

Precision measurements of electroweak parameters at the ATLAS Experiment

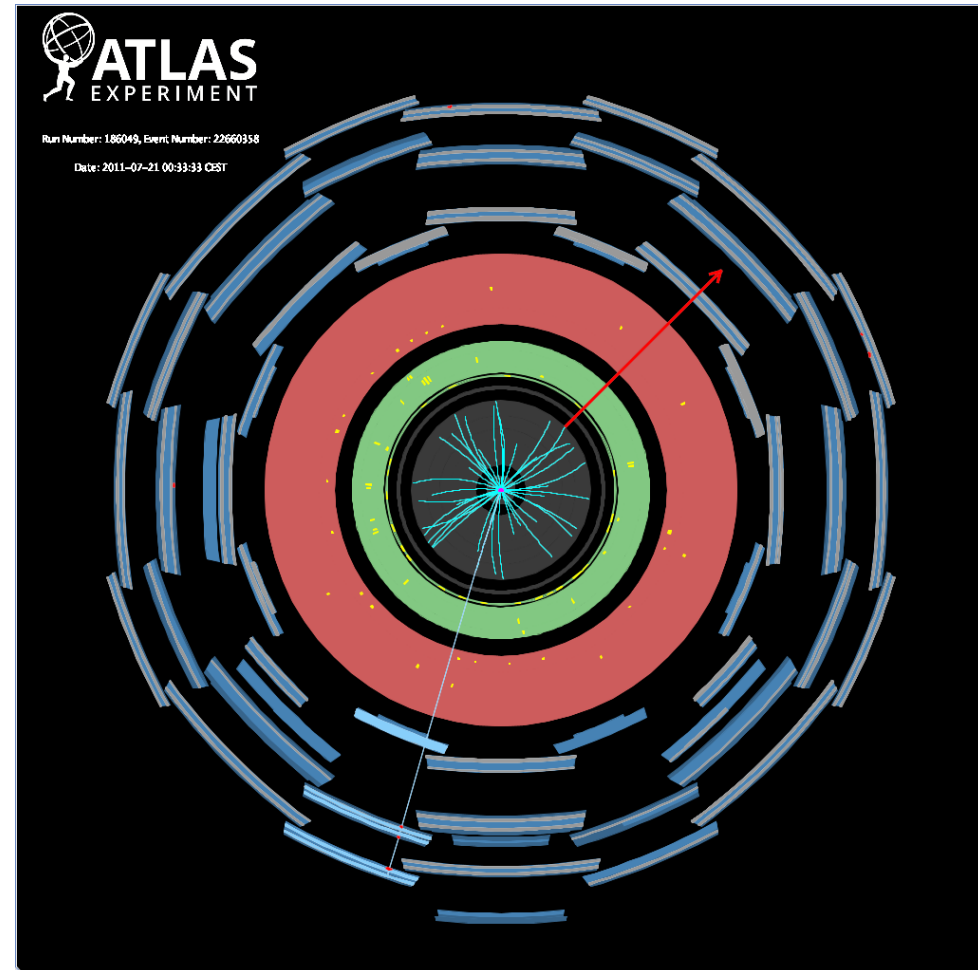
QCD2024

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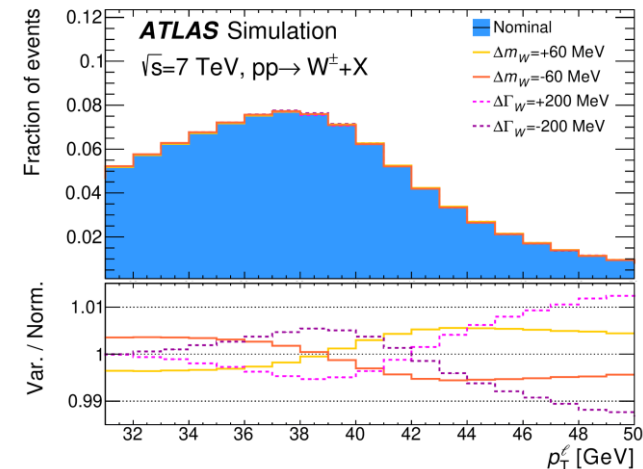
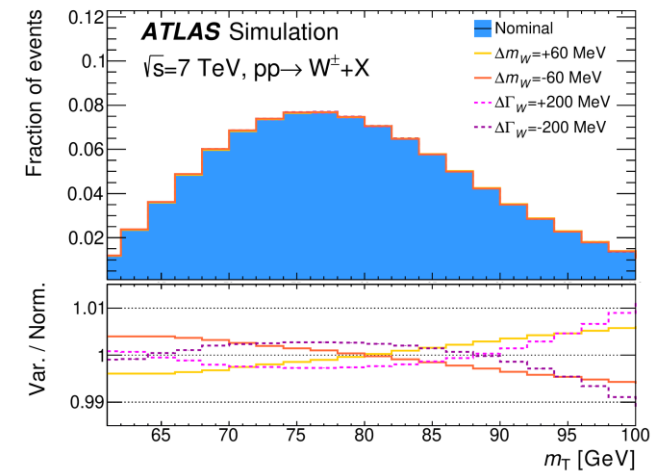
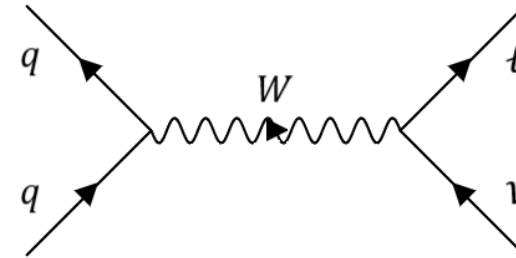
On behalf of the ATLAS Collaboration

Motivation

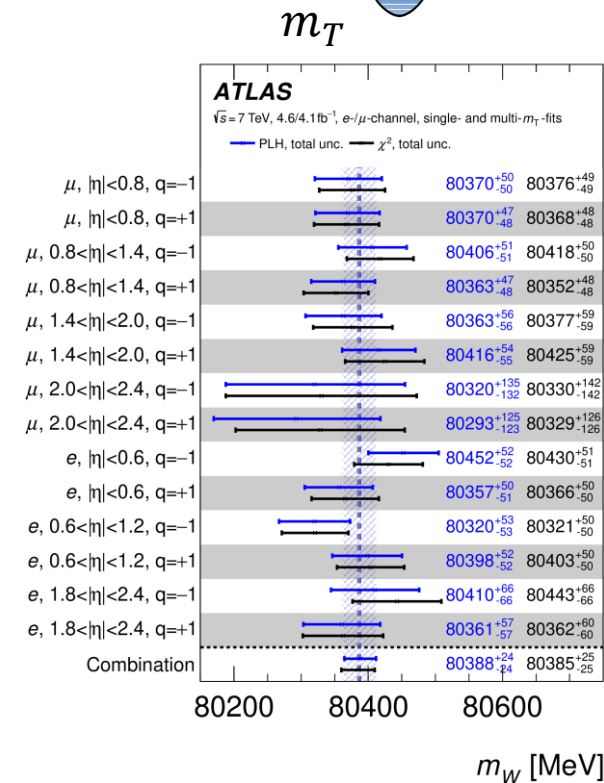
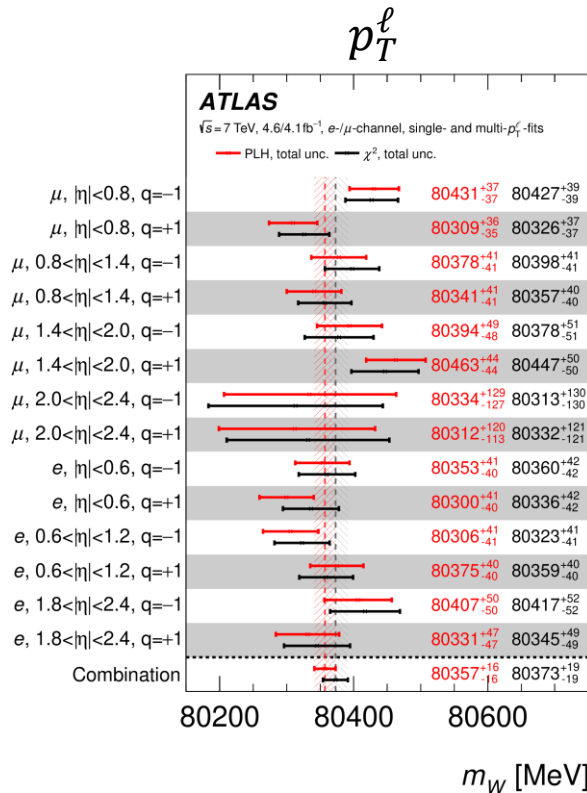
- Improvements in the precision of the SM parameters are important to reduce uncertainties in various calculations done in HEP.
- They probe the consistency of the SM, differences amongst measurements could indicate possible sources of new physics.
- Precision measurements provide strong constraints to PDFs.



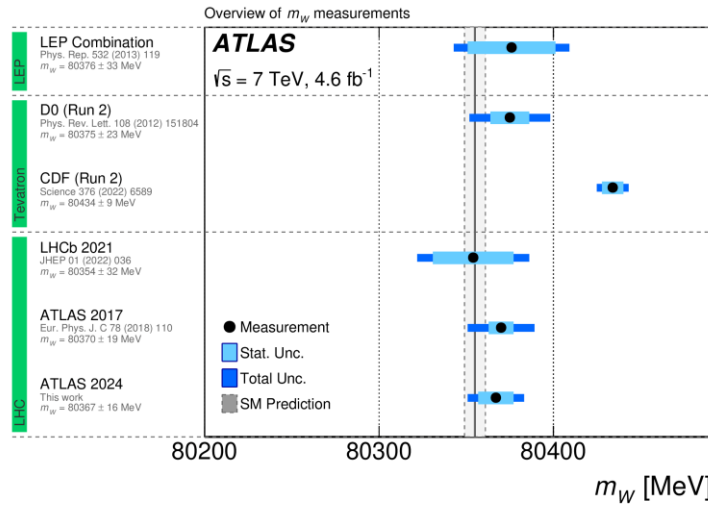
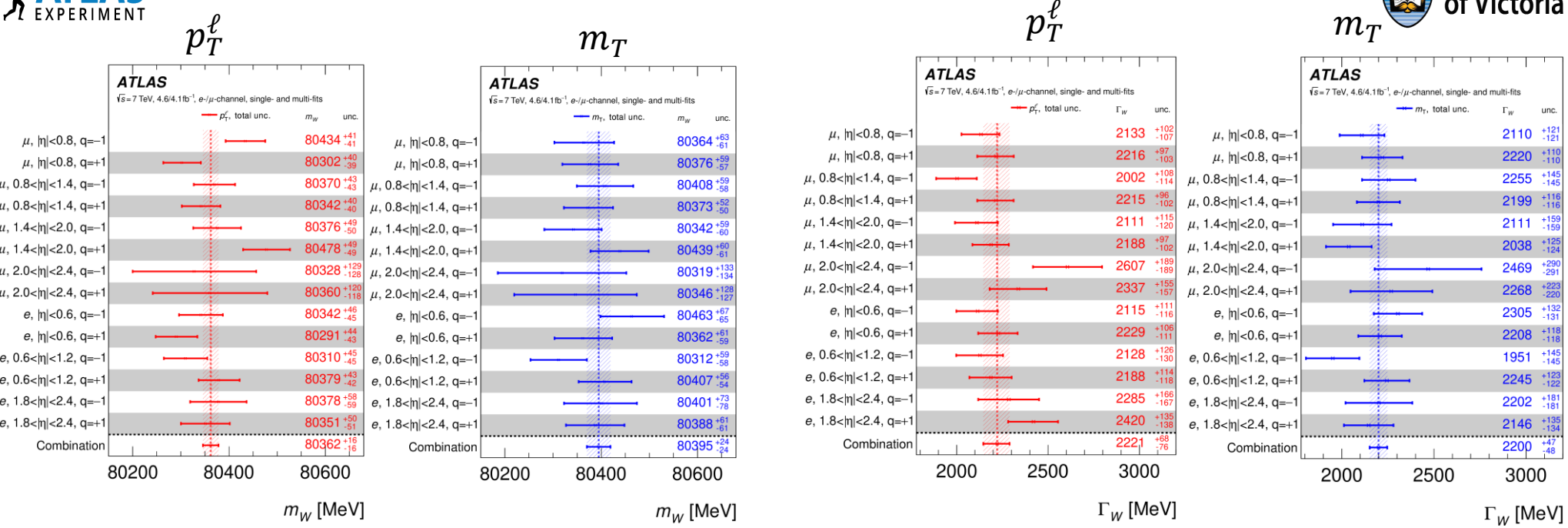
- The $\sqrt{s} = 7$ TeV (2011) dataset is used again
 - Improved determination of the W boson mass
 - First measurement of the W boson width
 - $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ candidate events are used
- MC samples generated at NNLO
 - Simulation of W and Z boson production and decay (e, μ and τ channels)
 - Background samples of $t, tt, WW, WZ,$ and ZZ
- Multijet background estimation is data-driven
- Kinematic distributions studied:
 - Charged lepton transverse momentum p_T^ℓ
 - W boson transverse mass m_T
 - Classified into 28 different categories based on charge, flavor and η
- Corrections and uncertainties
 - Lepton energy calibration from $Z \rightarrow \ell\ell$
 - Electroweak uncertainties using *PHOTOS*
 - QCD uncertainties using *PYTHIA*



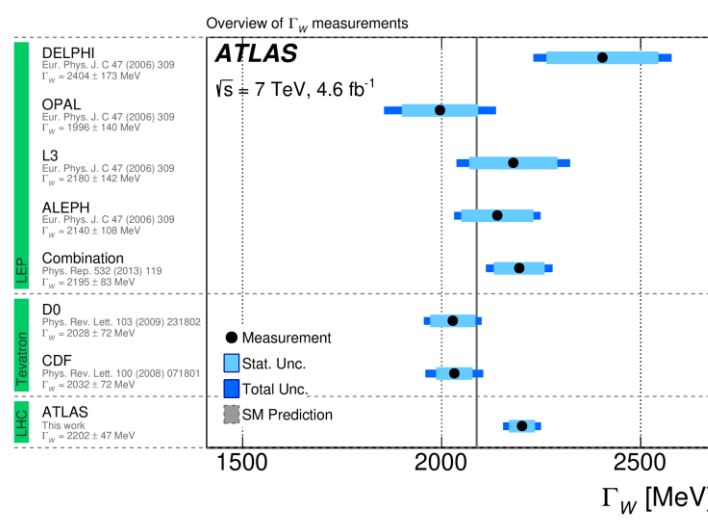
- Previous analysis:
 - m_W determined by χ^2 fit
 - Γ_W fixed to the SM prediction
 - CT10nnlo PDF set
- Present analysis:
 - simultaneous optimization of m_W (Γ_W) and nuisance parameters through a global profile likelihood fit (PLH).
 - For determination of m_W , Γ_W treated as source of systematic uncertainty. Opposite is used for determination of Γ_W .
 - CT10nnlo PDF for comparison with previous result
 - CT18 PDF set chosen as baseline for new result
- Comparison shows compatibility between old and new results



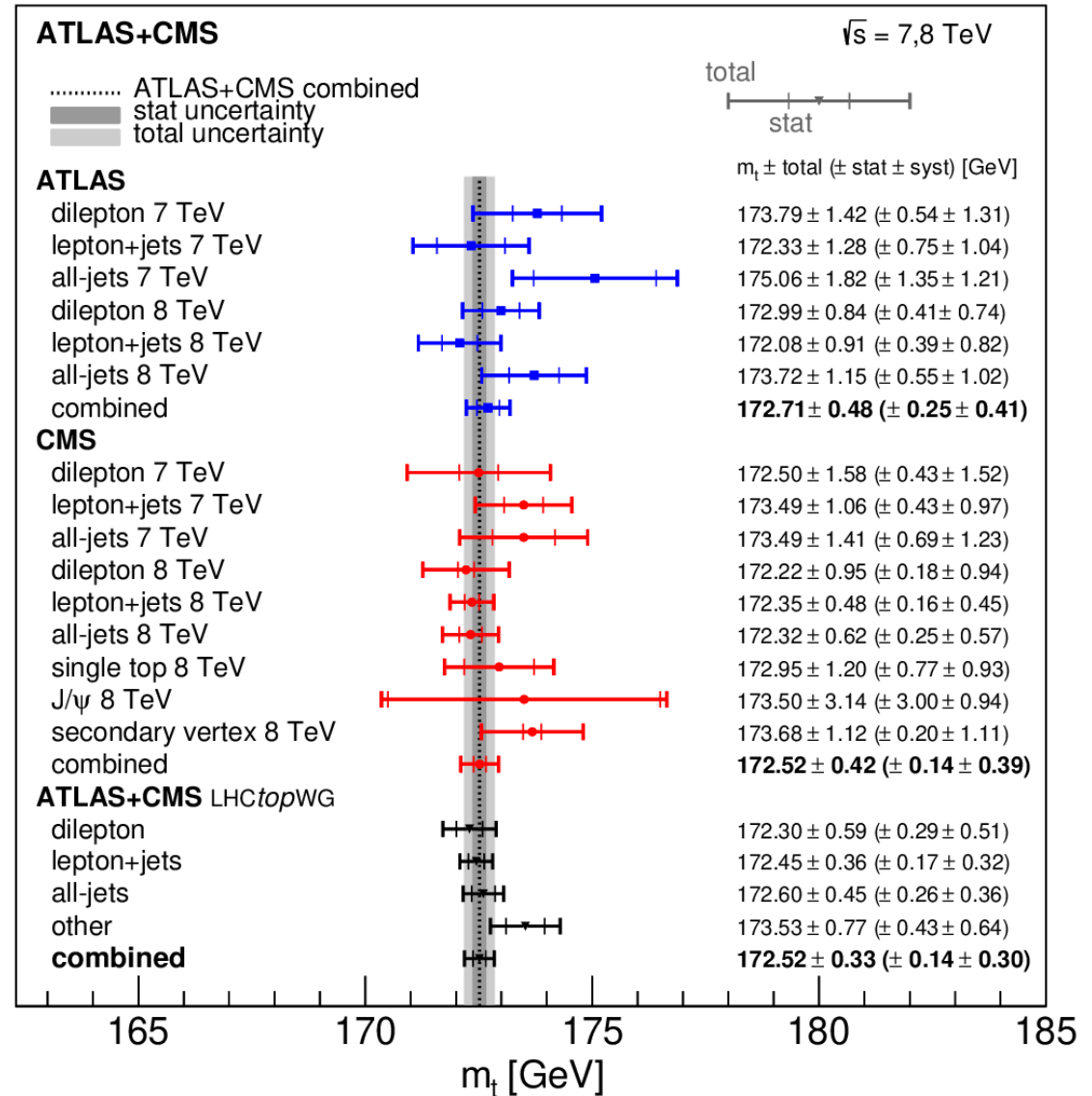
PDF set	p_T^ℓ fit				m_T fit			
	m_W	σ_{tot}	σ_{PDF}	$\chi^2/\text{n.d.f.}$	m_W	σ_{tot}	σ_{PDF}	$\chi^2/\text{n.d.f.}$
CT14	80358.3	+16.1 -16.2	4.6	543.3/558	80401.3	+24.3 -24.5	11.6	557.4/558
CT18	80362.0	+16.2 -16.2	4.9	529.7/558	80394.9	+24.3 -24.5	11.7	549.2/558
CT18A	80353.2	+15.9 -15.8	4.8	525.3/558	80384.8	+23.5 -23.8	10.9	548.4/558
MMHT2014	80361.6	+16.0 -16.0	4.5	539.8/558	80399.1	+23.2 -23.5	10.0	561.5/558
MSHT20	80359.0	+13.8 -15.4	4.3	550.2/558	80391.4	+23.6 -24.1	10.0	557.3/558
ATLASpdf21	80362.1	+16.9 -16.9	4.2	526.9/558	80405.5	+28.2 -27.7	13.2	544.9/558
NNPDF3.1	80347.5	+15.2 -15.7	4.8	523.1/558	80368.9	+22.7 -22.9	9.7	556.6/558
NNPDF4.0	80343.7	+15.0 -15.0	4.2	539.2/558	80363.1	+21.4 -22.1	7.7	558.8/558



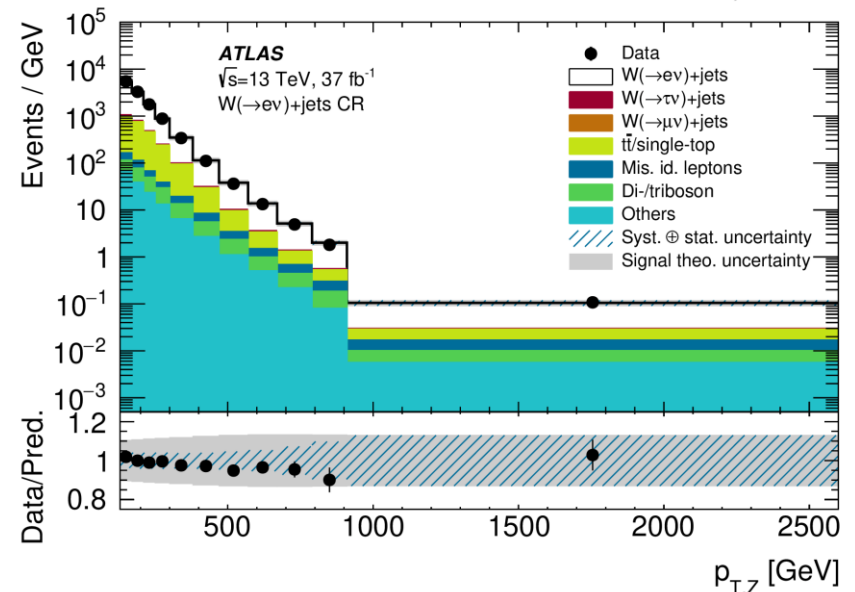
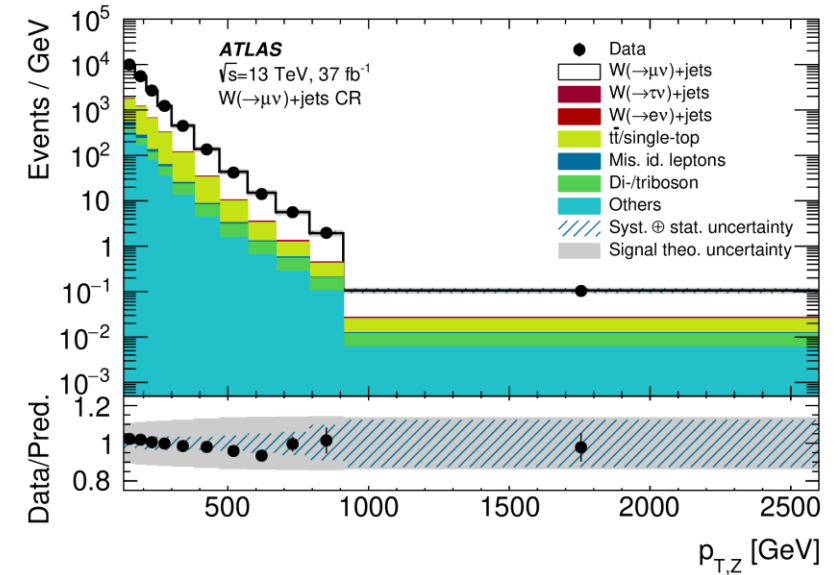
- Use of updated PDF set (CT18) improves uncertainty in m_W measurement
- Γ_W measured for first time at ATLAS
- New results:
 - $m_W = 80366.5 \pm 15.9 \text{ MeV}$
 - $\Gamma_W = 2202 \pm 47 \text{ MeV}$
- Results are consistent with most previous results



- 15 top quark measurements made by ATLAS and CMS are combined
 - $t\bar{t}$ events are used
 - $t\bar{t} \rightarrow \ell^+ \nu b \ell^- \bar{\nu} \bar{b}$
 - $t\bar{t} \rightarrow \ell^+ \nu b q \bar{q} \bar{b}$
 - $t\bar{t} \rightarrow q \bar{q} b q \bar{q} \bar{b}$
 - CMS also used single t events
 - $t \rightarrow \ell^+ \nu b$
 - $\bar{t} \rightarrow \ell^- \bar{\nu} \bar{b}$
 - Correlation between measurements of the different experiments is considered
 - Combination of all 15 input measurements is:
- $m_t = 172.52 \pm 0.33 \text{ GeV}$
- This is the most precise result to date

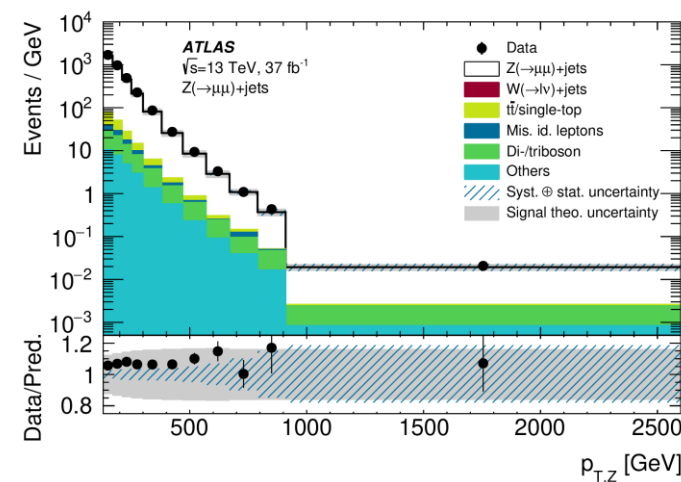
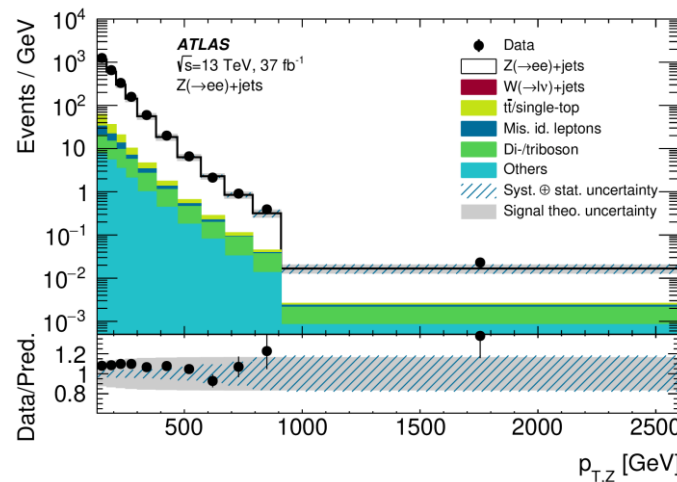
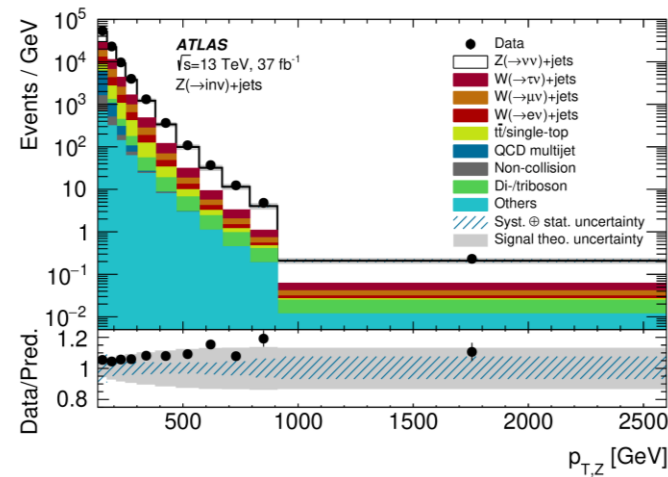
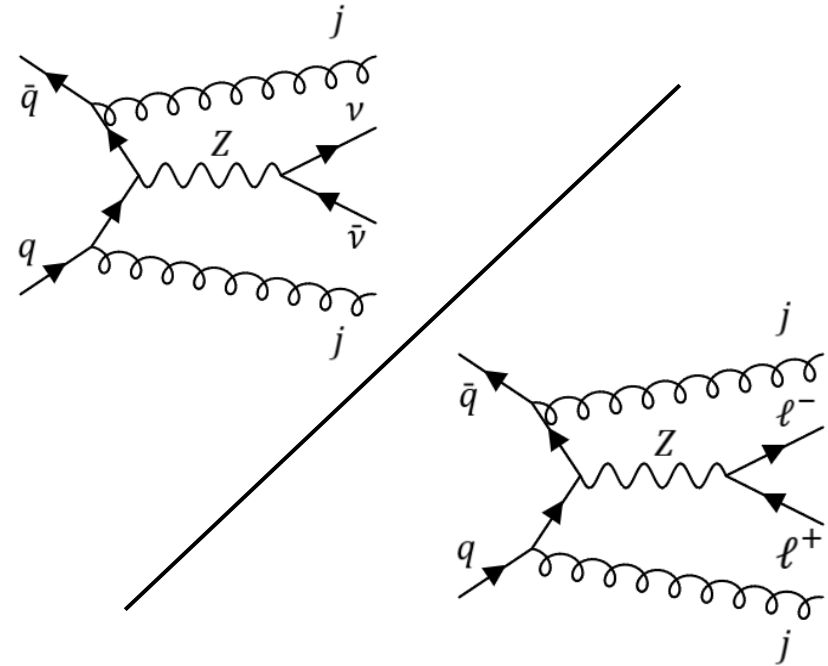


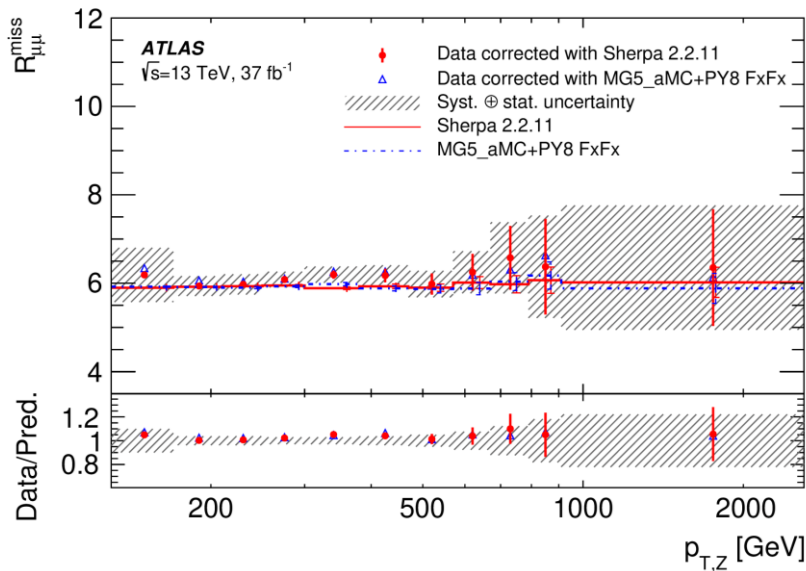
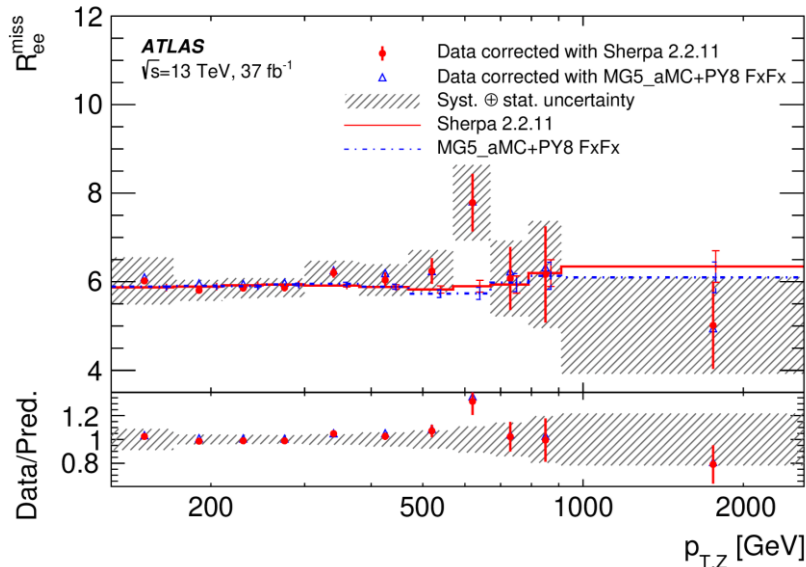
- ATLAS data from 2015-2016 at $\sqrt{s} = 13$ TeV is used
 - $Z \rightarrow$ invisible and $Z \rightarrow \ell\ell$ candidate events
- Event selection
 - Primary vertex
 - 2 track with $p_T > 500$ MeV
- Phase space
 - At least 1 jet, with leading jet $p_T \geq 110$ GeV and $|\eta| < 2.4$
 - $p_{T,Z} \geq 130$ GeV
- Control regions
 - $W(\rightarrow e\nu) + \text{jets}$ ($p_{T,Z} = p_{T,e} + E_T^{miss}$)
 - $W(\rightarrow \mu\nu) + \text{jets}$ ($p_{T,Z} = p_{T,\mu} + E_T^{miss}$)
- Signal regions
 - $Z \rightarrow \nu\nu + \text{jets}$ ($p_{T,Z} = E_T^{miss}$)
 - $Z \rightarrow ee + \text{jets}$ ($p_{T,Z} = p_{T,e1} + p_{T,e2} + E_T^{miss}$)
 - $Z \rightarrow \mu\mu + \text{jets}$ ($p_{T,Z} = p_{T,\mu1} + p_{T,\mu2} + E_T^{miss}$)



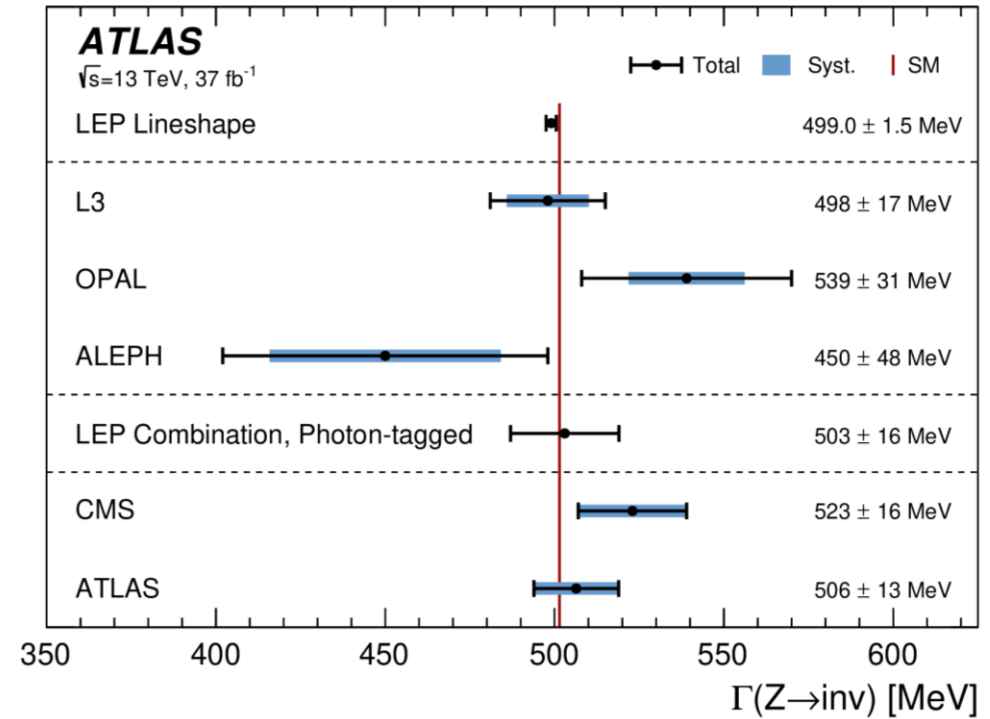
- Signal regions
 - $Z \rightarrow \nu\nu + \text{jets}$ ($p_{T,Z} = E_T^{\text{miss}}$)
 - $Z \rightarrow ee + \text{jets}$ ($p_{T,Z} = p_{T,e1} + p_{T,e2} + E_T^{\text{miss}}$)
 - $Z \rightarrow \mu\mu + \text{jets}$ ($p_{T,Z} = p_{T,\mu1} + p_{T,\mu2} + E_T^{\text{miss}}$)
- $\Gamma(Z \rightarrow inv)$ measured using ratio of $Z(\rightarrow inv)+\text{jets}$ to $Z(\rightarrow \ell\ell)+\text{jets}$:

$$\Gamma(Z \rightarrow inv) = R^{\text{miss}} \cdot \Gamma(Z \rightarrow \ell\ell)$$
- $R^{\text{miss}}(p_{T,Z}) \equiv \left(\frac{d\sigma(Z+\text{jets}) \times BR(Z \rightarrow inv)}{dp_{T,Z}} \right) / \left(\frac{d\sigma(Z+\text{jets}) \times BR(Z \rightarrow \ell\ell)}{dp_{T,Z}} \right)$

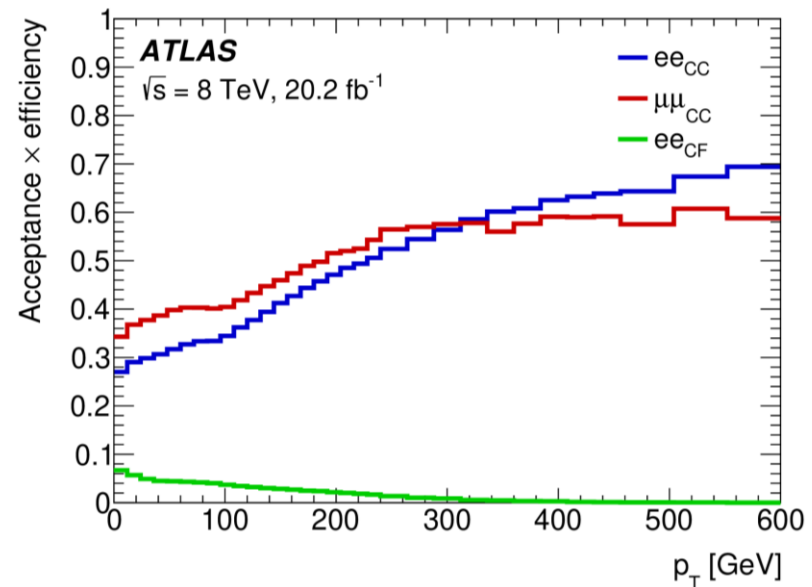
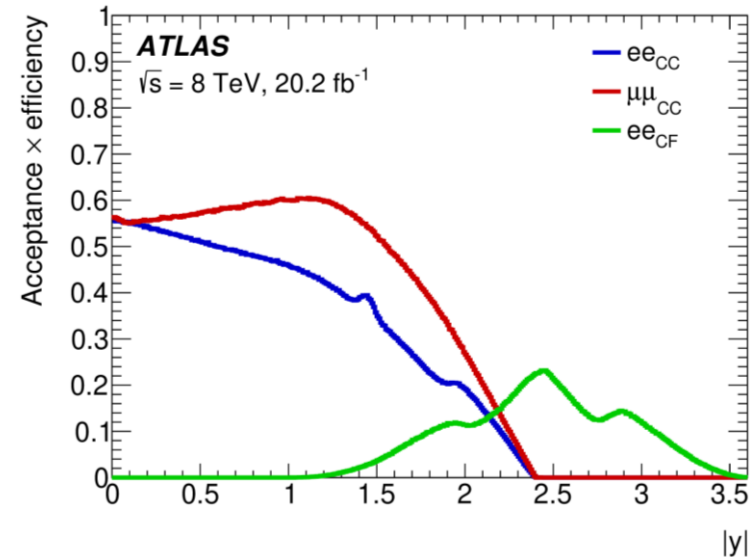




- Value of R^{miss} is determined by χ^2 minimization
- Width obtained:
 - $\Gamma(Z \rightarrow inv) = 506 \pm 13$ MeV
- Consistent with SM prediction



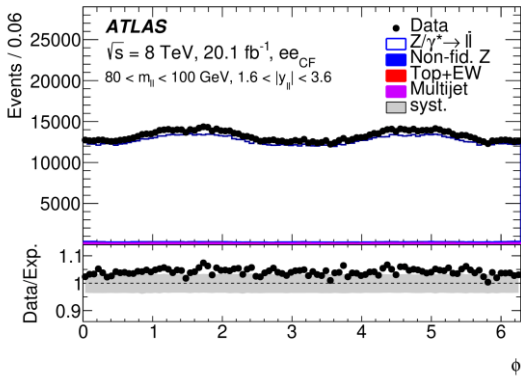
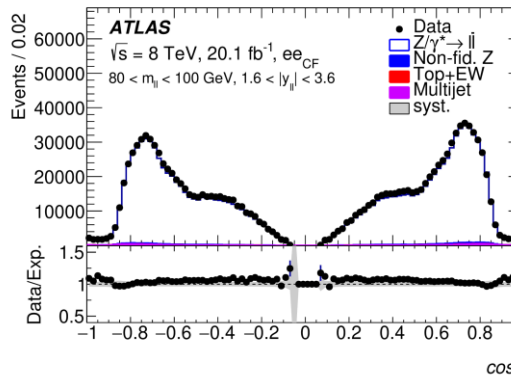
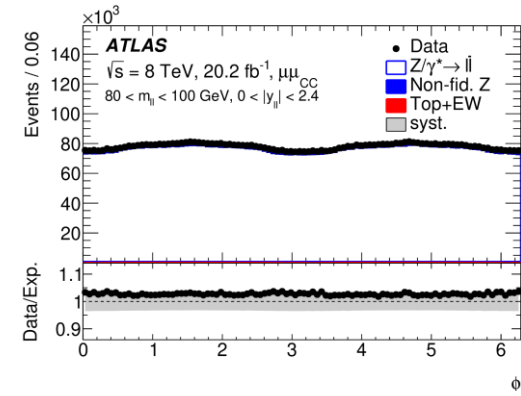
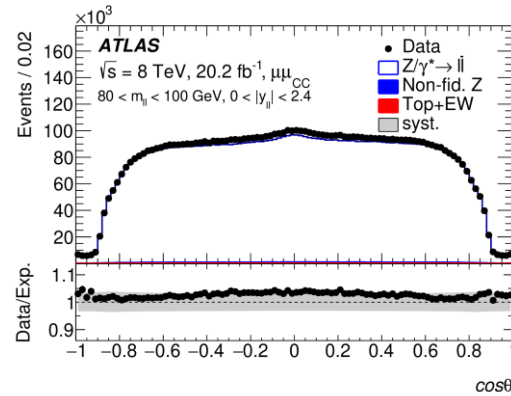
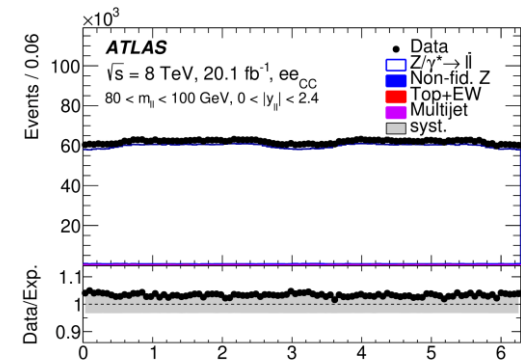
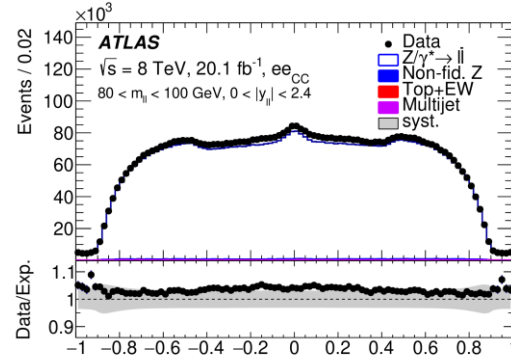
- ATLAS data from 2012 at $\sqrt{s} = 8$ TeV is used (20.2 fb^{-1})
- Measurement of double-differential Z boson cross section in $(p_T, |y|)$ is done
- First measurement at LHC performed in full lepton phase space
 - No theoretical extrapolation of fiducial lepton cuts to full phase space
 - Negligible theory uncertainties
 - Opens door to rich field of precise interpretations
- 3 orthogonal channels analyzed
 - Two central ($|\eta| < 2.4$) electrons (ee_{CC})
 - Two central muons ($\mu\mu_{CC}$)
 - One central and one forward ($2.5 < |\eta| < 4.9$) electron (ee_{CF})



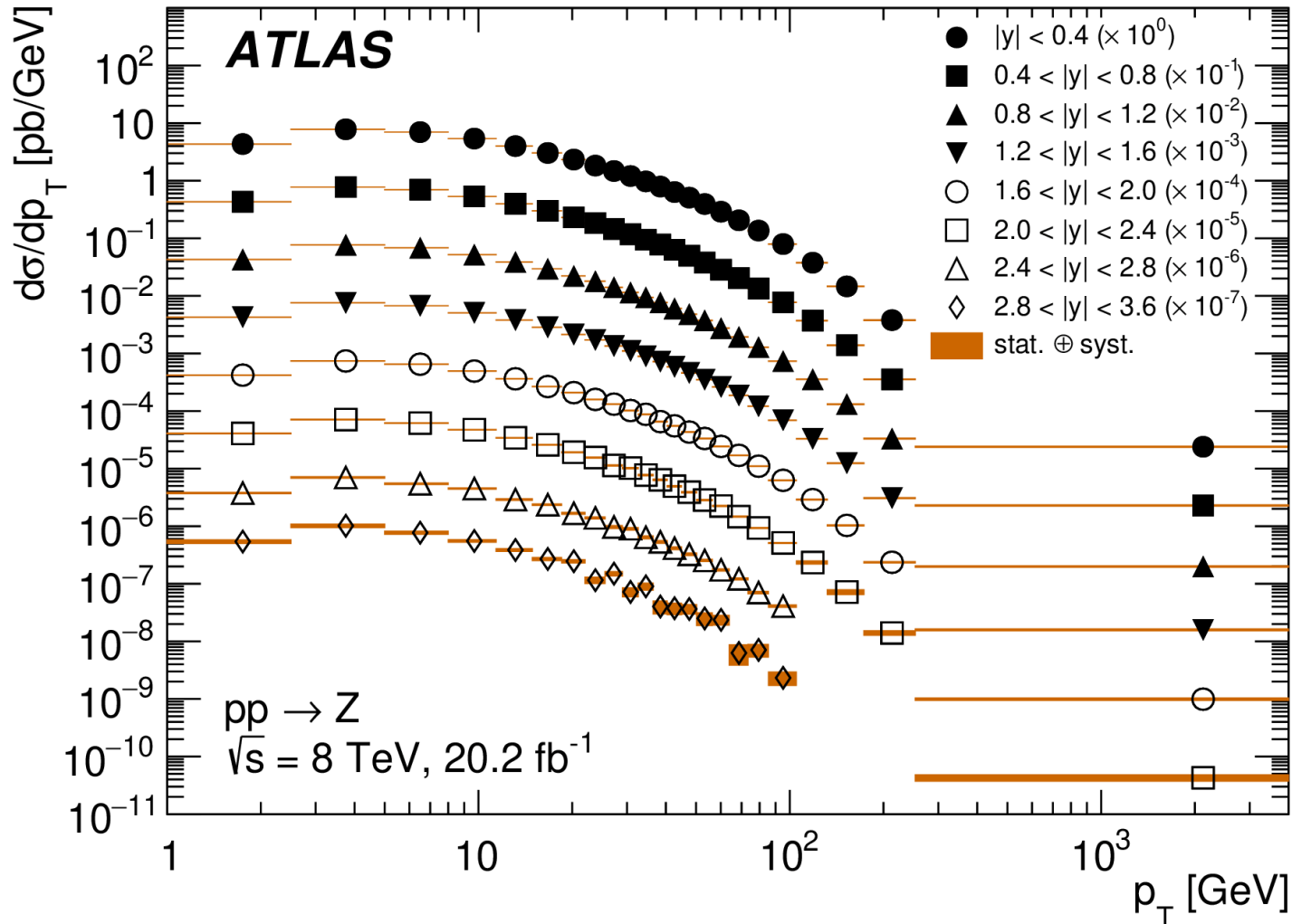
- Lepton pairs invariant mass required to be at the Z boson pole: $80 < m_{\ell\ell} < 100$ GeV
- Events binned into fine p_T and coarse $|y|$ bins
- Measurement relies on decomposition of lepton angular variables into spherical harmonics:

$$\frac{d\sigma}{dp_T dy dm d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T dy dm} \sum_{i=0}^8 A_i P_i(\theta, \phi)$$

- Templates of $P_i(\theta, \phi)$ polynomials are constructed, and PLH method is used to fit angular coefficients A_i and unpolarized cross section σ^{U+L}

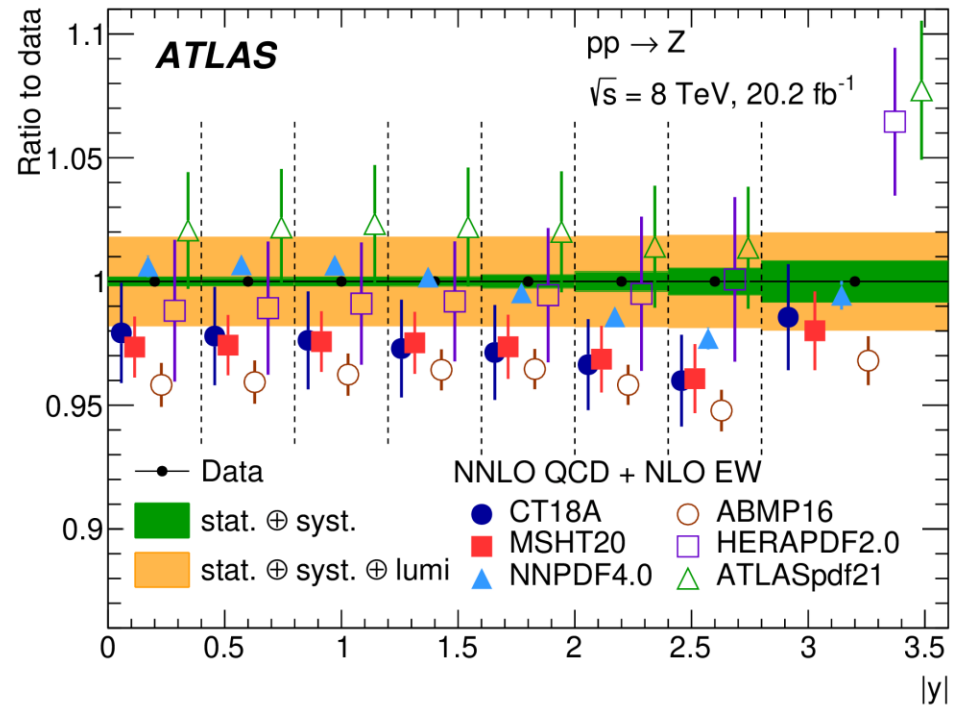
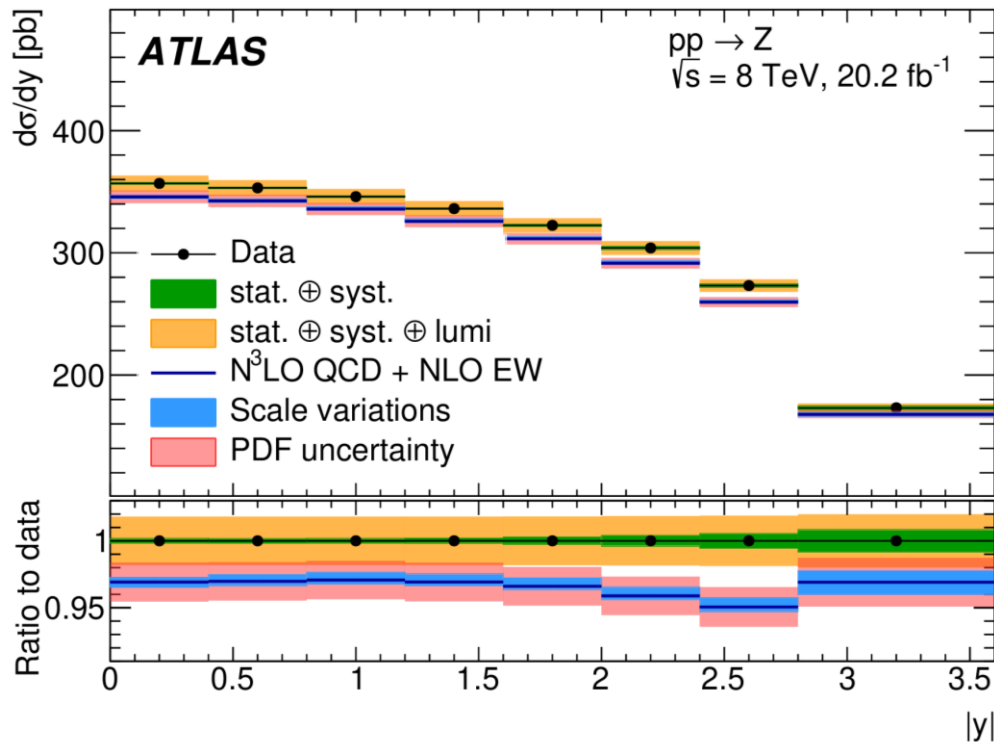


- Values of Z boson cross section as function of $(p_T, |y|)$ are obtained

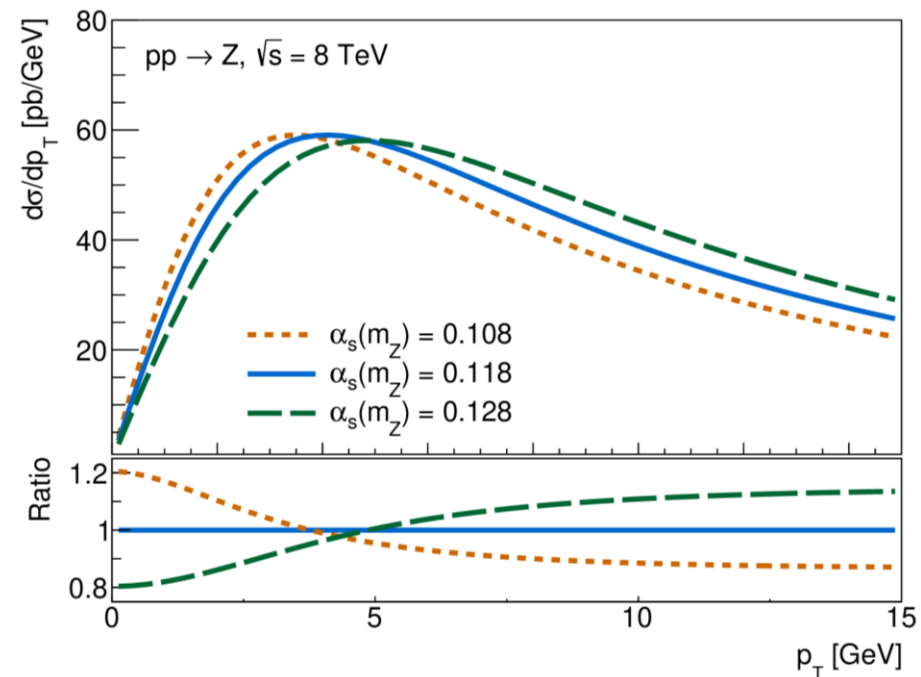
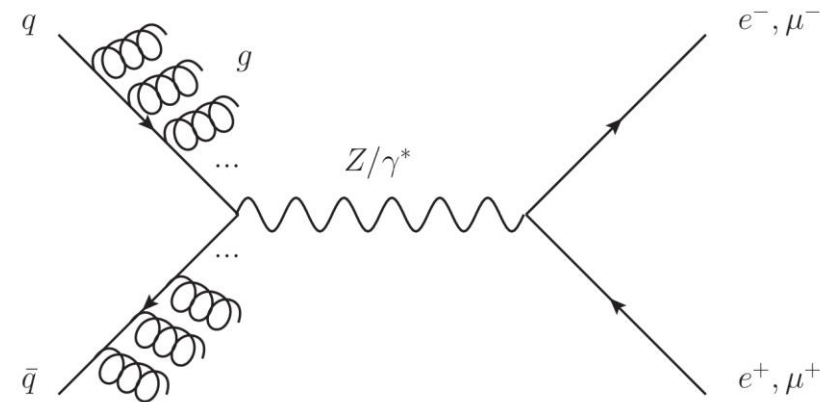


- Results are consistent with predictions at N³LO QCD + NLO EW
- Total cross section times BR of $Z \rightarrow \ell\ell$ for Z/γ^* production in the Z boson pole region ($80 < m_{\ell\ell} < 100$ GeV) within $|y| < 3.6$:

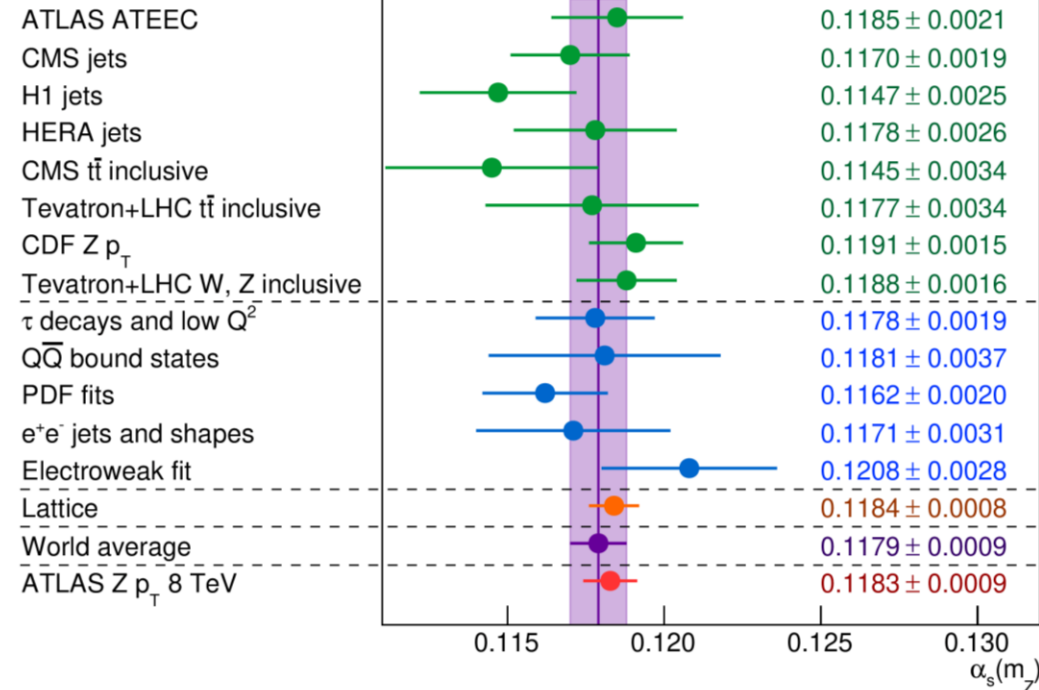
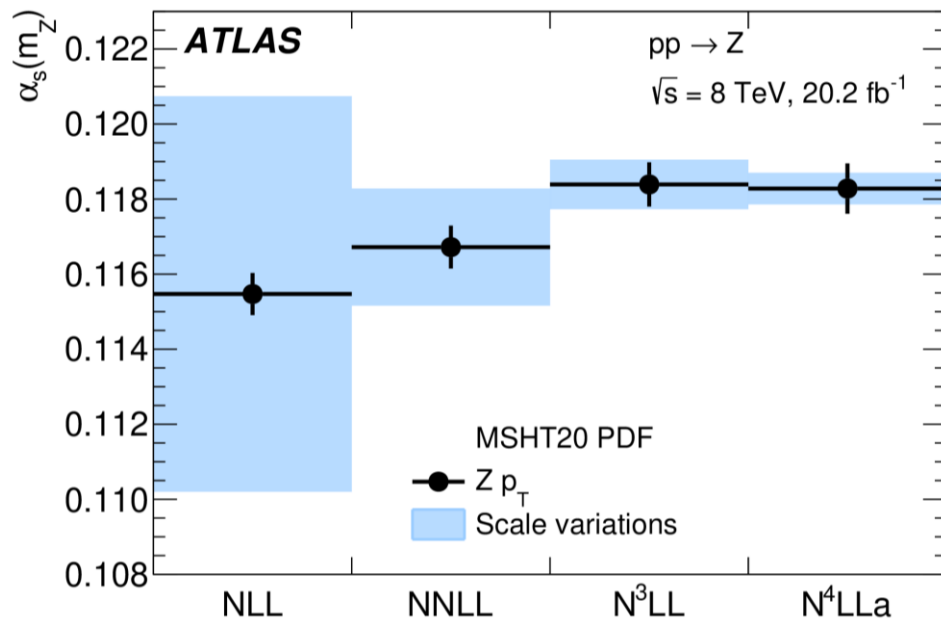
$$\sigma_Z = 1055.3 \pm 0.7 \text{ (stat)} \pm 2.2 \text{ (syst.)} \pm 19.0 \text{ (lumi)} \text{ pb}$$



- ATLAS data from 2012 with $\sqrt{s} = 8$ TeV is used (20.2 fb^{-1})
- Strong coupling constant is measured using the recoil of the Z boson against radiation from initial-state partons
- Low energy region of Z boson p_T used due to high probabilities of gluon emissions with vanishingly small momenta
- Measurements of double-differential cross sections of Z boson as function of p_T and $|\eta|$ used
- Sudakov region of the Z p_T distribution is used
 - Linear sensitivity to $\alpha_s(m_Z)$
 - High perturbative accuracy of theory predictions
 - Non-perturbative QCD effects are controllable (power corrections not linear, but quadratic)
- Events required to be in Z boson pole $80 < m_{\ell\ell} < 100$ GeV and with $p_{T,Z} < 29$ GeV

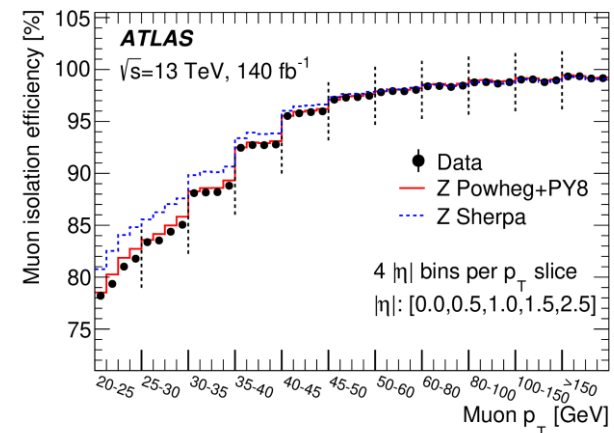
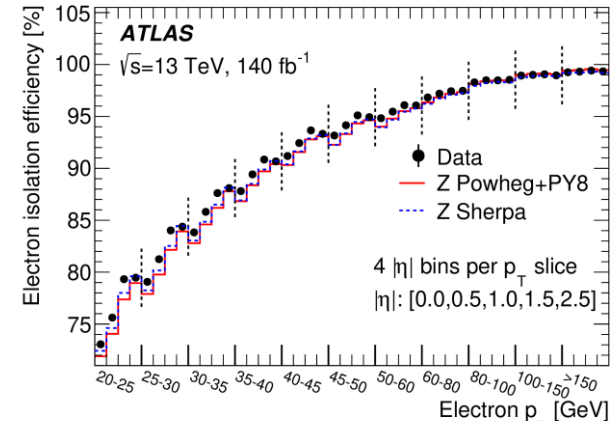
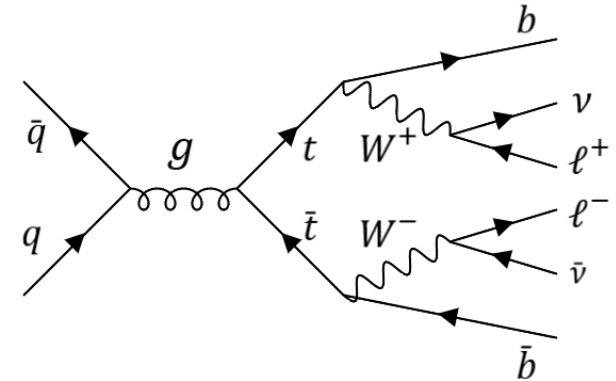


- $\alpha_s(m_Z)$ is determined by a χ^2 fit, repeated at various orders of QCD perturbative expansion
- $\chi^2/\text{d.o.f.}$ computed is 82/72 (p-value of 0.2)
- Value obtained is $\alpha_s(m_Z) = 0.1183 \pm 0.0009$
- Compatible with other determinations and world average
- Most precise experimental determination of $\alpha_s(m_Z)$ to date



- ATLAS data from 2015–18 with $\sqrt{s} = 13$ TeV is used (140 fb^{-1})
- Ratio of BRs of W to e and μ ($R_W^{\mu/e}$) obtained from $t\bar{t}$ production cross sections in the ee , $e\mu$ and $\mu\mu$ final states
- Uncertainties in lepton identification are reduced by measuring analogous ratio for Z bosons ($R_Z^{\mu\mu/ee}$) as well
- Main parameter of interest becomes

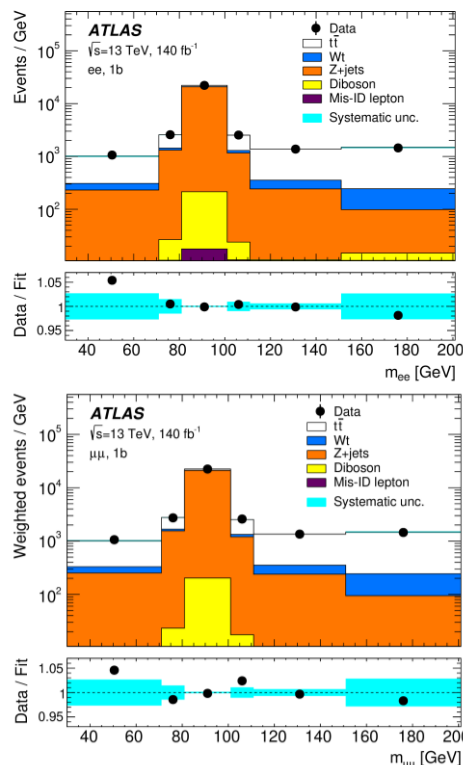
$$R_{WZ}^{\mu/e} = R_W^{\mu/e} / \sqrt{R_Z^{\mu\mu/ee}}$$
- Lepton isolation efficiency measured in situ to ensure low total uncertainty
- b-jet tagging+reconstruction efficiency also measured in situ



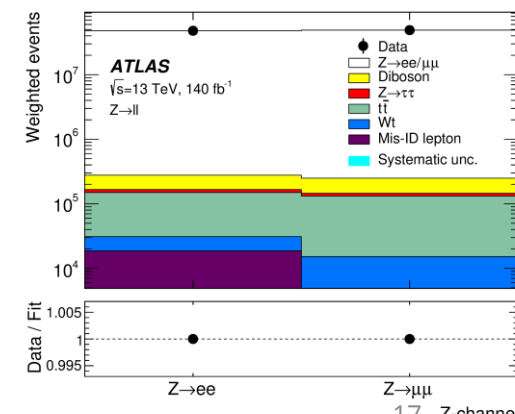
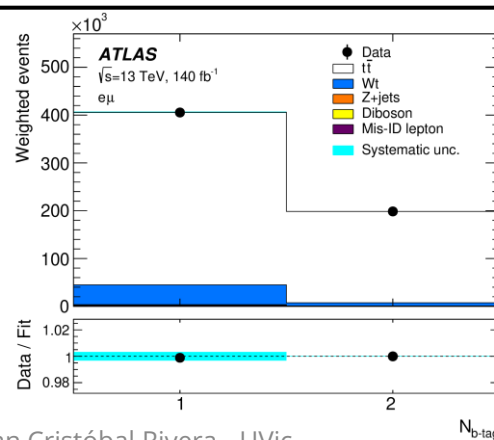
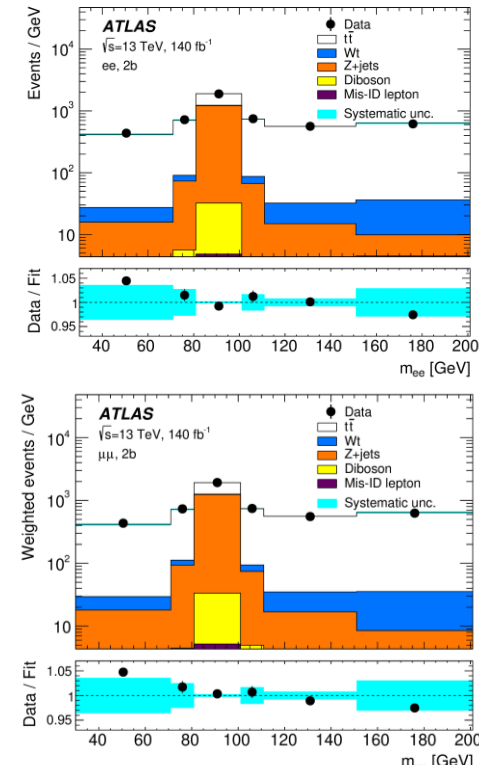
- Event requirements
 - Exactly 2 selected leptons
 - One or two b-tagged jets
 - In same-flavor events, $|m_{\ell\ell} - m_Z| > 10$ GeV
- Fit of $\sigma_{t\bar{t}}$, $\sigma_{Z\rightarrow\ell\ell}$, $R_{WZ}^{\mu/e}$ and $R_Z^{\mu\mu/ee}$ is done using single maximum likelihood, using the following event counts:
 - $N_{1b}^{e\mu}$ and $N_{2b}^{e\mu}$ are fit to events in $e\mu$ channel
 - $N_{1b,m}^{\ell\ell}$ and $N_{2b,m}^{\ell\ell}$ are fit to the $\ell\ell$ invariant mass bin
 - N_Z^{ee} and $N_Z^{\mu\mu}$ are fit to the inclusive $Z \rightarrow \ell\ell$ selections

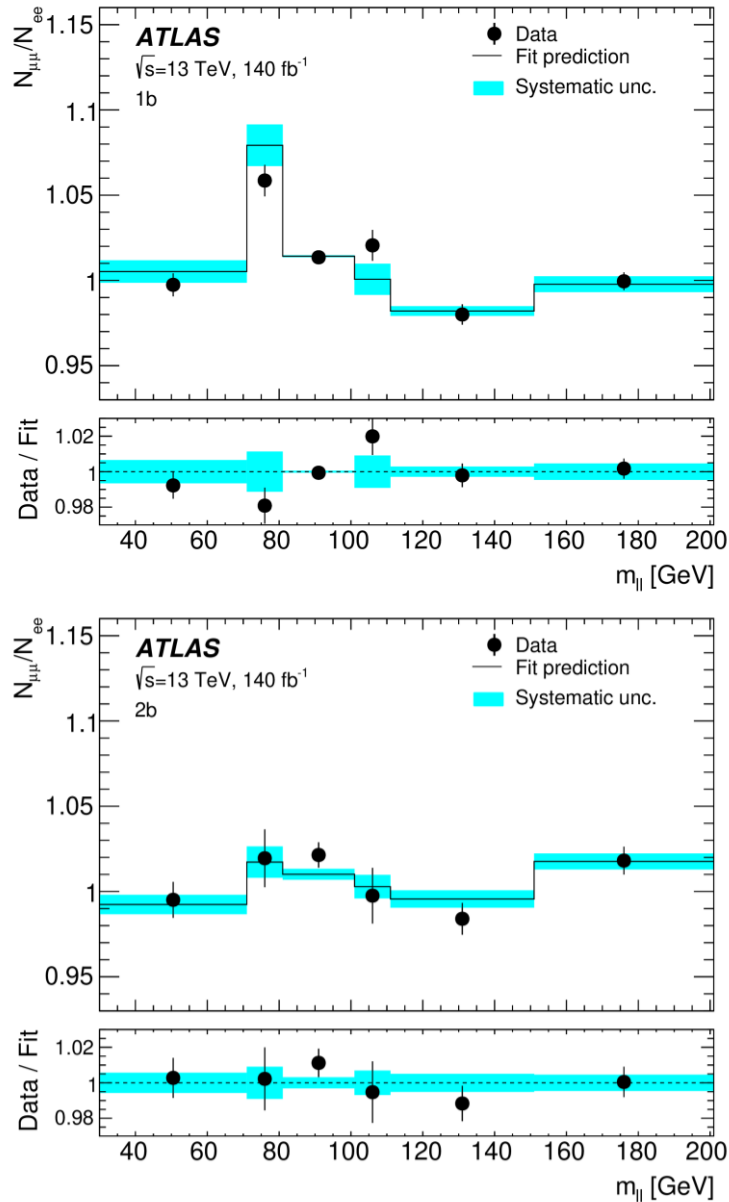
- Fit results:
 - $\sigma_{t\bar{t}} = 809.5 \pm 20.2$ pb
 - $\sigma_{Z\rightarrow\ell\ell} = 2019.4 \pm 26.7$ pb
 - $R_{WZ}^{\mu/e} = 0.9990 \pm 0.0042$
 - $R_Z^{\mu\mu/ee} = 0.9913 \pm 0.0045$

1b

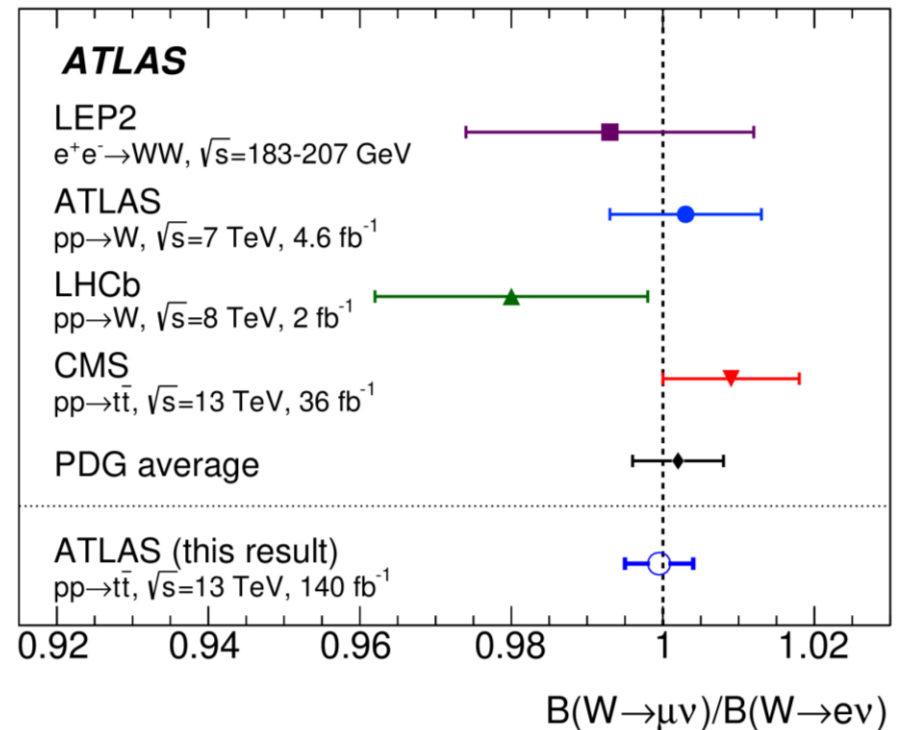


2b





- Resulting value of ratio of branching ratios is $R_W^{\mu/e} = 0.9995 \pm 0.0045$, which is consistent with assumption of lepton flavor universality
- Most precise measurement of $R_W^{\mu/e}$ to date



Conclusions

- The ATLAS Experiment has been used to obtain high precision measurements of various electroweak parameters of the SM
 - W Boson mass m_W and width Γ_W
 - Top quark mass (combination with CMS)
 - Z Boson invisible width $\Gamma(Z \rightarrow inv)$
 - Z Boson double-differential cross section
 - Strong coupling constant $\alpha_S(m_Z)$
 - $R_W^{\mu/e}$ as test of LF universality
- Most precise results to date across the board
- Results are consistent with global averages and SM predictions
- Run 3 of the LHC has started, with even more data to make new measurements and to improve existing ones

Precision measurements of electroweak parameters at the ATLAS Experiment

QCD2024

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On behalf of the ATLAS Collaboration

Backup

- χ^2 results using different PDF sets:

PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN ³ LO	13/8	0.11	1.2 ± 0.6
CT18A	12/8	0.17	0.9 ± 0.7
MSHT20	10/8	0.26	0.9 ± 0.6
NNPDF4.0	30/8	0.0002	0.0 ± 0.2
ABMP16	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0	22/8	0.005	-1.3 ± 0.8
ATLASpdf21	20/8	0.01	-1.1 ± 0.8

- Precision of the measurement provides strong PDF sensitivity

- χ^2 formula used:

$$\chi^2(\beta_{exp}, \beta_{th}) = \sum_{i=1}^{N_{data}} \frac{(\sigma_i^{exp} + \sum_j \Gamma_{ij}^{exp} \beta_{j,exp} - \sigma_i^{th} - \sum_k \Gamma_{ik}^{th} \beta_{k,th})^2}{\Delta_i^2} + \sum_j \beta_{j,exp}^2 + \sum_k \beta_{k,th}^2$$

- Where σ_i^{exp} are the measurements and σ_i^{th} are theory predictions, Δ_i^2 are the uncorrelated experimental uncertainties.
- β_{exp} and β_{th} are the experimental and theoretical nuisance parameter vectors, and the matrices Γ_{ij}^{exp} and Γ_{ik}^{th} encode their influence on the data and the theory predictions.
- At N⁴LLa+N³LO, only one PDF set (MSHT20aN3LO) is available. Determination of $\alpha_s(m_Z)$ is also repeated at lower order using various PDFs in a simultaneous fit.
- Value obtained using this method is $\alpha_s(m_Z) = 0.11866 \pm 0.00064$
- Result is in agreement with result from N⁴LLa+N³LO method

