Highlights from Standard Model Precision Measurements in ATLAS

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On Behalf of the ATLAS collaboration

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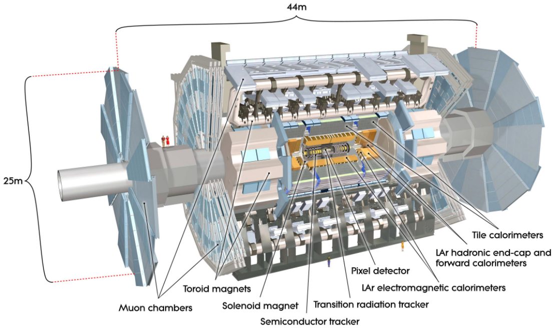
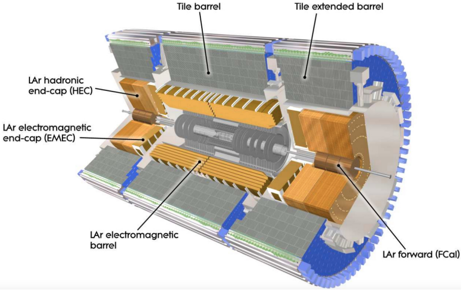
ATLAS Detector

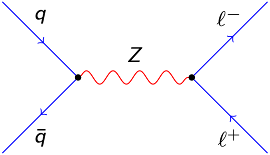


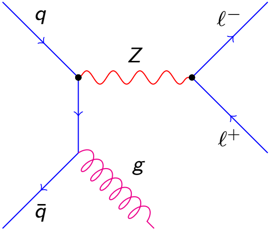
- A general purpose detector with large acceptance[a]
  - Electron: $|\eta| < 4.9$
  - Muon: $|\eta| < 2.7$
- Precision measurements in high y region



[a] 2008 JINST 3 S08003

Precision Measurements with Single Z Production





- Z: Precisely reconstructed from the two final state leptons
  - Enough statistics to observe the high-order effect

$$\frac{d\sigma}{dp_T dy dm d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T dy dm}\Big\{(1+\cos^2\theta)+\frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\} \quad (1)$$

- A joint fit to determine all these variables
  - Angular coefficient A_i: Defined in each bin of p_T, y and m
    - LO: A_4, NLO: $A_{0,1,2,3}$, NNLO: $A_{5,6,7}$
    - $A_4 = \frac{8}{3}A_{FB}$: Further used to extract $\sin^2\theta_W$
  - $\frac{d\sigma}{dp_T dy dm}$: Defined in full phrase space
    - In low p_T region, constrain non-perturbative function form
    - Further used to extract α_S

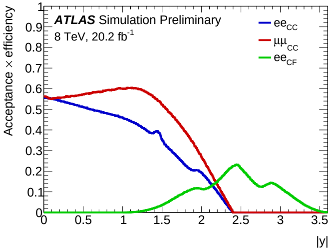
Measurements with $Z \to \ell^+\ell^-$ process at $\sqrt{s} = 8$ TeV

- Dataset: $20.3\ \text{fb}^{-1}$, $\sqrt{s} = 8$ TeV, collected in 2012, $\bar{\mu} = 20$[a]

- $Z \to \ell^+\ell^-$ events from 3 channels: ee_{CC}, ee_{CF} and $\mu\mu_{CC}$
  - Central(C): $|\eta^\ell| < 2.4$, Forward(F): $2.5 < |\eta^\ell| < 4.9$

Channel	ee_{CC}	ee_{CF}	$\mu\mu_{CC}$
p_T^ℓ	$p_T^e > 20$ GeV	C: $p_T^e > 25$ GeV F:$p_T^e > 20$ GeV	$p_T^\mu > 20$ GeV
$m_{\ell\ell}$		$80 < m_{\ell\ell} < 100$ GeV	
N_{Data}	6.19×10^6	1.25×10^6	7.81×10^6

- Background:
  - Physics: tt, Wt, Diboson, $Z \to \tau\tau < 0.3\%$
  - Detector: Multi-jet and W+jet
    (CC $\sim 0.1\%$ CF $\sim 1.0\%$)



- Able to observe the high y region ($2.5 < |y| < 3.6$)

[a] $\bar{\mu}$: Average interactions per bunch crossing

Analysis Strategy

- A joint fit of the cross section ($p_T^{\ell\ell} - y^{\ell\ell}$) and the angular coefficients

$$N_{\text{exp}}^{n} = \left\{\Sigma_i L\sigma_i \left[t_{8i}^{n}(\beta) + \Sigma_{j=0}^{7} A_{ji} t_{ji}^{n}(\beta)\right]\right\}\gamma^{n} + \Sigma_B T_B^{n}(\beta) \quad (2)$$

  - n: Bin index of the $(\cos\theta, \phi)$ distributions in each region and channel
  - i: $(p_T^{\ell\ell}, |y^{\ell\ell}|)$ region index
  - Fitting parameters: σ_i, A_{ji} and nuisance parameters (β and γ)
- Phase space cuts absorbed by the templates $t_{ji} \rightarrow \sigma_i$ defined in the full phase space
  - Number of observables: 22528
  - Number of parameters: 1584
- Using the profiled likelihood method[a]

$$\mathcal{L} = \prod_n Poisson(N_{\text{Data}}^{n} | N_{\text{exp}}^{n}) \times \prod_i Gaus(\theta_i) \quad (3)$$

- Measurement of the angular coefficients, $A_i \rightarrow$ Published in 2016[b]
  - Measurement of $\sin^2\theta_W$ from $A_4 \rightarrow$ Published in 2018[c]
- NEW:
  - Measurement of $\frac{d\sigma}{dp_T dy}$ in full phase space $\rightarrow$ ATLAS-CONF-2023-013
  - Measurement of $\alpha_S \rightarrow$ ATLAS-CONF-2023-015

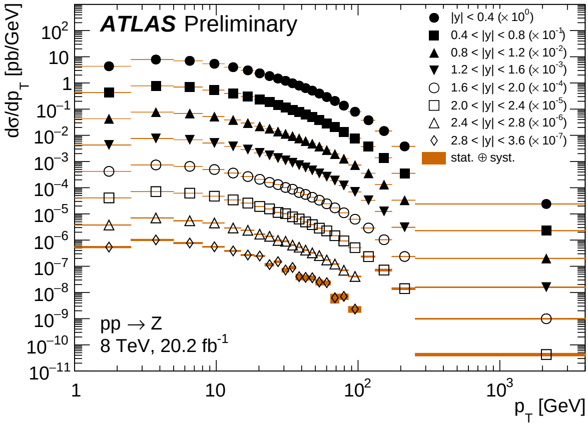
[a] Here θ_i is the ith nuisance parameter.

[b] JHEP 08 (2016) 159

[c] ATL-CONF-2018-037

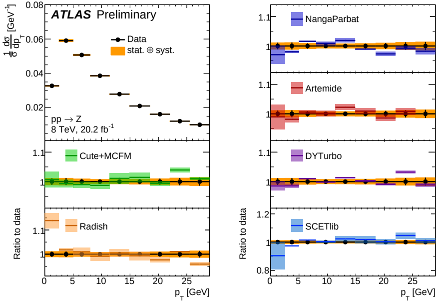
Differential Cross Section (2D)

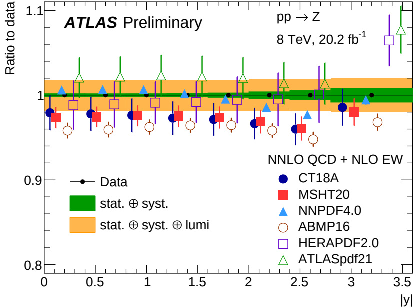
- Measured $(p_T^{\ell\ell}, |y^{\ell\ell}|)$ differential cross section:
  - Statistical uncertainty dominated



- Compared to several predictions at approximate N^{4}LL accuracy
  - Difference within 5% at $p_T^{\ell\ell}$ peak region

Differential Cross Section (1D)





- Good agreement with the predictions
- In most bins, difference within 3%

- Focus on the comparison to different PDFs

PDF	MSHT20aN^{3}LO	CT18A	MSHT20	NNPDF4.0	ABMP16	HERAPDF2.0	ATLASpdf21
χ^2/ndf	13/8	12/8	10/8	30/8	30/8	22/8	20/8
p-value	0.11	0.17	0.26	2×10^{-4}	2×10^{-4}	0.005	0.01

- Reasonable agreement: MSHT20aN^{3}LO, CT18A and MSHT20
- Poor agreement: NNPDF4.0, ABMP16

The Determination of the Strong-coupling Constant

- Directly using the previously measured differential cross section
- 8 $|y^{\ell\ell}|$ bins from 0 to 3.6 $\times$ 9 $p_T^{\ell\ell}$ bins from 0 to 29 GeV
- PDF: MSHT20aN^{3}LO, the only one at aN^{3}LO ($0.114 < \alpha_S(m_Z) < 0.120$)
  - Other NNLO PDFs tried as well
- The statistical analysis performed by the xFitter framework[a]

$$\alpha_S(m_Z) = 0.11828^{+0.00084}_{-0.00088} \quad (4)$$

  - Goodness of the fir: $\chi^2/ndf = 82/72 \rightarrow$ p-value $= 0.2$

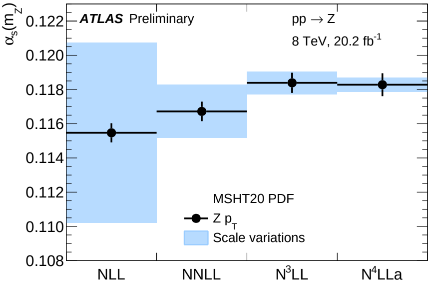
Uncertainty Source	Up($\times 10^{-5}$)	Down($\times 10^{-5}$)
Experimental	+44	-44
PDF	+51	-51
QCD Scale	+42	-42
Matching to fixed order	0	-8
Non-perturbative model	+12	-20
Flavour model	+21	-29
QED ISR	+14	-14
N^{4}LL approximation	+4	-4
Total	+84	-88

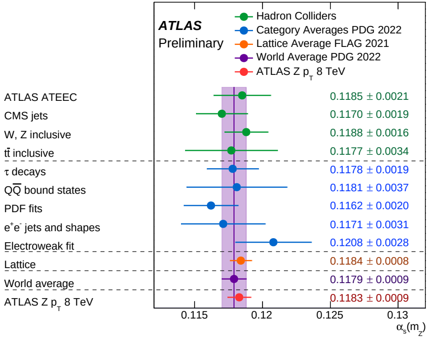
- The most precise experimental determination

[a] Eur. Phys. J. C 75 (2015) 304

Comparing to Other α_S Measurements

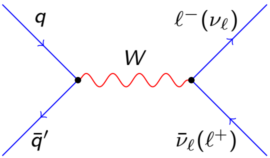
- First determination on aN^{4}LL+N^{3}LO predictions
- Also determined at lower orders $\rightarrow$ good perturbative series convergence

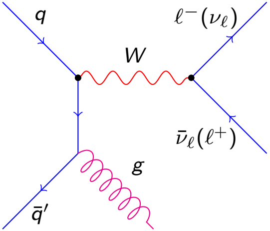




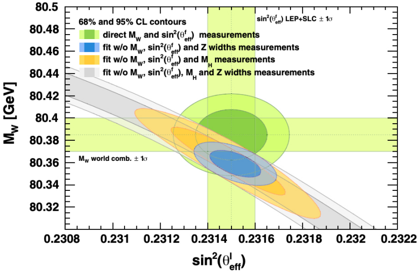
- Consistent with the world average value

Precision Measurements with Single W Production





- W: cannot be fully reconstructed due to the missing neutrino
  - The information in the transverse plane is still available by measuring $\vec{\not{E}}_T$
  - p_T^W, m_T, p_T^ℓ and η^ℓ can still be observed
- m_T and p_T^ℓ: used to extract m_W
  - Providing inputs for EW global fitting (together with $\sin^2\theta_W$)[a]
- p_T^W: reconstructed from the hadronic recoil $\vec{u}_T$
  - The universality of the non-perturbative calculation
  - Reduce the model uncertainty on m_W due to p_T^W modeling
- η^ℓ: W asymmetry used to constrain PDF



[a] Eur. Phys. J. C 74, 3046 (2014)

Improved W Mass Measurement using 7 TeV Dataset

- Previous result[a]:

$$
\begin{aligned}
m_W &= 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\ \text{MeV} \\
&= 80370 \pm 19\ \text{MeV}
\end{aligned}
\tag{5}
$$

- The template fitting method $\rightarrow$ The profile likelihood method (PLH)
  - The first time for the m_W measurement
- Rigorous checks have been performed
  - p_T^W modeling: validated with the latest measurement
  - Electroweak (EW) corrections: better agreement on lepton kinematic distributions (Allowed us to move to a PLH fit)
- Fitting Strategy:

	Nuisance Parameter	Fitting Range
p_T^ℓ	214	$30 < p_T^\ell < 50$ GeV
m_T	223	$60 < m_T < 100$ GeV

  - Finally, combined by BLUE[b] method with the correlation estimated from fluctuated toys

$$\rho = 63\% \pm 3\% \rightarrow w(p_T^\ell) \sim 95\% \tag{6}$$

  - Final result dominated by the p_T^ℓ fit

[a] Eur. Phys. J. C 78 (2018) 110

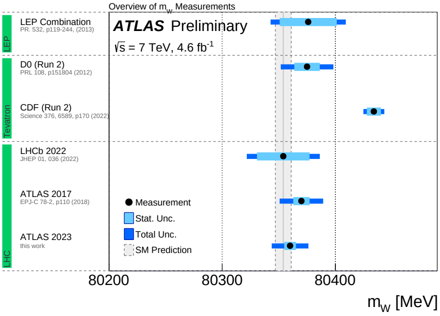
[b] Nucl. Instrum. Meth. A 270 (1988) 110

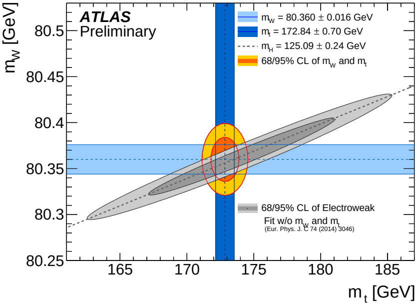
- A dependence on the PDF choice can be observed

	CT10	CT14	CT18	MMHT2014	MSHT20	NNPDF3.1	NNPDF4.0
Central Value	80355.8	80358.4	80360.4	80361.0	80356.3	80345.0	80342.9
Total Unc.	15.7	16.3	16.3	15.9	14.6	15.5	15.3

- CT18 is chosen as the baseline
  (Central Value: a decrease of 10 MeV Total Uncertainty: a reduction of 3 MeV)

$$\begin{aligned} m_W &= 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.})\ \text{MeV} \\ &= 80360 \pm 16\ \text{MeV} \end{aligned} \quad (7)$$





- No deviation from the SM expectation is observed

Measurements of W and Z transverse momentum

- Dataset: $255\ \text{pb}^{-1}$, $\sqrt{s} = 5.02$ TeV; $338\ \text{pb}^{-1}$, $\sqrt{s} = 13$ TeV collected in 2017 and 2018, $\bar{\mu} \sim 2$
  - Better hadronic recoil performance than the normal run ($\bar{\mu} \sim 34$)
- Trigger: one electron with $p_T > 15$ GeV OR one muon with $p_T > 14$ GeV
- Event selection

	Electron	Muon
p_T^ℓ	$p_T^e > 25\ GeV$	$p_T^\mu > 25\ GeV$
η^ℓ	$\lvert\eta^e\rvert < 2.47$	$\lvert\eta^\mu\rvert < 2.4$
Identification	Medium	
Isolation	Well-isolated	
Vertex	Associated with the Primary Vertex	

  - $W \to \ell\nu$: $\vec{E\!\!\!/}_T < 25$ GeV, $m_T > 50$ GeV, Second lepton with $p_T^\ell > 20$ GeV Veto
  - $Z \to \ell\ell$: $66 < m_{\ell\ell} < 116$ GeV
- Number of Events Selected:

	$W \to e\nu$	$W \to \mu\nu$	$Z \to ee$	$Z \to \mu\mu$
$\sqrt{s} = 13$ TeV	2.2×10^6	2.2×10^6	1.7×10^5	2.1×10^5
$\sqrt{s} = 5.02$ TeV	7.1×10^5	7.5×10^5	5.2×10^4	7.0×10^4

- Background estimation:
  - Multi-jet estimated by data-driven method
  - Other backgrounds estimated from MC predictions
- Multi-jet background fraction

$\sqrt{s}$	$W \to e\nu$	$W \to \mu\nu$	$Z \to ee$	$Z \to \mu\mu$
13 TeV	2.9%	0.6%	$< 0.1\%$	
5.02 TeV	0.8%	0.1%		

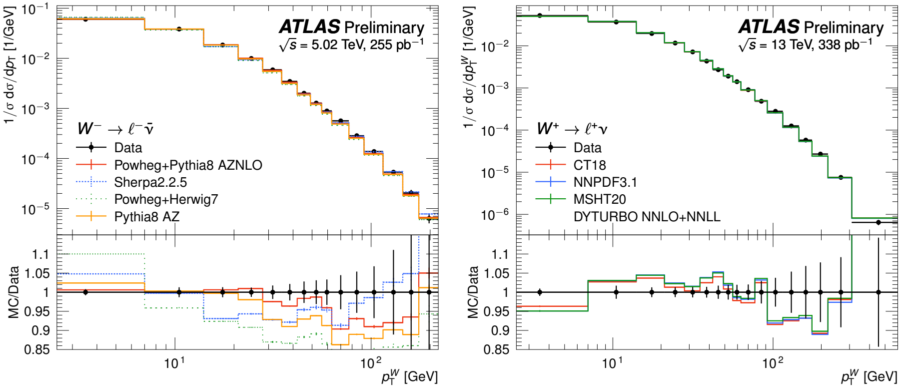
- Unfolding: using the Iterative Bayesian Unfolding Method[a]
  - Fiducial phase space: Close to the experimental acceptance

	$p_T^{\ell/\nu}$	η^ℓ	$m_T/m_{\ell\ell}$
$W \to \ell\nu$	$p_T^\ell > 25$ GeV, $p_T^\nu > 25$ GeV	$\lvert\eta^\ell\rvert < 2.5$	$m_T > 50$ GeV
$Z \to \ell\ell$	$p_T^\ell > 25$ GeV	$\lvert\eta^\ell\rvert < 2.5$	$66 < m_{\ell\ell} < 116$ GeV

  - p_T^W: unfolded from the hadronic recoil, $\vec{u}_T$
  - p_T^Z: unfolded from $p_T^{\ell\ell}$ and checked to be consistent with $\vec{u}_T$ unfolding
- Electron channel and muon channel are combined with BLUE method

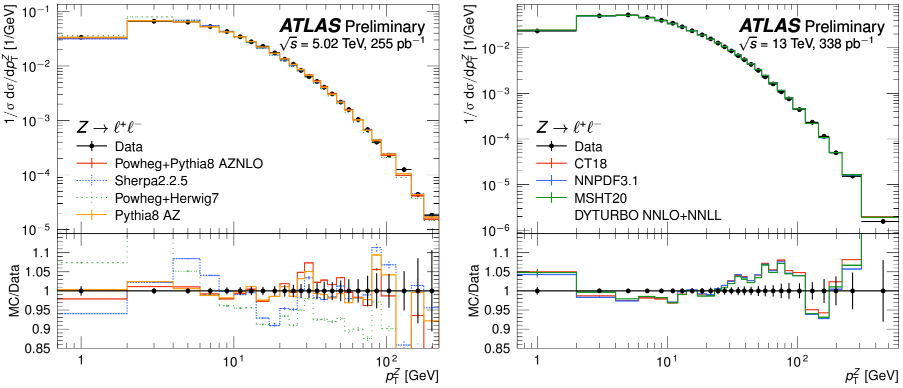
[a] Nucl. Instrum. Meth. A 362 (1995) 487

Final Results (p_T^W)



- Compared to several predictions:
  - Resummation calculation: DYTURBO + different PDFs
  - Parton shower approach: PYTHIA8, HERWIG7 and SHERPA

Final Results (p_T^Z)



- Compared to several predictions:
  - Resummation calculation: DYTURBO + different PDFs
  - Parton shower approach: PYTHIA8, HERWIG7 and SHERPA

- Reasonable agreement from the tune from ATLAS 7 TeV data in $p_T^{W/Z} < 40$ GeV region
- SHERPA matches the data best at higher $p_T^{W/Z}$
- DYTURBO: the best agreement across the spectrum, Difference $\sim \mathcal{O}(10^{-2})$

Measurements of W^+W^- Production Cross Sections

- W^+W^- Production: Sensitive to the self-couplings of vector bosons
- Dataset: 140 fb^{-1}, $\sqrt{s} = 13$ TeV, collected from 2015 to 2018
- Trigger: Single lepton trigger
- Event Selection: exactly 1 electron + 1 muon with opposite charges

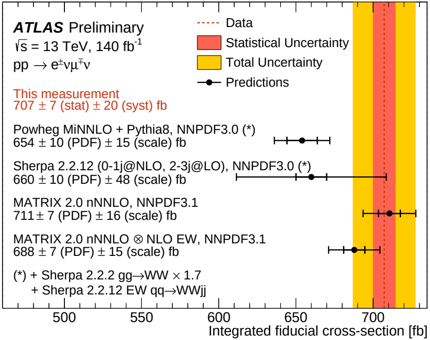
	Electron	Muon
p_T^ℓ	$p_T^e > 27\ GeV$	$p_T^\mu > 27\ GeV$
η^ℓ	$\|\eta^e\| < 2.47$	$\|\eta^\mu\| < 2.5$
Identification	Tight	Medium
Isolation	Well-isolated	
Vertex	Associated with the Primary Vertex	

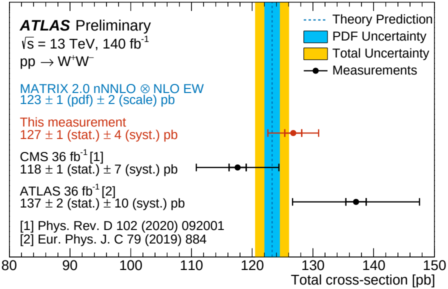
  - Additional b-jet veto to suppress t related background
  - $m_{e\mu} > 85$ GeV (Suppress $Z \to \tau\tau$ background and $gg \to H \to WW$ production)
  - Third loose lepton with $p_T^\ell > 10$ GeV veto (Suppress WZ and ZZ backgrounds)
- Background estimation:
  - Dominated by t related background $\to$ Estimated by a data-driven method

	Data	WW	t related	Drell-Yan	Fakes	Diboson
Number of events	144221	56900 ± 1100	66500 ± 1900	6500 ± 400	5000 ± 1300	4500 ± 600
Fraction	-	41%	48%	5%	4%	3%

- Total cross section fitted by the profile likelihood method
- Differential cross section unfolded with the iterative Bayesian unfolding method

W^+W^- Production Cross Sections





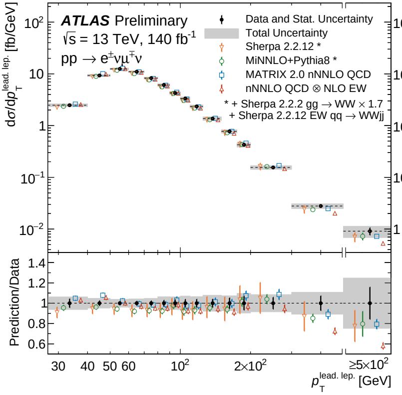
- Extrapolated to the full phase space with the acceptance from nNNLO MATRIX: $23.7\% \pm 0.3\%$

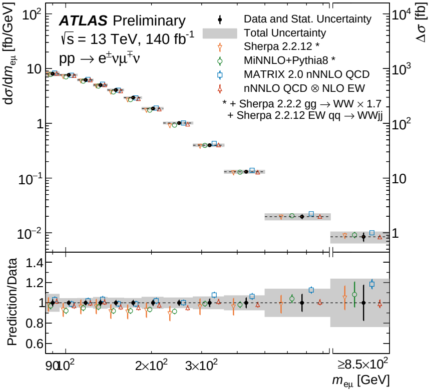
$$
\begin{aligned}
\sigma_{\text{fid}} &= 707 \pm 7(\text{stat.}) \pm 20(\text{syst.})\ \text{fb} \\
\sigma_{\text{total}} &= 127 \pm 1(\text{stat.}) \pm 4(\text{syst.})\ \text{pb}
\end{aligned}
\tag{8}
$$

- Excellent agreement with the fixed-order MATRIX prediction is observed

W^+W^- Differential Cross Section Measurements

- Differential cross-sections of 12 observables are measured





- Excellent agreement with the fixed-order MATRIX prediction
  - Electroweak correction applied to improve the modelling of high-mass events

Summary

- ATLAS 8 TeV $Z \to \ell\ell$ events have been fully analyzed, providing high precision measurements of A_i, $\sin\theta_W$, α_S and the 2D differential cross section
- 7 TeV m_W measurement have been improved to have a better precision and the p_T^V distribution has been measured from the low-μ dataset
- Precision measurements from other Standard Model processes as well, for example W^+W^- this time
- Further information about the measurements mentioned in this talk can be found in:
  - ATLAS-CONF-2023-004: W boson mass reanalysis at 7 TeV
  - ATLAS-CONF-2023-012: Measurements of WW production cross sections
  - ATLAS-CONF-2023-013: Z boson transverse momentum and rapidity measurement in full phase space at 8 TeV
  - ATLAS-CONF-2023-015: α_S determination using Z boson transverse momentum at 8 TeV
  - ATLAS-CONF-2023-028: Measurements of W and Z transverse momentum spectra at 5.02 TeV and 13 TeV