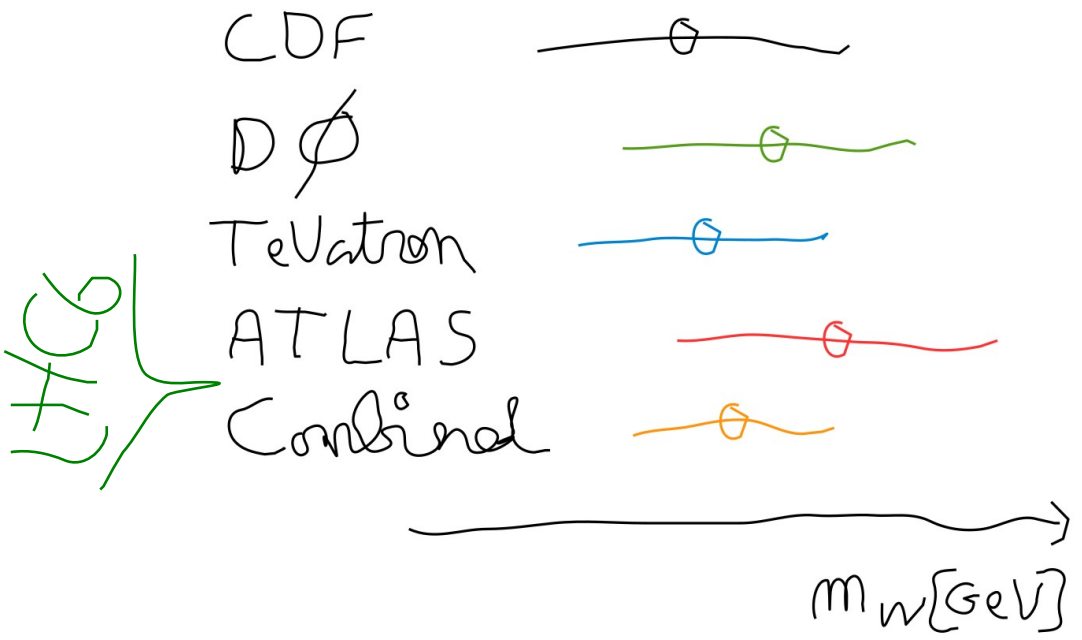
Status of the W-boson mass combination

- Objectives
- Reminders
- This year's developments
- Converging?
- Upcoming projects



CDF : Chris Hays
D0 : Boris Tuchming, Chen Wang
ATLAS : Jan Kretzschmar, M.Boonekamp, S.Amoroso (now CMS) and Nancy Andari (left)
CMS : Josh Bendavid
LHCb : Mika Vesterinen

https://indico.cern.ch/category/3290/
lhc-tevatron-wmass-combinations@cern.ch

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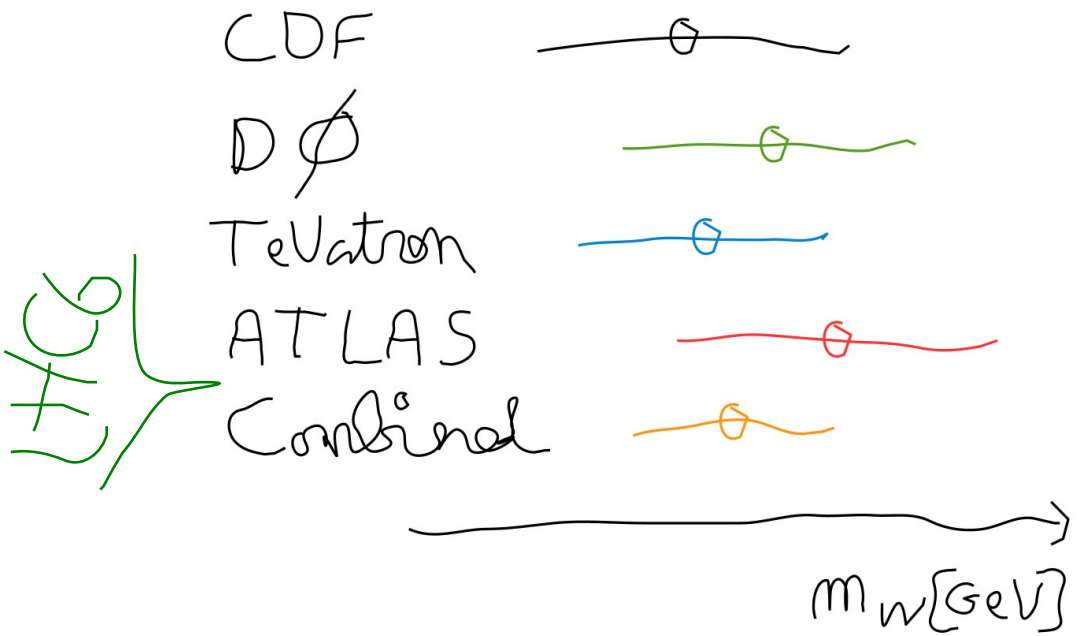


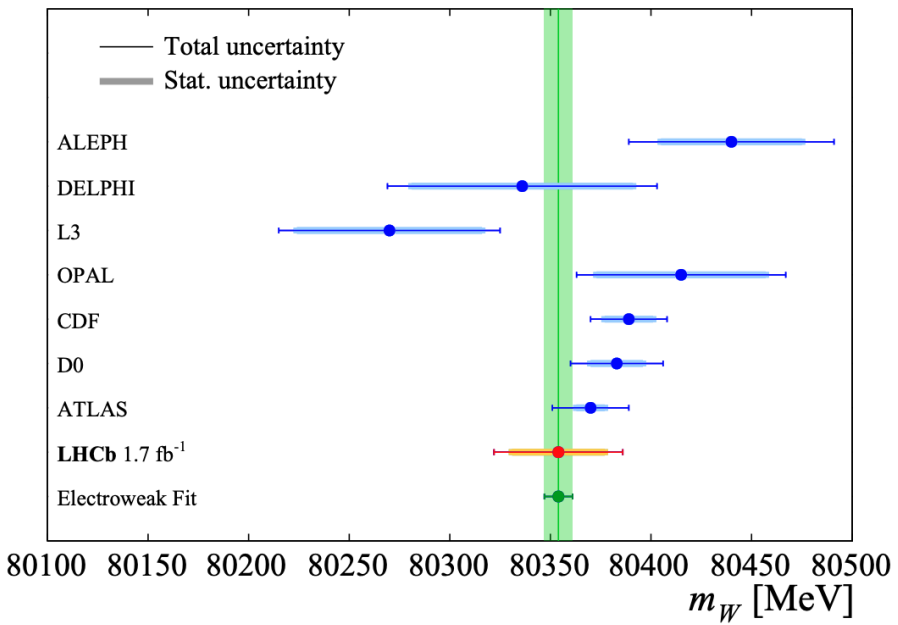
Previous presentations :

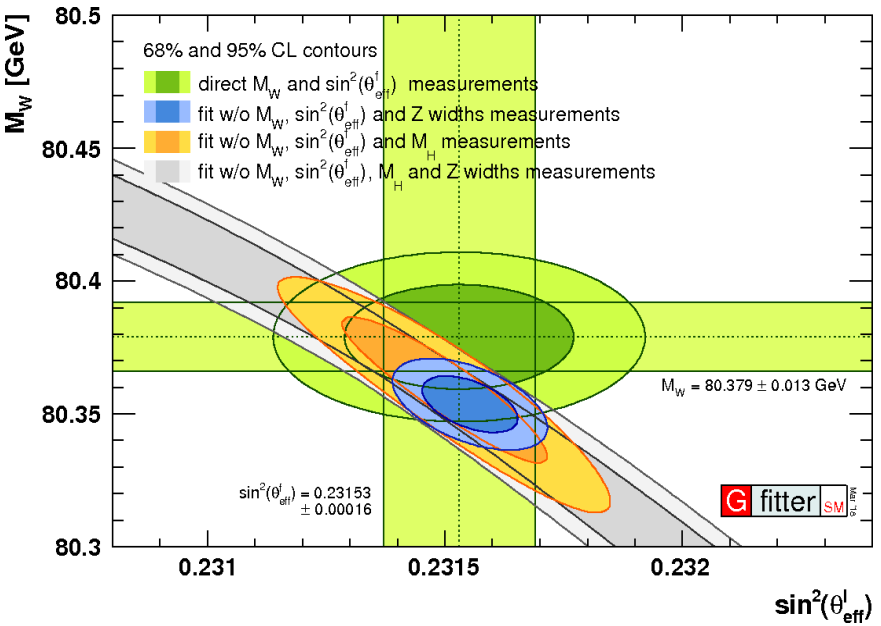
Feb. '21 https://indico.cern.ch/event/1006071/

Oct. '20 https://indico.cern.ch/event/941711/

Goals

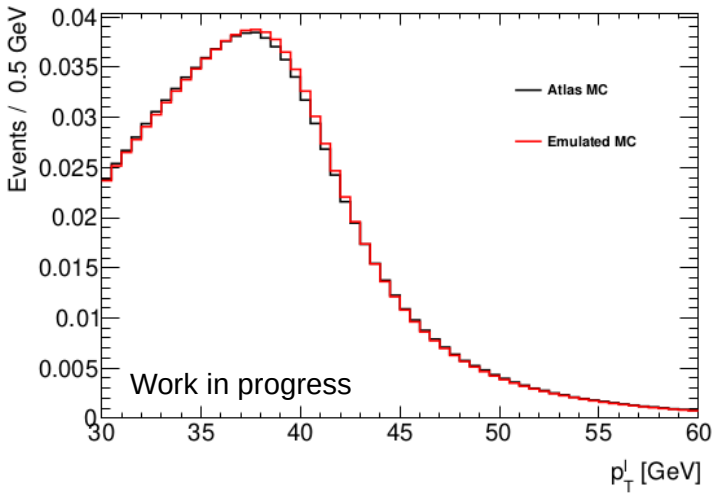
- Provide an endorsed world average combining existing hadron-collider results on m_W
  - Establish a methodology to combine present and future measurements
  - enable physics-modelling updates of past measurements (e.g. PDFs)
  - Properly correlate m_W and $\sin^2\theta_W$ measurements for global fits

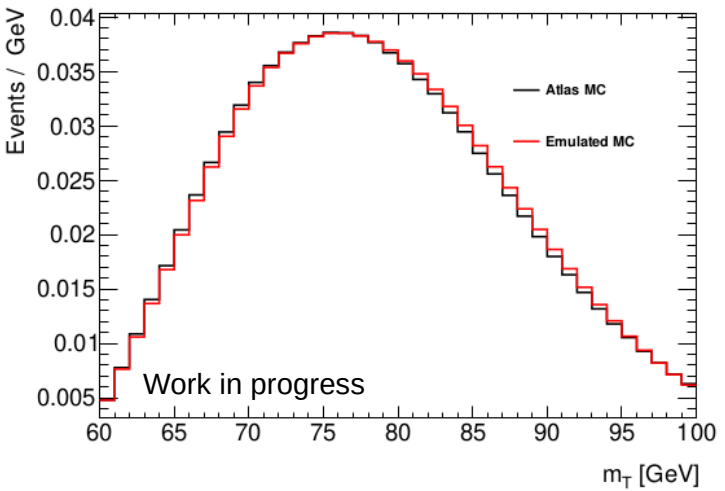




Analysis strategy : measurement emulation

- Parametrized detector response
  - Leptons : eta- and pT-dependent resolution curves & efficiencies
  - Recoil response and resolution, including dependence on boson pT and event activity





Reproduces published distributions at the % level, and allows propagating variations in the underlying physics with <1 MeV precision in m_W.

- Event selections and m_W fit ranges as in the publications.

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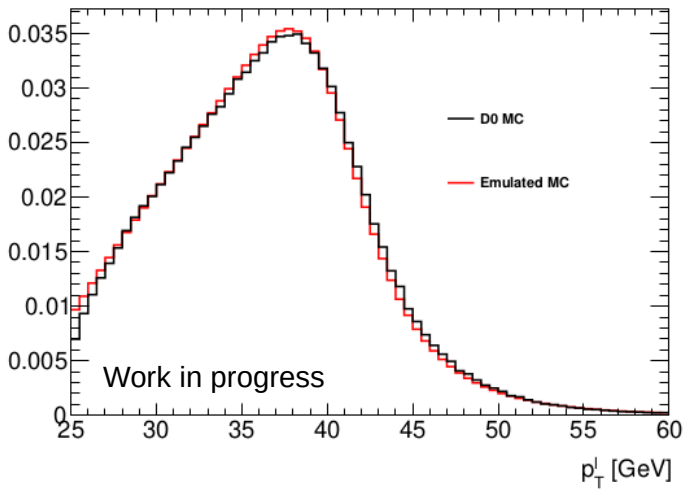

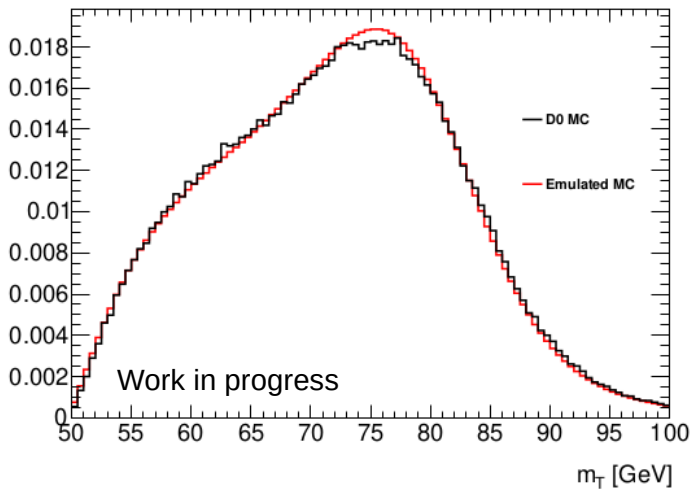

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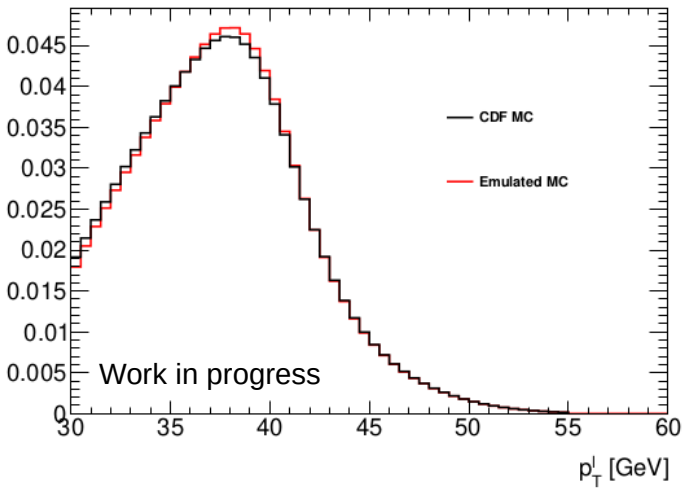

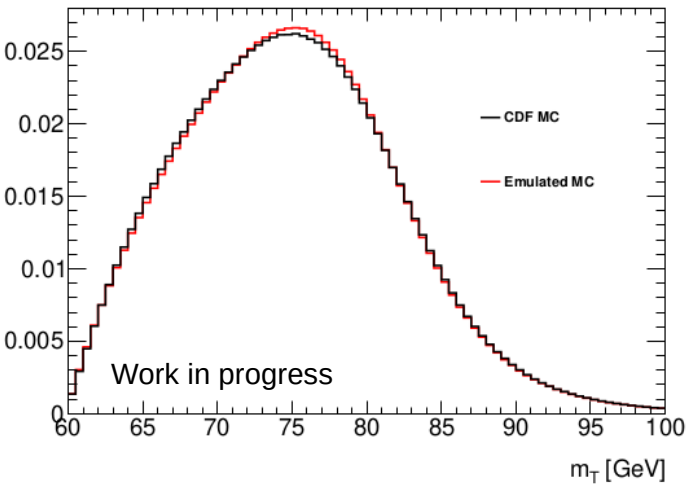

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Generators

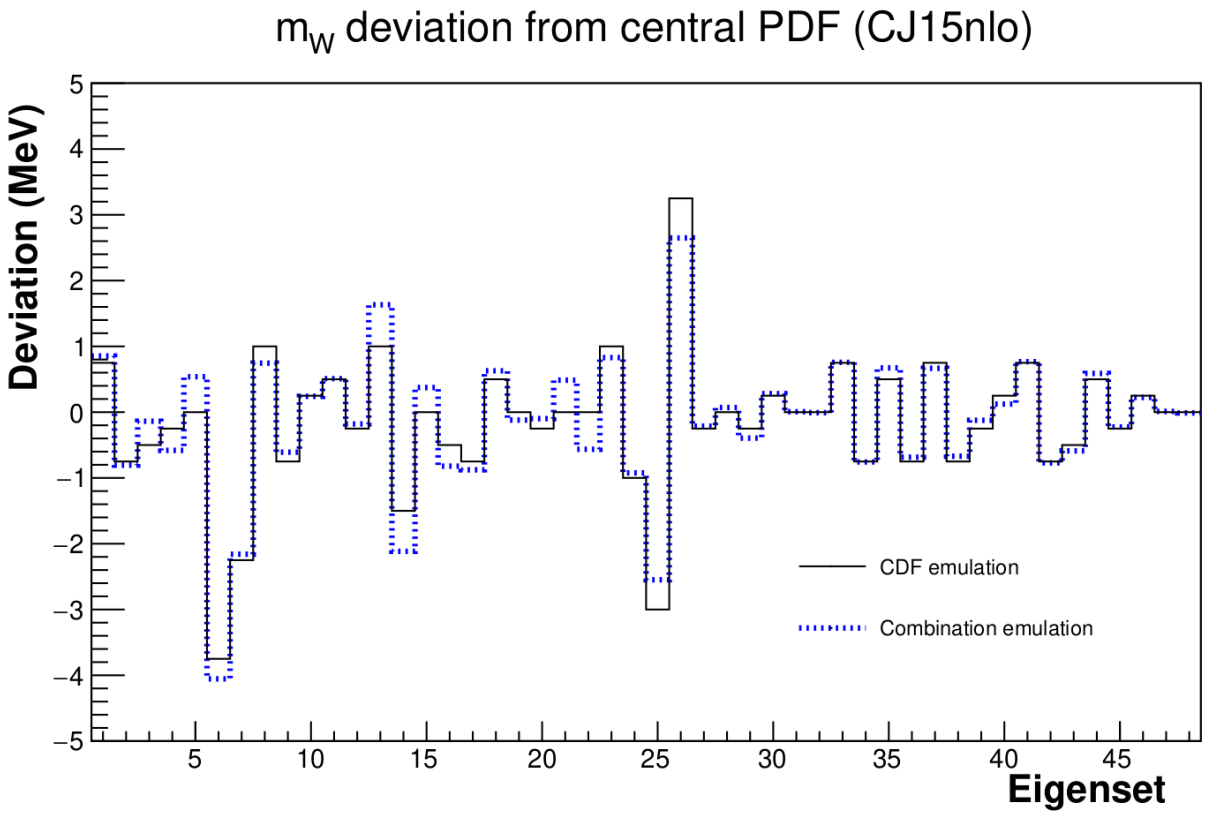
- Snapshot, to be updated :

Generator	Powheg	Powheg	MiNNLO	Resbos	Resbos
Sample type	Direct	Reweighted	Reweighted	Direct	Direct
QCD accuracy	NLO+NLL	NLO+NLL	NNLO+NLL	NLO+NLL	NNLO+NNLL
$\sqrt{s}$	2, 7 TeV	2, 7 TeV	2, 7 TeV	2 TeV	2 TeV
PDF set	Events				
CTEQ6M	5×10^8	10^7	5×10^7	2.5×10^9	2.5×10^9
CTEQ66	5×10^8	10^7	5×10^7	2.5×10^9	2.5×10^9
CT10	5×10^8	10^7 (*)	5×10^7	–	–
CT10nnlo	5×10^8	10^7	5×10^7	–	–
CT14	5×10^8	10^7	5×10^7	2.5×10^9	2.5×10^9
CT18	5×10^8	10^7	5×10^7	2.5×10^9	2.5×10^9
CJ15	5×10^8	10^7	5×10^7	–	–
MMHT14	5×10^8	10^7	5×10^7	2.5×10^9	2.5×10^9
MSHT20	5×10^8	10^7	5×10^7	–	–
ABMP16	5×10^8	10^7	5×10^7	–	–
NNPDF3.1	5×10^8	10^7	5×10^7 (*)	2.5×10^9	2.5×10^9

  - Adding MSTH20, NNPDF4.0; and Resbos samples at 7 TeV

Validation (examples)

- CJ15 uncertainty identical (2.9 MeV total) in the CDF and Combination emulations. Discrepancies <0.5 MeV for all eigenset variations



Chris Hays

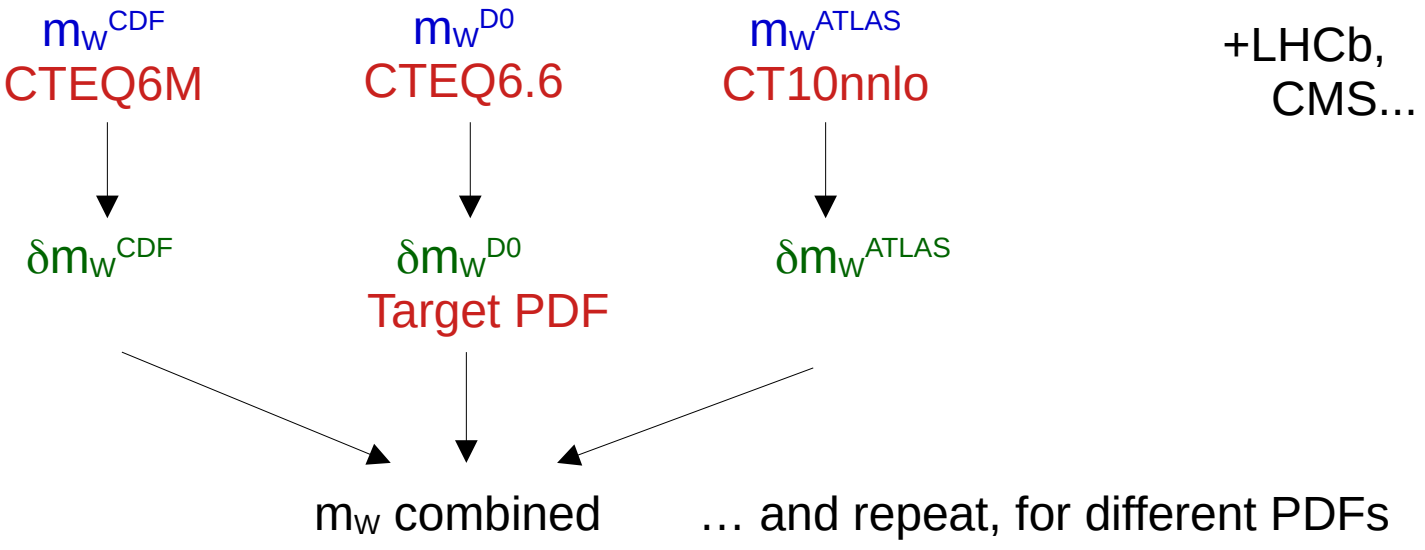
Validation (examples)

- Reproducing existing combinations using published information
  - PDF uncertainties re-calculated using smearing procedure, and used in combinations
  - PDF uncertainty found fully correlated between CDF and D0
  - Non-trivial correlations between the ATLAS measurement categories; accurately reproduced and combined result

	Tevatron	Tevatron+LEP	ATLAS
Published	80387 ± 16	80385 ± 15	80370 ± 19
Validation	80388 ± 16	80385 ± 15	80370 ± 19

New combinations

- PDFs are the main source of correlations
  - other sources are either small (EWK corrections) or arguably decorrelated ($p_T^{W/Z}$)
  - Two-step procedure : correct to common PDF; combination including correlations
  - At this point, PDF extrapolations and uncertainties are calculated using Powheg.



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CTEQ6.6	1.	2.	3.	4.
1. W^+ 2 TeV	1	1	0.37	0.45
2. W^- 2 TeV	1	1	0.36	0.46
3. W^+ 7 TeV	0.37	0.36	1	-0.42
4. W^- 7 TeV	0.45	0.46	-0.42	1

CT10	1.	2.	3.	4.
1. W^+ 2 TeV	1	0.99	0.26	0.51
2. W^- 2 TeV	0.99	1	0.31	0.52
3. W^+ 7 TeV	0.26	0.31	1	-0.23
4. W^- 7 TeV	0.51	0.52	-0.23	1

Example PDF correlations, separated by W-boson charge….

New combinations

- PDF uncertainty correlations, for various PDFs :
  - Overview, to be updated (CT18, MSHT, NNPDF)

PDF set	Tevatron/LHC correlation	
	NLO	NNLO
CTEQ6M	72 %	
CTEQ6.1	70 %	
CTEQ6.6	74 %	
CT10	75 %	76 %
CJ15	71 %	
CT14	81 %	71 %
MMHT14	63 %	66 %

… and summed over charges

New combinations

- Preliminary combinations for ATLAS+CDF+D0.
  - Central values may need corrections : hidden for now!
    - Model-dependence of PDF extrapolations?
    - Impact of generator mis-modellings?
  - Total (PDF) uncertainties : 11–13 MeV (3–7 MeV).
  - CT18, MSHT20 available too. NNPDF4.0 considered.

	CTEQ6M	CTEQ6.1	CTEQ6.6	CT10nnlo	MSTW2008
Central value					
PDF	9	9	9	9	5
Total	14	14	14	14	12
$\chi^2/ndof$	47/35	46/35	50/35	48/35	60/35

Table 1: Combination summary: Legacy PDFs

	CT10	CJ15	CT14nlo	MMHT2014nlo	NNPDF3.1nlo
Central value					
PDF	11	2	9	6	4
Total	16	11	14	13	11
$\chi^2/ndof$	46/35	53/35	48/35	58/35	49/35

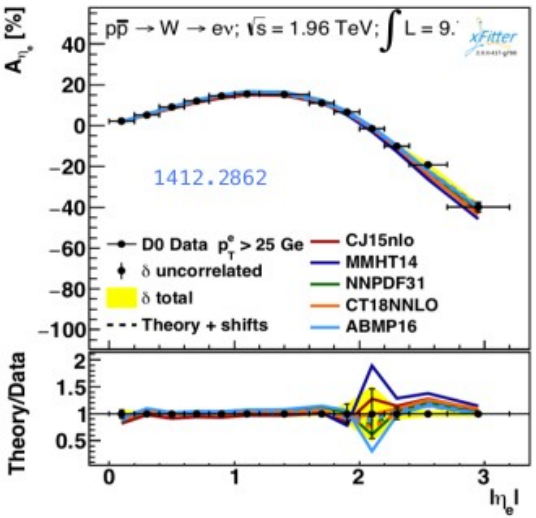
Table 2: Combination summary: NLO PDFs

	CT14nnlo	MMHT2014nnlo	ABMP16nnlo	NNPDF3.1nnlo
Central value				
PDF	10	7	3	4
Total	15	13	11	11
$\chi^2/ndof$	45/35	45/35	55/35	50/35

Table 3: Combination summary: NNLO PDFs

Choice of target PDFs for final numbers

- Comparisons between existing Drell-Yan data and “recent” NNLO PDFs
  - Example shown here : D0 lepton asymmetry
  - Similar exercises for CDF, LHC shown in back-up



Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
D0 W el nu lepton asymmetry ptl 25 GeV	32 / 13	24 / 13	19 / 13	17 / 13	23 / 13
Correlated χ^2	8.7	11	7.4	4.6	4.1
Log penalty χ^2	+0.00	+0.00	+0.00	+0.00	+0.00
Total χ^2 / dof	41 / 13	35 / 13	27 / 13	22 / 13	27 / 13
χ^2 p-value	0.00	0.00	0.01	0.05	0.01

→ consider MMHT14, NNPDF3.1, CT18NNLO, ABMP16
→ best overall description of the data by NNPDF3.1, CT18NNLO
→ to be repeated with MSHT20, NNPDF4.0

Step back : generator dependence?

- Full procedure, decomposed into generator and PDF effects :

$$m_W^{gen_i, PDF_i} = m_W^{gen_0, PDF_0} + \delta m_W^{gen_{0\to i}, PDF_0} + \delta m_W^{gen_i, PDF_{0\to i}}$$

  where
  - gen_0 , PDF_0 are the generator and PDF used in the publications
  - gen_i , PDF_i are the targets of the extrapolation

- Published measurements :
  - CDF : Resbos1 (NLO) CTEQ6M (NLO)
  - D0 : Resbos1 (NNLO) CTEQ6.6 (NLO)
  - ATLAS : Powheg corrected to NNLO CT10NNLO

- $\delta m_W^{gen_i, PDF_{0\to i}}$ Main PDF targets : modern NNLO sets
  ~Finalized, including generator dependence of PDF extrapolations.
- $\delta m_W^{gen_{0\to i}, PDF_0}$ Long neglected, and subject of ongoing work : Powheg, MiNNLO, New Resbos

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published

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published — Discussed above

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published New Discussed above

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Generator-dependence of PDF extrapolations ($\delta m_W^{gen_i, PDF_{0\to i}}$)

- Example, for CDF/D0 :

gen $_i$ →

$\delta m_W^{gen_i, PDF_{0\to i}}$ ↓

Generator Sample type QCD accuracy		Powheg Reweighted NLO+NLL	Powheg Direct NLO+NLL	MiNNLO Reweighted NNLO+NLL	Resbos Direct NLO+NLL	Resbos Direct NNLO+NNLL
PDF set				Shift		
CTEQ6M	NLO	0	0	0	0	0
CTEQ66	NLO	-15.4 ± 0.8	-15.8 ± 0.8	-14.0 ± 1.3	-17.8 ± 1.0	-16.6 ± 1.0
CT10	NLO	-6.3 ± 0.8	-6.2 ± 0.8	-4.2 ± 1.3	–	–
CT10nnlo	NNLO	-16.2 ± 0.8	-16.6 ± 0.8	-16.8 ± 1.3	–	–
CT14	NNLO	-4,1 ± 0.8	-3.9 ± 0.8	-6.8 ± 1.3	-7.1 ± 1.0	-6.9 ± 1.0
CT18	NNLO	-6.2 ± 0.8	-6.6 ± 0.8	-8.5 ± 1.3	-9.4 ± 1.0	-7.2 ± 1.0
CJ15	NLO	7.7 ± 0.8	7.9 ± 0.8	10.1 ± 1.3	–	–
MMHT14	NNLO	-6.2 ± 0.8	-6.4 ± 0.8	-6.9 ± 1.3	-8.1 ± 1.0	-3.5 ± 1.0
MSHT20	NNLO	-5.0 ± 0.8	-4.9 ± 0.8	-4.9 ± 1.3	–	–
ABMP16	NNLO	5.2 ± 0.8	5.0 ± 0.8	-0.2 ± 1.3	–	–
NNPDF3.1	NNLO	-13.8 ± 0.8	-14.3 ± 1.4	-14.1 ± 1.3	-15.8 ± 1.0	-8.0 ± 1.0

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PDF set				Shift		
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Generator		Powheg	Powheg	MiNNLO	Resbos	Resbos
Sample type		Reweighted	Direct	Reweighted	Direct	Direct
QCD accuracy		NLO+NLL	NLO+NLL	NNLO+NLL	NLO+NLL	NNLO+NNLL
PDF set				Shift		
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Generator-dependence of PDF extrapolations ($\delta m_W^{gen_i, PDF_{0\to i}}$)

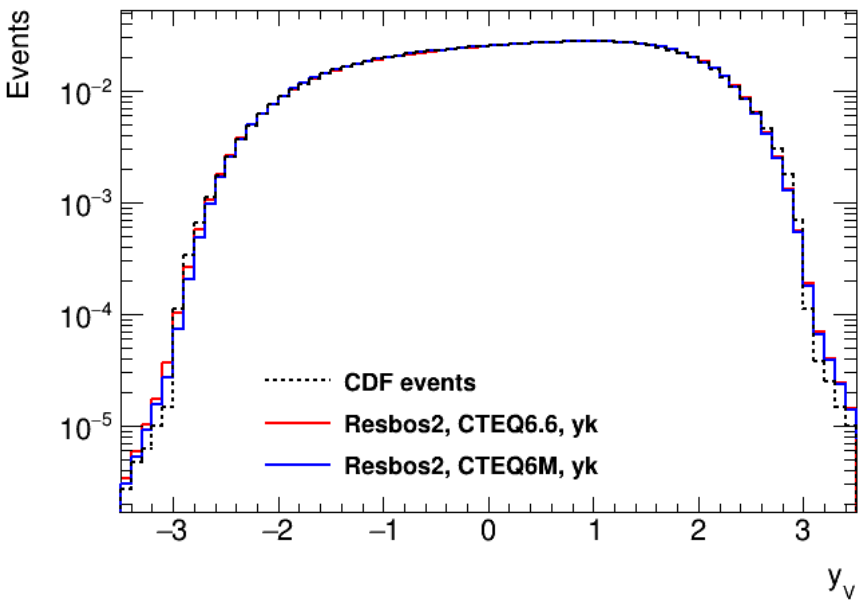
- Main findings
  - Significant difference between CTEQ6M and CTEQ6.6
  - Most often, PDF shifts agree across generators, within 1 MeV
  - Some counter-examples :
    - MMHT14, NNPDF3.1 : NNLO Resbos2 3-8 MeV different relative to other generators
- Residual differences under discussion.

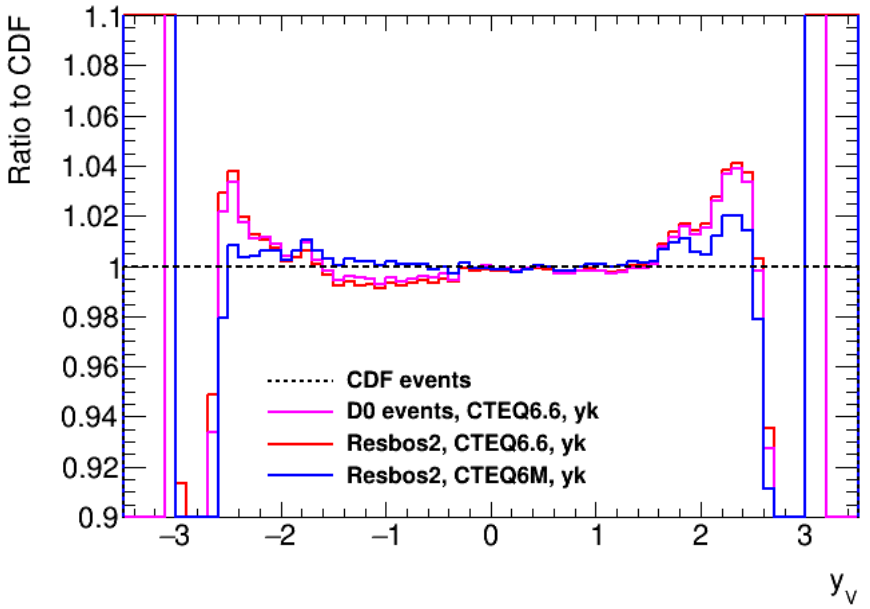
Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Question : accuracy of Resbos1, compared to modern generators?
  - Resbos1 distributions obtained from a sample shared by CDF, matching what was used for their publications. D0 shared their event generation set-up.
    - Resbos1 is a semi-private generator, and it is difficult to reproduce these distributions externally
  - Comparisons to Powheg, MiNNLO, and the New Resbos
    - The New Resbos is an upgrade of Resbos1, with (among others) improved NNLO QCD corrections, and improved treatment of spin correlations

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- W+ rapidity distribution for CTEQ6M (CDF setup), CTEQ6.6 (D0 setup)

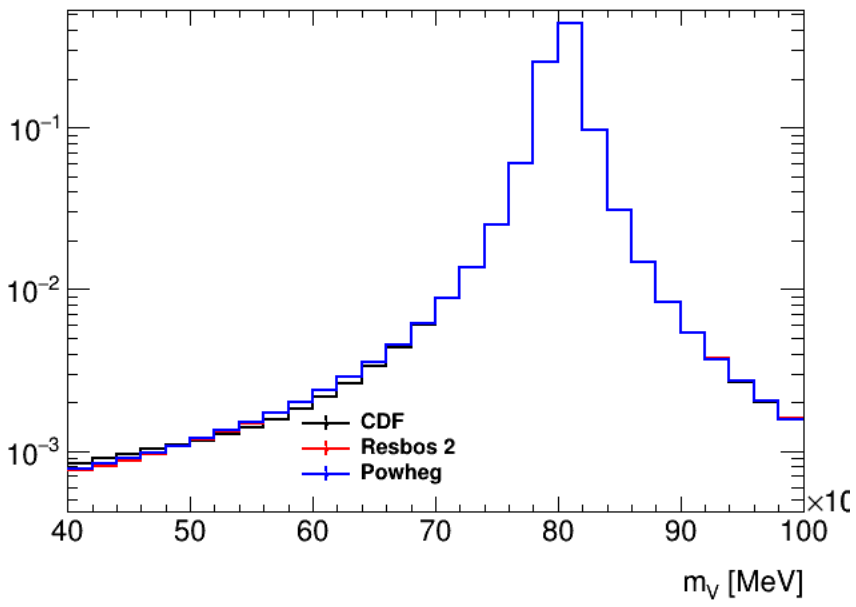


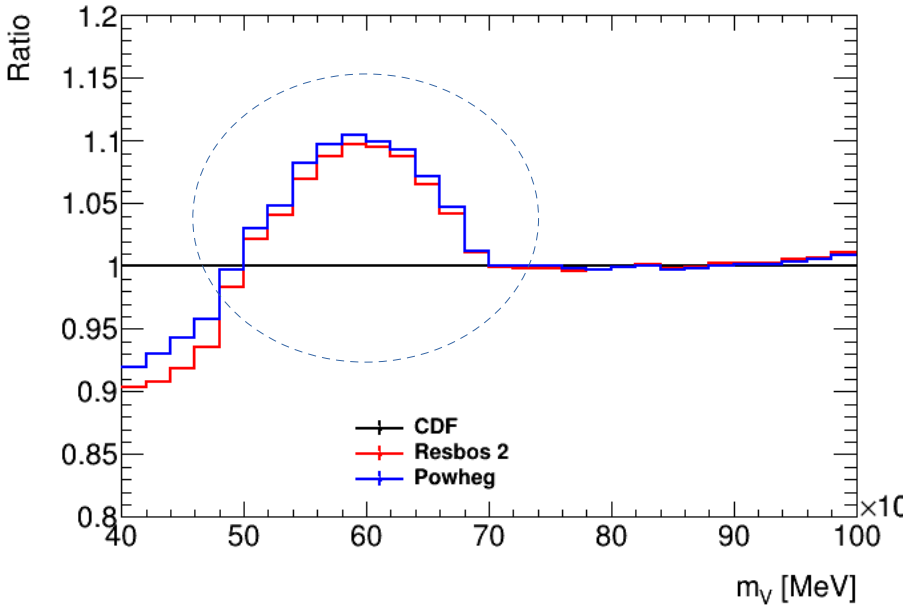


→ CDF events match Resbos2+CTEQ6M, with 1-2% residuals
→ D0 events match Resbos2+CTEQ6.6 closely (<0.5%).

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Invariant mass distribution in CDF events (before selections)

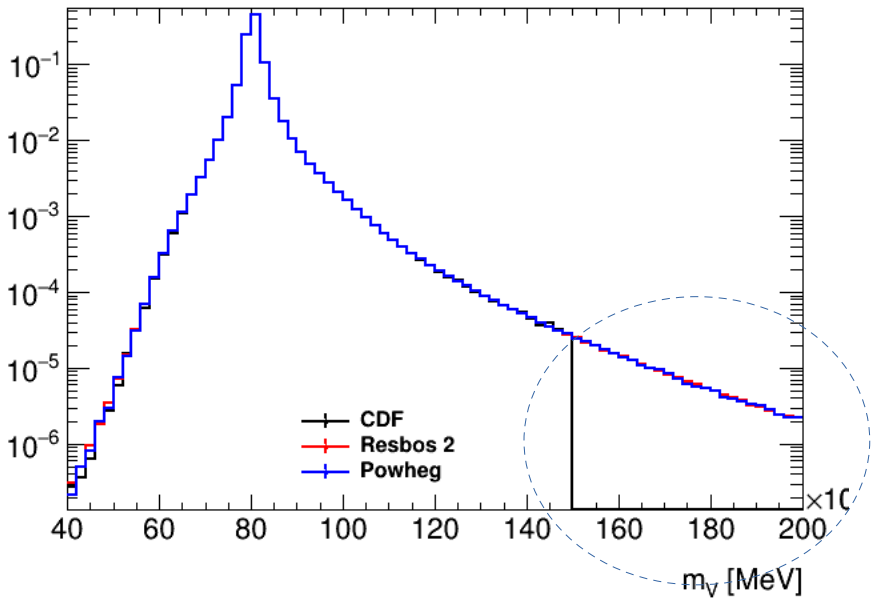


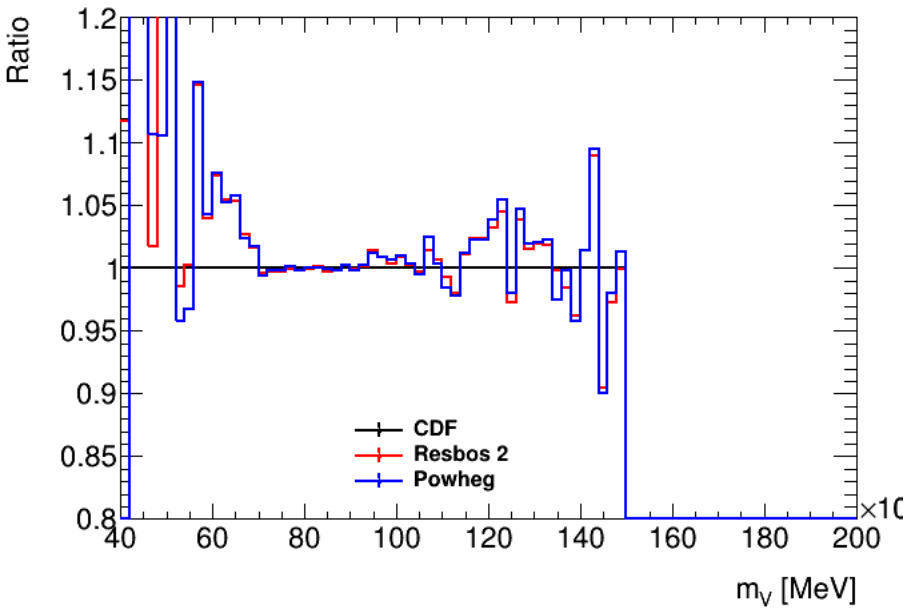


CDF events show deficit for m<70 GeV (then excess for m<50), compared to Powheg and Resbos2, for given m_W & Γ_W

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Invariant mass distribution in CDF events (after selections)





- CDF events stop at 150 GeV (not really a generator discrepancy; rather a generation setting).
- Resbos2, Powheg agree well above this value.
- Note this is after selections, so events with m>150 GeV contribute to the m_T, p_T^l plots, at high values.
  → combined effect of mass differences is estimated to be +2 MeV

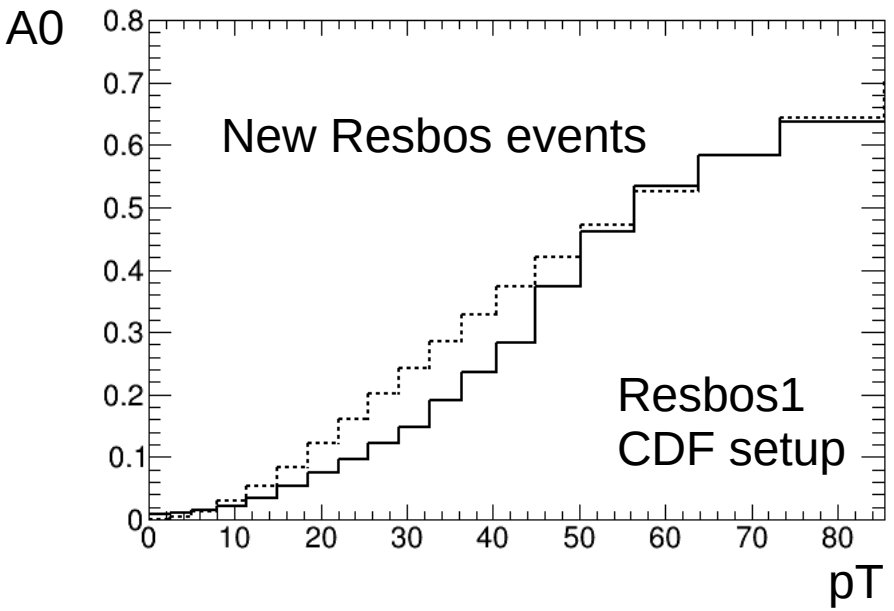
Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Spin correlations.
  - General formula describing a spin-1 resonance production and decay:

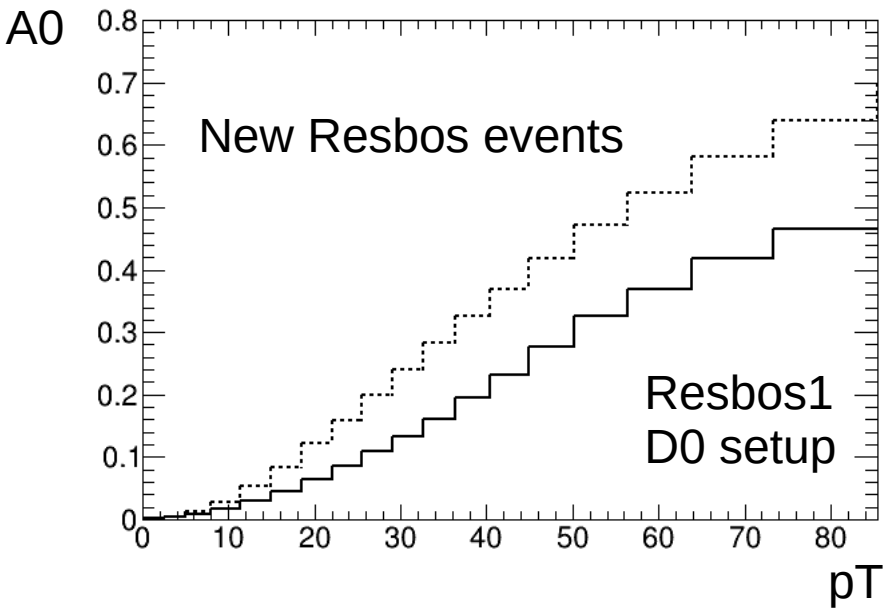
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm dp_T dy}\,[\,(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\,],$$

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Spin correlations



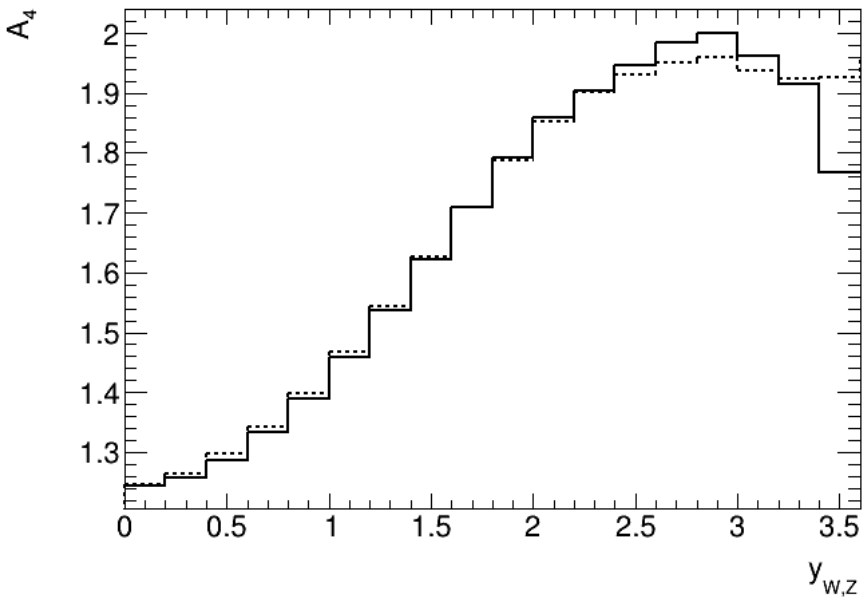
CDF, NLO



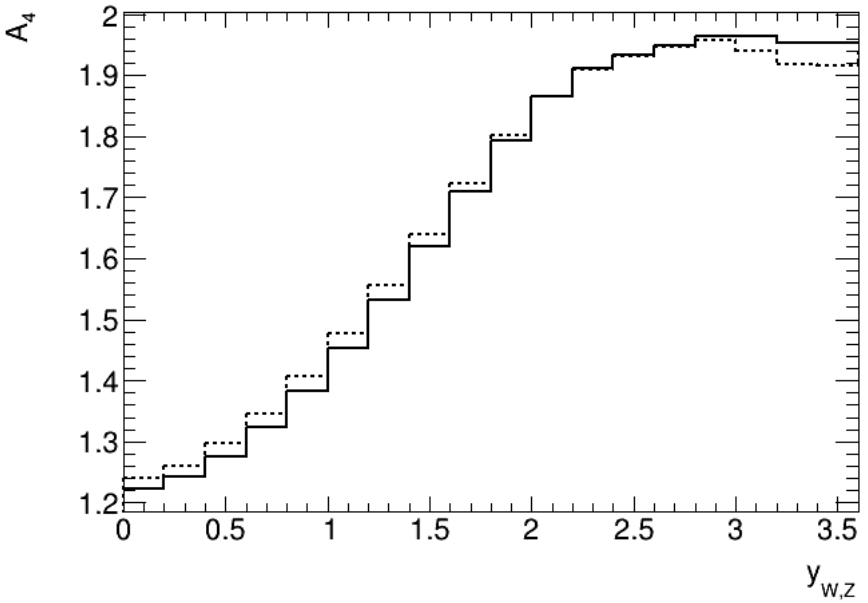
D0, NNLO

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Spin correlations



CDF, NLO



D0, NNLO

Discussion with Resbos authors

- Resbos 1 :
  - Unpolarised cross section is resummed
  - The polarised cross sections are at fixed order
- New resbos (and other MC's)
  - All helicity cross sections are resummed, assuming resummation effects universal
  - Universality proven for Z+j (and probably W+j), not for inclusive production
- Consequences
  - Recovers fixed-order behaviour of angular coefficients

$$A_i^{old}(p_T) = \sigma_i^{FO}(p_T)/\sigma_{unpol}^{Res}(p_T)$$

$$A_i^{new}(p_T) = \sigma_i^{Res}(p_T)/\sigma_{unpol}^{Res}(p_T) = \sigma_i^{FO}(p_T)/\sigma_{unpol}^{FO}(p_T) = A_i^{FO}(p_T)$$

Discussion with Resbos authors

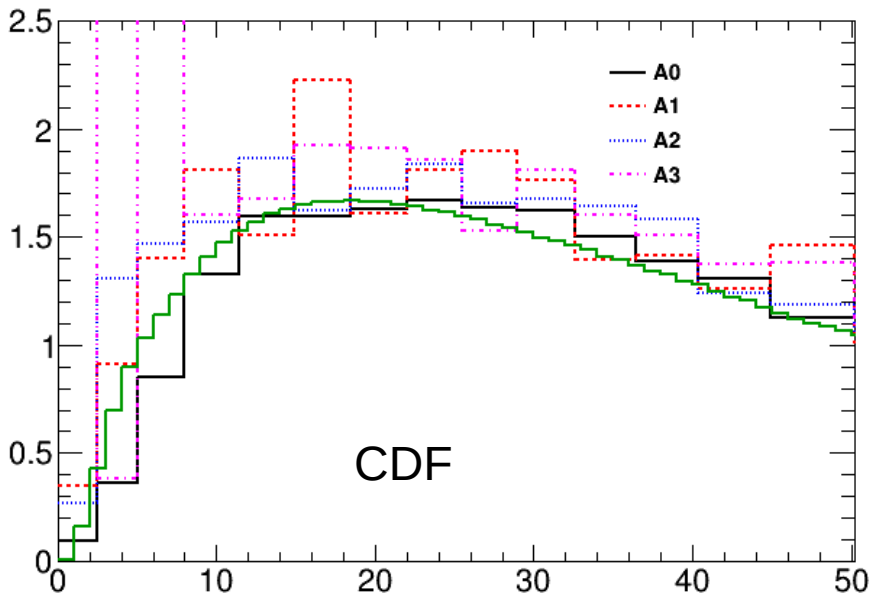
- Resbos 1 :
  - Unpolarised cross section is resummed
  - The polarised cross sections are at fixed order
- New resbos (and other MC's)
  - All helicity cross sections are resummed, assuming resummation effects universal
  - Universality proven for Z+j (and probably W+j), not for inclusive production
- Consequences
  - "prediction" : the ratio between "old" and "new" Ai's should match the ratio between resummed and fixed-order pT distributions

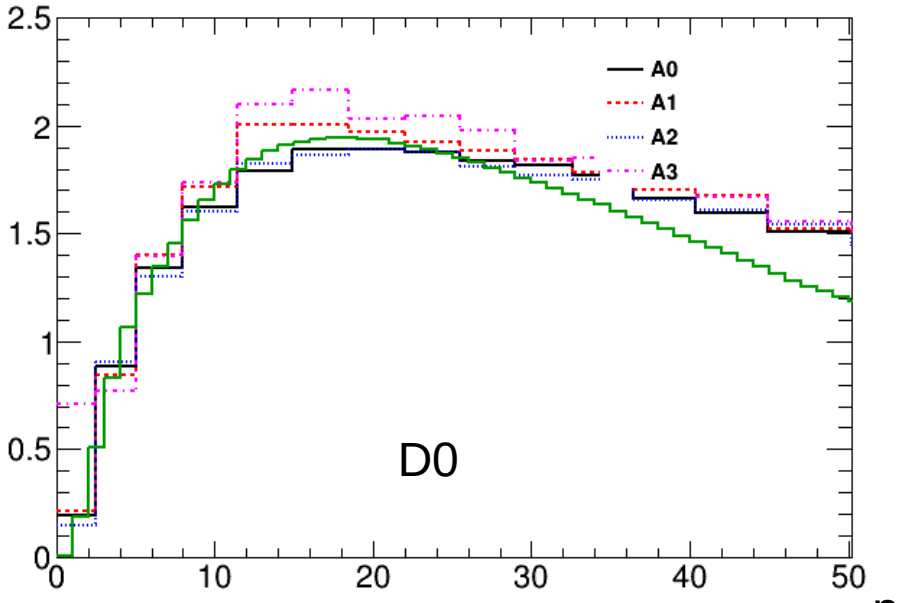
$$A_i^{new}(p_T)/A_i^{old}(p_T) = \sigma_i^{Res}(p_T)/\sigma_i^{FO}(p_T) = \sigma_{unpol}^{Res}(p_T)/\sigma_{unpol}^{FO}(p_T)$$

Discussion with Resbos authors

- Consequence: ratio between new and old angular coefficients should be universal, and match the ratio of resummed and fixed-order pT distributions

A_i^{new} / A_i^{old}



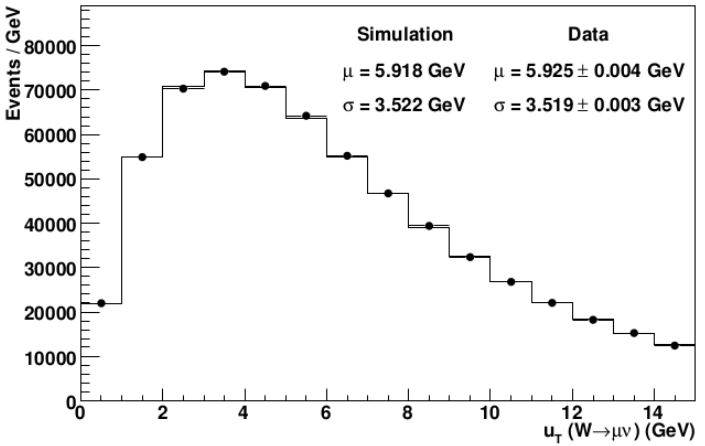


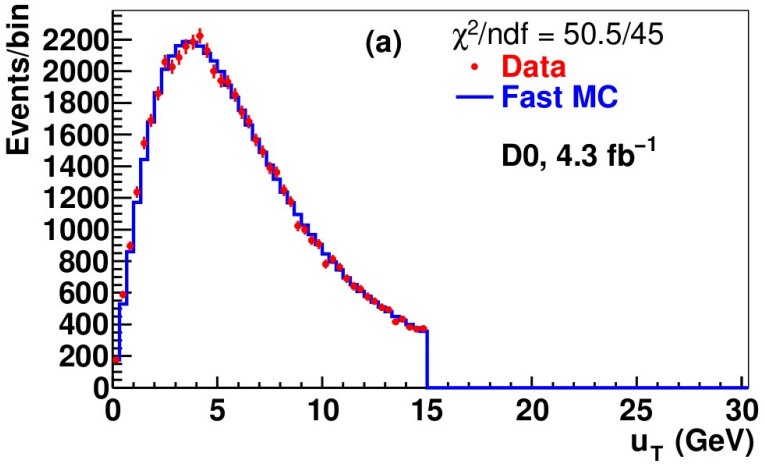
p_T

→ Universality : ✓. Note difference between CDF and D0 events at high pT.
→ with Resummed / FixedOrder pT distribution ratio. Not perfect, but qualitatively explains

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

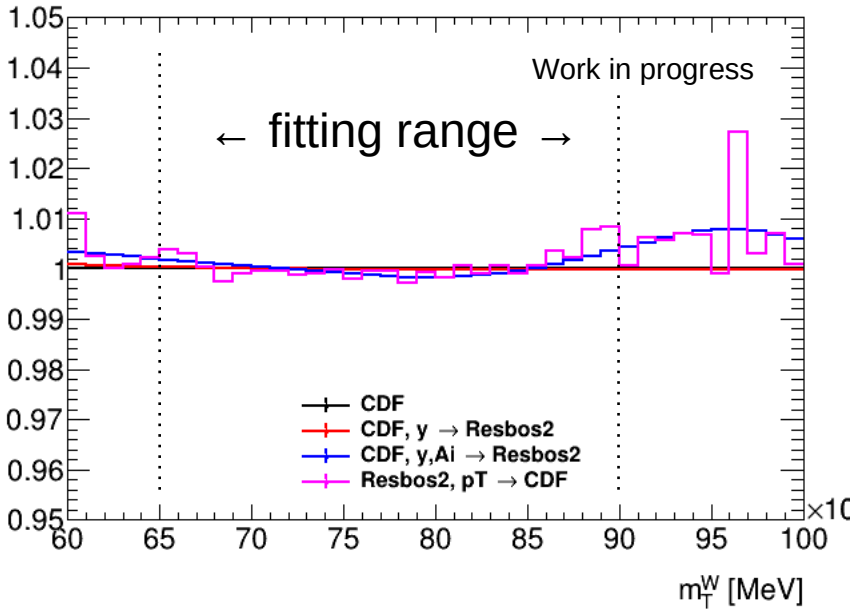
- Corrections evaluated, through reweightings or cuts :
  - Invariant mass shape and range
  - Rapidity
  - Angular coefficients, $A_0 \rightarrow A_4$
- In addition, direct comparisons are made between old and new samples, for same physics (PDF, QCD order, m_W and Γ_W)
- Note : all variations are studied assuming that the true p_T^W distribution does not change after selections, by virtue of successful u_T control plot in the Tevatron publications.
  - Control plots however do not have infinite statistics, so p_T^W has *some* freedom. Effects shown are therefore a lower bound

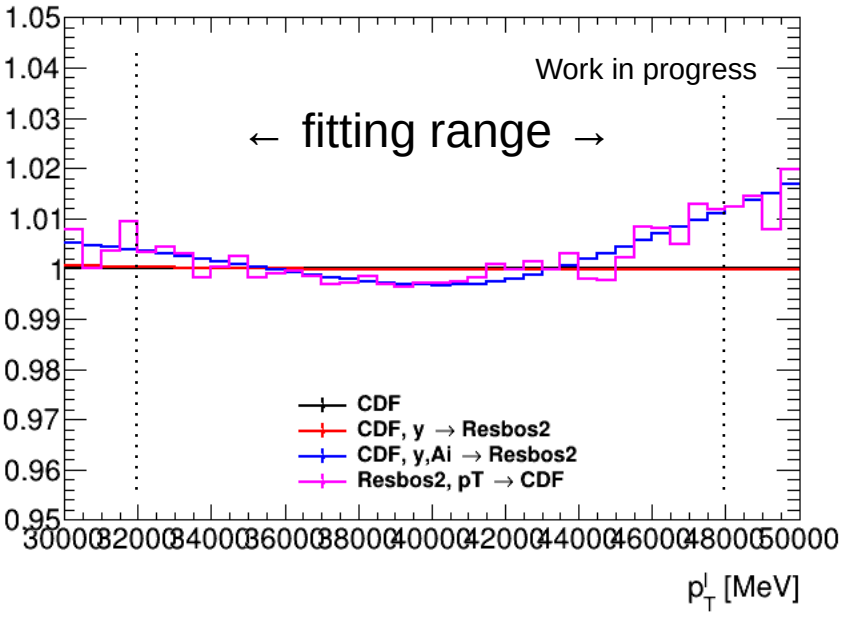




Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Impact on final-state distributions : transverse mass, lepton p_T – CDF

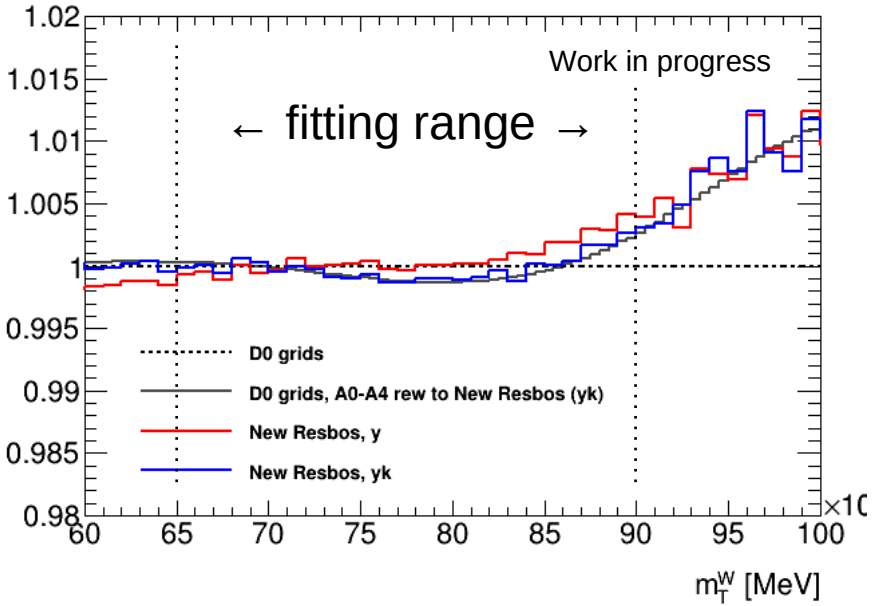


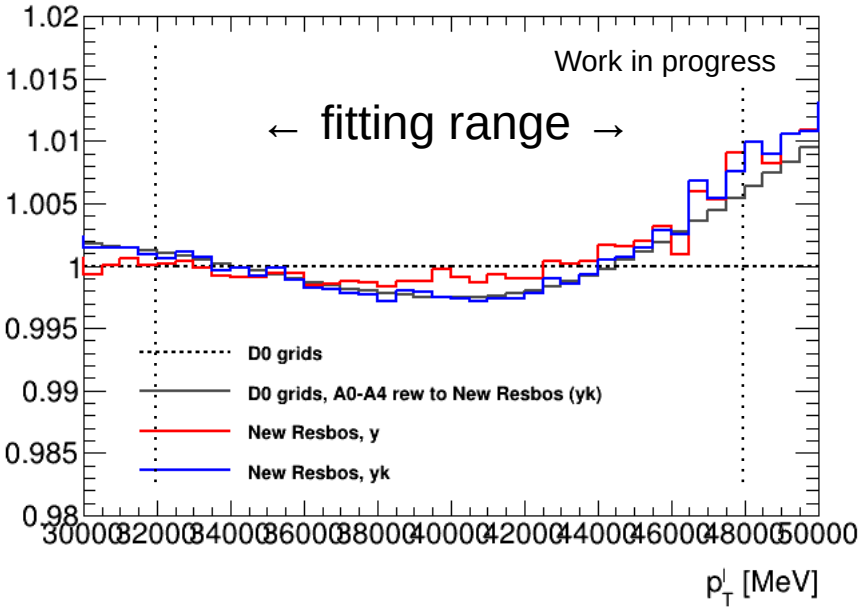


- CDF, New Resbos, CDF reweighted to New Resbos
- Effect up to 1% on the shapes from direct comparison between CDF and New Resbos (purple), qualitatively understood using reweighting studies (blue)
- Fluctuations in ratio are from limited size of CDF sample (=reference at 1)

Generator corrections ($\delta m_W^{gen_{0\to i}, PDF_0}$)

- Impact on final-state distributions : transverse mass, lepton p_T – D0





- Dashed – D0 reference at 1; full – D0 reweighted to New Resbos; blue – New Resbos
- Effect up to 1% on the shapes from direct comparison, qualitatively understood using reweighting studies

Generator effects : summary

- Effects not small compared to a reasonable m_W variation, and required to be at least evaluated
- Internally agreed on procedure to estimate the corresponding correction; finalizing numbers

- Effects shown before are a lower bound, as discussed; caution needed.

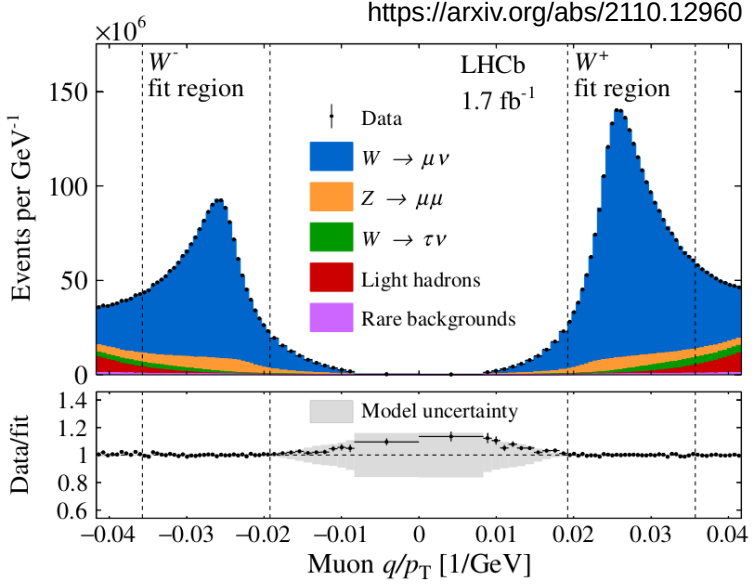
Conclusions and next steps

- Ambitious plan now to stop working and document
  - A few decisions have to be made regarding corrections and extrapolations (first proposal)
  - Then rerun all combinations, compile results and submit for internal review

Prospects : ATLAS+LHCb

- Should be much simpler, and highly interesting. Starting.
  - Detailed information available for all used PDFs; up-to-date generators and a complete set of systematic uncertainties (including spin correlations)
  - Expect negative correlations of PDF uncertainties between ATLAS and LHCb (reminiscent of what we gained from the η categories in ATLAS)

https://arxiv.org/abs/2110.12960



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

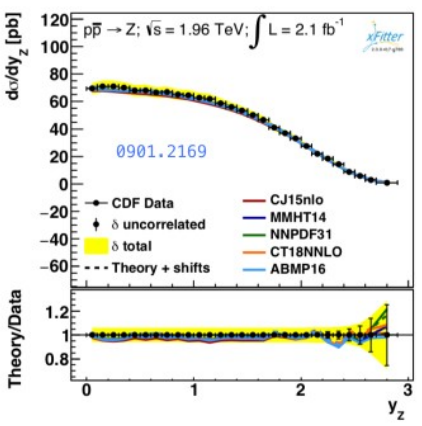
https://arxiv.org/abs/1508.06954

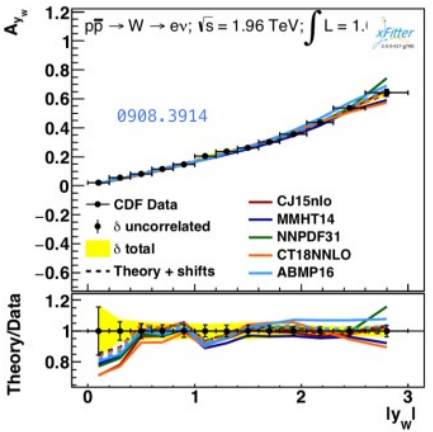
$$\rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}$$

Back up

Choice of target PDFs

- Comparisons between existing Drell-Yan data and “recent” NNLO PDFs
  - CDF



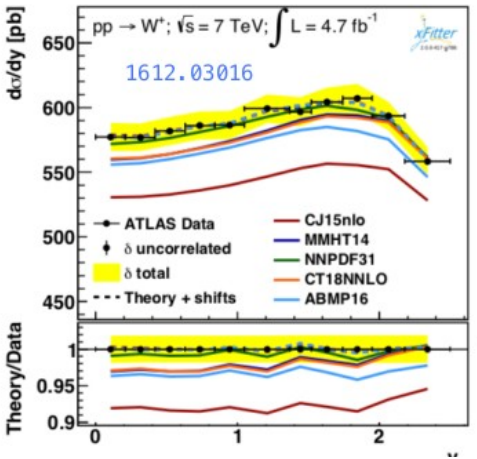


Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
CDF W asymmetry 2009	18 / 13	12 / 13	11 / 13	13 / 13	17 / 13
Correlated χ^2	1.6	1.7	2.6	2.9	6.5
Log penalty χ^2	-0.00	-0.00	-0.00	-0.00	-0.00
Total χ^2 / dof	19 / 13	14 / 13	13 / 13	16 / 13	23 / 13
χ^2 p-value	0.11	0.37	0.43	0.25	0.04

Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
CDF Z rapidity 2010	29 / 28	30 / 28	25 / 28	27 / 28	30 / 28
Correlated χ^2	1.5	0.99	1.7	0.49	0.69
Log penalty χ^2	-1.16	-0.63	-0.44	-0.60	-0.90
Total χ^2 / dof	30 / 28	30 / 28	26 / 28	27 / 28	30 / 28
χ^2 p-value	0.37	0.36	0.55	0.53	0.36

Choice of target PDFs

- Comparisons between existing Drell-Yan data and “recent” NNLO PDFs
  - ATLAS

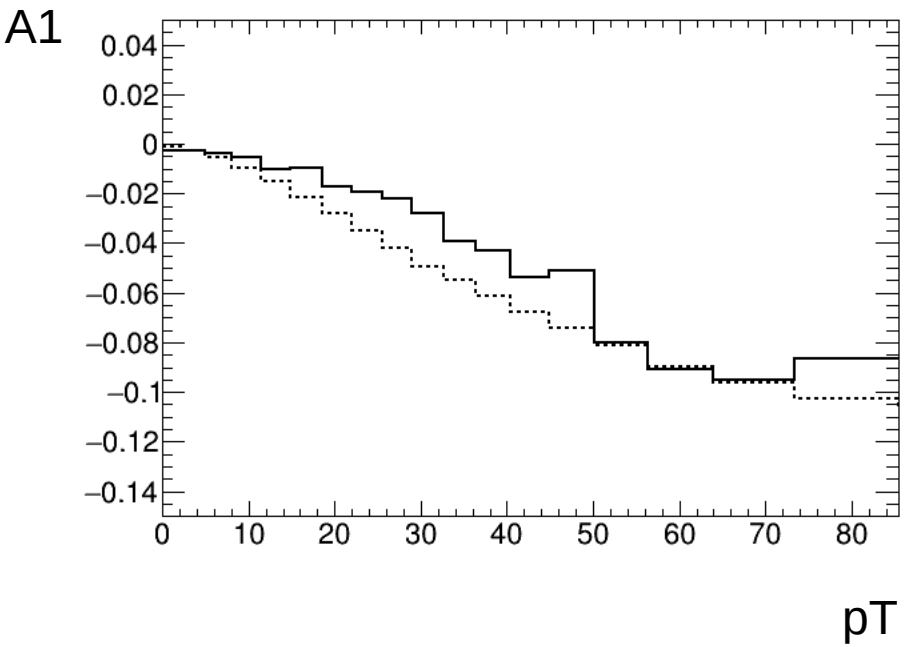


S.Amoroso

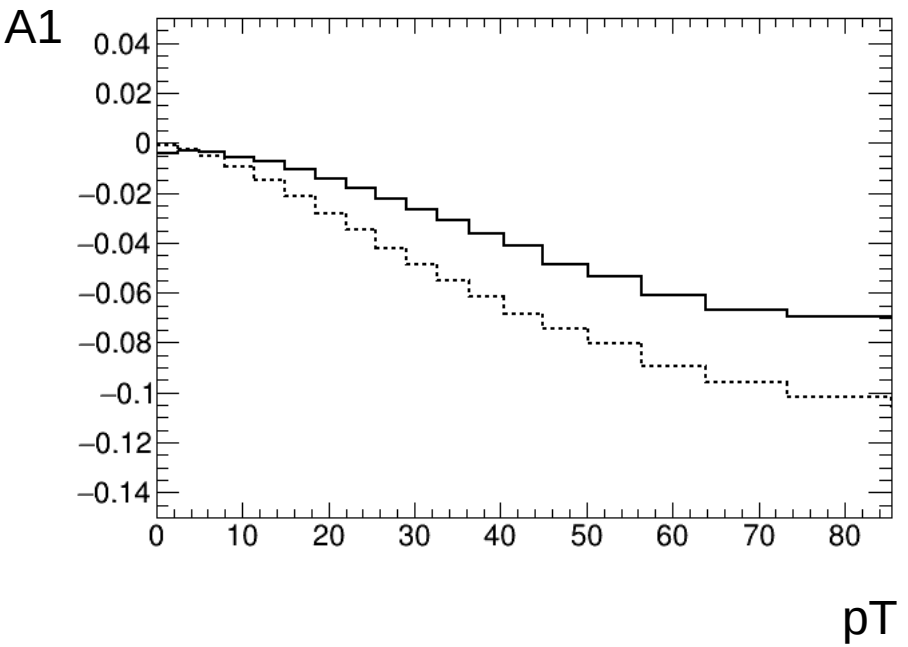
Dataset	CJ15nlo	MMHT14	NNPDF31	CT18NNLO	ABMP16
ATLAS low mass Z rapidity 2011	26 / 6	18 / 6	14 / 6	12 / 6	21 / 6
ATLAS peak CC Z rapidity 2011	52 / 12	21 / 12	12 / 12	16 / 12	24 / 12
ATLAS peak CF Z rapidity 2011	16 / 9	11 / 9	11 / 9	10 / 9	9.2 / 9
ATLAS high mass CC Z rapidity 2011	7.7 / 6	6.1 / 6	5.8 / 6	5.9 / 6	6.1 / 6
ATLAS high mass CF Z rapidity 2011	4.6 / 6	5.5 / 6	4.7 / 6	4.8 / 6	4.5 / 6
ATLAS W- lepton rapidity 2011	17 / 11	8.4 / 11	8.7 / 11	9.1 / 11	10 / 11
ATLAS W+ lepton rapidity 2011	16 / 11	11 / 11	11 / 11	10 / 11	13 / 11
Correlated χ^2	118	50	31	40	50
Log penalty χ^2	-9.09	-3.32	-2.45	-3.66	-4.22
Total χ^2 / dof	247 / 61	127 / 61	95 / 61	104 / 61	134 / 61
χ^2 p-value	0.00	0.00	0.00	0.00	0.00

→ consider MMHT14, NNPDF3.1, CT18NNLO, ABMP16
→ best overall description of the data by NNPDF3.1, CT18NNLO

Spin correlations : “Old” vs “New” Resbos



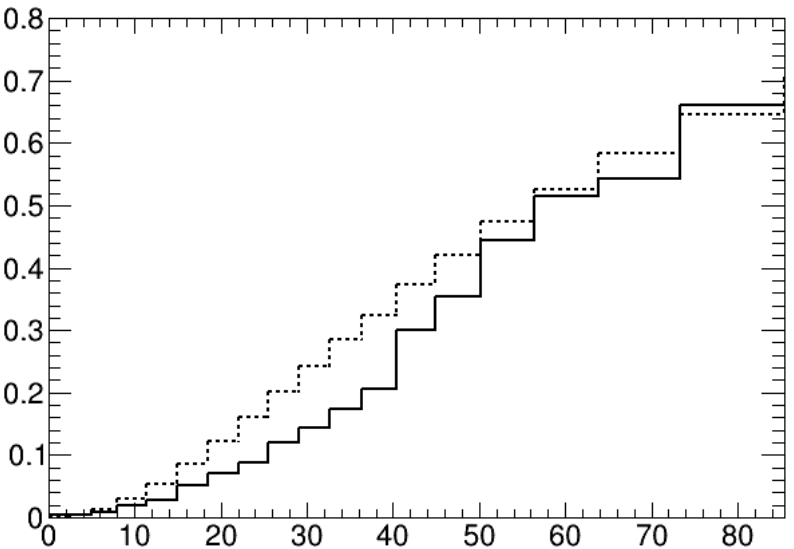
CDF, NLO



D0, NNLO

Spin correlations : “Old” vs “New” Resbos

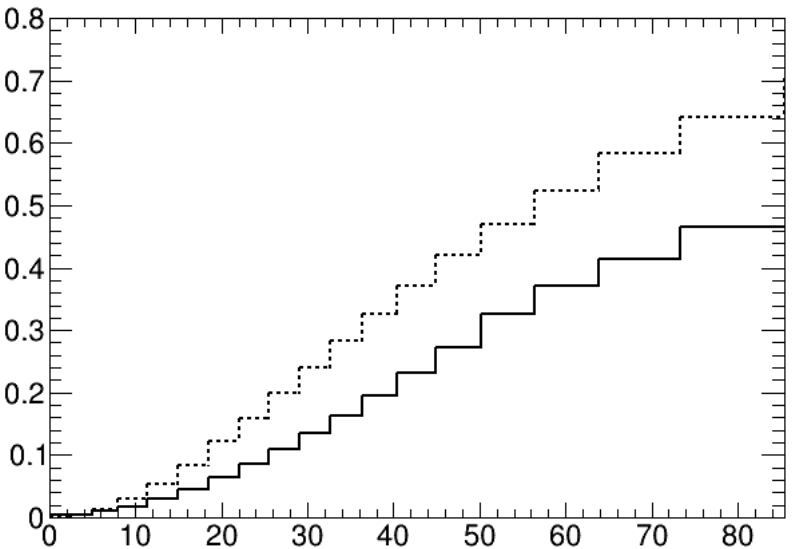
A2



pT

CDF, NLO

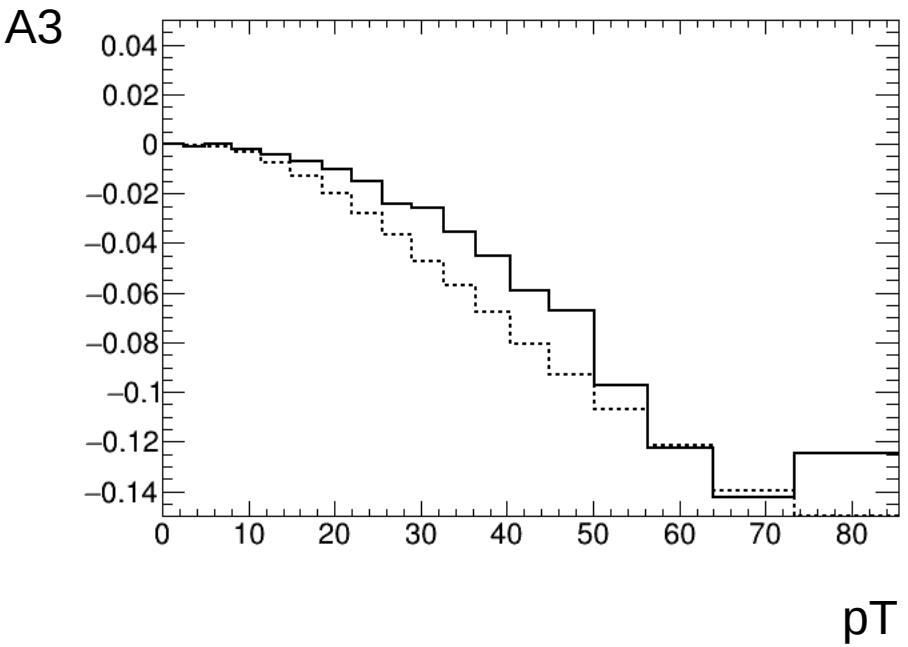
A2



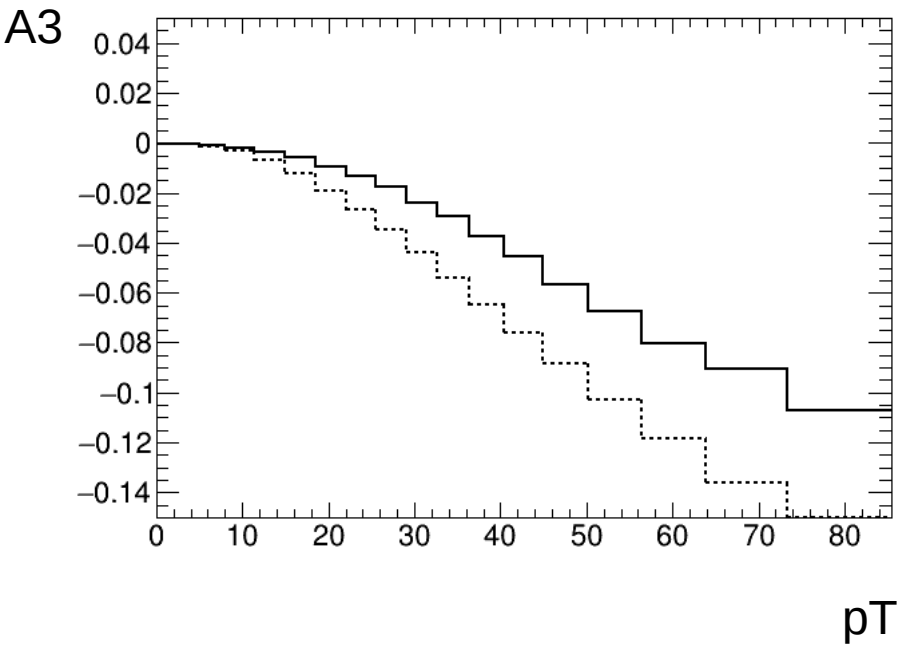
pT

D0, NNLO

Spin correlations : “Old” vs “New” Resbos



CDF



D0, NNLO