Precision measurements with W boson decays at the LHC

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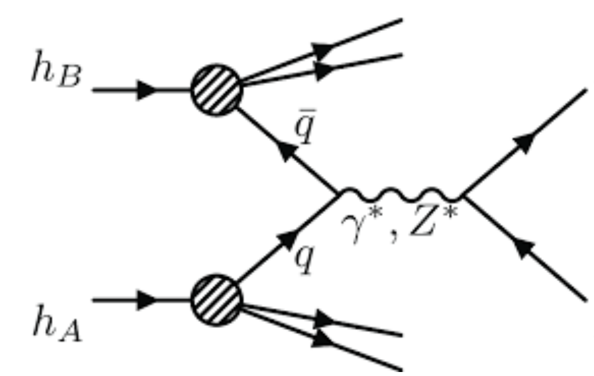
SM@LHC 2024 - Rome

W (and Z) bosons: why?

Building blocks of the standard model (SM) since early ’60s

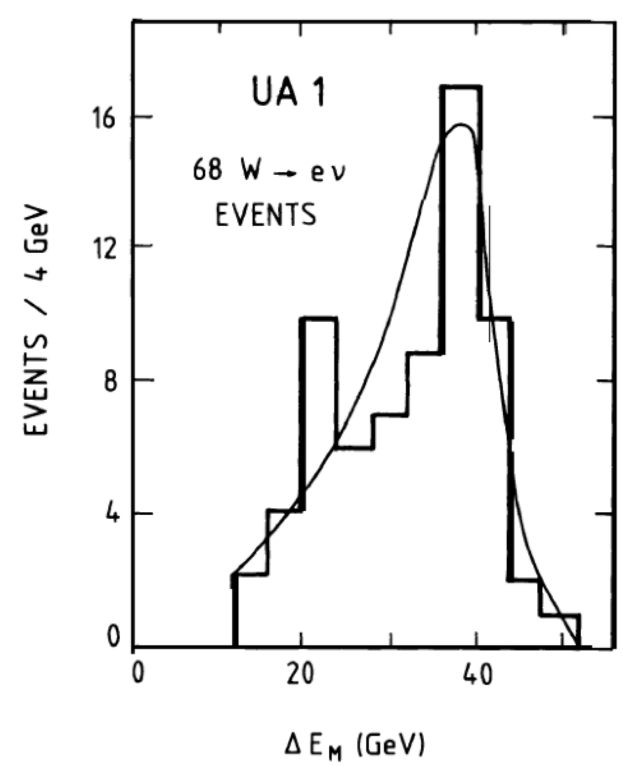
- discovered at CERN in 1983 in $p\bar{p}$ collisions
- The LHC with pp collisions is practically a W and Z factory

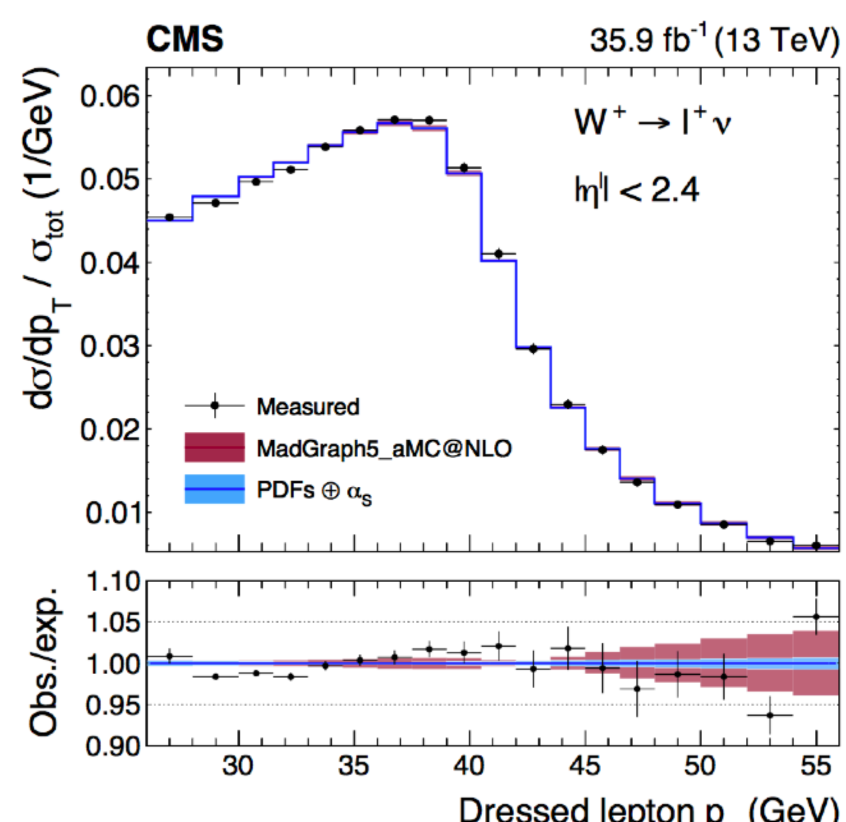
Drell-Yan process

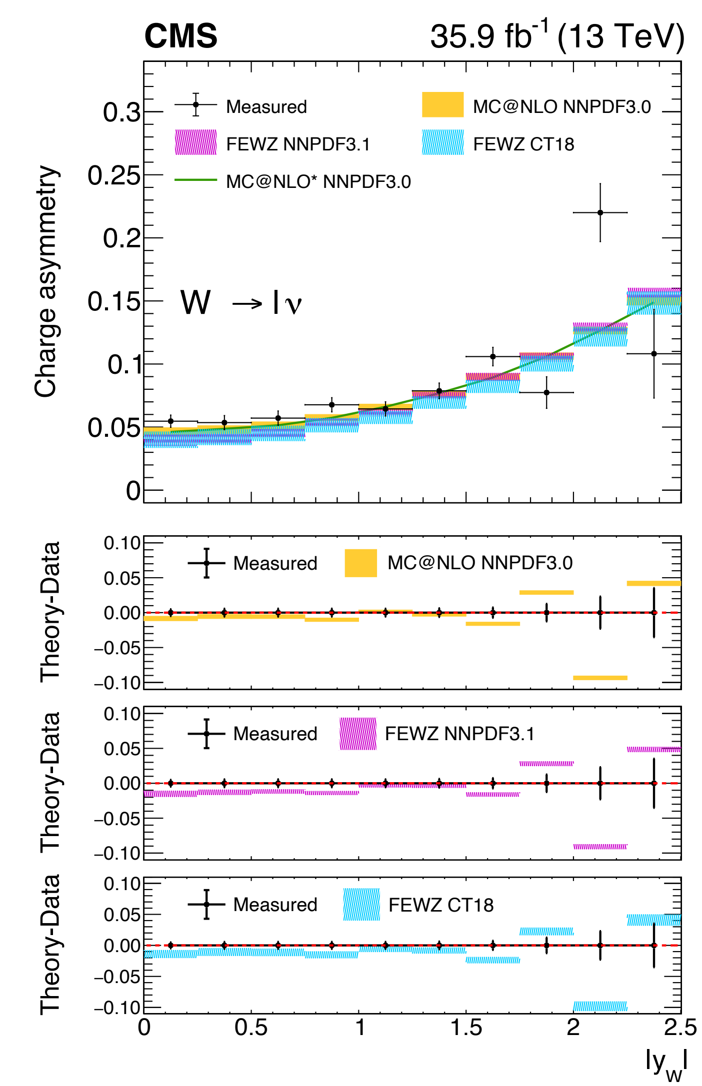


One of most prominent examples of hard scattering processes at hadron colliders

- validation of different generators to model hard scattering and parton shower
- tests of perturbative QCD and electroweak (EW) calculations
- constraints on parton distribution functions (PDFs)







PRD 102 (2020) 092012

Experimental aspects of W (and Z) bosons

Clean experimental signatures thanks to leptonic decay into e, μ

- e/μ efficiencies with ≈1% uncertainty, E/p_T resolution of ≈1% and scale better than 0.1%
- QCD multijet background experimentally challenging for W, use data-driven methods

W/Z are backgrounds in Higgs boson analyses and new physics (NP) searches

- For instance, missing transverse momentum (p_T^{miss}) from decays into neutrinos indistinguishable from dark matter production topology

Large and diverse Run 2 LHC data sets at 13 TeV, produced several 10^9 $W \to \ell\nu$

- Multi-differential cross section measurements with negligible statistical uncertainty
- Also low pileup (PU) data, less events but better control of p_T^{miss} systematic uncertainties

More data keep arriving in current Run 3 at 13.6 TeV

- Validate theory at different center of mass energies
- Breeding ground for new ideas to improve reconstruction or event selection in view of HL-LHC

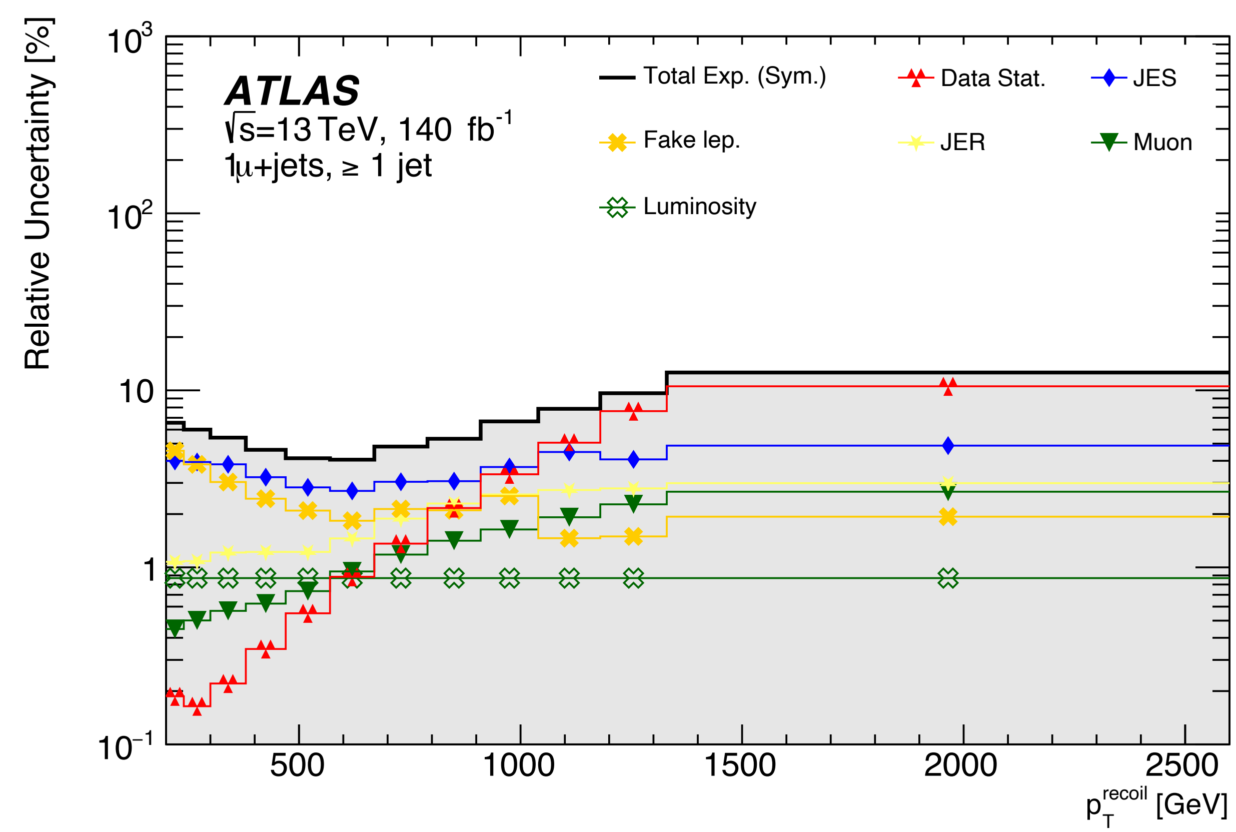
new

Differential study of p_T^{miss}+jets

Wide range of results with W(ℓν)/Z(νν)+jets, in >=1 jet or VFB topology

- Very comprehensive study, with W, Z, γ dominated selections
- Magnitude of hadronic recoil p_T^{recoil} a proxy for boson p_T for decays into neutrinos
- Uncertainty dominated by jet energy scale and resolution, important contribution from QCD background (limited size of data samples) at low (high) p_T^{recoil}
  - Room for improvement as new data are collected

Production process	Final-state event selection					
	p_T^{miss}+jets	$2e$+jets	2μ+jets	e+jets	μ+jets	γ+jets
$Z \to \nu\nu$ + jets	55%	–	–	–	–	–
$Z \to ee$ + jets	–	94%	–	–	–	–
$Z \to \mu\mu$ + jets	–	–	95%	–	2%	–
$W \to e\nu$ + jets	6%	–	–	68%	–	–
$W \to \mu\nu$ + jets	9%	–	–	–	67%	–
$W \to \tau\nu$ + jets	20%	–	–	5%	7%	–
γ + jets	–	–	–	–	–	>99%
Top	7%	3%	2%	25%	21%	–
Multi-boson	3%	3%	3%	2%	3%	<1%

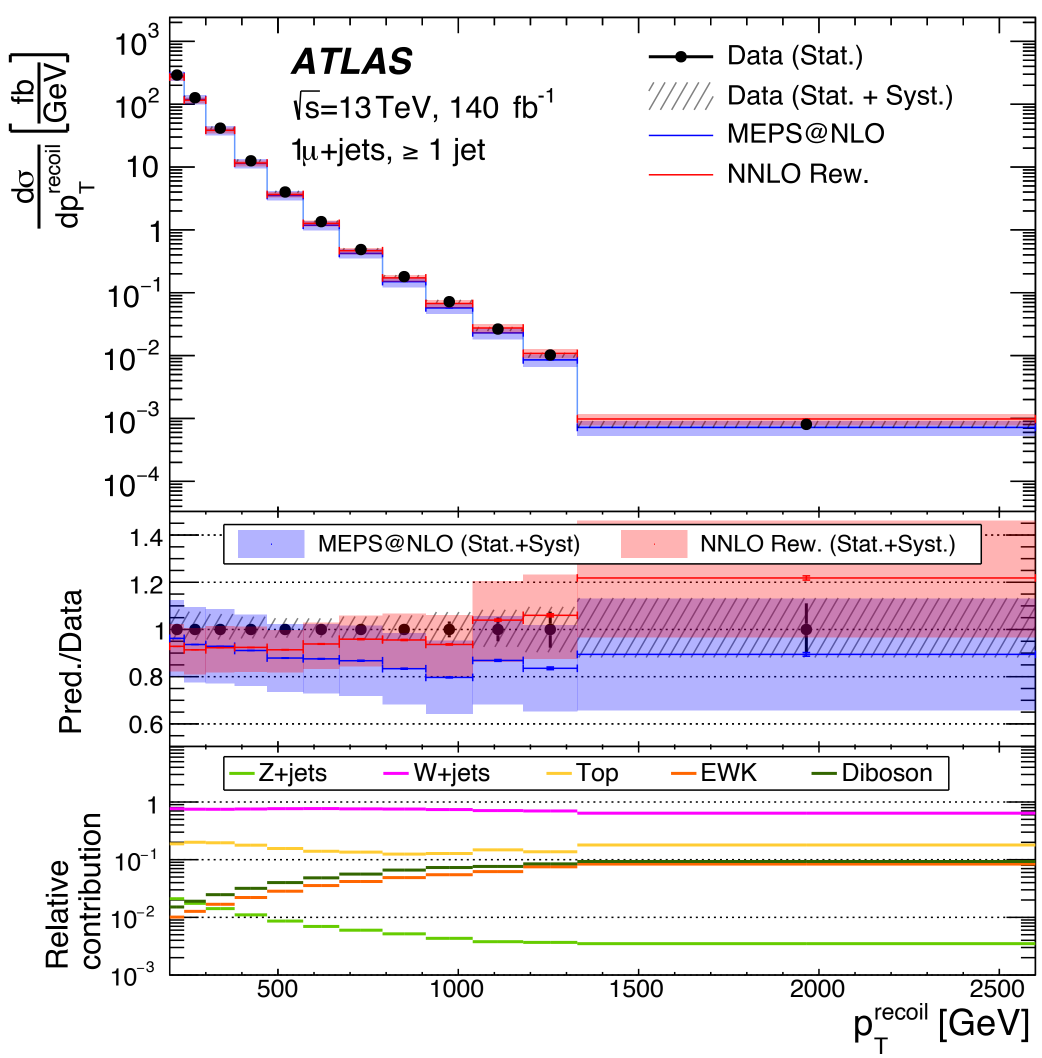


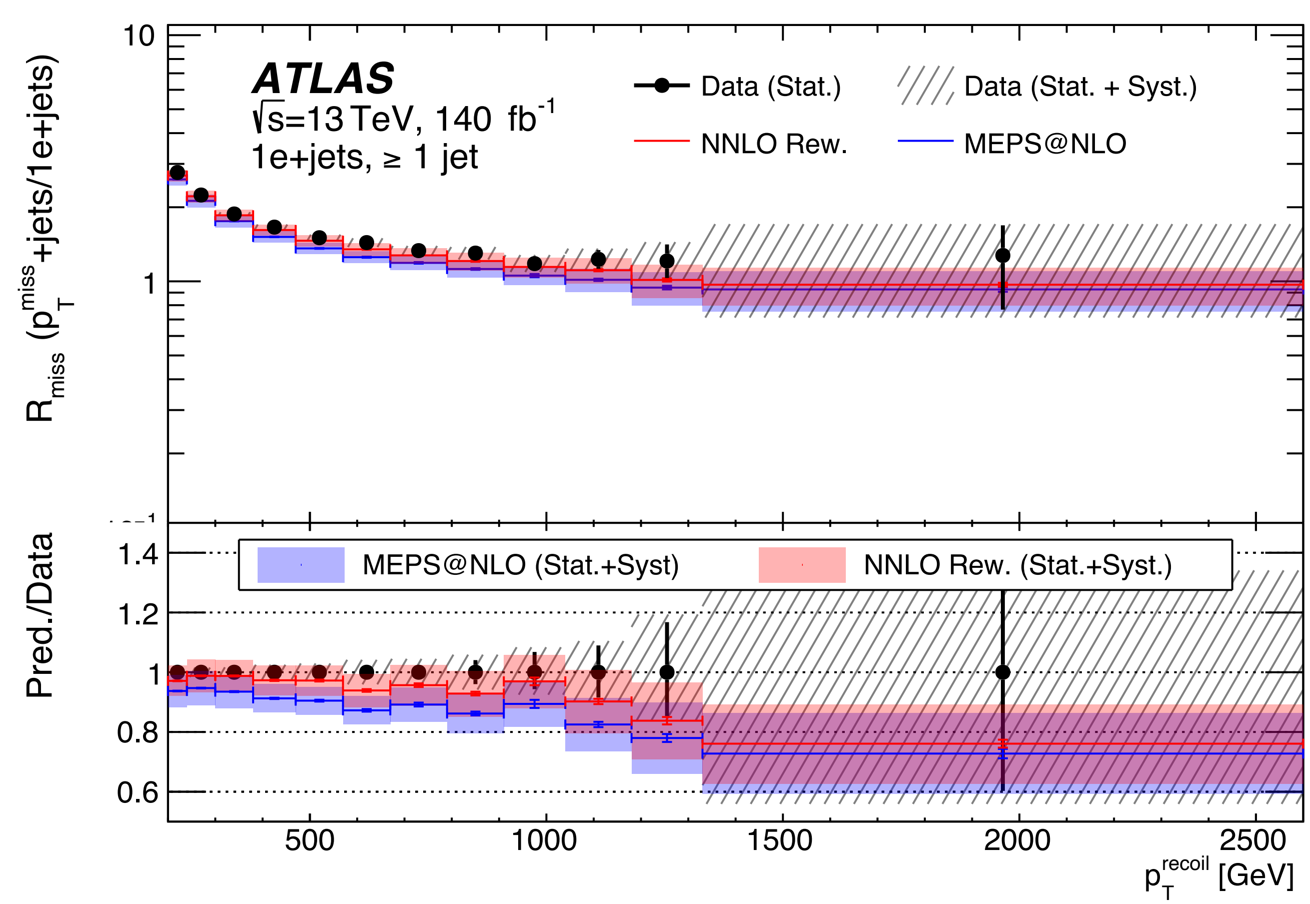
arxiv:2403.02793

new

Differential study of p_T^{miss}+jets

- Results unfolded to correct for detector resolution and efficiency, allowing for robust comparison with different theoretical predictions
- Test multiple generators and calculations up to high p_T^{miss} at the TeV scale
- Measured differential cross sections as well as R^{miss} ratio of p_T^{miss} and $p_T^{\ell(\ell/\nu)}$ spectra
  - predicted R^{miss} a key ingredient in NP searches to constrain invisible W/Z+jets background shapes from appropriate data-driven control regions with visible leptons



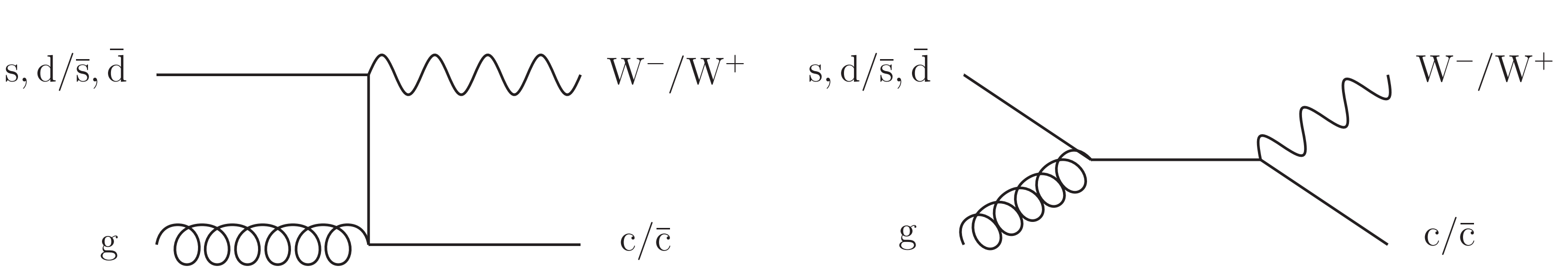


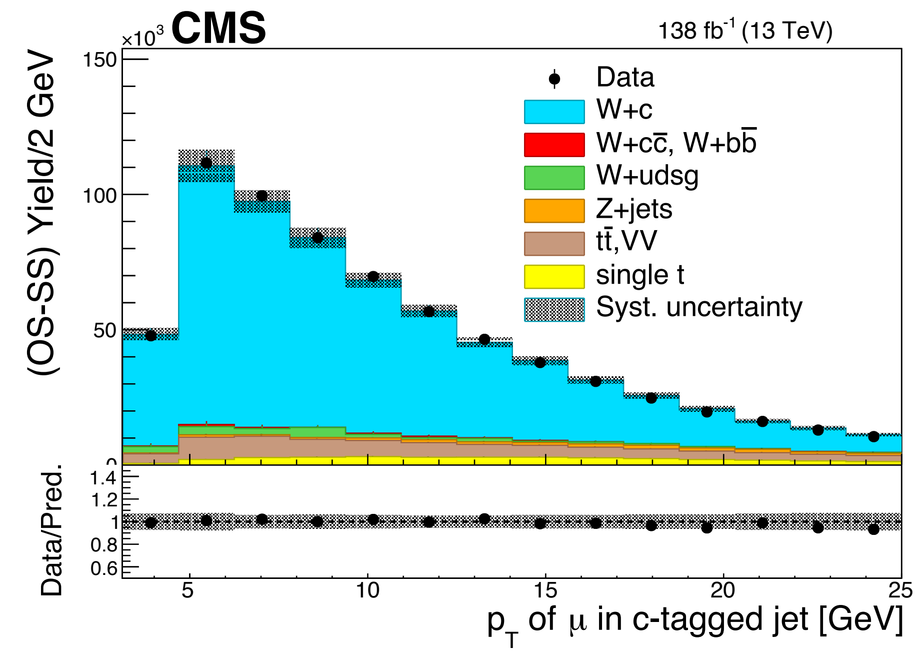
Eur. Phys. J. C 84 (2024) 27
Phys. Rev. D 108 (2023) 032012
LHC seminar by ATLAS

W boson and heavy flavour

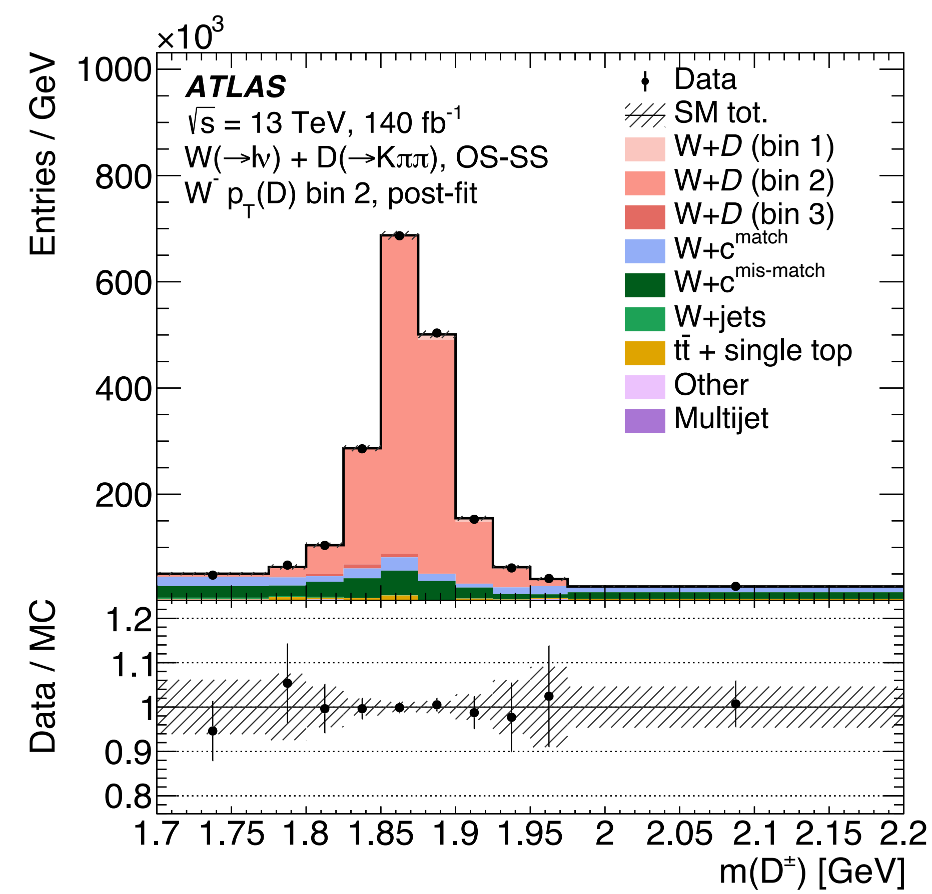
Associated production of W and charm quark sensitive to strange quark content of protons at energy scale of order m_W

- Probe strange quark PDF and possible s-$\bar{s}$ asymmetry
- help validate MC predictions for backgrounds in VH topologies with $H \to c\bar{c}$





- W boson reconstructed from decay into e or μ with opposite-sign (OS) charge with respect to c quark
  - Main backgrounds from same-sign (SS) charge
- Different c quark selection for ATLAS/CMS:
  - **CMS**: from charm jets tagged using a muon or secondary vertex inside the jet
  - **ATLAS**: from charmed mesons using $D^+ \to K^-\pi^+\pi^-$ or $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ and charge conjugate



W boson and heavy flavour

Eur. Phys. J. C 84 (2024) 27
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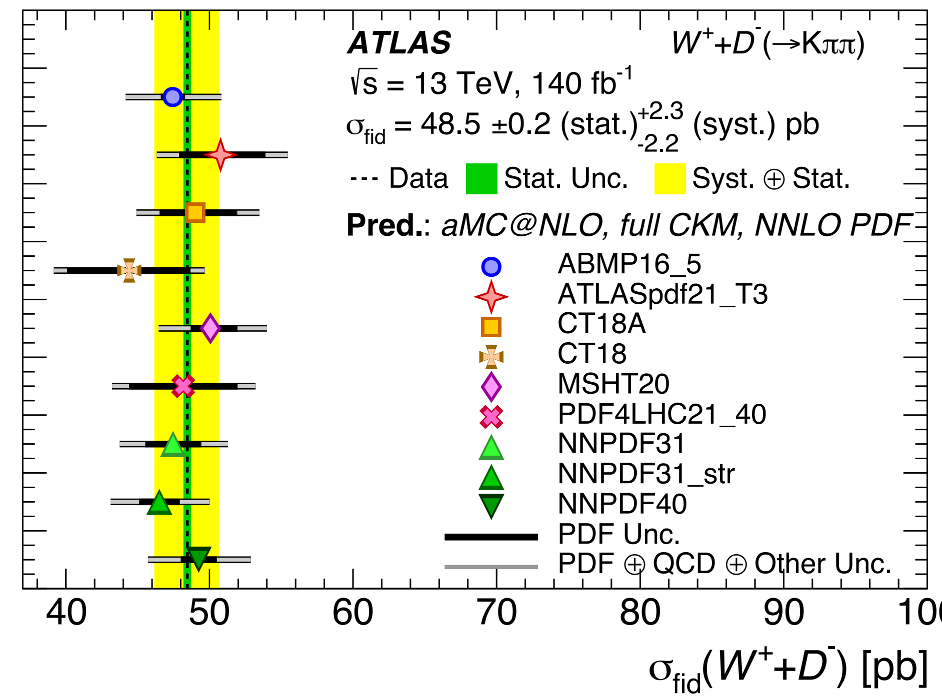
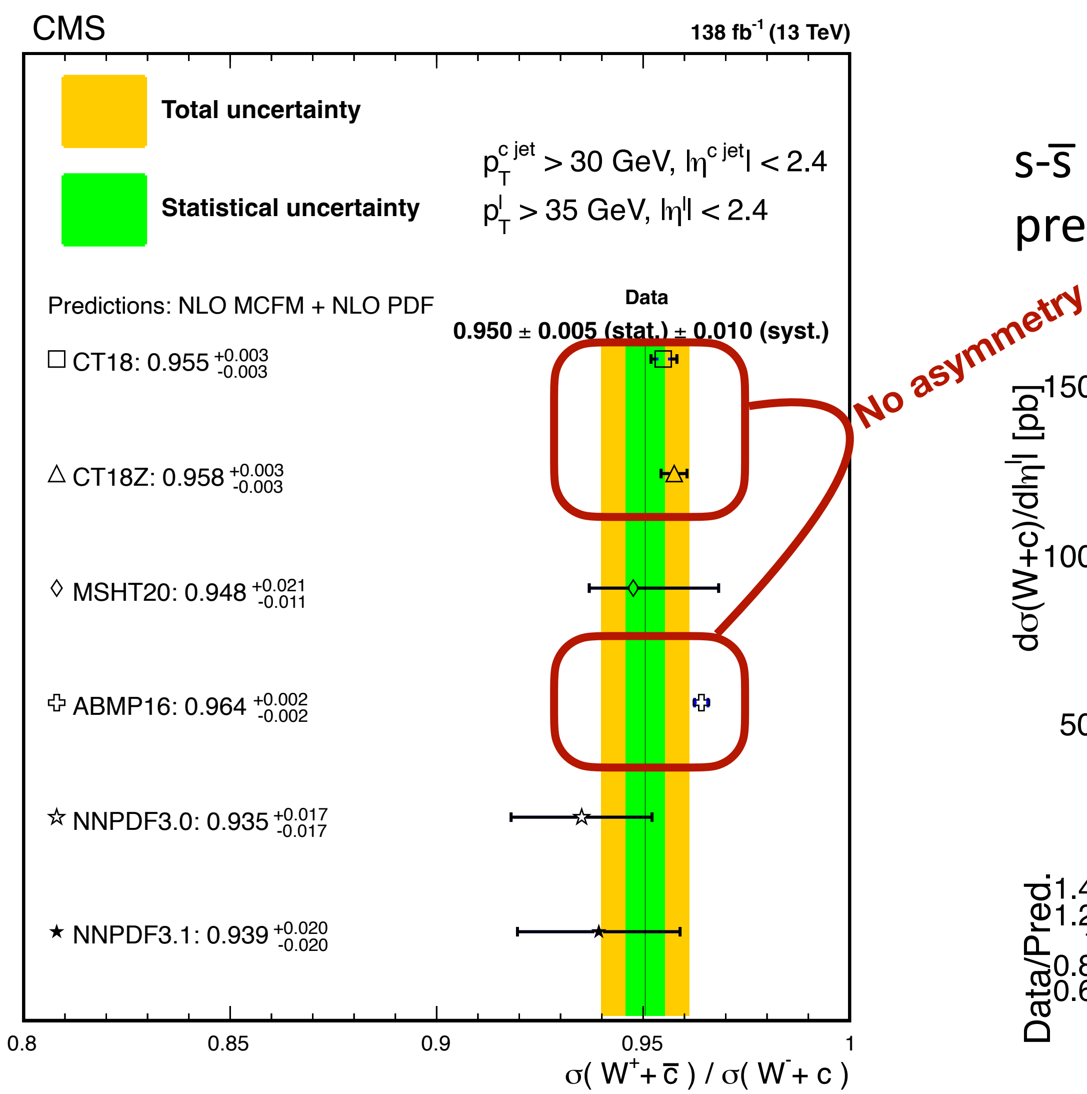
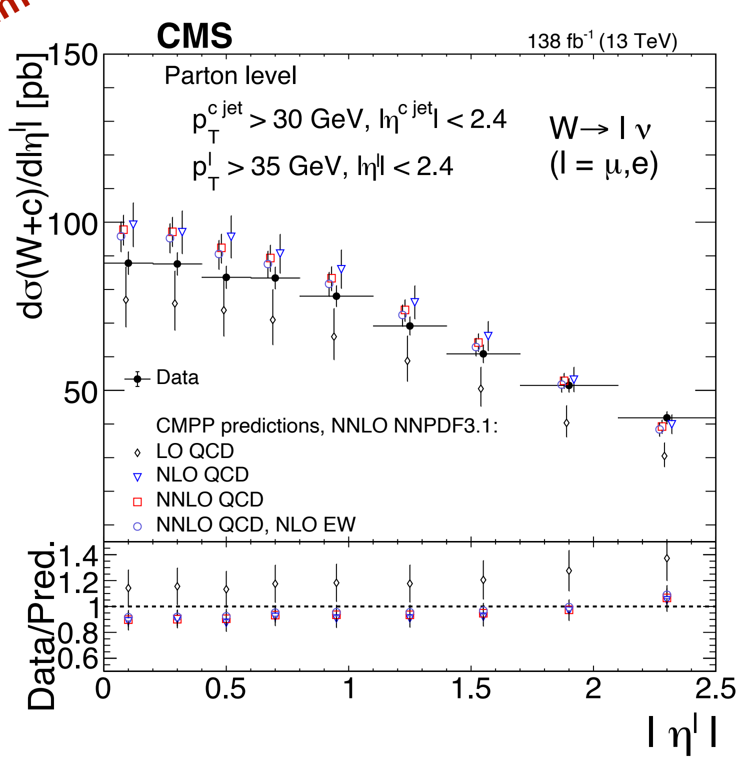
LHC seminar by ATLAS

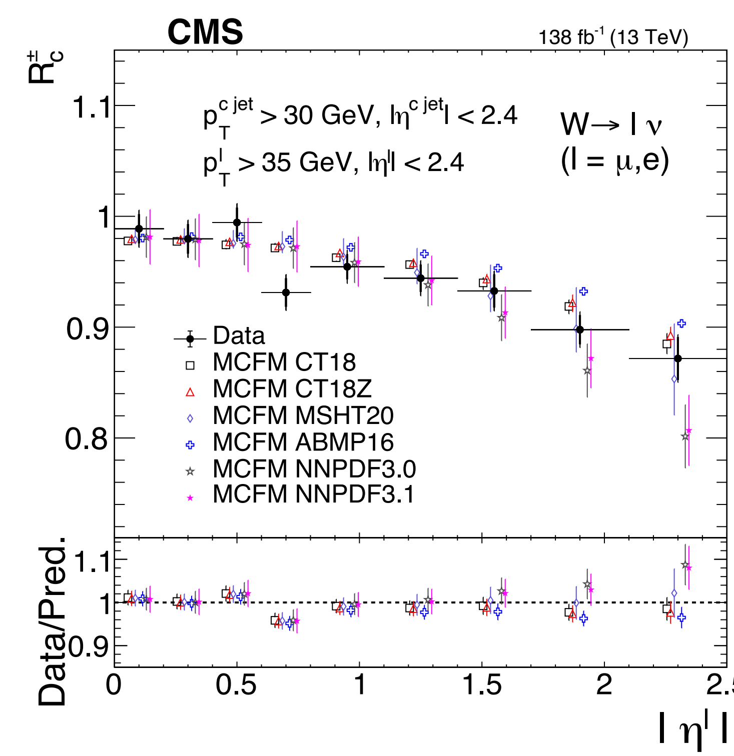
- Measured cross sections inclusively and differential
  - CMS: in bins of p_T or $|\eta|$ of lepton from W decay, xsec unfolded to particle and parton levels
  - ATLAS: in bins of D meson p_T and lepton $|\eta|$
- Charge cross section ratio sensitive to strangeness asymmetry in proton, interesting to compare different PDF predictions which implement or not s-$\bar{s}$ asymmetry





s-$\bar{s}$ asymmetry has larger effect at higher p_T or $|\eta|$, but no sufficient precision yet to distinguish between PDF predictions w and w/o it





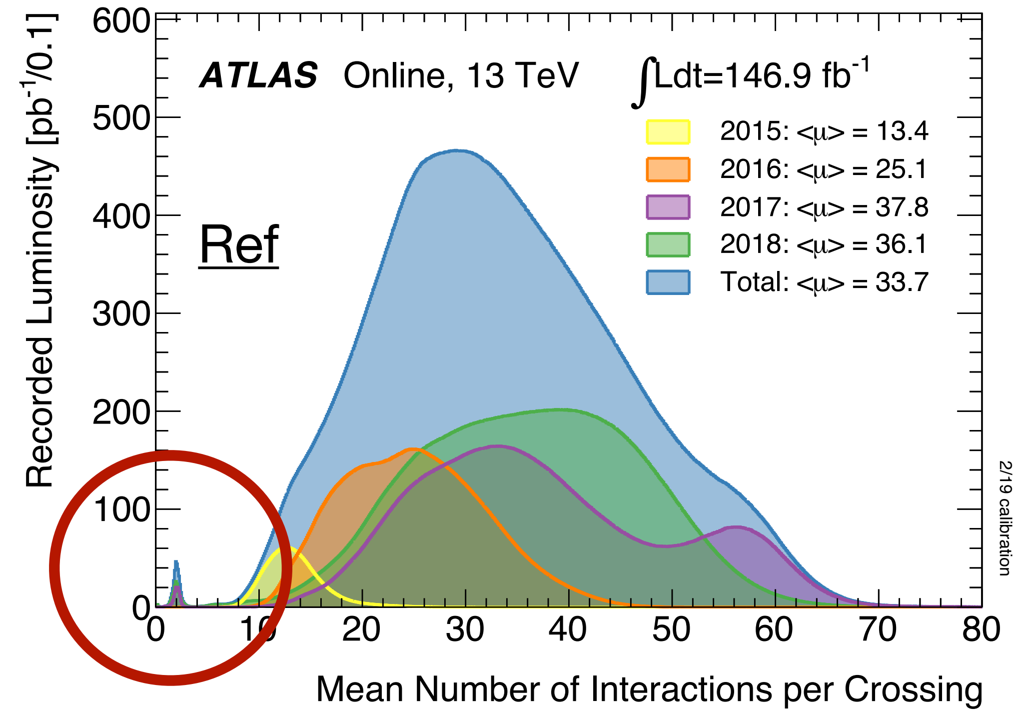
new

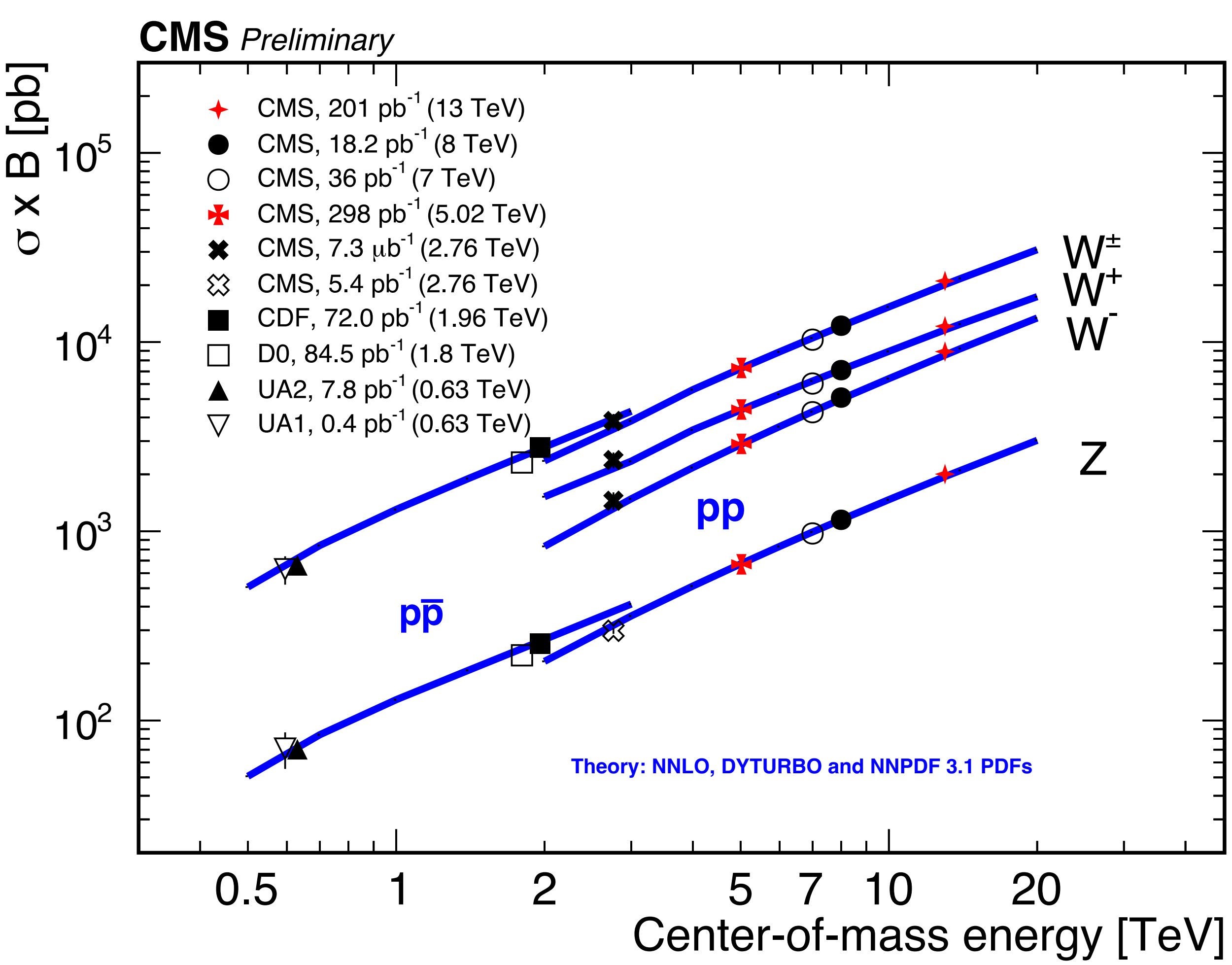
Special runs at low pileup

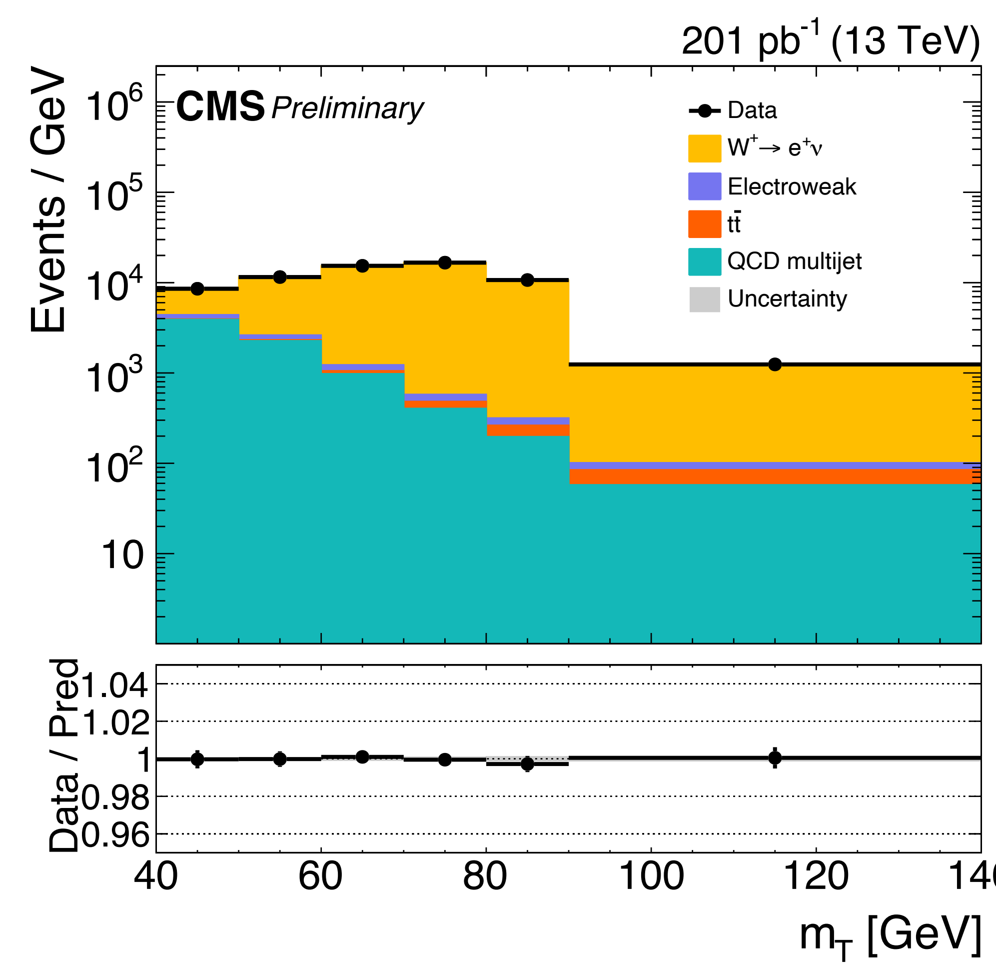
CMS-SMP-20-004
EPJC 84, 26 (2024)
ATL-DAPR-PUB-2021-001

Ideal for precise cross section measurements

- 200-350 pb^{-1} at 13 TeV + ~300 pb^{-1} at 5 TeV (heavy ion reference runs) collected in 2017
- lower lepton p_T trigger thresholds, better p_T^{miss} resolution (important for W recoil and m_T^W), more accurate control of QCD background
- Low PU runs also used as reference for luminosity monitoring using Z boson counting







new

Measurements at low pileup

CMS-SMP-20-004
arXiv:2404.06204

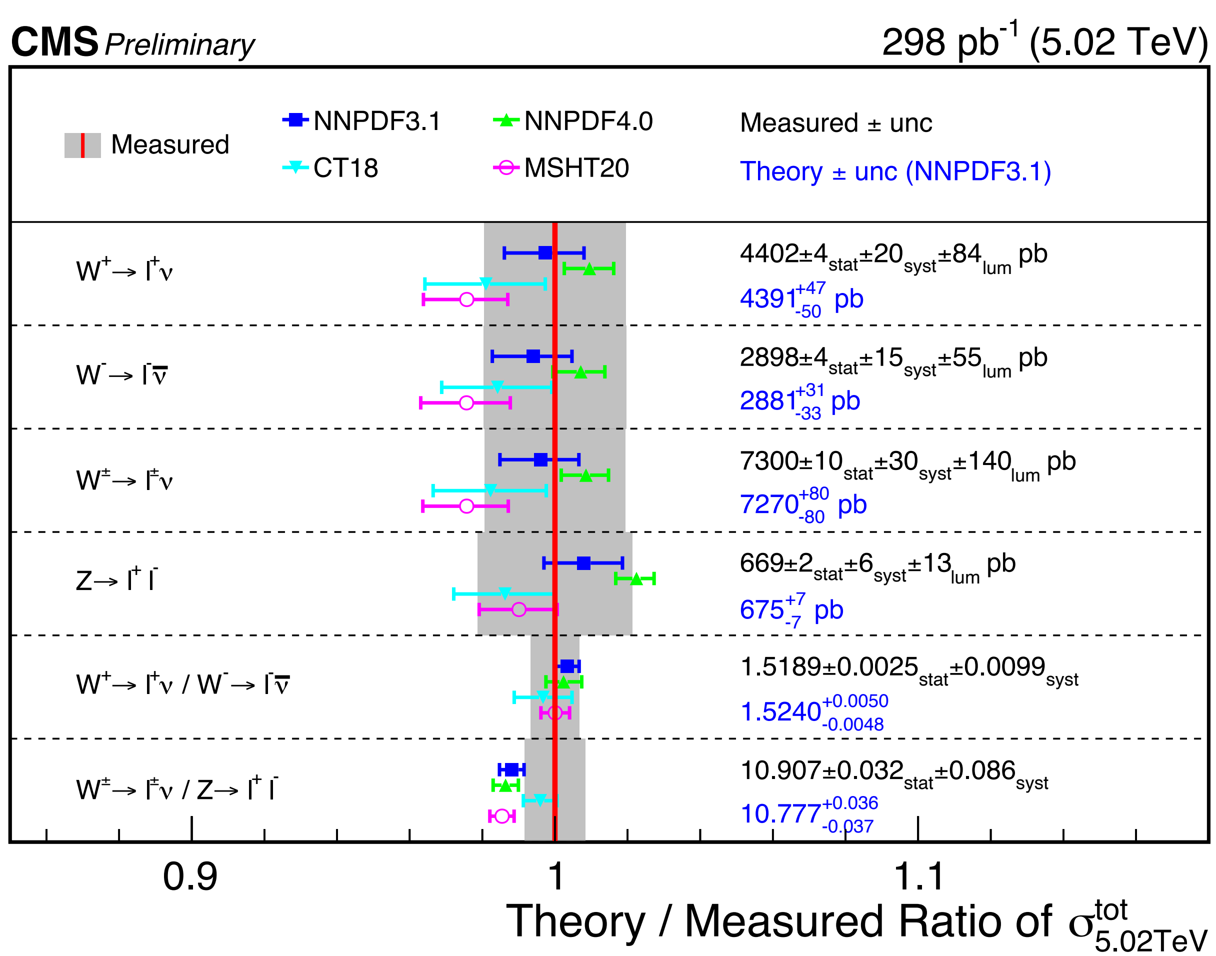
- Measured W cross sections validate theoretical calculations
- Ratios (by charge, with Z, or different √s) benefit from cancellation of correlated systematic uncertainties (e.g. luminosity), more stringent tests of theory predictions

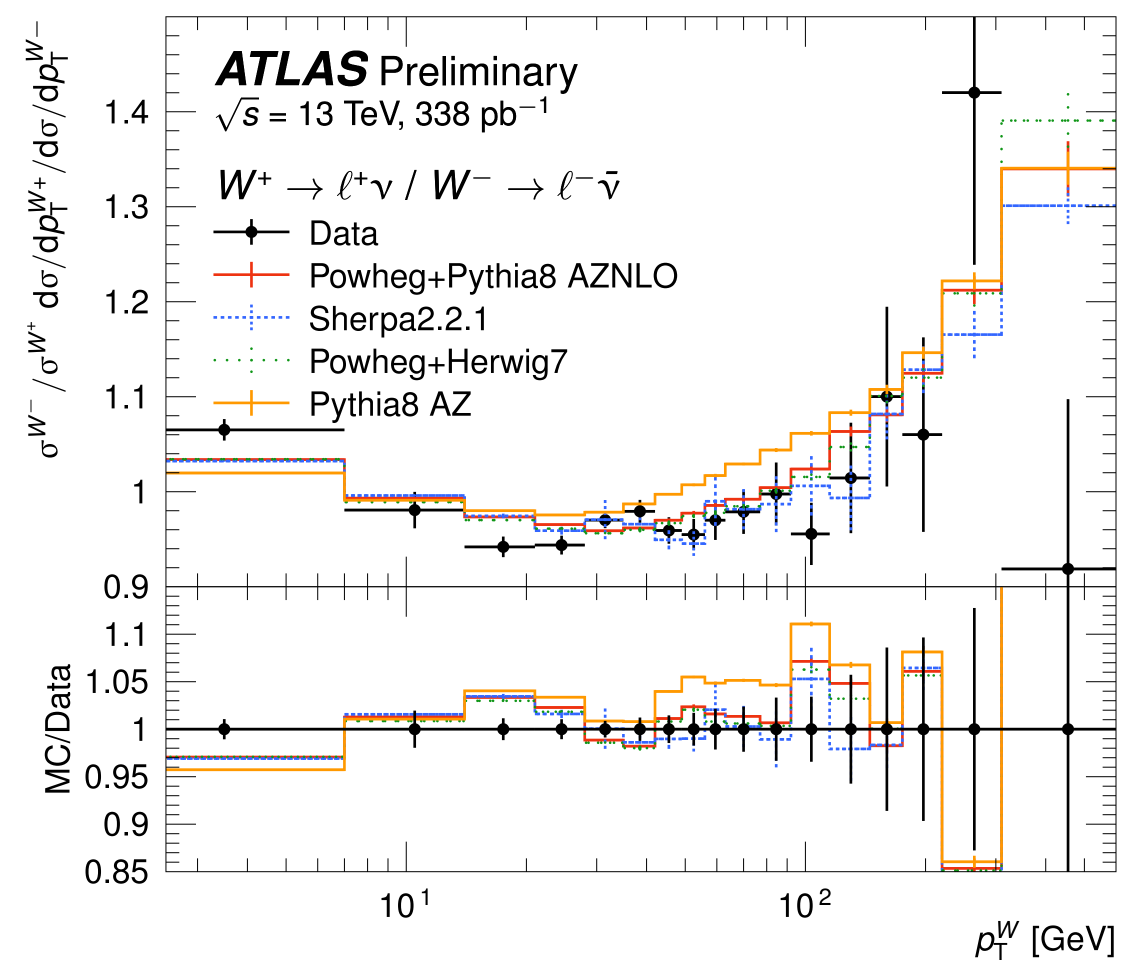
ATLAS

Processes	Cross-section ratio at 5.02 TeV	Cross-section ratio at $\sqrt{s} = 13$ TeV
W^+/W^-	1.611 ± 0.003 (stat.) $\pm\ 0.004$ (sys.)	1.312 ± 0.001 (stat.) $\pm\ 0.003$ (sys.)
W^-/Z	4.16 ± 0.01 (stat.) $\pm\ 0.05$ (sys.)	4.46 ± 0.01 (stat.) $\pm\ 0.07$ (sys.)
W^+/Z	6.69 ± 0.02 (stat.) $\pm\ 0.08$ (sys.)	5.84 ± 0.01 (stat.) $\pm\ 0.09$ (sys.)
$W^\pm/Z$	10.85 ± 0.04 (stat.) $\pm\ 0.11$ (sys.)	10.31 ± 0.02 (stat.) $\pm\ 0.15$ (sys.)

ATLAS

Process	Ratio $\sigma_{\text{fid}}(13\text{ TeV})/\sigma_{\text{fid}}(5.02\text{ TeV})$
$W^- \to \ell\nu$	2.517 ± 0.006 (stat.) $\pm\ 0.010$ (sys.) $\pm\ 0.036$ (lumi.)
$W^+ \to \ell\nu$	2.047 ± 0.004 (stat.) $\pm\ 0.009$ (sys.) $\pm\ 0.029$ (lumi.)
$Z \to \ell\ell$	2.340 ± 0.010 (stat.) $\pm\ 0.012$ (sys.) $\pm\ 0.032$ (lumi.)

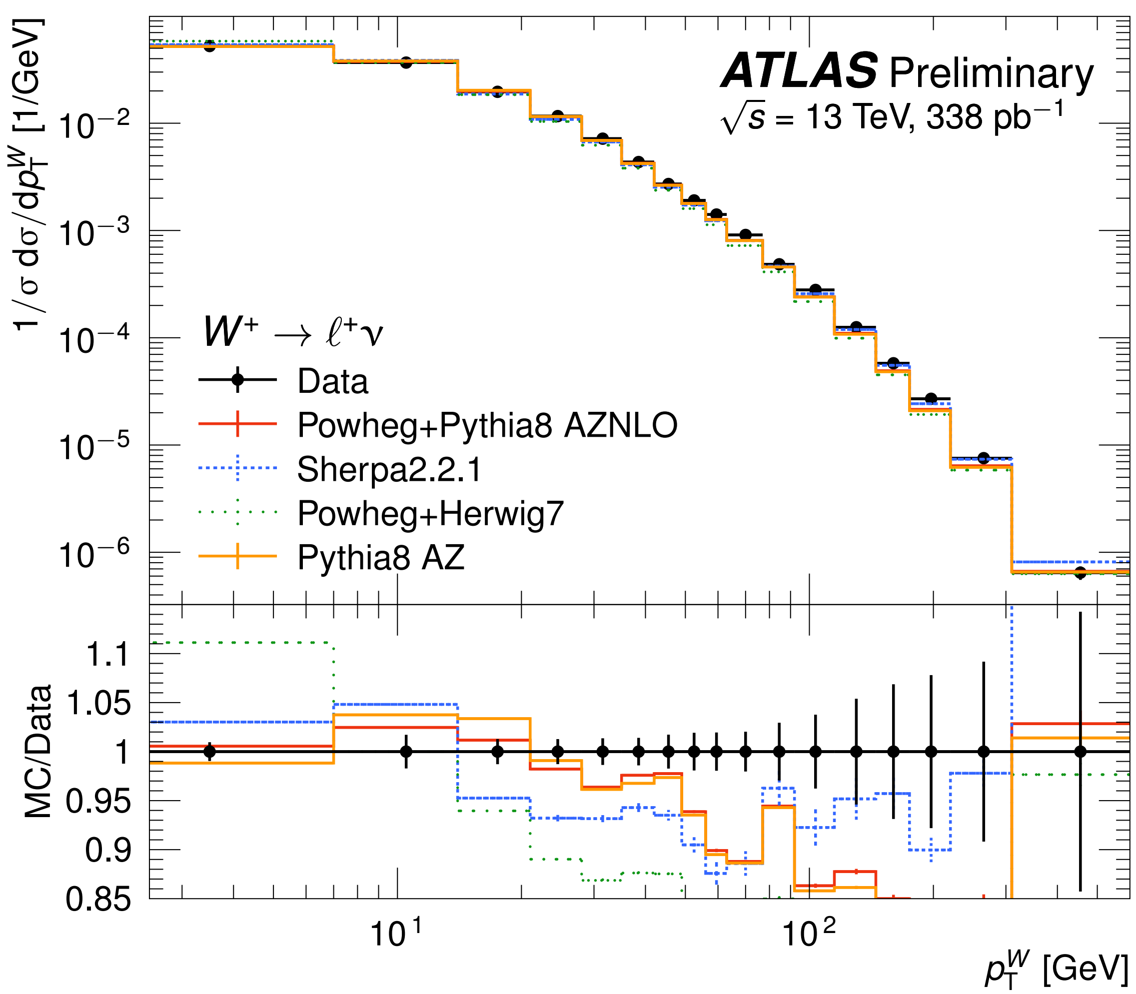


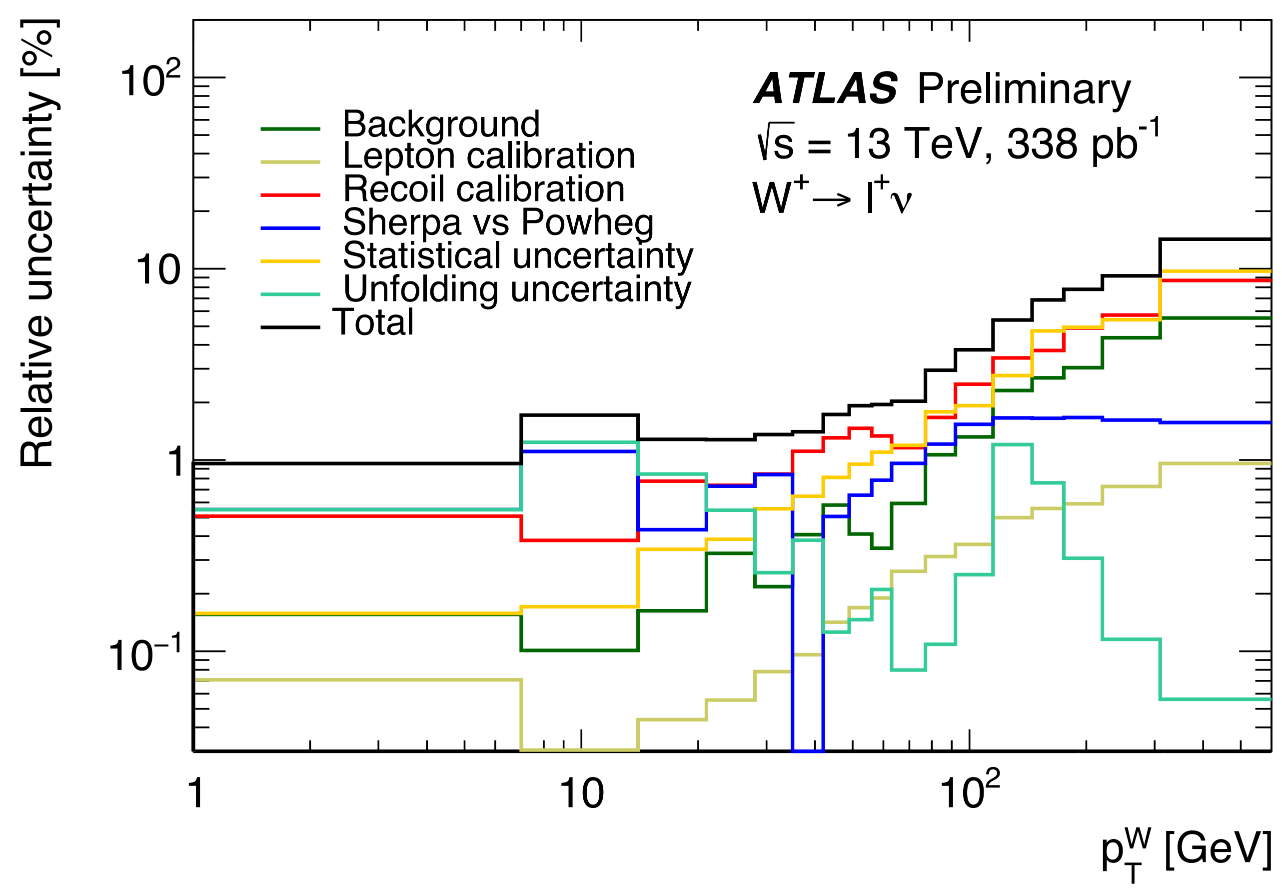


new

Measurements at low pileup

- Differential cross sections (e.g. p_T^W) vital inputs for other EW precision measurements
- Region with $p_T^W \lesssim 10$ GeV the most relevant for m_W, but also the hardest to predict (divergences and non perturbative effects) and measure (≈ 5 GeV recoil resolution)
- Uncertainty dominated by luminosity for absolute cross sections, and limited data stat, recoil calibration, and MC modelling for normalized ones

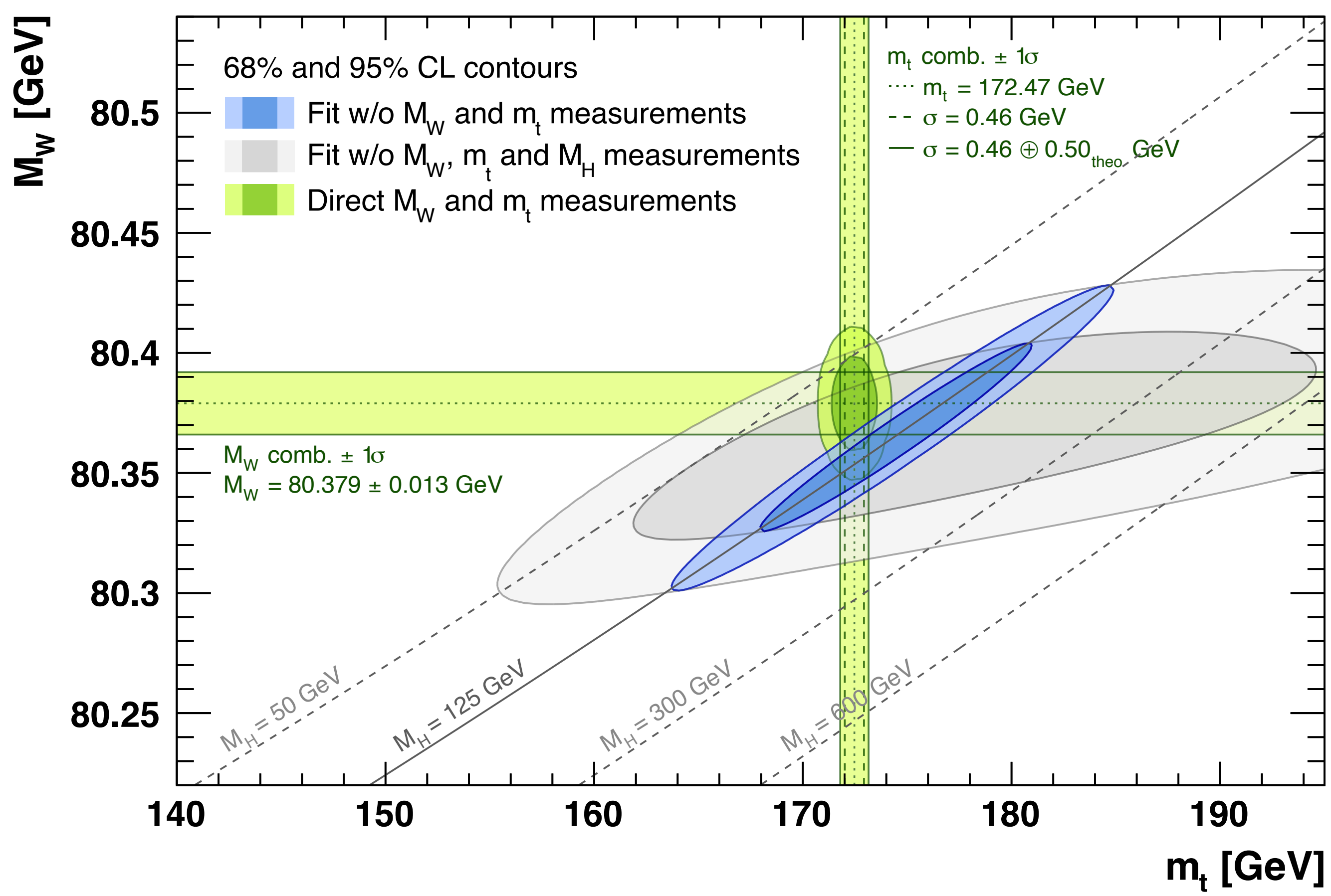




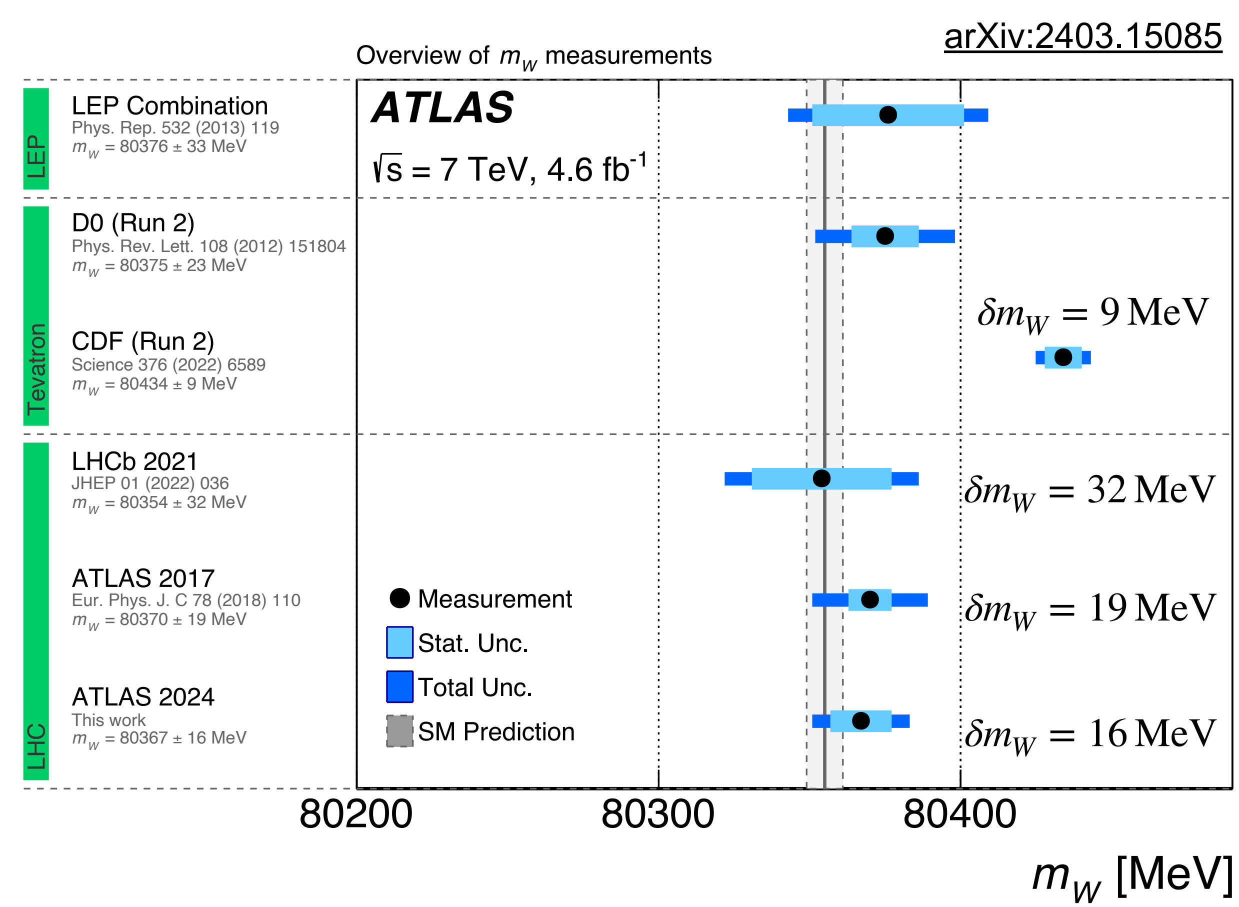
Tackling high precision: the m_W saga

Higgs boson discovery and mass measurement allowed for precise predictions of m_W, $\sin^2\theta_W$, and m_t from global EW fit of standard model (SM) parameters

- $\delta m_W \approx 6$ MeV from the global fit ($< 10^{-4}$ precision)
- For the experimental average $\delta m_W \sim 13$ MeV (before CDF Run 2 and ATLAS 2024)
- Pushing experimental precision on m_W below 10 MeV crucial to test internal consistency of SM and possibly probe new physics
  - CDF Run 2 result in significant tension with SM and all other measurements



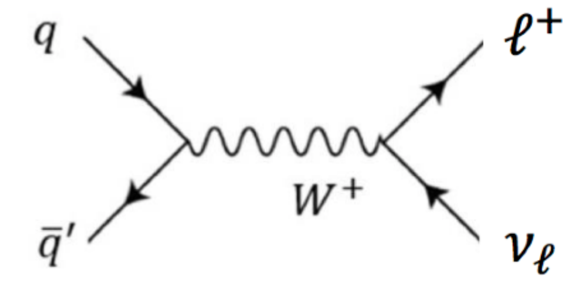
Eur. Phys. J. C78, 675 (2018)



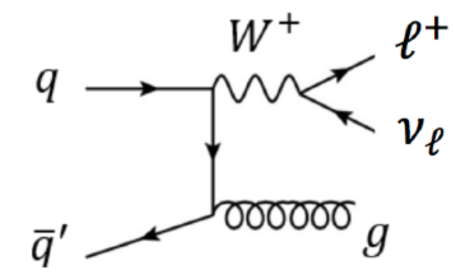
Measuring m_W at hadron colliders

Standard technique: fit p_T^ℓ or $m_T^{\ell\nu}$ distributions in data with simulated templates (possibly in bins of η^ℓ)

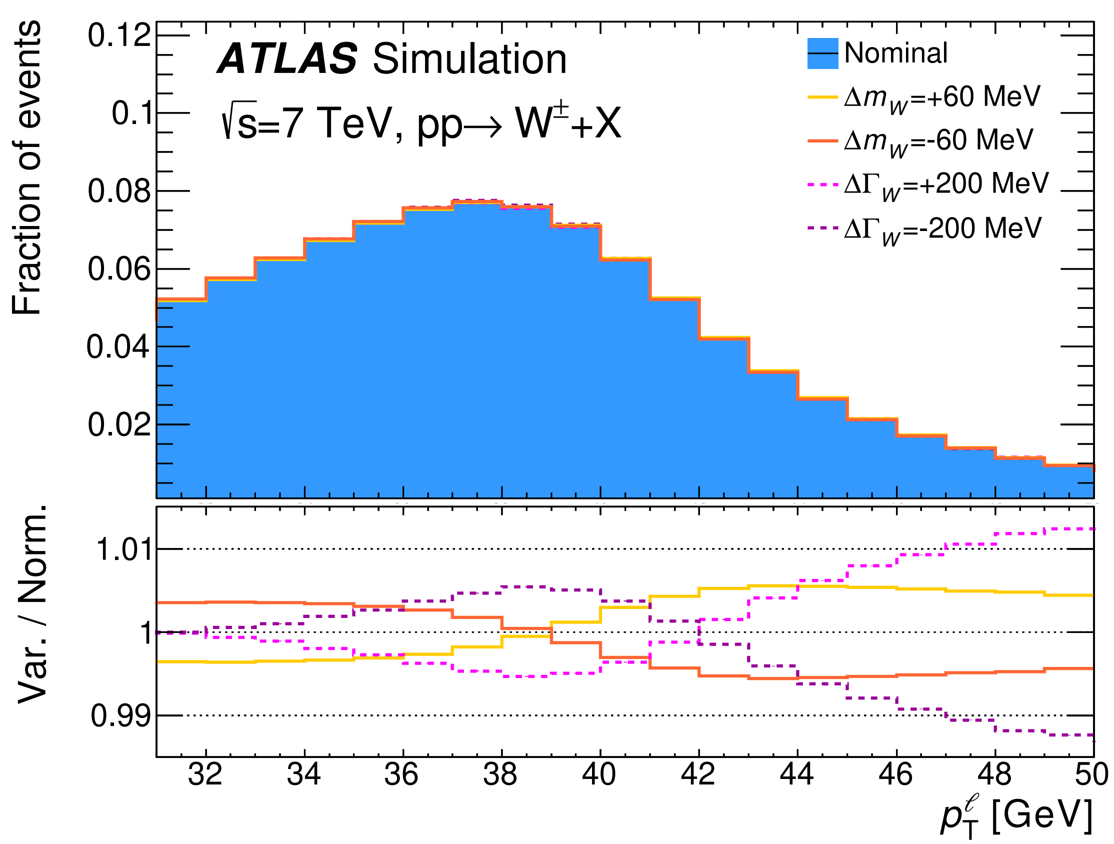
- Both observables require outstanding control of experimental and theoretical systematic uncertainties
- p_T^ℓ experimentally more precise for m_W, but more sensitive to theoretical uncertainties related to W polarization (PDFs) and p_T^W (QCD higher orders but also non perturbative effects)
- $m_T^{\ell\nu}$ better to measure width Γ_W

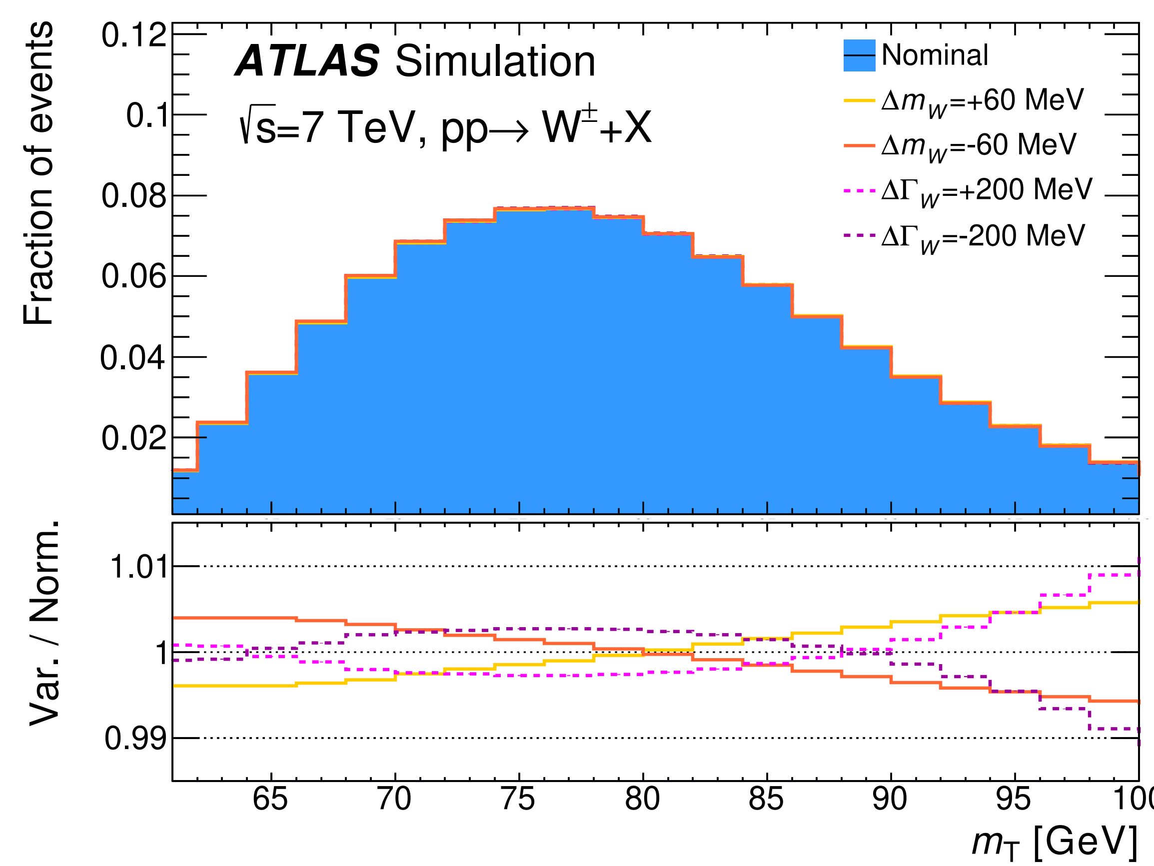


LO diagram: $p_T^W = 0$



NLO diagram: $p_T^W \neq 0$, additional hadronic activity





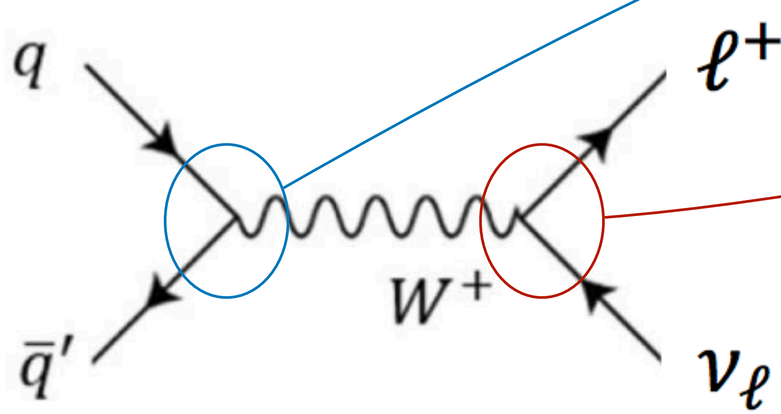
Theoretical digression: W bosons at hadron colliders

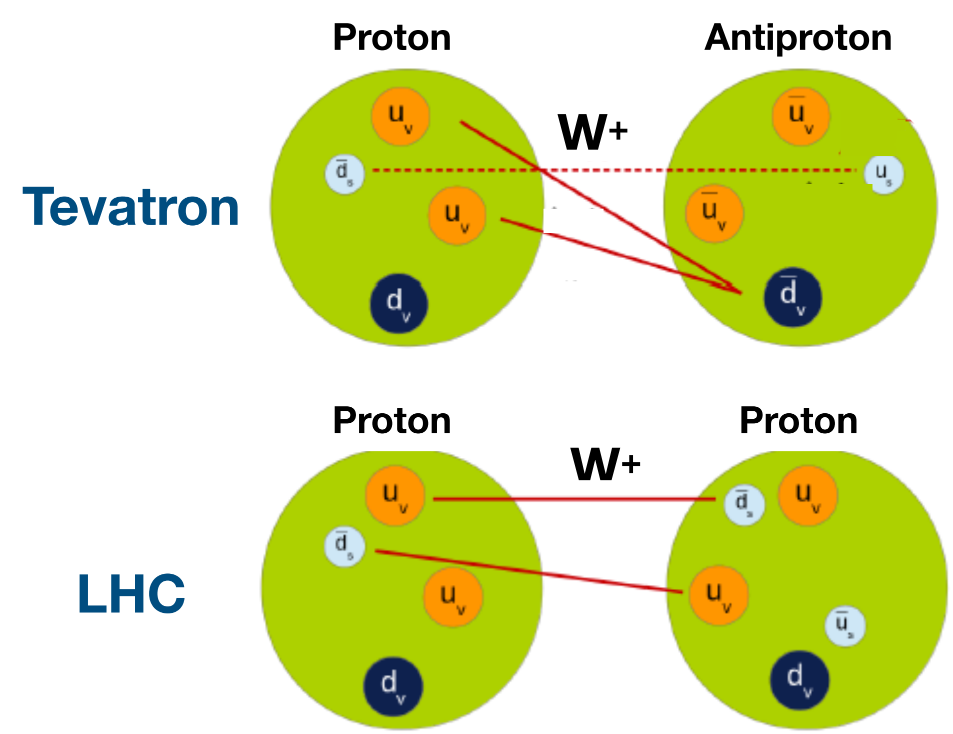
Production and leptonic decay described by 5D differential cross section

- Predicted by SM given m_W, up to uncertainties from PDFs and higher order corrections
- Decay encoded in 1+8 angular coefficients A_i dependent on p_T^W and rapidity Y_W

Decomposition for $d^5\sigma$ valid at any order in QCD

$$\frac{d^5\sigma}{dp_T^2\, dY\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma}{dp_T^2\, dY\, dm} \times \Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$





Leading order production from $q\bar{q}'$

- valence-valence at Tevatron, valence-sea at the LHC
- Stronger dependence on PDFs at the LHC
  - effect on W polarization and lepton kinematics
  - Non negligible effects from s and c quarks

W polarization and PDF uncertainty at the LHC

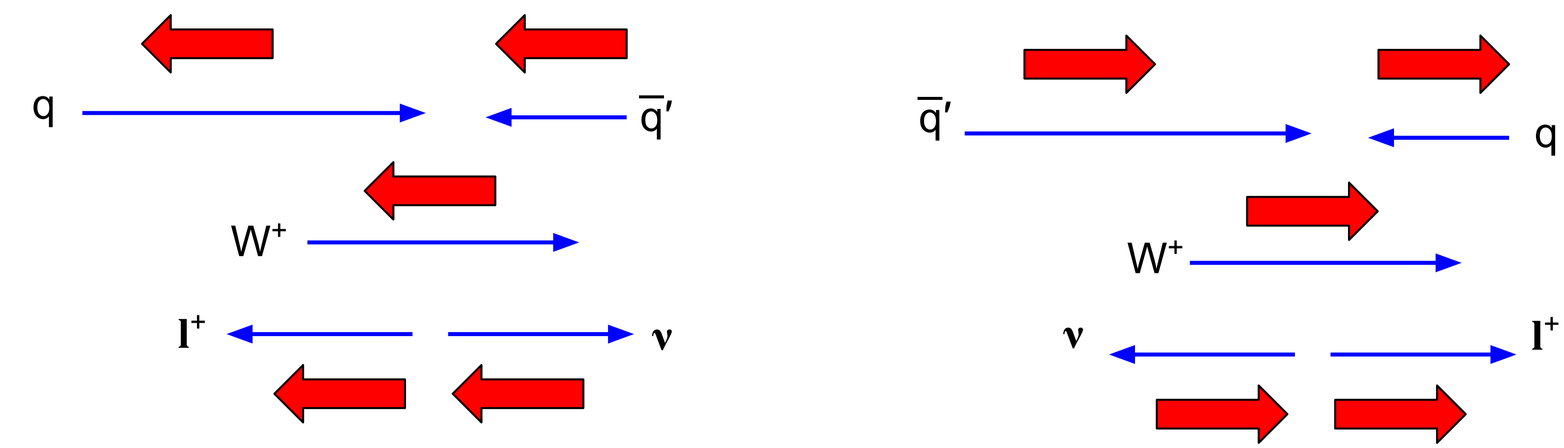
Pure left handed coupling of W bosons to fermions strongly correlates W polarization (h_W) and rapidity (Y_W) with direction of incoming quark vs antiquark

- And subsequently with direction of outgoing charged lepton

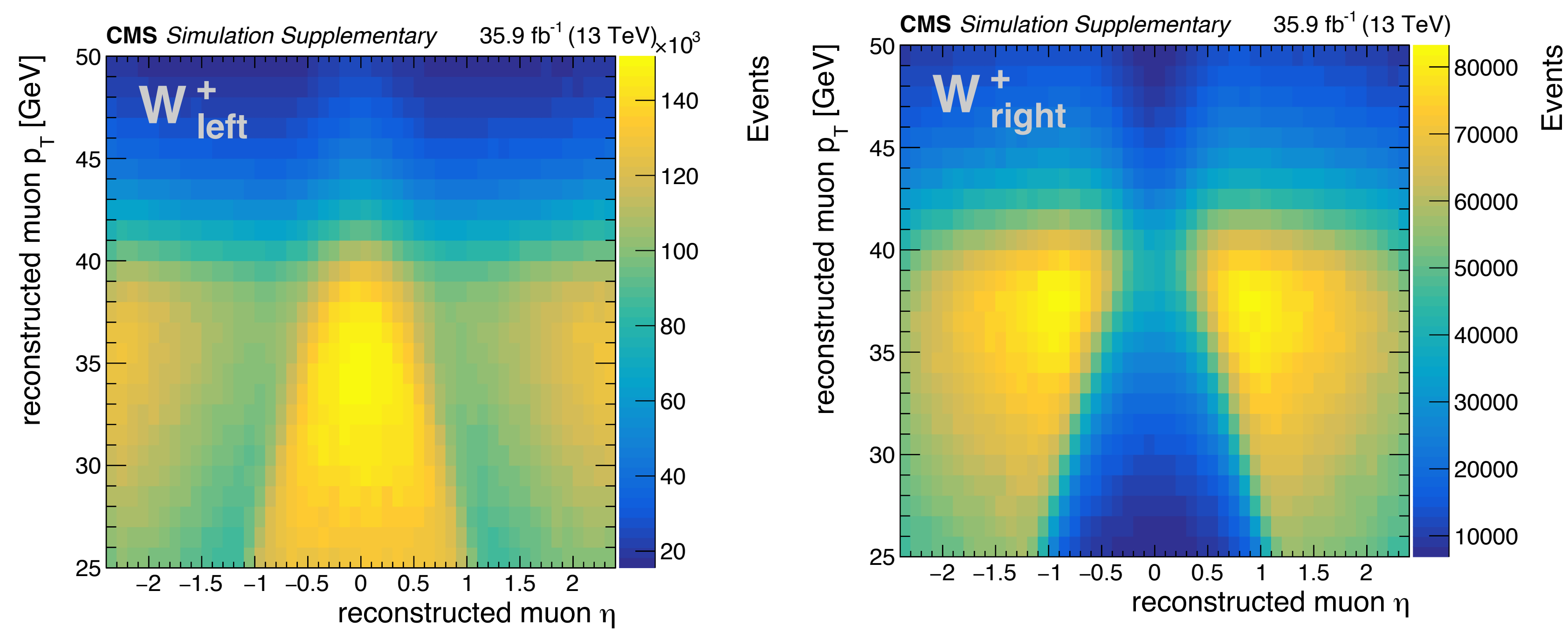
W boson helicity and rapidity fully determined by PDFs

h_W/Y_W affect lepton η-p_T through spin correlations

Left-handed W^+ / **Right-handed W^+**



Muon η-p_T distribution carries information on PDFs, can be exploited to measure the underlying W boson cross section with reduced theoretical uncertainty



Negative W bosons produce even more different shapes, simultaneous fit of both charges greatly reduces uncertainties (anticorrelated PDF uncertainties)

JHEP12(2017)130
PRD 102 (2020) 092012
CMS-SMP-18-012

new

ATLAS m_W and Γ_W

arXiv:2403.15085

Re-analysis of original 7 TeV result (published one year ago, recently updated again)

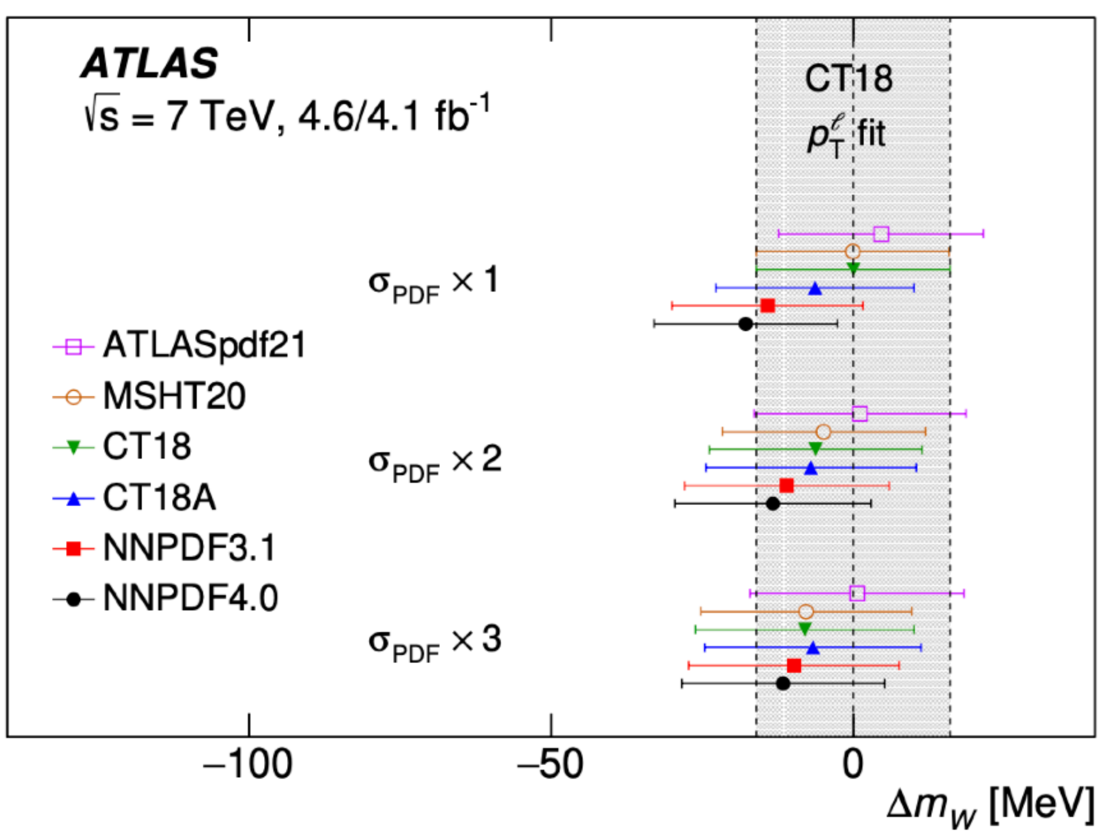
- Improved fit with likelihood minimization and uncertainty profiling rather than χ^2
- extended studies of PDFs, impact of profiling demonstrated by inflating pre-fit uncertainties
- m_W and Γ_W measured simultaneously or fixing one to SM

Updated m_W = 80366.5 ± 15.9 MeV (Γ_W fixed to SM)

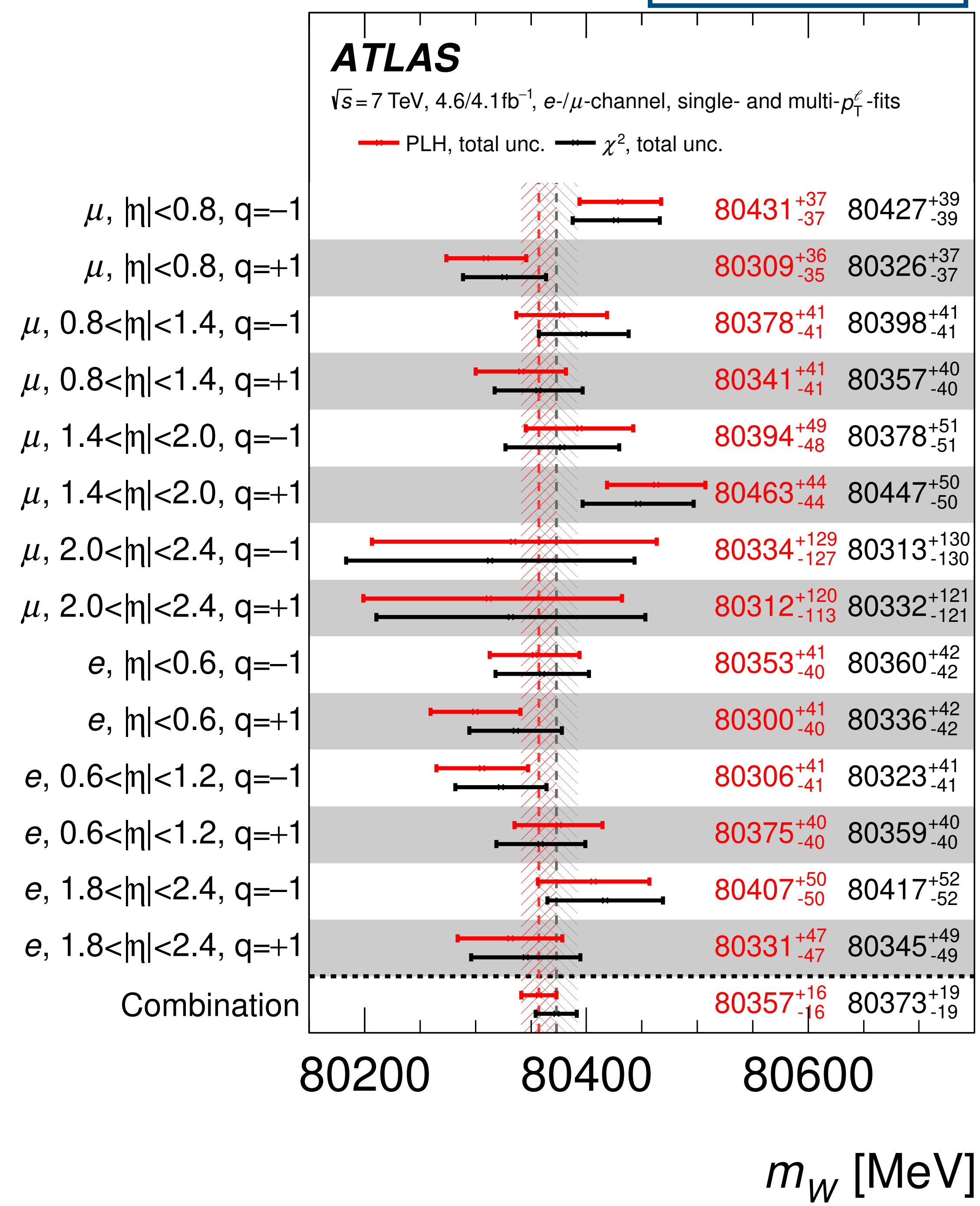
- It was δm_W ~ 19 MeV in 2017, with 9.2 MeV from PDFs

Using CT18 PDFs

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3



Using CT10nnlo PDFs



new

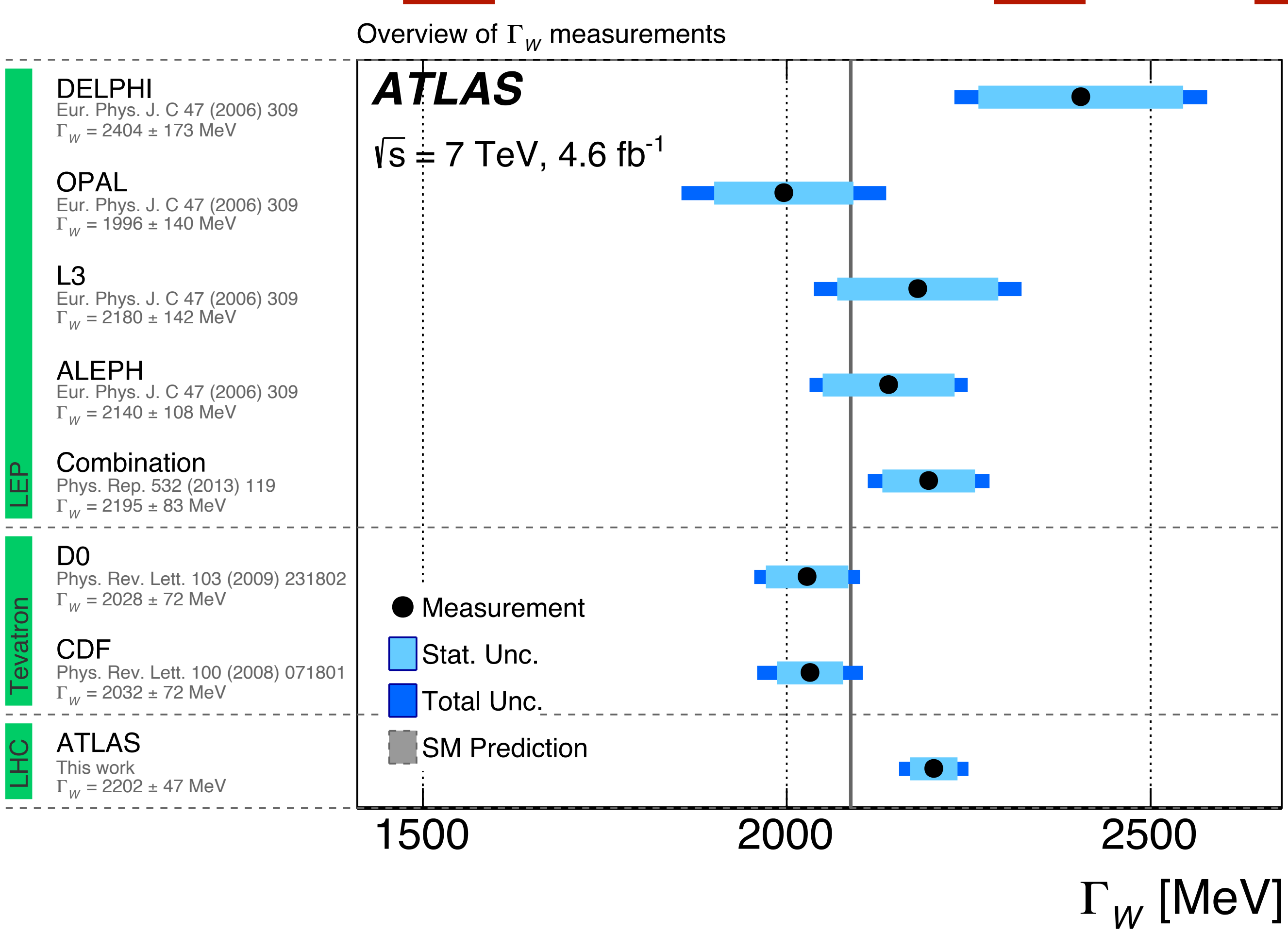
ATLAS m_W and Γ_W

First measurement of Γ_W at the LHC, most precise from single experiment

- Fixing m_W to SM, Γ_W = 2202 ± 47 MeV, ~2σ above SM
- Main uncertainty from MC modelling (shower tune variations) and recoil
- Smaller m_W value from simultaneous fit because of anticorrelation with Γ_W

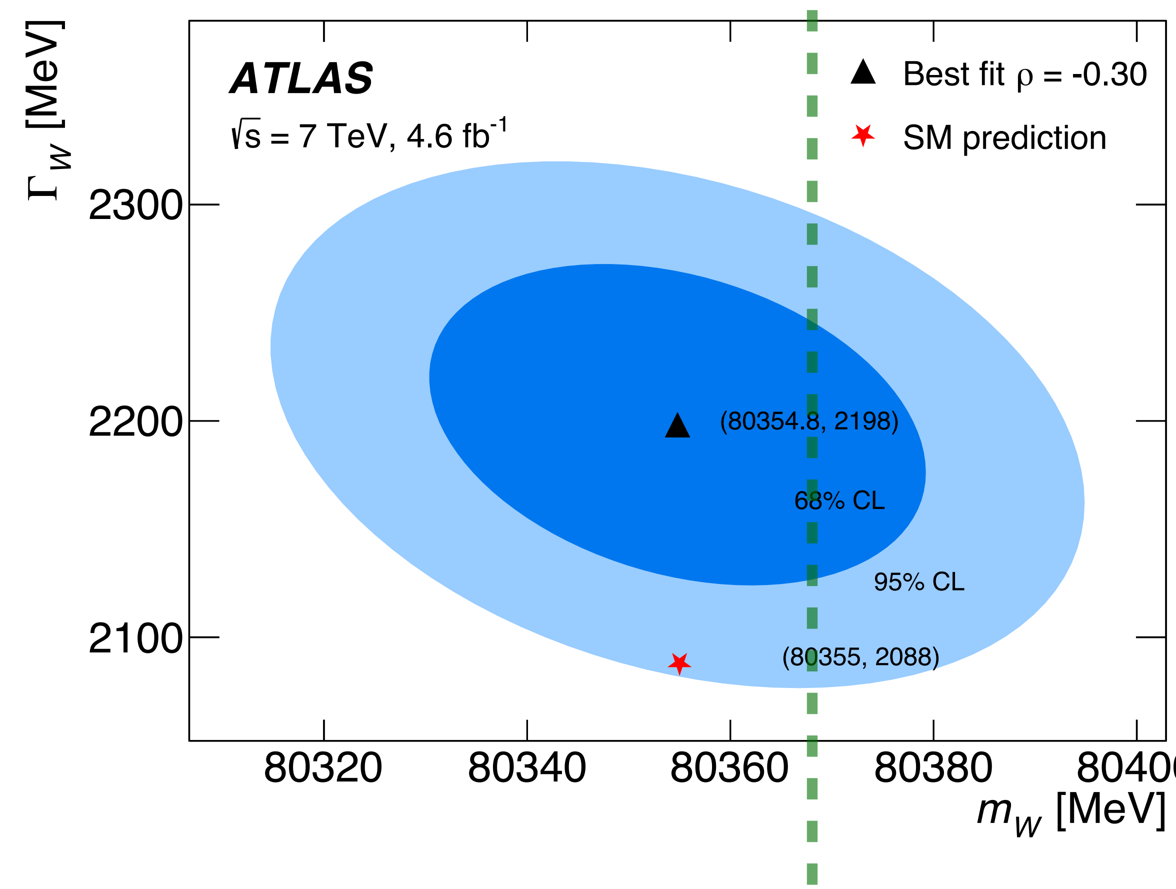
Using CT18 PDFs

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18



From simultaneous fit:

m_W = 80354.8 ± 16.1 MeV Γ_W =2198 ± 49 MeV



m_W with constrained Γ_W

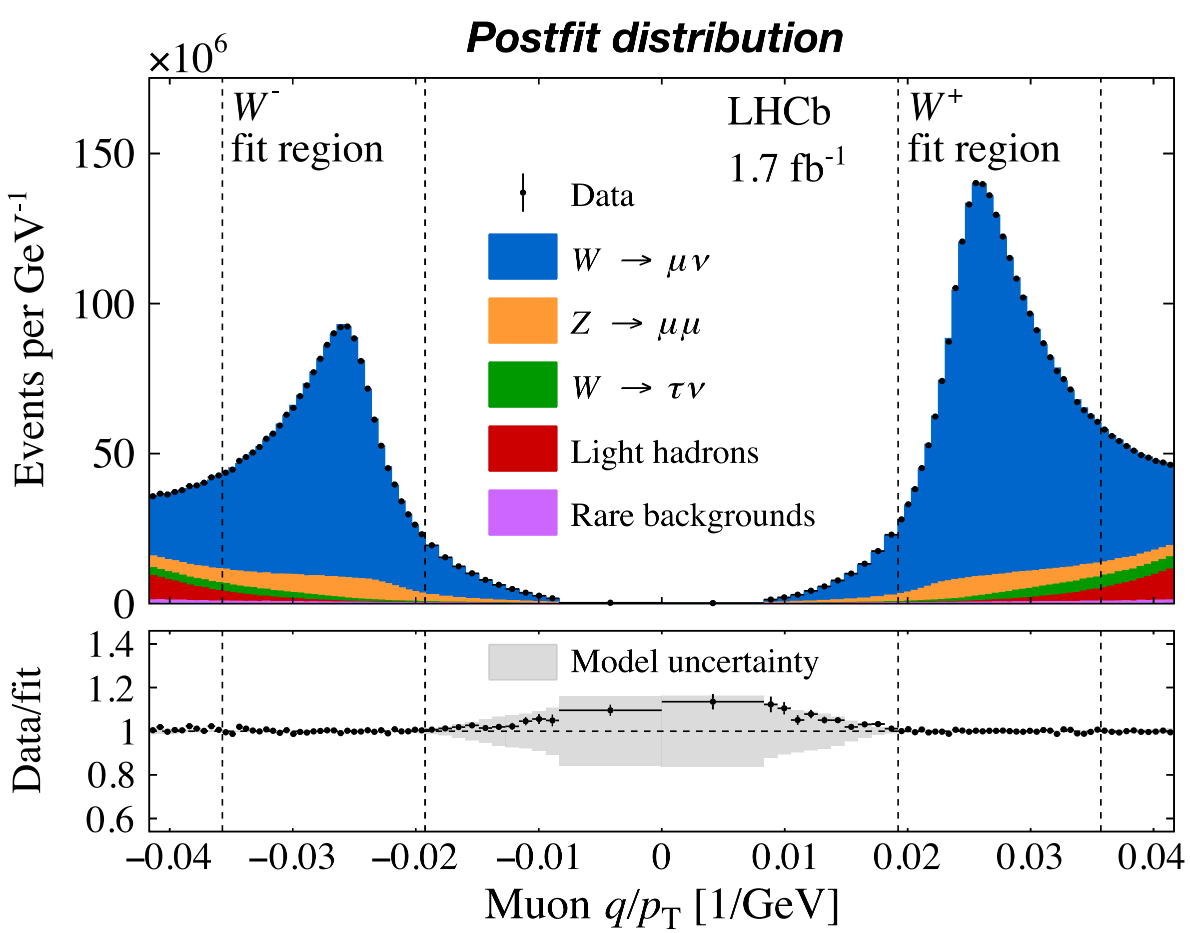
JHEP 01 (2022) 036

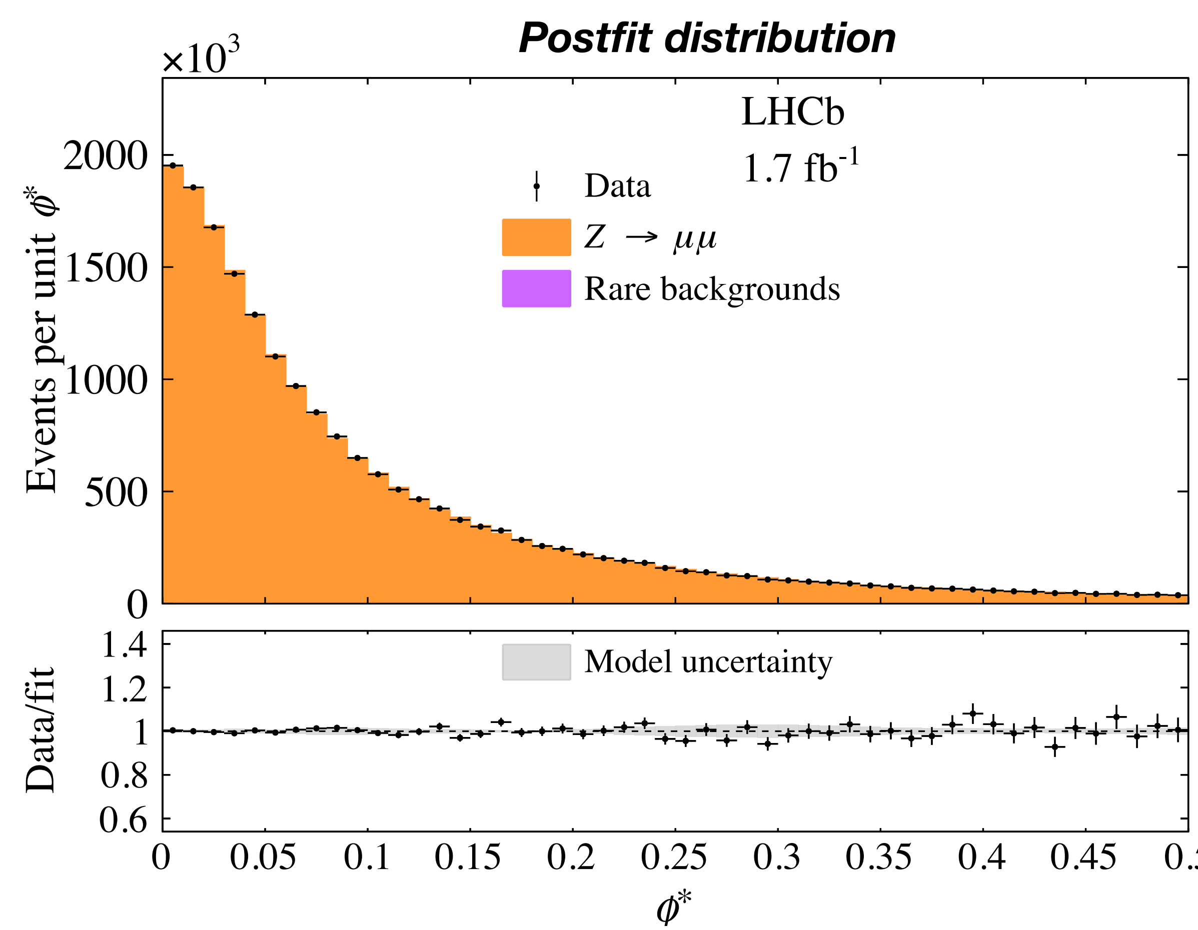
W boson mass at high η

LHCb measured m_W using muon kinematics in 2021

- $W \to \mu\nu$ events from 1.7 fb^{-1}, only 1/3 of full Run 2 data set
- simultaneous fit of muon charge/p_T and Z boson ϕ^* (correlated with p_T^Z but only dependent on angular variables, less susceptible to modelling uncertainties)
  - partial constraints on p_T^W thanks to in-situ p_T^Z measurement
- $\Delta m_W = 23_{stat} \pm 10_{exp.syst} \pm 17_{theory} \pm 9_{PDF}$ MeV = 32 MeV

$\phi^* \approx p_T^Z/m_{\ell\ell}$





new

Developments for m_W with LHCb

EPJC 79 (2019) 497
JINST 19 (2024) P03010

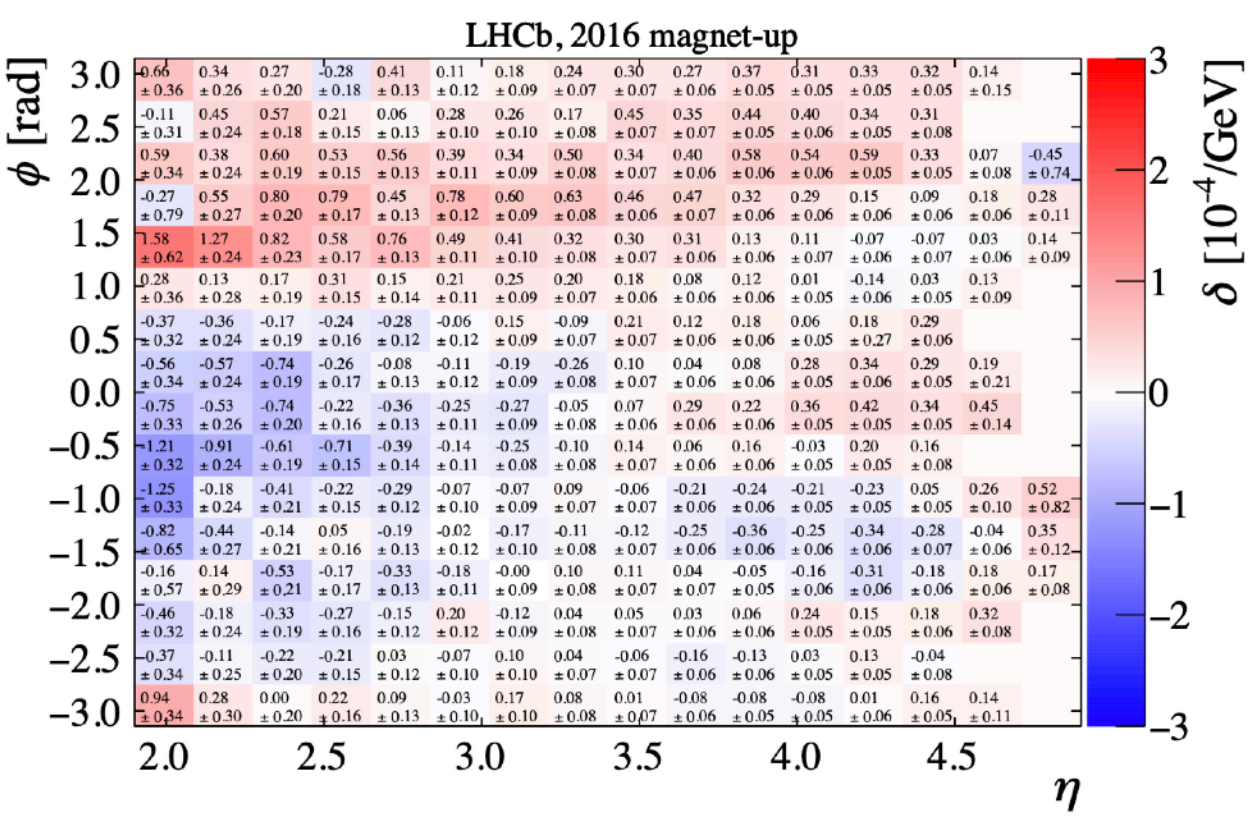
LHCb less precise than Tevatron/ATLAS (but no m_T or W→eν)

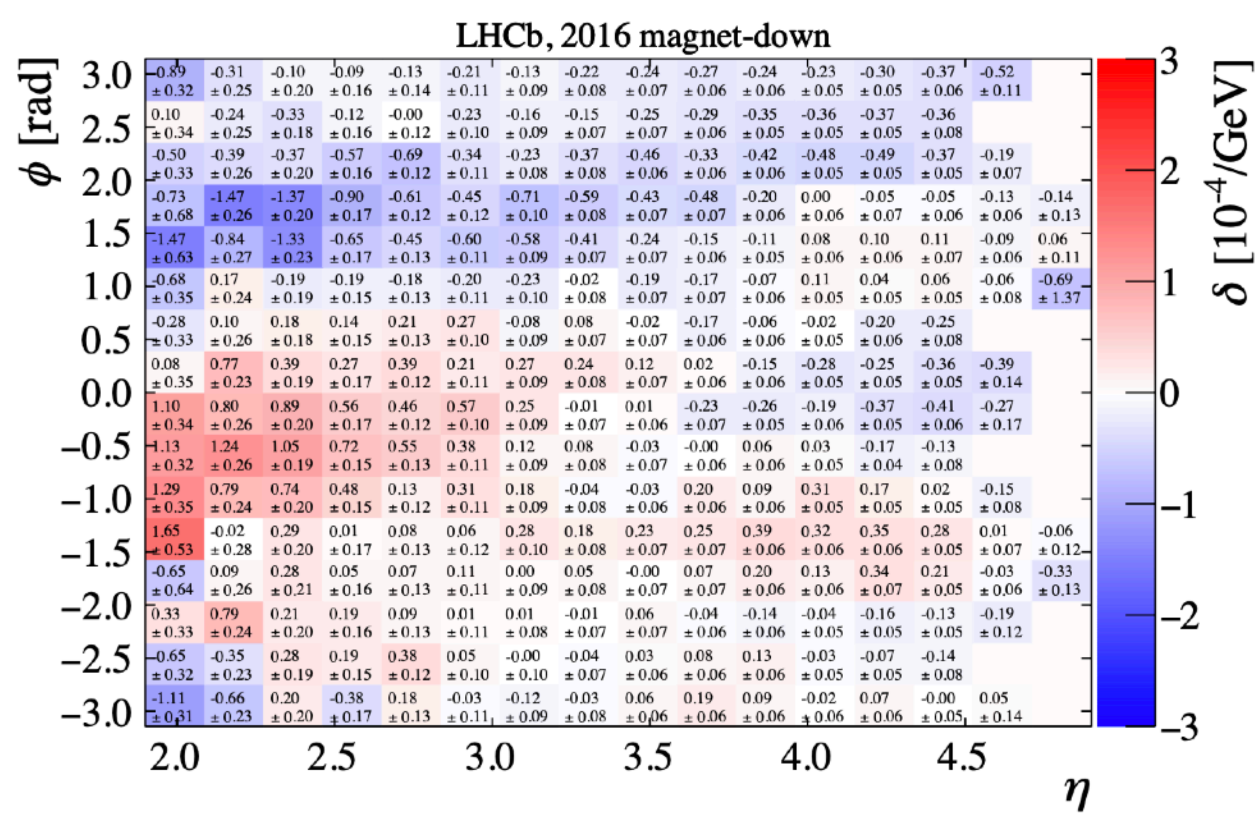
- However, explores complementary rapidity region compared to ATLAS and CMS, and can help constrain PDF uncertainties in future LHC combinations

New LHCb measurement in progress with full Run 2 data

$$\frac{q}{p} \rightarrow \frac{q}{p'} = \frac{q}{\alpha p} + \delta$$

- exploit 2D fit of muon q/p_T and η to reduce PDF uncertainties
- δm_W ~ 20 MeV should be possible
- Take advantage of improved understanding of muon p_T scale, see recent paper on curvature-bias corrections using the "pseudomass" method





Combining Tevatron-LHC m_W results

Active cross-collaboration effort focusing on m_W combination

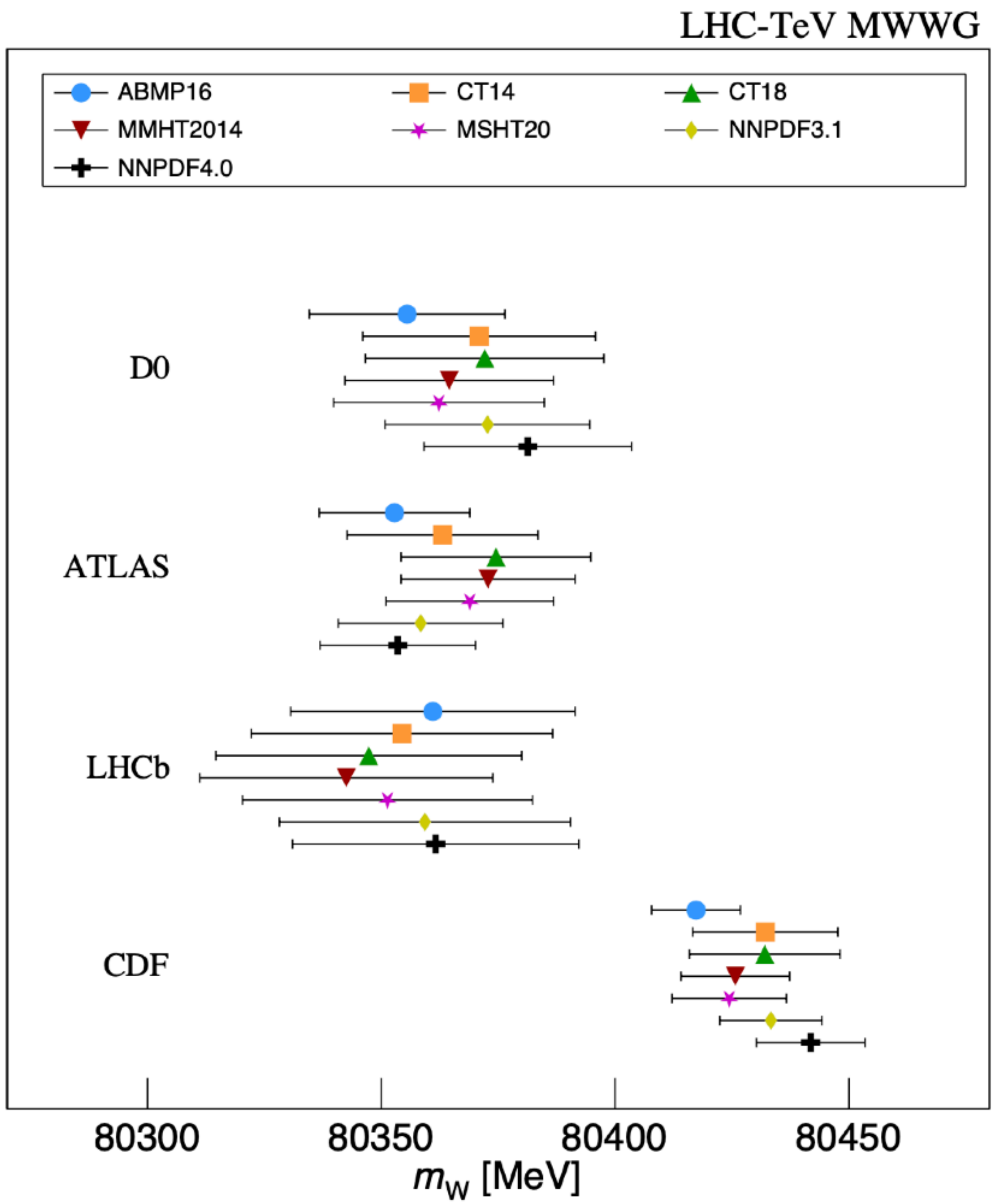
- ATLAS (2018), LHCb, D0, CDF (2022), CMS involved as spectator
- measurements performed at different times, using PDF sets available at the time
- Requires translation to common reference before combining

CDF incompatible with other results:

- Combination without CDF (CT18 PDFs)
  80369.2 ± 13.3 MeV (χ^2 prob. 91%)
- Combination with CDF (CT18 PDFs)
  80394.6 ± 11.5 MeV (χ^2 prob. 0.5%)
  (larger δm_W than CDF alone because of different PDF set in the combination)

Important practical lessons for future

- Consistent scheme for theoretical uncertainties (QCD in particular) is crucial
- profile-likelihood based fits can facilitate future combinations



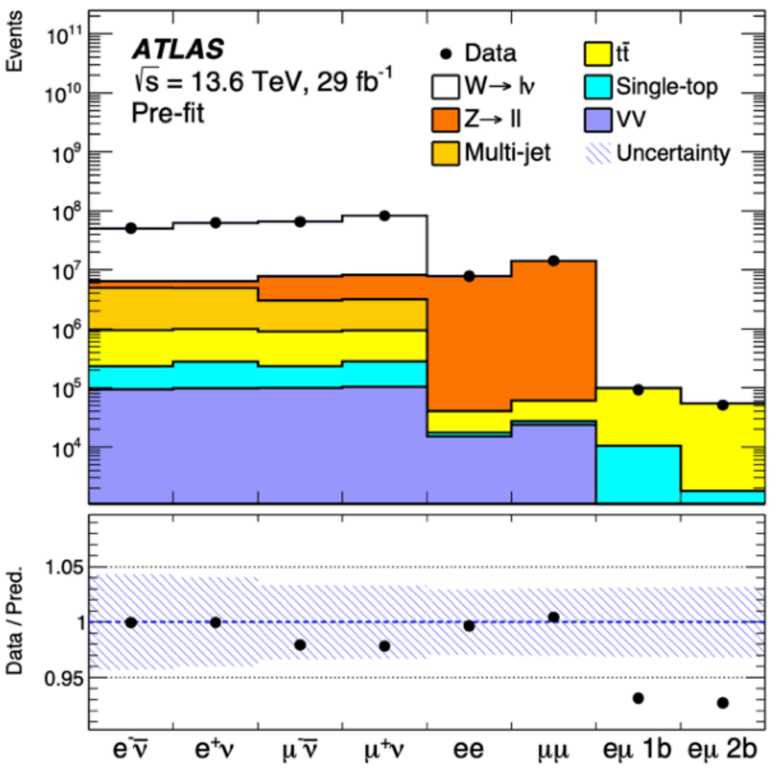
A glimpse at Run 3: W (and Z) cross section

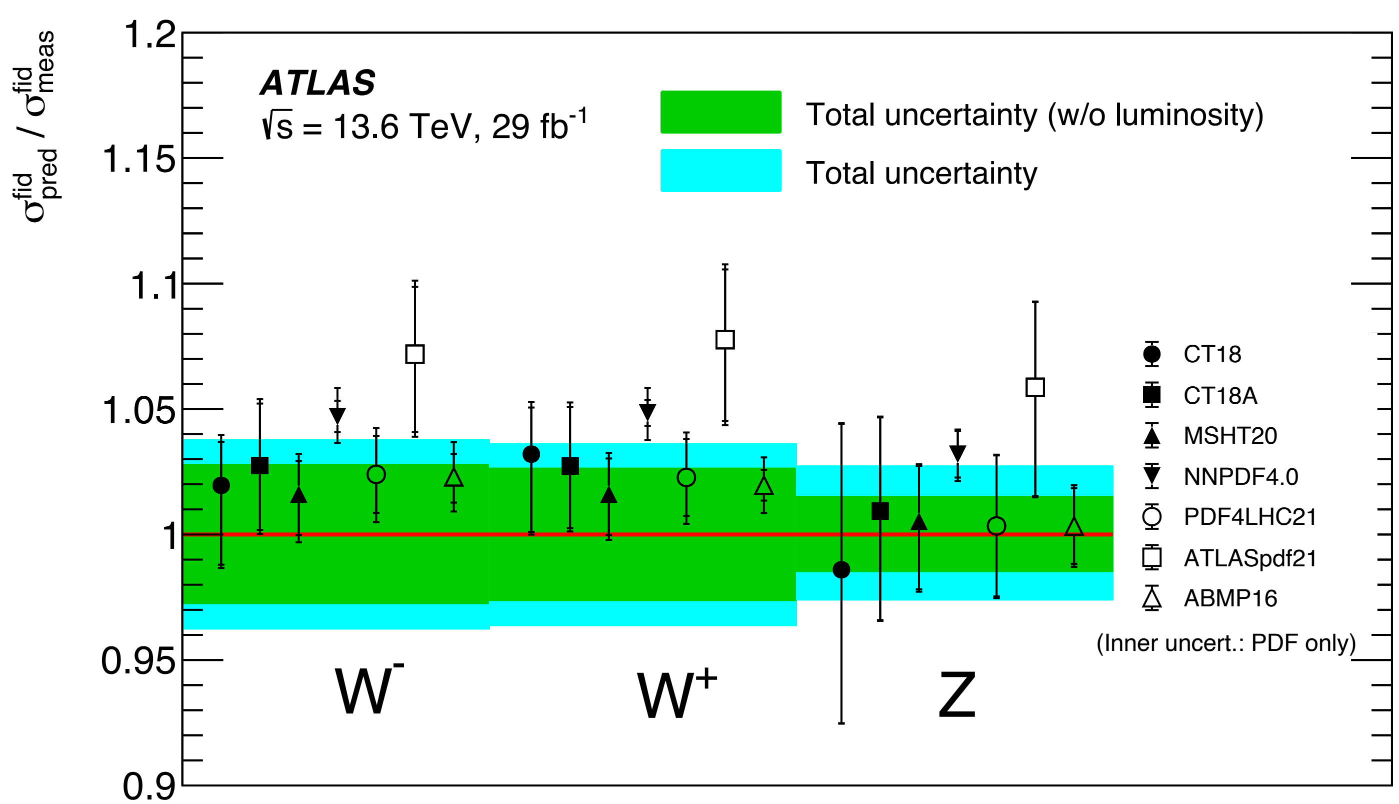
arxiv:403.12902

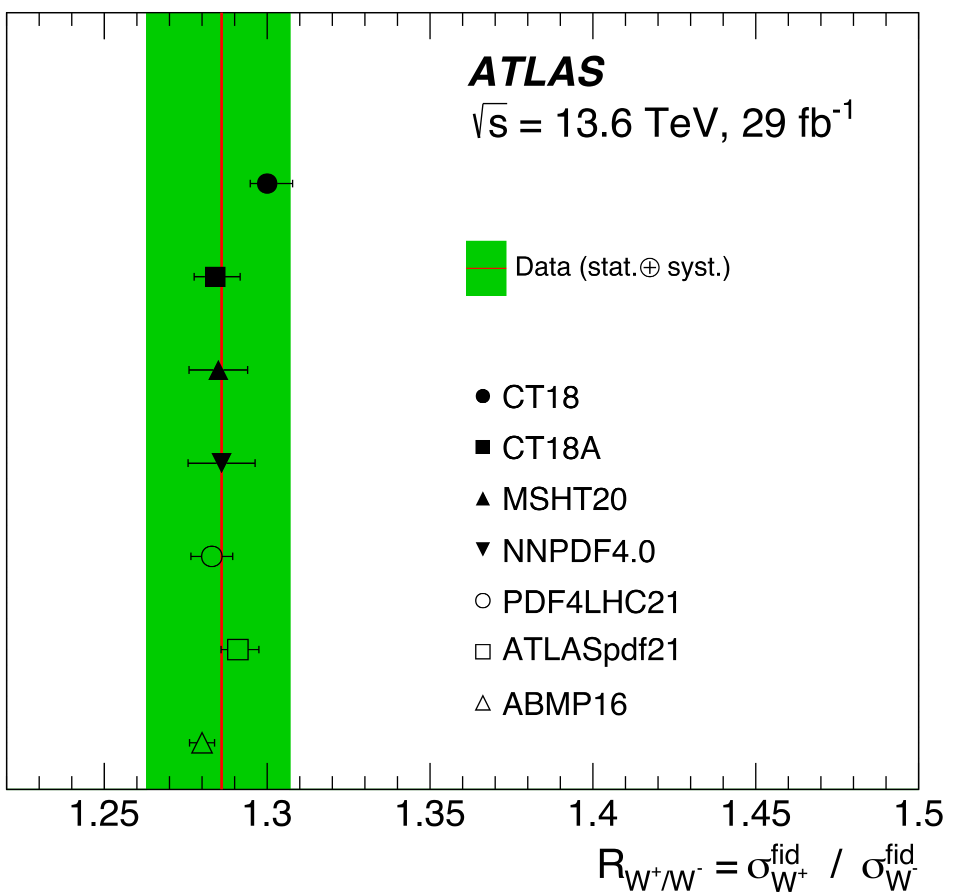
One of the first measurements at 13.6 TeV

- Test of perturbative calculations and input for PDFs
- ATLAS measured σ_W, σ_Z, and ratio from simultaneous fit to W/Z/$t\bar{t}$ using 2022 data
- CMS measured σ_Z, ongoing work for σ_W

Dedicated talks on EW results at 13.6 TeV on Thursday







Summary

Presented selection of recent results with single W bosons at the LHC

- valuable inputs to test theoretical calculations
- precise knowledge of production cross sections guarantees more accurate background predictions for Higgs boson physics and in new physics searches

Excellent performance of the LHC and experiments

- large Run 2 data set allow SM to be probed with unprecedented precision
- reducing systematic uncertainties mandatory
  - theoretical uncertainties to be constrained using data whenever possible

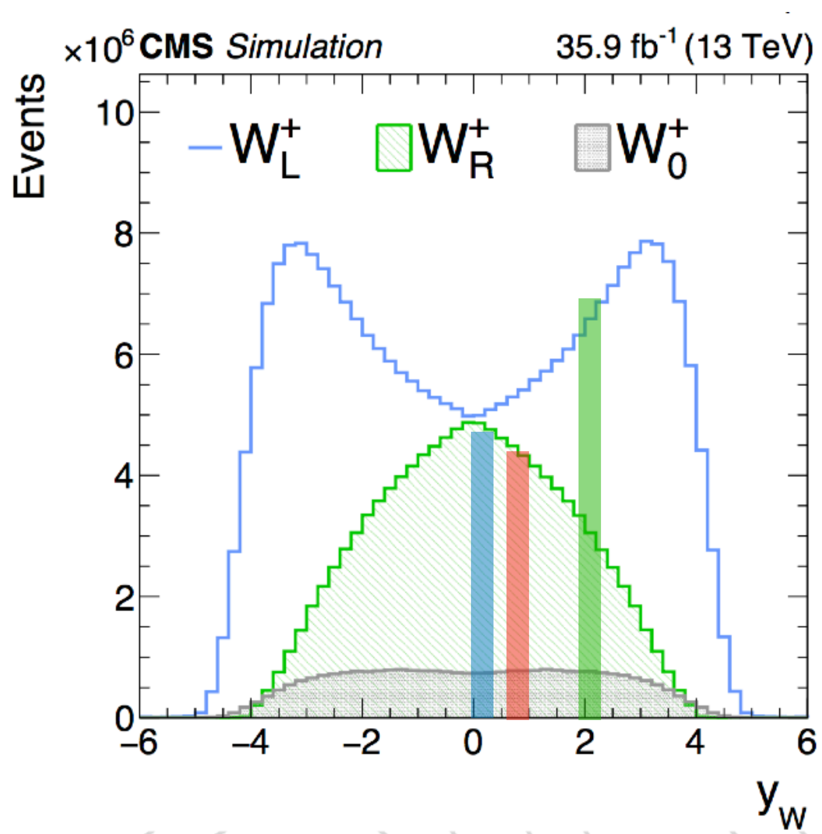
Run 2 still has a lot of potential, but looking forward to new Run 3 data

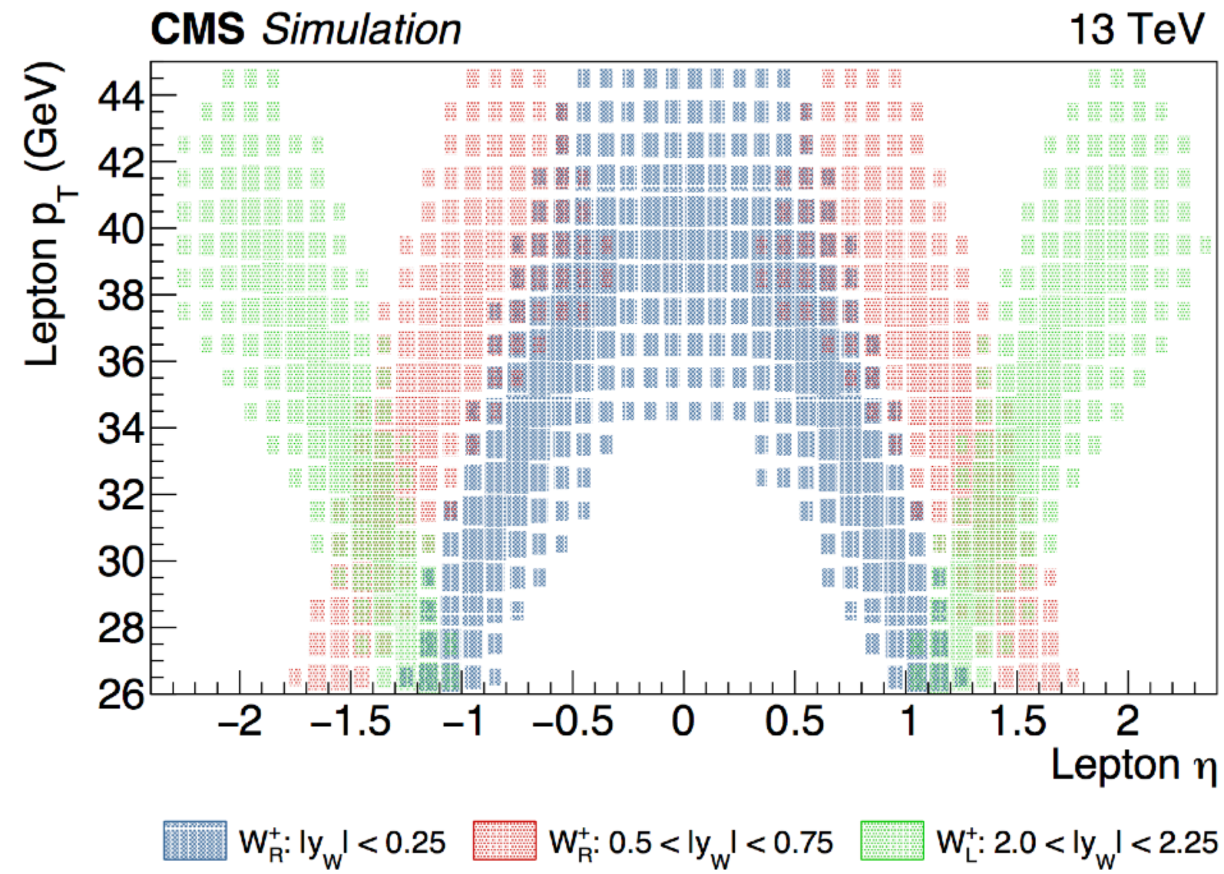
- new physics opportunities to further constrain SM
- collaboration with theorists paramount to chart the course of future measurements

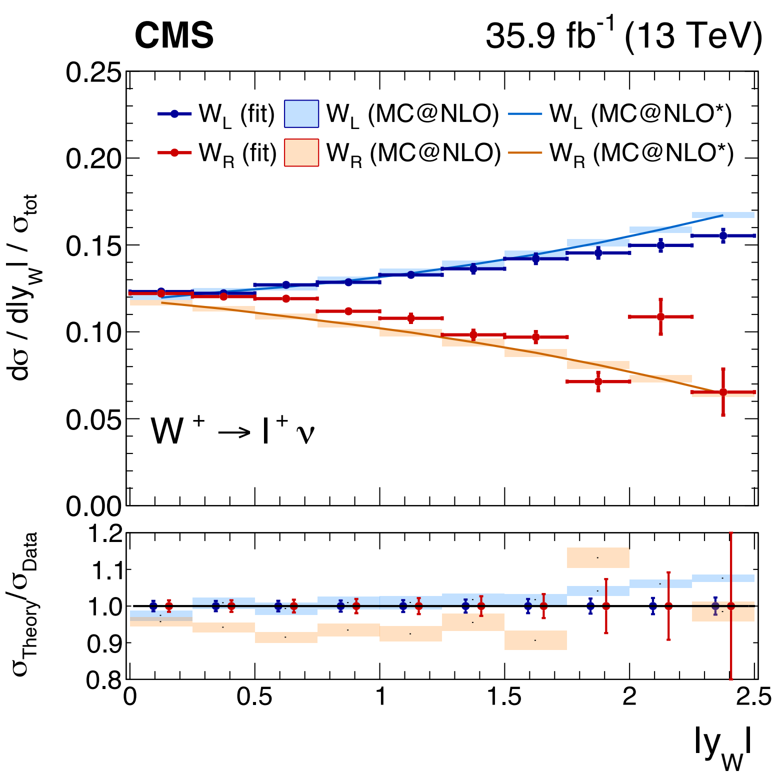
BACKUP

Measuring W polarization and rapidity

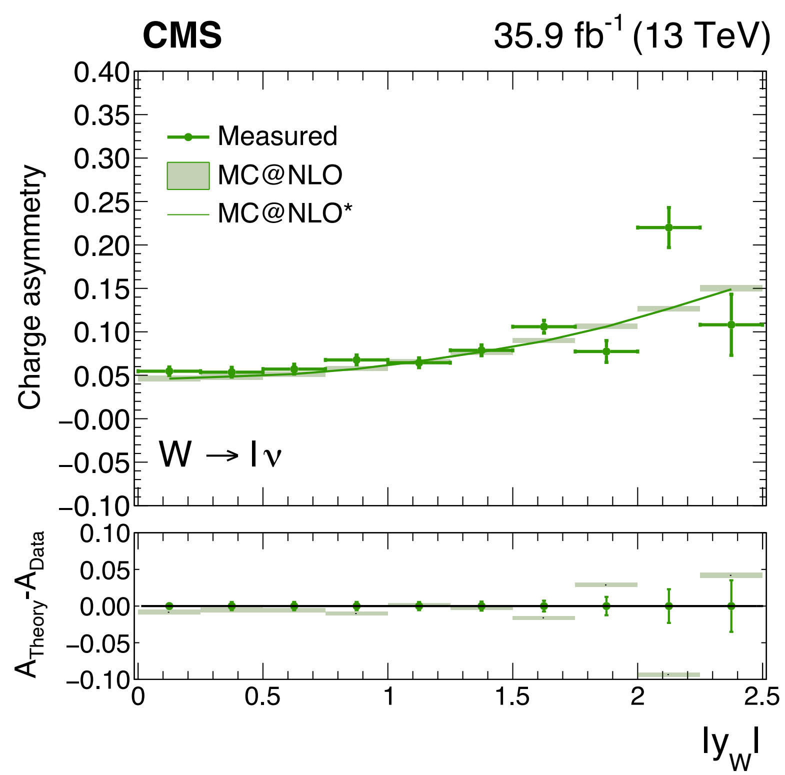
PRD 102 (2020) 092012
CMS-SMP-18-012



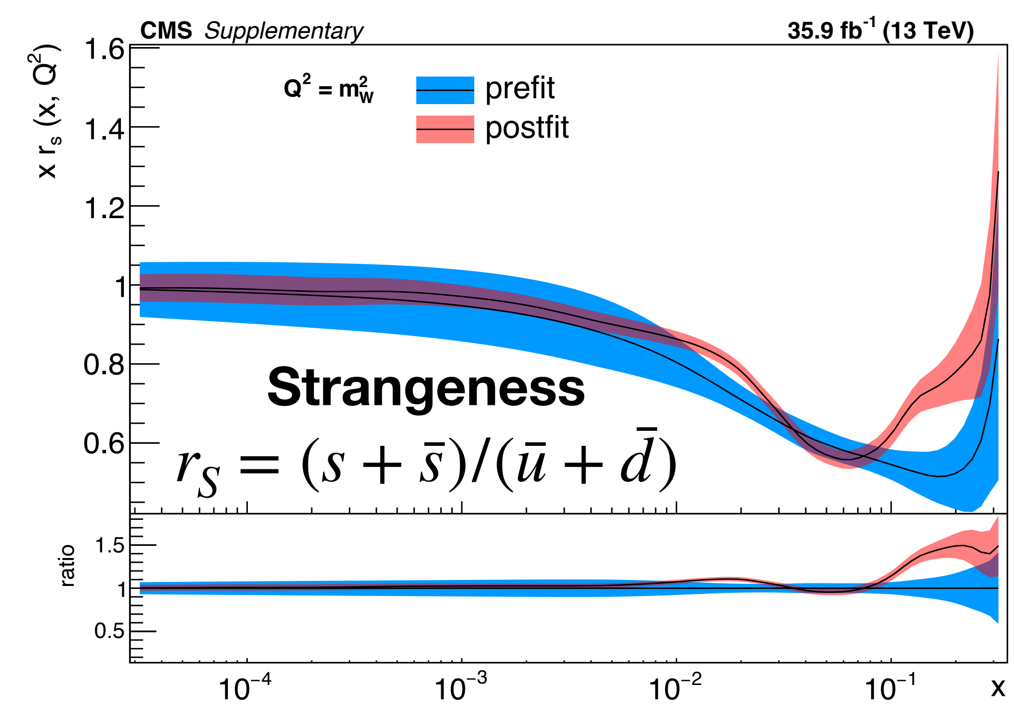




Polarized W cross section



Unfolded W charge asymmetry

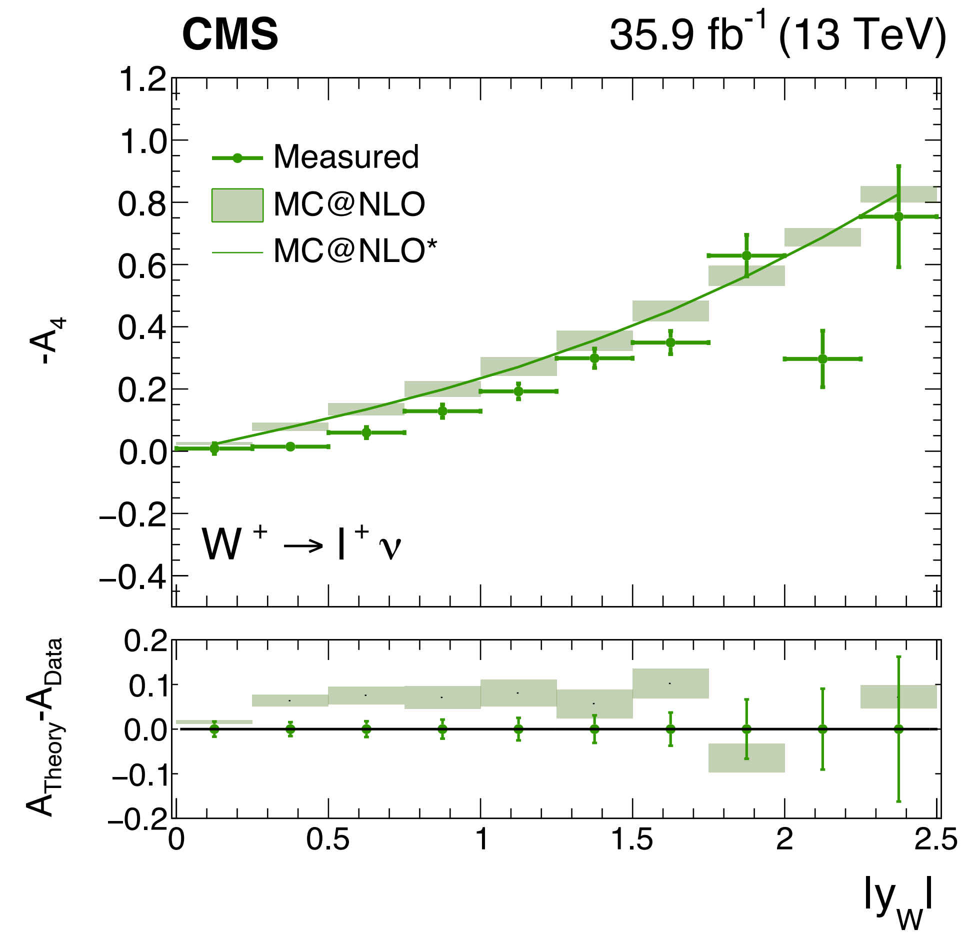


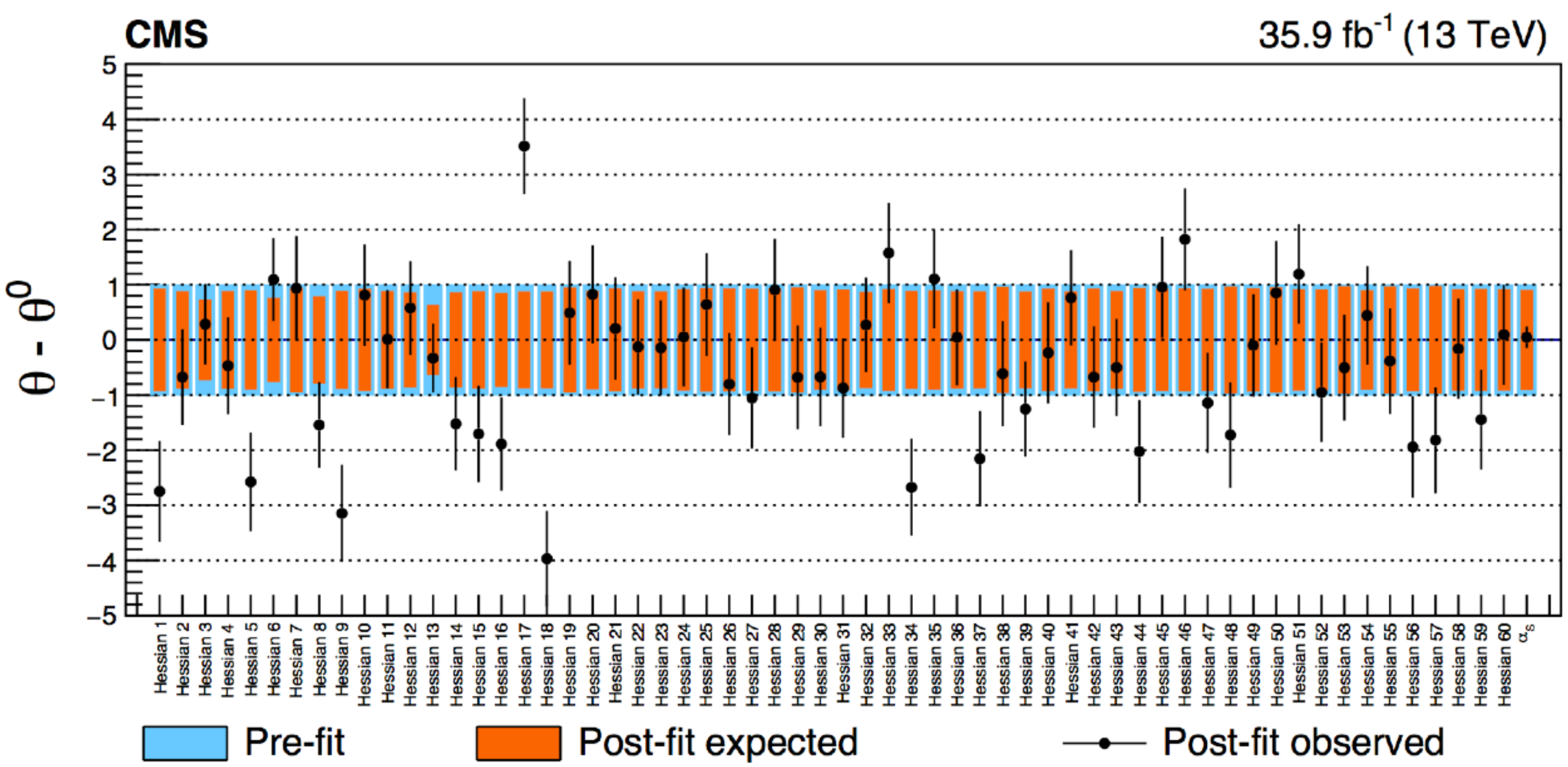
PDF constraints

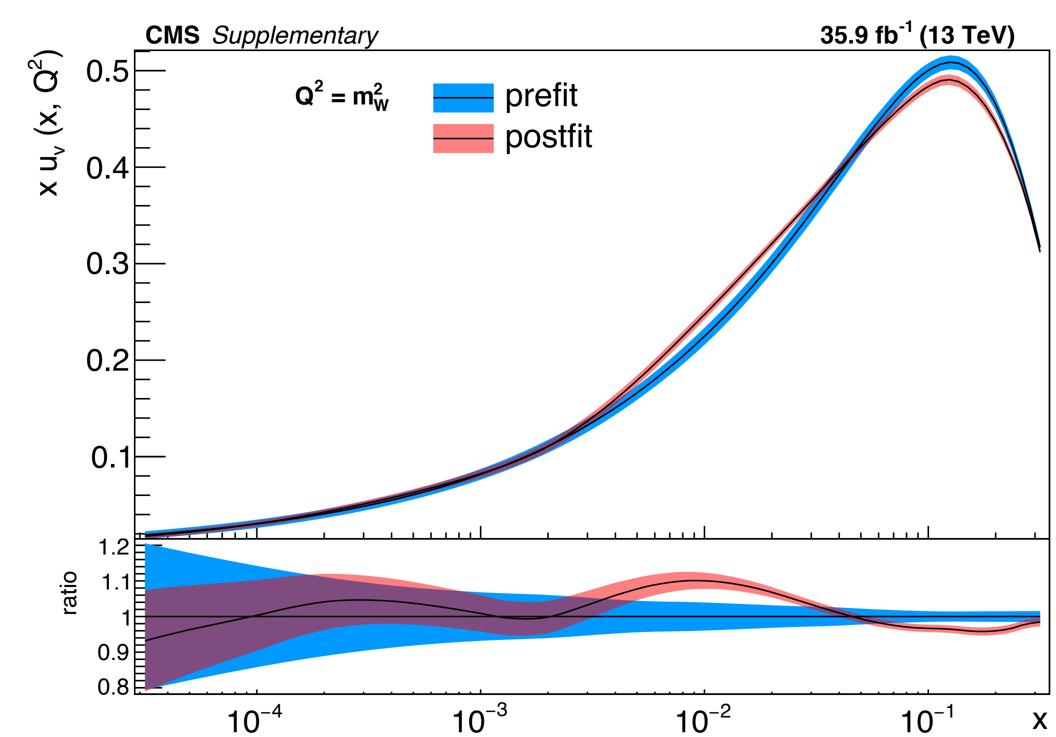
Measuring W polarization and rapidity

PRD 102 (2020) 092012
CMS-SMP-18-012

- A_4 related to forward-backward asymmetry and encodes parity violation in W decays
- Postfit PDF nuisance parameters can be translated back into PDF shapes:
  - not an actual QCD analysis: profiling procedure implies that one cannot interpret results as a rigorous PDF determination in case they are far from input PDFs
  - possible limitations of the used NNPDF3.0 PDF set with respect to newer sets



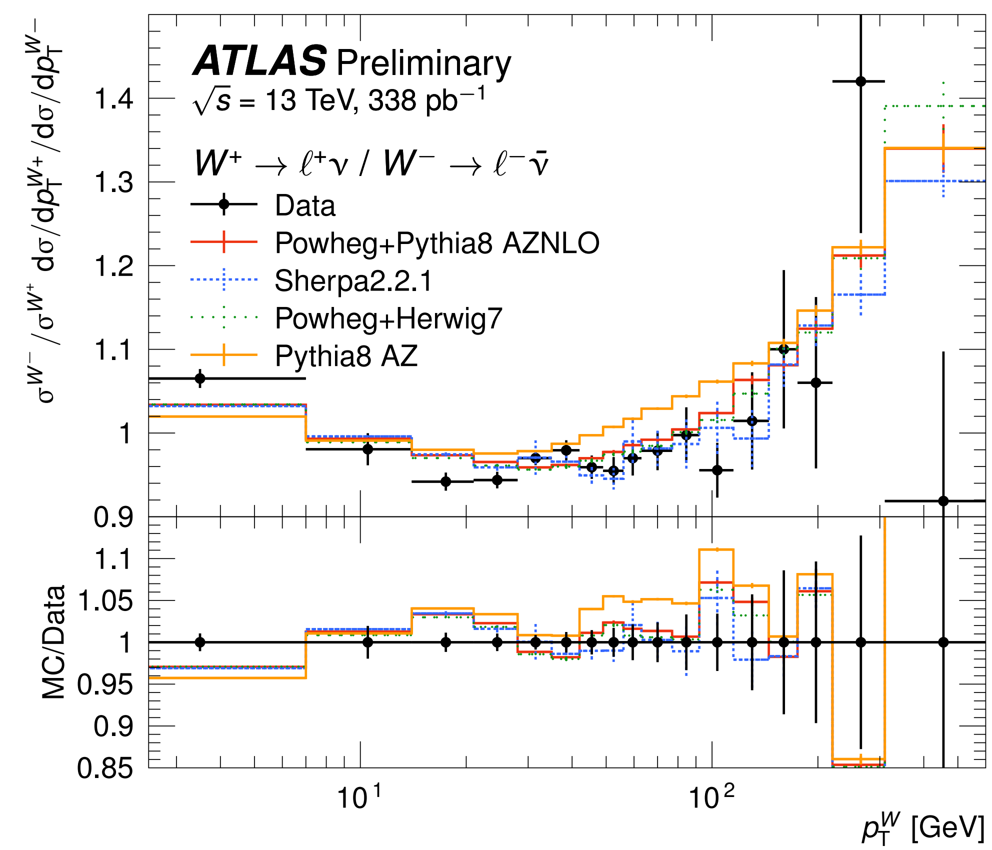


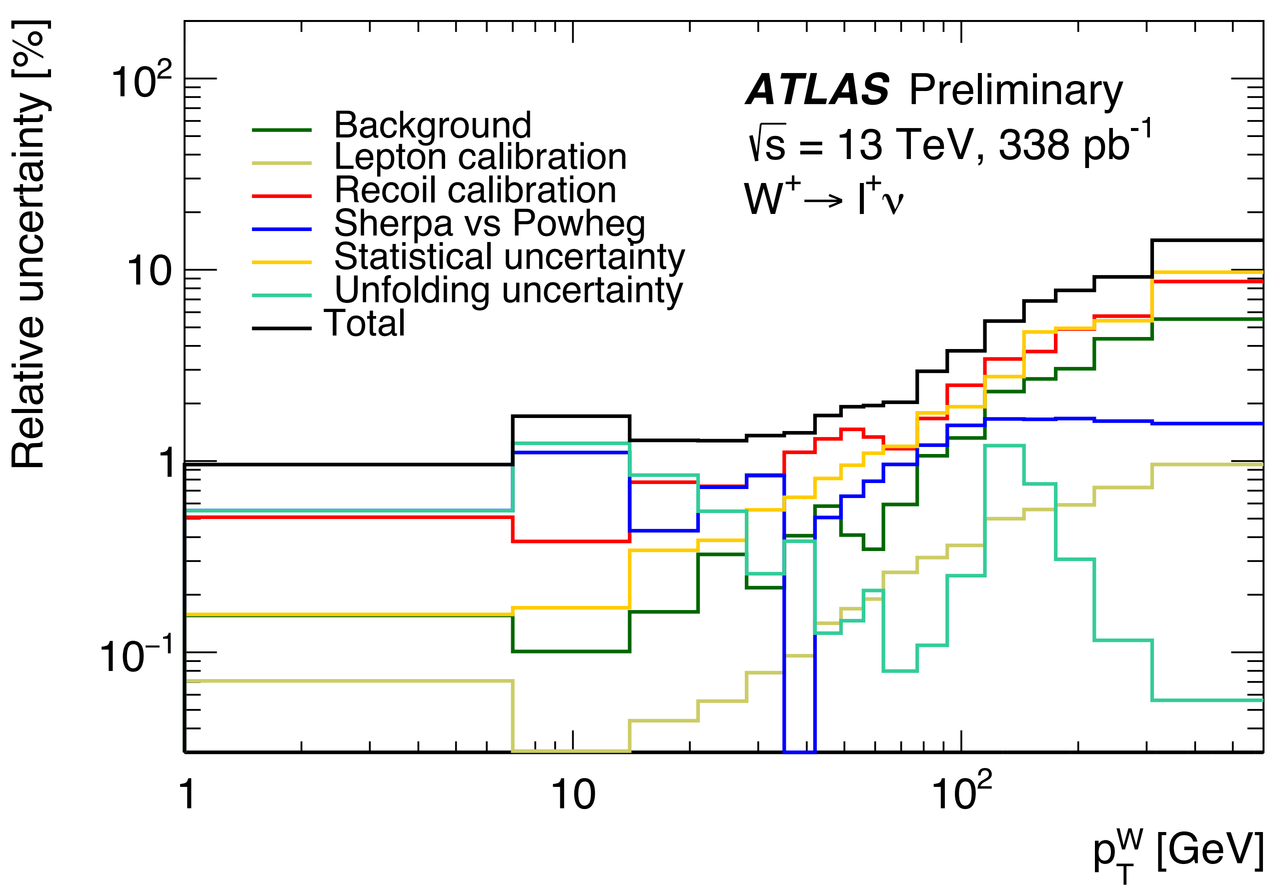


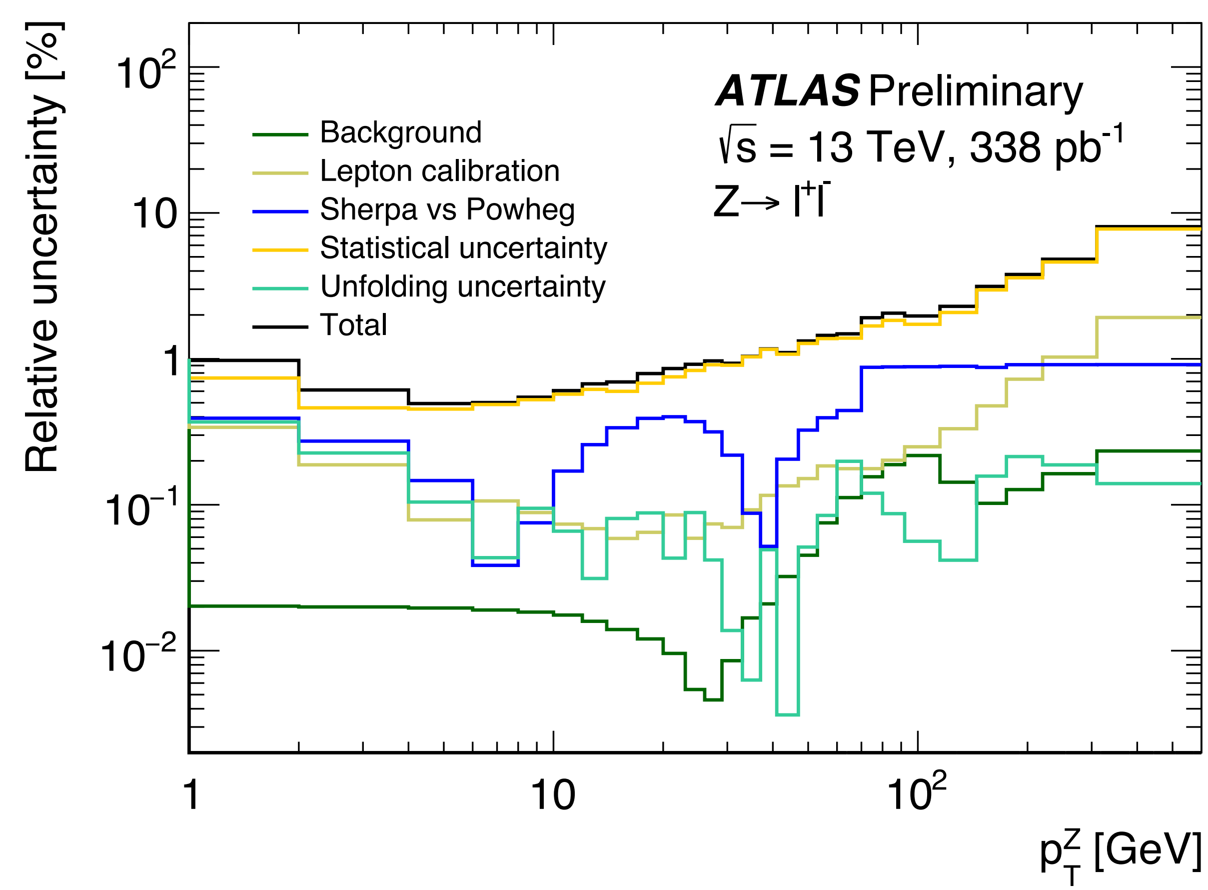
new

Measurements at low pileup

- Differential cross sections (e.g. p_T^W) vital inputs for other EW precision measurements like m_W
- Uncertainty dominated by luminosity for absolute cross sections, and limited data stat, lepton (recoil) calibration for Z (W), and MC modelling for differential ones
- more low PU data a possibility for Run 3, but detector ageing can degrade precision



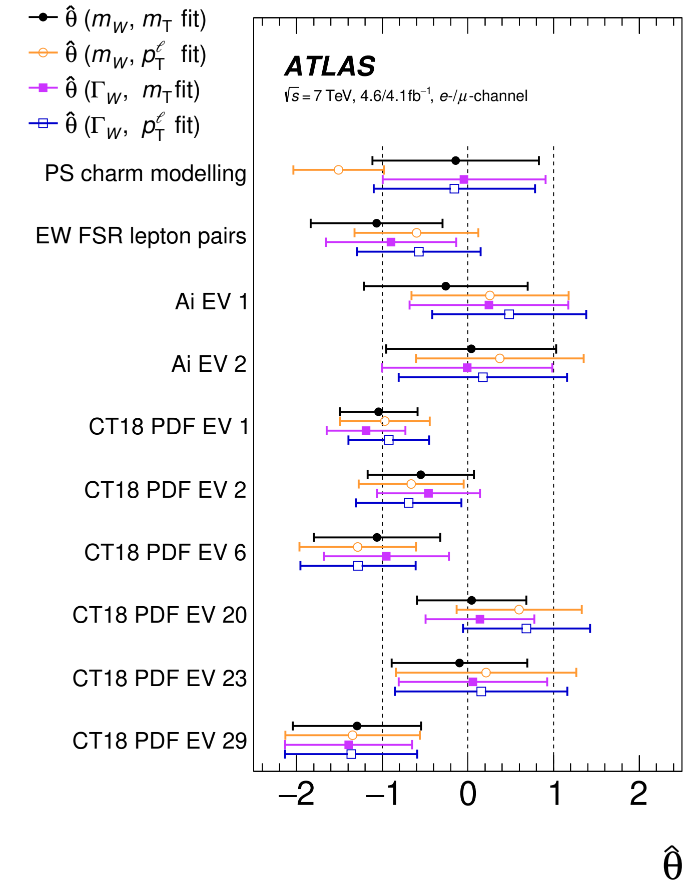


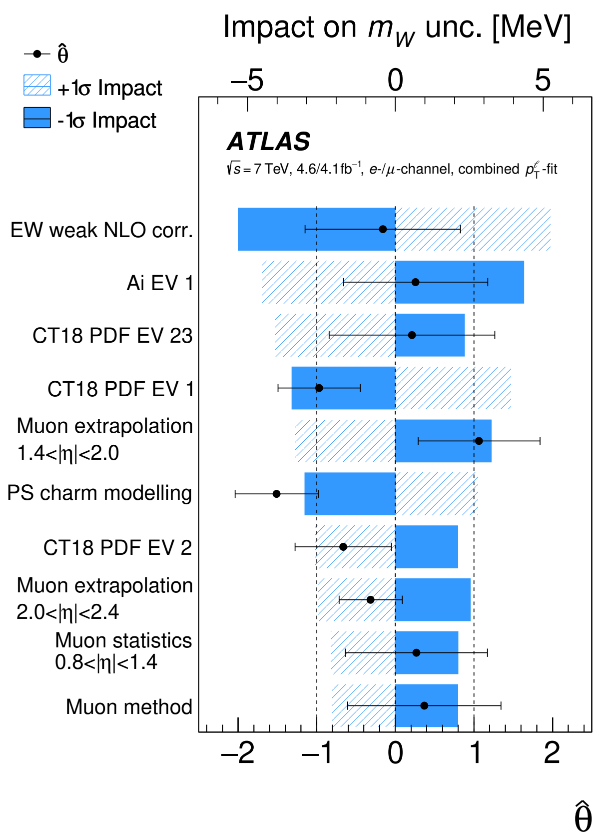


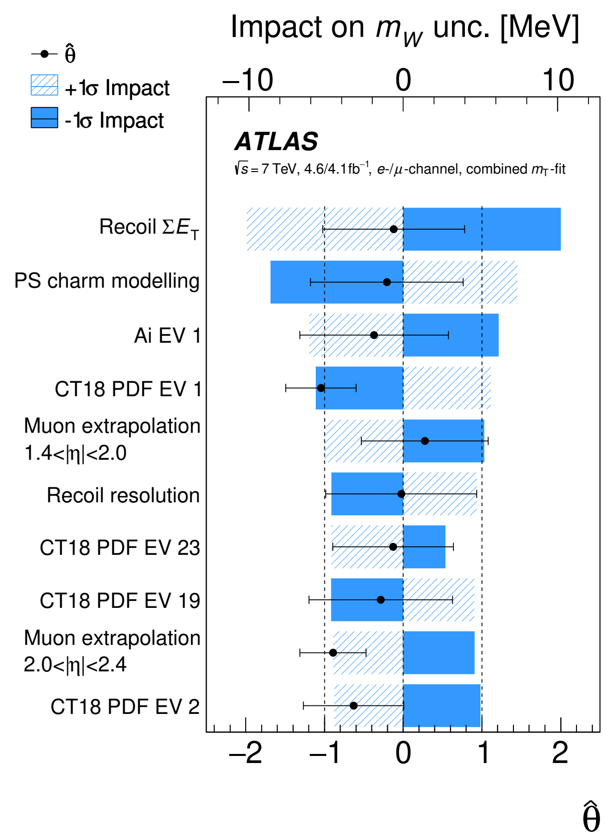
ATLAS m_W and Γ_W

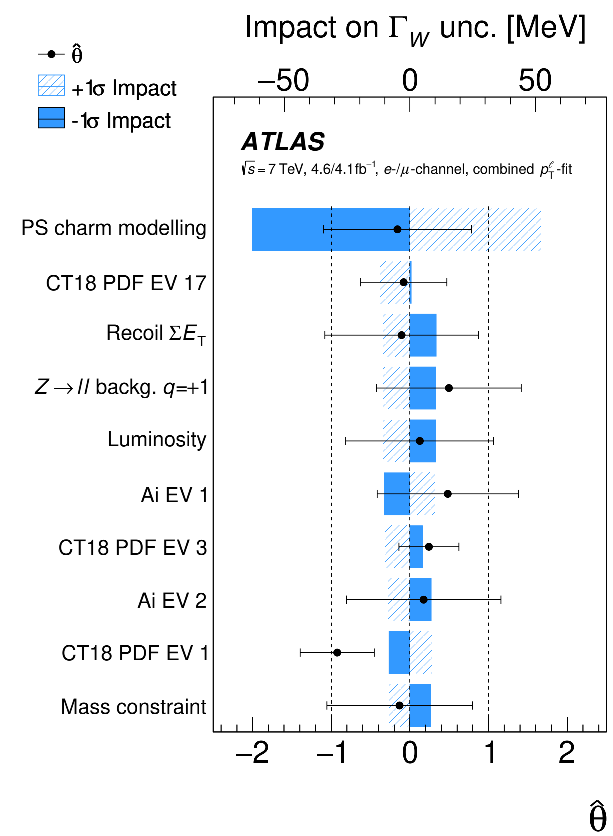
Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^ℓ, m_T	p_T^ℓ, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

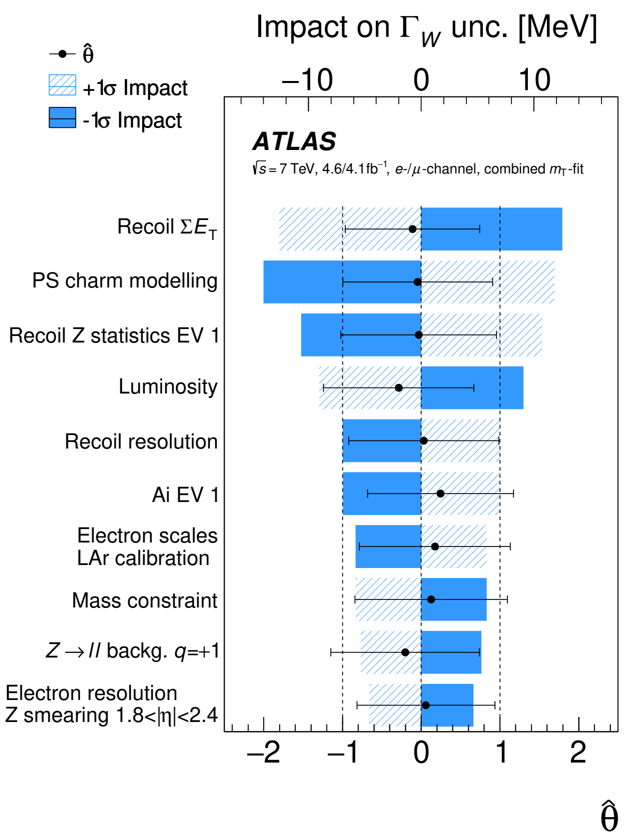
PDF set	Correlation	weight (p_T^ℓ)	weight (m_T)	Combined m_W [MeV]
CT14	52.2%	88%	12%	80363.6 ± 15.9
CT18	50.4%	86%	14%	80366.5 ± 15.9
CT18A	53.4%	88%	12%	80357.2 ± 15.6
MMHT2014	56.0%	88%	12%	80366.2 ± 15.8
MSHT20	57.6%	97%	3%	80359.3 ± 14.6
ATLASpdf21	42.8%	87%	13%	80367.6 ± 16.6
NNPDF3.1	56.8%	89%	11%	80349.6 ± 15.3
NNPDF4.0	59.5%	90%	10%	80345.6 ± 14.9







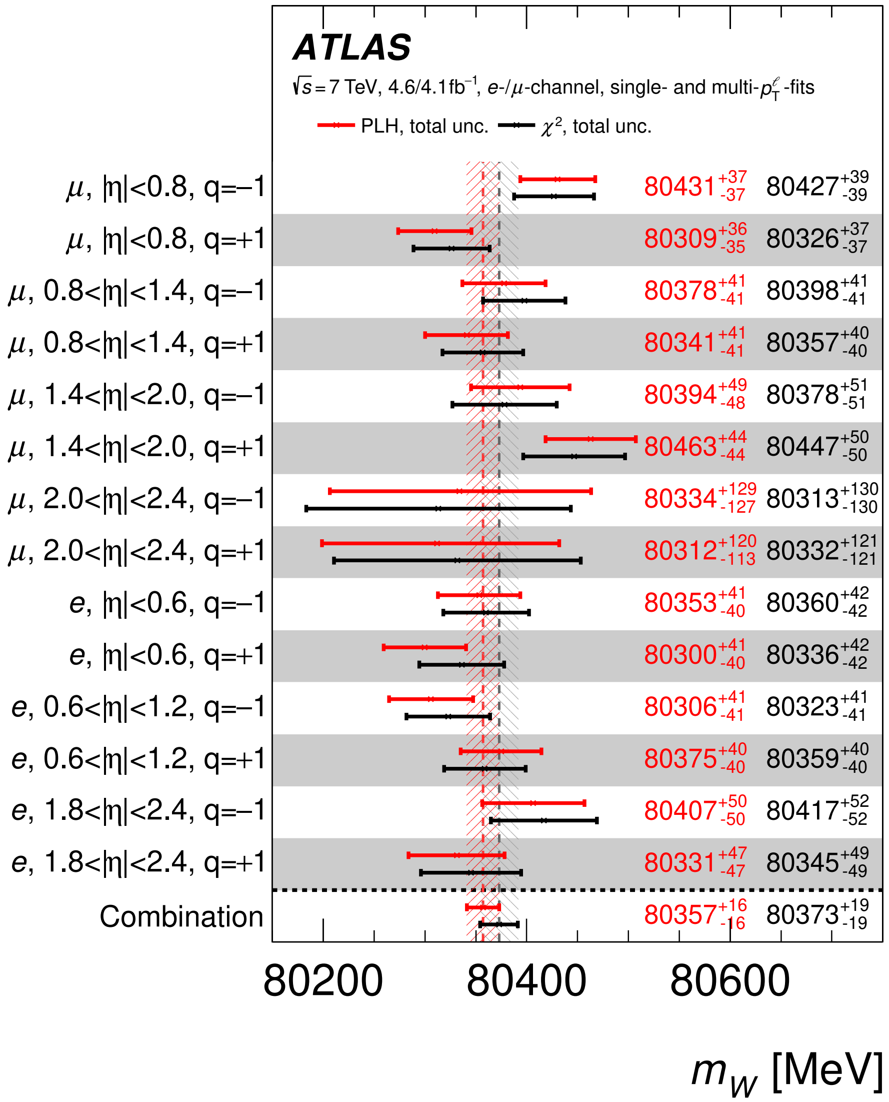




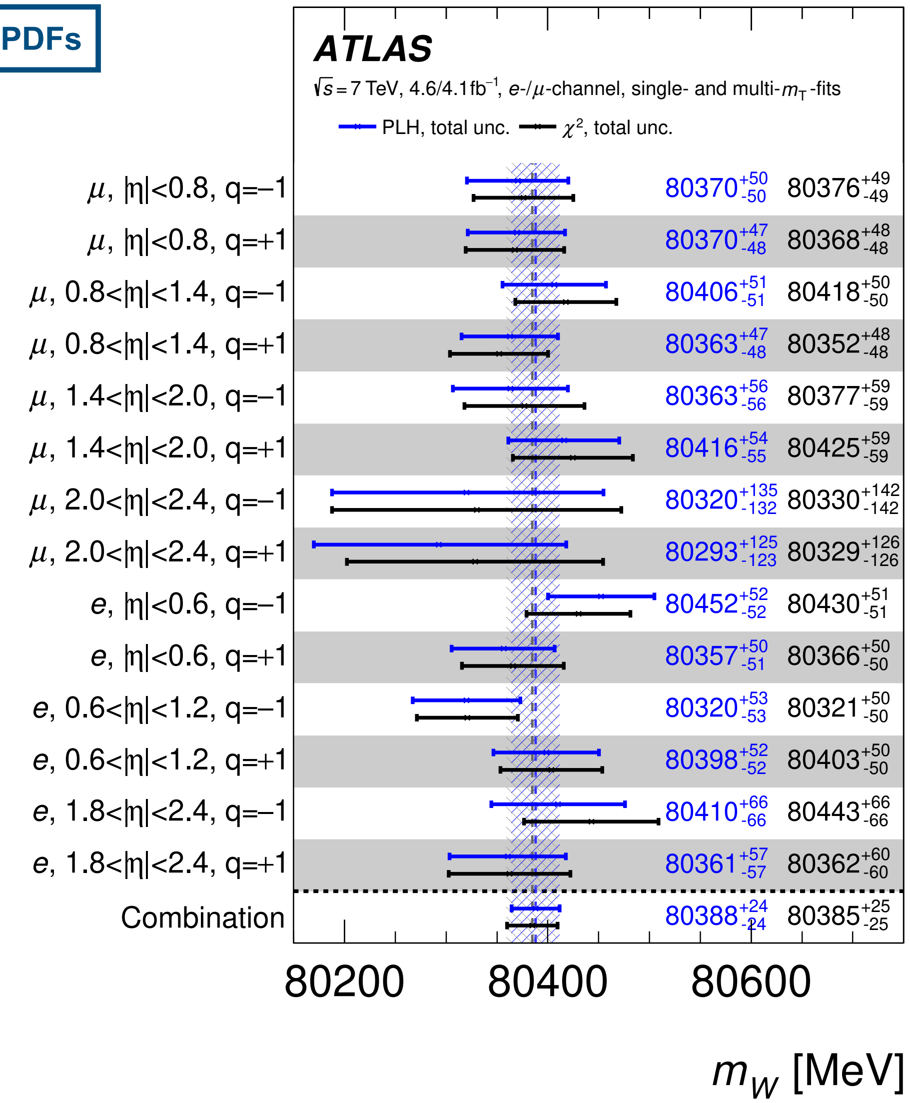
new

ATLAS m_W and Γ_W

arXiv:2403.15085



Using CT10nnlo PDFs



PDF set	p_T^ℓ fit m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	m_T fit m_W	σ_{tot}	σ_{PDF}	χ^2/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

PDF set	p_T^ℓ fit Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	m_T fit Γ_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	2228	$^{+67}_{-83}$	24	550.0/558	2202	$^{+48}_{-48}$	5	556.8/558
CT18	2221	$^{+68}_{-76}$	21	534.5/558	2200	$^{+47}_{-48}$	5	548.8/558
CT18A	2207	$^{+68}_{-75}$	18	533.0/558	2181	$^{+47}_{-48}$	5	550.6/558
MMHT2014	2155	$^{+71}_{-78}$	19	546.0/558	2186	$^{+48}_{-48}$	5	562.2/558
MSHT20	2206	$^{+66}_{-79}$	15	556.5/558	2179	$^{+47}_{-48}$	4	559.4/558
ATLASpdf21	2213	$^{+67}_{-73}$	18	531.3/558	2190	$^{+47}_{-48}$	6	545.6/558
NNPDF31	2203	$^{+65}_{-78}$	20	531.7/558	2180	$^{+47}_{-47}$	6	560.4/558
NNPDF40	2182	$^{+69}_{-68}$	12	550.5/558	2184	$^{+47}_{-47}$	4	564.0/558

arXiv:2308.09417v1

Combining Tevatron-LHC m_W results

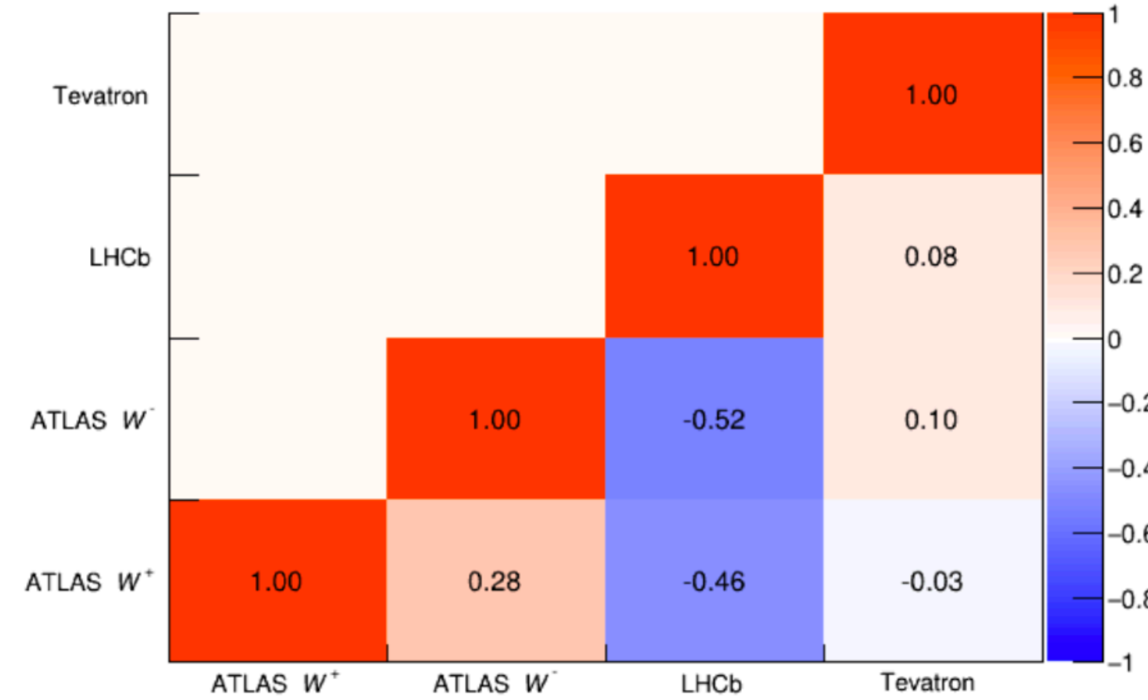
PDF set	D0	CDF	ATLAS	LHCb
CTEQ6	–	14.1	–	–
CTEQ6.6	15.1	–	–	–
CT10	–	–	9.2	–
CT14	13.8	12.4	11.4	10.8
CT18	14.9	13.4	10.0	12.2
ABMP16	4.5	3.9	4.0	3.0
MMHT2014	8.8	7.7	8.8	8.0
MSHT20	9.4	8.5	7.8	6.8
NNPDF3.1	7.7	6.6	7.4	7.0
NNPDF4.0	8.6	7.7	5.3	4.1

Table 4: Uncertainty in MeV for each PDF set after combining the individual fit categories.

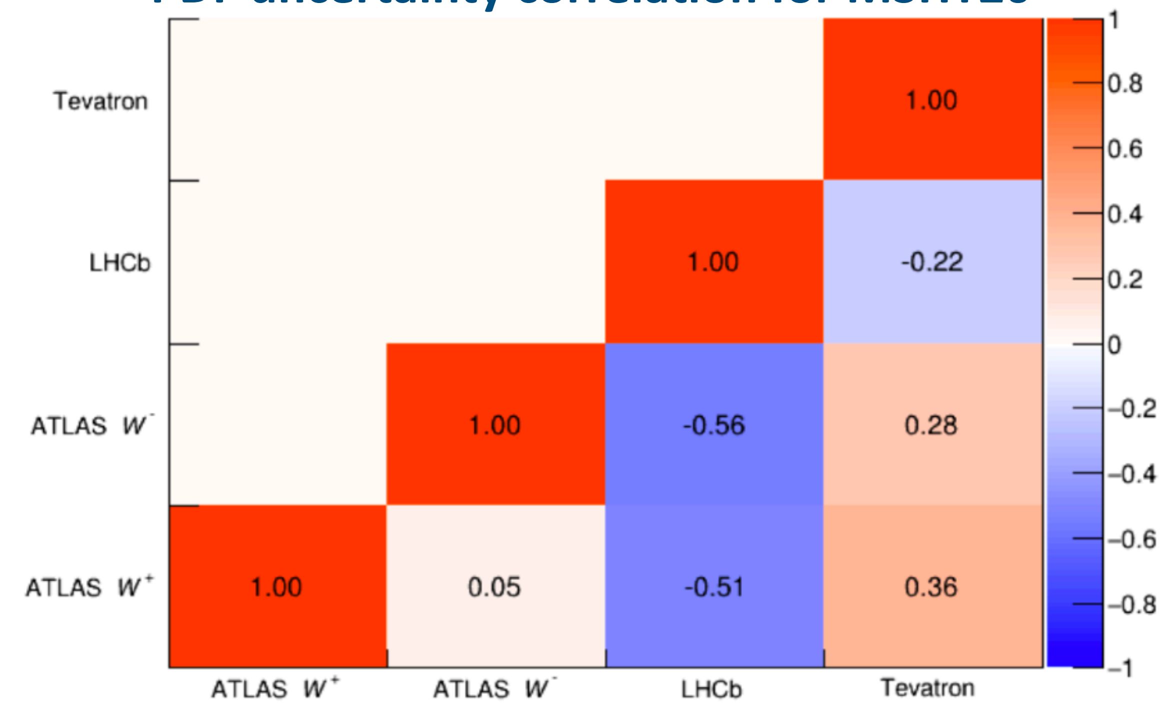
	All experiments (4 d.o.f.)			
PDF set	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	80392.7 ± 7.5	3.2	29	0.0008%
CT14	80393.0 ± 10.9	7.1	16	0.3%
CT18	80394.6 ± 11.5	7.7	15	0.5%
MMHT2014	80398.0 ± 9.2	5.8	17	0.2%
MSHT20	80395.1 ± 9.3	5.8	16	0.3%
NNPDF3.1	80403.0 ± 8.7	5.3	23	0.1%
NNPDF4.0	80403.1 ± 8.9	5.3	28	0.001%

	All except CDF (3 d.o.f.)			
PDF set	m_W	σ_{PDF}	χ^2	$p(\chi^2, n)$
ABMP16	80357.3 ± 11.2	2.6	0.4	94%
CT14	80365.4 ± 12.9	5.8	0.3	96%
CT18	80369.2 ± 13.3	6.2	0.5	92%
MMHT2014	80365.8 ± 12.1	4.7	0.8	85%
MSHT20	80365.1 ± 12.0	4.4	0.4	94%
NNPDF3.1	80364.7 ± 11.9	4.5	0.4	94%
NNPDF4.0	80364.5 ± 11.6	3.9	1.2	75%

PDF uncertainty correlation for CT18



PDF uncertainty correlation for MSHT20

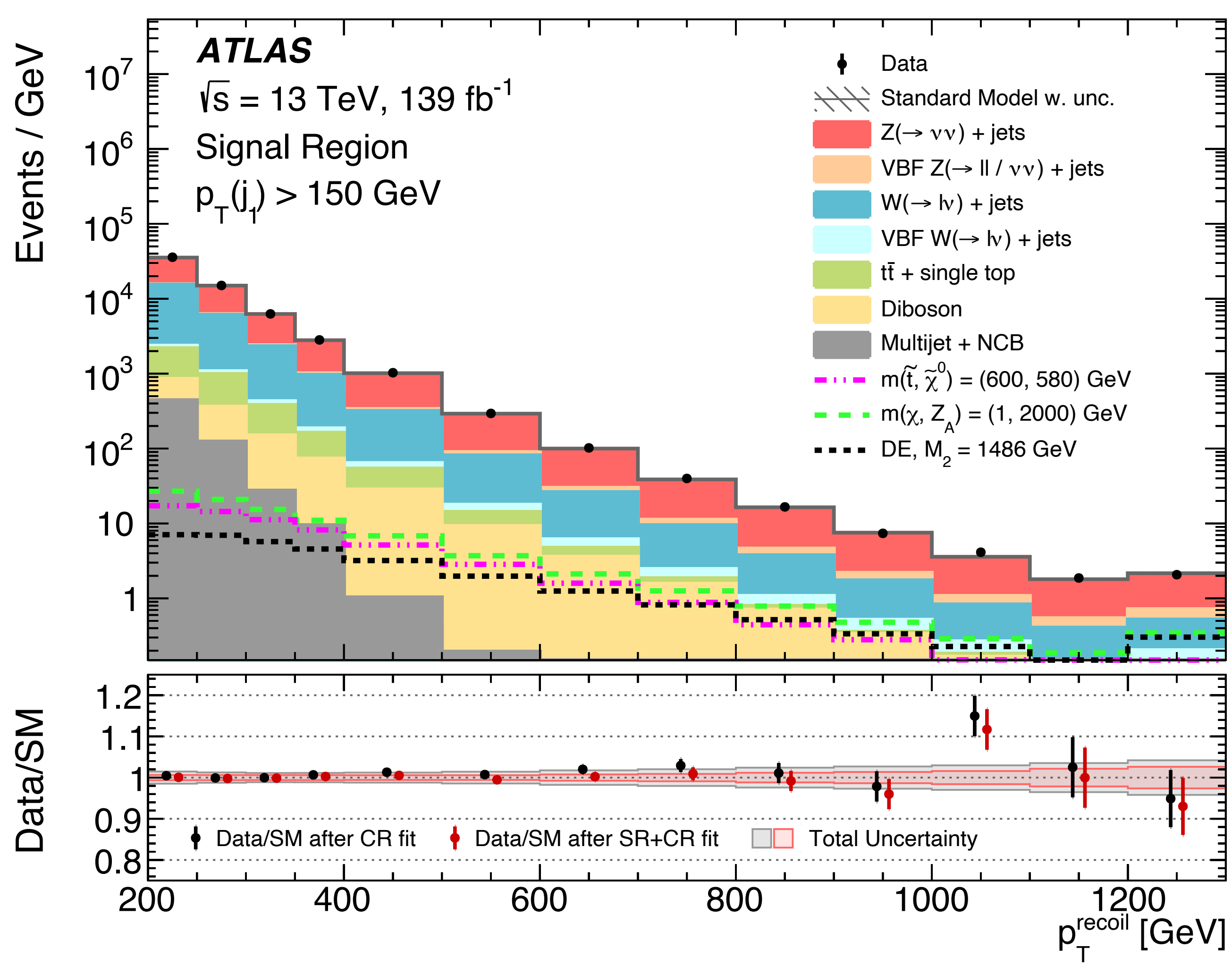


Probing new physics with EW bosons

W/Z+jets often main backgrounds in searches for new physics (NP)

- decays into neutrinos indistinguishable from dark matter production topology

Phys. Rev. D 103, 112006 (2021)



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