Highlights of $t\bar{t}$, tZq and $tt\gamma$ production measurements at ATLAS

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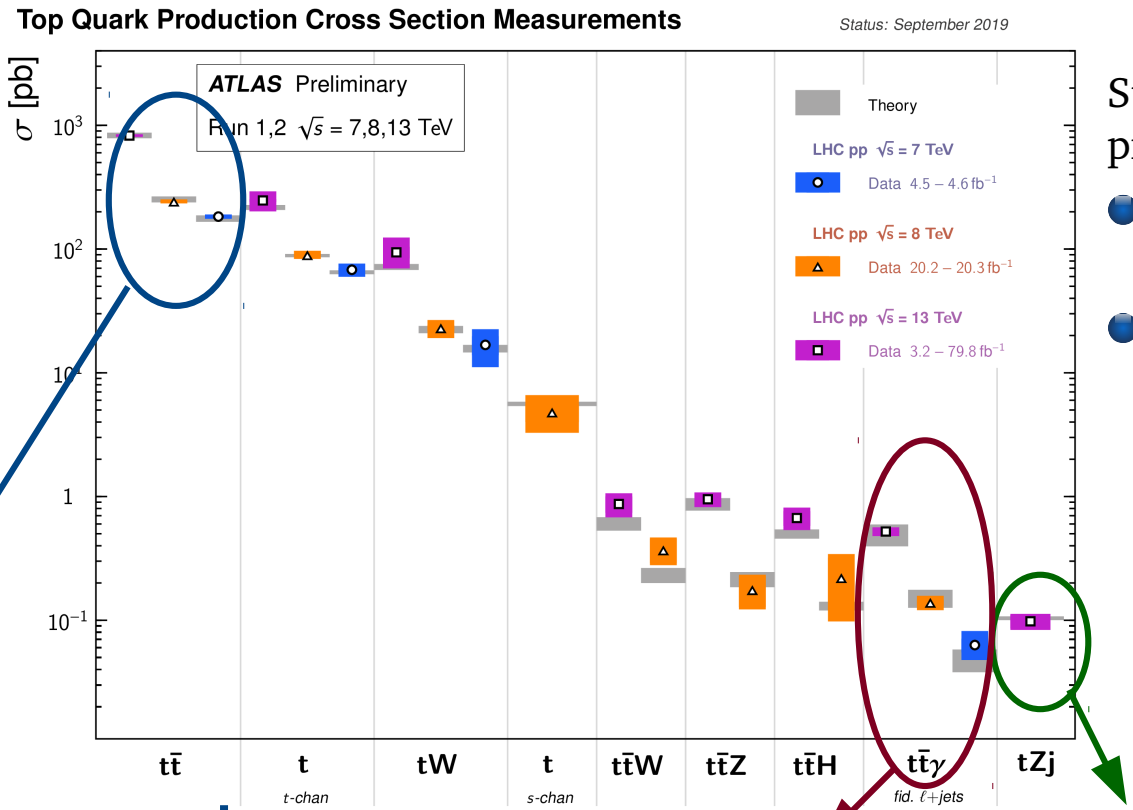
ATLAS

Overview

The top quark is the heaviest particle in the SM

- Involved in many processes BSM



Study of its property and production kinematic:

- Stringent test of the QCD
- Necessary for all BSM searches involving top in the final state

- Very high σ
- Easy to separate from background
  - Extensive study of differential distributions, including 2D
  - Possible investigate challenging regions
- Improve the modelling of the tt process
- Sensitive to PDFs, m_t and α_S

- Small σ
- Easy to separate the signal from the background
  - Possible to perform **differential measurements**
- Sensitive to tγ coupling

- Small σ
- Difficult to separate the signal from the background
  - First observation of the process
- Sensitive to WZ and tZ coupling
- Small QCD corrections to the predictions → easy EFT interpretation

Differential measurements of $\sigma(t\bar{t})$:

- l+jets channel: arXiv:1908.07305, Eur. Phys. J. C (2019) 79
- **NEW**: all-hadronic channel, ATLAS-CONF-2020-001
- Dilepton channel: arXiv:1910.08819, submitted to EPJC

dσ(tt̄): l+jets channel method

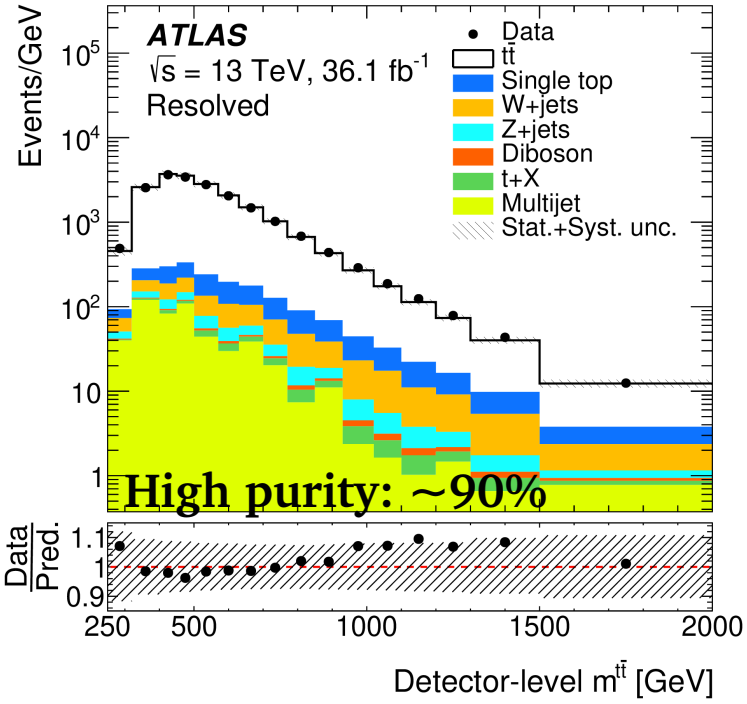
1) Select events:

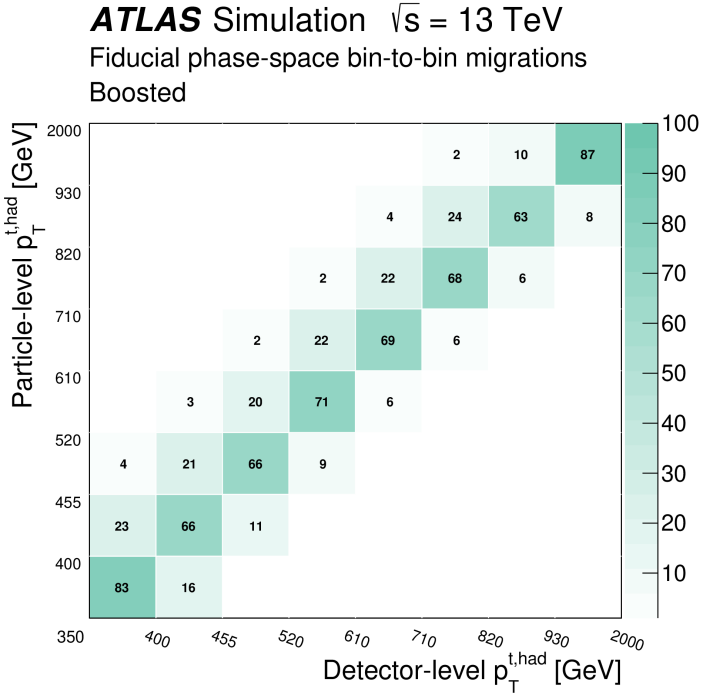
- At least 1 lepton
- At least 4 jets (2 + 1 large-R jet) in resolved(boosted)
- At least 2(1) b-tagged jets in resolved(boosted)

2) Reconstruct the tt̄ system:

Use the final state objects to reconstruct the ttbar system

- Resolved → pseudo-top algorithm/KLFitter
- Boosted → pseudo-top algorithm using a large-R jet





3) Unfolding

Correct the effect of limited acceptance and resolution of the detector.

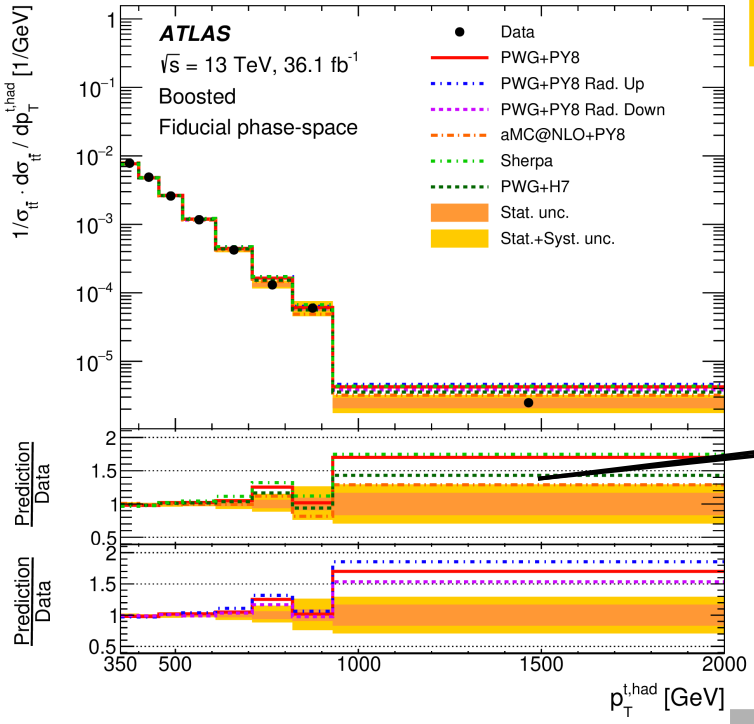
Take as input the migrations between the truth and the reconstructed kinematic

- Particle → fiducial phase space, object similar to reco-level
- Parton → full phase space, using top-quark after FSR

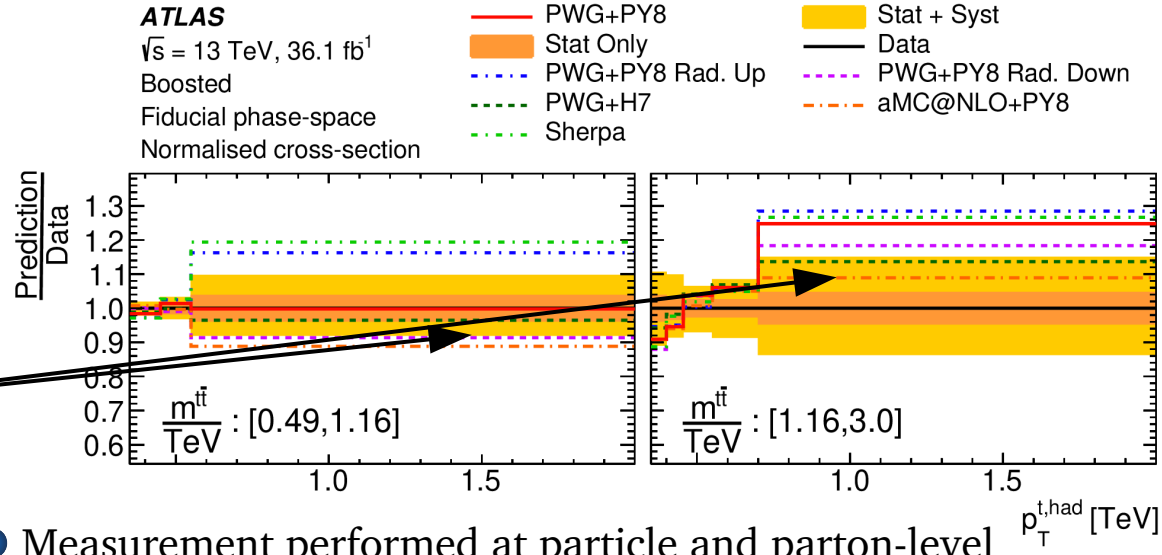
4) Evaluate systematic uncertainties

5) Calculate the results

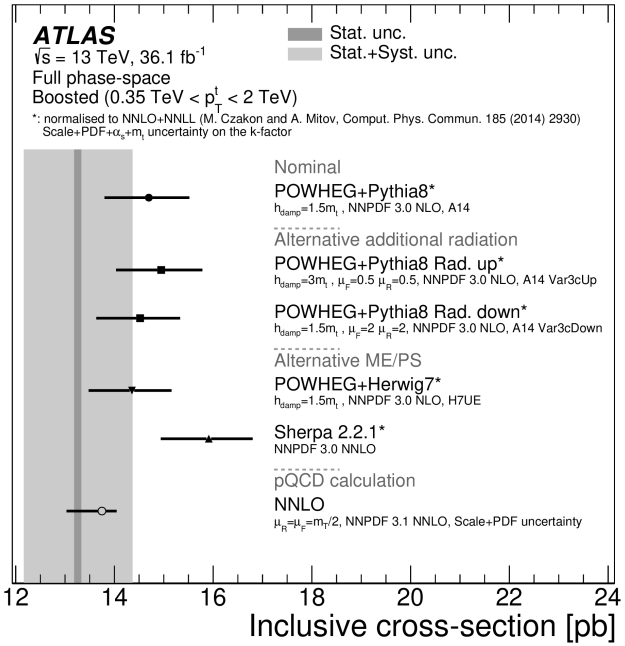
dσ(tt̄): l+jets channel particle-level results



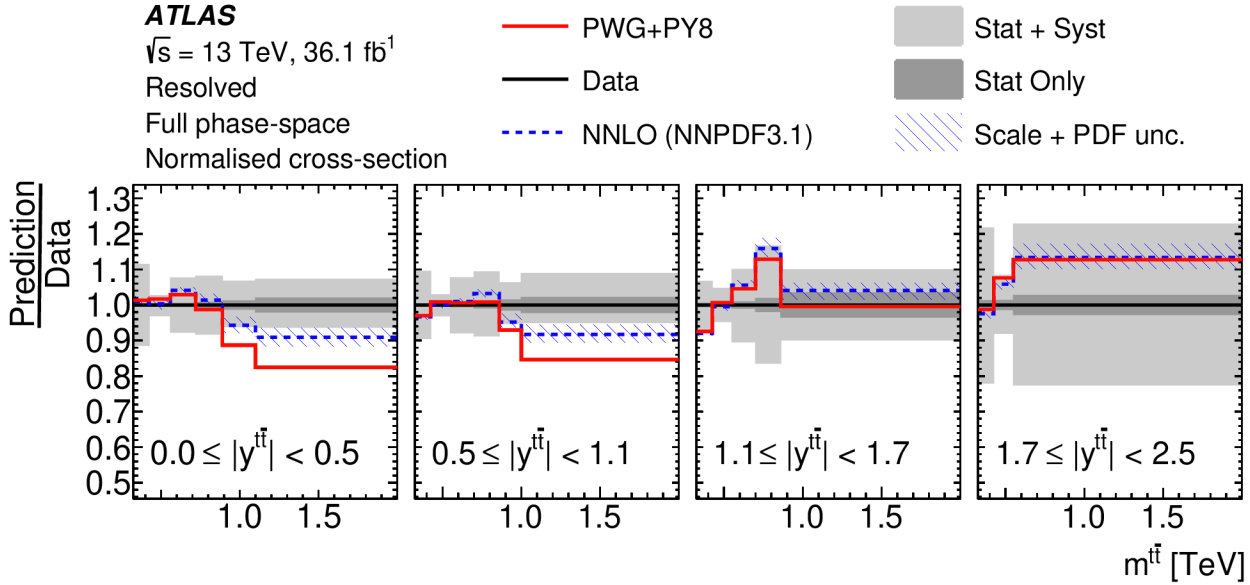
Particle level



- Measurement performed at particle and parton-level
- NNLO predictions generally improve the agreement with the data



Parton level



dσ(tt̄): all-hadronic channel method

Analysis strategy similar to the l+jets channel: **event selection**, **system reconstruction**, **background estimate**, unfolding to parton and particle level

Event selection:

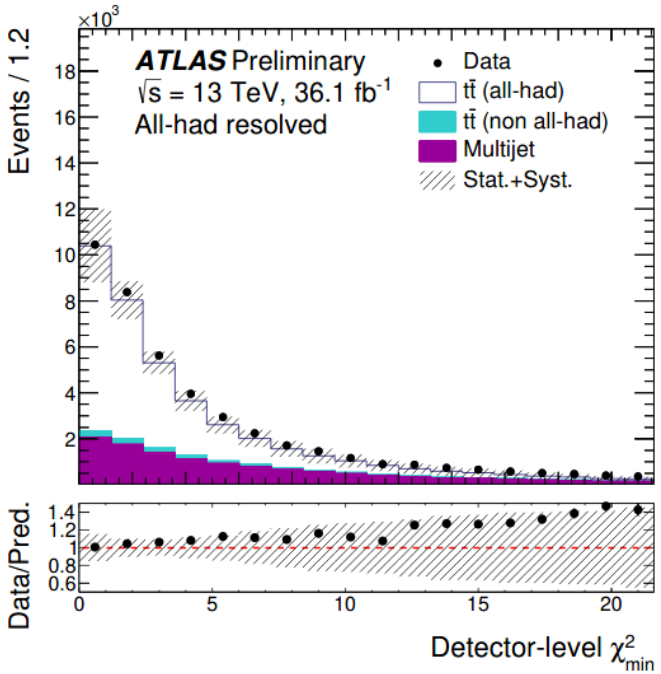
- At least 6 jets
- At least 2 b-jets
- Exactly 0 lepton
- Kinematic requirements on system reconstruction

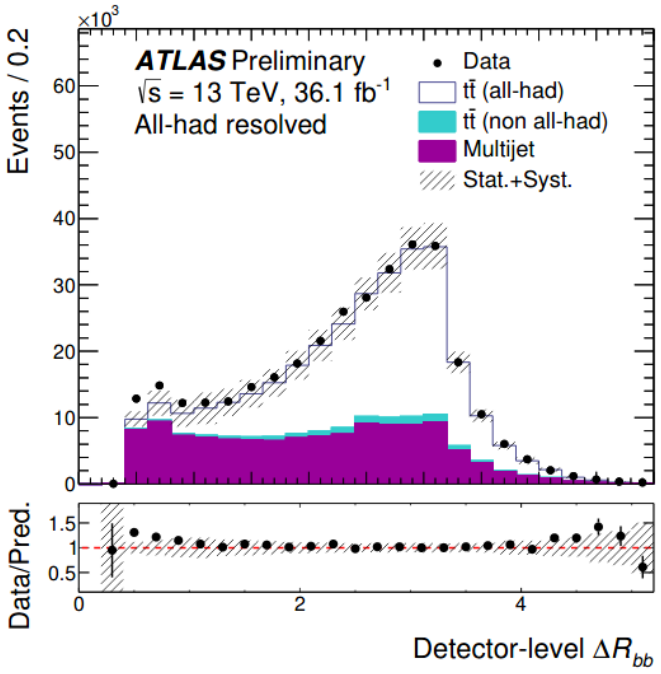
New

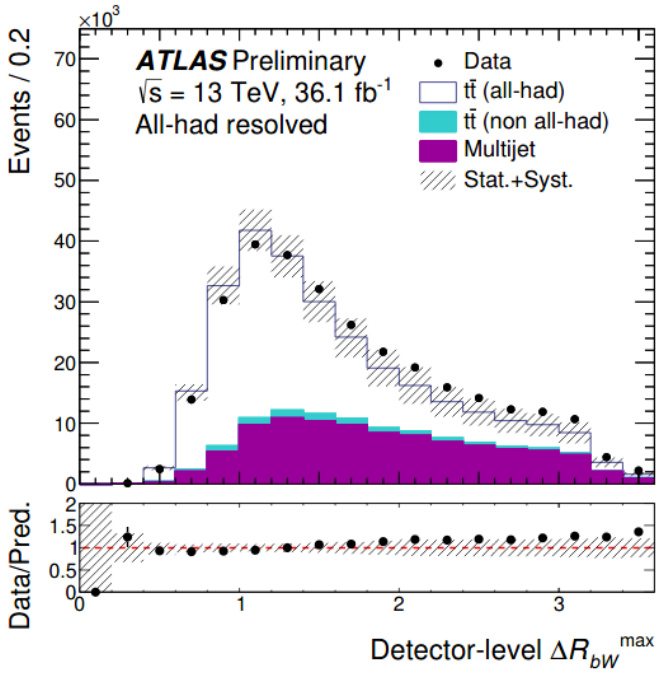
- Complex reconstruction of the tt̄ system: many possible combinations
  - Minimize the χ^2 to reconstruct the system

$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma_t^2} + \frac{(m_{j_1 j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3 j_4} - m_W)^2}{\sigma_W^2}$$

- Complex separation between the signal and the multijet background.
  - Employed a data-driven method
  - Cut also on the χ^2 result





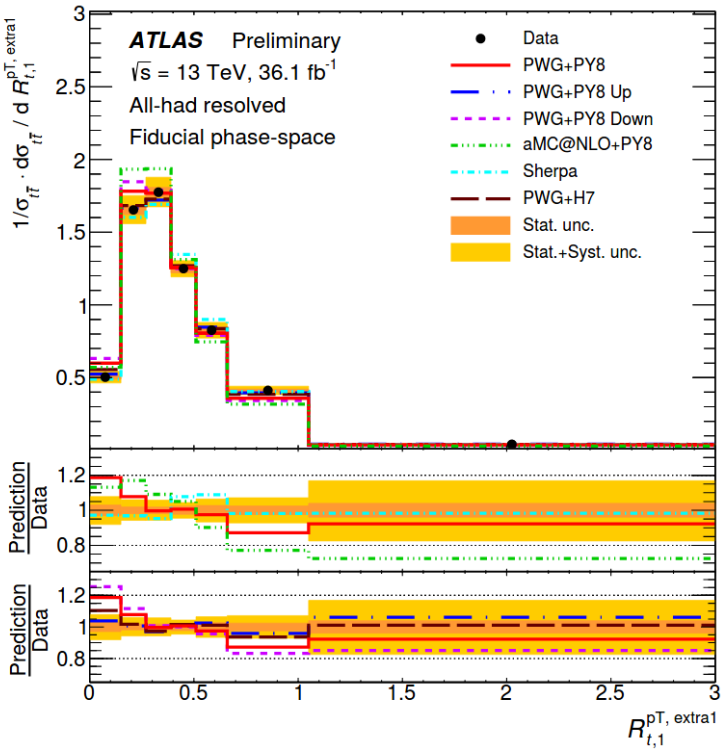


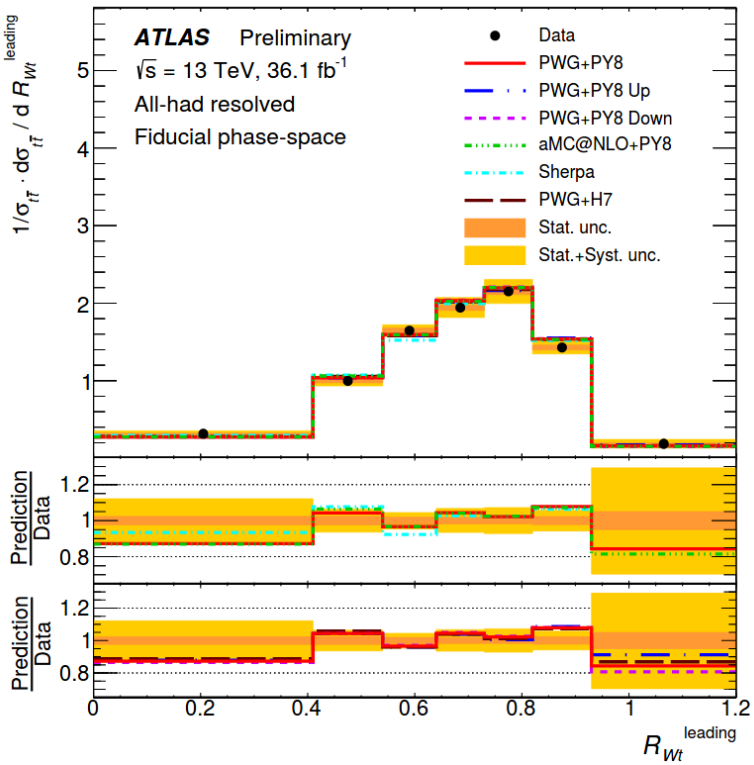
dσ(tt̄): all-hadronic channel results

- Measurement as a function of the top quarks and system kinematic
- Included many variables sensitive to additional radiations
- Including double differential observables

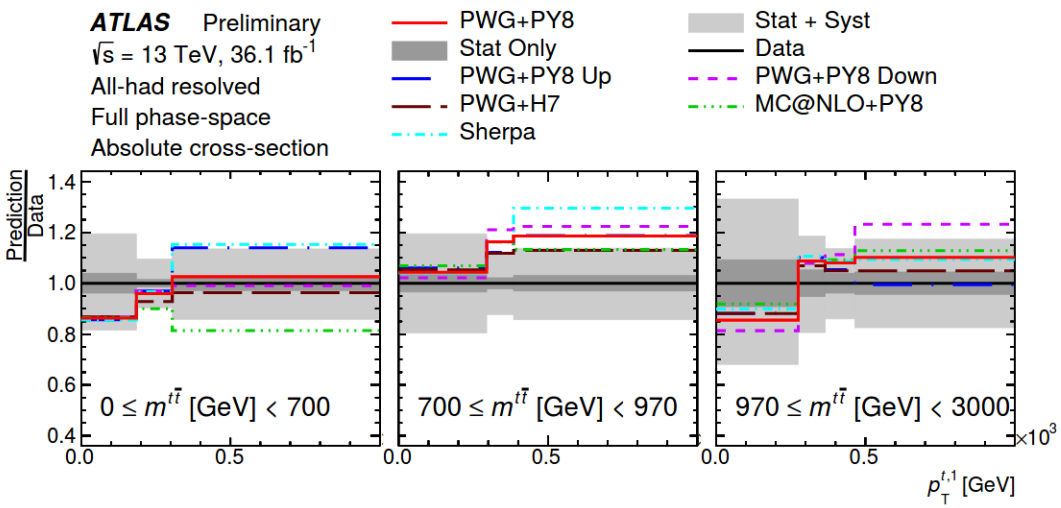
New

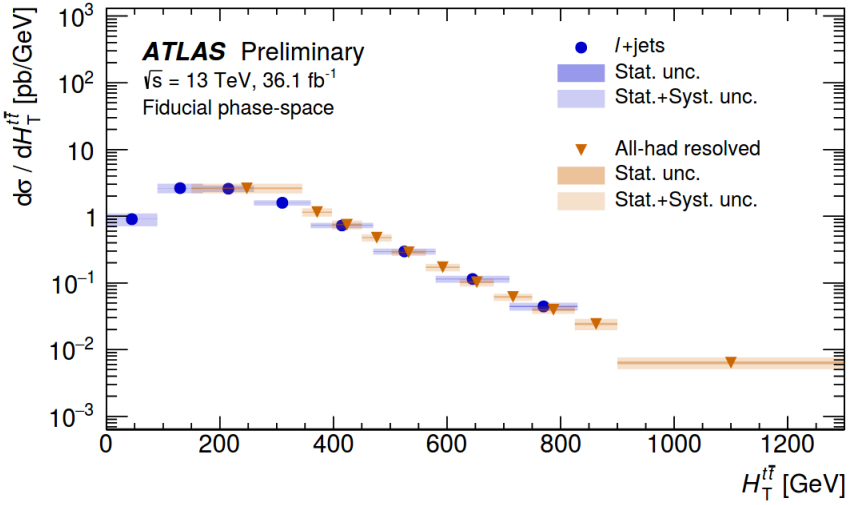
Particle level



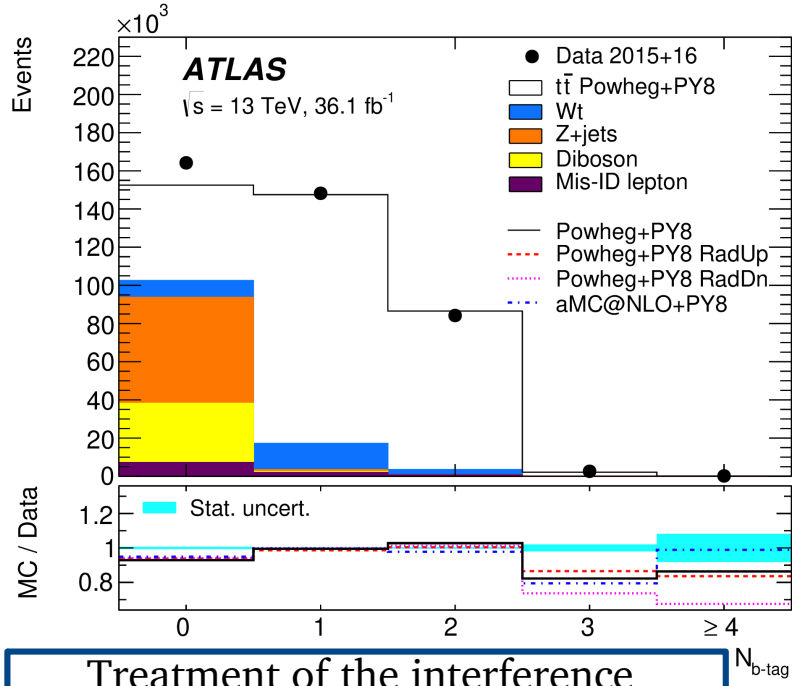


Parton level





dσ(tt̄): dilepton channel method

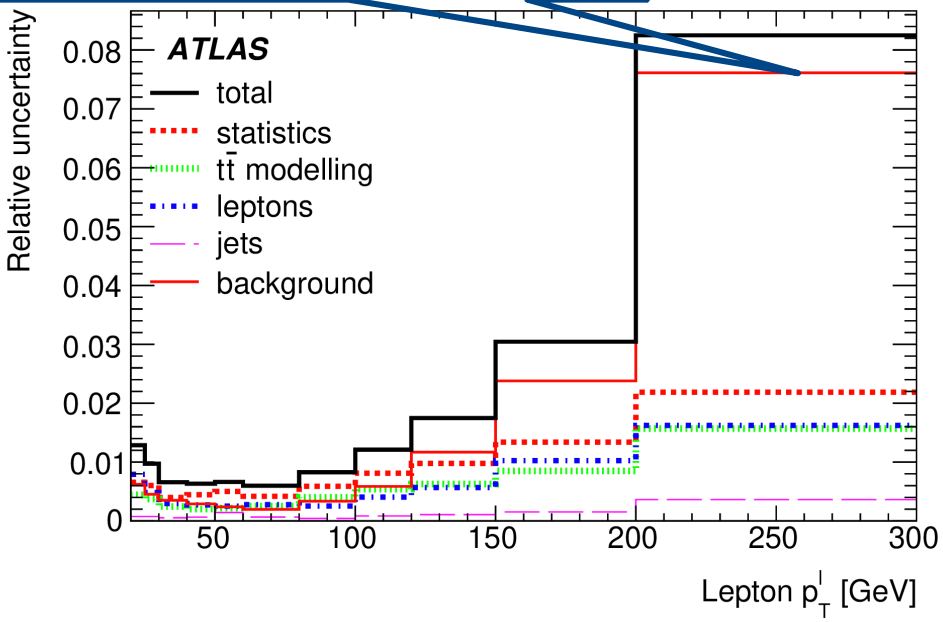


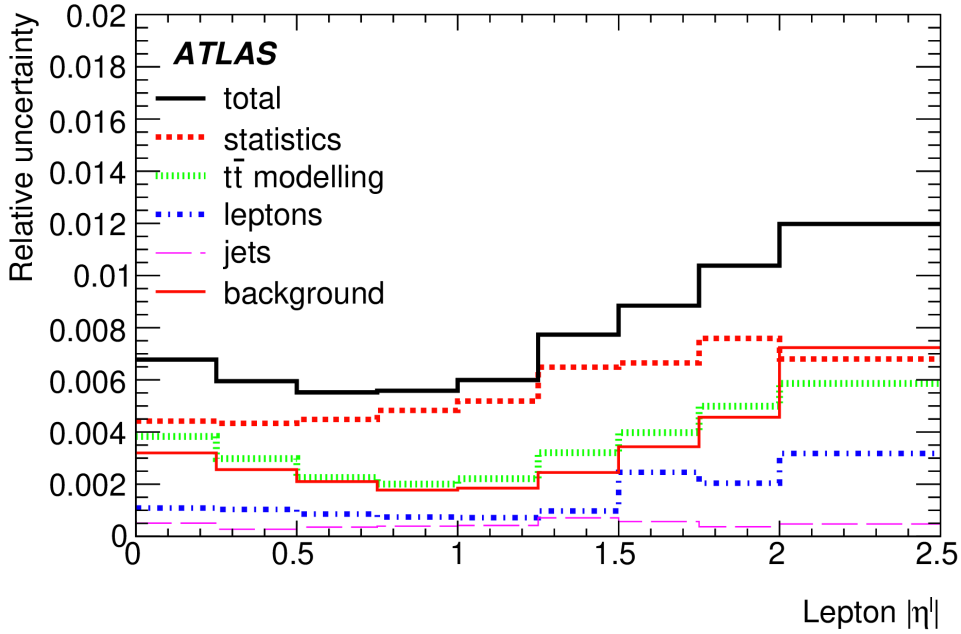
- Measured events in the eμ channel
- No jet requirements in pre-selection
- Events categorized in the 1 btag and 2 btag regions:

$$N_1^i = L\sigma_{t\bar{t}}^i\, G_{e\mu}^i 2\epsilon_b^i(1 - C_b^i\epsilon_b^i) + N_1^{i,\mathrm{bkg}},$$
$$N_2^i = L\sigma_{t\bar{t}}^i\, G_{e\mu}^i C_b^i(\epsilon_b^i)^2 + N_2^{i,\mathrm{bkg}},$$

- Highly reduce the b-tagging uncertainty → most precise xs measurement (2.4% on the inclusive)
- G incorporates the effects due to limited acceptance and efficiency of the detector
- Measure the cross-section as a function of the leptons kinematic

Treatment of the interference between tW and tt̄

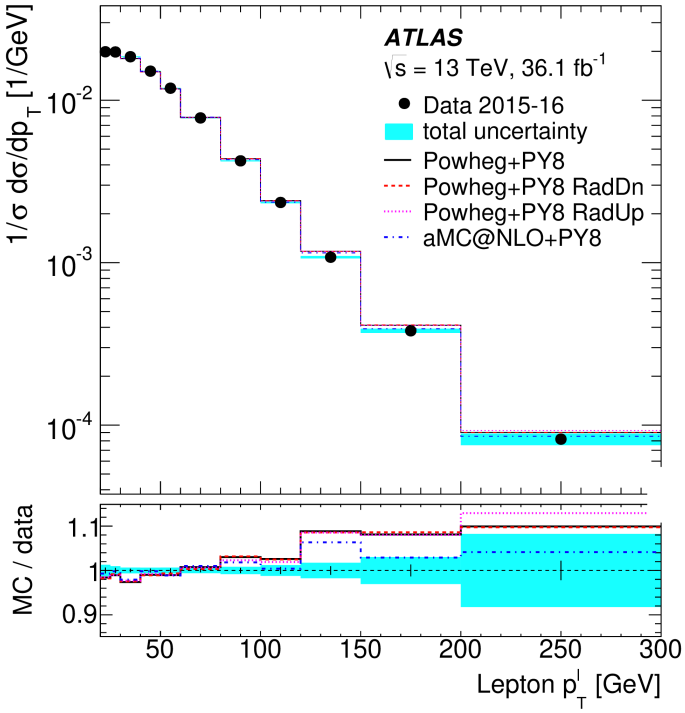


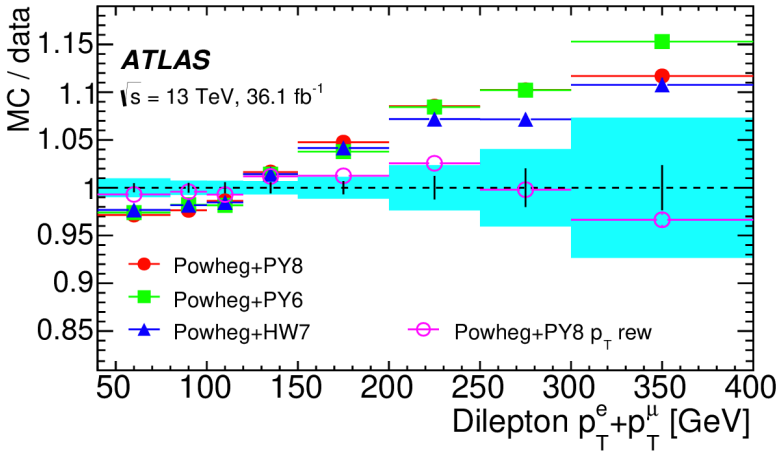


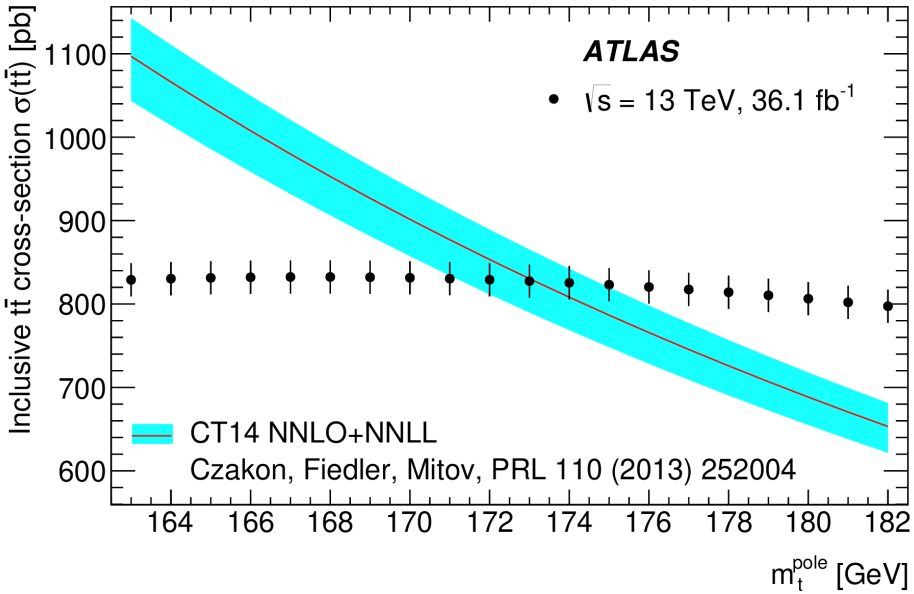
dσ(tt̄): dilepton channel results

Detailed comparison with many NLO predictions.

- fair agreement with many observables, except the lepton p_T
  - result of the top p_T mismodelling
- Re-weighting the PWG+PY8 to p_T to the measured one improves the modelling of several variables







The dependence of the xs from the top pole mass allows to extract the SM parameter from the inclusive measurement.

$$m_t^{pole} = 173.1^{2.0}_{-2.1}\, GeV$$

Measurements of ttγ:

- ATLAS-CONF-2019-044

Inclusive and differential measurement of σ(ttγ): method

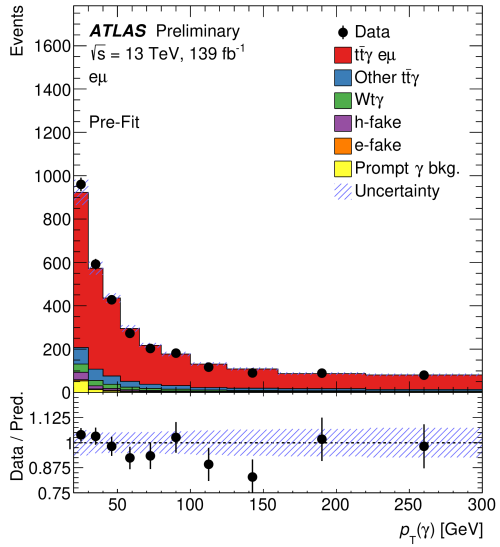
Event selection:

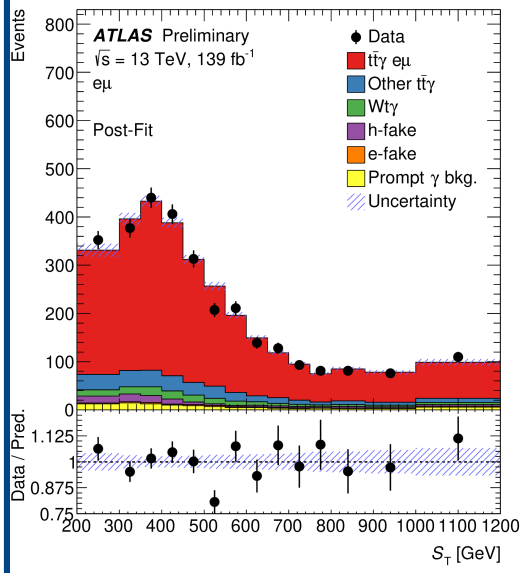
- One electron, one muon (p_T > 25 GeV)
- >=2 jets (>= 1bjet)
- 1 photon (ΔR(l,γ) > 0.4)

Fiducial region definition:

- Parton level → no hadronisation and showering effects considered
- Fiducial region similar to the signal region
  - Final state e,mu and γ are selected
  - At least 2 "parton b-jets"
  - All the objects need to be well separated (ΔR > 0.4)

	full data set
$t\bar{t}\gamma$ $e\mu$	2450 ± 120
Other $t\bar{t}\gamma$	266 ± 13
$Wt\gamma$	131 ± 22
h-fake	80 ± 40
e-fake	24 ± 12
Prompt γ bkg.	90 ± 40
Total	3030 ± 150
Data	3014

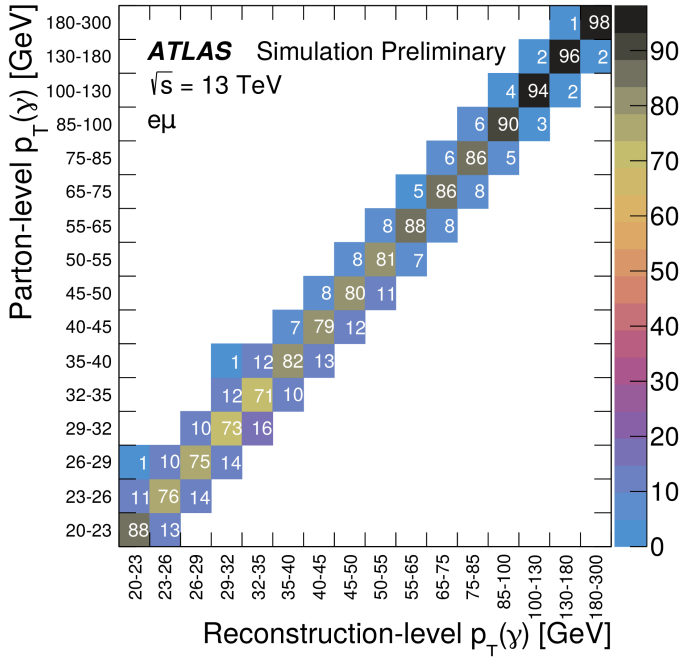




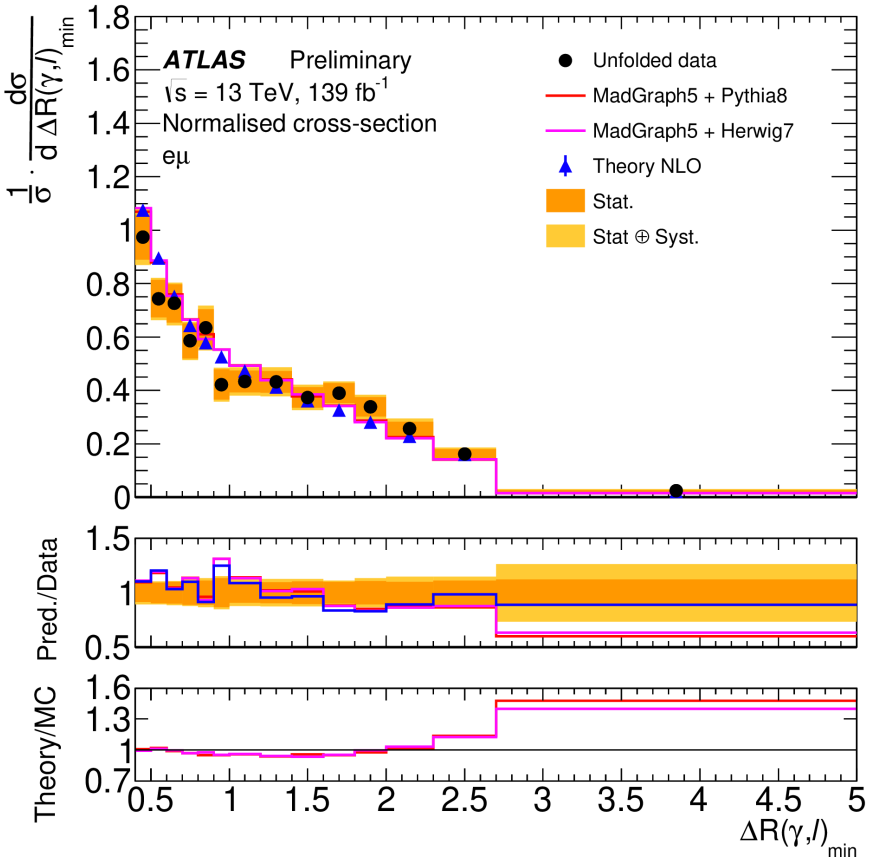
Inclusive measurement

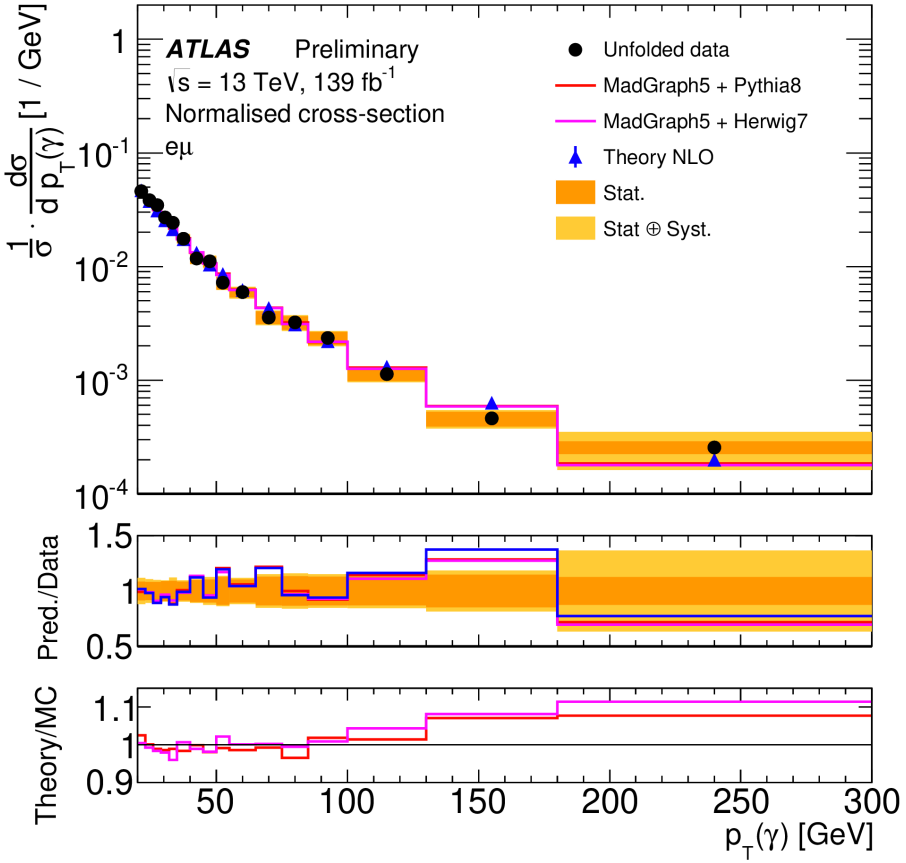
The inclusive cross section is calculated performing a likelihood fit on the S_T distribution (scalar sum of all p_T)

The **differential measurement** is obtained applying an iterative unfolding procedure.



Inclusive and differential measurement of σ(ttγ): results





- Main uncertainty coming from signal and background modelling
- Good agreement is observed between the LO MC and NLO differential distributions and the expectations.

The measured inclusive cross section:

σ=44.2 ±2.6 fb

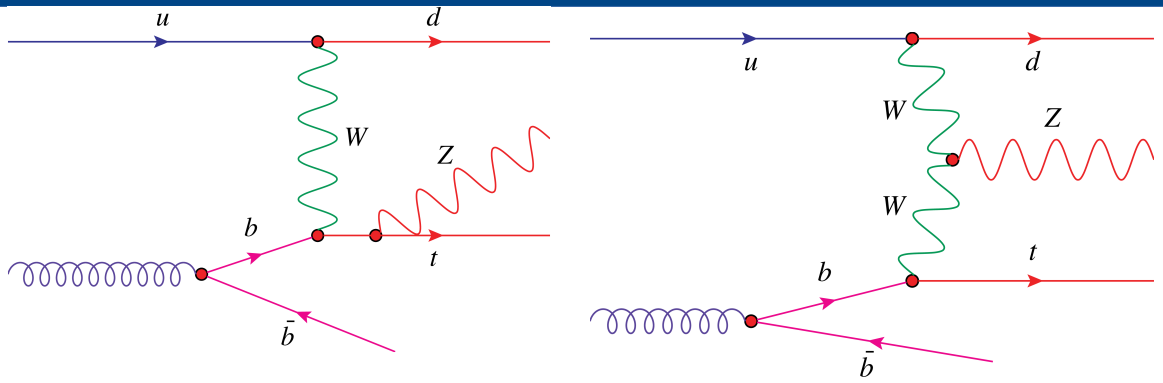
resulted slightly larger than the predicted NLO cross-section:

$$39.5^{0.56}_{-2.18}\left(scale\right)^{1.04}_{-1.18}\left(PDF\right)$$

Measurements of tZq:

- ATLAS-CONF-2019-043

Observation of tZq at √s=13 TeV: method

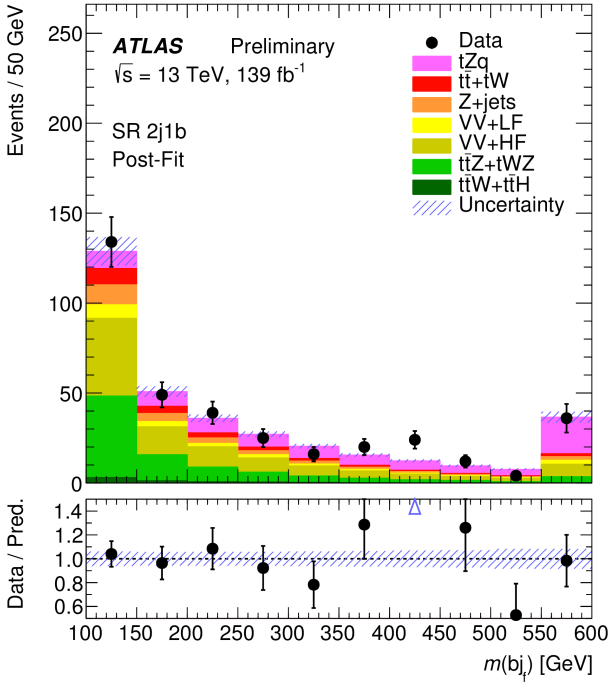


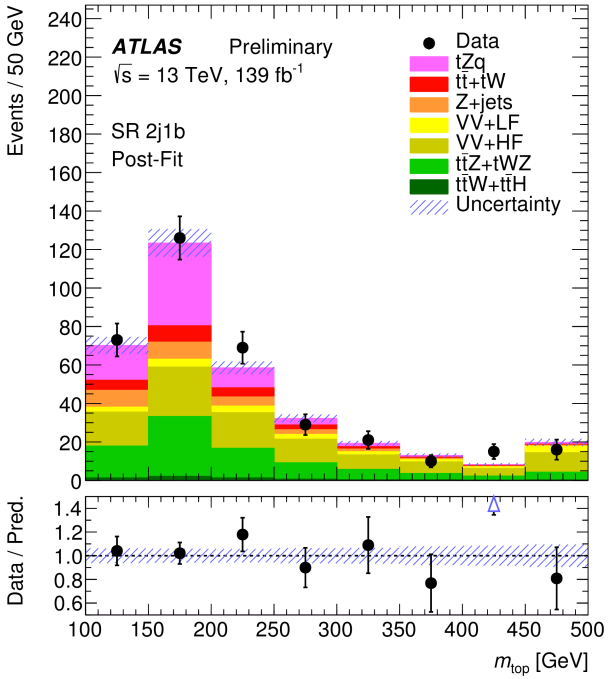
- Allow for the study of tZ and WZ couplings.
- Small NLO QCD corrections
  - Small deviations from the SM can be interpreted in the SMEFT

Event selection:

- 3 leptons (p_T > 28,20,20 GeV)
- At least 1 jet (p_T > 35 GeV)
- 1 b-tagged jet

- Main bkg : diboson, $t\bar{t}Z$ (3 real leptons) and $t\bar{t}$ and Z+jets(1 fake lepton from heavy hadron decay).
- Divided in several SR and CR based on b-jet and n-jet





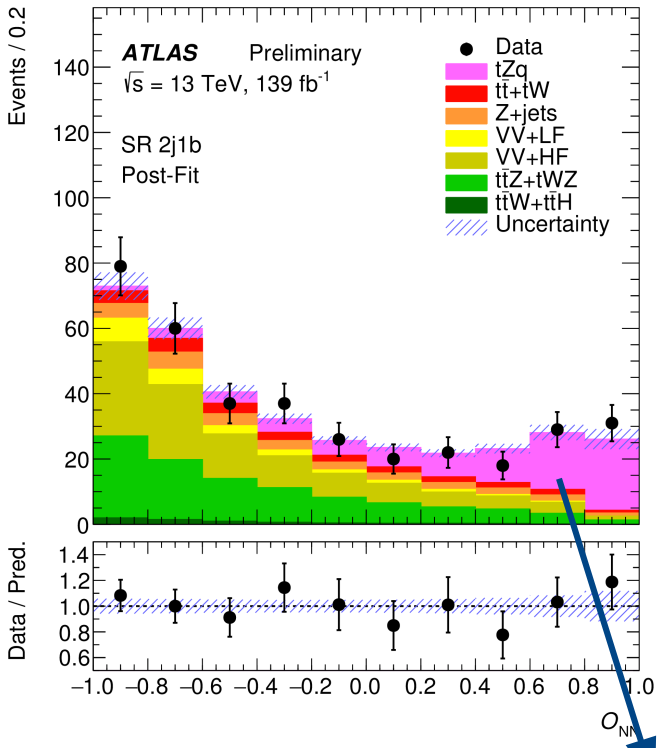
Discrimination signal and main backgrounds is reached using a NN built with:

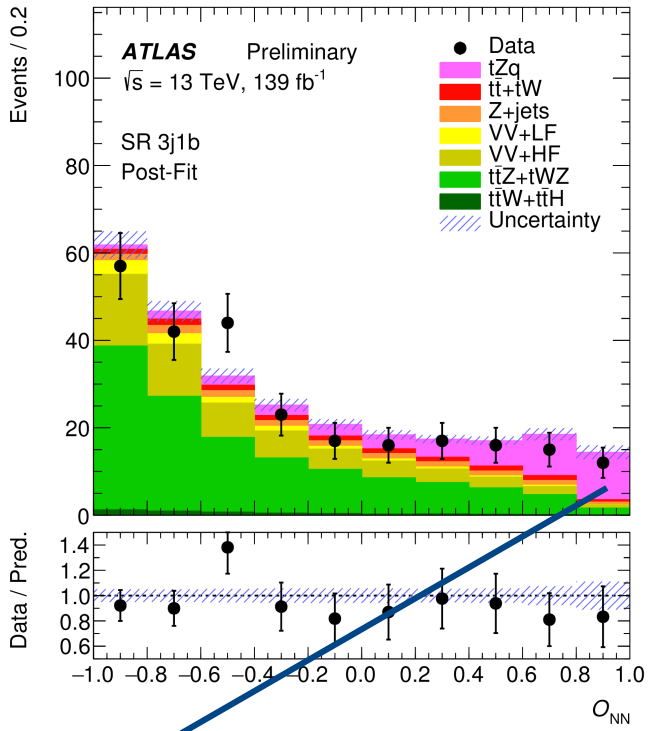
- kinematic variables of the final state objects (b,l,jets)
- reconstructed quantities as top mass and Z kinematic

Observation of tZq at √s=13 TeV: result

Cross section extracted using a binned maximum likelihood fit performed on the NN output in SRs and CRs

Process	SR (3j/2j+1b)
tZq	123.6
$t\bar{t}$+tW	34.8
Z+jets	40.7
VV+LF	30
VV+HF	161
$t\bar{t}$Z+tWZ	226
$t\bar{t}$H+$t\bar{t}$W	11.2
Total	626
Data	618





Good separation

Uncertainty source	$\Delta\sigma/\sigma$ [%]
tZq PDF	4.2
Prompt lepton background modelling and normalisation	3.4
Non-prompt lepton background modelling and normalisation	2.3
Jets+$E_{\mathrm{T}}^{\mathrm{miss}}$	2.1
Luminosity	1.7
Lepton reconstruction and calibration	1.7
Pile-up	1.2
MC statistics	1.0
tZq QCD radiation	0.8
b-tagging	0.4
Total systematic uncertainty	8.0
Statistical uncertainty	12

The measured σ is:

98 ±12(stat.)±8(syst.) fb (15%)

Consistent with the SM expectation of $102^{5}_{-2}\,fb$

Still statistically limited

Conclusions

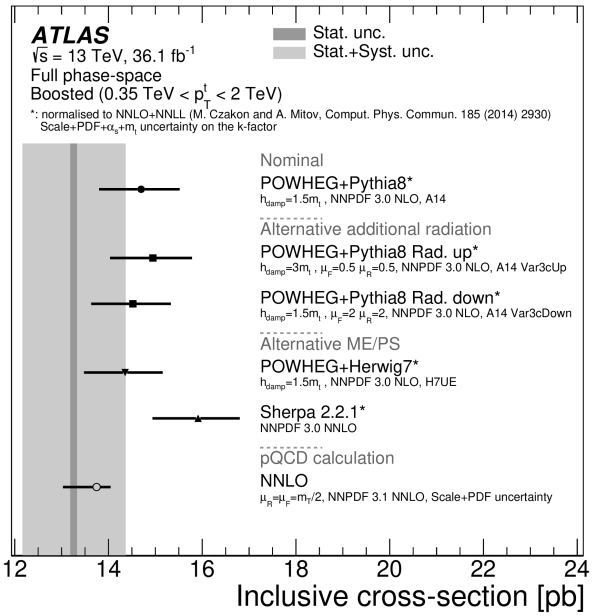
- Presented 3 recent differential measurements of $t\bar{t}$ production performed by ATLAS at $\sqrt{s}=13$ TeV, using 36 fb^{-1}:
  - In l+jets (resolved and boosted topologies), all-hadronic and dilepton channels.
  - As a function of many observables of $t\bar{t}$, jets and leptons kinematic, including double differential distributions
  - At particle and parton level, including the extraction of the pole mass from the inclusive measurement.
  - No significant differences with the SM have been observed
    - Some tension observed with the NLO predictions, in particular on double-differential distributions and variables related to the top p_T.

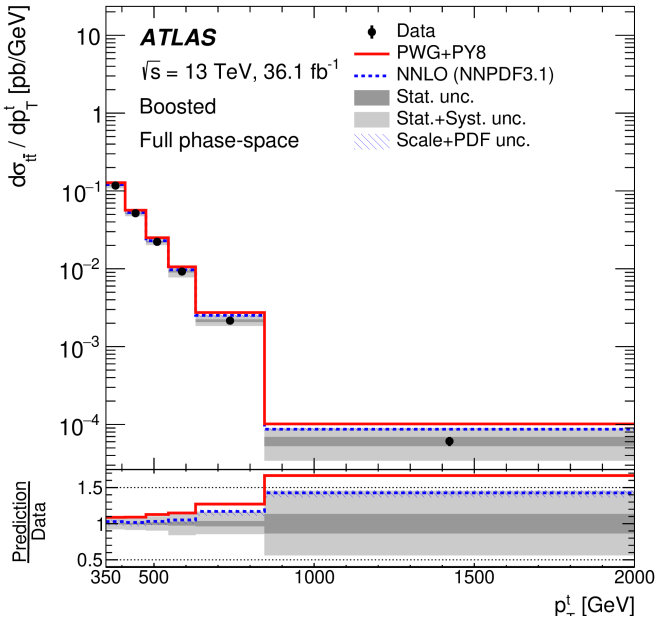
- Presented a recent inclusive and differential measurement of $tt\gamma$ production performed by the ATLAS experiment at $\sqrt{s}=13$ TeV, using 139 fb^{-1}.
  - No tension observed with the SM

- Presented the observation of the tZq production performed by the ATLAS experiment at $\sqrt{s}=13$ TeV, using 139 fb^{-1}.
  - No tension observed with the SM expectations
  - Reached a 15% precision

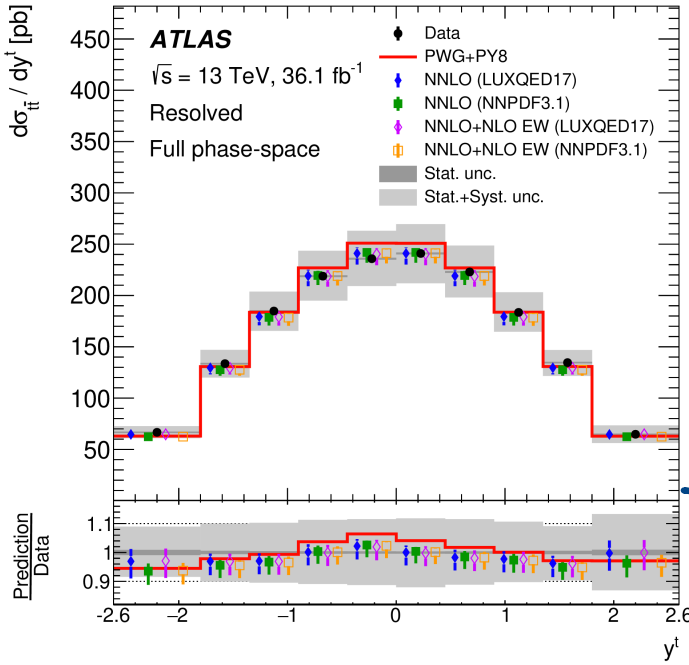
Thank you for your attention!

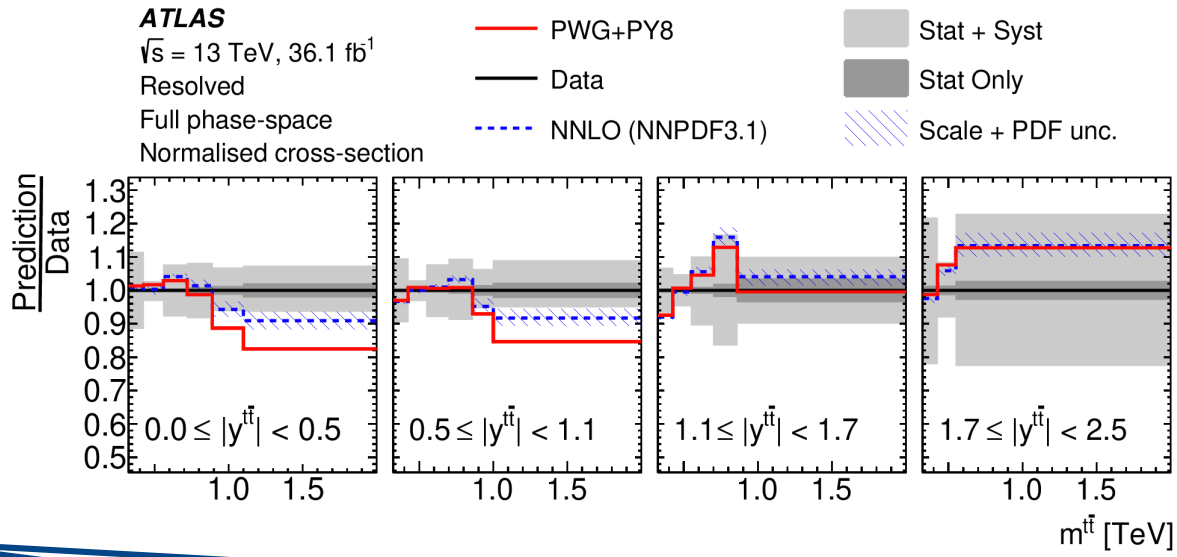
dσ(tt̄): l+jets channel parton-level results





- Measurement performed at parton-level to enable a comparison with fixed order calculations
- NNLO predictions generally improve the agreement with the data
- Comparison performed adding also EW corrections



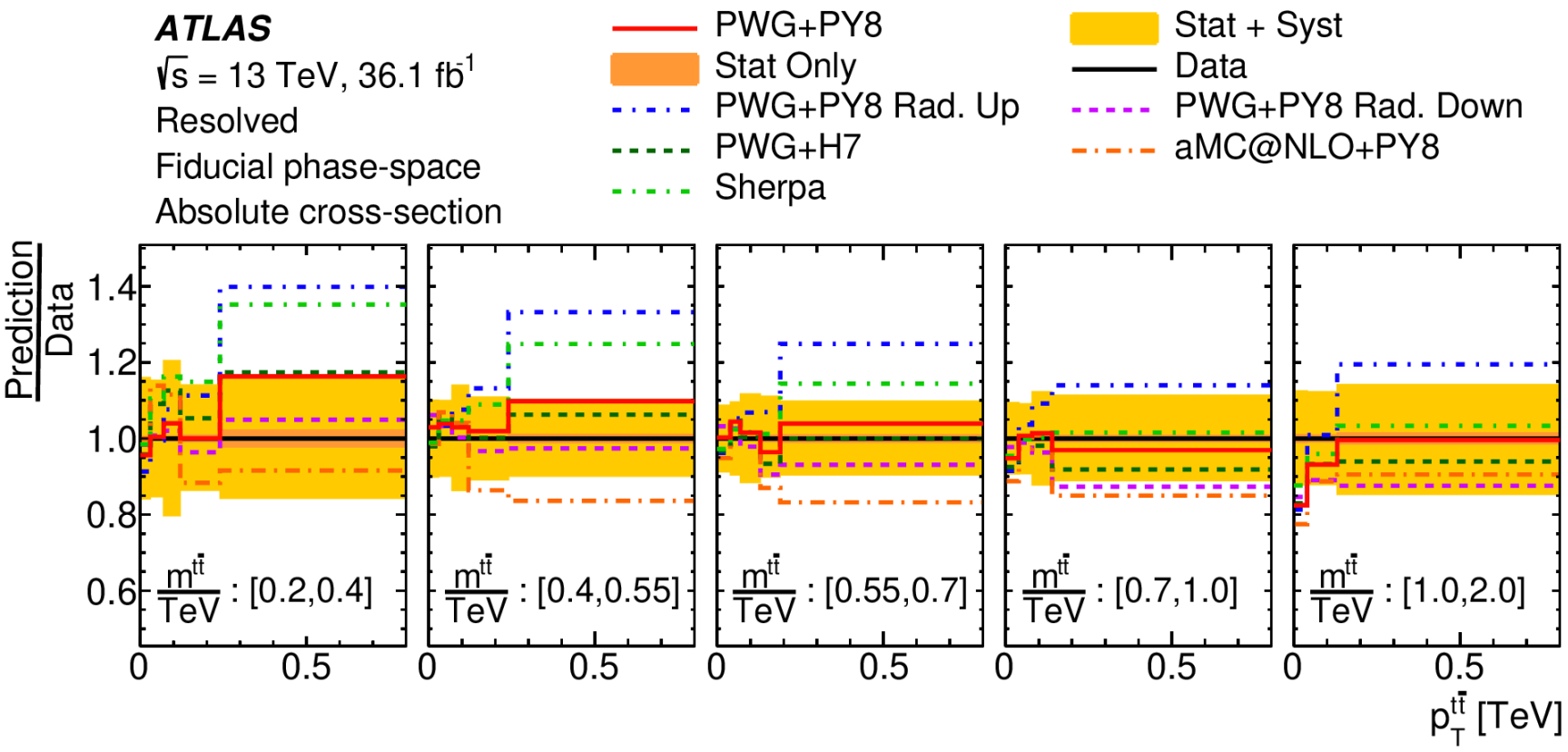


- Not large sensitivity to EW corrections in the range studied
- Employed the same binning of CMS measurement

dσ(tt̄): l+jets channel particle-level results

Double differential distributions provide a large discrimination among different generators.

- In general tensions are observed with many NLO generators that provide a good description of single differential observables



dσ(tt̄): dilepton channel results

Detailed comparison with many NLO predictions.

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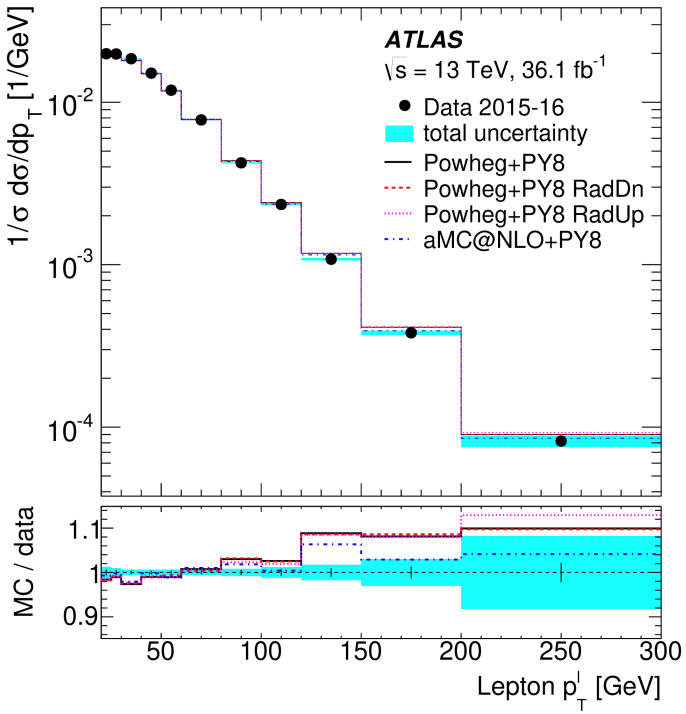
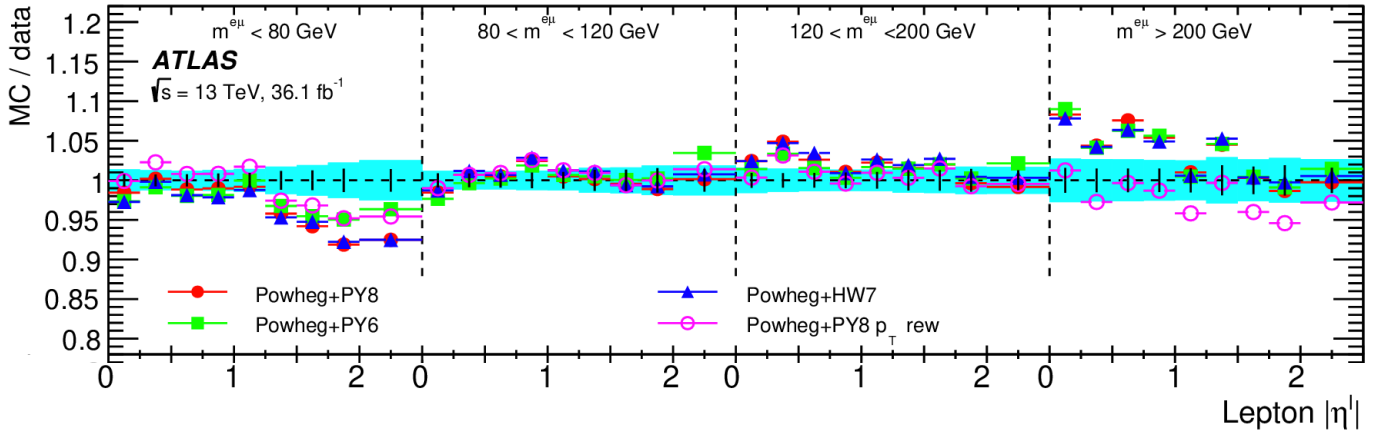
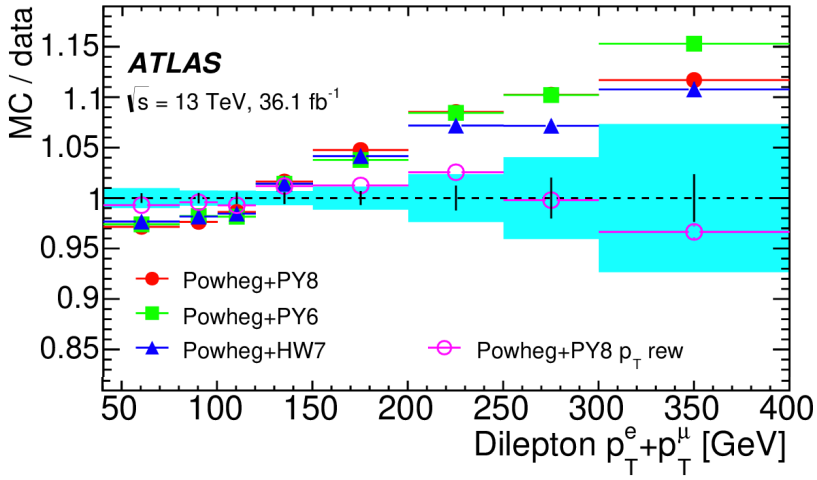
- reweigthing the PWG+PY8 top p_T to the measured one improves the modelling of several variables



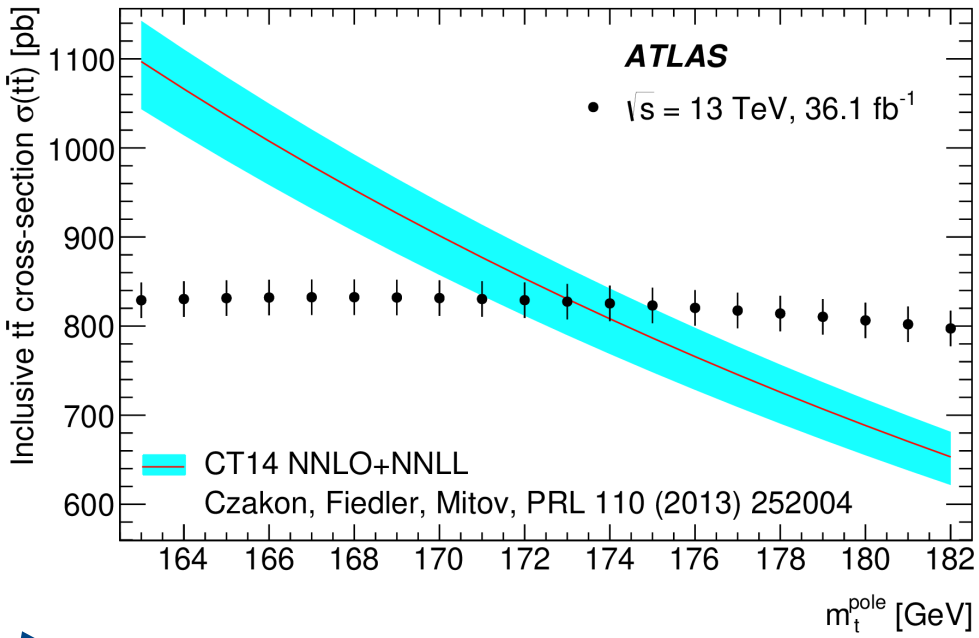




dσ(tt̄): dilepton channel re-interpretation

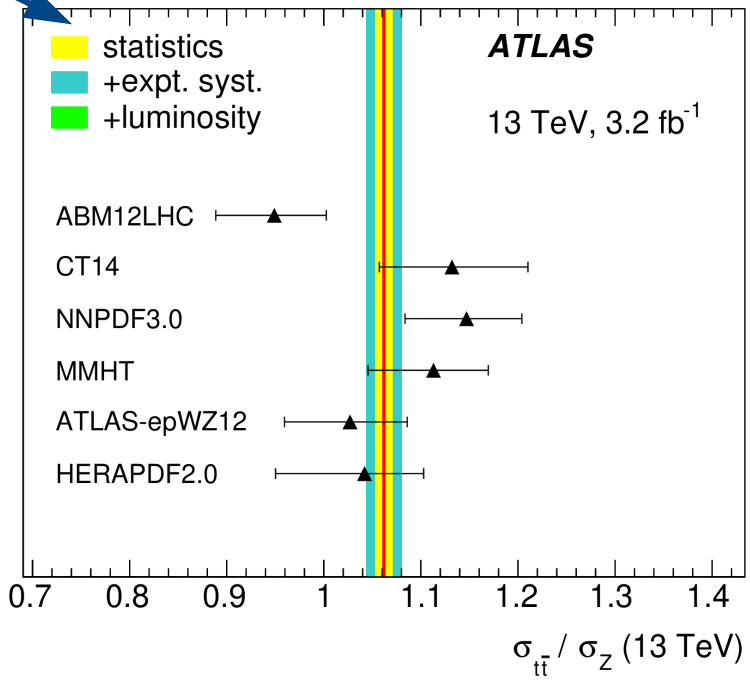
The dependence of the xs from the top pole mass allows to extract the SM parameter from the inclusive measurement.

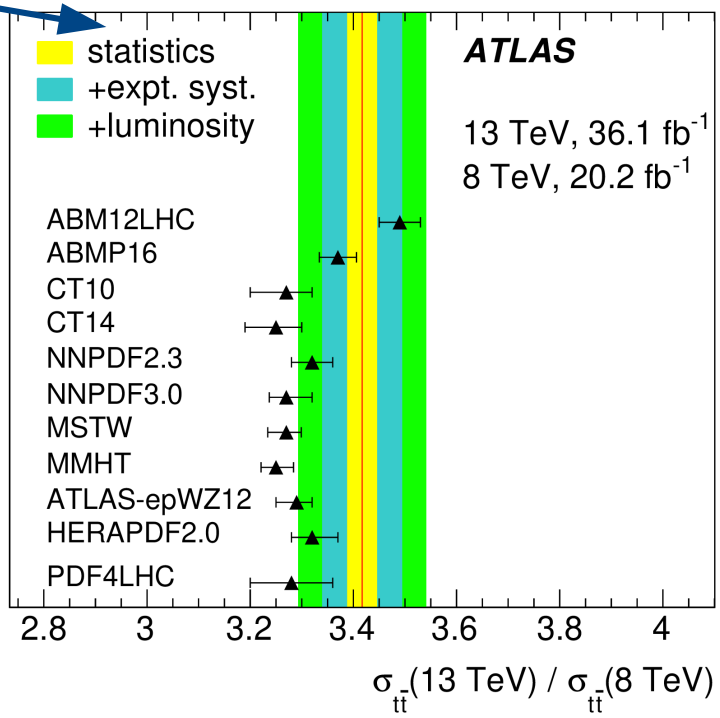
$$m_t^{pole} = 173.1^{2.0}_{-2.1}\, GeV$$



The cross section is sensitive to the gluon PDFs:

- In ratios the uncertainty is reduced → increasing the sensitivity
- Ratio among different years
- Ratio among different processes





dσ(tt̄) 1+jets, all-had: systematics

All-hadronic

Source	Uncertainty [%]	
	Particle level	Parton level
PS/Hadronisation	8.2	7.9
Multi-jet Syst.	7.7	7.7
JES/JER	6.7	6.7
ISR, PDF	3.3	3.5
ME Generator	2.4	5.3
Flavour Tagging	2.2	2.2
Luminosity	2.1	2.1
Multi-jet Stat.	0.6	0.6
MC Signal Stat.	0.3	0.3
Stat. Unc.	0.7	0.7
Stat+Syst Unc.	14	15

1+jets

Source	Uncertainty [%]			
	Particle level		Parton level	
	Resolved	Boosted	Resolved	Boosted
Flavour Tagging	7.1	2.1	7.1	2.1
JES/JER	4.9	4.1	5.7	4.0
Lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$	0.9	1.1	0.9	1.1
Backgrounds	2.5	3.9	1.9	3.9
Generator	3.1	0.9	4.5	4.7
Hadronisation	1.1	4.3	0.3	1.1
Rad., PDF, MC Stat.	0.5	0.7	0.8	2.3
Stat. Unc.	0.1	0.5	0.1	0.5
Stat+Syst Unc.	9.8	7.9	10.6	8.4