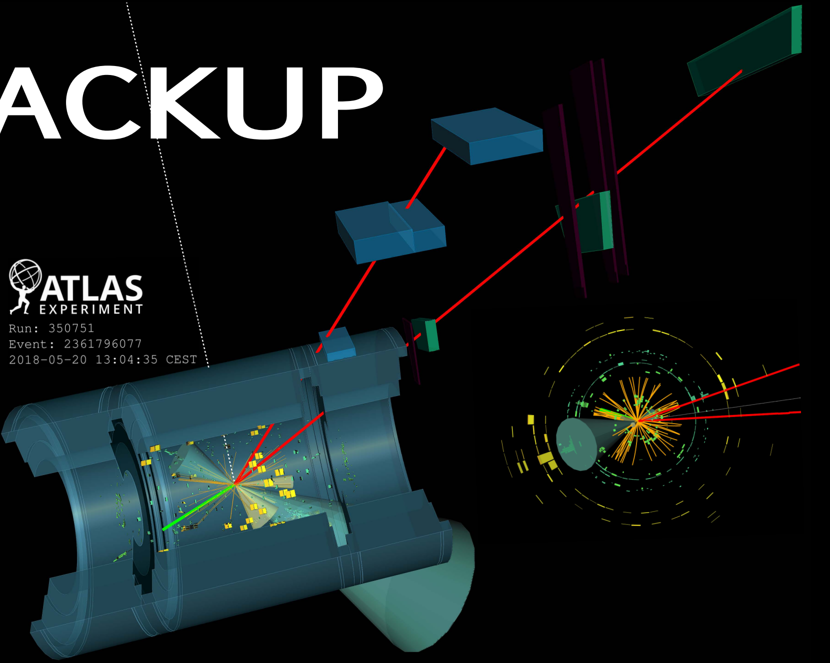
- Latest ATLAS $t\bar{t}Z$ cross section measurements with 139 fb^{-1} in 3ℓ and 4ℓ channels
- First differential cross section measurements with full LHC Run 2 dataset
- Profile-likelihood fit for inclusive measurement
- Unfolded 9 variables to particle and parton level to determine absolute and normalised differential cross sections
- Results consistent with Standard Model predictions
- More on this analysis at TOP 2020 by Rustem Ospanov on 15 Sep 2020, 15:30

  → "Measurements of top-quark production in association with gauge bosons"

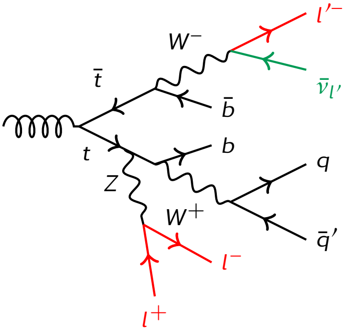




Backup

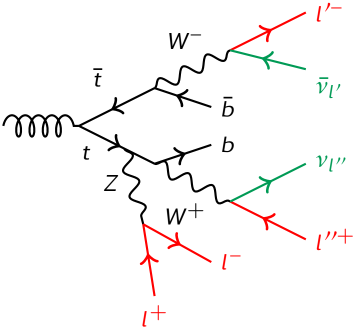

ATLAS
EXPERIMENT
Run: 350751
Event: 2361796077
2018-05-20 13:04:35 CEST

- Event cleaning
- Pass ≥ 1 single-e/μ trigger + matching
- $N_\ell(\ell = e, \mu) = 3$
- $p_{\mathrm{T}}(\ell 1, 2, 3) > 27, 20, 20\,\mathrm{GeV}$
- Sum of lepton charges ± 1
- ≥ 1 OSSF pair with $|m_{\ell\ell}^{Z} - m_Z| < 10\,\mathrm{GeV}$
- $m_{\mathrm{OSSF}} > 10\,\mathrm{GeV}$ (required for all OSSF lepton pairs)



	3ℓ-Z-1b4j-PCBT inclusive	3ℓ-Z-2b3j-PCBT inclusive	3ℓ-Z-2b3j differential
N_{jets}	≥ 4	≥ 3	≥ 3
$N_{b\text{-jets}}$	1 @60 % veto add. b-jets @70 %	2 @70 %	2 @85 %

- Event cleaning
- Pass ≥ 1 single-e/μ trigger + matching
- $N_\ell(\ell = e, \mu) = 4$
- $p_\mathrm{T}(\ell 1, 2, 3, 4) > 27, 20, 10, 7\,\mathrm{GeV}$
- ≥ 1 OSSF pair with $|m_{\ell\ell}^{Z} - m_Z| < 10\,\mathrm{GeV}$
- $m_\mathrm{OSSF} > 10\,\mathrm{GeV}$
- $N_\mathrm{jets} \geq 2$



	4ℓ-SF-1b	4ℓ-SF-2b	4ℓ-DF-1b	4ℓ-DF-2b
$\ell\ell^{\text{non-}Z}$	$e^\pm e^\mp$ or $\mu^\pm\mu^\mp$	$e^\pm e^\mp$ or $\mu^\pm\mu^\mp$	$e^\pm\mu^\pm$	$e^\pm\mu^\pm$
$N_{b\text{-jets}}$ @85 %	1	≥ 2	1	≥ 2
$E_\mathrm{T}^\mathrm{miss}$	$> 100\,\mathrm{GeV}$ if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z\rvert \leq 10\,\mathrm{GeV}$	$> 50\,\mathrm{GeV}$ if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z\rvert \leq 10\,\mathrm{GeV}$	–	–
	$> 50\,\mathrm{GeV}$ if $\lvert m_{\ell\ell}^{\text{non-}Z} - m_Z\rvert > 10\,\mathrm{GeV}$	–	–	–

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- Free parameters: $t\bar{t}Z$ signal strength and normalisation scales of WZ/ZZ+light-flavour jets backgrounds
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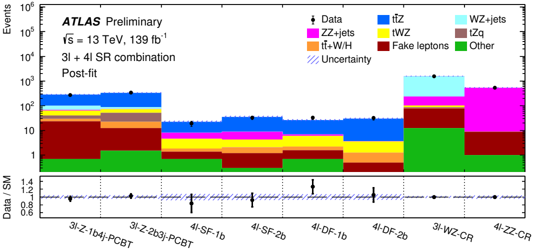

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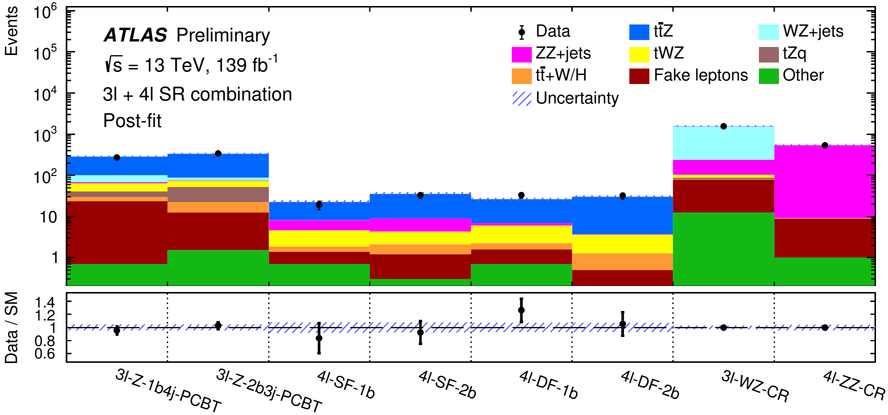


- Observed & expected yields in all individual signal/control regions
- Data/MC ratio shown below
- Combined systematic & statistical errors in shaded band

Experimental uncertainties:

- **JES/JER:** 30 NP
- **JFT:** 19 NP
- **Muon:** 15 NP (ID, Iso, trigger, TTVA, p_T scale & resolution)
- **Electron:** 4 NP (ID, Iso, trigger, reco)
- **ETmiss:** 3 NP (soft term scale & resolution)
- **EGamma:** 2 NP (p_T scale & resolution)
- **JVT:** 1 NP
- **PU:** 1 NP
- **Lumi:** 1 NP
- **Real/fake lepton rates:** 2 NP

Theoretical uncertainties:

- $t\bar{t}Z$: μ_F, μ_R, PDF & α_s
  uncertainties on modelling, shower and tune
- VV: μ_F, μ_R, PDF & α_s
  uncertainties on matching and resummation scale
  20 %/30 % uncertainty on $VV + c/b$
- tWZ: μ_F, μ_R, PDF & α_s
  modelling uncertainties from DR1↔DR2
- tZq: μ_F, μ_R, PDF & α_s
  tune variation, 30 % normalisation uncertainty
- $t\bar{t}H$: PDF & scale uncertainties from NLO calculations & flat PDF uncertainty
- All other processes have 50 % normalisation uncertainty

$$\underbrace{\frac{d\sigma}{dX_i}}_{\text{TRUTH}} = \frac{1}{\mathcal{L}\cdot\mathcal{B}\cdot\Delta X^i\cdot f^i_{\text{acc}}}\sum_j R^{-1}_{ij}\cdot\epsilon^i_{\text{eff}}\cdot\Big(\underbrace{N^j_{\text{obs}}}_{\text{DATA}} - N^j_{\text{bkg}}\Big)$$

with

- $\epsilon_{\text{eff}} = N^{\text{reco}\wedge\text{truth}}/N^{\text{reco}}$
- $f_{\text{acc}} = N^{\text{reco}\wedge\text{truth}}/N^{\text{truth}}$

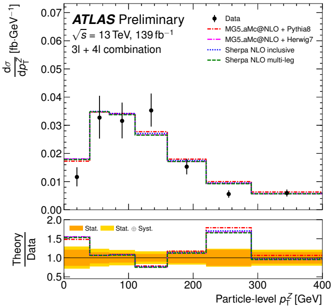
Recipe:

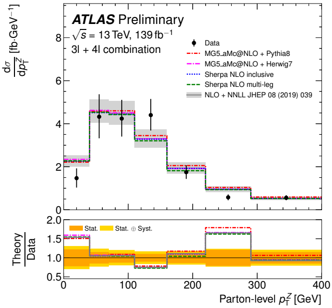
1. Subtract the MC background
2. Correct for "non-fiducial" event
3. Remove the detector smearing
4. Extrapolate into the truth phase space
5. Convert event count into cross section

Iterative Bayesian Unfolding (IBU)

- Iteratively approximate inverse of response matrix R
- Going after probabilities instead of truth estimators
- Take MC truth distributions as initial guess ("prior")
- Update guesses by applying Bayes′ theorem

Region	Variable	Definition
3ℓ & 4ℓ	N_{jets}	Number of reconstructed jets with $p_{\text{T}} > 25\,\text{GeV}$ and $\lvert\eta\rvert < 2.5$
3ℓ	$p_{\text{T}}^{\ell(\text{non-}Z)}$	Tranverse momentum of the lepton to associated with the Z boson
	$\lvert\Delta\phi(Z, t^{\text{lep}})\rvert$	Absolute angular separation in transverse plane between the Z boson and the top quark with the leptonically decaying W boson
	$\lvert\Delta y(Z, t^{\text{lep}})\rvert$	Absolute rapdity separation between the Z boson and the top quark with the leptonically decaying W boson
4ℓ	$\lvert\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)\rvert$	Absolute angular separation in tre transverse plane between the two leptons associated with the top quark pair
	$p_{\text{T}}^{t\bar{t}}$	Transverse momentum of the $t\bar{t}$ system, calculated as the vector sum in the ϕ-plane of the two b-jets, the non-Z lepton pair and $E_{\text{T}}^{\text{miss}}$
	$\lvert\Delta\phi(t\bar{t}, Z)\rvert$	Absolute angular separation in the transverse plane between the Z boson and the $t\bar{t}$ system (defined as for $p_{\text{T}}^{t\bar{t}}$)
$3\ell/4\ell$-comb.	$\lvert y^Z\rvert$	Absolute rapdity of the Z boson (reconstructed from the $m_{\ell\ell}^Z$ pair)
	p_{T}^Z	Tranverse momentum f the Z boson (reconstruced as for $\lvert y^Z\rvert$)


ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
3l + 4l combination
Data
MG5_aMC@NLO + Pythia8
MG5_aMC@NLO + Herwig7
Sherpa NLO inclusive
Sherpa NLO multi-leg
$\frac{d\sigma}{dp_T^Z}$ [fb·GeV^{-1}]
Stat.
Stat. ⊕ Syst.
Theory / Data
Particle-level p_T^Z [GeV]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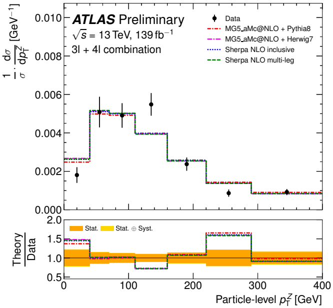
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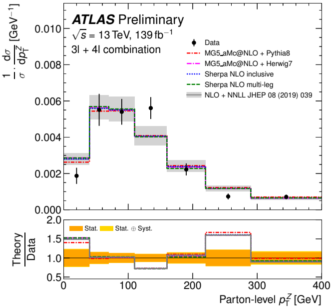
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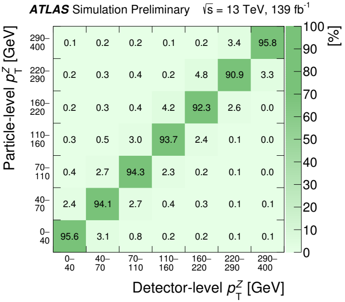
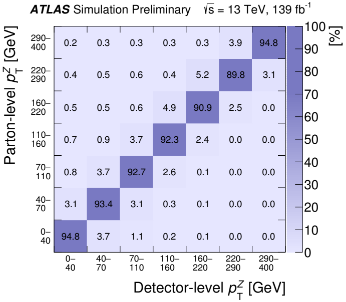

ATLAS Simulation Preliminary √s = 13 TeV, 139 fb-1
Particle-level p_T^Z [GeV]
Detector-level p_T^Z [GeV]
[%]
290–400: 0.1 0.2 0.2 0.1 0.2 3.4 95.8
220–290: 0.2 0.3 0.4 0.2 4.8 90.9 3.3
160–220: 0.2 0.3 0.4 4.2 92.3 2.6 0.0
110–160: 0.3 0.5 3.0 93.7 2.4 0.1 0.0
70–110: 0.4 2.7 94.3 2.3 0.2 0.1 0.0
40–70: 2.4 94.1 2.7 0.4 0.3 0.1 0.1
0–40: 95.6 3.1 0.8 0.2 0.2 0.1 0.1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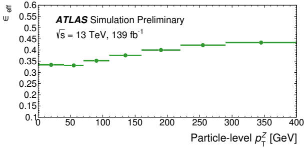
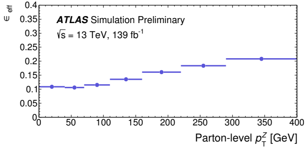
110–160: 0.7 0.9 3.7 92.3 2.4 0.0 0.0
70–110: 0.8 3.7 92.7 2.6 0.1 0.0 0.0
40–70: 3.1 93.4 3.1 0.3 0.1 0.0 0.0
0–40: 94.8 3.7 1.1 0.2 0.1 0.0 0.0


ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
ϵ_{eff}
Particle-level p_T^Z [GeV]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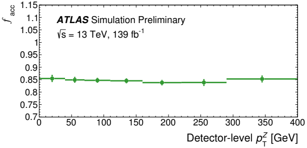
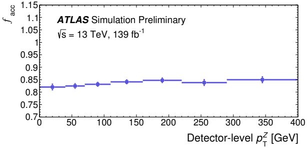
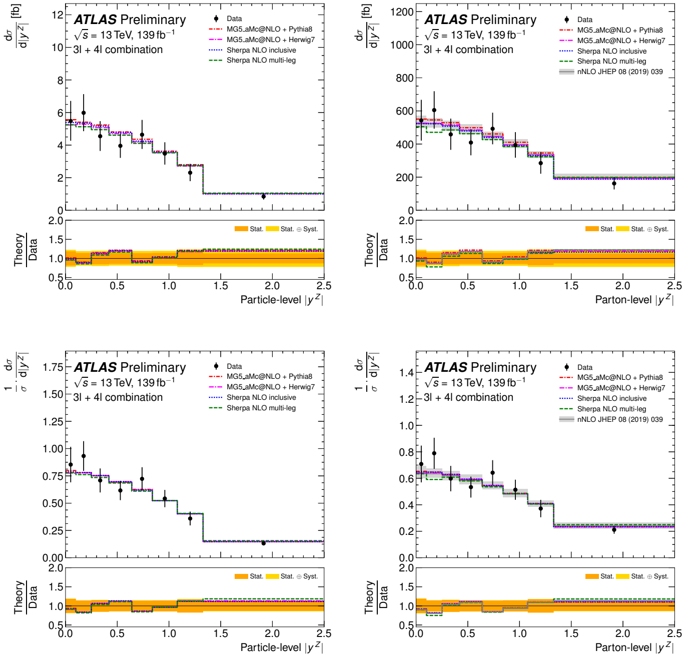
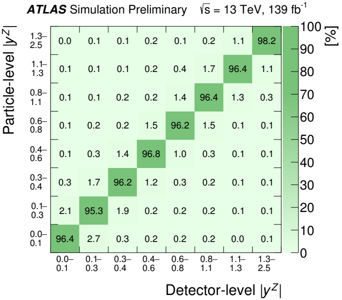
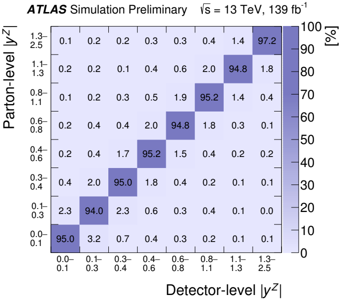
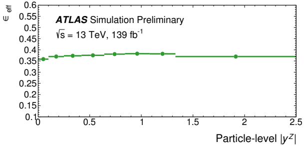

ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
f_{acc}
Detector-level p_T^Z [GeV]

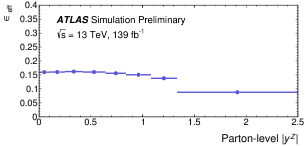

ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
f_{acc}
Detector-level p_T^Z [GeV]

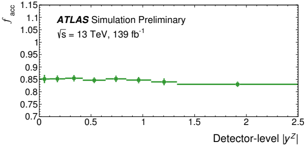

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
3l + 4l combination
Data
MG5_aMC@NLO + Pythia8
MG5_aMC@NLO + Herwig7
Sherpa NLO inclusive
Sherpa NLO multi-leg
nNLO JHEP 08 (2019) 039
Stat.
Stat. ⊕ Syst.
$\frac{d\sigma}{d|y^Z|}$ [fb]
$\frac{1}{\sigma} \cdot \frac{d\sigma}{d|y^Z|}$
Theory / Data
Particle-level $|y^Z|$
Parton-level $|y^Z|$

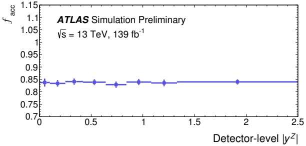

ATLAS Simulation Preliminary √s = 13 TeV, 139 fb-1
Particle-level |y^Z|
Detector-level |y^Z|
[%]
1.3–2.5: 0.0 0.1 0.1 0.2 0.1 0.2 1.1 98.2
1.1–1.3: 0.1 0.1 0.1 0.2 0.4 1.7 96.4 1.1
0.8–1.1: 0.1 0.1 0.2 0.2 1.4 96.4 1.3 0.3
0.6–0.8: 0.1 0.2 0.2 1.5 96.2 1.5 0.1 0.1
0.4–0.6: 0.1 0.3 1.4 96.8 1.0 0.3 0.1 0.1
0.3–0.4: 0.3 1.7 96.2 1.2 0.3 0.2 0.1 0.1
0.1–0.3: 2.1 95.3 1.9 0.2 0.2 0.2 0.1 0.1
0.0–0.1: 96.4 2.7 0.3 0.2 0.2 0.2 0.0 0.1
0.0–0.1 0.1–0.3 0.3–0.4 0.4–0.6 0.6–0.8 0.8–1.1 1.1–1.3 1.3–2.5


ATLAS Simulation Preliminary √s = 13 TeV, 139 fb-1
Parton-level |y^Z|
Detector-level |y^Z|
[%]
1.3–2.5: 0.1 0.2 0.2 0.3 0.3 0.4 1.4 97.2
1.1–1.3: 0.2 0.2 0.1 0.4 0.6 2.0 94.8 1.8
0.8–1.1: 0.1 0.2 0.3 0.5 1.9 95.2 1.4 0.4
0.6–0.8: 0.2 0.4 0.4 2.0 94.8 1.8 0.3 0.1
0.4–0.6: 0.2 0.4 1.7 95.2 1.5 0.4 0.2 0.2
0.3–0.4: 0.4 2.0 95.0 1.8 0.4 0.2 0.1 0.1
0.1–0.3: 2.3 94.0 2.3 0.6 0.3 0.4 0.1 0.0
0.0–0.1: 95.0 3.2 0.7 0.4 0.3 0.2 0.1 0.1
0.0–0.1 0.1–0.3 0.3–0.4 0.4–0.6 0.6–0.8 0.8–1.1 1.1–1.3 1.3–2.5

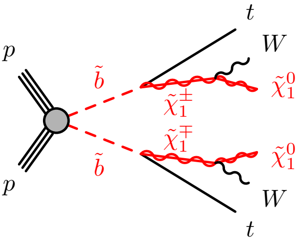

ε eff
ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
Particle-level |y^Z|


ε eff
ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
Parton-level |y^Z|

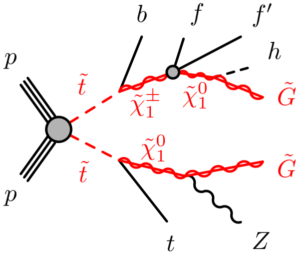

f acc
ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
Detector-level |y^Z|


f acc
ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
Detector-level |y^Z|

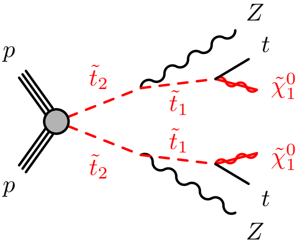
$\tilde{b}\tilde{b} \rightarrow ttWW\tilde{\chi}^0_1\tilde{\chi}^0_1$



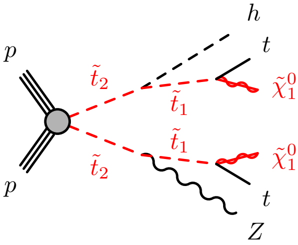
$\tilde{t}\tilde{t} \rightarrow bWthZ\tilde{G}\tilde{G}$

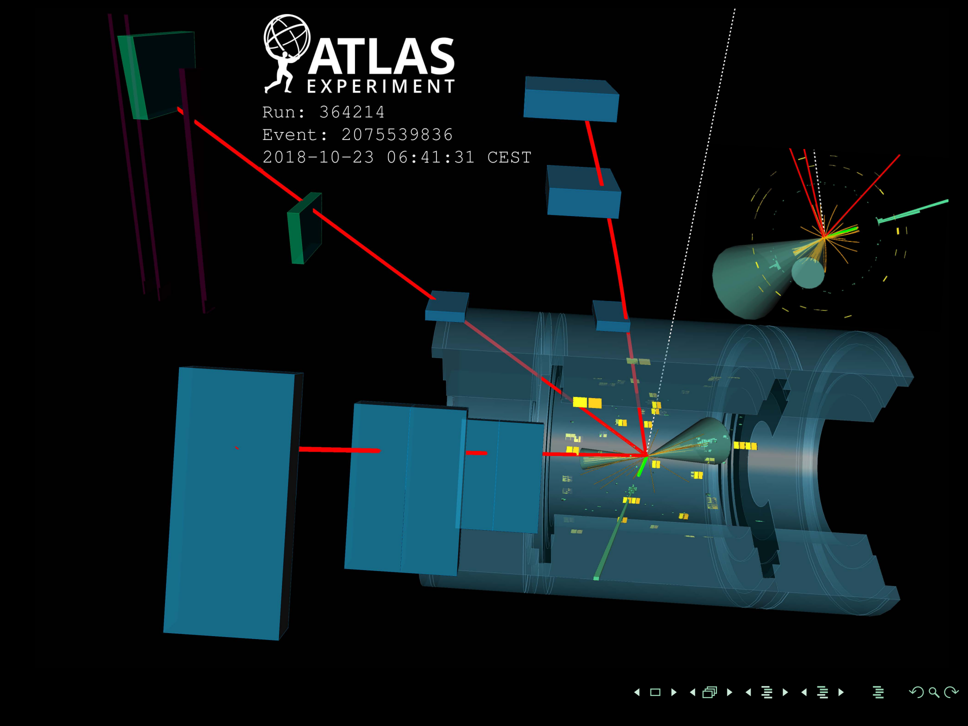


$\tilde{t}_2\tilde{t}_2 \rightarrow ZZtt\tilde{\chi}^0_1\tilde{\chi}^0_1$



$\tilde{t}_2\tilde{t}_2 \rightarrow Zhtt\tilde{\chi}^0_1\tilde{\chi}^0_1$




ATLAS
EXPERIMENT
Run: 364214
Event: 2075539836
2018-10-23 06:41:31 CEST