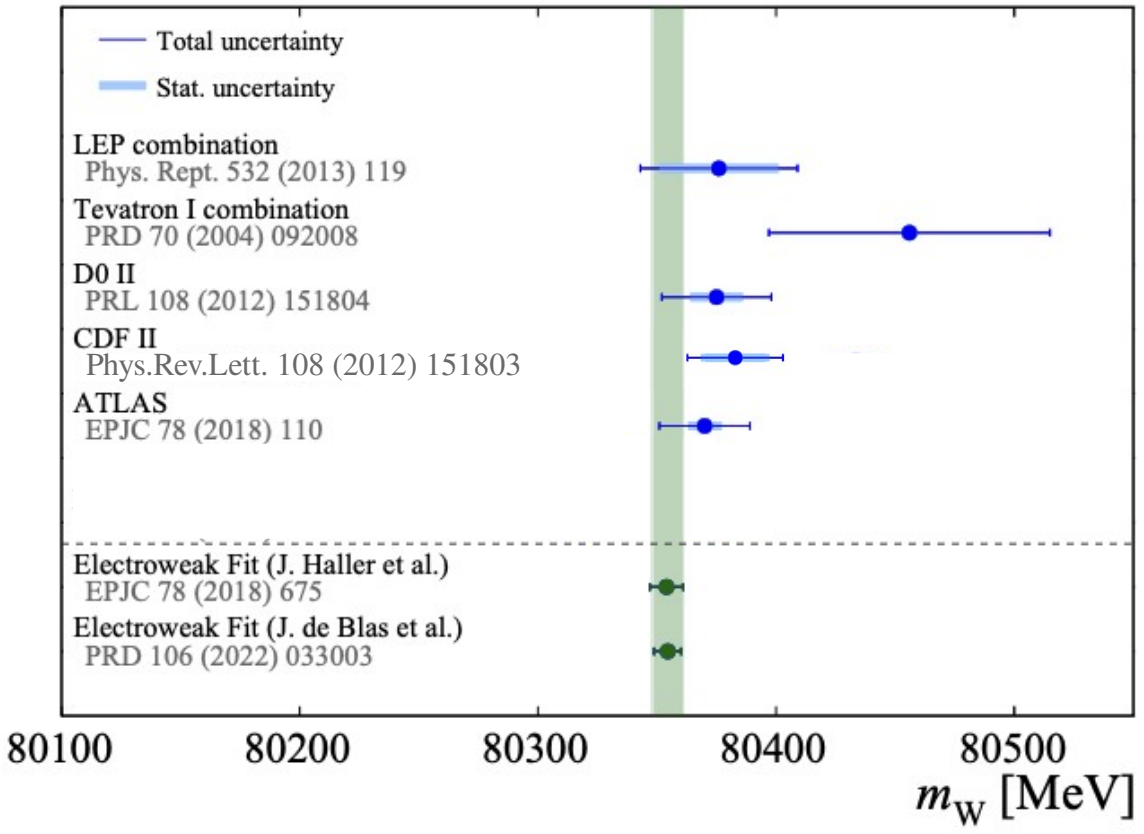
W-boson mass combination

M.Boonekamp, on behalf of the m_W combination working group

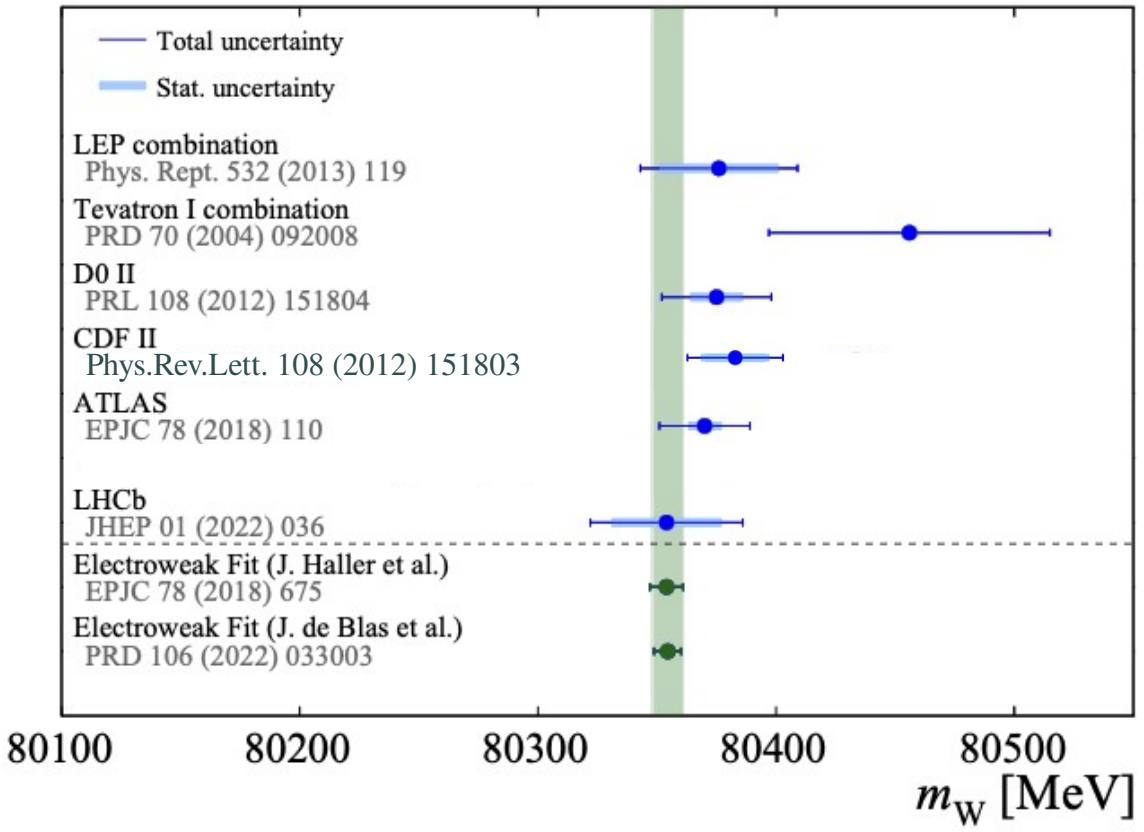
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/MWCOMB

https://cds.cern.ch/record/2815187

2019-2020


Total uncertainty
Stat. uncertainty
LEP combination
Phys. Rept. 532 (2013) 119
Tevatron I combination
PRD 70 (2004) 092008
D0 II
PRL 108 (2012) 151804
CDF II
Phys.Rev.Lett. 108 (2012) 151803
ATLAS
EPJC 78 (2018) 110
Electroweak Fit (J. Haller et al.)
EPJC 78 (2018) 675
Electroweak Fit (J. de Blas et al.)
PRD 106 (2022) 033003
80100
80200
80300
80400
80500
m_W [MeV]

2021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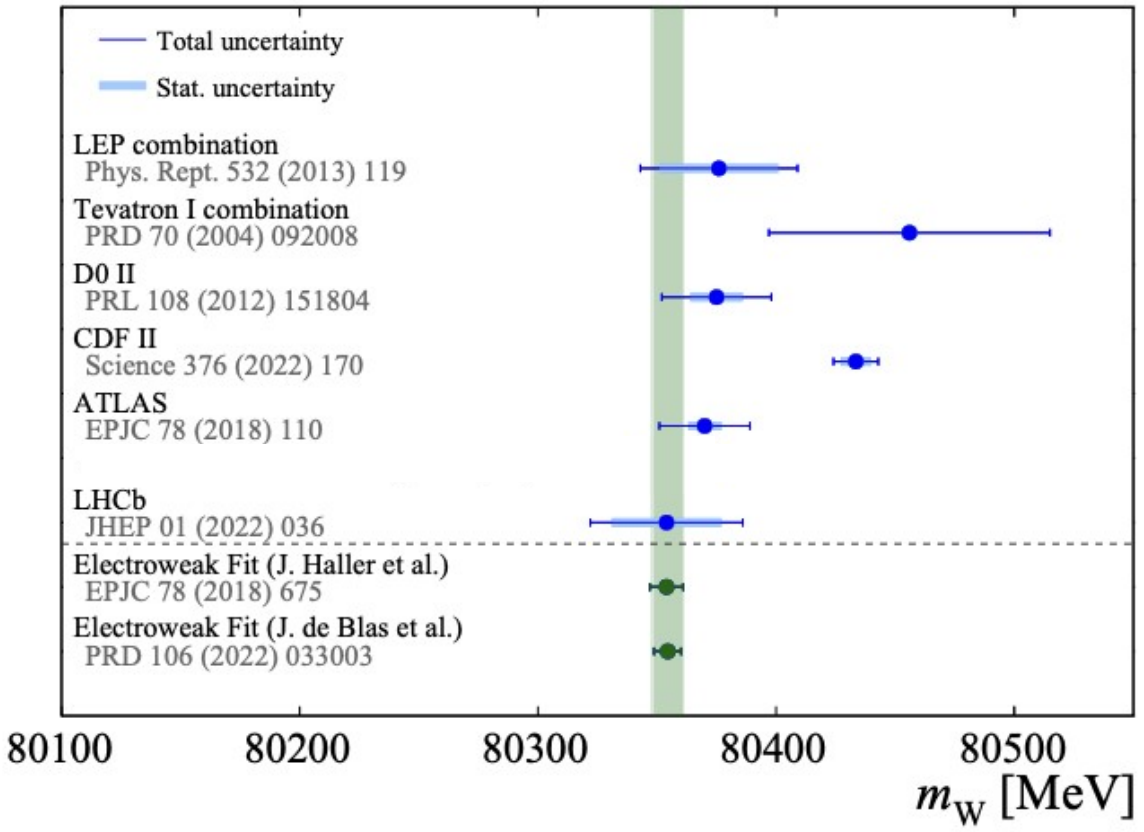
PRD 106 (2022) 033003
80100
80200
80300
80400
80500
m_W [MeV]

2022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Science 376 (2022) 170
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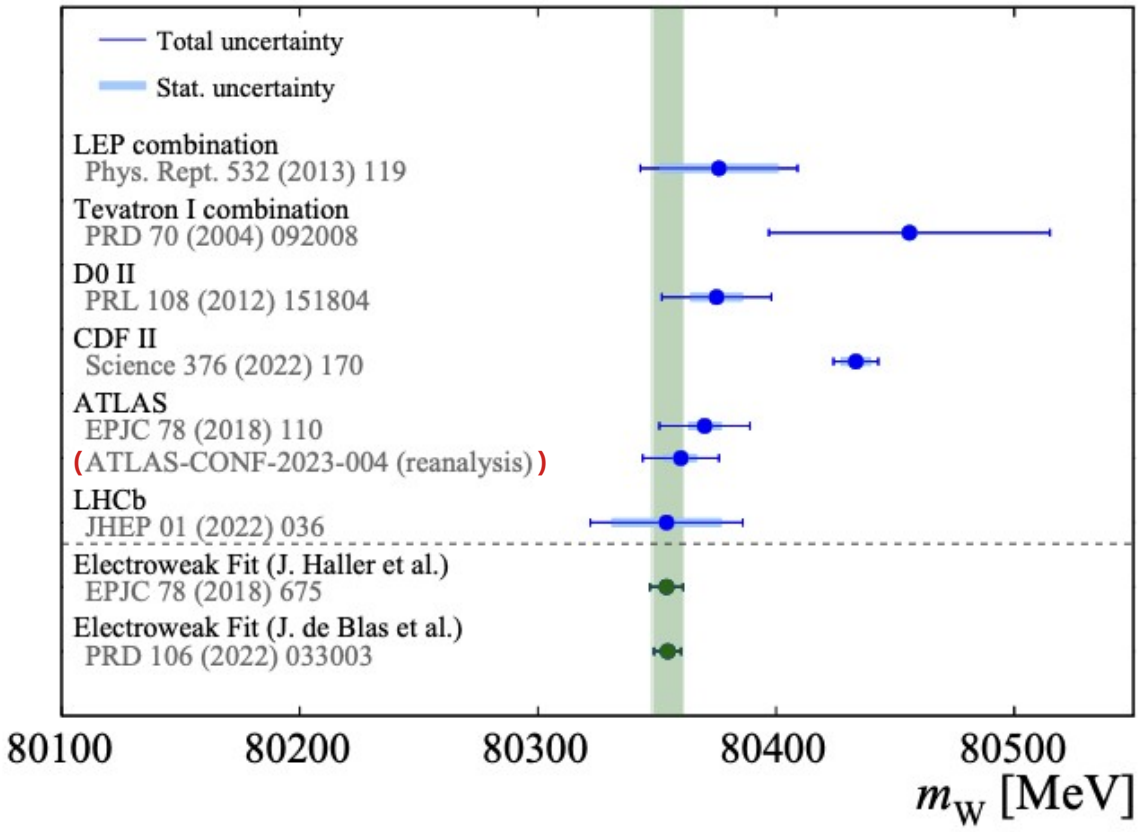
80100
80200
80300
80400
80500
m_W [MeV]

(2023)


Total uncertainty
Stat. uncertainty
LEP combination
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Tevatron I combination
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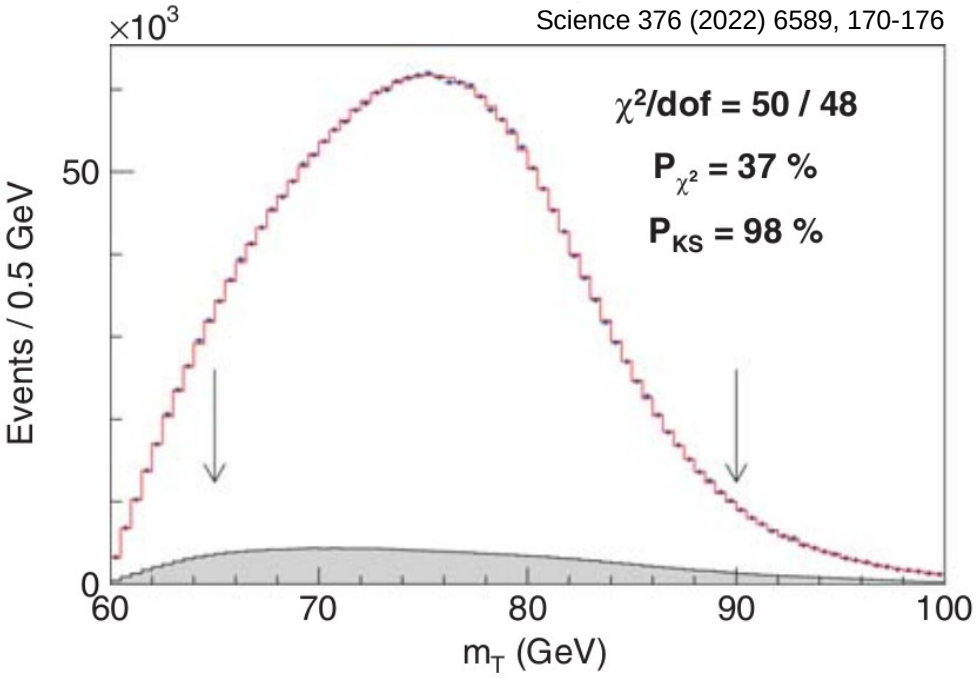
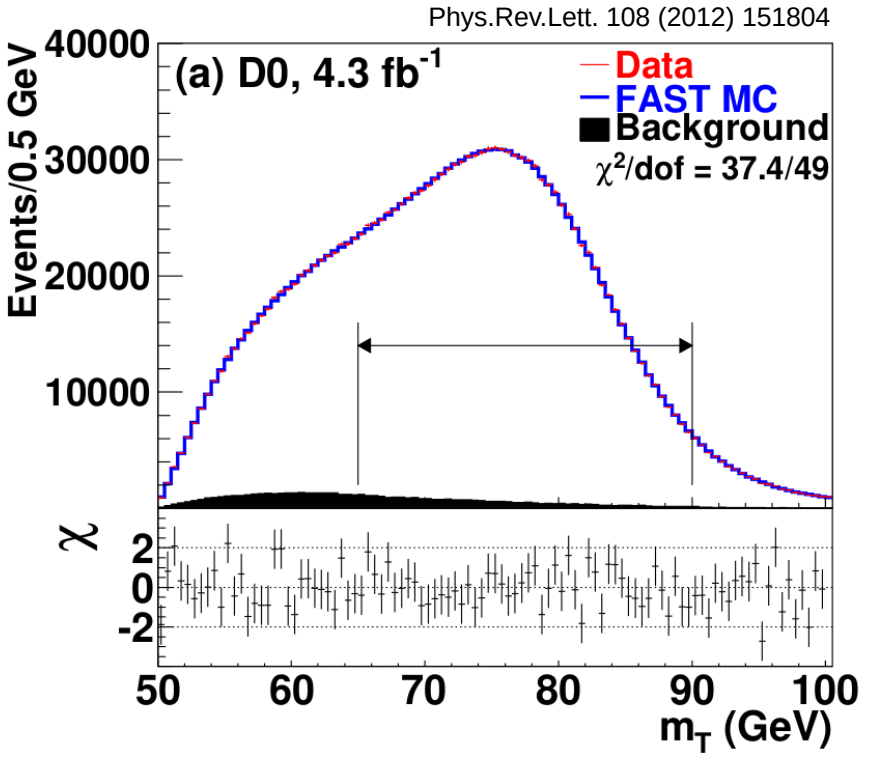
D0 II
PRL 108 (2012) 151804
CDF II
Science 376 (2022) 170
ATLAS
EPJC 78 (2018) 110
(ATLAS-CONF-2023-004 (reanalysis))
LHCb
JHEP 01 (2022) 036
Electroweak Fit (J. Haller et al.)
EPJC 78 (2018) 675
Electroweak Fit (J. de Blas et al.)
PRD 106 (2022) 033003
80100
80200
80300
80400
80500
m_W [MeV]

Measurements

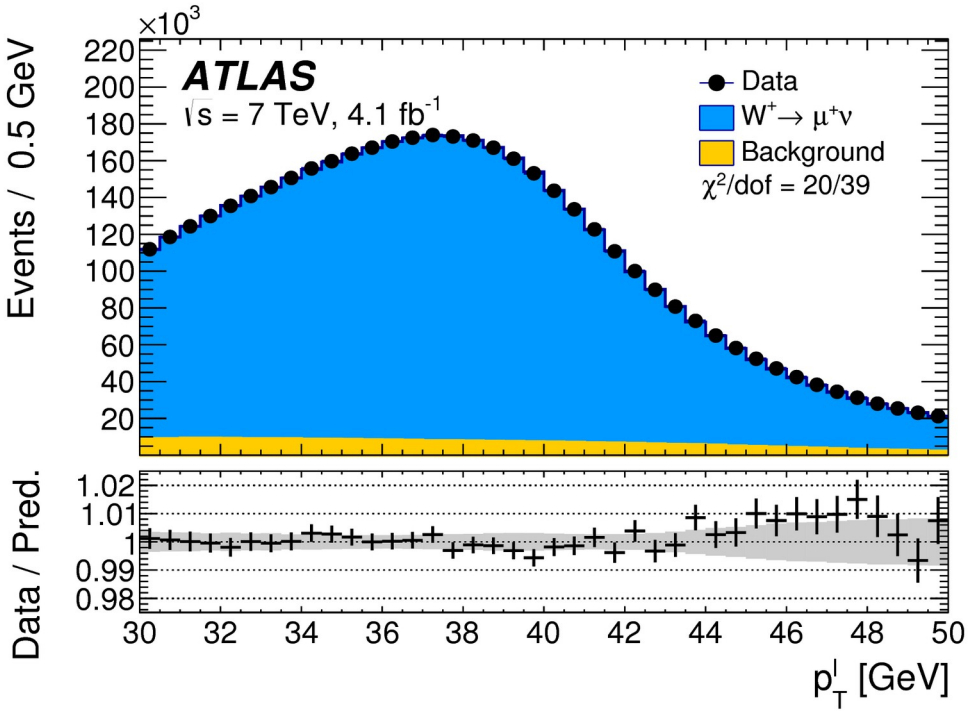
- CDF, D0 : charge-blind m_T fits (CP-even initial and final states)



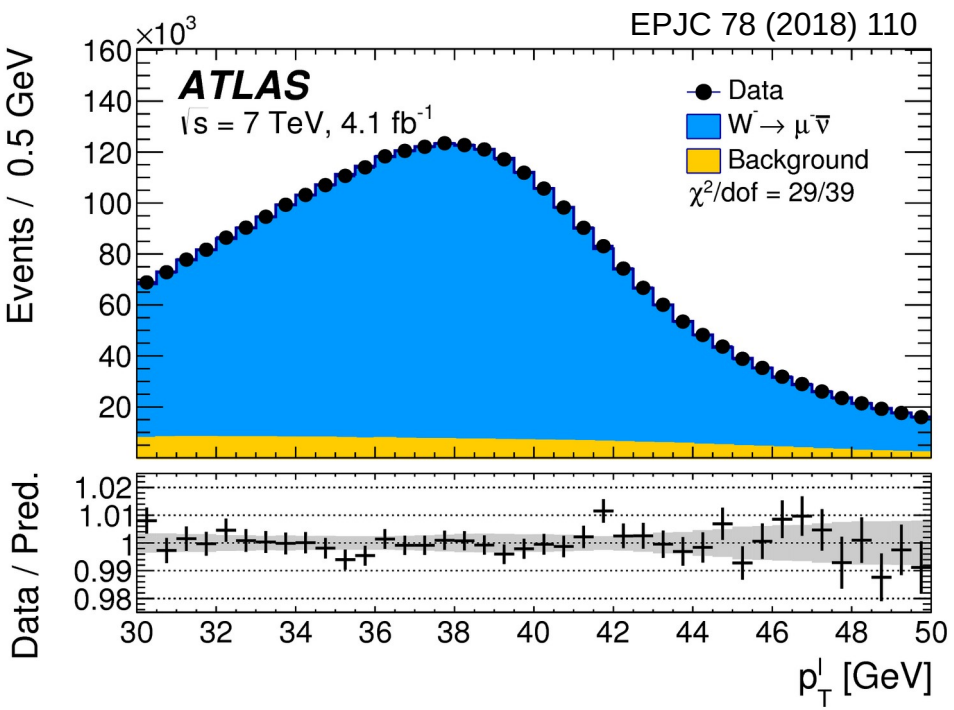


Measurements

- ATLAS : lepton p_T fits, separate by charge, and η bins



W+

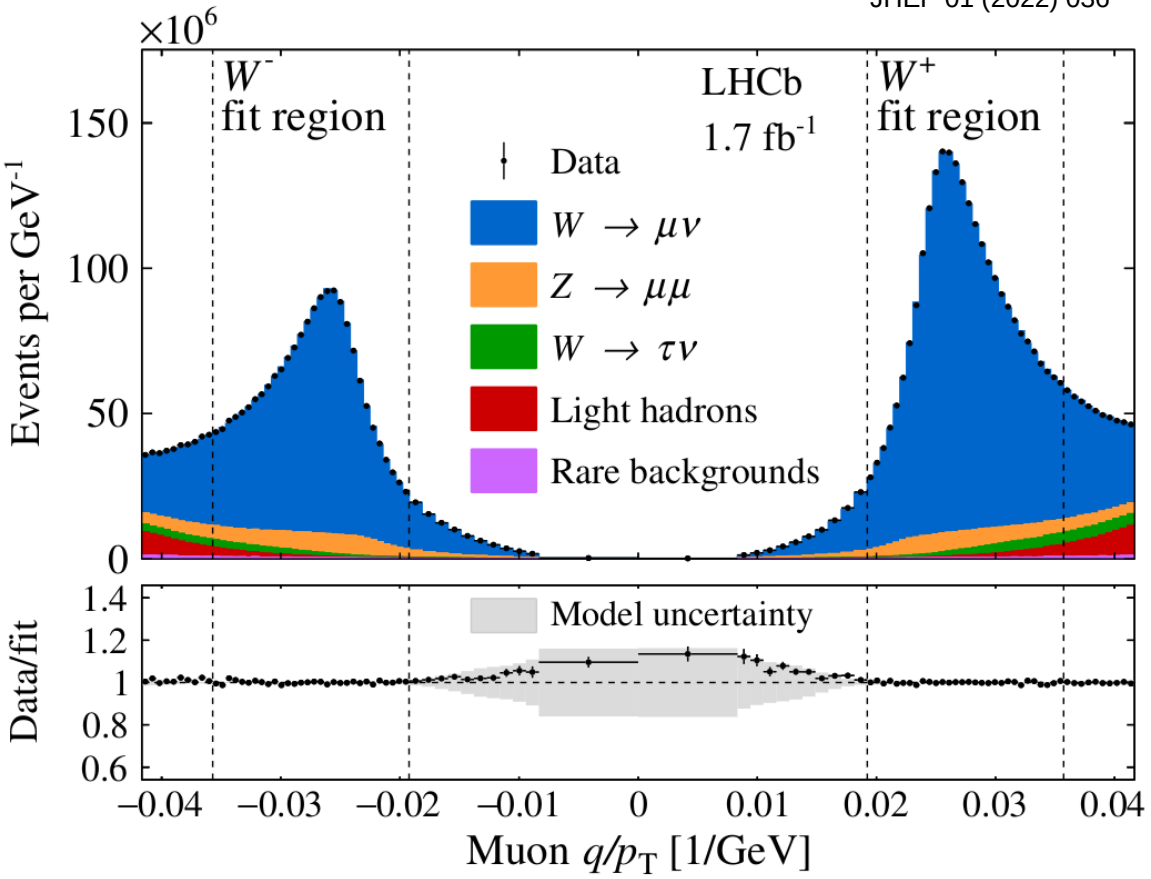


W-

Measurements

- LHCb

JHEP 01 (2022) 036

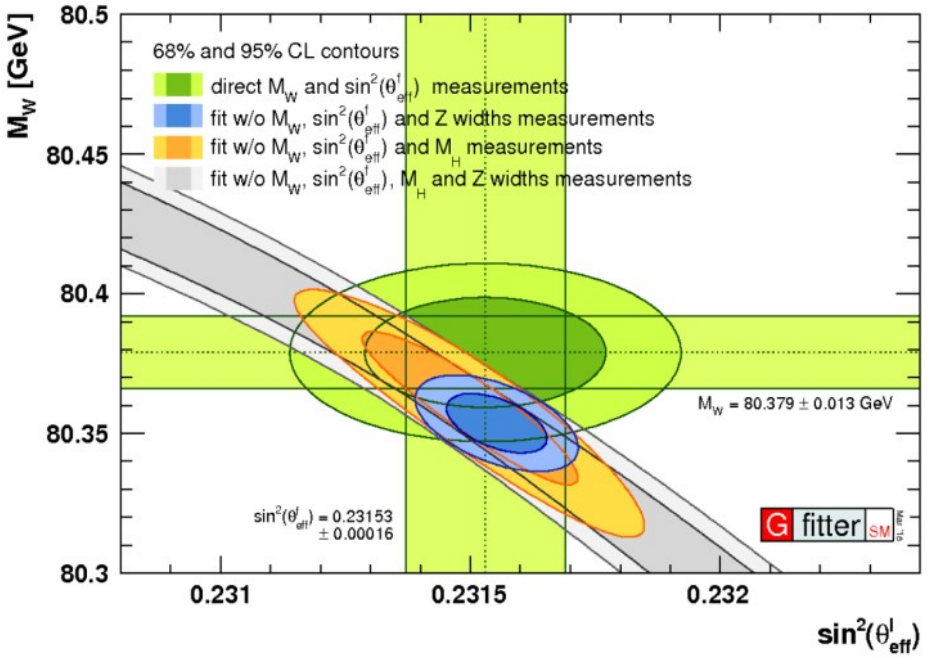


Objectives

- Provide endorsed comparison/combination of available m_W measurements

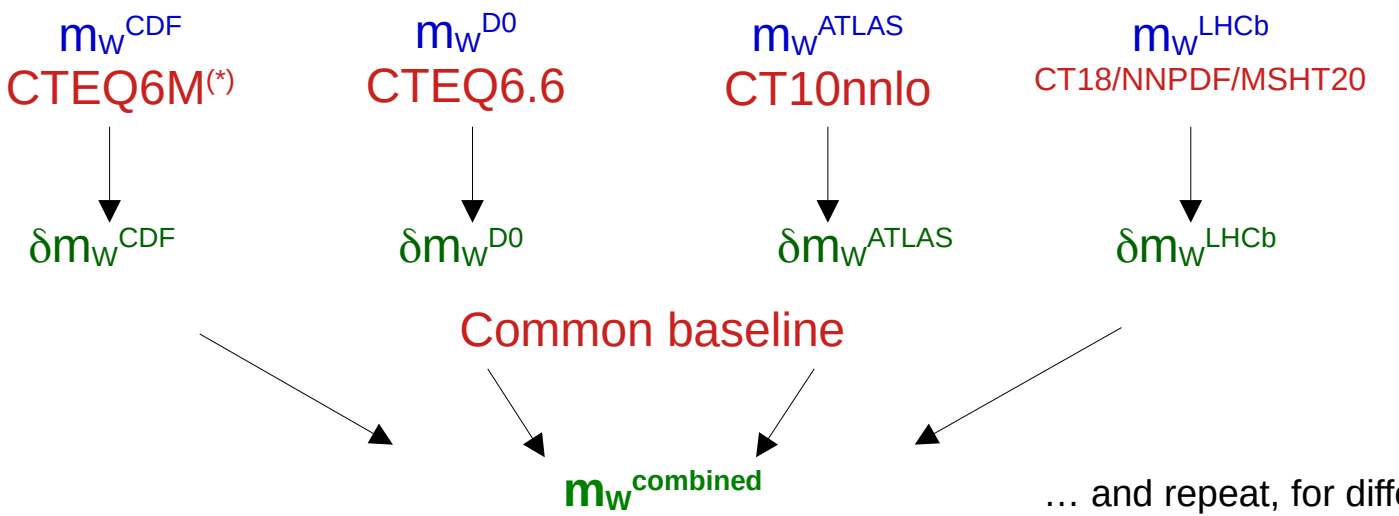
  - Establish combination methodology for present and future measurements
    - Enable modelling updates
    - Properly correlate m_W, $\sin^2\theta_W$ and other PDF-dominated measurements
  - Quantitative results
    - Combine all, if possible
    - Produce largest-possible combination and quantify discrepancy, if not

[*Eur. Phys. J.* **C74** (2014) 3046]



Analysis strategy

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



… and repeat, for different PDFs

Measurement extrapolations

- Full procedure, decomposed into generator and PDF effects :

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

published — Improved predictions, for reference PDF — PDF extrapolation

- Published measurements :
  - CDF : Resbos1 (NLO) — CTEQ6M (NLO)
  - D0 : Resbos1 (NNLO) — CTEQ6.1/6.6 (NLO)
  - ATLAS : Powheg+Pythia; rapidy+spin corr. at NNLO — CT10 (NNLO)
  - LHCb : Powheg+Pythia; spin corr. at NNLO — <NNPDF3.1,CT18,MSHT20> (NLO)
- Extrapolations (δm_W) evaluated using generator-level reweightings and “emulation” of detector effects
  - δm_W^{PDF} Main PDF targets : modern NNLO sets
  - δm_W^{QCD} Applies when generators or QCD improvements are beyond the quoted uncertainties.

Emulation

- Measurements performed at detector level : account for detector response when evaluating the effect of changes in the underlying physics.
  - ATLAS, CDF, D0 : “analysis emulation”
    - Parameterise lepton and recoil scales and resolutions, efficiencies, etc according to published information
    - Assumption : even with a simplified simulation, resolutions cancel in first order when making ratios with varying physics
    - Approximate, but affordable (systematics added). Done this way because it was acknowledged that insufficient resources were available to perform calculations with complete simulation.
  - LHCb analysis is “live” and provides all information from the actual measurement procedure – better!

Emulation : event generation

- Fully **reproduced the event generation chain** from the original measurements

  D0: Resbos CP (NNLO+NNLL) generated with CTEQ66 (NLO)

  CDF: Resbos C (NLO+NNLL) generated with CTEQ6M (NLO)

  ATLAS: Powheg+Pythia8 (NLO+PS); y_W + Ai at NNLO with CT10 (NNLO)

  LHCb: Powheg+Pythia8 (NLO+PS); Ai at NNLO,
  as PDF the average of NNPDF3.1,CT18,MSHT20 (NLO)

- Variety of predictions used to validate the PDF shifts and estimate the possible need of QCD correction to published m_W
  - Powheg (NLO+PS), MiNNLOPS (NNLO+PS), DYNNLO (NLO/NNLO F.O.)
  - In addition, updated integration grids from the Resbos authors (dubbed here Resbos2) at NLO+NNLL and NNLO+NNLL with improved treatment of spin correlations [*2205.02788*]

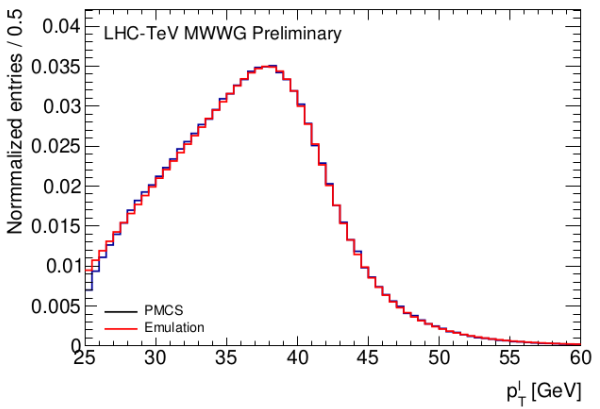
Emulation : selections and fitting ranges

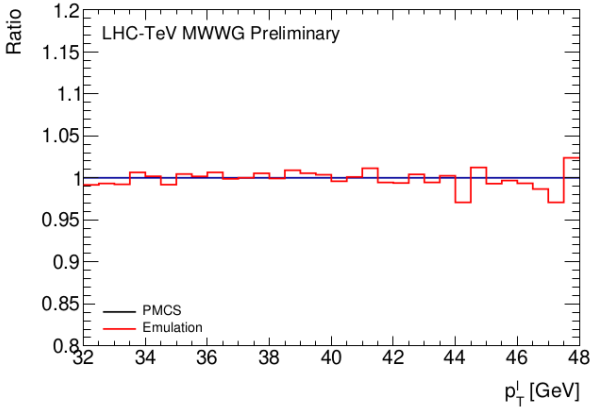
Experiment	Event selections	Fit ranges
CDF	$30 < p_{\mathrm{T}}^{\ell} < 55$ GeV, $\lvert\eta_{\ell}\rvert < 1$ $30 < E_{\mathrm{T}}^{\mathrm{miss}} < 55$ GeV, $60 < m_{\mathrm{T}} < 100$ GeV $u_{\mathrm{T}} < 15$ GeV	$32 < p_{\mathrm{T}}^{\ell} < 48$ GeV $32 < E_{\mathrm{T}}^{\mathrm{miss}} < 48$ GeV $65 < m_{\mathrm{T}} < 90$ GeV
D0	$p_{\mathrm{T}}^{\ell} > 25$ GeV, $\lvert\eta_{\ell}\rvert < 1.05$ $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, $m_{\mathrm{T}} > 50$ GeV $u_{\mathrm{T}} < 15$ GeV	$32 < p_{\mathrm{T}}^{\ell} < 48$ GeV $65 < m_{\mathrm{T}} < 90$ GeV
ATLAS	$p_{\mathrm{T}}^{\ell} > 30$ GeV, $\lvert\eta_{\ell}\rvert < 2.4$ $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV, $m_{\mathrm{T}} > 60$ GeV $u_{\mathrm{T}} < 30$ GeV	$32 < p_{\mathrm{T}}^{\ell} < 45$ GeV $66 < m_{\mathrm{T}} < 99$ GeV

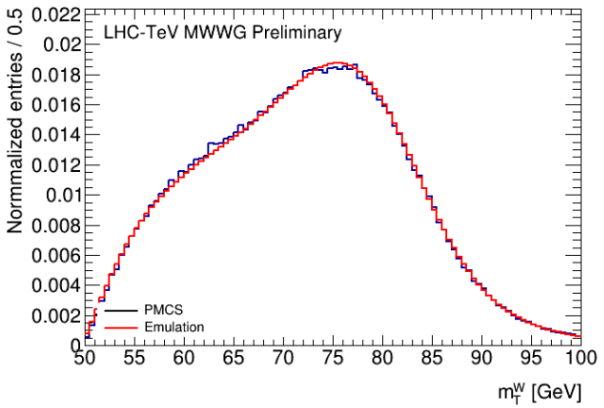
Table 3: Event selections and fit ranges for CDF, D0 and ATLAS.

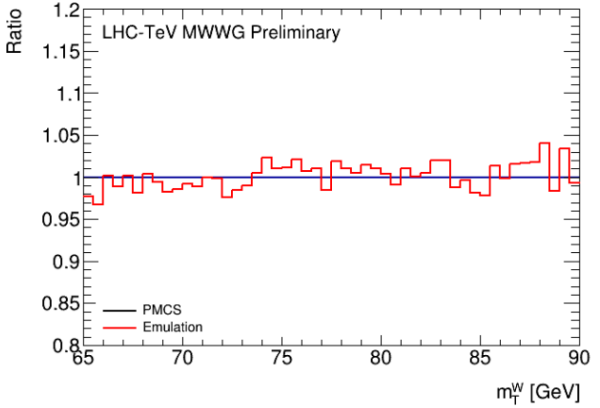
Emulation : D0

- Detector resolutions



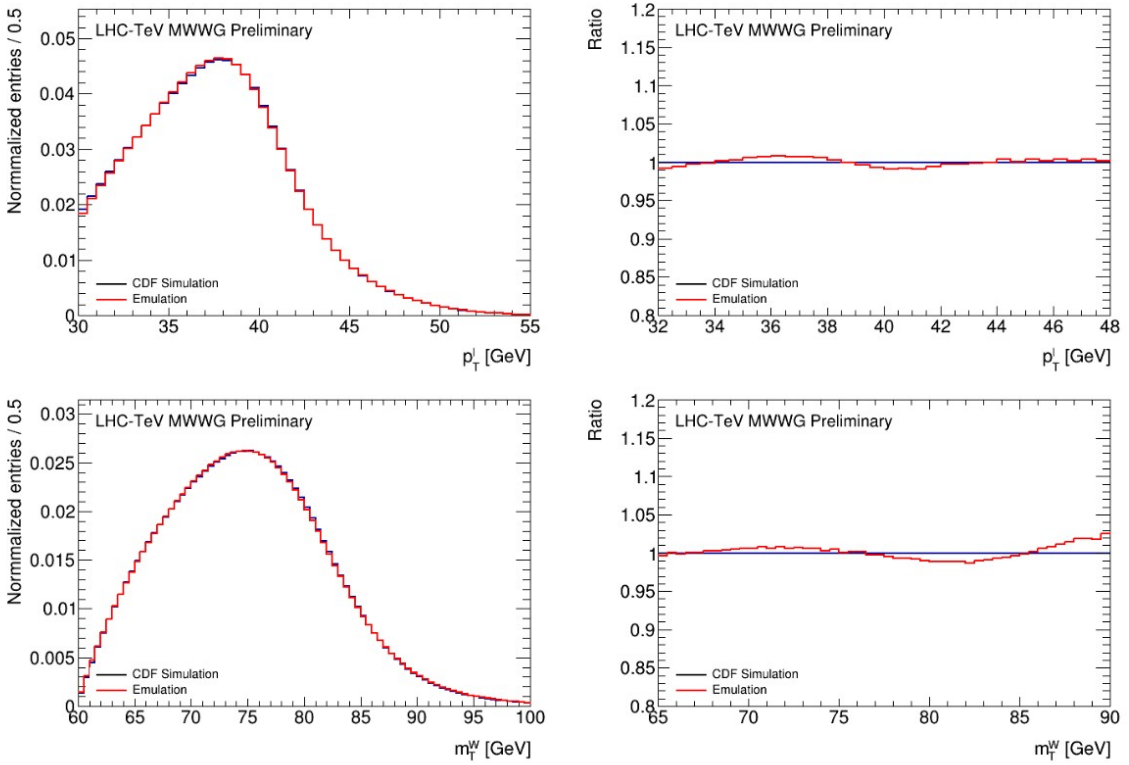






Emulation : CDF

- Detector resolutions
  - Systematics from parameterisation variations, as for D0



Emulation : ATLAS

- Detector resolutions

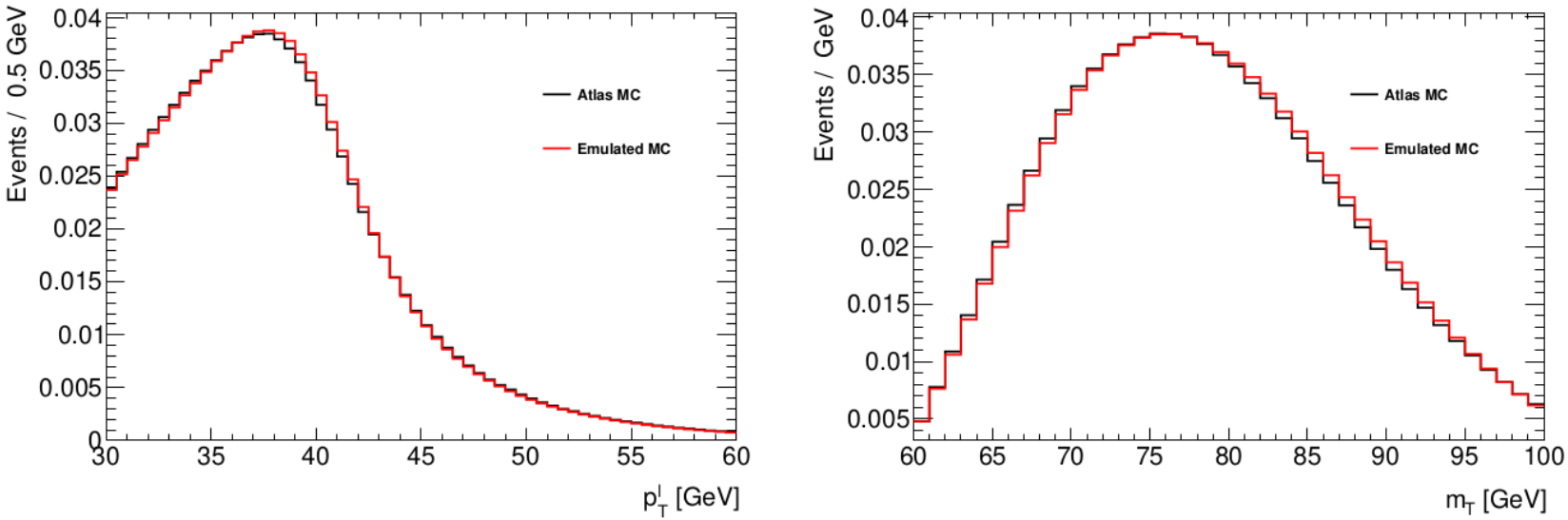


Figure 6: Comparison of the published and simulated p_{T}^{ℓ} (lefT) and m_{T} (right) distributions for ATLAS.

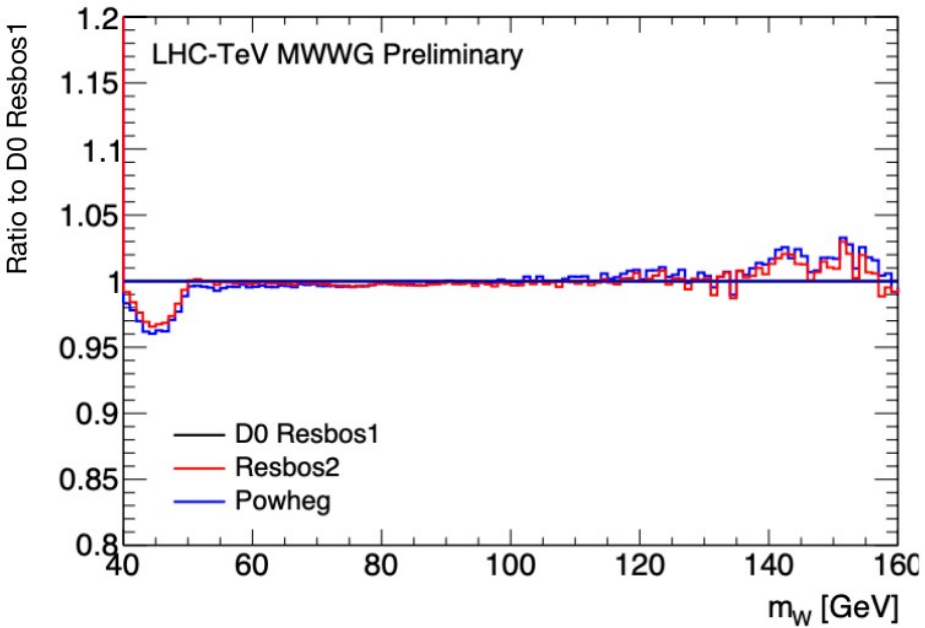
QCD corrections

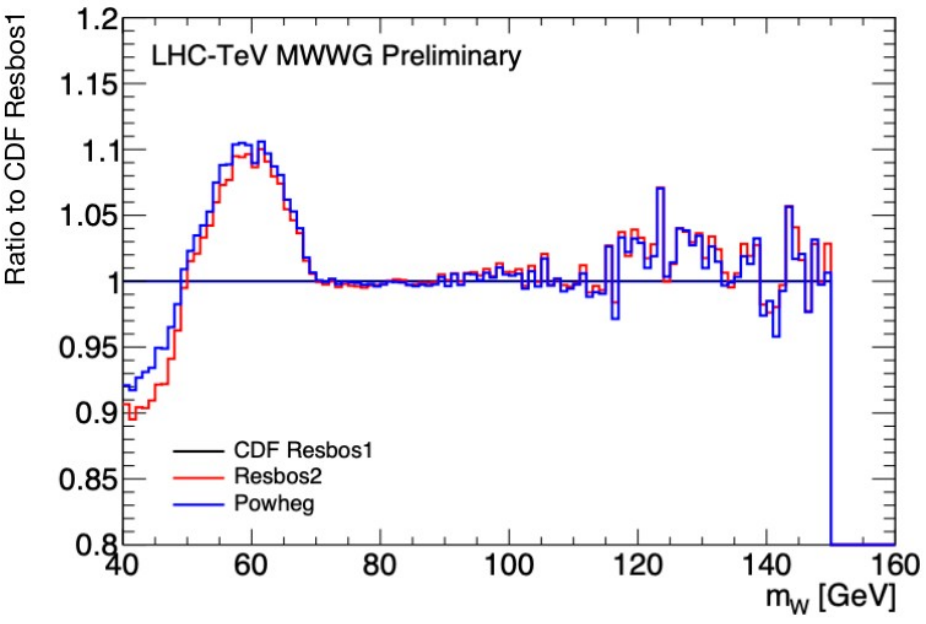
- Do we need to look back into the QCD predictions of previous experiments?
  - TeVatron tool (Resbos1) >20 years old; improved version (Resbos2) available
  - Should not lose the nice experimental precision!
- To look into this, decompose distributions according to canonical formula:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_{\mathrm{T}}\,dy}\,[\;(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\;]\,,$$

QCD corrections

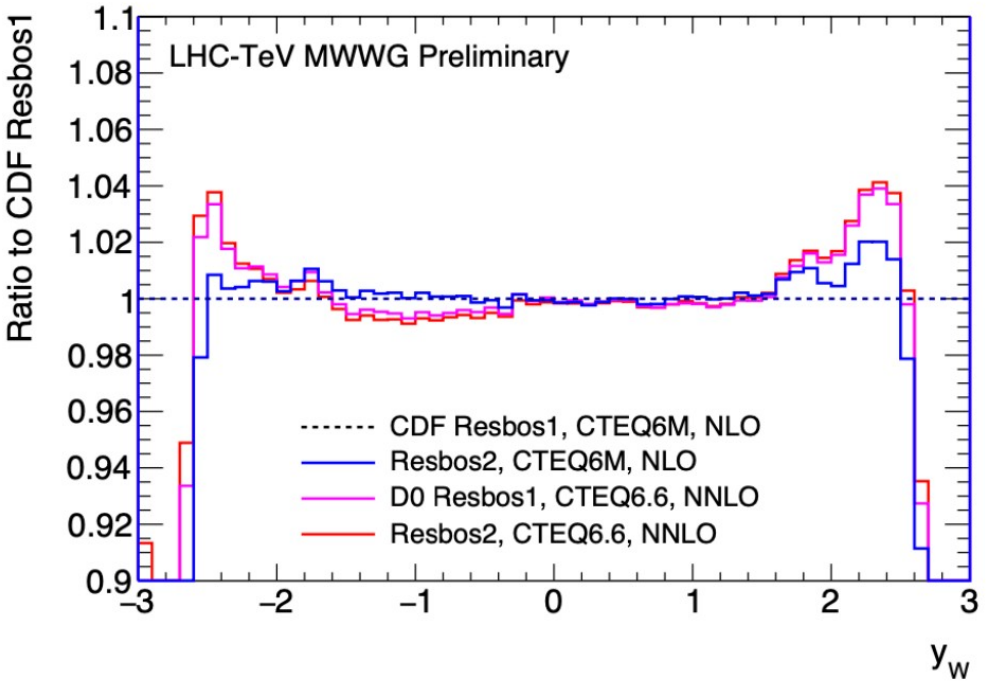
- Invariant mass distribution
  - Trends with respect to modern generators
    - Look mostly technical. Impact ~1 MeV





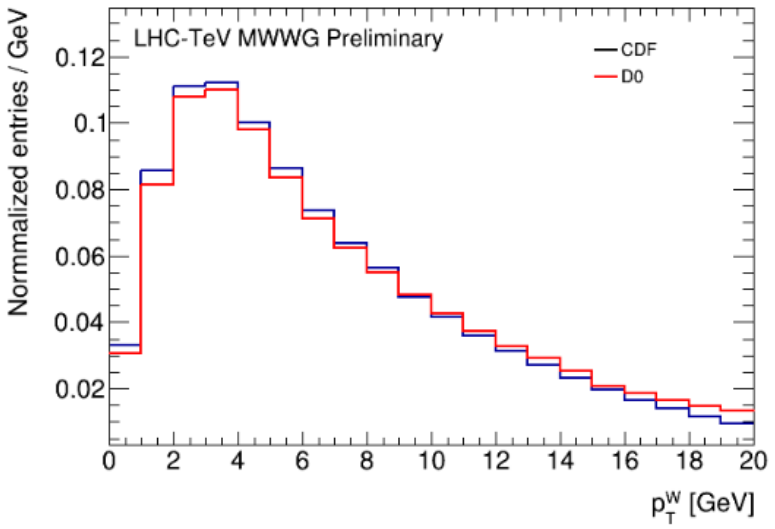
QCD corrections

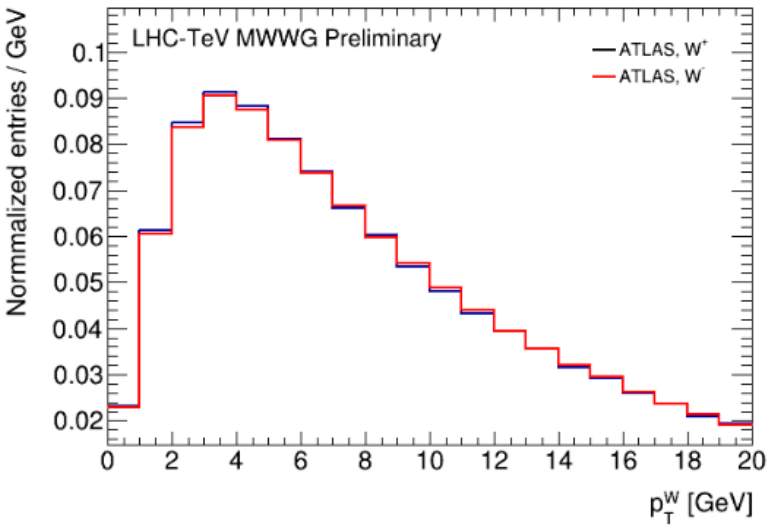
- Rapidity distribution
  - Percent-level between CTEQ6M distribution predicted in Resbos1 and Resbos2
  - Visible differences between CTEQ6M (CDF) and CTEQ66 (D0)



Transverse momentum distribution

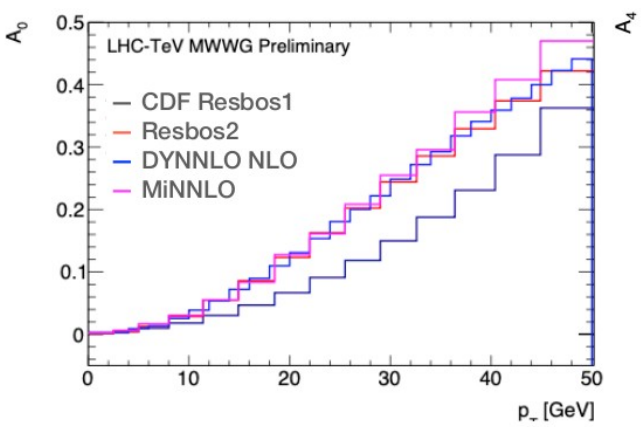
- Assume baseline distributions as published, and constrained under QCD / PDF extrapolations
  - Justified by successful recoil control plots
  - Tevatron : p_T^W distribution fixed; ATLAS fixes only the pTW/pTZ distribution ratio

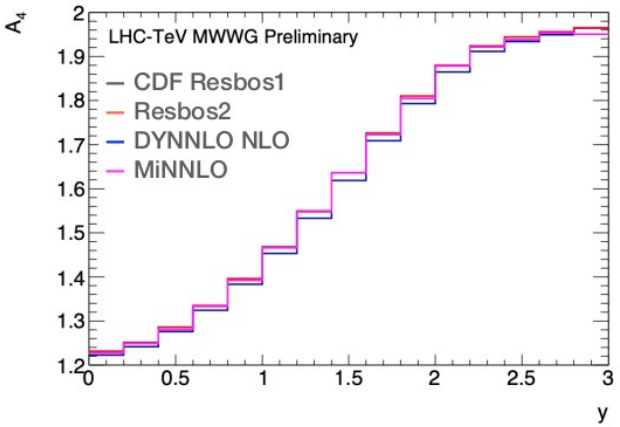


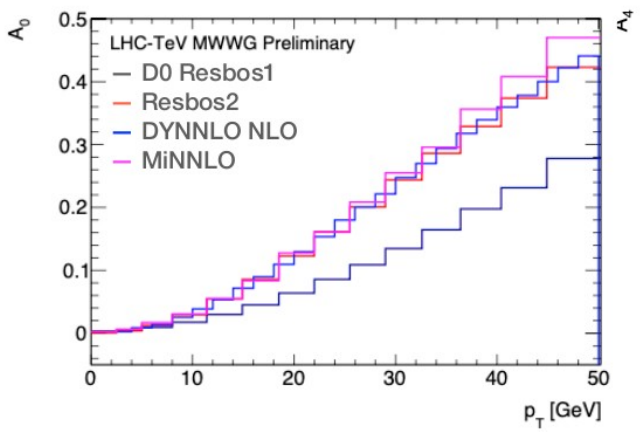


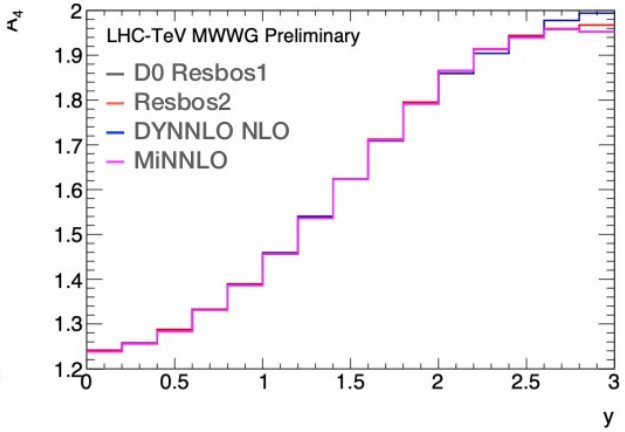
QCD corrections

- Angular coefficients





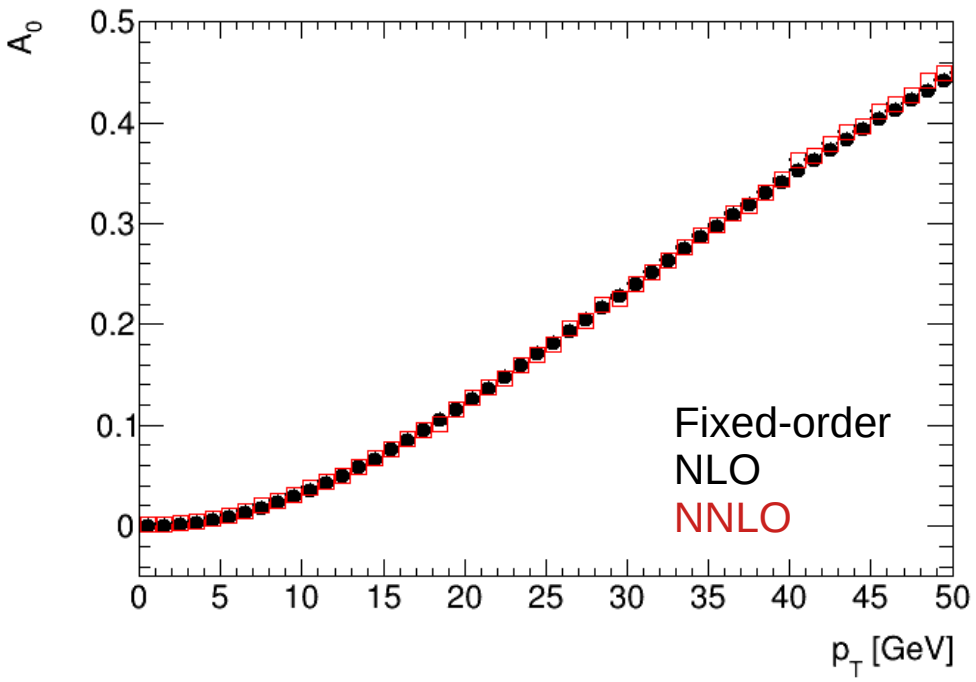


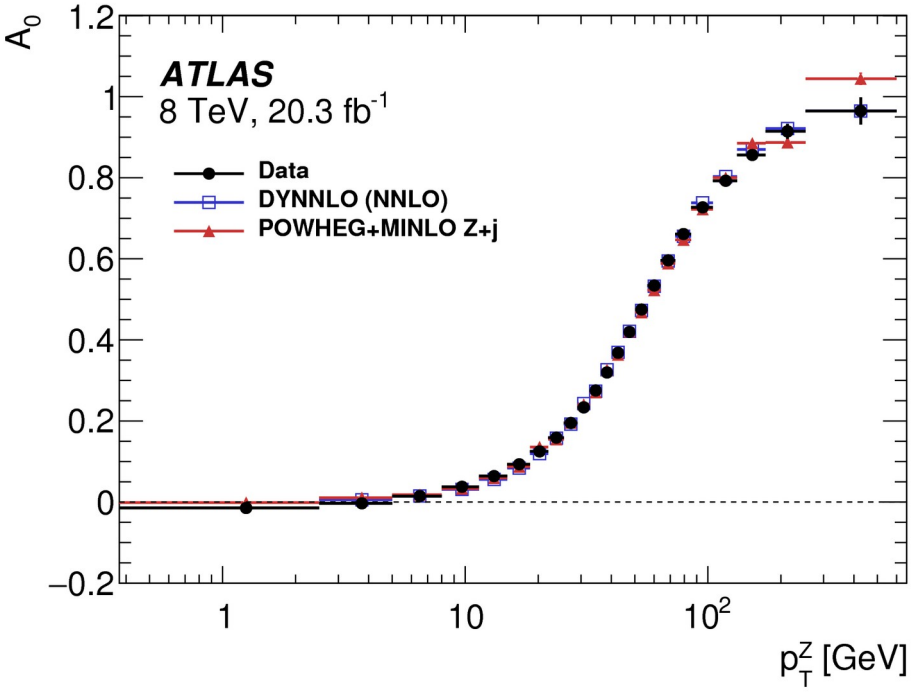


- Issue with resummation of helicity cross sections
  - Only unpolarised and A4 are resummed
  - differences wrt fixed-order Ai
- Differences visible comparing to DYNNLO, MiNNLOPS or Resbos2
- Motivates correction of Tevatron measurements to a common QCD calculation

QCD corrections

- Angular coefficients – why disfavour Resbos1?

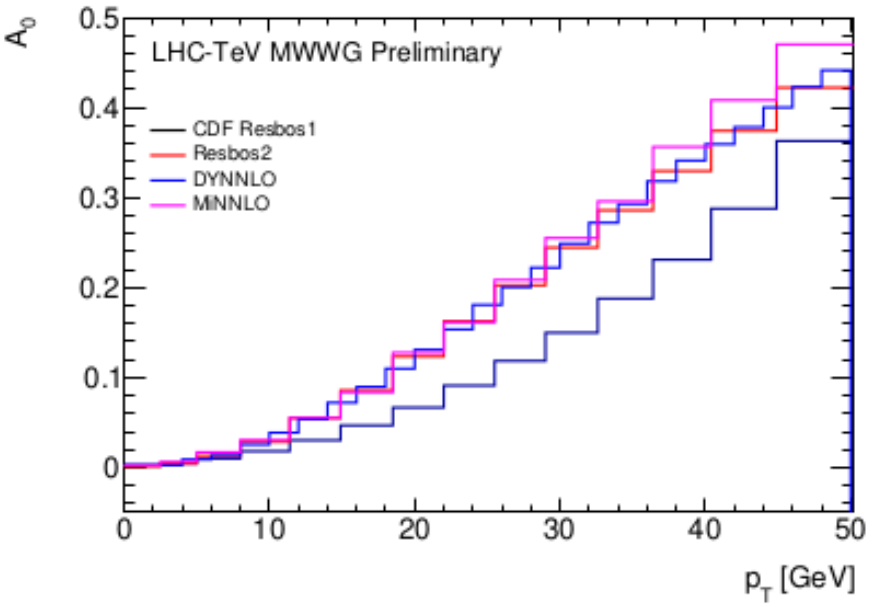




QCD corrections

- Angular coefficients

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm dp_T dy} [\ (1+\cos^2\theta) \ + \ \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \ + \ \dots\ ]$$



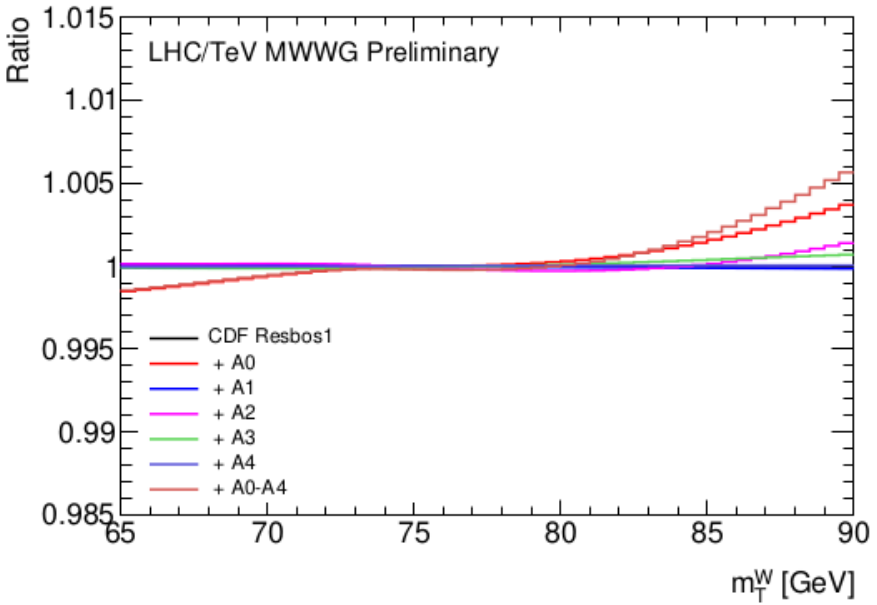
→ lepton distributions too “forward” in Resbos1
→ p_T distribution too soft

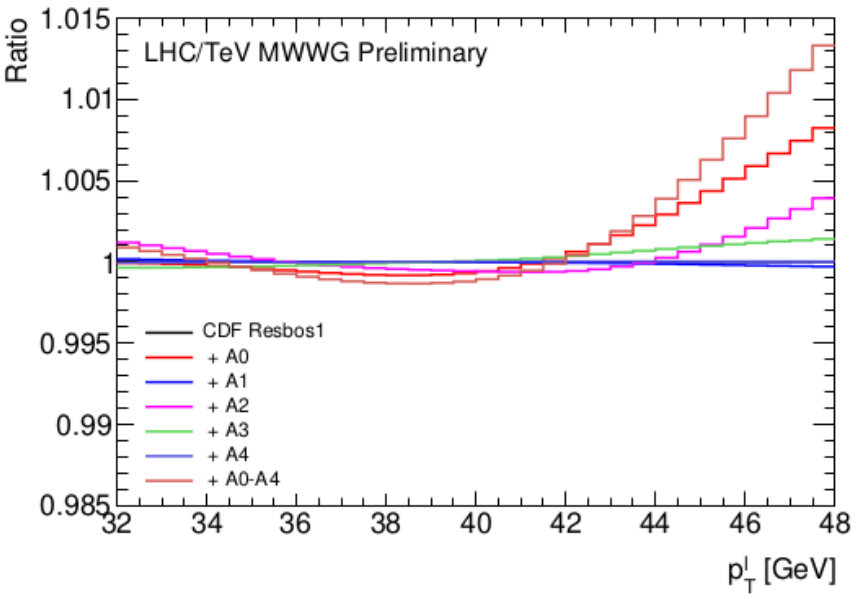
Expected effect of correction : increase of A_0
→ leptons more central
→ hardening of predicted p_T^l spectrum, for given m_W

→ measured value should **decrease**
→ quantitatively?

QCD corrections

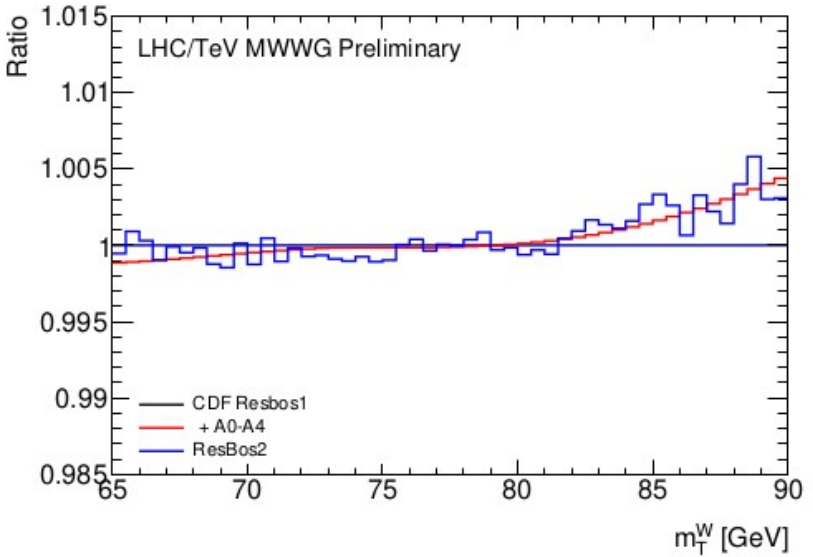
- Impact :
  - Reference : Resbos1

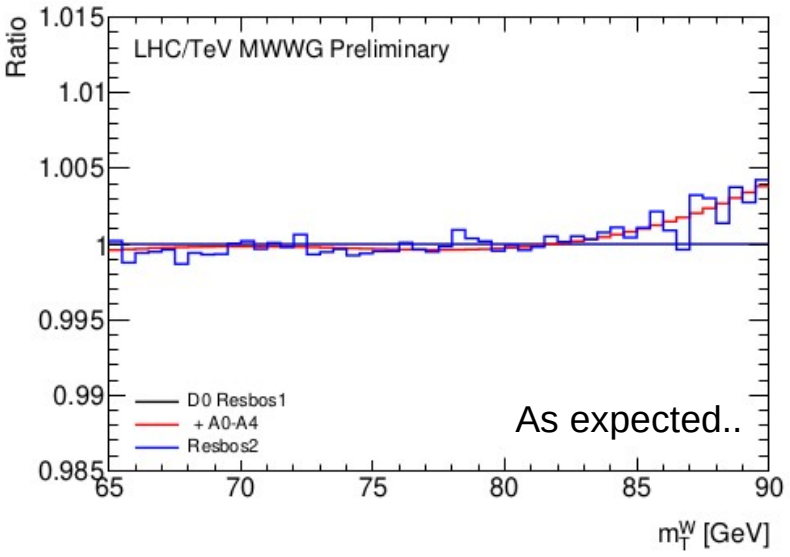




QCD corrections

- Impact :
  - Reference : Resbos1
  - Red line : Resbos1 + Ai corrections (reweightings)
  - Blue line : direct comparison with Resbos2





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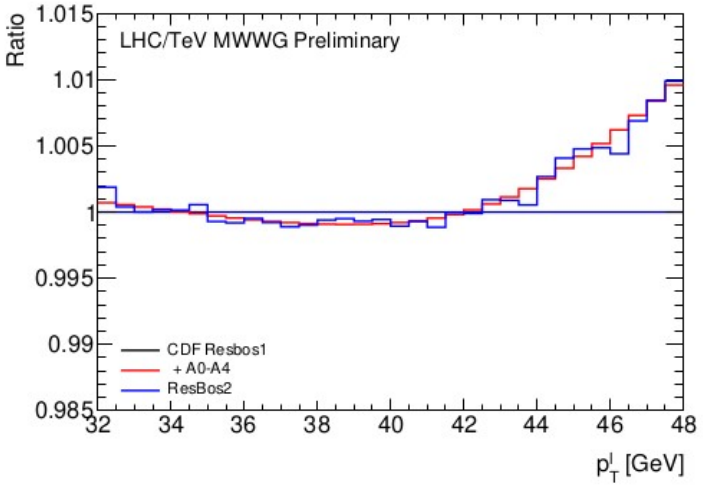
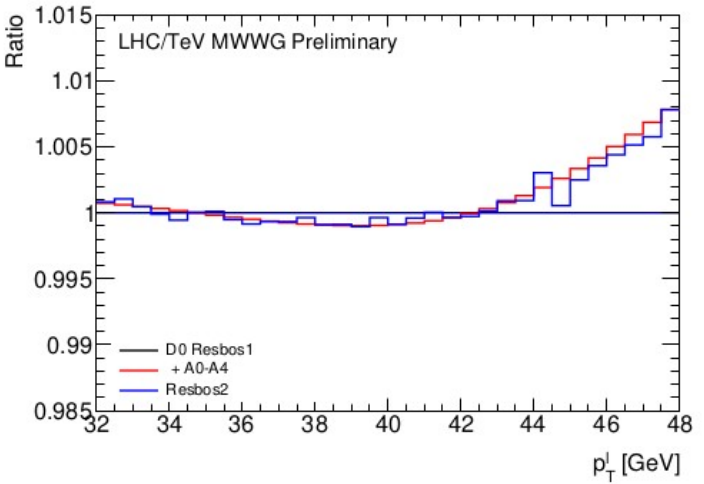
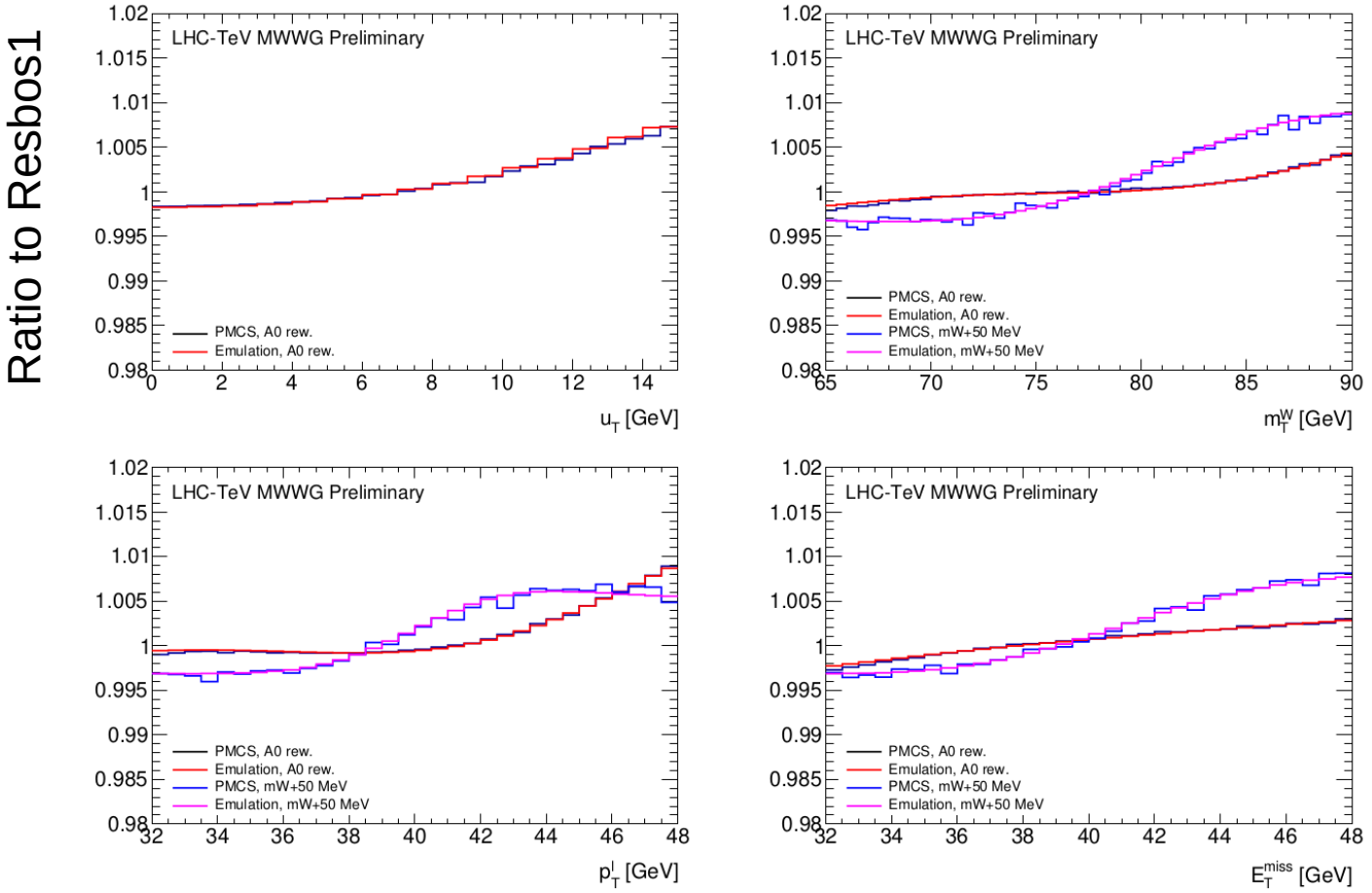




As expected..

Emulation and physics variations :



QCD/generator corrections

- Impact for D0 (similar numbers for CDF):

Correction	Shift [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	19.4
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

Effects understood quantitatively

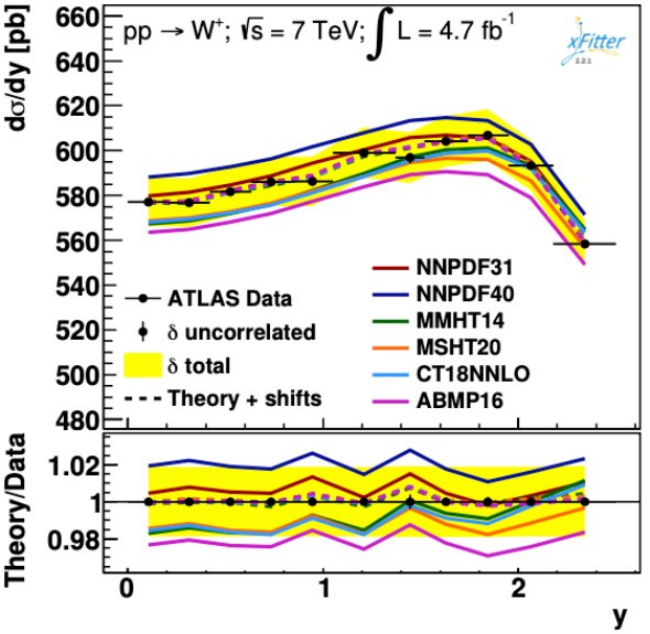
← measured value **decreases** by this amount

PDF extrapolations

- PDFs considered for the combination

  - Performed a benchmarking of PDF sets against Tevatron and LHC cross-section measurements
    - Considering measurements of W and Z cross-sections from Tevatron and LHC
    - Theory predictions at NNLO QCD x NLO EW

PDF set	Chi2/ndf	PDF set	Chi2/ndf
Cteq66	231/126	CT18NNLO	163/126
CT10	179/126	CT18ANNLO	170/126
NNPDF31	200/126	MSHT20	270/126
NNPDF40	195/126	ABMP16	236/126



  - Modern NNLO PDFs provide the best description, no set gives a χ^2/ndf~1
  - Decision on the final PDF will consider χ^2 and uncertainty of the combination itself

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PDF extrapolations

- Extrapolations calculated for
  - Legacy PDFs : CTEQ6; CTEQ6.6; CT10nnlo
  - Newer/current sets : ABMP16; CT14/CT18; MMHT2014/MSHT20; NNPDF3.1/4.0
  - Separately for CDF, D0, ATLAS, LHCb

- Generator comparisons (and associated systematics):
  - Tevatron : Powheg (reweighted & direct), Resbos, MiNNLO
  - LHC : Powheg (reweighted & direct), MiNNLO
  - In general, generators agree on PDF extrapolations to ~1 MeV in m_W.

PDF extrapolations

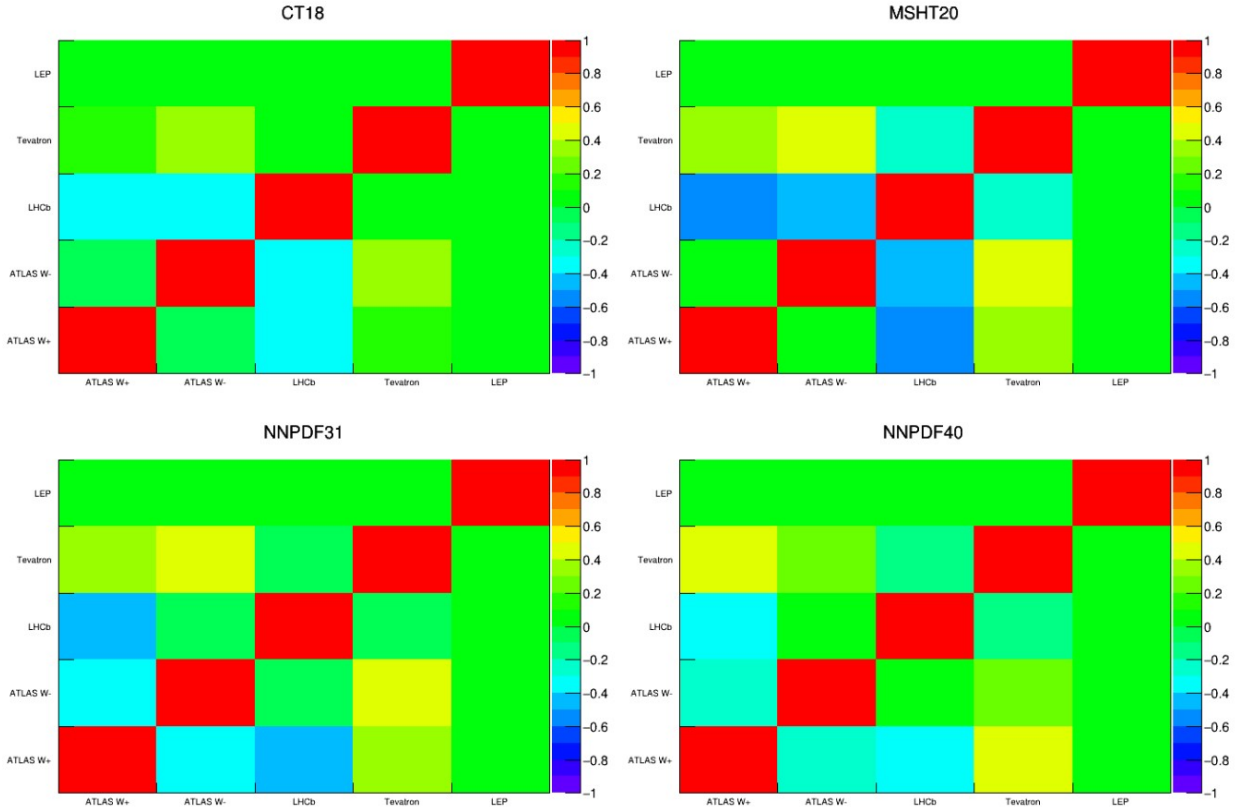
- Example, for Tevatron (similar effects at the LHC) :
  - Disclaimer : preliminary numbers (link), updated since.

    Just to show the relevance of these effects, and evaluate their generator dependence :

Generator	Powheg	Powheg	MiNNLO	Resbos
Sample type	Reweighted	Direct	Reweighted	Direct
QCD accuracy	NLO+NLL	NLO+NLL	NNLO+NLL	NLO+NLL
PDF set			Shift	
CTEQ6M	0	0	0	0
CTEQ66	-15.4 ± 0.8	-15.8 ± 0.8	-14.0 ± 1.3	-17.8 ± 1.0
CT10	-6.3 ± 0.8	-6.2 ± 0.8	-4.2 ± 1.3	–
CT10nnlo	-16.2 ± 0.8	-16.6 ± 0.8	-16.8 ± 1.3	–
CT14	-4,1 ± 0.8	-3.9 ± 0.8	-6.8 ± 1.3	-7.1 ± 1.0
CT18	-6.2 ± 0.8	-6.6 ± 0.8	-8.5 ± 1.3	-9.4 ± 1.0
CJ15	7.7 ± 0.8	7.9 ± 0.8	10.1 ± 1.3	–
MMHT14	-6.2 ± 0.8	-6.4 ± 0.8	-6.9 ± 1.3	-8.1 ± 1.0
MSHT20	-5.0 ± 0.8	-4.9 ± 0.8	-4.9 ± 1.3	–
ABMP16	5.2 ± 0.8	5.0 ± 0.8	-0.2 ± 1.3	–
NNPDF3.1	-13.8 ± 0.8	-14.3 ± 1.4	-14.1 ± 1.3	-15.8 ± 1.0

PDF correlations

- Non-trivial PDF correlations, with significant PDF model dependence!



Combinations

- Performed using BLUE procedure , as used by most/all experiments this far. Complete uncertainty decomposition available, including correlations
  - Validation : reproduce published combination results
- Anticipated set of results :
  - For each experiment:
    - Published
    - With QCD updates
    - PDF extrapolations
  - Combinations : Tevatron; LHC; “N-1”; full (including LEP)
    - QCD updates applied; all PDFs
    - Further PDF discrimination based on combination quality
  - Presentation of final results : under discussion

Status & prospects

- Studies documented in a public note: CERN-LPCC-2022-06
  - Validation of emulation
  - QCD effects quantified; impact ~10 MeV ultimately.
- All combinations and studies essentially finalized; currently under final review
- working out publication procedure

- Future updates will hopefully be smoother
  - Many future results eagerly awaited!
  - One more methodological step : uncertainty components in profile-likelihood fits