News from the W boson

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Seminar at Birmingham University

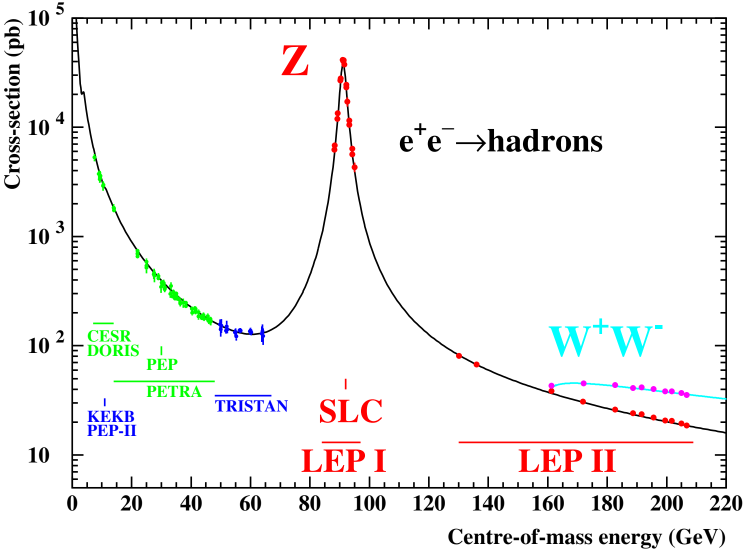
17.1.2024

40 years since the discovery of the W and Z bosons

- Force carriers of the electro-weak interaction, aquire their mass from the interaction with the Higgs boson (that was only discovered $\sim$ 30 years later)
- Discovered in $p\bar{p}$ collisions at CERN SPS

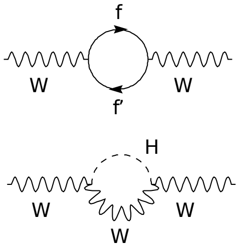
W and Z Physics

- Electroweak sector (almost) completely fixed with just three parameters, e.g. α, G_F, m_Z
- Dedicated $e^+e^- \to Z$ program at LEP (and SLAC) $\sim$ 20 million Z bosons, but only few W bosons



W-boson mass and Electroweak fit

[JHEP 12 (2013) 084, Gfitter, PRD 88 (2013) 052018]

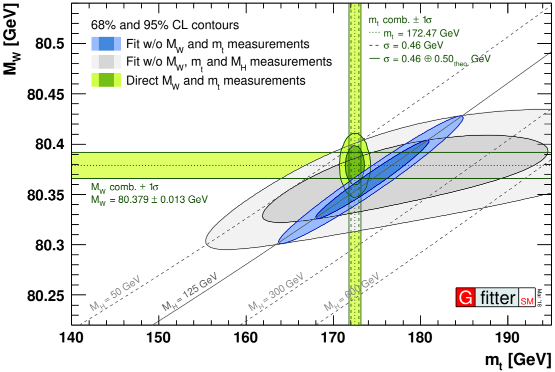


- W-boson mass related to other SM parameters

$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Precise value sensitive to loop-corrections: QED, top quark, Higgs boson
- Meanwhile, the indirect SM prediction of the W boson mass has become very precise and a great place to search for the indirect BSM search

$$\begin{aligned} M_W &= 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \\ &\quad \pm 0.0024_{\Delta\alpha_{\text{had}}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W}\ \text{GeV}\,, \\ &= 80.354 \pm 0.007_{\text{tot}}\ \text{GeV}\,, \end{aligned}$$

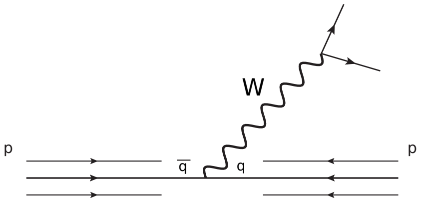


Results presented today

- *Compatibility and combination of world W-boson mass measurements*, arXiv:2308.09417, subm. to EPJC
- *Improved W boson Mass Measurement using $\sqrt{s} = 7$ TeV Proton-Proton Collisions with the ATLAS Detector*, ATLAS-CONF-2023-004
- *Precise measurements of W and Z transverse momentum spectra with the ATLAS detector at $\sqrt{s} = 5.02$ TeV and 13 TeV*, ATLAS-CONF-2023-028

How to measure the W-boson mass

- Ultimate goal: δm_W better than SM prediction, i.e. $\lesssim 8$ MeV $= 0.01\%$
- Single W bosons produced hadron collisions: $q\bar{q}' \to W$, e.g. TeVatron ($p\bar{p}$) and LHC (pp)



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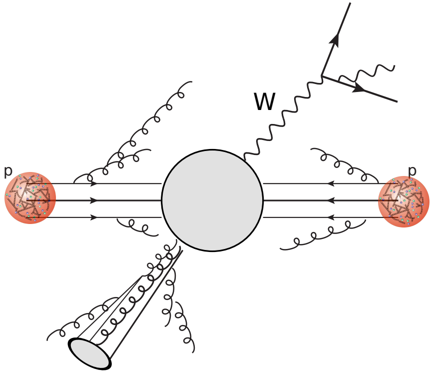
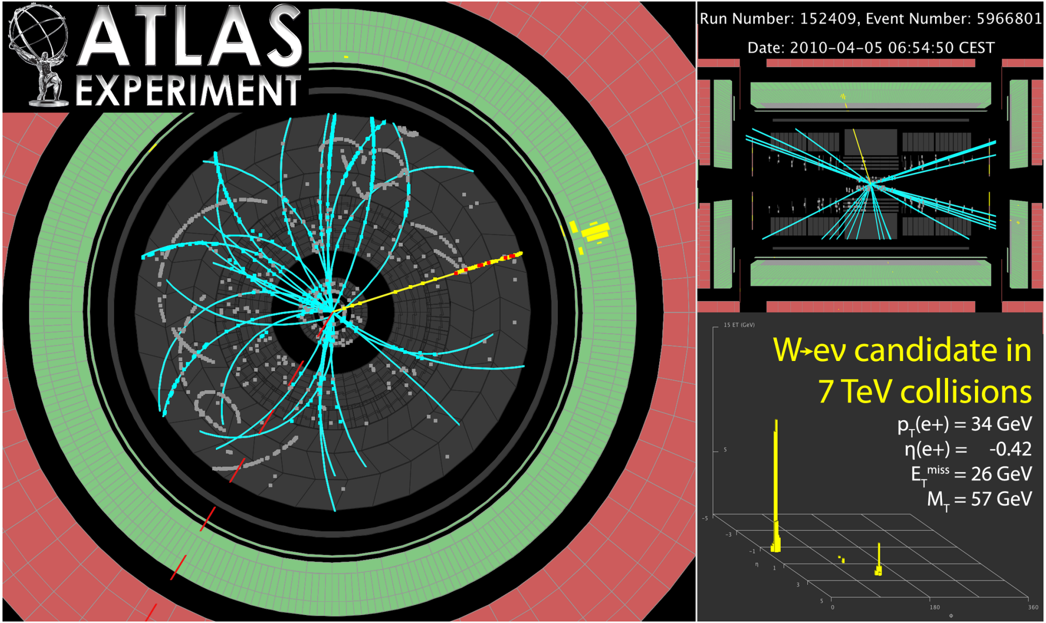
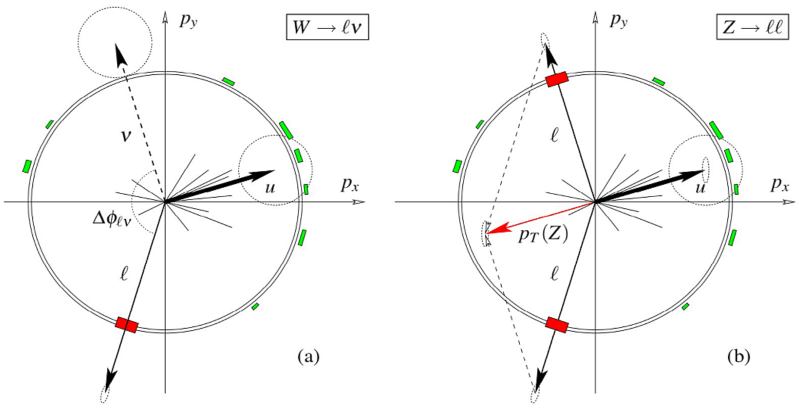


- Huge event samples available (millions), but unfortunately high-energy hadron collisions apriori not a "precision environment" – a tall mountain to climb:
  - Leptonic final state in Drell–Yan process $pp \to \ell\nu$ eliminates the worst problems from strong interactions, but we now have to compensate for the "missing" information from the neutrino
  - Z production $pp \to \ell\ell$ invaluable to constrain models and calibrate detector
  - Precision QCD and EW calculations and excellent knowledge of PDFs to compute Z-to-W differences

A $W \to e\nu$ candidate

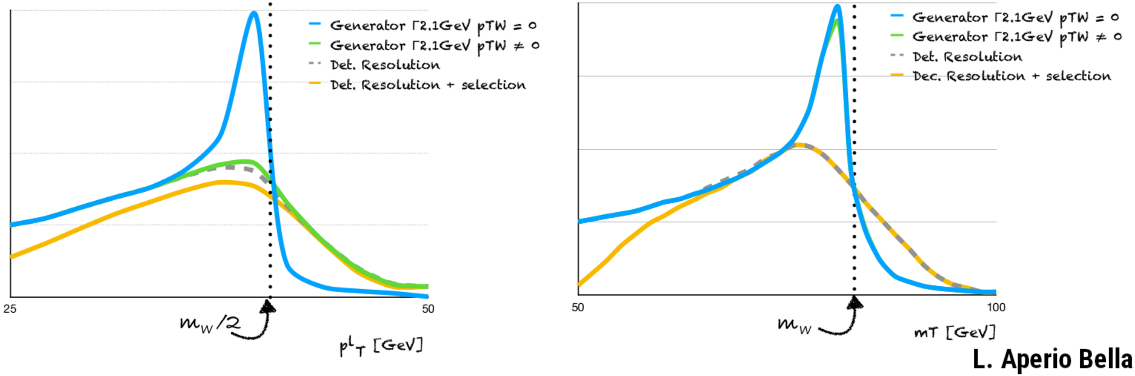


The transverse view



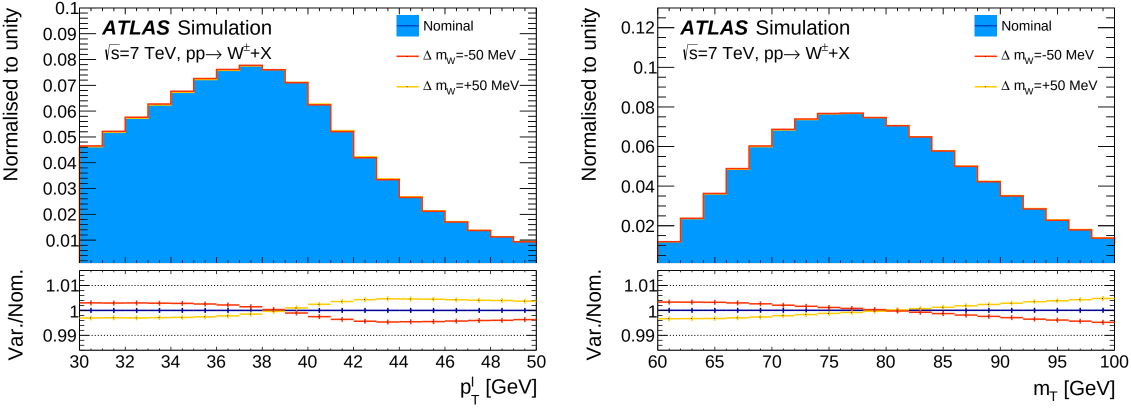
- Collision balanced transversely to the beam (but not longitudinally)
- Lepton transverse momentum p_T^ℓ
- Remainder of the event: "hadronic recoil" $\vec{u}_T = p_T^W$
- neutrino inferred using $\vec{p}_T^{\text{miss}} = -(\vec{p}_T^\ell + \vec{u}_T)$
- transverse mass $m_T = \sqrt{2 p_T^\ell p_T^{\text{miss}} (1 - \cos \Delta\phi)}$

The transverse view



- Quantities sensitive to m_W affected by "physics" and "detector effects", while we eventually need to understand them to 0.1%
- Some analyses (e.g. ATLAS) split the sample into many categories with $W^{\pm}$, e/μ, forward/central
- Obviously all these analyses are blinded w.r.t. the final m_W , sometimes in several steps

The transverse view



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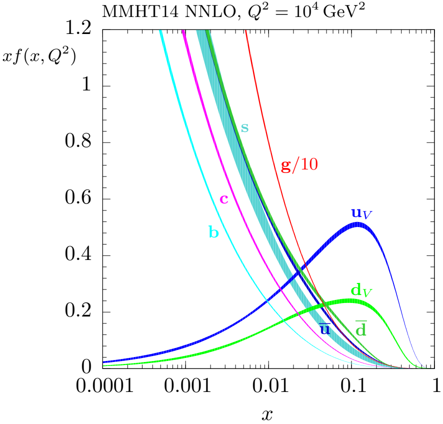
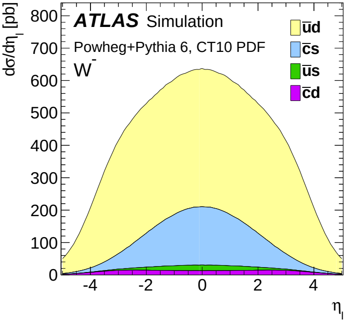
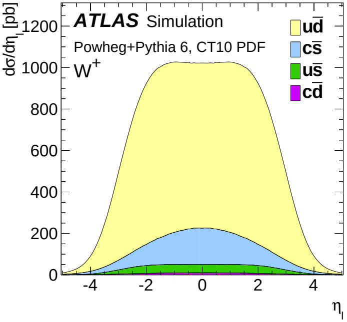
The longitudinal view

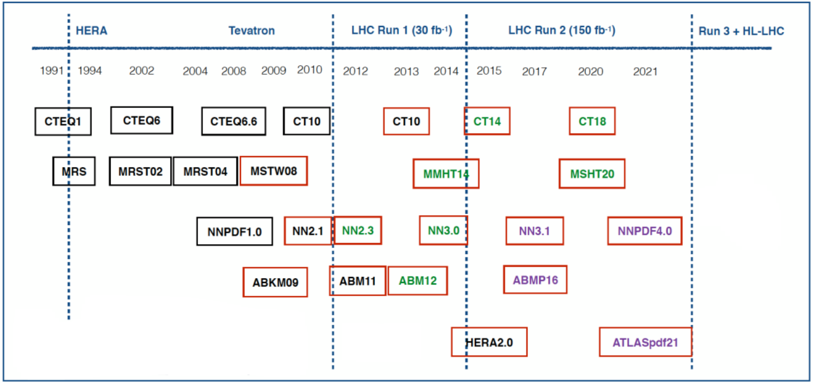
- Longitudinal imbalance in W production in hadron collisions due to variable and unknown momentum fractions x_1, x_2 of initiating quarks: statistically given by Pparton Distribution Functions (PDFs)
- Flavour matters as well: LHC has more heavy flavour contributions compared to TeVatron

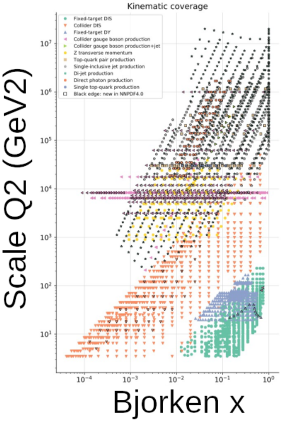






PDFs in a nutshell





- Input from Deep Inelastic Lepton-Nucleon scattering and other diverse data
- Last decades saw improvements in theory, input data and fit methodology: a lot of interesting QCD physics, and an art in itself
- Fit groups: CT, MMHT/MSHT, NNPDF, in addition ABM+, HERA and HERA+LHC analyses
- In principle, different groups fit mostly the same data with the same theory and provide uncertainties... good enough for m_W ?

The complete "physics model"

- Typical factorisation of five-dimensional DY cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_1 p_2} = \frac{\mathrm{d}\sigma}{\mathrm{d}m}\frac{\mathrm{d}\sigma}{\mathrm{d}p_T}\frac{\mathrm{d}\sigma}{\mathrm{d}y}\left[1 + \cos^2\theta_{CS} + \sum_{i=0}^{7} A_i(m, p_T, y) f_i(\theta_{CS}, \phi_{CS})\right]$$

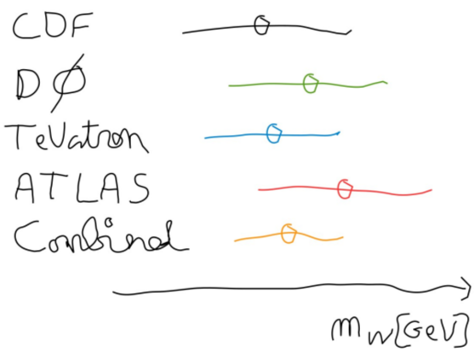
- $\frac{\mathrm{d}\sigma}{\mathrm{d}m}$: the Breit-Wigner resonance that contains m_W
- $\frac{\mathrm{d}\sigma}{\mathrm{d}p_T}$: transverse momement, typically constrained by $Z \to \ell\ell$ + theory, but can also be measured in W events
  - Will come back to this in the final part of the talk
- $\frac{\mathrm{d}\sigma}{\mathrm{d}y}$: rapidity dependence given by PDFs & higher order QCD
- Angular coefficients A_i assuming spin-1 boson: higher order QCD with some PDF dependence, can be validated in $Z \to \ell\ell$

The current status of m_W measurements

arXiv:2308.09417 (subm. to EPCJ)

- Best measurements from hadron colliders: non-trivial correlations in the physics model, hard to preserve the analyses
- The LHC-TeVatron EW working group took on the charge:
  - Improved understanding of QCD and PDF effects (and correlations)
  - Provide a collaboration endorsed world-average of m_W measurements

2018 – 2020



M. Boonekamp

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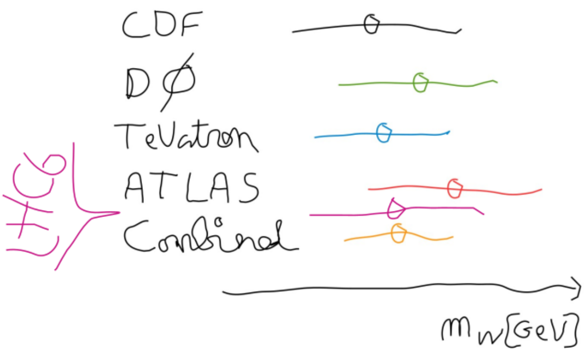
2021



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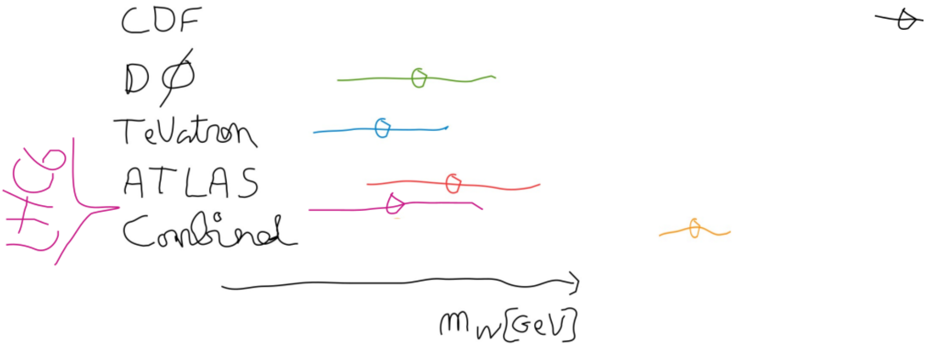
2022



M. Boonekamp

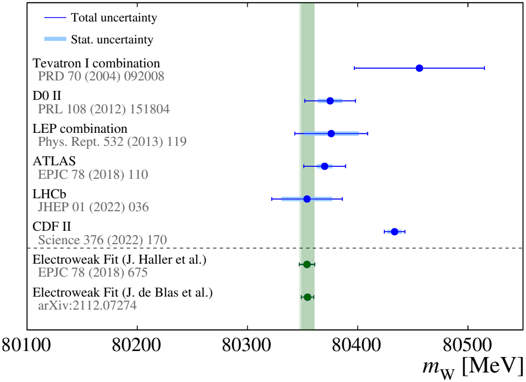
Inputs and Analysis strategy

- Challenging measurements typically take multiple years to deliver, using tools and theory modelling available at the time
- Developed an "update procedure":

$$m_W^{updated} = m_W^{ref.} + \delta m_W^{QCD} + \delta m_W^{PDF}$$

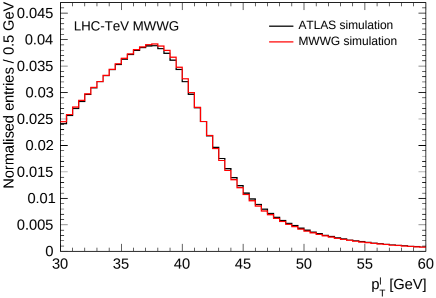
published | Improved predictions, for reference PDF | PDF extrapolation

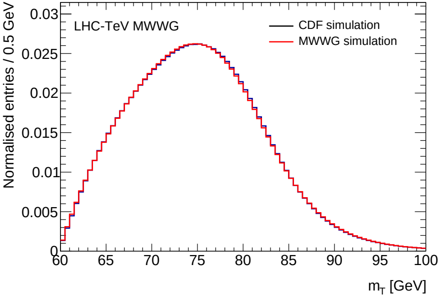
- $\delta m_W^{\mathrm{PDF}}$: Correct measurements to a new, common PDF baseline
- $\delta m_W^{\mathrm{QCD}}$: Correct theory "problems" post-hoc, if beyond the quoted uncertainties
- Need archeology to understand how m_W^{ref} was obtained (papers usually wrong...)



Starting point and Detector Emulation

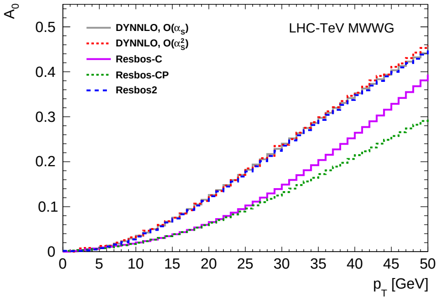
- Original QCD tools and PDFs
  - CDF: Resbos1 (NLO) with CTEQ6M (NLO), corrected post-hoc to NNPDF3.1
  - D0: Resbos1 (NNLO) with CTEQ6.6 (NLO)
  - ATLAS: Powheg+Pythia corrected to NNLO with CT10nnlo
  - LHCb : Powheg+Pythia with NNLO corrections and PDF average of NNPDF3.1,CT18,MSHT20 (NLO)
- The original detector-level analysis is usually not accessible (LHCb the exception so far) – instead generate large samples (Powheg NLO and NNLO) and apply fast emulation of detector effects
- Verified to be good enough to assess shifts from changed theory δm_W at better than 1 MeV





QCD/generator corrections for TeVatron

- Uncovered a wrong modelling of decay angular coefficients in ResBos used for TeVatron analyses: correction of about $\delta m_W = -10$ MeV
- In addition: inconsistent W width assumption (D0), distortion/cutoffs in line shape...
- CDF (unknowingly?) performed a single correction for PDFs and angular coefficient modelling and eventually needs little correction



Coefficient	m_T	p_T^ℓ	p_T^ν
A_0	-6.3	-2.6	-9.1
A_1	1.1	1.3	0.3
A_2	-0.7	0.4	-3.2
A_3	-2.1	-4.1	1.0
A_4	-1.4	-3.3	-1.6
$A_0 - A_4$	-9.5	-8.4	-12.5
ResBos2	-10.2 ± 1.1	-7.6 ± 1.2	-11.8 ± 1.4
Difference	-0.7 ± 1.1	0.8 ± 1.2	0.7 ± 1.4

Table 7: Values of $\delta m_W^{\rm pol}$ in MeV associated with reweighting each A_i coefficient from ResBos-C to ResBos2 for the CDF detector, as well as the result of a direct fit to ResBos2. The result of the direct fit is consistent with that of the reweighting.

PDF extrapolations

- A fact conveniently ingored in all (!) previous m_W combinations: measurements should be corrected to the same PDF set before combination
- Effects can easily be of the same order as the quoted PDF uncertainty

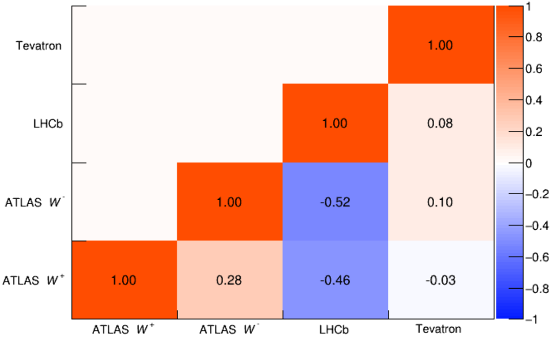
PDF set	D0 p_T^ℓ	D0 p_T^ν	CDF p_T^ℓ	CDF p_T^ν	ATLAS W^+	ATLAS W^-	LHCb
CTEQ6	−17.0	−17.7	0.0	0.0	–	–	–
CTEQ6.6	0.0	0.0	15.0	17.0	–	–	–
CT10	0.4	−1.3	16.0	16.3	0.0	0.0	–
CT14	−9.7	−10.6	5.8	6.8	-1.2	−5.8	1.1
CT18	−8.2	−9.3	7.2	7.7	12.1	−2.3	−6.0
ABMP16	−19.6	−21.5	−1.4	−2.4	−22.5	−3.1	7.7
MMHT2014	−10.4	−12.7	6.1	5.5	−2.6	9.9	−10.8
MSHT20	−13.7	−15.4	3.6	4.1	−20.9	4.5	−2.0
NNPDF3.1	−1.0	−1.2	14.0	15.1	−14.1	-1.8	6.0
NNPDF4.0	6.7	8.1	20.8	24.1	−22.4	6.9	8.3

Table 3: Values of $\delta m_W^{\rm PDF}$ in MeV for each PDF set using the p_T^ℓ (all experiments) or p_T^ν (CDF and D0) distribution, determined using the WJ-MiNNLO calculation.

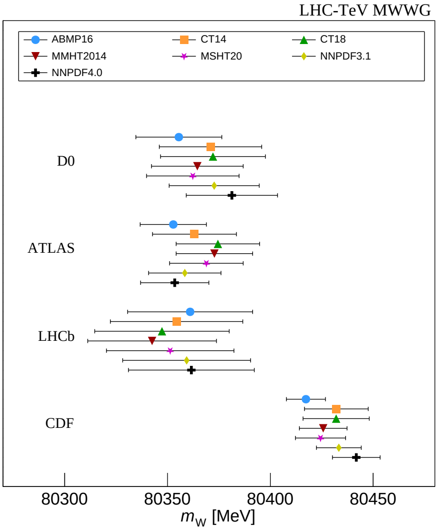
PDF uncertainties and correlations

- Uncertainty perfectly reproduced for ATLAS, while published values for CDF (3.9 MeV) and D0 (11 MeV) established to be underestimates
- Vast difference in uncertainties using different PDF sets
- Non-trivial PDF correlation pattern across $p\bar{p}$, pp and central/forward
- Choose the CT18 PDF set due to the best compatibility with PDF-sensitive data (not shown) – largest uncertainty on m_W

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



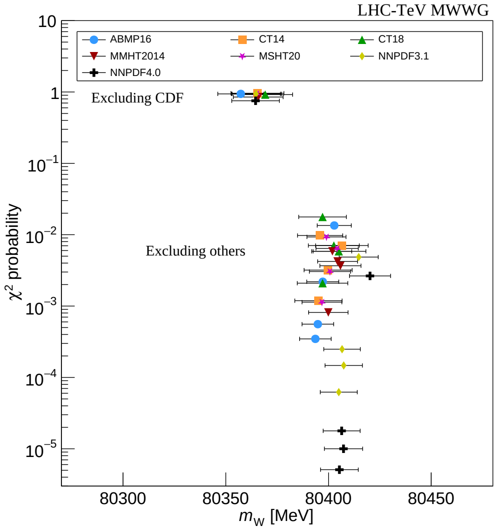
Combination



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%

- After all corrections applied: combination fails for each PDF set

Conclusion for the Combination



- Excluding single experiments gives a clear pattern:
  - Combinations without CDF work regardless of PDF set

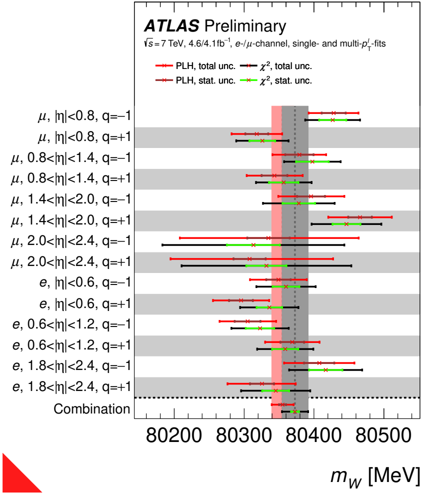
$$m_W = 80369.2 \pm 13.3\,\mathrm{MeV}$$

    with 91% probability for the CT18 PDF set
  - The new CDF measurement is incompatible at 3.6σ, even though the PDF uncertainty using CT18 is far larger than the published one
- Where next?

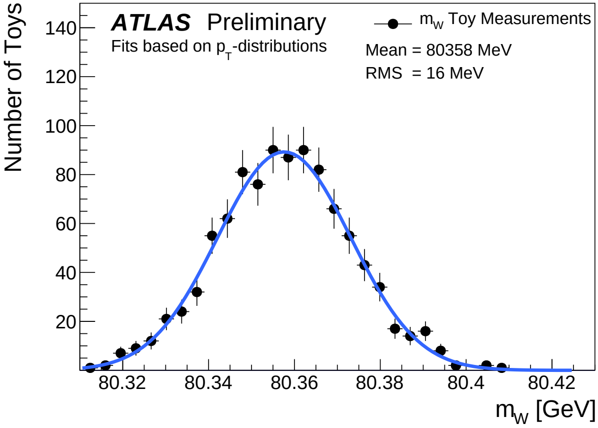
Revisiting the ATLAS m_W measurement

EPJC 78 (2018) 110, ATLAS-CONF-2023-004

- First m_W measurement at the LHC was published by ATLAS in late 2016: $m_W = 80370 \pm 19$ MeV
- At the time proof "it could be done" and tied for best uncertainty with CDF
- Reanalysis with a Profile Likelihood fit joined across all categories instead of "classic" χ^2 fits with offset error propagation



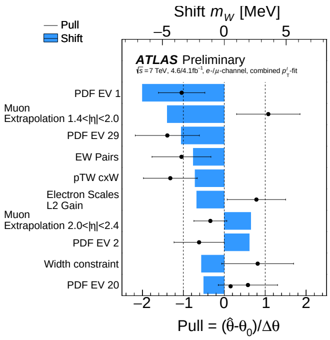
- Expected a reduction of uncertainty, shift in central value of $O(16$ MeV$)$ possible

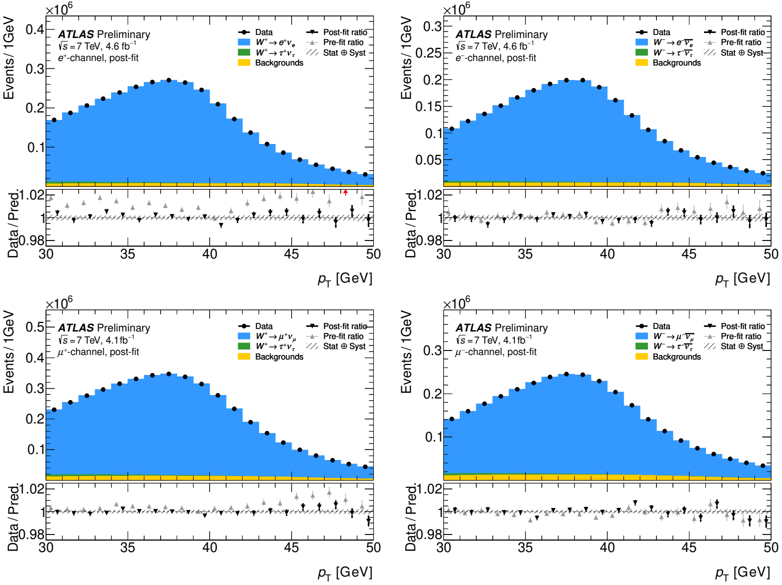


Sensitive distributions

ATLAS-CONF-2023-004

Parameters controlling the correlated uncertainties are shifted and constrained: shift in central value, smaller uncertainty, better Data/Prediction ratios

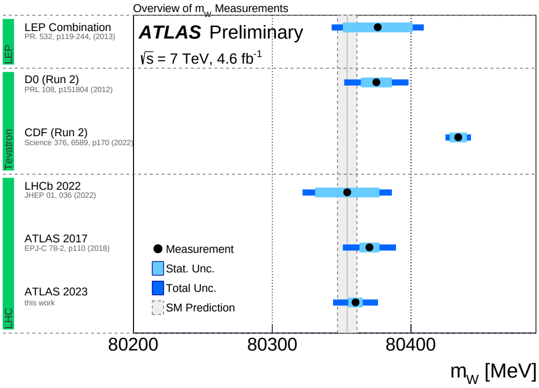




ATLAS Reanalysis results

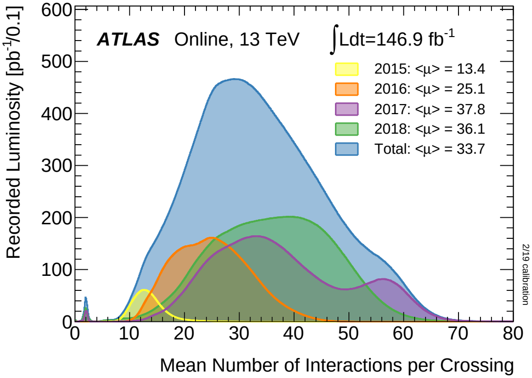
- Study of PDF dependence: all results lower than previous result, NNPDF again significantly lower
- Using CT18 set: $m_W = 80360 \pm 16$ MeV
  - 15% better uncertainty than previous publication
  - One also notices this is closer to the SM and further away from CDF...

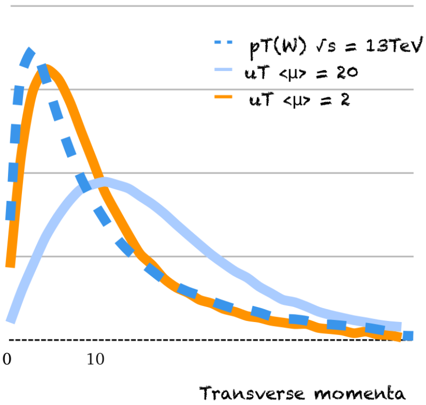
PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$



Analysis of ATLAS low-pileup data

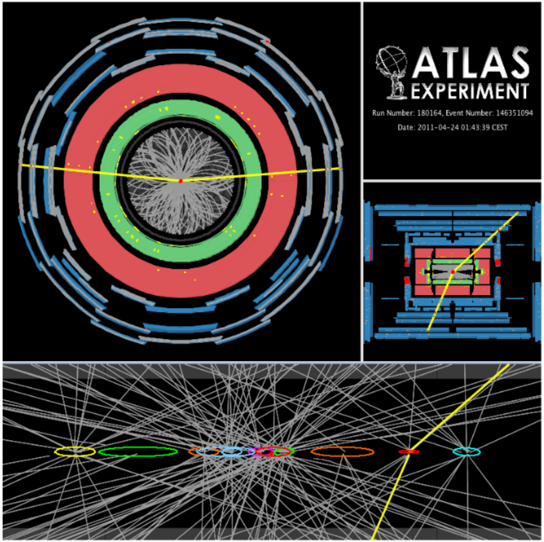
- Usually LHC delivers maximum luminosity to ATLAS and CMS: average of 20-70 simultaneous *pp* collisions
- Pileup fills the calorimeters with noise and worsens the "hadronic recoil" measurement
- However, ATLAS took some special datasets at $\sqrt{s} = 5$ and 13 TeV: direct measurement of p_T^W (now) , bringing back m_T into the game for m_W (future)
- Also profit from the best luminosity measurements ever at a hadron collider: $\Delta\mathcal{L} \lesssim 1\%$



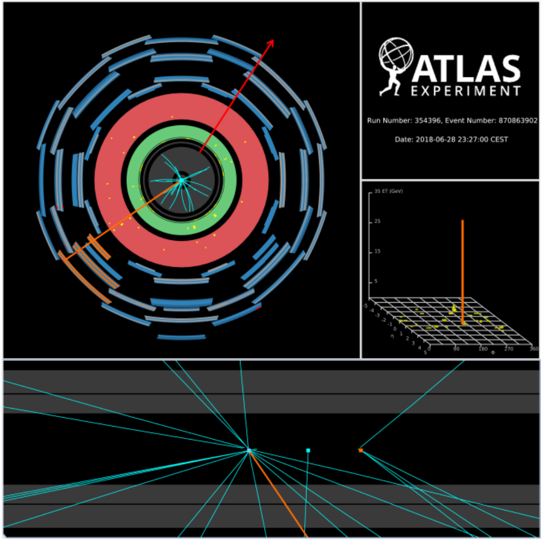


L. Aperio Bella

ATLAS low-pileup data



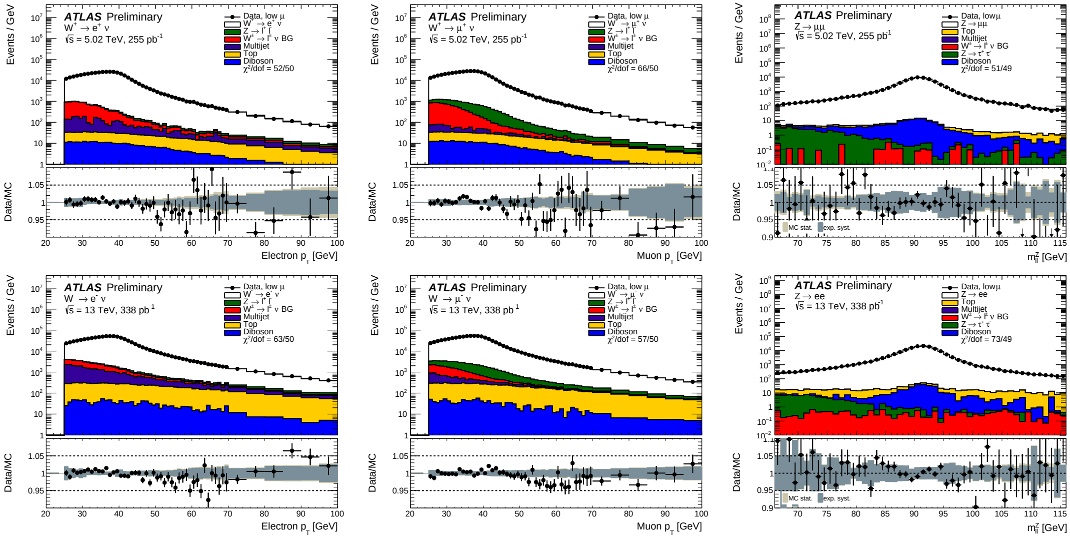
9 additional reconstructed vertices



2 additional reconstructed vertices

ATLAS low-pileup data

- Obviously, we had to calibrate the leptons and the hadronic recoil and determine the backgrounds

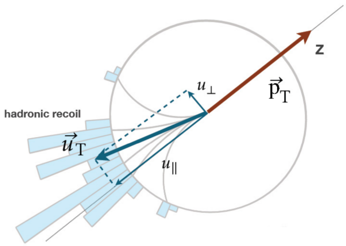


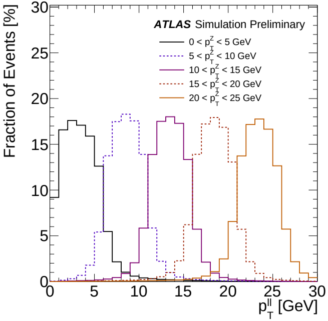
Results and Cross checks

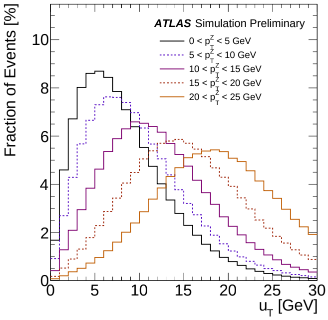
- Among the most precise cross W and Z cross sections at a hadron collider, good agreement with NNLO+NNLL QCD predictions from DYTURBO

Process	Cross section at $\sqrt{s} = 5.02\,\text{TeV}$ [pb]	Cross section at $\sqrt{s} = 13\,\text{TeV}$ [pb]
$W^- \to \ell\nu$	1385 ± 2 (stat.) ± 5 (sys.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (sys.) ± 34 (lumi.)
$W^+ \to \ell\nu$	2228 ± 3 (stat.) ± 8 (sys.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (sys.) ± 44 (lumi.)
$Z \to \ell\ell$	333.0 ± 1.2 (stat.) ± 2.2 (sys.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (sys.) ± 7.1 (lumi.)

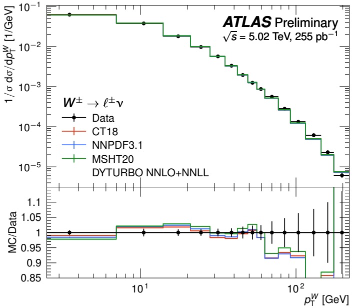
- Differential measurement of boson p_T distributions challenging to unfold with 5 – 10 GeV wide bins

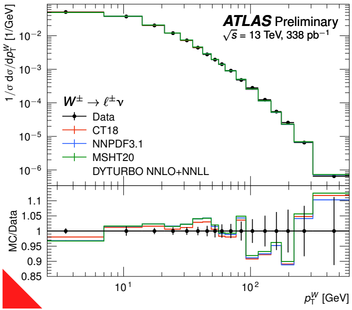






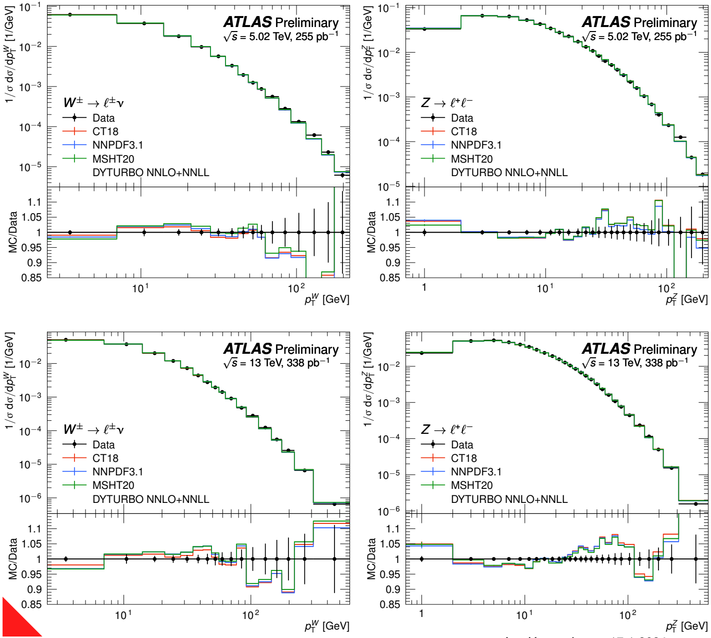
Boson p_T measurement: NNLO+NNLL QCD





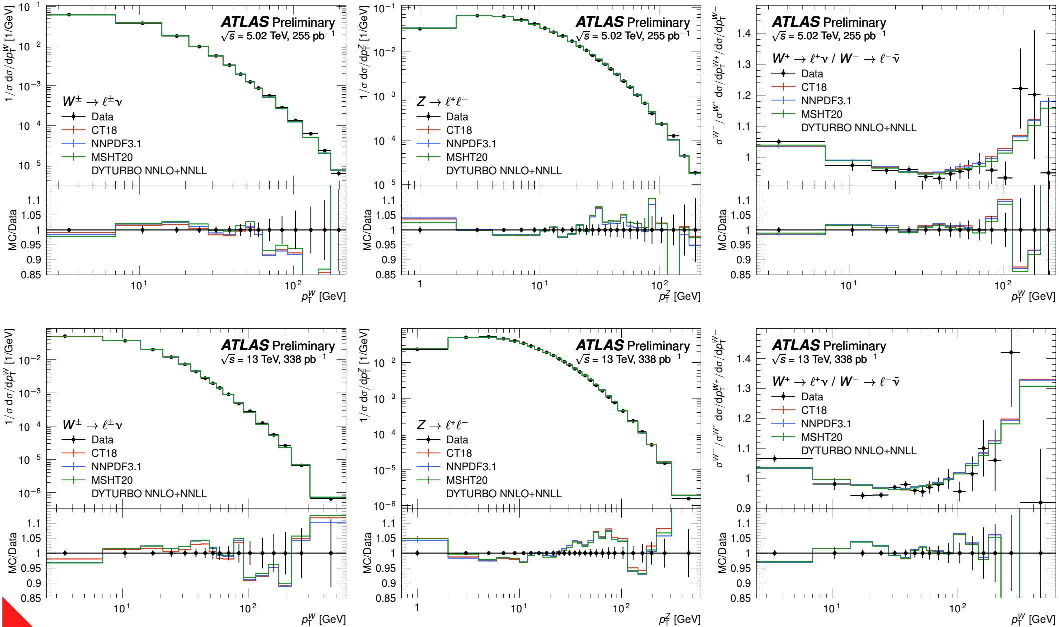
- A p_T^W measurement in $\sim$ 7 GeV bins at 1–2% accuracy
- Acceptable agreement with NNLO+NNLL QCD prediction

Boson p_T measurement: NNLO+NNLL QCD

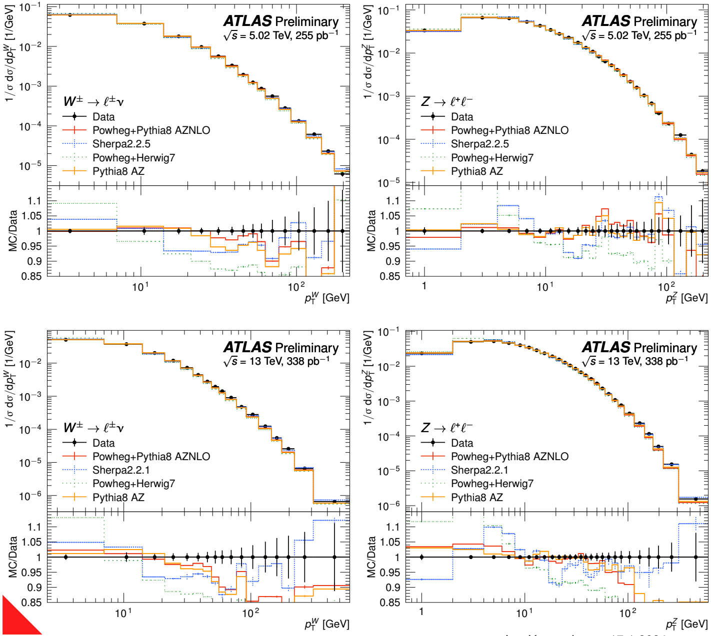


- A p_T^Z measurement in ~ 3 GeV bins at $< 1\%$ accuracy
- Acceptable agreement with NNLO+NNLL QCD prediction

Boson p_T measurement: NNLO+NNLL QCD



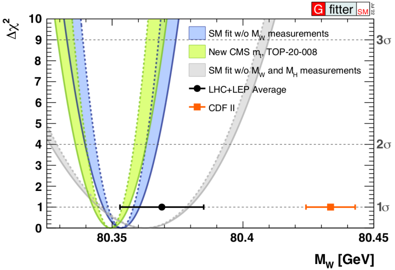
Boson p_T measurement: MC generators with Parton showers



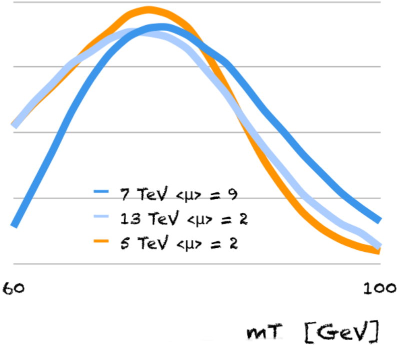
- Huge variability in parton shower MCs
- Those carefully tuned to $\sqrt{s} = 7$ TeV ATLAS data and used for m_W – Pythia8 AZ – do a good job, especially at $\sqrt{s} = 5$ TeV

Conclusions

- The W boson mass is among the key observables to constrain Beyond SM physics
- The experimental situation is not satisfactory: combination of All-CDF has excellent compatibility and similar precision as CDF alone, $> 3.6\sigma$ experimental discrepancy
- Preliminary improved ATLAS m_W reanalysis pushes the experimental measurement further towards the SM and away from CDF
- New (preliminary) ATLAS results on W and Z transverse momentum spectra at $1-2\%$ precision using dedicated low-pileup data open the road towards improvements in modelling for future m_W analyses and a competitive m_W measurement using m_T at LHC
- PDF knowledge appears yet insufficient to go below $\Delta m_W \sim 10$ MeV: exploit different environments & new data



L. Aperio Bella



Backup

June 26, 2022

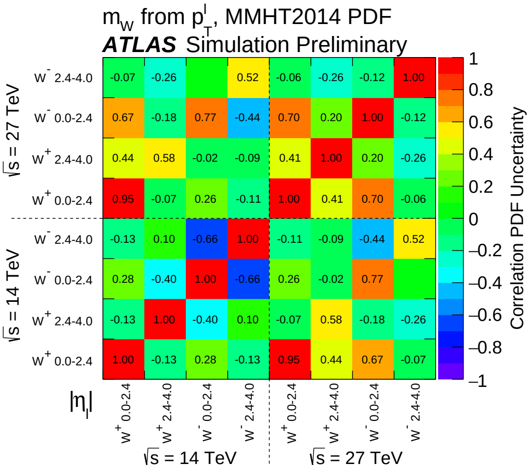
In 2012, D0 published a measurement of the W boson mass using 5.3 fb^{-1} of Tevatron data (Phys. Rev. Lett. **108**, 151804 (2012)), with a subsequent longer description (Phys. Rev. D **89**, 012005 (2014)). This measurement, **m_W = 80,375 ± 23 MeV**, remains the official D0 result.

A study of the remaining approximately 5 fb^{-1} of data taken between 2009 and 2011 showed that the deterioration of the detector due to radiation damage effects, combined with the higher pileup owing to the increased instantaneous luminosity, precludes a further precision measurement of the W boson mass.

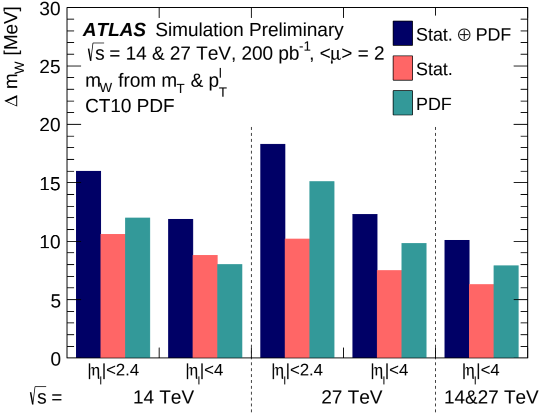
Correction	δm_W^{QCD} [MeV]					
	p_T^W-constrained			No constraint		
	p_T^ℓ	m_T	p_T^ν	p_T^ℓ	m_T	p_T^ν
Invariant mass	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Rapidity	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
A_0	7.6	10.0	15.8	16.0	12.6	19.5
A_1	-2.4	-1.9	-1.8	-1.2	-1.6	-1.4
A_2	-3.0	-2.6	2.9	-4.2	-3.0	2.3
A_3	2.9	1.6	-0.5	3.5	1.8	-0.2
A_4	2.4	-0.1	-0.5	0.1	-0.7	-1.0
$A_0 - A_4$	7.6	7.0	16.0	14.1	9.1	18.9
Total	7.6	7.0	16.0	14.1	9.1	18.9
ResBos2	7.3±1.1	8.4±1.0	16.6±1.2	13.9±1.1	10.3±1.0	19.8±1.2
Non-closure	-0.3±1.1	1.4±1.0	0.6±1.2	-0.2±1.1	1.2±1.0	0.9±1.2

Table 5: Effect of reweighting the angular coefficients in the D0 ResBos1 events to those of ResBos2, as well as a direct fit of ResBos1 to ResBos2. Good closure is observed.

W-boson mass



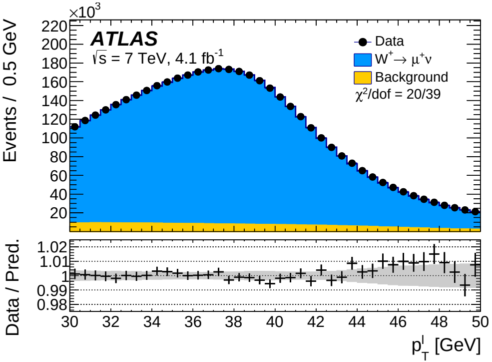
m_W from p_T^l, MMHT2014 PDF
ATLAS Simulation Preliminary
Correlation PDF Uncertainty
√s = 27 TeV
√s = 14 TeV
|η_l|

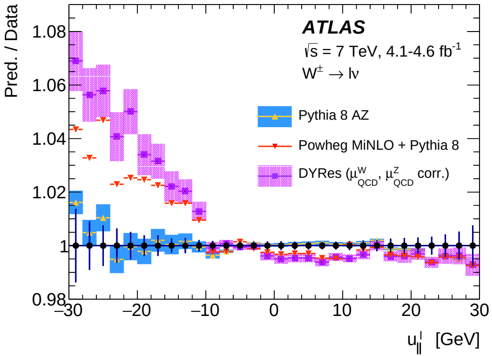


ATLAS Simulation Preliminary
√s = 14 & 27 TeV, 200 pb^-1, <μ> = 2
m_W from m_T & p_T^l
CT10 PDF
Stat. ⊕ PDF
Stat.
PDF
Δ m_W [MeV]
|η_l|<2.4
|η_l|<4
√s =
14 TeV
27 TeV
14&27 TeV

ATLAS Measurement of m_W

[EPJC 78 (2018) 110, ATL-PHYS-PUB-2018-004]



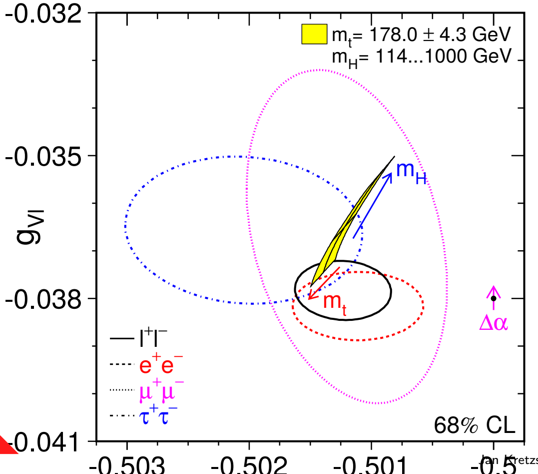


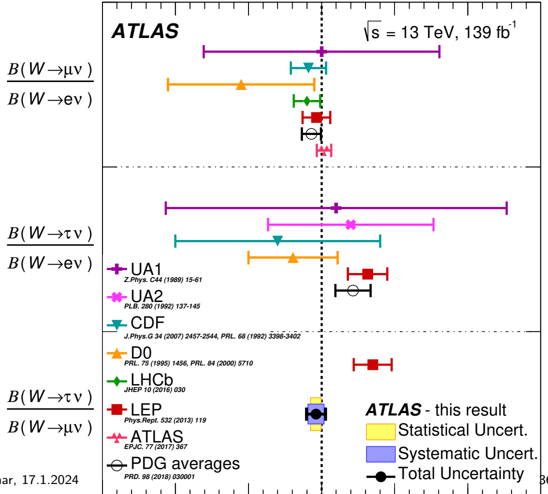
	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
W^+	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4
W^-	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4
$W^\pm$	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

[MeV]

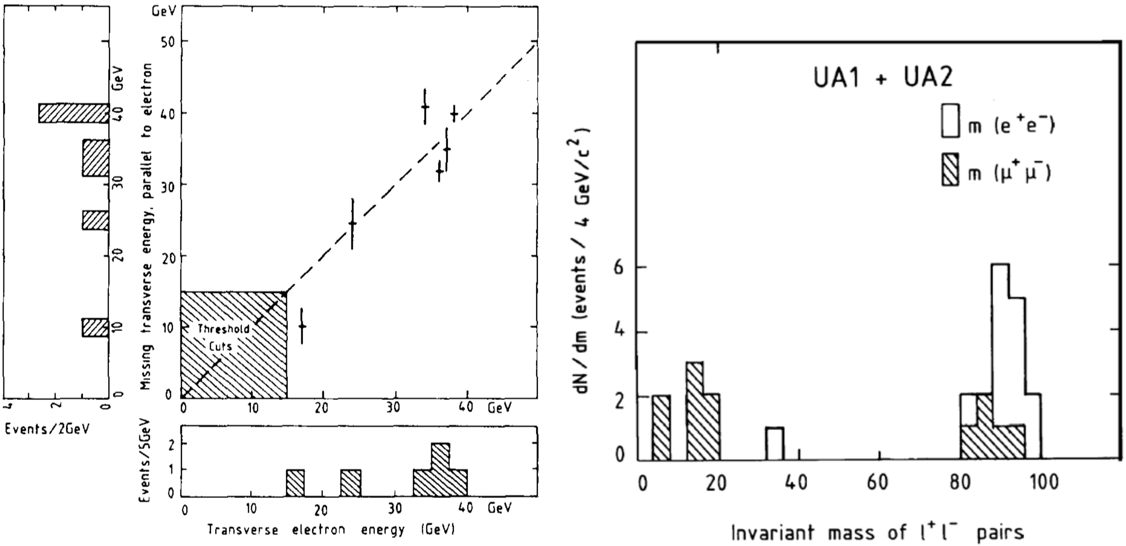
Lepton Universality

- In the SM the couplings of the leptons e, μ, τ to W and Z bosons are all the same, leading to same branching fractions
  (ignoring different masses — calculable effect)
- Very precisely measured at LEP for $Z \to ee, \mu\mu, \tau\tau$
- For W nowadays strongtest constraints from LHC (ATLAS) data

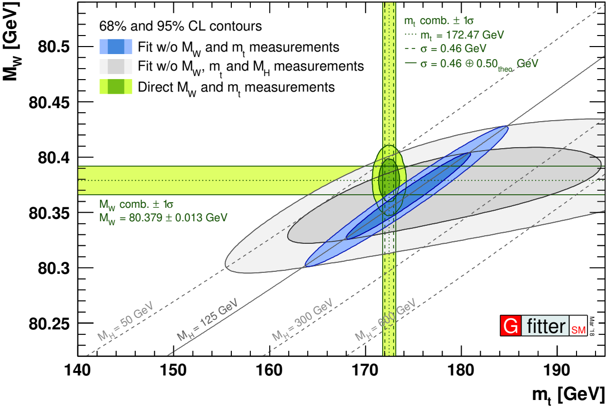


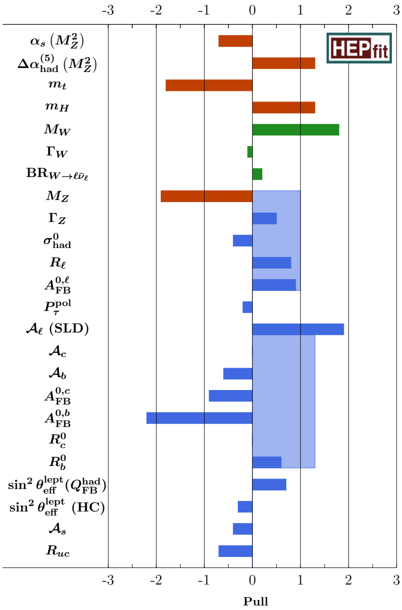


W and Z Physics



Precision Observables

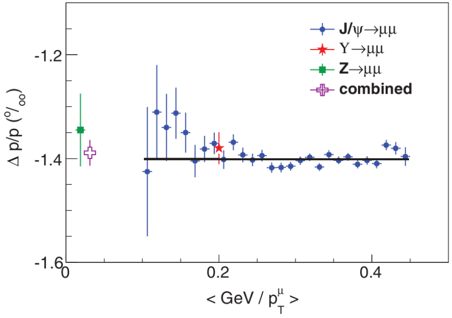


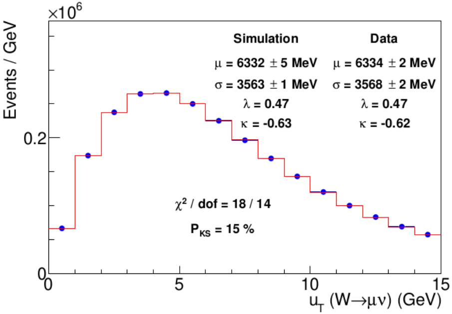


EPJC 78 (2018) 675 , arXiv:2112.07274

CDF W-boson mass

- Muons calibrated using high-statistics $J/\psi \to \mu\mu$ sample and transferred to electrons via E/p
- Measurement of Z-boson mass: $M_Z = 91\,192.0 \pm 6.4(\text{stat}) \pm 4.0(\text{syst})$ MeV in agreement with LEP
- W and Z boson production and decay simulated using RESBOS, $p_T(Z)$ spectrum tuned to Z data and validated on W
- Fit to m_T, p_T^ℓ and p_T^ν for $W \to e\nu$ and $W \to \mu\nu$





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Science 376, no.6589, 170 (2022)

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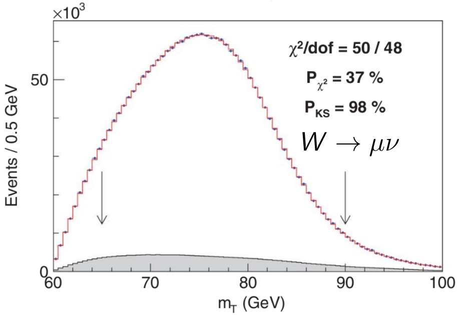

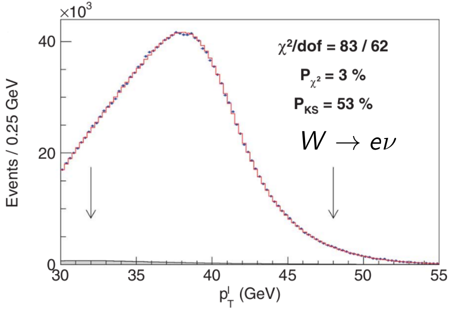

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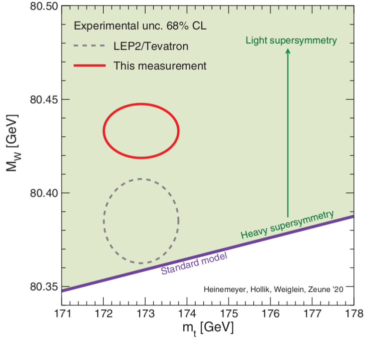
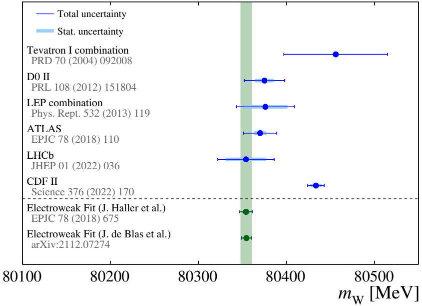
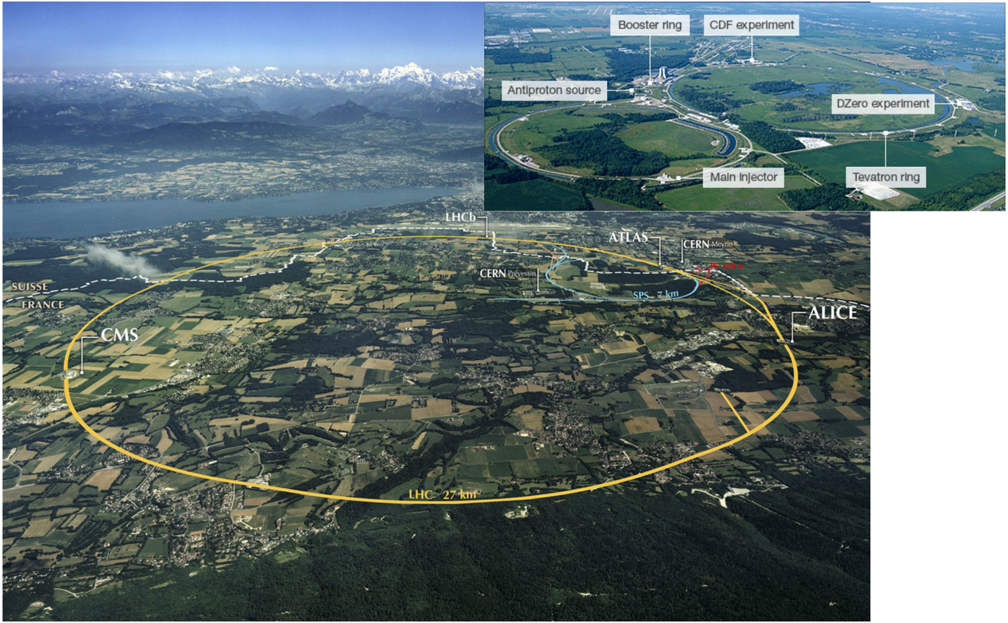
- Measurement of W-boson mass: $M_W = 80\,433.5 \pm 6.4(\mathrm{stat}) \pm 6.9(\mathrm{syst})$ MeV
  - Factor 2 better precision than any previous result
  - 7σ away from the SM EW fit prediction!





Colliders


Booster ring
CDF experiment
Antiproton source
DZero experiment
Main injector
Tevatron ring
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km