(Towards a quantitative study of)
Flavour effects on the determination of M_W

giuseppe bozzi

in collaboration with
A.Bacchetta, P.Mulders, M.Radici, M.Ritzmann, A.Signori

Istituto Nazionale di Fisica Nucleare

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The *W* mass

ATLAS, EPJC 78, 110 (2018)

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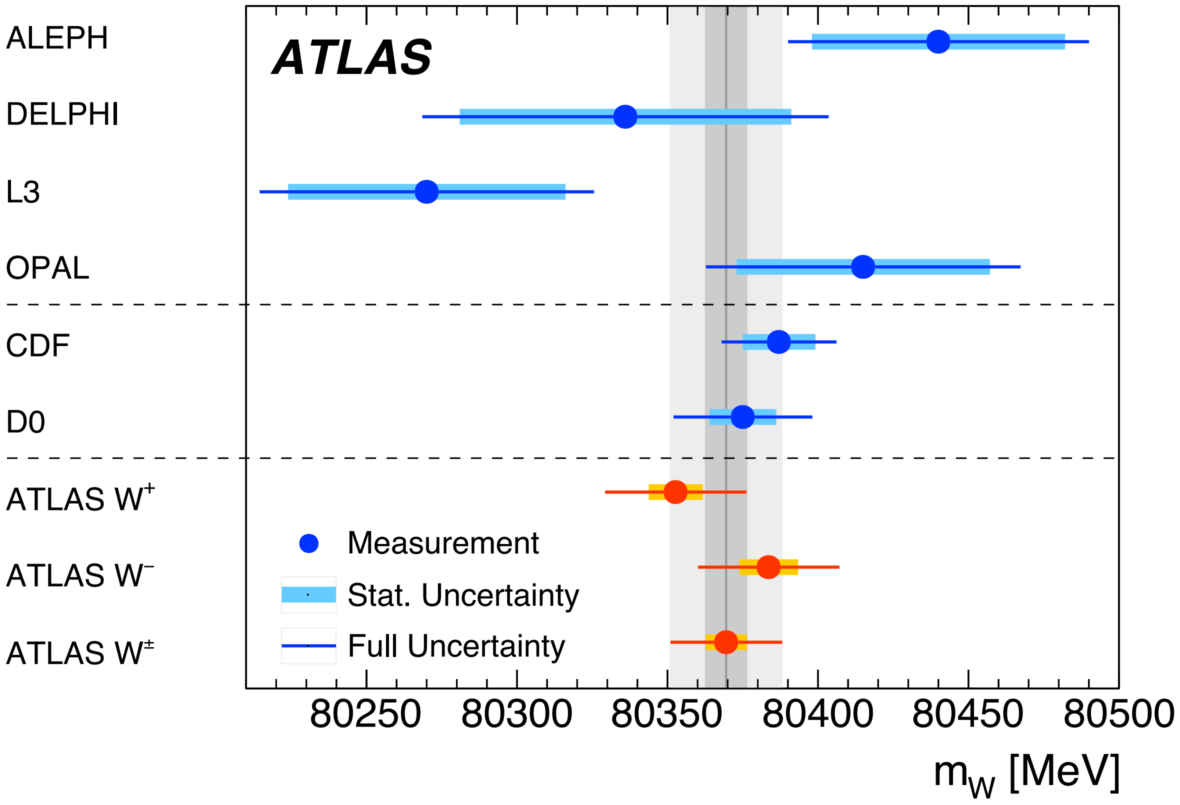

Experimental measurements

$$m_W = 80370 \pm 19 \text{ MeV}$$

(7 stat, 11 exp, 14 th)

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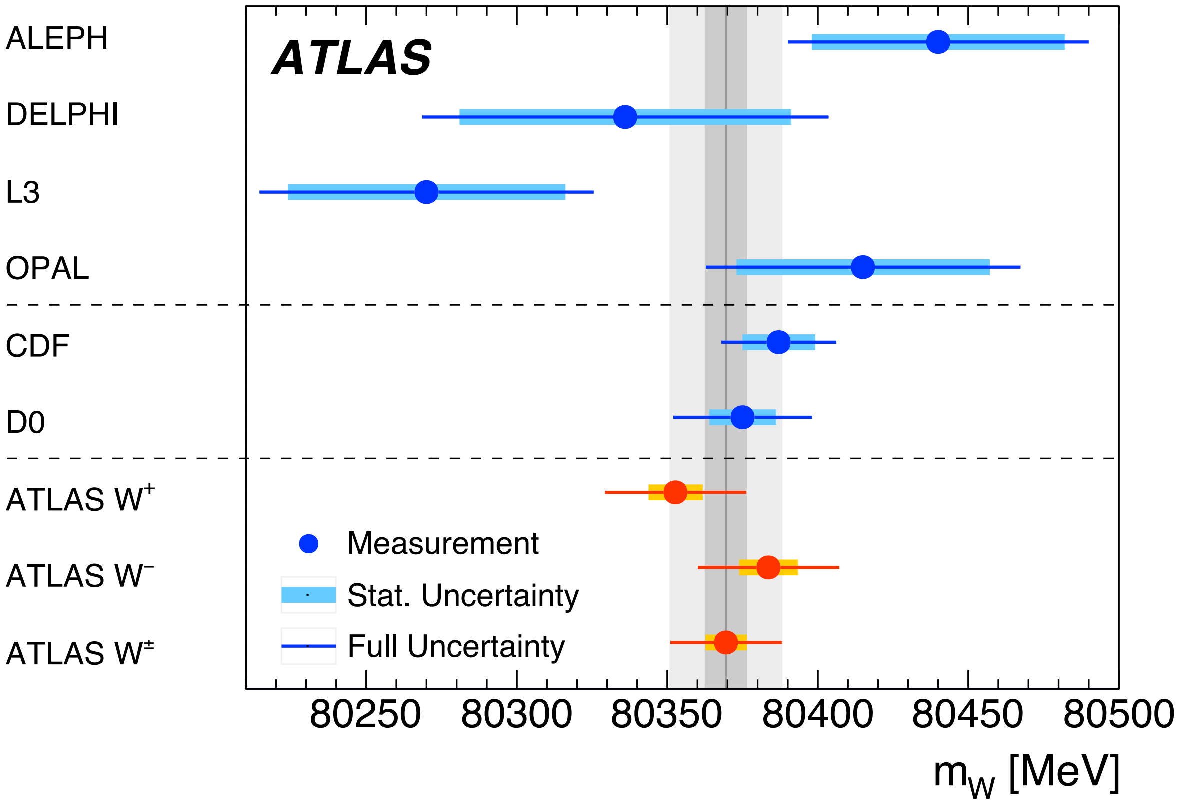

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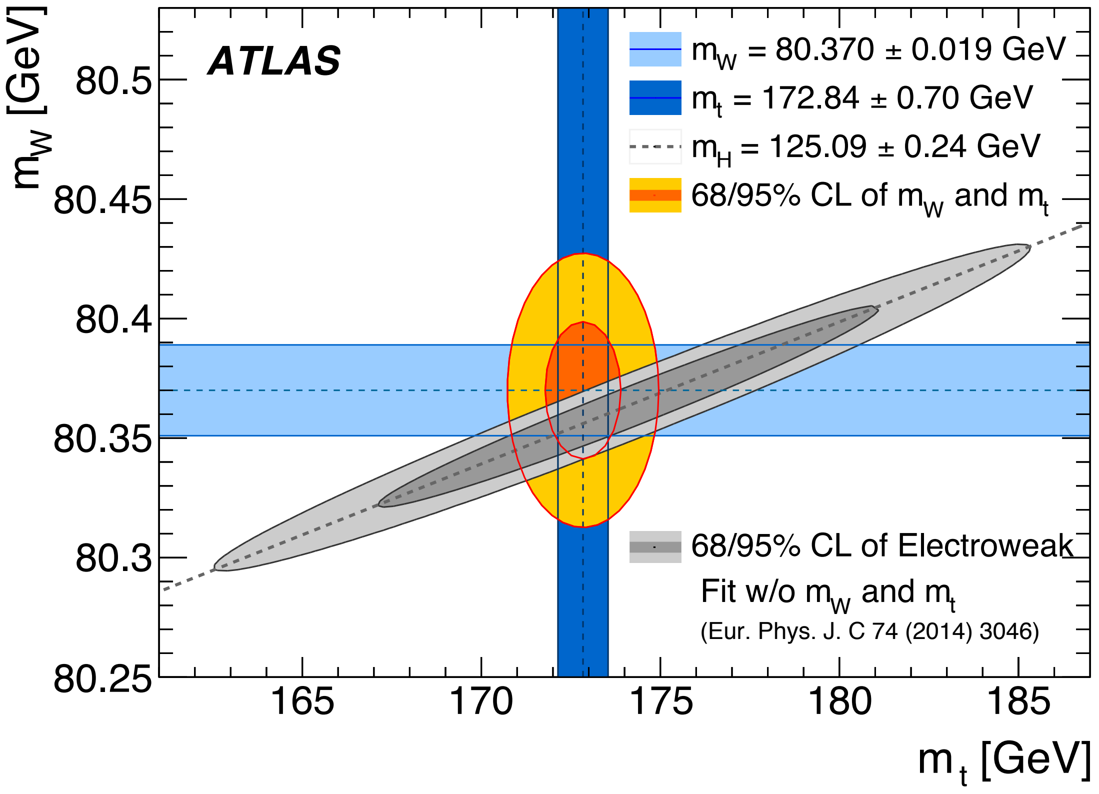

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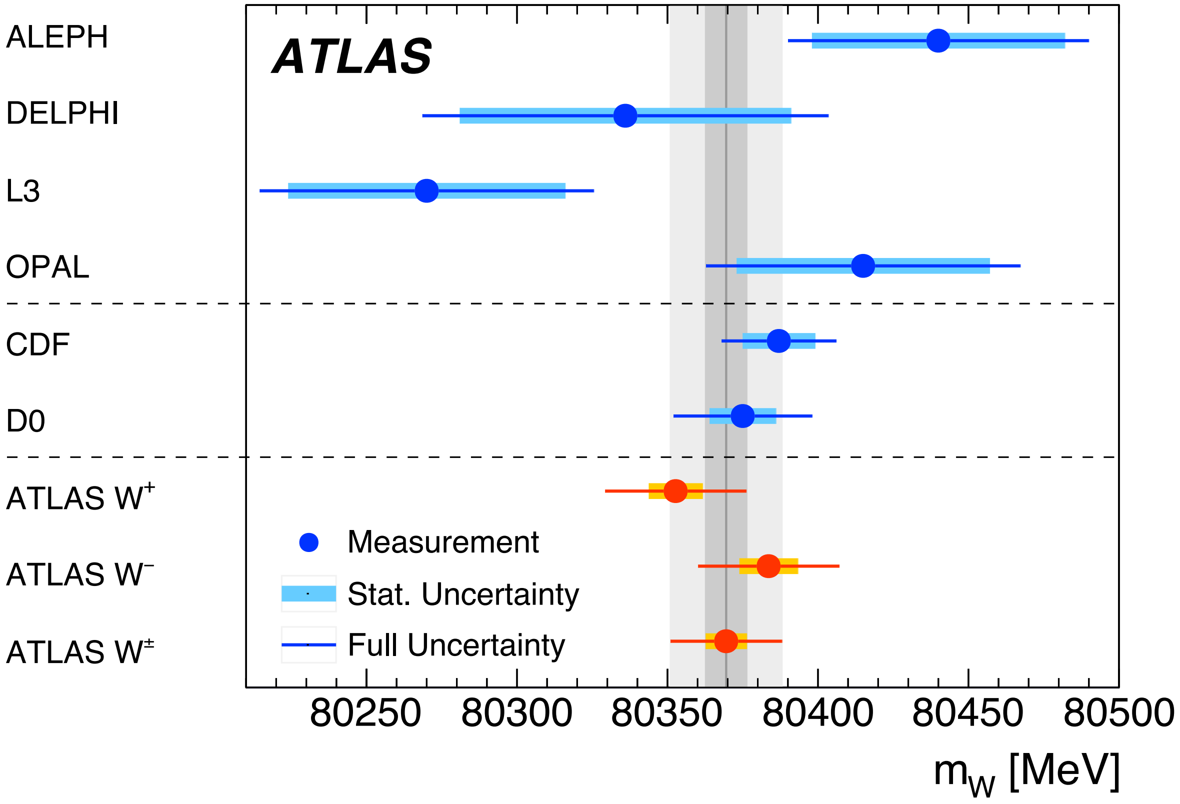

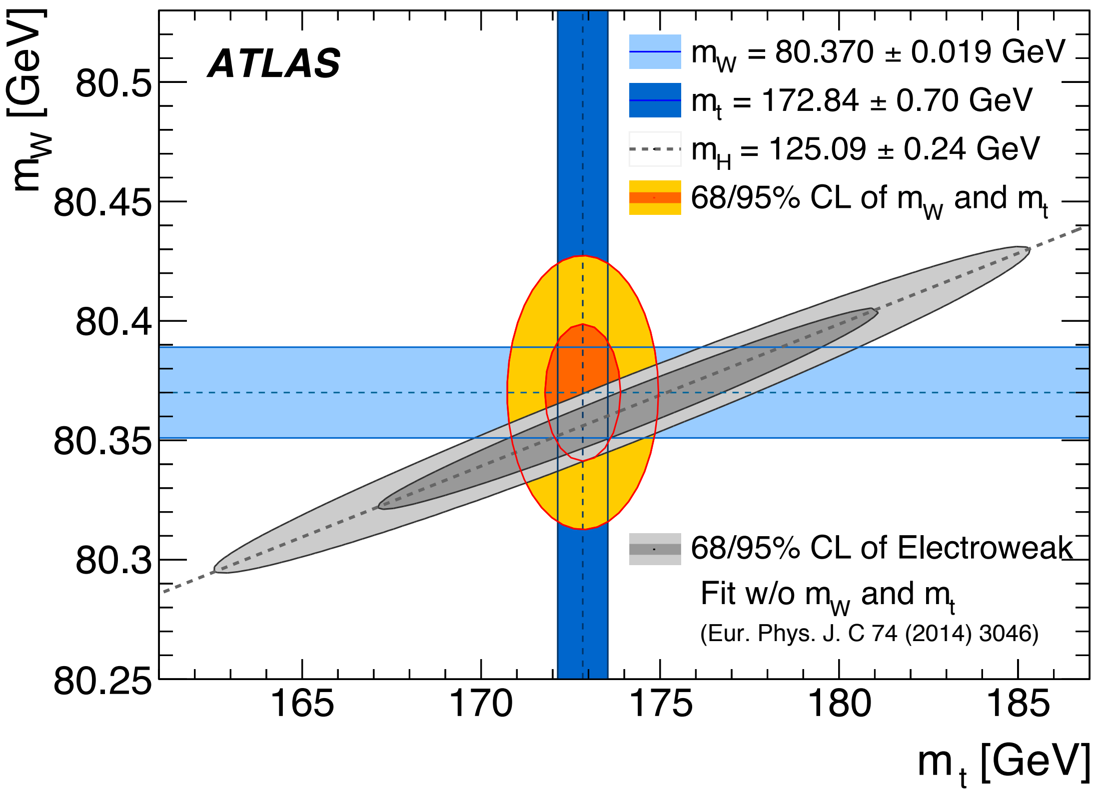

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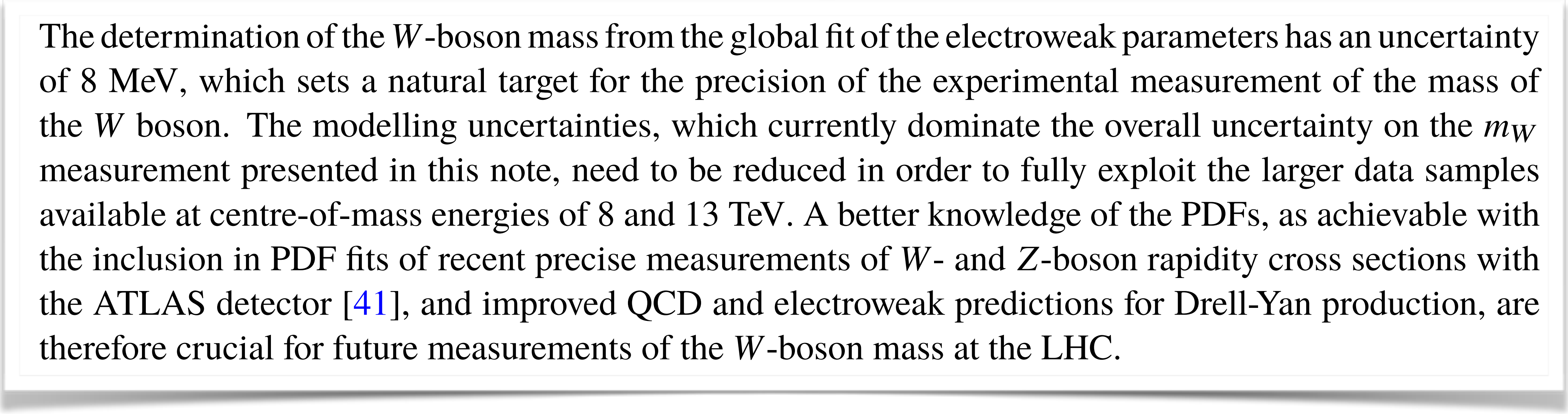
The determination of the W-boson mass from the global fit of the electroweak parameters has an uncertainty of 8 MeV, which sets a natural target for the precision of the experimental measurement of the mass of the W boson. The modelling uncertainties, which currently dominate the overall uncertainty on the m_W measurement presented in this note, need to be reduced in order to fully exploit the larger data samples available at centre-of-mass energies of 8 and 13 TeV. A better knowledge of the PDFs, as achievable with the inclusion in PDF fits of recent precise measurements of W- and Z-boson rapidity cross sections with the ATLAS detector [41], and improved QCD and electroweak predictions for Drell-Yan production, are therefore crucial for future measurements of the W-boson mass at the LHC.

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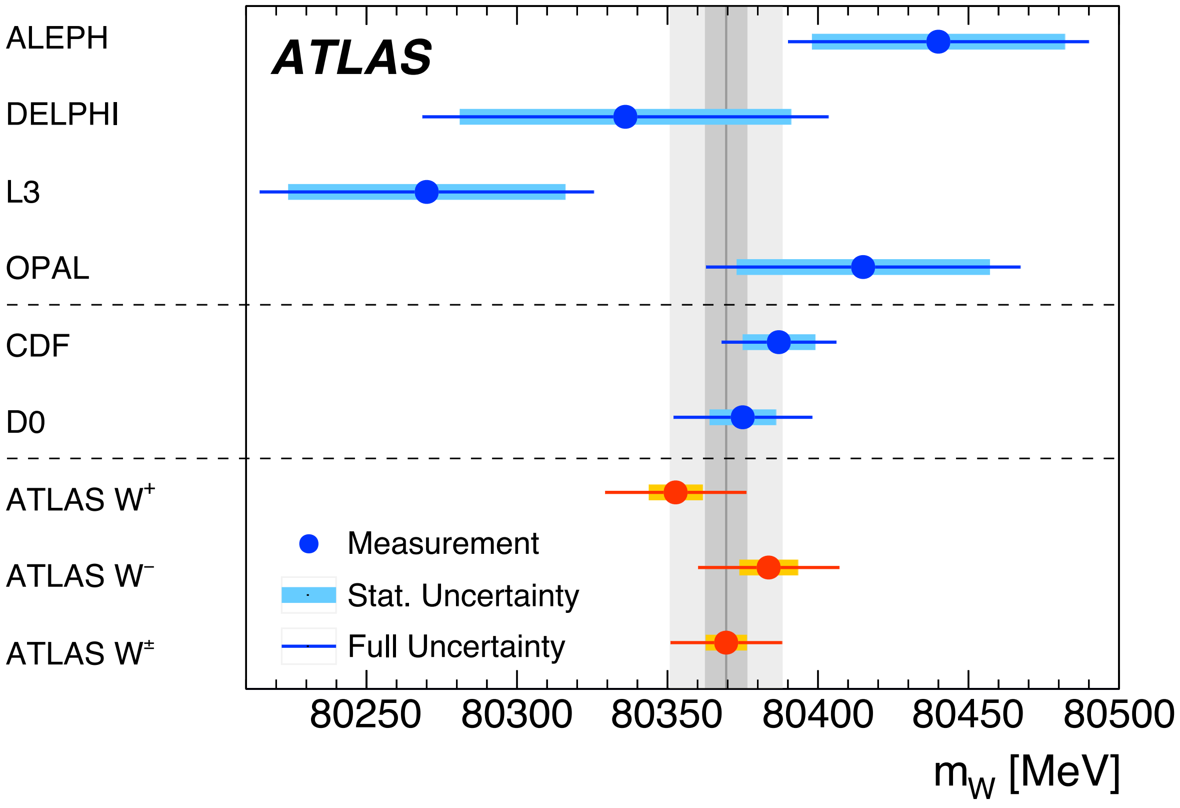

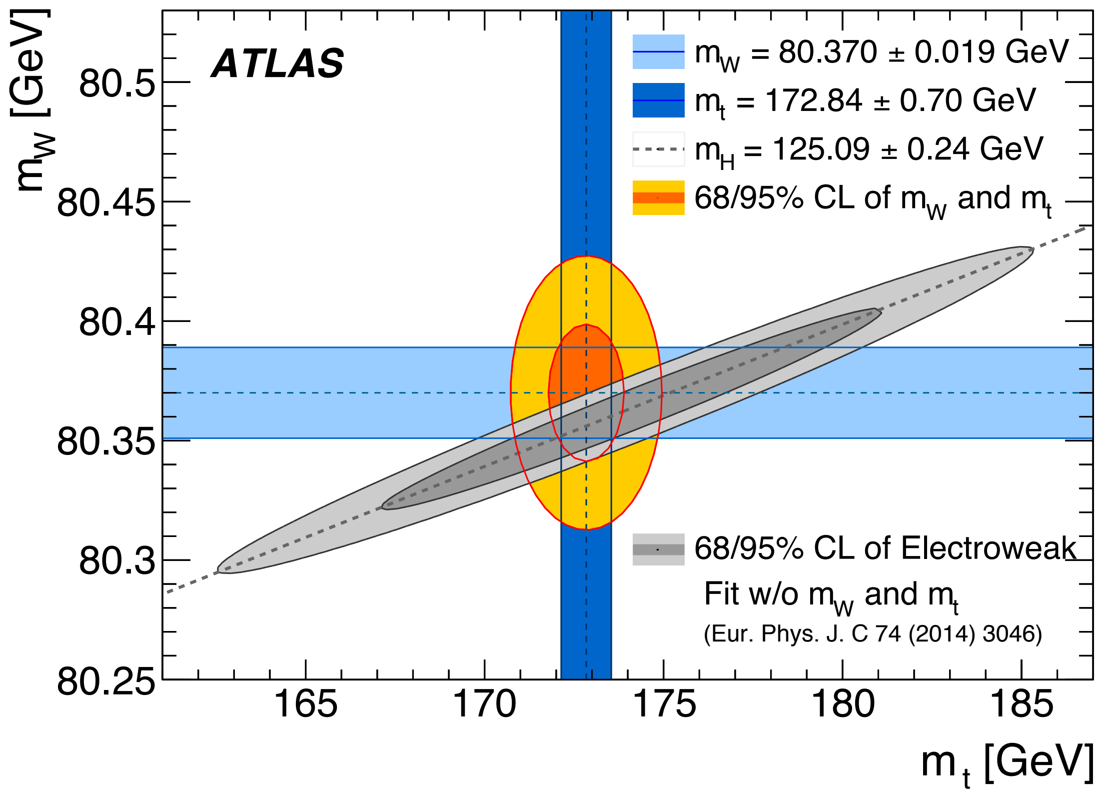

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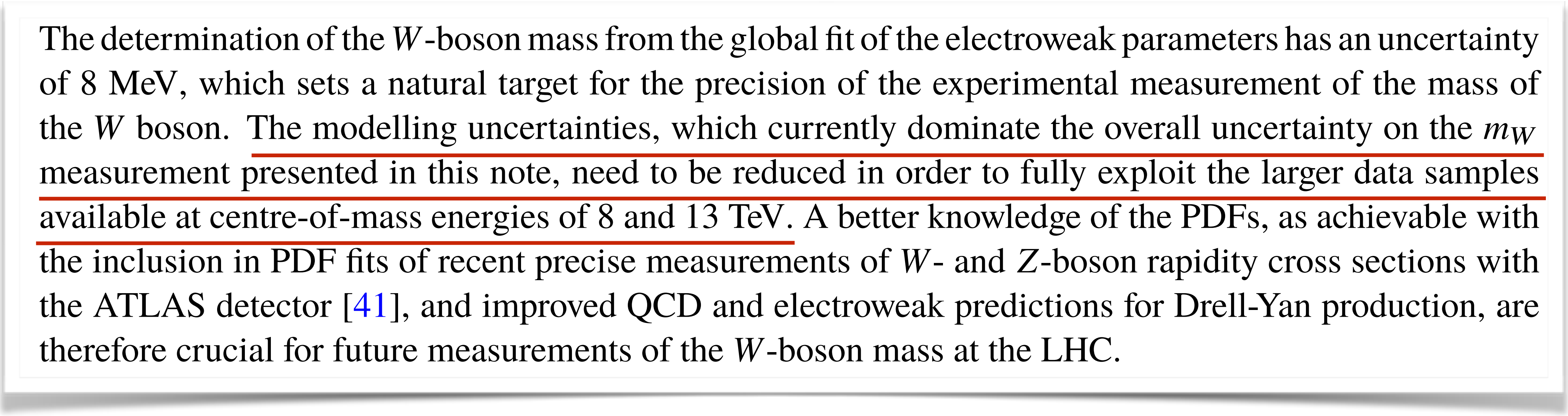
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Observables

- accessible via counting experiments: cross sections and asymmetries

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Pseudo-Observables

- functions of cross sections and symmetries
- require a model to be properly defined
  - M_Z at LEP as pole of the Breit-Wigner resonance factor
  - M_W at hadron colliders as fitting parameter of a *template fit* procedure

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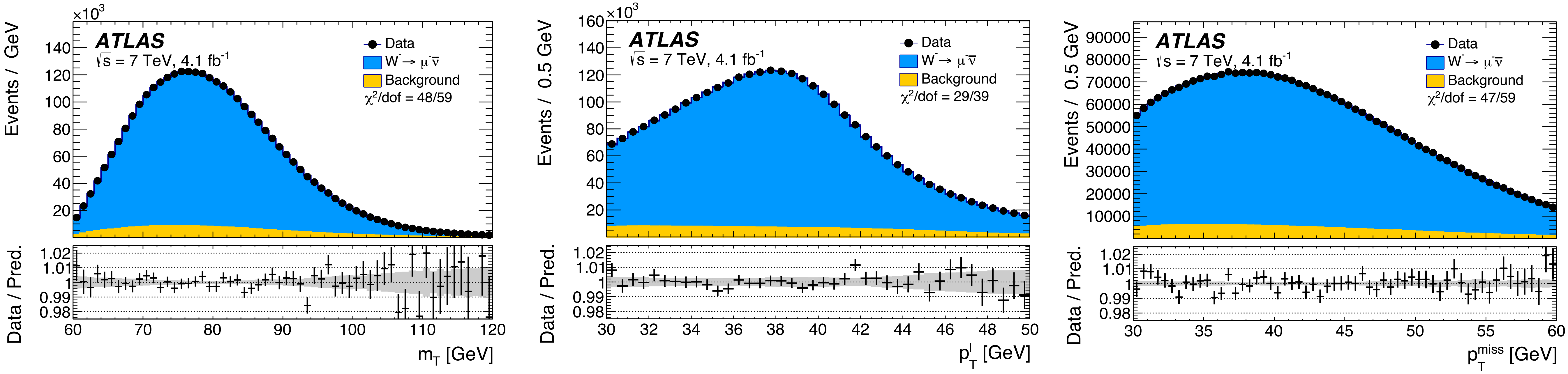
➡ the result of the fit depends on the hypotheses used to compute the templates (PDFs, scales, non-perturbative, different prescriptions, …)

➡ these hypotheses should be treated as theoretical systematic errors

Observables and techniques



M_W extracted from the study of the shape of m_T, p_{Tl}, p_{Tmiss}

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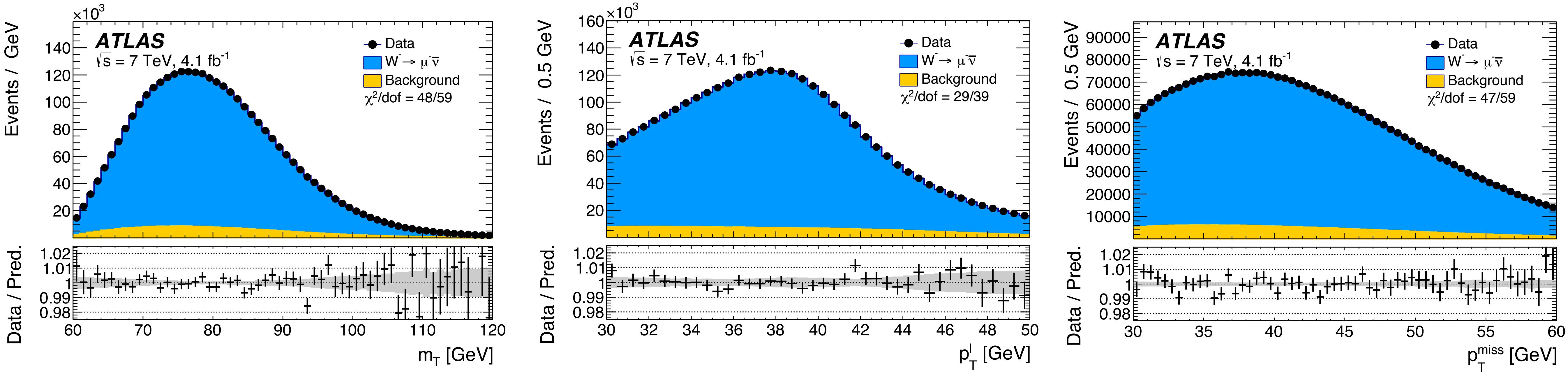

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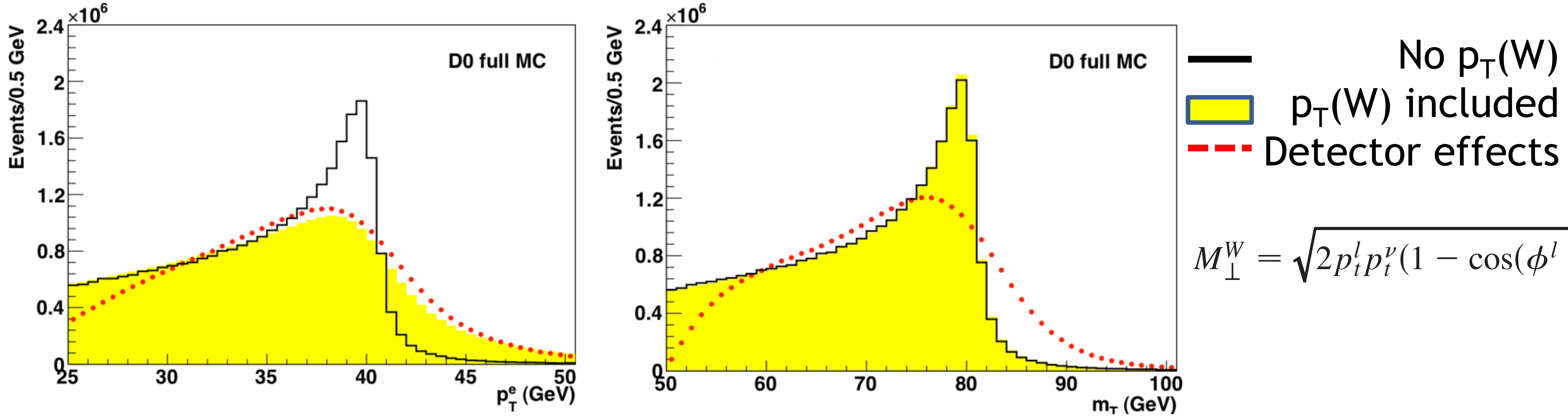
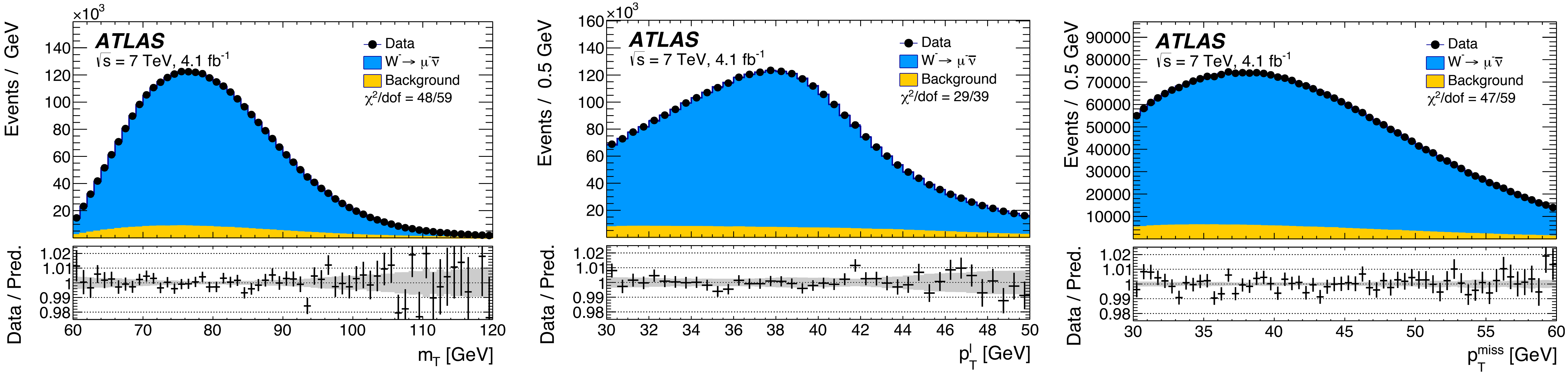


$$M_{\perp}^{W} = \sqrt{2p_t^l p_t^\nu (1 - \cos(\phi^l - \phi^\nu))},$$

Transverse mass: important detector smearing effects, weakly sensitive to p_{TW} modelling

Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

Observables and techniques



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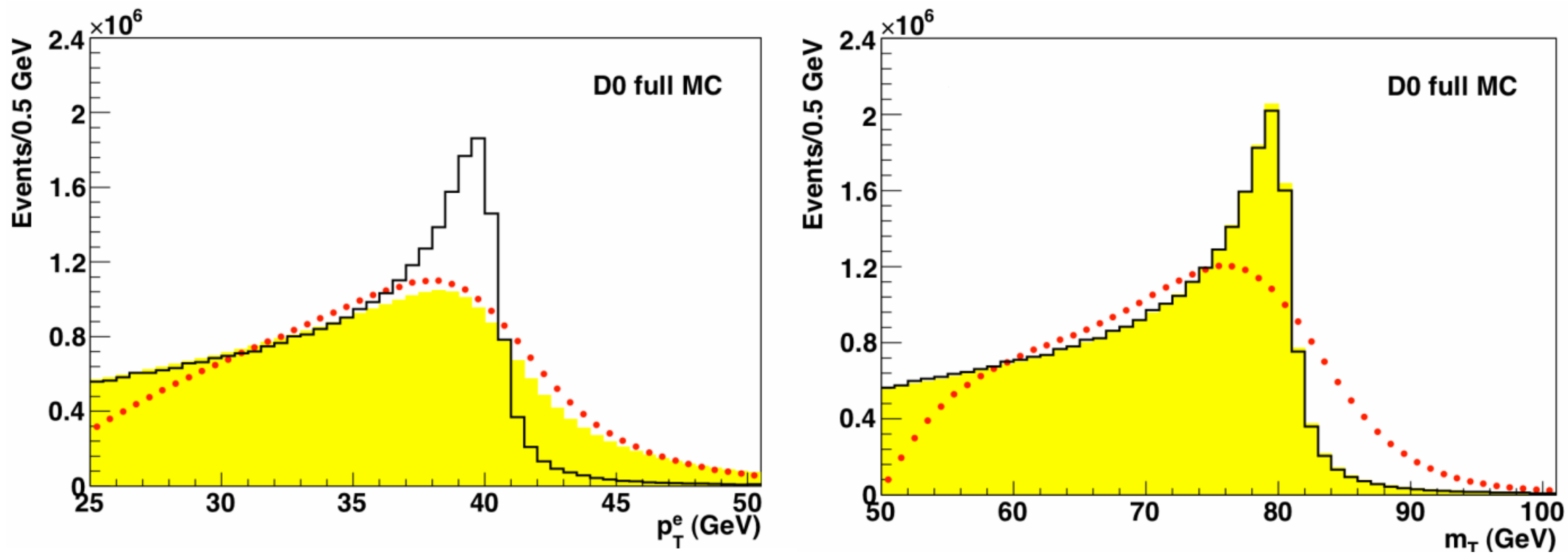

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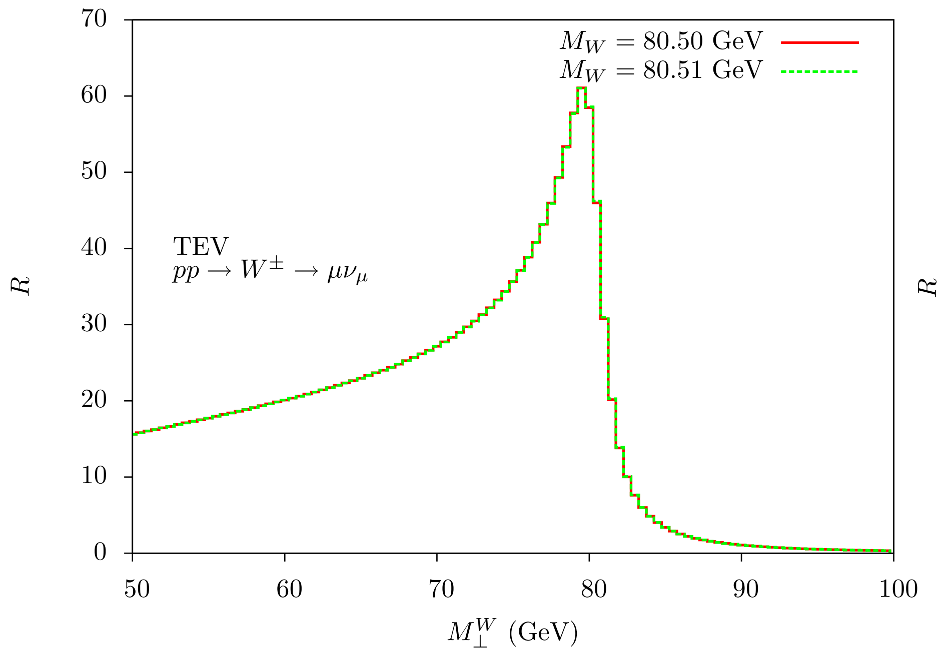
Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

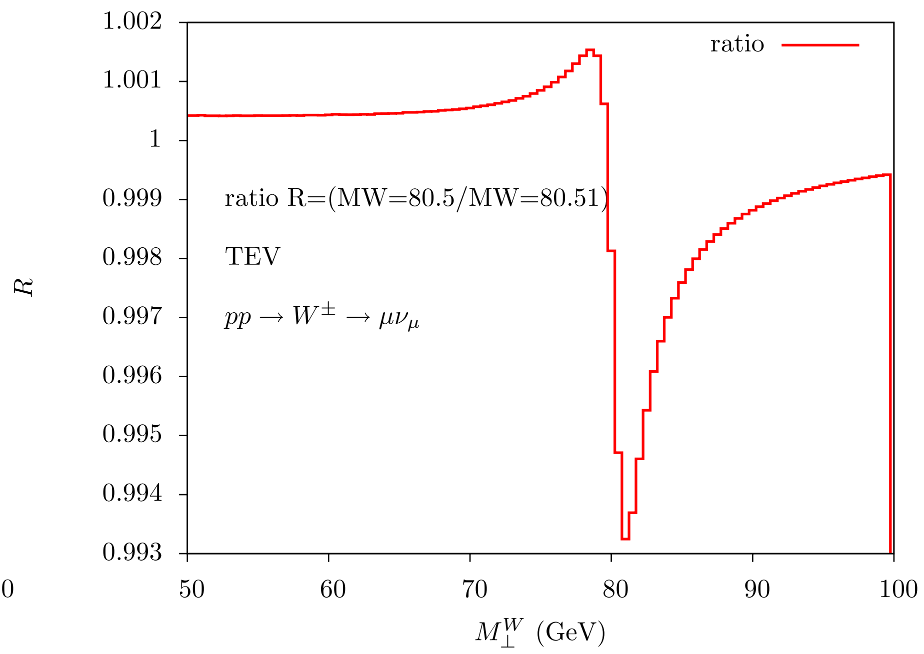
p_{TW} modelling depends on flavour and all-order treatment of QCD corrections

Observables and techniques

Challenging shape measurement: a distortion at the few per mille level of the distributions yields a shift of O(10 MeV) of the M_W value

m_T





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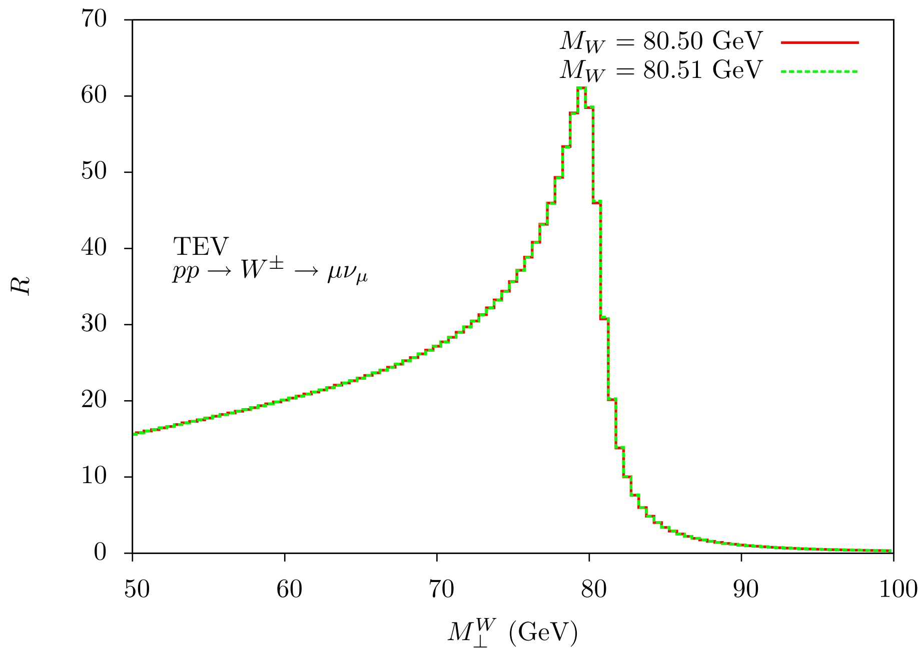
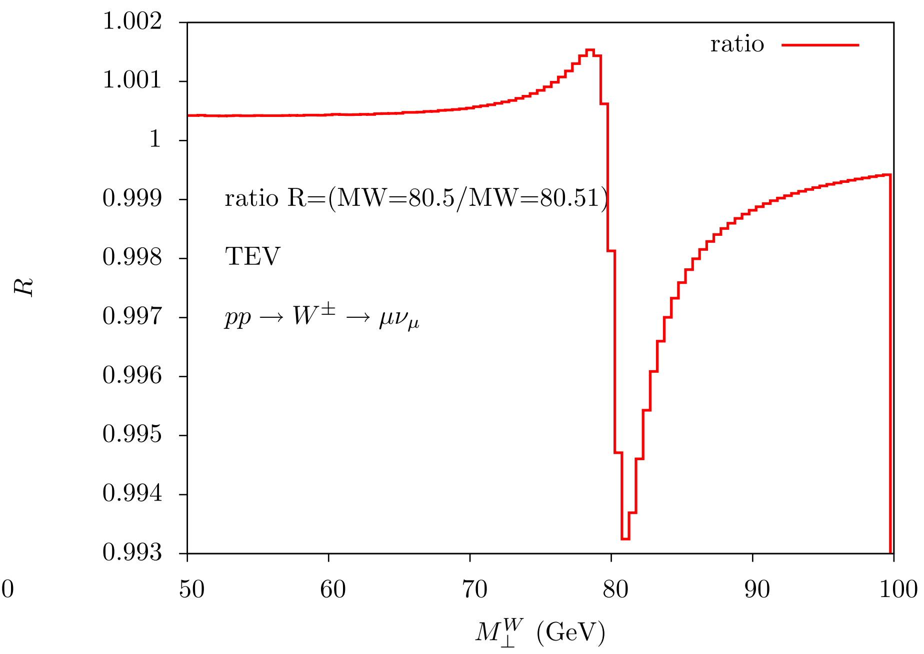
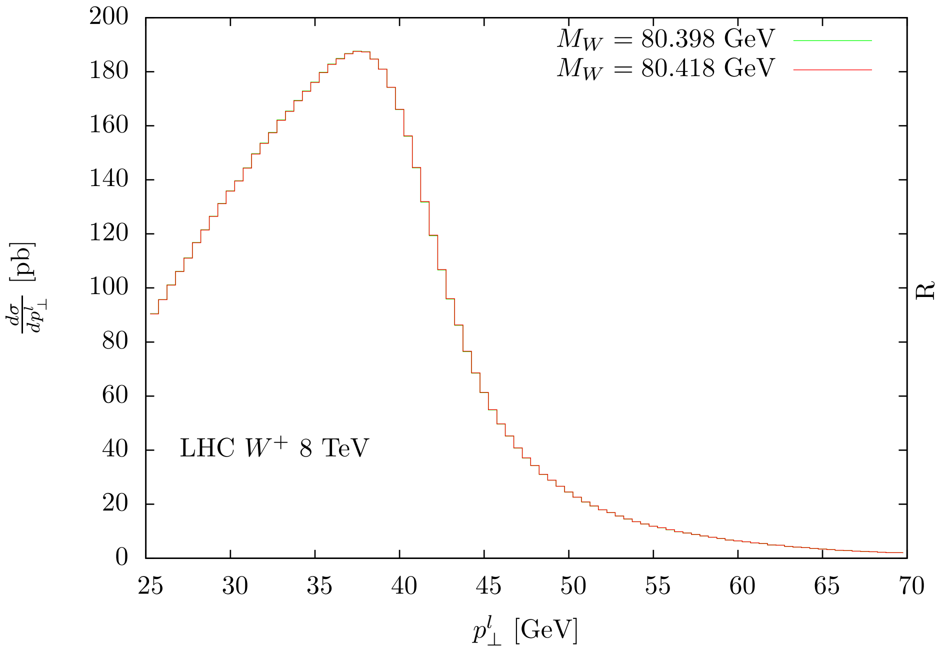
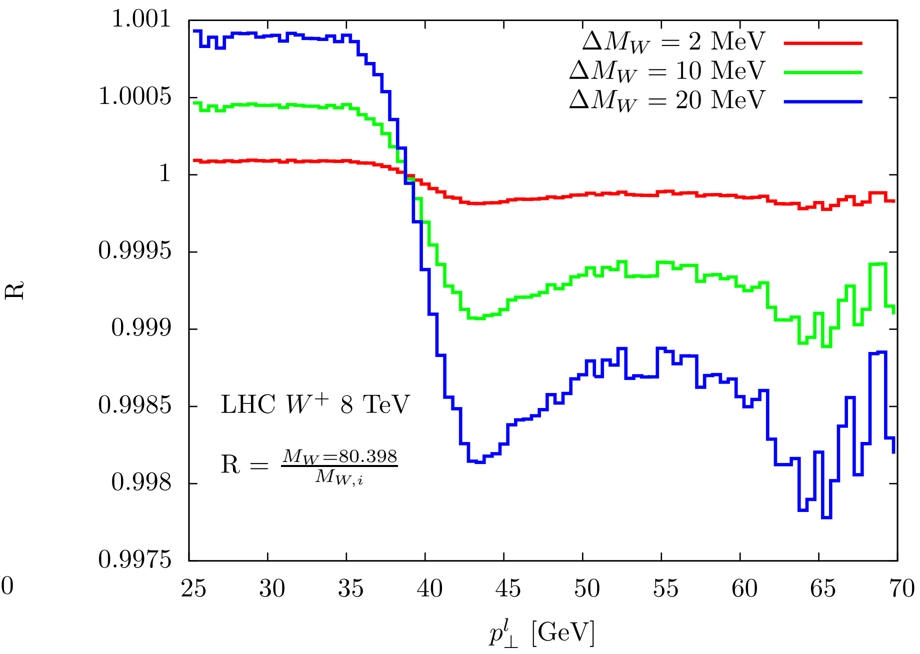




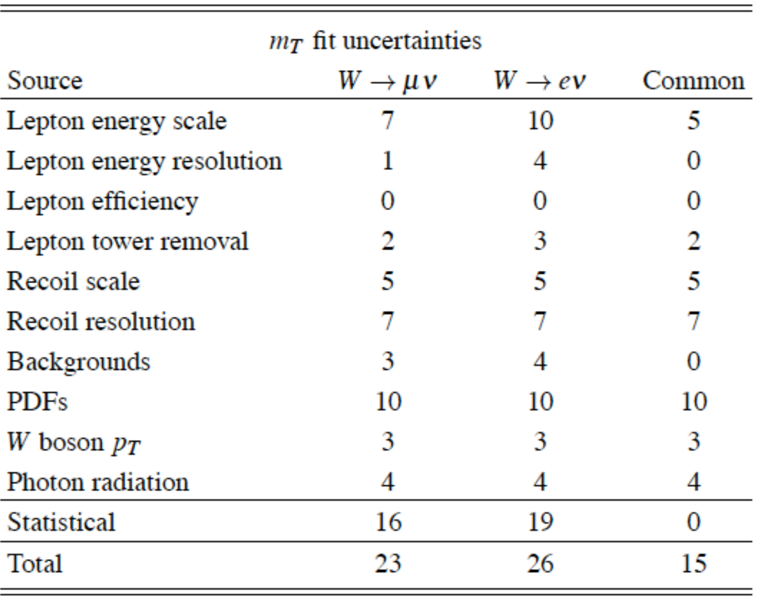
p_{Tl}



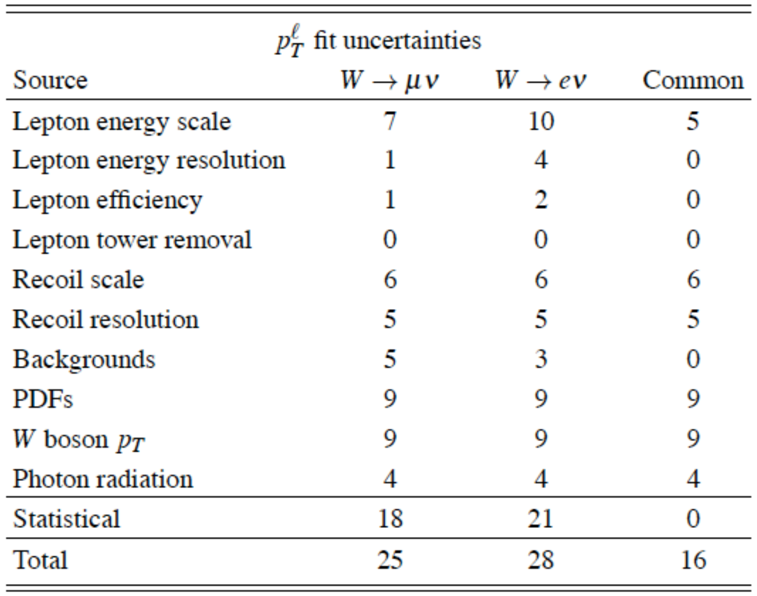


Breakdown of uncertainties

CDF

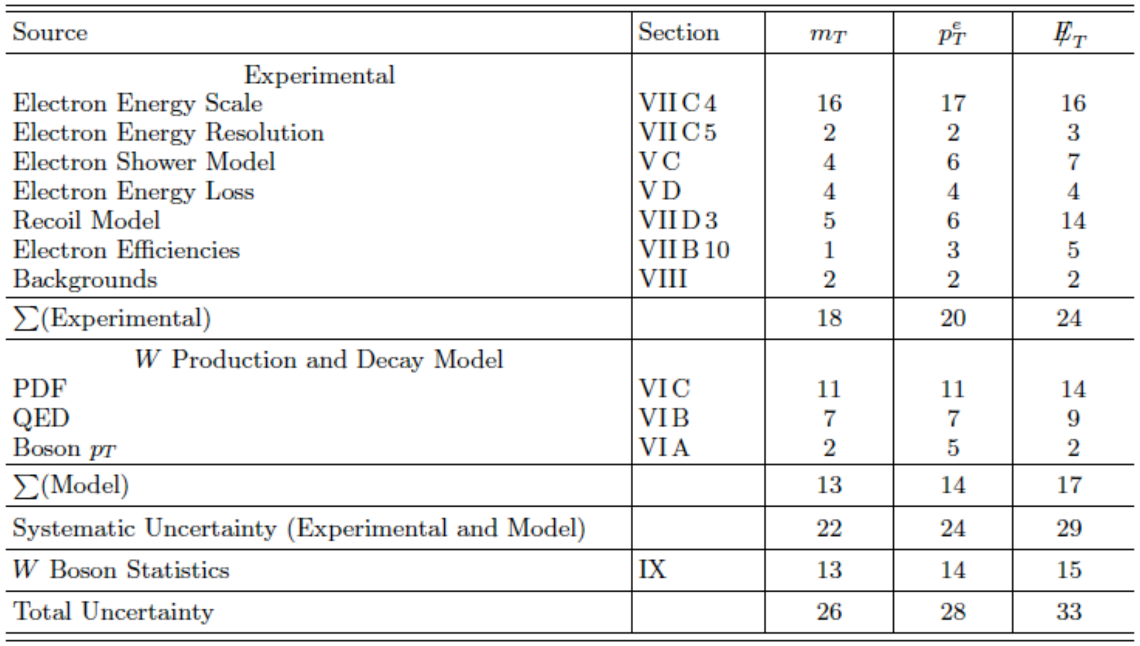


m_T fit uncertainties			
Source	$W\to\mu\nu$	$W\to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15



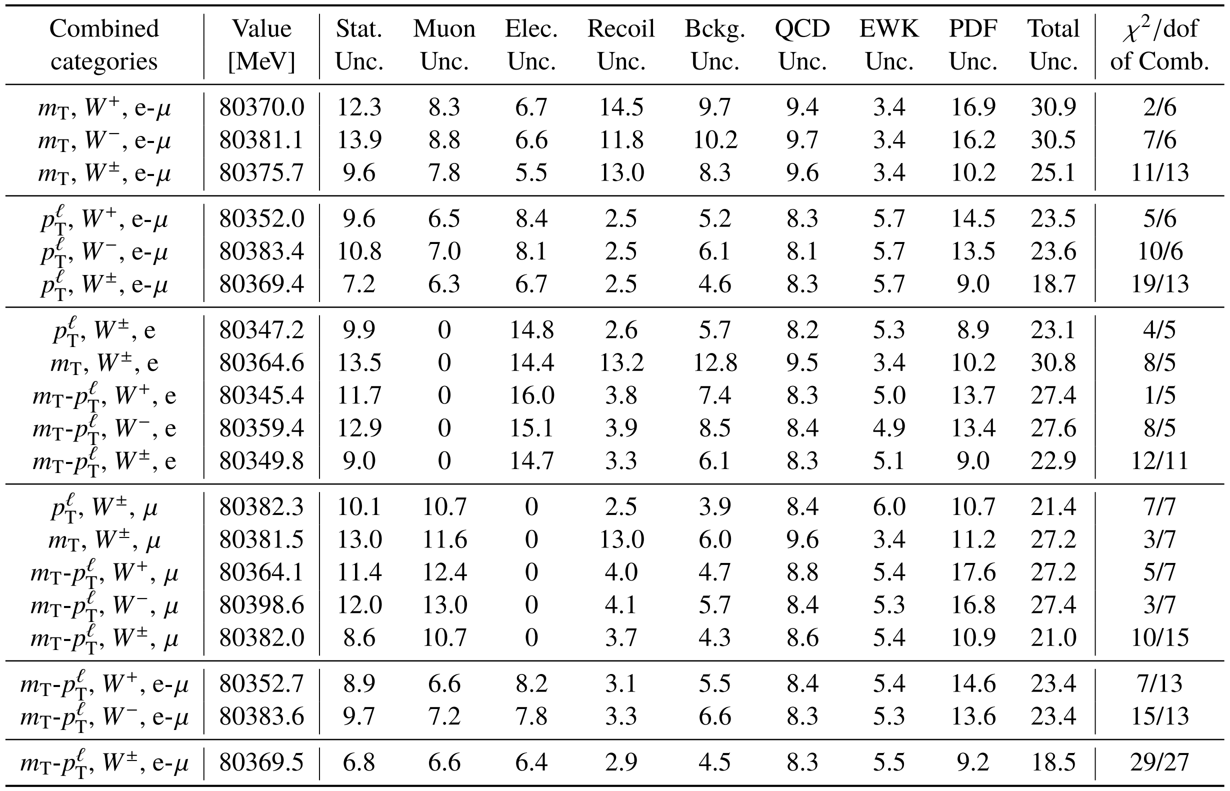
p_T^ℓ fit uncertainties			
Source	$W\to\mu\nu$	$W\to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

D0



Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

ATLAS



Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T-p_T^ℓ, $W^\pm$, e	80349.8	9.0	0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
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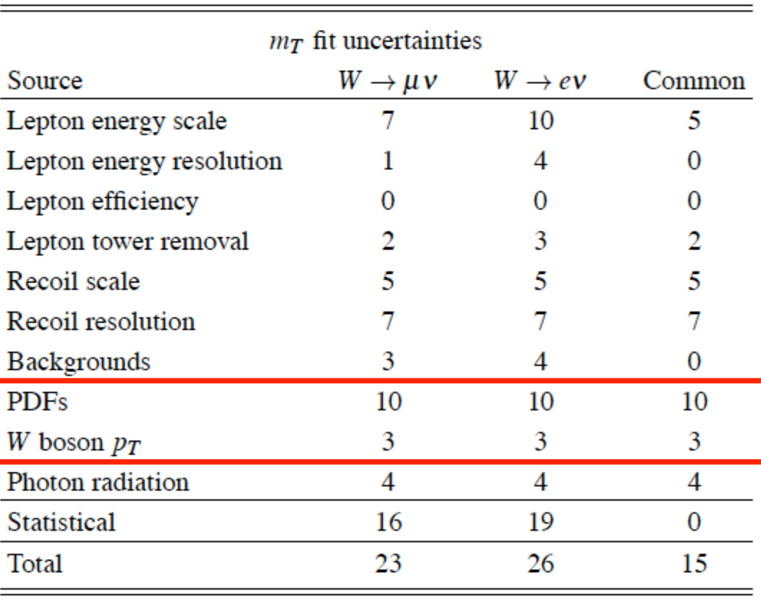

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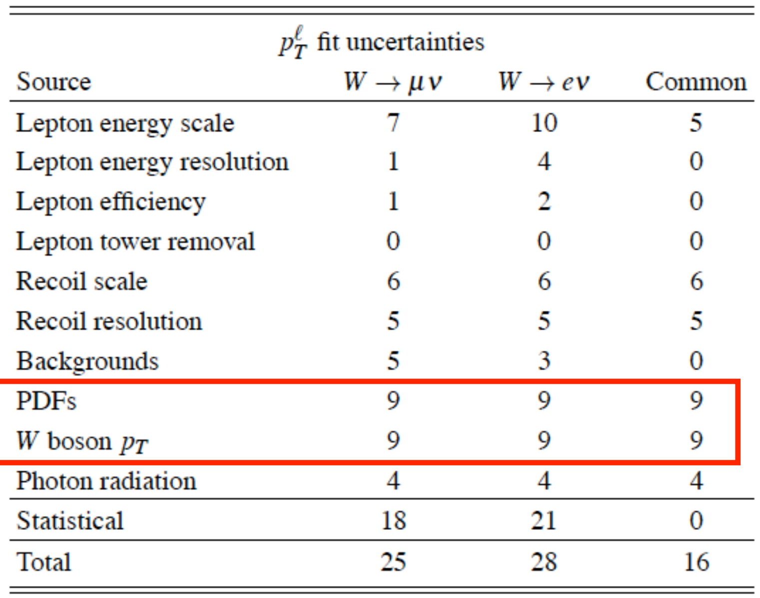

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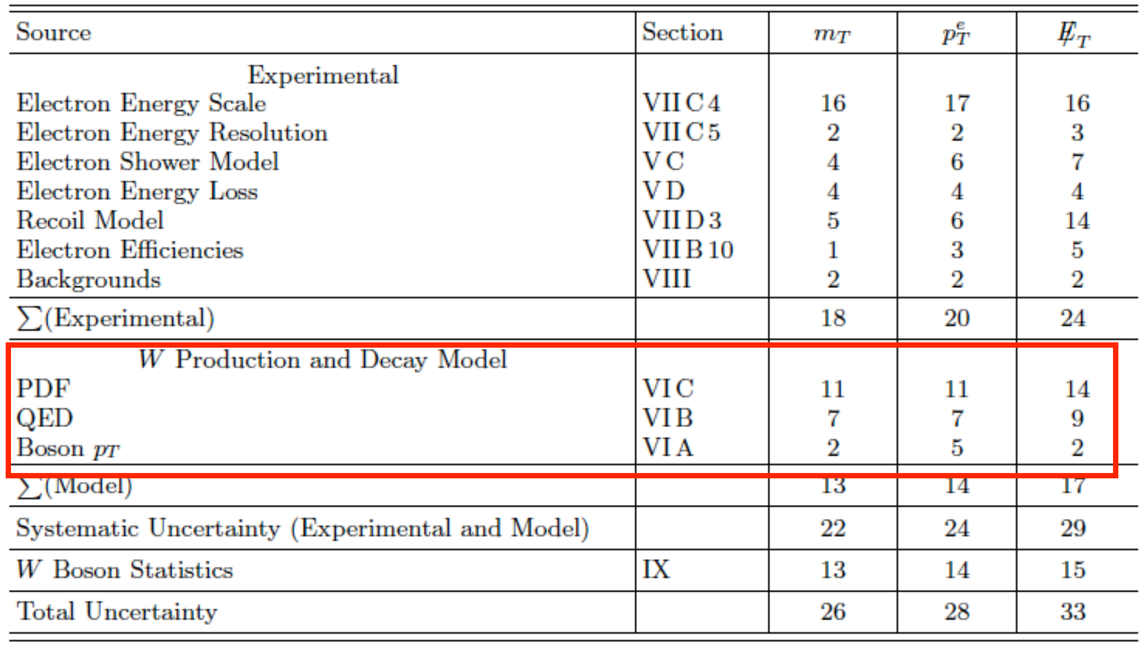

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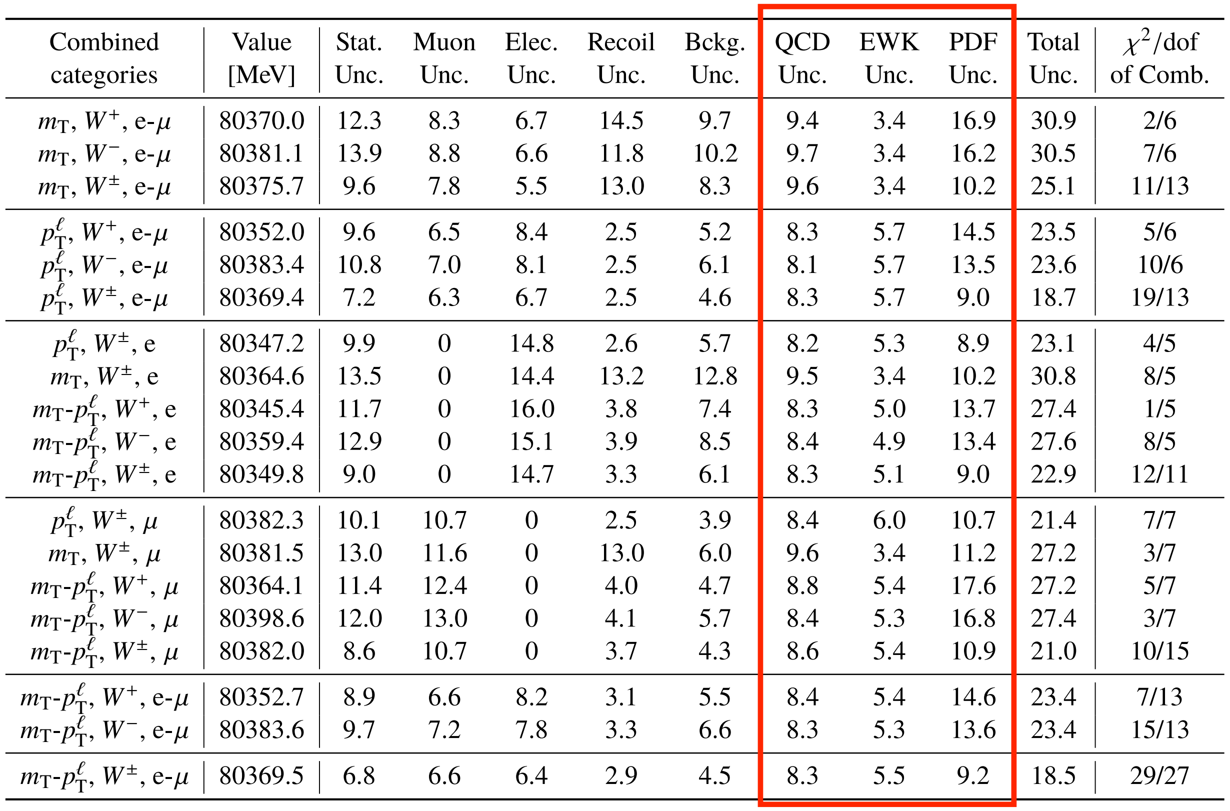

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p_T^ℓ, $W^\pm$, μ	80382.3	10.1	10.7	0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, $W^\pm$, μ	80381.5	13.0	11.6	0	13.0	6.0	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, W^+, μ	80364.1	11.4	12.4	0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T-p_T^ℓ, W^-, μ	80398.6	12.0	13.0	0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T-p_T^ℓ, $W^\pm$, μ	80382.0	8.6	10.7	0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
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

Shift induced by PDFs: general fitting strategy

Bozzi, Rojo, Vicini PRD 83, 113008 (2011)

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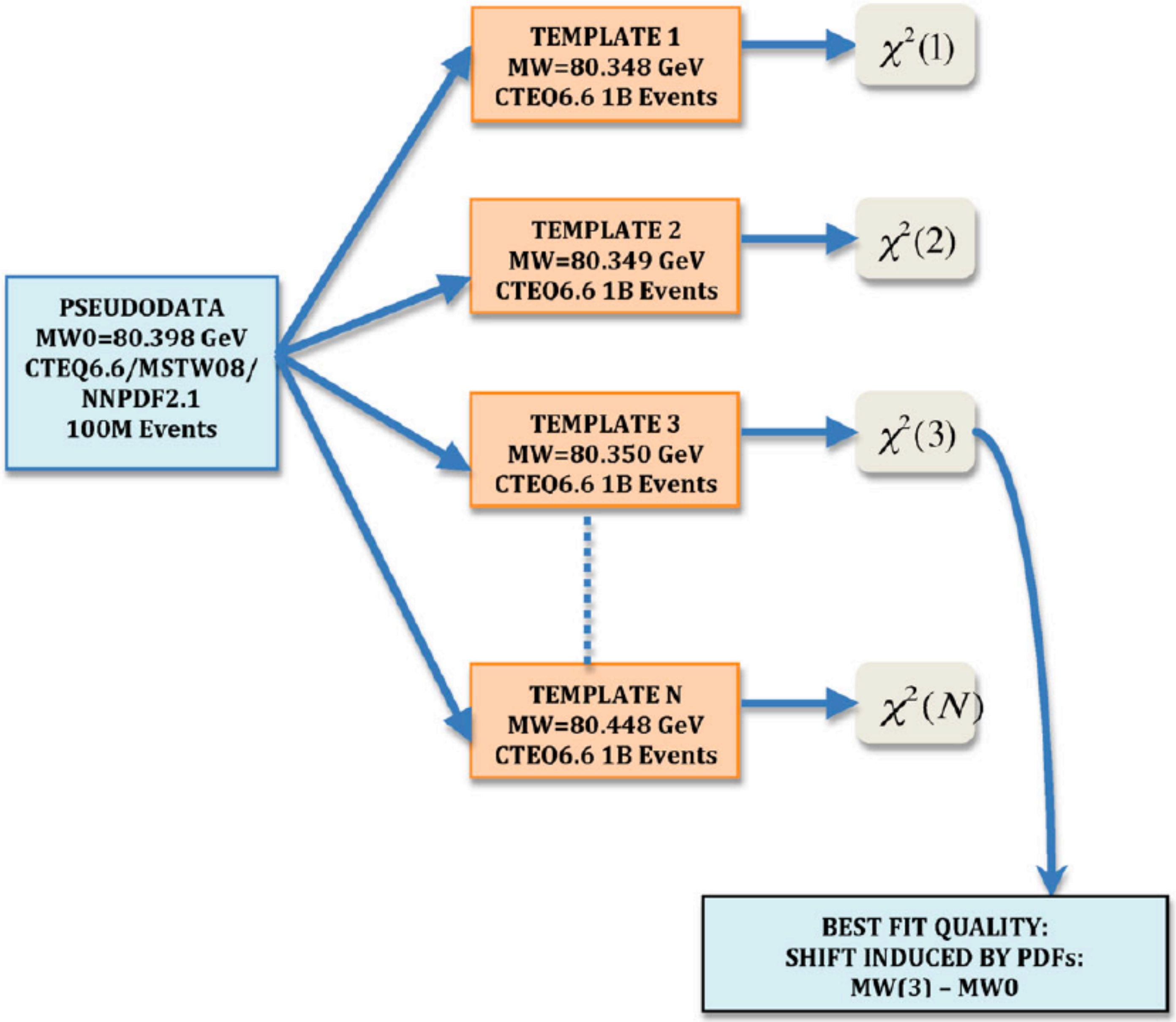

PSEUDODATA
MW0=80.398 GeV
CTEQ6.6/MSTW08/
NNPDF2.1
100M Events

TEMPLATE 1
MW=80.348 GeV
CTEQ6.6 1B Events

$\chi^2(1)$

TEMPLATE 2
MW=80.349 GeV
CTEQ6.6 1B Events

$\chi^2(2)$

TEMPLATE 3
MW=80.350 GeV
CTEQ6.6 1B Events

$\chi^2(3)$

TEMPLATE N
MW=80.448 GeV
CTEQ6.6 1B Events

$\chi^2(N)$

BEST FIT QUALITY:
SHIFT INDUCED BY PDFs:
MW[3] – MW0

Shift induced by PDFs: general fitting strategy

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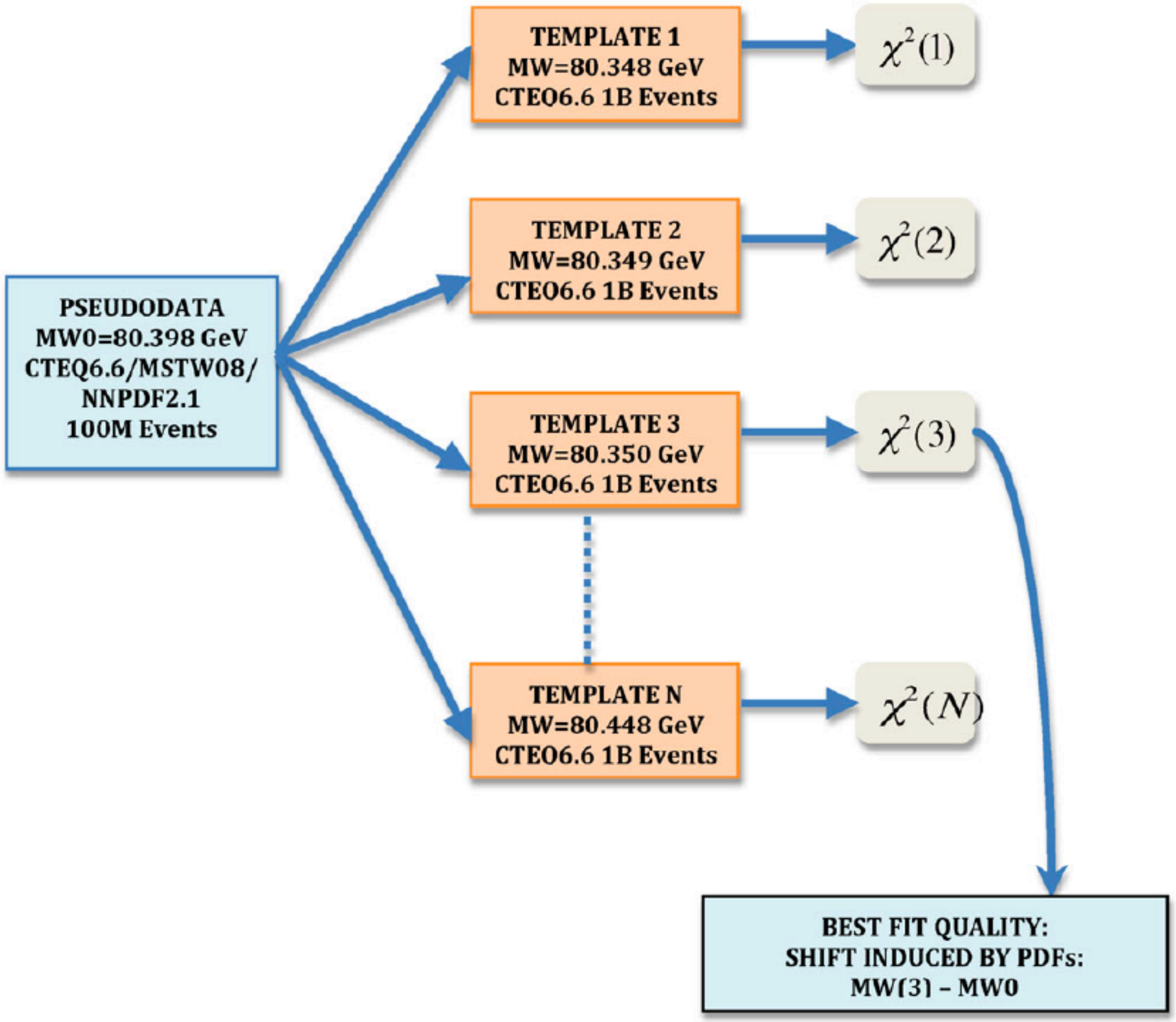

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- PDF error = combination of different M_W results from each replica, according to the formulae recommended by the PDF collaborations

Hessian: CTEQ, MSTW

$$\sigma_X^2 = \frac{1}{4}\sum_{k=1}^{N}[X(S_k^+) - X(S_k^-)]^2$$

Montecarlo: NNPDF

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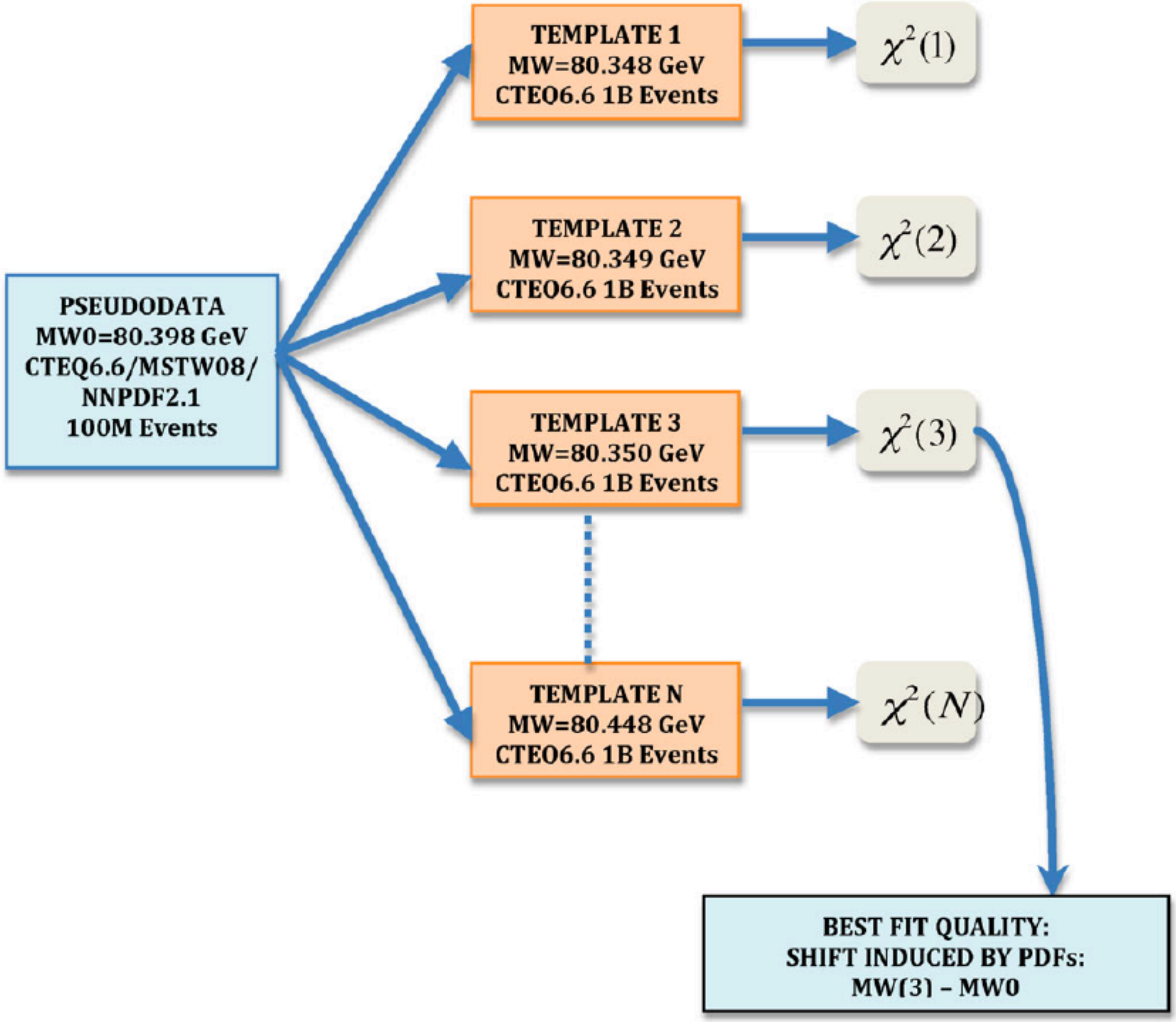

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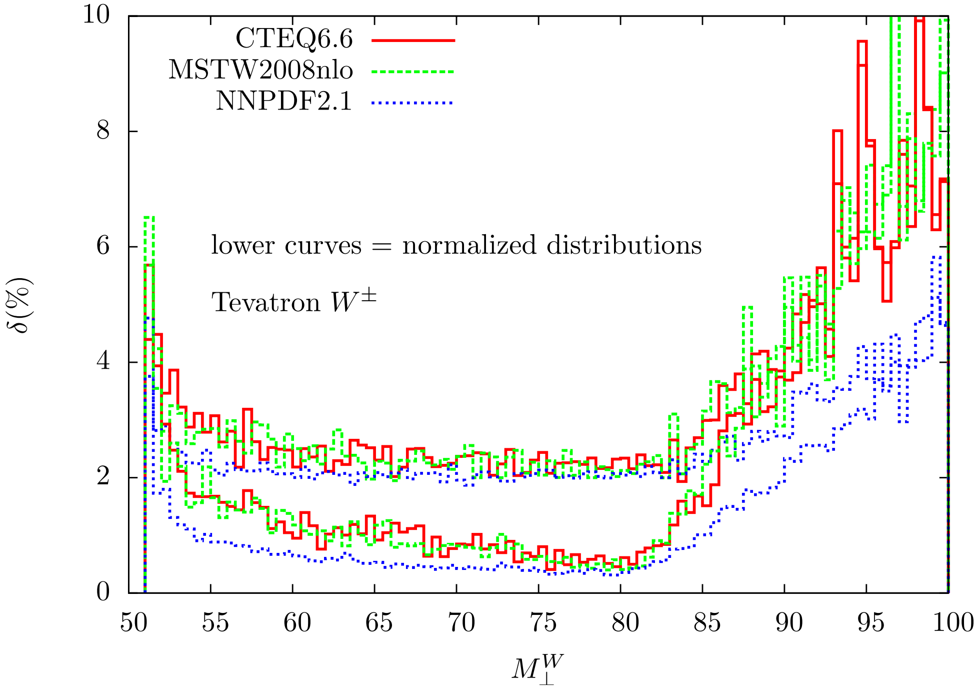
- M_W shift = distance between the PDF set under study and the reference set

Effects on transverse mass



Bozzi, Rojo, Vicini PRD 83, 113008 (2011)

- Normalised distributions: reduced sensitivity to PDFs
- Ratio of (non-)normalised distributions w.r.t. to central PDF set
- Distributions obtained with **DYNNLO**

in first approximation the PDF effects factorise w.r.t. all other theoretical and experimental factors

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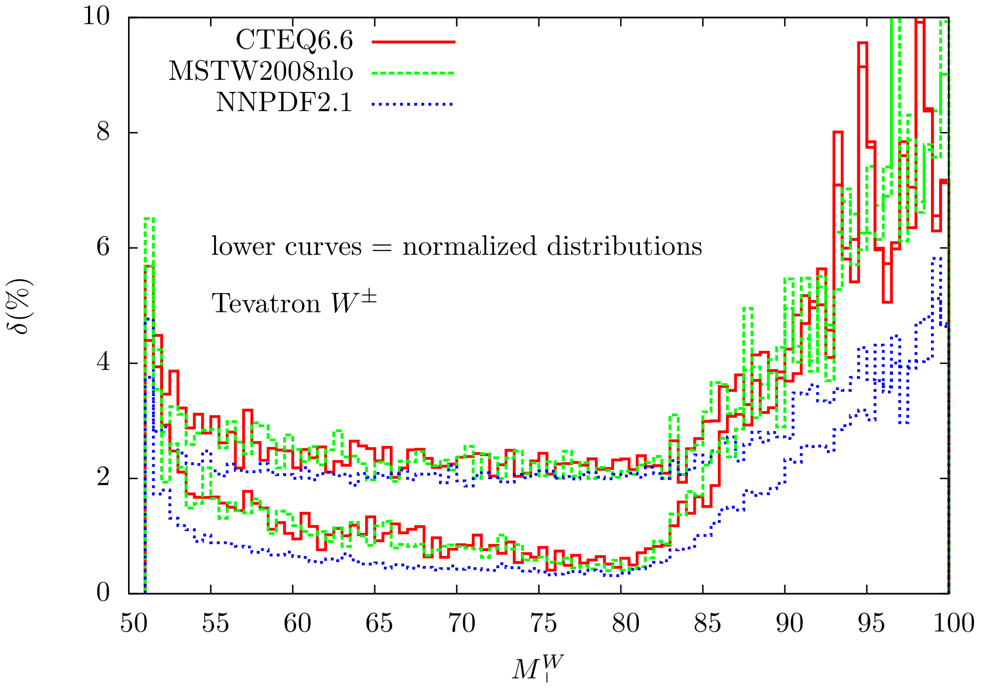

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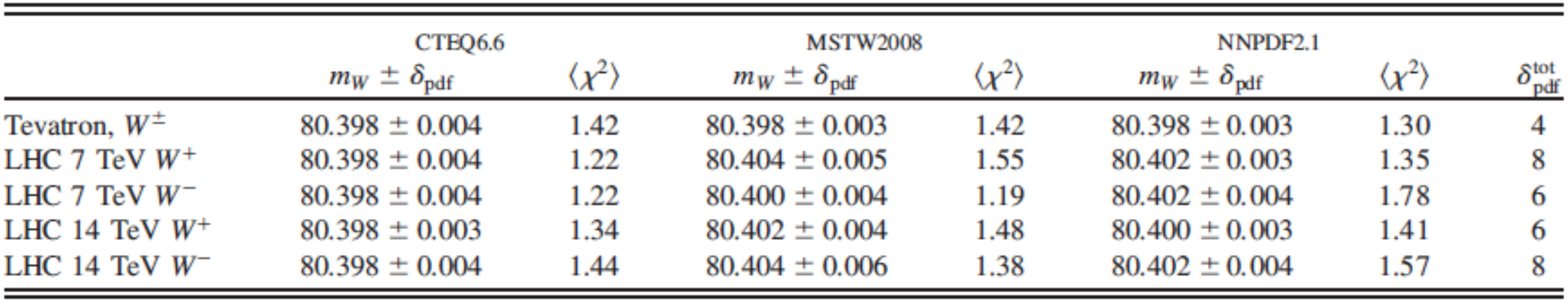
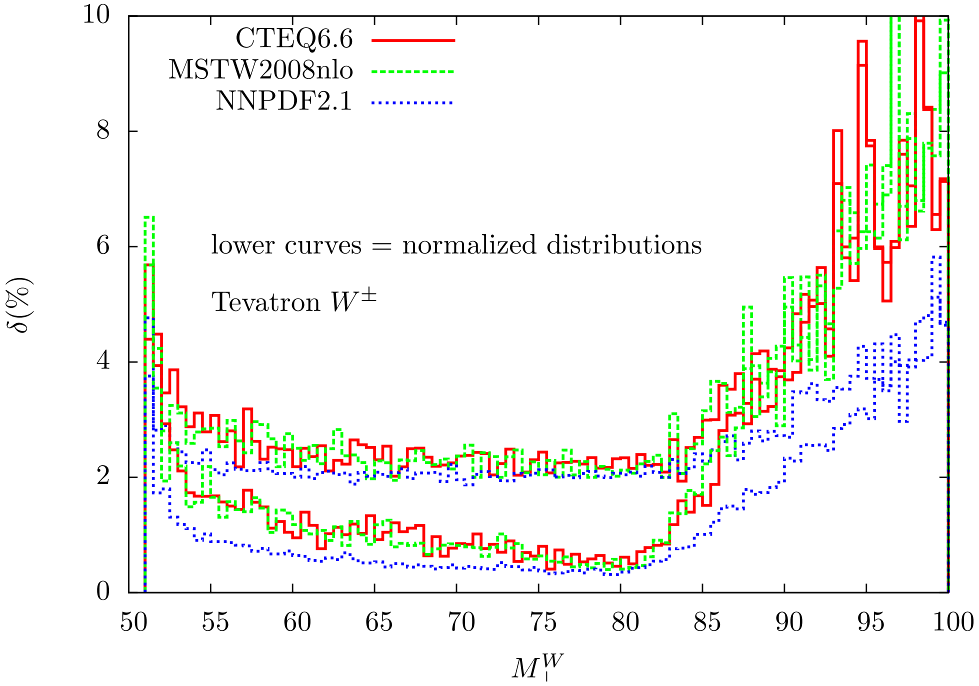


	CTEQ6.6		MSTW2008		NNPDF2.1		
	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$\delta_{\rm pdf}^{\rm tot}$
Tevatron, $W^{\pm}$	80.398 ± 0.004	1.42	80.398 ± 0.003	1.42	80.398 ± 0.003	1.30	4
LHC 7 TeV W^{+}	80.398 ± 0.004	1.22	80.404 ± 0.005	1.55	80.402 ± 0.003	1.35	8
LHC 7 TeV W^{-}	80.398 ± 0.004	1.22	80.400 ± 0.004	1.19	80.402 ± 0.004	1.78	6
LHC 14 TeV W^{+}	80.398 ± 0.003	1.34	80.402 ± 0.004	1.48	80.400 ± 0.003	1.41	6
LHC 14 TeV W^{-}	80.398 ± 0.004	1.44	80.404 ± 0.006	1.38	80.402 ± 0.004	1.57	8

Effects on transverse mass



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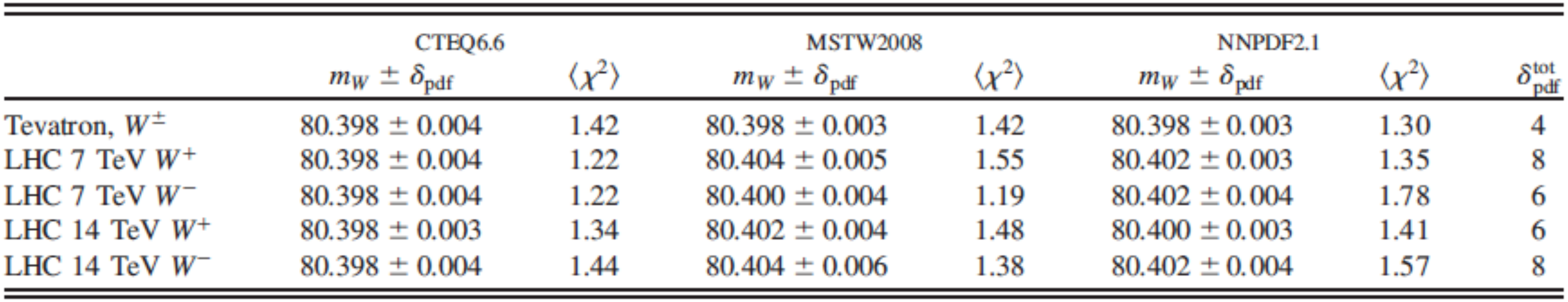

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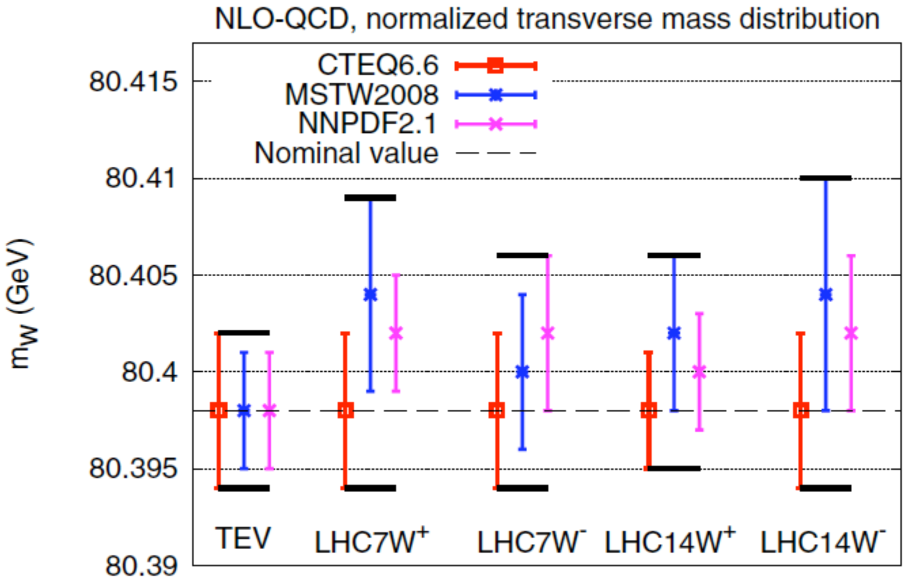
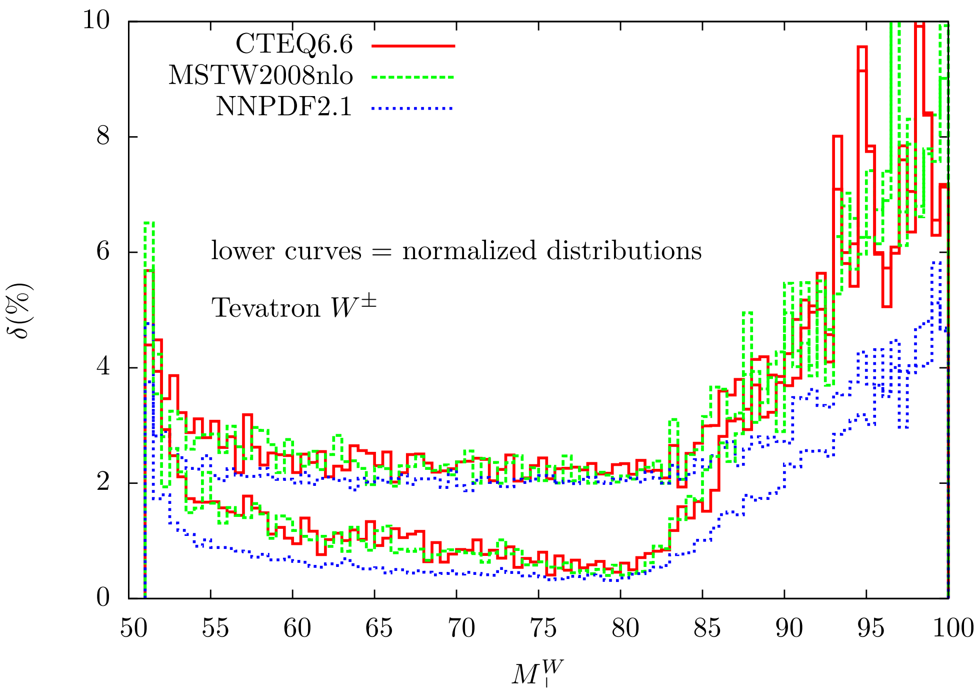

NLO-QCD, normalized transverse mass distribution

Effects on transverse mass



Bozzi, Rojo, Vicini PRD 83, 113008 (2011)

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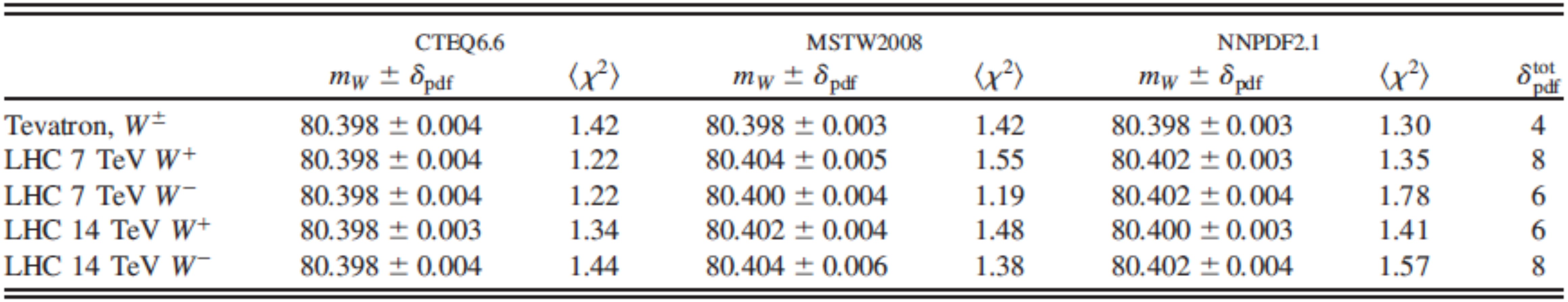

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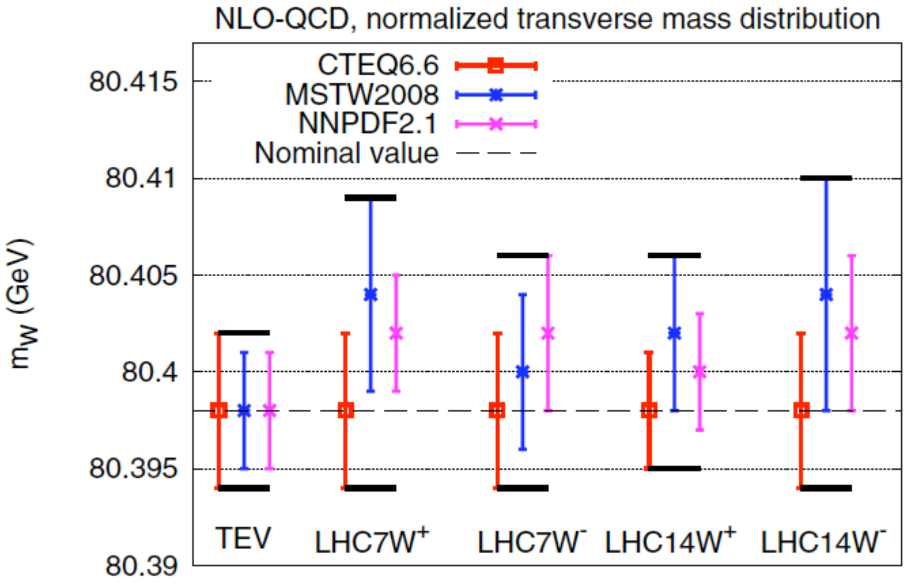
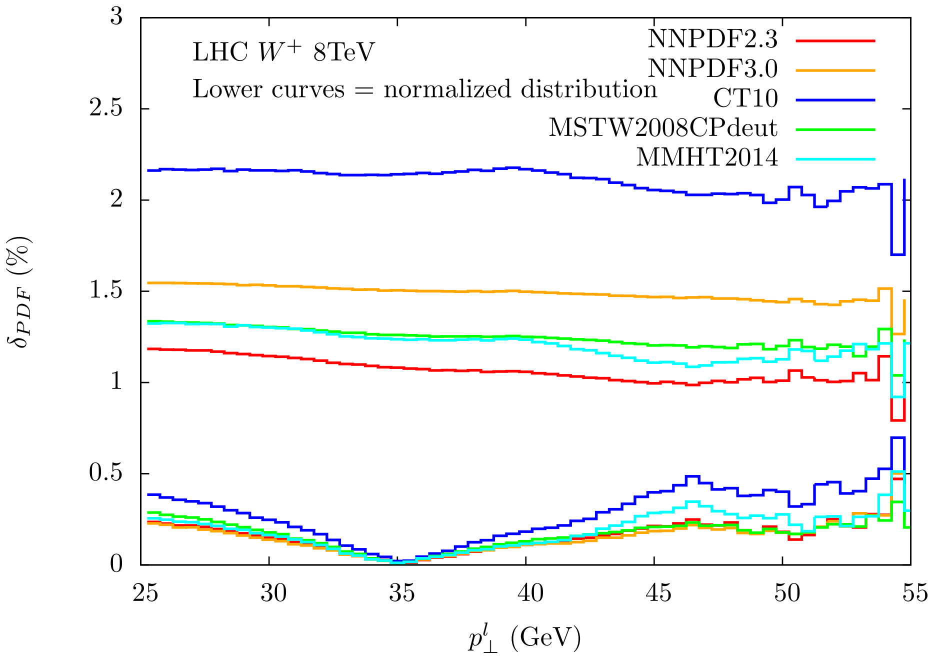


- Accuracy of templates essential: highly demanding computing task!
- For transverse mass distribution, a fixed-order NLO-QCD analysis is sufficient to assess this PDF uncertainty
- PDF error is moderate at the Tevatron but also at the LHC

Effects on lepton p_T

Bozzi, Citelli, Vicini PRD 91, 113005 (2015)



- Conservative estimate of the PDF uncertainty: CC-DY channel alone
- Distributions obtained with **POWHEG+PYTHIA 6.4**
- PDF uncertainty over relevant p_T range almost flat: O(2%)
- Uncertainty of normalised distributions: below the O(0.5%) level (but still sufficient to yield large M_W shifts)

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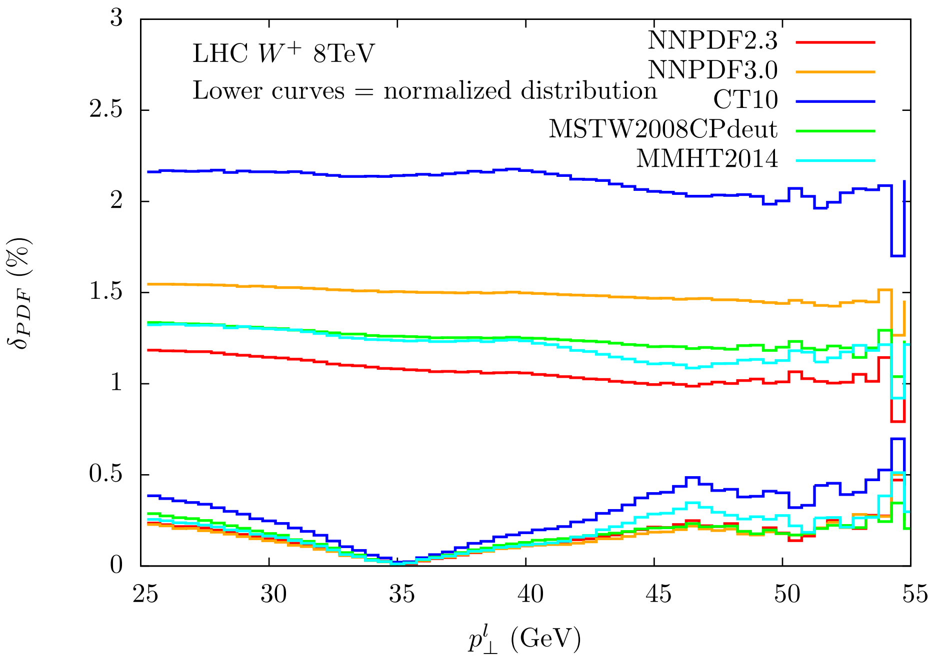

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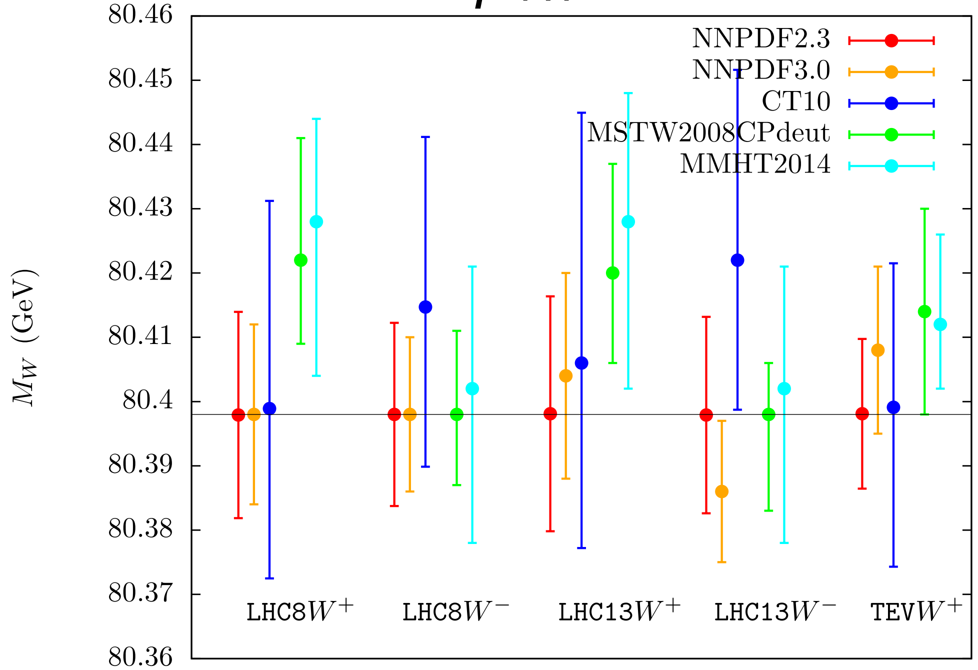
	no $p_\perp^W$ cut		$p_\perp^W < 15$ GeV	
	δ_{PDF} (MeV)	Δ_{sets} (MeV)	δ_{PDF} (MeV)	Δ_{sets} (MeV)
Tevatron 1.96 TeV	27	16	21	15
LHC 8 TeV W^+	33	26	24	18
W^-	29	16	18	8
LHC 13 TeV W^+	34	22	20	14
W^-	34	24	18	12

- Individual PDF sets provide non-pessimistic estimates: ΔM_W ~ O(10 MeV)
- Global envelope still shows large discrepancies of the central values
- p_{TW} cut is relevant

no p_{TW} cut



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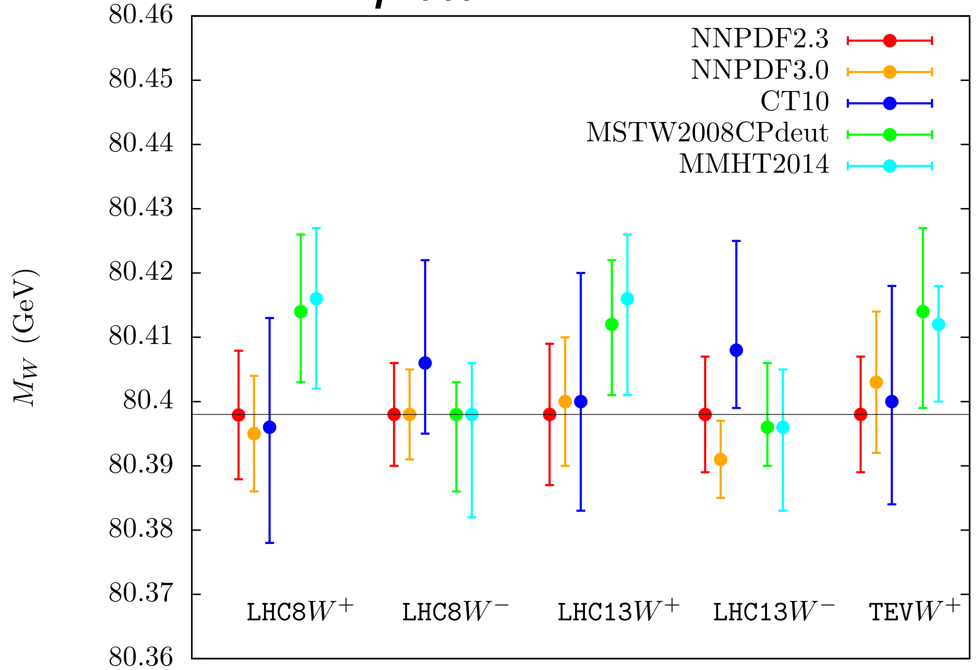

p_{TW} and the modelling of intrinsic-k_T

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- p_{Tl} ⇦ p_{TW} ⇦ QCD initial state radiation + intrinsic k_T (usually, a Gaussian in k_T)

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- Intrinsic *kT* effects measured on *Z* data and used to predict *W* distributions, *assuming universality* Konychev, Nadolsky, PLB 633, 710 (2006)

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different flavour structure

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but

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—> different Gaussian factors for different flavours

$$f_1^a(x, k_T) = f_1^a(x)\, \frac{1}{\pi \langle k_T^2 \rangle_a(x)}\, e^{-\frac{k_T^2}{\langle k_T^2 \rangle_a(x)}}$$

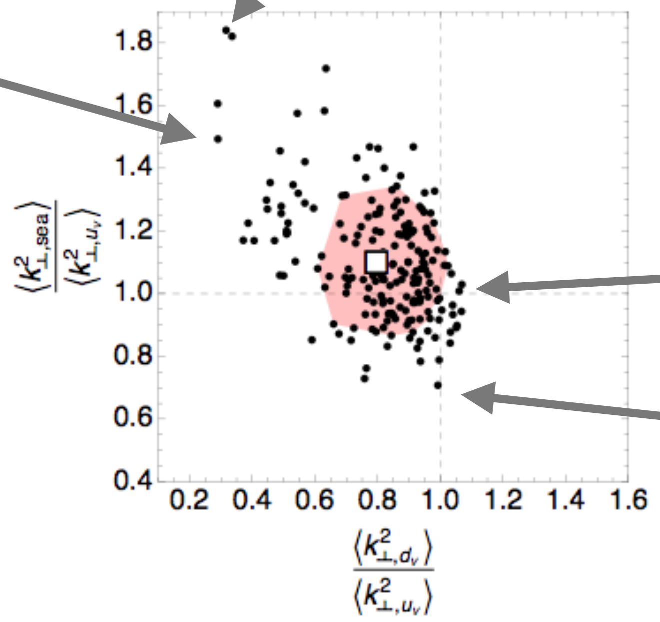
$$\langle k^2_{\perp,\mathrm{u_v}} \rangle \neq \langle k^2_{\perp,\mathrm{d_v}} \rangle \neq \langle k^2_{\perp,\mathrm{sea}} \rangle$$

Flavor and kinematic dependent widths

Extraction of parameters from SIDIS

Signori, Bacchetta, Radici, Schnell, JHEP 1311, 194 (2013)

template fit on HERMES data: distribution of parameters



replica 149
χ^2/dof = 1.87

replica 73
χ^2/dof = 1.70

replica 130
χ^2/dof = 1.77

replica 186
χ^2/dof = 1.38

sea width
> (mostly)
u_v width

point of
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d_v width < (mostly) u_v width

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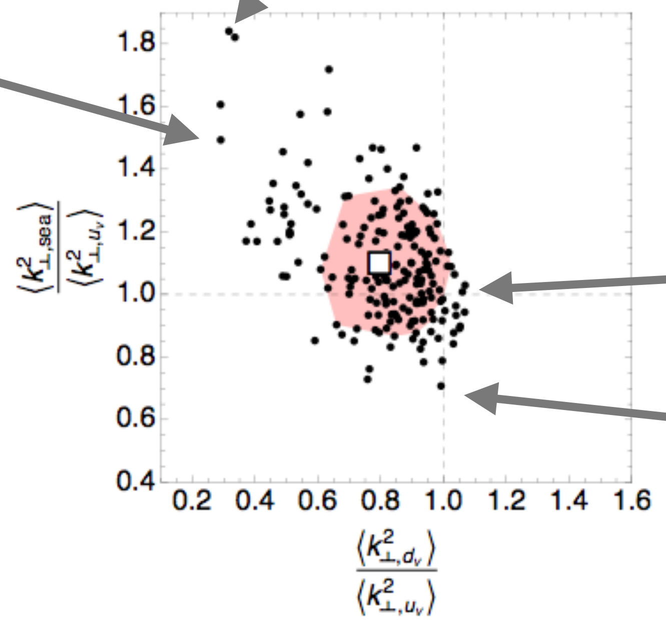

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On average, *sea > u_v > d_v*

Application to W/Z p_T spectrum

Application to *W/Z* p_T spectrum

$$\frac{d\sigma^{Z/W^\pm}}{dq_T} \sim \mathrm{FT} \sum_{i,j} \exp\left\{ - g_{ij}\; b_T^2 \right\}$$

$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$

g comes from 2 TMD PDFs
and ***controls the position of the peak***

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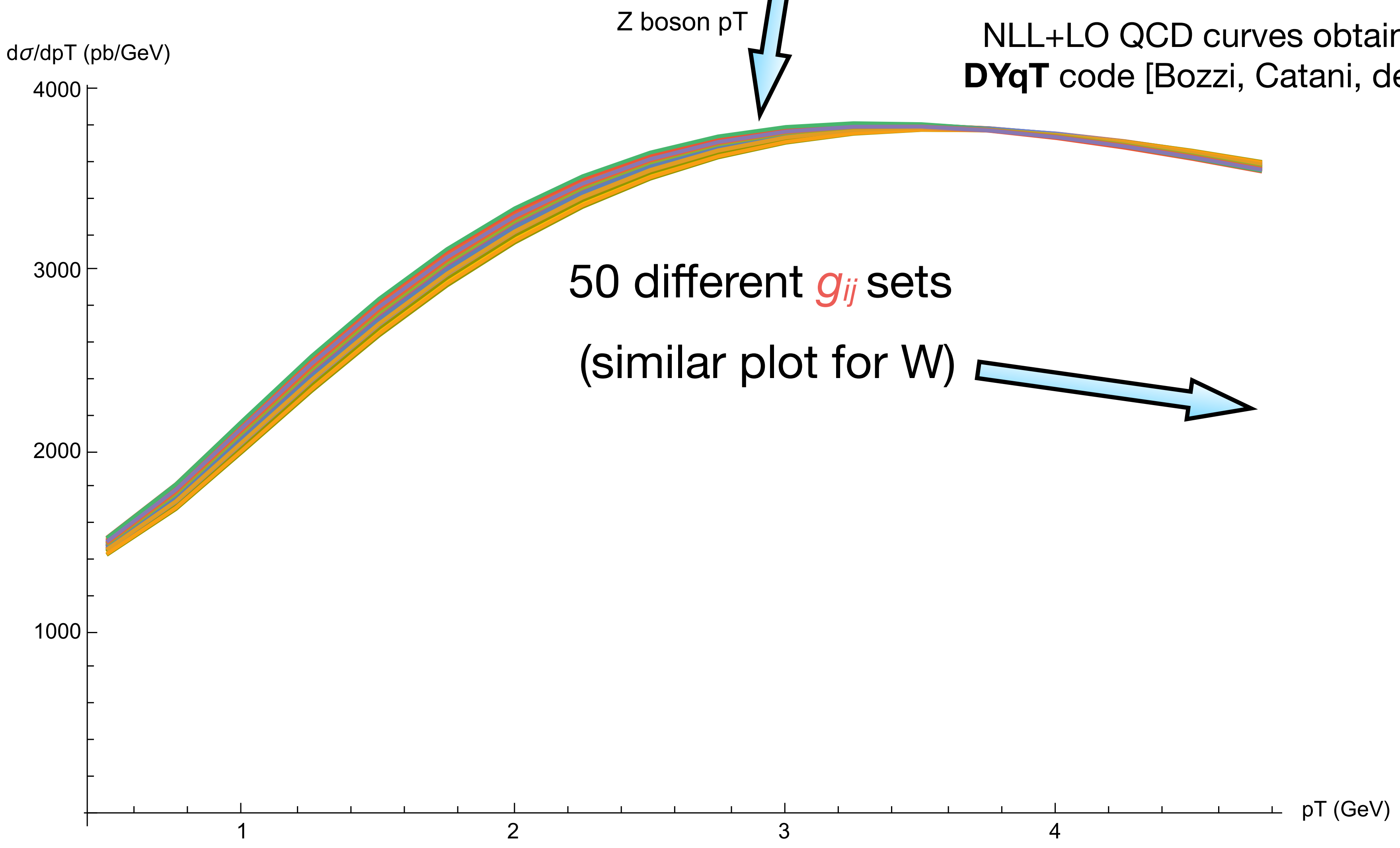
NLL+LO QCD curves obtained through a modified version of the **DYqT** code [Bozzi, Catani, deFlorian, Ferrera, Grazzini (2009,2011)]



50 different g_{ij} sets

(similar plot for W)

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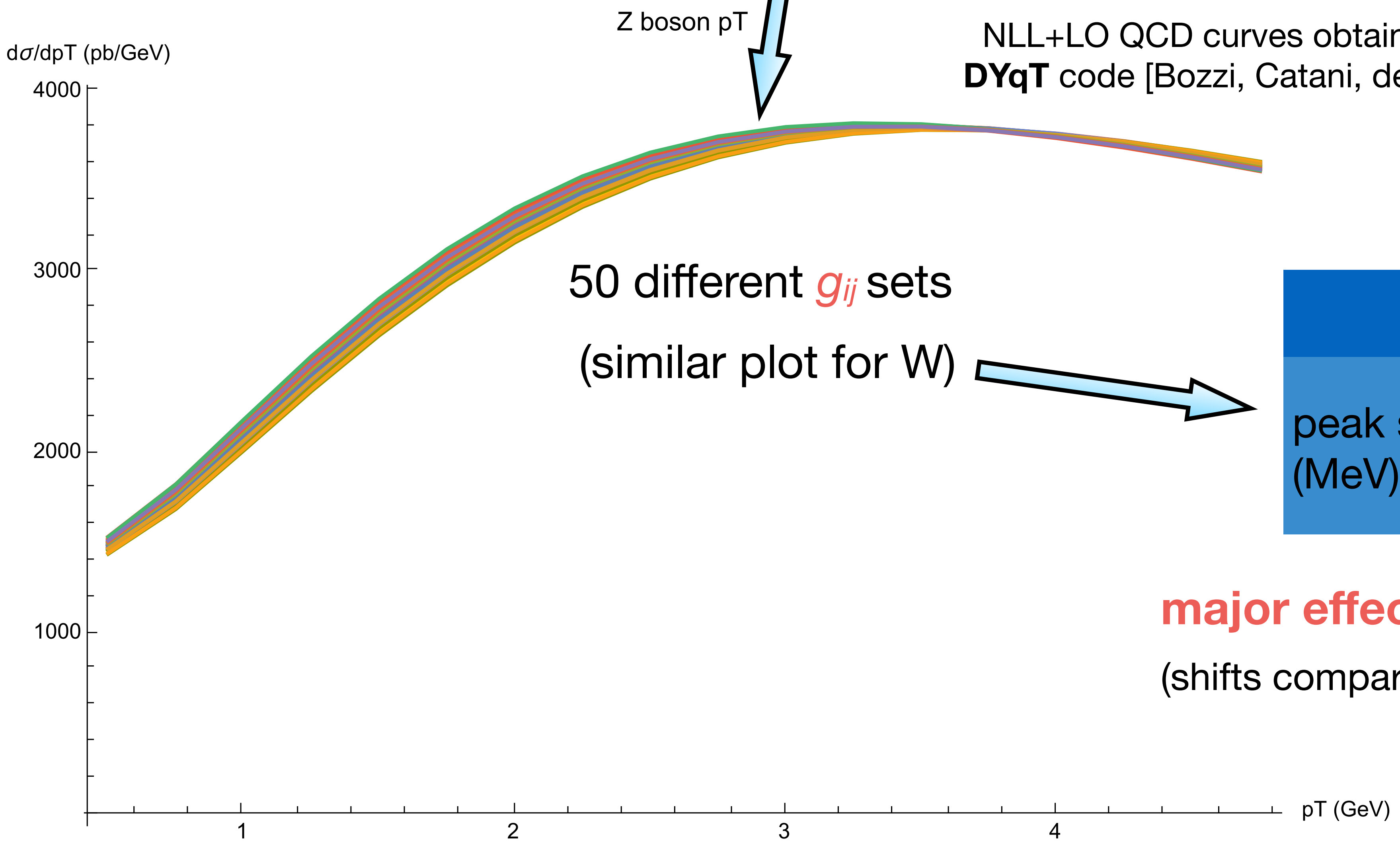

50 different g_{ij} sets

(similar plot for W)

	W+	W-	Z0
peak shift (MeV)	-70 MeV +60 MeV	-60 MeV +90 MeV	< 10 MeV

major effects on W from “Z-equivalent” sets

(shifts comparable to the ones induced by PDFs)

Impact on the determination of M_W: preliminary results

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- **perform the template fit procedure and compute the shifts induced by flavour effects**

NLL+LO QCD analysis obtained through a modified version of the
DYRes code [Catani, deFlorian, Ferrera, Grazzini, JHEP 1512, 047 (2015)]

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➡ these are our **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**
- transverse mass: few MeV shifts, generally favouring lower values (preferred by EW fit)

transverse mass

Set	ΔMW
1	-3
2	-3
3	-1
4	-1
5	-3
6	-1
7	-3
8	-2
9	-2
10	-1
11	-3
12	-2
13	-2
14	-3
15	-3

NLL+LO QCD analysis obtained through a modified version of the **DYRes** code [Catani, deFlorian, Ferrera, Grazzini, JHEP 1512, 047 (2015)]

Impact on the determination of M_W: preliminary results

- Select 15 *flavour-dependent* NP sets for which Δ(Z peak) < 100 MeV and compute *low-statistics* m_T and p_{Tl} distributions

➡ these are our **pseudodata**

- Select a universal (*flavour-independent*) NP parameter and compute *high-statistics* m_T and p_{Tl} distributions for 30 different values of M_W

➡ these are our **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

- transverse mass: few MeV shifts, generally favouring lower values (preferred by EW fit)

- lepton pt & missing pt: quite important shifts (envelope: 21 MeV)

transverse mass

Set	ΔMW
1	-3
2	-3
3	-1
4	-1
5	-3
6	-1
7	-3
8	-2
9	-2
10	-1
11	-3
12	-2
13	-2
14	-3
15	-3

lepton pt

Set	ΔMW
1	2
2	2
3	2
4	-4
5	-11
6	-4
7	-14
8	1
9	-15
10	5
11	1
12	-1
13	6
14	-3
15	0

missing pt

Set	ΔMW
1	-6
2	-6
3	-3
4	-13
5	-15
6	-13
7	-15
8	-4
9	-15
10	1
11	-4
12	-4
13	-5
14	-10
15	-6

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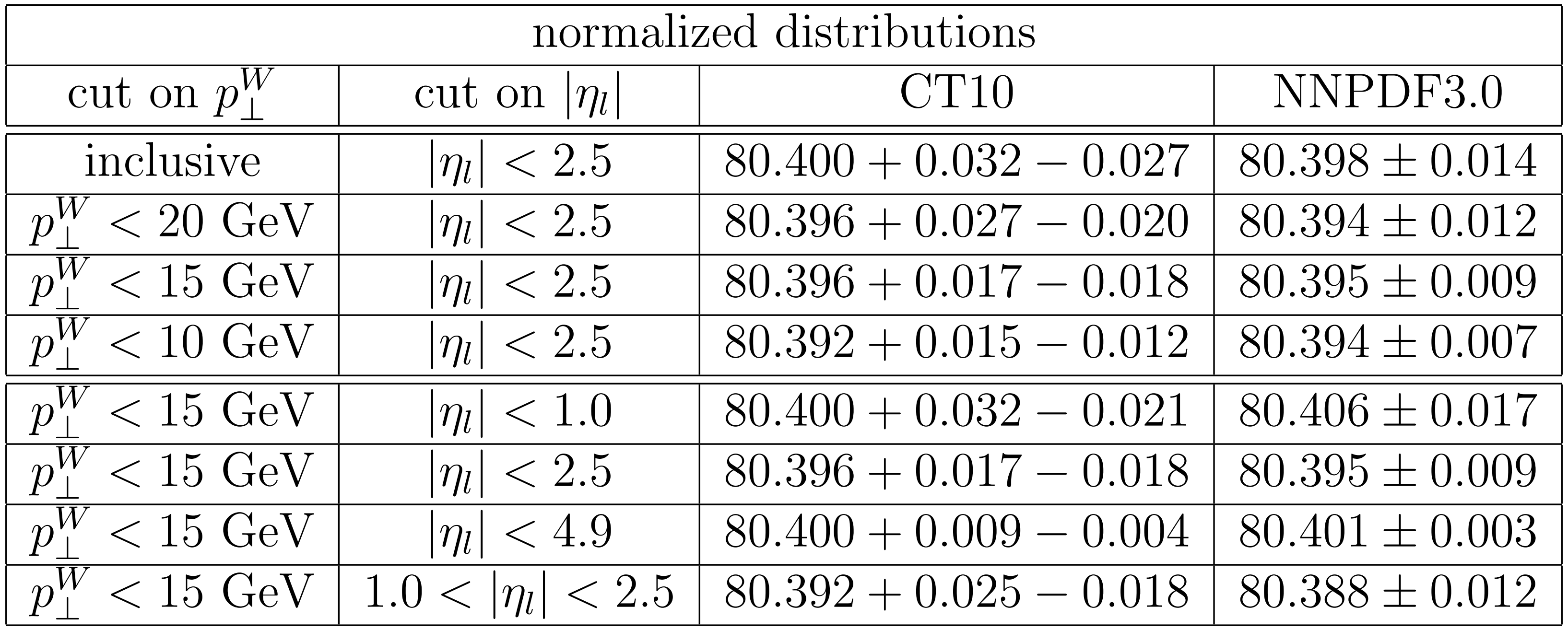
- *An especially blended flavour paper soon on your screen by your favourite flavorists!*

Backup slides

Acceptance cuts: interesting insights

Bozzi, Citelli, Vicini PRD 91, 113005 (2015)



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cut on $p_\perp^W$	cut on $\|\eta_l\|$	CT10	NNPDF3.0
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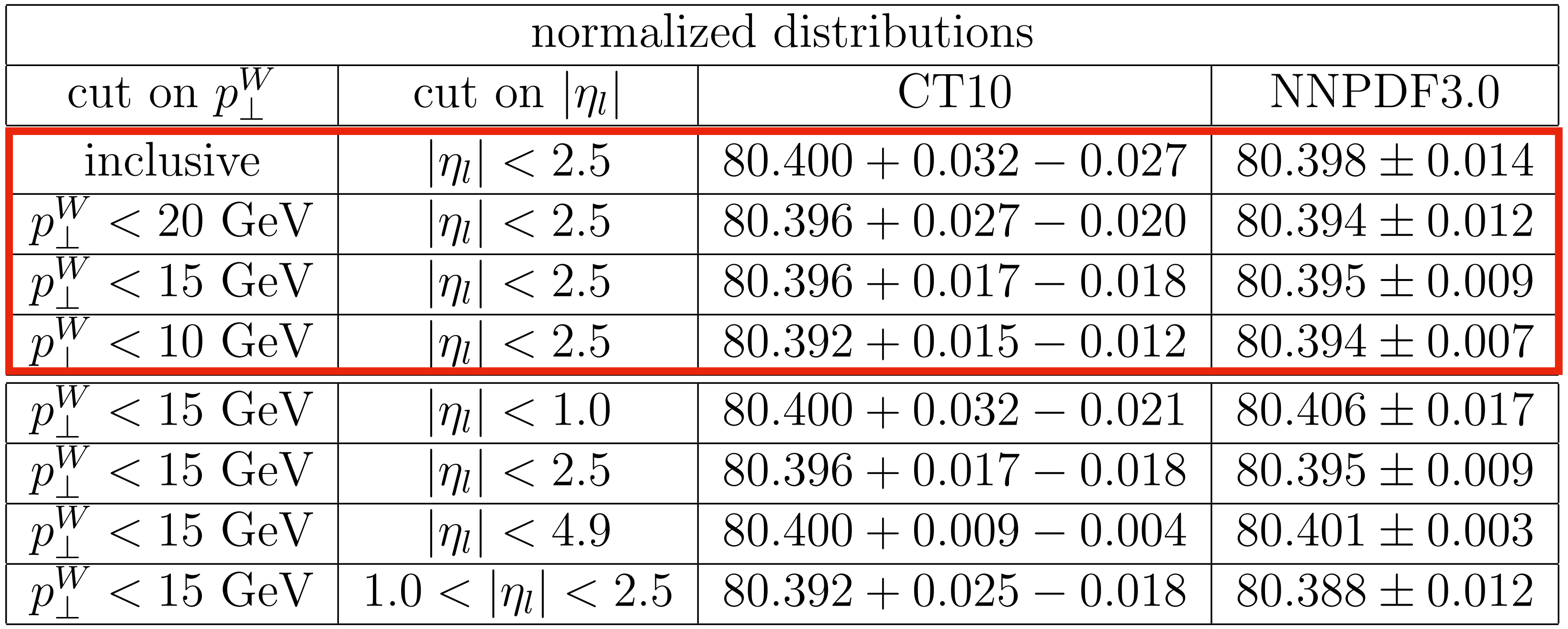

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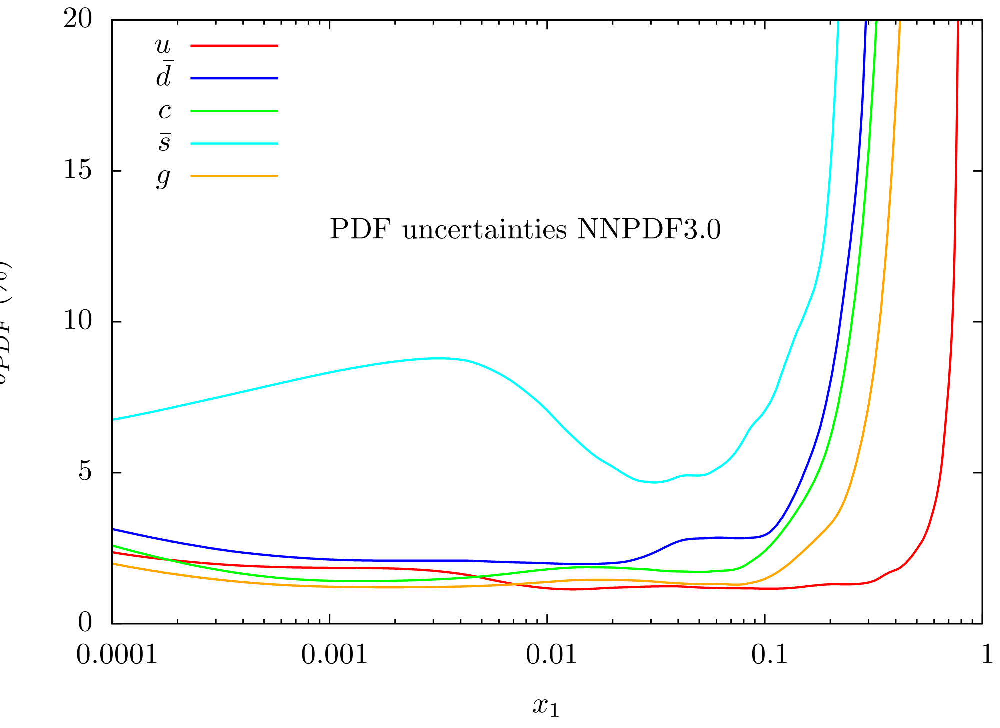

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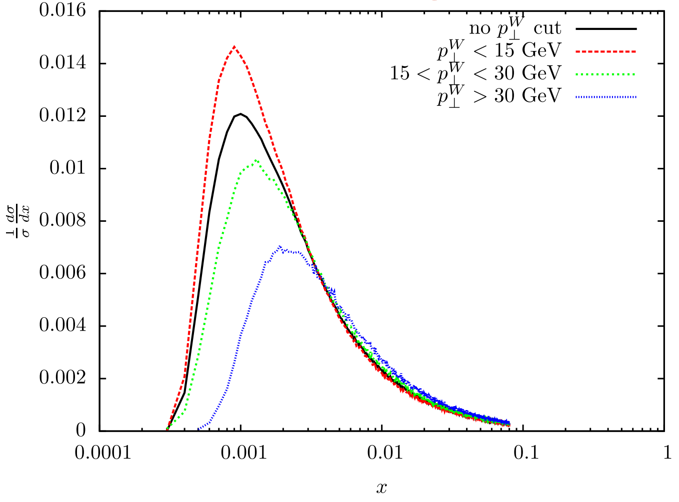

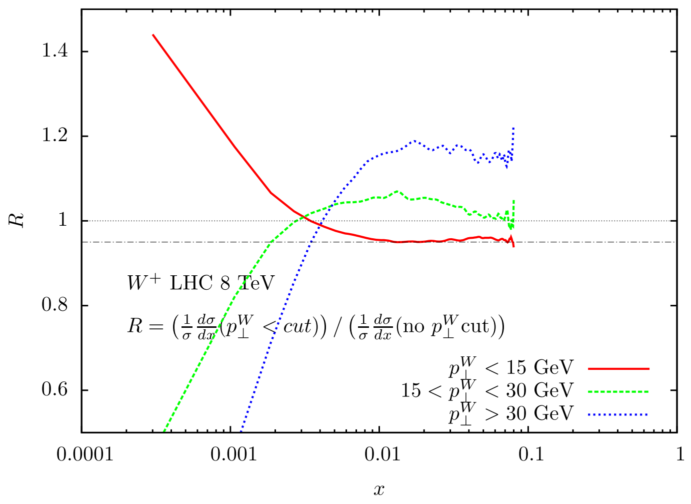

suppression of the large-*x* region

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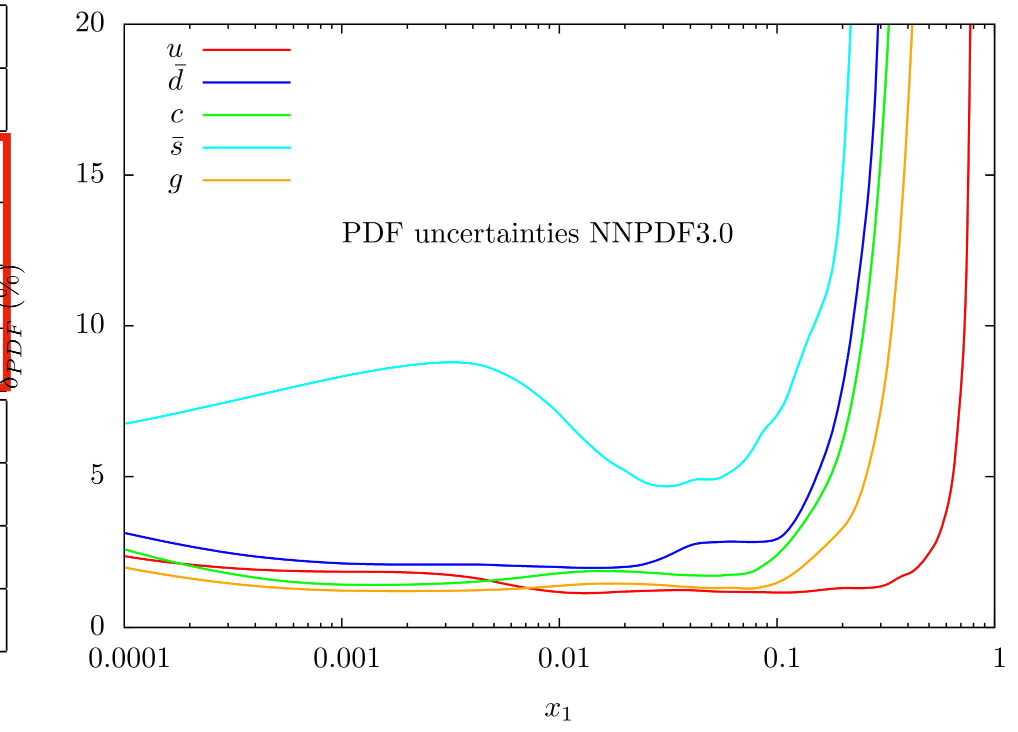

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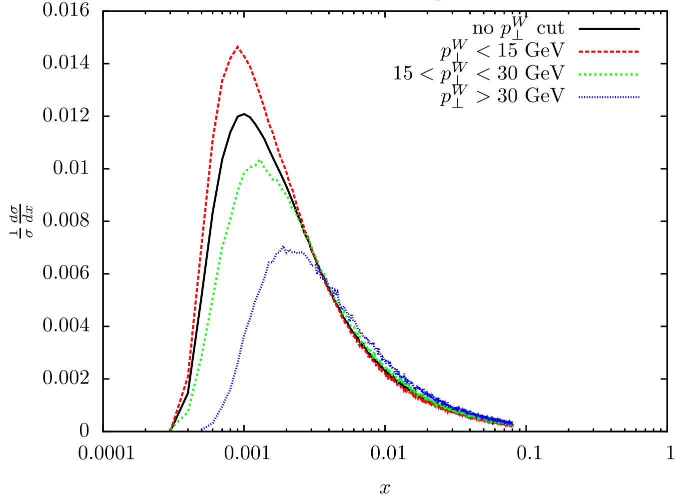

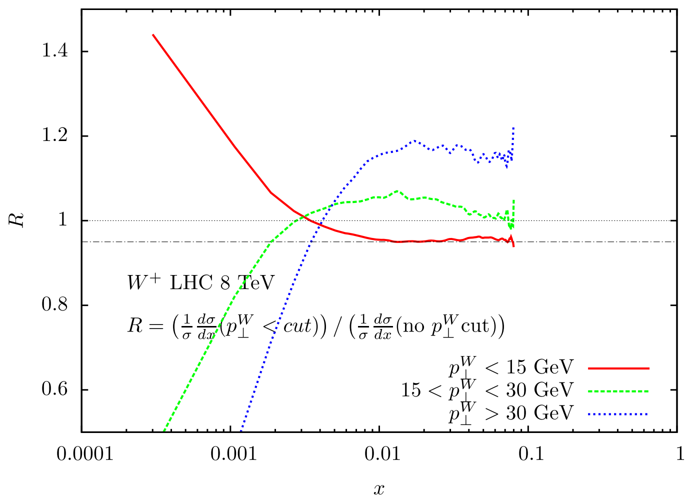

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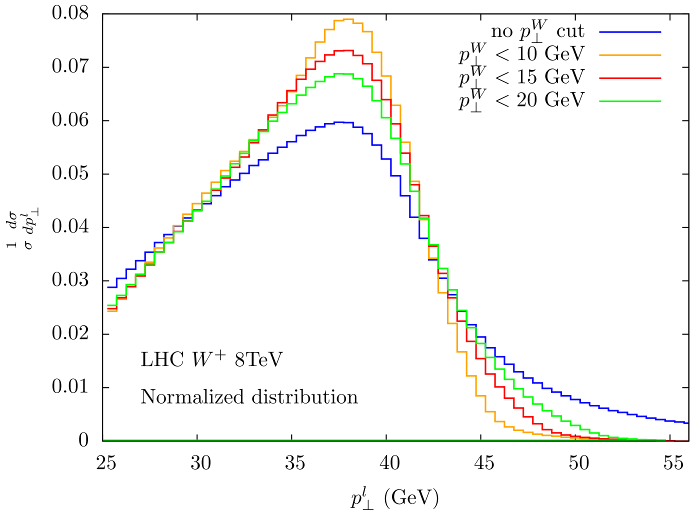
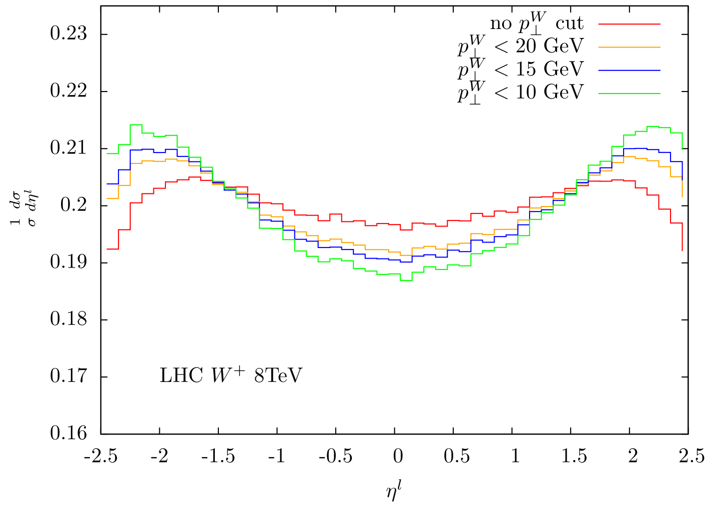


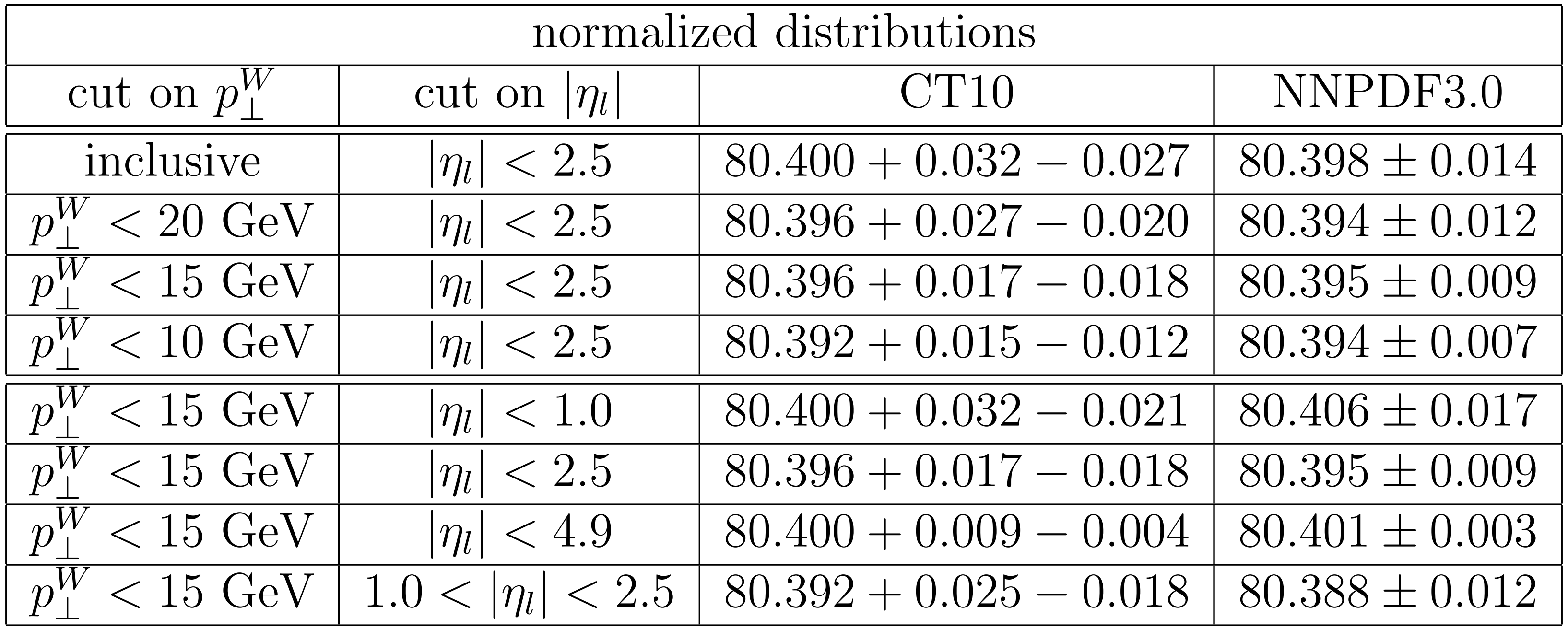


steeper shape of the p_{Tl} distribution

enhancement of high rapidity regions

Acceptance cuts: interesting insights

Bozzi, Citelli, Vicini PRD 91, 113005 (2015)



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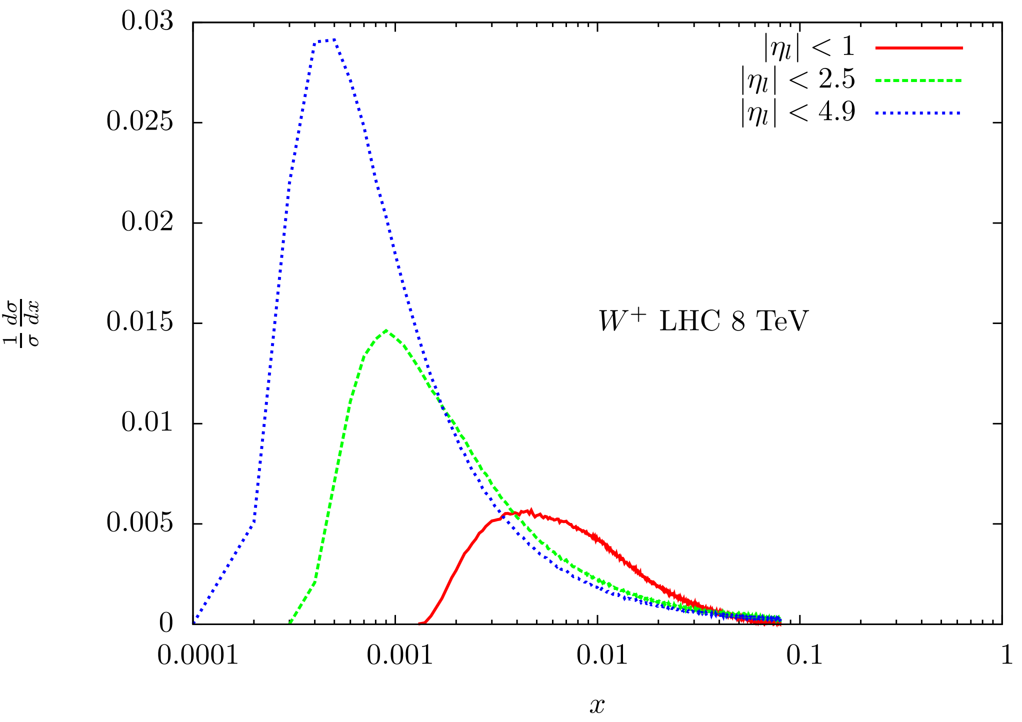

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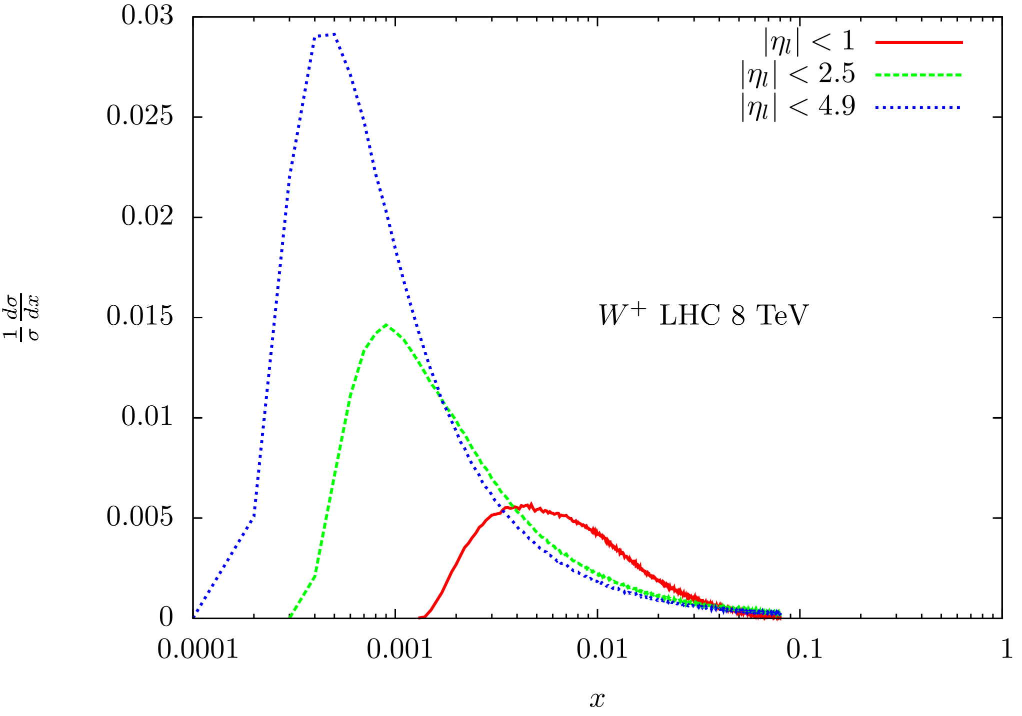

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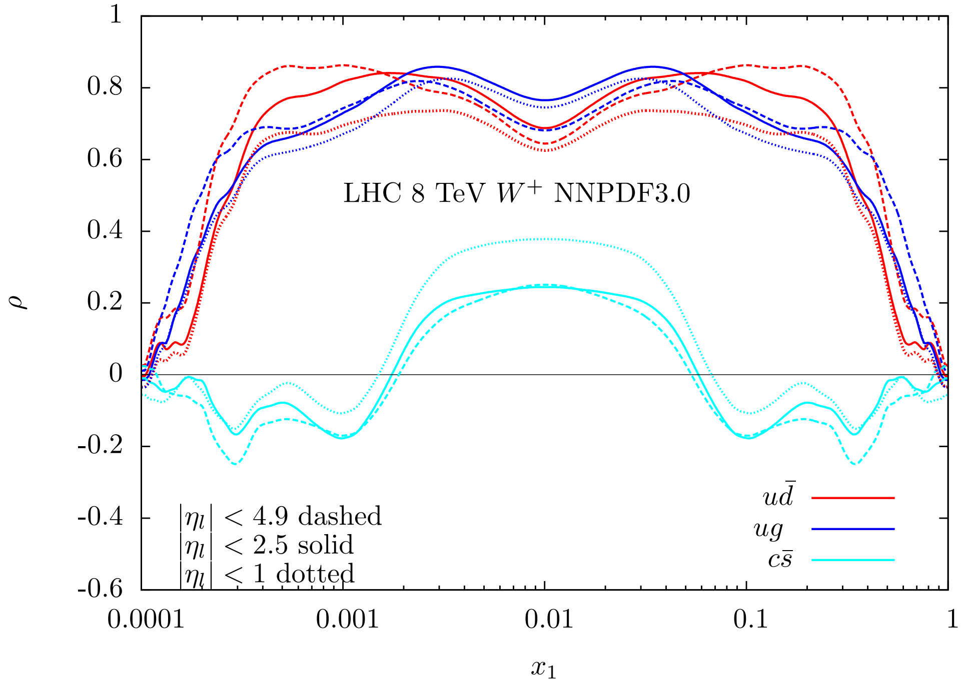
correlation of parton luminosities within the 40.5 GeV p_{Tl} bin



$$\rho(x,\tau) = \frac{\langle \mathcal{P}_{ij}(x,\tau)\,\frac{d\sigma}{dp_\perp^l}\rangle - \langle \mathcal{P}_{ij}(x,\tau)\rangle\langle\frac{d\sigma}{dp_\perp^l}\rangle}{\sigma^{\rm PDF}_{\mathcal{P}_{ij}}\,\sigma^{\rm PDF}_{d\sigma/dp_\perp^l}},$$

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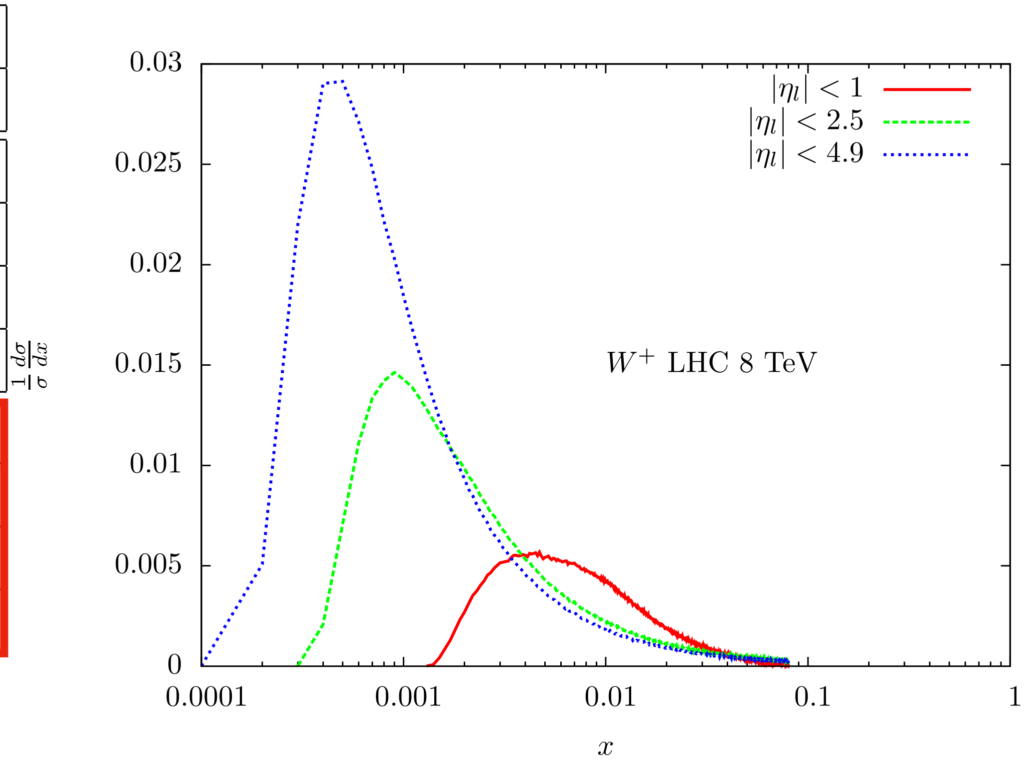

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- PDF sum rules → *non trivial compensations between different rapidity intervals among different flavours*

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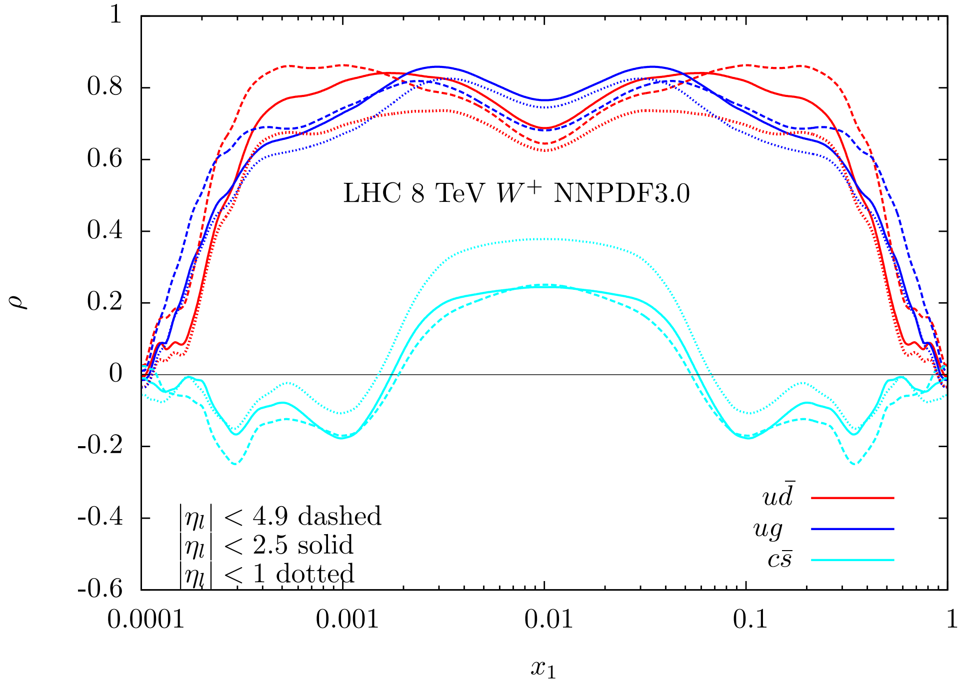

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