First measurement of high-mass $t\bar{t}\ell\ell$ and LFU-inspired EFT interpretations with the ATLAS detector

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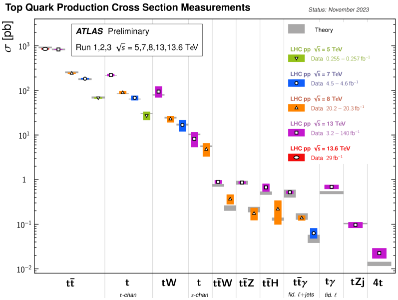
Top quark measurements with ATLAS

- Top quark is the heaviest fundamental particle $\rightarrow$ special role to probe SM:
  - measure top coupling to other particle (such as Yukawa coupling)
- Large collected data set of proton-proton collisions ($140\,\text{fb}^{-1}$) allows for precision measurements of rare processes, such as $t\bar{t}V$ with $V = \gamma, Z, W$



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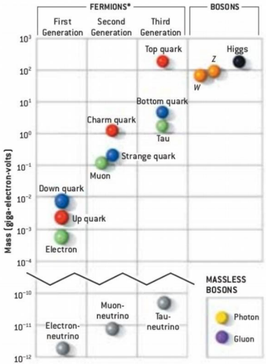

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Effective field theory

- Search for deviations from SM in model independent way
- Assume that energy scale of new interaction much larger than considered energy
  - can neglect momentum dependence in propagator
  - get an effective coupling independent of exact process (similar to Fermi's description of the β decay)
- Expand Lagrangian with effective coupling in a low energy limit:

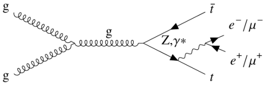
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- Cross-section of specific process given by:

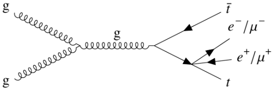
$$\sigma = \sigma_{SM} + \sigma_{interference} + \sigma_{BSM}$$

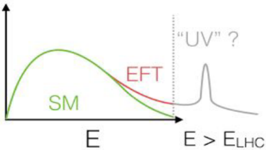
- Additionally EFT can have an impact on the shape of some distributions

SM coupling



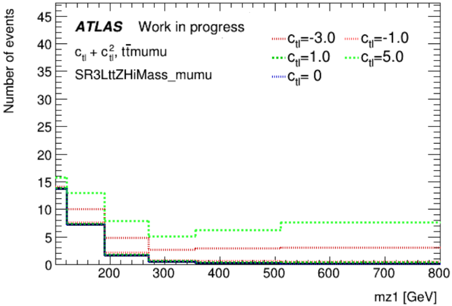
Effective coupling





Theory behaviour at higher energies (Mimasu, LHCP 2020)

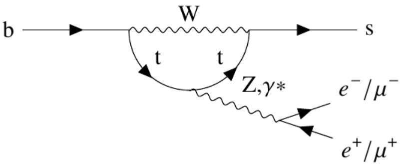
- Probe effective $t\bar{t}\ell\ell$ coupling
- Target four-fermion EFT operators: currently poorly constrained (CMS top EFT paper: arXiv:2307.15761)
- Impact of these EFT operators grows with energy $\rightarrow$ focus on high-mass regime
- Binning of signal region: di-leptonic invariant mass of OSSF lepton pair (in case of 2 OSSF pairs take m_{ll} closest to Z mass)



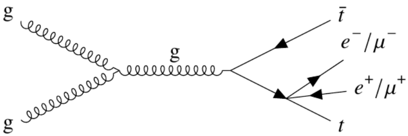
Motivation for the high-mass $t\bar{t}\ell\ell$ analysis

- Constrain four-fermion operators (O_{tl}, O_{te}, O_{Qe}, O^1_{Ql}, O^3_{Ql}):
  - flavour inclusively
  - separately for $t\bar{t}ee$ and $t\bar{t}\mu\mu$ coupling → gives access to potential flavour universality violation
- $t\bar{t}\ell\ell$ vertex is also one of the contributing processes in B decays (and therefore contributes to $R(K^*)$)

$t\bar{t}\ell\ell$ coupling in B decays

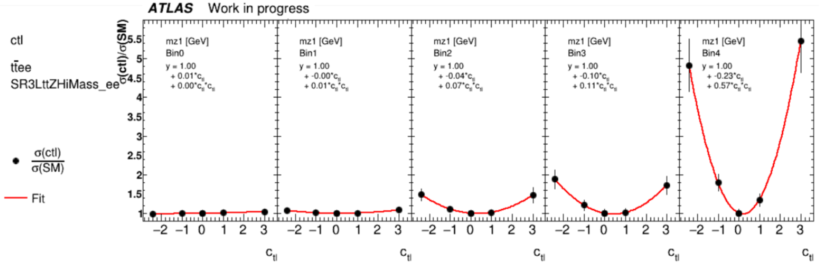


$t\bar{t}\ell\ell$ effective coupling



EFT parameterisation

- Use MadGraph+Pythia $t\bar{t}\ell\ell$ sample
- Internal MadGraph reweighting of distribution to some non-zero values of different Wilson coefficients
- Use reweighted distributions to parameterise $t\bar{t}\ell\ell$ event yield in each bin as function of WCs

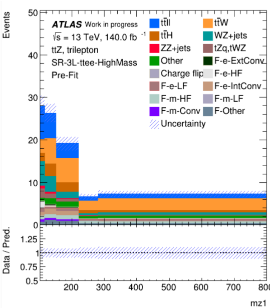


Signal regions

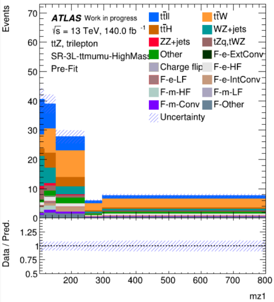
ATLAS EXPERIMENT

- Use ATLAS $t\bar{t}Z$ measurement as starting point (arXiv:2312.04450)
- Consider 3l channel with at least one OSSF lepton pair
- High-mass regime: $m_{ll} > m_Z + 10\,\text{GeV}$

ttee signal region



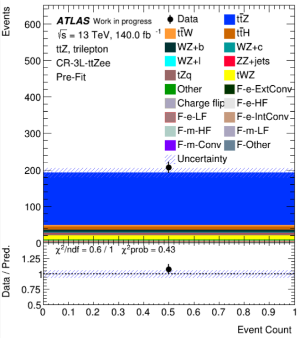
$tt\mu\mu$ signal region



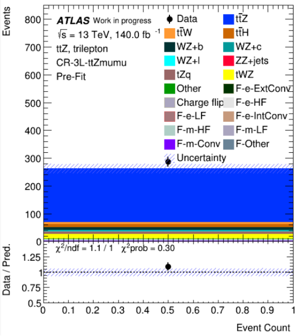
- Treatment of backgrounds:
  - assume that shape of backgrounds is well modelled by MC (with some modelling uncertainties, such as ME or PS), except for the charge flip background (fully data-driven estimation)
  - determine normalisation of dominant backgrounds from data in background enriched control regions

- 3l CRs targeting on-shell $t\bar{t}Z$ and WZ+jets

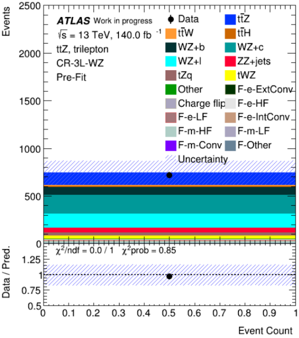
$t\bar{t}Z(\rightarrow ee)$ CR



$t\bar{t}Z(\rightarrow \mu\mu)$ CR



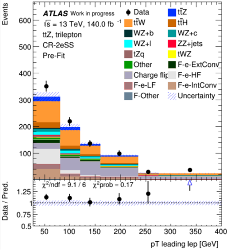
WZ+jets CR



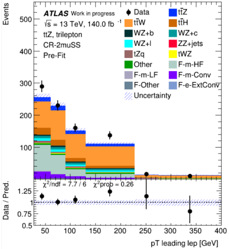
- Good pre-fit data MC agreement

- $2lSS$ CRs targeting $t\bar{t}W$

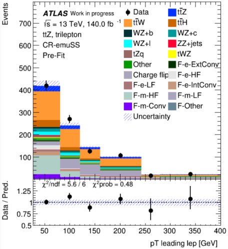
$2eSS$ CR



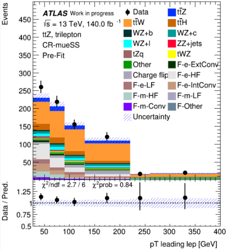
$2\mu SS$ CR



$e\mu SS$ CR



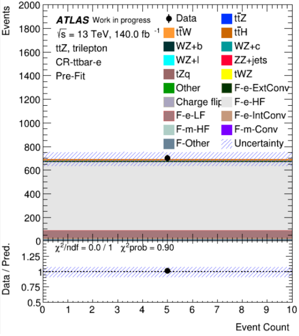
μeSS CR



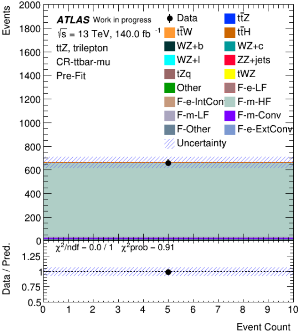
- CRs split by flavour to disentangle non-prompt backgrounds
- MC predictions underestimate data
  - expected, as measured $t\bar{t}W$ cross-section higher than theory predictions

- 3l CRs targeting heavy and light flavour fake leptons:
  - heavy flavour fake lepton: lepton in heavy quark jet or mimicked by heavy flavour jet
  - light flavour fake lepton: lepton mimicked by light flavour jet
- Regions selecting $t\bar{t}$ and Zjets events
- Loosen lepton reconstruction criteria for one of the leptons to enrich regions in non-prompt leptons

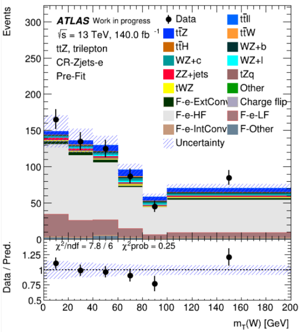
HF fake e CR



HF fake μ CR



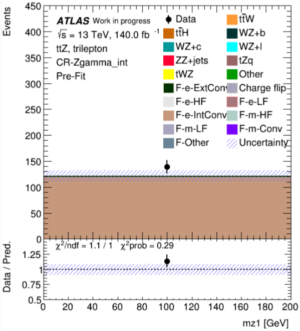
LF fake e CR



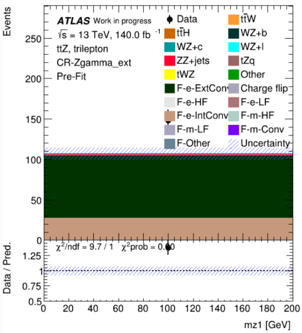
Non-prompt background estimation

- 3/ CRs targeting conversion electrons:
  - internal conversion: electron from virtual photon undergoing pair-production
  - material conversion: electron from photons converting in detector material
- Regions selecting $Z(\rightarrow \mu\mu)\gamma$ with one e events

Internal conversions CR



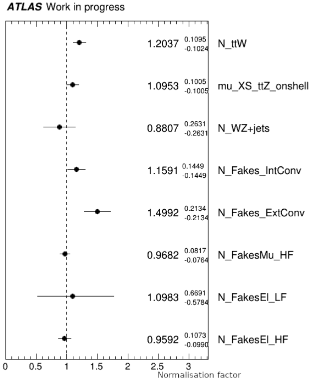
Material conversions CR



CR only fit

- Perform fit without including EFT variations of $t\bar{t}\ell\ell$
- Include only CRs
- Measure normalisation factor of dominant backgrounds

- $t\bar{t}W$ normalisation factor slightly above current cross-section calculations compatible with ATLAS $t\bar{t}W$ cross-section measurement (arXiv:2401.05299)
- $t\bar{t}Z$ normalisation factor also compatible with ATLAS $t\bar{t}Z$ cross-section measurement (arXiv:2312.04450)
- Normalisation factors for fake backgrounds mostly close to one

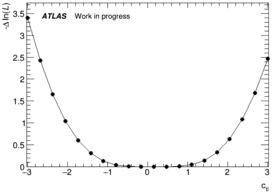


Preliminary expected results

- Signal regions not yet unblinded → only expected results
- Not final binning in SRs

WC/Λ^2	1σ Interval
c_{tl11}	$[-2.36, 2.71]$
c_{tl22}	$[-1.78, 2.05]$
c_{te11}	$[-1.42, 1.76]$
c_{te22}	$[-1.68, 2.33]$
c_{Qe11}	$[-2.52, 2.62]$
c_{Qe22}	$[-2.18, 2.32]$
$c_{Ql^1 11}$	$[-1.68, 2.41]$
$c_{Ql^1 22}$	$[-1.60, 2.41]$
$c_{Ql^3 11}$	$[-2.40, 1.67]$
$c_{Ql^3 22}$	$[-2.40, 1.58]$

WC/Λ^2	1σ Interval
c_{tl}	$[-1.64, 1.93]$
c_{te}	$[-1.23, 1.65]$
c_{Qe}	$[-1.92, 2.03]$
c_{Ql^1}	$[-1.31, 2.05]$
c_{Ql^3}	$[-2.04, 1.31]$



- Good constraining power for all operators
- Sensitivity still largely statistics dominated

Summary

- Probe SM with EFT approach
- $t\bar{t}\ell\ell$ analysis targets effective $t\bar{t}\ell\ell$ coupling in high-mass regime
- Set constrains on four-fermion operators
- Access potential LFU violation through separate constrains on $t\bar{t}ee$ and $t\bar{t}\mu\mu$

Backup Slides

Systematic uncertainties

- Normalisation factors of dominant backgrounds added as free floating parameters
- Additional theoretical and experimental uncertainties added as nuisance parameters in fit:
  - cross-section uncertainties
  - modelling uncertainties (matrix element, parton shower, tune, ...)
  - PDF uncertainties
  - lepton reconstruction uncertainties (trigger, isolation, ID, ...)
  - jet and MET reconstruction uncertainties
  - flavour tagging uncertainties
  - data-driven charge flip estimation uncertainties (statistics, extrapolation, ...)

- Target potential LFU violation by measuring the difference between $t\bar{t}ee$ and $t\bar{t}\mu\mu$ EFT operators (for example: $c_{tl22} - c_{tl11}$)
- Fitting the difference helps to cancel some flavour independent systematics

- Sensitivity to $\Delta(c_{tl22}, c_{tl11})$ worse than for c_{tl11} and c_{tl22} separately
- Results statistics dominated:
    - results for c_{tl11} and c_{tl22} mainly independent
    - canceling of systematics minor effect
- Proof of principle: sensitivity will improve with more collected data