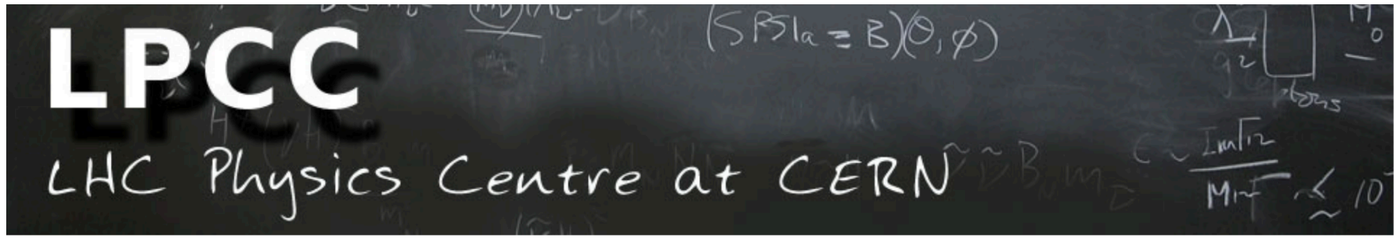


Status of the Tevatron/LHC W-boson mass combination

ICHEP 2022

July 7th, 2022, Bologna

Simone Amoroso (DESY),
for the Tevatron/LHC M_W WG

HADRON COLLIDER MEASUREMENTS OF M_W

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*]

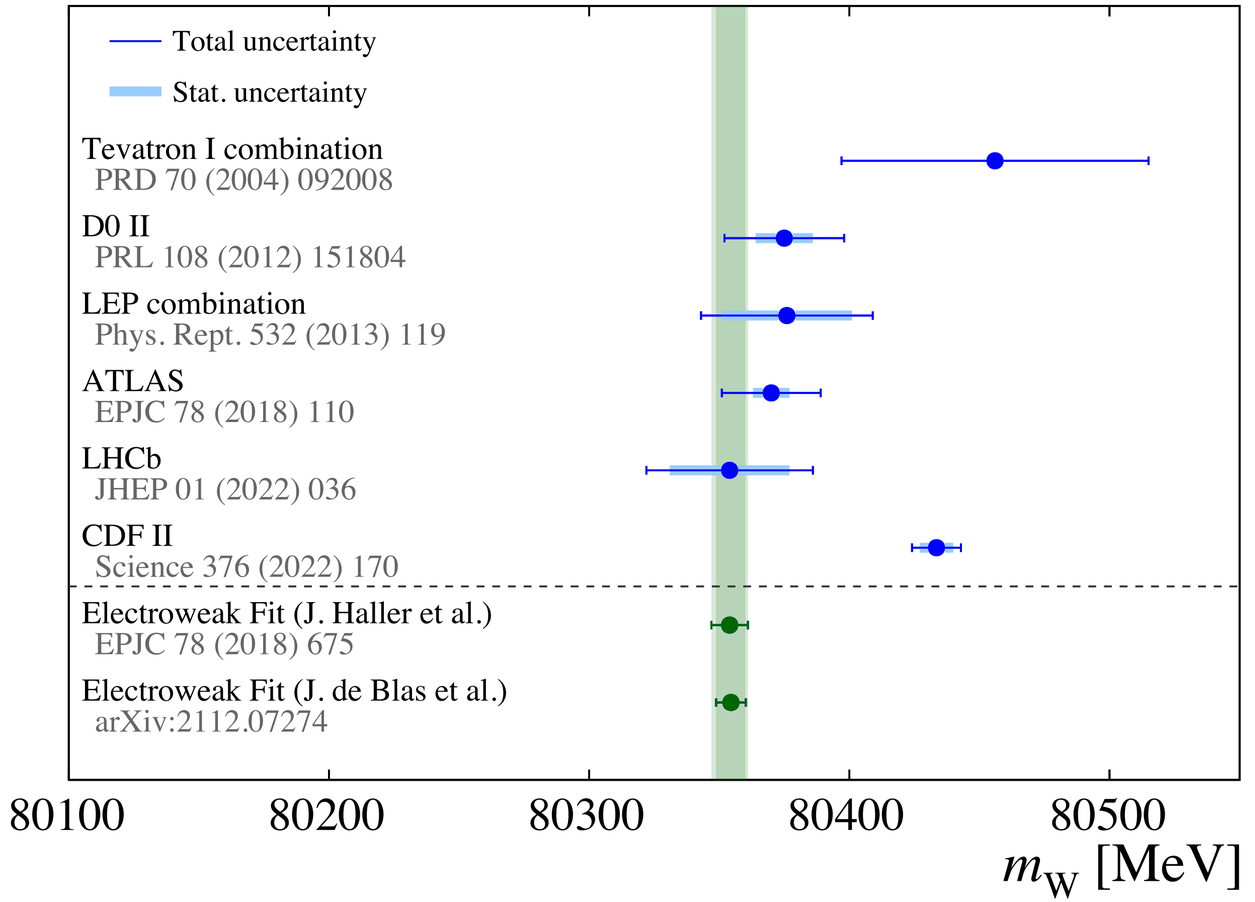
m_W = 80433.5 ± 6.4 (stat.) ± 6.9 (sys.) MeV

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

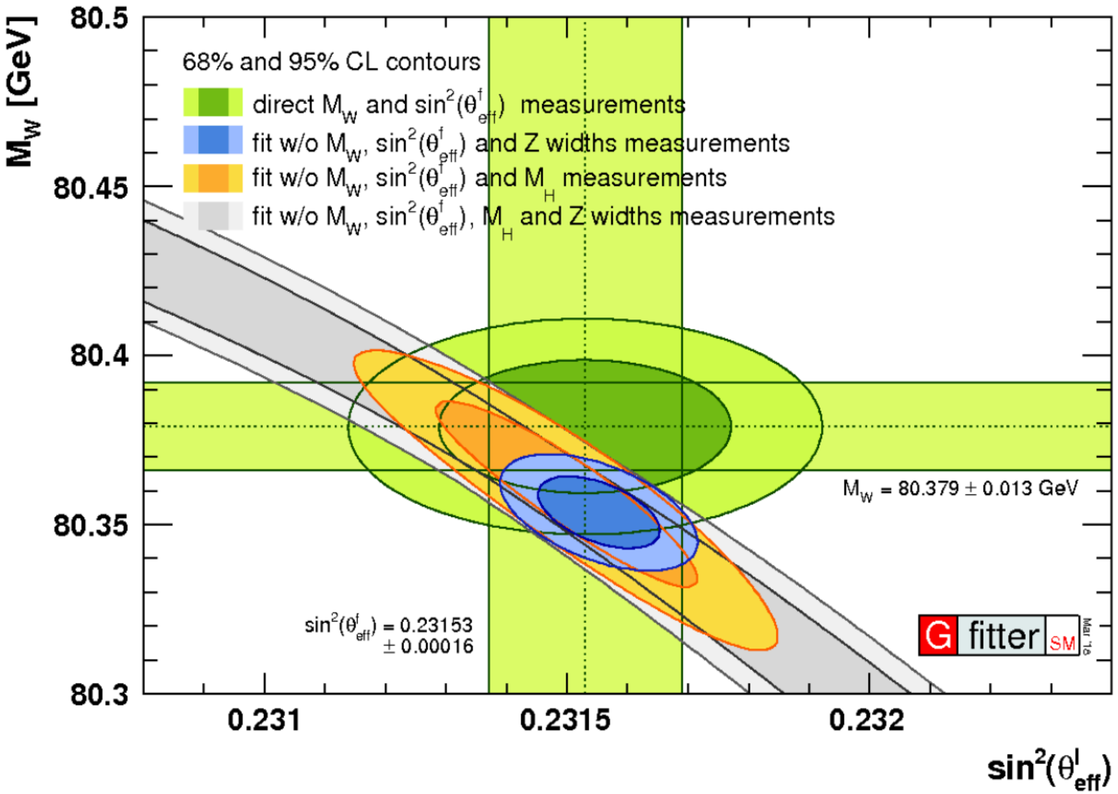


Tevatron/LHC W-mass combination

- Provide endorsed **world average combination** of hadron collider m_W results

  - Establish a **methodology** to combine present and future measurements
  - Enable **physics modelling updates** of past measurements (i.e. PDFs, p_T^W)
  - Properly **correlate m_W and $\sin^2\theta^l_{eff}$** measurements in EW fits

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



Combination Strategy

- PDFs main source of correction and uncertainty correlations
  - Other sources very small (EW corrections) or mostly decorrelated (p_T W/Z)

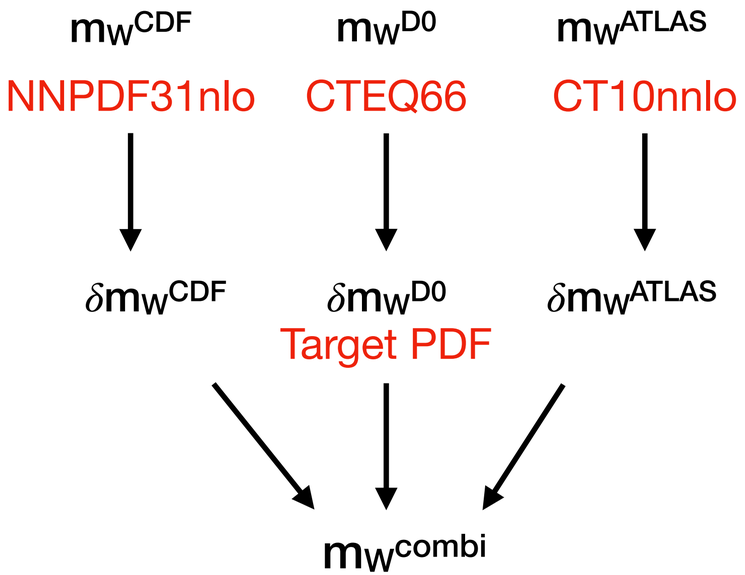
$$m_W^{new} = m_W^{ref} - \delta m_W^{QCD} - \delta m_W^{PDF}$$

published value | Improved predictions | PDF extrapolation

δm_W^{PDF} correction to reference PDF

δm_W^{QCD} correction to QCD modelling beyond quoted uncertainties

- Correction applied in a two-step procedure:
  1. Correct all measurements to a common PDF/QCD
  2. Combine them properly including correlations

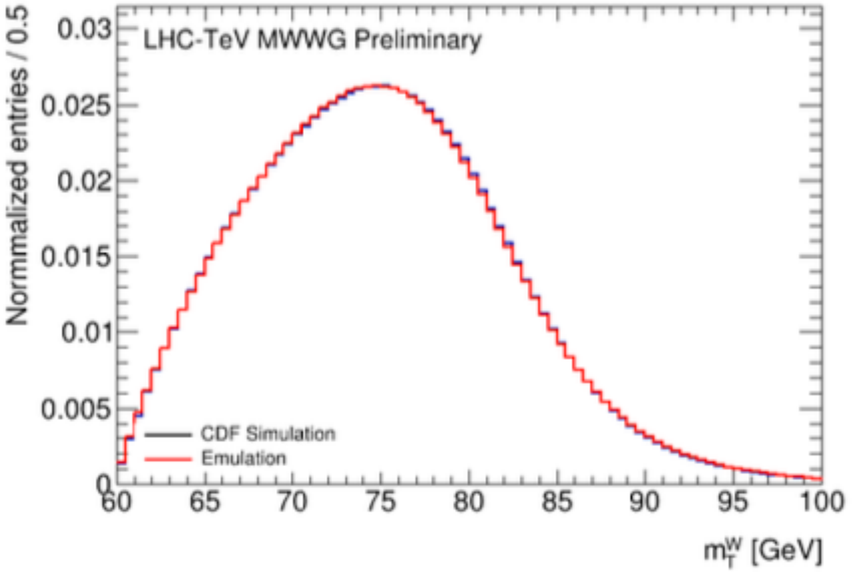


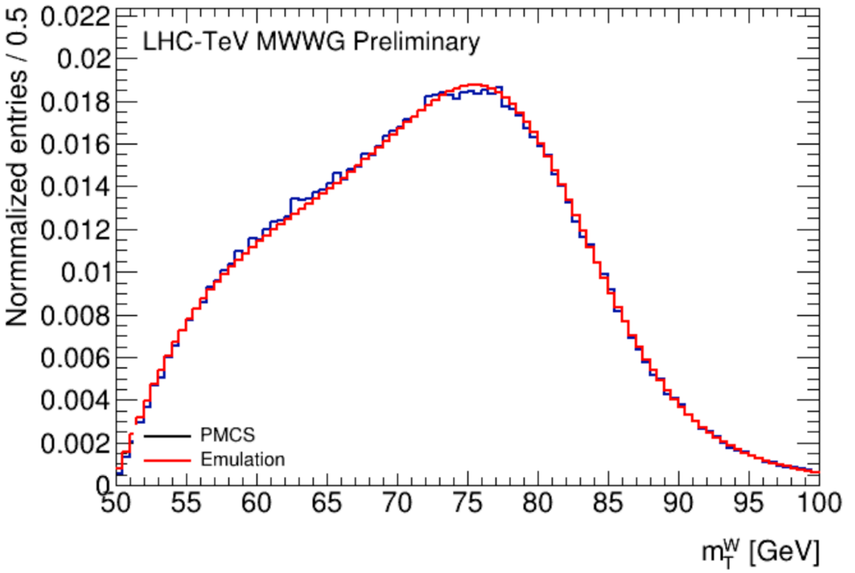
Detector emulation

- Original analyses and detector simulations cannot be easily reproduced
  - Exception is LHCb for which the analysis will be rerun

- Use **parametrized detector response**, following published information
  - Leptons : η- and p_T-dependent energy/momentum scale as well as resolution and efficiencies
  - Recoil response: include “lepton removal” effects, dependence on boson p_T and event activity
  - Reproduces published distributions at the % level corresponding to **~1-2 MeV precision in** $\delta m_W^{QCD,PDF}$

- Event selection and fit ranges from publications





Generator corrections

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

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

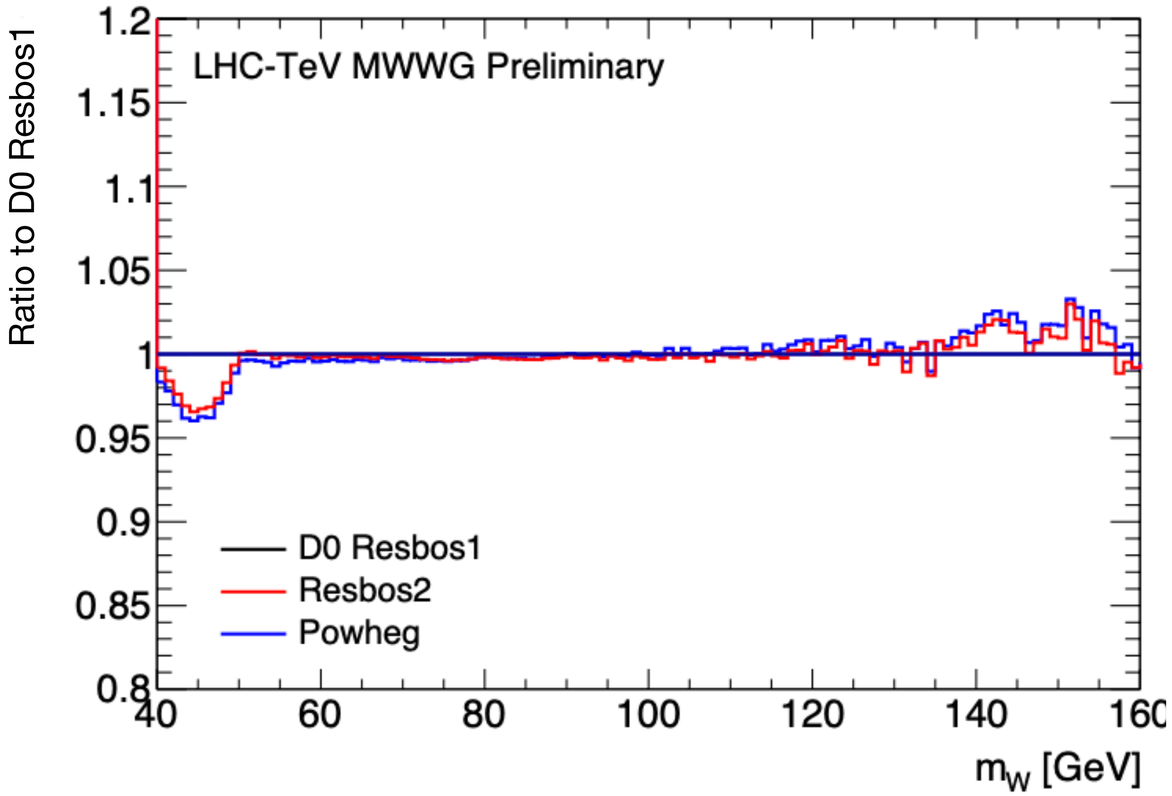
  CDF: Resbos C (NLO+NNLL) generated with CTEQ6M (NLO)

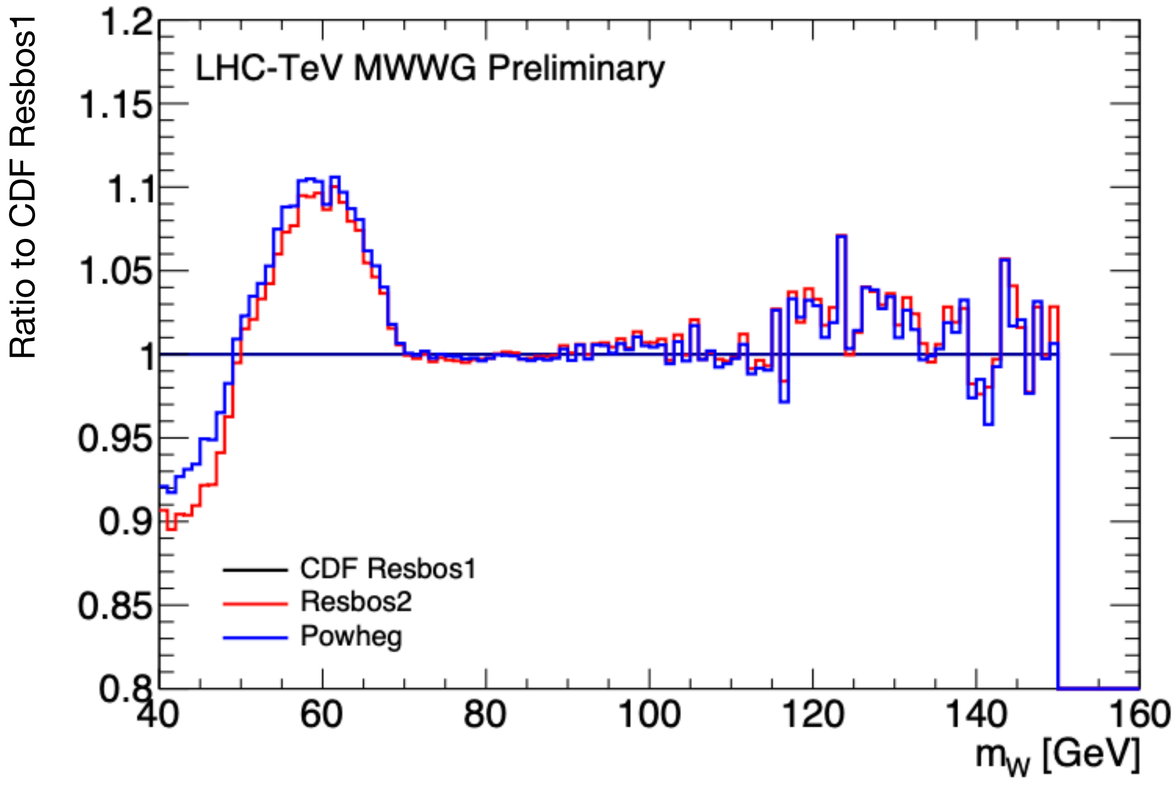
  ATLAS: Powheg+Pythia8 (NLO+PS); y_W + Ai at NNLO with CT10 (NNLO)

  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*]

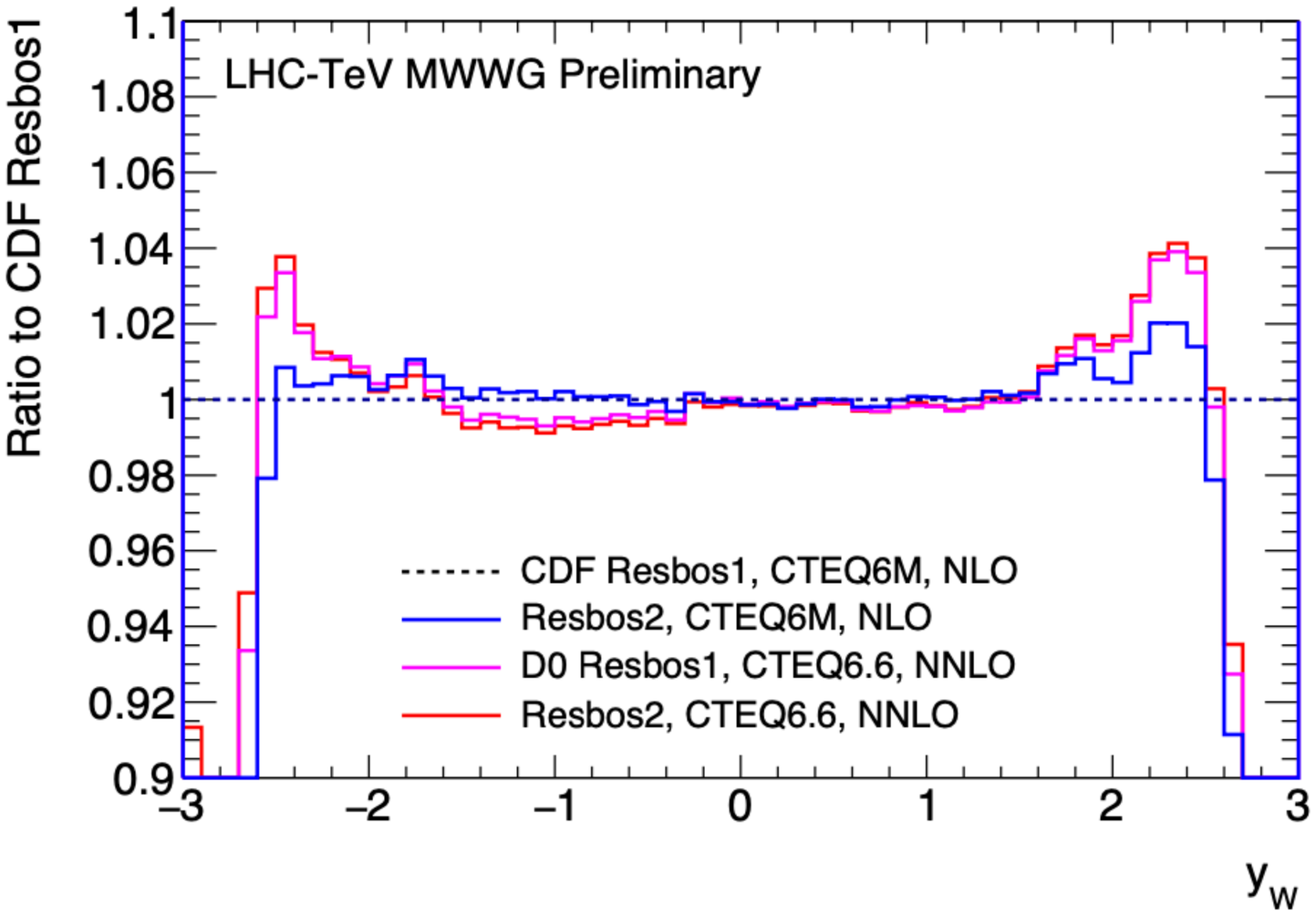
W-boson Invariant mass





- Invariant mass distribution shows trends wrt modern generators
  - Visible **cut of m_W<150 GeV** in the CDF Resbos sample, small bias on m_W
  - Structures at **low invariant masses** (m_W<50 GeV for D0, m_W< 70 GeV for CDF) and **small overall slope** through the full mass range, negligible impact on m_W

W-BOSON RAPIDITY



- D0 Resbos events agree with the updated Resbos predictions
- For the CDF Resbos, differences at the 1-2% level for high boson rapidity, $|y_W| > 1.5$
  - Reflecting differences in mass
  - Small in size, affects few events at the edge of the phase-space

Spin Correlations in W-boson decays

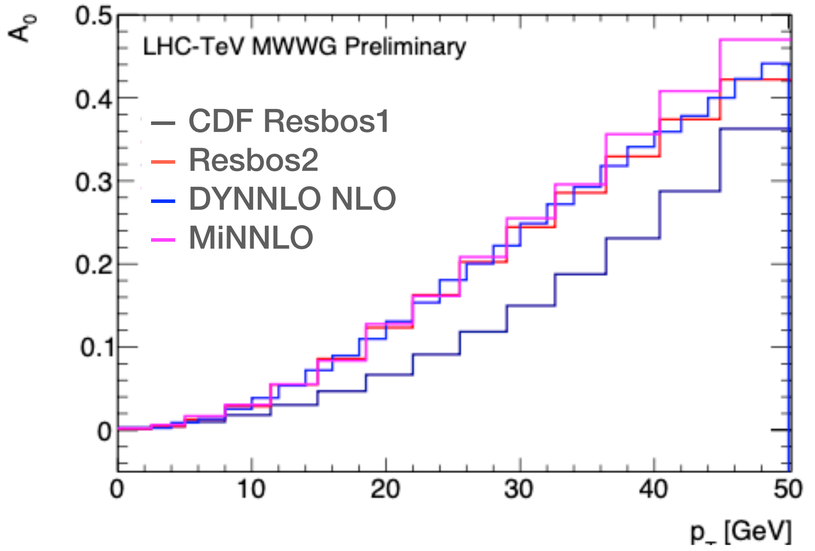
- The cross-section for the production of a spin-1 resonance can be expanded to all-orders in QCD into an **angular coefficients decomposition**:

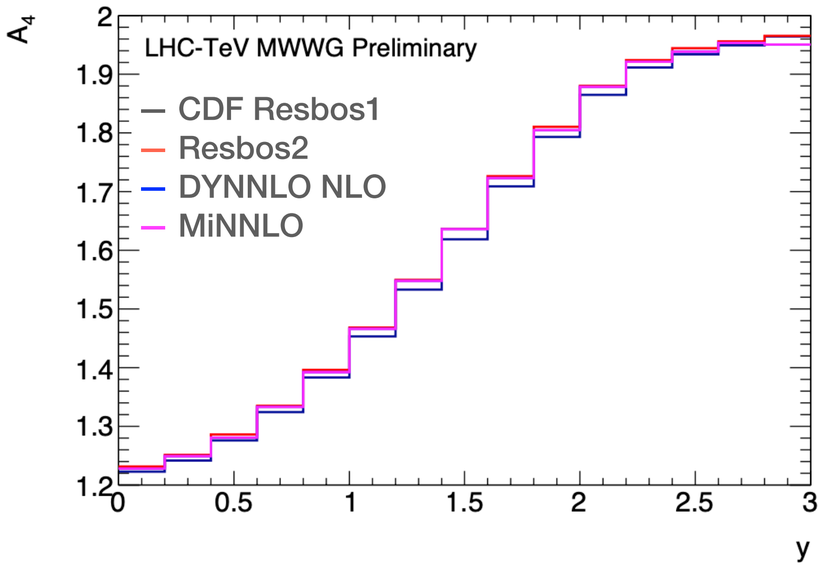
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm dp_{\mathrm{T}} dy} \left[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \right.$$
$$+ \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi$$
$$+ A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi$$
$$\left. + A_6 \sin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

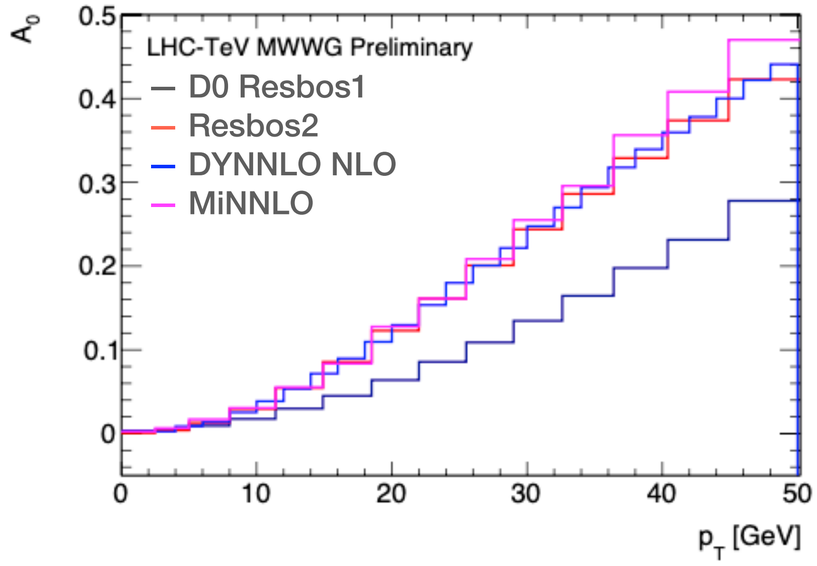
- A_4 the only term at LO QCD; $A_{5,6,7}$ start at $O(\alpha_S^2)$ and remain small
- Measured to high precision in Z events at the LHC [*JHEP* 08(2016) 159, 2203.01602] and well described by fixed-order calculations (known to $O(\alpha_S^3)$ [*JHEP* 11 (2017) 003])

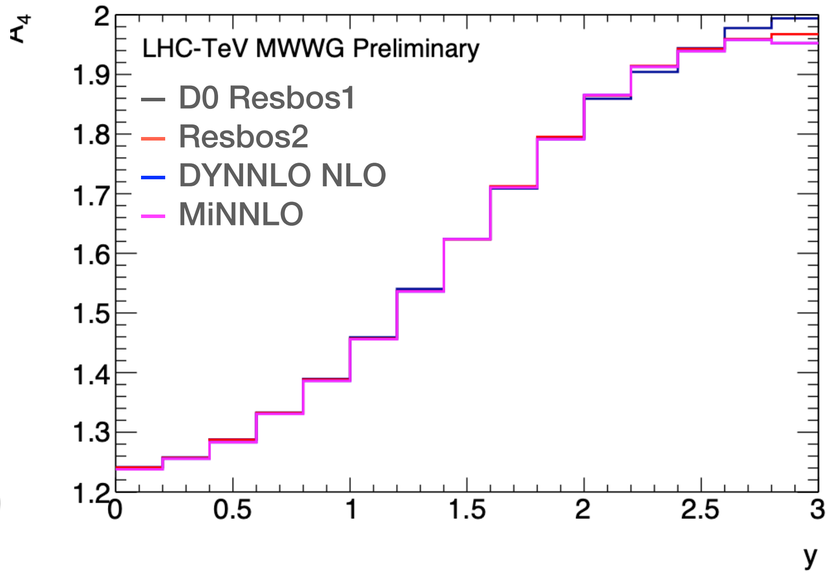
Spin Correlations in Resbos

- Boson polarisation in legacy Resbos different from Resbos2 and other codes





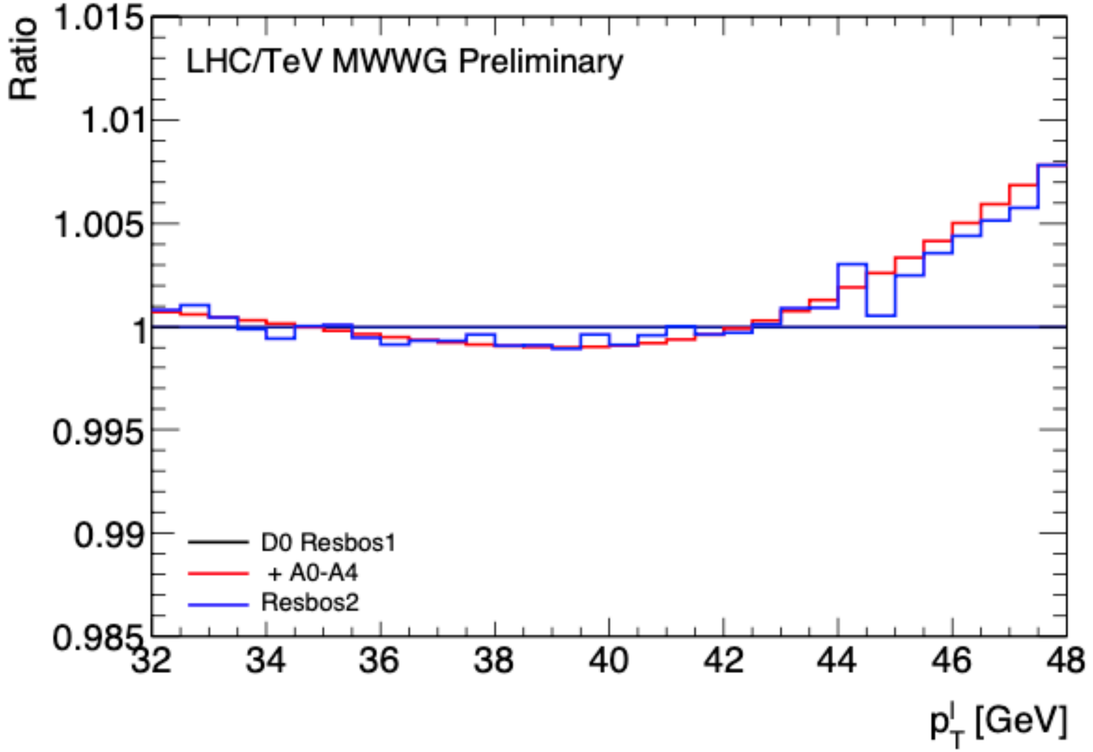


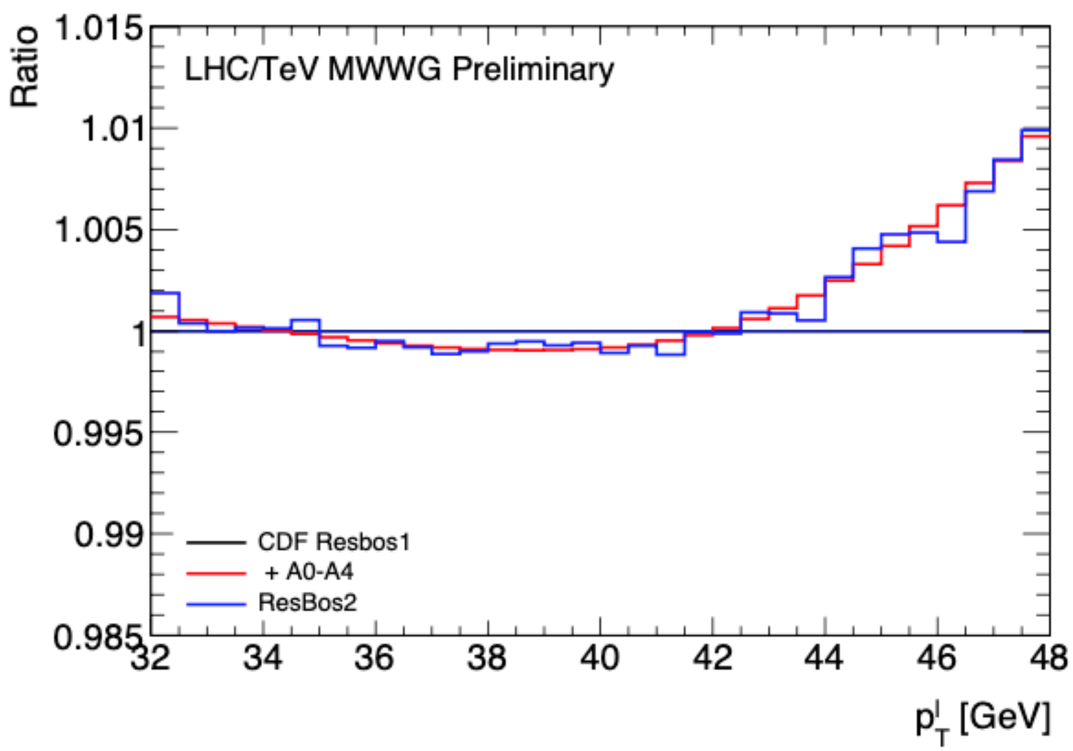


- NNLO matching in Resbos not fully differential
  ➜ affects D0
- Issue with Ai resummation,
  ➜ affects CDF/D0
  - Only unpolarised and A_4 resummed, leads to differences from fixed-order Ai
  - Differences visible comparing to DYNNLO or MiNNLOPS
- Motivates a correction of Tevatron measurements to a common QCD calculation

Spin Correlations in W-boson decays

- Impact of change in Ai to the new Resbos well-reproduced by reweighting $A_{0\text{-}4}$
  - Effect of up to 1% on detector-level distributions
  - Distributions become harder, m_W in data expected to decrease





- Change in the full phase-space Ai modifies the fiducial $p_T^{W/Z}$ distribution
  - Overestimate δm_W as measurements tune their p_T^W model to data
  - To gauge an uncertainty, change evaluated also constraining the p_T^W distribution

Impact on the (D0) W-boson mass

- δm_W^{QCD} reweighing the D0 Resbos-CP NNLO+NNLL predictions to the newer Resbos2 at NLO+NNLL

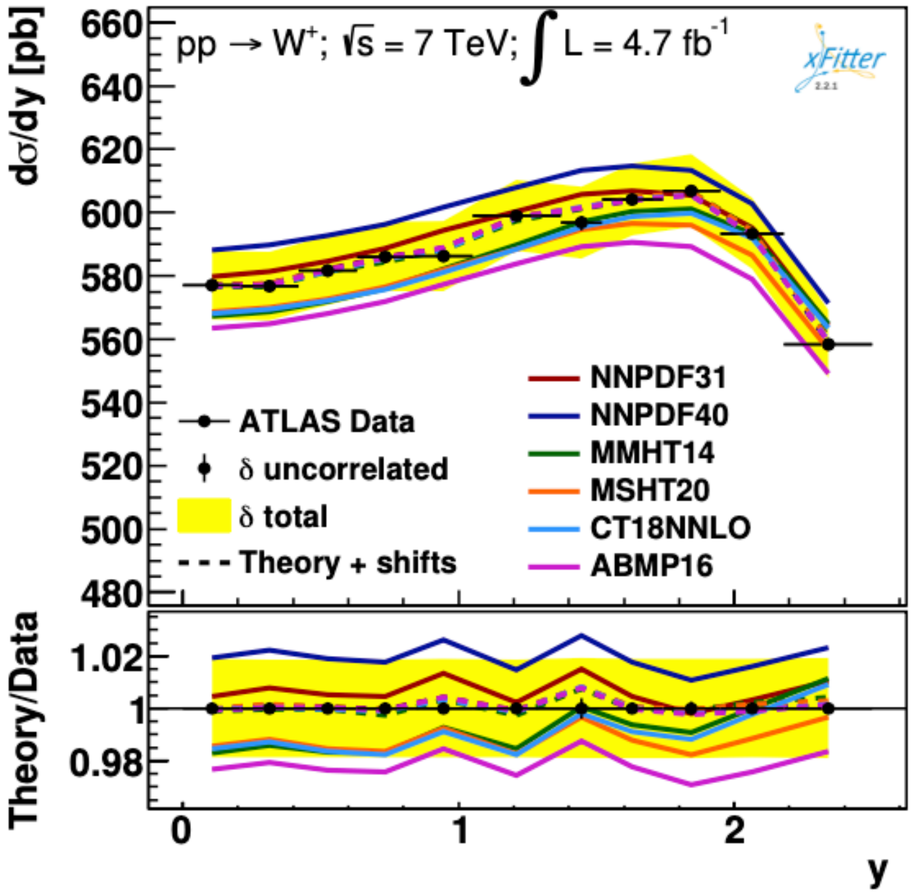
- Negligible effect of correcting y_W and m_{Inv}
- Ai-reweighting dominated by A_0 coefficient
- δm_W about -10 MeV depending on distribution and p_T^W constraint
- ~2 MeV uncertainty from systematics on the emulation

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

Choice of PDF set

- 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

Conclusions

- Presented studies towards a **combination of Tevatron and LHC W-mass** measurements

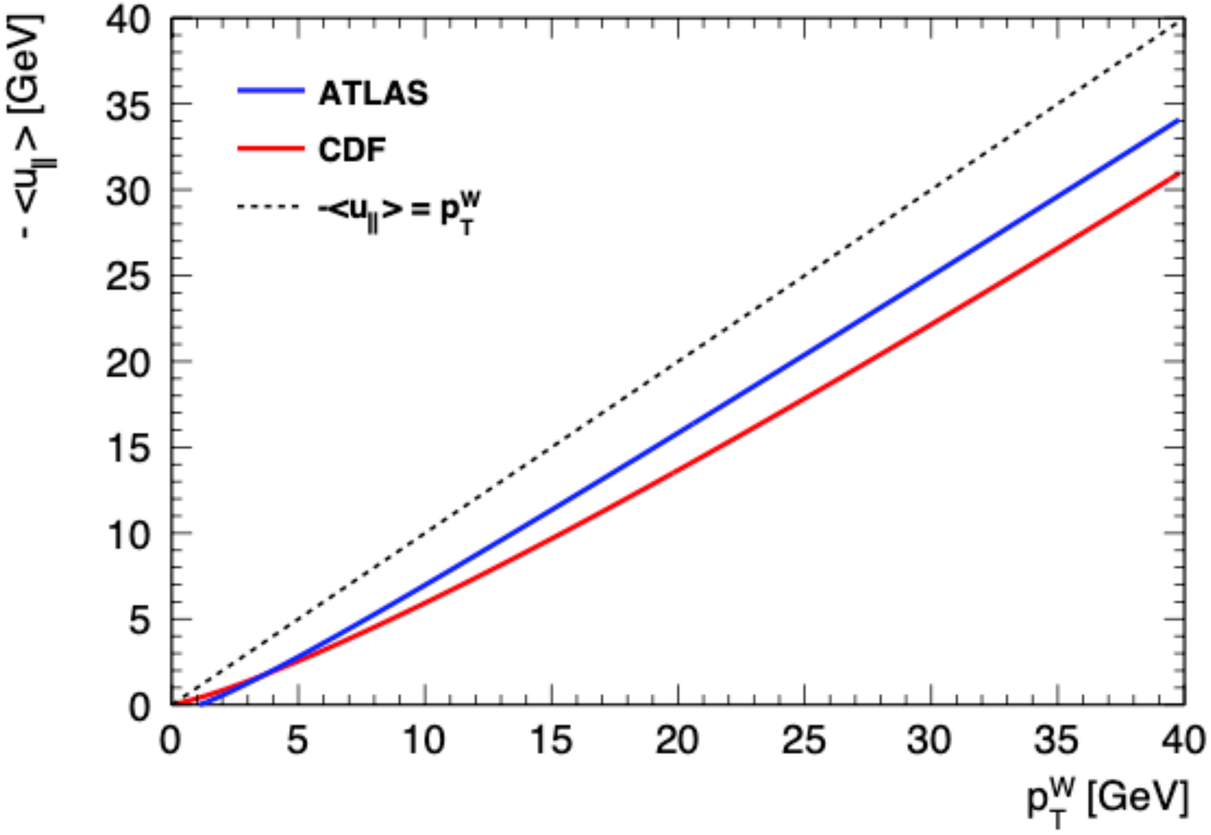
- Measurement correlations dominated by **PDF uncertainties**
  - Evaluated through a simplified emulation of the detector response
  - Benchmarking at NNLO QCDxNLO EW shows all **modern global PDFs a suitable choice**

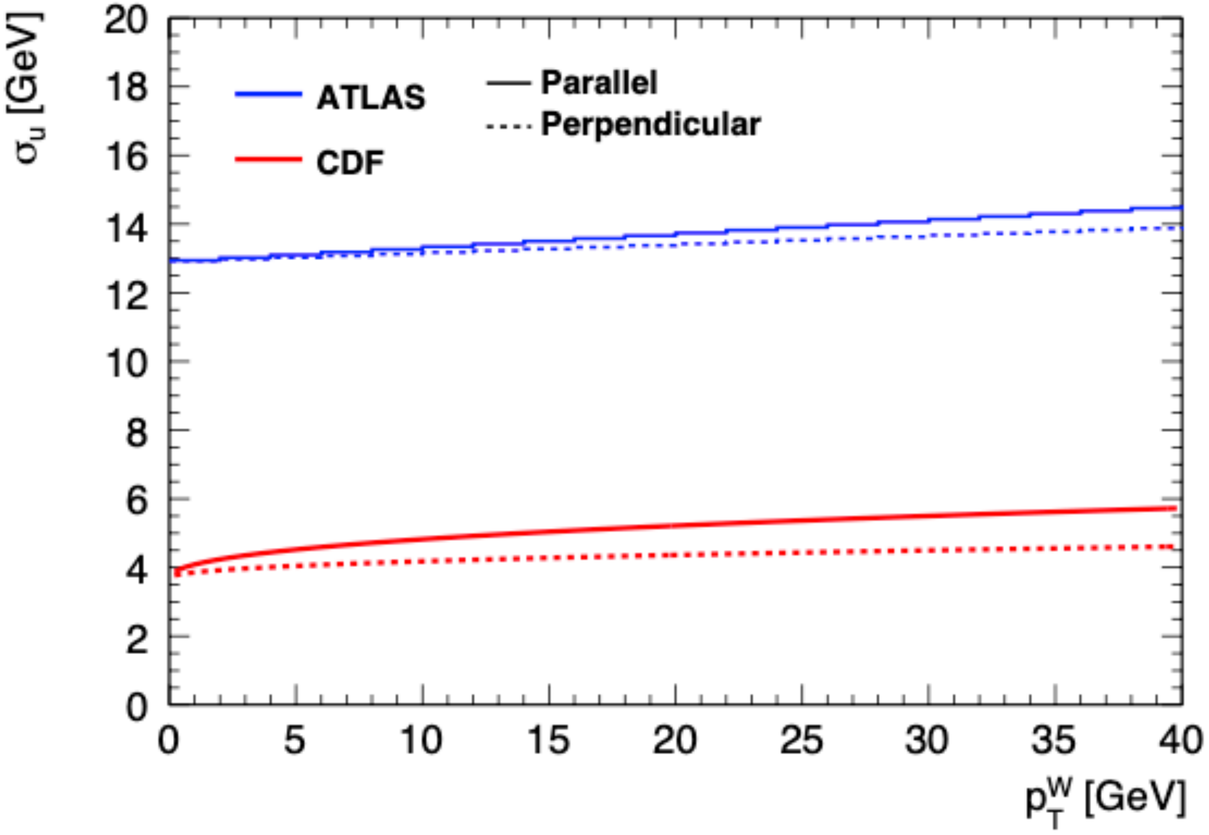
- Some issues in the description of **W spin correlations in legacy Resbos** codes
  - Motivates **update of Tevatron measurements** to $O(\alpha_S^2)$ fixed-order QCD predictions for the Ai
  - Preliminary numbers for D0 show a **correction at the level of -10 MeV**

- Studies documented in a **public note:** CERN-LPCC-2022-06
  - Full combination coming ~soon, pending further validation of emulations
  - Will include LHCb, with known PDF anti-correlation to ATLAS measurement

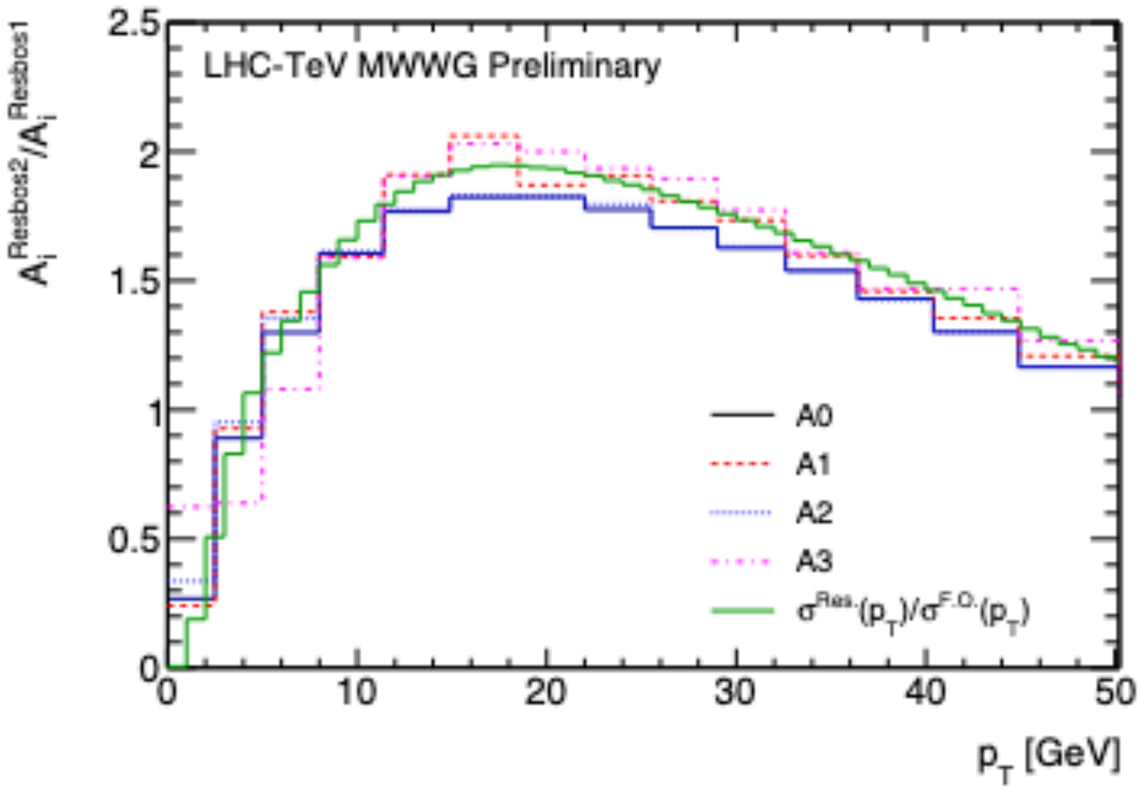
Backup

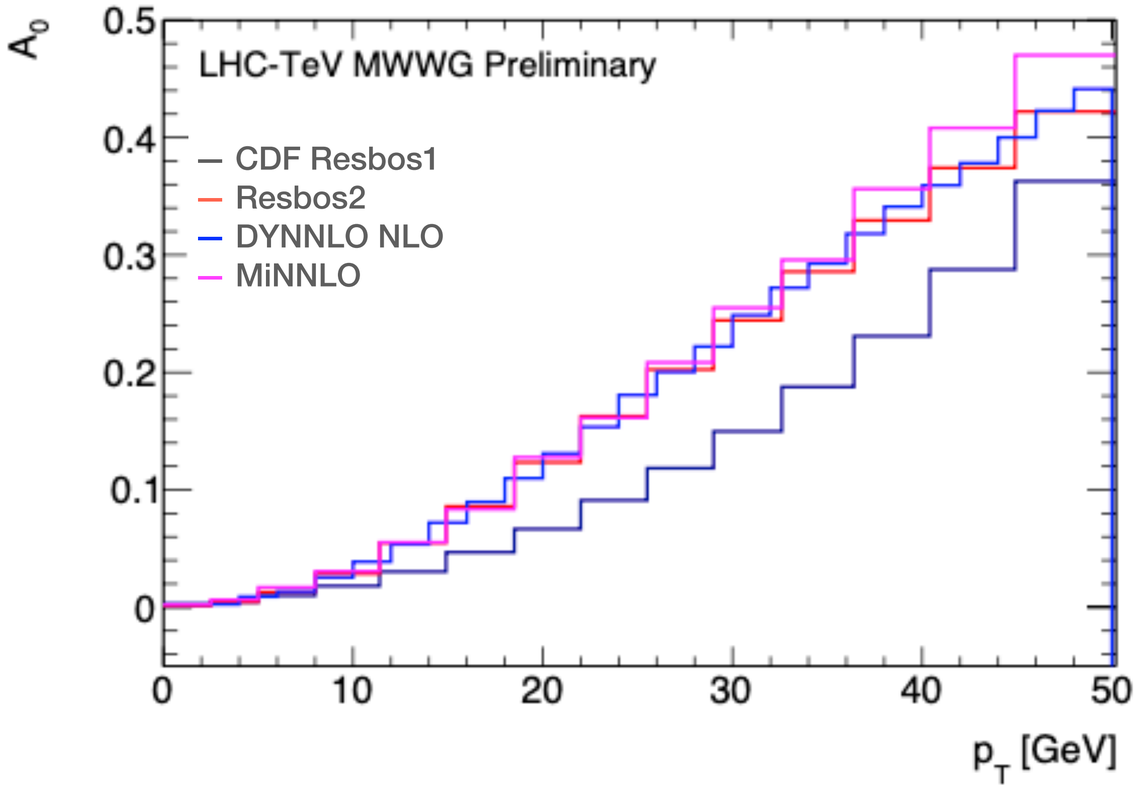
Recoil resolution Tevatron/LHC





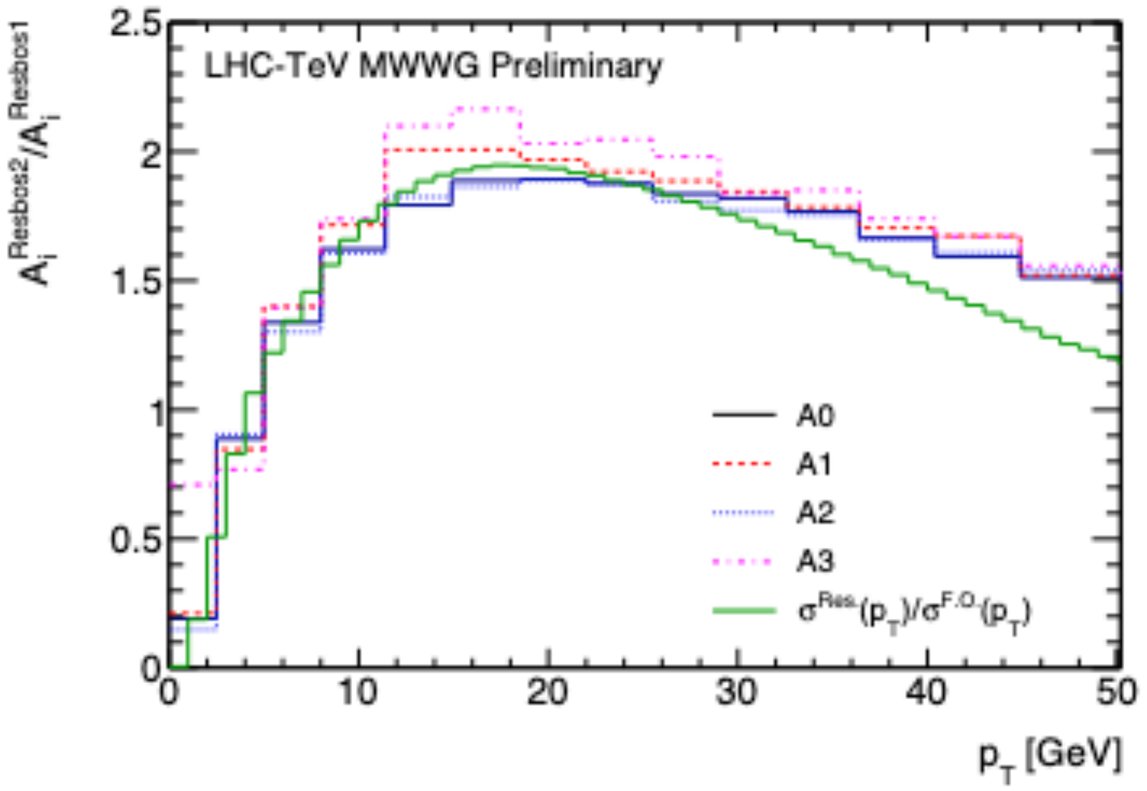
Resummation of Angular coefficients - CDF

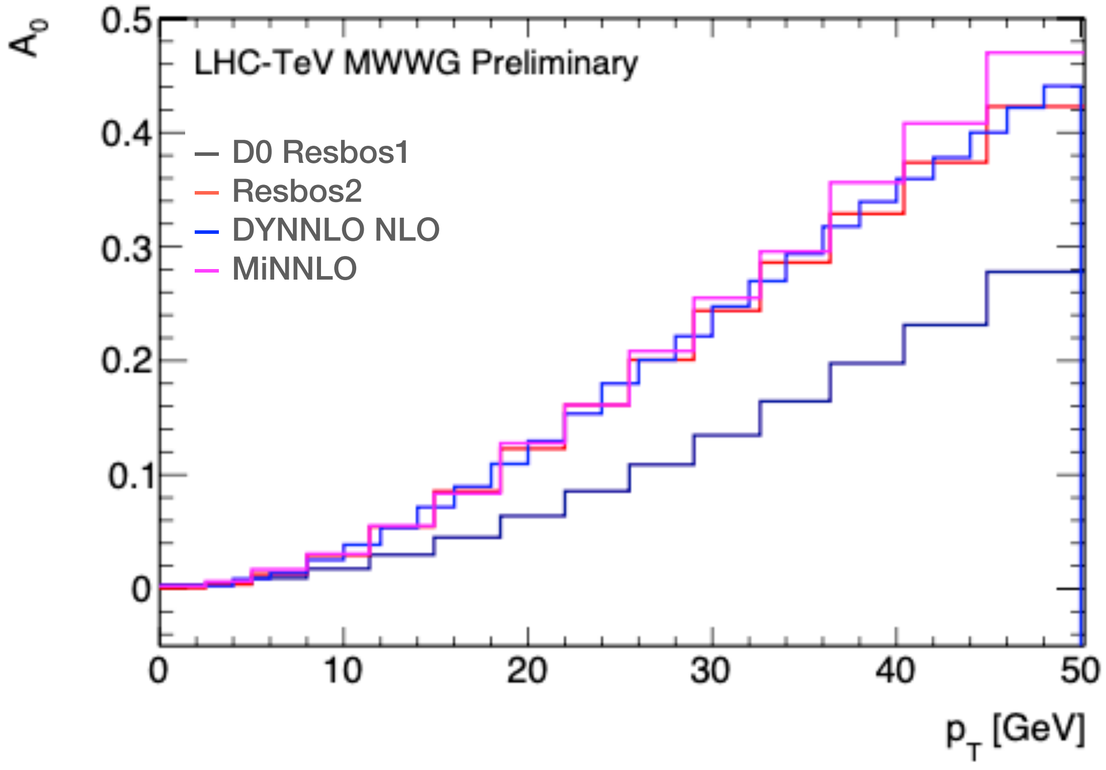




- Ratio of the $A_{0\text{-}3}$ angular coefficients in the legacy CDF Resbos to the Resbos2 samples is broadly consistent with resumming or not the helicity cross-sections

Resummation of Angular coefficients - D0





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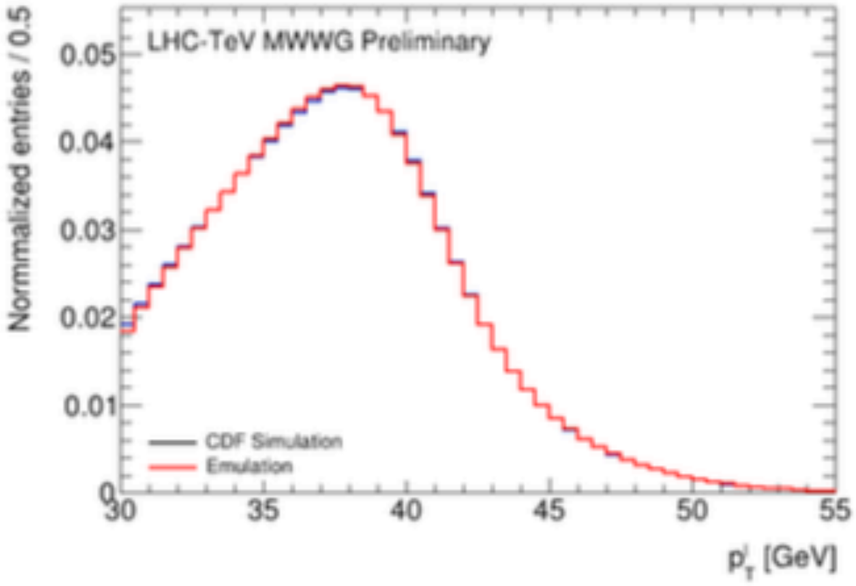
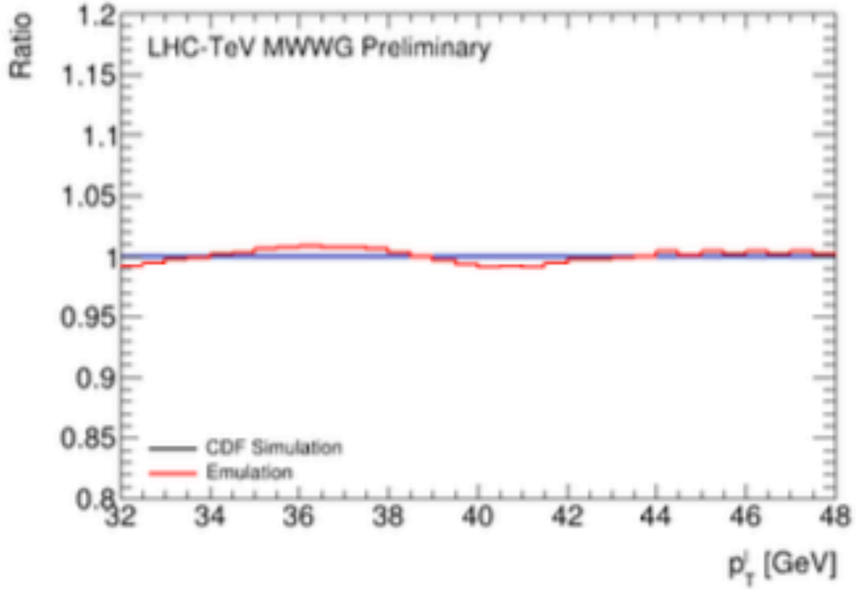
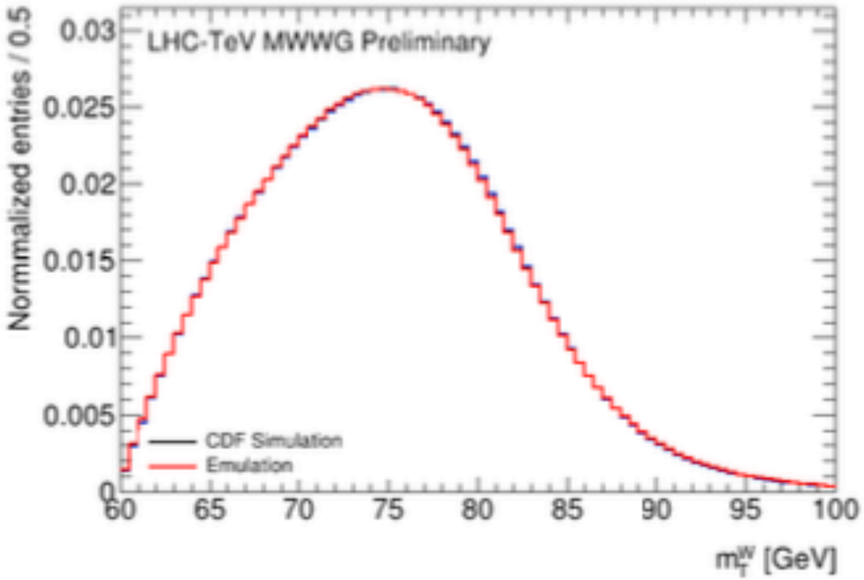
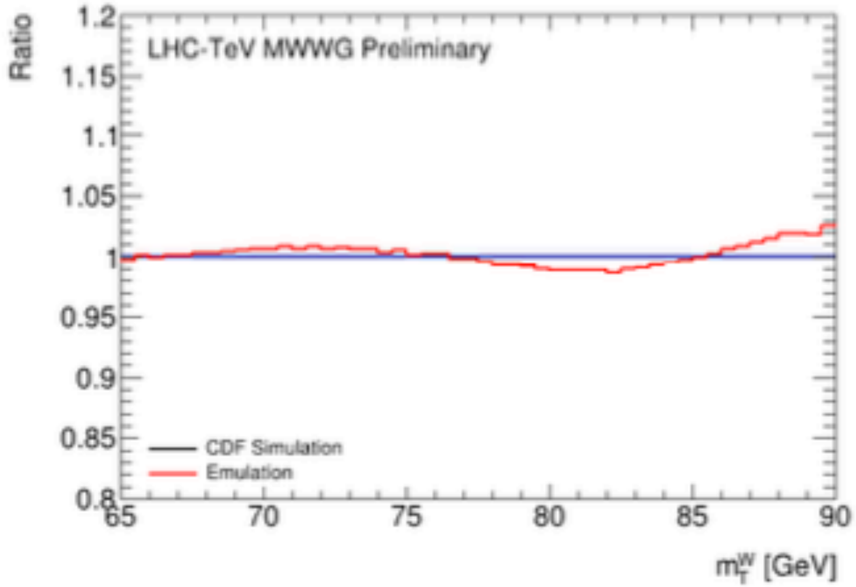
CDF EMULATION

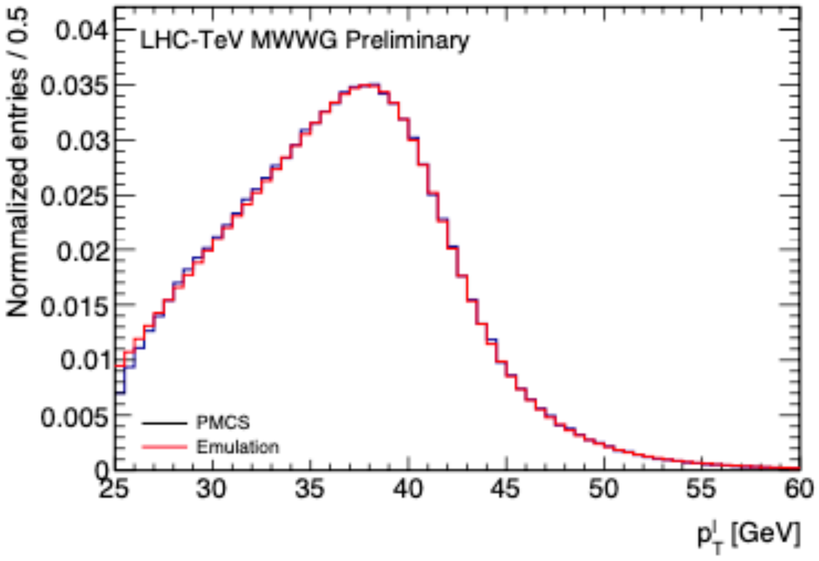


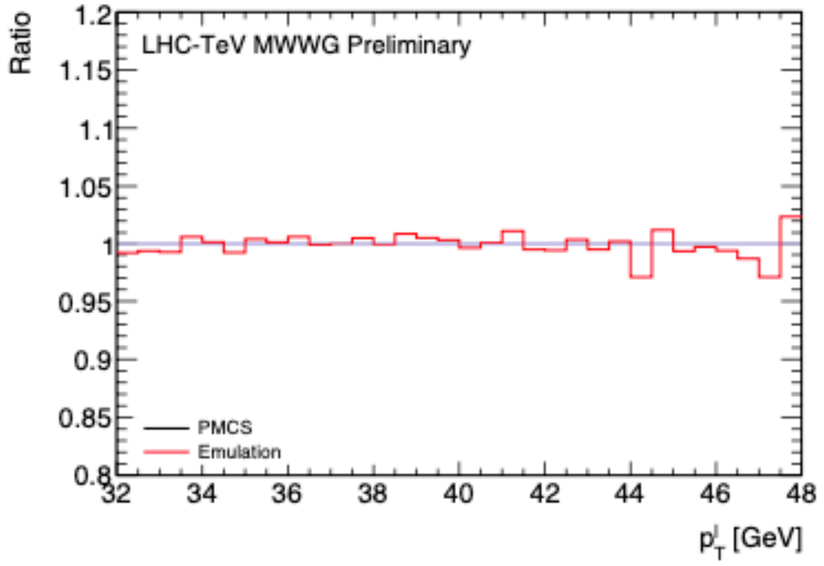


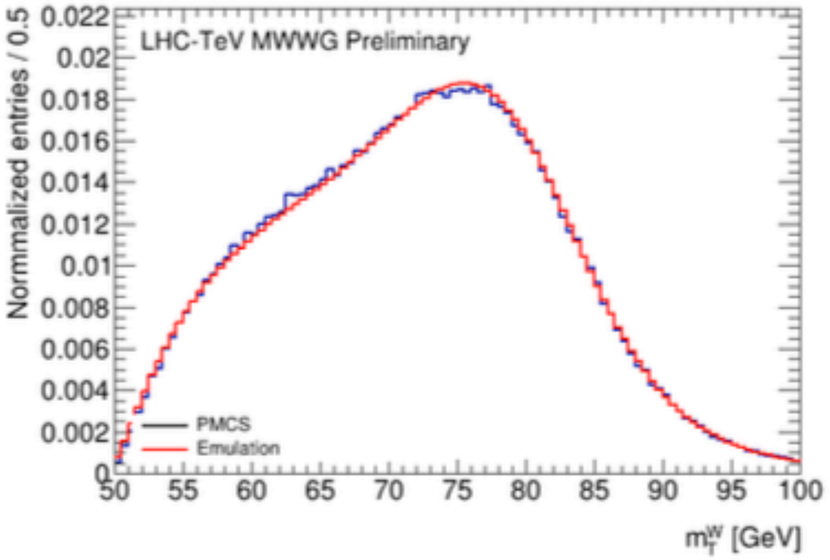


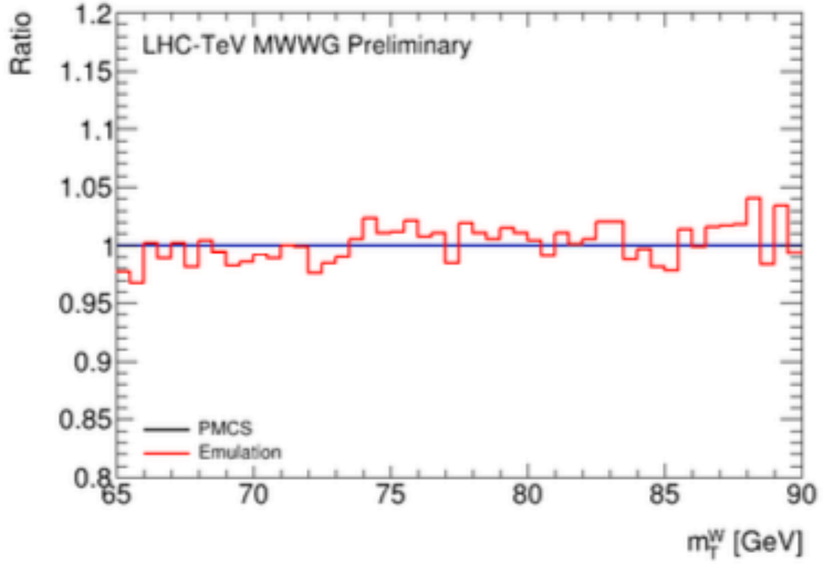


DO EMULATION

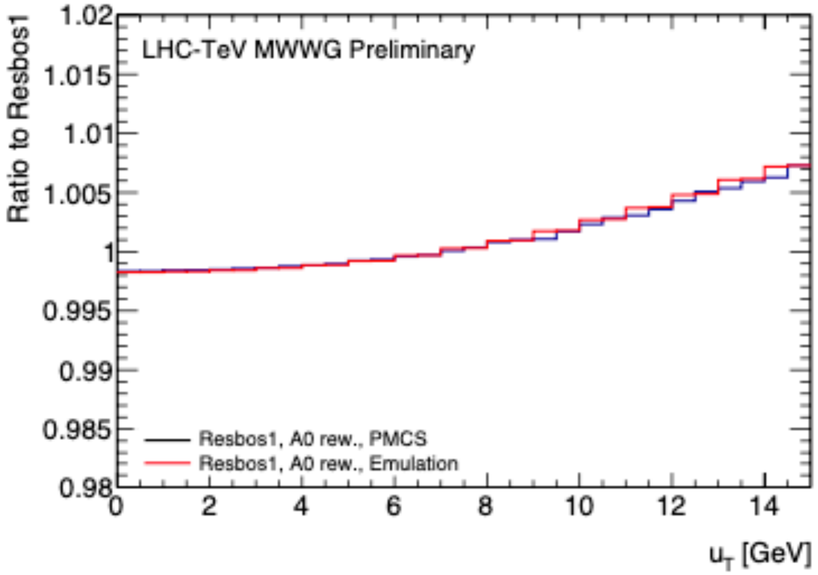


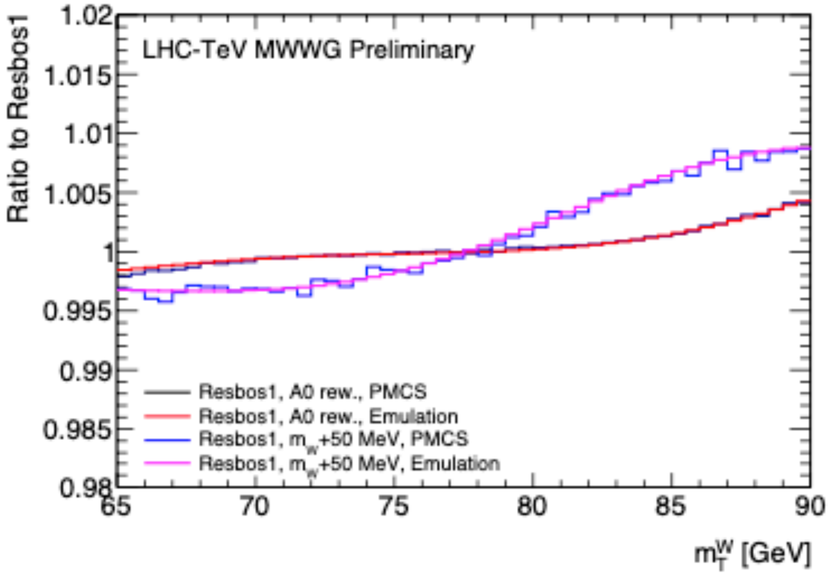


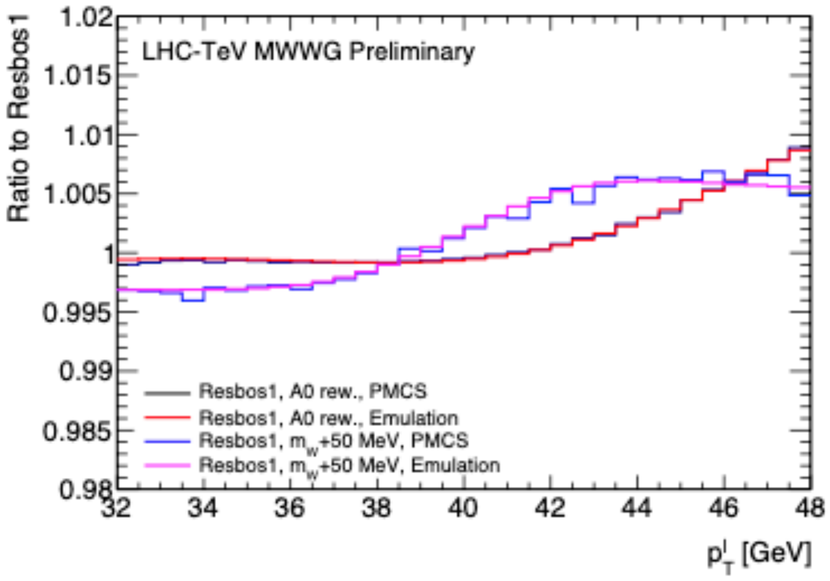


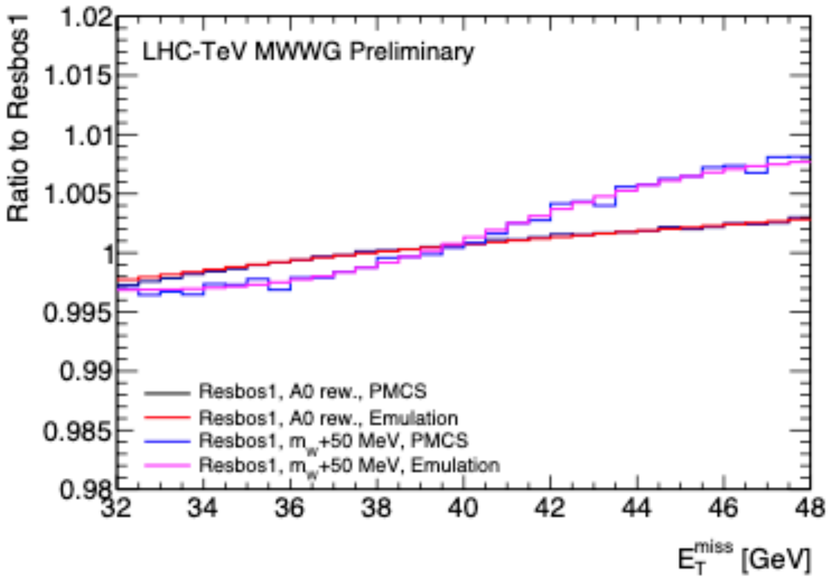


D0 emulation - II

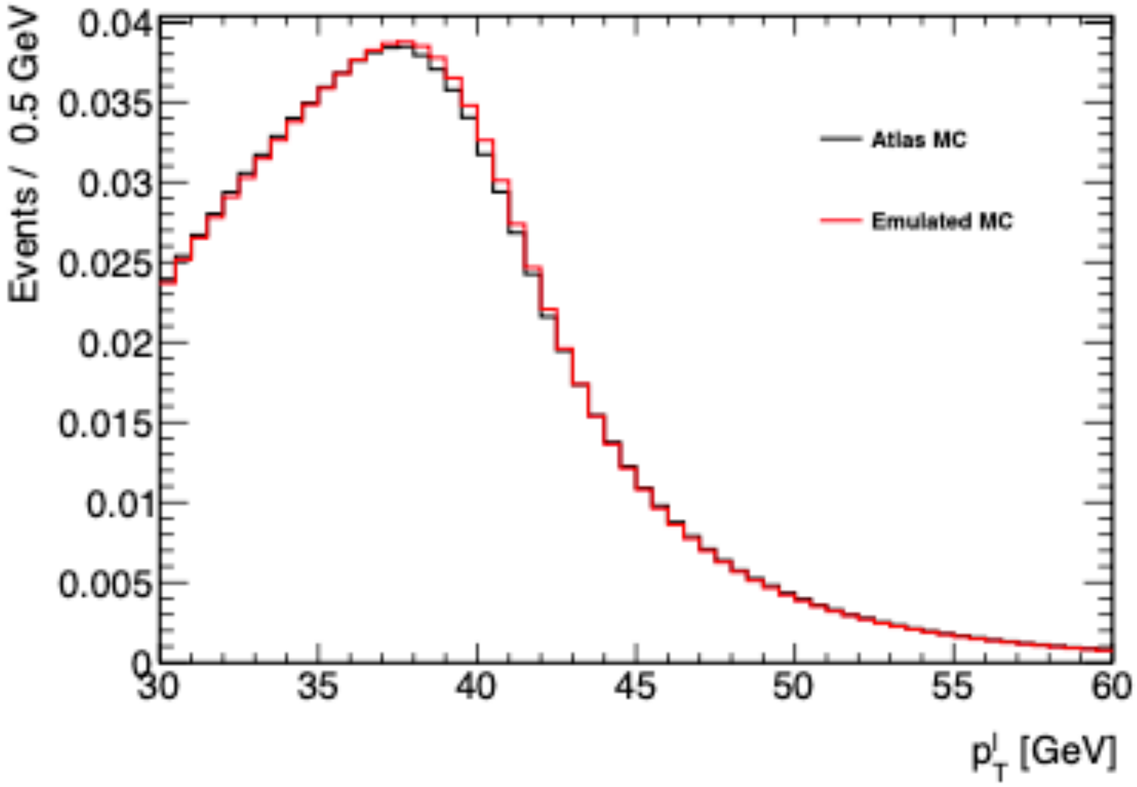


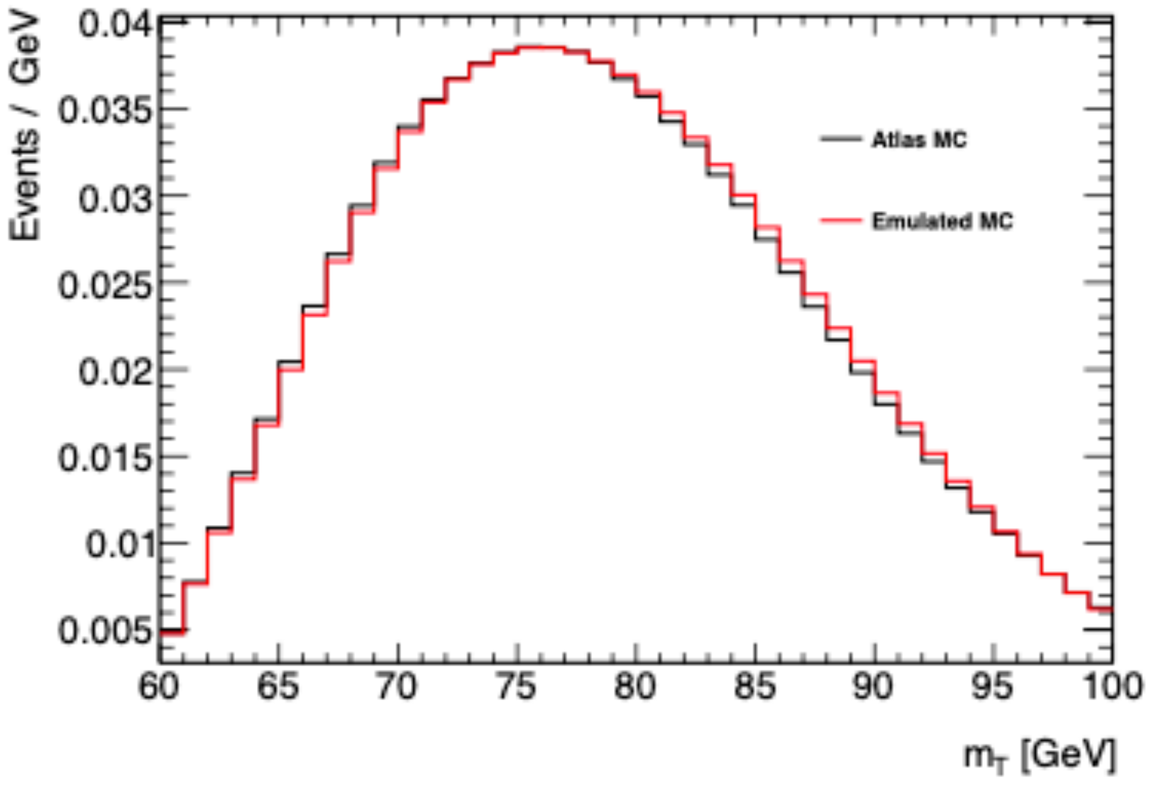




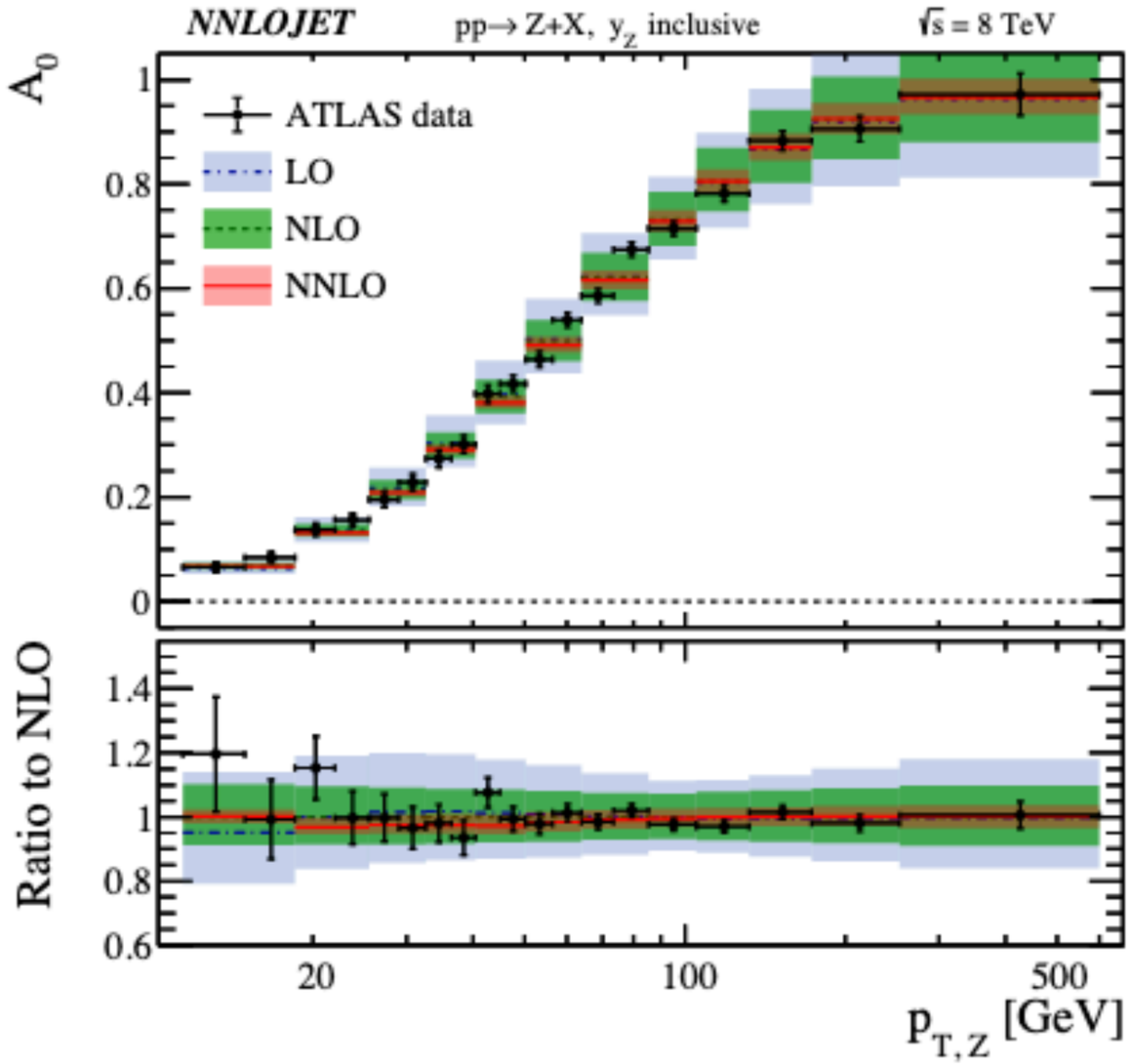


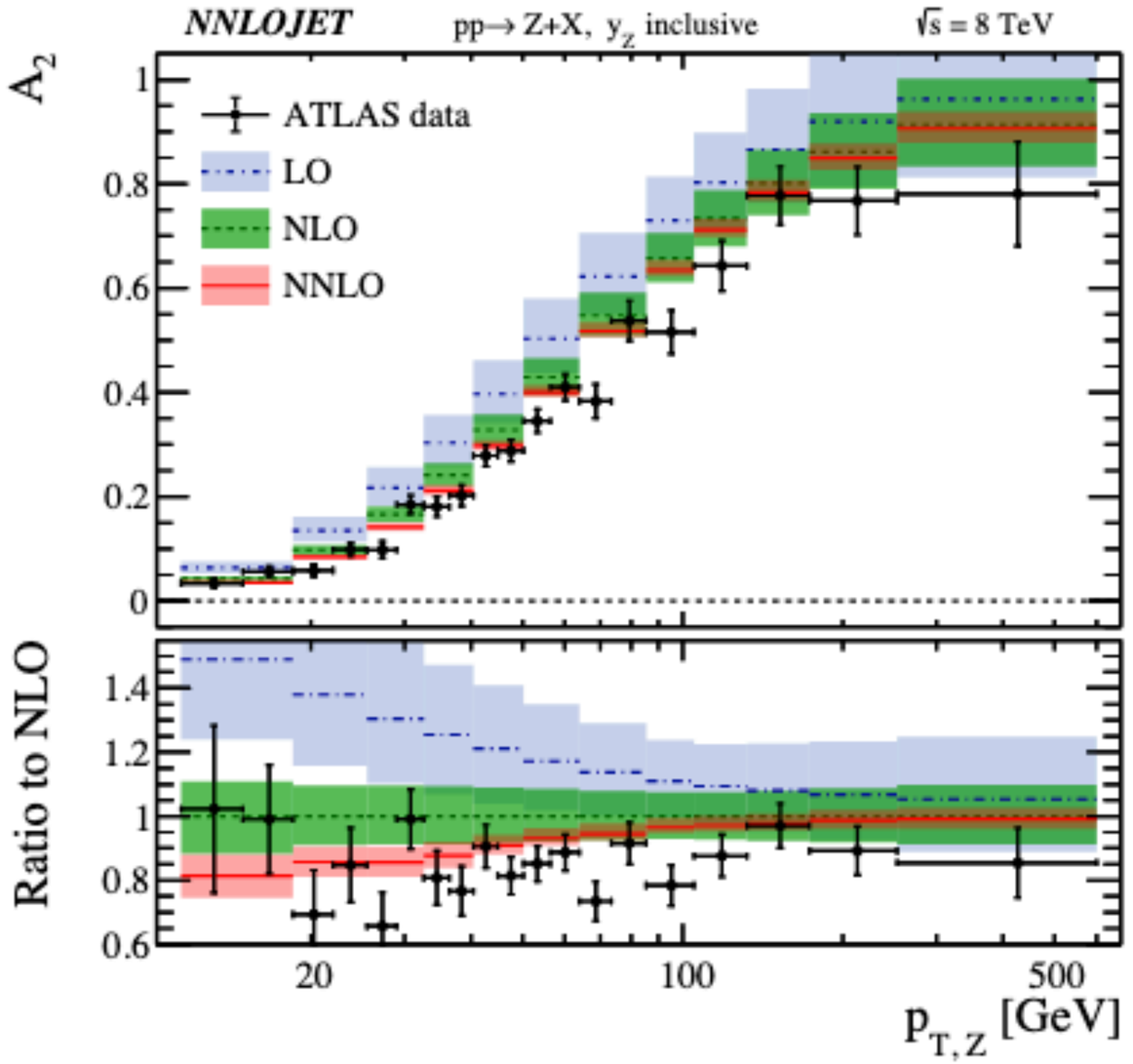
ATLAS EMULATION



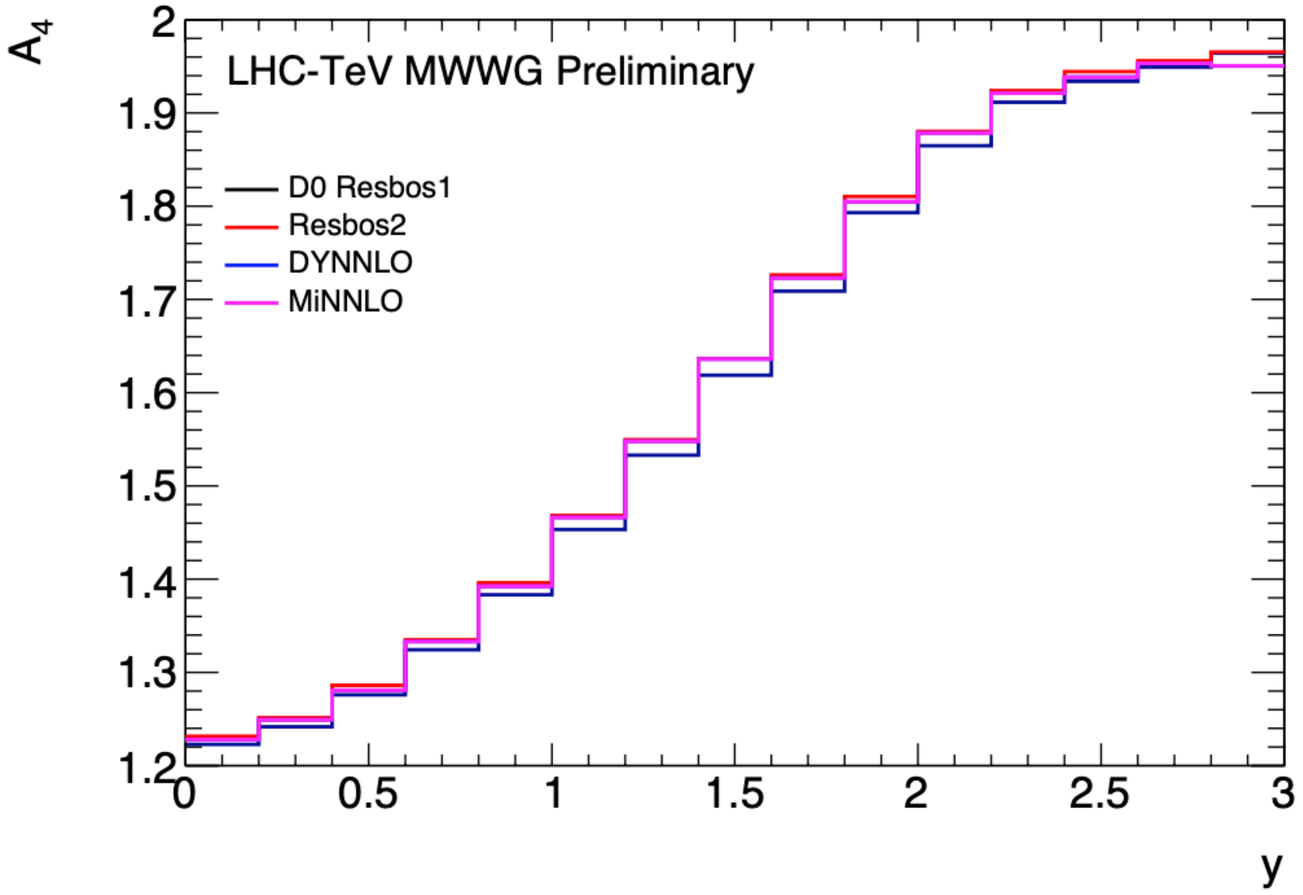


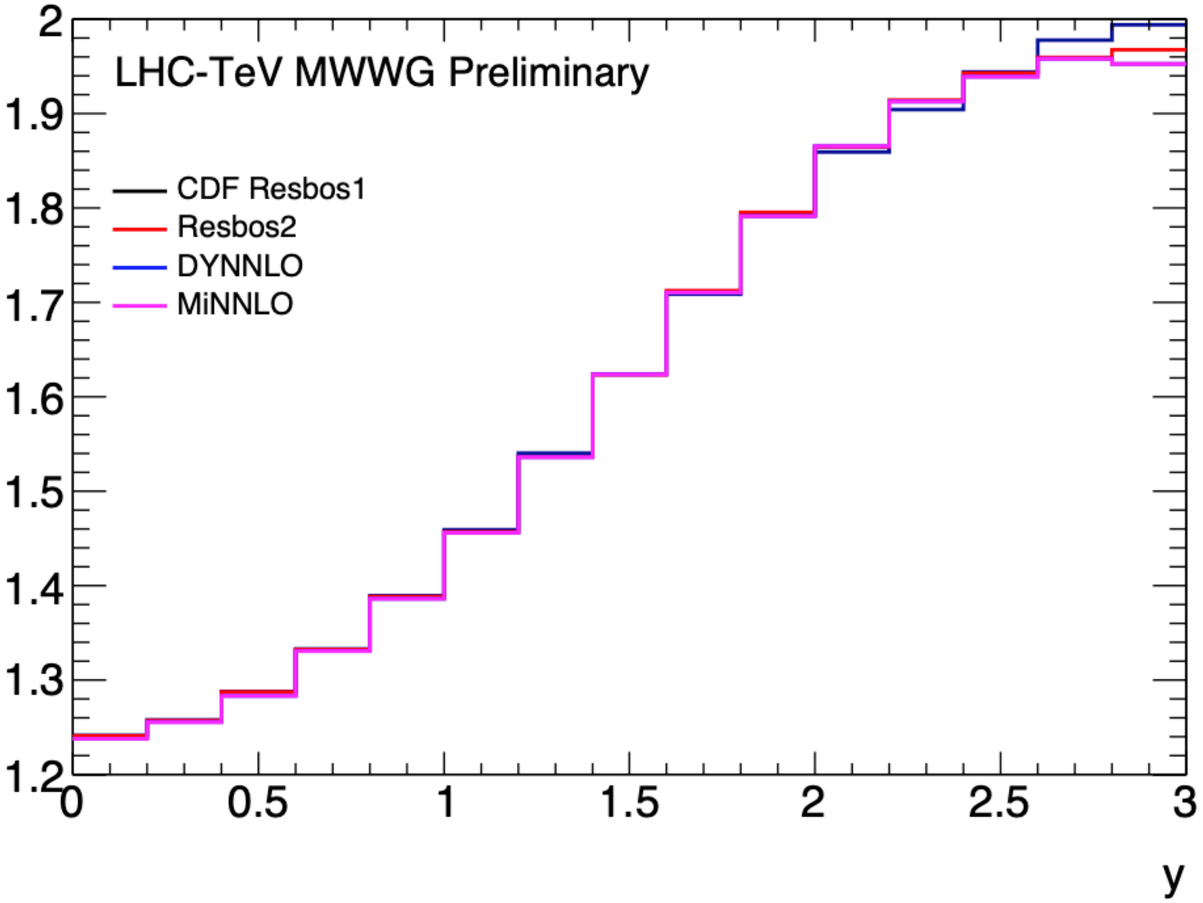
A_0 in Z events at the LHC



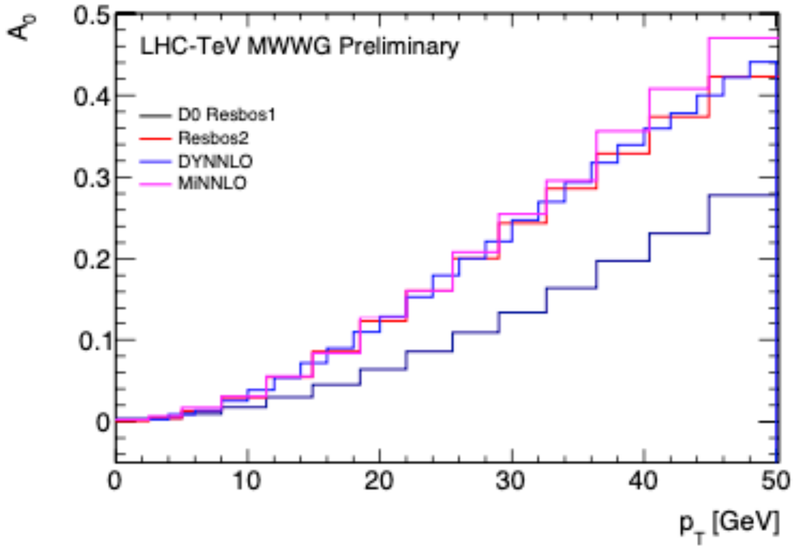


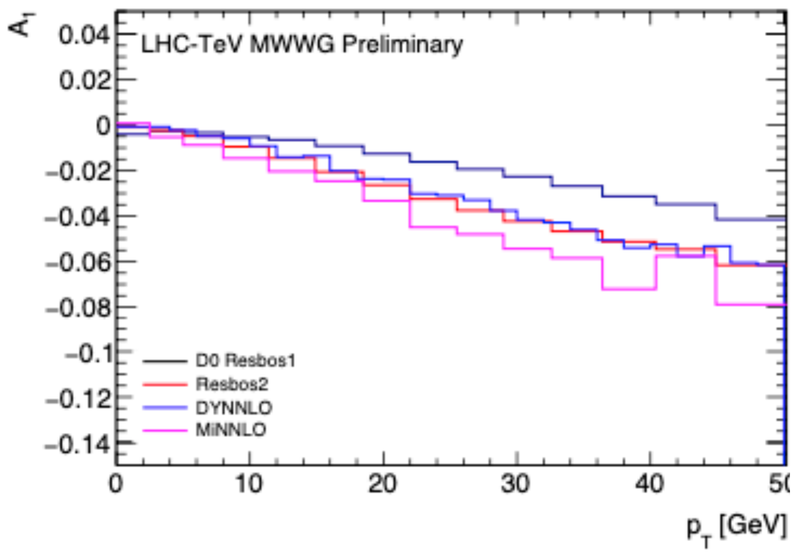
A_0 comparison - D0/CDF Y_W

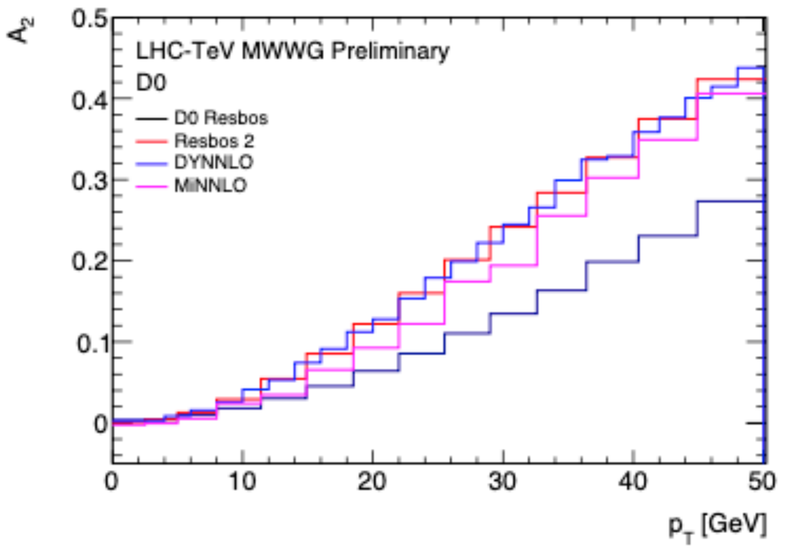


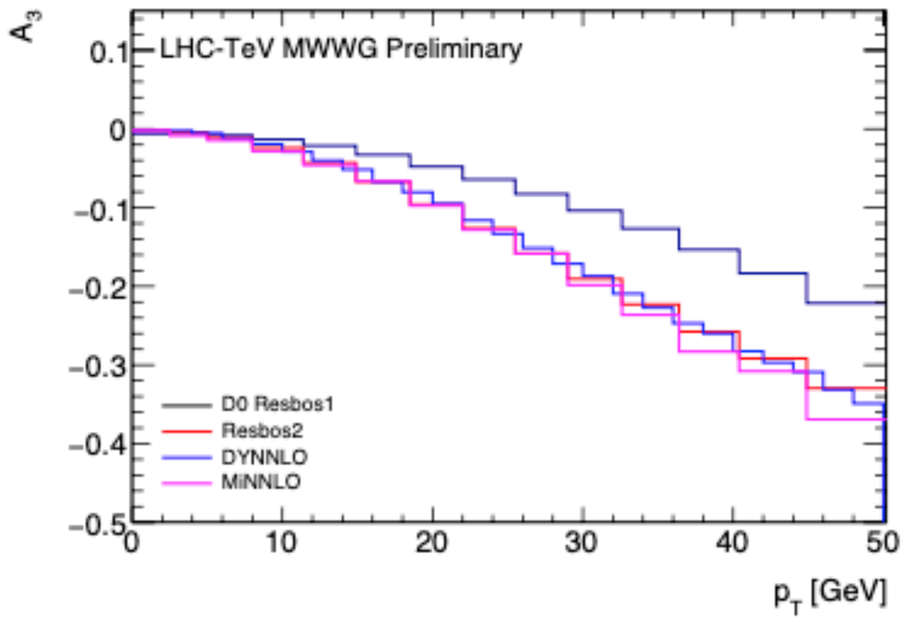


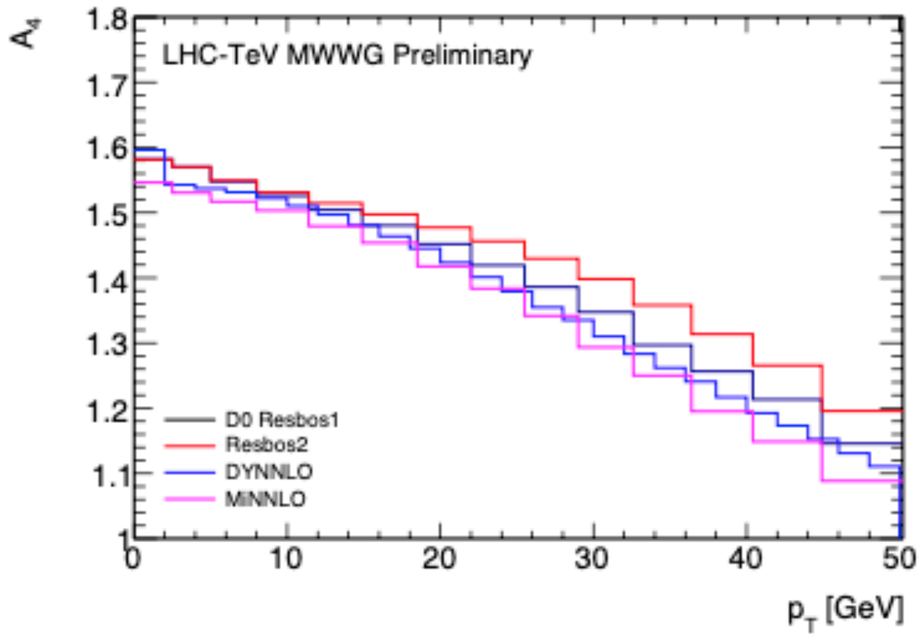
A$_i$ comparison - D0



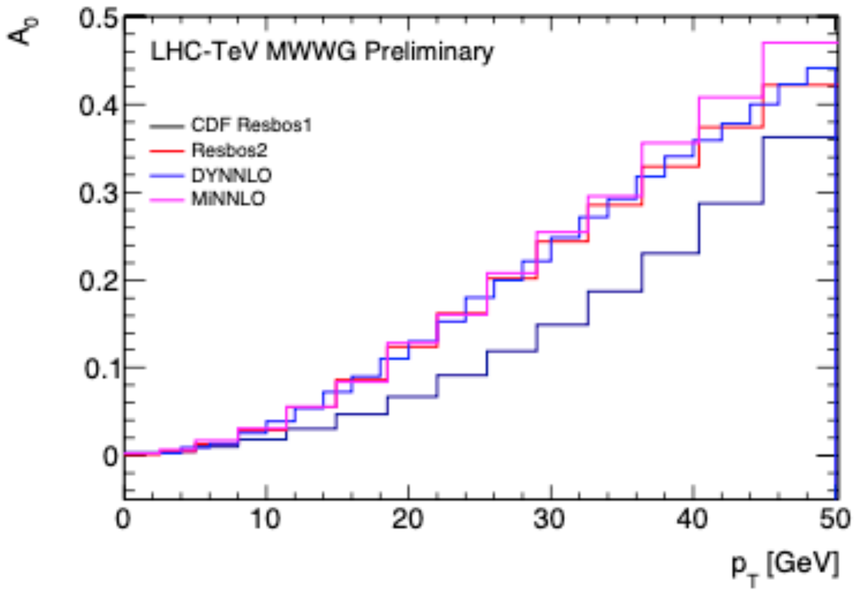


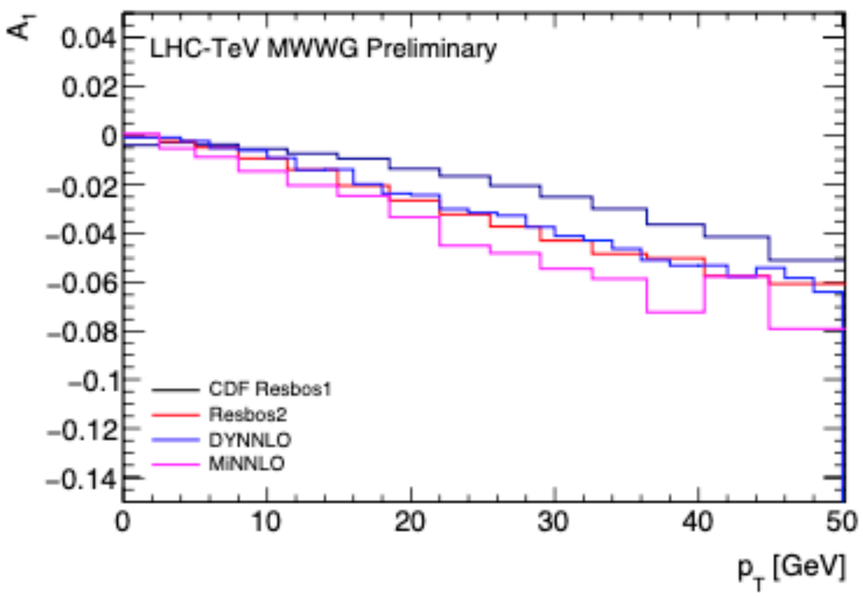


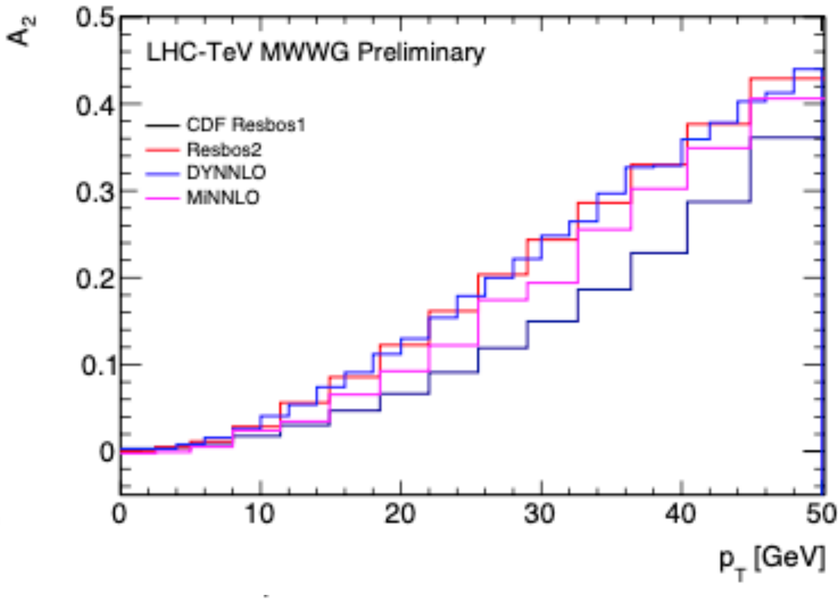


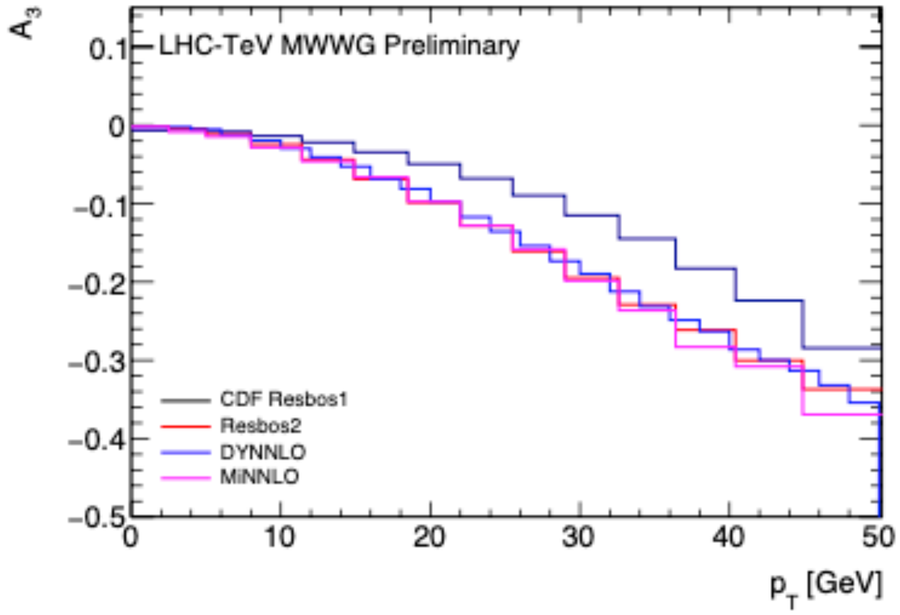


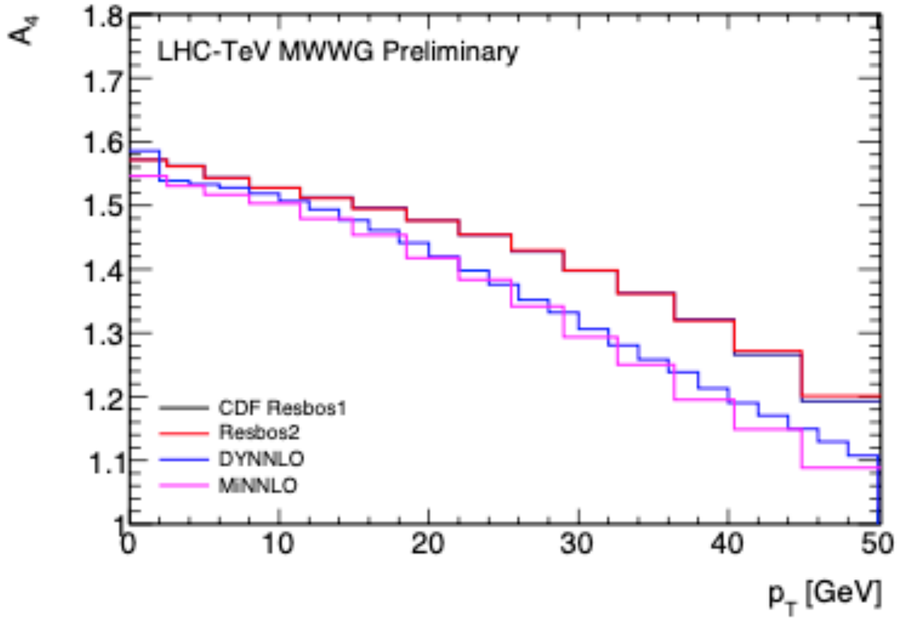
Ai comparison - CDF



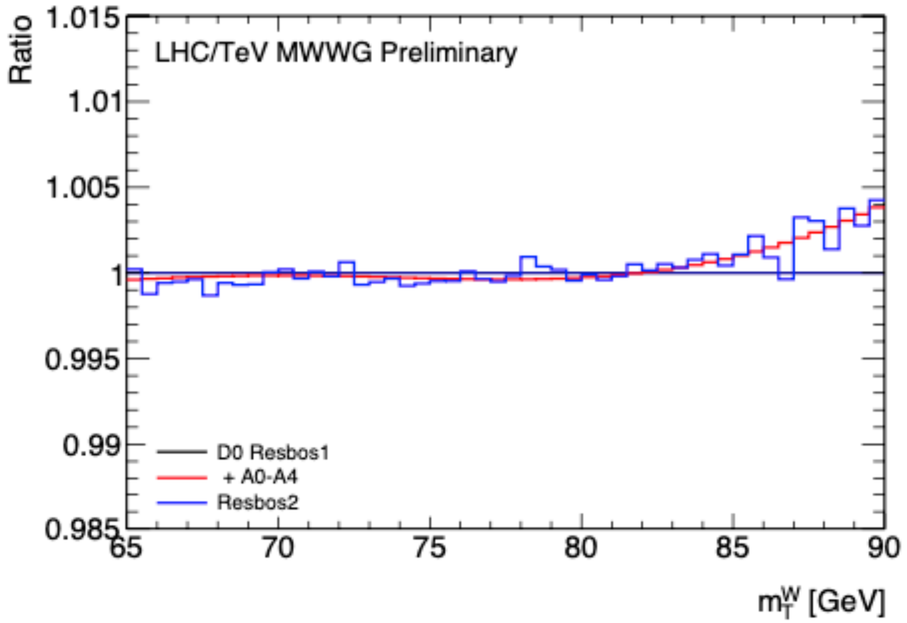


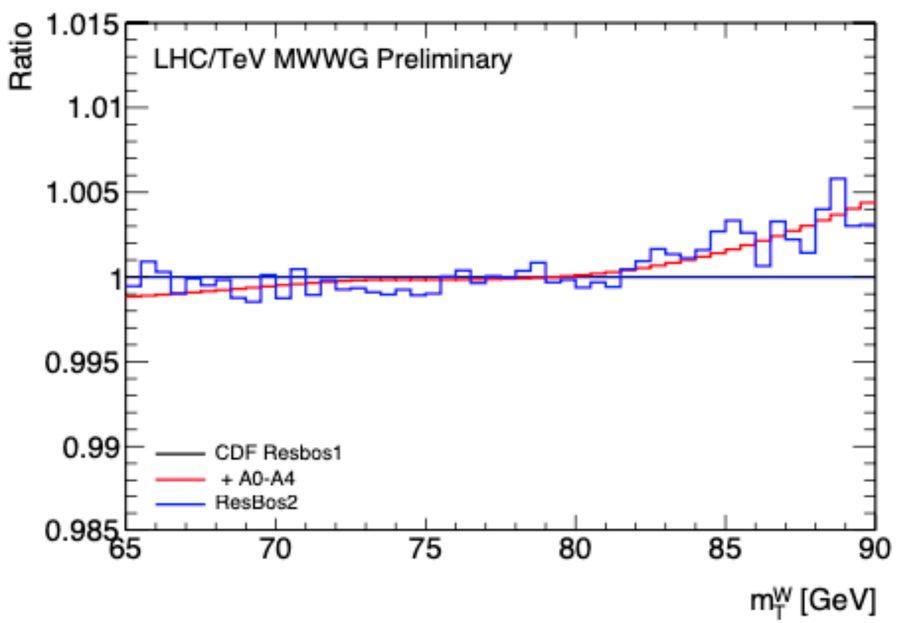


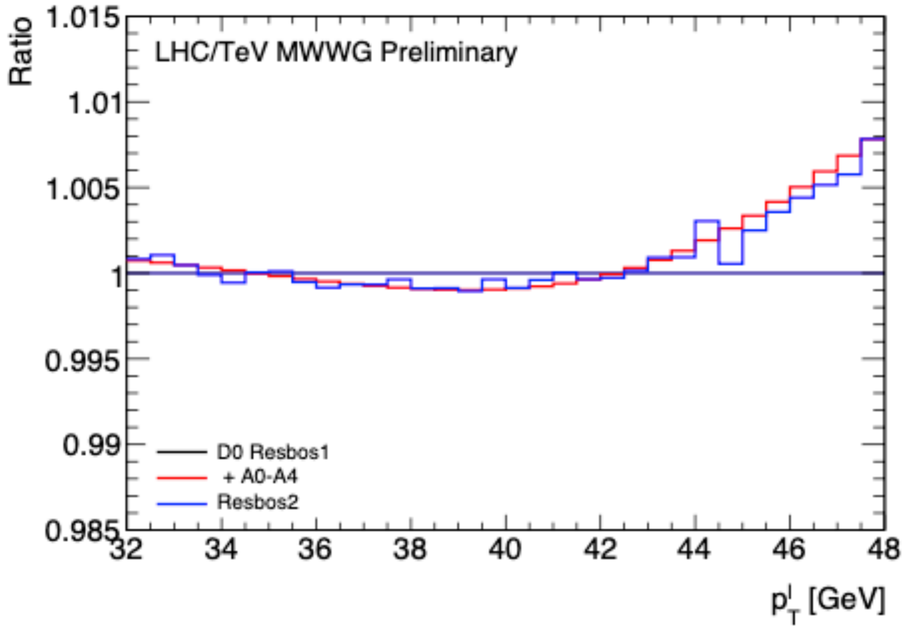


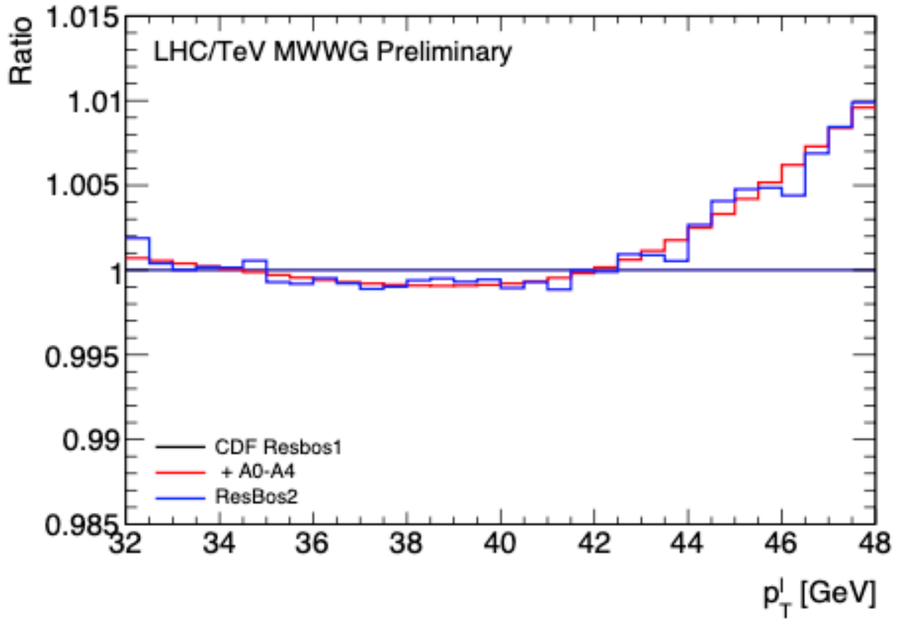


AI REWEIGHTING FOR CDF/D0









PDF benchmarking - I

Dataset	CT10	cteq6	cteq66
CDF Z rapidity	29|33 / 28	33|29 / 28	31|32 / 28
CDF W asymmetry	14|22 / 13	14|21 / 13	16|18 / 13
D0 Z rapidity	22|22 / 28	22|22 / 28	22|22 / 28
D0 $We\nu$ lepton asymmetry	20|33 / 13	20|22 / 13	22|26 / 13
D0 $W\mu\nu$ lepton asymmetry	11|13 / 10	12|13 / 10	11|12 / 10
ATLAS peak CC Z rapidity	14|25 / 12	21|214 / 12	18|29 / 12
ATLAS W^- lepton rapidity	10|25 / 11	21|38 / 11	14|44 / 11
ATLAS W^+ lepton rapidity	11|28 / 11	12|59 / 11	12|59 / 11
Correlated χ^2	52|166	158|513	90|236
Log penalty χ^2	-3.94|-3.94	-7.70|-7.70	-4.37|-4.37
Total χ^2 / dof	179|364 / 126	306|923 / 126	231|472 / 126
χ^2 p-value	0.00	0.00	0.00

PDF benchmarking - II

Dataset	NNPDF31	NNPDF40	MMHT14	MSHT20	CT18NNLO	ABMP16
CDF Z rapidity	24|28 / 28	28|30 / 28	30|31 / 28	32|32 / 28	27|27 / 28	31|31 / 28
CDF W asymmetry	11|57 / 13	14|17 / 13	12|13 / 13	28|27 / 13	11|35 / 13	21|43 / 13
D0 Z rapidity	22|22 / 28	23|23 / 28	23|23 / 28	24|23 / 28	22|22 / 28	22|22 / 28
D0 $We\nu$ lepton asymmetry	22|32 / 13	23|29 / 13	52|51 / 13	42|40 / 13	19|32 / 13	26|24 / 13
D0 $W\mu\nu$ lepton asymmetry	12|14 / 10	12|16 / 10	11|14 / 10	11|13 / 10	12|13 / 10	11|12 / 10
ATLAS peak CC Z rapidity	13|18 / 12	13|17 / 12	58|89 / 12	17|19 / 12	11|77 / 12	18|32 / 12
ATLAS W^- lepton rapidity	12|18 / 11	12|15 / 11	33|33 / 11	16|17 / 11	9.9|28 / 11	14|17 / 11
ATLAS W^+ lepton rapidity	8.9|13 / 11	8.6|11 / 11	15|21 / 11	12|13 / 11	9.4|16 / 11	10|12 / 11
Correlated χ^2	76|110	63|83	212|236	91|102	43|251	86|108
Log penalty χ^2	-0.62|-0.62	-0.58|-0.58	-1.62|-1.62	-2.89|-2.89	-1.68|-1.68	-2.72|-2.72
Total χ^2 / dof	200|312 / 126	195|242 / 126	445|509 / 126	270|283 / 126	163|499 / 126	236|300 / 126
χ^2 p-value	0.00	0.00	0.00	0.00	0.02	0.00

PDF benchmarking - III

Dataset	CT18ANNLO	CT18ZNNLO	CT18XNNLO	CT14nnlo	CT10nnlo	CJ15nlo
CDF Z rapidity	28|29 / 28	28|29 / 28	28|27 / 28	29|29 / 28	29|28 / 28	32|30 / 28
CDF W asymmetry	12|30 / 13	12|28 / 13	11|33 / 13	12|28 / 13	16|34 / 13	21|27 / 13
D0 Z rapidity	22|22 / 28	22|23 / 28	22|22 / 28	22|22 / 28	22|22 / 28	23|22 / 28
D0 $We\nu$ lepton asymmetry	21|33 / 13	21|29 / 13	21|31 / 13	20|32 / 13	24|69 / 13	39|49 / 13
D0 $W\mu\nu$ lepton asymmetry	11|12 / 10	11|12 / 10	11|13 / 10	11|13 / 10	11|18 / 10	17|26 / 10
ATLAS peak CC Z rapidity	10|19 / 12	9.7|21 / 12	12|71 / 12	13|42 / 12	12|27 / 12	60|104 / 12
ATLAS W^- lepton rapidity	10|17 / 11	10|17 / 11	13|27 / 11	11|27 / 11	10|41 / 11	23|27 / 11
ATLAS W^+ lepton rapidity	8.7|10 / 11	8.1|9.5 / 11	8.9|15 / 11	9.3|12 / 11	9.6|43 / 11	14|15 / 11
Correlated χ^2	49|113	43|113	82|230	63|175	58|198	269|314
Log penalty χ^2	-1.69|-1.69	-0.33|-0.33	-1.05|-1.05	-2.04|-2.04	-1.51|-1.51	-5.38|-5.38
Total χ^2 / dof	170|284 / 126	165|280 / 126	209|468 / 126	187|376 / 126	190|478 / 126	492|610 / 126
χ^2 p-value	0.01	0.01	0.00	0.00	0.00	0.00