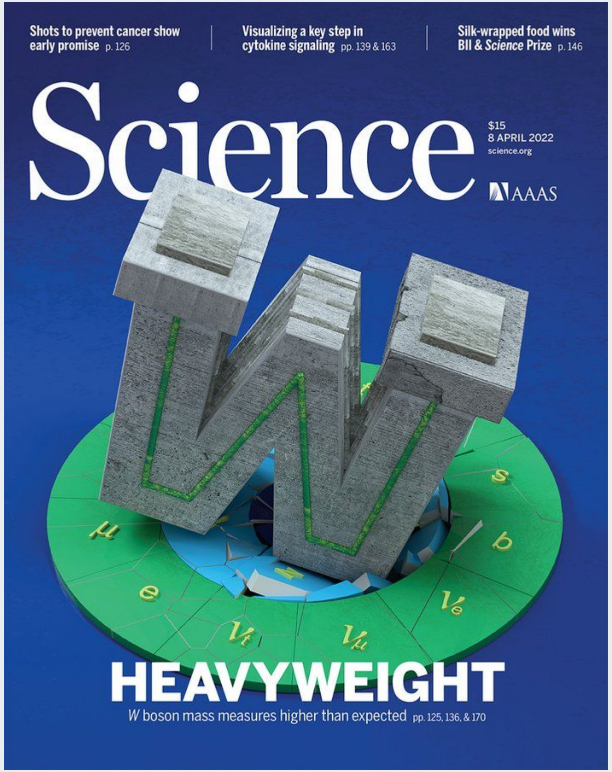
Current status of Global W Mass Measurement



Suvankar Roy Chowdhury, INFN Sezione di Pisa

ICHEPAP 2023, SINP Kolkata 11 December, 2023

Introduction

- Motivation for measuring W boson mass

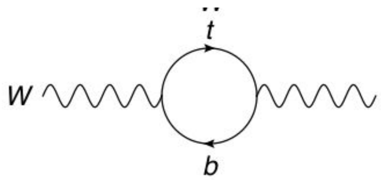
- Focus of this talk will be on measurements at hadron colliders
  - General strategy
  - Measurements from CDF, ATLAS, LHCb
  - W-like measurement from CMS

- Combination of measurements

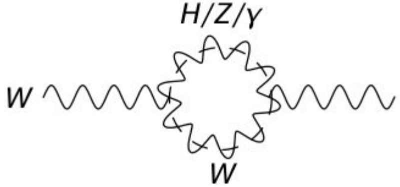
ElectroWeak Sector and W boson mass

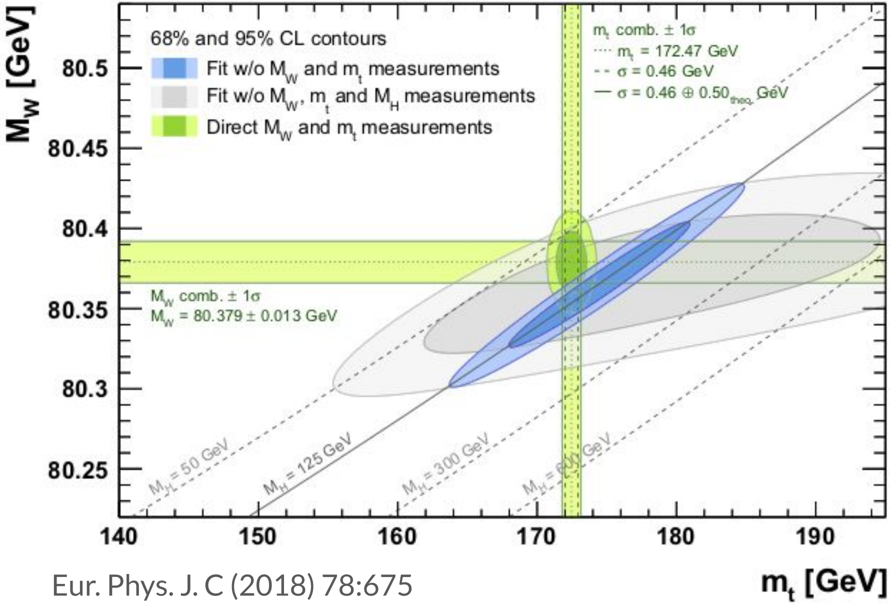
- The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters → α, G_F, m_Z
- The W mass (m_W) can be expressed as →

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha_{\text{EM}}(M_Z)}{\sqrt{2}G_F(1-\Delta r)}$$



- In SM, the term **Δr** receives loop corrections → dominated by top and Higgs
  - BSM theories can also contribute to **Δr**



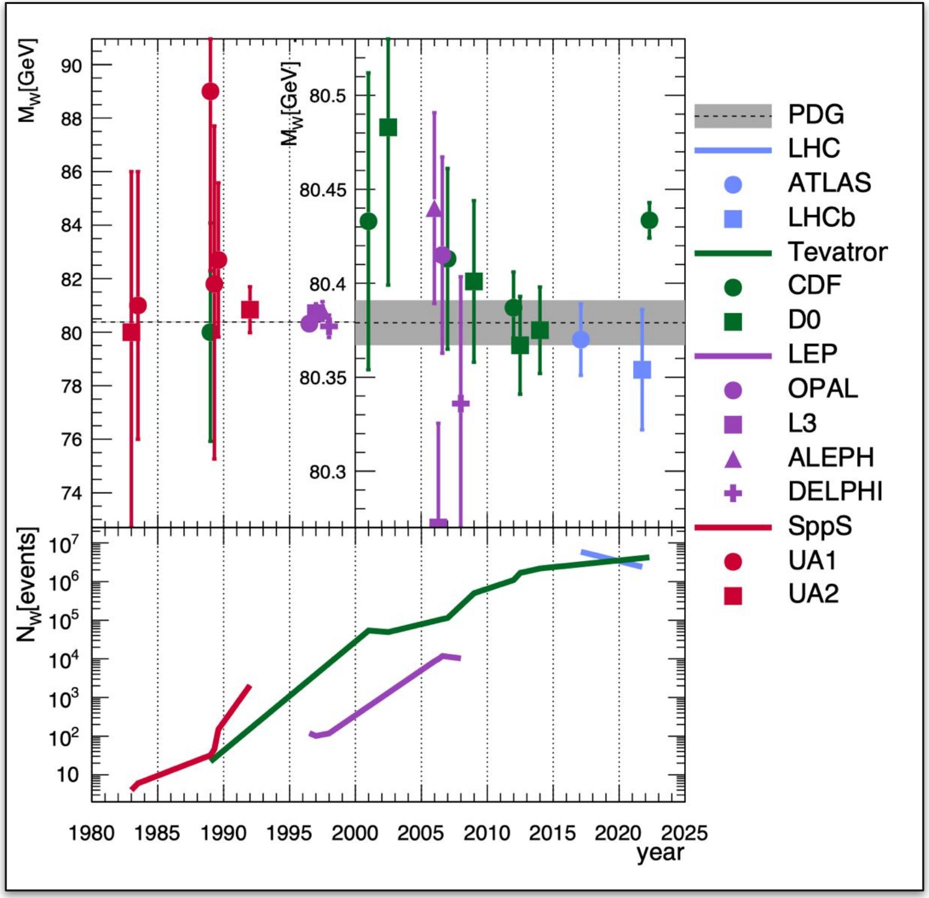


Eur. Phys. J. C (2018) 78:675

- The relation between m_W, m_t & m_H provides a stringent test of the SM
- The discovery of the Higgs and the measurement of its mass allowed (more) precise predictions of m_W(Δ~ 8MeV) → motivation for direct measurement < 10 MeV

Measurement history

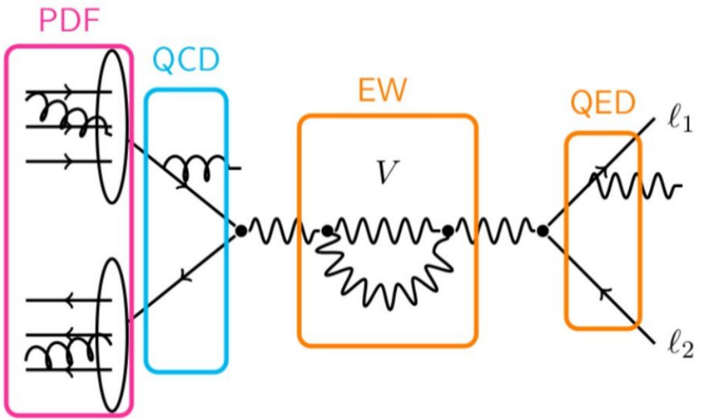
- 1983 CERN SPS – W discovery
- 1983 – UA1
  - m_W = 81 ± 5 GeV
- 1992 – UA2
  - m_W = 80.35 ± 0.37 GeV
- 2013 – LEP combined
  - m_W = 80.376 ± 0.033 GeV
- 2013 – Tevatron combined
  - m_W = 80.387 ± 0.016 GeV
- 2017 – ATLAS
  - m_W = 80.370 ± 0.019 GeV
- 2021 – LHCb
  - m_W = 80.354 ± 0.032 GeV
- 2022 – CDF
  - m_W = 80.434 ± 0.009 GeV
- 2023 – ATLAS
  - m_W= 80.360 ± 0.016 GeV



W production and decay

- Differential Drell-Yann cross-section can be expressed as

$$\frac{d\sigma}{dp_T^W\,dy\,dM\,d\cos\vartheta\,d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^W\,dy\,dM}$$
$$\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi$$
$$+ A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta$$
$$+ A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}$$



- W/Z production described by differential xsec + angular coefficients driven by polarization
- Unpolarized cross-section & Ai's can be can be determined in pQCD
- PDF-dependent
- Known at NNLO QCD + NLO EWK
- Resummation-improved calculations available at N3LL+NNLO.

arXiv:2207.07056

Common strategy

- All measurements rely on theoretical modeling of W production
  - Ultimately limited by model-uncertainties: PDFs, p_T and A_i
- Improve lepton identification efficiency
  - Lepton isolation suffers from increasing pileup
- The absolute energy/momentum scale has to be determined from Jpsi, Y and/or Z
  - Extrapolation to W events
- Validation on Z , e.g. w-like measurements
- m_W is extracted from a χ^2 fit of data to MC-based templates → Need for large-scale MC simulations – most challenging at the LHC

Tevatron and LHC

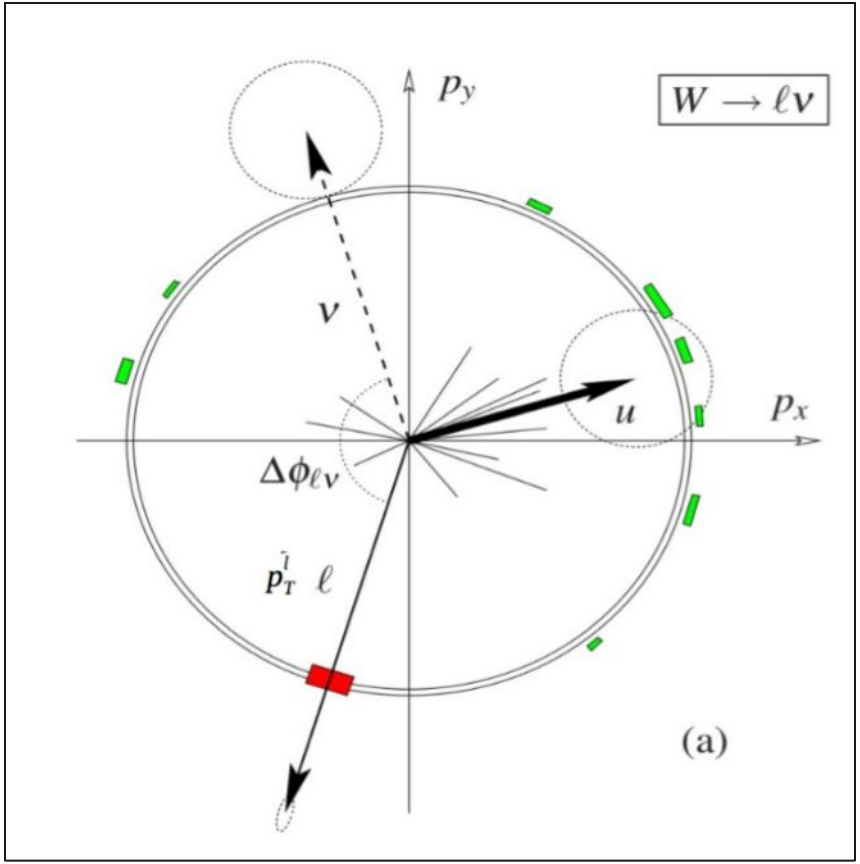
- Tevatron
  - $p\bar{p}$ collider at $\sqrt{s}$ = 1.96 TeV, with <μ> = 2-3
  - Dominant contribution from valence u/d quark – well known from DIS
  - Better recoil resolution
  - Less detector material

- LHC
  - pp collider at $\sqrt{s}$ = 7-13 TeV, with <μ> = 20-50
  - Large contribution from gluon and c/s sea – less well known
  - Poorer recoil resolution
  - Larger material budget
  - Harsher data taking conditions

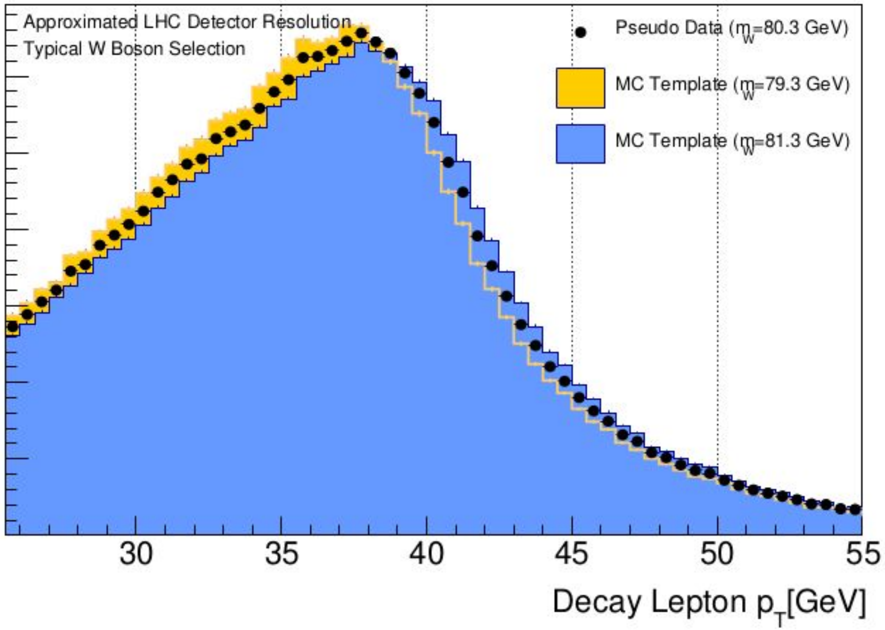
W boson detection at hadron colliders

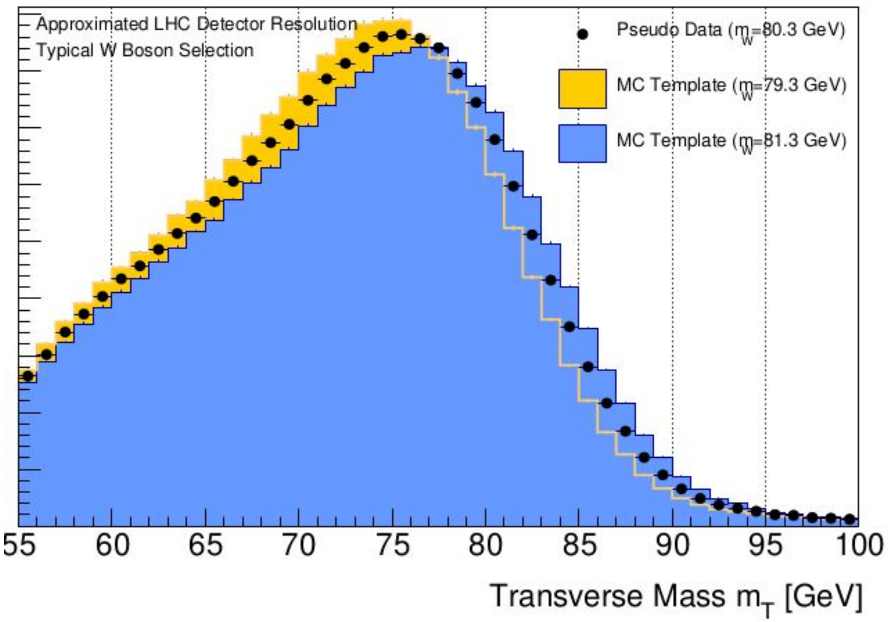
- Detection channel : W → $l\nu$
- Incomplete kinematics → neutrino escapes detection
  - Cannot reconstruct invariant mass
  - Exploit momentum conservation in transverse plane → momentum imbalance gives the neutrino momentum: p_T miss
- Detector signature -
  - Final state prompt and isolated lepton (electron or muon) → p_T
  - Recoil : sum of "everything else" in the event → uT Measure of boson p_T
  - $$\vec{p}_T^{\,\text{miss}} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right).$$
  - Transverse mass

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} (1 - \cos \Delta\phi)}$$



Sensitivity to m_W

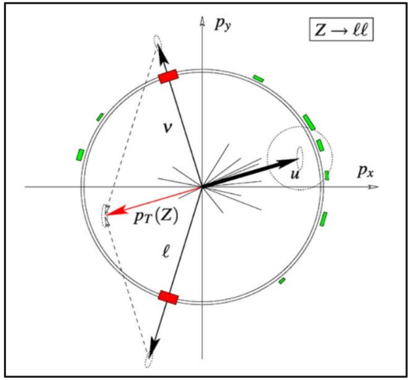




- Lepton p_T Jacobian edge ~ $m_W/2$
- mT peaks ~ m_W
- Mass measurement : produce models ("templates") of the final state distributions for different mass hypotheses; compare to data

Calibrations and modell

- Calibration of the detector to an unprecedented level is needed for m_W extraction
- Lepton momentum calibrations ~ 10^{-4}
  - Alignment
  - Material estimate
  - Momentum scale & resolution
  - Use known resonances → Z, J/ψ, Υ (1S)



- Recoil calibrations
  - Recoil response & resolution calibrated using kinematics in Z events
  - Affected by pileup

- Modelling of W-p_T
  - W limited by recoil resolution
  - Initial state radiation involves large corrections to p_T W
  - Adjust model parameters with Z events → well measured from data.

CDF II measurement

- First measurement from Tevatron Run II dataset
  - 80413 ± 48 MeV (CDF, 2006)
  - 80401 ± 43 MeV (DØ, 2009)

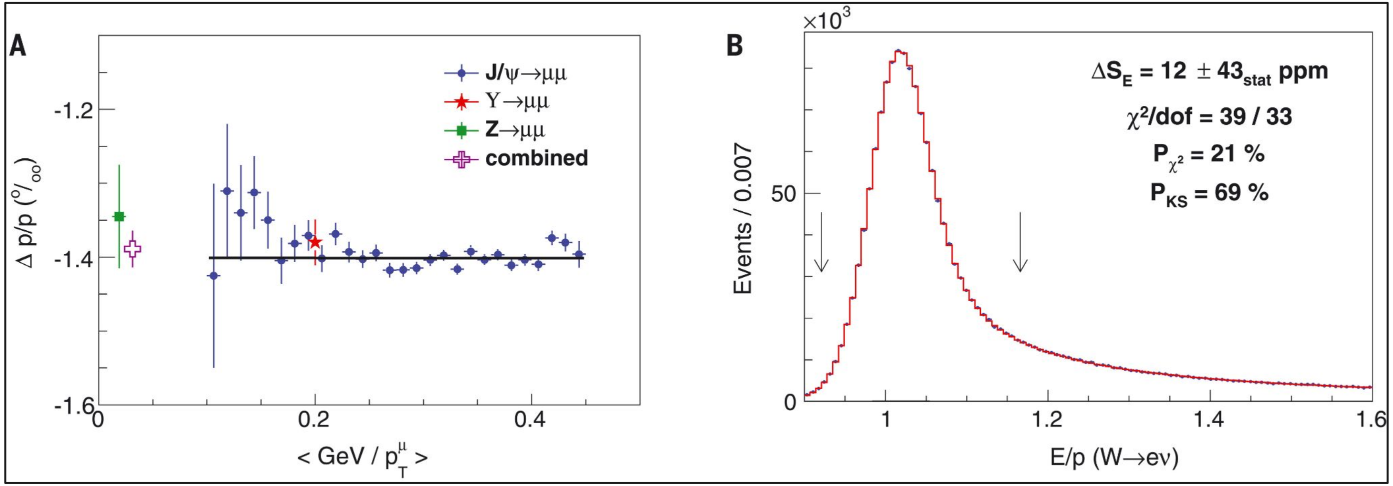
- In 2022, CDF reported the m_W with full Run II dataset (8.8 /fb) [Science 376, 170 (2022)]

- Use of both the muon and the electron channel

- Physics modeling: CTEQ6M+ResBosP1 + Photos

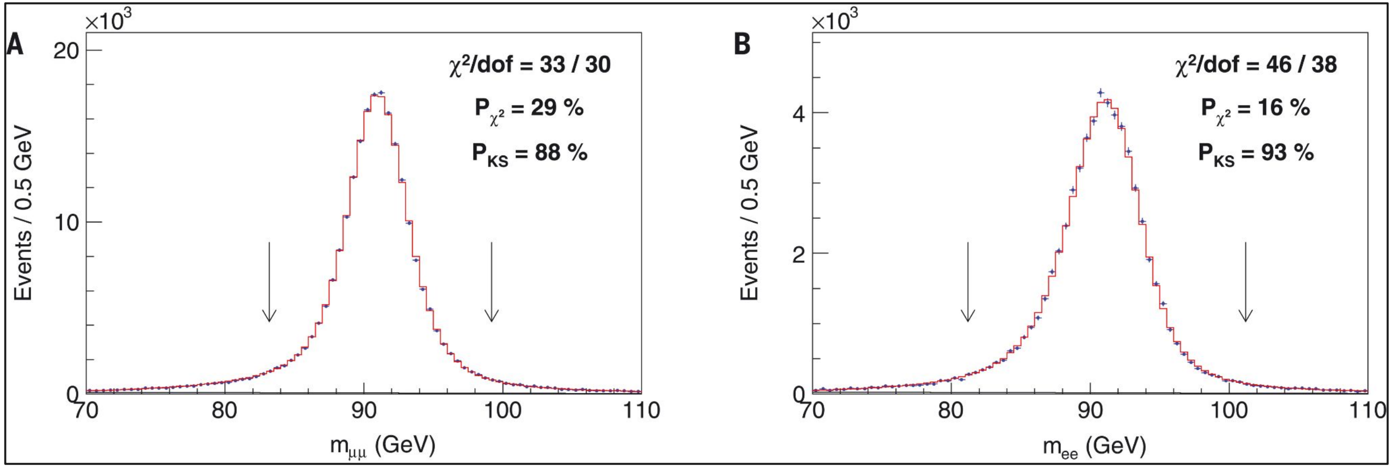
- Template fit to m_T, $p_T l$, and $p_T \nu$ → combination of six channels → to extract the mass.

CDF II measurement



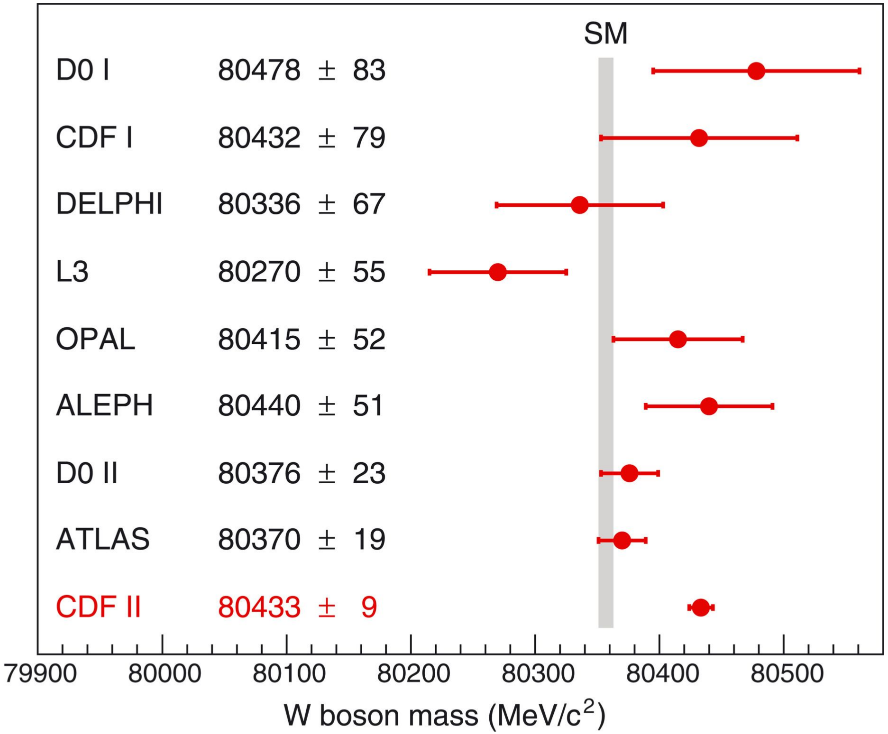
Muon momentum calibration from J/ψ, Υ, Z

Calorimeter response by fitting E/p in W→ eνevents and validated with Z→ ee events



Distribution of di-muon and di-electron mass compared to simulation

CDF II measurement



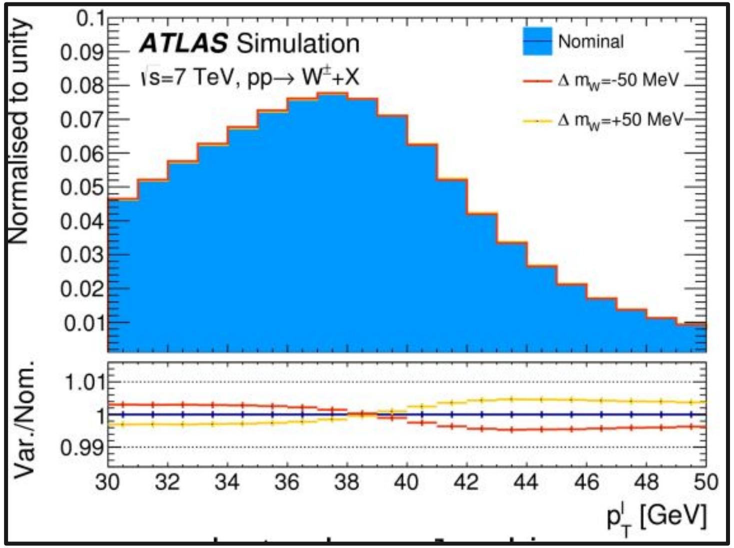
Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

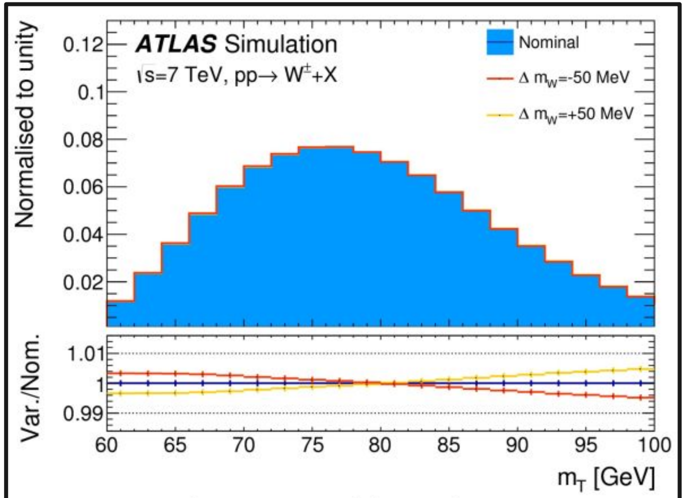
Table 2

- m_W = 80433.5±9.4 MeV → Significant tension with SM prediction!

ATLAS measurement

- Measurement with 4.6 /fb and 4.1 /fb at √s = 7 TeV for muon and electron channels.
- m_W extracted from the p_T lepton and transverse mass (mT) distributions
  - m_W variation done using Breit–Wigner parameterisation
- CT18 PDF Set chosen as new baseline
- Fit done separately for +/- W bosons,
  - 3 bins of |η| in the electron decay channel
  - 4 bins of |η| in the muon decay channel
  - 28 categories

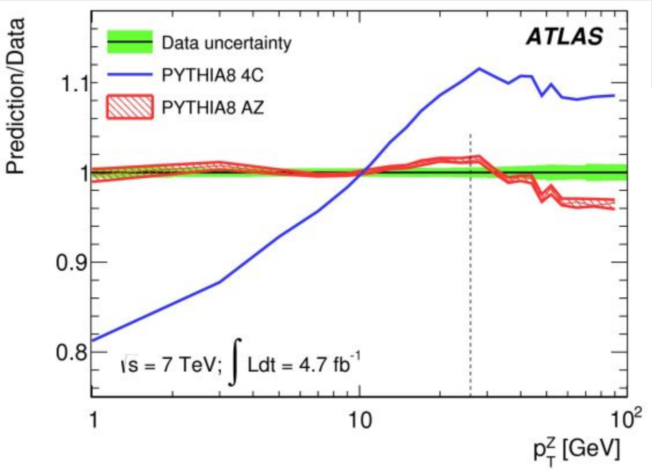


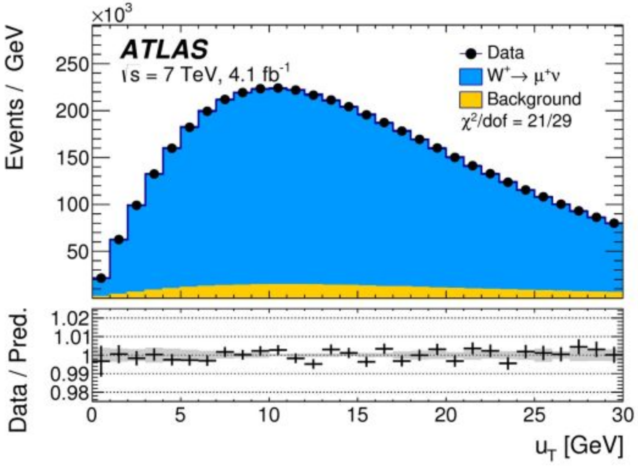


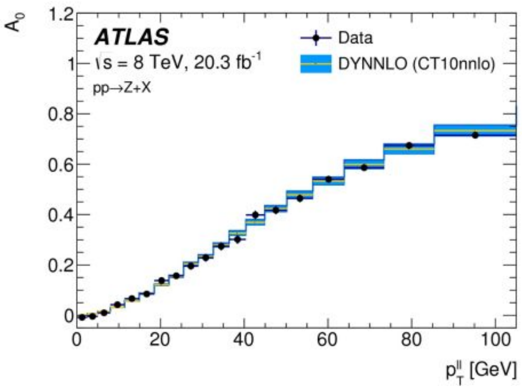
m_T has a Jacobian edge at m_W

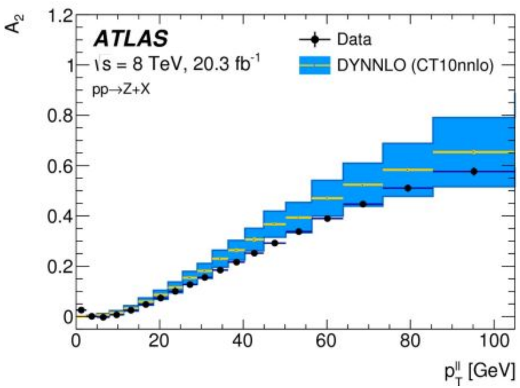
ATLAS physics modelling

- The Pythia8 as model for the p_T W
- The Pythia8 AZ tune describe the p_T Z data within 2% inclusively and in rapidity bins
- Pythia8 is used to transfer from the p_T Z to the p_T W distribution and to evaluate theory uncertainties on the W/Z p_T ratio
- Angular coefficients are modelled with fixed order perturbative QCD at NNLO → predictions validated by comparisons to the Z measurement at 8 TeV







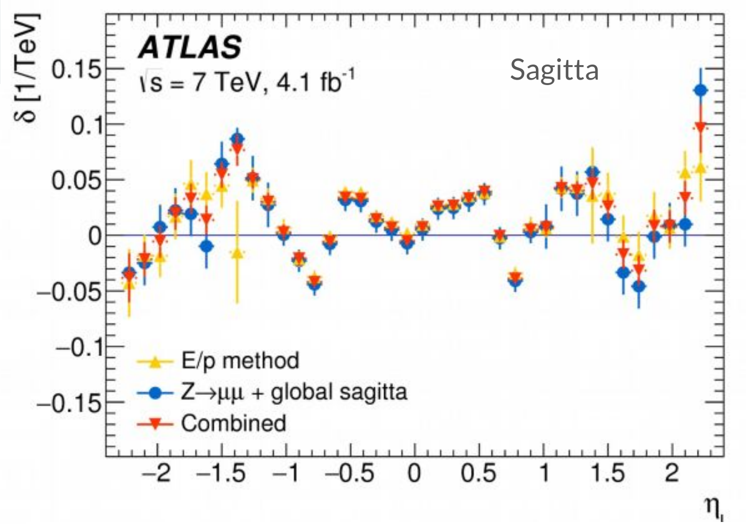


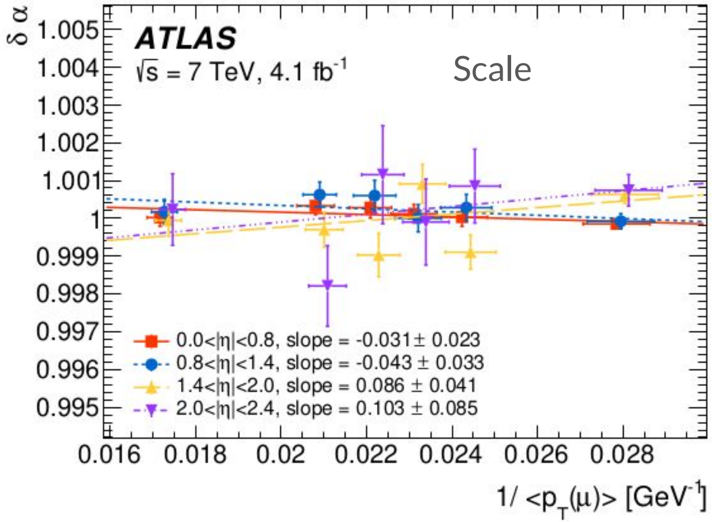
ATLAS Calibrations

- **Muon momentum** calibrations derived from Z→ mumu events
- Parameterisation of momentum corrections in bins of lepton $\boldsymbol{\eta}, \phi \rightarrow$ derived per charge
  - radial bias (scale) $\rightarrow$ detector movements along the particle trajectory
  - sagitta bias $\rightarrow$ curl distortions
  - resolution correction

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}}^{\mathrm{MC}} \times \frac{1+\alpha(\eta,\phi)}{1+q\cdot\delta(\eta,\phi)\cdot p_{\mathrm{T}}^{\mathrm{MC}}}\left[1+\beta_{\mathrm{curv}}(\eta)\cdot G(0,1)\cdot p_{\mathrm{T}}^{\mathrm{MC}}\right]$$

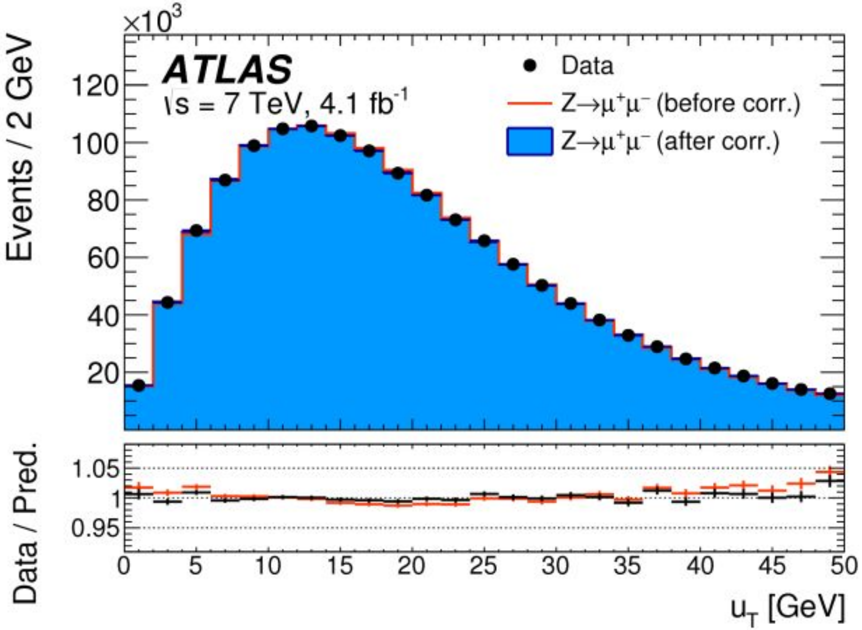
- Scale corrections from Z→$\mu\mu$
- Sagitta bias charge-dependent corrections both from Z→$\mu\mu$ and E/p of W→eν

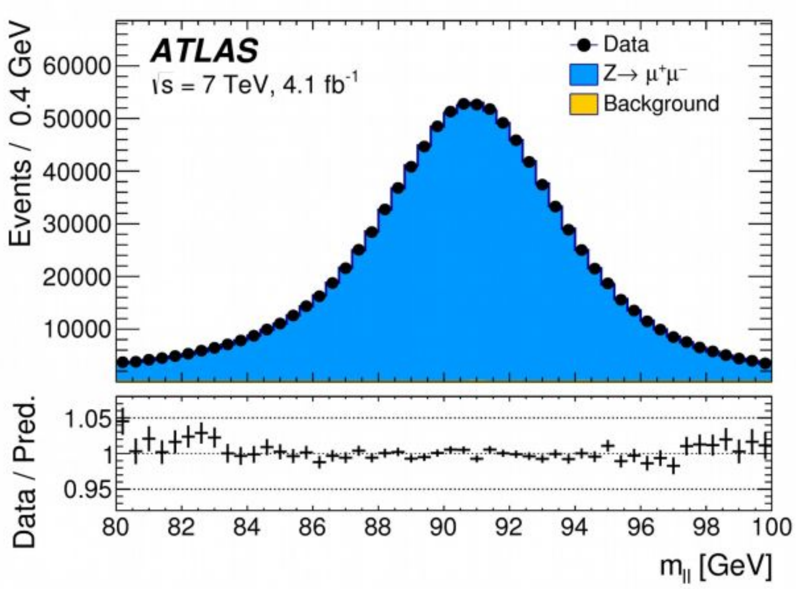




ATLAS Calibrations

- Good modelling of Z lineshape after applying the Corrections
- **Recoil calibration** → use p_T balance in Z events
    - Correct pile-up multiplicity in MC to match the data

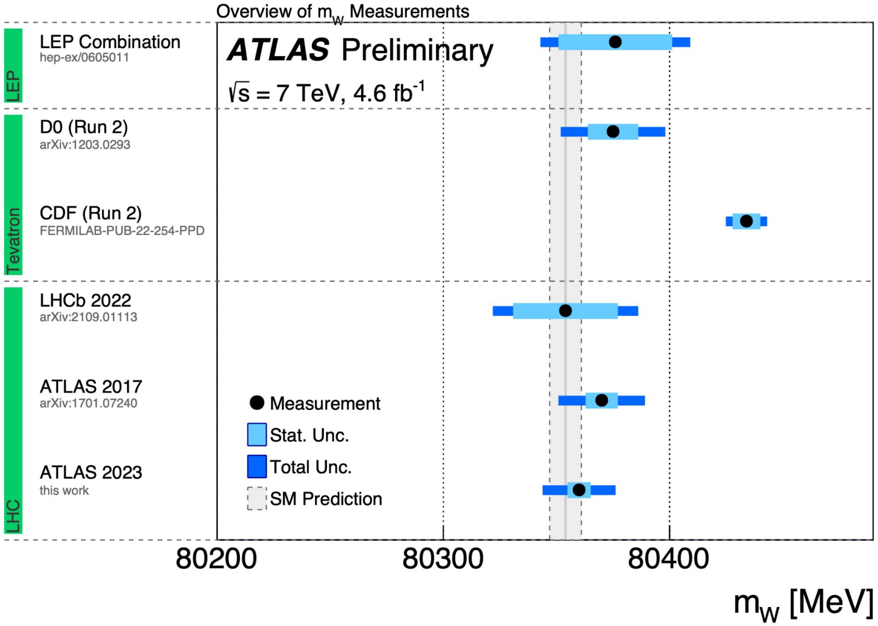


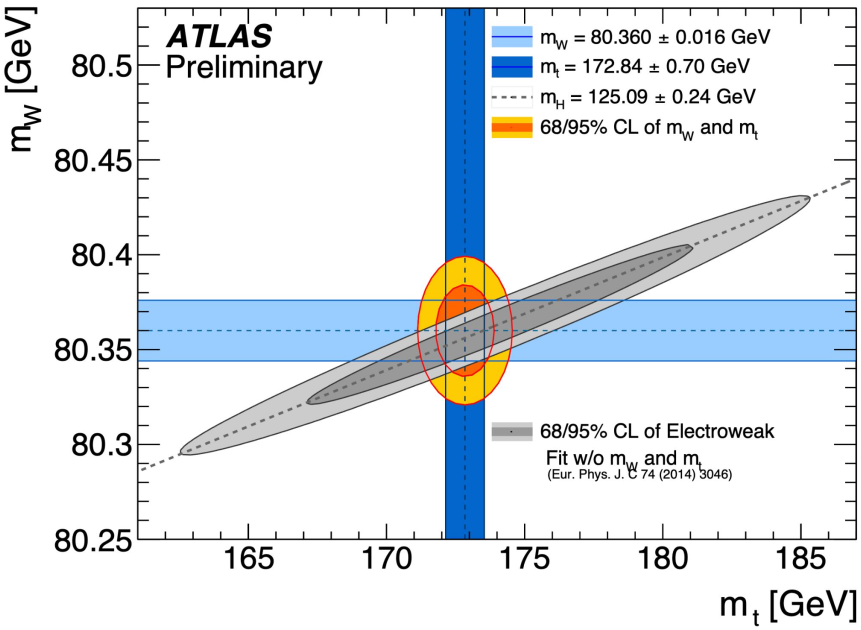


EPJC 78 (2018) 110

ATLAS results

ATLAS-CONF-2023-004

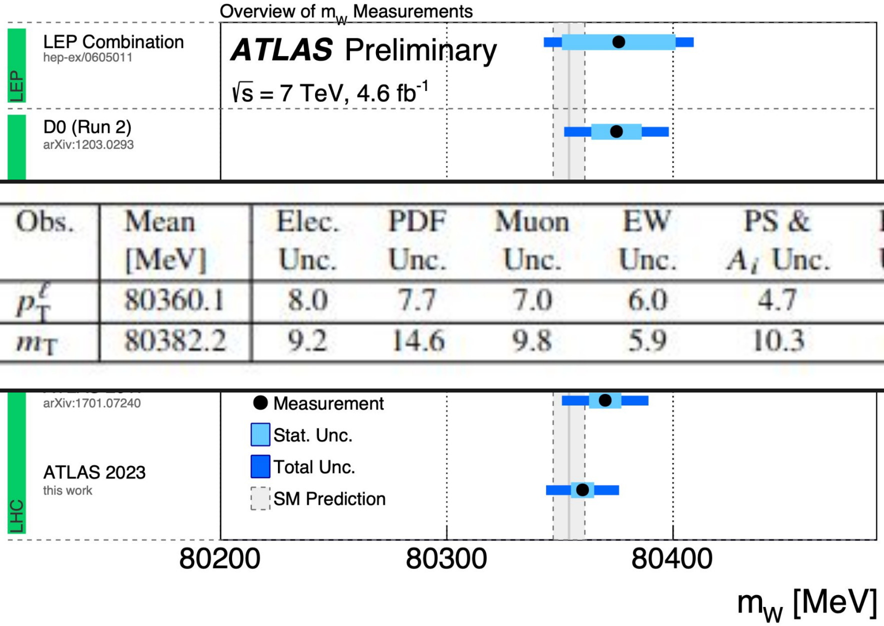


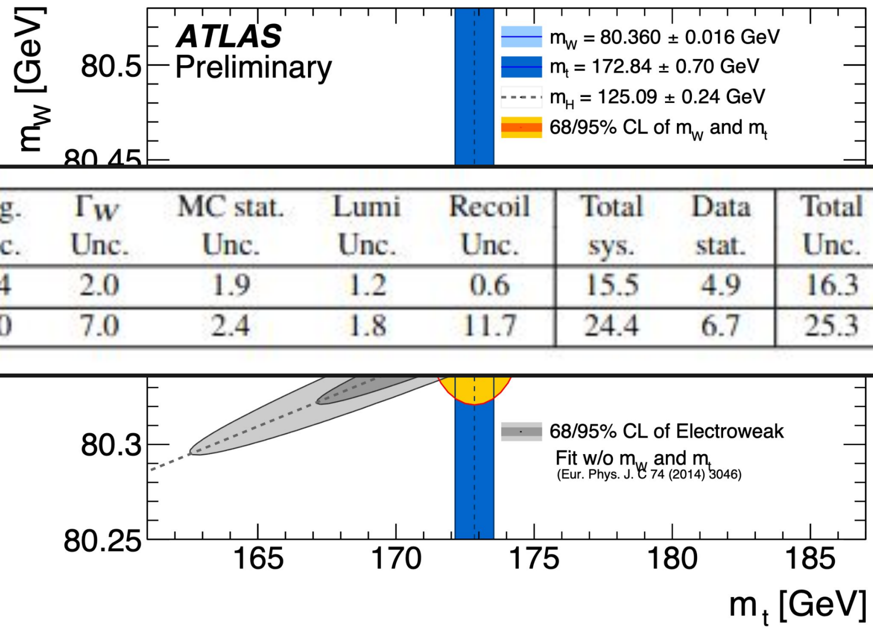


- ATLAS m_W 2023 measurements yields a value of
  m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV
- Legacy ATLAS m_W 2017 measurement
  m_W = 80370 ± 19 MeV

ATLAS results

ATLAS-CONF-2023-004



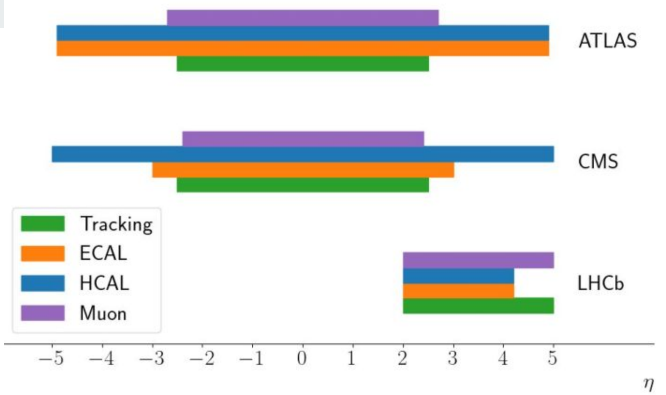


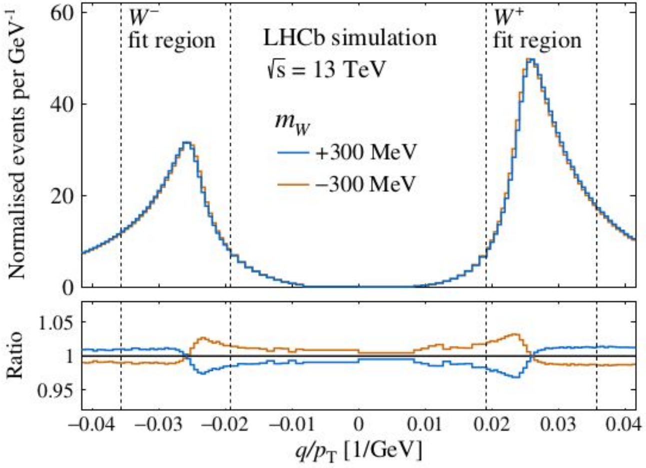
Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

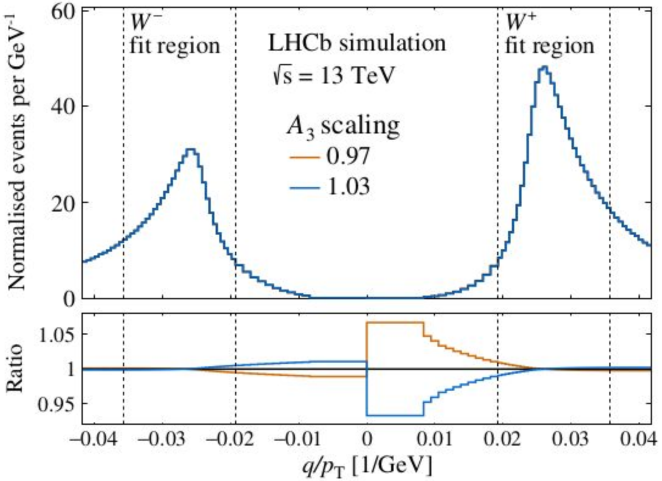
- ATLAS m_W 2023 measurements yields a value of m_W = 80360 ± 16 MeV
- Legacy ATLAS m_W 2017 measurement m_W = 80370 ± 19 MeV

LHCb measurement

- Used LHC Run 2 data at √s = 13 TeV
- Measurement in a complimentary fiducial range compared to ATLAS/CMS
- No recoil measurement
- Simultaneous fits to m_W and Z($\phi*$)
- Physics modeling: NNPDF31/CT18/MHST20+Powheg(*DYTurbo)+Pythia(*ϕll$*$) +Photos

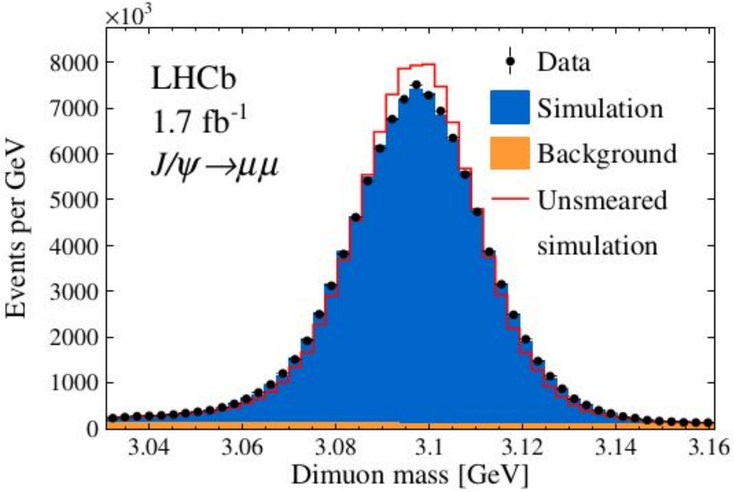


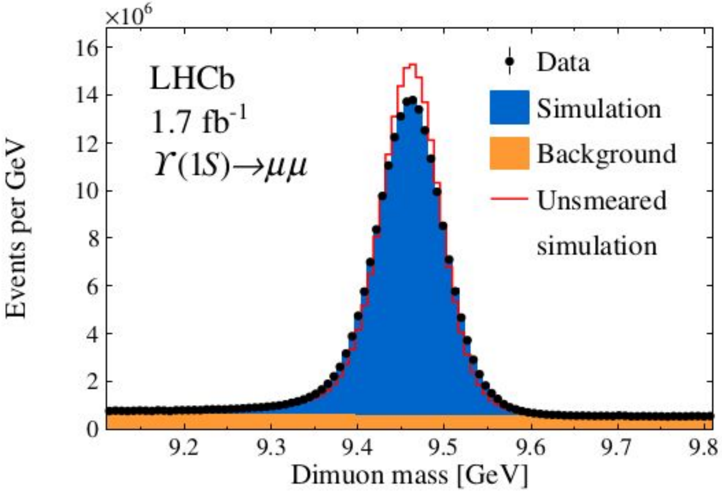


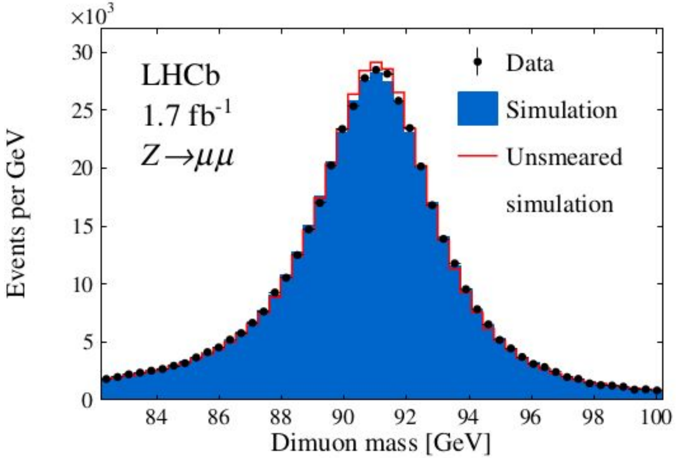


LHCb measurement

- Muon momentum calibrations with resonances
- For both muons 2 < |η| < 4



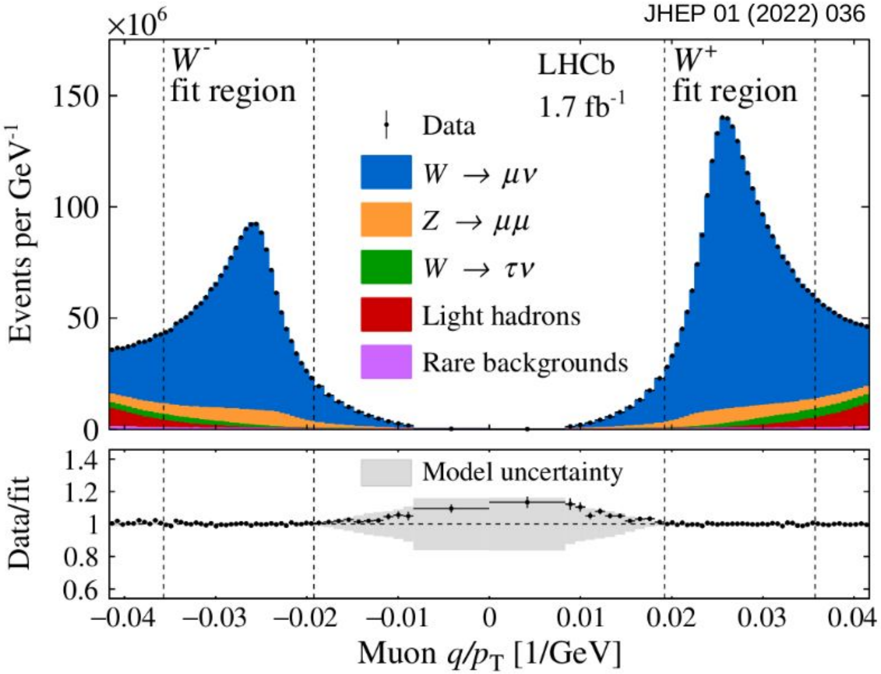




JHEP 01 (2022) 036

LHCb measurement

JHEP 01 (2022) 036

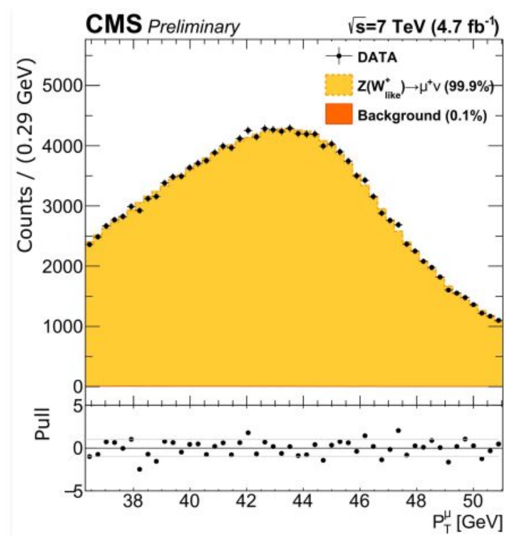


Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

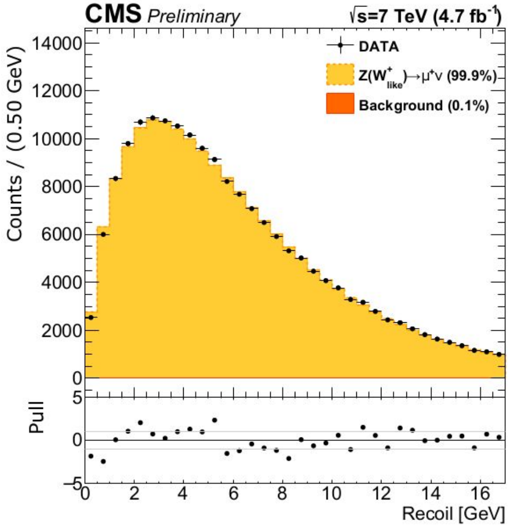
- m_W = 80354 ± 23stat ± 10exp ± 17theory ± 9PDF MeV

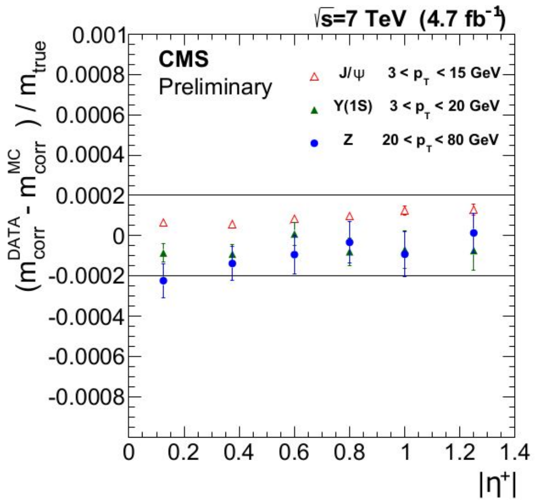
CMS

- "W-like" measurement of the Z mass with 7 TeV data
  - Remove one muon
- Central muons only (|η|< 0.9)
- Step towards establishing experimental techniques for m_W measurement
- Muon momentum calibration with J/ψ and Y(1S)
  - Validated on Z events
- Track based Recoil correction in Z events



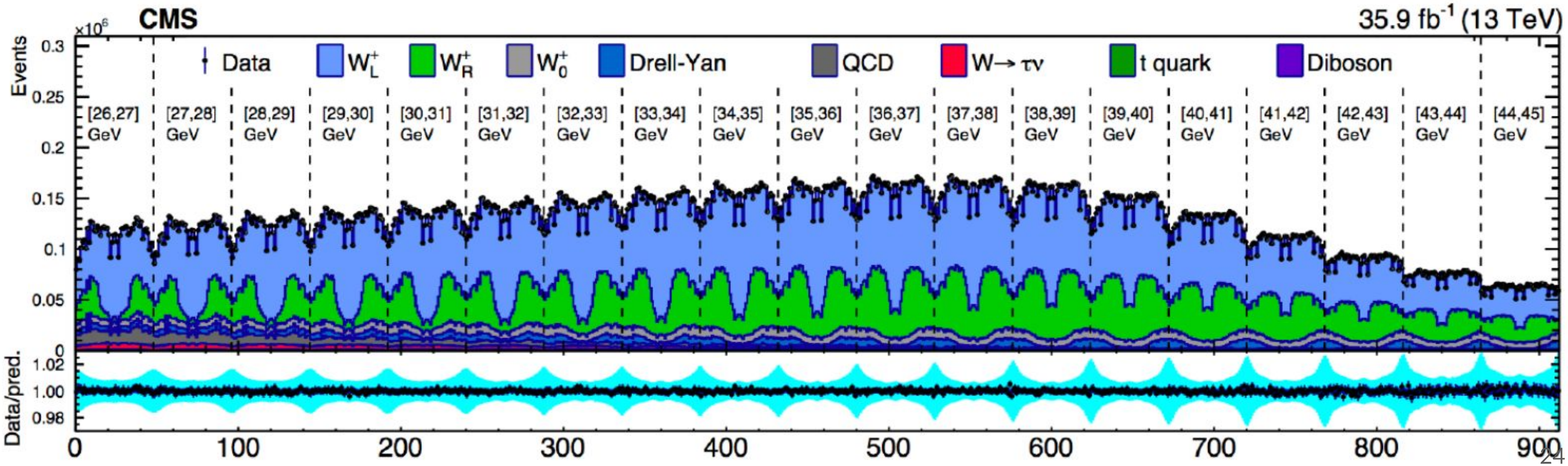
CMS PAS
SMP-14-007





CMS

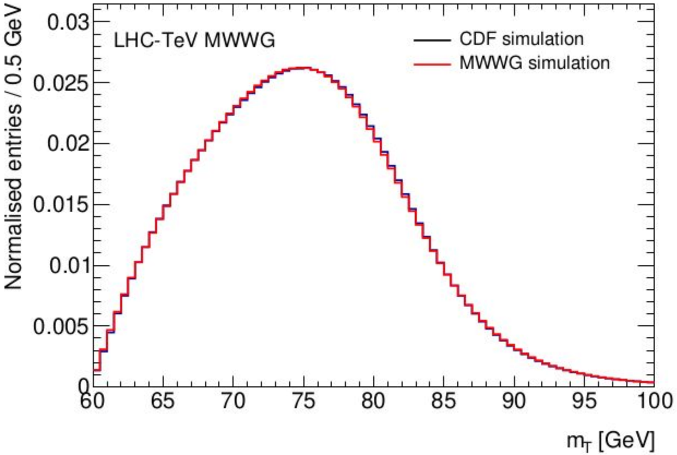
- Intermediate milestone O(100 M) W events within detector fiducial acceptance in just 2016 data-taking → Differential measurement of W rapidity, helicity, and charge asymmetry
- Pure left handed coupling of the W means that polarization and rapidity of the W are strongly correlated with the direction of the incoming quark vs antiquark, and subsequently with the direction of the outgoing charged lepton
  - W rapidity and helicity are inferred statistically from lepton p_T-eta distribution
  - Sensitivity to constrain PDFs directly from data



Combination of m_W

- Effort to combine the measurements at Tevatron and LHC
- Non-trivial to start with → Measurements performed at different times, using different baseline PDFs and QCD tools, different experimental conditions
- Strategy
  - correct to common PDF & QCD accuracy
  - Detector simulations used in the original ATLAS, CDF, and D0 measurements are simplified so that large event samples can be simulated for a variety of PDF sets → study effects of using different PDF sets

arXiv:2308.09417v1



- Average of all measurements except CDF : m_W = 80369.2 ± 13.3 MeV
- New, independent measurements required !!!

Outlook

- 40 years since the discovery of W/Z
  - Still important for precision tests of the SM

- Measurements of m_W already have a long history.
  - Crucial parameter → deviation from SM predictions → indirect evidence of BSM physics

- Developments in both experimental techniques and accuracy of theoretical predictions

- Main challenges
  - Modelling of W production and decay
  - Detector calibrations

- CDFII measurement in significant tension with SM predictions

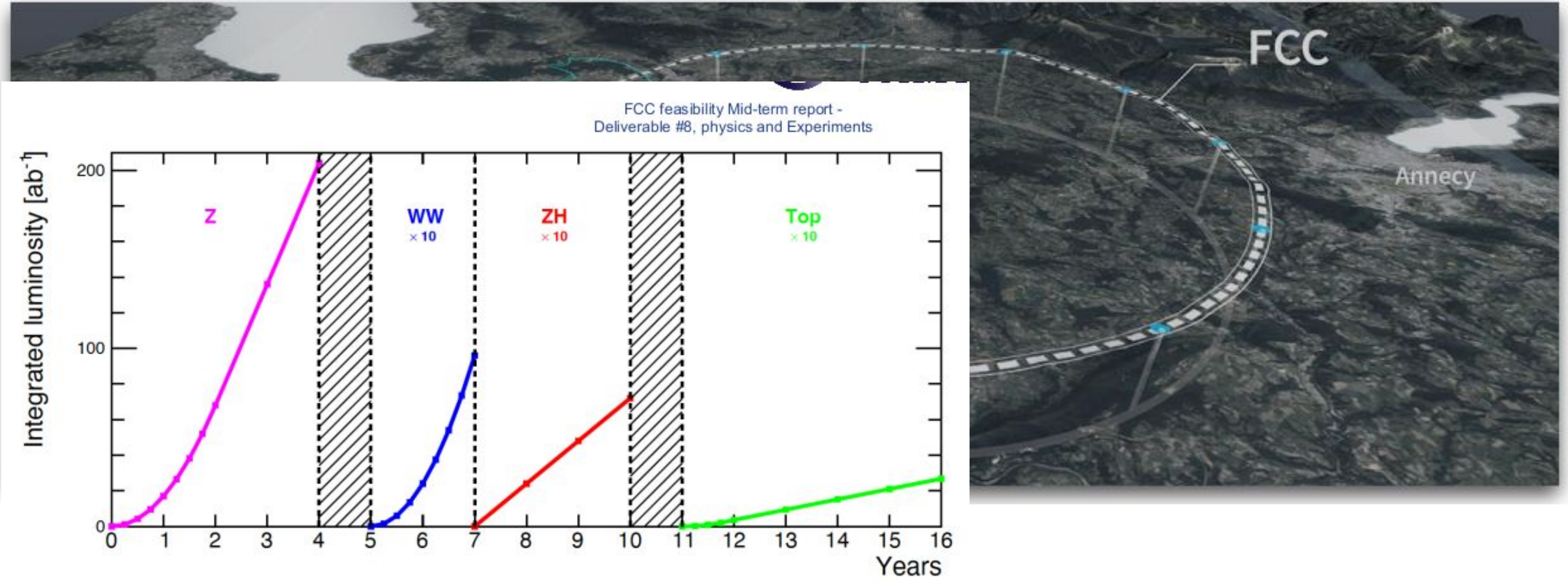
- New measurements are needed → LHC full Run 2 gives an excellent opportunity to improve the measurements

- Target at LHC $\Delta m_W < 10$ MeV

Back to the Future

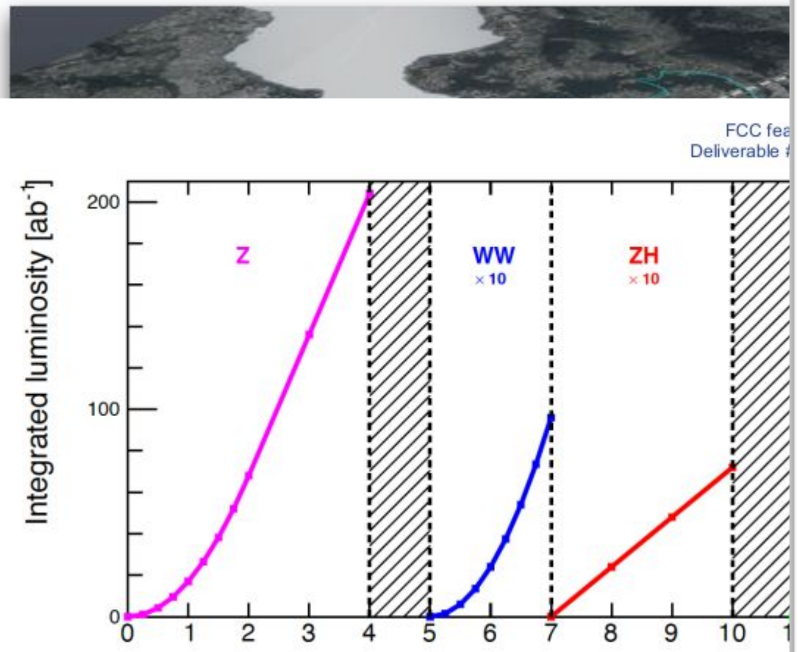
- 1st stage collider, FCC-ee: electron-positron collisions 90-365 GeV → precision measurements of W, Z, H

Back to the Future



- 1st stage collider, FCC-ee: electron-positron collisions 90-365 GeV → precision measurements of W, Z, H
- Physics operation: 2048-2063

Back to the Future



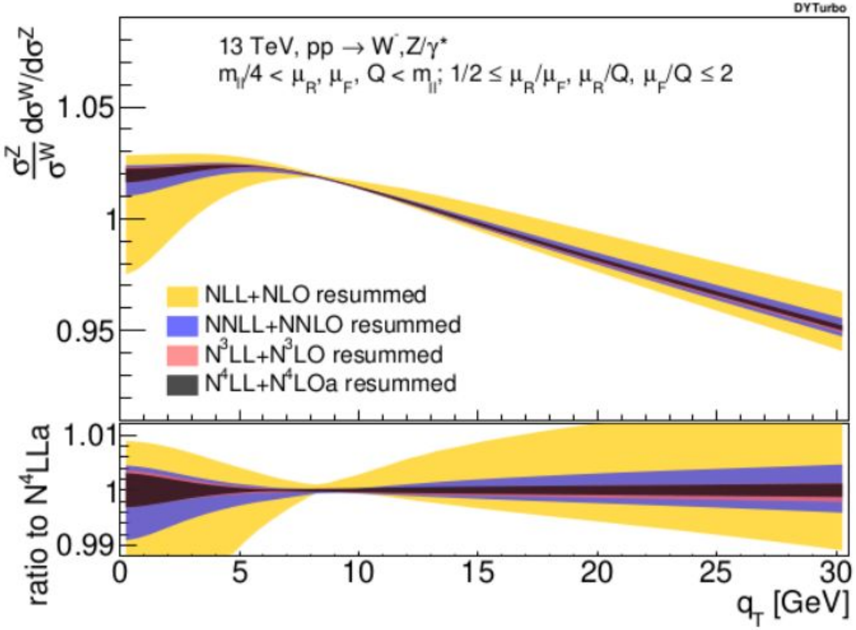
Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration

- 1st stage collider, FCC-ee: electron-positro
- Physics operation: 2048-2063
- **Sub MeV precision**
  - **10E13 W events**

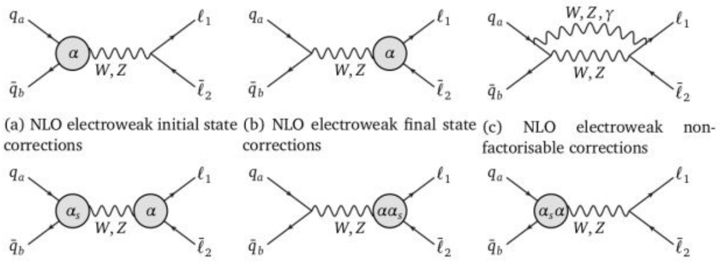
BACKCUP

Theory corrections

Phys.Lett.B 845 (2023) 138125 + Refs.



QCD x EW corrections
SciPost Phys. Proc. 7, 003 (2022)



(a) NLO electroweak initial state corrections (b) NLO electroweak final state corrections (c) NLO electroweak non-factorisable corrections

δm_W [MeV]		$\mu = m_V/4$	$\mu = m_V/2$	$\mu = m_V$
Inclusive	NLO EW	−0.1	0.3	0.2
	QCD-EW	−5.1	−7.5	−9.3
Fiducial	NLO EW	0.2	2.3	4.2
	QCD-EW	−16	−17	−19
Tuned fiducial	NLO EW	−4.4	−2.5	−0.8
	QCD-EW	3.9	−1.0	−5.7