# Electroweak and Top Measurements at ATLAS

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**On behalf of the ATLAS Collaboration**

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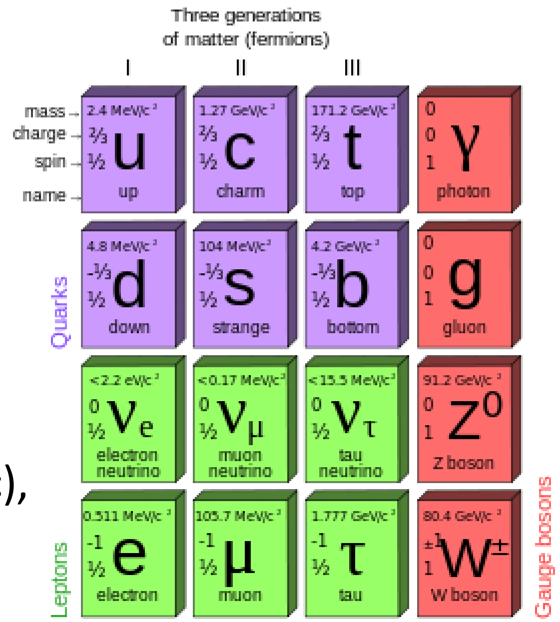
# Standard Model measurements now



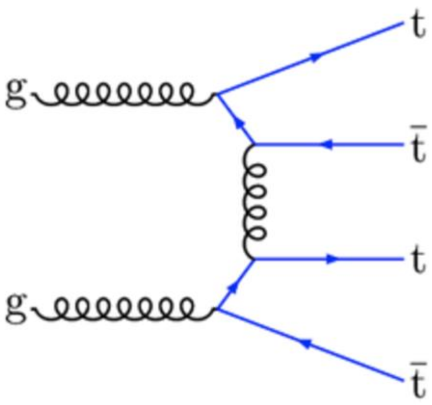

- Standard Model (SM) is extremely predictive theory since its inception, which successfully passes precise experimental tests for **about 50 years**.

- After the discovery of Higgs boson, SM measurements have two main goals, which are the following:
  - Validate SM in new energy regime and improve precision of known SM parameters;
  - Test SM for **new physics (NP)** contributions (indirect search: anomalous couplings, etc), provide information about SM processes – backgrounds to direct **new physics** searches.

- **Electroweak and top physics** have a great potential in both of these goals:
  - Theoretical predictions for most of the processes can be calculated with high precision (perturbative region);
  - A lot of rare processes predicted by SM, where the loop contributions (e.g. from NP particles) can give sizable effect, become sensitive tools to probe the NP models.

**Almost 200 papers** dedicated to electroweak and top measurements were published by ATLAS since the start of LHC. Only few recent analyses are presented in these slides, more available:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

# Top physics



# Top: BR(W→τν) / BR(W→μν) in μ-μ and e-μ ttbar events

Nature Physics (2021)

- There is a clear deviation of the experimental result from the SM prediction in rare decays in b-physics:
  - $BR(B^+\to K^+\mu^+\mu^-) / BR(B^+\to K^+e^+e^-)$ deviates from SM prediction on 3.1σ (latest LHCb result);
  - $BR(B^0\to D^{*+}\tau^-\bar{\nu}) / BR(B^0\to D^{*+}\mu^-\bar{\nu})$ deviates from SM prediction on 3.4σ (LHCb+Belle+Babar result).

These and other results show the possibility of the violation of the lepton flavor universality (LFU).

- The checks of LFU in other processes become very important.

- **This analysis is the first LHC test of LFU in W boson decays**. Previous result from LEP had a deviation of 2.7σ from SM.

Data: $L=139\ fb^{-1} \pm 1.7\%$

*ttbar/Wt, W bosons decay leptonically,* $W\to\tau\nu_\tau\to\mu\nu_\mu\nu_\tau\nu_\tau$ / $W\to\mu\nu_\mu$

Opposite charge μμ, eμ final states are used

MC signal: Powheg+Pythia8, with differential reweighting to NNLO prediction in QCD top quark $p_T$;

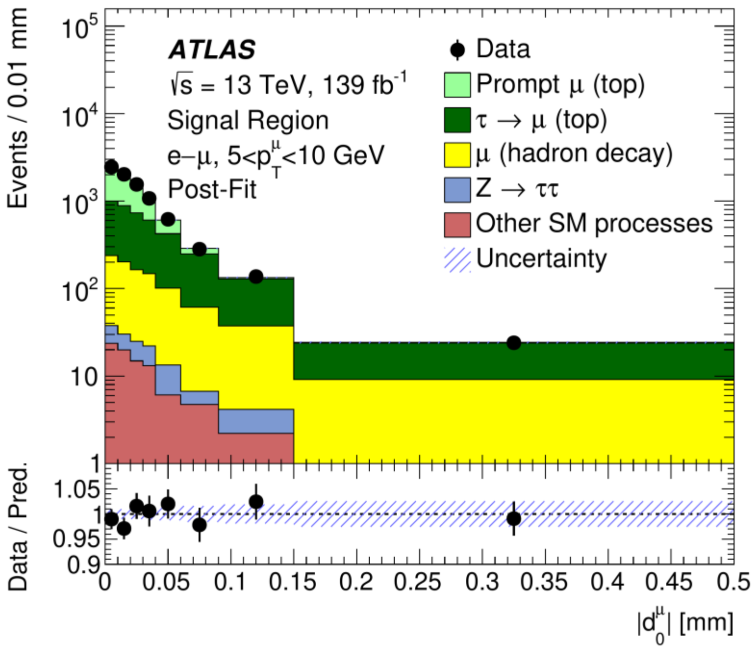
Main bkgs: Z(→μμ)+jets; events with probe muon not from W (μ from hadrons, Z→ττ, etc).

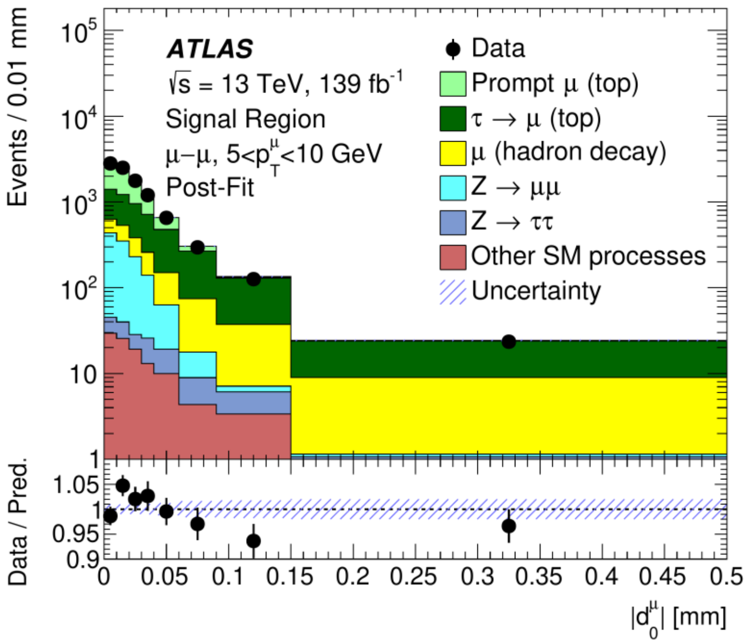
- Main features:
  - To distinguish events of numerator from denominator, τ lifetime information was used (through $d_0^\mu$);
  - Z(→μμ) events selected in region $85<m_{\mu\mu}<100$ GeV, were used to calibrate the shape of $d_0^\mu$ distribution;
  - Normalization for Z(→μμ)+jets bkg was taken from data control region, the fit of peak region ($50<m_{\mu\mu}<140$ GeV) was performed with Voigt profile (for the resonance) and with third-order Chebychev polynomial (for bkg);
  - A data-driven method was used to estimate the background of prompt μ not from W: control regions of same-sign μ-μ ana e-μ were constructed, which have high purity for this kind of background.

# Top: BR(W→τν) / BR(W→μν) in μ-μ and e-μ ttbar events

[Nature Physics (2021)](#)

- The $d_0^{\mu}$ distributions in the signal region for e-μ and μ-μ final states



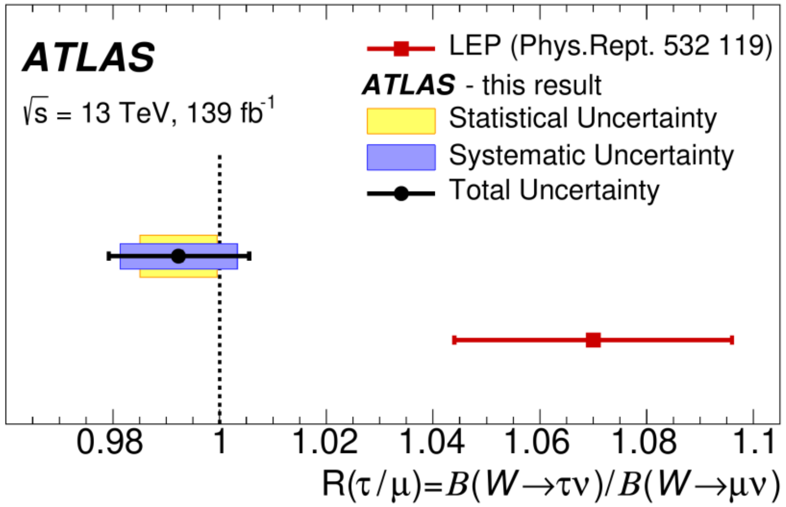

Main uncertainties are from:

- $d_0^{\mu}$ template tail (to account that templates are from Z(μμ) calibration region and applied to SR);
- signal parton showering and hadronization modelling;
- muon isolation.

- <u>Result:</u>

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat})\ \pm\ 0.011\ (\text{syst})].$$

This <u>agrees</u> well with the Standard Model prediction and is the most precise measurement of R(τ/μ) to date.



# Top: Measurement of four-top-quarks production cross section

Submitted to JHEP, arXiv:2106.11683

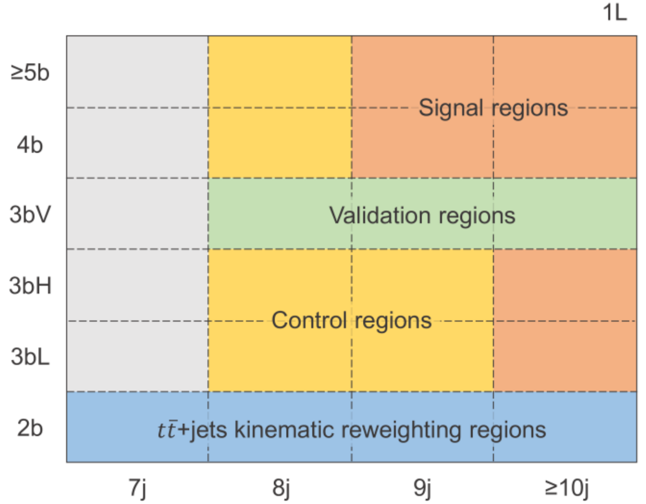
- **4-top** production is a rare process, which **was not observed previously**. Its cross section is sensitive to properties of the top quark coupling to the Higgs boson, hypothetical new particles and to various four-fermion couplings in the context of the effective field theory (EFT) framework.

Data: $L=139\ fb^{-1} \pm 1.7\%$

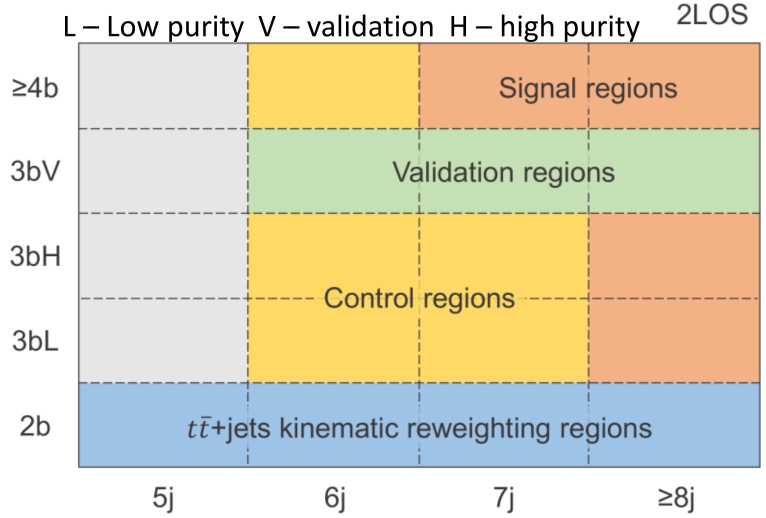
1L/2LOS final state: 1 lepton or 2 leptons with opposite signs [57% of all 4-top] (this analysis);
2LSS/3L final state: 2 leptons (e/μ) with same signs or 3 leptons [13%] (for combination from Eur. Phys. J. C 80 (2020) 1085).

MC signal: MG5+Pythia8 at NLO in QCD
Main bkgs: tt+jets (with c quarks / with b quarks).

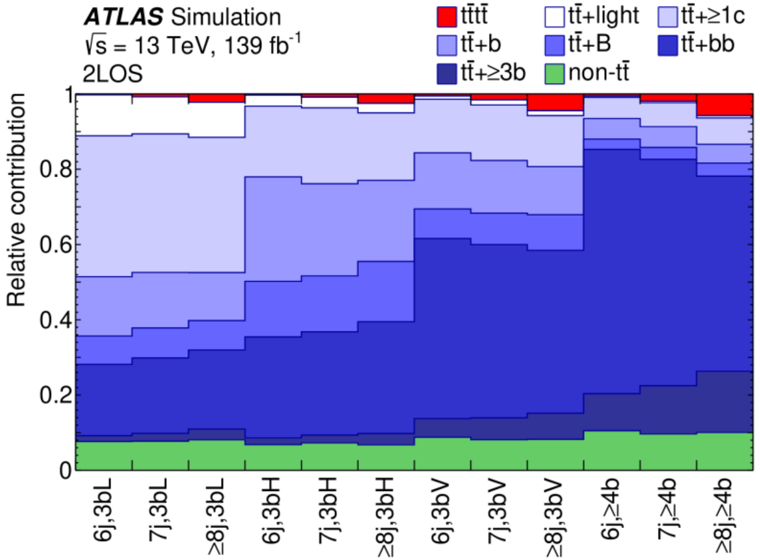
- Categorization into different regions according to the lepton and jet multiplicities and different $b$-tagging requirements. Categories are used as signal, validation and control regions.




L – Low purity V – validation H – high purity



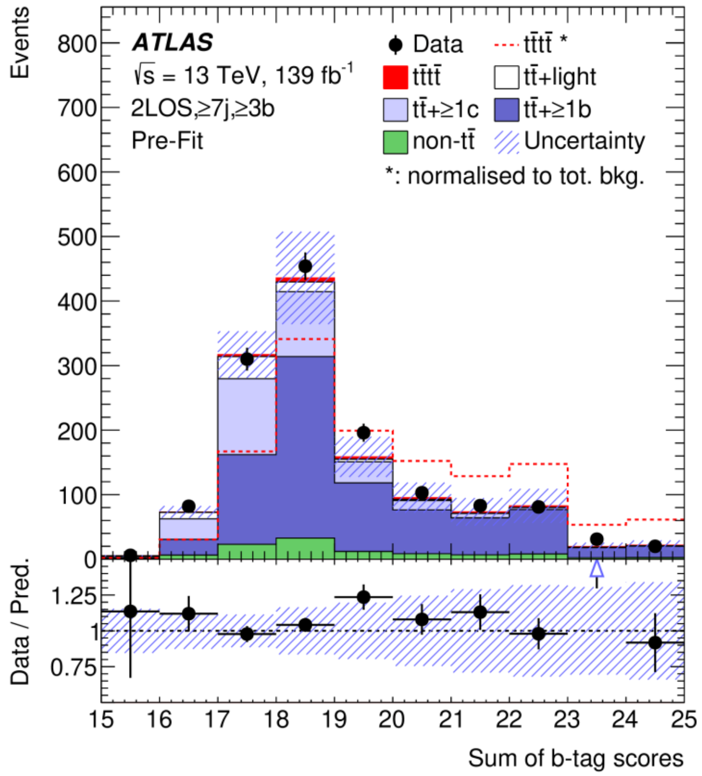

- tt+jet bkg flavor rescaling and sequential kinematic reweighting were applied.



# Top: Measurement of four-top-quarks production cross section

Submitted to JHEP, arXiv:2106.11683

- A multivariate analysis (BDT) is performed in the signal regions to discriminate 4-top signal from the background. Modelling of all input variables was checked:




- Results (1L/2LOS):

$$\mu = 2.2 \pm 0.7\,(\text{stat.})\,^{+1.5}_{-1.0}\,(\text{syst.}) = 2.2\,^{+1.6}_{-1.2},\qquad \sigma^{SM}_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4\text{ fb} \quad \text{(NLO)},$$

$$\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8\,(\text{stat.})\,^{+15}_{-13}\,(\text{syst.})\text{ fb} = 26\,^{+17}_{-15}\text{ fb}.$$

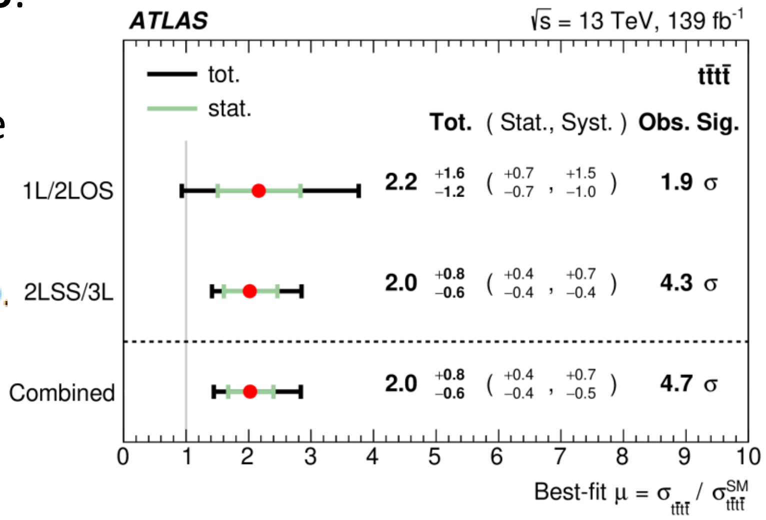
Obs (exp) signal significance of **1.9 (1.0)σ**.

- Combination with 2LSS/3L final state

$$\mu = 2.0 \pm 0.4\,(\text{stat.})\,^{+0.7}_{-0.5}\,(\text{syst.}) = 2.0\,^{+0.8}_{-0.6}$$

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.})\text{ fb} = 24\,^{+7}_{-6}\text{ fb}.$$

Obs (exp) significance of the combined 4-top cross section is **4.7 (2.6)σ**.




Some tension exists.

Main systematic sources are from:
Signal parton showering modelling, 4-top cross section in 2LSS/3L and normalizations of tt+c-quarks background.

# Top: Measurement of ttZ cross section

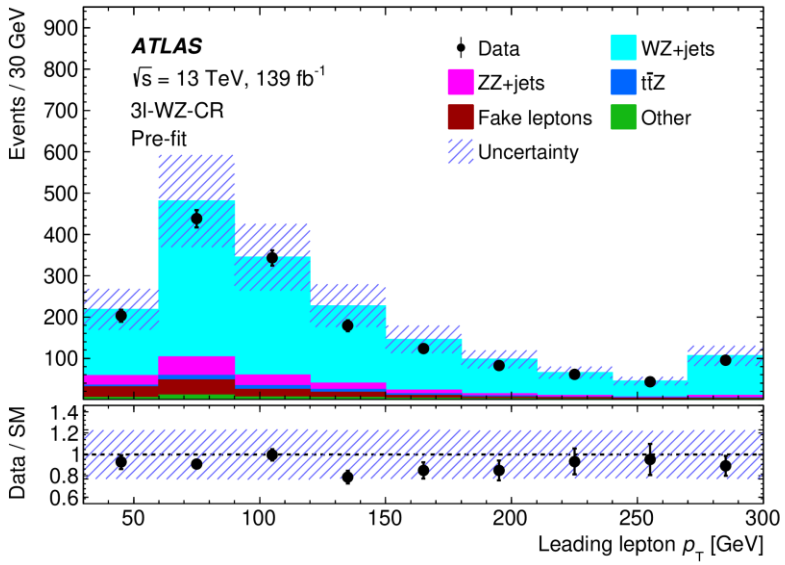
Submitted to EPJC, arXiv:2103.12603

- The $ttZ$ production process provides direct access to the neutral coupling of the top quark to the electroweak gauge bosons. The deviation of the coupling from SM can come from NP models, it can be probed in the context of EFT.

Data: *L=139 fb$^{-1}$ ± 1.7%*
MC signal: MG5+Pythia8 at NLO in QCD
Main bkgs: prompt lepton background (WZ for 3-lep region and ZZ for 4-lep region),
fake lepton bkgs (dileptonic tt decays with leptons from hadrons).

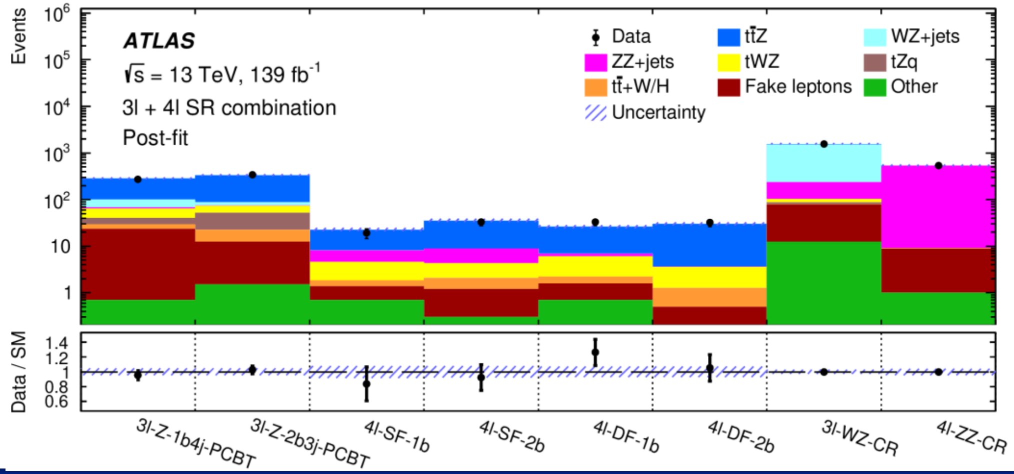
Final states with exactly 3 or 4 isolated leptons

One or both t-quarks decay: t→Wb→lvb




- Prompt lepton backgrounds are estimated from MC with normalization derived from data in WZ+jets and ZZ+jets CRs (1 or 2 pairs of leptons with opposite signs, $m_{ll}$ in Z mass window).
- Fake lepton backgrounds are estimated with fully data driven "matrix" method. It relies on the prompt and fake leptons having different probabilities of passing the identification, isolation and impact parameters requirements.

- Results from simultaneous fit of all the regions:




Main systematic sources are from: Signal parton showering modelling, tWZ modelling and b-tagging.

# Top: Measurement of ttZ cross section

Submitted to EPJC, arXiv:2103.12603

- Integrated cross section:

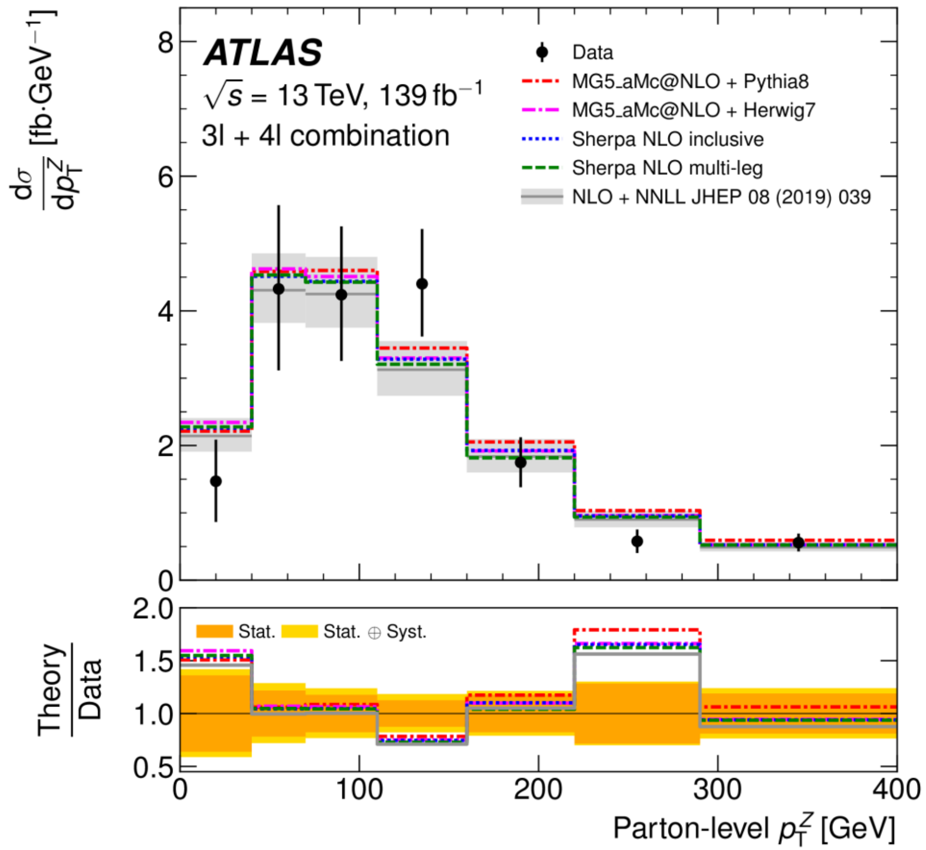
$$\sigma(pp \to t\bar{t}Z) = 0.99 \pm 0.05\,(\text{stat.}) \pm 0.08\,(\text{syst.})\text{ pb.}$$

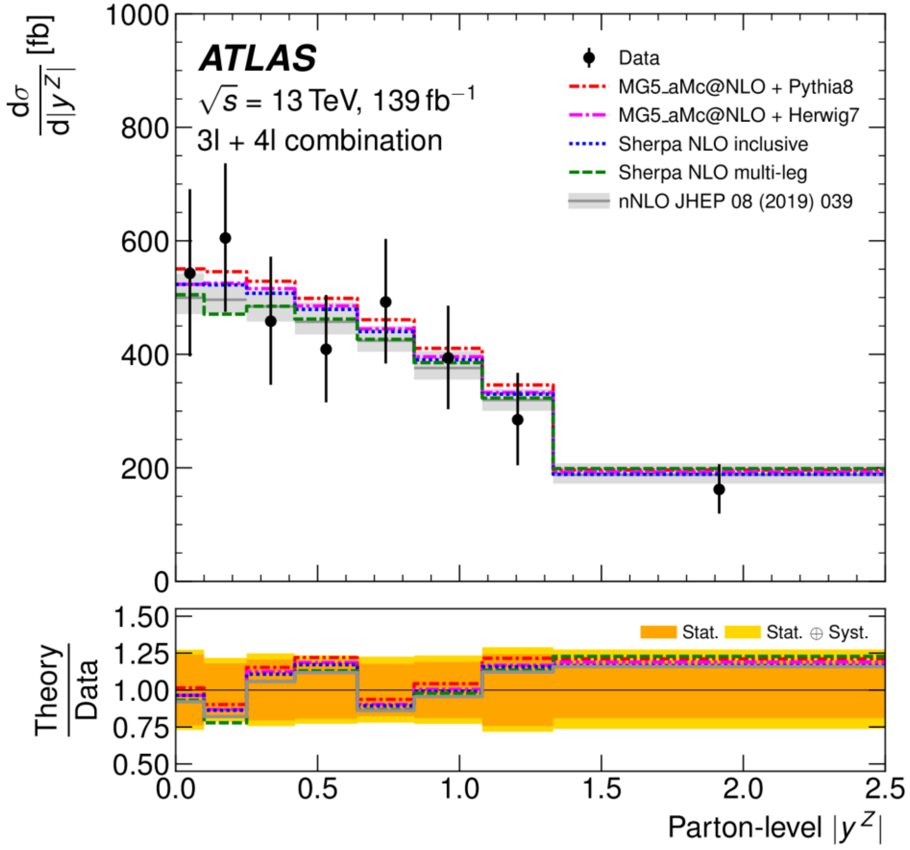
$$\sigma_{\text{SM}} = 0.84^{+0.09}_{-0.10}\text{ pb at NLO QCD and EW accuracy}$$

- Signal strength:

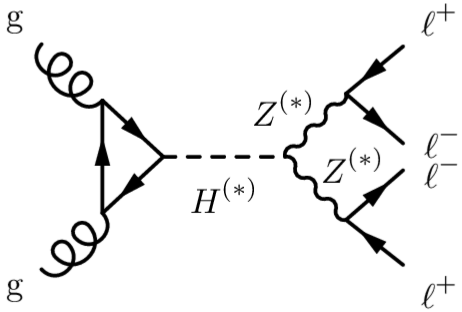
| Channel | $\mu_{t\bar{t}Z}$ |
|---|---|
| Trilepton | $1.17 \pm 0.07\,(\text{stat.})\,^{+0.12}_{-0.11}\,(\text{syst.})$ |
| Tetralepton | $1.21 \pm 0.15\,(\text{stat.})\,^{+0.11}_{-0.10}\,(\text{syst.})$ |
| Combination ($3\ell + 4\ell$) | $1.19 \pm 0.06\,(\text{stat.}) \pm 0.10\,(\text{syst.})$ |

- Differential cross sections:



# Electroweak physics



# EWK: Inclusive four-lepton differential cross sections

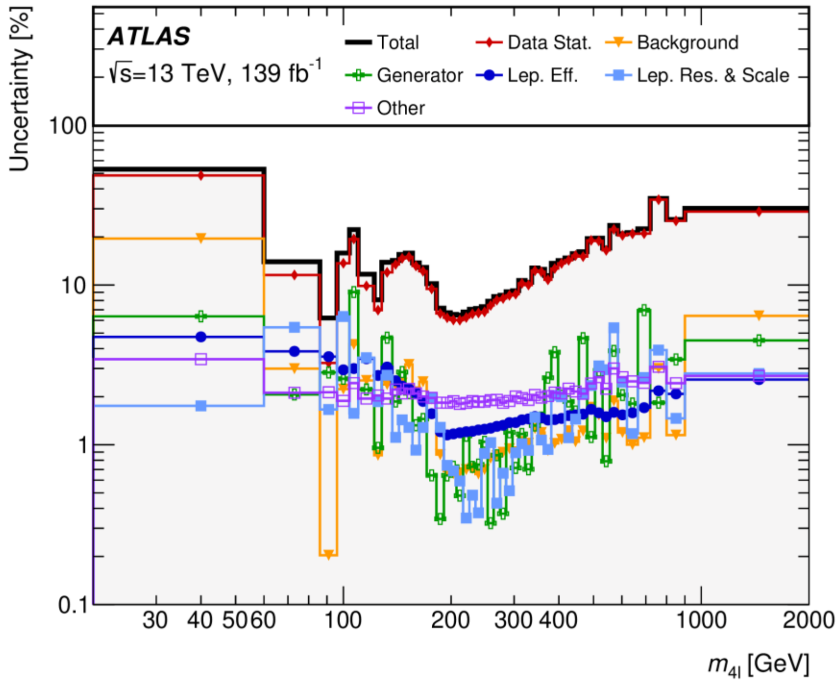
Accepted by JHEP, arXiv:2103.01918

- Several interesting Standard Model processes contribute to this final state, with the possibility of additional contributions from beyond-the-SM (BSM) physics, can be interpreted using EFT formalism.

Data: *L=139 fb$^{-1}$ ± 1.7%* Final states: $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$
MC signal: Sherpa 2.2.2, 0 and 1 jets at NLO, 2 and 3 jets at LO. Alternative sample: PowHeg+Pythia8 at NLO.
All processes except fake lepton background (Z+leptons from hadron decays, tt + leptons from hadron decays) – are considered as signal.

- Background estimated with fake-factor data driven technique. Fake factor is measured in special CR in data, enriched in non-prompt leptons. This factor accounts for the transfer from baseline-not-signal region to the signal one.
- Dominant uncertainty is statistical, next one comes from background estimation.
- Results:

| | Region | | | | |
|---|---|---|---|---|---|
| | Full | $Z \rightarrow 4\ell$ | $H \rightarrow 4\ell$ | Off-shell $ZZ$ | On-shell $ZZ$ |
| Measured fiducial cross-section [fb] | 88.9<br>±1.1 (stat.)<br>±2.3 (syst.)<br>±1.5 (lumi.)<br>±3.0 (total) | 22.1<br>±0.7 (stat.)<br>±1.1 (syst.)<br>±0.4 (lumi.)<br>±1.3 (total) | 4.76<br>±0.29 (stat.)<br>±0.18 (syst.)<br>±0.08 (lumi.)<br>±0.35 (total) | 12.4<br>±0.5 (stat.)<br>±0.6 (syst.)<br>±0.2 (lumi.)<br>±0.8 (total) | 49.3<br>±0.8 (stat.)<br>±0.8 (syst.)<br>±0.8 (lumi.)<br>±1.3 (total) |
| SHERPA | 86±5 | 23.6±1.5 | 4.57±0.21 | 11.5±0.7 | 46.0±2.9 |
| POWHEG + PYTHIA8 | 83±5 | 21.2±1.3 | 4.38±0.20 | 10.7±0.7 | 46.4±3.0 |




Good agreement observed.

# EWK: Inclusive four-lepton differential cross sections

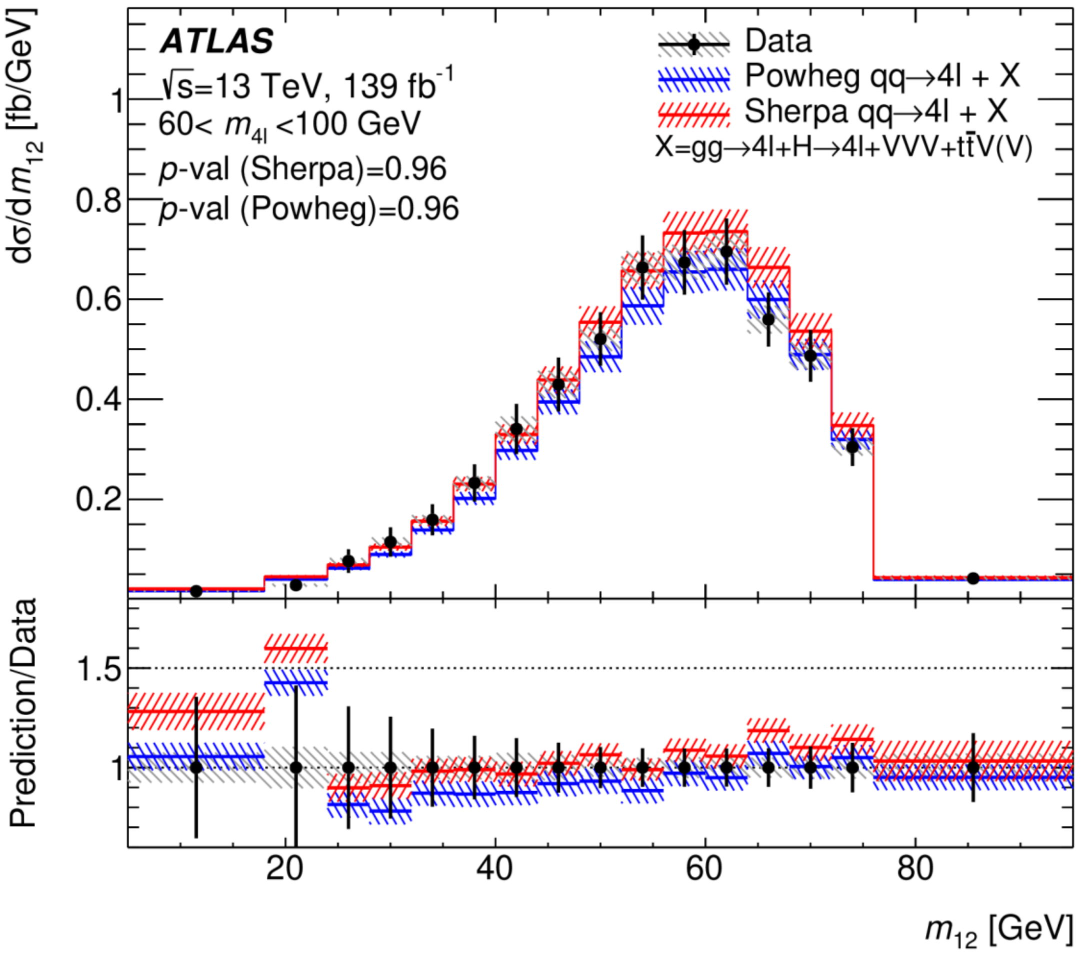
[Accepted by JHEP](), [arXiv:2103.01918]()

- Z→4l branching ratio:

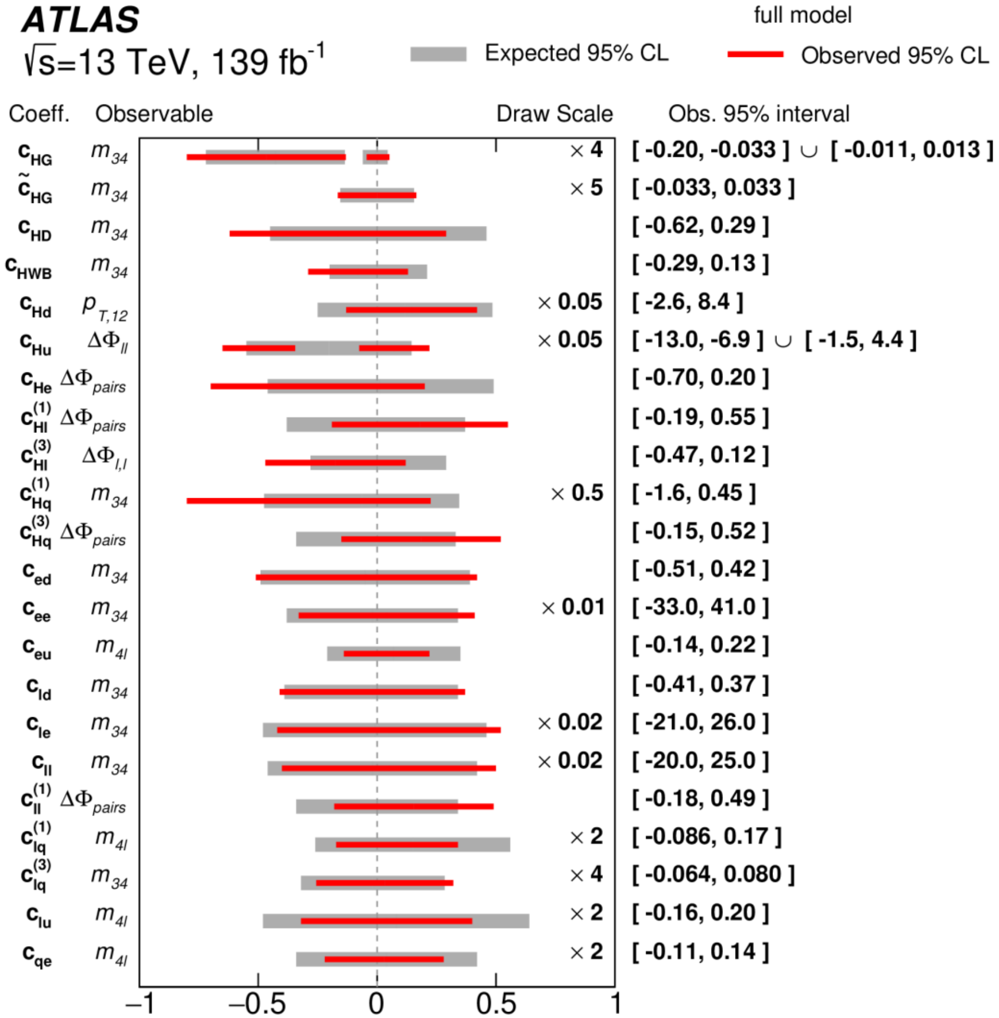
$$\mathcal{B}_{Z\to 4\ell} = (4.41 \pm 0.13\,(\text{stat.}) \pm 0.23\,(\text{syst.}) \pm 0.09\,(\text{theory}) \pm 0.12\,(\text{lumi.}))\times 10^{-6} = (4.41 \pm 0.30)\times 10^{-6},$$

$$\mathcal{B}^{\text{Powheg}}_{Z\to 4\ell} = (4.50 \pm 0.01) \times 10^{-6}$$

- Differential and double differential cross sections:




- EFT interpretation



# EWK: WW+1jet differential cross sections

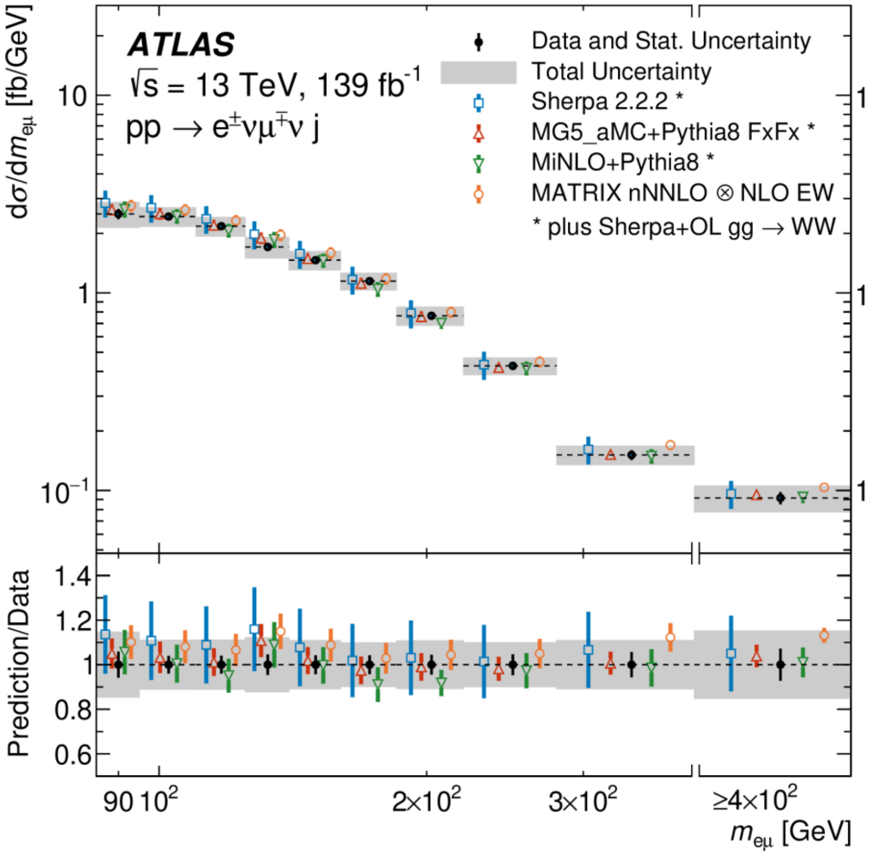
JHEP 06 (2021) 003

Data: *L=139* $fb^{-1}$ *± 1.7%* *only lepton decay modes were used ($e^+\mu^-$, $e^-\mu^+$), where lepton=e/μ + at least 1 jet*

MC signal: Sherpa 2.2.2, 0 and 1 jets at NLO, 2 and 3 jets at LO. Alternative sample: PowHeg+Pythia8 at NLO

Main bkgs: top bkg (tt, Wt) (From CRs), Zjets (from MC), non-prompt and misidentified leptons (data-driven from dedicated CRs)

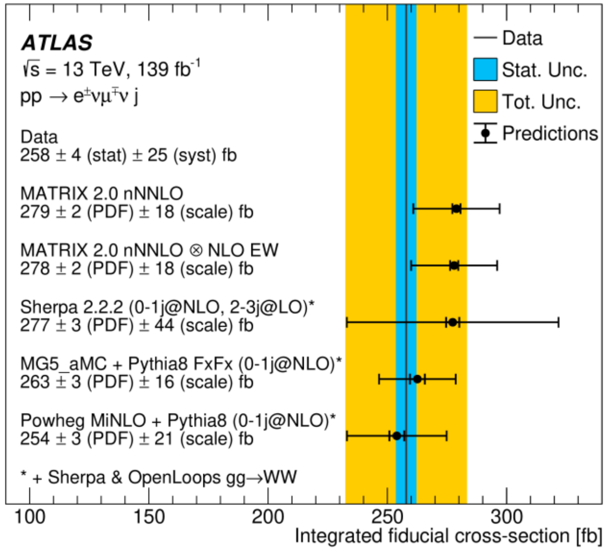
- Configuration with ≥1 jet is very sensitive to NP, probed using EFT formalism.
- **Measurement** of integrated and differential cross-sections (vs. $p_T$[lead l], $m_{e\mu}$, $\Delta\varphi_{e\mu}$, etc)




$$\sigma_{\text{fid}} = 258 \pm 4\ (\text{stat.}) \pm 25\ (\text{syst.})\ \text{fb},$$

$$\sigma_{\text{MATRIX}} = 279 \pm 2\ (\text{pdf})\ ^{+20}_{-16}\ (\text{scale})\ \text{fb}$$

- Main systematic sources are from:
  - jet calibration,
  - top-modelling,
  - fake-lepton bkg.




- Setting limits on anomalous TGC in **EFT** formalism ( $c_W/\Lambda^2$ parameter):

| Jet $p_T$ | Linear only | 68% CI obs. | 95% CI obs. | 68% CI exp. | 95% CI exp. |
|---|---|---|---|---|---|
| > 30 GeV | yes | [−1.64, 2.86] | [−3.85, 4.97] | [−2.30, 2.27] | [−4.53, 4.41] |
| > 30 GeV | no | [−0.20, 0.20] | [−0.33, 0.33] | [−0.28, 0.27] | [−0.39, 0.38] |
| > 200 GeV | yes | [−0.29, 1.84] | [−1.37, 2.81] | [−1.12, 1.09] | [−2.24, 2.10] |
| > 200 GeV | no | [−0.43, 0.46] | [−0.60, 0.58] | [−0.38, 0.33] | [−0.53, 0.48] |

# EWK: Observation of γγ->WW

Phys. Lett. B 816 (2021) 136190

- In the SM, the $\gamma\gamma \to WW$ process proceeds through trilinear and quartic gauge-boson interactions, so it is extremely sensitive to anomalous gauge-boson interactions.

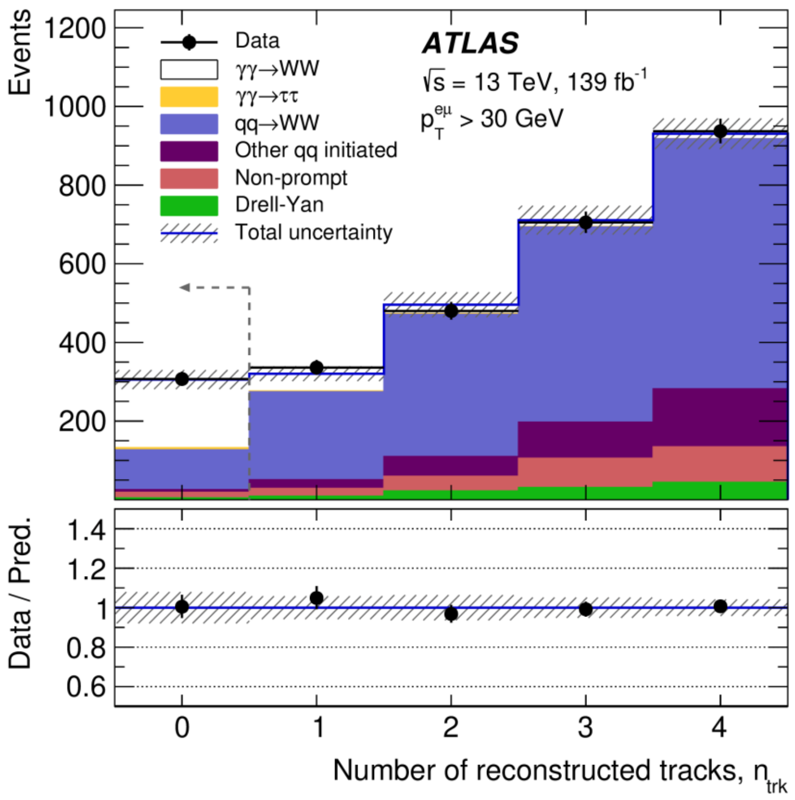
Data: *L=139 fb$^{-1}$ ± 1.7%* *only lepton decay modes were used ($e^+\mu^-$, $e^-\mu^+$), where lepton=e/μ*
MC signal: Herwig7+BudnevQED photon flux at LO (elastic component), then it is corrected to include the rest.
Main bkgs: qq→WW, DY ($Z/\gamma* \to \tau\tau$), non-prompt and misidentified leptons (W+jets).

- The interaction vertex is reconstructed from the two leptons in the event, lep1 and lep2. The veto of ID tracks (except tag leptons) inside small window ($n_{trk}$=0) around this vertex is used for exclusivity selection.
- DY and qq→WW backgrounds are constrained from CRs, based on $p_T$(eμ) and $n_{trk}$.
- Non-prompt lepton bkg is estimated using CR, where 1 lepton fails lepton ID criteria.
- Dominant uncertainty are from stat error on misID leptons bkg, WW modelling and signal modelling.
- Results:

$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\text{ fb} \qquad \sigma_{\text{Herwig7}} = 2.34 \pm 0.27\text{ fb}$$

$$\mu = 1.33^{+0.14}_{-0.14}\,(\text{stat.})^{+0.22}_{-0.17}\,(\text{syst.})$$ (8.4σ observed)

- The result is in agreement with the theoretical predictions and may serve as **input into EFT interpretations**.



# Summary

- Precision Run2 analyses with exciting results are coming out.

- Chosen recent results from Top and Electroweak measurements were presented:
  - Results are still in agreement with SM, however some tensions exist.
  - Limits on anomalous couplings become important result from any electroweak measurement and a powerful tool to constrain the BSM models.

- Tests of SM become more and more powerful. It seems that new physics signs are really nearby.

LHC Run3 is approaching. We will have more data to find them!

# Back-up slides

# LHC and ATLAS dataset

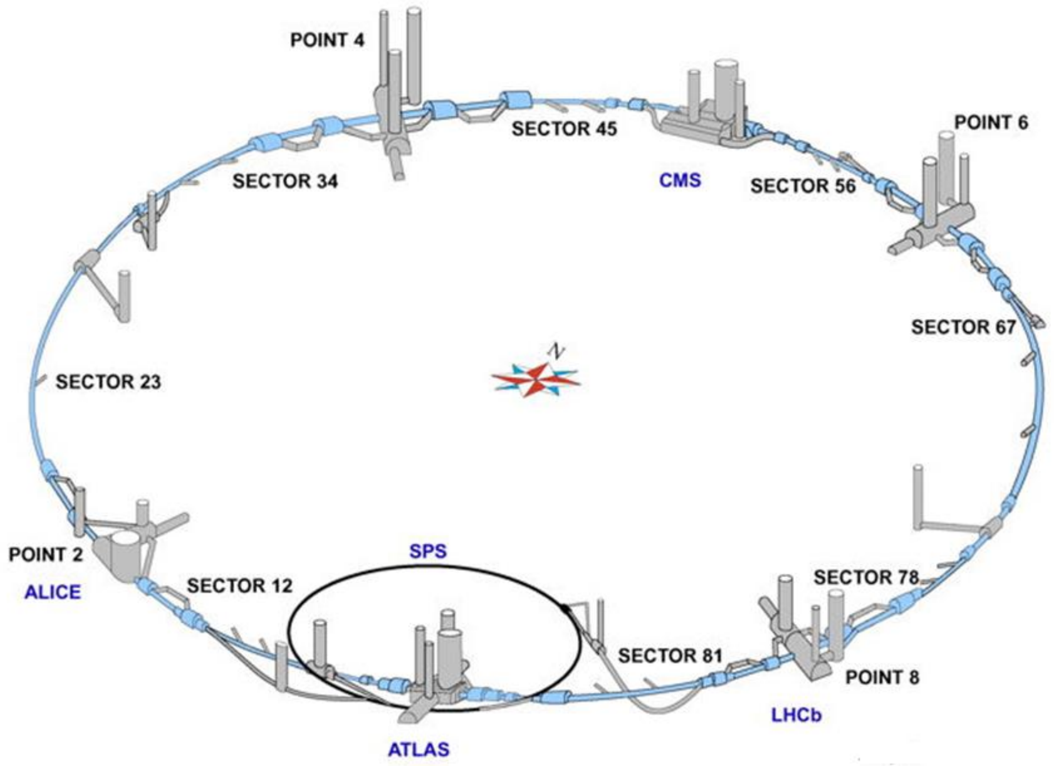
Run1:

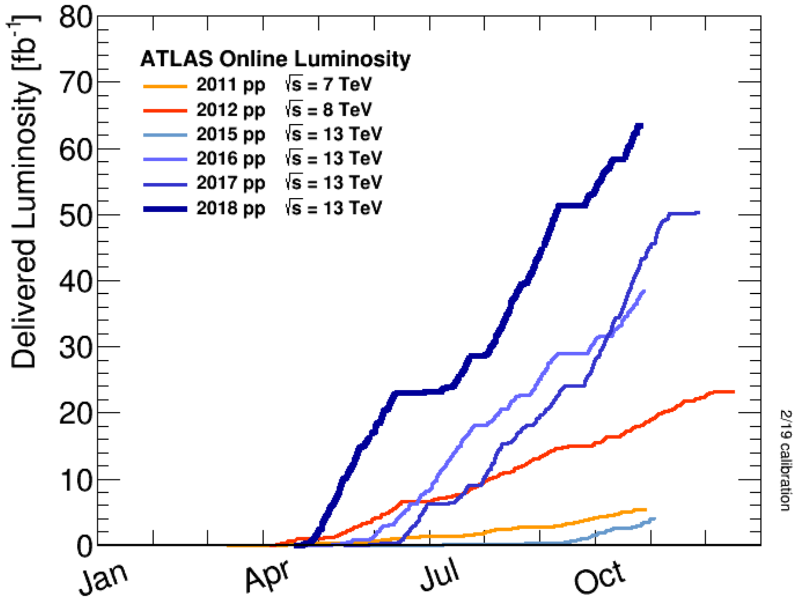
2011: √s = 7 TeV – **4.6 fb$^{-1}$**

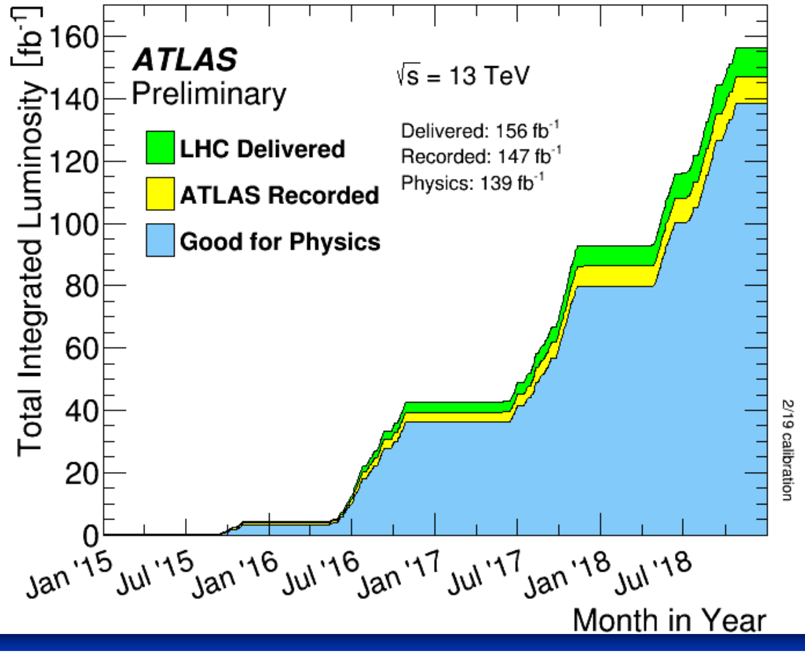
2012: √s = 8 TeV – **20.3 fb$^{-1}$**

Run2:

2015-2018: √s =13 TeV – **139 fb$^{-1}$**



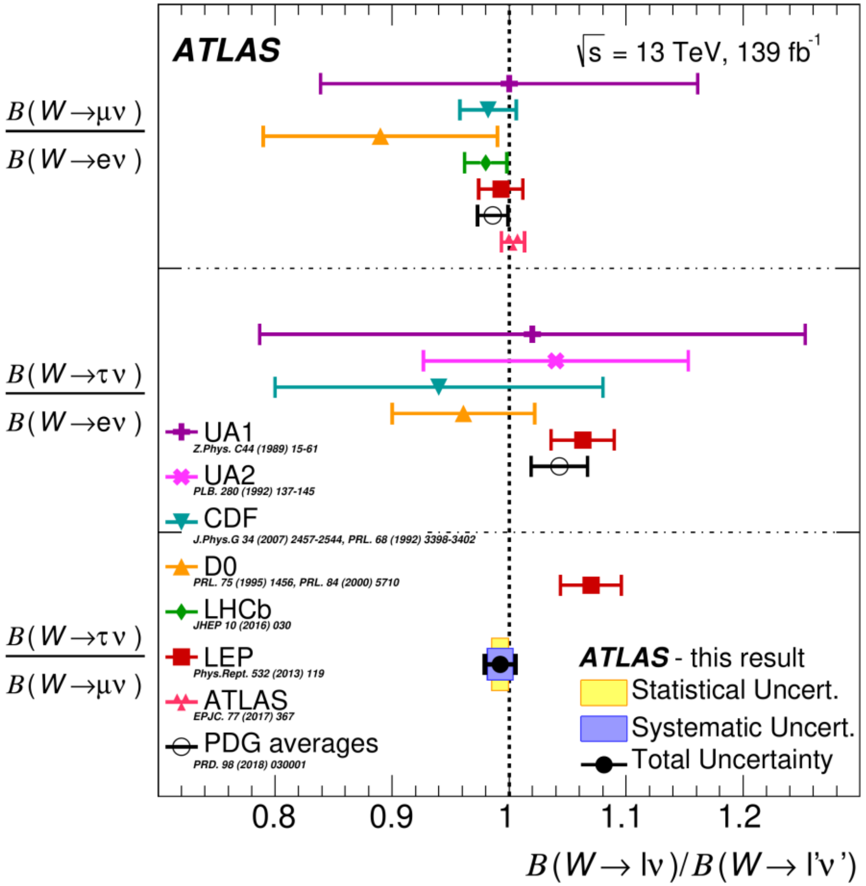



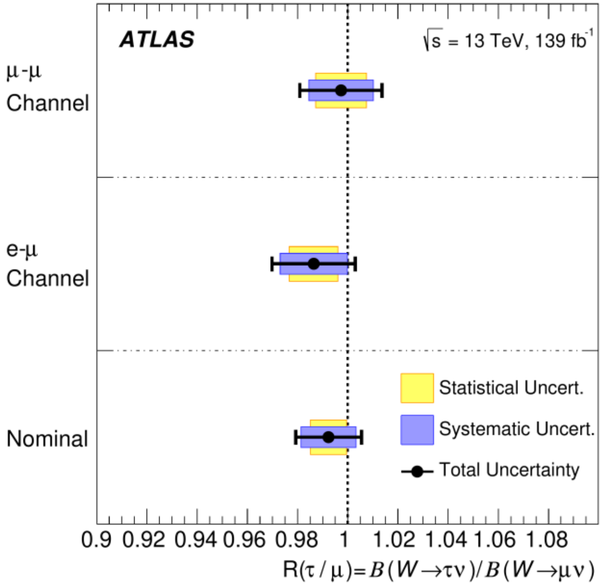
# Top: BR(W→τν) / BR(W→μν) in μ-μ and e-μ ttbar events

[Nature Physics (2021)](#)

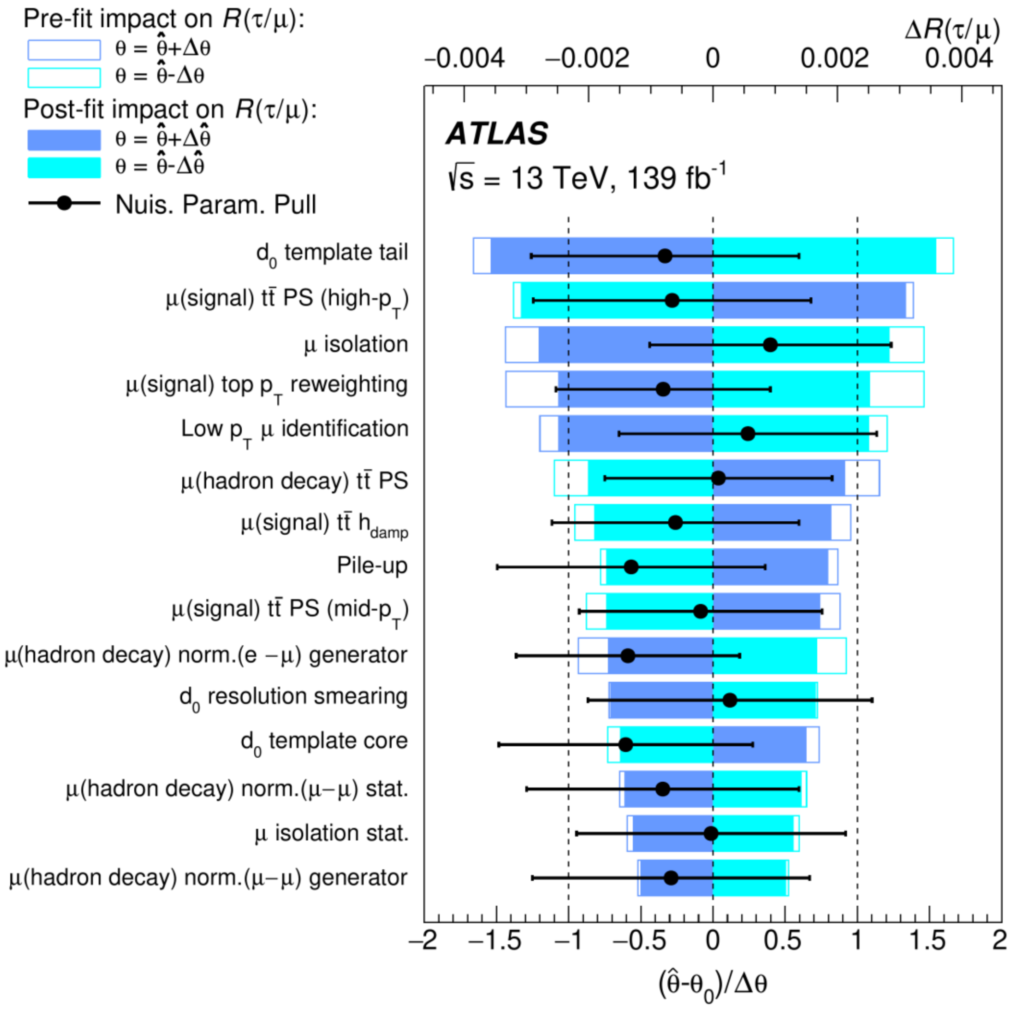
- Full comparison with previous results




- Results in different final states




- Detailed systematics breakdown



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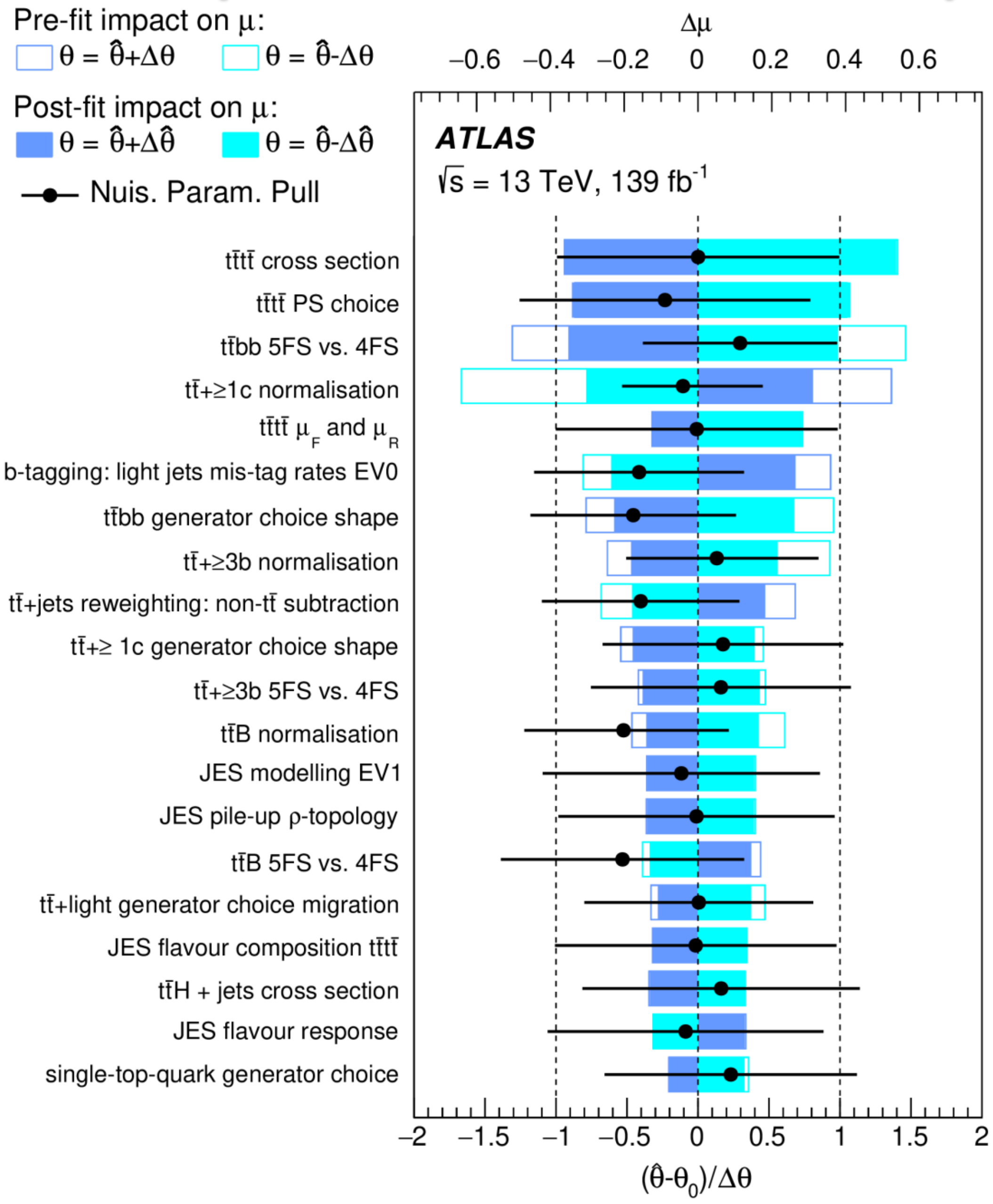


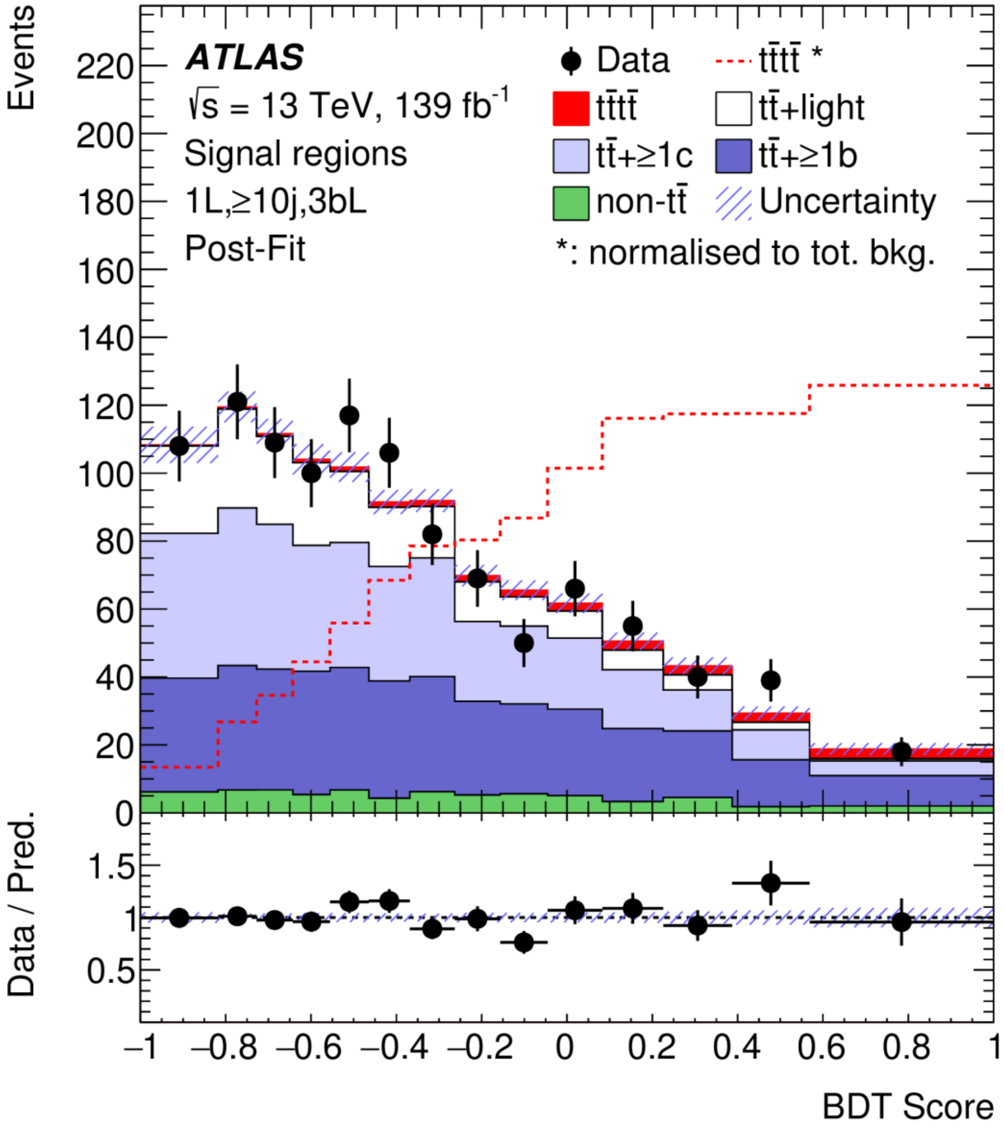

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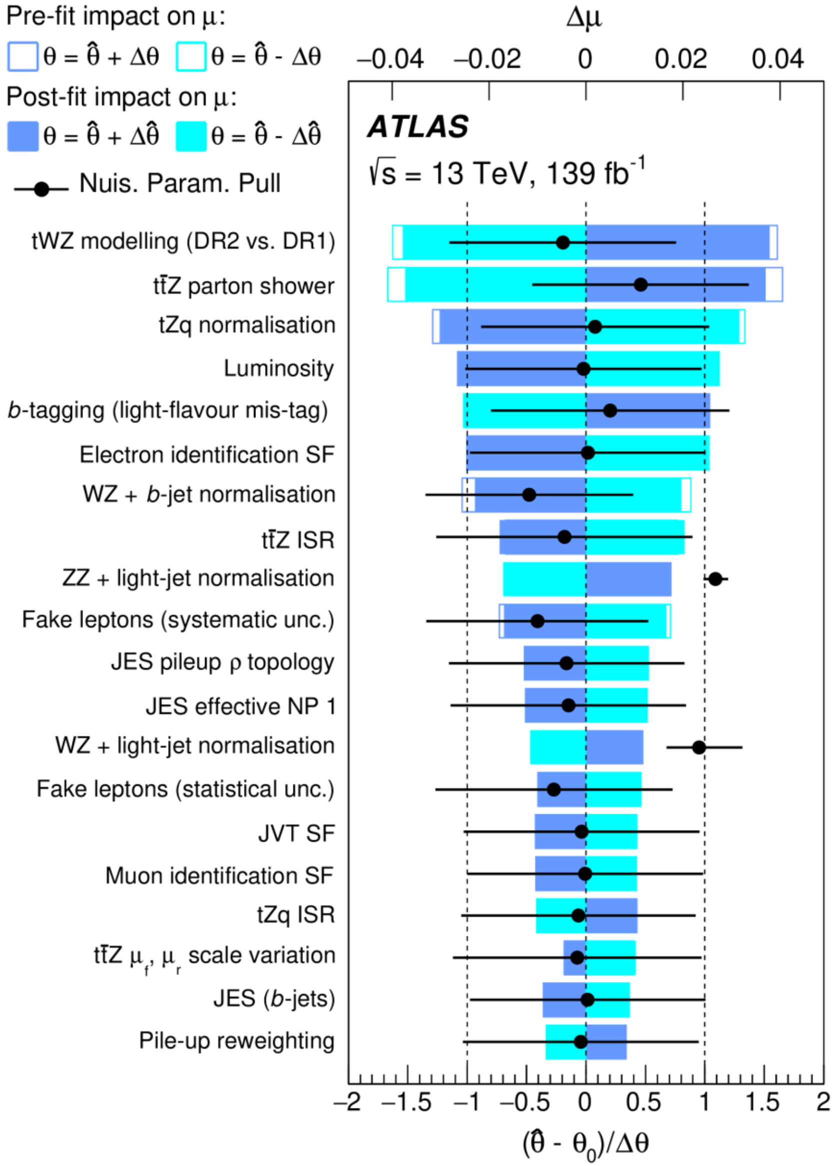


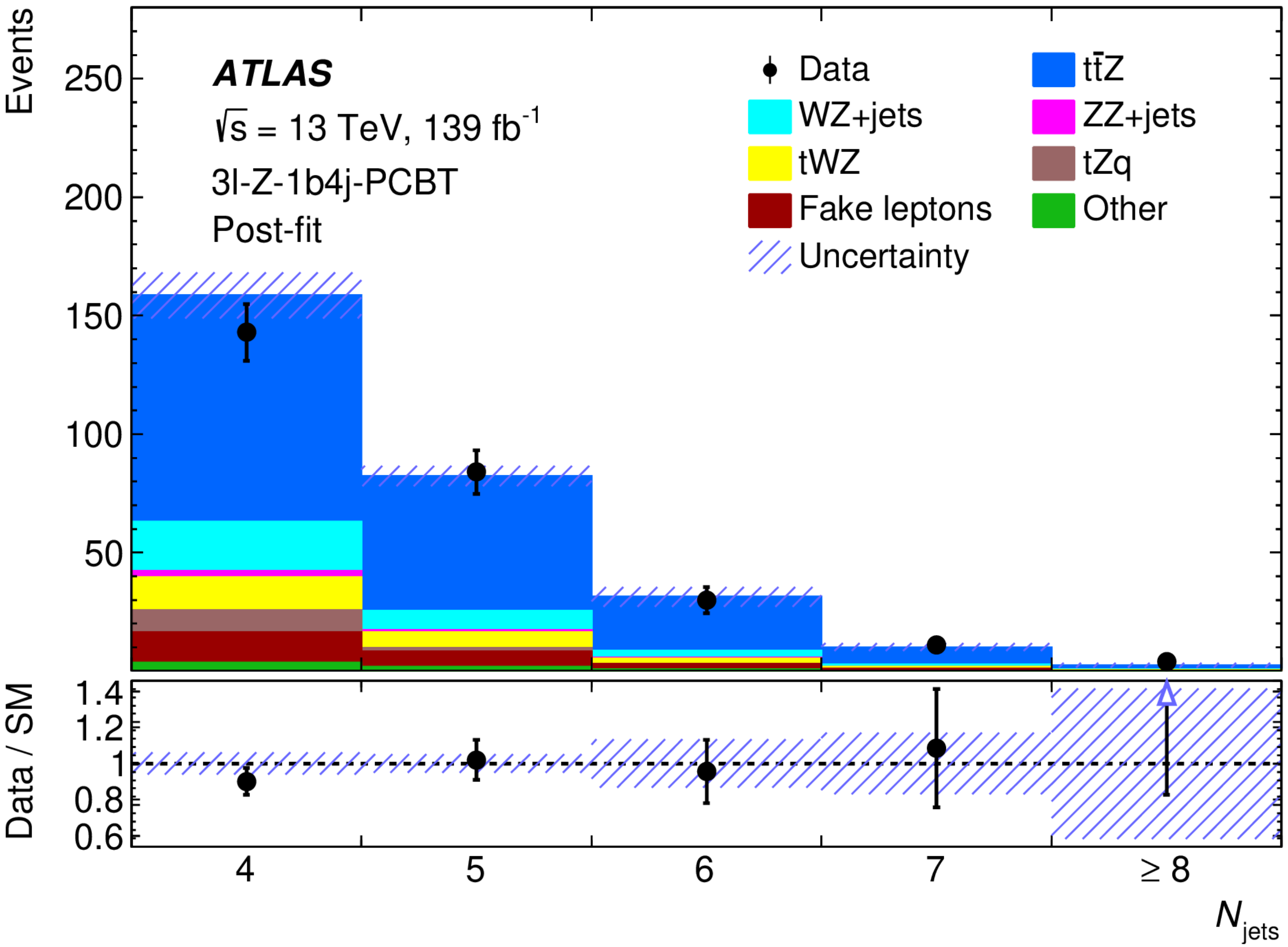

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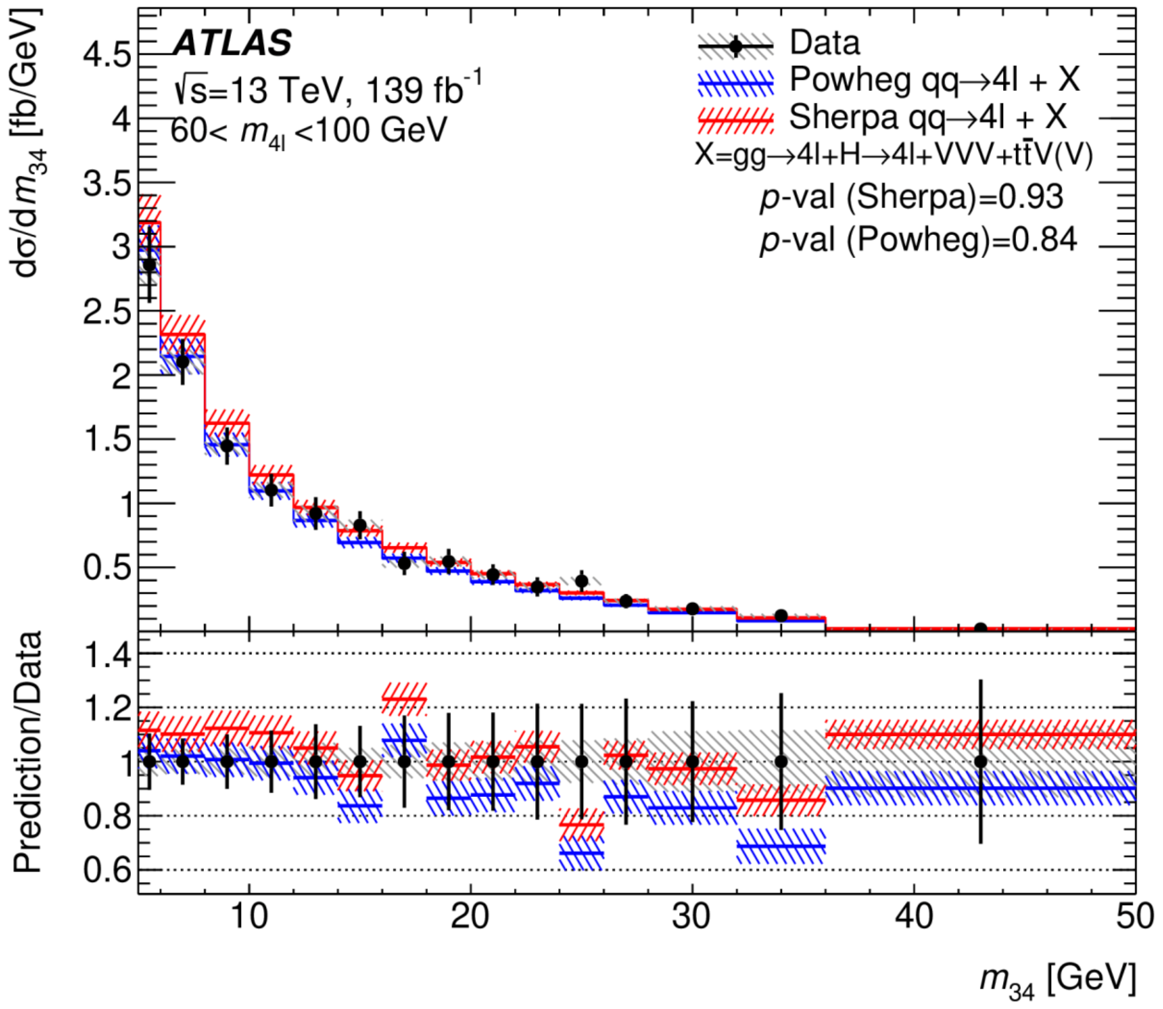
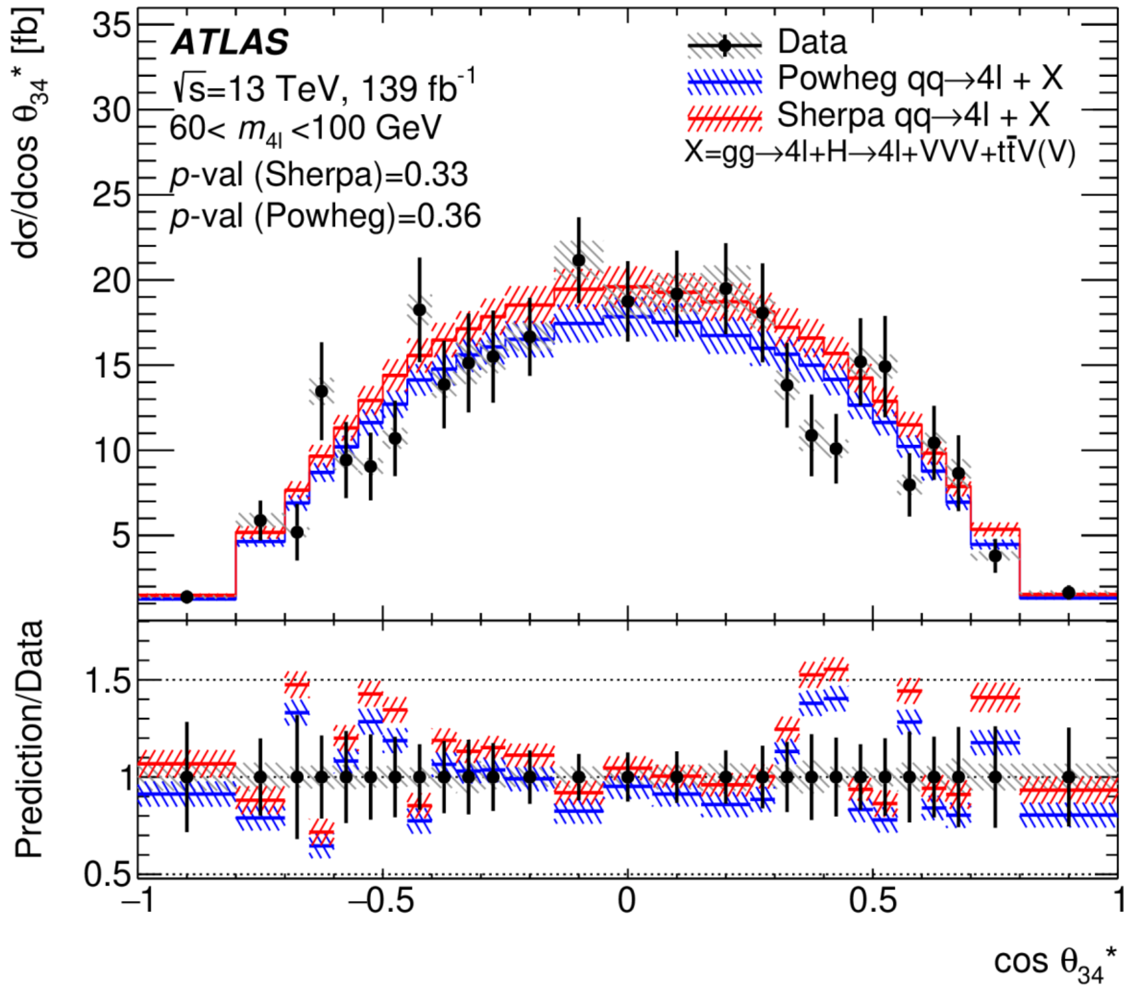
Accepted by JHEP, arXiv:2103.01918



# EWK: WW+1jet differential cross sections

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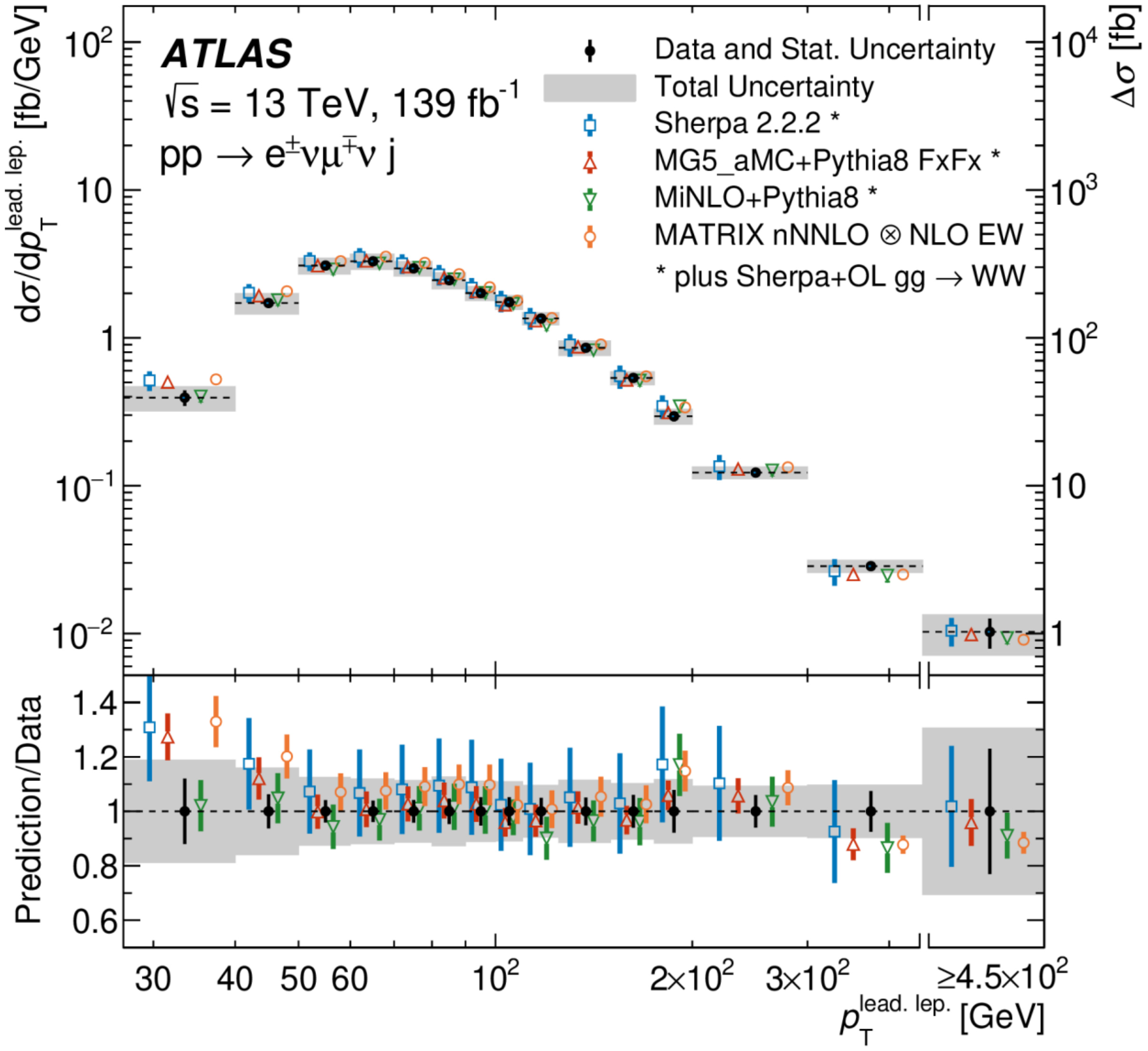


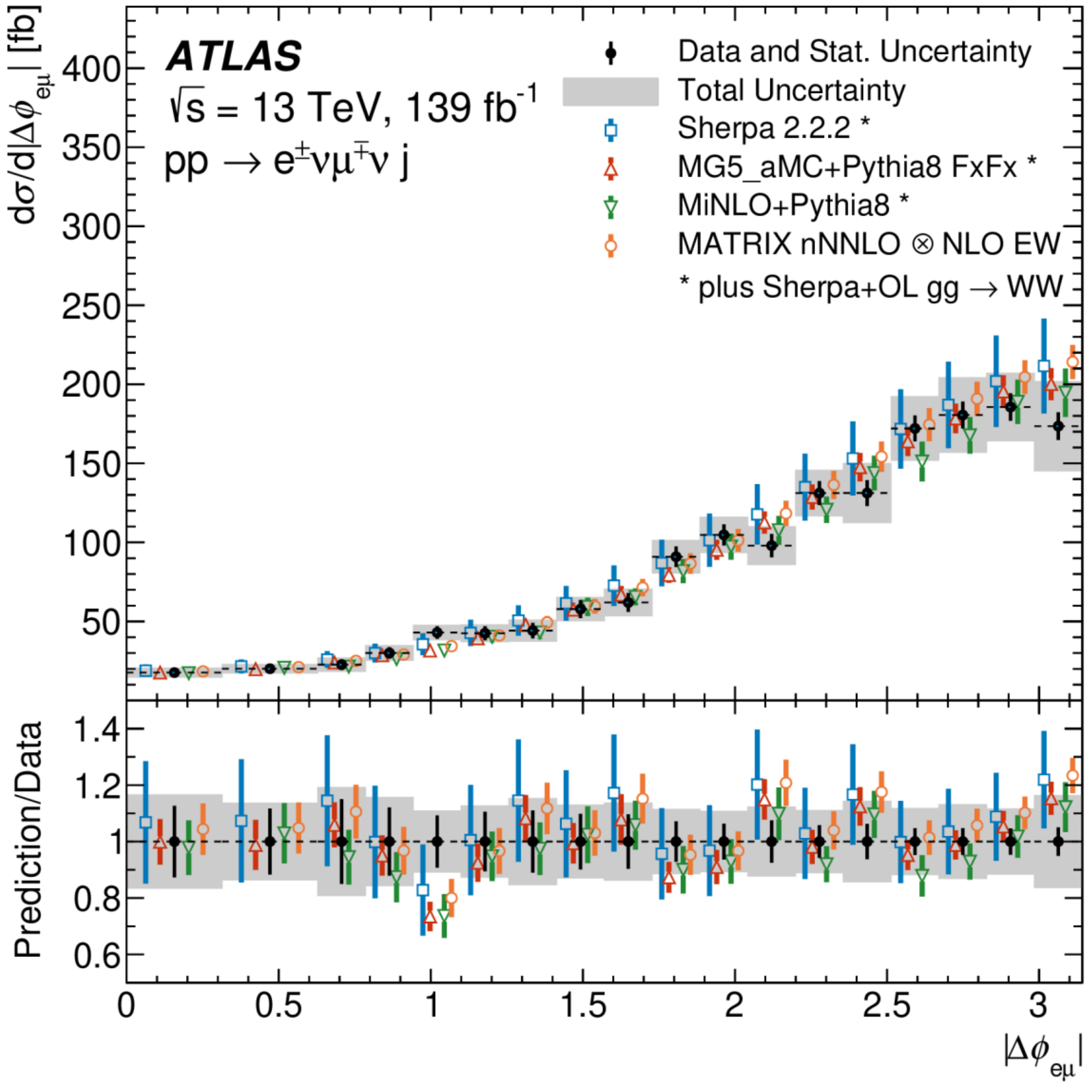

# EWK: Observation of γγ->WW

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