W-boson mass and width

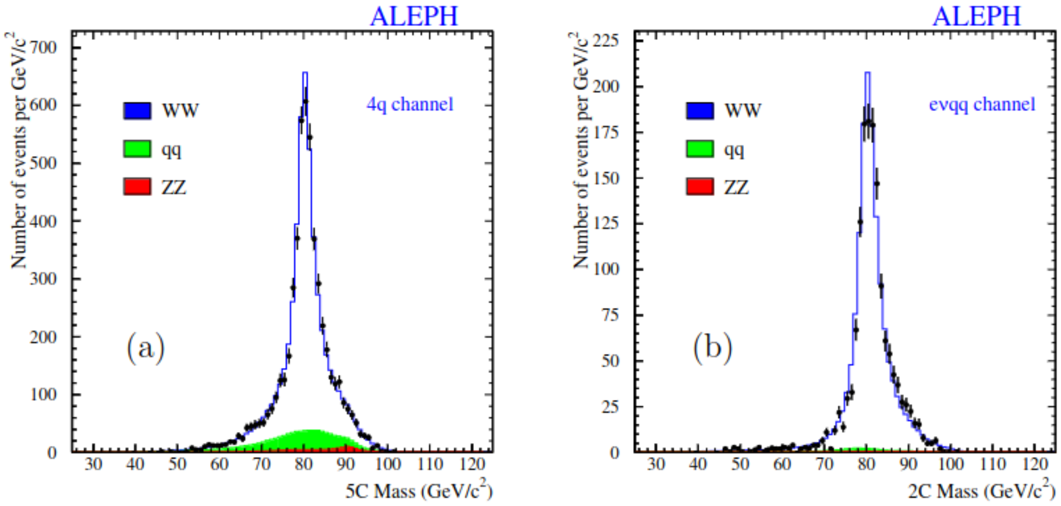
Status and perspectives

M.Boonekamp, EWWG meeting
July 11, 2024

Published results

- LEP

~35k $e^+e^- \rightarrow W^+W^-$ candidate events



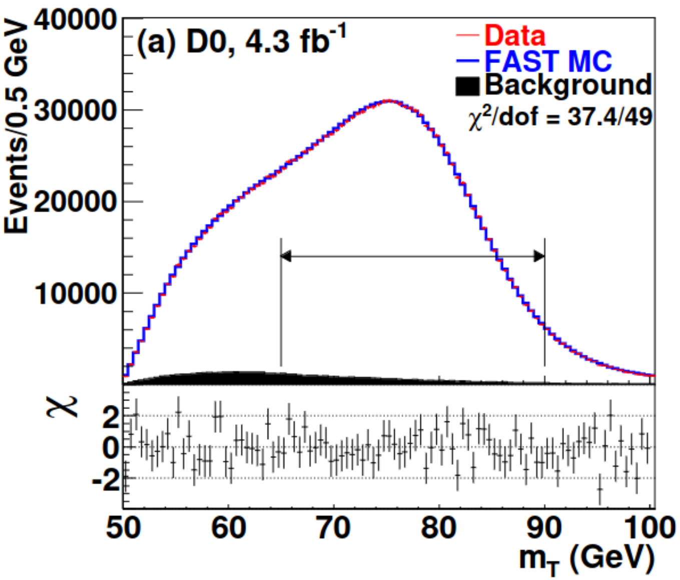
$$m_W = 80.376 \pm 0.025(\mathrm{stat.}) \pm 0.022(\mathrm{syst.})\ \mathrm{GeV}\,.$$

Source	Systematic Uncertainty in MeV			
	on m_W			on Γ_W
	$q\bar{q}\ell\nu_\ell$	$q\bar{q}q\bar{q}$	Combined	
ISR/FSR	8	5	7	6
Hadronisation	13	19	14	40
Detector effects	10	8	9	23
LEP energy	9	9	9	5
Colour reconnection	–	35	8	27
Bose-Einstein Correlations	–	7	2	3
Other	3	10	3	12
Total systematic	21	44	22	55
Statistical	30	40	25	63
Statistical in absence of systematics	30	31	22	48
Total	36	59	34	83

Published results

- Tevatron – D0

~1.68M W → eν candidate events

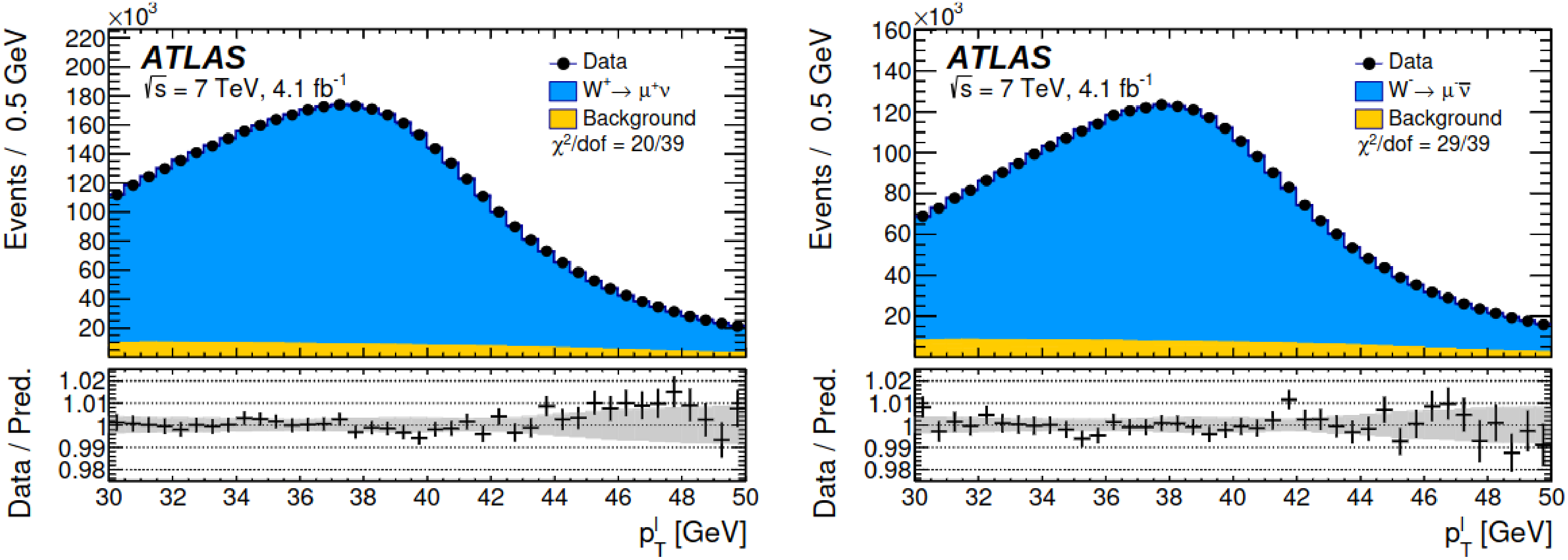


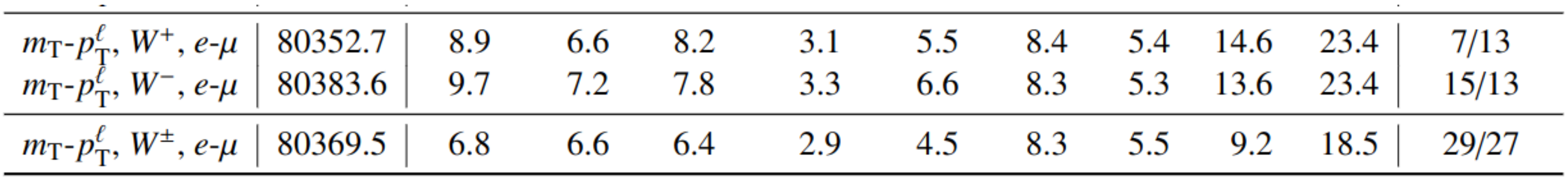
$$\begin{aligned} M_W &= 80.375 \pm 0.011\ (\text{stat.}) \pm 0.020\ (\text{syst.})\ \text{GeV} \\ &= 80.375 \pm 0.023\ \text{GeV}. \end{aligned}$$

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

Published results

- LHC – ATLAS   7 TeV   ~15M W → eν, μν candidates

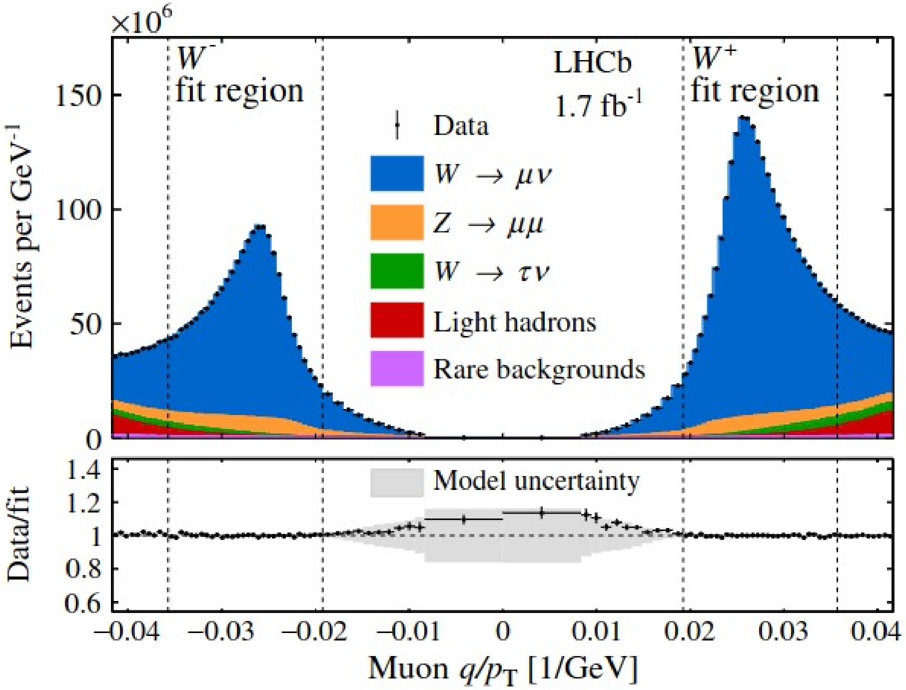




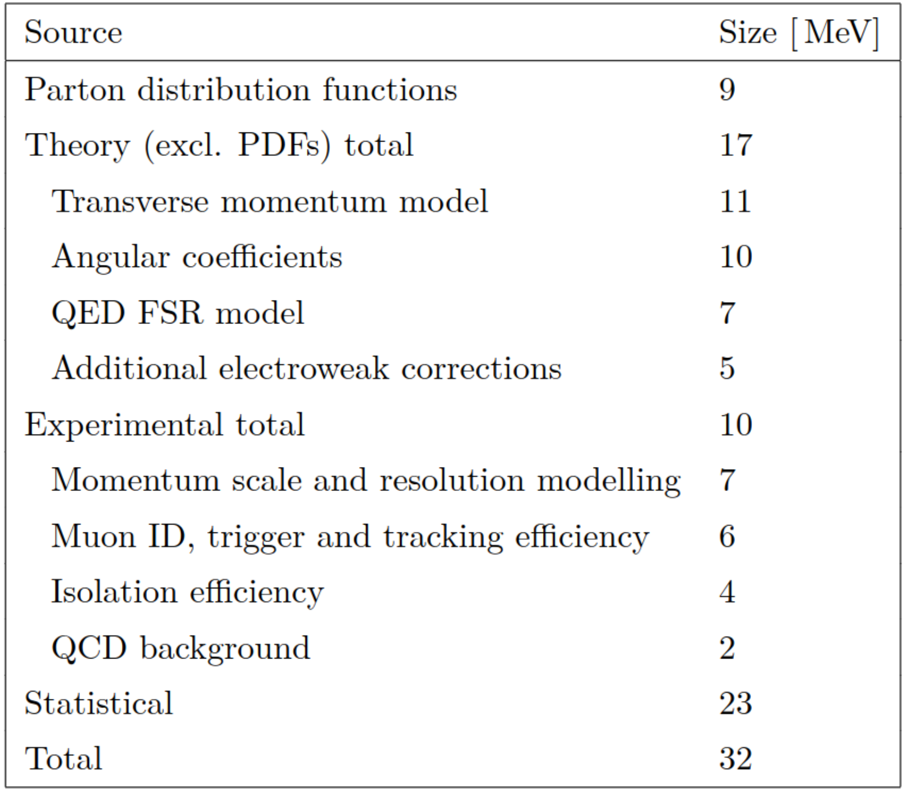
m_T-p_T^ℓ, W^+, e-μ	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
m_T-p_T^ℓ, W^-, e-μ	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Published results

- LHC – LHCb 13 TeV ~2.4M W → μν candidates



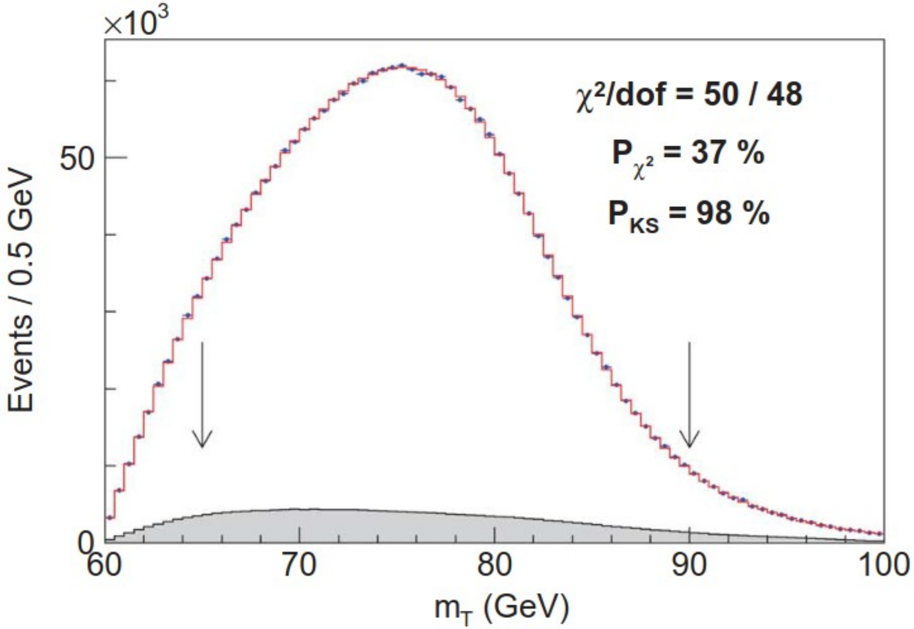
$$m_W = 80354 \pm 23_\mathrm{stat} \pm 10_\mathrm{exp} \pm 17_\mathrm{theory} \pm 9_\mathrm{PDF}\,\mathrm{MeV}.$$



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

Published results

- Tevatron – CDF ~4M W → $e\nu$, $\mu\nu$ candidates



$$M_W = 80{,}433.5 \pm 9.4\,\mathrm{MeV}$$

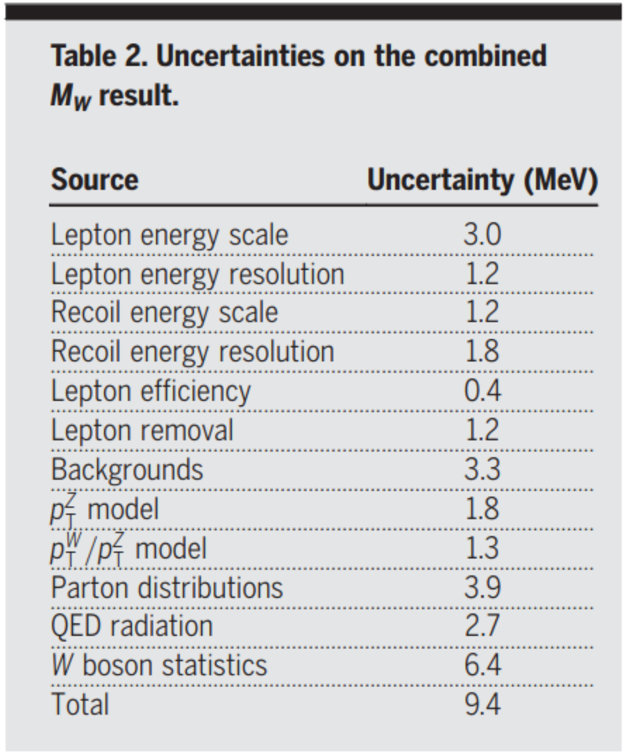


Table 2. Uncertainties on the combined M_W result.

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

Published results

- Overall picture

D0 (4.3+1.1 fb^{-1}) [*Phys. Rev.* ***D89*** *(2014) 012005*]

m_W = 80375 ± 11 (stat.) ± 20 (sys.) MeV

CDF (8.8 fb^{-1}) [*Science* ***376*** *(2022) 170*]

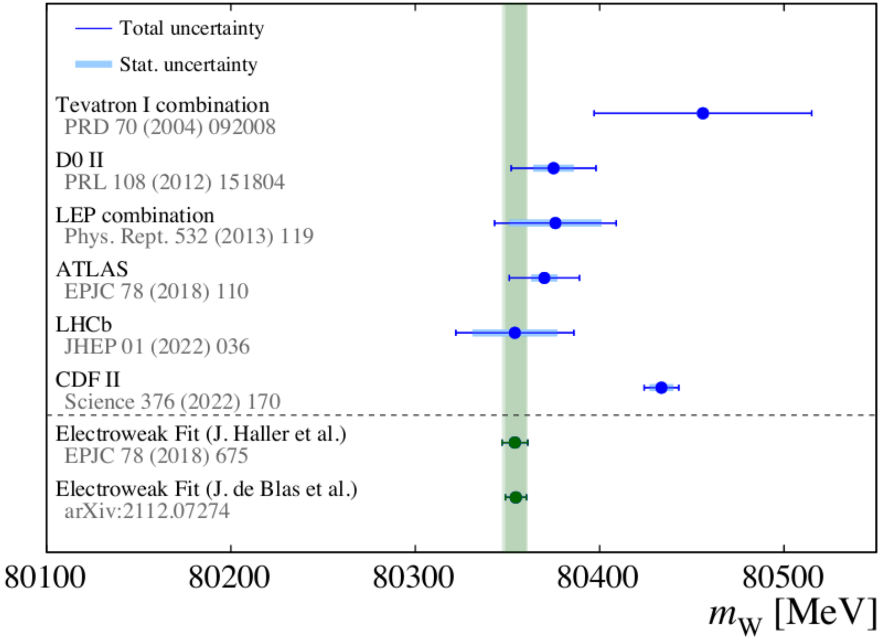
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

ATLAS (4.6 fb^{-1}) [*Eur. Phys. J.* ***C78*** *(2018) 110*]

m_W = 80370 ± 7 (stat.) ± 18 (sys.) MeV

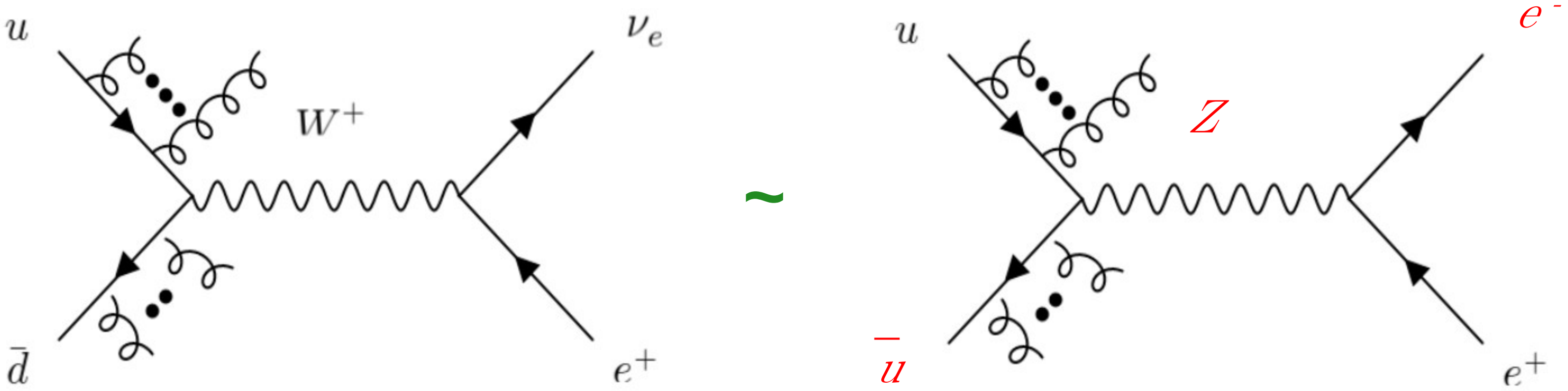
LHCb (1.7 fb^{-1}) [*JHEP* ***01*** *(2022) 036*]

m_W = 80354 ± 23 (stat.) ± 22 (sys.) MeV



Modelling : transverse momentum distribution

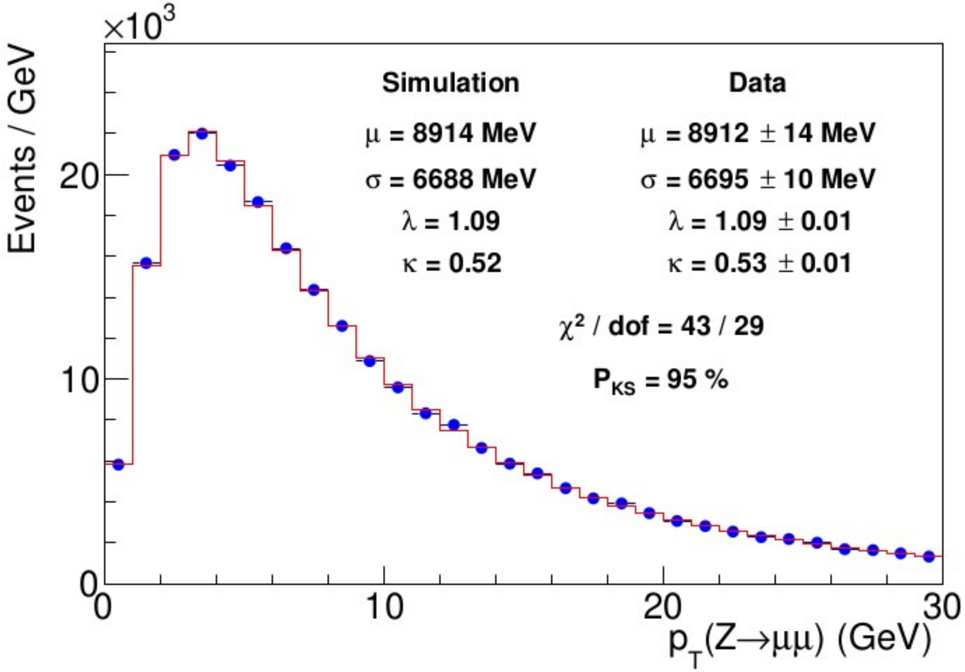
- Initial state radiation involves large corrections, and is in part non-perturbative. W events are only partly measured (neutrino!)
- Approach : adjust model parameters using Z events, which are close to W's and can be measured precisely; extrapolate to W production

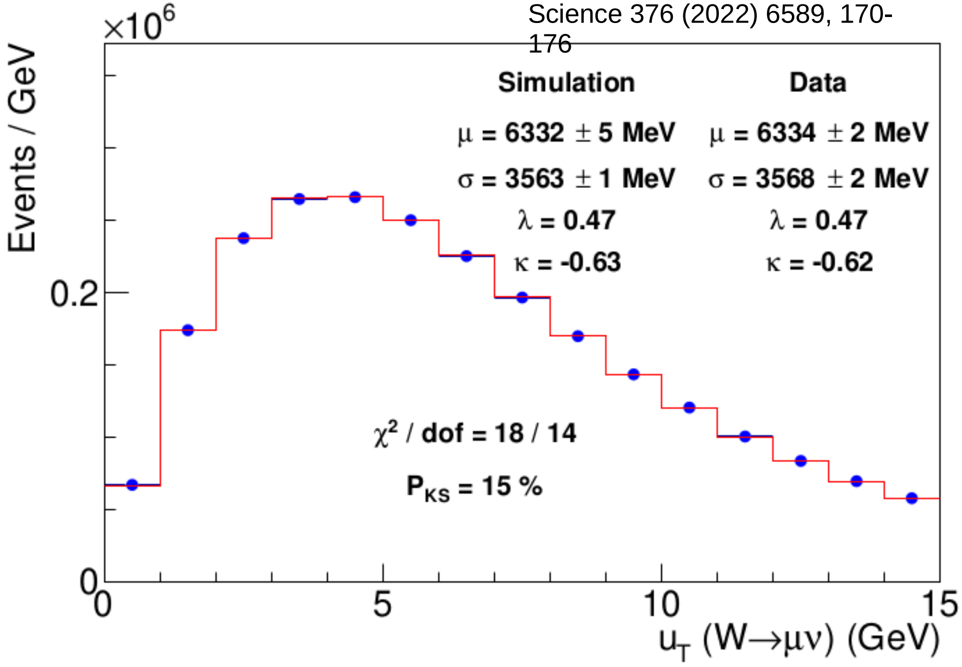


Modelling : transverse momentum distribution

- **Tevatron** : Z-based model tuning (Resbos)

  no extrapolation uncertainties, but validation with W events





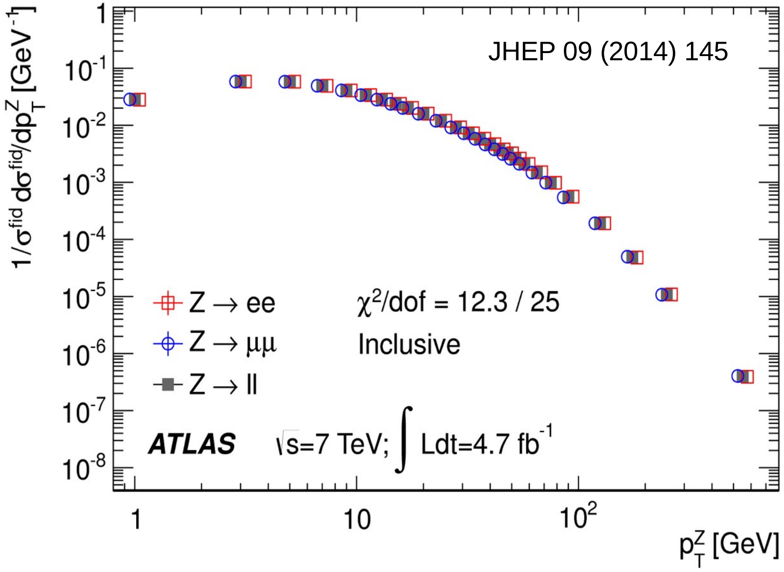
Science 376 (2022) 6589, 170-176

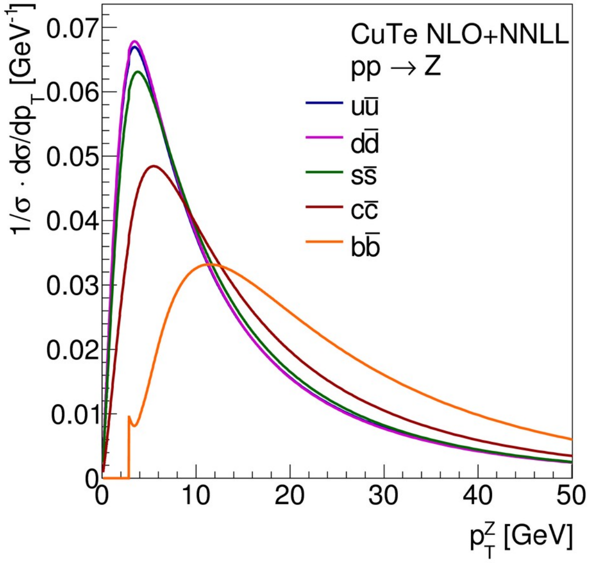
Modelling : transverse momentum distribution

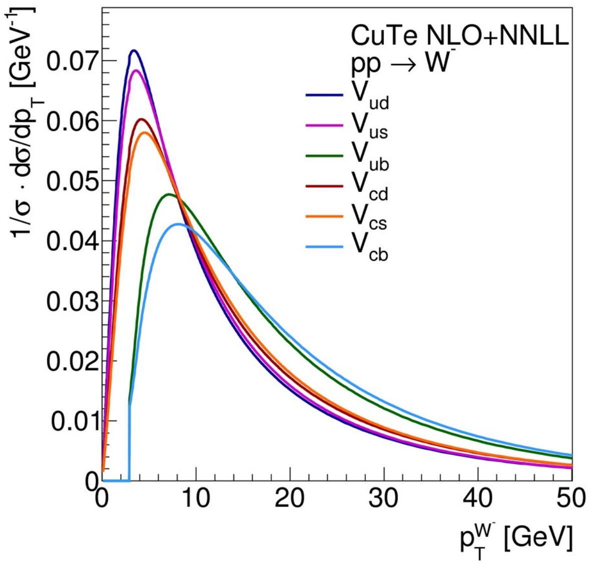
- **ATLAS** : Z-based model tuning (Pythia) + Z → W extrapolation

Corresponding uncertainties : HQ mass treatment in showers/resummation and PDFs

Measurement precision ~0.5%

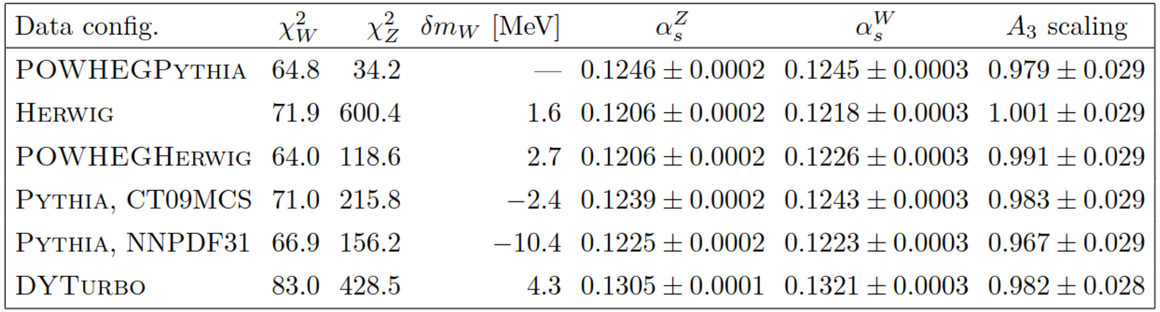




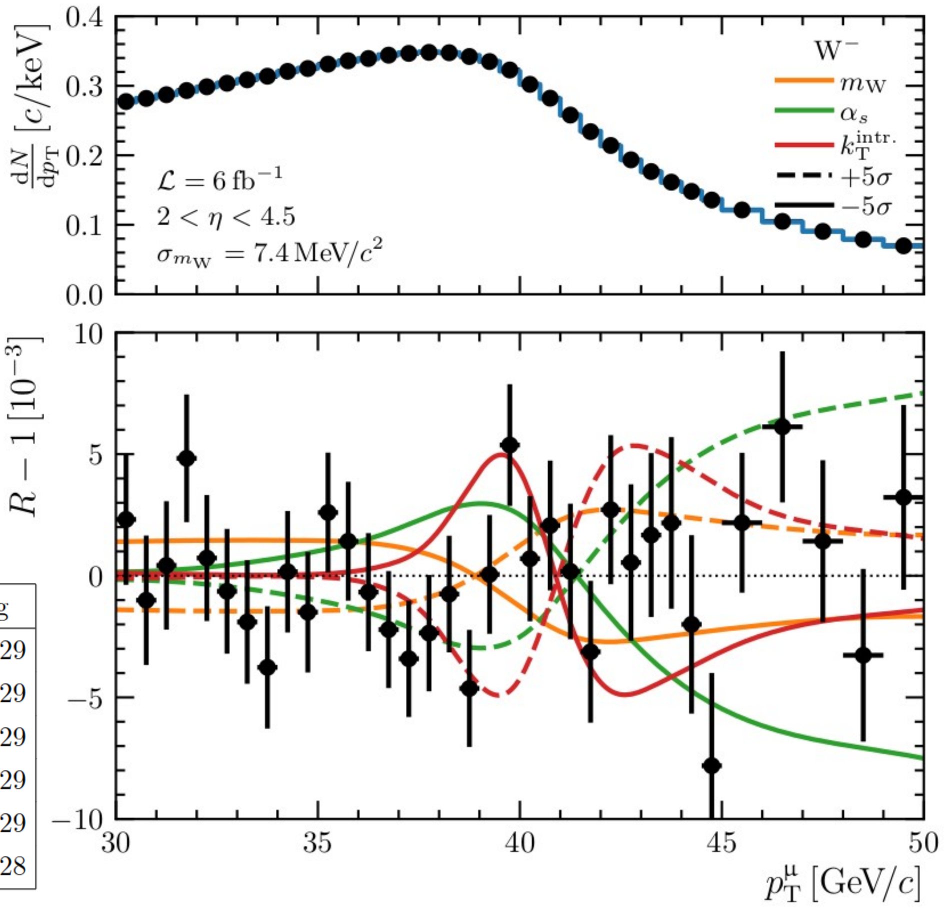


Modelling : transverse momentum distribution

- **LHCb** :
  - Z data : p_T^Z, ϕ^*
  - simultaneous fits to m_W and p_T^W in W events
  - repeated for different models :

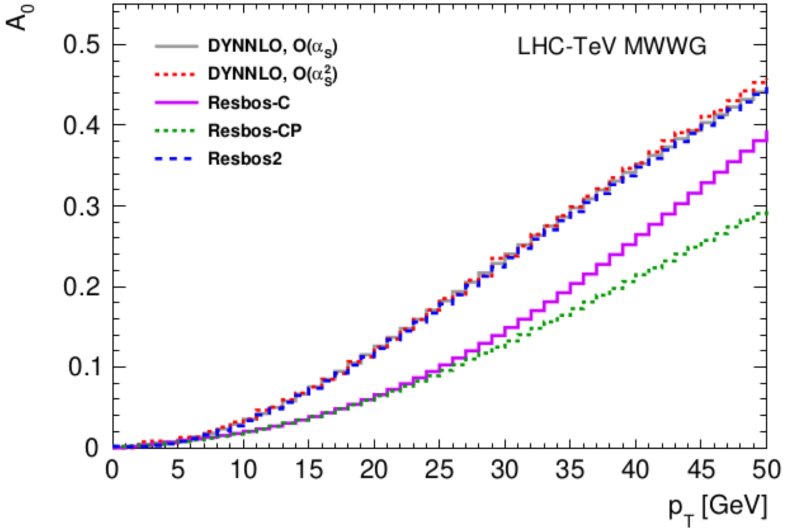


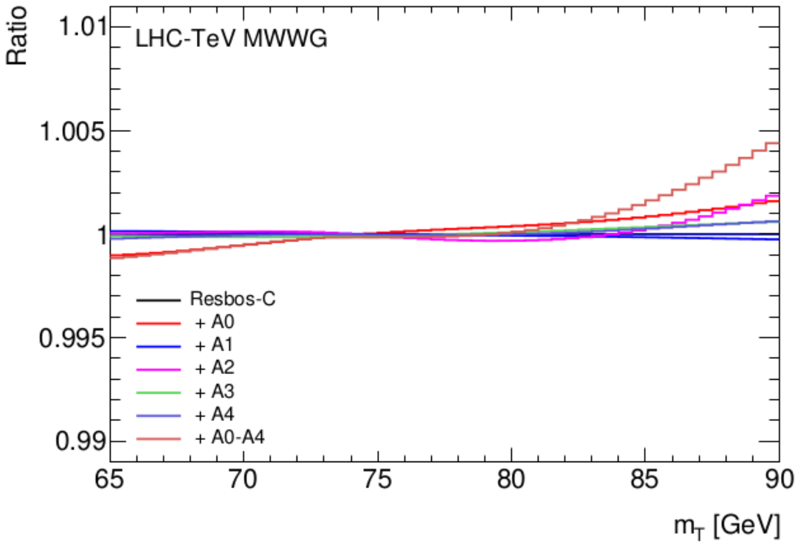
Data config.	χ^2_W	χ^2_Z	δm_W [MeV]	α_s^Z	α_s^W	A_3 scaling
POWHEGPythia	64.8	34.2	—	0.1246 ± 0.0002	0.1245 ± 0.0003	0.979 ± 0.029
Herwig	71.9	600.4	1.6	0.1206 ± 0.0002	0.1218 ± 0.0003	1.001 ± 0.029
POWHEGHerwig	64.0	118.6	2.7	0.1206 ± 0.0002	0.1226 ± 0.0003	0.991 ± 0.029
Pythia, CT09MCS	71.0	215.8	−2.4	0.1239 ± 0.0002	0.1243 ± 0.0003	0.983 ± 0.029
Pythia, NNPDF31	66.9	156.2	−10.4	0.1225 ± 0.0002	0.1223 ± 0.0003	0.967 ± 0.029
DYTurbo	83.0	428.5	4.3	0.1305 ± 0.0001	0.1321 ± 0.0003	0.982 ± 0.028



Modelling : spin correlations

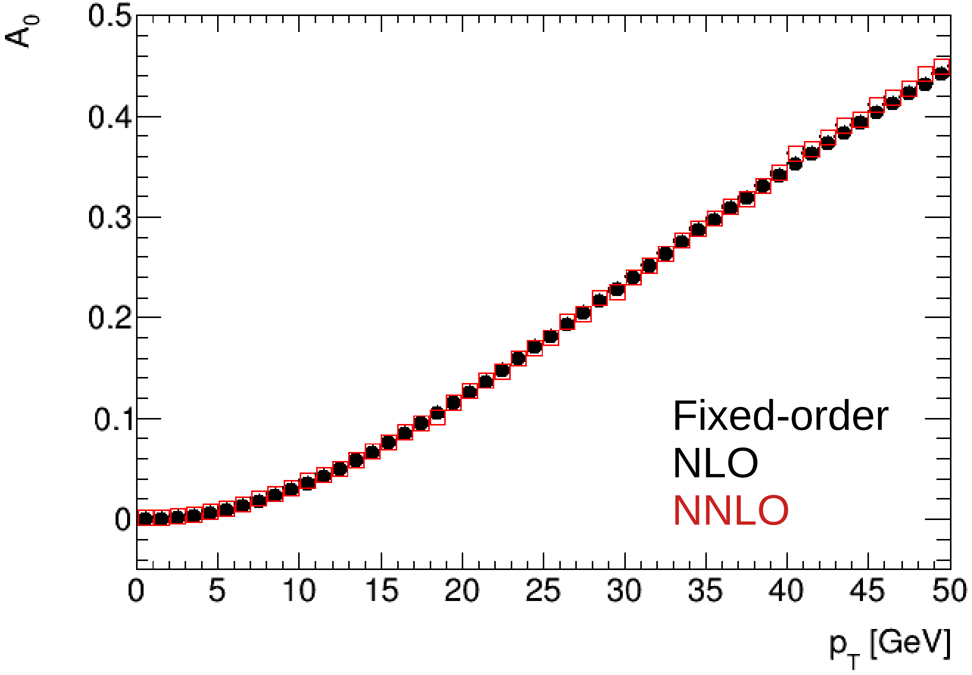
- Resbos extensively used at the Tevatron ; LHC analyses correct their respective MCs to fixed-order calculations
  - Undershoot of e.g A_0 in Resbos yields softer m_T and p_T^l distributions → m_W biased upwards (~10 MeV effect)

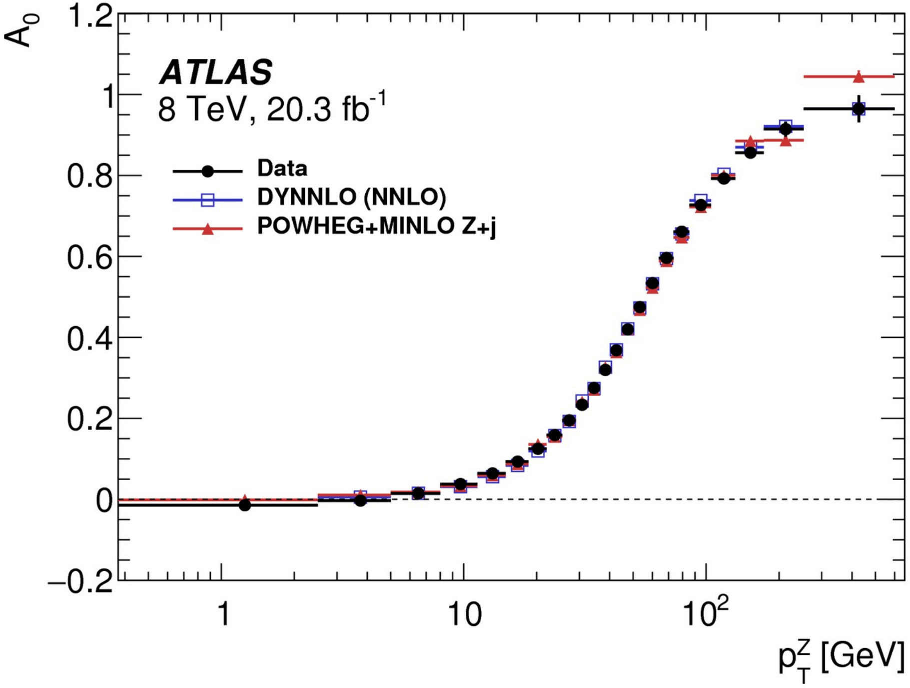




Modelling : spin correlations

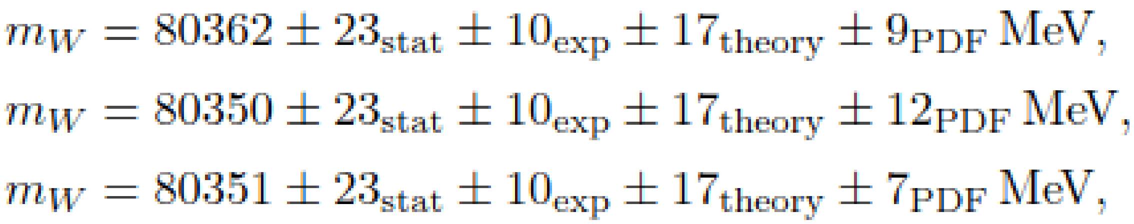
- Angular coefficients – why disfavour Resbos1?





Modelling : PDFs

- Experiments use the state of the art of their time, and gradually realize the impact of PDF choices on their measurements
  - D0, CDF (2013): CTEQ6.1, CTEQ6.6
  - ATLAS (2017) : CT10 (cross checks with CT14, MMHT2014, ~4 MeV)
  - LHCb (2022) : <NNPDF31, CT18, MSHT20>



$$m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV},$$

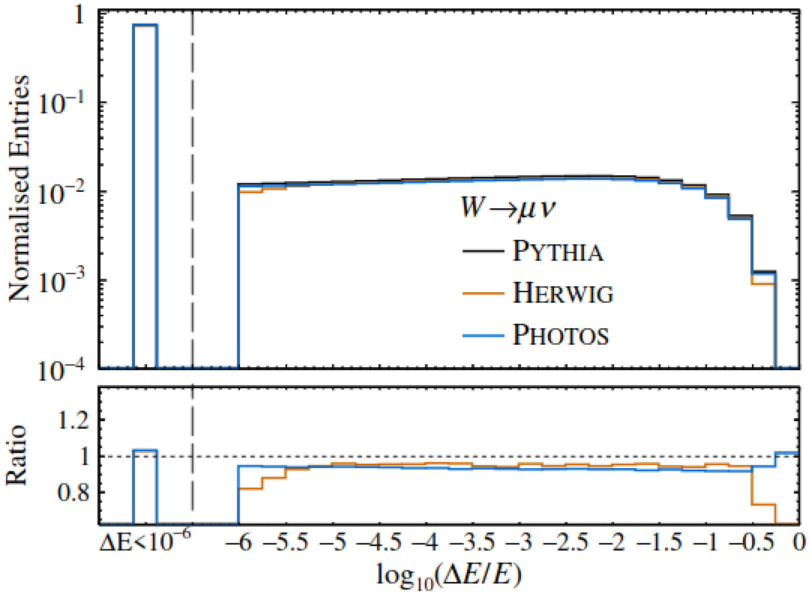
$$m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}\ \text{MeV},$$

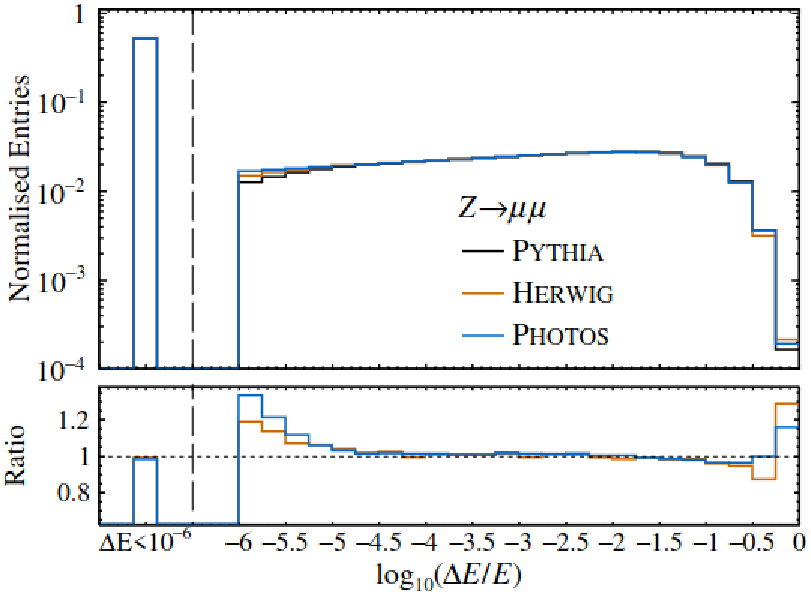
$$m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}\ \text{MeV},$$

  - Later updated use 6-7 PDF sets : up to ~20 MeV effects

Modelling : QED / EW corrections

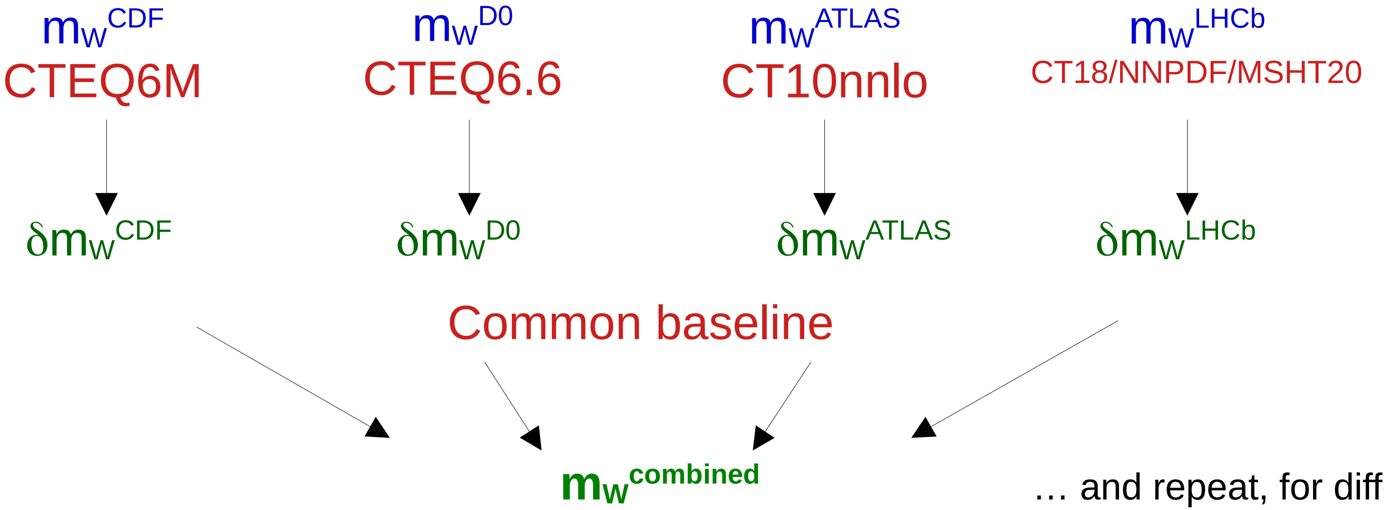
- Baseline fits still based on pure QED FSR. Uncertainties estimated to ~6-7 MeV:
  - QED radiation calculation
  - Higher-order effects: $\gamma^* \rightarrow$ ll spitting, EW corrections





Combination

- Measurements performed at different times, using different baseline PDFs and QCD tools : existing result extrapolated to a common baseline
- Two-step procedure :
  - correct to common PDF & QCD accuracy
  - combination including correlations



m_W^{CDF} CTEQ6M

m_W^{D0} CTEQ6.6

m_W^{ATLAS} CT10nnlo

m_W^{LHCb} CT18/NNPDF/MSHT20

δm_W^{CDF}

δm_W^{D0}

δm_W^{ATLAS}

δm_W^{LHCb}

Common baseline

$m_W^{combined}$

… and repeat, for different PDFs

Combination

- Full procedure, decomposed into generator and PDF effects :

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

published

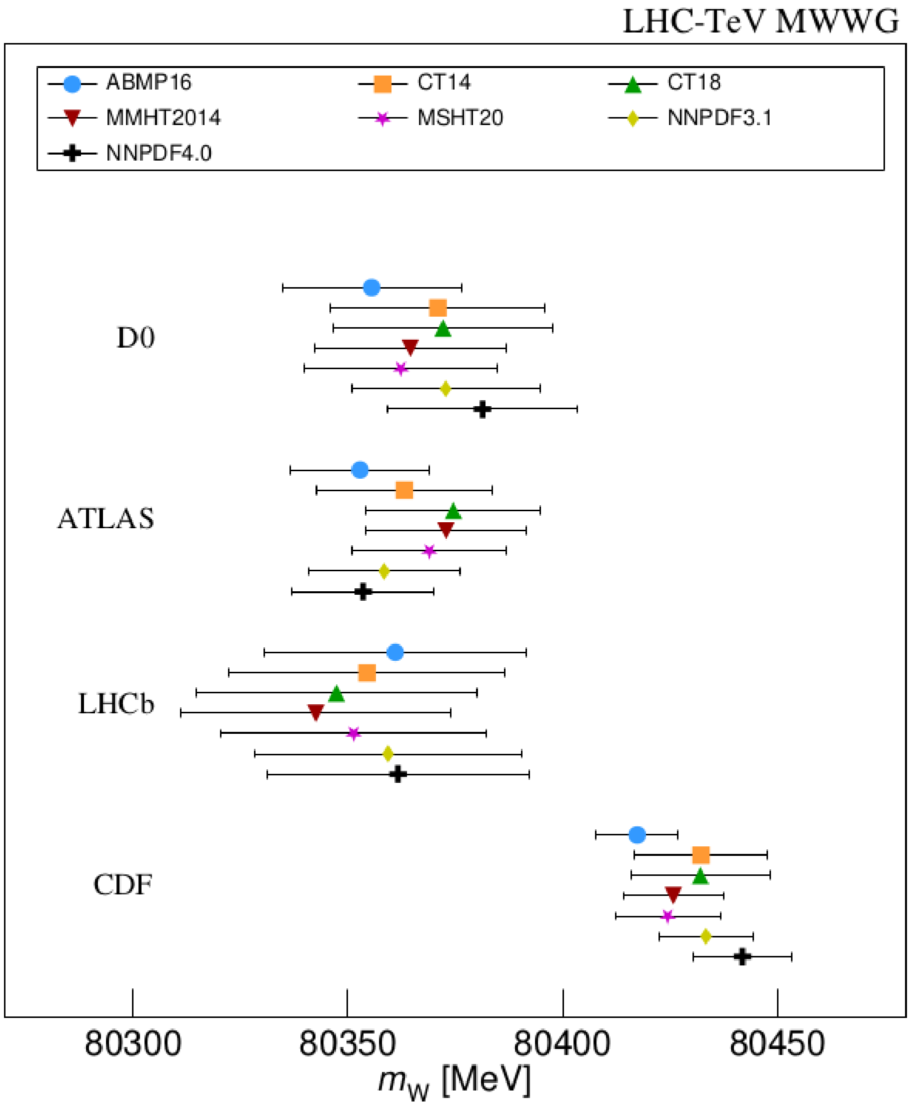
Improved predictions, for reference PDF

PDF extrapolation

- Extrapolations (δm_W) evaluated using generator-level reweightings and “emulation” of detector effects
  - δm_W^{PDF} : APMB16, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0
  - δm_W^{QCD} essentially covers for improvements in the spin correlations

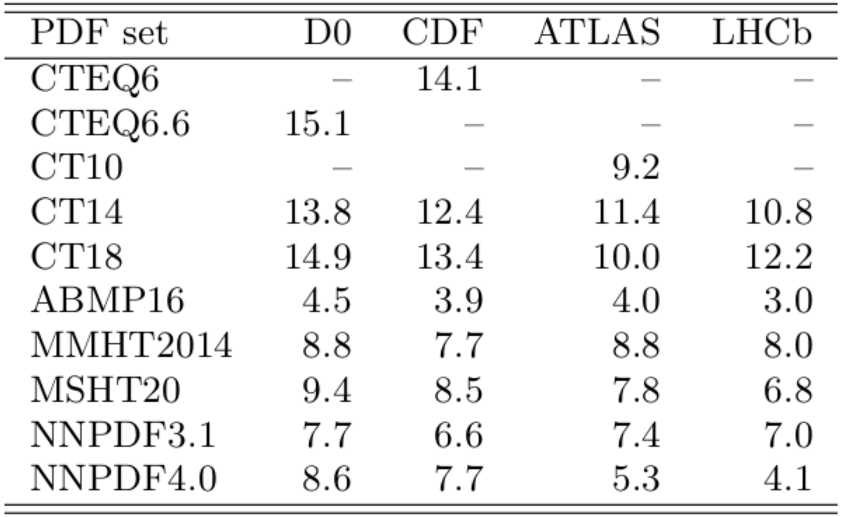
Combination

- PDF extrapolations
  - Large effects on separate experiments
  - Opposite trend stabilize combination

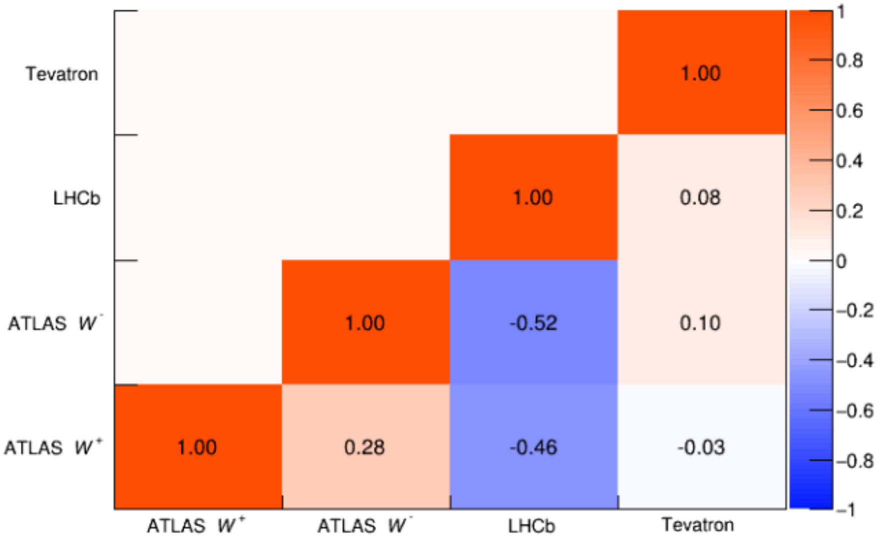


Combination

- PDF uncertainties and correlations :



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

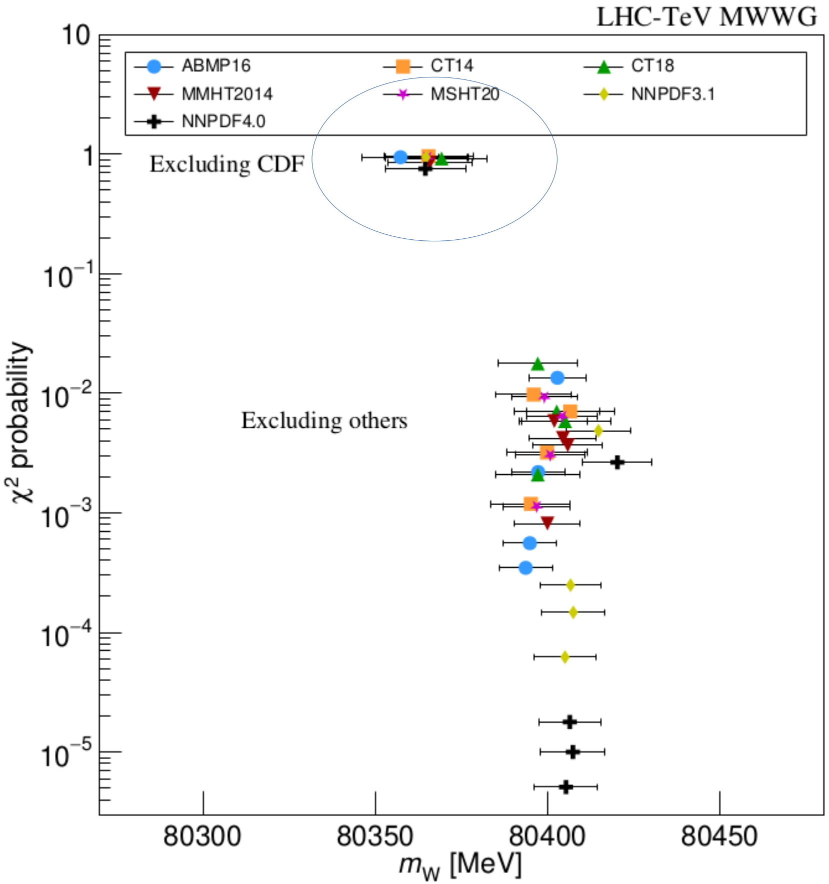


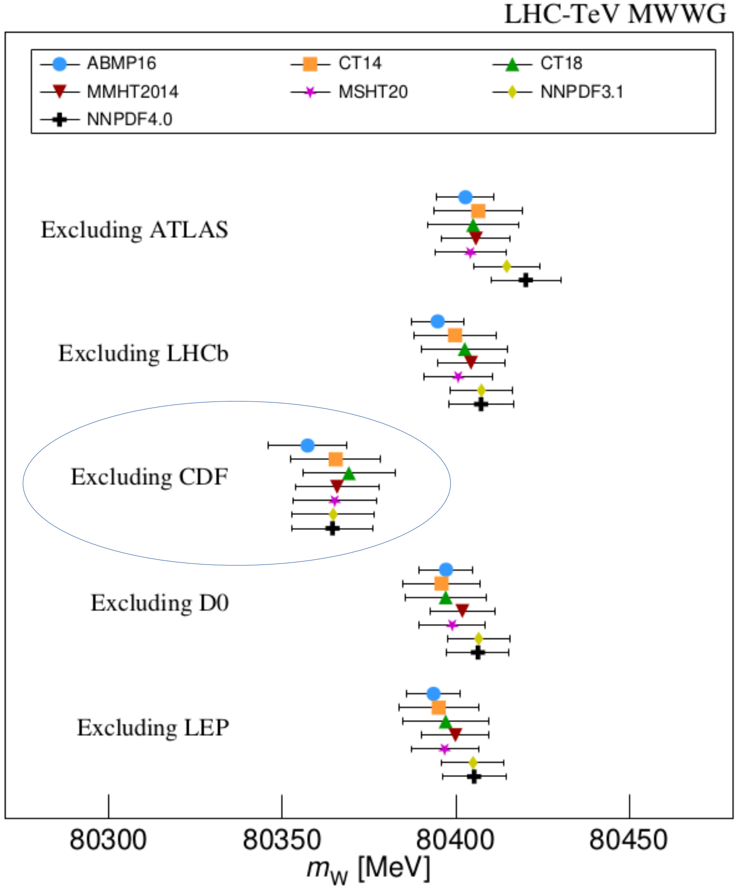
	ATLAS W^+	ATLAS W^-	LHCb	Tevatron
Tevatron				1.00
LHCb			1.00	0.08
ATLAS W^-		1.00	-0.52	0.10
ATLAS W^+	1.00	0.28	-0.46	-0.03

CT18

Sometime partial or negative correlations → stabilizes PDF effects on combinations

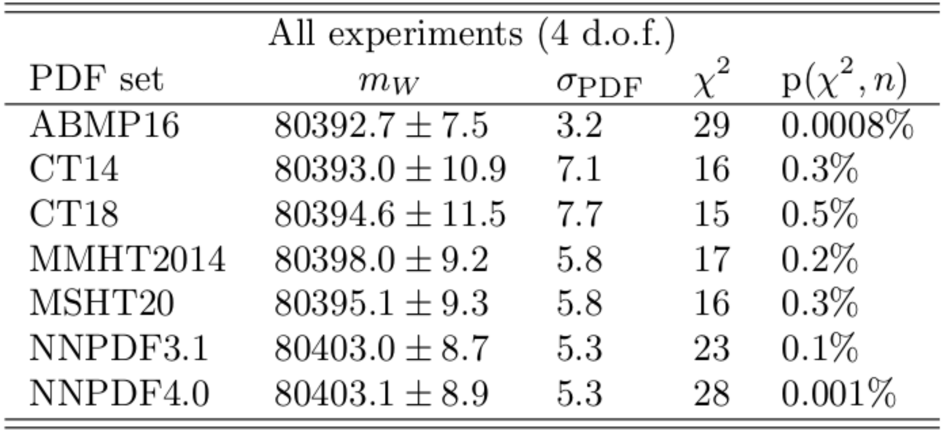
Results


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
Excluding CDF
Excluding others
χ^2 probability
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
80300
80350
80400
80450
m_W [MeV]


LHC-TeV MWWG
ABMP16
CT14
CT18
MMHT2014
MSHT20
NNPDF3.1
NNPDF4.0
Excluding ATLAS
Excluding LHCb
Excluding CDF
Excluding D0
Excluding LEP
80300
80350
80400
80450
m_W [MeV]

Combination results

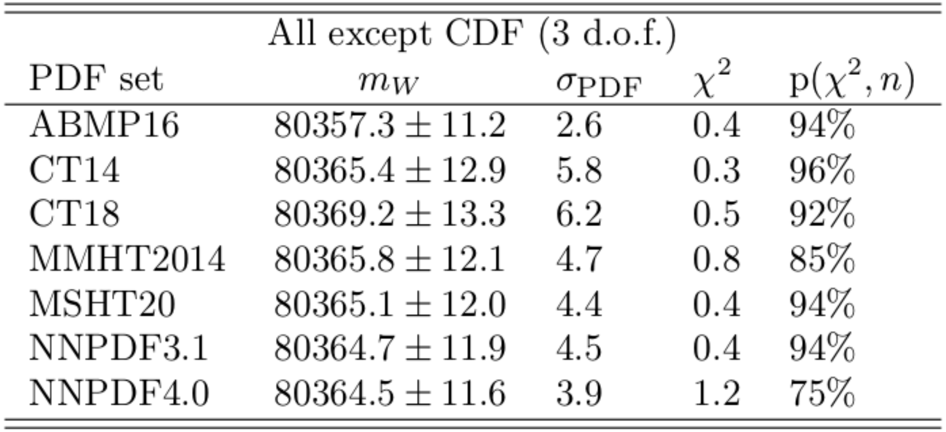
- All experiments



All experiments (4 d.o.f.)

PDF set	m_W	σ_{PDF}	χ^2	$\mathrm{p}(\chi^2, n)$
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



All except CDF (3 d.o.f.)

PDF set	m_W	σ_{PDF}	χ^2	$\mathrm{p}(\chi^2, n)$
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%

Combination results

- CT18 PDF set used as baseline as it is most conservative, and given the observed PDF dependence of the combination results
- Full world average :

m_W = 80394.6 ± 11.5 MeV P(χ^2) = 0.5%

  - Quoted for completeness, but not considered a meaningful number
  - We consider the discrepancy can not be explained by an under-estimation of quoted uncertainties; error scaling does not apply

- Average of all measurements except CDF :

m_W = 80369.2 ± 13.3 MeV P(χ^2) = 91%

  - PDF envelope 5 MeV (12 MeV when including ABMP16)
  - This average and the published CDF result considered on equal footing but incompatible

Updates

- ATLAS : re-analysis of 7 TeV data

- Three purposes :
  - Update and extend study of PDF dependence of m_W
  - Measurement of W-boson width
  - Improved statistical method

… everything else unchanged (or almost)

Updates

- ATLAS : re-analysis of 7 TeV data
- Likelihood :

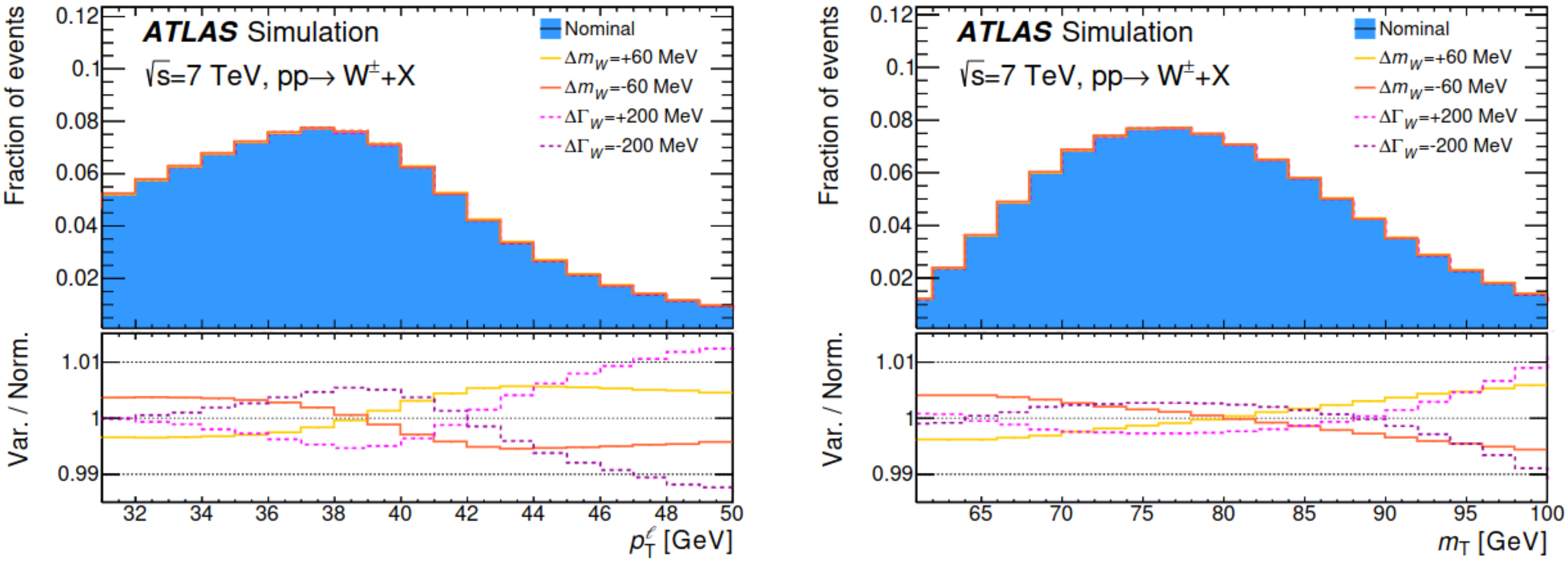
$$\mathcal{L}(\vec{m}|\vec{\theta},\vec{\alpha}) = \prod_i \underbrace{\text{Poisson}(m_i|\nu_i(\vec{\theta},\vec{\alpha}))}_{\text{Poisson likelihood for each bin}} \cdot \prod_r \underbrace{\text{Gauss}(\alpha_r|a_r)}_{\text{Constraint terms for the nuisance parameters: Systematics are assumed to be Gaussian distributed.}}$$

- m_i: Observed data per bin
- $\vec{\theta}$: POI (m_W)
- $\vec{\alpha}$: NP for systematics
- $\vec{a}$: Global observable for nuisance parameter.
- ν_i : Total prediction per bin →

$$\begin{aligned}\nu_{ji}\left(\vec{\theta},\vec{\alpha}\right) = \Phi \times \left[S_{ji}^{\text{nom}} + \sum_p \theta_p \times \left(S_{ji}^{\theta_p} - S_{ji}^{\text{nom}}\right)\right] \\ + \sum_s \alpha_s \times \left(S_{ji}^{s} - S_{ji}^{\text{nom}}\right) \\ + B_{ji}^{\text{nom}} + \sum_b \alpha_b \times \left(B_{ji}^{b} - B_{ji}^{\text{nom}}\right),\end{aligned}$$

Updates

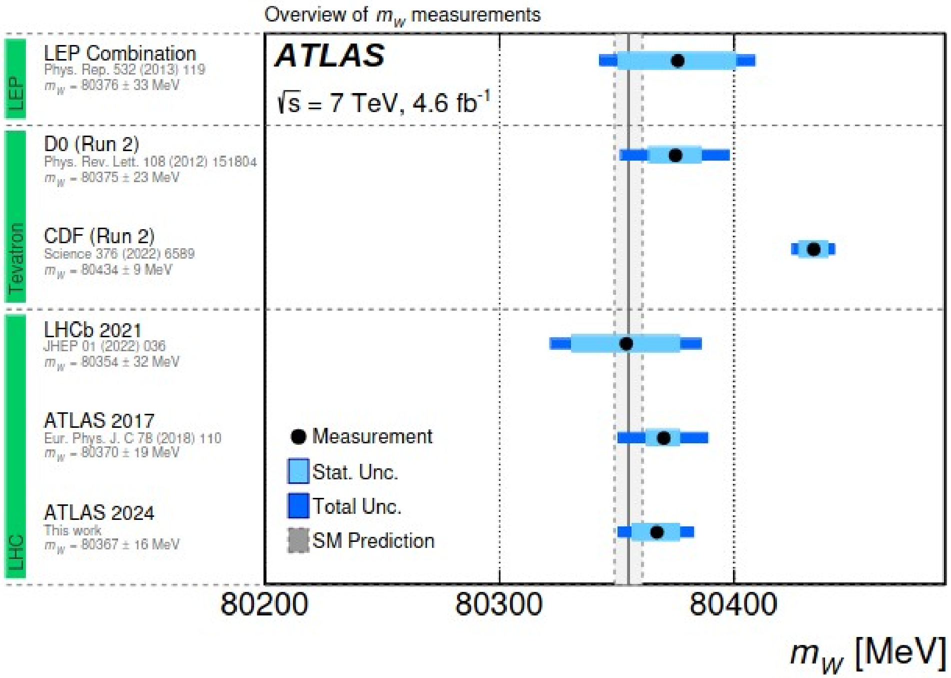
- ATLAS : re-analysis of 7 TeV data
- Sensitivity to the width :

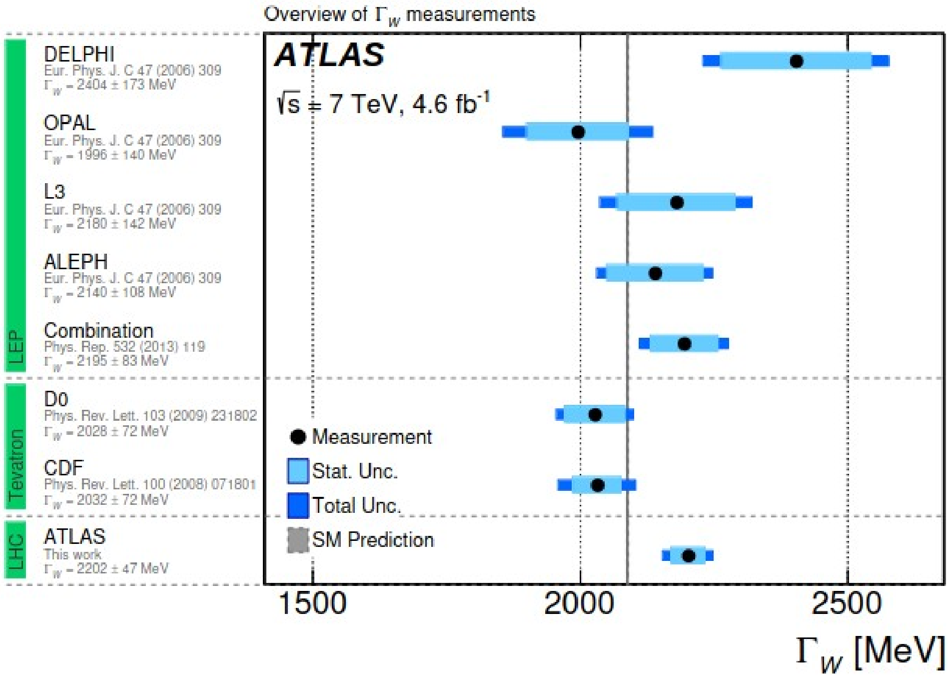


  - NB : extending to m_T<150 GeV gives a factor ~2 more sensitivity, but we lacked a sufficient model for systematics in this region

Updates

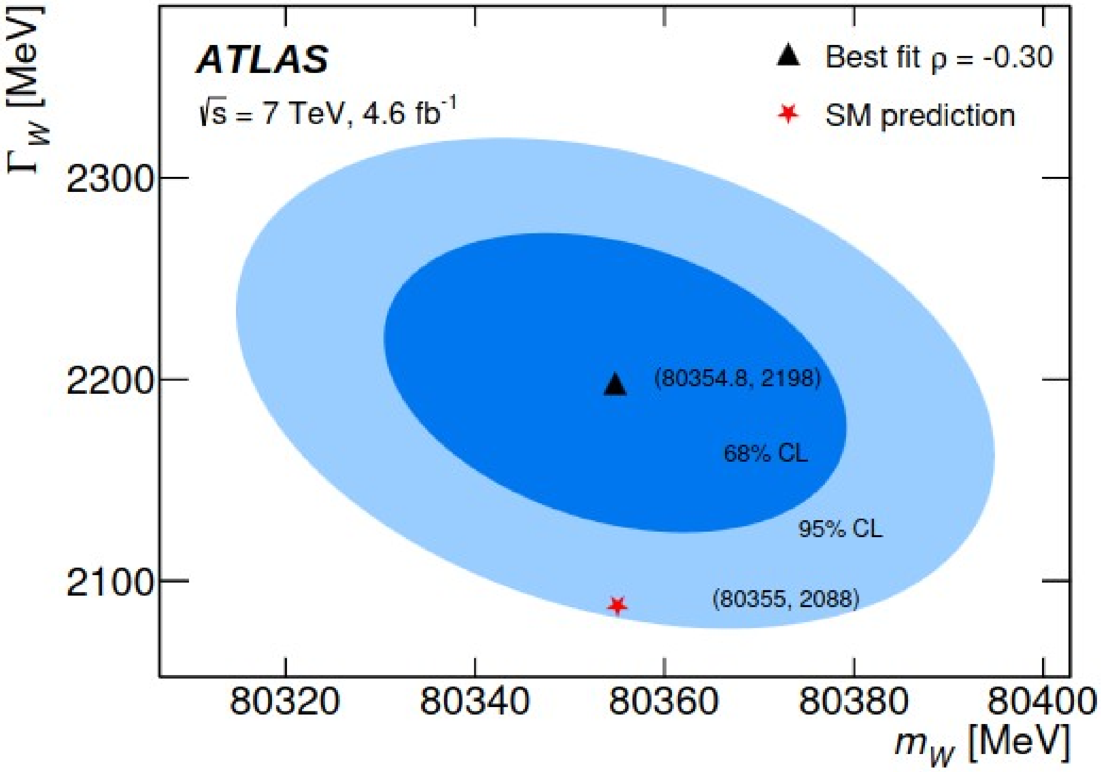
- ATLAS : re-analysis of 7 TeV data
- Results :





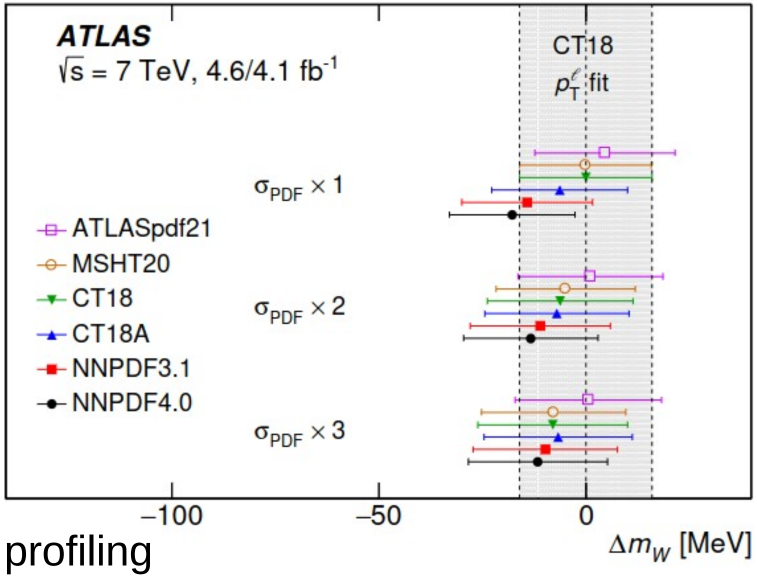
Updates

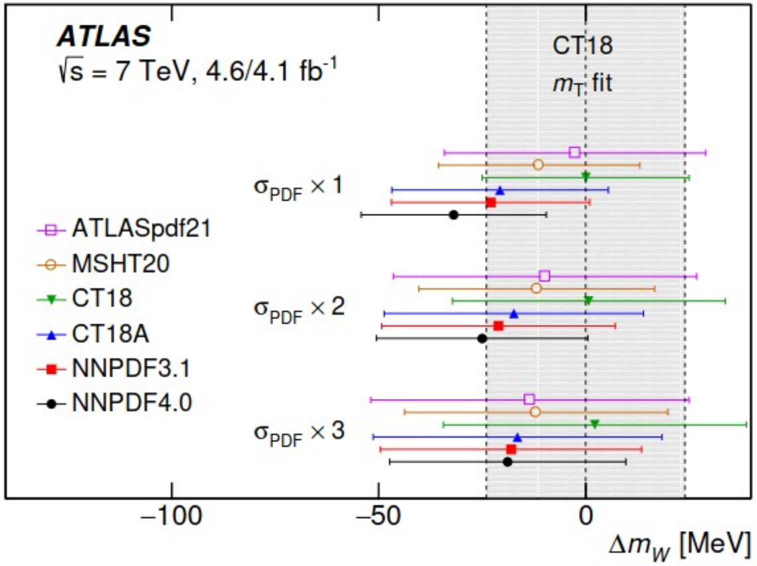
- ATLAS : re-analysis of 7 TeV data
- Results :



Updates

- PDFs



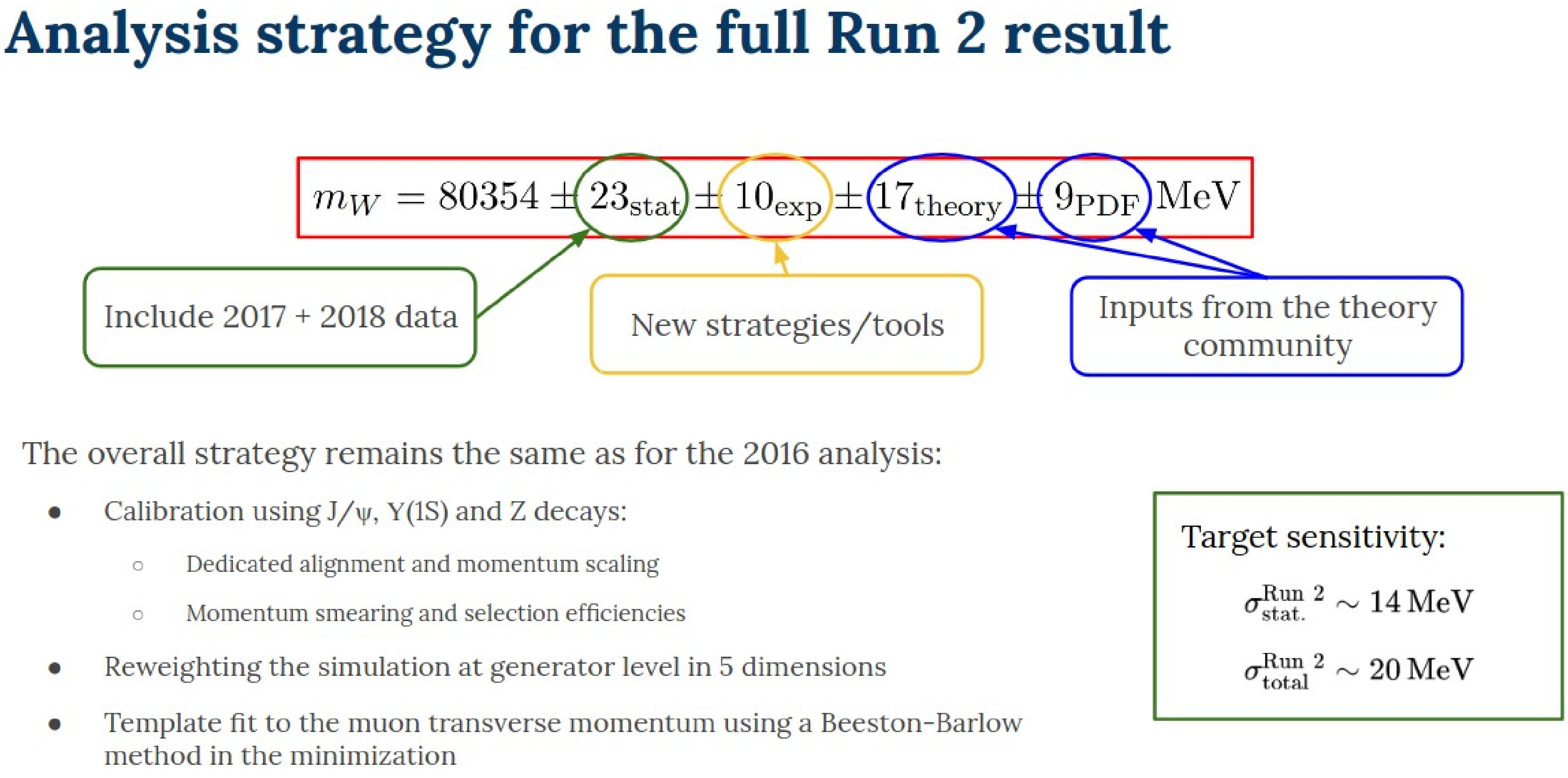


  - Note re. profiling
    - the primary aim of PL fits is to make models more flexible, enabling them to detect miscalibrations or underestimated uncertainties. However, fitting models can not go without constraining the parameters…
    - Including tolerance in the (PDF) nuisance parameters would prevent the fit from constraining the corresponding uncertainties, but also rigidify the model again
    - Studying the dependence of results on pre-fit uncertainties seems like a better way to go

Prospects

- LHCb

(Miguel Ramos Pernas, Orsay, ‘23



Analysis strategy for the full Run 2 result

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Include 2017 + 2018 data

New strategies/tools

Inputs from the theory community

The overall strategy remains the same as for the 2016 analysis:

- Calibration using J/ψ, Υ(1S) and Z decays:
  - Dedicated alignment and momentum scaling
  - Momentum smearing and selection efficiencies
- Reweighting the simulation at generator level in 5 dimensions
- Template fit to the muon transverse momentum using a Beeston-Barlow method in the minimization

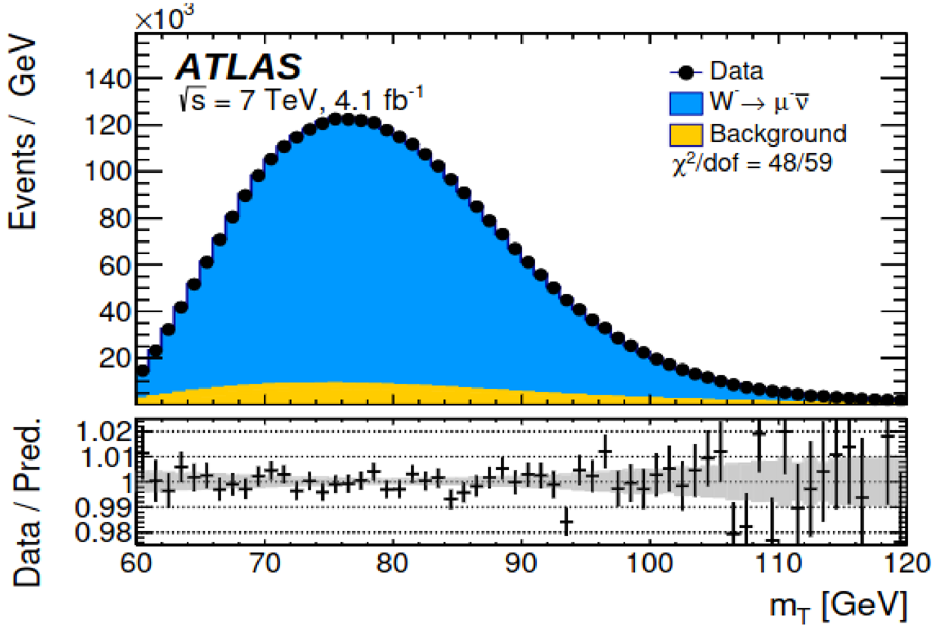
Target sensitivity:

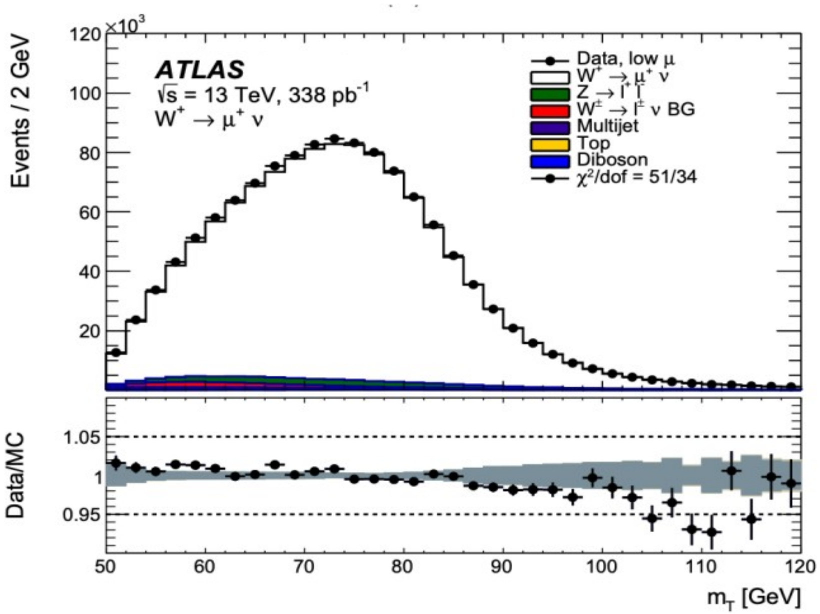
$$\sigma_{\text{stat.}}^{\text{Run 2}} \sim 14\,\text{MeV}$$

$$\sigma_{\text{total}}^{\text{Run 2}} \sim 20\,\text{MeV}$$

Prospects

- Low-pile-up data in ATLAS : compared to 7 TeV, the loss in statistics (/7) is good part compensated by the sensitivity per event (x3)
- 1 fb^{-1} of such data would be an extremely good investment in this respect





Prospects

- CMS

Prospects

- Combination : methodological developments to properly correlate « offset » measurements and profile-likelihood fit results
  - Using properly decomposed PL fit uncertainties (arXiv:2307.04007)
  - Using post-fit covariance :

$$\left(\begin{array}{cccccc|cccccc}
c^{A}_{11} & \cdots & c^{A}_{1r} & \cdots & c^{A}_{1n} & \epsilon^{A}_{1} & & & & & & \\
\vdots & & \vdots & & \vdots & \vdots & & & & & & \\
c^{A}_{u1} & \cdots & c^{A}_{ur} & \cdots & c^{A}_{un} & \epsilon^{A}_{u} & & & \ldots\ \text{etc}\ \ldots & & & \\
\vdots & & \vdots & & \vdots & \vdots & & & & & & \\
c^{A}_{n1} & \cdots & c^{A}_{nr} & \cdots & c^{A}_{nn} & \epsilon^{A}_{n} & & & & & & \\
\epsilon^{A}_{1} & \cdots & \epsilon^{A}_{r} & \cdots & \epsilon^{A}_{n} & (\sigma^{A}{}_{\theta})^{2} & & & & & & \\
\hline
 & & & & & & 1 & \cdots & 0 & \cdots & 0 & \epsilon^{B}_{1} \\
 & & \vdots & & & & \vdots & & \vdots & & \vdots & \vdots \\
 & & \sum_{t} c^{A}_{tr} c^{B}_{ts} & \cdots & \sum_{t} \epsilon^{A}_{t} c^{B}_{ts} & & 0 & \cdots & \delta_{sv} & \cdots & 0 & \epsilon^{B}_{s} \\
 & & \vdots & & & & \vdots & & \vdots & & \vdots & \vdots \\
 & & & & & & 0 & \cdots & 0 & \cdots & 1 & \epsilon^{B}_{n} \\
 & & \sum_{t} c^{A}_{tr} \epsilon^{B}_{t} & \cdots & \sum_{t} \epsilon^{A}_{t} \epsilon^{B}_{t} & & \epsilon^{B}_{1} & \cdots & \epsilon^{B}_{v} & \cdots & \epsilon^{B}_{n} & (\sigma^{B}{}_{\theta})^{2}
\end{array}\right)$$

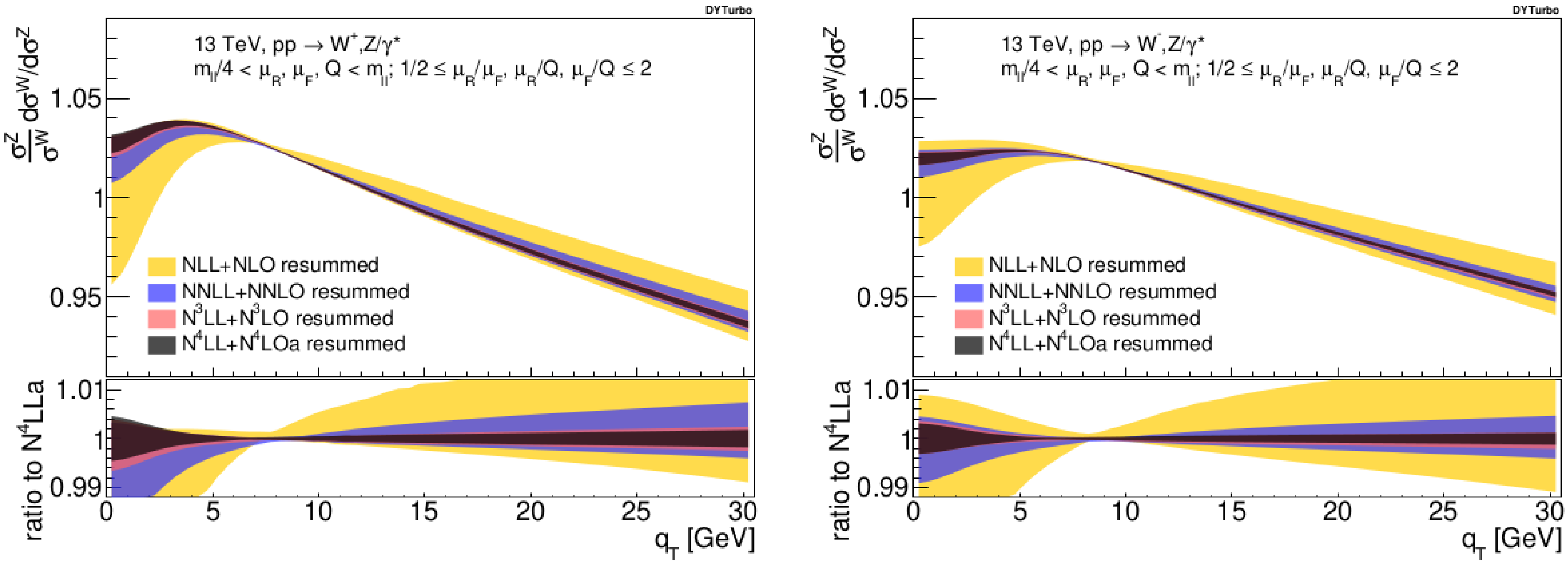
First discussions and tests

in this direction

Progress and limitations

- Analytical resummation – now at approximate N4LO+N4LL

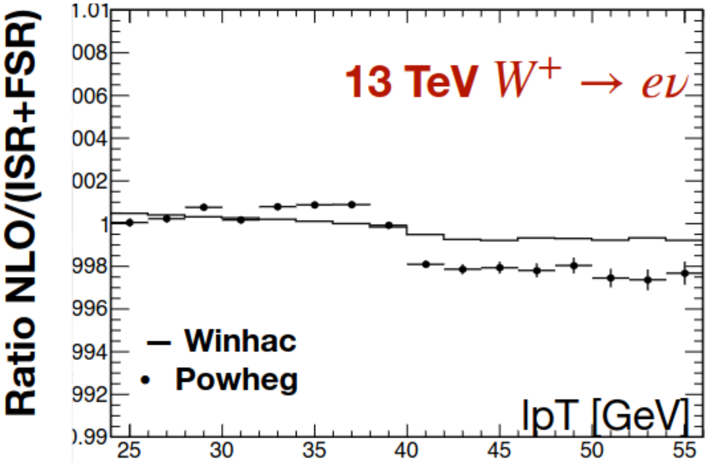
2303.12781



  - Essentially removing any uncertainty in the W/Z pT distribution ratio, but….
  - flavour-dependent intrinsic kT; heavy-quark mass effects; process-dependent EWK effects… are not (yet) addressed (and matter for mW)

Progress and limitations

- Electroweak corrections : NLO EW / FSR only (ATLAS perspective)
  - Used Winhac in the past ; PowhegEW as second generator would be an extremely useful cross check
  - Aim : use NLO EW as baseline, and residual scheme dependence as systematic (currently consider full NLO/FSR effect as systematic)
  - However, differences seem unnaturally large so far :



Xuewei Jia

More investigations would be extremely helpful, in collaboration with the authors

Summary and conclusions

- Current measurement uncertainties range from ~10 to ~30 MeV.
- Combining compatible measurements yields dm_W = 13 MeV
- Limitations :
  - $p_T^{W,Z}$ distribution : huge progress, but still not much on the p_T^W/p_T^Z
  - PDF dependence and PDF uncertainties… how to address this quantitatively ?
  - Electroweak corrections : many results on EW and mixed QCDxEW corrections, but limited MC implementations
- Prospects : next generation of measurements hopefully reaches ~10-20 MeV precision, maybe better combined.

  Real progress, or instead highlighting limitations in the modelling ?